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Mesure de la production de dibosons WZ auprès du LHC avec l'expérience ATLAS.

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To My Father

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Introduction

In the will of understanding the constituents of our universe, one of the most basic questions the human being once asked and tried to answer was: what are things made of ?

The understanding of the basic constituents of matter has changed over time in human history. The concept of the classical elements started around the sixth century BC with Thales and his successors Anaximander and Anaximenes. The idea of the atom was first proposed in the fifth century BC by the Greek philosopher Demokritos who introduced the idea of the indivisible constituents of matter. In the fourth century BC a proposal of the basic elements of the universe was given by the theory of Empedocles where he declared that anything consists of four elements: air, fire, earth, and water. It took humanity more than a millennium and a half to put a first scientific theory for the definition of an element. In 1789, Antoine Lavoisier has defined an element as a substance that could not be divided into further pieces and in 1869 the Russian chemist Dimitri Mendeleev classified these elements according to their atomic properties in a table which we are familiar today with as the “periodic table”. With this revolution and the continuous evolving of science, today in the twenty first century we have been able to classify the basic elements of matter in a different way. The idea of the “elementary” has gone far beyond what it was previously known. With large machines like the Large Hadron Collider (LHC), we are able to explore the “infinitely small” and look through today’s elementary particles. After long chain of studies through years, science has converged to group the elementary particles and build a mathematical model according to their properties, the Standard Model (SM). The Standard Model of particles physics contains particles called quarks, leptons, and bosons. These particles can interact through the electromagnetic, weak, and (or) strong interactions. The particles of the Standard model are split into two categories, “matter” particles and “force” particles, where the “force” particles mediate the interaction between the “matter” particles.

Among the particles predicted by the SM, this thesis will present measurements concerning the WZ bosons production in pair. W and Z bosons are the mediators of the Weak interaction. Their production as a pair is predicted by the SM. Hence this thesis will mainly provide the measurement of the WZ pair production cross section with the latest experimental data from the ATLAS experiment and with the highest precision with respect to previous measurements.

Chapter 1 will present a theoretical introduction to the SM of particle physics. It will also present the phenomenology of proton-proton collisions at the LHC as well as the WZ pair production mechanisms. Finally, a theoretical outlook about physics beyond the SM with diboson will be explained, through the effective field theory approaches.

Chapter 2 will explain the Large Hadron Collider machine and its running during the years 2011 and 2012. It will give technical details about the ATLAS detector and its sub-components. Also in this chapter, the reconstruction inside the detector of particles, used to identify leptonic decays of produced WZ system, such as electrons, muons, and neutrinos will be explained.

A part of the work of this thesis was dedicated to align in time the ATLAS Liquid Argon Calorimeter (LAr), contributing to improve the quality of the data collected during the 2012 LHC running period. The procedure and implementation of this time alignment of the LAr calorimeter are presented in chapter 3.

Chapter 4 presents the steps of the selection of WZ diboson events. It presents the selection criteria and the motivation behind them. Also in this chapter, the description and extraction of the background events contributing in this selection are detailed. Finally, the yields of obtained events and kinematic distributions are presented to control the agreement between data and Monte Carlo predictions.

Chapter 5 explains the extraction of the $W^\pm Z$ production cross section in the total and fiducial phase spaces. The measurement starts in the fiducial phase space, which represents a restricted region of the phase space very close to that where the reconstruction of events takes place. This measurement is then extrapolated to the total phase space in order to facilitate the comparison of the results with those from other experiments. Then, the first measurement, using the data collected in 2012 by ATLAS, of the W^+Z to W^-Z cross sections ratio is presented.

Chapter 6 presents measurements of the normalized differential cross section of the WZ production in the fiducial phase space as a function of four different kinematic variables, p_T^Z , p_T^W , M_{WZ} , and $y_Z - y_{W,l}$. The aim is to observe in more details the comparison of the kinematic spectra with respect to predictions of the Standard Model, as the presence of new physics can affect the shape of these spectra.

Finally, this thesis will be closed with a summary of all the presented results and an outlook to the future expectations from the LHC and the ATLAS experiment.

Chapter 1

Theoretical considerations

This chapter will present a summary of the theoretical considerations needed for the measurements presented in this thesis. Section 1.1 presents a summary of the formalism of the Standard Model of particle physics. Section 1.2 introduces the phenomenology of the $p - p$ collisions and discusses the calculation of the WZ dibosons production at the leading and next to leading order in QCD. It also presents the different MC generators predicting the WZ cross section and the theory uncertainty on them. Finally, section 1.3 summarizes the physics scenarios involving dibosons, beyond the SM. Approaches using an effective field theory are presented to estimate anomalous triple gauge couplings.

1.1 The Standard Model: a gauge field theory

Particles that are recognized as elementary in our days are very few and countable. These particles are believed to be indivisible or do not have any constituents. The Standard Model (SM) [1] [2] [3] of particle physics is the only mathematical model that groups all experimentally observed elementary particles, describes their behavior and their interactions. In this model “standard particles” interact via mediators or “force particles”. Therefore the SM groups the particles in two categories: the fermions and the bosons. Where fermions are the “standard particles” and bosons the “force particles”. Fermions have a spin that is an odd multiple of $\hbar/2$. Quarks and leptons are categorized as fermions. Quarks interact via the strong interaction and carry a color charge. They also have a fractional electric charge with values of $\pm 1/3$ or $\pm 2/3$. Leptons such as electrons, do not undergo strong interaction. The charged leptons are subjected to the electromagnetic interaction and carry an electric charge of ± 1 . All SM fermions interact through the weak interaction characterized by the weak isospin charge which is the weak quantum number equivalent to the electric (color) charge of the electromagnetic (strong) interaction. Fermions with negative chirality, also called left-handed fermions, have weak isospin values of $\pm 1/2$. Whereas right-handed fermions with positive chirality have a weak isospin that is zero.

The bosons of the SM have a spin that is multiple of $\hbar$ and they are the mediators of weak, strong, and electromagnetic interactions. The photon is massless and mediates the electromagnetic interaction. The gluon, also massless, is responsible for the strong interaction, and the force carriers of the weak interaction are the massive $W^\pm$ and Z^0 gauge bosons. The last particle that completes the standard model is the Higgs boson, that explains the mechanism with which $W^\pm$ and Z^0 bosons became massive. The Higgs boson was a missing piece from the SM for long time after its prediction in 1964 simultaneously by Peter Higgs, Francois Englert, and Robert Brout. On July 4 2012, the ATLAS and CMS experiments of the LHC have observed a new resonance around an invariant mass of 125 GeV. This resonance was consistent with the predicted mass of

the SM Higgs boson. After measuring the properties of this particle (such as its spin that was predicted to be 0) it was deduced that this new particle's properties match the SM Higgs particle ones'.

1.1.1 Fundamental interactions and particles

Four fundamental forces govern the laws of nature. The first one, discovered by Isaac Newton in the seventeenth century, is the gravitational force. Isaac Newton followed the work of Galileo Galilei and founded today's classical mechanics based on this discovery. The gravitational force can extend to infinity. It depends on the masses of the bodies interacting and it follows a square inverse law as a function of their distance.

Until the 19th century, electric and magnetic forces were thought to be different from one another. In 1873, James Clerk Maxwell showed in a unique publication [4] that these forces are different aspects of the same force, the electromagnetic force. At low energies, the coupling constant of this interaction is given by the fine structure constant $\alpha \approx 1/137$. The electromagnetic force is the second fundamental force of nature. It can also extend to infinity following an inverse square law that depends on the distance of electrically charged bodies.

More recently in the 20th century, Enrico Fermi proposed for the first time a theory of the weak interaction by explaining the beta decay. Radioactive β decay of subatomic particles are the results of the weak interaction. This force is called weak because its field strength over a given distance is many orders of magnitude lower than that of the strong and electromagnetic forces. However at energies lower than the mass of the gauge bosons, the weak coupling constant $\alpha_w = g_w^2/4\pi \approx 1/30$ with $g_w^2 = 8G_F M_W^2$, G_F being the Fermi's coupling constant, is of the same order of magnitude as the electromagnetic coupling constant.

Until the 1970s, physicists could not explain the reason for which the atomic nucleus was held together and not falling apart, knowing that it is composed of protons with positive charge and chargeless neutrons. Positive charges should have repelled based on the laws of electromagnetism. However, if that was the case our existence today would not have been possible. Therefore, a force with a stronger strength was postulated that had to overcome the electromagnetic repulsion, holding the nucleus of an atom together. This force was called the strong force and it represents the fourth and last fundamental force of nature. Its strength exceeds that of all the other forces and it acts on a very short range of about 10^{-15} m.

Except the gravitational interaction, all other interactions are well described and grouped by the SM. There are other models beyond the SM, such as SuperSymmetry (SUSY) that give an explanation of all fundamental interactions. However, none of the particles composing this model are yet observed. This leads to the fact that the SM, even that it misses the gravitational force, is today's only model in which all particles are observed.

Particles that are called elementary or fundamental are particles which are not composite or at least experiments were not able to break them down to observe directly their components. Until the years of 1930s, protons and neutrons were thought to be elementary and today it is well known that they have sub-components, particles that we call quarks.

The SM of particle physics groups the elementary particles according to their properties and similarities. Figure 1.1 shows the particles belonging to this model.

The SM contains six quarks, six leptons, and four gauge bosons. Quarks and leptons belong to the family of fermions, being spin half particles. Fermions follow the Fermi-Dirac statistics and according to the Pauli exclusion principle they cannot occupy the same quantum state twice.

The up and down quarks are the lightest ones, they are followed by the charm and strange quarks which have heavier mass and finally the bottom and the top quarks are heavier than

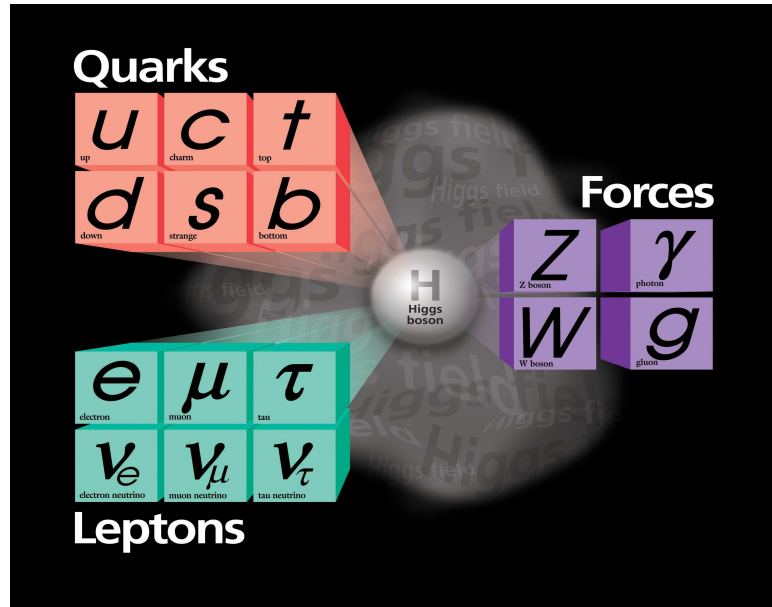


Figure 1.1: The building blocks of the Standard Model of particles physics [5].

all other quarks with the top the heaviest among all. Quarks are electrically charged particles with fractions of $1/3$ or $2/3$. They can decay to one another through weak interaction under the law of four-momentum conservation. Besides the electric charge, quarks carry a color charge. According to Quantum Chromodynamics (QCD) quarks can possess one of the three primary colors; red, green, or blue. The color property can decide how quarks can be bound to each other. Quarks with a color charge can be bound only to quarks with anti-color (for example: green, anti-green). In case a bound system is formed with more than two quarks, the condition is to have a combination of colors that will give white. QCD explains the interaction between quarks as strong interaction mediated by gluons. Gluons themselves carry color charge and they are always exchanged between quarks. When quarks emit or absorb gluons their color is changed depending on the color of the emitted gluon. This continuous process of gluon exchange, leads to an asymptotic freedom meaning weaker interaction between quarks when they come closer. However, the interaction between two quarks is very strong when these two are pulled apart. Only above a certain energy thresholds, pairs of quarks and anti-quarks will be created forming new hadrons. Therefore quarks do not exist in non bound states, a phenomenon that is called a color confinement.

The family of leptons is composed of electrons, muons, taus, and three neutrinos with different leptonic flavors. The first three leptons carry an electric charge and mass while neutrinos are chargeless and considered massless in the SM¹.

In the world of quantum fields, forces are manifested through the exchange of particles. These particles that will carry the fundamental forces are called the bosons. The bosons are spin zero or integer multiples of $\hbar$ particles and they follow the Bose-Einstein statistics, where a particle can occupy the same quantum state many times. Because of this property of bosons, when two bosons of the same type are exchanged during an interaction, the result of the interaction will remain intact. This is the reason we call them force carriers and each of the fundamental forces has its own mediating particle. The massless photon is the mediator of the electromagnetic force.

¹In the years when the SM was written, the neutrinos were thought to be massless particles. In the following years neutrinos turned out to have mass. Even though the SM considers them massless, mathematically it is not complicated to incorporate the mass of neutrinos in the model.

The gluon, also massless, mediates the strong interaction. Finally the W and Z bosons mediate the weak interaction. These last two bosons differ from other mediators because they are massive. They can interact and decay to other lighter particles. Being relatively heavy, they have a very short lifetime and decay relatively fast.

Why the W and Z bosons are massive and why do they decay ? This will be explained in the following paragraphs.

1.1.2 Gauge Theories

In general a Lagrangian will quantify the configuration of an object in movement. In classical mechanics it is defined as the difference between the kinetic energy of an object and its potential energy. In quantum field theory, the definition of the Lagrangian is similar except that it is introduced as a density and postulated as the free propagation of the field and the interaction of the field with other fields or with itself. Since in particle physics, all particles are present due to excitation of fields then the last definition of the Lagrangians will be considered in this thesis.

A theory is called a gauge theory when the Lagrangian is invariant under a local gauge transformation. Gauge transformations are represented by the symmetry groups or Lie-groups [6].

For each symmetry group, a vector field can be associated so that when it is transformed according to the given symmetry group and then substituted in the Lagrangian of an interaction, this last will remain invariant. The gauge particles are then the products of the quantization of the gauge fields.

A perfect example of a gauge theory is the Quantum Electrodynamics (QED) that is invariant under the $U(1)$ symmetry group. $U(1)$ is the unitary abelian (commutative) group representing the circle group. The Lagrangian of the QED, using the transformation of a field representing an electrically charged particle under the unitary group, can be written as:

$$L = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}\gamma^\mu\partial_\mu\psi - m\bar{\psi}\psi + e\bar{\psi}\gamma^\mu A_\mu\psi, \quad (1.1)$$

where

$$F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu. \quad (1.2)$$

$F_{\mu\nu}$ is the electromagnetic field strength tensor, ψ and $\bar{\psi}$ represent the fields of the electrically charged particles, γ_μ are the Dirac matrices, and A_μ represents covariant four-potential of the electromagnetic field generated by the electron. The first and second terms in this Lagrangian represent the kinetic term of the free electromagnetic field and free fermion, respectively. The last two terms represent the free fermion of mass m at rest and the interaction of the fermion with the electromagnetic field. As we see in the equation, there is no mass term corresponding to the A_μ field which represents the photonic field, therefore the photon is shown to be massless. Similarly to the QED approach, the Quantum Chromodynamics (QCD) Lagrangian was shown to be invariant under the $SU(3)$ group transformation. Considering a quark color field that is invariant under the $SU(3)$ transformation, the QCD Lagrangian can be written as [7]:

$$L = \bar{q}(i\gamma^\mu\partial_\mu - m)q + g(\bar{q}\gamma^\mu T_a q)G_\mu^a - \frac{1}{4}G_{\mu\nu}^a G_a^{\mu\nu}, \quad (1.3)$$

where

$$G_{\mu\nu}^a = \partial_\mu G_\nu^a - \partial_\nu G_\mu^a - gf_{abc}G_\mu^b G_\nu^c. \quad (1.4)$$

This form of the Lagrangian is different than the QED one because the $SU(3)$ Lie group is non-abelian thus non-commutative. It leads to the existence of some extra factors that take into consideration the anti-commuting terms. However it has the same structure of the QED Lagrangian with the middle term of equation 1.3 representing the interaction of the G_μ^a field to

the quarks. The corresponding particle that will rise up as the result of the quantization of the theory are then the 8 gluons that similarly to the photon have no mass term appearing in the Lagrangian. The appearance of a mass term in both of the QED and QCD Lagrangians destroys the local gauge invariance, also experimental measurements have shown that photons and gluons are indeed massless.

Finally the fundamental interaction that remains to be explained in this section is the weak interaction. Theorists have tried to take the same approach as for QED and QCD using gauge transformations and invariance of the Lagrangian. However, as we have seen for the cases of QED and QCD, gauge invariance the way it is applied leads to the appearance of massless gauge bosons. This contradicts with the experimental fact proving that the weak interaction mediators, the W and Z bosons, are massive. Therefore, a different approach needs to be taken in order to describe the mass of these bosons. This approach will be the spontaneous symmetry breaking that will be explained in the next paragraph.

1.1.3 Spontaneous Symmetry Breaking

There are two ways to generate mass to a particle. Either by introducing a mathematical mass term in the Lagrangian or breaking the symmetry. In the case of the QED and QCD we didn't introduce mass terms neither we broke the symmetry because there was no need to that, the photon and the gluon are massless particles. However, in the case of weak interaction the W and Z bosons are massive. Introducing a mass term in the Lagrangian is prohibited as it destroys the local gauge invariance. The only way to give mass to these particles is by breaking the symmetry.

What does it mean breaking the symmetry ?

It can be illustrated in the example of a ferromagnet. The Lagrangian of this system is invariant under the $O(3)$ group that represents the rotation in space. Above the Curie temperature the spin of all elementary particles are randomly oriented forming thus a symmetric ground state. Below the Curie temperature the spin of the particles are all aligned in a given direction and the rotational symmetry is spontaneously broken and a new symmetry is defined by the random direction of the magnetization.

In particle physics, the spontaneous symmetry breaking is the reason why the W and Z bosons have mass. Mathematically, it can be demonstrated by considering the Lagrangian of a scalar field which is postulated as [7]:

$$L = \frac{1}{2}(\partial\phi)^2 - \left(\frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4\right), \quad (1.5)$$

In case where the $\mu^2 > 0$ and $\lambda > 0$, the ground state corresponds to zero. However, when $\mu^2 < 0$ and $\lambda > 0$ we can see that the state with minimum energy is no longer zero but has a specific value. This minimum potential can be calculated as the following:

$$\frac{\partial V}{\partial \phi} = \phi(\mu^2 + \lambda\phi^2) = 0. \quad (1.6)$$

The minimum of the potential is for $\phi = \pm\sqrt{-\frac{\mu^2}{\lambda}}$ which is different than 0. When the ground state with minimum energy is different than zero we can say that we have a spontaneous symmetry breaking. Figures 1.2 shows the variation of the potential with respect to the field in case when we have no spontaneous symmetry breaking (Figure a) and when we have one (Figure b).

In Figure b the two minima show the possible new ground states corresponding to the minimum potential of the field. According to this figure, the potential equal zero is no longer stable,

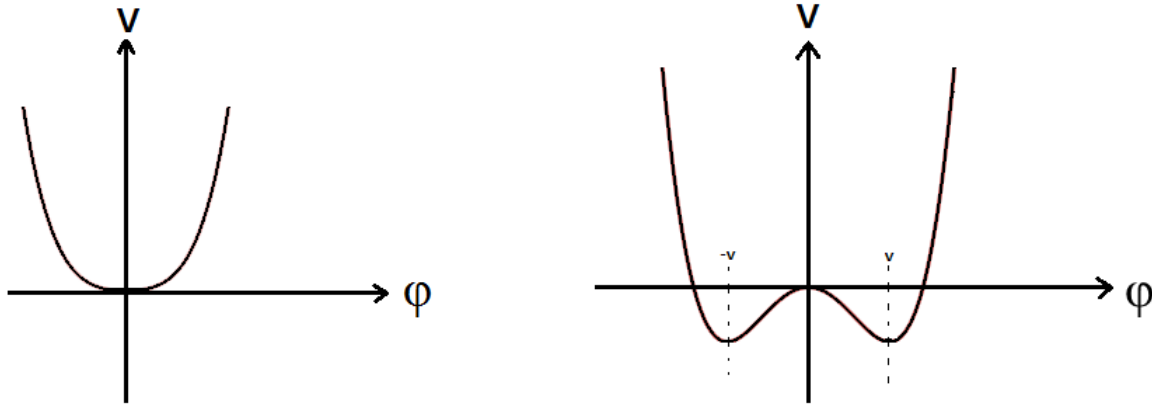


Figure 1.2: The variation of the potential V as a function of the field ϕ in case of a single minimum (a) and in case of double minima (b).

therefore quantum fluctuations are considered around the new chosen potential minimum that will represent the physics vacuum v .

$$\phi(x) = v + \eta(x), \quad (1.7)$$

where the fluctuations around the minimum are represented by η . Replacing the $\phi(x)$ in the Lagrangian defined above, we fall on:

$$L' = \frac{1}{2}(\partial_\mu \eta)^2 - \lambda v^2 \eta^2 - \lambda v \eta^3 - \frac{1}{4} \lambda \eta^4. \quad (1.8)$$

The new form of the Lagrangian contains a correct mass term corresponding to the field $\eta(x)$ so that $m_\eta = \sqrt{2\lambda v^2}$. This means that the spontaneous breaking of the symmetry lead to the generation of mass for the particle associated to the scalar field. A similar approach will be used to generate the mass for the W and Z bosons described the next paragraph.

1.1.4 The Electro-Weak interaction

After the explanation of the beta decay by Fermi, a theory of the weak interaction was built. This interaction was called weak due to the longer observed lifetimes of particles decaying through it such as the lifetimes of charged pions and muons. While particles that decay through strong or electromagnetic interactions have had shorter lifetimes. Also, experiments on the polarized ^{60}Co decay, K decay, π decay, etc. have shown that this interaction violates parity. The interaction therefore acts only on left handed particles and right handed anti-particles. However, this conclusion was drawn before the discovery of the neutral Z boson which allowed the inclusion of the right-handed components in the theory later on.

We know that for each of the electromagnetic and strong forces, there is an associated charge that is remained conserved all along any interaction involving these forces. In the case of the electromagnetic force the electric charge Q is associated, as for the strong force the color charge of the quarks is associated. However, Gell-Man Nishijima have reformulated the electric charge as:

$$Q = Y_W/2 + I_3, \quad (1.9)$$

where the Y_W is the weak hypercharge and I_3 is the weak isospin. While Q generates the group $U(1)_Q$, the hypercharge Y_W operator generates the group $U(1)_Y$, and I_3 generates the $SU(2)$ group associated to the weak interaction. This relates in a sense the electromagnetic and weak interactions forming the Electro-Weak interaction to which the $SU(2)_L \times U(1)_Y$ symmetry group is associated. In this theory, the $U(1)_Y$ group applies to all fermions. Left-handed fermions transform as $SU(2)_L$ doublets and right-handed ones as $SU(2)_L$ singlets. In 1979, a Nobel prize was attributed to Steven Weinberg, Abdus Salam, and Sheldon Glashow, for unifying these two forces.

1.1.4.1 Neutral and charged currents

QED has shown invariance under the $U(1)_Q$ symmetry group and the weak interaction has shown invariance under the $SU(2)$ non-abelian symmetry group. The electro-weak force is therefore invariant under the $SU(2)_L \times U(1)_Y$ symmetry group. The electro-weak model contains three massless gauge fields of spin 1, W_μ^i , $i = 1, 2, 3$, that belong to the $SU(2)$ lie group with a coupling strength g and one $U(1)$ massless spin 1 gauge field which we will call B_μ with a coupling strength g' [8].

The following linear combination of the first two fields

$$W_\mu^\pm = \frac{1}{\sqrt{2}}(W_\mu^1 \mp iW_\mu^2),$$

give two charged bosons ($W^\pm$) that are the mediators of the charged current weak interactions. Two other neutral fields, Z_μ^0 and A_μ , are responsible for the weak neutral current and electromagnetic interactions respectively. The particles corresponding to these fields are the Z^0 boson and the γ photon. These fields can be written as:

$$\begin{aligned} A_\mu &= \sin \theta_W W_\mu^3 + B_\mu \cos \theta_W, \\ Z_\mu &= \cos \theta_W W_\mu^3 - B_\mu \sin \theta_W, \end{aligned} \tag{1.10}$$

where θ_W is the Weinberg angle. At this stage, all particles were considered massless and only transversely polarized in the SM. However, experimental measurements show that the W and Z bosons are massive. Therefore, there was the need of breaking spontaneously the electroweak symmetry and generating mass to these particles through the Higgs mechanism [9][10][11].

1.1.4.2 The Higgs mechanism

To describe this mechanism we first re-write the part of the Lagrangian representing the kinetic term of the gauge bosons as [7]:

$$L_{Kin} = -\frac{1}{4}W_{\mu\nu}^i W^{\mu\nu i} - \frac{1}{4}B_{\mu\nu} B^{\mu\nu}, \tag{1.11}$$

where

$$W_{\mu\nu}^i = \partial_\nu W_\mu^i - \partial_\mu W_\nu^i + g\epsilon^{ijk}W_\mu^j W_\nu^k, \tag{1.12}$$

$$B_{\mu\nu} = \partial_\nu B_\mu - \partial_\mu B_\nu. \tag{1.13}$$

A complex scalar field Φ is introduced as:

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix}.$$

The potential of the given scalar field is written as:

$$V(\Phi) = \mu^2 |\Phi^\dagger \Phi| + \lambda (|\Phi^\dagger \Phi|)^2, \quad (1.14)$$

The same way as explained in the previous paragraph, for μ^2 negative the minimum of the potential is not at zero. There is the possibility of choosing many values for this non zero vacuum. However, only one is chosen by nature so that:

$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}.$$

The particular choice of the ground state for the scalar doublet breaks spontaneously the electroweak $SU(2) \times U(1)$ symmetry while keeping the ground state invariant under the $U(1)_Q$ group, hence without breaking the electromagnetism. This leads to the known configuration of $SU(2)_L \times U(1)_Y \rightarrow U(1)_Q$.

The complex gauge invariant Lagrangian describing the scalar doublet is written as:

$$L_s = (D^\mu \Phi)^\dagger (D_\mu \Phi) - V(\Phi), \quad (1.15)$$

where

$$D_\mu = \partial_\mu + igW_\mu^k I_k + i\frac{g'}{2}B_\mu Y, \quad (1.16)$$

Y being the weak hypercharge, I the weak isospin, g and g' the weak coupling strengths so that the weak coupling constant $\alpha_W = g^2/4\pi \approx 1/30$.

To generate mass to the gauge bosons by breaking spontaneously the symmetry, perturbation theory will be used. The scalar doublet can therefore be written as:

$$\langle \Phi \rangle = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix},$$

where $H(x)$ is a perturbation around the vacuum.

Using this scalar doublet of the field, if we look at the invariance of the Lagrangian given in equation 1.15, we can re-write the gauge fields as:

$$\begin{aligned} W_\mu^\pm &= \frac{1}{\sqrt{2}}(W_\mu^1 \mp iW_\mu^2), \\ Z_\mu &= \frac{-g'B_\mu + gW_\mu^3}{\sqrt{g^2 + g'^2}}, \\ A_\mu &= \frac{g'B_\mu + gW_\mu^3}{\sqrt{g^2 + g'^2}}. \end{aligned} \quad (1.17)$$

This leads to the obtention of the gauge boson masses, so that:

$$\begin{aligned} M_W^2 &= \frac{1}{4}g^2v^2, \\ M_Z^2 &= \frac{1}{4}(g^2 + g'^2)v^2, \\ M_A &= 0. \end{aligned} \quad (1.18)$$

The weak mixing angle, which is experimentally measured, relates between the weak field strengths in such a way that:

$$e = g \sin \theta_W = g' \cos \theta_W. \quad (1.19)$$

Finally, the masses of the fermions can also be explained by adding a term representing the Yukawa coupling of the fermion to the scalar field of the Higgs boson. These features make the SM a complete theory describing the interactions and masses of all the elementary particles that are experimentally observed at the LHC.

1.1.4.3 Self boson couplings

The electroweak $SU(2) \times U(1)$ symmetry group in the SM has a non-abelian structure. This structure gives rise to the gauge bosons self couplings as derived from equation 1.11 and 1.12. In the SM, triple and quartic gauge boson couplings are predicted. Figure 1.3 shows the possible triple and quartic gauge couplings in the SM.

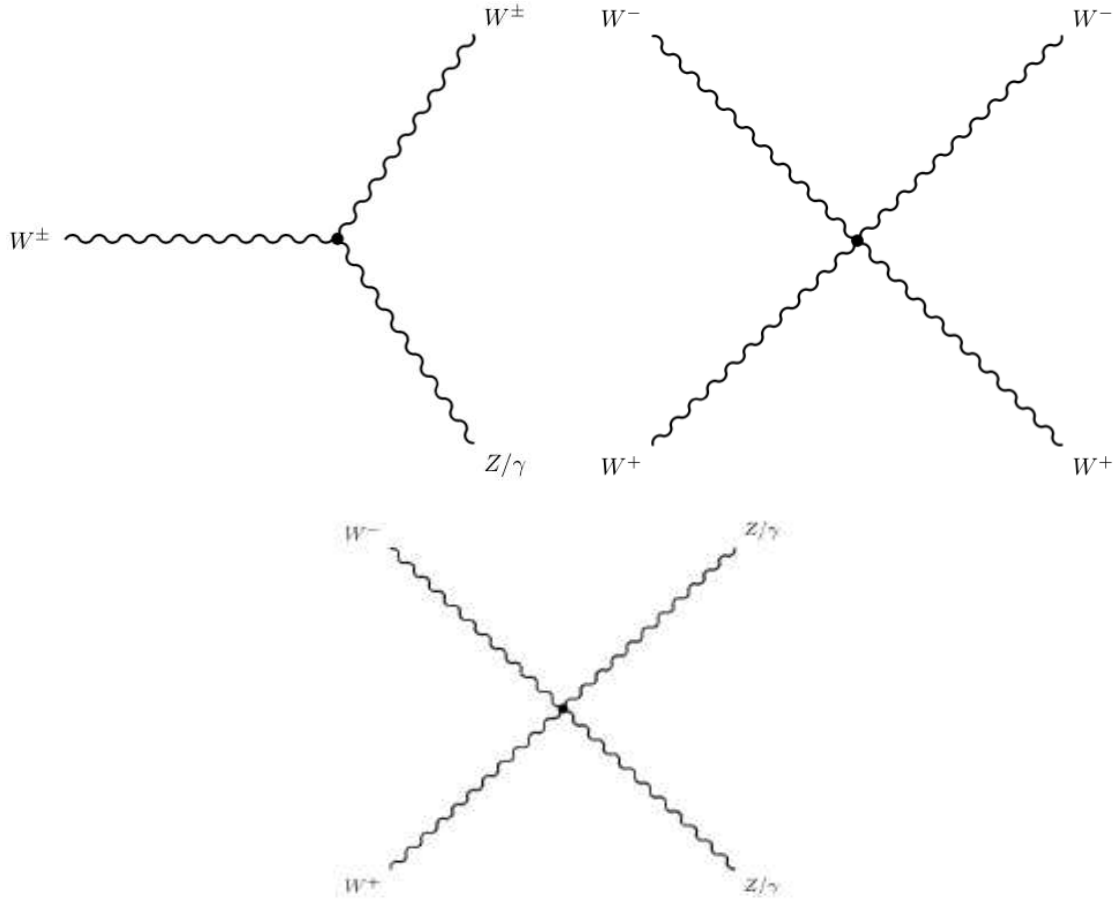


Figure 1.3: Diagrams illustrating the triple and quartic gauge couplings in the SM.

It is necessary to test experimentally these couplings for them being a living proof for the electroweak symmetry breaking and Higgs mechanism. Also, through this kind of approach, the search for atypical couplings can be performed. For example, the SM forbids the $ZZ\gamma$, $Z\gamma\gamma$, and ZZZ couplings at the tree level. It also forbids the $\gamma\gamma\gamma$ couplings at all levels. If these kind of couplings are experimentally proven to exist, it means that they necessarily belong to a

physics beyond the SM. Even the couplings that are predicted by the SM, can deviate from their SM values showing also signs of new physics. The deviations of the coupling from the SM are called anomalous couplings and which will be detailed in the following sections.

Many theoretical models other than the SM, such as SuperSymmetry (SUSY), already predict new physics signatures through diboson final states. Hence, the importance of this study.

1.1.5 Quantum Chromodynamics (QCD)

The theory of strong interaction is called the Quantum Chromodynamics (QCD). Gluons are the mediating particles for this interaction and the charge associated to them is the color charge. The idea of a color charge was introduced after the statistical problem imposed in the construction of the Δ^{++} particle's wavefunction. This particle is composed of three same flavor quarks with exactly the same quantum numbers (uuu) which builds a state that is forbidden by the Fermi statistics. To solve this problem, a new color charge, representing an additional degree of freedom for quarks, was introduced. So that in the Δ^{++} particle, each of the u quarks have the red, blue, and green colors in a way that their combination gives white which is the equivalent of “neutral” for the electrical charges. Anti-colors are associated to anti-quarks. All observed particles are supposed to have a “white” color charge as they are supposed to be unchanged by rotation in the colors space.

Based on the introduction of a color charge QCD was built as a quantum field theory invariant under the SU(3) rotation group. The gluons which mediate the interaction are massless such as photons. However, as they carry a color charge, they interact not only with quarks and also with each other. This aspect gives two important properties to QCD: color confinement and asymptotic freedom. The strong coupling strength g_s is given by $g_s^2 = 4\pi\alpha_s$, where α_s is the strong coupling constant. Figure 1.4 shows the running of the strong coupling constant [12], namely that α_s depends on the energy at which the interaction occurs.

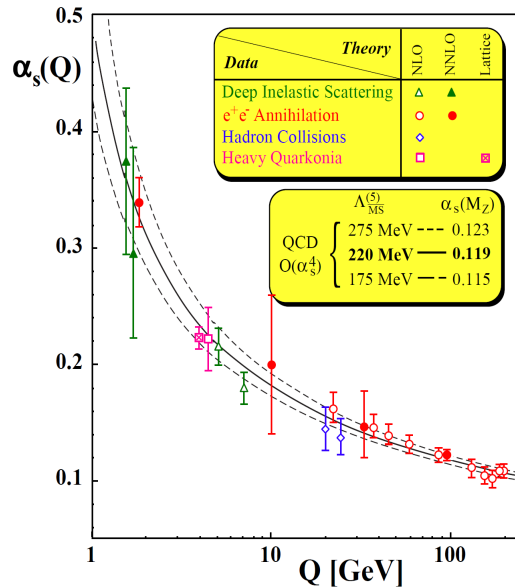


Figure 1.4: Running of the strong coupling constant as a function of the energy scale.

Since α_s becomes larger and larger when the interaction energy decreases, for relatively long distances corresponding to energies lower than 1 GeV, the interaction strength between

quarks and gluons increases. As we try to separate the quarks from each other, a new gluon is created in the vacuum strengthening the interaction. This property is called confinement and its consequence is to keep quarks in strongly bound states with a global neutral color charge. As the distances shorten, for energies much greater than 1 GeV, the strong coupling constant decreases and vanishes asymptotically. This aspect is called the asymptotic freedom that facilitates the description of high energy interactions between the hadron as it enables the use of perturbation theory thus calculation of the interaction cross sections in orders of α_s .

1.1.6 Success and limitations of the Standard Model

The SM has been successfully describing all the fundamental particles and their interactions. Specifically after the discovery of the SM like Brout-Englert-Higgs (BEH) boson, this model is now almost completed. However, it also presents many limitations and unexplained phenomena of that require the necessity of its extension. Among the limitations of the SM, is mainly the *Hierarchy problem*. This problem addresses the question why the weak force is 32 orders of magnitude stronger than the gravitational force. In fact the Higgs boson's mass which is around 125 GeV contains quadratic corrections making it too low with respect to what we expect if we extend the theory to the Planck scale. This means that above the cut-off scale of the SM, the mass term of the Higgs potential needs to be fine-tuned to keep the weak scale small with respect to the Planck scale.

Otherwise, the SM also lacks many explanations to fundamental physics phenomena such as:

- A candidate particle for Dark matter. Cosmological observations have shown that the masses of cluster of galaxies are larger than the amount of ordinary matter they contain. This lead to the conclusion of the existence of an unknown type of matter different than the SM ones, filling 27% of the known universe [13].
- An explanation for the matter anti-matter asymmetry. We know that our universe is made out of mostly matter while matter and anti-matter should have been created equally at the beginning of the universe. [14]
- An explanation of the neutrino masses that are considered massless in the SM. Experiments such as Super-Kamiokande study a phenomenon called the neutrino oscillation showing that neutrinos do have mass [15].
- An explanation of gravity. The SM does not explain gravity nor associate a particle mediating this interaction.

1.2 $p - p$ collisions and diboson production at the LHC

The proton is a system containing three valence quarks bound together with gluons. When a gluon inside the proton splits this gives rise to the sea quarks which in their turn can annihilate to produce a gluon. The results of this gluons splits and creations is called the “sea” inside the proton. During $p - p$ collisions, most interactions are those between the quarks and gluons (partons). Hence, the strong interaction is the governing one. Therefore, QCD is used to describe the dynamics of the $p - p$ interactions. Figure 1.5 sketches a $p - p$ collision showing the interactions occurred during the collision and the outgoing products.

At low energies, due to the confined nature of the strong interaction, non-perturbative or soft QCD theoretical calculations are applied in order to describe the interacting quarks and gluons.

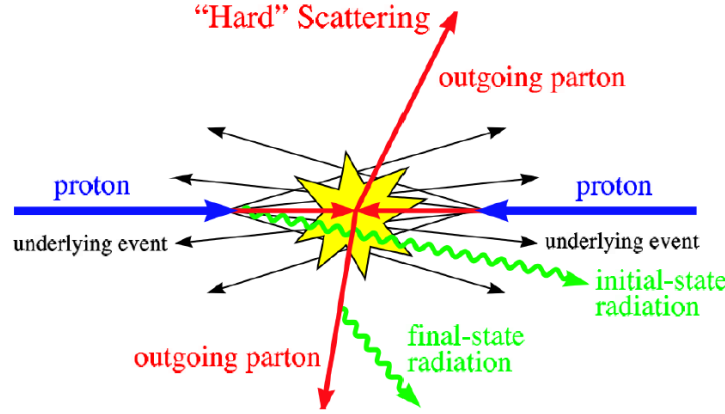


Figure 1.5: Scheme of a $p - p$ collision showing the hard scattering and the underlying event.

In general, the soft processes in a $p - p$ collision represent the underlying event which means any interaction besides the most interesting physics processes. The soft processes act as an important background to the interesting interactions that rise from the hard scattering.

This means that, preferentially the partons with the highest momentum fractions produce the hard scattering, therefore, a process at high energy where perturbative QCD can be applied. As the strong coupling constant decreases asymptotically, the partons interacting during the hard scattering can be considered as free. The total cross section of the hard interaction can be obtained using the factorization theorem which takes into account the soft and hard components during the collision [16][17].

The cross section calculation of the hard interaction makes use of the Parton Distribution Functions (PDF)s, as they will provide the longitudinal momenta distributions of the interacting partons in the hard scattering. The second term needed for this cross section calculation, is the cross section of the interacting partons each with a longitudinal momentum fraction $p_{1,2} = x_{1,2}P$ where $x_{1,2}$ is the momentum fraction of each of the partons and P is the momentum of the proton. The interaction taking place is depicted in figure 1.6.

We can apply the factorization theorem for the calculation of a hard scattering process and express the cross section in terms of soft components represented by the PDFs and a hard component represented by the partonic cross section so that [18]:

$$\sigma_{AB} = \int dx_a dx_b f_{a/A}(x_a, \mu_F^2) f_{b/B}(x_b, \mu_F^2) \times \hat{\sigma}_{ab}(\alpha_s, \mu_R^2). \quad (1.20)$$

where $x_{a,b}$ are the momentum fractions of the two interacting partons, f represent the PDFs, α_s is the strong coupling constant, μ_F is the factorization scale which represents the scale separating long- and short-distance physics. Finally, μ_R is the QCD running coupling renormalization scale.

As introduced before, the PDFs provide the probability of finding a parton with a momentum fraction x inside the proton and are obtained experimentally by performing a fit to experimental data.

Parton distribution functions are non-perturbative inputs necessary to calculate cross-sections for scattering processes involving hadrons in the initial state. They are obtained by fitting theoretical predictions to various sets of experimental measurements, many of which come from Deep Inelastic Scattering experiments. Among these, the experiments at the HERA electron-proton collider have played a crucial role, providing sets of data which cover the widest kinematic re-

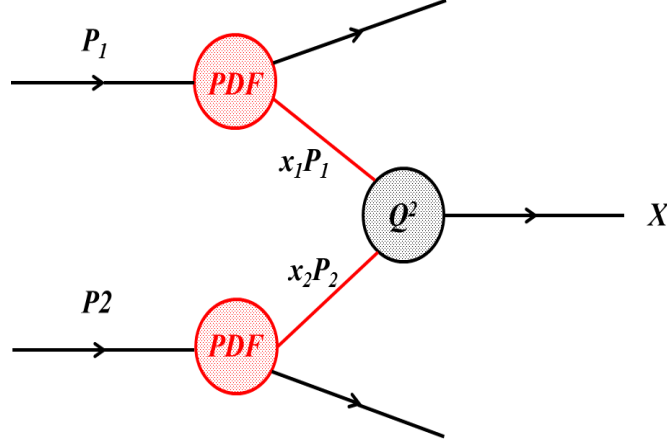


Figure 1.6: Schematic representation of the hard scattering process via the interaction of two partons from the proton. $P_{1,2}$ are the momenta of the interacting protons, $x_{1,2}$ represent the parton momentum fractions, Q^2 is the square of the transferred momentum between the two interacting partons.

gion. Hadron-hadron scattering measurements, from the Tevatron or more recently the LHC, are also used to provide supplementary informations. Figure 1.7 shows the PDFs obtained using data from the H1 and ZEUS experiments at HERA, at the scale of $Q^2 = 10000 \text{ GeV}^2$ corresponding to the energy scale of the EW gauge boson production.

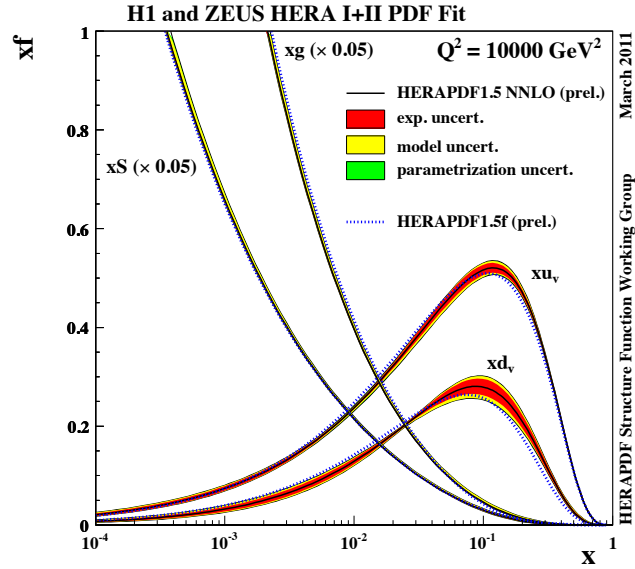


Figure 1.7: The parton distributions from HERAPDF1.0 at $Q^2 = 10000 \text{ GeV}^2$ [19][20].

1.2.1 Production of two vector bosons at the LHC

For a given center-of-mass energy, the different production cross section of two vector bosons are shown in table 1.1.

Among these processes, as we see in the table, the WW has the highest cross section. However, when it decays to leptons, its signature is accompanied with two neutrinos. These are not directly detectable with detectors such as ATLAS, and therefore the background in experimental measurement of this process is relatively large. On the other hand, the ZZ process presents a very clean signature in its leptonic decay channel. However, due to its low cross sections, it lacks statistics. The optimal channel in terms of average cross section and background is the WZ channel, which falls between the WW and ZZ channels.

The diboson production cross sections at the LHC during the 2011 running period, where the center-of-mass energy of the proton-proton collisions was 7 TeV, were at least four times higher than those of the Tevatron. For the future, when the LHC will run at a center-of-mass energy of 14 TeV, at least ten times higher production cross sections than at Tevatron are expected. As shown in table 1.1, this increase in the cross sections, makes the LHC more sensitive to deviations from the SM predictions and to potential discovery of new physics.

SM cross section	Tevatron ($p\bar{p}$, 1.96 TeV, [pb])	LHC (pp , 7 TeV, [pb])	LHC (pp , 14 TeV, [pb])
WW	10.9	42.7	116.3
WZ	3.7	16.4	47.1
ZZ	1.3	5.7	16.0

Table 1.1: Predicted Next-to-Leading Order cross sections within the SM for the production of dibosons at the Tevatron and at the LHC [21]. The dynamic scale M_{VV} , where V is W or Z , is chosen for the renormalization and factorization scales.

Experimentally, the cross sections of a large range of SM processes including the diboson cross sections, have already been measured at the LHC by ATLAS and CMS experiments using data at $\sqrt{s} = 7$ and 8 TeV. Figure 1.8 shows the measurements performed by both experiments. These measurements are compared also to the theoretical predictions as shown in the figure. No deviations from theory has been yet observed in any of the SM processes.

1.2.2 WZ diboson production

During $p - p$ collisions at the LHC, dibosons can be produced from a quark anti-quark interaction. Figure 1.9 show the Leading Order (LO) Feynman diagrams for the possible diboson productions. W and Z bosons can be produced in pairs via the s, t, and u-channels. The production of dibosons through the s-channel shows the creation of an off-shell W boson that decays to an on-shell W and Z through an interaction vertex. This vertex is called a Triple Gauge Coupling (TGC) vertex and is sensitive to the self interactions of vector bosons.

We should note that the production rate of W^+Z events is different than the W^-Z one. The dominant W^+Z production is from the interaction of an u -quark with a $\bar{d}$ -quark and the W^-Z is produced mostly when an $\bar{u}$ -quark interacts with a d -quark. Due to the dominance of the valence u -quarks in the proton, the W^+Z production is enhanced with respect to the W^-Z production. The kinematics of production for each of these processes is different.

Figures 1.10 and 1.11 show the WZ production, when QCD corrections at the Next-to-Leading-Order (NLO) are taken into account. In the first figure it is shown that these corrections allow the WZ production through quark-gluon interaction with an additional quark production in the final state. Also in this figure, we observe the WZ production through $q - \bar{q}$ interaction

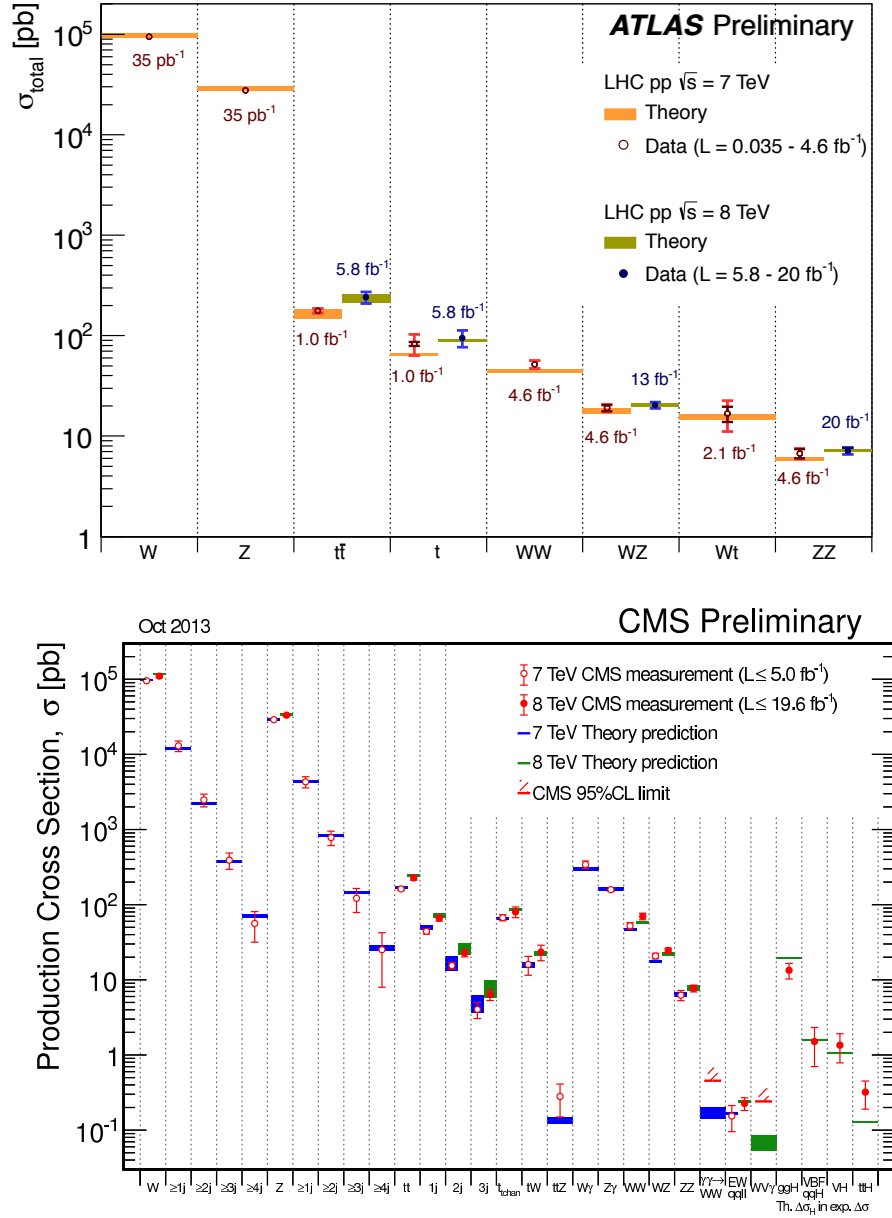


Figure 1.8: Cross sections of Standard Model processes as measured by the ATLAS and CMS experiments with 7 and 8 TeV data [22] [23].

with a gluon radiation in the final state [24]. Whereas the second figure, shows the virtual gluon loops contributions to the WZ production [25]. To calculate the total NLO cross section of WZ , these diagrams must be convoluted with the proton PDFs.

In the SM only charged TGCs are predicted, neutral TGCs are forbidden. Any anomaly that can be measured is a sign for new physics beyond the SM.

New physics can also appear through the search for new resonances with diboson final states. Many possible decays to dibosons are predicted in the frame of non-SM theories. For example, the following process (and many others) predicted by SUSY:

$$pp \rightarrow W^* \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow (W^\pm \tilde{\chi}_1^0)(W^0 \tilde{\chi}_1^0). \quad (1.21)$$

Also models such as minimal SuperGravity (mSUGRA) predict a graviton decaying to a pair

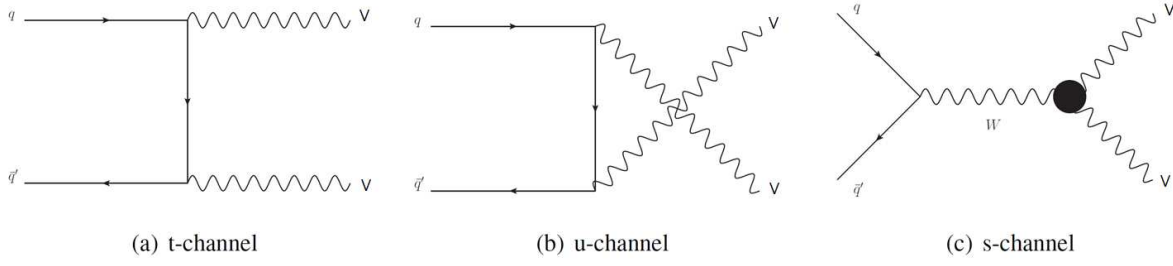


Figure 1.9: Diagrams of the WZ production at QCD LO.

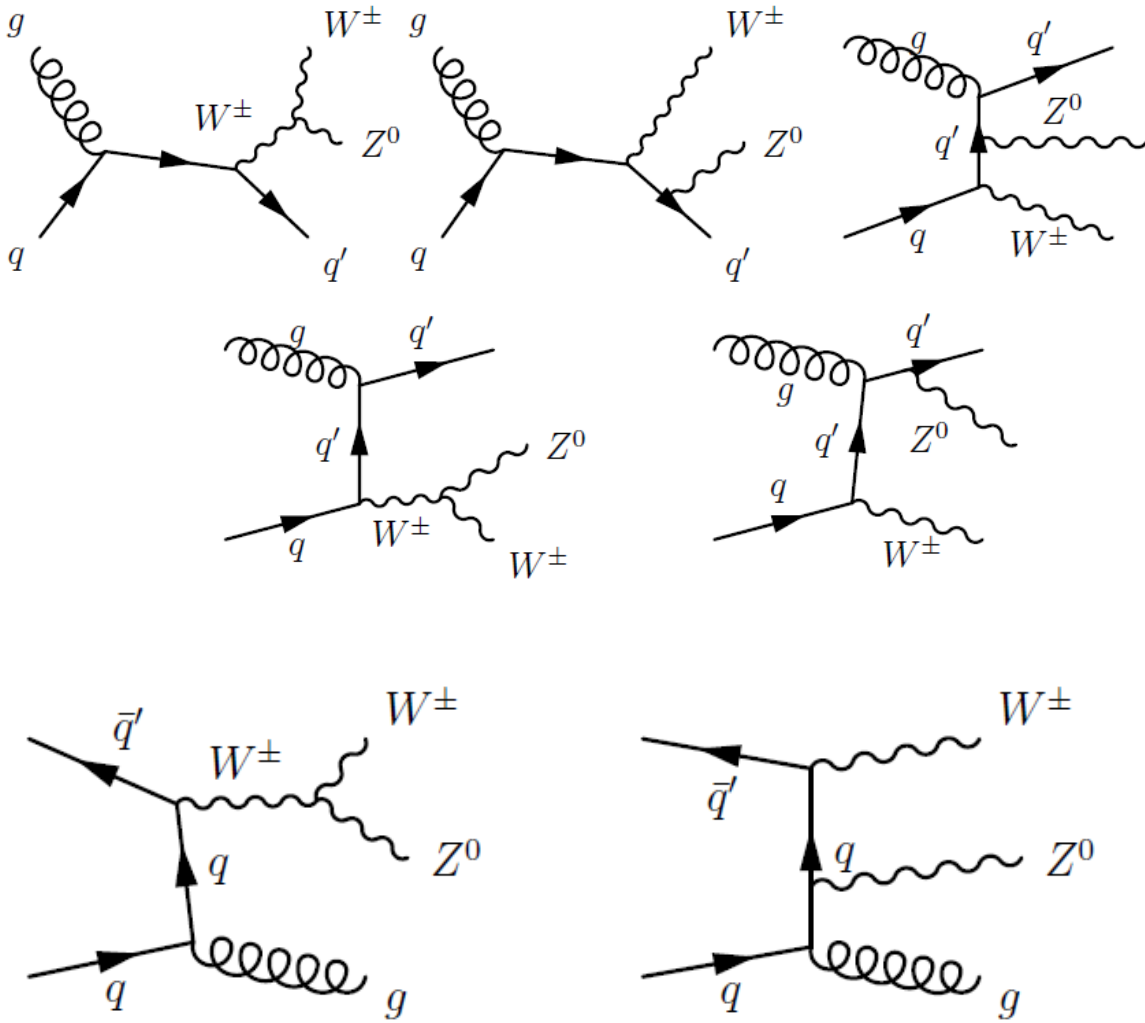


Figure 1.10: WZ production real emission NLO diagrams [26].

of W bosons, or models such as the technicolor, predict a techni- ρ decaying to a pair of WZ bosons.

Therefore, the field of search for new physics with diboson final states is vast. The searches can be performed either by searching for new resonances, or by probing anomalies or atypical behaviors with respect to the SM predictions.

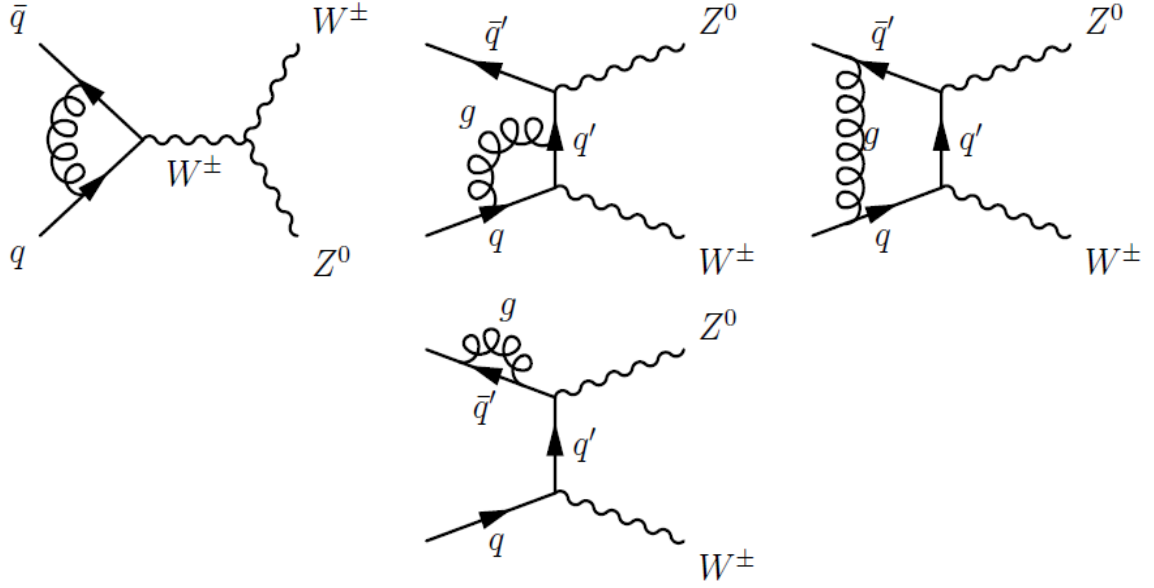


Figure 1.11: Diagrams contributing to the WZ production at NLO via virtual gluon loops [26].

Experiment	$\sqrt{s}$ [TeV]	σ_{WZ} [pb]	Theory Prediction [pb]
ATLAS	7	$19^{+1.4}_{-1.3} \text{ (stat)} \pm 0.9 \text{ (syst)} \pm 0.4 \text{ (lumi)}$	$17.6^{+1.1}_{-1.0}$
CMS	7	$20.76 \pm 1.32 \text{ (stat)} \pm 1.13 \text{ (syst)} \pm 0.46 \text{ (lumi)}$	$17.8^{+0.7}_{-0.5}$
CMS	8	$24.61 \pm 0.76 \text{ (stat)} \pm 1.13 \text{ (syst)} \pm 1.08 \text{ (lumi)}$	$21.17^{+1.17}_{-0.88}$
CDF	1.96	$3.93^{+0.60}_{-0.53} \text{ (stat)}^{+0.59}_{-0.46} \text{ (syst)}$	3.50 ± 0.21
D0	1.96	$4.5 \pm 0.61 \text{ (stat)}^{+0.15}_{-0.25} \text{ (syst)}$	3.21 ± 0.19

Table 1.2: WZ total cross sections as measured by ATLAS [27], CMS [28], D0 [29], and CDF [30] experiments. Theory predictions for each center-of-mass energy are presented.

Table 1.2 summarizes the WZ total cross sections as measured by the ATLAS, CMS, D0, and CDF experiments at the LHC and Tevatron, respectively. The results are also compared to theory predictions and as it is shown, within the uncertainty levels, until today all results are in a good agreement with the SM theory prediction.

1.2.3 Calculations and MC generators for the modeling of WZ events

Monte Carlo (MC) simulation methods rely on computational algorithms that are capable of modeling a given physical process. In particle physics, the MC generators predict the particle interactions for a known process. However, these particles cannot be used directly for a physics analysis with collision events. They need to pass through the detector simulation framework to take into account for the response of the detector and the reconstruction [31].

During $p - p$ collisions it is required from the MC generator to provide a full modeling of the event. This means that a matrix element calculation, a Parton Showering (PS), and a modeling for the hadronization should be provided.

In the $W^\pm Z$ production processes in their pure leptonic decay modes, the POWHEG MC generator is used. Powheg uses the CT10 [32] Parton Distribution Function (PDF) and provides a next-to-leading-order (NLO) QCD matrix element calculation. POWHEG [33] is interfaced to

the PYTHIA [34] program to simulate the PS. Also POWHEG is interfaced to the PHOTOS [35] program to account for the QED final state radiation. All along the text of this thesis, the notation POWHEGPYTHIA will be used to refer to the POWHEG program that is interfaced to the PYTHIA parton shower program.

Comparisons of $W^\pm Z$ analysis results is performed also using the SHERPA [36] MC generator. SHERPA provides a leading order (LO) calculation of the matrix element, however it includes tree level multi-parton emissions up to six fermions ($WZ+2$ -jets emission) in the final state while POWHEG implements NLO perturbative QCD calculations limited to final states with five fermions ($WZ+1$ -jet emission).

Total cross sections from these generators are compared to the cross section calculated at NLO with MCFM 6.6 which is a theoretical calculation that is explained in detail in [21].

We will show in the next paragraph, that the cross section predicted by POWHEGPYTHIA is found to be equal to the one by MCFM. However, for SHERPA a difference of 3% is observed, the cross section predicted by SHERPA being larger than the one of MCFM.

Finally, for completion, a comparison to the cross section predicted by the MC@NLO event generator [37] [38] which calculates as well the cross section fully to the NLO, will also be shown. However, contributions from γ^* and interferences between γ^* and Z are not implemented in MC@NLO.

Calculation of the $W^\pm Z$ cross section by MCFM and MC generators

The WZ theoretical cross section can be calculated using the MCFM calculation [21]. In order to enhance the contribution from on-shell Z bosons, the cross section is calculated in a mass window that is close to the Z mass pole. In ATLAS, the Z mass window within 66 and 116 GeV was chosen.

The total WZ MCFM cross section calculation is compared to the POWHEGPYTHIA, SHERPA, and MC@NLO MC predictions and a baseline theoretical prediction is chosen to compare to experimental results.

POWHEGPYTHIA uses the CT10 PDF to calculate the cross section. In order that the comparison is not affected by the differences among the PDF sets, the MCFM, MC@NLO, and SHERPA PDFs are also set to CT10. Table 1.3 shows the main differences that are present between these calculations.

Table 1.4 shows the comparison of the MCFM, POWHEGPYTHIA, SHERPA and MC@NLO cross sections using the CT10 PDF. The total cross section results for POWHEGPYTHIA and MCFM predictions are in a very good agreement within the statistical uncertainty. The cross section prediction for MC@NLO is about 2% higher than the MCFM calculation.

As shown in the table, the maximum difference in the total cross sections is seen between the predictions of POWHEGPYTHIA and SHERPA and it reaches up to 3%.

The POWHEGPYTHIA prediction agrees with the MCFM calculation. It will be used as baseline theory prediction to compare to our measurements all along this thesis. As shown in table 1.4 the statistical uncertainty on this prediction is very small.

1.2.4 Theory uncertainties on the WZ production cross section

The statistical uncertainties on the theoretical cross sections are in general very small. However, the theory uncertainties mainly due to QCD and electroweak corrections, as well as PDF, scale,

Prediction	Description
MCFM	NLO calculation, it does not include the QED FSR No parton shower
POWHEGPYTHIA	NLO, it includes the QED FSR Parton shower It does not include some diagrams for electroweak production of vector bosons
SHERPA	LO including real emission NLO diagrams QED FSR and parton shower included It includes the diagrams for electroweak production of vector bosons
MCATNLO	NLO event generator It does not contain the Z/γ^* interference and γ^* contribution QED FSR and parton shower included

Table 1.3: Main differences between the MCFM calculation performed in this thesis and the MC event generators.

NLO Prediction (CT10)	cross section [pb]
MCFM	$20.2 \pm 0.05(\text{stat.})$
POWHEGPYTHIA	$20.2 \pm 0.05(\text{stat.})$
SHERPA	$20.8 \pm 0.05(\text{stat.})$
MC@NLO	$20.6 \pm 0.3(\text{stat.})$

Table 1.4: Comparison of the MCFM, POWHEGPYTHIA, SHERPA, and MC@NLO WZ total cross section predictions. Dynamic renormalization scale M_{WZ} is used for MCFM, POWHEG, and MC@NLO

and generator uncertainties, are important. The paragraphs below give a summary of the main sources of theory uncertainties on the existing theoretical calculations of WZ production.

Signal statistical uncertainties

The statistical uncertainty on the signal rise from the statistics of the MC sample used to extract the theoretical cross section. In this thesis, the POWHEGPYTHIA MC sample with high statistics (6 million events) is used. Thus the order of magnitude of this uncertainty negligible of 0.07%.

Electroweak Corrections

Although NLO QCD correction for the WZ production are available since long time for off-shell and on-shell bosons, only very recently the full NLO EW corrections, restricted to on-shell bosons, have become available [39][40]. This calculation however does not take into account the photon-quark induced processes.

Another publication [41] has provided the full NLO EW calculations for on-shell vector boson production cross sections.

In the energy range of the LHC, electroweak corrections increase with the squared logarithm of the energy, therefore they depend on the energy, at high transverse momenta these corrections may become important and reach tens of percents [42]. These are dominated in general by single

and double logarithmic contributions rising from the ratio of the energy to the electroweak scale. First analyses on one loop logarithmic corrections [43] have shown that they are as important as the present experimental statistical uncertainties. In references [39] and [40], virtual EW corrections, as well as real corrections due to photon radiations have been estimated. Figure 1.12 shows the running of the LO cross section calculated by the HERWIG++ MC generator for all the VV processes including the WZ . The figure also shows the order of magnitude of the electroweak corrections, that range from -5% to -20% increasing with the Z boson's p_T in the case of the WZ production. These distributions correspond to a center-of-mass energy of 8 TeV at the LHC and for the basic kinematic cuts of $p_{T,V} > 15$ GeV and $|y_V| < 2.5$.

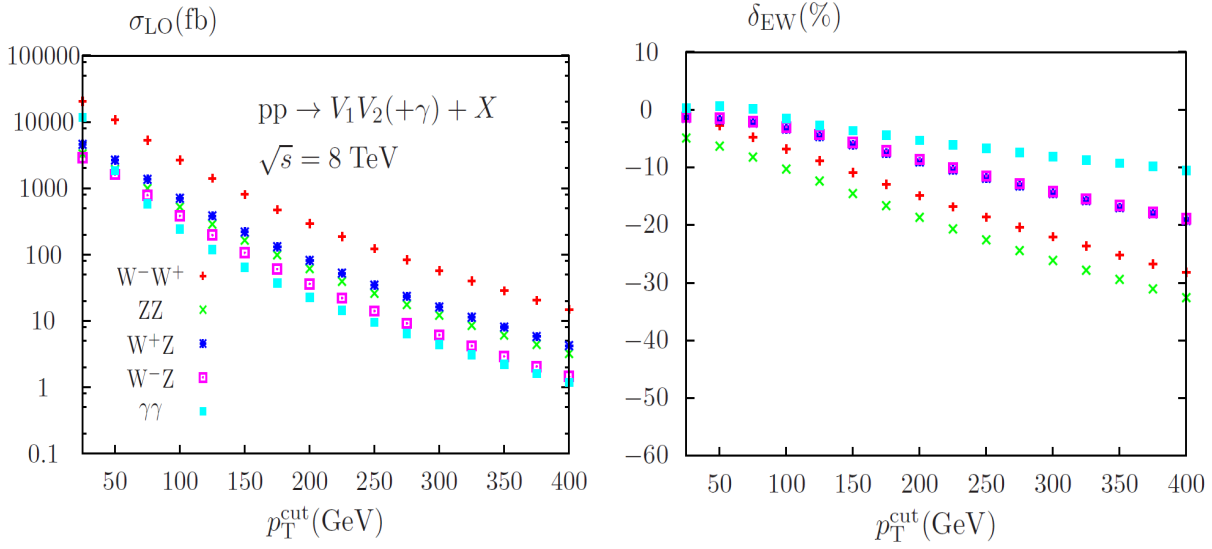


Figure 1.12: VV production cross section running as a function of p_T^{cut} , where V is a W , Z or γ (left). Order of magnitude of the electroweak corrections on the VV production [40] (right), the same color code as in the left figure is used.

More recently, in [41], the full NLO EW+QCD calculation of the WZ cross section have been provided. In this publication, it has been shown that at a center-of-mass energy of 14 TeV, the EW corrections explained in the previous paragraph are being canceled when the photon-quark-induced processes are included. Figure 1.13 shows the magnitude of these corrections for the W^+Z and W^-Z processes separately. Indeed, the final total electroweak correction (shown in black in the figure) shows that the order of magnitude of these corrections reaches up to 2% only which is very small compared to the QCD corrections. Calculations have been also performed for a center-of-mass energy of 8 TeV and a similar conclusion holds that the EW NLO corrections of the total $W^\pm Z$ cross section, are predicted to be negligible.

PDF Uncertainties

Another source of theoretical uncertainties results from the uncertainty on the determination of the PDFs. Using the POWHEGPYTHIA MC generator, the effect of the different PDFs on the WZ total and fiducial cross sections can be studied. This is shown in table 1.5 where the WZ cross sections are calculated with POWHEGPYTHIA using the MSTW08, CT10 and ATLASPDF PDFs. A difference of up to 3% is observed on the predicted total cross section between the CT10 and ATLAS PDF sets.

The total PDF uncertainty on the total and fiducial cross sections is calculated by adding

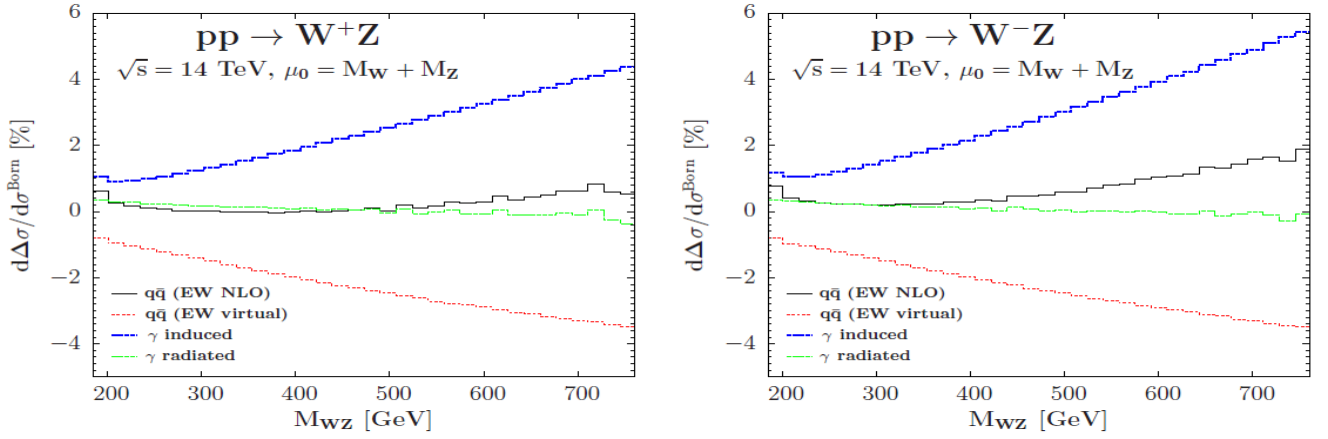


Figure 1.13: EW corrections in percentage as a function of the invariant mass of the WZ system for a center-of-mass energy of 14 TeV at the LHC.

	$W^\pm Z$		$W^+ Z$		$W^- Z$	
	total	fiducial	total	fiducial	total	fiducial
CT10 eigenvectors $\left(\sigma^+_{-}\right)$ (68% C.L.)	+1.9% -2.2%	+2.0% -2.3%	+2.1% -2.4%	+2.2% -2.5%	+2.3% -2.5%	+2.3% -2.5%
CT10 to MSTW08	+0.8%	+1.4%	+0.4%	+0.1%	+2.8%	+3.9%
CT10 to ATLAS PDF	+2.6%	+1.5%	+1.3%	+0.2%	+5.0%	+3.6%

Table 1.5: PDF uncertainties on the absolute cross section for WZ , W^+Z , and W^-Z productions in the total and fiducial phase spaces defined in section 5.1.1.

quadratically the cross section difference between the nominal value and that of all the 52 CT10 eigenvector sets. The result is divided by 1.645 to obtain 68% C.L. intervals. The resulting positive and negative uncertainties are calculated as [18]:

$$\sigma^+ = \sqrt{\sum_{i=1}^{i=52} \left(\max\{\sigma_{W^\pm}^i - \sigma_{W^\pm}^{default}, 0\} \right)^2}, \quad (1.22)$$

$$\sigma^- = \sqrt{\sum_{i=1}^{i=52} \left(\min\{\sigma_{W^\pm}^i - \sigma_{W^\pm}^{default}, 0\} \right)^2}. \quad (1.23)$$

They are noted in also in table 1.5 showing a PDF uncertainty of about 2% on the total and fiducial cross sections. This uncertainty is smaller than the difference in the predicted cross section between CT10 and ATLAS PDF sets. Therefore the quadrature sum of the uncertainty coming from the CT10 eigenvectors and the maximal difference between these three PDF sets tested will be used as total uncertainty on the WZ production cross section arising from our knowledge of the PDFs.

QCD Scale Uncertainties

An additional uncertainty source on the theoretical total and fiducial cross sections is the QCD scale uncertainty. The WZ theoretical cross section needs to be corrected for QCD effects that are increasing most particularly for WZ events with high transverse momenta. The calculations

show the importance of NLO calculations for the production cross sections and arrangements to make NNLO calculations as the experimental accuracy at the LHC is now increasing importantly. The NLO QCD corrections, include the loop corrections with one gluon in the loops and real emission corrections with an additional parton (quark or gluon) in the final state. Figure 1.14 shows the WZ cross section calculated to LO, NLO, and approximate NLO ($\bar{n}$ NLO, adding to the NLO a set of real and real-virtual diagrams) at $\sqrt{s} = 8$ TeV at the LHC as a function of the leading lepton p_T . The ratios of the cross sections with respect to the leading order calculation, denoted as K factors, show the importance of the QCD corrections that are already at the level of 15% for $p_T^{l,max}$ around 200 GeV. More information about these corrections can be found in reference [44].

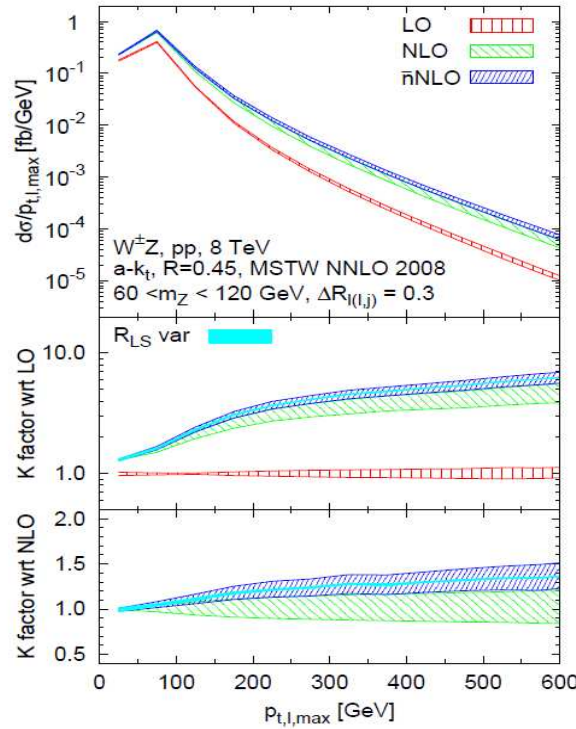


Figure 1.14: WZ production cross section as a function of $p_T^{l,max}$, where l_{max} is the leading lepton [44].

The QCD scale uncertainties are estimated by varying independently the renormalization and factorization scales (μ_R and μ_f) by factors of 0.5, 1, and 2. The deviation percentage with respect to the nominal value obtained using a fixed scale $\mu_R = \mu_f = (M_W + M_Z)/2$ is taken as the scale systematic uncertainty. This is shown in table 1.6 where a maximum deviation of $\sim 5\%$ is calculated. As we see in the table, the main QCD scale uncertainty is coming from the variation of the renormalization scale, while the variation of the factorization scale does not introduce a deviation in the cross section not more than 1%.

The scale variation effect is also tested by replacing the factorization and renormalization fixed scale equal to $(M_W + M_Z)/2$, with a dynamic scale equal to M_{WZ} . This variation of the scale produces a 6.5% decrease on the total cross section. This difference is larger than any of the differences obtained by varying the renormalization and factorization scales. Therefore it will be considered as an upper bound to the QCD scale uncertainty on the WZ total cross section.

Scale variation		Phase space	
x_R	x_F	total	fiducial
0.5	0.5	5.1%	5.7%
0.5	1	4.4%	4.9%
0.5	2	3.9%	4.4%
1	0.5	0.5%	0.6%
1	1	0.00%	0.00%
1	2	-0.4%	-0.4%
2	0.5	-3.2%	-3.6%
2	1	-3.6%	-4.0%
2	2	-3.9%	-4.0%
$\mu_R = \mu_F = M_{WZ}$		-6.5%	-6.9%

Table 1.6: Relative deviations of the absolute WZ production cross section for different choices of the QCD scales compared to the nominal value with $\mu_F = \mu_R = (M_W + M_Z)/2$. x_R and x_F represent the factors applied on the renormalization and factorization scales respectively. These scales are varied independently by x_R and x_F . The last line represents the uncertainty obtained when the dynamic scale $\mu_F = \mu_R = M_{WZ}$ is used.

Finally, the total theoretical WZ production cross section is calculated using POWHEG as:

$$\begin{aligned}
 \sigma_{WZ}^{th}(total) &= 21.7^{+0.02}_{-0.02}(\text{stat})^{+0.41}_{-0.48}(\text{CT10})^{+0.57}_{-0.57}(\text{PDF})^{+1.39}_{-1.39}(\text{QCDscale}) \text{ pb} \\
 &= 21.7^{+1.6}_{-1.6} \text{ pb},
 \end{aligned}
 \tag{1.24}$$

The NLO calculation containing the full NLO corrections shown in [41], calculates a WZ total cross section as:

$$\sigma_{WZ}^{th}(total) = 22.7^{+2.7}_{-2.3} \text{ pb},
 \tag{1.25}$$

which is in agreement within the uncertainty, with the result obtained using POWHEG. The difference of 4% between both results is because the calculation in reference [41] uses an on-shell approximation and has no γ^* and $\gamma^* - Z$ interference contributions.

1.3 Diboson physics beyond the SM

To search for physics beyond the SM, a search for new resonances can be performed. Otherwise, a search for new interactions leading to the same final states is also a way to find new physics. In the case of the vector bosons pair production via the s-channel, we have seen that TGCs were involved, pointing to the self interaction of gauge boson. Deviations from the SM in this case, can result from loops containing new particles propagators, or from internal structures of particles we think of as fundamental such as W and Z bosons which have sub-constituents.

Two assumptions can be made to search for new physics. It either occurs at an energy scale that we are probing, and this can be performed by searching directly for a new resonance. Another assumption is to consider that new physics occurs at an energy scale higher than the scale of the LHC. In this case an indirect search of the effects of this new physics on SM variables can be performed. For the last scenario, two approaches have been adopted to study the anomalies of the TGCs, namely the aTGCs. The first approach, is a classical one, uses the most general effective Lagrangian and the other one, recently adopted, uses an effective field theory.

1.3.1 Anomalous Couplings

As shown on the Feynman diagram of figure 1.9, the SM predicts TGCs. anomalous TGCs (aTGCs) can therefore be included in the SM Lagrangian formulation as additional terms on the interaction vertices. Equation (1.26) shows the Lagrangian that contains the anomalous couplings [45].

$$\begin{aligned}
L_{WWV}/g_{WWV} = & ig_1^V(W_{\mu\nu}^\dagger W^\mu V^\mu - W_\mu^\dagger V_\nu W^{\mu\nu}) + i\kappa_V W_\mu^\dagger W_\nu V^{\mu\nu} \\
& + i\frac{\lambda_V}{m_W^2} W_{\lambda\mu}^\dagger W_\nu^\mu V^{\nu\lambda} - g_4^V W_\mu^\dagger W_\nu (\partial^\mu V^\nu + \partial^\nu V^\mu) \\
& + g_5^V \epsilon^{\mu\nu\lambda\rho} (W_\mu^\dagger \partial_\lambda W_\nu - \partial_\lambda W_\mu^\dagger W_\nu) V_\rho \\
& + i\tilde{\kappa}_V W_\mu^\dagger W_\nu V^{\mu\nu} + i\frac{\tilde{\lambda}_V}{m_W^2} W_{\lambda\mu}^\dagger W_\nu^\mu V^{\nu\lambda}, \tag{1.26}
\end{aligned}$$

The m_W is the mass of the W boson. The W^μ and V^μ represent the W and V fields, where V can be a Z boson or a photon γ . The overall coupling constants $g_{WW\gamma} = -e$ and $g_{WWZ} = e\cot\theta_W$ with θ_W being the weak mixing angle. Finally, the parameters g_1^V , λ_V , and κ_V represent the CP conserving triple gauge couplings and g_4^V , g_5^V , $\tilde{\kappa}_V$ the CP violating parameters. All of these couplings have value equal to zero in the SM except for g_1^V and κ_V which have a SM value equal to one.

The Lagrangian written above contain terms that violate the invariance under Charge conjugation and Parity (CP). If we discard the CP violating terms, the same Lagrangian can be written as:

$$L_{WWV}/g_{WWV} = ig_1^V(W_{\mu\nu}^\dagger W^\mu V^\mu - W_\mu^\dagger V_\nu W^{\mu\nu}) + i\kappa_V W_\mu^\dagger W_\nu V^{\mu\nu} + i\frac{\lambda_V}{m_W^2} W_{\lambda\mu}^\dagger W_\nu^\mu V^{\nu\lambda}, \tag{1.27}$$

This Lagrangian contains directly the anomalous couplings and thus they are considered as constants. This fact leads to the growth of the amplitude as s/M_W^2 violating the unitarity bound at high energy. Therefore, this approach makes use of form factors in order to restore the unitarity so that:

$$\alpha \rightarrow \frac{\alpha}{(1 + \hat{s}/\Lambda_{FF}^2)^n}. \tag{1.28}$$

where α is the anomalous coupling in question, $\hat{s}$ is the square of the VV mass, and Λ_{FF} is a cutoff scale. The larger the cutoff scale the smaller is the second term on the denominator and it finally tends to zero for a cutoff scale of infinity where no form factor is applied.

1.3.2 Effective Field Theory (EFT)

The most natural way to procede and perform searches beyond the SM, is through its extension in a frame of a model independent formalism. This can be done using an effective field theory.

An effective Lagrangian can be written in the form of a standard Lagrangian, by defining an effective action S_{eff} that contains all the excitations of energy above the scale Λ , so that:

$$S_{eff}^\Lambda = \int d^4x L_{eff} = \int d^4x \sum \alpha_i(\Lambda) O_i, \tag{1.29}$$

where L_{eff} is the effective Lagrangian density or what we will call an effective Lagrangian, the α_i are the coupling coefficients, and O_i are operators that will define the interactions between the particles.

The condition to write such a Lagrangian is that it should recover for the SM at Λ going to infinity, it should be Lorentz invariant, and it should respect the SM $SU(3) \times SU(2) \times U(1)$ symmetry group. It should also be possible to calculate all radiative corrections for the SM and beyond with such a theory. Therefore, the effective Lagrangian can be written as:

$$L_{eff} = L_{SM} + \sum_i \frac{c_i}{\Lambda^2} O_i^{(6)} + \frac{e_i}{\Lambda^4} O_i^{(8)} + \dots \quad (1.30)$$

In this formalism of the Lagrangian, the operators with odd dimension numbers are not considered since they violate the Leptonic and Baryonic numbers. The factors c_i and e_i represent the coupling coefficients.

The effective field theory is very general and it captures the low energy effects of new physics. If aTGCs exist, dimension six operators are expected to be the most sensitive to them. Dimension eight operators are most sensitive to the quartic gauge couplings. Therefore, to search for new physics, we start looking term by term in this Lagrangian, which means we start by studying the dimension six operators effects and neglecting the effects of all the others since they are smaller.

There are five dimension six operators, three of which conserve the CP and two of which violate it. The CP conserving operators can be written as [46][45]:

$$\begin{aligned} O_{WWW} &= Tr[W_{\mu\nu} W^{\nu\rho} W_{\rho}^{\mu}], \\ O_W &= (D_{\mu}\Phi)^{\dagger} W^{\mu\nu} (D_{\nu}\Phi), \\ O_B &= (D_{\mu}\Phi)^{\dagger} B^{\mu\nu} (D_{\nu}\Phi). \end{aligned} \quad (1.31)$$

The CP violating operators can be written as [46][45]:

$$\begin{aligned} O_{\tilde{W}WW} &= Tr[\tilde{W}_{\mu\nu} W^{\nu\rho} W_{\rho}^{\mu}], \\ O_{\tilde{W}} &= (D_{\mu}\Phi)^{\dagger} \tilde{W}^{\mu\nu} (D_{\nu}\Phi). \end{aligned} \quad (1.32)$$

With this approach to look for new physics, dimension six operators yield to terms in the amplitude growing as s/Λ^2 that will violate eventually unitarity at very high energies. However, the scale Λ of new physics is fixed and the aim of this theory is to study the low energy effects of new physics working on scales with which experimental data can be produced. Therefore, the unitarity bound will not be violated using this approach.

Although the formalism of the anomalous couplings approach differs from the effective field theory's modern approach, however at a fixed scale, where the new physics is expected, they can

be linked through a series of equations. These can be written as [46] [45]:

$$\begin{aligned}
g_1^Z &= 1 + c_W \frac{m_Z^2}{2\Lambda^2}, \\
\kappa_\gamma &= 1 + (c_W + c_B) \frac{m_W^2}{2\Lambda^2}, \\
\kappa_Z &= 1 + (c_W - c_B \tan^2 \theta_W) \frac{m_W^2}{2\Lambda^2}, \\
\lambda_\gamma &= \lambda_Z = c_{WWW} \frac{3g^2 m_W^2}{2\Lambda^2}, \\
g_4^V &= g_5^V = 0, \\
\tilde{\kappa}_\gamma &= c_{\tilde{W}} \frac{m_W^2}{2\Lambda^2}, \\
\tilde{\kappa}_Z &= -c_{\tilde{W}} \tan^2 \theta_W \frac{m_W^2}{2\Lambda^2}, \\
\tilde{\lambda}_\gamma &= \tilde{\lambda}_Z = c_{\tilde{W}WW} \frac{3g^2 m_W^2}{2\Lambda^2}.
\end{aligned} \tag{1.33}$$

The g , κ , and λ factors are used in the anomalous couplings approach, presented in section 1.3.1, so that Δg_V , $\Delta \kappa_V$, and λ_V different than zero shows the existence of an anomalous coupling, V being the vector boson in question, W or Z or γ .

The c_W , c_B , and c_{WWW} factors are defined in the effective field theory approach and they represent directly the non SM couplings.

This means that, at the scales which can be probed by data, the two approaches are valid and complementary.

1.3.3 Effect of aTGCs on the cross sections

The aTGCs, if they exist, appear in the form of an increase in the diboson production total cross sections shown in table 1.1. They could also be studied by controlling the differential distributions of the cross sections as a function of the kinematic variables. In fact, the aTGCs change the kinematics of the event. Therefore, the differential cross section as a function of variables such as the transverse momentum of the Z boson or the invariant mass of the VV system, where V could be W or Z , can be good candidates to study the anomalies of triples gauge couplings. Therefore aTGCs will appear as an increase in the tails of the differential cross section distributions. In figure 1.15, the effect of the different anomalous couplings on different kinematic variables is shown. These distributions are obtained using the MC@NLO event generator [47]. A form factor is used so that in equation (1.28) $n = 2$ and the cut-off scale Λ_{FF} is 2 TeV. The black lines show the expected distribution of the normalized differential cross section according to the SM prediction. The colored lines show the behavior of the differential cross section when the anomalous coupling is present. In these distributions, one anomalous coupling is varied at a time while fixing the others to their standard model values. The figure 1.15(a) shows that the cross section behavior with respect to the anomalous couplings is quadratic. This is because of the linearity of the anomalous couplings with the matrix elements. Since the cross section is proportional to the square of the matrix element, it leads then to a quadratic dependence between both.

Among the distributions shown in this figure, the transverse momentum of the Z boson shows the strongest sensitivity to the anomalous couplings. However, these variables are very sensitive to electroweak corrections effects and also QCD corrections effects. Therefore, it is also favor-

able to consider the study of the cross section as a function of variables that are less sensitive to these corrections such as the rapidity of the Z boson.

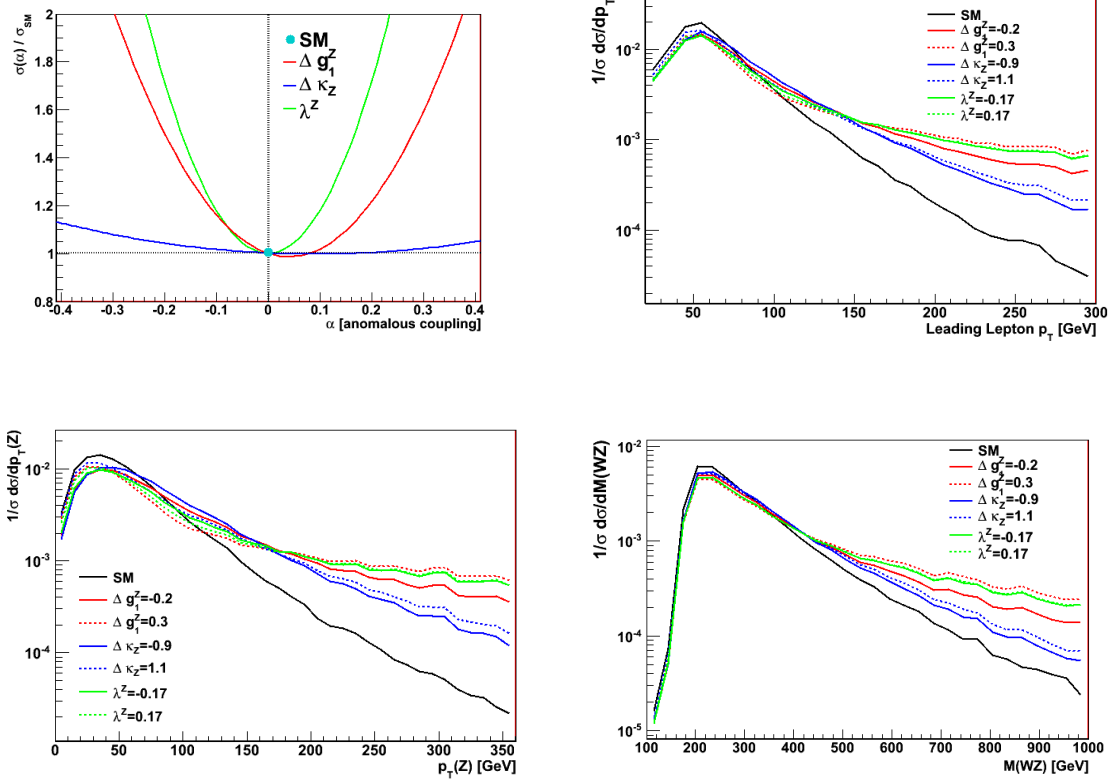


Figure 1.15: Effect of the anomalous triple gauge couplings on different kinematic variables. These distributions are obtained using MC@NLO event generator. A form factor with $n=2$ and a cut-off scale $\Lambda_{FF}=2$ TeV is used.

1.3.4 Previous experimental results on the anomalous triple gauge couplings

The first measurement of the anomalous triple gauge couplings took place at the Large electron-positron collider (LEP). The center-of-mass energy of collisions at LEP2 reached about 200 GeV. This allowed to produce diboson final states composed of WW and ZZ bosons, which enabled the computation of the $WW\gamma$ and WWZ couplings in parallel. Table 1.7 shows the combination of the LEP results with 95% Confidence Level (CL) and at a fixed cut-off scale $\Lambda=2$ TeV.

The LEP measurements were followed by updated ones from the Tevatron experiments. The Tevatron is a proton-anti-proton collider the center-of-mass energy of which reached 2 TeV. All the diboson final states were possible to be produced due to the interaction of hadrons. The limits that were set by the Tevatron on the aTGCs in the case of the WWZ couplings is shown in table 1.8. These limits are comparable to the results from LEP.

Experiment	Δg_1^Z	$\Delta \kappa_\gamma$	λ_Z
LEP2	[-0.051, 0.034]	[-0.105, 0.069]	[-0.060, 0.026]

Table 1.7: Best limits on the WWV anomalous couplings by the LEP experiments, where $\lambda_Z = \lambda_\gamma$ and $\kappa_Z = g_1^Z - \tan^2\theta_W(\kappa_\gamma - 1)$ [48].

Experiment	Δg_1^Z	$\Delta \kappa_Z$	λ_Z
D0	[-0.056, 0.154]	[-0.400, 0.675]	[-0.077, 0.093]
CDF	[-0.08, 0.20]	[-0.39, 0.90]	[-0.08, 0.10]

Table 1.8: Limits on the WWZ anomalous couplings by the Tevatron experiments using $\Lambda_{FF}=2$ TeV [49][50].

With the startup of the LHC, the limits on the aTGCs were expected to improve with respect to those from the Tevatron and LEP. The cross sections of production at the LHC are higher than those of the Tevatron, therefore a production with higher statistics is expected at the LHC and this will lead to more precise results. Table 1.9 show the results from the ATLAS and CMS experiments obtained with the 7 TeV collision data in 2011. These results are already comparable to the results from Tevatron with a better limit on the λ_Z coupling.

Experiment	Δg_1^Z	$\Delta \kappa_Z$	λ_Z
ATLAS	[-0.16, 0.24]	[-0.8, 1.0]	[-0.14, 0.14]
CMS	[-0.095, 0.095]	[-0.21, 0.22]	[-0.048, 0.048]

Table 1.9: Present limits on the WWZ anomalous couplings by the LHC experiments for $\Lambda_{FF}=\infty$ [51] [52].

In this thesis, using the 8 TeV whole 2012 ATLAS data, the WZ integrated and differential cross sections will be measured. Also, constraints on the aTGCs will be set. With higher statistics, further improvements with respect to the previous ATLAS and CMS measurements will be shown.

Chapter 2

The LHC machine and the ATLAS detector

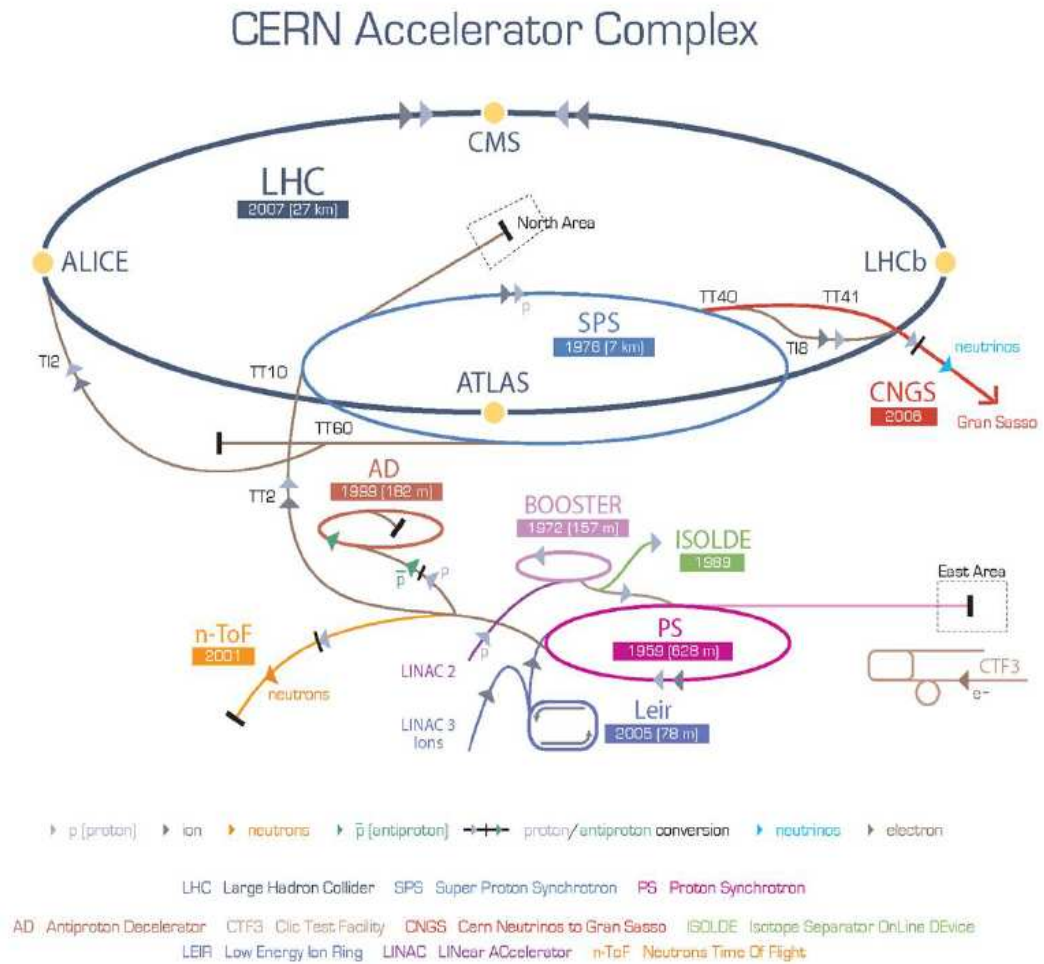


Figure 2.1: The LHC complex schematic view.

In this chapter, the Large Hadron Collider (LHC) machine and the ATLAS apparatus used for this PhD thesis, will be described. First an explanation about the way LHC functions will be presented, then the quantity of collected data from the $p - p$ collisions will be shown by defining the luminosity variable. Also, the ATLAS detector used in this thesis to identify the produced particles from the $p - p$ collisions, will be described with all its sub-components.

2.1 The LHC machine

The LHC [53] is the world's largest particle accelerator. The LHC is a large circular tunnel that has a circumference of 27 km and it is installed at on average 150 m in depth under the Jura Mountains on the Franco-Suisse border. The LHC is a proton collider and also can be used to accelerate heavy ions such as lead. It is used to probe the fundamental constituents of matter from the electroweak scale (a few hundreds of GeV) to a few TeV. The first successful operation of the LHC was on November 20, 2009 where beams collided at a center of mass energy of 900 GeV. The center of mass energy was then progressively increased to reach 7 TeV in 2010 and 2011, and 8 TeV in 2012. Then it went to a long shut down with the goal of restarting in 2015 with $p - p$ collisions at a center-of-mass energy of 13 TeV.

This section provides a brief summary about the LHC structure and functioning. Following references [53] [54] [55] [56] were used as sources and detailed information about the LHC can be found in them.

2.1.1 Operation of the LHC

The LHC accelerator complex is illustrated on figure 2.1. The LHC contains two accelerators built in the same system to accelerate two beams of proton in opposite directions. Two sets of dipole and quadrupole magnets are used to bend and focus the proton beams respectively. Figure 2.2 shows an image of the LHC NbTi dipole magnet components. These magnets are cooled down to 1.9 K and traversed by a current of about 12 kA, so that the superconducting coils produce a magnetic field of ~ 8 T, required to bend the beams of protons (at the nominal energy).

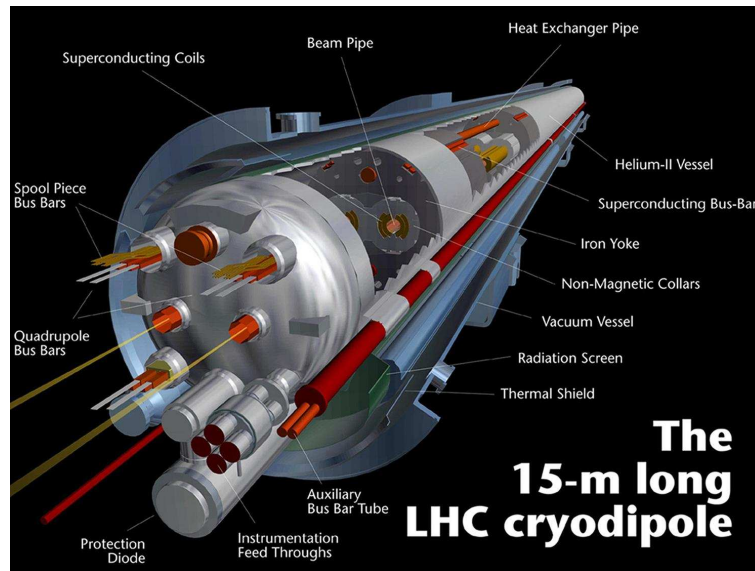


Figure 2.2: A dipole magnet illustration of the LHC [57].

The protons are obtained by stripping the electrons from the Hydrogen atoms and they are first accelerated in the linear accelerator (LINAC), to reach an energy of 50 MeV. After this step, the protons are injected into the Proton Synchrotron Booster (PSB) which accelerates them to an energy of 1.4 GeV. Then they are then fed to the Proton Synchrotron (PS), with 25 ns nominal bunch spacing, where they are collected in bunches so that each bunch contains $\sim 10^{11}$ protons.

In the PS they are accelerated to 25 GeV and sent to the Super Proton Synchrotron (SPS) where they are accelerated to 450 GeV. With this final energy, the beams are transmitted to the LHC in a clockwise and anti-clockwise directions where they are accelerated for about 20 min to their nominal center-of-mass energy.

The proton-proton interactions at the LHC, take place at four main points, points 1, 5, 2, and 8 as shown in figure 2.1. At these points the four main experiments of the LHC, ATLAS, CMS, ALICE, and LHCb, are installed. Among these experiments, ATLAS and CMS are general purpose experiments. The LHCb experiment is more specifically designed to perform precision measurements related to the CP violation and flavor physics studies. Finally ALICE, is dedicated to heavy ions collisions and to explore the physical properties of matter under the strong interaction by studying the formation and properties of gluon-quark plasma.

2.1.2 The LHC luminosity

By definition, luminosity is the quantity that measures the ability of a particle accelerator to produce a given number of interactions. In mathematical formulation, this can be written as:

$$\frac{dN}{dt} = \mathcal{L} \cdot \sigma, \quad (2.1)$$

where N is the number of events, σ is the cross section of the interaction, and $\mathcal{L}$ is the luminosity.

The unit of the luminosity is $\text{cm}^{-2}\text{s}^{-1}$. The integral of the luminosity over time is called the integrated luminosity the unit of which is the inverse barn, b^{-1} , (usually the fb^{-1} will be used in this thesis) and it is a quantity that is widely used in particle physics experiments to refer to the quantity of data that was collected.

At the LHC, the instantaneous luminosity is mathematically written as [53]:

$$\mathcal{L} = \frac{N_p n_b^2 f_{rev} \gamma_r}{4\epsilon_n \beta^*} \times F, \quad (2.2)$$

where N_p is the number of protons per bunch, n_b is the number of bunches per beam, f_{rev} is the revolution frequency, γ_r is the relativistic gamma factor, ϵ_n is the normalized transverse beam emittance representing the volume occupied by the beam, β^* is the value of the β amplitude function at the collision point, and finally F is a geometric luminosity reduction factor dependent on the crossing angle at the interaction point.

According to the LHC design, the nominal bunch spacing is 25 ns and each proton nucleus can reach an energy of up to 7 TeV. The nominal instantaneous luminosity of the LHC is $10^{34} \text{ cm}^{-2}\text{s}^{-1}$. At the LHC, the instantaneous luminosity did not reach its nominal value so far but it attained more than $10^{33} \text{ cm}^{-2}\text{s}^{-1}$. In 2011, the quantity of data collected corresponded to an integrated luminosity of about 5 fb^{-1} and $\sim 20 \text{ fb}^{-1}$ in 2012. The bunch spacing was 50 ns (nominal value is 25 ns) and the center-of-mass energy of the proton collisions was 7 and 8 TeV in 2011 and 2012, respectively.

Figures 2.3 (a) and (b) show the evolution of the integrated luminosity recorded by the ATLAS experiment during the 2011 and 2012 data taking periods.

The LHC has also limitations. A first limitation is related to the machine. The high magnetic field in the magnets and their heating because of the radiation losses of the beam put limits on the

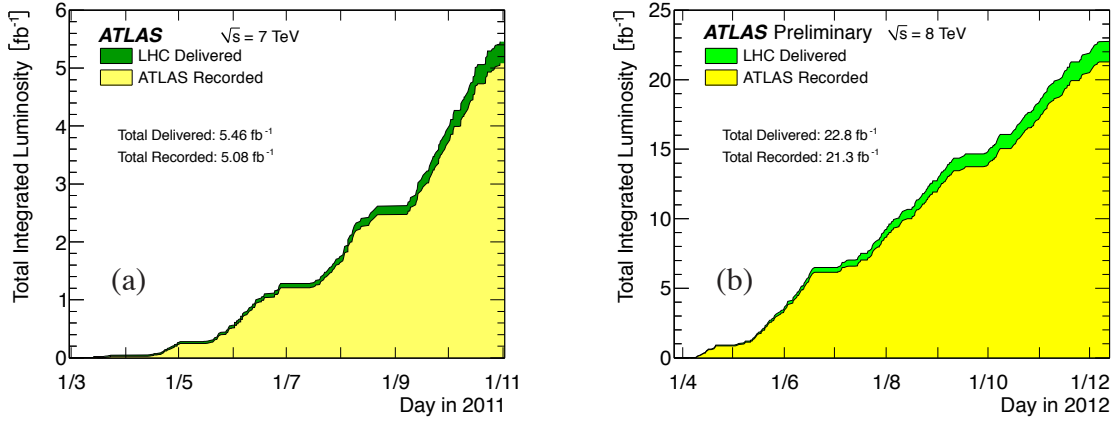


Figure 2.3: The evolution of the total integrated luminosity during the 2011 (a) and 2012 (b) ATLAS data taking [58].

intensity of the beam. However, the main challenge of the LHC is physics related. The interactions that occur near the main interaction point result in the production of particles that interact in the detector. This phenomenon is called “pile-up”. The pile-up events are usually softer and less energetic than the events coming from the main interaction point. They are categorized in two series: *in-time* and *out-of-time* pile-up events. The term *in-time* refers to the secondary events that are produced by multiple interactions of the protons in the same bunch crossing. The *out-of-time* pile-up events are produced during the crossing of two or more successive bunches. Figure 2.4 shows the average number of additional superimposed collisions per bunch crossing, a variable called $\langle \mu \rangle$, during the 2012 data taking. The distribution is peaked around $\langle \mu \rangle = 20$ and this means that almost 20 interactions are taking place in a single bunch crossing. At high luminosities, the pile-up increases and this adds complication especially in the energy calibration of the detected particles that are interesting for physics analyses. A good understanding and modeling of the pile-up events is compulsory for the analysis of ATLAS data.

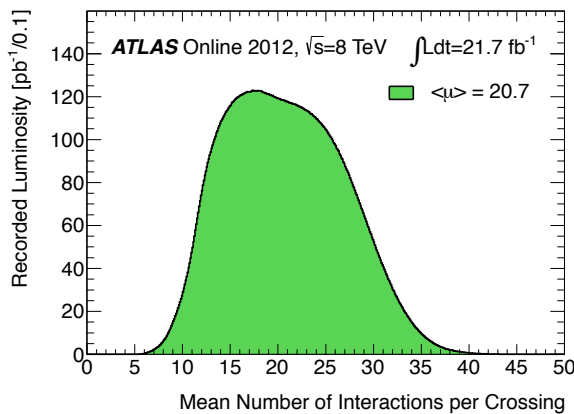


Figure 2.4: Distribution of the average interaction per bunch crossing integrated over the whole 2012 data taking [58].

2.2 The ATLAS detector

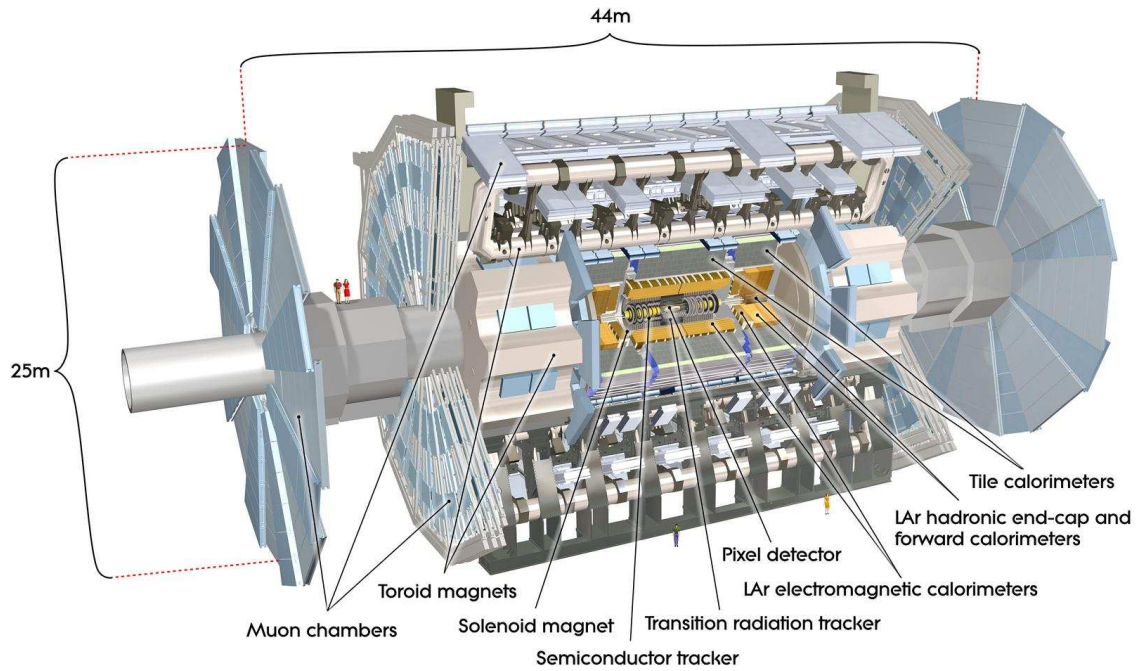


Figure 2.5: A complete view of the ATLAS detector and all its components [59].

In this section the description of the ATLAS detector will be presented.

2.2.1 Architecture and coordinate system

ATLAS is the acronym of “A Toroidal LHC Apparatus”. The detector is located at the point 1 cavern of the LHC where collisions take place. ATLAS is a general purpose detector, designed to identify and measure energies and directions of charged and neutral elementary particles created at the interaction point such as e.g. electrons, muons or hadronic-jets.

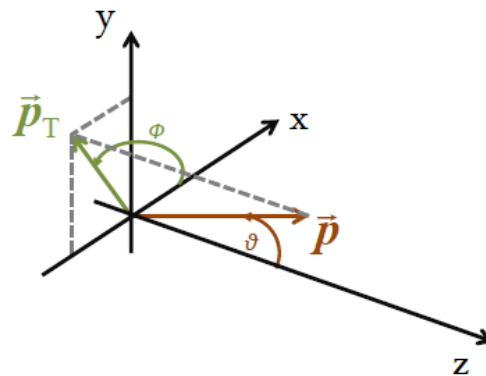


Figure 2.6: The coordinate system used for the ATLAS detector.

As shown in Figure 2.6, the x, y, z Cartesian coordinate system is used by ATLAS. The interaction point is at the center of the detector which also represents the origin of the coordinate system. The z -axis is along the beam line while the plane formed by the x and y axes form the transverse plane. The positive direction of the x -axis points towards the LHC center and the positive y -axis is upwards. To position the different components of the detector, spherical coordinates θ and ϕ are used. θ is the polar angle and ϕ is the azimuth angle. More frequently, a quantity called the pseudorapidity η , which is a function of the polar angle, is used so that: $\eta = -\ln|\tan(\theta/2)|$. In more general cases the rapidity

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right), \quad (2.3)$$

is used in a way that when $E \rightarrow \infty$, $y \rightarrow \eta$. In the detector, the distance between two objects in the (η, ϕ) plane is defined by the variable $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$.

In ATLAS, it is very common to use the transverse kinematic quantities of objects such as the transverse momentum, p_T . The reason we are interested in the transverse variables is because the collisions occur initially along the beam line, this means that the total energy in the transverse plane is initially zero, the transverse impulsion of the initial partons being close to zero. Therefore, performing measurements in the transverse plane enables to determine the signature of particles that do not interact with the detector such as the neutrinos. They can be identified by a measurement of a missing energy in the transverse plane which is called the Missing Transverse Energy (E_T^{miss}).

A particle's four-momentum vector can be written as $(E, \mathbf{p})$ where $\mathbf{p}$ is the vector momentum (p_x, p_y, p_z) . The transverse momentum is defined as $p_T = \sqrt{p_x^2 + p_y^2}$ as well as the transverse energy $E_T = E \sin(\theta)$.

ATLAS [59] has a cylindrical geometry with 44 m long and 25 m high. It weighs about 7000 tonnes and covers about 4π of the geometrical acceptance. It is composed of an Inner Detector (ID) which is used to measure the trajectory of charged particles and infer their momenta. The ID is immersed in a 2 T magnetic field delivered by a solenoid magnet. It is built based on three types of technologies: the micro-strip technology, the semi-conductor technology, and a final one using straw drift tubes with a transition radiation detector to help identifying the electrons. On the outer part of the ID the calorimeters are placed to measure the energy of neutral and charged particles. The ATLAS calorimeters are composed of an ElectroMagnetic part (EM), based on the liquid Argon technology and used to measure the energy of photons and electrons and a hadronic part, the Tile calorimeter using the tile scintillator technology to measure the energy of hadronic jets. The EM calorimeter is known for its very high granularity, therefore it provides measurements with very high resolution. Finally, the Muon Spectrometer (MS), located on the edge of the detector, is immersed in a variable magnetic field delivered by a system of toroid magnets. This spectrometer, is used specifically to detect muons. Muons interact first in the ID, unlike all other particles they pass through the calorimeters losing only a very small amount of their energy and leaving tracks in the MS. This allows the double measurement of the muon tracks in the ID and MS and hence matching their track momenta using the information from both detectors.

The required resolution and the coverage, in terms of pseudorapidity η , of each of the ATLAS subsystems is given in table 2.1

Sub-detector	Resolution	η coverage measurement	η coverage trigger
Inner Detector	$\sigma_{p_T}/p_T = 0.05\% p_T \oplus 1\%$	$ \eta < 2.5$	-
EM Calorimeter	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$	$ \eta < 3.2$	$ \eta < 2.5$
Tile Calorimeter Barrel and end-cap	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$	$ \eta < 3.2$	$ \eta < 3.2$
Forward Calorimeter	$\sigma_E/E = 100\%/\sqrt{E} \oplus 10\%$	$3.1 < \eta < 4.9$	$3.1 < \eta < 4.9$
Muon Spectrometer	$\sigma_{p_T}/p_T = 10\%$ at 1 TeV	$ \eta < 2.7$	$ \eta < 2.4$

Table 2.1: Performance goals of the main ATLAS sub-detectors [59]. The p_T and E units are in GeV.

More detailed explanations about the detector and all its sub-components can be found in references [59] [60] [61].

2.2.2 The Magnet System

The momentum of a charged particle can be measured by the bending of its trajectory in a magnetic field. Therefore, the two tracking systems of the ATLAS detector are immersed in magnetic fields delivered by solenoid and toroid magnets. The solenoid magnet delivers a 2 T magnetic field to the inner detector. The axis of this solenoid is the beam line, it has a length of 5.8 m and an outer diameter of 2.56 m. To bend the tracks of muons, a system of three toroid magnets is used for the Muon Spectrometer. One magnet in the barrel region and two in the end-caps. The barrel magnet is composed of eight coils and produces a magnetic field of about 0.5 T. While the end-cap magnets are also composed of 8 coils and produce a magnetic field of ~ 1 T. Figure 2.7 show the layout of the ATLAS magnet system which present a total diameter of 22 m and a total length of 26 m.

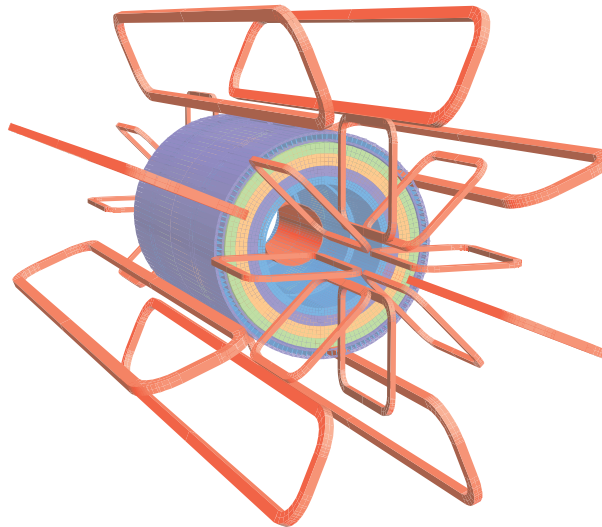


Figure 2.7: Layout of the ATLAS magnet system [59].

2.2.3 The Inner Detector

In the core of the ATLAS detector, the ID is installed in the form of a cylinder with the beam line as the axis. It is 6.2 m long with a radius of 1.15 m. The ID provides a total coverage in $|\eta|$ of 2.5 and it aims in measuring the trajectory of charged particles and deducing their momenta. The solenoid magnet of ATLAS is installed in a way to cover the ID and the 2 T magnetic field that is delivered, bends the tracks of charged particles. The degree of curvature of a track enables the measurement of the particle momentum. The ATLAS ID is composed of three independent sub-detectors as shown in Figures 2.8 (a) and (b). A silicon pixel detector, a Semi-Conductor Tracker (SCT) built of stereo pairs of silicon microstrips, and a Transition Radiation Tracker (TRT) containing layers of straw tubes filled with gas. In Figure (b) we can see the space occupied by each sub-detector and each of their sub-components.

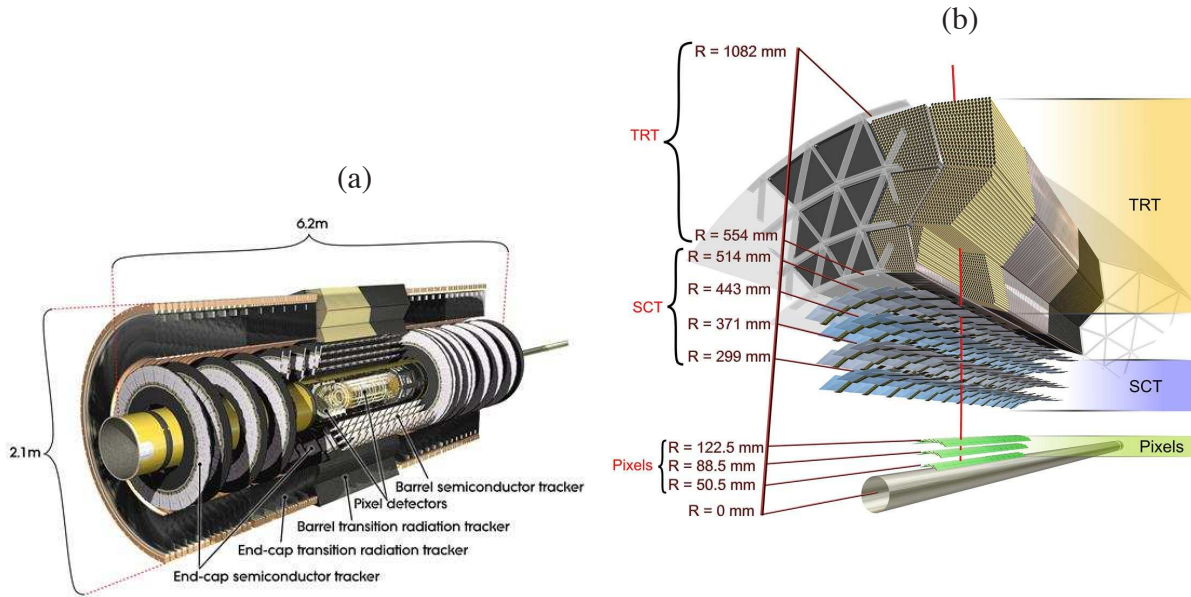


Figure 2.8: (a) Scheme of the Inner Detector of ATLAS with all its components. (b) Scheme of a transverse section of the ID with its three sub-detectors and the dimension occupied by their sub-components [59].

The silicon pixel detector is the innermost detector with respect to the beam line. Its main function is to reconstruct tracks and measure displaced vertices rising from an interaction. The pixel detector is composed of three barrel and three end-cap layers. Its first layer enables building secondary vertices issued from b -quarks. From where it is named the b -layer. The nominal size of each pixel is $50 \times 400 \mu\text{m}^2$. The intrinsic resolution of the pixel detector is $10 \mu\text{m}$ in the $(R-\phi)$ plane and $115 \mu\text{m}$ in the z direction. In total the pixel detector is composed of 1744 modules each connected to 46080 readout channels equivalent to about 80 million pixels in total.

The Semi-Conductor Tracker is composed of silicon strips. It surrounds the pixel detector with also a cylindrical shape. It is however, not as granular as the pixel detector. The SCT has barrel and endcap modules. The barrel contains four cylindrical layers. The detector uses stereo strip positions with stereo angle of 40 mrad. In the end-cap region, each end-cap is composed of nine disks. The strips are also placed at an angle of 40 mrad but they run radially outwards from the beam line. In total each module of the SCT contains 768 strips per side. The micro-strip sensors of each module of the SCT are placed back-to-back to provide a double coordinate measurement of the track-hit system. This kind of geometry enables a precise measurement with

a reduction of the noise. The intrinsic accuracy of the SCT modules is $17\ \mu\text{m}$ in the $(R-\phi)$ plane and $580\ \mu\text{m}$ in the z direction for the barrel. For the end-cap disks, it is $17\ \mu\text{m}$ in the $(R-\phi)$ plane and $580\ \mu\text{m}$ in the R direction. With this kind of design, the SCT allows measurement of at least eight hits per track, which provides a very precise tracking complementing the detection started in the pixel detector.

The Transition Radiation Tracker is the final component of the ID and it is placed in a cylinder after the SCT and up to a radius of about 1 meter. It is composed of 73 barrel straw planes and two end-caps with 160 straw planes each. The straws are filled with Xe-CO₂ gas with 70% Xe, 27% CO₂, and 3% O₂ proportions. About 351000 straw tubes of 4 mm of diameter each provide a large number of hits of about 36 hits per track to enable the precise following of the track to up to $|\eta| = 2$. The emitted transition radiation is dependent on the Lorentz factor γ . As electrons are much lighter than charged pions, for the same energies, the transition radiation emitted by electrons is much more important than that of charged pions. A threshold is therefore set on the signal amplitudes in order to discriminate between pions and electrons. The intrinsic accuracy of the TRT is $130\ \mu\text{m}$ in the $(R-\phi)$ plane. The information provided in the longitudinal direction is not accurate. Although the resolution of this detector is lower than that of the SCT and the pixel detector, the large number of hits it provides can help in track finding through pattern recognition. Otherwise, its large radial extension ($\sim 1\ \text{m}$) leads to a substantial path integral in the magnetic field which improves the momentum resolution.

2.2.4 The Calorimeters

The ATLAS calorimeter is used to detect and measure the energy of hadronic and electromagnetic particles. It is composed of two parts: Electromagnetic and Hadronic. For the electromagnetic calorimetry the Liquid Argon (LAr) is used as the active medium and lead accordion shaped electrodes as the passive medium. An accordion geometry is used to provide a complete ϕ symmetry and avoid azimuthal cracks. The LAr electromagnetic calorimeter contains an electromagnetic barrel (EMB), an endcap (EMEC), and a forward calorimeter (FCAL). In the hadronic part the liquid argon technology is used in the hadronic endcap (HEC) that covers an $|\eta|$ region of 1.8 up to 3.2 for radii less than 2.2m. Barrel and end-cap presamplers are used to recover for the energy loss in the material in front of the calorimeter (mainly material in the solenoid magnet). The hadronic calorimetry is also completed with the Tile calorimeter that uses scintillating tiles and aims in measuring the energy of hadronic depositions from jets. A cryostat is needed for the LAr calorimeter to keep the liquid argon at a temperature of 90 K and therefore a barrel cryostat contains the EMB and two endcap cryostats contain the EMEC, FCAL, and HEC.

2.2.4.1 The presampler

The presampler is a separate thin active layer located in front of the electromagnetic calorimeters. An electron, a positron or a photon may start a shower while crossing the material in the inner detector, as cables, support material or material for services, before arriving to the calorimeter. Also, the 2 T magnetic field can bend the trajectory of some of these secondary particles in a way that they hit the calorimeter in an inactive or dead region. Therefore, the energy measured in the calorimeter is smaller than the initial energy of the incident particle. The presampler provides a recovery for this energy loss. A barrel and endcap LAr presamplers are implemented in front of the barrel and endcap calorimeters. The barrel presampler covers the pseudorapidity region up to $|\eta|=1.3$. The situation is critical in the transition region between the barrel and the end-cap where $|\eta|$ is around 1.4 and a scintillator layer is used to recover for the jet energy measurements. The

complications created by the transition region led to the construction of an endcap presampler to cover a pseudorapidity range of up to $|\eta|=1.8$ [62].

2.2.4.2 The LAr Calorimeter

Figure 2.9 shows a picture of the LAr Calorimeter with all its four partitions.

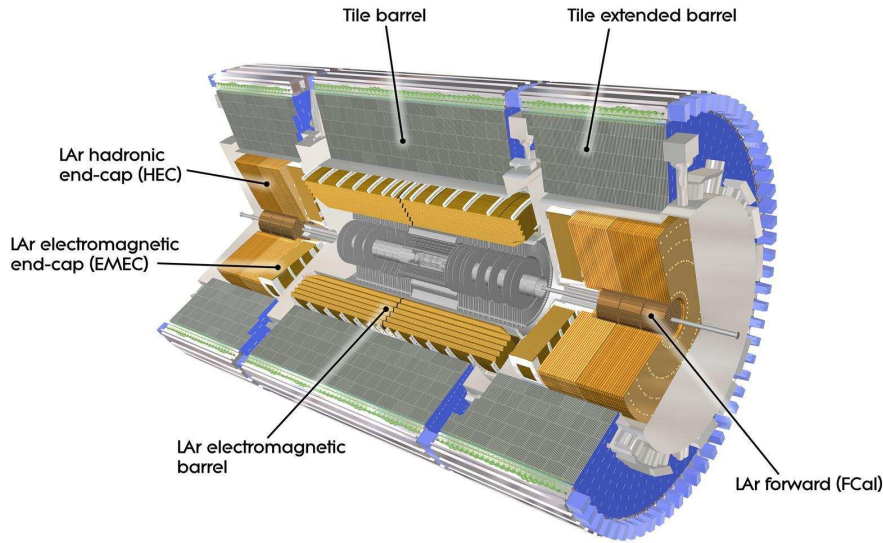


Figure 2.9: The ATLAS LAr Calorimeter [59].

- The central and end-caps LAr Calorimeters

The electromagnetic calorimeters are liquid Argon-lead sampling calorimeters, they provide a full azimuth coverage, and they contain globally 173312 readout channels of which 99.96% are functional [63].

In the central cryostat, the EMB is installed covering the central pseudorapidity range up to $|\eta| < 1.475$. It consists of two identical half-barrels with a gap of few millimetres in between. The EMB consists of 1024 accordion shaped absorbers with 1024 read out electrodes.

In the end-cap cryostat the EMEC is installed covering the pseudorapidity range $1.375 < |\eta| < 3.2$. The EMEC is a cylindrical wheel, with the accordion wave amplitude decreasing at larger radii, creating mechanical constraints and the need of a second independent wheel. Therefore, the EMEC is composed of two wheels, an outer one covering a pseudorapidity up to $|\eta|=2.5$ with three depth segments and an inner wheel, covering the range from $|\eta|=2.5$ to $|\eta|=3.2$ with two depth segments [62]. The EMB and EMEC calorimeters are each segmented in three layers, each having different cell granularities. A transverse and longitudinal section of the EMB calorimeter is represented in Figure 2.10 exemplifying the granularities of the different layers and the accordion shape. The shower development can be shown by a longitudinal segmentation.

- The Forward LAr Calorimeter

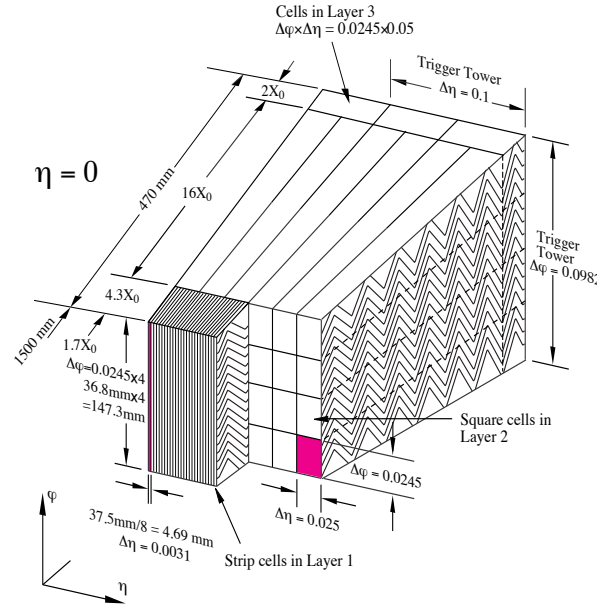


Figure 2.10: A longitudinal and transverse view of the LAr barrel calorimeter that shows the accordion structure and the difference in granularity between the different layers [59].

The FCAL is a LAr sampling calorimeter. The FCAL provides electromagnetic and hadronic coverage in the range $3.2 < |\eta| < 4.9$, it contains 3524 readout channels of which 99.94% are operational [63]. It consists of three modules in each end-cap made of copper and tungsten.

The FCAL modules consist of regularly spaced longitudinal channels forming a metal matrix. The channels are filled with an electrode structure that consists of concentric rods and tubes parallel to the beam axis. The active medium (LAr) is filled in the gaps between the rods and the tubes.

The FCAL is a very challenging detector since it is submitted to a high level of radiation due to its location close to the beam axis. For that reason, the FCAL was designed using radiation resistant materials, mechanical simplicity, high average density, maximum projective thickness and a minimum number of projective thin spots.

- The Hadronic End-Cap LAr Calorimeter

The HEC is also based on LAr technology. It consists of two independent wheels located behind the EMEC and sharing the same LAr cryostat. The first wheel is made of 25 mm copper plates and the second of 50 mm plates. The plates are spaced by 8.5 mm LAr gaps. Three electrodes divide the 8.5 mm gaps into four LAr drift zones. Each zone is supplied with high voltage (HV) and these HV planes form an electrostatic transformer structure which has the advantage of providing redundancy in case of HV faults.

The HEC covers a pseudorapidity range of $1.5 < |\eta| < 3.2$ and it contains 5632 readout channel from which 99.61% are functional [63].

2.2.4.3 The LAr electronics

When charged particles traverse the liquid argon, they ionize it, creating an ionization current which is then measured on the readout cells of the electrodes. The original signal has a triangular shape, and is received by the Front End Boards (FEBs) where it is amplified, shaped, and

digitized as shown in Figure 2.11. The LAr calorimeter signals are sampled at 40 MHz LHC bunch crossing frequency and then stored in an analog pipeline called Switch Capacitor Array before being triggered. The triggered signals are digitized by a 12 bit Analog-to-Digital Converter (ADC) and five samples around the peak spaced by 25 ns are selected. The signals are then sent through an optical link to the ReadOut Drivers (RODs) that are a part of the back-end electronics. In the ROD amplitude and time delay of the signal are computed. Finally, the ROD outputs are received by the Data acquisition (DAQ) where events are selected and data is recorded.

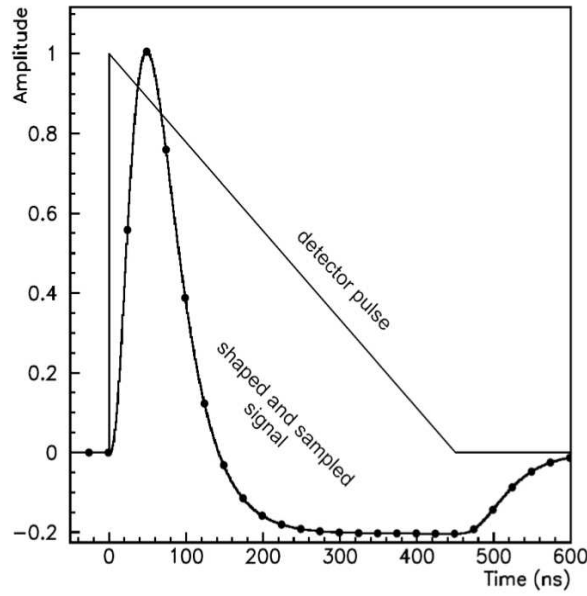


Figure 2.11: The original and shaped pulse shapes [62].

• The Front End Boards

The number of FEBs is 1524 in total. Each FEB contains 128 cells and the position of the cells connected to a FEB can be defined by the slots and FeedThroughs (FT) (these are the cables connected to the FEBs). The FT numbers define the position of the cells in ϕ and the slots numbers define the position of the FEBs in η within each FT. The number of FEBs in the EMB is 824. The EMEC contains 552 FEBs. In the HEC the number of FEBs is 48 and finally the FCAL has 28 FEBs. In general each FT contains 16 slots and the number of FTs in total is 32 [64]. The number of FTs per LAr calorimeter partition is given in Table 2.2.

partition	EMB	End-Cap
Number of FTs	0-31	0-19

Table 2.2: Summary of the number of FTs in each LAr partition.

Inside a FEB, the signal is first pre-amplified. Then shapers, that function in a way to limit the system bandwidth to match the 40 MHz sampling frequency, produce three output signals with three linear gains: High (gain ratio=82), Medium (gain ratio = 8.4), and Low (gain ratio = 0.8) each having a dynamic range better than 12 bits. The output shaped signal is sampled

at 40 MHz and 5 samples around the peak spaced by 25 ns are extracted and sent to a 12-bit ADC.

- The Readout Drivers

The ROD modules receive raw data from the FEBs and use the Optimal Filtering method described in the next section, to calculate the energy of the deposition and its time. Also, a quality factor, which is a χ^2 like quantity, that compares the measured pulse shape to the predicted one, is computed. There are 192 RODs and each can be connected to up to 8 FEBs [65].

Figure 2.12 shows the architecture of the front-end electronics of the LAr calorimeter readout system.

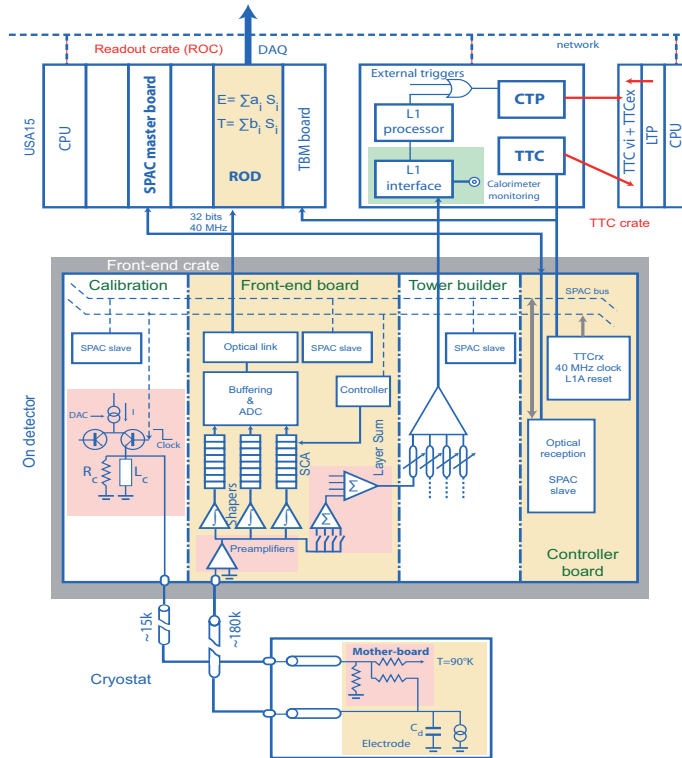


Figure 2.12: The architecture of the front-end electronics of the LAr calorimeter readout system [59].

2.2.4.4 The Optimal Filtering method (OF)

As explained in the previous section, the bipolar signal is sampled every 25 ns and 5 samples are digitized and used in the signal reconstruction. For these 5 samples two quantities are computed. One is the maximum amplitude of the signal, $A_{(max)}$, which is proportional to the energy of the electromagnetic deposition and the other is the time shift Δt of the signal with respect to a reference time, equal to the time of the proton-proton collision. In ATLAS, the OF algorithm is used to compute these quantities. The OF algorithm is a digital filtering method. It concentrates on the effect of the signal distortion caused by thermal noise and physics noise (coming from “pile-up” events). The easiest way to determine the amplitude of the signal is to make a single measurement at the peak of the pulse. However due to variations between different channels, it is better to combine the samples in an optimal way to achieve an accuracy that exceeds that of a single sample. The amplitude and time definitions computed with the OF algorithm defined by [66] :

$$A_{max} = \sum_{i=0}^n a_i (s_i - p), \quad (2.4)$$

$$\Delta t = \frac{1}{A_{max}} \sum_{i=0}^n b_i (s_i - p). \quad (2.5)$$

The coefficients a_i and b_i represent the OF coefficients (OFCs) and are used to calculate energy and time. They are computed such that the noise contribution and pile-up effects are reduced.

s_i are the samples and p is the electronic pedestal. n represents the number of samples, which in this case is always equal to 5. The OFCs are extracted from the good knowledge of the pulse shape normalized to one and from its derivative. It provides a good minimization of the noise contributions. Today, with high energy signals only one set of OFCs in bins of $\Delta t = \frac{25ns}{24} = 1.04$ ns are calculated, where Δt is the minimal time distance between two consecutive samples. The numerator presents the time of sampling the signal. The denominator presents the binning of the OFC phases.

If the samples are phased in time, this leads to wrong computation of OFCs. Therefore, for a time shift corresponding to ~ 5 ns, a 0.5% bias on the energy reconstruction is introduced. The OFCs can be performed by the ATLAS offline software. They are loaded in the Digital Signal Processors (DSPs) located on the back end RODs and play a key role in the energy and time measurement of the depositions inside the calorimeter.

2.2.5 The Tile calorimeter

The Tile calorimeter (TileCal) [67] is a sampling calorimeter that envelopes the ATLAS EM calorimeter. It uses steel plates as the absorber and scintillating tiles of polystyrene as the active material. It is composed of a barrel and two extended-barrel modules. The former covers a pseudorapidity range of $|\eta| < 1.0$ and the latter cover for $0.8 < |\eta| < 1.7$. The Tile Calorimeter has an inner radius of 2.28 m and an outer one of 4.25 m. The tiles are positioned perpendicular to the beam line. The signal is produced when hadronic particles interact with the active medium emitting light which is detected by photo-multipliers present at the end of each tile module. This is shown in Figure 2.13.

This calorimeter, together with the FCAL and HEC provides the energy reconstruction of hadronic jets and the missing transverse energy.

Figure 2.14 shows the amount of material for each of the ATLAS calorimeter parts. The figure shows that the calorimeters provide at least 10 interaction lengths as a function of η . This means that the full hadronic showers can be contained in the calorimeters up to very high energies.

2.2.6 The Muon Spectrometer

The Muon Spectrometer [68] as shown in Figure 2.15 is the outermost part of the ATLAS detector located right after the calorimeters. It is designed to measure the tracks and deduce the momenta of the charged particles leaving the calorimeters, namely the muons. It covers a pseudorapidity range $|\eta| < 2.7$ and it is composed of precision chambers as well as trigger chambers that can cover up to $|\eta| = 2.4$. Any measurement in the MS only is called a stand-alone measurement. Muons loose about 3 GeV from the interaction with the material in the calorimeters. Therefore, the stand-alone muons estimated momenta values are lower by ~ 3 GeV than their original momenta. The muon momentum resolution is about 10% for 1 TeV muons. This detector gives an

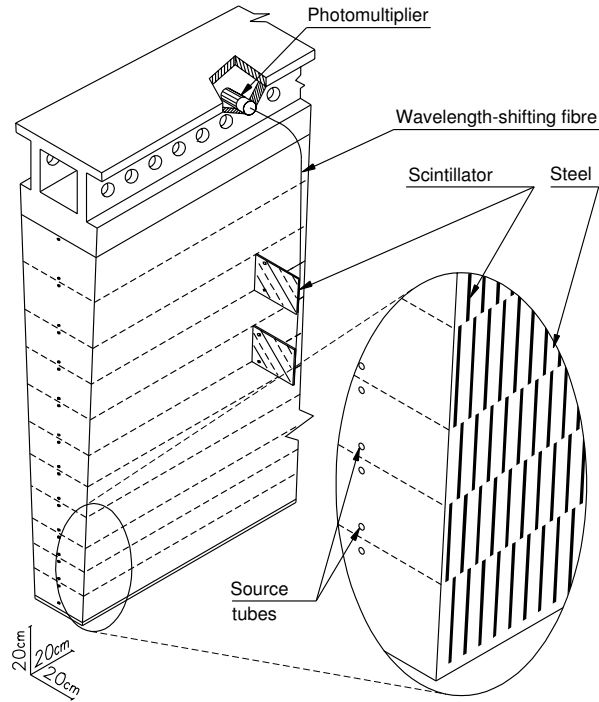


Figure 2.13: Schematic view of a module of the Tile Calorimeter [59].

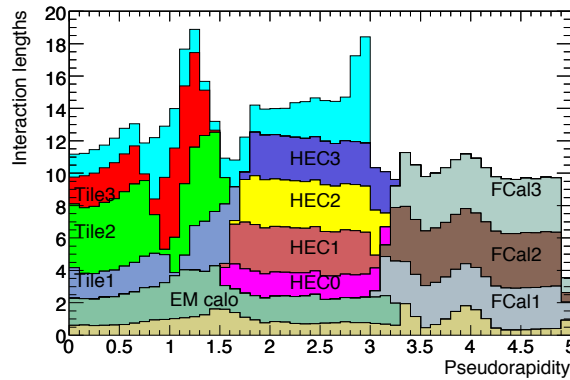


Figure 2.14: The amount of material in the calorimeters in units of interaction length as a function of the pseudorapidity.

excellent measurement of the muon track curvature leading to the precise measurement of the muon momentum. The muon charge is deduced from the sign of the track curvature.

The MS is composed of four sub-detectors. The Monitored Drift Tubes (MDT) that measure precisely the momentum of muons. In the forward region, where higher fluxes of particles exist, the MDTs are replaced with the Cathod Strip Chambers (CSC). In addition to the precision chambers, there exist two chambers for triggering. In the central part of the MS the triggering is performed through the Resistive Plate Chambers (RPC) and the Thin Gap Chambers (TGC) are used in the end-cap parts.

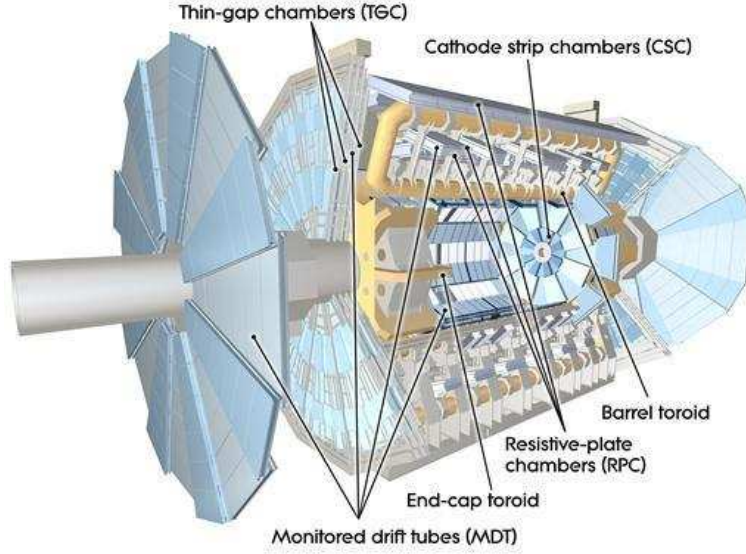


Figure 2.15: A schematic view of the ATLAS Muon Spectrometer [59].

2.2.6.1 The Monitored Drift Tubes

The MDT chambers are built with 3 bars pressurized tubes of diameter ~ 30 mm filled with Ar/CO₂ gas. In the center of the tubes a tungsten-rhenium wire of diameter of $50\mu\text{m}$ collects the ionization electrons produced through the interaction of the charged particles with the gas and this provides our signal. The chambers are built with many layers of the tubes. In the barrel part, they are rectangular while in the end-caps they are trapezoidal. The direction of the tubes both in the barrel and end-caps are along the ϕ direction. In the barrel, all tubes have the same length while in the end-cap chambers the lengths of the tubes vary as a function of R . The single MDT hit resolution is about $80\mu\text{m}$.

2.2.6.2 The Cathod Strip Chambers

The MDTs will no longer be on a safe functioning mode when the particles flow exceed the rate of 150 Hz/cm^2 . This kind of scenario takes place in the MS for $|\eta| > 2.0$. Therefore, for that region the MDTs are replaced by cathode-strip chambers which occupy a large space, provide a high tracking resolution and an ability to receive safely the particles with a rate of up to 1000 Hz/cm^2 .

The CSC contains two large disks with eight chambers each. Each chamber is built of four CSC planes providing four (η, ϕ) independent measurements for each muon track. Similarly to MDTs, the CSCs also have anode wires and the strips act as the cathode. They are filled also with Argon and Carbon dioxide gases with 80% and 20% of proportions respectively. The resolution of a CSC plane can reach up to $60\mu\text{m}$.

2.2.6.3 The Resistive Plate Chambers

The RPCs are part of the triggering system of the MS. They are installed in the barrel module of the MS in the form of three concentric cylinders around the beam line, called trigger stations. Besides triggering, they also provide a measurement of the second-coordinate of a track in the barrel region. Each station is composed of two detector layers that provide a separate measurements in (η, ϕ) . Therefore, for each track, RPCs provide six (η, ϕ) measurements.

Unlike the MDTs and CSCs, the RPCs are parallel plate devices with no wires. The plates are built with phenolic-melaminic plastic laminate separated at a distance of 2 mm. They are filled with gas composed of $C_2H_2F_4$ with 94.7%, $Isobutane - C_4H_{10}$ with 5%, and SF_6 with 0.3%. When a particle enters the chamber, it ionizes the gas and produces electron avalanches that create the signal. This signal is read out by capacitive metallic strips that are mounted on the outer part of the RPC resistive plates. The chamber resolution of the RPCs is 10 mm in the z and ϕ directions.

2.2.6.4 The Thin Gap Chambers

The TGCs are the analog of the RPCs but they are installed in the end-cap region of the MS. They also provide a triggering capacity and a measurement of the second-coordinate in the ϕ direction. This complements the measurement provided by the MDT in the η direction.

The TGCs are composed of multi-wire proportional chambers. The distance from the wires to the cathode is 1.4 mm while the distance from one wire to another is 1.8 mm. The gas mixture inside the chambers is Carbon Dioxide by 55% and n-pentane by 45%. As the charged particle traverses the gas, it ionizes it. The electrons produced are then drifted to the anode creating the signal. The thin gaps of this detector provide a very fast signal response with a hit time resolution of 4 ns. The TGCs contain seven layers that are grouped in a triplet and two doublets. These are mounted on two circular outer and forward concentric disks. The resolution of these chambers is 2-6 mm in the η direction and 3-7 mm in the ϕ direction.

2.2.7 The Trigger System

For the $p - p$ collisions at the LHC considered for our studies, the bunch crossing time for the ATLAS detector was 50 ns which is different than its nominal value (25 ns). The consequence of this high rate of bunch crossings is the production of huge amounts of data that cannot be easily stored with today's technological tools. Besides, not all the events that are produced in a collision can be interesting for physics analyses, some being very soft and noisy events. The ATLAS trigger system was therefore built to provide a way to filter the ATLAS data, from initially at a bunch crossing rate of 20 MHz to a rate of 40 Hz. The trigger system of ATLAS has three components, the Level-1 trigger (L1), the Level-2 trigger (L2), and the Event Filter (EF). The L2 and EF triggers form a system called the High Level Triggers (HLT). Complex algorithms are used by these triggers to recognize the events of interest and keep them for analysis.

The L1 trigger is hardware based. For muons, it uses the information from the muon spectrometer trigger chambers and for all other objects such as the EM cluster, jets, etc. it uses the information from the calorimeters. This information is used to define Regions of Interest or RoIs where the energy deposition is higher than a certain threshold. This trigger has a very high granularity so that $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$. The trigger response is of the order of $2.5 \mu s$ and reduces the 20 MHz data rate to 75 kHz.

The L2 trigger is based on commercial computers. It uses the output of the L1 trigger and searches for events of interest in the RoIs using refined computations and higher granularity than at the L1 Trigger. Events are kept in the regions where future possible objects such as electrons or muons are identified. The L2 trigger decision occurs within 40 ms and reduces further the data rate to about 4 kHz.

Finally, the event filter, also based on commercial computers, uses the most sophisticated algorithms among all other trigger levels. It uses object reconstruction algorithms similar to

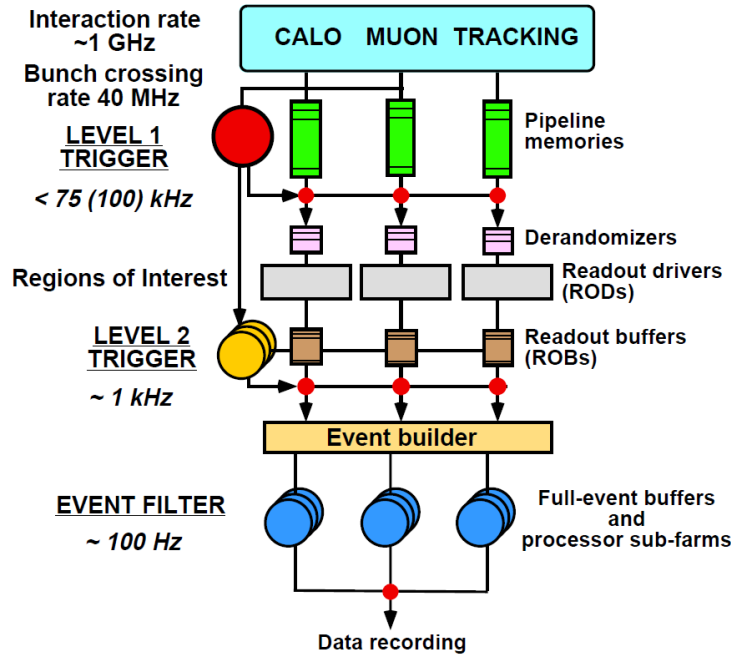


Figure 2.16: A schematic view of the ATLAS trigger system [69].

those used during the offline object reconstruction, in order to reduce the data frequency rate from 4 kHz to 400 Hz.

2.2.8 ATLAS GEANT simulation

All the MC simulated events pass then through the simulation of the ATLAS detector which is done by the Geant4 [31] program. The ATHENA software provides a digitization and an offline reconstruction of these signals. In general the reconstruction of the simulated events is performed in an exact similar way such as the data event reconstruction. However, some differences are observed for the reconstruction, identification, and trigger efficiencies between the data and the MC simulation. Therefore, the MC is corrected for these differences by applying scale factors on an event by event basis. This procedure is done only to correct the total number of the MC events so that it matches that of the data. Finally, the pile up conditions are different between data and MC. This can be visualized through a data to MC comparison of the distribution of the mean number of interactions per bunch crossing (called $\langle \mu \rangle$). If these discrepancies are not corrected, they might affect on the data to MC agreement of kinematic variables such as the E_T^{miss} because a difference in the pile-up conditions vary the energy calculated inside the calorimeter, thus leading to such differences. The PYTHIA generator provides therefore correcting weights for each event. A detailed explanation of the pile-up re-weighting procedure is given in section 4.1.2.

2.3 ATLAS Physics Object Reconstruction

The particles produced by the collision of protons interact differently with material inside the detector leaving tracks or/and energy deposits in it. These tracks and deposits are then analyzed via the electronic readout systems of the detector and then interpreted. The interpretation of the

electronic signals produce the physics objects. The term “object” is used to categorize each type of detected particles. We will mainly discuss about electron, muon, and MET objects, as they are the only ones used in the WZ analysis presented in this thesis. Other objects such as jets, are also built in the detector.

2.3.1 Electrons Reconstruction

The main algorithm to reconstruct electrons starts in the calorimeter by looking at the energy deposits by the electrons in the calorimeter cells. Once an EM cluster is identified, a search starts in the ID for an associated track to this cluster. The fact that information from two detectors, ID and calorimeter, is used enables the “clean” reconstruction of electrons which means the reduction of noise and mainly the differentiation of an electron from a photon.

The electron reconstruction and identification details can be found in [70] and [71]. The information from these references are summarized in this section.

2.3.1.1 Electron reconstruction algorithms

For the central part of the detector ($|\eta| < 2.47$) a “sliding window” algorithm is used to reconstruct the electron clusters. In the second layer of the EM calorimeter, seed clusters are searched in towers of 3×5 cells in $\eta \times \phi$, with each cell having a size of $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$.

The collected cell signals are then converted to energies and seed clusters are required to have a transverse energy above 2.5 GeV. The final cluster size is defined by a collection of seed clusters with a typical size of 3×7 longitudinal towers in $\eta \times \phi$ in the barrel and 5×5 towers in the end-caps. After building the clusters, duplicates from neighboring seeds are removed by the algorithm. Inside the inner detector tracks with a transverse momentum of at least 0.5 GeV are associated to the cluster. The (η, ϕ) coordinates of the impact point are compared to the cluster’s barycenter coordinates in the middle layer. The closest tracks to the cluster (the coordinate difference of which is below a certain threshold) are announced as “matching” tracks. Among the “matching” tracks, the one with the most SCT hits and with the smallest distance $\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$ is chosen.

The final electron candidate’s energy is then calibrated. This calibration takes place in two steps. First, using the MC simulation it corrects the measurement for the energy deposited outside the cluster. This means that the “corrected” energy of the cluster is calculated as the sum of four contributions: the energy in the cluster, the lateral and longitudinal leakages outside the cluster, and the energy lost in front of the calorimeter. Each of these terms are parametrized as a function of the energies measured in the presampler and all three layers of the electromagnetic calorimeter in order to take into account the differences between reconstructed and true deposited energies. The determination of these parameters have been performed using the MC simulations of the energy deposits as described in reference [72].

Another *in-situ* calibration to the cluster’s energy is applied in order to improve the calibration obtained using the MC simulation. $Z \rightarrow e^+e^-$ events are used to determine the corrections to the measured energy so that:

$$E_i^{meas} = E_i^{true}(1 + \alpha_i), \quad (2.6)$$

where α_i is a coefficient correcting for the energy scale of the electrons for each calorimeter region i . It is extracted by using a maximum likelihood fit on the Z boson’s invariant mass profiles.

In the forward region of the detector ($2.5 < |\eta| < 4.9$), electrons are reconstructed using only the calorimeter energy deposits since no tracking information is provided.

2.3.1.2 Electron identification

After finding the electron candidate, quality criteria are applied to the track and to the track and cluster shower shape of the electron candidate to reduce the rate of mis-identified electrons as much as possible.

Three identification levels are defined in ATLAS [71]. The “loose”, “medium”, and “tight” levels.

- **loose selection:** For this category, cuts on the shower shape (on the lateral shower width) in the middle layer of the EM calorimeter are set. Also cuts on the hadronic leakage, mainly cuts on the energy fraction in the hadronic calorimeter are included.
- **medium selection:** On the top of the loose selection criteria, medium electrons contain cuts on the shower shape based on the first layer of the EM calorimeter, additional cuts on the quality track from the inner detector are also set (at least 1 hit in the pixel detector and 7 hits in the SCT) also a cut on the transverse impact parameter, $|d_0| < 5$ mm, is put. Finally, a track matching between the cluster and the track is performed by requiring $\Delta\eta < 0.01$ between the cluster and the track.
- **tight selection:** They include the cuts for the medium electrons and additional cuts on the hits in the b -layer of the ID. Also during the track matching, additional requirement of $\Delta\phi < 0.02$ between the cluster and the track is set and a more strict threshold on $\Delta\eta < 0.005$ is required. To have a better track quality, a tighter cut on the transverse impact parameter, $|d_0| < 1$ mm, is put. Also, a certain number of TRT hits is required. Finally, electron candidates that match to reconstructed converted photons are rejected.

The tight identification is very powerful in terms of rejection of fake electrons mis-identified in jets. However, it presents a low efficiency for true electrons. In the contrary, the loose identification has a low purity but a high efficiency for true electrons. The medium is an optimization between these two identification levels. The order of magnitude of the jet rejection rates for these three identification levels are of the order of 500, 5000, 50000 for loose, medium, and tight identifications, respectively.

The electron reconstruction identification efficiencies estimated using the 2012 data collected by ATLAS are shown in Figure 2.17. The tag-and-probe method explained in reference [71] uses the $Z \rightarrow e^+e^-$ and $J/\Psi \rightarrow e^+e^-$ events to estimate these efficiencies. Figure 2.17 (a) shows that in 2012, the reconstruction efficiencies as a function of the electron’s transverse energy, agree well with the MC and they are higher than 97%. The Figure 2.17 (b) shows that there are some discrepancies between data and MC for the medium and tight identification efficiencies, with at least 65% of efficiency for the tight level. Due to differences between the measurements and the MC simulations, corrections are applied to the MC simulation for each identification level.

2.3.1.3 Electron isolation

In order to further reduce the rate of hadrons being mis-identified as electrons, electrons are required to be isolated from other energy deposits in the detector. The isolation of the electron candidate to calorimetric energy deposits or to other reconstructed tracks can be tested.

The calorimetric isolation is measured by counting the sum of the calorimetric cell energies in a given size of cone with a radius x , measured in η and ϕ , around the barycenter of the EM cluster.

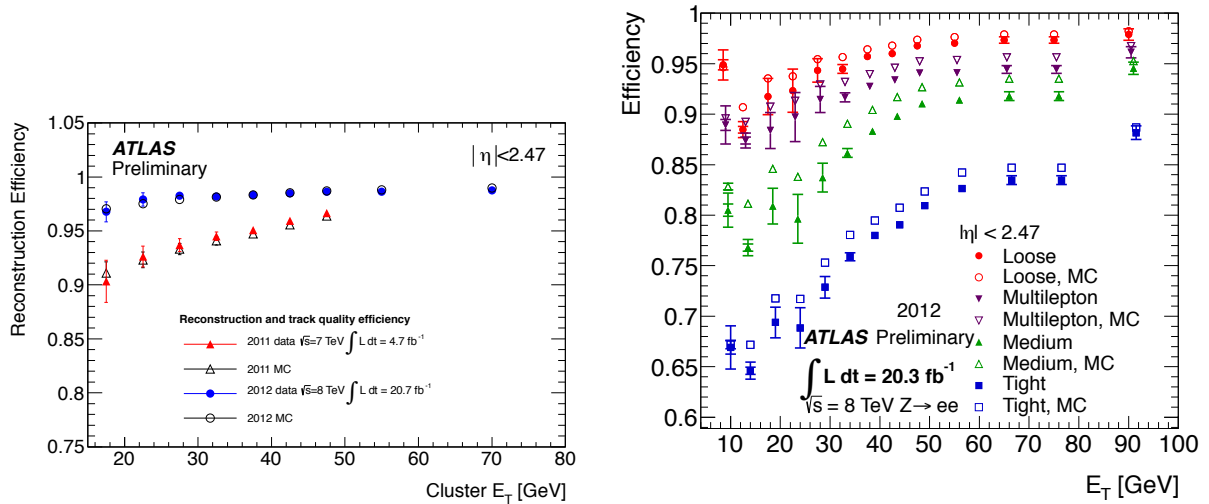


Figure 2.17: Electron reconstruction (left) and identification (right) efficiencies using the 2012 ATLAS data [73].

In the analysis presented in this thesis, a relative isolation criterion is set on all the electron candidates. This criterion requires a threshold on the ratio of the energy deposited in the defined cone to the transverse energy of the selected electron. This ratio is usually required to be greater than 0.15 so that at least 85% of the energy in the cone to be corresponding to the selected electron.

The track isolation works similarly to the calorimetric isolation, however it sums over the transverse momenta of the tracks in a given cone in the ID with a radius x . The condition to sum over the tracks p_T in the cone is that they satisfy the following list:

- $p_T > 0.4 \text{ GeV}$
- $|d_0| < 1.5 \text{ mm}$ (longitudinal impact parameter)
- $|z_0| > 1.0 \text{ mm}$ (transverse impact parameter)
- at least one b -layer hit
- at least 9 SCT hits
- no pixel holes
- electrons and conversion tracks are removed

Also a relative track isolation is required in all the electrons used in the analysis presented in this thesis. It is required that the ratio of sum of the transverse momenta of the tracks in a given cone to the electron candidate's transverse momentum to be greater than at least 0.15. This means that the transverse momentum of the electron candidate occupies energetically at least 85% of the cone.

2.3.1.4 Electrons used in the WZ analysis

This section will give a few details about the electrons that are going to be used in the WZ analysis presented in this thesis and that will be explained in detail in chapter 4.

In the $W^\pm Z$ analysis, electrons are required to pass the “loose” electron identification requirements as explained in section 2.3.1. Data could have some quality issues related to the electronics system of the liquid argon calorimeter. To reduce these kind of events, the electron candidates are required to pass the object quality cut (OQ). The OQ cut uses a bitmask to define a bad electron and its cluster is labeled as affected if at least one of the three conditions listed below is satisfied:

- The presence of a dead front-end board in the first or second sampling layer
- A dead region affecting the three samplings
- A masked cell in the core.

Otherwise, to ensure that the candidates are coming from the primary vertex, the $|z_0 \cdot \sin(\theta)|$ with respect to the primary vertex must be less than 0.5 mm and the d_0 significance must be less than 6. To select “good” electrons, i.e. to ensure the presence of inner detector tracking coverage and to avoid the transition region between the barrel and endcap calorimeters where the energy is not well measured, the electrons must be reconstructed using a cluster with $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$ in the ATLAS absolute coordinate system. All electron identification criteria are applied to reject background, as listed in Table 4.3. The energy of the electron is taken from the calorimeter measurement, when the η and ϕ are taken from the track. The transverse momentum of the electron is defined as $p_T = E \cosh(\eta)$, where E is the total energy of the electron taken from the calorimeter and η taken from the inner detector track measurement. The electron candidates are required to pass a p_T threshold of 15 GeV.

Finally, a relative isolation cut is applied to the electron candidate to reject further the background events. The sum of the calorimeter cells transverse energy in a cone of $\Delta R = 0.2$ around the electron candidate, not including the energy of the candidate itself, and corrected for p_T leakage and the number of primary vertex candidates in the event, must be less than 14% of the E_T . The sum of the transverse momenta of all tracks with $p_T > 1$ GeV in a cone of $\Delta R = 0.2$ around the electron candidate, not including the transverse momentum of the candidate itself, must be less than 13% of the p_T . The calorimetric isolation is used to distinguish prompt electrons and photons from jets and non prompt objects. It is corrected for the energy deposited by particles belonging to the underlying event, for pile-up and for energy leakage outside the cluster. The track isolation variable is computed using tracks originating from the same vertex. It therefore complements the calorimetric isolation being more pile-up robust and showing a better background rejection especially for W/Z +jets events.

In data, a residual energy scale calibration is applied to electrons. The residual correction factors were calculated in 26 η bins from a sample of $Z \rightarrow e^+e^-$ events in 2012 data. The energy of the electrons in the MC simulations is smeared to match for scale and resolution, the electron direction is kept fixed. Also the electron identification and reconstruction efficiency scale factors, calculated with the tag-and-probe method in $Z \rightarrow e^+e^-$ events, are applied for each event to the MC, in order to correct for the discrepancies seen with respect to the data efficiencies. These efficiencies are usually higher than 99% and they increase as the number of electrons in the event increase.

2.3.2 Muons Reconstruction

In this section, the muons detection, identification, and reconstruction will be explained. Three muon reconstruction algorithms, STACO, MUID, and Third Chain, developed in ATLAS will be detailed. The STACO and MUID algorithms are currently used to reconstruct the muon object.

Whereas the Third Chain algorithms is a combination of both STACO and MUID, which is under preparation and it will be used at the restart of the LHC in 2015.

2.3.2.1 Detection and identification of muons

As explained in section 2.2.6, the MS is specifically designed to detect muons. The system lives inside a magnetic field delivered by three large air-core superconducting toroid magnets. One large magnet in the barrel region and two smaller ones installed at both ends of the barrel toroid serving for the end-cap region. Because of the position of the magnets, the magnetic field is orthogonal to the muons trajectory. In the presence of multiple scattering this configuration of the magnets avoids the degradation of the muon momentum resolution. The magnetic field bends the trajectory of the muons leading to the measurement of their curvature therefore their charge and momenta. For muons with energy in the range of the GeV the momentum resolution of the MS is 2-3% (i.e. worse than that of the ID), while for very energetic muons with energy around the TeV the resolution is worsens to $\sim 15\%$ but is much better than that provided by the ID.

To measure the momenta of muons, the MS uses precision chambers and a trigger system. The MDTs and CSCs provide a precision measurement of the coordinates of muons in the bending direction. In the barrel and end-cap regions the trigger system is composed of the RPCs and TGCs respectively. The triggers provide a “second-coordinate” in the bending direction, on the top of the one provided by the MDTs and CSCs. In the barrel region MDTs and RPCs are placed in 3 cylinders around the beam axis: inner, middle, and outer. Also in the end-cap region the CSC and TGCs are placed with the same structure. A station is a system formed by a pair of (precision, trigger) chambers on the cylinders. Each muon is supposed to pass three stations. In case when a muon passed two stations only, the interaction point is chosen as the third. This three-stage procedure enables to increase the precision on the muon momentum measurement and it requires high accuracy in the determination of each point in each station [68].

As explained in the section 2.2.6, the four systems of the muon spectrometer are composed of chambers that contain non-flammable and nature friendly gases. The muon, while passing through the detector, will ionize the atoms of the gas producing electrons. These electrons will then be collected by the anode (wires or strips). Using the induced electrical current, the time taken by the electrons to reach the anode can be measured. This will lead in deducing the initial position of the secondary electrons. The determination of this position is like the determination of the muon position in the chamber. This information is called a “hit”. Hits will be used to determine the track of the muon traversing the MS. First, using hits in the trigger system, regions of interests (RoI)s are defined. Inside the RoIs hits from precision chambers are searched. Inside the precision chambers small tracks are built. Since a muon track is obtained using information from three stations, in each station segments are formed using maximum number of hits. Then a fit is made to combine all segments from all stations.

When a muon track is reconstructed inside the MS as explained in the previous lines, the muon is identified as a Stand Alone muon. However all ATLAS sub-detectors can be used to reconstruct the muon tracks. When so, different identifications are associated to muons according the way they were reconstructed. A muon track can be formed by combining the MS and ID information. This will be explained in detail in the next section. Muons reconstructed this way will have a Combined identification. Also an ID track can be matched to a MS track, in this case the muon is identified as a Segment Tagged muon.

2.3.2.2 Muon reconstruction algorithms

In ATLAS, two main and equally successful muon reconstruction algorithms are used. First is the STACO algorithm and second is the MUID algorithm. Besides the tracks produced in the MS, the muon leaves also a track in the ID. In order to improve the muon momentum measurement precision, an ID track is combined to an MS track in two different approaches used by each algorithm. This matching of both ID and MS tracks, allows to reject muons forming a background such as muons from secondary particles or decay-in-flight particles from Kaons or Pions.

- The STACO chain

The STACO chain contains three different algorithms. The MuonBoy algorithm uses the hits in the MS to form tracks and segments [74]. These are then extrapolated to the vertex taking into account the energy loss inside the calorimeters that is about 3 GeV. The second algorithm is STACO, that will combine an inner detector track to a muon spectrometer track using a statistical method, from where its name STACO, meaning STATistical COMbination.

This method consists on combining two independent measurements using their covariance matrices and then by computing the χ^2 of the system. Consider that each track has a parameter vector called P_1 and P_2 . Their covariance matrices are given by C_1 and C_2 . The combination of these parameters give [75]:

$$(C_1^{-1} + C_2^{-2}) \times P = (C_1^{-1} \times P_1 + C_2^{-2} \times P_2), \quad (2.7)$$

where

$$C = (C_1^{-1} + C_2^{-2})^{-1}, \quad (2.8)$$

Finally the χ^2 of this system of equations is given by:

$$\chi^2 = (P - P_1)^T \times C_1^{-1} \times (P - P_1) + (P - P_1)^T \times C_2^{-1} \times (P - P_2). \quad (2.9)$$

In the (η, ϕ) plane the matching of the tracks is done in a way to pick the tracks that match the best. If different combinations are found, the track with the best χ^2 is chosen.

In the STACO chain, the last method used is the MuTag algorithm. Inversely to STACO, it identifies muons by associating an ID track to segments formed in the MS using the MuonBoy algorithm. It is important to know that this algorithm uses tracks that are not used by STACO during the combination. Therefore there is no overlap between both.

- The MUID chain

The muons in the MUID chain, which means MUon IDentification, are reconstructed using four different algorithms. For track finding in the MS Moore and Muid Standalone algorithms are used. Moore combines the hit information in the MS to form tracks and segments. Then Muid standalone extrapolates these segments to the interaction vertex and enables to express the muon track parameters at the vertex. The second algorithm of this chain is the MUID combined algorithm. It uses the track formed in the MS and combines it to an ID track using a global re-fit. In the MUID combined algorithm, the MS tracks are expressed at the vertex by propagating them through the magnetic field taking into consideration the energy loss inside the calorimeters and the multiple scattering. Therefore the track parameters and their covariance matrices are expressed at the point of the closest approach to the interaction point. To match ID tracks to the extrapolated MS tracks, a χ^2 with 5 degrees of freedom is formed using the difference between the track parameters and summing up the covariances. If the χ^2 is greater than a given threshold,

a combined fit is performed to the tracks that match. The third algorithm in the MUID chain is the `MuGirl`. It uses an ID track as a seed to search for tracks and segments inside the MS. It then performs a combined fit to the tracks. Finally the `MuTagIMO` algorithm identifies muons by associating an inner detector track with `Moore` segments.

All these algorithms are processed by the ATLAS offline framework and they aim to fully reconstruct all muons in the event. Unlike the STACO chain, the MUID chain algorithms result in overlaps while running all MUID algorithms at the same time. These are removed while merging all muons from the muon containers.

- Unified muon chain or THIRD chain

Both of the algorithms presented above have shown their success in reconstructing muons. Different analyses have chosen one of the algorithms according to its performance within the specific physics analysis. For example, MUID presents higher reconstruction efficiency whereas STACO presents higher background rejection. For many years, physicists have been working to combine both muon reconstruction chains and present a unified chain that will be used in the re-start of the LHC data taking in 2015.

This new algorithm used for muon reconstruction, also called Third Chain (TC), is practically a combination of both STACO and MUID algorithms taking the best options from both.

First in the MS, the segment finding is based on the STACO chain `MuonBoy` algorithm. Using hits from the trigger system, Regions of Activity (ROA) in the (η, ϕ) space are defined. The requirement is to have at least one hit in the RPCs or TGCs in η and ϕ . The segment search is done first in the outer and middle stations of the barrel and inner and middle MDT stations in the end-cap. These segments that are found must be associated to at least one hit from the trigger system. As a next stage, using CSC clusters, a 3D reconstruction of segments is performed in the CSC. A second looser search is also applied to recover for efficiency loss in critical regions. This is done by keeping only ROA defined using the hits from one of the trigger or MDT systems. This search is based on using available hits in the defined ROA. When no trigger hit is available to give the segment's second-coordinate (ϕ), ϕ is determined by trying five positions along the tube and keeping the one which gives the best χ^2 .

After building the segment, MS tracks are built. The track building is based on `Moore` that is an algorithm used in the MUID chain. This is done by first choosing segments that will be used as a seed. For each station layer, segments with good quality are grouped. Good segments that pass certain quality criteria but that do not belong to a track are used as a seed. A combination of these seed segments with segments from other stations on other layers is performed. First the positions and angles of the segments are compared until matching segments are found. This is called the loose matching. After finding matching pairs, a track fit is applied to compute the momentum of the matched pairs and to reject furthermore bad combinations. The extension of the track candidates with segments in other stations will form the full track. The full tracks are then fitted. Material effects and the track bending effects in the magnetic field are taken into consideration. After forming the full track, hits that are crossed by it and not associated to it are added to the track. Finally, after recalibrating all MDT hits on the track a final track fit is performed.

In the ID, muon tracks are also reconstructed with very high efficiency, since muons interact less with the detector material than other charged particles.

The energy loss while traversing the calorimeters is in the order of 3 GeV for muons. This energy loss is taken into account when muon candidate tracks from the MS are extrapolated back to the ID, and vice versa.

Most muons with a momentum above ~ 6 GeV produce a full track in the MS and can be

reconstructed with high precision as one single trajectory made from the tracks in ID and MS. To perform a final combined track reconstruction all possible combined algorithms are run in parallel. The STACO, MUID, MuGirl, and MuTag. Priority is given to MUID since it performs a combined re-fit and gives a slightly higher muon momentum resolution. If overlaps take place by running these several algorithms, they are removed. Figure 2.18 presents all the muon identification chains used in ATLAS. On the figure, we can see the different algorithms that are used in different parts of the detector and also the muon object collections that are reconstructed.

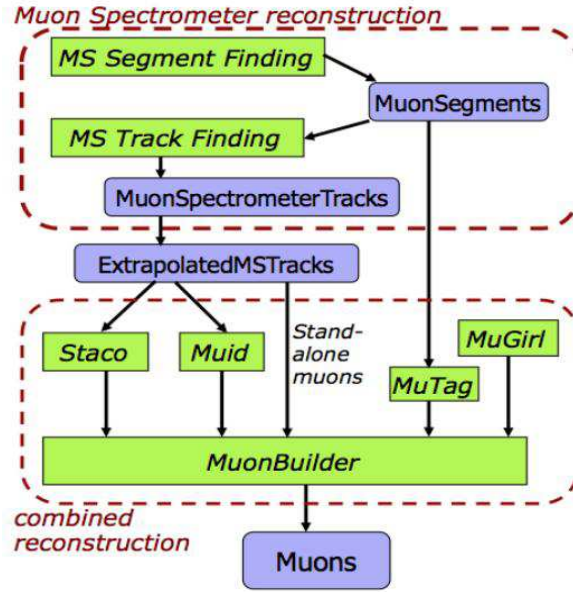


Figure 2.18: Muon identification chain in ATLAS. Algorithms (green) in different detector parts produce collections of reconstructed objects (blue) as a part of the Muon Spectrometer and Combined reconstruction.

The unified chain muons performance has been tested within the ATLAS performance groups and shown an improvement in the muon reconstruction efficiency. The background rejection rate is found of the same order but lower higher than that obtained using the STACO algorithm.

Physics analyses, such as the WZ analysis presented in this thesis, tested the performance of these newly reconstructed muons, background rejection rate and their reconstruction efficiency have been also studied.

2.3.2.3 Muons used in the WZ analysis

The muons reconstructed by the STACO algorithm are used in the WZ analysis. The type of these muons is Combined (CB) or Segment-Tagged (ST) muons. In addition, a few kinematic cuts are applied to reject muons coming from pile-up collisions and from multi-jet background. In particular, the ID track associated to the muon is required to originate from the primary reconstructed vertex. To ensure that the muon candidate is originated from the primary vertex, the absolute distance in the longitudinal z -direction of the muon track, $|z_0 \cdot \sin(\theta)|$, with respect to the primary vertex's z position must be less than 0.5 mm and the transverse impact parameter significance with respect to the primary vertex must be < 3 . The impact parameters of the tracks are computed after removing the track from the primary vertex definition. All muon quality selections are listed in Table 4.2.

The ID track used in the CB or ST muon must be isolated from other tracks to reject secondary muons from hadronic jets. The isolation requirement is $\sum_{\Delta R < 0.2} p_T(i)/p_T < 0.15$. Additionally, inner detector tracks must have a minimum number of hits in each silicon sub-detector: at least 1 hit in Pixel layers including the number of crossed dead pixel sensors, at least 5 hits in the SCT including the number of crossed dead sensors, and less than 3 holes (no hit in a layer crossed by the track) in all silicon layers (Pixel and SCT). Finally, an $|\eta|$ dependent condition on TRT hits and outliers is applied: for $0.1 < |\eta| < 1.9$, we require hits + outliers > 5 and outliers/(outliers+hits) < 0.9 .

The tag-and probe method using $Z \rightarrow \mu^+ \mu^-$ events are used to measure the muon reconstruction efficiency. This is described in detail in ref [76]. Additional event weights are applied to the MC samples to match the measured efficiency in data. All systematic uncertainties due to these scale factors are computed independently (see section 4.3).

2.3.3 Missing Transverse Energy Reconstruction

As we know that the neutrino particle does not interact within the ATLAS detector and remains invisible to it. Since the $p - p$ interaction takes place in the longitudinal direction only, the total energy in the transverse plane is always zero. Neutrinos carrying energy, they appear in the form of a missing energy in the transverse plane or more precisely a missing transverse momentum, called E_T^{miss} .

A detailed description of the E_T^{miss} is given in reference [77]. The E_T^{miss} is calculated using the energy depositions from the calorimeters and the muon spectrometer so that:

$$E_{x(y)} = E_{x(y)}^{miss,calo} + E_{x(y)}^{miss,\mu}; \quad (2.10)$$

$$E_T^{miss} = \sqrt{E_x^2 + E_y^2}; \quad (2.11)$$

$$\phi^{miss} = \arctan(E_y^{miss}, E_x^{miss}). \quad (2.12)$$

E_T^{miss} is reconstructed using the cells from three dimensional topological clusters except for electrons and photons which have different clustering algorithms. These clusters are seeded by a cell with an energy deposit above $4 \times \sigma_{noise}$ and built iteratively by adding the neighboring cells with energy deposits above $2 \times \sigma_{noise}$ and then adding all neighbors of accumulated cells [77].

The calorimetric term in the E_T^{miss} calculation is computed using the energy deposited in the calorimeter cells associated to electrons, photons, hadronically decaying τ s, and jets. Also, the cells in topoclusters that are not associated to the objects listed above are included and this term is called *soft term*. Therefore the calculation of the missing transverse energy from the calorimeter is given by:

$$E_{x(y)}^{miss,calo} = E_{x(y)}^{miss,e} + E_{x(y)}^{miss,\gamma} + E_{x(y)}^{miss,\tau} + E_{x(y)}^{miss,jets} + E_{x(y)}^{miss,SoftTerm} \quad (2.13)$$

Then for each of the terms in this equation E_x and E_y are calculated as the following:

$$\begin{aligned}
E_x^{miss,term} &= - \sum_{i=1}^{N_{cell}^{term}} E_i \sin\theta_i \cos\phi_i, \\
E_y^{miss,term} &= \sum_{i=1}^{N_{cell}^{term}} E_i \sin\theta_i \sin\phi_i,
\end{aligned} \tag{2.14}$$

where E_i , θ_i , and ϕ_i are the total energy, the polar angle, and the azimuth angle for each cell.

The muon term calculation of the E_T^{miss} is performed in the pseudorapidity range of the MS ($|\eta| < 2.7$) given by:

$$E_{x(y)}^{miss,\mu} = - \sum p_{x(y)}^\mu. \tag{2.15}$$

In this calculation, in the region of $|\eta| < 2.5$, only combined muons are considered. These muons are well reconstructed in the MS and their track is combined to a track in the ID. Because of the matching of the MS track to an ID track, a significant reduction of fake muons arising from very energetic jets punching from the calorimeter to the MS, is observed.

E_T^{miss} studies within ATLAS have shown that the performance of E_T^{miss} has a strong dependence on the pile-up. Its resolution worsens with the increasing number of pile-up interactions. The most affected parts in the E_T^{miss} calculation are the soft and hard jets terms.

In order to improve the resolution of the E_T^{miss} against the pile-up, a discriminant variable called jet vertex fraction, JVF , is defined as:

$$JVF = \frac{\sum_{\text{tracks}_{jet}, PV} p_T}{\sum_{\text{tracks}_{jet}} p_T}. \tag{2.16}$$

The sums are over tracks matched to the jet and PV¹ denoting the tracks matched to the primary vertex. Jets with no associated tracks have $JVF = -1$. Any jet with $|JVF| \leq 0.5$, calibrated $p_T < 50$ GeV, and $|\eta| < 2.4$ are discarded from the E_T^{miss} calculation. The JVF variable is therefore used to select jets which are likely to come from the primary vertex of the hard scattering.

The pile-up effect on the soft terms is suppressed using tracks that are unmatched to physics objects. These are used to calculate the soft term vertex fraction, $STVF$, which has a similar definition to JVF .

$$STVF = \frac{\sum_{\text{tracks}_{SoftTerm}, PV} p_T}{\sum_{\text{tracks}_{SoftTerm}} p_T}. \tag{2.17}$$

The denominator is the p_T sum over unmatched tracks and the numerator is the p_T sum of unmatched tracks that are associated to the primary vertex. The $E_T^{miss, SoftTerm}$ is then multiplied by the $STVF$ fraction.

The final E_T^{miss} is therefore calculated using both JVF and $STVF$ fractions. It shows a better resolution with respect to the increasing pile-up interactions. This calculation is the one used for the analysis presented in this thesis.

¹The primary vertex is identified as the vertex that has the highest Σp_T^2 of associated tracks

Chapter 3

Time alignment of the LAr Calorimeter

The ATLAS Liquid Argon calorimeter is used to measure the energy of particles like electrons and photons. When particles such as electrons traverse the LAr calorimeter, they deposit a certain amount of energy at a given time t . Due to many imperfections in the electronic system, the time difference δt between the deposition of the energy and the detection of a signal by the electronic system of the calorimeter is not always zero. The computation of δt and the energy of a deposition in the calorimeter are complementary in ATLAS. If δt is not around zero, a bias is introduced in the energy reconstruction (section 2.2.4.4). This affects the quality of the data and all measurements performed in all the physics analyses. The way δt is calculated will be explained in detail in the following sections. A precise time alignment is also needed for physics studies beyond the Standard Model. It helps to search for highly ionizing [78] or long living [79] exotic particles inside the calorimeter. Otherwise, for very high luminosities, the time information could be used to reject the pile-up events from neighboring bunch crossings. In order to be sensitive to these kinds of analysis, it is very important to have correct time inter-calibration between the LAr channels.

This chapter will present in detail the timing study of the LAr calorimeter with the 2012 ATLAS data.

3.1 Methods and definitions

3.1.1 The reference time

The reference time with respect to which the time of the energy deposits in the LAr calorimeter is measured, is the clock of the LHC. Timing signals from the LHC clock are transmitted to the detector via kms long optical fibers. After the collision, the particles travel different distances inside the detector, until they are detected by the electronic system. The travel time needed by the particles to reach the different parts of the detector is called the time of flight. The traveling delay of the signals through the optical fibers is already corrected in ATLAS as well as the time of flight of the particles. It was discovered however that the LHC clock signals could drift in time by offsets that could increase until ~ 1 ns. These drifts are due to variations in the length of the optical fibers according to the daily weather and they need to be corrected. In 2012, these drifts were corrected on a run by run basis except for a few data runs because of some minor technical problems. However, due to other imperfections in the electronic system, the time between the deposition of the energy and the detection of a signal is still not zero. The goal of this study is therefore to have all parts of the LAr calorimeter well aligned in time.

In this study, the time of the LAr calorimeter is defined, and measured, with respect to the signal time of the LHC clock, t_{clock} . Drifts of the t_{clock} can be detected by monitoring the global

time of all LAr calorimeter partitions (defined in section 3.3.2), when a common drift of time is seen in all four LAr partitions. It is calculated by determining the mean time of each LAr calorimeter partition, then by doing the difference with respect to the mean time in a run for which no LHC clock drift has been seen. The t_{clock} should be the same in all four LAr calorimeter partitions, since it is due to a global problem affecting all subdetectors. Figure 3.1 shows a plot of Δt_{clock} between a given run and the reference run (run 203602) versus the run numbers. As expected, it is shown that the drift in time is the same for all four partitions for each run. We observe that there is a constant offset, which needs to be corrected for each run and which is due to a drift of the LHC clock. However, these delays created by the clock signals existed mostly at the beginning of the 2012 data taking, where no specific procedure existed to correct them for each run. Later on an automatic procedure was developed by other ATLAS working teams to correct for these delays at the beginning of every run.

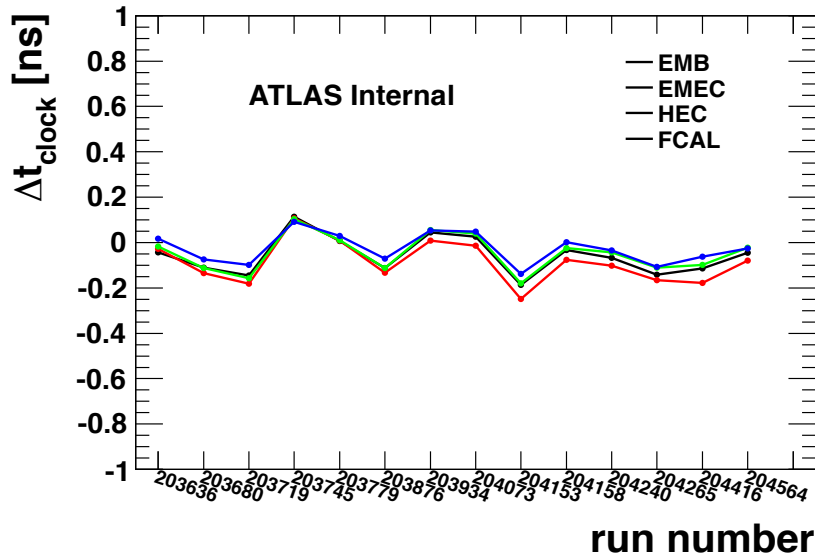


Figure 3.1: The average time difference, Δt_{clock} , between a given run and the run of reference 203602.

3.1.2 The time resolution

When a particle deposits energy in the calorimeter, the time measured in a calorimeter cell is different than the time measured in another cell. When a distribution of these different cell times is made, it presents a certain spread. This spread is known as the time resolution. The time resolution depends on the noise level inside the calorimeter, which is decreasing when the energy increases. Other non-energy dependent effects, as differences in time synchronization of calorimeter cells, can also deteriorate the time resolution. The evolution of the LAr time resolution σ_t as a function of the energy deposit can therefore be parametrized by:

$$\sigma_t = \frac{p_{res}}{E} \oplus p_{const}, \quad (3.1)$$

where p_{res} is correlated with the noise level and therefore has a different value in each calorimeter layer. p_{const} is a constant term gathering up all other residual effects. At high energy, the first term of equation (3.1) becomes negligible and the resolution will be dominated by the constant term.

3.2 LAr Event selection

The timing of the LAr Calorimeter will be studied at three different levels. First, at the level of each sub-part of the calorimeter. This study gives a general idea about the time alignment in the given part. Each sub-detector is connected to a given number of Front End Boards (FEB)s which are the part of the calorimeter electronic readout system that receive the raw signal when a particle deposits energy in the LAr calorimeter. The second step is then to compute the timing of these energy deposits for each individual FEB. Finally, each FEB being connected to ~ 128 cells, the timing of the energy deposits in each cell will be studied. The aim of this study at the level of LAr cells is to further improve the time alignment and resolution of the time response of the LAr calorimeter.

The analysis presented in this section is performed with collision data recorded in 2012 at a center-of-mass energy of 8 TeV. In 2012 the integrated luminosity of a typical data run was around 80 pb^{-1} . For some very long runs an integrated luminosity of more than 200 pb^{-1} has been reached.

An event is identified by energy deposits in the LAr calorimeter that are triggered with the list of `LArCells_stream` triggers. Events used for this analysis are first selected using different quality requirements in order to minimize the effect of the different sources of noise on the determination of the time:

- Events below certain energy thresholds defined in Table 3.1 are rejected.
- Only events having an energy deposit larger than 5 times the spread of the total noise distribution in that particular channel are accepted.
- Bad channels (e.g. dead, noisy, not calibrated ...) are removed.
- The noise burst (representing high amount of calorimeter noisy cells in an event) is cleaned by removing noisy flagged events.
- Events with times greater than 20 ns or smaller than -20 ns are rejected.
- In the presampler, being more affected by noise, only events with a time within [-10, 10] ns are accepted.
- In the EMEC, cells in layer 3 have usually a time distribution presenting large positive tails. In order to remove a part of this tail, events with a quality factor, Q [80], which is a χ^2 like quantity used to discriminate pathological signals from regular ones, greater than 10000 are rejected.
- Also in the EMEC, events with large positive tails were observed mostly in slots 13, 14, and 15 especially FTs 2, 9, 15, 21. To reduce the effects of this noise, for channels in these FEBs, events with a quality factor $Q > 4000$ are rejected. Figure 3.2 shows an example of a time distribution of a FEB in the EMEC with and without the quality factor requirement applied.

LAr Partition	Layer 0	Layer 1	Layer 2	Layer 3
	$E_{Threshold}$ [GeV]	$E_{Threshold}$ [GeV]	$E_{Threshold}$ [GeV]	$E_{Threshold}$ [GeV]
EMB	1	1	3	1.5
EMECO	1.5	1	3	2
EMECI	-	3	3	-
FCAL	10	10	10	10
HEC	3.5	3.5	3.5	3.5

Table 3.1: Optimized cell energy thresholds, in GeV, used for each LAr partition and layer.

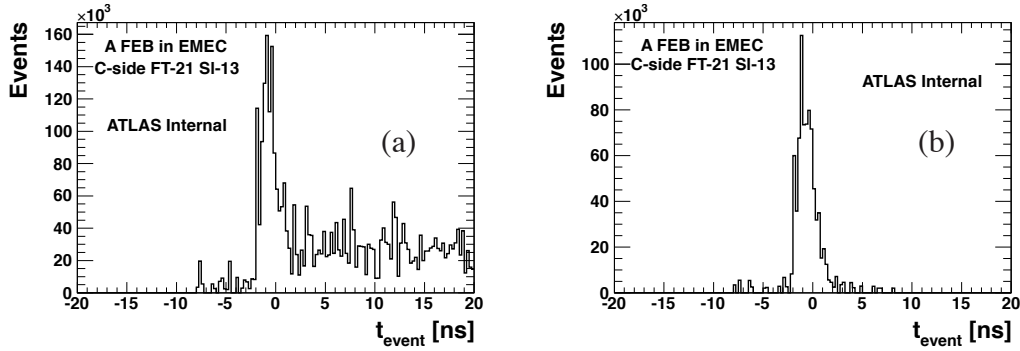


Figure 3.2: Distribution of time of events within a FEB of the EMEC, if no cut on the Q factor is applied (a), or after removing events with a Q factor > 4000 (b).

3.2.1 Energy weighing

All the distributions that will be presented in this chapter use events that are weighted with the energy. The energy weighting of events was not performed in any of the previous timing analyses with the 2011 and 2010 data.

In 2012, one of the reasons of using energy weighted events is the improvement of the time resolution at higher energies. Events with more energy are therefore used primarily to determine the time. Also, the time distributions in the different parts of the LAr calorimeter are not completely Gaussian, some of them having large tails. Such tails are mostly due to noisy cells. In many cases noisy cells have lower energies than cells with real signal. Therefore, weighting the time distributions with the energy reduces the importance of these tails. Finally, we are interested in events with high energies, since that is what we use in most of physics analyses.

Figure 3.3 shows an example of the effect of the energy weighting on the time distribution of a FEB in the EMEC. We observe a reduction of the tail of the distribution if events are weighted by their energy. We can also observe a global time offset between the two distributions obtained with and without energy weighting. This global time shifts of the order of 400 ps because it was seen in a different ATLAS analysis (internal communication) that the time of clusters in the middle layer EM Barrel is dependent on the energy deposited.

3.3 LAr time definition and measurements

In this section the definitions of the time of a run, the global partition time, the FEB time and the Cell time will be given. Also, the alignment results of the LAr FEB and cell times will be

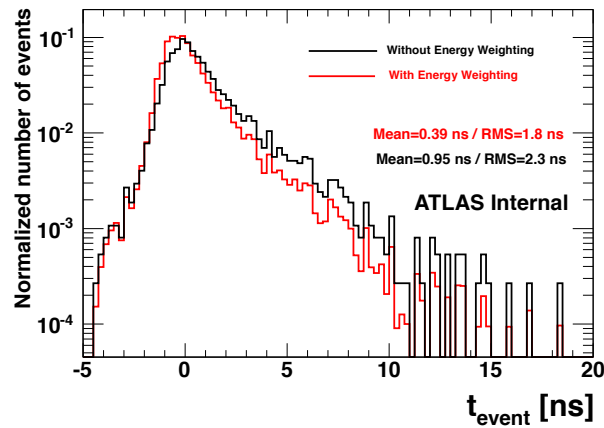


Figure 3.3: Example of a distribution of the time of all events in a FEB. The shape of the distributions obtained when the energy weighting of events is applied (red) or not applied (black) are compared. The two distributions are normalized to the same integral.

presented.

3.3.1 Run time calculation

The run time calculation is performed by looking at the time of all the events in one run. Therefore, the time of all events in all partitions are placed in one distribution. A fit with a Gaussian function is applied to the core of that distribution. The mean of the fit is then considered as the average time of a run.

3.3.2 Global partition time calculation

After selecting events of interest and considering the energy dependence of time, the global partition time is calculated for each of the four LAr calorimeter partitions. The energy weighted distribution of time of all events from all the cells per partition is made. Then the core of the distribution is adjusted with a Gaussian function. The mean of the fit provides an estimate of the global time of each partition.

The global time situation in the four partitions of the LAr calorimeter at the restart of 2012 data taking, is presented in Figure 3.4.

The global mean time in each LAr partition is shifted from 0 by different offsets. A first explanation for this shift is the energy weighting now used to construct time distributions. As seen in Figure 3.3, the use of the energy weighting introduces a shift of ~ 0.4 ns. The second explanation of this shift is that at the beginning of the 2012 data taking, the time corrections were not updated to align the LAr cells in time.

A larger shift compared to other partitions is observed in the FCAL. The reason is that the medium gain output of the FCAL is now used, in order to avoid a saturation of the energy measurement. The cell time in medium gain was therefore not correctly adjusted before. After the period of May 2011 and during the 2012 data taking, the high gain is used for the EMB and EMEC and the medium gain for the HEC and FCAL.

The observed shifts from zero mean that new corrections are needed for the time alignment of the LAr calorimeter cells. The corrections can be done at the level of the FEBs and at the level of the LAr cells.

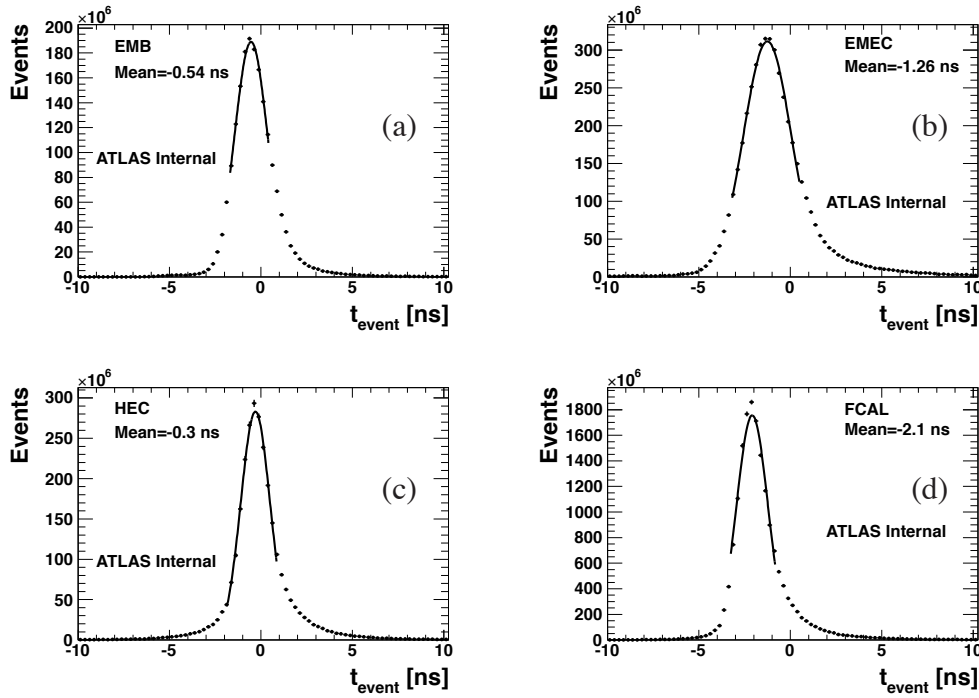


Figure 3.4: Distributions of energy weighted events from all calorimeter cells per partition at the beginning of the 2012 data taking (run 200926 recorded on April 6th 2012). Lines represent the results of a Gaussian adjustment on the core of the distribution.

3.3.3 Time alignment of LAr FEBs

3.3.3.1 Determination of the average FEB time

The method used for the determination of the average FEB time, $\langle t \rangle_{FEB}$, consists on calculating the average of times of all the events within a FEB, using a Gaussian fit. The method to compute the $\langle t \rangle_{FEB}$ is described below.

- Individual times of all events within a FEB are used through a single distribution.
- In building the distribution of the time of all events in one FEB, a weighting of each event by its energy is introduced.
- The core of each FEB time distribution is adjusted with a Gaussian function, using a double iterative fit procedure. The first fit is performed in the range of $[-5, 5]$ ns. This fit allows to have a global idea about the aspect of the distribution and of its spread. The second fit is performed in the range $[t_{max} - \delta t_1 \times \sigma_t, t_{max} + \delta t_2 \times \sigma_t]$, where t_{max} is the time value of the bin containing the maximum number events, σ_t is the standard deviation of the first fit, finally δt_1 and δt_2 are optimized factors to make symmetric or asymmetric fits based on the shape of the distributions in different FEBs.

Table A.1 in appendix A.1 gives the values of δt_1 and δt_2 estimated for groups of specific FEBs defined by conditions on their position (slot or FT) or on the width (RMS) of their time distribution. Figure A.1 shows an example of the $\langle t \rangle_{FEB}$ computation in one FEB in the EMEC, using a single fit and a double iterative fit. The mean of the single fit is biased towards higher time values by the presence of a tail in the time distribution. Therefore, the average FEB time is not estimated correctly in this case. However, we observe that using

the double iterative fit procedure, the core of the FEB time distribution is well fitted and the mean is correctly estimated.

This means that in many cases where the FEB time distributions are not completely Gaussian a single fit in a given fixed range is not enough to correctly estimate the average FEB time. The error $\delta \langle t \rangle_{FEB}$ is defined as the statistical error on the mean value obtained from the Gaussian fit used to determine the $\langle t \rangle_{FEB}$. In cases for which the result of the fit is not used, the error corresponds to the statistical error on the median.

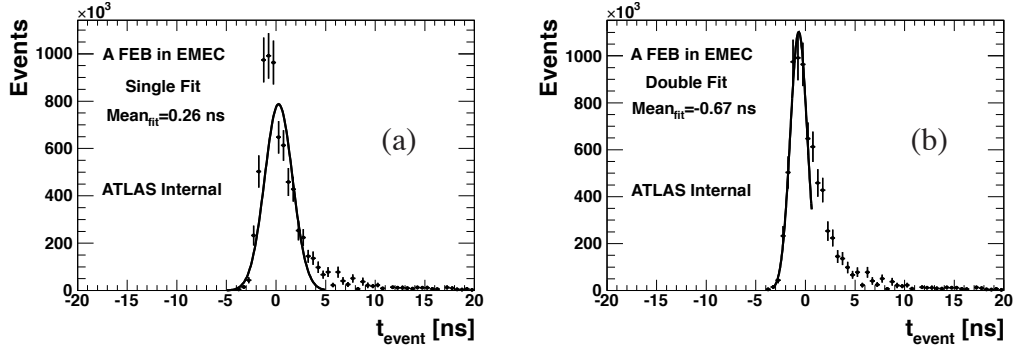


Figure 3.5: Examples of the estimation of the average FEB time $\langle t \rangle_{FEB}$ in a given FEB, using a single fit in the range $[-5, 5]$ ns (a) and a double iterative fit (b).

- Finally, if the fit converges, the time $\langle t \rangle_{FEB}$ is defined as the mean value of the final fit. If the fit did not converge or if the error on the fit was larger than the fit mean value or the σ of the fit was larger than 1.5 times the RMS of the corresponding FEB time distribution, the weighted median of the distribution is used instead. The median of weighted events is defined as the value, in this case the time, for which the sum of weights of all events before and after it is 50%.

Values of the mean time of each FEB $\langle t \rangle_{FEB}$ are extracted and used to correct the average FEB time. The correction of the average FEB time is defined as:

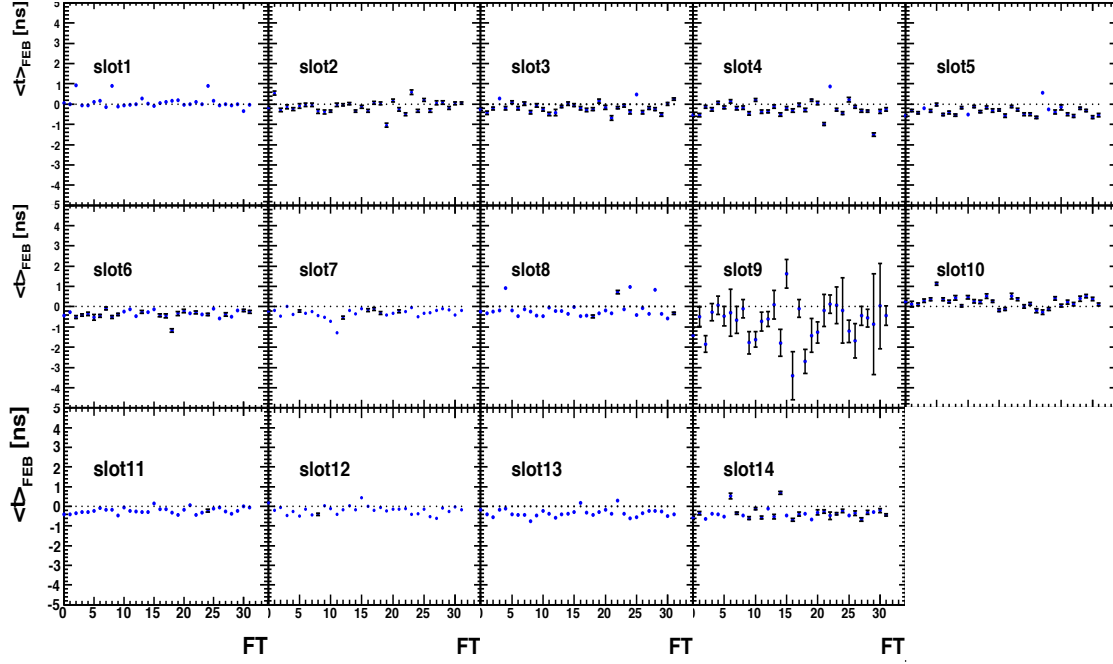
$$C_{FEB} = \langle t \rangle_{FEB} - t_0, \quad (3.2)$$

where t_0 is a reference time, considered zero in this case.

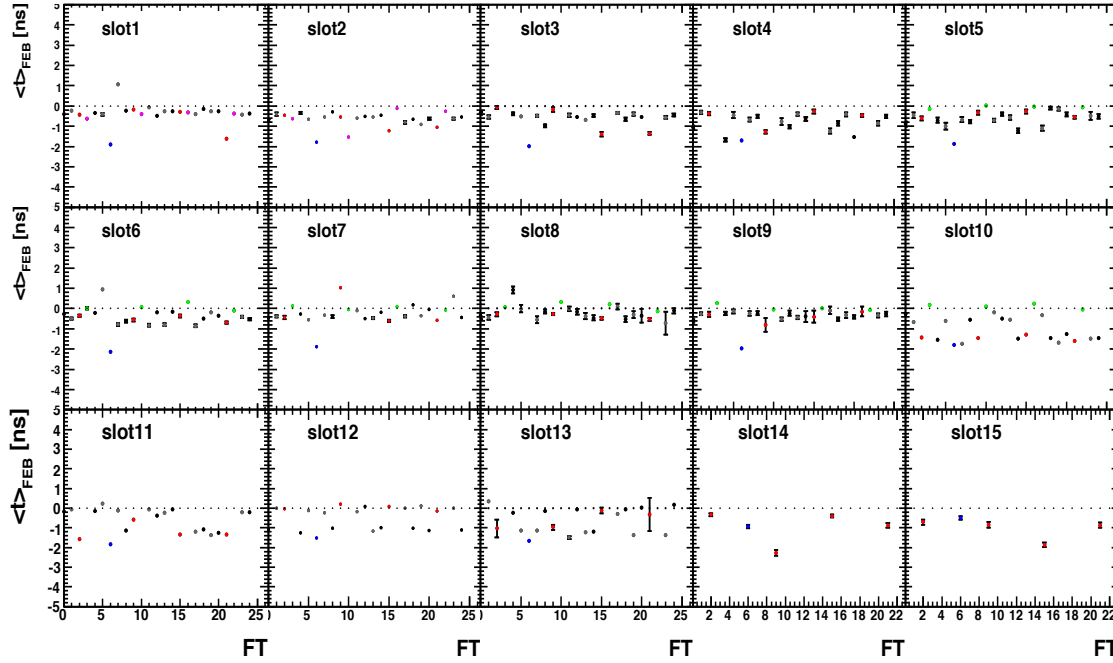
The average time of the FEBs for each FT and slot as seen in October 2011, is presented in Figure 3.6, for all four LAr Calorimeter partitions in side A (cells with $\eta > 0$). Similar behavior is seen in side C (cells with $\eta < 0$). At the end of 2011 all the FEBs were not accurately aligned in time and a lot of FEBs with time offsets of 1 to 2 ns from zero are observed in Figure 3.6, in particular in slot 9 in EMB and slots 10 to 15 in the endcap region.

New FEB time corrections were extracted using 255 pb^{-1} of 2012 ATLAS data (runs 203195, 203258, and 203277). With this data and the method used, the event statistics within each FEB is enough to use Gaussian fits to extract FEB corrections, as defined in Equation (3.2). The corrections are applied in a way to correct for the time delay of a given FEB.

To control the statistical significance of the extracted corrections, the ratio of the $\langle t \rangle_{FEB} / \delta \langle t \rangle_{FEB}$ is built, where $\delta \langle t \rangle_{FEB}$ is the error on $\langle t \rangle_{FEB}$. The distribution of this ration for the time corrections for all FEBs is presented in Figure 3.7. The resulting plot has an RMS of about 7, larger than 1, which means that the errors on the estimated $\langle t \rangle_{FEB}$ values are much smaller than the corrections. The tails are due to FEBs having large time corrections with a small



(a)



(b)

Figure 3.6: Distributions of the average time of FEBs $\langle t \rangle_{FEB}$ per slot and FT, before time alignment. Figure (a) represents the FEB time for EMB A-side. Figure (b) represents the FEB time for EndCap A-side. In Figure (b) EMEC standard and special partitions are represented in black and red, respectively. The FEBs of the HEC and FCAL partitions are represented in green and blue, respectively. The error bars represent the statistical error on the mean value of the FEB time $\langle t \rangle_{FEB}$. A portion of the 2011 data, with an integrated luminosity of 27 pb^{-1} , is used.

statistical error, so by corrections which are statistically significant. These FEBS corresponds, for example, to FEBs with very low statistics of slot 9 of the EMB or FCAL FEBs with very large and asymmetric distributions and which were largely shifted in time at the beginning of the 2012 data taking. On May 16th 2012, these FEB time corrections have been introduced inside the ATLAS online software and were applied online during the rest of the 2012 data taking.

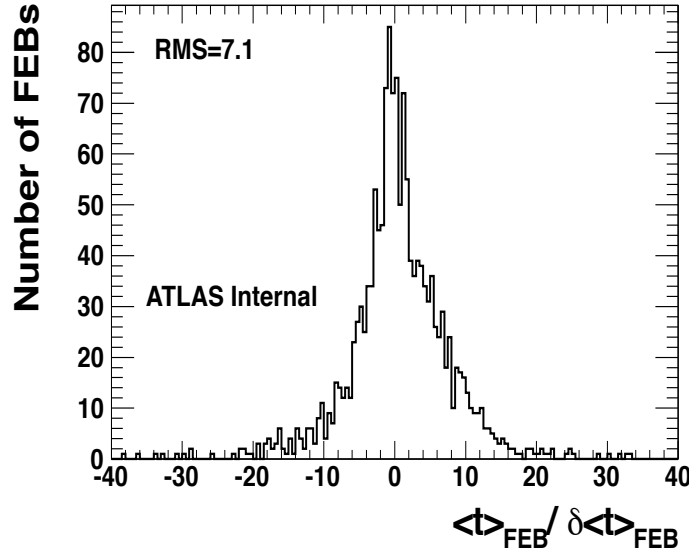


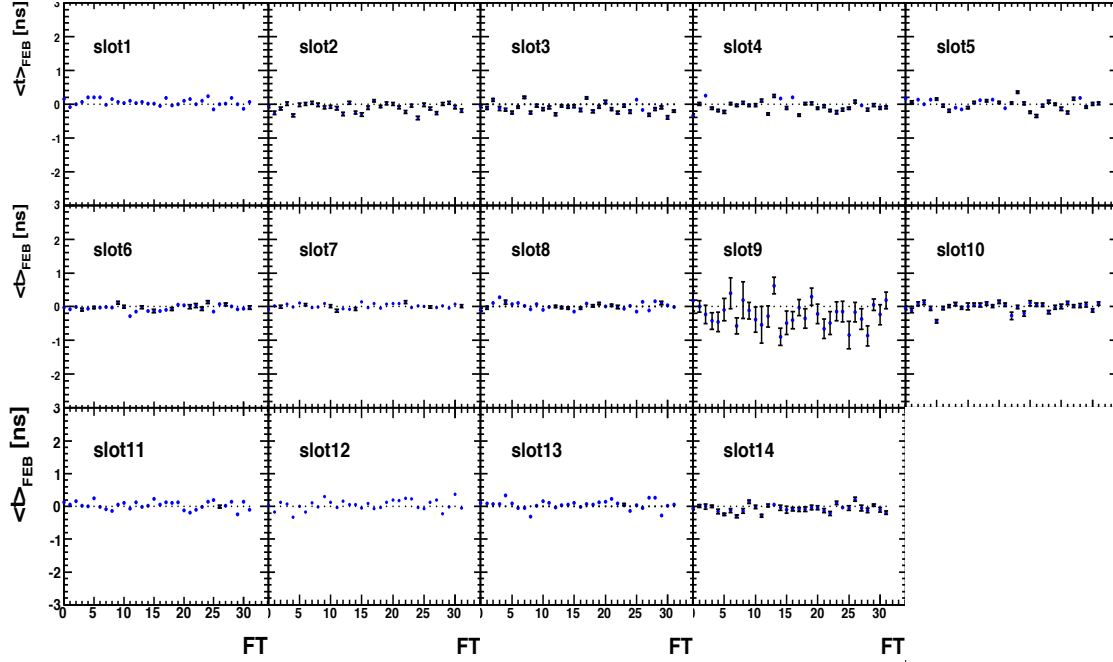
Figure 3.7: Distribution of the average FEB times $\langle t \rangle_{FEB}$ divided by their error $\delta \langle t \rangle_{FEB}$.

3.3.3.2 FEB time after correction and monitoring

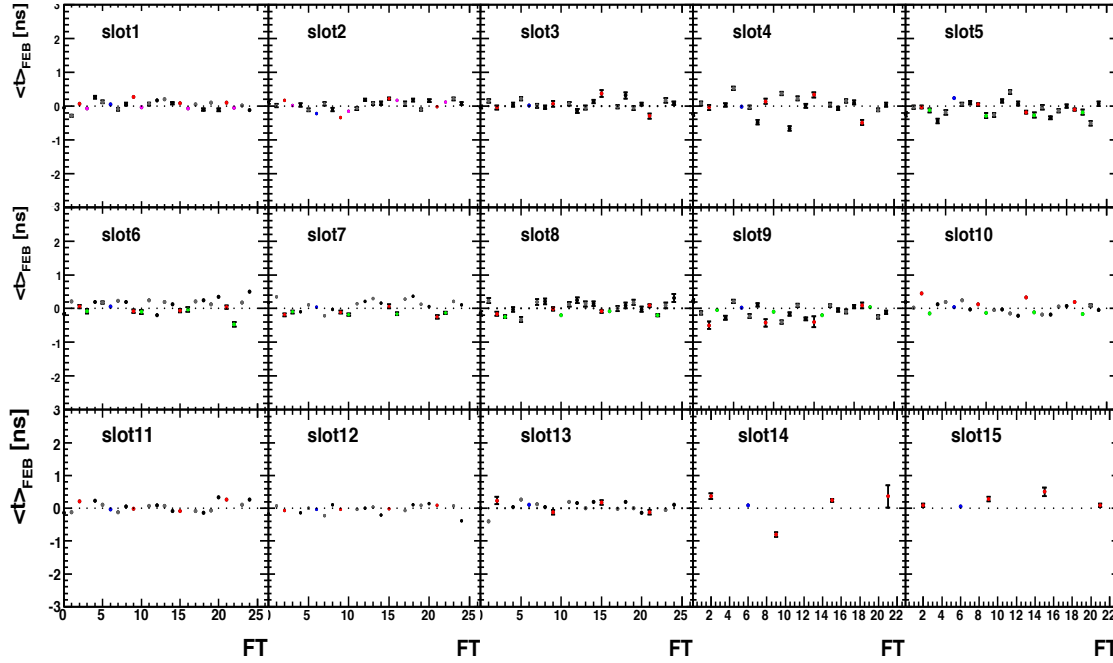
Figure 3.8 presents the average FEB time $\langle t \rangle_{FEB}$ per FT and slot for all partitions in side A, after applying the FEB time corrections determined in section 3.3.3.1. The timing situation is improved compared to the last 2011 data as presented in Figure 3.6. Outliers have disappeared, for example in slot 15 in the endcap. All the FEBs are all aligned at zero with 150 ps.

A global comparison of the old and new FEB mean time for all partitions is presented in Figure 3.9. Generally, the spread of the distributions is reduced after applying the corrections. In the EMB and EMEC partitions, some outliers are observed before applying the corrections. In the EMB partition they are due to the FEBs in slot 9 which contain very low statistics due to their location at a very large η . These FEBs were therefore not properly aligned in 2011 data. After applying the corrections, the timing of these outliers is corrected. In the EMEC, outliers are due to FEBs in slots 13, 14, and 15, FTs 2, 9, 15, and 21. The time distributions of these FEBs have very large positive tails and extremely non Gaussian behaviors. After applying the FEB time corrections extracted with the new method presented in section 3.3.3.1, these outliers have disappeared. As already discussed in section 3.3.2, the time distribution of the FCAL was shifted by ~ -1 ns before the corrections since it was never aligned in time for the medium gain output. The average time of the FCAL FEBs is now aligned at zero.

After the FEB alignment, the mean of the distributions is centered at zero and an average spread of FEB mean time of the order of 150 ps is reached. This corresponds to a reduction of the time spread, with respect to the situation before the implementation of the corrections, by 15% to 42% in the EMEC and EMB partitions, respectively.



(a)



(b)

Figure 3.8: Distributions of the average time of FEBs $\langle t \rangle_{FEB}$ per slot and FT, after time alignment. Figure (a) represents the FEB time for EMB A-side. Figure (b) represents the FEB time for EndCap A-side. In Figure (b) EMEC standard and special partitions are represented in black and red, respectively. The FEBs of the HEC and FCAL partitions are represented in green and blue, respectively. The error bars represent the statistical error on the mean value of the FEB time $\langle t \rangle_{FEB}$. A portion of the 2012 data, with an integrated luminosity of 255 pb^{-1} , is used.

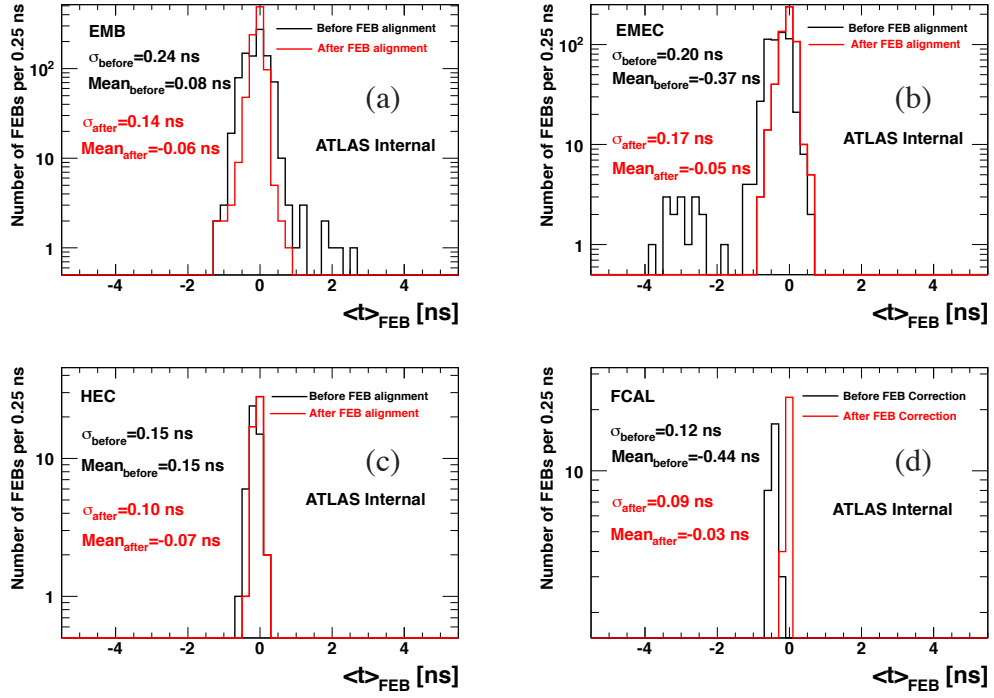


Figure 3.9: Distribution of the average FEB time $\langle t_{FEB} \rangle$ before (black histograms) and after (red histograms) FEB time alignment in all LAr partitions. 120 pb^{-1} of data is used for the distribution in black, and 78 pb^{-1} of data is used for the distribution in red. The number of entries in each distribution corresponds to the number of FEBs per partition.

In 2012 the FEB time was monitored on a run by run basis. This constant monitoring is used to detect potential hardware problems in a FEB or mis-alignment following hardware exchanges or manual interventions. Even after the complete alignment of the FEBs in time, hardware problems were discovered in the ATLAS calorimeter thanks to this constant monitoring (section 3.3.4.3).

3.3.4 Cell time definition and alignment

Even though the alignment of the FEBs is a very important procedure for online monitoring of the LAr time, aligning the channels within the FEBs is necessary as well. The aim is to further improve the global time resolution by reducing the spread in time of all cells in each FEB. Due to the large number of LAr cells, of the order of 300000 cells, the amount of data accumulated in a single run is not enough to accurately determine the timing of all LAr cells. Therefore, to extract the cell time alignment corrections, an integrated luminosity of 2 fb^{-1} of 2012 data have been used. To obtain 2 fb^{-1} data, 15 different runs are used, these runs are shifted respectively by time offsets of the order of 200 ps due to the drift of the LHC clock, t_{clock} . The global time of each run, defined in section 3.3.1, is therefore corrected by an offset Δt_{clock} given in Table 3.2 and defined as:

$$\Delta t_{clock} = \langle t \rangle_{run} - \langle t \rangle_0, \quad (3.3)$$

where $\langle t \rangle_{run}$ is the average time of a run. It is defined as the mean of the Gaussian fit applied to the core of the global time distribution (The time distribution obtained when plotting the time of all events from all the channels for each partition). $\langle t \rangle_0$ is the average time of a reference run, which is in this case chosen to be the run 203602.

run number	203602	203636	203680	203719	203745	203779	203876	203934
Δt_{clock} [ns]	0	0.04	0.11	0.14	-0.11	-0.003	0.11	-0.04
run number	204073	204153	204158	204240	204265	204416	204564	
Δt_{clock} [ns]	-0.02	0.19	0.04	0.06	0.14	0.11	0.04	

Table 3.2: The global time offsets applied for each run to correct for the drift of the LHC clock.

3.3.4.1 Determination of the average cell time corrections

The average cell time $\langle t \rangle_{cell}$ is determined using the same event selection as used for the FEB time calculation and a also the same procedure as the average FEB time calculation with slight difference explained in appendix A.2. This difference consists on the optimization on the asymmetric fit range that is applied to the core of each cell time distribution.

Using the calculation method of the average cell time described in A.2, time corrections are extracted for each cell. The cell corrections are defined as:

$$C_{cell} = \langle t \rangle_{cell} - \langle t \rangle_{FEB} . \quad (3.4)$$

These corrections are used to reduce the spread of the cell time fluctuations within a FEB.

The fit method is used to extract 88 % of the cell time corrections. The median method is used for 11 % of the corrections, because of a low event statistics. The remaining 1 % of the channels, correspond to channels with enough statistics but abnormal timing distributions. In this case, the average cell time is estimated using the fit method but the fit applied to these distributions does not converge, leading to the use of the median method.

Table 3.3 presents for each partition the percentage of channels for which the time correction have been extracted using the median or using the fit method, as well as the percentage of channels having a low statistics with less than 50 events. We observe that in the EMB, EMEC, and

Partition	Median	Fit	Low Statistics
EMB	7%	93%	6%
EMEC	18%	82%	17.7%
HEC	25%	75%	22%
FCAL	13%	87%	0.1%

Table 3.3: For all four LAr calorimeter partitions, the percentage of channels for which time corrections are extracted using either the median or the fit method, as well as the percentage of channels having a low statistics.

HEC partitions, most of the channels for which the median method is used to extract the time corrections correspond to channels having a low event statistics. This means that if the fit method is chosen, according to the available statistics, the fit converges and provides a correct result most of the times. Concerning the FCAL, for which enough statistics is available in almost all of its channels, 13 % of its channel time corrections are determined using the median method. The reason is that the FCAL is a sub-detector exposed to a lot of radiation due to its position close to the beam. Therefore, in many channels the time distributions present a non-Gaussian behavior.

3.3.4.2 Impact of the cell time corrections on the FEB time

To test the impact of the cell time corrections, these corrections have to be applied on a different set of data. Figure 3.10 represents the spread of cell time within the FEBs $\langle t \rangle_{\text{cell}} - \langle t \rangle_{\text{FEB}}$ per partition before and after applying them for the run 205071 (randomly chosen, yielding $\sim 235 \text{ pb}^{-1}$).

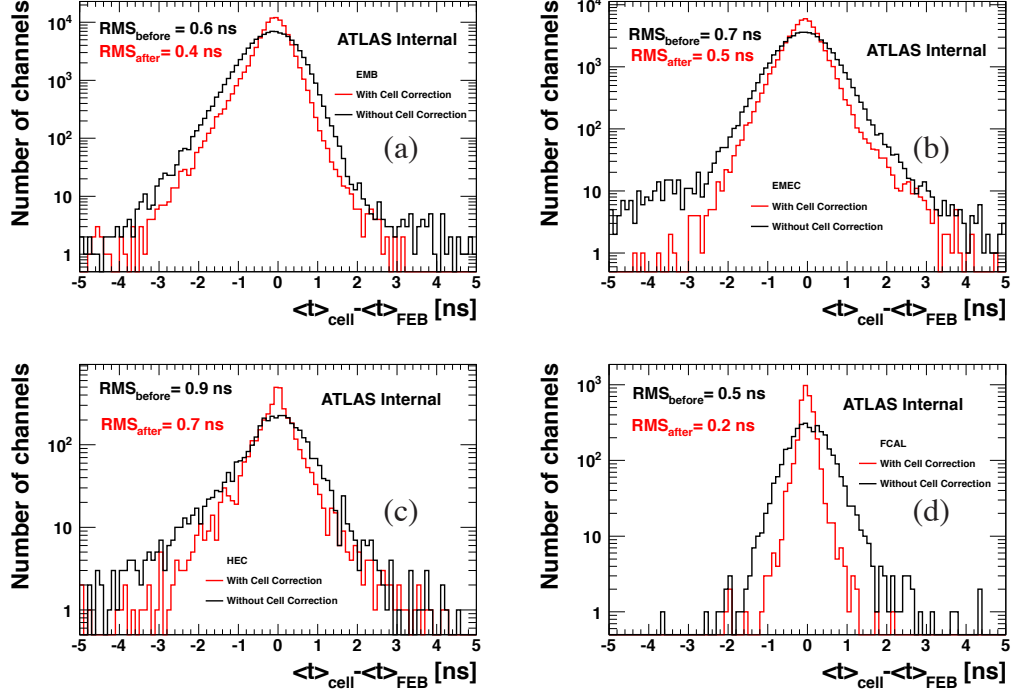


Figure 3.10: Distributions of $\langle t \rangle_{\text{cell}} - \langle t \rangle_{\text{FEB}}$ values per partition before (black) and after (red) applying the cell time corrections for the run 205071 ($\sim 235 \text{ pb}^{-1}$).

The effect of the corrections is a reduction of the RMS of the distributions in all partitions by $\sim 0.2 \text{ ns}$. The tails are reduced as well after correction but not as much as the core.

Before applying the cell time corrections, the percentage of channels for which the mean cell time deviates by more than 3 ns from the mean FEB time was 0.47%. After applying the corrections this percentage decreases to 0.007%. Also, after applying the corrections, the percentage of channels aligned within $\pm 500 \text{ ps}$ is about 98% whilst it was 68% before applying the corrections. While extracting the corrections $\sim 10\%$ of the channels have low statistics (less than 50 events per channel). Some of these channels, more precisely the remaining 2% of the channels that are not within $\pm 500 \text{ ps}$ after correction, we cannot count on for being accurate due to lack of statistics in them.

The cell time corrections are applied in order to reduce the spread of the channel times, within a FEB. Figure 3.11 represents the time of all the events from the 128 channels of a given FEB in the EMEC partition. As shown in the figure, after the alignment of the cells in time, the spread of the channels within the FEB is reduced, as expected, and the distribution is narrower. The mean value of the distribution remains always centered at zero.

Figure 3.12 presents the time distribution of events in each of the calorimeter partition before and after applying the cell time corrections. After the application of the cell time corrections, the global cell time resolution is improved in each partition by 0.1 to 0.2 ns corresponding to a reduction of the cell time spread by 15 to 25%.

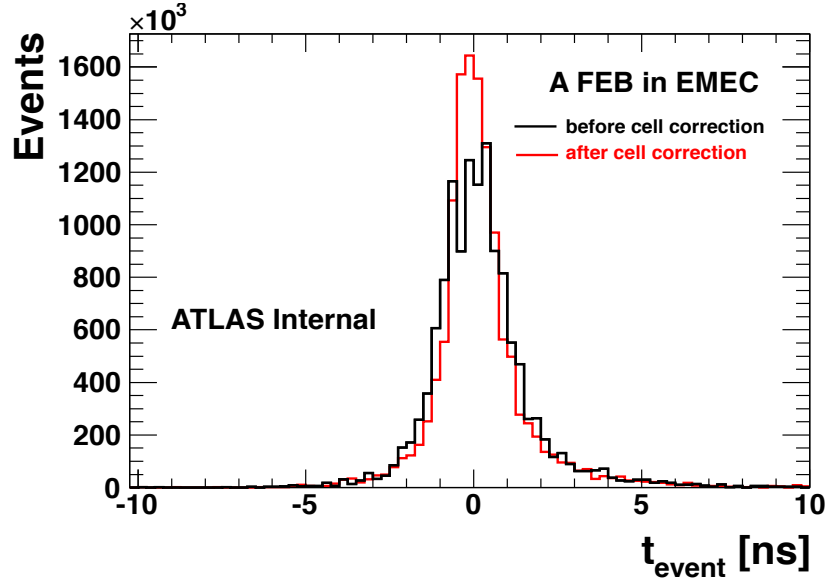


Figure 3.11: Time distribution of all the events from the channels within a given FEB in the EMEC, before (black) and after (red) time alignment of the cells. The run 207809 with $\sim 163 \text{ pb}^{-1}$ is used.

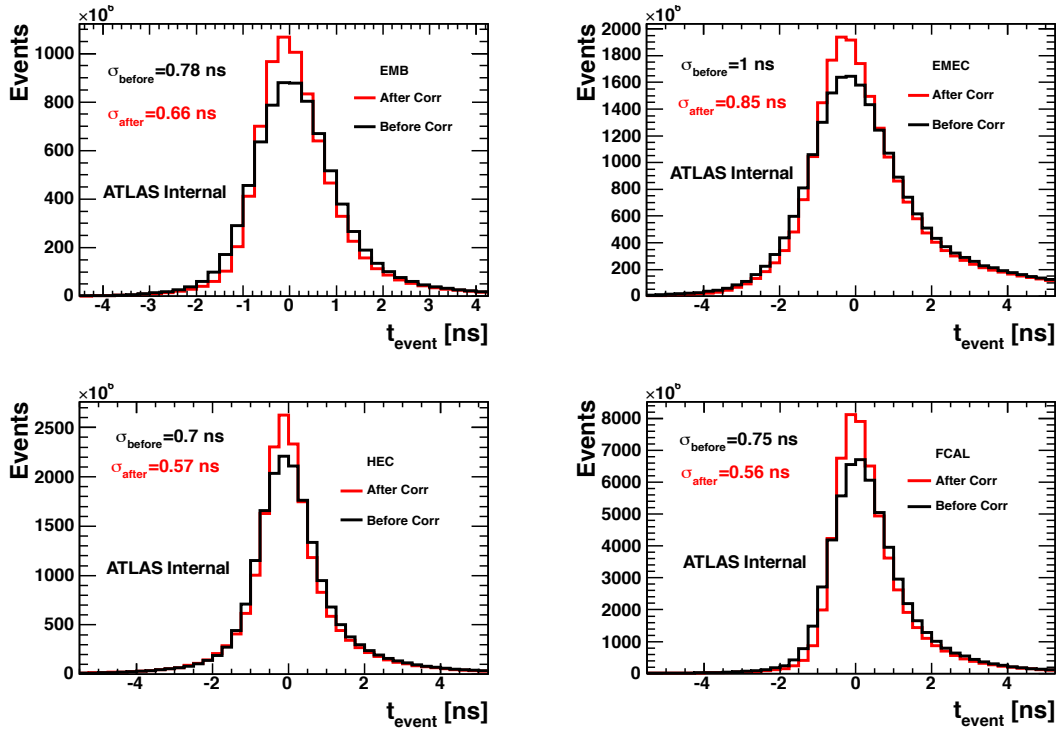


Figure 3.12: Time distribution of events, t_{event} , per partition of the LAr calorimeter before (black) and after (red) applying cell time corrections. The run 207809 with $\sim 163 \text{ pb}^{-1}$ is used.

The effect of the cell time corrections on the average FEB time is also checked. The cell corrections are applied in the analysis framework and the $\langle t \rangle_{FEB}$ is recomputed. The results are presented in Figure A.3 where the $\langle t \rangle_{FEB}$ distribution obtained with and without cell

corrections is shown. We observe that the cell time corrections have no effect on the global FEB time average. Therefore, they do not create time offsets in FEBs and can be determined and applied independently of the FEB timing adjustment.

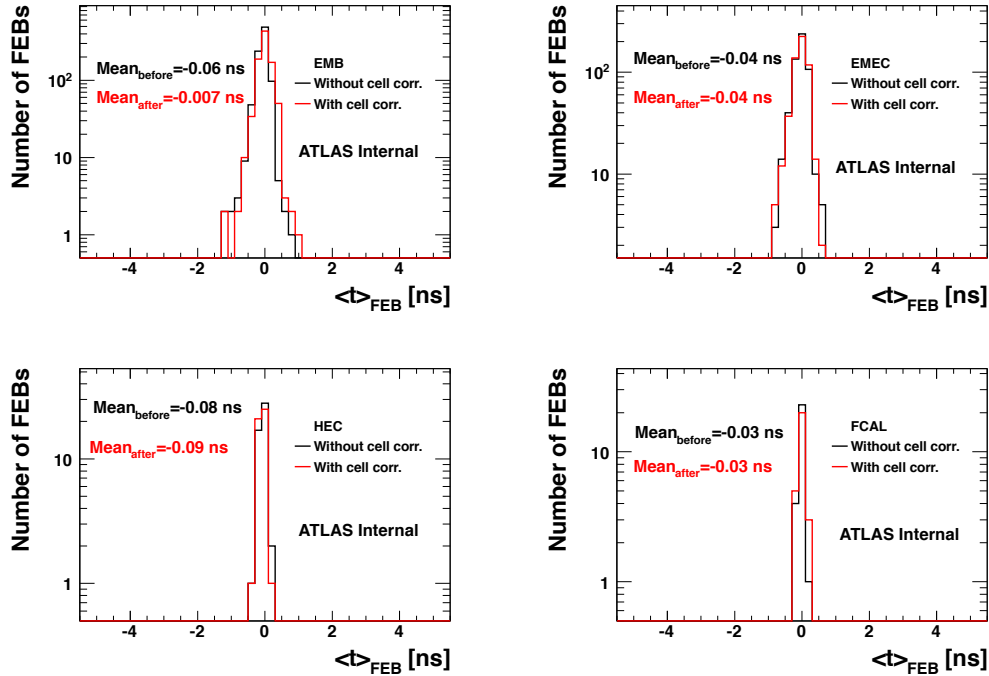


Figure 3.13: Distributions of the average FEB time, $\langle t \rangle_{FEB}$, for the four LAr calorimeter partitions, before (black) and after (red) applying cell time corrections. The data used correspond to an integrated luminosity of 2 fb^{-1} .

3.3.4.3 Application of cell time correction for reprocessed 2012 data

After testing the validity of the derived cell time corrections, as described in section 3.3.4.2, the corrections have been uploaded in the ATLAS offline database in October 2012 and used for a reprocessing of the 2012 data. Online data taken after October 2012, also benefited from these corrections. At the beginning of the 2012 data taking, the data benefited only old FEB time corrections that were extracted using the 2011 data collected under different conditions. Until enough data was collected in 2012 to extract the updated and new FEB time corrections, many data runs remained uncorrected. In order to standardize the time alignment for all the 2012 data, FEBs which were not properly corrected online have been corrected during the reprocessing campaign. The timing stability along 2012 is shown in the Figure 3.14. The remaining fluctuations are due to drifts of the LHC clock which were not corrected for a few runs. The clock drifts are usually corrected at the beginning of each run through a specific dedicated software. In order not to create overlaps and confusion with that correction system, it was decided not to correct the few fluctuations left. Deviations observed from run 206368 to run 207397, are due to a small problem in the FCAL that was detected while monitoring the FEB time. During the exchange of a high voltage module, a bad grounding connection caused a drift in the FCAL timing in some FEBs. This was not corrected because the global effect on the physics analyses is negligible.

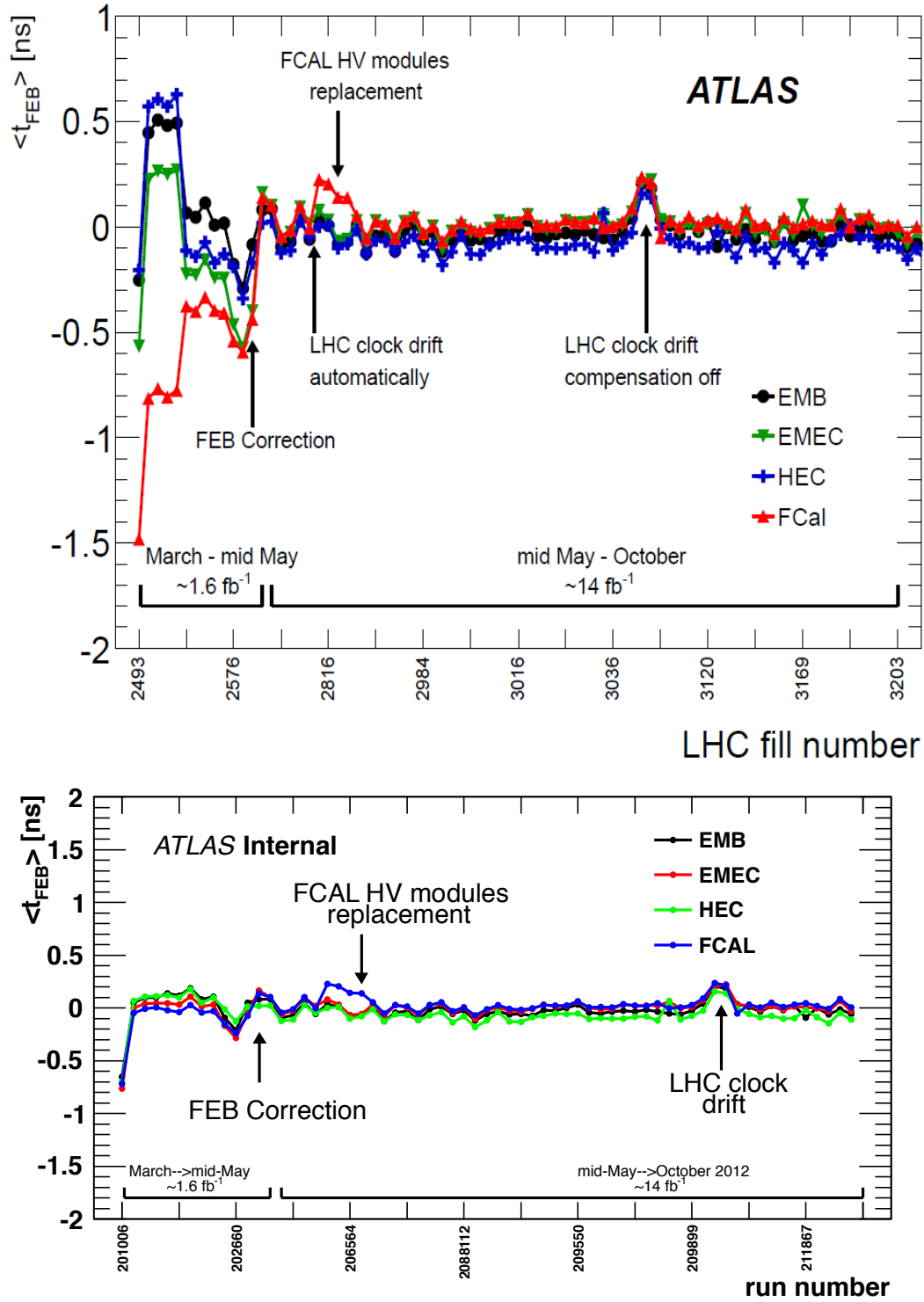


Figure 3.14: Evolution of the average FEB time, $\langle t_{FEB} \rangle$, per LAr partition, as a function of the run number before (upper) [81] and after (lower) applying the cell corrections [82].

3.3.4.4 Impact of the cell corrections on the global time resolution

In this section, measurements of the LAr time resolution at the detector level, after the reconstruction step, will be used to exemplify the impact of the time synchronization of LAr cells on it.

The time resolution of high gain cells in the middle layer of the EM barrel, where most of the electromagnetic shower is collected, is measured as a function of the cell energy. As already explained in section 3.1.2 the time resolution is the spread of the cell times that improves with the increase of the energy. The time resolution is therefore calculated by fitting the core of the time distributions with a Gaussian function in different energy bins. The width of the fitted Gaussian function, σ_t , is used to define the time resolution in each energy bin. The result is presented in Figure 3.15(a), before applying any time alignment corrections to LAr channels, after applying the FEB time corrections, and after applying the FEB and cell time alignment corrections. The figure shows the improvement of the resolution after aligning the FEBs in time. The resolution improves significantly after applying the cell by cell time corrections. An evolution of the time resolution with the energy as described in section 3.1.2 by the equation (3.1) is observed. For each curve, the value of the constant term p_{const} can be determined by adjusting a function of the form of equation (3.5) to the data points. The distributions are fitted with the following function:

$$\sigma_t = \sqrt{\frac{p_{res}^2}{E^2} + p_{const}^2}, \quad (3.5)$$

where p_{const} and the p_{res} are the fit parameters, and p_{const} represents the time constant.

Without any time alignment corrections, the measured constant term is $p_{const} = 0.64 \pm 0.01$ (stat) ns, whilst it is reduced to $p_{const} = 0.42 \pm 0.01$ (stat) ns after applying the FEB and cell time alignment corrections. Only statistical errors are quoted. Any additional systematic errors should affect almost equally the time resolutions measured before and after the cell time alignment. Therefore, they should not bias the comparison between the time resolution measurement presented here. The results shown in this analysis are obtained using online data and that does not benefit from any additional correction except the extracted cell by cell corrections.

Figure 3.15 presents the σ_t parameter of the Gaussian fit of the time distributions per energy bin before and after applying the FEB and cell corrections. The σ_t of the Gaussian fit concerns only the core of the time distribution and does not take into account the tails. As we observe in the figure, the resolution in the core of the time distributions per energy bin is slightly improving for low energies after applying the FEB time correction, and it is significantly improving by ~ 200 ps after applying the cell time corrections.

Figure 3.16 shows on the other hand the RMS of the time distributions per energy bin before and after applying the cell time corrections. Also it shows the comparison of these distributions to the σ_t evolution. We observe that the RMS of the time distributions per energy bin are not improving as importantly as the σ_t . This means that the global improvement due to the alignment of the cells is better in the core than in the tails, since the RMS of the distributions is still wide. However, after aligning the LAr cells, the constant term p_{const} obtained from the fit from both the RMS and σ distributions is of the order of 400 ps. This appears also on Figure 3.16 where for energies above 30 GeV the RMS and σ_t distributions coincide.

A summary of the evolution as a function of the energy of the time resolution in the four LAr partitions, are presented in Figure 3.17.

In each partition the resolution is improved by ~ 200 ps by the application of the cell time corrections. Comparing the time constant in the barrel for cells in high gain obtained in the 2012 analysis, to that obtained in the 2011 analysis, an improvement of about 22% is reached. The time constant term improves from 537 ps to 421 ps. A precise cell by cell time correction is therefore important in order to improve the time resolution.

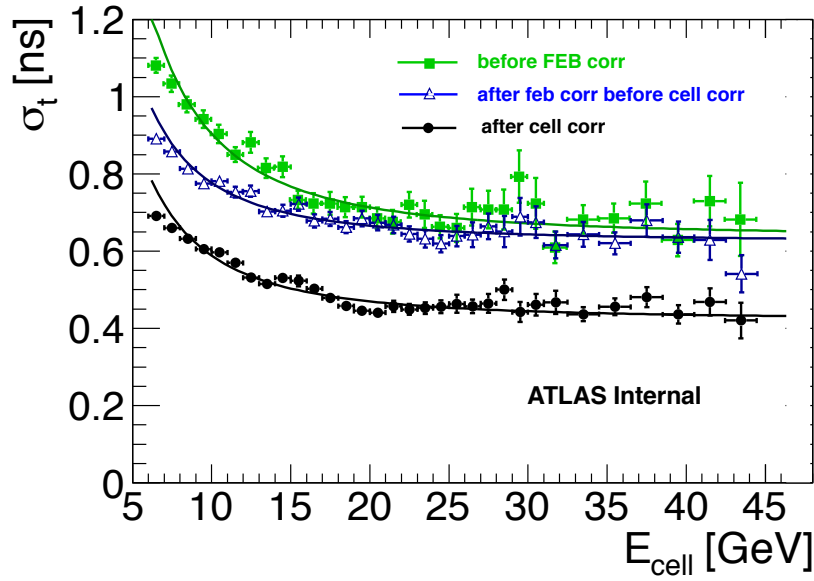


Figure 3.15: Evolution of the time resolution as a function of the cell energy for cells in the middle layer of the EMB. The time resolution at three different stages of the analysis.

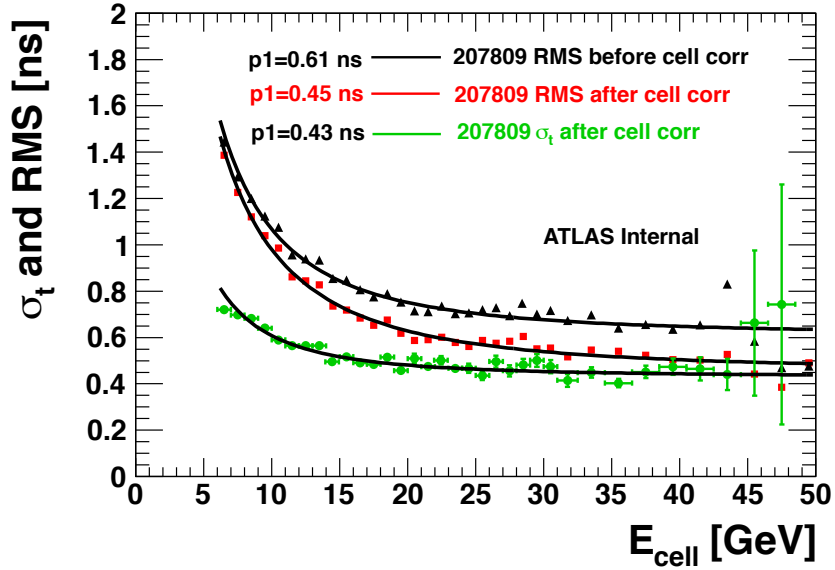


Figure 3.16: Evolution of the time resolution (green) compared to the RMS before (black) and after (red) the time alignment of the cells.

3.4 Conclusion

This study was performed by developing a fully automatized framework that is capable of monitoring the time of the LAr calorimeter on a run by run basis. The FEB and cell time corrections that were extracted and applied in the ATLAS online and offline softwares respectively. The impact of these corrections resulted in significant improvements of the time alignment in all the partitions of the calorimeter. Also the time resolution was improved by ~ 150 ps after applying the cell time corrections. The results of this study have been included in a recent publication

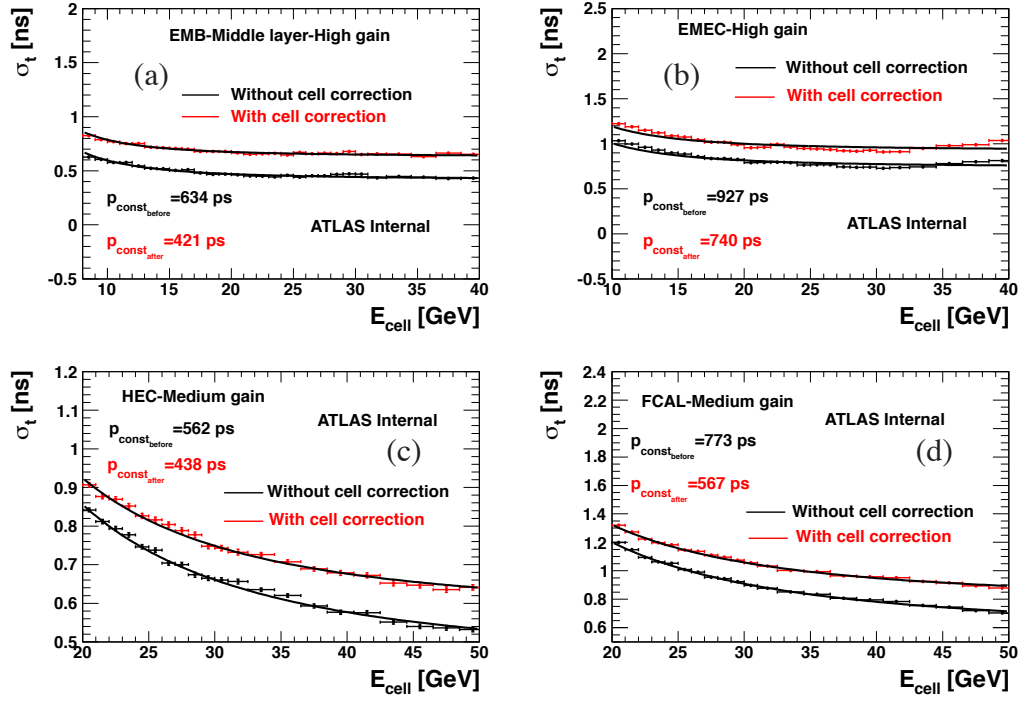


Figure 3.17: The time resolution in all of the four LAr partitions, before (red) and after (black) applying the cell by cell time corrections. The data used correspond to an integrated luminosity of 2 fb^{-1} .

by the ATLAS collaboration [81] which is currently submitted to the Journal of Instrumentation (JINST).

A complete documentation of all the results presented in this chapter can also be found in an ATLAS internal note [82].

Further improvements on the time resolution are also possible using the W and Z events and applying physics corrections, as shown in the note [83]. In this reference, using 2011 data, a time resolution of ~ 300 ps was achieved by adding time corrections not only related to time alignment of LAr cells.

Chapter 4

$W^\pm Z$ Analysis with the 2012 ATLAS data

In this chapter the electron and muon decay modes of the WZ bosons will be described. Four different channels will be therefore studied separately. Table 4.1 present the decay modes of the WZ production under study. For each channel a shortcut nomination is set as shown in the table and this shortcut will be used all along the thesis. The decays to τ leptons will be considered as a background in this analysis and their treatment will be explained in section 4.2.1

The selection of the physics objects such as electrons, muons, and E_T^{miss} will be presented. Events with three leptons (e or μ) and a missing transverse energy will be selected. First an electron, muon, and E_T^{miss} objects selection will be performed by putting several quality criteria of the candidate objects. Then an event selection will set additional criteria on the quality of the event. Even with a strong selection criteria for WZ processes, other physics processes in the bosonic and quark sectors can produce the same WZ final states which will be considered as backgrounds. The main background sources for the WZ final states are the ZZ , $Z\gamma$, $t\bar{t}$, and $Z + jets$ processes. A detailed explanation of the estimation of these processes will be presented. Finally, yields of selected data events compared to the predictions will be presented and also a comparison of the data behavior with respect to the MC prediction will be shown through distributions of kinematic variables.

4.1 Selection of $W^\pm Z$ events

In this section the data and MC samples used for the WZ analysis will be described. The different selection steps of all objects as well as the WZ events selection will be presented.

Process	decay mode	shortcut naming
$W^\pm Z$	$e^\pm \nu e^+ e^-$	eee
	$e^\pm \nu \mu^+ \mu^-$	$\mu\mu e$
	$\mu^\pm \nu e^+ e^-$	$ee\mu$
	$\mu^\pm \nu \mu^+ \mu^-$	$\mu\mu\mu$

Table 4.1: Table showing the different decay modes of the WZ bosons that are studied in this thesis.

4.1.1 Data and MC samples

Data samples

In this analysis the data used is from the proton-proton collisions at the LHC collected between April and December 2012 at a center-of-mass energy of 8 TeV. The quality of the data is controlled by setting conditions that show the well functioning of all the sub-detectors and the trigger systems. Based on these quality flags, events are selected per luminosity block, and the results are saved in a list containing run numbers that correspond to “clean” data collections. In 2012, the integrated luminosity of this data qualified as “good”, is 20.3 fb^{-1} with an uncertainty of 2.8% [84]. At the analysis level, data events are subjected to additional cleaning procedures in order to reduce the noise. Among these procedures:

- **E_T^{miss} cleaning:** This cut tests the jets with $p_T > 20 \text{ GeV}$ that are not overlapping with a selected lepton ($\Delta R_{\text{jet-lepton}} > 0.3$). It uses these jets to examine some of the common sources of noise or non $p-p$ collision energy deposits in the calorimeters through a list of quality criteria¹ on the jets. The event is rejected if the jet passes any of the “bad” quality criteria.
- **Event cleaning:** During the ATLAS reconstruction, several flags are defined referring to the quality of the event. Events that are flagged with a Liquid Argon or Tile Calorimeters noise errors are removed from data. Events are also removed if the flag for corrupted events is set. This is performed using a specific data quality flag provided within the ATLAS reconstruction.

In this thesis, channels containing only muons and electrons are treated. Therefore the data used is from two trigger streams: muons and electrons. These streams require a list of muon or electron triggers to select events containing these objects.

The trigger system of the ATLAS detector is described in detail in section 2.2.7. In this analysis, the $W^\pm Z$ candidate events with three leptons in their final states are recorded with single muon or electron triggers. The term “single” means that at least one of the leptons in the event (muon or electron respectively) have triggered one of these triggers.

The single muon triggers have p_T thresholds of 24 GeV or 36 GeV. The trigger with the lowest p_T threshold uses isolation criteria as well as requires a combined muon quality. Where the trigger with the highest p_T threshold, requires no isolation criteria but a combined muon quality. Similarly, the single electron triggers require p_T thresholds of 24 GeV or 60 GeV, respectively. The trigger with the lowest p_T threshold requires an isolated electron with the “medium” quality criteria. Additionally, hadronic leakage and dead material corrections are applied for this trigger. The 60 GeV threshold trigger requires only a “medium” electron quality criterion.

In the WZ channels decaying to same flavor leptons, namely the eee and $\mu\mu\mu$ channels, one of the single electron or single muon triggers are used respectively. In the channels with mixed lepton flavors, both electron and muon triggers are tested. In order to avoid the double counting of the events in data, when a data event is triggered by both triggers, the event is chosen from the muons trigger stream.

Finally, a trigger matching is performed. One of the offline reconstructed leptons in the event associated with the W or Z decay, with a p_T of at least 25 GeV, should match the online reconstructed lepton that triggered the event. The trigger matched lepton should be isolated if the corresponding EF trigger was fired.

¹criteria checking the quality of the jet based on information from the calorimeters

The MC simulations model the trigger efficiencies with a percentage higher than 99%. However, to correct the remaining differences, the ratio of the data trigger efficiencies to that of the MC efficiencies are estimated. These are applied to the reconstructed events in the MC to match better the data. With the presence of three leptons with large p_T , the trigger efficiencies for $W^\pm Z$ events is higher than the single lepton trigger efficiency, since the total inefficiency is the product of each of the single lepton inefficiencies. The scale factors accounting for mis-modeling in the MC have been derived using the tag-and-probe method (T&P) on $Z \rightarrow l^+ l^-$ events. The scale factors are applied to leptons forming the W and Z candidate and satisfying the leading lepton p_T cut. The per event scale factor depends on the lepton flavor and the p_T of the individual leptons,

$$SF = \frac{1 - \prod_{n=1}^{N_l} (1 - \epsilon_{Data, l_n})}{1 - \prod_{n=1}^{N_l} (1 - \epsilon_{MC, l_n})}, \quad (4.1)$$

where N_l is the number of leptons identified as coming from $W^\pm$ or Z and passing the leading lepton p_T cut, and $\epsilon_{Data, l_n}(\epsilon_{MC, l_n})$ is the trigger efficiency determined with T&P from data (MC) for the lepton flavor of lepton l_n . The scale factors are derived in two dimensions: for muons they are binned in (η, ϕ) as for electrons they are binned in (η, E_T) . Systematic uncertainties due to the application of these scale factors are studied independently for electron and muon triggers and these are explained in section 4.3.

Monte Carlo signal samples

The MC generator used to compare to the data measurements performed in this thesis is the POWHEGPYTHIA generator. This generator models the WZ signal behavior using NLO matrix element calculation. Section 1.2.3 gives the description of this MC generator and as it is explained POWHEGPYTHIA uses the CT10 PDF which is also calculated to NLO.

4.1.2 Reconstructed vertexes and Pileup correction

In this analysis, a primary reconstructed vertex in an event is defined as the vertex with the highest sum of tracks transverse momenta. At least 3 “good” tracks should be associated to this vertex in order to avoid the vertexes of secondary (soft) interactions that are not associated to the hard $p - p$ scattering.

The number of these primary vertexes and the average interaction number per bunch crossing $\langle \mu \rangle$ are related in the sense that when the $\langle \mu \rangle$ variable is not well described by the Monte Carlo simulation usually this means a mis-description in the number of the primary vertexes.

The high LHC luminosity of 2012 and the bunch separation of 50 ns, lead to the increase of the number of proton-proton interactions occurring in the same bunch crossing to an average of 20.7 interactions per bunch crossing. This condition needs to be matching between the data and MC and therefore these pile-up events require the use of dedicated algorithms and corrections to minimize their impact on the reconstruction of leptons and jets. Residual differences in the pile-up between data and Monte Carlo simulation have been corrected by re-weighting the Monte Carlo events to reproduce the average number of interactions per bunch-crossing, $\langle \mu \rangle$, observed in data. The distribution of the number of primary vertexes in data and MC after the pile-up reweighting are shown in Figure 4.1.

As most of the corrections applied on the MC, that depend on the pile-up (e.g. calorimetric isolation for electrons) are applied as a function of the primary vertexes, it is important that this

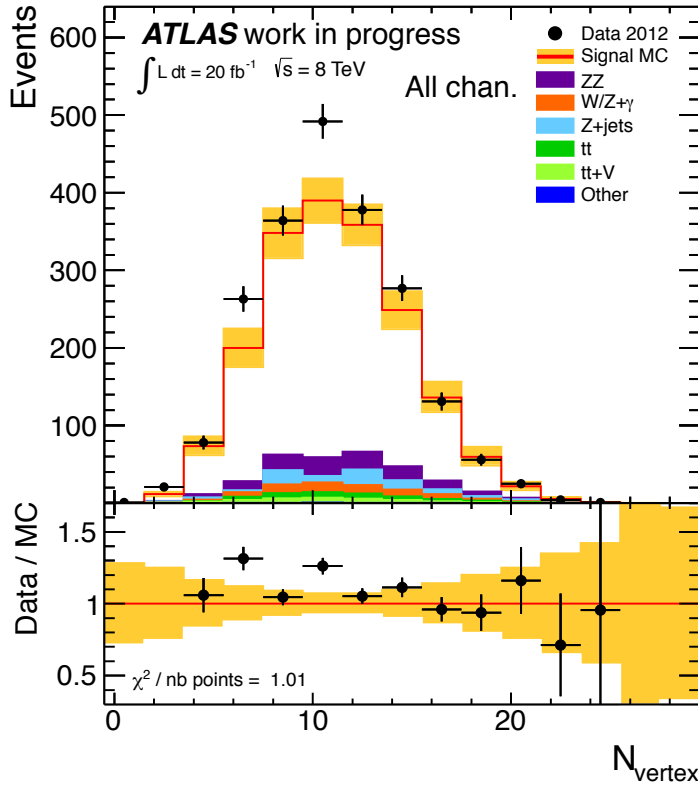


Figure 4.1: Control distribution for the sum of all channels of the number of primary vertexes. All MC expectations are scaled to the integrated luminosity of the data using the predicted MC cross sections of each sample. The orange band represents the quadrature sum of all systematic uncertainties on the total MC expectation. It includes an uncertainty of 2.8% for the integrated luminosity of the data and an uncertainty of 4% on the pile-up reweighting.

distribution is well described after the pile-up reweighting. The figure shows that after the pile-up reweighting, the data to MC description of the number of vertexes is fair. The yellow bands represent the systematic uncertainty on the total MC expectation which include also the systematic uncertainty on the pile-up that is of the order of 4% and obtained by varying the $\langle \mu \rangle$ distribution in the MC by 4%.

4.1.3 Muons

The muon candidates are selected according to the description given in section 2.3.2.3. Additionally, the selected candidate muons are required to have $p_T > 15$ GeV with $|\eta| < 2.5$. Table 4.2 summarized all the quality cuts that the selected muons subject.

4.1.4 Electrons

The electron candidates are selected according to the description given in section 2.3.1.4. Additionally, the selected candidates are required to have $E_T > 15$ GeV with $|\eta| < 2.47$ outside the detector's transition region. Table 4.3 summarizes all the quality cuts required to selected electrons.

Muon Selection
Reconstructed combined or segment tagged STACO muon
Kinematic Acceptance: $p_T > 15 \text{ GeV}$
Geometrical Acceptance: $ \eta < 2.5$
Muons from Z decay:
Track Isolation Requirement: $\sum_{\Delta R < 0.2} p_T(i) < 0.15 \cdot p_T(\mu)$
Muons from W decay:
Track Isolation Requirement: $\sum_{\Delta R < 0.3} p_T(i) < 0.10 \cdot p_T(\mu)$

Table 4.2: Criteria applied to select muons in this analysis.

Electron Selection
Kinematic Acceptance: $E_T > 15 \text{ GeV}$
Geometrical Acceptance: $ \eta < 2.47$, outside crack region $1.37 \leq \eta \leq 1.52$
Identification Criteria: Tight for electrons coming from W decay
Medium for electrons coming from Z decay
Z electrons:
Calorimeter Isolation Requirement: $\sum_{\Delta R < 0.2} E_T(i) < 0.14 \cdot E_T(e)$
Track Isolation Requirement: $\sum_{\Delta R < 0.2} p_T(i) < 0.13 \cdot p_T(e)$
W electrons:
Calorimeter Isolation Requirement: $\sum_{\Delta R < 0.3} E_T(i) < 0.14 \cdot E_T(e)$
Track Isolation Requirement: $\sum_{\Delta R < 0.3} p_T(i) < 0.10 \cdot p_T(e)$

Table 4.3: Criteria applied to select electrons in this analysis.

4.1.5 Missing Transverse Energy

The missing transverse momentum (E_T^{miss}) is defined as the transverse momentum imbalance in the detector. This was explained in section 2.3.3. In the WZ analysis, no direct E_T^{miss} cut is required, however this quantity is used to calculate the transverse mass of the W boson, that will be used to reduce the background contributions as it will be explained in the next section.

4.1.6 Reconstruction of W and WZ candidates

The W candidate reconstruction is performed right after the Z candidate reconstruction. As the event contains exactly 3 leptons, once two of them are associated to the Z boson, the last one remaining is associated directly to the W boson. As ATLAS does not reconstruct the longitudinal component of neutrinos, the E_T^{miss} and the selected lepton's p_T are used to calculate the transverse mass of the W boson as the following:

$$M_T^{W^2} = 2E_T^\ell E_T^\nu - 2\mathbf{p}_T^\ell \mathbf{p}_T^\nu. \quad (4.2)$$

From the other side, the longitudinal component of the neutrino, is estimated through an approximate calculation. It is performed by fixing the W mass to its PDG value and solving for a quadratic equation obtained through the four-vector momentum conservation. When the equation has two solutions for the longitudinal component of the neutrino momentum, the one with the smallest magnitude is chosen. According to truth studies, the smallest p_l^ν provides a better resolution with respect to the highest one. In case when one of the solutions is imaginary, only

the real solution of this quadratic equation is considered.

The longitudinal component of the neutrino is needed to calculate the invariant mass of the WZ system. This quantity will be used to calculate later on the WZ differential cross section as a function of it.

Finally, the transverse mass of the WZ system cannot be defined as equation 4.2 since this equation can be only used in the relativistic limit where particles are considered massless. As we know that the W and Z bosons are massive, then the following possibilities can be used to calculate the transverse mass of the WZ system:

- An inclusive definition from the PDG [85] so that

$$M_T^{WZ} = \sqrt{M_{WZ}^2 + (p_x^{WZ})^2 + (p_y^{WZ})^2}; \quad (4.3)$$

- Another general definition from the PDG [85]

$$M_T^{WZ} = \sqrt{(E_T^W + E_T^Z)^2 - (p_T^{WZ})^2}; \quad (4.4)$$

- A definition from an ATLAS publication for $W\gamma$ production [86]

$$M_T^{WZ} = \sqrt{(\sqrt{M_{3l}^2 + p_{T,3l}^2} + p_{T,\nu})^2 - (p_{T,3l+\nu})^2} \quad (4.5)$$

where M_{3l} and $p_{T,3l}$ are the invariant mass and transverse momentum of the 3 final state leptons associated to the W and Z candidates, respectively. $p_{T,\nu}$ is the E_T^{miss} .

- The definition used for this thesis was also used in the ATLAS WZ analysis with the 7 TeV data [27] and it is simply by building the final state leptons, associated to the W and Z , only in the transverse plane by neglecting their longitudinal component. Then the transverse mass is defined as the invariant mass of the system build with these 3 leptons with transverse components and the E_T^{miss} .

All of these four definitions of the transverse mass have been tested and the comparison of their resolutions is shown on figure 4.2. The figure shows that the definition used for this thesis has the best resolution. Hence it was decided to be used for this analysis.

4.1.7 Selection of $W^\pm Z$ candidates

After the definition and selection of all the objects that were presented in the previous sections, the WZ event selection is performed. The WZ analysis is cut-based, with event selection criteria that are presented below. The four $\mu\mu\mu$, $ee\mu$, $\mu\mu e$, and eee WZ decay channels are considered. There is no additional requirement on the number of jets.

Similar conditions are applied for all four channels except for small differences between the electron and muon channels. Several event cleaning cuts such as the good runs list, apply only to data samples; they only remove a small fraction of the events ($< 1\%$).

The event selection criteria are described in the following list:

1. **Primary vertex:** A primary vertex must be reconstructed (as explained in section 4.1.2).
2. **ZZ veto:** In order to decrease background from ZZ , events with 4 or more leptons passing the selection criteria listed in Section 2.3.3 but with a lower p_T threshold of 7 GeV, are discarded.

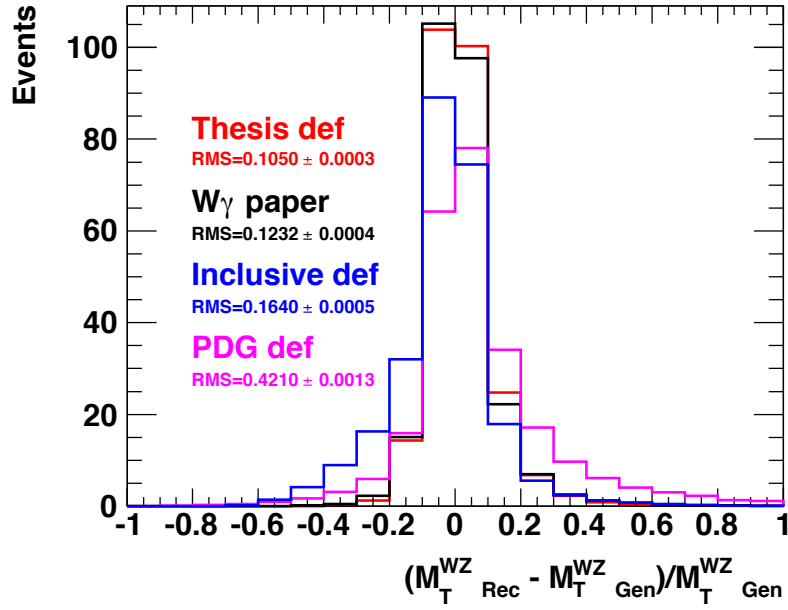


Figure 4.2: Resolution of the transverse mass for the WZ system for the four different definitions.

3. **Z candidate:** The event must contain two selected same flavored leptons with opposite charge, and an invariant mass that is consistent with the Z mass peak so that: $|M_{ll} - 91.1876| < 10$ GeV. If more than one pair of leptons build a Z candidate in one event, the candidate with the invariant mass closest to the PDG Z mass, is considered.
4. **exactly 3 leptons:** The event must contain exactly 3 leptons passing the selection criteria as in Section 2.3.3. The lepton that is not associated to the Z boson candidate must satisfy the combined (“tight”) quality definition for muons (electrons). The third lepton should have a $p_T > 20$ GeV and satisfy relative isolation requirements in a cone of $\Delta R = 0.3$.
5. **W transverse mass:** The transverse mass of the W boson, must be greater than 30 GeV.

These criteria are optimized in a way to increase as much as possible the significance and purity of the signal events. However, background processes will still contribute in the selected events and this is explained in the next section.

4.2 Estimation of background events

In the WZ analysis, the major systematic uncertainty on the measurement of the cross section corresponds to the background estimation. In order to perform a data analysis with high precision and sensitive to new physics, it is important to reduce as much as possible the systematic uncertainty on the background estimation.

In general, MC generators are able to generate all kind of physics processes. However, in some cases the uncertainty on the generated processes can be very large. First, for many physics processes, the theoretical uncertainty on the calculated cross sections are relatively high. Therefore, when data is compared to MC prediction in a given physics analysis, the total number (normalization) of a given background process can be different in MC than in data. Also sometimes

the MC cannot model correctly the corresponding physics process. For example, the modeling of the production of jets is very critical. From one side, the theoretical perturbative calculations can only be performed in fixed orders (LO, NLO, NNLO) due to the complications of these calculations. From the other side, the strong interaction has a confined nature and contains non-perturbative processes that cannot be calculated using the conventional perturbation theory. These jets can be modeled by MC using models that make approximations and use parameters that are tuned to data, which means that they have large uncertainties.

The data contains the real physics, therefore a process to all orders. Some discrepancies may be found between data and MC due to the fixed order MC calculations. Otherwise, because of the large uncertainties on the jet modeling, a difference in the shape of the MC background can be observed when compared to data. Finally, processes with very high cross sections are technically critical to be generated with enough statistics (such as multi-jet events), then in that case the MC will have large statistical fluctuations. Even if an inclusive background MC process itself reproduces well the data behavior, when put in a different phase space, the behavior of the MC can change and it may no longer reproduce the data well. In these cases the kinematic cuts may bias the shape and the normalization of the predicted background. This shows the motivation to estimate the background in using data in special background selections.

The main SM processes that can mimic the WZ final states are summarized in the following:

- $Z + jets$ and $t\bar{t}$: This background is due to a lepton within a jet or a jet reconstructed as a lepton, that is falsely associated to the W or the Z boson.
- $Z\gamma$: In the eee and $\mu\mu e$ channels, where the W boson decays to electrons, a photon can be easily mis-identified as an electron. This creates a false W boson reconstruction enhancing the $Z\gamma$ background.
- ZZ : These are due to processes containing four leptons (electrons or muons) one of which has not been reconstructed being lost in the detector's transition regions. This creates a false E_T^{miss} and fakes the WZ final states.

Other SM processes such as the $t\bar{t} + V$ (where V is a vector boson) contribute as importantly as the $t\bar{t}$ background. Finally, VVV processed containing three bosons in their final states can also mimic the WZ signatures. However, these do not contribute in the same importance as the processes listed above.

In the WZ analysis presented in this thesis, the modeling of the $t\bar{t}$, $Z + jets$, $Z\gamma$, and ZZ backgrounds will be controlled using special data selections. Also the total normalization of these backgrounds will be extracted using the control regions developed from data.

4.2.1 tau decays of WZ events

The POWHEGPYTHIA MC generator provides separate samples for WZ events decaying into tau leptons. These samples either contain single decays to tau leptons or multiple decays to it. Therefore, they can be used to estimate the behavior of events with final states containing taus. In this thesis, during the calculation of the integrated cross section of the WZ production in the total and fiducial phase spaces, the background related to the taus will be considered only according to equation 5.1. Whereas, in the measurement of the differential cross sections, described in chapter 6, the differential distributions obtained only for events containing taus, will be added to the total background contributions described in the following sections, and thus subtracted

directly from the data measurement. As it will be shown in chapters 5 and 6 that these processes do not contribute more than 4% to the total measurement.

4.2.2 $Z + jets$ and $t\bar{t}$ backgrounds contamination

One of the most challenging backgrounds in the WZ analysis are the $Z + jets$ and $t\bar{t}$ backgrounds, where a lepton in a jet or a jet reconstructed as a lepton, is falsely associated to one of the W or Z bosons. The SHERPA and POWHEGPYTHIA MC generators give a prediction of these backgrounds, respectively. Another background from the $W + jets$ processes, predicted by the ALPGEN LO MC generator, is due to events containing one good lepton associated to the W boson accompanied with missing transverse energy and another lepton in a jet. This means that the event contains two leptons and missing transverse energy. Knowing that WZ events contain three leptons and E_T^{miss} , the contribution of this background is very small.

The scenario that usually takes place is when a lepton fragmented from a jet or a jet reconstructed as a lepton, is associated to the W or Z boson in a WZ event. First a study using MC truth will be performed in order to quantify the rate of fake reconstructed W or Z bosons. Then, control regions using data will be built to control the differences between data and MC for two scenarios: when a “fake” lepton is associated to the Z candidate and when it is associated to the W candidate.

Fake leptons contributions through MC Truth studies

The fake W or Z reconstruction in WZ events, can appear in the $Z + jets$ and $t\bar{t}$ processes. For the $Z + jets$ processes, a lepton in a jet or a fake lepton is falsely associated to the W or Z boson. In a $t\bar{t}$ process, the decay of the top quark is given by $t \rightarrow Wb$ so that $t\bar{t} \rightarrow W^+bW^-\bar{b}$. In this process when the W bosons decay leptonically, it is expected to observe fake WZ signatures.

To quantify the contribution of the “fake” reconstructed W and Z candidates in the $Z + jets$ and $t\bar{t}$ samples, first truth studies are performed using the MC. In all of the four WZ channels, the true mother particle associated to the W or Z leptons is checked. This is performed only using $Z + jets$ and $t\bar{t}$ MC for the leading and sub leading Z leptons and for the corresponding lepton associated to the W boson.

Table 4.4 shows the percentage of “fake” reconstructed leptons² in each of the eee , $\mu\mu e$, $\mu\mu\mu$ and $ee\mu$ channels. The following equation is applied to extract each of the percentages shown in the table:

$$fake_{fraction} = \frac{N_{fake}^{process}}{N_{tot}^{process}}, \quad (4.6)$$

where $N_{fake}^{process}$ represents the number of “fake” leptons in a given process ($Z + jets$ or $t\bar{t}$) and $N_{tot}^{process}$ is the total number of events in the MC for that process passing all cuts. The aim of this table is to show the source of the contribution of the “fake” leptons in each of the $Z + jets$ and $t\bar{t}$ processes. The table shows that for the leading Z lepton, the fake reconstruction is very small in all channels. For the sub-leading Z lepton, it is the most important in the $t\bar{t}$ decays where they contribute by proportions of 70% to 86%. A non negligible contribution from the Z

²In case of muons, the term “fake” refers usually to non-isolated muons in jets, where for electrons this term refers to jets reconstructed as electrons

sub-leading fake leptons is also present in the channels with same lepton flavors, eee and $\mu\mu\mu$, for the $Z + jets$ MC with contributions of 13% and 46%, respectively. Finally, the fake leptons percentage associated to the W boson are the most important in the $Z + jets$ MC and they contribute with a maximum fraction of 26% in the $t\bar{t}$ MC.

This table also shows that in channels having the same flavor leptons, fake Z leptons are included in both $Z + jets$ and $t\bar{t}$ processes. While in the channels with mixed flavors the fake leptons associated to the Z are only existing in the $t\bar{t}$ process. This means that maybe in the same flavor channels, fake leptons within jets that should have been associated to the W boson, were falsely associated to the Z boson because of a bias in the recipe of the lepton to its mother boson association.

In conclusion, the background contamination containing a fake Z boson candidate is mainly arising from the $t\bar{t}$ processes. Also an average of 30% contribution in this background can be accounted from the $Z + jets$ processes. While the background containing a fake W is mainly arising from the $Z + jets$ processes with a small contribution from $t\bar{t}$.

Channel	Process	Z leading lep fake[%]	Z sub-leading lep fake[%]	W lep fake[%]
eee	$Z + jets$	3	13	84
	$t\bar{t}$	18	70	12
$\mu\mu e$	$Z + jets$	0	0	100
	$t\bar{t}$	17	78	5
$ee\mu$	$Z + jets$	0	0	100
	$t\bar{t}$	12	62	26
$\mu\mu\mu$	$Z + jets$	2	46	52
	$t\bar{t}$	10	86	4

Table 4.4: Percentage of fake leptons associated to the W and Z boson candidates in the $Z + jets$ and $t\bar{t}$ MC samples.

General definition of data control region enriched with fake Z contamination

For the selection of this control region, we expect to have a real W boson in the event and a pair of leptons that are identified as “fake”. These leptons, will pass the lepton reconstruction criteria in the WZ analysis and with a given probability they will fake the Z . In order to build a data sample that is enriched with events containing a real W and fake Z , we should ensure that the event selection in the control region is close to the WZ signal selection, in order to avoid any possible biases introduced by extreme cuts. These kind of events are usually dominated by the $t\bar{t}$ processes as already shown in the MC truth studies. The MC modeling will therefore be controlled in the specific data selections that will be explained in the next sections.

General definition of data control region with fake $W \rightarrow e\nu$ contamination ($Z + e$ channels)

In the channels where the W boson decays electronically, it is possible to mis-reconstruct a jet as an electron. This jet will satisfy all the quality criteria of the selected lepton that will be associated to the W boson. The data control regions in this case, are built in a way to contain a real Z in the event and a fake W that decays to an electron and a neutrino. In order to do so, in

the control regions the selection of the Z boson is remained unchanged with respect to the WZ signal selection while the selection cuts on the W electron are loosened or inverted in a way to enrich the sample with fake electrons. The selected cuts for these control regions, are optimized in a way to enrich the region with a real Z and a fake electron with a minimal contamination from other processes. Therefore, these control regions are expected to be dominated by the $Z + jets$ processes.

General definition of a control region with a fake $W \rightarrow \mu\nu$ contamination ($Z + \mu$ channels)

In the channels with a real Z and a fake W decaying to muons, the situation is slightly different than the case of a W boson decaying to an electron. The signature of muons is cleaner than that of electrons, therefore the probability of reconstructing a jet as a muon is lower than that reconstructed as an electron. In general, since muons are mainly the disintegration products of heavy flavor quarks, in many cases they can disintegrate specifically from b quarks. A sample containing a real Z boson and enriched with muons in jets that will be associated to the W boson, will be chosen to build these kind of control samples. This sample will be equally dominated by $Z + jets$ and $t\bar{t}$ processes, as for the $t\bar{t}$ the top quark disintegrates to a W boson decaying leptonically and another bottom quark decaying also to leptons.

4.2.2.1 Backgrounds associated to a fake W reconstruction

Control region with a fake W boson in the $Z + e$ channels

A special selection in the eee and $\mu\mu e$ channels is applied in a way to enrich the sample with Z bosons accompanied with jets. In these channels the aim is to build “good” Z bosons with well reconstructed leptons and a “bad” W boson for which an electron fragmented from a jet or a jet mis-reconstructed as an electron will be associated. Since events are selected in a way to keep the Z boson reconstruction robust, the same Z selection as for the signal region is remained for this control region (section 4.1.7). To have a “loose” W boson selection, first the 30 GeV threshold on the W boson’s transverse mass is removed. Then, in order to reduce any signal contamination, the track isolation requirement of the electron associated to the W boson is removed and its calorimetric isolation is required to be greater than 0.05. The reason of requiring large calorimetric isolation on the electron is to reduce the contamination from the $Z + \gamma$ processes (see figure 4.15). Also to reduce the rate of signal events, a “loose” and not “medium” nor “tight” electron is selected and associated to the W boson. As the electrons associated to the W boson have all an identification that is “loose”, then the ID track associated to them have a very poor quality. This means that it is very easy to misidentify these mis-reconstructed electrons also with photons by associating the energy deposition of a photon in the calorimeter to a track in the inner detector. Even with the optimization of the cuts, a small contamination from $Z\gamma$ events of 8% remain in this control region. It will be subtracted from the data using the MC predictions. However, the $Z + jets$ processes are the dominant ones overall.

To control the MC normalization with respect to the data measurement, the total yields for data and all MC contributions for these channels are shown in Table 4.5.

The table shows that $\sim 90\%$ of events in this control region contain a real Z and an electron-like jet ($Z + jets$). The $Z + \gamma$ processes represent $\sim 8\%$ of the control region and as in the previous section it was shown that the MC describes correctly these processes, therefore they are

Event yields		
Process	eee	$\mu\mu e$
Data	1127 ± 34	1584 ± 40
Total Expected	1026.1 ± 26.1	1496.9 ± 32.3
WZ	7.3 ± 0.3	8.1 ± 0.3
$Z + jets$	919 ± 26	1350 ± 32
$W/Z\gamma$	84.5 ± 3.1	120.5 ± 3.7
$t\bar{t}$	12.7 ± 1.9	15.5 ± 2.2
ZZ	1.5 ± 0.1	1.7 ± 0.1
WW	0.5 ± 0.2	0.6 ± 0.2
$t\bar{t} + V$	0.5 ± 0.1	0.6 ± 0.1

Table 4.5: Yields of data compared to MC expectations from different MC samples, for the eee and $\mu\mu e$ channels in the $Z + jets$ control sample.

going to be removed from data using the MC predictions. Then, we will remove the remaining non $Z + jets$ processes from the data distribution also by counting on the MC. The ratio between the remaining data and the $Z + jets$ MC in the control region will give a normalization factor that should be applied on the $Z + jets$ MC processes in the signal region.

This is shown in Table 4.6. Sherpa MC is used for the $Z + jets$ MC sample. The table shows the need of an upward scaling this MC by about 8% in the $\mu\mu e$ channel and about 13% in the eee channel. Therefore, given that the shape of the $Z + jets$ background is described well by the MC, it needs a global upward scaling normalization factor of the order of 10%.

channel	Normalisation factor
eee	$f_{Z+jets}=1.13 \pm 0.05$
$\mu\mu e$	$f_{Z+jets}=1.08 \pm 0.04$

Table 4.6: Normalization factors for the $Z + jets$ background in the eee and $\mu\mu e$ channels. These factors are extracted in the $M_Z - M_{pdg} < 10$ GeV range and they can be used directly in the signal region.

To control the agreement between the data and the MC predictions in the control region after applying the normalization factors to the $Z + jets$ MC, figure 4.3 shows the invariant mass distribution of the Z boson, in both eee and $\mu\mu e$ channels. In this figure, the dominating process is the $Z + jets$ with a $\sim 20\%$ contribution from the $Z + \gamma$ processes. The ratio of the data measurement with respect to the MC predictions shows that the MC is describing the data correctly.

Control region selection for event with a fake W in the $Z + \mu$ channels

In the channels with a Z boson and a W decaying to muons, the source of the background with a fake W is mostly from a muon that is the decay product of a heavy flavor jet such as a b jet. Therefore, a muon fragmented from a jet can be associated to the W boson enhancing this background in the $\mu\mu\mu$ and $ee\mu$ channels. Since the source of this background is different than that of the $Z + e$ channels, a different selection will be used to build the corresponding control region.

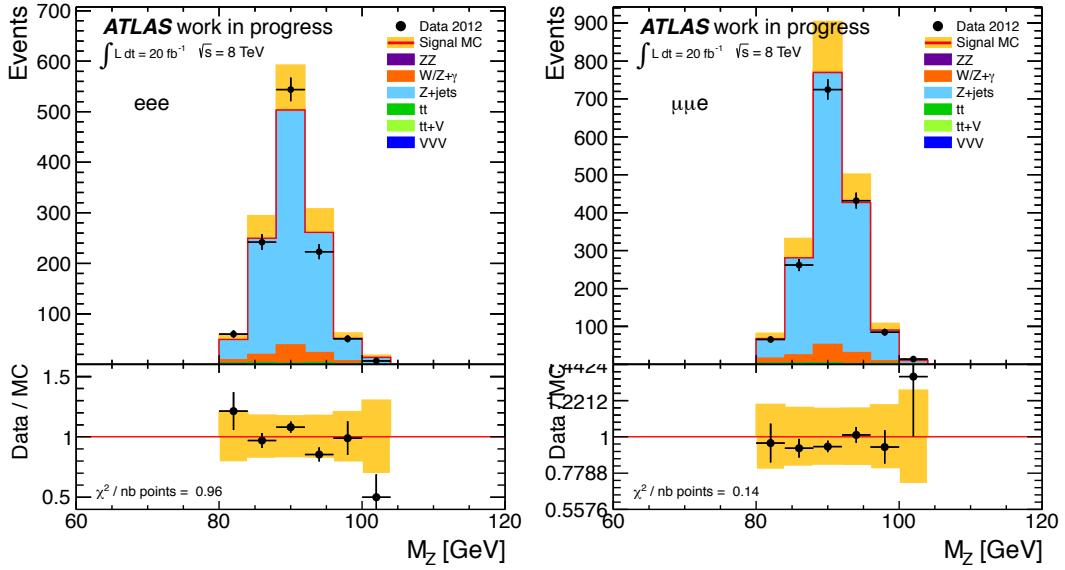


Figure 4.3: The invariant mass distributions of the Z boson candidate in the eee (left) and $\mu\mu e$ (right) channels in the $Z + jets$ control sample. The orange band represents the quadrature sum of the statistical uncertainties of the MC expectations. A global 15% and 5% normalization uncertainty is used for each of the $Z + jets$ and $Z\gamma$ MC expectations, respectively.

For the selection of the control region, the Z boson is selected the same way as in the signal region (see section 4.1.7) except that the Z mass window is extended to the range of [50, 140] GeV. As for the muon that is supposed to be fragmented from a jet, the impact parameter significance cut is inverted in order to enhance events containing b or c jets. Also, the track isolation cut of the muon is removed in order to increase the probability of a muon to be in a jet. All the other selection cuts are remained the same as for the signal region. This control region will be called “B”.

In this region, for the $Z + jets$ processes, the invariant mass of the Z boson has the shape of a Breit-Wigner function that is convoluted with a one-sided Crystal Ball function.

As for $t\bar{t}$, it has the shape of a polynomial of the second order. This difference is normal because no Z peak is expected to appear in the $t\bar{t}$ processes.

Therefore this aspect eases the extraction of the contribution of each of these processes and a combined fit with the listed functions, can be applied on the M_Z distribution in each of the $Z + \mu$ channels.

Before applying the fit on data events in this control region, it should be tested on MC events to define the order of magnitude of the fit parameters and to minimise their errors as much as possible. This is what we call a closure test and it is shown on Figure 4.4. A Breit-Wigner function convoluted with a Crystal Ball function added to a polynomial of the second order is applied on the $Z + jets$ and $t\bar{t}$ MCs.

After comparing the total event number obtained from the fit to the total MC number, we calculate a ratio that is around one within the errors of the fit (as shown on the figure). This shows that the fit is applied reasonably with large statistical uncertainty on the MC samples. This fit is therefore ready to be applied on the data.

Figure 4.5 shows the fit to the data using the same function.

The χ^2 of the fit divided by the degrees of freedom, is small around one. This means that the fit has a good quality and correct normalization factors can be extracted for each of the different

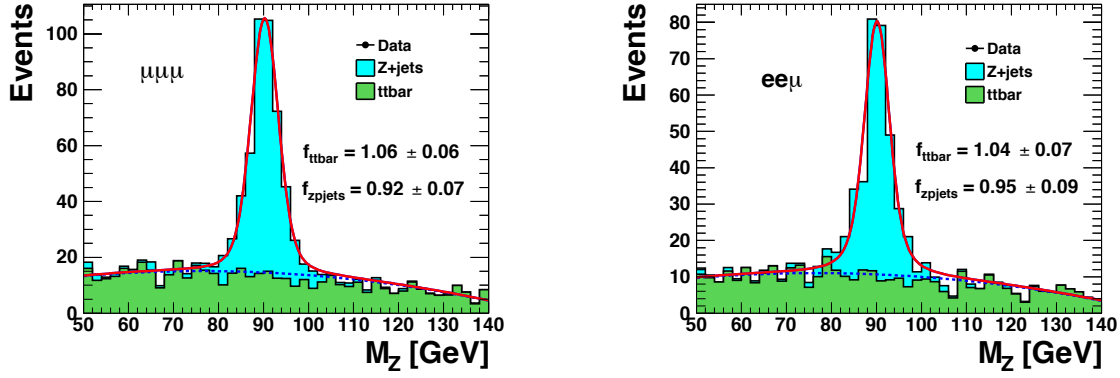


Figure 4.4: Fit of the invariant mass distributions of the Z candidate in the $\mu\mu\mu$ (left) and $ee\mu$ (right) channels for the $Z + jets$ and $t\bar{t}$ MC samples. These plots represent a closure test to show the stability of the fit.

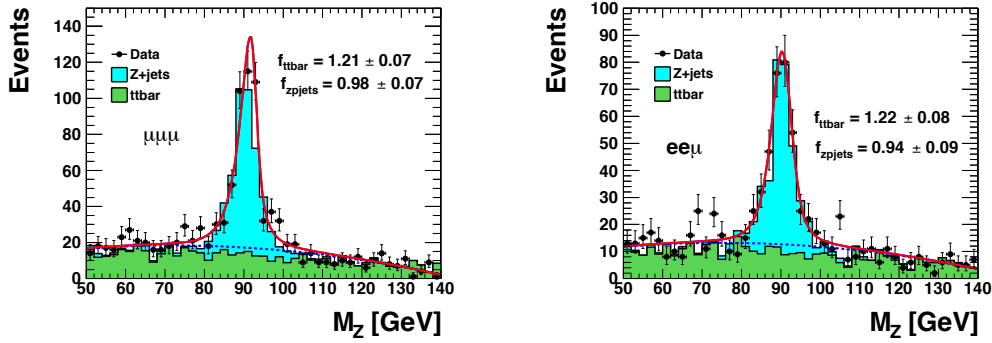


Figure 4.5: Fit of the invariant mass distributions of the Z candidate in the $\mu\mu\mu$ (left) and $ee\mu$ (right) channels for the $Z + jets$ and $t\bar{t}$ processes in the control sample.

MC contributions. These normalization factors will be calculated according to the equation,

$$\text{normalization factor} = n_f = \frac{N_{Data(fromfit)}^{CR}}{N_{MC}^{CR}}, \quad (4.7)$$

Table 4.7 shows that in both of the $ee\mu$ and $\mu\mu\mu$ channels the $Z + jets$ background needs to be normalized down by $\sim 6\%$ and the $t\bar{t}$ background needs to be up-scaled by about 20%. The normalization factors are consistent in both channels because the source of the fake muons is the same in both of them.

Normalization factor		
Channel	$Z + jets$	$t\bar{t}$
$\mu\mu\mu$	$f_{Z+jets}=0.98 \pm 0.07$	$f_{t\bar{t}}=1.21 \pm 0.07$
$ee\mu$	$f_{Z+jets}=0.94 \pm 0.09$	$f_{t\bar{t}}=1.22 \pm 0.08$

Table 4.7: Normalization factors for the $Z + jets$ and $t\bar{t}$ backgrounds in the $\mu\mu\mu$ and $ee\mu$ channels. These factors are extracted in the $M_Z - M_{pdg} < 10$ GeV range and they can be used directly in the signal region.

Figure 4.6 shows the invariant mass distributions of the Z boson in this control region for the $\mu\mu\mu$ and $ee\mu$ channels in the region “B” after rescaling the $Z + jets$ and $t\bar{t}$ MC contributions with the scaling factors determined above. We observe that the data and MC agreement in the

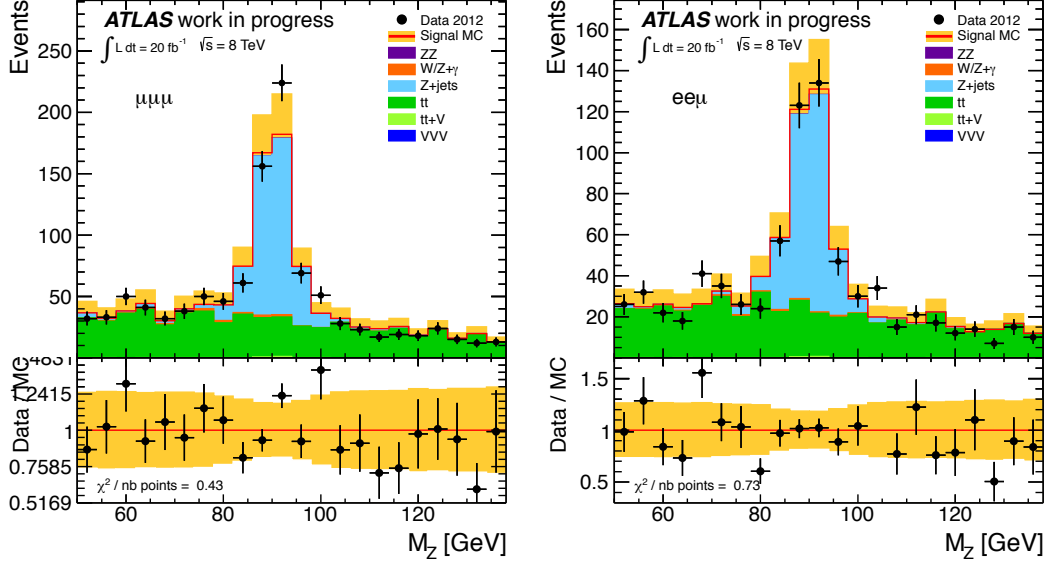


Figure 4.6: The invariant mass distributions of the Z boson in the $\mu\mu\mu$ (left) and $ee\mu$ (right) channels in the $Z + jets$ and $t\bar{t}$ control sample.

region “B” is correct after rescaling with the factors determined for each of the $t\bar{t}$ and $Z + jets$ MCs.

To cross check the results obtained in the control region “B”, another equivalent control region will be defined and the same fitting procedure will be applied to extract the normalization factors between data and MC. The aim is to recompute each of the normalization factors in the new control region and compare it to that obtained with the original selection defined above. The other control region is called “C”. The starting point for the selection of this control region is the same as the previous selection “B” except that the cuts applied on the muon associated to the W boson are slightly different and they are itemized below.

- The longitudinal impact parameter cut on the muon associated to the W candidate is relaxed.
- The track isolation cut, that has a threshold of 0.1 in the signal selection, is inverted.

The control region “C” is built in order to check the consistency with the results found using the region “B”. This region, the same as the region “B”, is dominated with the $Z + jets$ and $t\bar{t}$ processes.

The fitting procedure with the same fit functions used for the control region “B” is applied on the invariant mass distribution of the Z boson in each of the region. The normalization factors extracted using equation 4.7, show the difference in the normalization between data and MC in the control region and they are presented in Figure 4.7.

The figure shows that in both $ee\mu$ and $\mu\mu\mu$ channels, the normalization factors in the regions “B” and “C” are fluctuating around the same values for both $Z + jets$ and $t\bar{t}$ backgrounds. This gives more confidence on the results since they are consistent. Therefore, in the $Z + \mu$ channels, a normalization factor of: $f_{t\bar{t}} = 1.22 \pm 0.04$ is found for the $t\bar{t}$ MC and a normalization factor

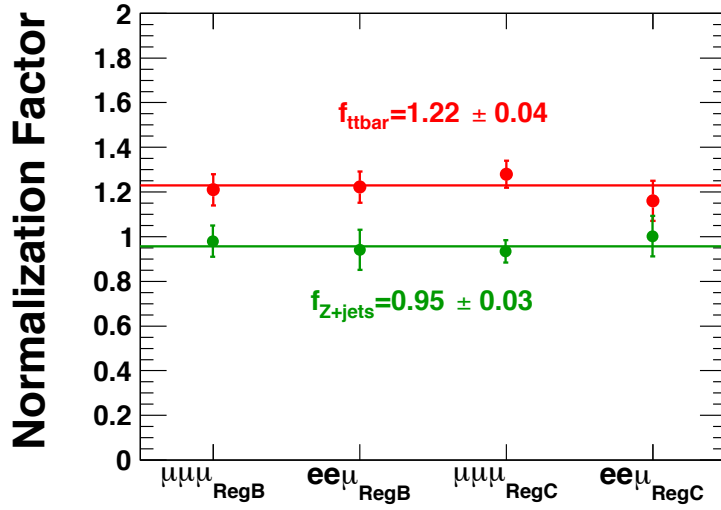


Figure 4.7: Normalization factors of $Z + jets$ and $t\bar{t}$ in each of the “B” and “C” control regions, corresponding to regions with a muon fragmented from a jet and falsely associated to the W candidate.

of: $f_{Z+jets} = 0.95 \pm 0.03$ for the $Z + jets$ MC. These numbers are obtained by averaging the normalization factors calculated over all $Z + \mu$ channels and the two methods.

4.2.2.2 Backgrounds associated to a fake Z reconstruction

Selection of events with a fake Z in all WZ channels

Control regions are built in order to enrich each of the WZ channels with fake Z bosons. The selection of these control regions starts by selecting a good W boson the same way as in the signal selection. As for the Z selection, the 10 GeV mass window requirement around the Z peak is removed, the isolation requirements on the leptons associated to the Z boson is removed. For the $W(Z \rightarrow \mu\mu)$ channels, the Z muons impact parameter significance cut is inverted. As for the $W(Z \rightarrow ee)$ channels, “loose” and not “medium” Z electrons are required. For the $ee\mu$ channel, a reversed isolation requirement of $\sum_{\Delta R < 0.2} p_T(i) > 0.1 \cdot E_T(e)$ is also required for the “loose” electron, in order to reduce the contribution of WZ signal events. With these criteria, the invariant mass of the Z boson is built in all four WZ channels to control the behavior of this background. This is shown in figure 4.8.

In this figure, both of the $Z + jets$ and $t\bar{t}$ MC samples are rescaled with the normalization factors extracted in the previous sections. The figure shows a very good agreement between data and the sum of the MC expectations is observed in all four control regions, corresponding to all four channels of the analysis. For channels with leptons of opposite flavor ($ee\mu$ and $\mu\mu e$), only $t\bar{t}$ events are contributing, whilst in channels with leptons of the same flavor (eee and $\mu\mu\mu$) $Z + jets$ events also contribute, due to the possible mis-pairing of the leptons to form the Z candidate.

If the $t\bar{t}$ MCs were not rescaled in all four of these control regions, the same normalization factors as the ones calculated in section 4.2.2.1 are found. This is shown in table 4.8, where an average normalization factor of 10% is found in all four control region. The table shows that in some of these control regions, specifically the one corresponding to the eee channel, the sensitivity to the $t\bar{t}$ is very low.

Hence, two other control regions containing a real W candidate and a fake Z candidate will be defined in order to validate the results presented in this paragraph. The first control regions

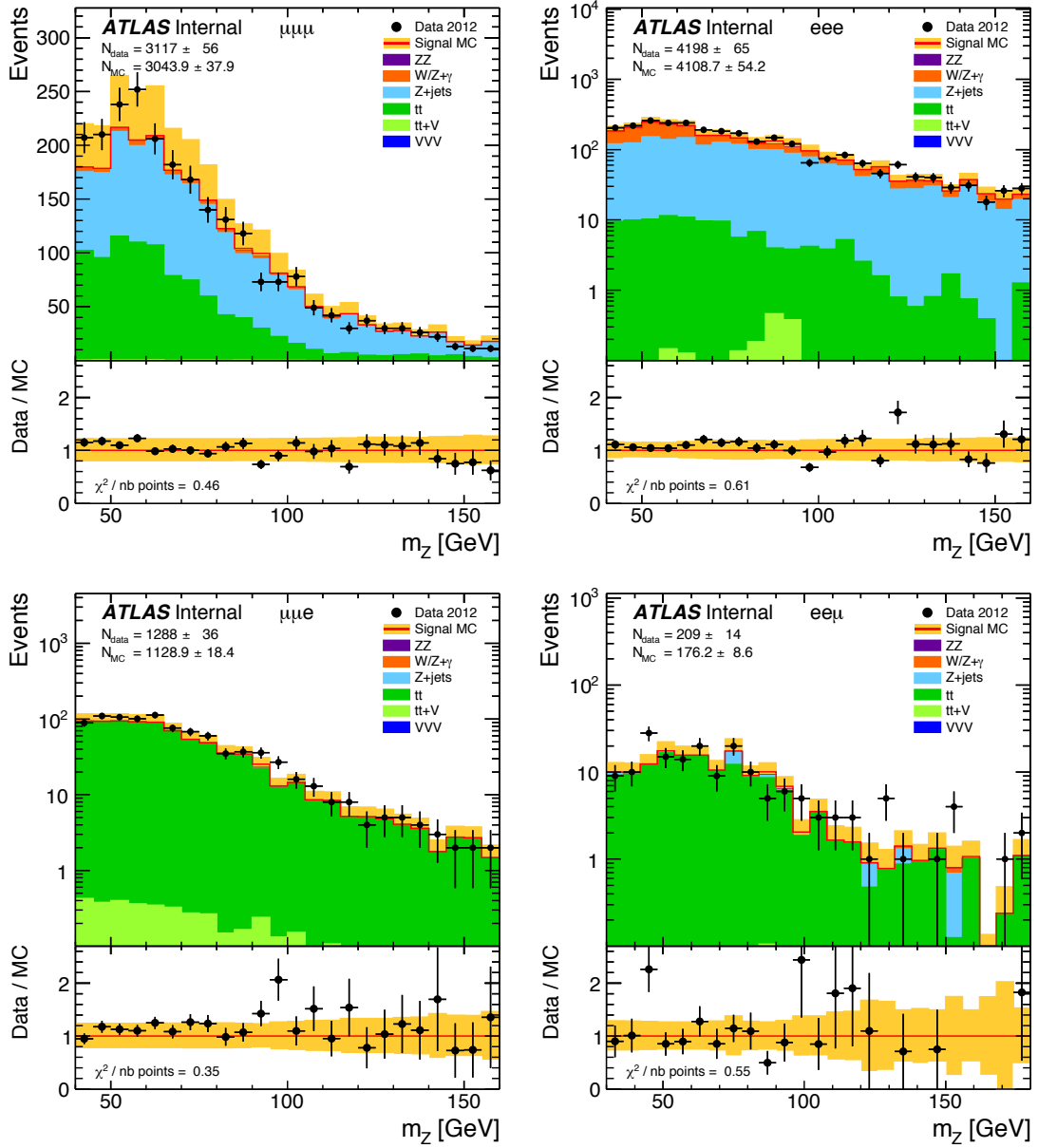


Figure 4.8: Control distributions of the $M_{\ell\ell}$ invariant mass of the two leptons associated to the Z candidates in control regions enriched in fake leptons associated to the Z candidate. All MC expectations are scaled to the integrated luminosity of the data. The orange band represents the quadrature sum of the statistical uncertainties of the MC expectations. A global of 8% normalization uncertainty is used for the ZZ MC expectations. It includes also an uncertainty of 2.8% for the integrated luminosity of the data.

Normalization factor				
Channel	eee	$\mu\mu e$	$ee\mu$	$\mu\mu\mu$
f_{fakeZ}	1.58 ± 0.69	1.14 ± 0.04	1.21 ± 0.13	1.06 ± 0.07

Table 4.8: Normalization factors obtained from the control regions with a fake Z candidate in four of the WZ channels.

will be labeled as OFOC referring to a selection with Opposite Flavor Opposite Charge leptons associated to the Z candidate. While the second control region will be labeled SFSC standing for Same Flavor Same Charge leptons associated to the Z candidate.

$t\bar{t}$ OFOC selection

To select events that will contain a fake Z , the W boson selection needs to be kept as robust as possible. Therefore, the W boson is selected the same way as the selection presented in section 4.1.7. However, in order to increase the statistics, the identification of the W electron is loosened from “tight” to the “medium” identification criterion. To make sure that the selected Z is a fake boson, the isolation requirement and the transverse impact parameter significance cut on the leptons associated to the Z boson are removed. The selected leptons are then required to have opposite charge and opposite flavor. This is why this will be referred to as OFOC (Opposite Flavor Opposite Charge).

Finally, the Z boson that is reconstructed with these leptons should be within 10 GeV around the PDG mass of the Z . Therefore, this channel contains one muon and two electrons. To reduce furthermore the signal, the event is removed if the electron associated to the Z and the one associated to the W pass the Z boson selection criteria.

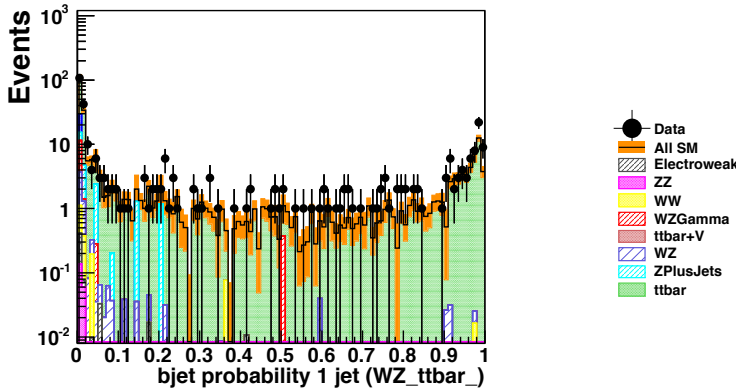


Figure 4.9: The b jet weight distribution for events with at least one jet.

We expect from the events in these control region to be dominated by $t\bar{t}$ processes which contain an additional b jet. Therefore, for events containing at least one jet, it is important to study the behavior of the probability distribution for this jet to be a b jet. A b -tagging algorithm is used that makes the assumption that the decay vertexes of the weakly decaying B/D hadrons lie on the same flight axis. The algorithm gives a weight for all jets in events for being a b -jet. This distribution of the weights is shown in Figure 4.9 for selected events. It shows that a major proportion of all the non $t\bar{t}$ processes have a b jet probability less than 0.1. Therefore by cutting on this variable at 0.1, the contamination of other processes to the control sample can be reduced.

However this threshold only can remove the non- $t\bar{t}$ processes in events that contain at least one jet. Events with no jets are not affected by it. Therefore, this sample contains of about 4% contamination from the $Z + jets$ processes. Table 4.9 shows the total yields for data and all MC processes in the $t\bar{t}$ control region. These numbers show that 95% of the total MC composition is $t\bar{t}$. The remaining 5% are due to small contamination from signal and $Z + jets$ events. Also the table shows that there is a difference in the normalization between the data and the total MC in the control region. The obtained data sample after the final selection is shown in Figure 4.10

and it is dominated with $t\bar{t}$ events. The figure shows a data to MC comparison of the Z boson's invariant mass distribution. The shape of the M_Z distribution seems to be correctly simulated by the MC.

Process	Event yields
Data	223 ± 15
Total Expected	203 ± 8
WZ	0.5 ± 0.1
$t\bar{t}$	192.7 ± 7.5
$Z + jets$ Sherpa	7.3 ± 2.4
$t\bar{t} + V$	2.1 ± 0.1
$W/Z\gamma$	0.2 ± 0.2

Table 4.9: Yields of data compared to MC expectations from different MC samples in the $t + \bar{t}$ OFOC control sample. The other MC samples that are not listed in the table have no contribution in this control region.

Using the total yields in the control region, a normalization factor, $f_{t\bar{t}}$, can be calculated for this background so that:

$$f_{t\bar{t}}^{OFOC} = \frac{N_{Data}^{CR} - N_{non-t\bar{t}}^{CR}}{N_{t\bar{t}}^{CR}} = 1.11 \pm 0.09(stat) \quad (4.8)$$

This factor can then be applied to the $t\bar{t}$ MC prediction in the signal region. This factor is applicable to the $WZ \rightarrow eee$ and $WZ \rightarrow \mu\mu e$ channels.

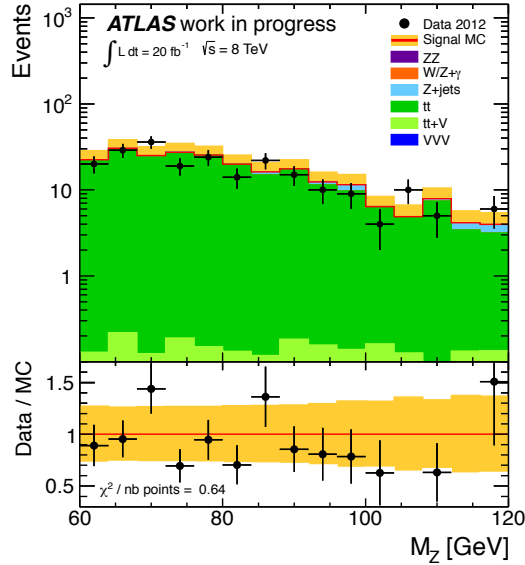


Figure 4.10: Invariant mass of the Z candidate in the OFOC $t\bar{t}$ control region after all selection cuts.

$t\bar{t}$ SFSC selection in the $\mu\mu e$ channel

In order to cross check the results in the $\mu\mu e$ channel, this method consist of selecting events

that contain two muons that will form a “fake” Z and an electron that will be associated to the real W boson in the aim of building a control region. A special event selection is made within the $WZ \rightarrow \mu\mu e$ channel. The electron associated to the W is expected to pass all the kinematic and quality cuts the same way as for the signal. However the “medium” identification is required instead of “tight”. As for the Z muons, the isolation requirement and the impact parameter significance cut are removed. Both muons are required to have the same charge. Finally, the “fake” Z formed with these muons is expected to be within a mass window of 30 GeV from the PDG mass of the Z . Because of the low charge mis-identification rate for muons, the probability to form a real Z with such a selection is very low. Therefore, the signal events and other background processes are reduced in this sample while the statistics is kept high. This region is referred to as SFSC standing for Same Flavor Same Charge.

The total data and MC yields in this control sample are shown in Table 4.10. The table shows that 96% of the sample is composed of $t\bar{t}$ events. The remaining processes are negligible except the contribution from the $Z + jets$ background which contaminates in a small amount the control sample.

Process	Event yields
Data	809 ± 28
Total Expected	689.9 ± 14.4
WZ	1.4 ± 0.1
$t\bar{t}$	679 ± 14
$t\bar{t} + V$	3.7 ± 0.2
$Z + jets$	3.2 ± 1.9
WW	2.0 ± 0.4

Table 4.10: Yields of data compared to MC expectations from different MC samples in the $t\bar{t}$ SFSC control sample.

The advantage of this selection is that it contains large statistics and low contamination from non $t\bar{t}$ processes. This ensures the statistical significance of the results.

The normalization factor as calculated according the equation 4.8 is equal to 1.18 ± 0.05 . This is in a good agreement with the results from all the other methods.

Figure 4.11 shows the invariant mass distribution of the obtained sample.

The $t\bar{t}$ MC in this figure is rescaled with the normalization factor determined about 15%. The data to MC ratio in the figure, shows that the M_Z distribution seems to be well described by the MC in this control region.

4.2.2.3 Conclusion

All results from the data control regions dominated by contributions from a fake W or Z boson candidates, show that the shape of the $t\bar{t}$ and $Z + jets$ backgrounds can be estimated from the MC since, within the statistical fluctuations, it always agrees well with data. Results however show that the $t\bar{t}$ and $Z + jets$ MCs need to be globally normalized. This normalization factor is estimated for each of the $WZ \rightarrow \ell\ell\nu$ channels using the different control regions described in the previous sections. Then, the final values of the normalization factors for each process are calculated using the weighted mean of all the normalization factors calculated per channel so that:

$$f_{normalization} = \frac{\sum_{i=1}^4 f_i \times w_i}{\sum_{i=1}^4 w_i}, \quad (4.9)$$

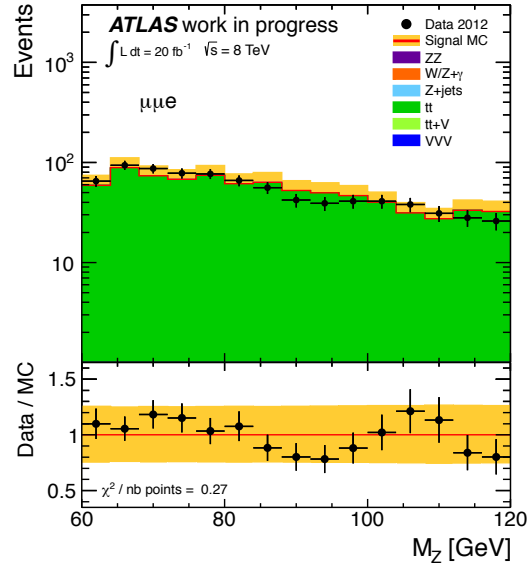


Figure 4.11: Invariant mass distribution of the fake Z candidate in the $\mu\mu e$ channel in the SFSC control region with a fake Z .

where f_i is the normalization factor for each channel i and w_i is the weight associated for each normalization factor, so that $w_i = \frac{1}{\delta f_i^2}$, where δf_i is the statistical uncertainty on the normalization factor.

Although the composition of the backgrounds in the different channels is not the same, a common normalization factor is found for the $t\bar{t}$ background that averages around 1.16. For the $Z + jets$ background, the normalization factors between the channels where the W boson decays to electron is around 1.1 and it differs than those where the W decays to a muon in which the factor is ~ 0.96 . Figure 4.12 shows a summary of the normalization factors obtained in all four channels under study.

These factors are applied on the MC $Z + jets$ and $t\bar{t}$ background processes and they are used all along the following measurements of this thesis.

Table 4.11 summarizes the final results of the normalization factors for each of the $t\bar{t}$ and $Z + jets$ processes.

process	Normalization factor
$t\bar{t}$	$f_{t\bar{t}} = 1.16 \pm 0.02 \text{ (stat)}$
$Z + jets (Z\mu)$	$f_{Z\mu} = 0.96 \pm 0.06 \text{ (stat)}$
$Z + jets (Ze)$	$f_{Ze} = 1.10 \pm 0.03 \text{ (stat)}$

Table 4.11: Normalization factors extracted for each of the $t\bar{t}$, $Z + jets$ MC processes.

The same procedures for extraction of the different backgrounds explained in the previous sections, are also applied separately on the W^+Z or W^-Z selected samples. As the $Z + jets$ and $t\bar{t}$ backgrounds were the only ones that have shown a difference in the normalization between the data and MC, hence the same normalization factors will be computed for each of the W^+Z and W^-Z selections. The followed strategies are exactly the same as described for the $W^\pm Z$ events. The results of the obtained normalization factors for all four channels for the $t\bar{t}$ and

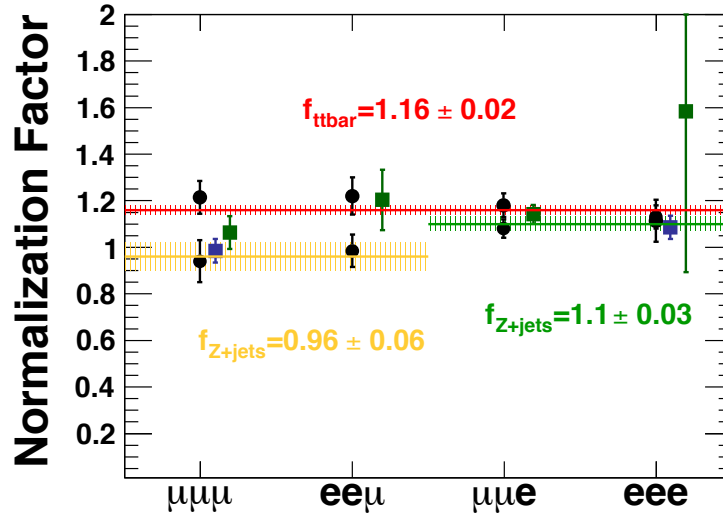


Figure 4.12: Normalisation factors of $Z + jets$ and $t\bar{t}$ backgrounds in all four channels. Green squares represent the normalization factors determined in the fake- Z control regions for $t\bar{t}$ processes. Blue squares represent the normalization factors in the fake- Z control regions for the $Z + jets$ processes. Black dots represent the normalization factors obtained from the fake- W control regions. The red solid line represents the weighted mean of all the $t\bar{t}$ normalization factors from all control regions in all of the four channels. The orange and green solid lines represent the weighted mean of all the $Z + jets$ normalization factors from all control regions for the $Z + \mu$ and $Z + e$ channels, respectively. Only statistical uncertainty is quoted.

$Z + jets$ backgrounds is shown in figure 4.13. The figure shows that the W^+Z , W^-Z , and $W^\pm Z$ normalization factors for the $t\bar{t}$ processes are in a very good agreement around 1.16. For the $Z + jets$ background in the $Z + e$ channels, these factors are also all in agreement fluctuating around 1.1. Finally, the $Z + jets$ background normalization factors in the $Z + \mu$ channels seem to have tendency of being higher for the W^+Z events and lower for the W^-Z events however these differences remain within the statistical error bars showing a global downscaling factor around 0.96 for all.

For each of the $t\bar{t}$ and $Z + jets$ processes, the difference observed between the normalization factors computed in each channels and also for the W^+Z and W^-Z processes, is taken as a systematic uncertainty.

This is computed by calculating a pull such as:

$$pull = \frac{(f - \bar{f})}{\sqrt{\delta f^2 + (\delta bkg_{sys} \times \bar{f})^2}}, \quad (4.10)$$

where f is the given normalization factor, $\bar{f}$ is the weighted mean of all factors, δf is the statistical uncertainty on f , and δbkg_{sys} is the systematic uncertainty to be defined. The δbkg_{sys} is chosen in a way that the maximum pull obtained using the normalization factors f is less than 1. Therefore a systematic uncertainty of 8% is defined for $t\bar{t}$ and 5% for the $Z + jets$ processes.

Finally, other WZ ATLAS analyses chains have developed different background estimation methods such as a template fit method or a matrix method which rely mostly on data to estimate

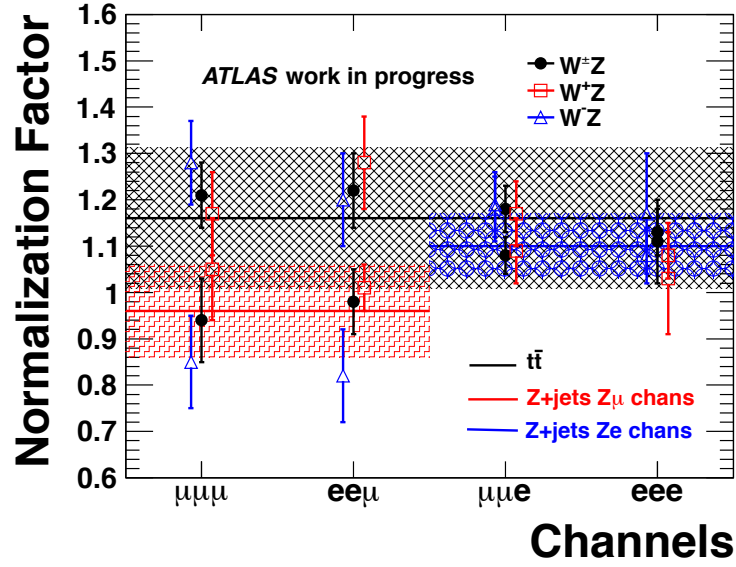


Figure 4.13: Normalisation factors of $Z + jets$ and $t\bar{t}$ backgrounds in all four channels obtained from the fake- W control regions. Black dots represent the normalization factors for events with fake- $W^\pm$. Red dots represent the normalization factors for events with fake- W^+ . Blue dots represent the normalization factors for events with fake- W^- . The uncertainty band is the quadratic sum of statistical and systematic uncertainties.

together the $Z + jets$ and $t\bar{t}$ backgrounds contributions. A comparison of the number of $Z + jets$ and $t\bar{t}$ background events in the signal region for each WZ channel using the MC reweighted with the normalization factors to those from the other ATLAS analyses chains using the matrix method or the template fit method is shown in figure 4.14. The figure shows that the results are in an overall agreement with fluctuations of the order of 15% remaining especially in the $ee\mu$ and $\mu\mu e$ channels. Therefore, a conservative systematic uncertainty of 15% is chosen for $Z + jets$ and $t\bar{t}$ backgrounds, in order to cover the differences observed with other background extraction methods developed within ATLAS for the same WZ analysis.

4.2.3 $Z\gamma$ background contamination

The second dominant source among the backgrounds is due to the $Z\gamma$ processes. This background exists only in the eee and $\mu\mu e$ channels where the W boson decays to electron and a neutrino. In this case, a photon is mis-identified as an electron and associated to the W boson throughout the analysis chain. The SHERPA MC generator is used to simulate the $Z\gamma$ processes. Similarly to the ZZ background, in this section we are going to control the modeling of the $Z\gamma$ background for the WZ analysis by developing a dedicated control region in which the contribution of the $Z\gamma$ events is enhanced compared to the measurement region, while the phase space of both signal and control regions stay close.

The data sample built is enriched with a real Z boson and a photon reconstructed as an electron associated to the W boson. In this control region, the Z boson is selected as described in section 4.1.7. The third lepton, which should be an electron, associated to the W boson is selected in a way to enhance its mis-identification with a photon in the event. Therefore this electron is required to have the “loose”, not “medium”, not “tight” identification. This will reduce the quality of the track of the selected electron hence increasing the probability for it to be a photon.

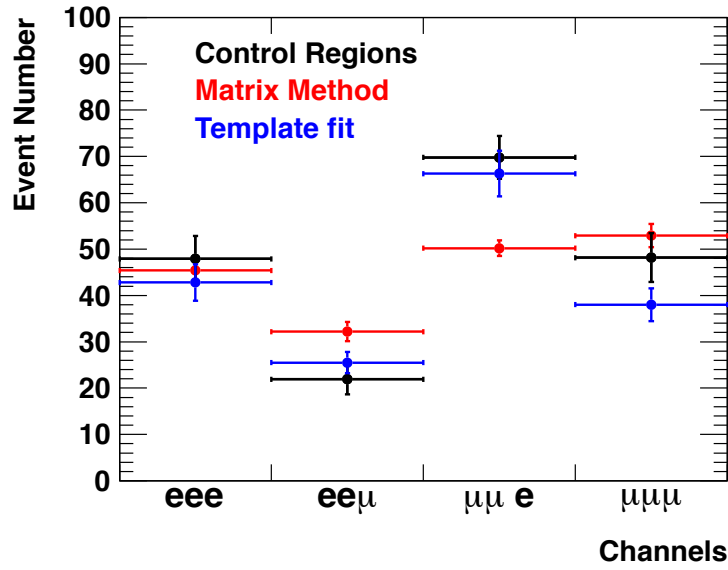


Figure 4.14: Total $Z + jets$ and $t\bar{t}$ background contributions in the signal region for each of the four WZ channels using the MC reweighted with the normalization factors (black), the matrix method (red), and the template fit method (blue). Only Statistical uncertainty is quoted.

This kind of selection, however, can also be contaminated by $Z + jets$ processes. To reduce this contamination as much as possible, variables showing a significant separation between both backgrounds are used. Figure 4.15 shows the distributions of the relative calorimetric isolation of the electron and that of the electron's longitudinal impact parameter significance. According to these distributions we observe a separation between the $Z\gamma$ and the $Z + jets$ backgrounds. Therefore, the electron's relative calorimetric isolation is required to be less than 0.05 and its the longitudinal impact parameter significance greater than 2.6. With these criteria, the dominant processes in this data control region are the $Z\gamma$.

Figure 4.16 shows the different contributions to the invariant mass distribution of the Z boson in this control region in both eee and $\mu\mu e$ channels. The ratio between the data and MC of these distributions, shows that the MC is modeling correctly the $Z\gamma$ processes in data.

Because of the difficulty of separation between a lepton within a jet or a photon mis reconstructed as an electron, the main challenge in building this control region is the low statistics. Even with the large statistical fluctuations, the remaining $Z\gamma$ data events are enough to validate the modeling the the $Z\gamma$ MC.

The total yields for data and MC in the eee and $\mu\mu e$ channels in the $Z\gamma$ control region for data and MC are shown in table 4.12. The table shows that $\sim 80\%$ of the control region is composed of events that contain a photon reconstructed as an electron or a photon converted to an electron that is associated to the W boson. After removing the contamination from all the non $Z + \gamma$ events from the data distribution by using the MC predictions, the ratio between the data and the $Z + \gamma$ MC in the control region gives the normalization factor that the MC prediction needs to rescale to the data in the signal region. This is shown in Table 4.13.

As shown in the table, the statistical error on these factors is of the order of 20%, because of the lack of statistics in this control region. The table shows that in both of the eee and $\mu\mu e$ channels there is no need to rescale the $Z + \gamma$ background MC. Also, the ratio between data and MC in figure 4.16 have shown the correct modeling of the MC with respect to the data. Therefore,

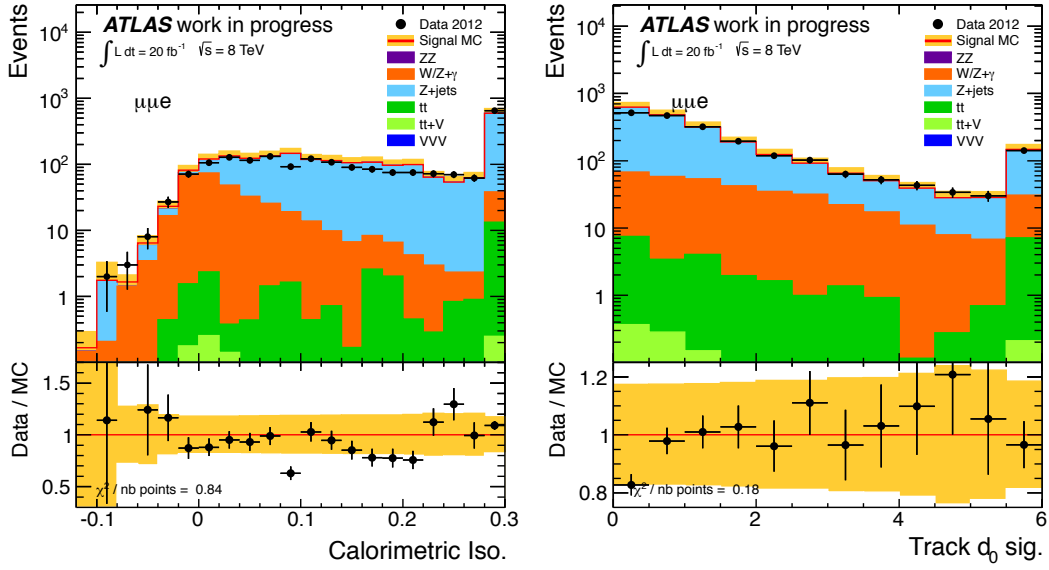


Figure 4.15: The calorimetric isolation variable distribution (left) and the longitudinal impact parameter significance distribution (right) in the $\mu\mu e$ channel. The last bin of the distributions contains the events in the overflow. The orange band represents the quadrature sum of the statistical uncertainties of the MC expectations. A global 15% normalization uncertainty is used for each of the $t\bar{t}$ and $Z + jets$ MC expectations.

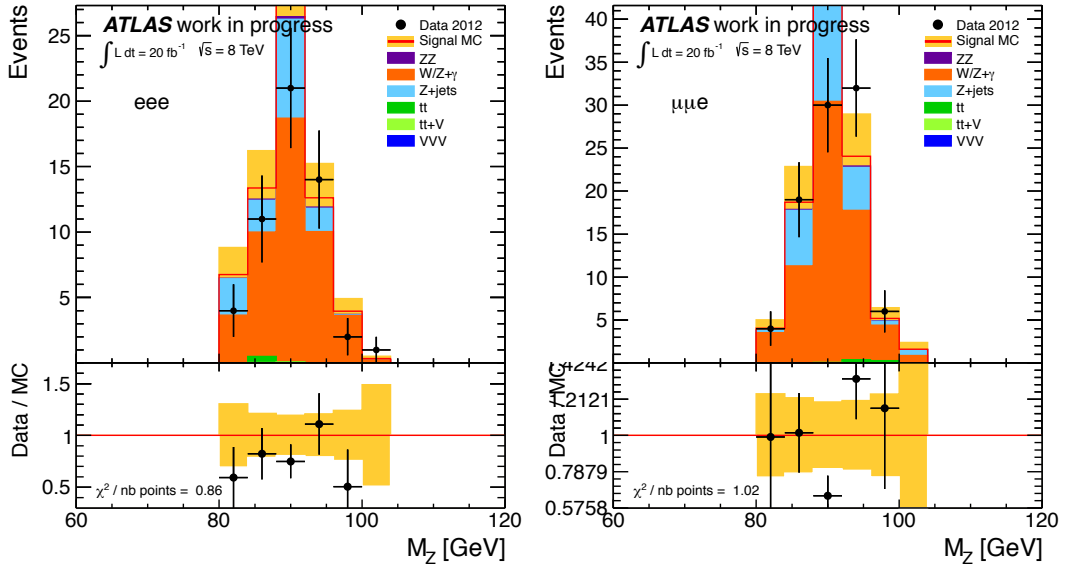


Figure 4.16: The invariant mass distributions of the Z boson candidate in the eee (left) and $\mu\mu e$ (right) channels in the $Z + \gamma$ control sample.

the $Z\gamma$ background will be estimated using fully the SHERPA MC predictions.

A conservative theoretical systematic uncertainty of 9% is defined for the $Z\gamma$ processes. This uncertainty is mainly coming from the variation of the scale, PDFs, and photon isolation. More details can be found in [86].

Event yields		
Process	eee	$\mu\mu e$
Data	53 ± 7	91 ± 10
Total Expected	63.3 ± 3.5	97.3 ± 5.2
WZ	3.8 ± 0.2	5.0 ± 0.3
$W/Z+\gamma$	45.6 ± 2.3	67.6 ± 2.8
$Z+\text{jets}$	13.2 ± 2.7	23.5 ± 4.4
ZZ	0.5 ± 0.0	0.6 ± 0.0
$t\bar{t}$	0.2 ± 0.2	0.4 ± 0.2
$t\bar{t}+V$	0.1 ± 0.0	0.2 ± 0.0
WW	0.0 ± 0.0	0.0 ± 0.0

Table 4.12: Yields of data compared to MC expectations from different MC samples, for the eee and $\mu\mu e$ channels in the $Z + \gamma$ control sample.

channel	$N_{Z\gamma}^{data}/N_{Z\gamma}^{MC}$
eee	$f_{Z\gamma}=0.89 \pm 0.20$
$\mu\mu e$	$f_{Z\gamma}=0.98 \pm 0.20$

Table 4.13: Ratio between data after subtracting all non- $Z\gamma$ processes using MC and $Z\gamma$ MC events for the eee and $\mu\mu e$ channels in the $Z + \gamma$ control sample.

4.2.4 ZZ background contamination

The ZZ diboson processes decaying leptonically can mimic the WZ final states. This is one of the most dominant backgrounds in all the WZ decay channels. One of the Z boson's leptons is in fact lost in the detector creating a fake E_T^{miss} . This can appear when one of the four ZZ leptons is reconstructed outside the detector's acceptance or when one of these leptons is lost in the detector's transition regions. Therefore, a signature that is similar to the WZ signal can be created. In general, this process is well modeled by the MC. The POWHEGPYTHIA MC generator's predictions are used in this thesis to estimate the ZZ background. In order to validate the well modeling of this background by the MC, a special data selection is applied to enrich the region with ZZ events.

This is performed by inverting the ZZ veto cut (that states to remove events with more than 3 leptons) and selecting only events with four leptons. To build the first Z candidate, the same procedure as explained in section 4.1.7 is followed. The third lepton should pass the quality criteria similarly to a lepton associated to the W boson also explained in section 4.1.7, however the cut on m_T^W of 30 GeV on the built W candidate is removed. This cut is sensitive to E_T^{miss} , therefore removing it will enhance the contribution of the fake missing transverse energy. Finally, the event should contain at least four leptons with p_T greater than 7 GeV. This selection is therefore enriched with ZZ events. The MC modeling can be controlled via kinematic distributions in this control region such as the Z boson's invariant mass distribution.

This is shown in figure 4.17 where the M_T^W , p_T^W , M_{WZ} , and E_T^{miss} distributions for the sum of all the eee , $\mu\mu e$, $\mu\mu\mu$, and $ee\mu$ channels in the ZZ control region are presented. The MC is describing well the data. The shape is correctly modeled by the MC as well as the normalization.

Even that the statistical fluctuations are large for this selection, it is enough to validate the well modeling of the MC for the ZZ process.

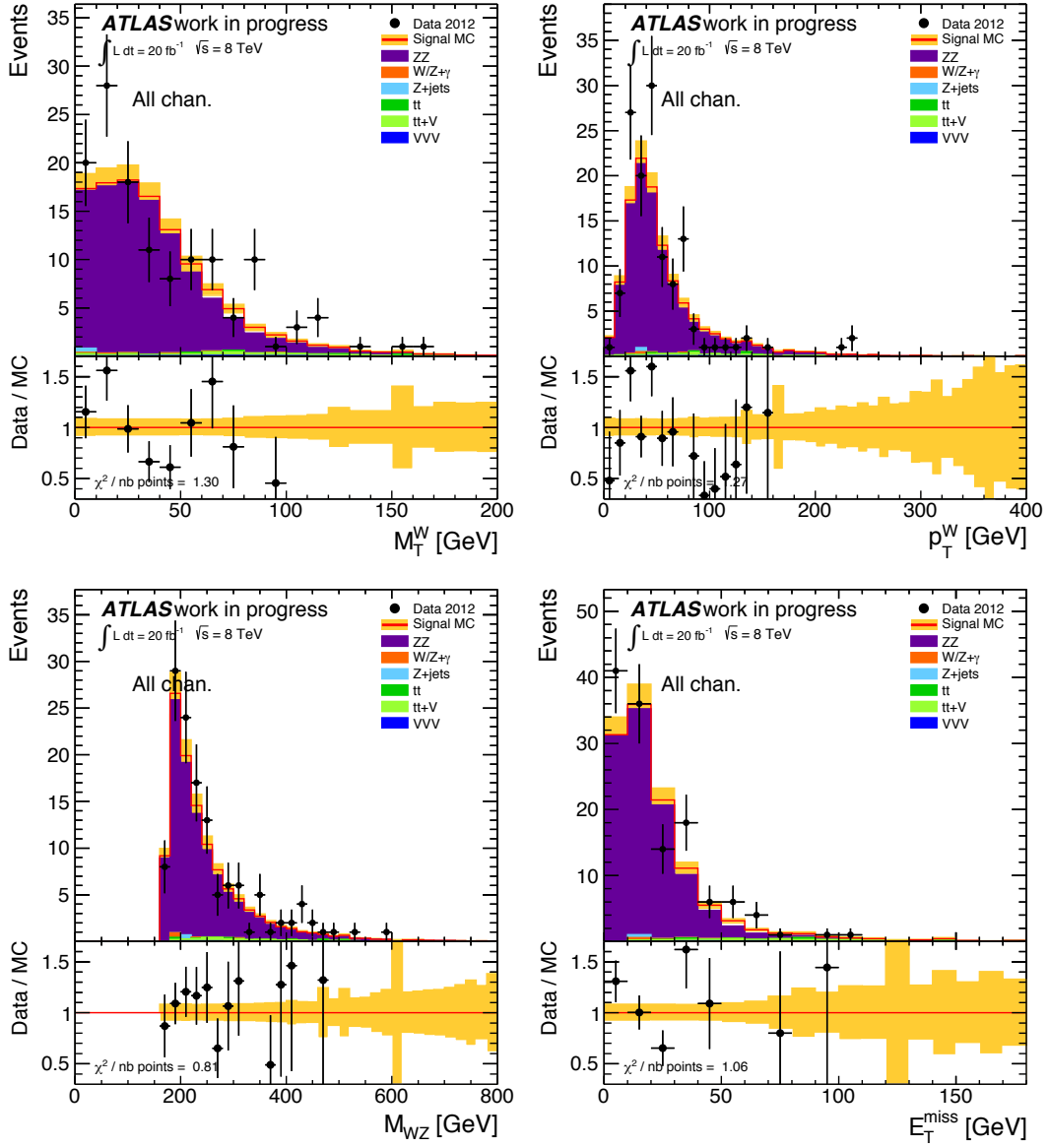


Figure 4.17: The transverse mass and transverse momentum distributions of the W candidate (upper plots), the invariant mass of the WZ system and E_T^{miss} distributions (lower plots) in the ZZ control region for the sum of all the WZ channels.

If a normalization factor is calculated for the ZZ using this defined control region for the sum of all four electronic and muonic channels, it is found to be:

$$f_{ZZ} = \frac{N_{Data}^{CR}}{N_{ZZ}^{CR}} = 1.1 \pm 0.1 \quad (4.11)$$

where N_{Data}^{CR} is the number of data events in the control region subtracted from non ZZ processes numbers and N_{ZZ}^{CR} is the number of ZZ MC events in the control region. The statistical uncertainty on this normalization factor is of the order of 9%, showing that the difference found between the data and ZZ MC in the control region is within the statistical bounds. Therefore no additional reweighting is applied to the ZZ MC in the signal region. s

In the signal region, the ZZ background contributes by about 6% in the WZ events selection and it is the most important background among all the other processes that will be described below.

A recent publication [87] concerning the ZZ production at QC DNNLO, has shown that a K factor of 1.12 is found between the NLO and NNLO ZZ cross sections. The NNLO calculation takes into account the ZZ production through the gluon-gluon fusion. In the MC samples used for this analysis, the ZZ cross section is calculated at NLO but it takes into account the ZZ production through gluon fusion. This means that a K factor smaller than 1.12 is needed for our MC. Also, the EW NLO corrections to ZZ amount of -3%, which makes the K factor needed even smaller. Taking into account the statistical uncertainty on the measurement of ZZ using data and the uncertainty due to the theory calculations, a theoretical systematic uncertainty of 8% is defined for the ZZ processes.

4.2.5 Other backgrounds contributions

Besides the background sources mentioned above, other processes such as the WW , VVV (where V is a vector boson), $VV(DPI)$ (diboson produced from double parton interactions) and $t\bar{t} + V$ also contaminate the WZ signal selection. The $t\bar{t} + V$ background contribute in our signal selection by about 1.5% as importantly as the $t\bar{t}$ background which contributes by about 2%. However, the sum of the remaining processes contribution is very low and of the order of 0.6%.

The POWHEGPYTHIA, MADGRAPHPYTHIA, and MC@NLO MC generators are used to estimate the WW , VVV , and $t\bar{t} + V$ backgrounds, respectively.

A conservative theory systematic uncertainty of 30% is defined for the sum of all these MC processes. This uncertainty is mainly coming from the $t\bar{t} + V$ processes and from the variation of the scale and PDFs [88].

Finally, a background contributing in a very small amount is due to the Double Parton Scattering processes that produce final states containing W and Z bosons. PYTHIA simulation is used to estimate this background. A conservative systematic uncertainty of 50% is used for this background [89].

4.3 Systematic uncertainties

Two global sources of systematic uncertainties exist in all physics analyses. Theoretical uncertainties and experimental ones. The theoretical uncertainties arise from the cross sections of all the MC background and signal predictions. These have different sources associated to the Parton Distribution Functions (PDFs), the renormalization and factorization scales (μ_R and μ_F), and the generator uncertainties due to the differences between the different MC generators. The theory uncertainties were explained in section 1.2.4. On the other hand, experimental uncertainties arise from the different reconstruction of objects which have uncertainties due to their efficiencies and resolution measurements. Each systematic uncertainty is obtained using separately the signal or the backgrounds MC samples. In this section, the estimation of each object systematic uncertainty will be explained.

4.3.1 Experimental uncertainties

The experimental uncertainties arise from the efficiencies and resolutions of all the objects used in a WZ event. Therefore these uncertainties are due to the trigger, muons, electrons, and E_T^{miss} objects. They are obtained by varying with a certain fraction, up and down the number of the MC signal for each source of systematic uncertainty and then quantifying in % the difference with respect to the nominal value. The same procedure can be applied on the sum of all the background MCs to show the effect of the object systematics on the backgrounds.

Luminosity

A global normalization uncertainty of 2.8% is defined for the integrated luminosity [84]. This uncertainty is the same across all the $W^\pm Z$ channels and thus considered fully correlated among all

Pile-up

A systematic uncertainty on the pile-up is estimated by varying the $\langle \mu \rangle$ (number of interactions per bunch crossing) distribution in the MC. The effect of this uncertainty on the number of expected WZ signal events, is of the order of 0.3%.

Trigger

The uncertainty on the trigger arises from the trigger scale factors defined in section 4.1.1. The triggers used in this thesis are single lepton triggers and the uncertainty on their scale factors is determined using the $Z \rightarrow ee(\mu\mu)$ events in a tag-and-probe method by taking into consideration the uncertainty on the subtracted backgrounds and varying fractionally the lepton selection cuts, the Z boson selection cuts, and the trigger matching. The level of variation of these cuts is within 1%. The difference introduced in the total signal events due to these variations with respect to the nominal value is considered as the trigger systematic uncertainty.

Muons

The systematic uncertainties attributed to the muons arise from three sources: The muons reconstruction efficiency, the transverse momentum resolution, and the transverse momentum scale.

- *Reconstruction Efficiency:* These uncertainties are related to the precision to which the muon reconstruction scale factors have been determined. The scale factors are varied within their uncertainties and the effect on the signal MC or MC backgrounds is estimated as the difference with respect to their nominal values.
- *Transverse momentum scale and resolution:* The muon transverse momentum determination is affected by the scale and resolution uncertainties. The evaluation of the resolution uncertainties are obtained by varying up and down with a given percentage the p_T of the muon and then quantifying the effect of this variation on the MC signal or background. This is done separately for the Inner Detector muon tracks and Muon Spectrometer tracks. The scale uncertainty is also obtained in a similar way by varying fractionally the scale and checking the effect on the MC.

Electrons

The contribution of the electron systematics to the signal acceptance is determined from MC. This contribution is evaluated by taking into account the uncertainties associated with the electron reconstruction and identification efficiency, energy scale and energy smearing and calorimeter isolation. The contributions are quantified by varying each systematic within its associated uncertainty and observing the fractional change in the number of events passing the selection. The systematic uncertainties on the expected event yields are estimated as follows:

- *Reconstruction and identification efficiency:* The differences observed in the reconstruction and identification efficiencies between the data and MC are taken into account by weighting the simulation by scale factors provided by the ATLAS electron working group. The systematics are then determined by varying the scale factors within their quoted uncertainties. This is done for each scale factors individually. The uncertainties on the scale factors are added in quadrature to obtain the combined electron identification uncertainty.
- *Energy scale and smearing:* The systematics on the energy scale derived from the 2012 data using on the MC to obtain the associated uncertainty on the signal acceptance. The set of individual uncertainties regarding the energy scale of an electron is summed in quadrature and the results is applied as an overall shift to the electron kinematic. Since the MC does not reproduce the observed energy resolution in data, a smearing on the transverse momentum of its track is applied to it.
- *Smearing:* The systematic uncertainties associated with the smearing procedure are obtained similarly to the muon smearing uncertainty by varying with a given fraction the p_T of the electron track.
- *Isolation:* Electron isolation efficiencies are derived using the the Z tag-and-probe method. Differences are observed between the data and MC events creating a source of uncertainty. The systematics were then determined by varying the electron isolation efficiency within their provided uncertainties and propagating it through the analysis chain.

Missing transverse energy

In the missing transverse energy calculation used in this analysis, the E_T^{miss} is built from other reconstructed objects in the event such as jets, muons, and electrons. The uncertainties on these objects can be propagated to the E_T^{miss} , for example, by varying the energy scale of the jets since jets are directly used in the E_T^{miss} calculation. Similarly, electron and muon energy scales, smearing, etc. are varied and the created effect is propagated to the E_T^{miss} calculation.

The main sources of systematic uncertainty, which enter the analysis as systematic error on the acceptance of the m_T^W cut, are the uncertainty on the soft components entering the E_T^{miss} calculation, energy scale and resolution that include the uncertainty arising from pile-up, the uncertainty on the muon energy scale and resolution, the uncertainty on the electron energy scale and resolution, the uncertainty on the jet energy scale, the description of pileup by the MC.

For the E_T^{miss} calculation in 2012, the soft terms resolution uncertainty is 1% and the scale uncertainty is 6%. The effect of the scale systematic is calculated by shifting $E_{x,y}^{softTerms}$ up and down by 6% and recalculating E_T^{miss} . The effect of the resolution systematic is calculated selecting a random Gaussian shift from the resolution uncertainty and applying it to $E_{x,y}^{softTerms}$.

Similarly for the other uncertainties, the uncertainties are propagated as recommended by the ATLAS performance groups to the E_T^{miss} to obtain uncertainties due to these sources. The

uncertainties from the muon and electron scale and resolution uncertainties are also propagated to the reconstruction of E_T^{miss} , but their effect on E_T^{miss} will be accounted for in the uncertainty sources for muons and electrons.

A summary of all systematic uncertainties considered in the thesis, affecting reconstructed WZ signal events, is provided in Table 4.14.

The relative effect in percent on the number of reconstructed WZ signal events of $\pm 1\sigma$ variations of the different “object” systematics is presented. All the sources of systematic uncertainties on reconstructed events is also propagated to all backgrounds expectations from the MC events.

Total Relative Uncertainties [%]				
Source	eee	$ee\mu$	$\mu\mu e$	$\mu\mu\mu$
e - energy scale	-0.70 +0.83	-0.30 +0.50	-0.39 +0.43	+0.01 -0.01
e - energy smearing	+0.17 -0.14	+0.13 -0.09	+0.03 -0.00	+0.00 -0.00
e - id. efficiency	-2.56 +2.51	-1.59 +1.58	-0.93 +0.93	+0.00 +0.00
e - rec. efficiency	-0.96 +0.95	-0.64 +0.64	-0.30 +0.30	+0.00 +0.00
μ - p_T scale	+0.00 +0.00	-0.03 +0.03	-0.03 +0.04	-0.08 +0.08
μ - p_T smearing	+0.00 +0.00	+0.02 +0.00	+0.07 -0.02	+0.01 -0.01
μ - rec. efficiency	+0.00 +0.00	-0.44 +0.44	-0.75 +0.74	-1.18 +1.17
E_T^{miss}	-0.02 +0.11	-0.03 +0.02	+0.02 -0.10	-0.01 -0.02
jet - JES Total	0.26 0.23	0.15 0.13	0.21 0.21	0.13 0.13
Trigger (e and μ)	-0.09 +0.09	-0.10 +0.10	-0.16 +0.16	-0.29 +0.29
Pile-up	+0.23 -0.28	+0.08 -0.04	+0.12 -0.12	+0.16 -0.16
Total (no lumi)	2.95 2.94	1.90 1.92	1.37 1.38	1.26 1.25

Table 4.14: Summary of the effect of $\pm 1\sigma$ variations of the main experimental systematics on the number of reconstructed WZ signal events from the MC samples. Upper and lower numbers corresponds to a $+1\sigma$ and -1σ variation of the corresponding systematic uncertainty source, respectively. The line labeled “jet-JES Total” is unsigned as it corresponds to the quadrature sum of the different sources of systematic uncertainties on the jet energy scale.

Charge mis-identification

The uncertainty associated to a possible mis-measurement of the charge of leptons associated to the W decays has to be considered. The measurement of the charge mis-identification is detailed in reference [90]. It is calculated within the ATLAS same sign $W^\pm W^\pm$ production analysis, where data is used to measure the probability that the lepton charge is mis-reconstructed. The $Z \rightarrow e^+e^-$ inclusive events are used to apply the tag-and-probe method and estimate the electron

charge mis-identification rate.

For electrons, they can interact with the material in front of the EM calorimeter creating secondary electrons via bremsstrahlung or photon conversions. When the emitted photon converts into a pair of e^+e^- with very asymmetric p_T , the wrong track from one of the secondary electrons can be associated to the original electron cluster in the calorimeter. This leads to the measurement of the wrong curvature for the electron thus to a charge mis-identification.

For the muons, they undergo less bremsstrahlung and therefore the charge mis-identification rate for these particles is negligible.

To evaluate the charge mis-identification of electrons, a control region using data is built in a way to fulfill the $W^\pm W^\pm$ selection cuts but only for opposite sign electron decays. The rate of electron charge mis-identification is therefore measured, using data, in different bins of p_T and η of the electron. The measurements from the $W^\pm W^\pm$ analysis, are therefore used in this thesis to propagate the uncertainty due to the electron charge mis-identification on the cross sections of the W^+Z and W^-Z cross sections respectively.

This uncertainty affects only channels where the W boson decays to electrons. This is because the probability of the charge mis-identification for a muon is negligible. The size of this uncertainty integrated over all the measurement range is of the order of 0.3%. Figure 4.18 shows however that the charge mis-identification rate is increasing with the increase of the electron pseudorapidity and it can reach to up to 3% for pseudorapidities around 2.5. The figure also shows that, the description of the charge mis-identification by the simulations worsens as the pseudorapidity increases.

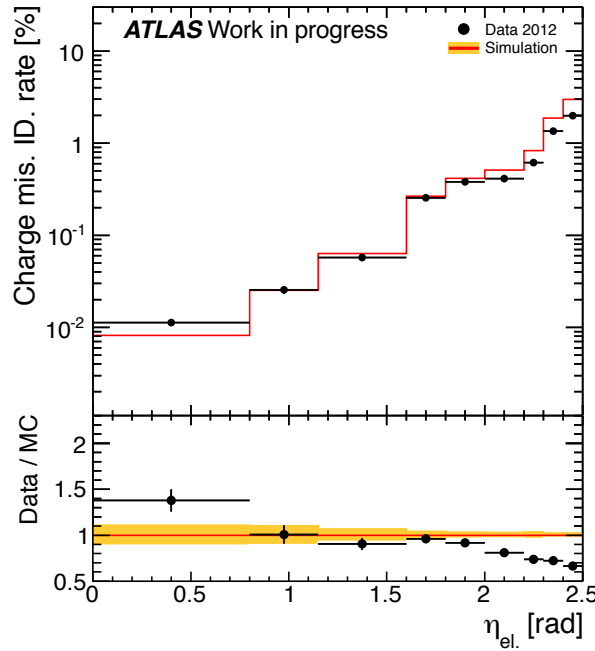


Figure 4.18: The charge mis-identification rate as a function of the η of the electron.

4.3.2 Uncertainties on background contributions

Table 4.15 summarizes the total theory uncertainty for the dominant background processes. As explained in section 4.2.2.3, a conservative systematic uncertainties of 15% is used for the $Z + jets$ and $t\bar{t}$ MC contributions. This number includes the theory uncertainty and also the

Process	ZZ	$Z\gamma$	$Z + jets$	$t\bar{t}$	$t\bar{t} + V$	VV_{DPI}
Uncertainty [%]	8%	9%	15%	15%	30%	50%

Table 4.15: Summary of theory uncertainties on the background processes.

differences of the normalization factors applied to the MC obtained using different control regions.

Global normalization uncertainties of 9% and 30% are attributed to the $W/Z + \gamma$ and to the sum of $t\bar{t} + V$ MC contributions, respectively [86][88]. These uncertainties are coming mainly from the PDFs and scale variations. Finally, a global normalization uncertainty of 8% is used for the ZZ contribution [87], that takes into account the difference between the ZZ NLO and NNLO cross sections.

Finally, a source of background producing W and Z bosons in the final states from double parton scattering [89], contribute in a negligible amount of the order of 0.5%. This background is denoted as VV_{DPI} and a conservative systematic uncertainty of 50% is attributed to it [91].

4.4 Kinematic distributions and yields of selected events

In this section the final yields of selected events will be presented. Also, a series of kinematic distributions will be shown in order to control the agreement between the data and the MC. We should note that all the background processes are estimated using the MC predictions. Only, the $Z + jets$ and $t\bar{t}$ processes are scaled with normalization factors estimated in section 4.2 using the results of the data selections for these backgrounds. The normalization factor used for $t\bar{t}$ is 1.16 while for the $Z + jets$ in the $Z + \mu$ channels is 0.96 whereas it is 1.1 in the $Z + e$ channels. The difference in the normalization factors for the $Z + jets$ between the different channels ($Z + \mu$ and $Z + e$) is because of the different sources of leptons we call “fake” for the WZ analysis. In the case of muons, in general a “fake” means a muons that is fragmented from a jet. While in the case of electrons, in general a jet is mis-reconstructed as an electron. Therefore, for the $Z + jets$ and $t\bar{t}$ backgrounds, the results are shown after rescaling them with the corresponding factors.

4.4.1 Yields of observed and expected events

After the selection of events and estimation of all the backgrounds, the total event yields for data and all MC can be seen in table 4.16 for the $W^\pm Z$ processes. The table contains only statistical uncertainties. The last two rows in the table corresponds to the fractional difference between data and MC yields and the overall Signal-to-Background ratio. These two quantities help use to quantify the differences seen between the data and MC as well as the importance of the signal with respect to the contamination of the backgrounds.

This table shows that 2091 WZ data events are selected after adding all four decay channels together. Among these a total background rate of 15% is observed. According to the MC predictions the WZ signal rate is about 73% from the total data selected events.

The dominant background among all processes is the ZZ background which is of the order of 6% for the combination of all channels. The sub-dominant background process is the $Z\gamma$ which affects only the channels where the W boson decays to electrons. This is because it is rare to mis-identify a muon as a photon. The $Z + jets$ processes come at the third level and they affect all channels equally. Finally, the $t\bar{t}$ and $t\bar{t} + V$ processes show equal contributions in all channels.

	$\mu\mu\mu$	$\mu\mu e$	$ee\mu$	eee	All
Data	663 ± 26	539 ± 23	483 ± 22	406 ± 20	2091 ± 46
Total Expected	614.3 ± 5.6	494.8 ± 4.8	405.8 ± 3.4	341.1 ± 5.0	1856.0 ± 9.5
WZ Signal	514.2 ± 1.6	379.2 ± 1.1	348.0 ± 1.1	260.4 ± 1.1	1501.8 ± 2.5
Total Bkg.	100.1 ± 5.3	115.6 ± 4.6	57.8 ± 3.3	80.7 ± 4.9	354.2 ± 9.2
ZZ	38.0 ± 0.3	34.6 ± 0.3	25.4 ± 0.3	24.6 ± 0.2	122.6 ± 0.5
$W/Z+\gamma$	1.1 ± 0.3	34.9 ± 2.0	0.0 ± 0.0	26.2 ± 1.7	62.1 ± 2.6
$Z+\text{jets}$	29.5 ± 4.7	19.8 ± 3.5	12.7 ± 2.7	16.3 ± 4.4	78.3 ± 7.8
$t\bar{t}$	17.6 ± 2.4	15.1 ± 2.3	9.2 ± 1.7	5.5 ± 1.2	47.3 ± 4.0
$t\bar{t}+V$	10.0 ± 0.3	7.9 ± 0.3	7.3 ± 0.3	5.9 ± 0.2	31.2 ± 0.5
WW	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.3 ± 0.1
VVV	1.0 ± 0.0	0.8 ± 0.0	0.7 ± 0.0	0.5 ± 0.0	3.1 ± 0.1
VV_{DPI}	2.6 ± 0.2	2.1 ± 0.2	2.1 ± 0.1	1.4 ± 0.1	8.2 ± 0.3
S/B	5.1	3.3	6.0	3.2	4.2

Table 4.16: Summary of observed and expected yields for $W^\pm Z$, in each channel of the analysis and for the sum of all channels. Only statistical uncertainties on the observed number of events and MC expectations are shown. The signal over background ration, S/B in each channel is also mentioned.

Among the four WZ channels, the best measurement is in the $\mu\mu\mu$ channel due to the large signal to background ratio and higher signal efficiency. The worst measurement is in the eee channel, as the reconstruction of electrons and their separation from the background is more difficult than for muons.

4.4.2 $W^\pm Z$ kinematic distributions

Using the WZ selected events, distributions of kinematic and other variables of the reconstructed W and Z bosons as well as the WZ diboson system can be built. These are presented in Figures 4.19 to 4.23. These distributions use the sum of all the WZ decay channels. The SHERPA MC generator is used to model the $W^\pm Z$ signal expectation. All background processes are estimated using the MC where $Z + \text{jets}$ and $t\bar{t}$ backgrounds are rescaled using the global normalization factors summarized in section 4.2. In these distributions all MC expectations are scaled to the integrated luminosity of the data using the predicted MC cross sections of each sample.

4.4.3 W^+Z or W^-Z kinematic distributions

W^+Z and W^-Z events can be split and the kinematic distributions in each sample can be controlled. This is shown in figure 4.23 that shows a discrepancy between the data and MC in both W^+Z and W^-Z kinematic distributions. Therefore splitting the $W^\pm Z$ sample according to the charge of the W boson does not show any specific behavior with respect to the total $W^\pm Z$ kinematic distributions.

The total yields in each of the W^+Z and W^-Z channels with their combination is shown in tables 4.17 and 4.18. The background apportionment is the same as seen in the $W^\pm Z$ channels. Thus the same normalization factors defined for the $W^\pm Z$ events were used to re-weight each of the $Z + \text{jets}$ and $t\bar{t}$ backgrounds for the W^+Z and W^-Z events.

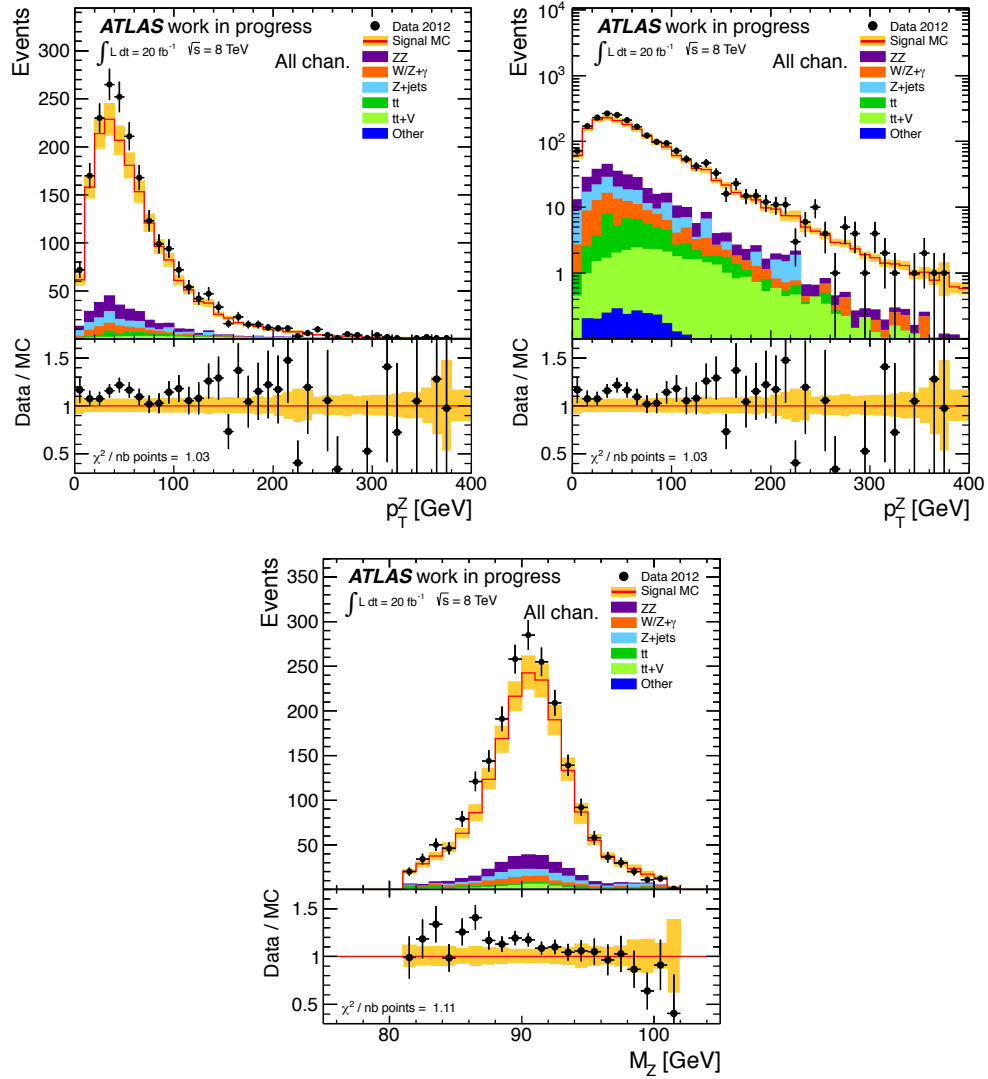


Figure 4.19: Control distributions for the sum of all channels of Z boson kinematic variables: p_T^Z , m_Z . All MC expectations are scaled to the integrated luminosity of the data. The orange band represents the quadrature sum of all systematic uncertainties on the total MC expectation (see text for details). It includes an uncertainty of 2.8% for the integrated luminosity of the data.

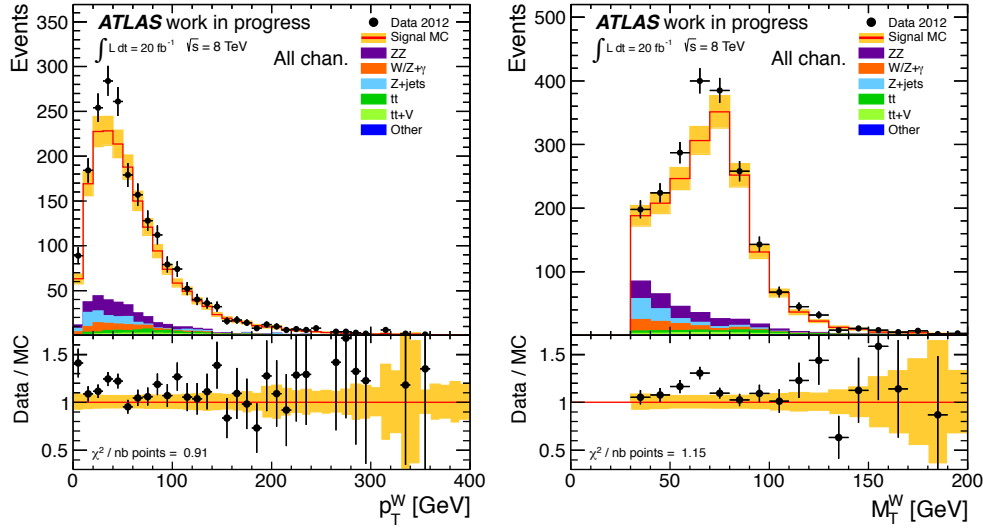


Figure 4.20: Control distributions for the sum of all channels of W boson kinematic variables: p_T^W and m_T^W . All MC expectations are scaled to the integrated luminosity of the data. The orange band represents the quadrature sum of all systematic uncertainties on the total MC expectation (see text for details). It includes an uncertainty of 2.8% for the integrated luminosity of the data.

	$\mu\mu\mu$	$\mu\mu e$	$ee\mu$	eee	All
Data	388 ± 20	293 ± 17	309 ± 18	232 ± 15	1222 ± 35
Total Expected	376.6 ± 3.9	293.0 ± 3.4	250.6 ± 2.7	201.7 ± 4.1	1121.9 ± 7.1
WZ Signal	324.1 ± 1.4	235.3 ± 1.0	219.3 ± 0.9	161.9 ± 0.9	940.5 ± 2.1
Total Bkg.	52.5 ± 3.6	57.7 ± 3.2	31.3 ± 2.6	39.8 ± 4.0	181.4 ± 6.8
ZZ	19.8 ± 0.2	17.5 ± 0.2	13.4 ± 0.2	12.5 ± 0.2	63.2 ± 0.4
$W/Z+\gamma$	0.8 ± 0.2	17.2 ± 1.4	0.0 ± 0.0	11.6 ± 1.1	29.5 ± 1.8
$Z+\text{jets}$	14.5 ± 3.1	9.1 ± 2.4	7.7 ± 2.3	8.8 ± 3.7	40.1 ± 5.8
$t\bar{t}$	9.9 ± 1.8	8.0 ± 1.7	4.6 ± 1.2	2.9 ± 0.9	25.4 ± 2.9
$t\bar{t}+V$	5.3 ± 0.2	4.0 ± 0.2	3.8 ± 0.2	3.0 ± 0.2	16.0 ± 0.4
WW	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.1 ± 0.1	0.3 ± 0.1
VVV	0.6 ± 0.0	0.5 ± 0.0	0.4 ± 0.0	0.3 ± 0.0	1.7 ± 0.1
VV_{DPI}	1.5 ± 0.1	1.2 ± 0.1	1.3 ± 0.1	0.7 ± 0.1	4.6 ± 0.2
S/B	6.2	4.1	7.0	4.1	5.2

Table 4.17: Summary of observed and expected yields for W^+Z , in each channel of the analysis and for the sum of all channels. Only statistical uncertainties on the observed number of events and MC expectations are shown. The signal over background ratio, S/B in each channel is also mentioned.

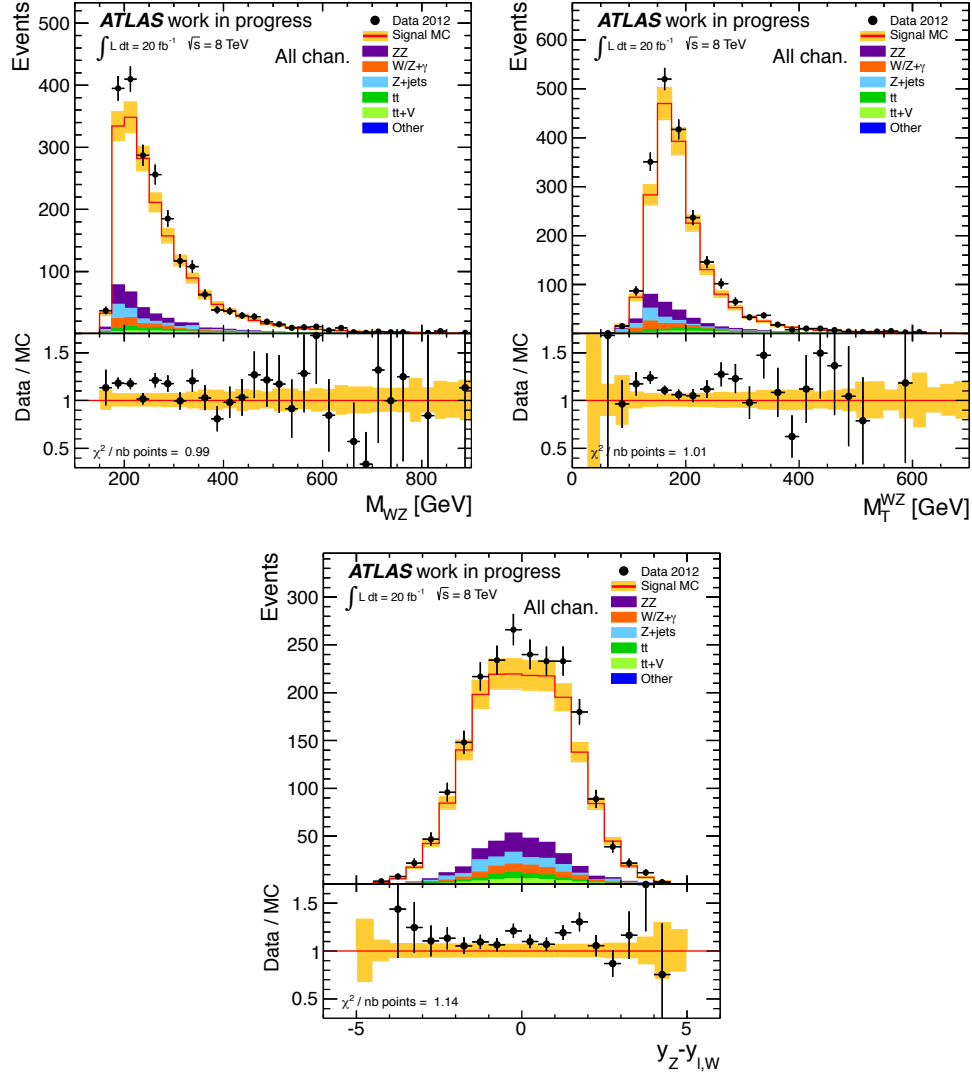


Figure 4.21: Control distributions for the sum of all channels of kinematic variables of the WZ di-boson system: p_T^W , m_T^W , and the difference in rapidity between the Z boson and the lepton of the W decay $y_Z - y_{\ell,W}$. All MC expectations are scaled to the integrated luminosity of the data. The orange band represents the quadrature sum of all systematic uncertainties on the total MC expectation (see text for details). It includes an uncertainty of 2.8% for the integrated luminosity of the data.

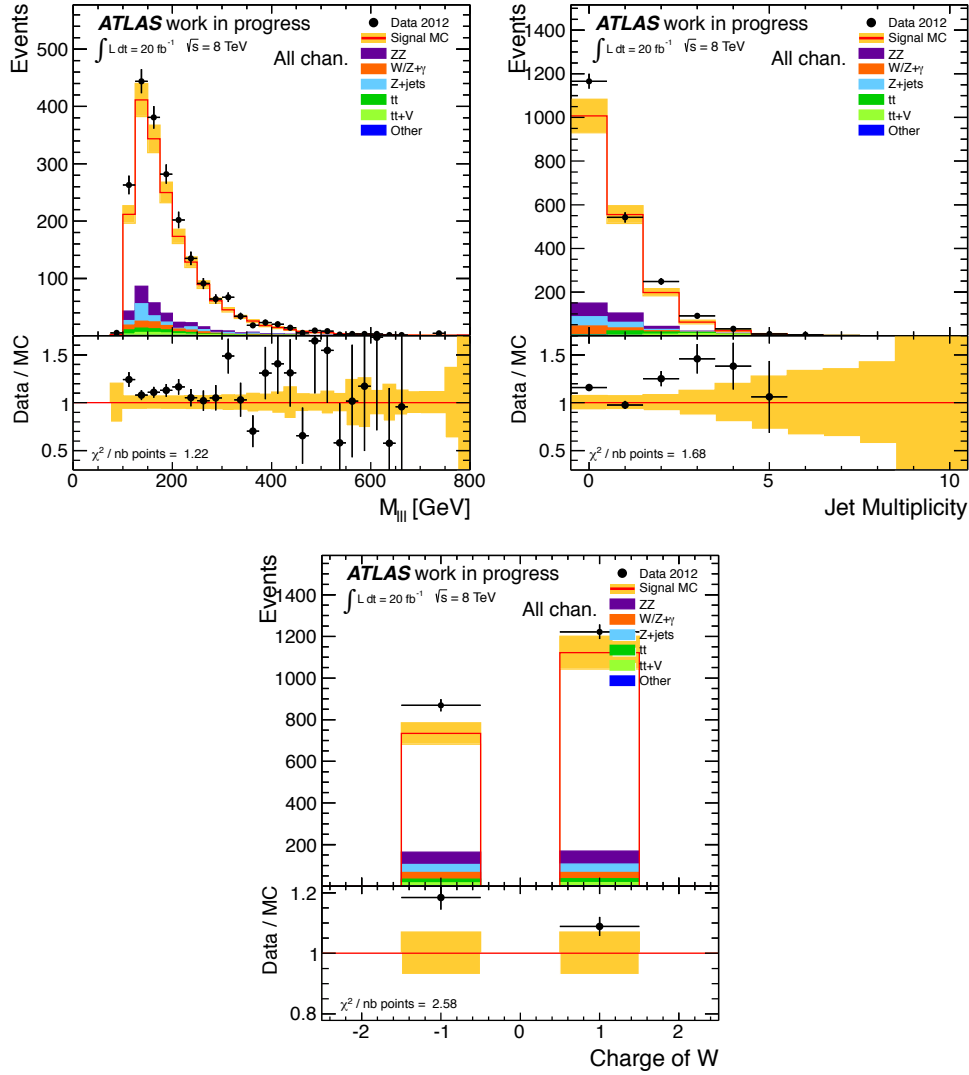


Figure 4.22: Control distributions for the sum of all channels of the invariant mass of the three leptons $m_{\ell\ell\ell}$, the jet multiplicity N_{jets} and the reconstructed charge of the W boson. All MC expectations are scaled to the integrated luminosity of the data. The orange band represents the quadrature sum of all systematic uncertainties on the total MC expectation (see text for details). It includes an uncertainty of 2.8% for the integrated luminosity of the data.

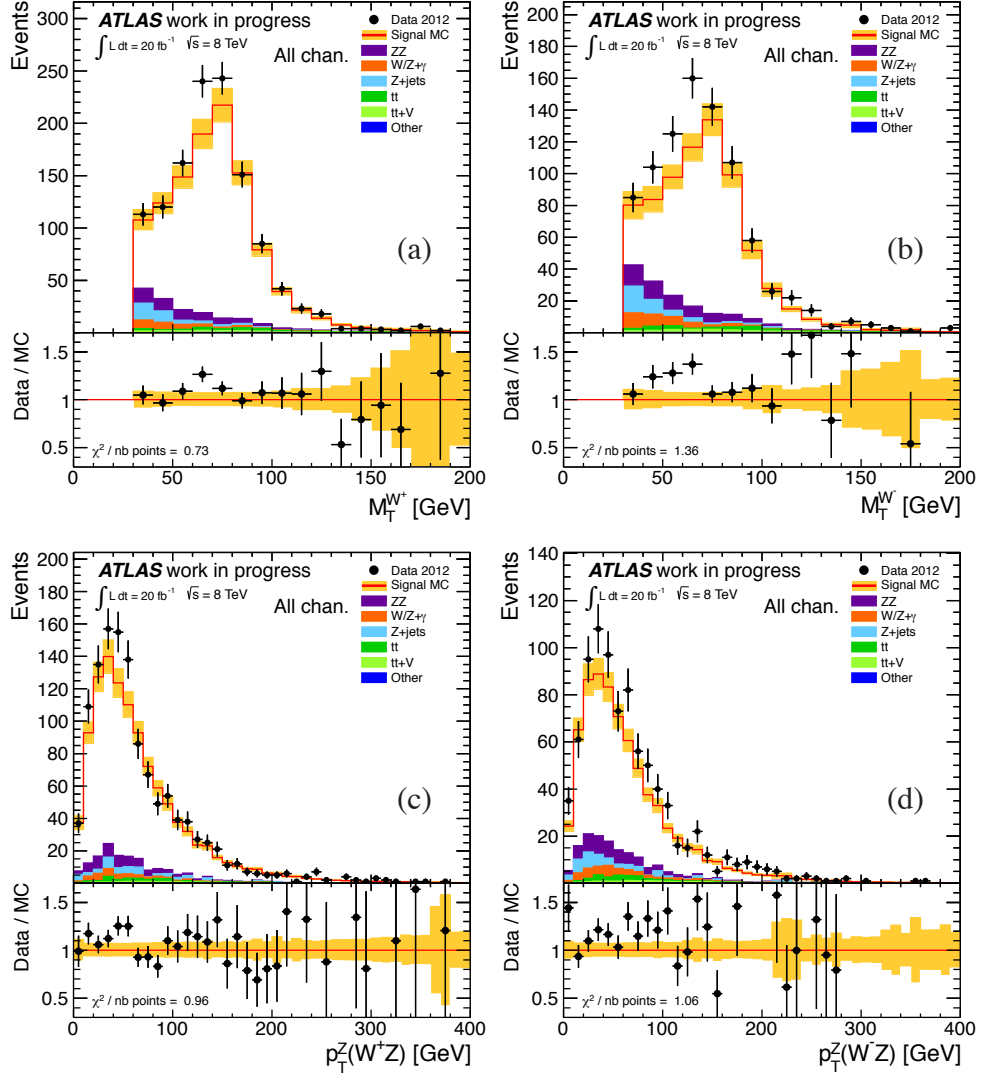


Figure 4.23: Control distributions for the sum of all channels of kinematic variables m_T^W and p_T^Z for W^+Z (a and c) and W^-Z (b and d) events, respectively. All MC expectations are scaled to the integrated luminosity of the data. The orange band represents the quadrature sum of all systematic uncertainties on the total MC expectation (see text for details). It includes an uncertainty of 2.8% for the integrated luminosity of the data.

	$\mu\mu\mu$	$\mu\mu e$	$ee\mu$	eee	All
Data	275 ± 17	246 ± 16	174 ± 13	174 ± 13	869 ± 29
Total Expected	237.7 ± 4.0	201.7 ± 3.4	155.2 ± 2.1	139.4 ± 3.0	734.1 ± 6.3
WZ Signal	190.2 ± 0.8	143.8 ± 0.6	128.8 ± 0.5	98.5 ± 0.6	561.3 ± 1.3
Total Bkg.	47.6 ± 3.9	57.9 ± 3.3	26.5 ± 2.0	40.9 ± 2.9	172.8 ± 6.2
ZZ	18.2 ± 0.2	17.1 ± 0.2	12.1 ± 0.2	12.1 ± 0.2	59.4 ± 0.4
$W/Z+\gamma$	0.3 ± 0.2	17.8 ± 1.4	0.0 ± 0.0	14.6 ± 1.3	32.7 ± 1.9
$Z+\text{jets}$	15.1 ± 3.5	10.6 ± 2.5	5.0 ± 1.5	7.4 ± 2.4	38.0 ± 5.2
$t\bar{t}$	7.7 ± 1.6	7.1 ± 1.6	4.6 ± 1.2	2.7 ± 0.9	22.0 ± 2.7
$t\bar{t}+V$	4.7 ± 0.2	4.0 ± 0.2	3.6 ± 0.2	2.9 ± 0.2	15.2 ± 0.4
WW	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0	0.0 ± 0.0
VVV	0.4 ± 0.0	0.4 ± 0.0	0.3 ± 0.0	0.3 ± 0.0	1.4 ± 0.0
VV_{DPI}	1.1 ± 0.1	1.0 ± 0.1	0.8 ± 0.1	0.7 ± 0.1	3.6 ± 0.2
S/B	4.0	2.5	4.9	2.4	3.2

Table 4.18: Summary of observed and expected yields for $W^\pm Z$, in each channel of the analysis and for the sum of all channels. Only statistical uncertainties on the observed number of events and MC expectations are shown. The signal over background ration, S/B in each channel is also mentioned.

Chapter 5

Integrated total and fiducial cross section measurement

In this chapter, the measurement of the WZ integrated fiducial and total cross sections will be presented. Section 5.1 will define the fiducial and total phase spaces in which the measurement is performed. Section 5.1.2 will show the results of the fiducial efficiency and total acceptance measurement. Sections 5.2 and 5.3 will present the cross section measurement results for WZ and W^+Z/W^-Z ratio respectively. Finally, a conclusion will be drawn in section 5.4.

5.1 Methodology of cross section measurements

The integrated WZ cross section measurements are reported in two phase spaces, total and fiducial. The reasons for defining two phase spaces for the measurement is because of certain benefits we get from each of them. The fiducial volume defines a restricted region in the phase space, very close to the acceptance of the experimental measurement. This allows to report a measurement that is less sensitive to theoretical uncertainties such as the ones arising from the knowledge of the PDFs. Indeed these theoretical uncertainties become more important when the measurement has to be extrapolated to the total phase space, as this extrapolation rely only on the precision of the theoretical prediction. From the other side, the advantage of the total phase space extrapolation is that the quoted result is independent from the selection criteria and allows to compare easily to results obtained by different experiments.

5.1.1 Definition of measurement phase spaces

5.1.1.1 Fiducial phase space definition

The fiducial PS is defined to be very close to the PS where the experimental measurement is performed. It is also chosen in a way to stay as close as possible to the acceptance of the detector.

The fiducial volume is defined using a list of selection criteria on the truth leptons listed below:

- the invariant mass of the leptons originating from the decay of the Z boson of $66 < m_{\ell\ell} < 116$ GeV,
- $p_T^\ell > 15$ GeV for the two charged leptons from the Z decay,
- $p_T^\ell > 20$ GeV for the charged lepton from the W decay,
- $|\eta_\ell| < 2.5$ for each of the three charged leptons,

- $|m_{\ell\ell} - m_Z| < 10$ GeV for the invariant mass ($m_{\ell\ell}$) of the generated Z candidate,
- $m_T^W > 30$ GeV for the transverse mass (m_T^W) of the generated W candidate,
- $\Delta R(\ell, \ell) > 0.3$ between leptons associated to the W candidate and Z candidate and $\Delta R(\ell, \ell) > 0.2$ between the two leptons associated to the Z candidate.

Only electrons and muons originating from the W and Z decays are used. For final state charged truth leptons, the “dressed” definition is used. “Dressed” final state charged leptons are obtained starting from “bare” leptons (right after QED final state radiation (FSR)) and summing the momenta of all photons within a cone of $\Delta R < 0.1$ around the “bare” lepton direction. This dressing procedure, enables to correct partially for the QED FSR and reduces the dependence of the measurement on the modeling of the soft and collinear photon radiations from the leptons. The electrons and muons are affected by QED FSR, this correction to dressed leptons allows to combine measurements performed with electrons or muons.

5.1.1.2 Total phase space definition

The measurement performed in the fiducial phase space is then extrapolated to an enlarged phase space, called total phase space. The only requirement for this PS is on the invariant mass of the leptons originating from the decay of the Z boson which should be in the window of $66 < m_{\ell\ell} < 116$ GeV. The reason for this requirement is to stay close to the Z mass pole and avoid the interferences with the γ^* , as we are interested in W and Z measurements for the production of on-shell W and Z bosons.

5.1.2 Cross section extraction

In particle physics, a cross section is the probability that two or more particles collide and react in a certain way. In terms of measurement, it consists on counting the number of observed events for a given process with respect to the total number of created events during the $p - p$ collisions. Technically, the WZ production cross section is the ratio of the total WZ data events subtracted by the number of estimated background events, to the integrated luminosity of the p-p collisions. This ratio is then corrected by factors representing the efficiency and acceptance of the detector.

Fiducial cross section

For a $WZ \rightarrow \ell\nu\ell'\ell'$ production in the electron and muon decay channel the fiducial cross section is defined as:

$$\sigma_{fid}(pp \rightarrow WZ X) = \frac{N_{\text{data}} - N_{\text{bg}}}{\mathcal{L} \cdot C_{WZ}^{\ell, \ell'}} \times \left(1 - \frac{N_{\text{MC,rec}}^{\tau}}{N_{\text{MC,rec}}^{\text{all}}} \right), \quad (5.1)$$

where $\ell, \ell' = e, \mu$, $\text{all} = e + \mu + \tau$, $C_{WZ}^{\ell, \ell'}$ is the fiducial efficiency that we will define by equation 5.2, $\mathcal{L}$ is the integrated luminosity, N_{data} and N_{bg} are the number of data and background events respectively. Since in this analysis, the WZ events decaying to τ lepton decays are not considered, this cross section is corrected for the WZ decays to tau leptons. In fact the τ leptons can decay to electrons or muons in the detector. However, since in this analysis, only electrons and muons directly originating from the W and Z bosons are considered, a corrective factor for the reconstructed τ leptons contribution is included in the cross section expression. This factor

is estimated using the POWHEGPYTHIA MC predictions and it is found to be of the order of 4%, as shown in table 5.1, in all of the WZ channels.

The WZ processes are studied in their electron and muon decay channels. Four final state topologies are possible and they are the: eee , $ee\mu$, $\mu\mu e$, and $\mu\mu\mu$ topologies. The C_{WZ} fiducial efficiency factor is used to bring the total number of reconstructed events in the data to that in the truth MC within the fiducial volume. Therefore this factor will correct the number of observed data events to the number corresponding to really produced events in the fiducial volume. The advantage of applying this kind of correction to the fiducial cross section is that it is less sensitive to theoretical uncertainties especially those on the PDFs (see section 5.1.3)

For each topology, the fiducial efficiency, $C_{WZ}^{\ell\ell'}$, is computed using the simulated signal events from the POWHEGPYTHIA MC generator. The trigger and reconstruction efficiencies are different between the measurement in data and the MC. Therefore, the MC signal events used to compute the fiducial efficiency are corrected by scale factors on an event-by-event basis in order to reproduce the data. The C_{WZ} factor is therefore defined as:

$$C_{WZ}^{\ell,\ell'} = \frac{N_{MC,rec,cuts}^{tot}}{N_{MC,gen,fid}^{tot}}, \quad (5.2)$$

where $N_{MC,rec,cuts}^{tot}$ and $N_{MC,gen,fid}^{tot}$ are for each channel, the number of reconstructed selected events in the signal sample and the number of generated signal events after the fiducial cuts. “Dressed” final state charged leptons are used to compute $N_{MC,gen,fid}^{tot}$.

Total cross section

The fiducial WZ cross section is then extrapolated to the total phase space and a total cross section is defined for each of the four final stat topologies as:

$$\sigma_{tot}(pp \rightarrow WZ X) \cdot Br_{W \rightarrow \ell\nu} \cdot Br_{Z \rightarrow \ell'\ell'} = \frac{\sigma_{fid}}{A_{WZ}}, \quad (5.3)$$

where A_{WZ} represents the total acceptance (defined by equation 5.4), a factor that extrapolates the measurement in the fiducial volume to the total phase space. $Br_{W \rightarrow \ell\nu}$ and $Br_{Z \rightarrow \ell'\ell'}$ are the $W \rightarrow \ell\nu$ and $Z \rightarrow \ell'\ell'$ branching ratios equal to $10.8 \pm 0.09\%$ and $3.3658 \pm 0.0023\%$ respectively [85].

This factor corrects for the total event count generated in the fiducial volume to the total number of generated events in the total PS. The total acceptance or extrapolation factor, A_{WZ} , is defined for each topology by the following relation:

$$A = \frac{N_{MC,gen,fid}^{tot}}{N_{MC,gen}^{tot}}, \quad (5.4)$$

where $N_{MC,gen}^{tot}$ in the denominator corresponds to all signal events within the region $66 < M_{\ell+\ell^-} < 116$ GeV (the full phase space) and the $N_{MC,gen,fid}^{tot}$ is the number of generated signal events in the fiducial volume. The theoretical uncertainties on the cross section have a major effect on this factor as it will be shown in section 5.1.3.

Finally, the product of the A_{WZ} and C_{WZ} factors define the total extrapolation factor from the reconstructed level to the total phase space.

Channel	A_{WZ}	C_{WZ}	$N_{MC,rec}^\tau / N_{MC,rec}^{All}$
eee	0.394 ± 0.001	0.404 ± 0.001	0.0412 ± 0.0007
$ee\mu$	0.394 ± 0.001	0.539 ± 0.001	0.0360 ± 0.0005
$\mu\mu e$	0.395 ± 0.001	0.586 ± 0.001	0.0385 ± 0.0005
$\mu\mu\mu$	0.394 ± 0.001	0.801 ± 0.002	0.0366 ± 0.0005

Table 5.1: Values of the A_{WZ} and C_{WZ} factors for each of the eee , $ee\mu$, $\mu\mu e$, and $\mu\mu\mu$ channels, calculated using the POWHEGPYTHIA MC event generator. The last column, represents the proportion of events without tau leptons at the reconstructed level, predicted by the POWHEGPYTHIA MC generator. The uncertainties correspond to the statistical uncertainties of the MC events.

Total acceptance and fiducial efficiency measurement

Table 5.1 shows the $C_{WZ}^{\ell\ell'}$ and A_{WZ} factors for each of the WZ decay channels. The PowHeg-Pythia MC event generator is used for these results. For this generator, the final state leptons are associated to the W and Z bosons using a built-in assignment algorithm. The same algorithm is used to compute the A_{WZ} and C_{WZ} factors. The table shows that the C_{WZ} factor has a dependence on the different channels because it depends on the number of reconstructed events. In fact, the reconstruction of muons is more efficient than that of electrons in an event. Therefore, the efficiency in the $\mu\mu\mu\nu$ channel is the highest of about 80%. The A_{WZ} factor however, has a channel dependence that is lower than 0.3%, corresponding to the statistical uncertainty of the MC samples used for its computation. This is because only truth information is used to compute this quantity which does not depend on reconstruction efficiencies and predicts similar electron and muon production rates.

5.1.3 Systematic uncertainties

The effect of the PDF uncertainties explained in section 1.2.4, have to be propagated to the A_{WZ} and C_{WZ} factors. This is shown in table 5.2. The table shows that by summing quadratically on the CT10 eigen vectors, the effect of the PDF uncertainties on the C_{WZ} factor is negligible whereas it is more important on the total acceptance factor. The picture does not change when PDFs different than the CT10 are used. The main effect remains always on the A_{WZ} factor and a per mille level effect only on the fiducial efficiency factor.

This verifies the statement made in the previous sections that the fiducial correction with a C_{WZ} factor has the advantage of not being affected by the theoretical uncertainties, as the one arising from the uncertainties on the PDFs.

	$W^\pm Z$		$W^+ Z$		$W^- Z$	
	A_{WZ}	C_{WZ}	A_{WZ}	C_{WZ}	A_{WZ}	C_{WZ}
CT10 eigenvectors (68% C.L.)	+0.43% -0.45%	+0.02% -0.02%	+0.58% -0.57%	+0.03% -0.03%	+0.95% -1.00%	+0.02% -0.02%
CT10 to MSTW08	+0.55%	+0.01%	+0.21%	+0.02%	+1.00%	+0.03%
CT10 to ATLAS PDF	+1.15%	+0.05%	+1.09%	+0.07%	+1.36%	+0.02%

Table 5.2: PDF uncertainties on the A_{WZ} and C_{WZ} correction factors.

The QCD scale uncertainties are also propagated to the A_{WZ} factor and this is shown in table 5.3. The uncertainty on the C_{WZ} factors are expected to be small and thus they are neglected.

Scale variation		
x_R	x_F	A_{WZ}
0.5	0.5	0.60%
0.5	1	0.40%
0.5	2	0.18%
1	0.5	0.08%
1	1	0.00%
1	2	-0.30%
2	0.5	-0.20%
2	1	-0.47%
2	2	-0.54%
$\mu_F = \mu_R = (M_W + M_Z)/2$		0.50%

Table 5.3: Relative deviations of A_{WZ} for different scale choices compared to the nominal value with $\mu_F = \mu_R = M_{WZ}$. The renormalization and factorization scale are varied independently by x_R and x_F . The deviation between the nominal scale values and fixed scales of $\mu_F = \mu_R = (M_W + M_Z)/2$ is presented in the last line.

Each of the object uncertainties presented in section 4.3, are propagated to the estimated number of signal and background events, as they are determined using the MC prediction. The uncertainty propagation on the signal affects the C_{WZ} factor, while its propagation on the background affects the term N_{bkg} in equation (5.1). Finally, the propagation of the luminosity systematic uncertainty, calculated by varying up and down the integrated luminosity by its uncertainty of 2.8%, affects also the number of the background events N_{bkg} as they are determined using the MC.

5.2 Integrated fiducial and total cross section measurement

5.2.1 Combination procedure

The fiducial and total cross sections are calculated in each of the WZ four decay channels separately. To increase the precision of the cross sections measurement, the results from each channel need to be combined. The combination will decrease the statistical uncertainty and correlated systematic uncertainties. This averaging of the results from the individual channels is performed using a χ^2 minimization that takes into account the correlated systematic uncertainties. Therefore a final single measurement of the cross section will be compared at the end to the theoretical predictions.

The χ^2 function used for the combination is defined as:

$$\chi_{\text{exp}}^2(\mathbf{m}, \mathbf{b}) = \sum_{\ell} \sum_i \frac{\left[m^i - \sum_j \gamma_{j,\ell}^i m^i b_j - \mu_{\ell}^i \right]^2}{\delta_{i,\text{stat},\ell}^2 \mu_{\ell}^i \left(m^i - \sum_j \gamma_{j,\ell}^i m^i b_j \right) + (\delta_{i,\text{uncor},\ell} m^i)^2} + \sum_j b_j^2. \quad (5.5)$$

In this combination method a basic assumption is made by defining common values m_i , representing underlying physical quantities, for all the channels ℓ and for each interval or bin, i , of

the variable in question, in this case the total or fiducial cross section. The m_i are also determined by the χ^2 minimization method described in [92, 93]. The μ_ℓ^i represents the measured value of the cross section in a bin i of the channel ℓ and $\gamma_{j,\ell}^i$, $\delta_{i,\text{stat},\ell}$ and $\delta_{i,\text{uncor},\ell}$ are the relative correlated systematic, relative statistical and relative uncorrelated systematic uncertainties, respectively. The different systematic uncertainty sources are denoted by j . For uncorrelated systematic uncertainties between channels with electrons and muons, the corresponding factors $\gamma_{j,\ell}^i$ are non-zero for one of the electron or muon channels only. The function χ_{exp}^2 depends on the averaged values m^i , denoted as the vector $\mathbf{m}$, and the nuisance parameters b_j for the systematic uncertainty sources j , denoted as the vector $\mathbf{b}$. The nuisance parameters are centered at zero and have a standard deviation of one, as controlled by the penalty term $\sum_j b_j^2$.

The equation (5.5) takes into account that the quoted uncertainties are based on measured cross sections, which are subject to statistical fluctuations. Under the assumption that the statistical uncertainties are proportional to the square root of the number of events and that the systematic uncertainties are proportional to $\mathbf{m}$, the minimum of the equation 5.5 provides an unbiased estimator of $\mathbf{m}$.

The different sources of systematic uncertainties affecting reconstructed leptons and jets have a contribution in all the WZ decay channels through the reconstruction of the E_T^{miss} . Therefore, these sources of systematic uncertainties are considered as fully correlated between the four decay channels. Uncertainties on the predicted number of background events by the different MC generators also affect all channels and are therefore also considered to be fully correlated between all four channels. The data averaging procedure through this χ^2 function takes into account all the correlated systematic uncertainties. This can allow a reduction of the effect of a given systematic uncertainty, if it affects differently each of the measurements in the given channels.

5.2.2 Fiducial cross section measurement

The WZ cross section is calculated in the fiducial phase space defined in section 5.1 according to equation (5.1). The results are obtained for each of the eee , $ee\mu$, $\mu\mu e$, and $\mu\mu\mu$ channels, separately. Their combination is performed using the χ^2 minimization method described in section 5.2.1. Table 5.4 shows the final results with the corresponding statistical, systematic and luminosity uncertainties. As shown in the table, the measurement of the fiducial cross section is dominated by the statistical uncertainty. A breakdown of the systematic uncertainties on the fiducial cross section in each channel is given in table 5.5. The table shows that the most important systematic uncertainty sources arise from the control of the background contributions, of the order of 3%, and from systematic uncertainties on the electron and muon identifications by $\sim 1\%$.

This measurement is also compared to the theoretical prediction obtained using sc PowHeg and using renormalization and factorization fixed scales equal to $\mu_R = \mu_F = (M_W + M_Z)/2$. The CT10 PDF set is employed.

The combination of all four channels is performed using the χ^2 method described in section 5.2.1. This method enables the reduction of some of the most important systematic uncertainties as they are fully correlated between the channels. Table 5.5 shows the statistical and the average systematic uncertainty contributions corresponding for each object systematics. As we see in table, the systematic uncertainty due to the electron and muon identifications is reduced by a factor of two in the result of the combination. The combination of the cross section yields a total χ^2 per degree of freedom (n_{dof}) of $\chi^2/n_{\text{dof}} = 3.6/3$, which shows a good agreement among

channel	$\sigma_{fiducial}(pp \rightarrow WZ; \sqrt{s} = 8 \text{ TeV}) [\text{fb}]$			
eee	37.91	± 2.36 (stat.)	± 1.81 (sys.)	± 1.14 (lumi.)
$ee\mu$	36.91	± 1.94 (stat.)	± 0.96 (sys.)	± 1.10 (lumi.)
$\mu\mu e$	34.03	± 1.88 (stat.)	± 1.45 (sys.)	± 1.03 (lumi.)
$\mu\mu\mu$	33.54	± 1.53 (stat.)	± 0.77 (sys.)	± 1.00 (lumi.)
σ_{fid}^{comb}	35.11	± 0.93 (stat.)	± 0.74 (sys.)	± 1.08 (lumi.)
$\sigma_{th.}$	31.03	± 0.03 (stat.)	± 0.83 (PDF)	± 2.31 (QCD Scale)

Table 5.4: The fiducial cross section in the fiducial phase space in fb for each of the eee , $ee\mu$, $\mu\mu e$, and $\mu\mu\mu$ channels and for their combination. The prediction from the POWHEGPYTHIA MC generator is also indicated.

each of the measurements in the four channels.

The sign convention in the table is calculated during the averaging of the up and down systematic variations so that:

$$\sigma_{sys}^{avg} = \frac{1}{2} \times sign \times (|\sigma_{sys}^{up} - \sigma_{nominal}| + |\sigma_{sys}^{down} - \sigma_{nominal}|); \quad (5.6)$$

where $\sigma_{nominal}$, σ_{sys}^{up} , and σ_{sys}^{down} are the nominal cross section, the cross section after an up systematic variation, and the one after a down systematic variation, respectively. The $sign$ is positive when the up variation of the cross section results in a greater value than $\sigma_{nominal}$ and negative otherwise.

5.2.3 Total cross section measurement

The fiducial cross section is extrapolated to the total phase space according to equation 5.3. It is also calculated in each individual WZ channel and then combined using the χ^2 minimization method. Table 5.6 shows the results of the total cross section in each channel together with the result of the combination. The combination of the cross section yields a total χ^2 per degree of freedom (n_{dof}) of $\chi^2/n_{dof} = 3.65/3$, which shows a good agreement among each of the other measurements in the four channels.

A breakdown of the individual contributions of the different sources of systematic uncertainties is shown in table 5.7. In this table, the statistical uncertainties of the signal MC and background are considered as uncorrelated uncertainties and treated as one during the combination of the results. The dominant source of systematic uncertainties is arising from the background estimates, especially from the $Z + jets$ background. These are followed by the uncertainties on the identification of the electron and muon objects. These uncertainties are correlated between the WZ channels and they are reduced by a factor of $\sim$ two when the χ^2 combination is performed.

The total order of magnitude of the systematic uncertainties on this measurement is 3% which is of the same order of the statistical uncertainty on the data measurement. This means that even though the systematic uncertainties are important, the order of magnitude of the statistical uncertainties on the measurement remain equally important.

Finally, to compare the total cross section to the POWHEGPYTHIA predictions presented in section 1.2.3, Figure 5.1 presents the ratio of the measured cross section to the theoretical predictions from POWHEG, equal to $21.68 \pm 0.02(\text{stat}) \pm 1.6(\text{PDF\&Scale})$ pb. Within the experimental and theoretical uncertainties, the final combination result agrees with the theory

Systematic Unc. [%]	eee	$ee\mu$	$\mu\mu e$	$\mu\mu\mu$	combined
δ_{data}^{stat}	6.19	5.17	5.48	4.57	2.64
δ_{sys}^{tot}	4.41	2.56	2.65	2.17	2.09
δ_{lumi}	-3.24	-2.97	-3.26	-3.00	-3.09
δ_{sig}^{stat}	0.36	0.22	0.21	0.20	0.54
δ_{bkg}^{stat}	1.51	0.77	1.10	0.95	
$\delta_{bkg}^{Z\gamma}$	-0.72	-0.00	-0.74	-0.02	-0.30
δ_{bkg}^{Z+jets}	-0.25	-0.32	-0.53	-0.47	-0.48
$\delta_{bkg}^{t\bar{t}}$	-0.75	-0.45	-0.70	-0.79	-0.41
δ_{bkg}^{ZZ}	-0.61	-0.48	-0.66	-0.54	-0.57
δ_{bkg}^{MCoth}	-0.68	-0.67	-0.72	-0.68	-0.69
δ_e^E	-1.10	-0.58	-0.73	0.01	-0.49
δ_e^{Res}	0.21	0.20	-0.14	0.00	-0.05
δ_e^{ID}	-3.31	-1.84	-1.25	-0.00	-1.21
δ_e^{Reco}	-1.24	-0.73	-0.41	-0.00	-0.48
δ_e^{Iso}	-0.88	-0.55	-0.27	-0.00	-0.34
δ_μ^E	-0.00	-0.03	-0.04	-0.08	-0.05
δ_μ^{Res}	-0.00	-0.02	0.10	-0.08	-0.01
δ_μ^{ResID}	-0.00	-0.00	0.11	-0.03	0.01
δ_μ^{ID}	-0.00	-0.50	-0.95	-1.40	-0.83
δ_{jet}^{JESTot}	0.60	0.26	0.31	0.24	0.32
δ_{jet}^{Res}	-0.37	-0.09	0.02	0.09	-0.05
δ_{MET}	0.17	0.04	0.25	0.12	0.11
δ_{Trig}	-0.12	-0.12	-0.20	-0.37	-0.22

Table 5.5: Relative systematic and statistical uncertainties on the fiducial cross section in each of the eee , $ee\mu$, $\mu\mu e$, and $\mu\mu\mu$ channels and for their combination. The sign convention is chosen as explained by equation 5.2.2.

channel	$\sigma(pp \rightarrow WZ; \sqrt{s} = 8 \text{ TeV})$ [pb]			
eee	26.64	± 1.65 (stat.)	± 1.29 (sys.)	± 0.86 (lumi.)
$ee\mu$	26.20	± 1.35 (stat.)	± 0.83 (sys.)	± 0.78 (lumi.)
$\mu\mu e$	23.90	± 1.31 (stat.)	± 0.81 (sys.)	± 0.78 (lumi.)
$\mu\mu\mu$	23.35	± 1.07 (stat.)	± 0.70 (sys.)	± 0.70 (lumi.)
σ_{tot}^{comb}	24.54	± 0.65 (stat.)	± 0.50 (sys.)	± 0.76 (lumi.)
σ_{th}	21.68	± 0.02 (stat.)	± 0.75 (PDF)	± 1.39 (QCD Scale)

Table 5.6: The total cross section in the total phase space in pb for each of the eee , $ee\mu$, $\mu\mu e$, and $\mu\mu\mu$ channels and for their combination. The prediction from the POWHEGPYTHIA MC generator is also indicated.

prediction. It has however a tendency to be $\sim 10\%$ higher than the theory prediction. The same tendency was observed in the previous ATLAS measurement at 7 TeV [27] and in the preliminary results reported by CMS [28]. Figure 5.2 shows the comparison of the total cross section for each channel and their combination for the CMS experiment. Due to differences in conditions between ATLAS and CMS the measurements in the individual channels show slight differences however,

Systematic Unc. [%]	eee	$ee\mu$	$\mu\mu e$	$\mu\mu\mu$	combined
δ_{data}^{stat}	6.19	5.17	5.48	4.57	2.64
δ_{sys}^{tot}	4.76	3.13	3.20	2.82	2.09
δ_{lumi}	-3.24	-2.97	-3.26	-3.00	-3.09
δ_{sig}^{stat}	0.37	0.25	0.24	0.24	0.54
δ_{bkg}^{stat}	1.51	0.77	1.10	0.95	
$\delta_{bkg}^{Z\gamma}$	-0.72	-0.00	-0.74	-0.02	-0.30
δ_{bkg}^{Z+jets}	-0.25	-0.32	-0.53	-0.47	-0.48
$\delta_{bkg}^{t\bar{t}}$	-0.75	-0.45	-0.70	-0.79	-0.41
δ_{bkg}^{ZZ}	-0.61	-0.48	-0.66	-0.54	-0.57
$\delta_{bkg}^{MCoother}$	-0.68	-0.67	-0.72	-0.68	-0.69
δ_e^E	-1.10	-0.58	-0.73	0.01	-0.49
δ_e^{Res}	0.21	0.20	-0.14	0.00	-0.05
δ_e^{ID}	-3.31	-1.84	-1.25	-0.00	-1.21
δ_e^{Reco}	-1.24	-0.73	-0.41	-0.00	-0.48
δ_e^{Iso}	-0.88	-0.55	-0.27	-0.00	-0.34
δ_μ^E	-0.00	-0.03	-0.04	-0.08	-0.05
δ_μ^{Res}	-0.00	-0.02	0.10	-0.08	-0.01
δ_μ^{ResID}	-0.00	-0.00	0.11	-0.03	0.01
δ_μ^{ID}	-0.00	-0.50	-0.95	-1.40	-0.83
δ_{jet}^{JESTot}	0.60	0.26	0.31	0.24	0.32
δ_{jet}^{Res}	-0.37	-0.09	0.02	0.09	-0.05
δ_{MET}	0.17	0.04	0.25	0.12	0.11
δ_{Trig}	-0.12	-0.12	-0.20	-0.37	-0.22
δ_{PDF}	1.15				
δ_{Scale}	0.6				

Table 5.7: Relative statistical and systematic uncertainties on the cross section in the total phase space in each of the eee , $ee\mu$, $\mu\mu e$, and $\mu\mu\mu$ channels and for their combination. The sign convention is chosen as explained by equation 5.2.2.

the final result of the combination shows a good agreement between both experiments. Similar trend was also observed in measurements at the Tevatron in $p - \bar{p}$ collisions [29][30].

The WZ full NLO cross section calculated in reference [41] equal to $22.7^{+2.7}_{-2.3}$ pb shows a higher cross section than that calculated using POWHEG. Thus it is in a better agreement with the experimental measurement presented in this thesis.

5.3 Measurement of the $\sigma_{W+Z}/\sigma_{W-Z}$ total cross section ratio

As explained in the introduction of this chapter that since the LHC is a proton-proton collider, the production rates of the W^+Z and W^-Z processes are not equal. Therefore, in this section the W^+Z and W^-Z total cross sections will be measured separately and their ratio defined as: $R = \sigma_{W+Z}/\sigma_{W-Z}$ will be calculated. This will be done for each of the four individual channels and the χ^2 minimization will be used to combine the results.

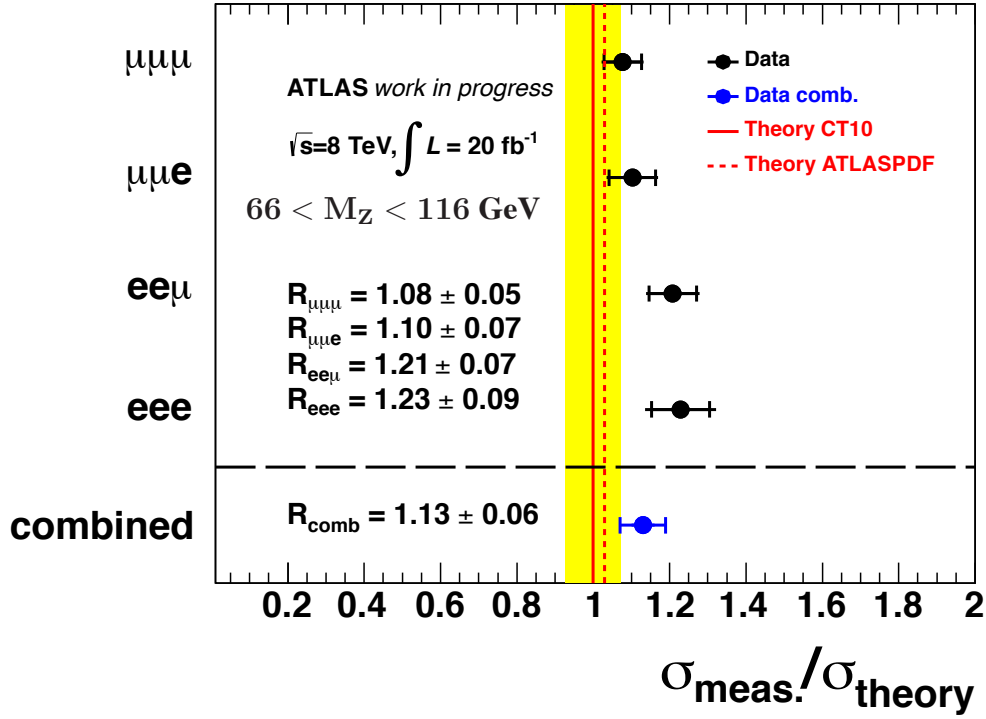


Figure 5.1: The total cross section in the total phase space in each of the four channels and their combination. The error bars on data measurements represent the quadratic sum of the statistical and systematic uncertainties.

5.3.1 W^+Z and W^-Z total cross section

To measure the W^+Z and W^-Z total cross sections, a similar event selection is performed as for the WZ analysis. The only difference is that the selected events are split according to the charge of the W boson. To make sure that the results for the backgrounds estimated using data are independent from the W charge, a cross check is performed by repeating all the methods used to estimate the WZ backgrounds for W^+Z and W^-Z separately. Indeed, a similar picture as for the WZ analysis is found as shown in the figure 4.13 of chapter 4.

Using the results of separate W^+Z and W^-Z event selections, the total cross sections for each is calculated according to equation (5.3).

Figure 5.3 shows the A_{WZ} and C_{WZ} factors for each of the W^+Z and W^-Z selections. In general the C_{WZ} factors are in good agreement for both selections. However, the A_{WZ} acceptance factor is 3% lower for the W^+Z selection with respect to the W^-Z one. This means that a lower extrapolation factor from the fiducial to the total phase space is needed for the positively charged WZ events.

Table 5.8 shows the total cross section results in each of the four decay channels and their combination for the W^+Z and W^-Z channels. As expected, the W^+Z cross section is larger than the W^-Z one because of the dominance of the W^+Z production due to the predominance of the u -quarks in the proton. The statistical uncertainty is always dominant for this measurement and the systematic uncertainty sources are the same as for the measurement of the integrated $W^\pm Z$ cross section.

The comparison of the measurement of the total cross section to the W^+Z and W^-Z theoretical prediction show that the W^+Z measured cross section is slightly higher by $\sim 9\%$ from

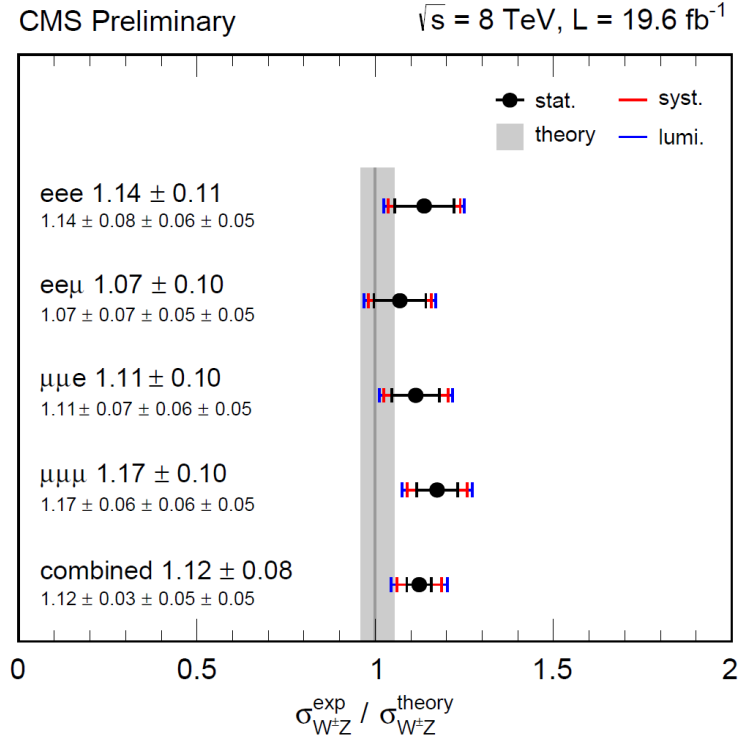


Figure 5.2: The total cross section in the total phase space in each of the four channels and their combination for the CMS experiment. The total phase space is defined for the M_Z range in [71, 111] GeV. The error bars on data measurements represent the quadratic sum of the statistical and systematic uncertainties [28].

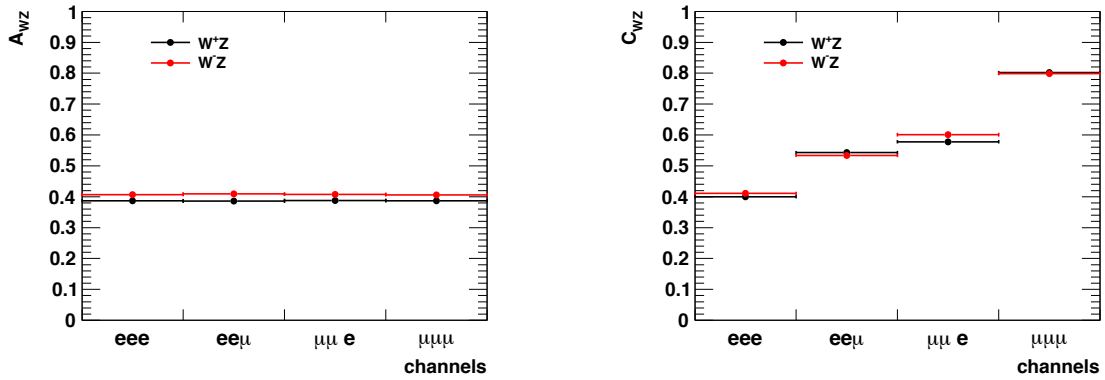


Figure 5.3: W^+Z and W^-Z A_{WZ} and C_{WZ} factors for each of the WZ channels. Statistical uncertainties from MC events are included, but are smaller than the bullets showing the central values.

the predicted one. However, the W^-Z measured cross section shows a difference of about 20% with respect to the prediction.

Using the results of table 5.8, the ratio between the W^+Z events combined for all channels

channel	$\sigma(pp \rightarrow WZ; \sqrt{s} = 8 \text{ TeV}) [\text{pb}]$			
eee	16.21	± 1.28 (stat.)	± 0.79 (sys.)	± 0.51 (lumi.)
$ee\mu$	17.37	± 1.10 (stat.)	± 0.54 (sys.)	± 0.51 (lumi.)
$\mu\mu e$	13.71	± 1.00 (stat.)	± 0.45 (sys.)	± 0.44 (lumi.)
$\mu\mu\mu$	14.14	± 0.83 (stat.)	± 0.40 (sys.)	± 0.42 (lumi.)
σ_{tot}^{comb}	15.12	± 0.55 (stat.)	± 0.32 (sys.)	± 0.46 (lumi.)
σ_{th}	13.87	± 0.01 (stat.)	± 0.38 (PDF)	

channel	$\sigma(pp \rightarrow WZ; \sqrt{s} = 8 \text{ TeV}) [\text{pb}]$			
eee	10.36	± 1.03 (stat.)	± 0.55 (sys.)	± 0.35 (lumi.)
$ee\mu$	8.85	± 0.79 (stat.)	± 0.31 (sys.)	± 0.27 (lumi.)
$\mu\mu e$	10.06	± 0.84 (stat.)	± 0.37 (sys.)	± 0.33 (lumi.)
$\mu\mu\mu$	9.18	± 0.67 (stat.)	± 0.30 (sys.)	± 0.28 (lumi.)
σ_{tot}^{comb}	9.47	± 0.40 (stat.)	± 0.23 (sys.)	± 0.30 (lumi.)
σ_{th}	7.81	± 0.01 (stat.)	± 0.44 (PDF)	–

Table 5.8: W^+Z and W^-Z cross section in the total phase space in [pb] for each of the eee , $ee\mu$, $\mu\mu e$, and $\mu\mu\mu$ channels and for their combination. The theoretical cross section calculated with POWHEG using the CT10 PDF sets is also indicated.

and the theory prediction is:

$$\frac{\sigma_{W^+Z}^{meas}}{\sigma_{W^+Z}^{theo}} = 1.09 \pm 0.07,$$

$$\frac{\sigma_{W^-Z}^{meas}}{\sigma_{W^-Z}^{theo}} = 1.21 \pm 0.10.$$

Therefore, the slight excess observed for the measured total $W^\pm Z$ cross section seems to be more pronounced in the W^-Z events than in W^+Z events.

5.3.2 Results of the $\frac{\sigma_{W^+Z}}{\sigma_{W^-Z}}$ ratio

The ratio of W^+Z and W^-Z production cross section in the fiducial phase space is then calculated. Statistical and systematic uncertainties are directly propagated analytically to the measured ratio $\frac{\sigma_{W^+Z}}{\sigma_{W^-Z}}$. The following equation presents the statistical uncertainty propagation on R :

$$\delta_R^{stat} = \frac{\sigma_{W^+Z}}{\sigma_{W^-Z}} \times \sqrt{\left(\frac{\delta_{\sigma_{W^+Z}}^{stat}}{\sigma_{W^+Z}}\right)^2 + \left(\frac{\delta_{\sigma_{W^-Z}}^{stat}}{\sigma_{W^-Z}}\right)^2}. \quad (5.7)$$

The systematic uncertainties are calculated by shifting the object systematics up and down for the W^+Z and W^-Z processes separately, then the ratios R^{up} and R^{down} are calculated. The final systematic uncertainty on the ratio R_{fid} is obtained by symmetrizing the up and down ratios as the following:

$$\delta_R^{sys} = \frac{1}{2} \times sign \times (|R^{up} - R| + |R^{down} - R|), \quad (5.8)$$

where $sign$ is equal to 1 when R^{up} is greater than R and equal to -1 otherwise.

The results for each of the four channels with their combination are summarized in table 5.9. The combination of the cross section ratio measured in the four decay channels is performed using the χ^2 combination method defined by equation 5.5. The same correlation scheme of systematic uncertainty sources as considered for the combination of the WZ integrated cross section is used. The combination of the cross section ratios yields to a total χ^2 per degree of freedom of $\chi^2/n_{\text{dof}} = 5.3/3$. The reason of this high χ^2/n_{dof} is the presence of some tensions between the ratio R_{fid} measured in the $ee\mu$ and $\mu\mu e$ channels. Ratios measured in these two channels seem to be shifted in opposite directions, while the ratios in the eee and $\mu\mu\mu$ channels agree around $R_{fid}=1.50$.

channel	$R_{fid} = \sigma(pp \rightarrow W^+Z)/\sigma(pp \rightarrow W^-Z); \sqrt{s} = 8 \text{ TeV [pb]}$			
eee	1.49	± 0.19 (stat.)	± 0.05 (sys.)	± 0.003 (lumi.)
$ee\mu$	1.85	± 0.20 (stat.)	± 0.03 (sys.)	± 0.002 (lumi.)
$\mu\mu e$	1.30	± 0.14 (stat.)	± 0.03 (sys.)	± 0.001 (lumi.)
$\mu\mu\mu$	1.47	± 0.14 (stat.)	± 0.03 (sys.)	± 0.001 (lumi.)
R_{comb}^{fid}	1.50	± 0.08 (stat.)	± 0.02 (sys.)	± 0.002 (lumi.)
R_{th}^{fid}	1.69	± 0.001 (stat.)	± 0.07 (PDF)	

Table 5.9: The ratio $\frac{\sigma_{W^+Z}}{\sigma_{W^-Z}}$ of the W^+Z and W^-Z integrated cross sections measured in the fiducial phase space for each of the eee , $ee\mu$, $\mu\mu e$, and $\mu\mu\mu$ decay channels, and for the combination of all channels.

A breakdown of all the systematic uncertainties for the R_{fid} ratio is presented in table 5.10. This table shows that many of the systematic uncertainties are canceled after the propagation to the ratio. The contribution of systematic uncertainties on the amount of background events is also largely reduced for the ratio $\frac{\sigma_{W^+Z}}{\sigma_{W^-Z}}$ cross sections measurement but it remains one of the most important ones among the other systematics.

Therefore the final W^+Z to W^-Z cross sections ratio is measured as:

$$R_{fid} = \frac{\sigma_{W^+Z}}{\sigma_{W^-Z}} = 1.50 \pm 0.08 \text{ (stat.)} \pm 0.02 \text{ (sys.)} \pm 0.002 \text{ (lumi.)}.$$

Figure 5.4 shows the measured ratio $\frac{\sigma_{W^+Z}}{\sigma_{W^-Z}}$ divided by the theoretical prediction calculated using POWHEG. The Figure shows that the measurement is deviated by about 10% from the theory prediction when the CT10 PDF is used. While the measurement is in a better agreement with the theory prediction when ATLAS PDF is used.

The measurement of the W^+Z to W^-Z cross sections ratio in the fiducial and total phase spaces is calculated using the predictions of POWHEG MC generator for different PDFs. This is shown in table 5.11. The table shows that the measurement in the fiducial phase space is lower by about 4% than the measurement in the total phase space. However, both measurements have similar sensitivities to the difference between the PDFs. Also the calculation shows a -3.1% uncertainty due to the variation of the PDFs in the total phase space, which is of the same order of the PDF uncertainty in the fiducial phase space. The conclusion is the same when the PDF uncertainty is calculated using the CT10 eigen vectors as explained in section 1.2.4.

The effect of the PDF uncertainty on the ratio measurement can be calculated on the A_{W^-Z} and A_{W^+Z} factors that are used in the $\frac{\sigma_{W^+Z}}{\sigma_{W^-Z}}$ calculation. As it can be seen in table 5.2, in the total phase space the effect of PDF uncertainty on the measurement is of the order of 1.2%. While in the fiducial phase space, it has an effect of 0.03%.

This motivates the measurement of the ratio $\frac{\sigma_{W^+Z}}{\sigma_{W^-Z}}$ in the fiducial phase space, as it has the same

Systematic Unc. [%]	eee	$ee\mu$	$\mu\mu e$	$\mu\mu\mu$	combined
δ_e^E	0.33	0.18	0.09	0.00	0.12
δ_e^{Res}	-0.92	0.16	0.09	0.00	-0.11
δ_e^{ID}	0.19	0.10	-0.00	-0.00	0.05
δ_e^{Reco}	0.09	0.05	0.01	-0.00	0.03
δ_e^{Iso}	0.07	0.04	0.01	-0.00	0.02
δ_μ^E	-0.00	0.01	-0.01	0.09	0.03
δ_μ^{Res}	-0.00	-0.06	-0.27	-0.23	-0.17
δ_μ^{ResID}	-0.00	-0.01	-0.18	-0.05	-0.07
δ_μ^{ID}	-0.00	0.05	0.05	0.08	0.05
$\delta_{jet}^{JES Tot}$	0.43	-0.10	-0.28	0.11	0.02
δ_{jet}^{Res}	-0.06	-0.29	-0.64	-0.10	-0.28
δ_{MET}	0.27	0.11	0.32	0.19	0.07
δ_{Trig}	-0.02	0.01	-0.00	0.02	0.00
δ_{Charge}	-0.17	-0.00	-0.30	-0.00	-0.12
δ_{bkg}^{ZZ}	0.21	0.27	0.13	0.17	0.19
$\delta_{bkg}^{Z\gamma}$	0.45	0.00	0.19	-0.01	0.13
δ_{bkg}^{Z+jets}	0.08	0.22	0.05	0.06	0.09
$\delta_{bkg}^{t\bar{t}}$	0.15	0.09	0.26	0.35	0.17
$\delta_{bkg}^{MCothers}$	0.23	0.34	0.12	0.15	0.20
δ_{lumi}	0.21	0.10	0.11	0.06	0.11
δ_{uncorr}^{tot}	3.09	1.70	2.28	2.06	1.15

Table 5.10: Uncertainties on the measured ratio $\frac{\sigma_{W+Z}}{\sigma_{W-Z}}$ of W^+Z and W^-Z integrated cross sections in the fiducial phase space for each of the eee , $ee\mu$, $\mu\mu e$, and $\mu\mu\mu$ decay channels, and for their combination.

	R_{fid}	R_{tot}
POWHEG (CT10)	1.69 ± 0.07	1.77 ± 0.07
POWHEG (MSTW08)	1.62 ± 0.07	1.72 ± 0.07
POWHEG (ATLASPDF)	1.63 ± 0.07	1.71 ± 0.07

Table 5.11: The calculated ratio $R = \frac{\sigma_{W+Z}}{\sigma_{W-Z}}$ for the POWHEGPYTHIA MC generator using different PDFs in the fiducial and total phase spaces. The quadratic sum of statistical and PDF theory uncertainties are quoted.

sensitivity to PDFs as that in the total phase space and a negligible PDF uncertainty on the measurement.

The ratio $\frac{\sigma_{W+Z}}{\sigma_{W-Z}}$ was measured in the total phase space by the CMS experiment [28]. The results obtained by CMS for the combination of all four channels is $R_{tot} = 1.81 \pm 0.12(stat.) \pm 0.03(sys.)$. This measurement cannot be directly compared to the ratio results presented in this thesis as they are both measured in different phase spaces. As shown in table 5.11 the ratio in the total phase space is expected to be $\sim 4\%$ higher than that in the total phase space. However this factor could be different between ATLAS and CMS as the fiducial phase space definition by CMS is different than that of ATLAS. However, the ratio to the theory prediction of $\frac{\sigma_{W+Z}}{\sigma_{W-Z}}$ can be compared as it is shown in figure 5.4. The results show that both experiments measurements

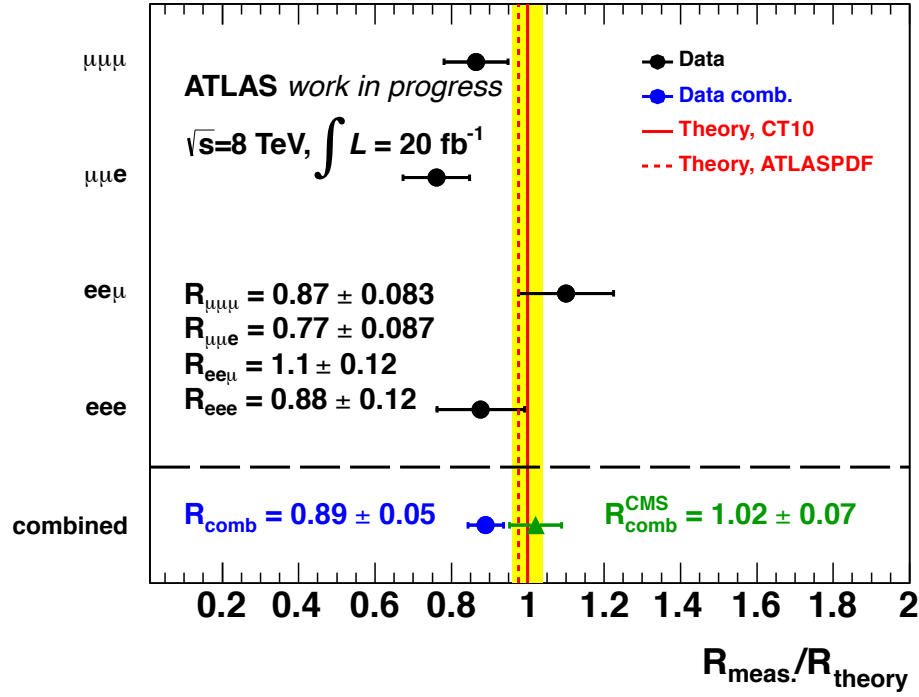


Figure 5.4: The ratio in the fiducial phase space of measured $\frac{\sigma_{W+Z}}{\sigma_{W-Z}}$ cross sections ratios with respect to the theory prediction calculated using POWHEG and CT10 PDFs. A comparison to the theory calculation using ATLAS PDF is also shown. Systematic and statistical uncertainties are included.

are very close if the uncertainty on these measurements is taken into account.

5.4 Conclusions and discussion

In this chapter, the WZ bosons integrated fiducial and total cross sections measurements have been presented. Also measurements of the W^+Z and W^-Z integrated cross sections and of their ratios have been performed. The results were compared to the theoretical predictions from POWHEG. Fluctuations from the prediction in each of the individual channels is observed, however the final combination shows a fair agreement with respect to the theory prediction.

Chapter 6

Normalized differential cross section measurement

In this chapter, measurements of the WZ normalized differential cross section as a function of different kinematic variables will be presented. These measurements are performed in order to provide a first SM measurement of the normalized differential cross sections with the full 2012 ATLAS data at $\sqrt{s} = 8$ TeV. It was also shown in chapter 1 on figure 1.15, that the anomalous triple gauge couplings could create an enhancement on the tails of differential distributions related to the energies of produced particles p_T^Z or M_{WZ} . Therefore, measurements of the shape of such differential distributions are important to control the agreement with the SM of observed events.

6.1 Methodology

In this section, the general definition of the normalized differential cross section will be detailed and the different methods used to unfold the data will be presented. The results of this measurement will be presented only in the fiducial phase space, where the impact of theoretical uncertainties on the measurement are strongly reduced compared to the total phase space.

6.1.1 Definition of the normalized differential cross section

The normalized differential cross section in the fiducial phase space can be measured by computing in each bin of a kinematic distribution, the fiducial cross section and then normalizing this quantity with the integrated fiducial cross section measured over all bins. The reason for normalizing the differential cross section is because we want to be independent from any difference in the normalization between the data measurement and the predictions. The idea is to control the shape of the differential cross section measured with data to that predicted by the MC. This normalization of the differential measurements also allows to reduce the effect of experimental systematics, calculating global effects if the systematic uncertainties which might affect equally all bins of the measurement (e.g. the luminosity uncertainty).

The normalized fiducial differential cross section is calculated in each bin using the following equation:

$$\frac{\Delta\sigma_i^{fid}}{\sigma_{tot}^{fid}} = \frac{N_i^{data} - N_i^{bkg}}{N_{tot}^{data} - N_{tot}^{bkg}} \frac{C_{WZ,tot}}{C_{WZ,i}}, \quad (6.1)$$

where $\Delta\sigma^{fid}$ is fiducial cross section measured in each bin i , N_i^{data} is the number of data events,

N_i^{bkg} is the number of background events, and $C_{WZ,i}$ is the efficiency factor defined in equation 5.2. The N_{tot}^{data} , N_{tot}^{bkg} , and $C_{WZ,tot}$ represent the total integrated data number, background number and efficiency factor respectively. The C_{WZ} factors are applied to correct the data measurement from the efficiency of the detector and the resolution effects. The process of correcting the data from these effects is called unfolding.

6.1.2 Combination of the WZ decay channels

The normalized differential cross sections results will be presented for the sum of all the WZ four channels ($eee, ee\mu, \mu\mu e, \mu\mu\mu$). The combination of channels using the χ^2 method explained in chapter 5 is not applied here. This is because the statistical uncertainty is still the dominant one. For differential distributions in each individual channel, there are some bins with number of events below 20 which makes the distribution no longer normal. A simple addition of all events from the four channels will therefore be performed in order to decrease the statistical uncertainty.

For this measurement, the contribution of the WZ decays to τ leptons are not treated the same way as in chapter 5. The contribution of WZ events decaying to τ leptons, as estimated using the predictions from the POWHEGPYTHIA MC generator, are treated as a background contribution added to the numbers N_i^{bkg} and N_{tot}^{bkg} . Events with the τ lepton decays contributes by about 4% in each of the individual channels. Their effect on the shape of the kinematic distributions is shown in figure 6.1 showing the p_T^Z and M_{WZ} distributions normalized to one for WZ events decaying only to electrons and muons and those containing at least one tau decays. The figure shows that in general the shape of the spectrum of p_T^Z and M_{WZ} is harder for events containing tau leptons than those containing only electrons and muons.

This effect is mainly arising from the $W^\pm Z$ decays where the W candidate decays to a τ lepton and a neutrino. Events where the Z decays to $\tau^+\tau^-$ are suppressed strongly by the requirement to have reconstructed Z candidate in a mass window of 10 GeV of the PDG Z mass. The spectra of p_T^Z and M_{WZ} are not similar for events containing τ leptons and those not containing them. The normalized distributions of p_T^Z and M_{WZ} shown in figure 6.1 show that a maximum difference of the order of 15% can be observed between the spectra of events with or without tau leptons. However, as this background due to the events with taus contributes only by 4% to the total measurement, then a global effect of 0.6% (which is 15% of the 4%) is estimated on the variation of these distributions.

In order to account for the observed differences, a global conservative 10% of systematic uncertainty is defined for the contribution of these events.

6.1.3 Unfolding methods

Data measurements are affected by the detector efficiency and the resolution effects. In order to be able to compare to the theoretical predictions, an unfolding procedure that will correct for these effects is needed. Many unfolding methods are commonly used in physics data analyses. Among these, the bin-by-bin unfolding and the Iterative Bayesian unfolding that are explained in the next sections. The idea behind the definition of an unfolding method depends on the Purity, P , of the differential distribution. The purity is defined as:

$$P_i = \frac{N_{rec\&gen}^i}{N_{rec}^i}, \quad (6.2)$$

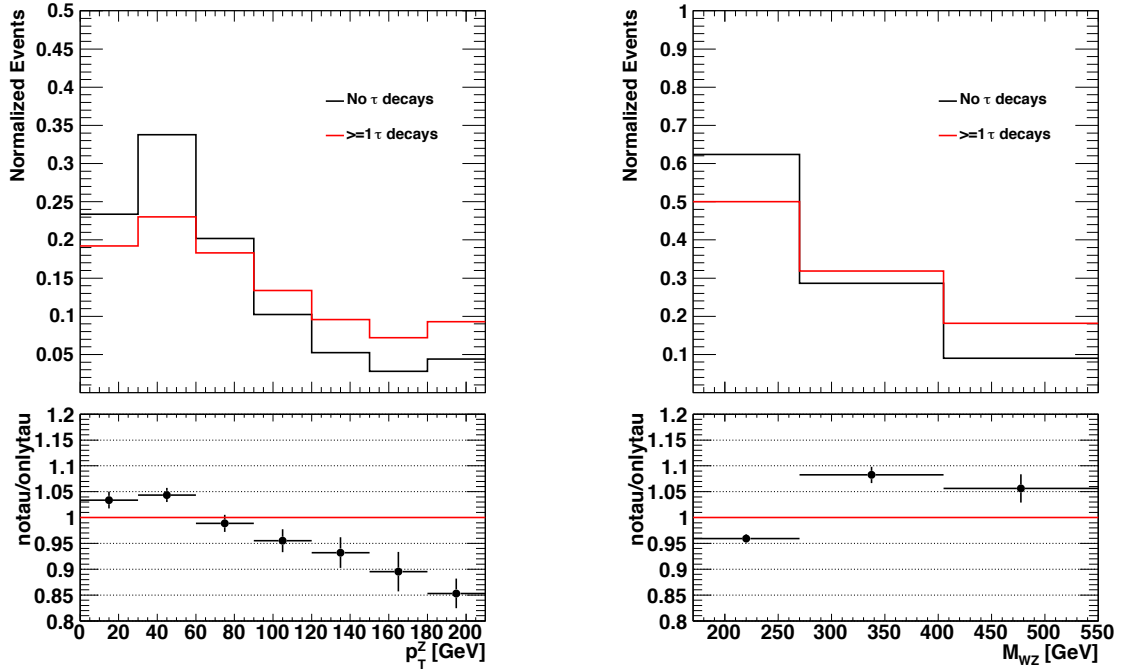


Figure 6.1: p_T^Z (left) and M_{WZ} (right) distribution normalized to one, for WZ signal events containing at least one tau decay (red) and those that do not constrain a tau decay.

where the $N_{rec\&gen}^i$ presents the number of events generated and reconstructed in the same bin i and the N_{rec}^i represents the number of reconstructed events in the same bin. This quantity represents the migrations among the bins of the differential distributions that are present due to imperfections of the resolution of the detector. The choice of the binning of the kinematic distributions that will be used for the differential cross section measurements depends therefore on the purity. It has to be optimized in a way to have the finest possible binning and highest purity. If the purity is high both of the unfolding methods that will be explained below are expected to behave similarly. In the case of lower purities, the iterative Bayesian unfolding method is preferred due to the many iterations it performs until the results converge.

In this thesis, the normalized differential cross sections will be measured as a function of the p_T^Z and M_{WZ} kinematic variables. For the chosen binning, the purities for these variables are shown in figure 6.2. This figure shows that the purity as a function of p_T^Z is always higher than 80% while a lower purity is observed for the M_{WZ} distribution of the order of 70%.

6.1.3.1 The bin-by-bin method

This unfolding method, consists on correcting the fiducial cross section with the C_{WZ} factor defined by equation 6.1 in each bin of a kinematic distribution. This method is simple calculation wise and most of the time it provides accurate results when the MC prediction is sufficiently similar to data. The C_{WZ} factor is calculated using the signal MC. Therefore, a statistical uncertainty on the signal MC is introduced due to this corrective factor. The propagation of this uncertainty on the differential cross section can be computed by first rewriting the C_{WZ} ratio as the sum of uncorrelated quantities:

$$C_{WZ} = \frac{N_{stay} + N_{come}}{N_{stay} + N_{leave}} = \frac{a}{b}, \quad (6.3)$$

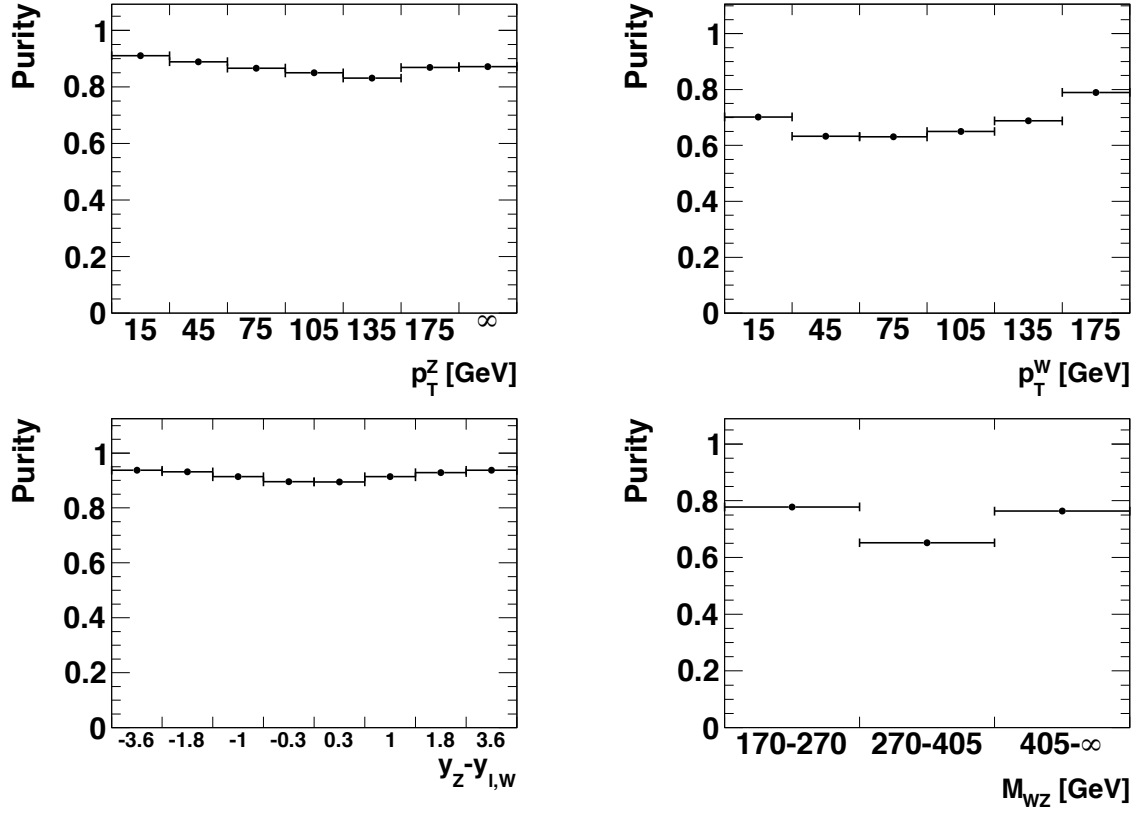


Figure 6.2: The purity in each bin of the p_T^Z , p_T^W , $y_Z - y_{W,l}$, and M_{WZ} variables, as calculated by equation (6.2).

where N_{stay} is the number of events reconstructed and generated in the same bin, N_{come} is the number of events reconstructed in a bin and generated outside of it, and N_{leave} is the number of events generated in a bin and reconstructed outside of it.

The statistical uncertainty on this factor, coming from the limited number of available MC events, can be propagated as:

$$\Delta C_{WZ}^2 = \frac{(b-a)^2}{b^4} \times \delta N_{stay}^2 + \frac{1}{b^2} \times \delta N_{come}^2 + \frac{a^2}{b^4} \times \delta N_{leave}^2. \quad (6.4)$$

The propagation of the C_{WZ} factor's uncertainty on the normalized differential cross section in each bin can be written as:

$$\frac{\delta \sigma_i^{fid}}{\sigma_{tot}^{fid}} = \frac{\Delta \sigma_i^{fid}}{\sigma_{tot}^{fid}} \times \frac{\Delta C_{WZ}}{C_{WZ}}. \quad (6.5)$$

The implementation of this unfolding method is simple and as it was shown in the previous section, that the expected purities for this measurement are always higher than 70%. This means that this method can provide as competitive results as any other unfolding method when the MC reproduces the data sufficiently well. Otherwise, due to its simplicity, the bin-by-bin unfolding method is also expected to give the lowest statistical uncertainty. The fact that the C_{WZ} factor is calculated using a specific MC generator, this makes the method dependent on the MC model, but this is a common problem among all the unfolding methods.

6.1.3.2 The iterative Bayesian method

This unfolding method was first introduced by D’Agnostini [94]. A simple way to understand it is to write the relation between the reconstructed events and the truth ones as the following:

$$R_i = \sum_j M_{ij} T_j, \quad (6.6)$$

where R_i is the reconstructed data events in a bin i . The backgrounds contribution needs to be subtracted from the reconstructed data events for each bin. T_j represent the truth events in the bin j . M_{ij} is the response matrix which is the correlation between the reconstructed and generated events. Therefore, off diagonal terms of this matrix give the probability that an event reconstructed in a bin i is generated in a bin j or vice versa.

Intuitively, an inversion of the response matrix should be enough to unfold the data from the reconstructed to the truth level. However, it is not guaranteed that the response matrix can be inverted nor that the solution of the inversion is unique. Therefore this method uses Bayes’ theorem to calculate the probability that different causes were responsible to the observed effects. This can be performed by calculating the probability of a given effect from a defined cause which is usually known. It is estimated using information from the response matrix on the migration between the bins, also the efficiency and resolution information from the kinematic distribution of the reconstructed events in the signal region using the WZ signal MC.

An iterative procedure using Bayes’ theorem is performed, in order to unfold the reconstructed data from the detector effects. The convergence is reached only with a few iterations until the migration effects disappear and a good χ^2 is reached between the reconstructed and true measurement in the MC pointing to the inversion of the response matrix. The advantage of the iterative procedure is that it may also reduce the MC model dependence of the method but it does not entirely remove it.

Once the kinematic distribution is unfolded, it is directly used to calculate the normalized differential cross section. This procedure is equivalent to dividing the differential distribution by the C_{WZ} factor.

6.1.4 Statistical and systematic uncertainties

The statistical uncertainty introduced to the normalized differential cross section measurement due to this iterative unfolding method is complicated because it needs to take into account all the statistical effects per bin between the measured and corrected distributions. This is usually calculated using the covariance matrix due to these errors. However, this calculation is very slow if all the effects are taken into account [95]. Therefore, in this thesis, the statistical uncertainty on data, signal MC, and backgrounds is calculated in a more simple way using MC toys. For data, the kinematic distribution of the measured quantity is fluctuated using toys in each bin according to a Poisson distribution. Then the unfolding is performed with the fluctuated data distribution. The procedure is repeated 2000 times and a histogram with the fluctuated unfolded data results is filled for each bin. The standard deviation of each unfolded distribution per bin is then considered as the statistical uncertainty of the data in that bin.

A similar approach is applied to the signal MC by fluctuating in parallel the response matrix and the reconstructed MC distribution along a Gaussian function. Finally, for the backgrounds statistical uncertainty, the procedure is also the same but in this case the background distribution is

p_T^Z	σ_{Norm}^{fid}	σ_{Norm}^{fid} (reweighted)	Difference [%]
0–30	0.2202	0.2192	0.45
30–60	0.3580	0.3559	0.57
60–90	0.1835	0.1829	0.35
90–120	0.1043	0.1027	1.59
120–150	0.0602	0.0600	0.17
150–180	0.0243	0.0239	1.22
180– ∞	0.0494	0.0503	-1.83

Table 6.1: Systematic uncertainty in percent on the normalized differential cross section due to the Bayesian iterative unfolding method per bin of p_T^Z .

fluctuated along a Gaussian and the background's statistical uncertainty is taken as the standard deviation of the unfolded results in each bin.

Uncertainty on the unfolding method

A systematic uncertainty is also computed on the iterative unfolding method. This is done by extracting weights that will correct the MC truth in a way to match the data after a first unfolding. These weights are then applied on the generated MC events and a new reweighted reconstructed MC kinematic distribution and response matrix are obtained. These are then fed to the unfolding program and the unfolding procedure is repeated. The difference between the results is taken as the systematic uncertainty. This was performed for the kinematic distribution as a function of p_T^Z and table 6.1 shows the calculation of the normalized differential cross section after a first and second reweighted unfoldings. These results show that a maximum of 2% deviation between both unfoldings is obtained. It should be noted that this value is certainly overestimated because the extracted weights used to modify the generated MC distribution are affected by the statistical fluctuations of the data in each bin. Even with this overestimation, this systematic uncertainty remains very small with respect to the data statistical uncertainty in each bin which reaches sometimes up to 20% as it will be shown later in this chapter.

In order not to be affected by the statistical fluctuations coming from the measurement on data, another possibility is to reweight the generated MC distributions with weights corresponding to another renormalization and factorization scale (e.g. fixed scale of $(M_W + M_Z)/2$). The response matrix should be re-built using these weights and the unfolding procedure will be repeated. This procedure was not performed for this thesis work yet. However, if this is applied, the unfolding outputs using weighted or unweighted distributions are expected to be more consistent among bins and not varying by more than 0.5% in each bin.

Therefore, considering the statistical fluctuations introduced by the method used in this thesis, a global unfolding uncertainty of 0.5% is defined for all the bins of p_T^Z variable, as the difference observed in the shape is not bigger than the fluctuation on the MC.

propagation of systematic uncertainty

All object systematic uncertainties are explained in section 4.3. These uncertainties are propagated to the normalized differential cross section by varying up and down each object systematic

p_T^Z bins	σ_{Norm}^{fid}		$\delta\sigma_{Norm}^{fid}(stat)$ [%]		$\delta\sigma_{Norm}^{fid}(sys)$ [%]	
	bin-by-bin	iterative	bin-by-bin	iterative	bin-by-bin	iterative
0–30	0.221	0.219	5.14	5.81	1.61	1.81
30–60	0.358	0.363	3.64	4.11	0.92	1.19
60–90	0.186	0.184	5.72	6.88	1.38	1.62
90–120	0.104	0.104	8.02	9.61	2.04	2.27
120–150	0.057	0.058	11.08	12.99	2.59	2.95
150–180	0.048	0.048	12.04	10.51	2.43	2.33
180– ∞	0.026	0.026	16.38	24.42	3.77	5.35

Table 6.2: Normalized differential cross section with the statistical and systematic uncertainties per bin of p_T^Z using the bin-by-bin and Bayesian iterative unfolding methods.

for each bin of the studied differential distributions. The uncertainty propagation on the signal affects the $C_{WZ,i}$ factor for each bin i , while its propagation on the background affects the term $N_{bkg,i}$ for each bin, in equation (6.1). Finally, the propagation of the luminosity systematic uncertainty, calculated by varying up and down the integrated luminosity by its uncertainty of 2.8%, affects also the number of the background events $N_{bkg,i}$ as they are determined using the MC.

6.1.4.1 Comparison of both unfolding methods

In the bin-by-bin unfolding approach a differential distribution is divided by the C_{WZ} factor for each bin. In the iterative approach, the unfolding outcome is directly comparable to the distribution corrected bin-by-bin by the efficiency factor.

Table 6.2 shows the results of the normalized differential cross sections per bin of the p_T^Z accompanied with the statistical and systematic uncertainties computed using each of the bin-by-bin and Bayesian unfolding methods. The results show that the normalized differential cross section's central values per bin are consistent using both unfolding methods. The statistical and systematic uncertainties are of the same order between results using the bin-by-bin and iterative unfolding methods with the statistical uncertainty being the dominant one that goes up to 20% in some bins. Also, the uncertainties obtained using the iterative unfolding method gives systematically higher statistical and systematic uncertainty values. This is normal because the bin-by-bin unfolding is expected to give the lowest uncertainty due to its simplicity.

In this thesis, the normalized differential cross sections were computed using both unfolding methods. However, final results are shown using the iterative Bayesian unfolding method, due to its more evolved aspects with unfolding the data iteratively.

6.2 Normalized differential cross section measurements

The normalized differential cross section will be measured as a function of the p_T^Z and M_{WZ} kinematic variables. The binning choice was performed in a way to maximize the purity while keeping the finest possible binning as shown in figure 6.2. Therefore for the p_T^Z distribution 7 bins of size 30 GeV are defined with the last bin extending to infinity. The p_T^W distribution has 6 bins of variable sizes from 30 to 70 GeV with the last bin also extending to infinity. For the M_{WZ} distribution, the bin migrations being higher, only 3 bins are defined that are [170, 270], [270, 405], and [405, ∞] GeV. Finally, 8 bins are defined for the $y_Z - y_{W,l}$ distribution with the first and last

bins of size 2.8 and the rest of size 0.8.

Both bin-by-bin and Bayesian iterative unfolding methods are used to compute the normalized differential cross sections. This is done using equation (6.1) for the bin-by-bin unfolding and also for Bayesian iterative unfolding except the for this last the output distribution from the unfolding is used instead of dividing by the C_{WZ} factor.

In figure 6.3, the results of the differential cross section as a function of the Z boson's transverse momentum and the invariant mass of the WZ system are presented using the Bayesian unfolding method.

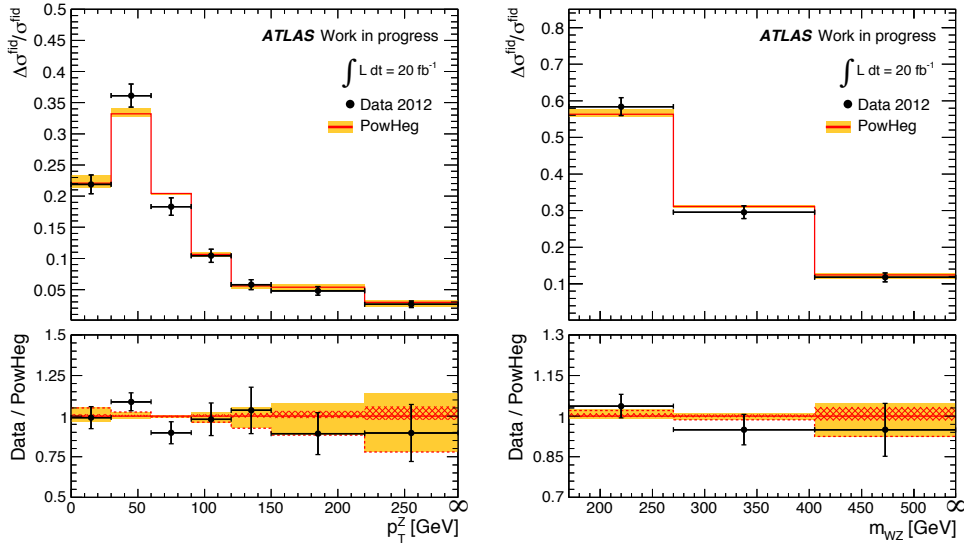


Figure 6.3: The normalized differential fiducial cross section, as a function of p_T^Z and M_{WZ} , for all WZ decay channels. The error bars on the data points represent the total uncertainties. The prediction from POWHEGPYTHIA using fixed renormalization and factorization scale $(M_W + M_Z)/2$ is presented by the red histogram. The red band presents the statistical and PDF uncertainties added quadratically. The orange band represents the quadratic sum of the statistical, PDF, and scale uncertainties. The red dashed histogram in the ratio plot represents the prediction from POWHEGPYTHIA using dynamic renormalization and factorization scales equal to M_{WZ} .

The results are compared to the POWHEGPYTHIA MC predictions. A good agreement is seen with respect to the SM prediction with POWHEGPYTHIA. This means that the shape of the predicted cross section is in a good agreement with the shape of the data measurement. The existing fluctuations of the order of 5% on the integrated cross section between the data and theory prediction shown in chapter 5 can be mainly related to a global normalization and not to the shape description of the p_T^Z and M_{WZ} distributions.

Other differential cross sections as a function of p_T^W and $y_Z - y_{W,l}$ are also measured. The aim is always to control the deviations from the SM for these variables. For the p_T^W , new physics is expected to appear on the tails of the distribution similarly to p_T^Z . The $y_Z - y_{W,l}$ variable is an angular variable that has a higher experimental resolution in general than the p_T^W and p_T^Z . Hence, it is interesting to compare the data behavior to the SM predictions for this variable. New physics in this case is expected to appear as a variation of the shape of the differential distribution in the core of the $y_Z - y_{W,l}$ distribution [96].

This is shown in figure 6.4. The POWHEGPYTHIA MC predictions are describing well in general the shape of the data distributions.

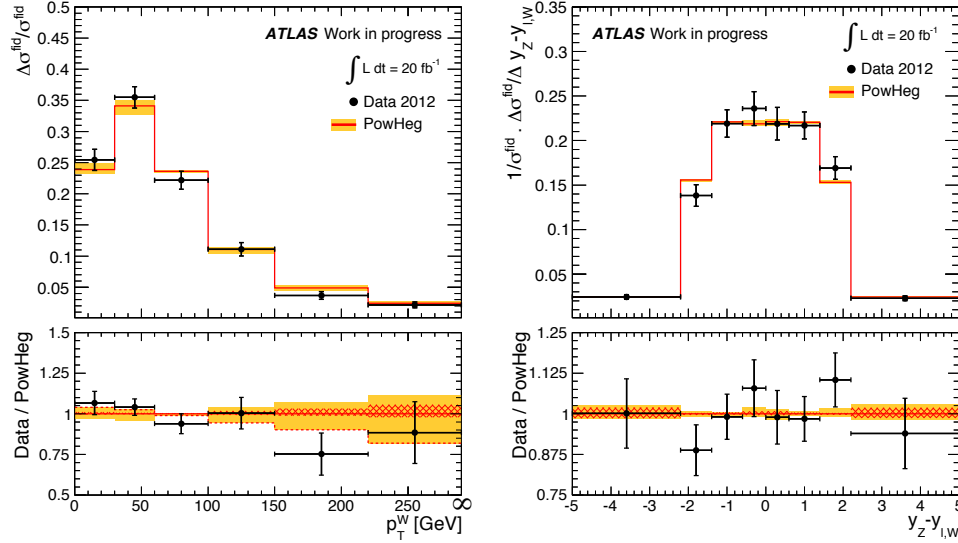


Figure 6.4: The normalized differential fiducial cross section, as a function of p_T^W and $y_Z - y_{W,l}$, for all WZ decay channels. The error bars on the data points represent the total uncertainties. The prediction from POWHEGPYTHIA using fixed renormalization and factorization scale $(M_W + M_Z)/2$ is presented by the red histogram. The red band presents the statistical and PDF uncertainties added quadratically. The orange band represents the quadratic sum of the statistical, PDF, and scale uncertainties. The red dashed histogram in the ratio plot represents the prediction from POWHEGPYTHIA using dynamic renormalization and factorization scale M_{WZ} .

6.3 Normalized differential cross section measurement for W^+Z and W^-Z events

In this section the normalized differential cross section's measurement will be presented for W^+Z and W^-Z events as a function of the p_T^Z variable. The ratio of both normalized cross sections will be also measured in order to probe the W^+Z and W^-Z different kinematics.

6.3.1 W^+Z and W^-Z normalized differential distributions

The normalized differential cross section can also be measured for the W^+Z and W^-Z separately. The results will be shown only for the p_T^Z distribution. Similar behavior is seen for the other kinematic distributions. Figure 6.5 shows the splitting by charge of the normalized differential cross section. In this figure, we observe that the W^-Z distribution seems to show a better agreement between data and the MC than the W^+Z one. For the latter, in the second and third bins of the p_T^Z distribution, there seems to be a disagreement between the data and MC of the order of 20%. This means that, besides the disagreement of the integrated cross sections, the shape of the differential distributions for the W^+Z case is not well described. When both W^+Z and W^-Z distributions are put together, these differences seem to disappear due to fluctuations that are going in opposite directions between these two channels.

These distributions are needed to measure the ratio R of the W^+Z and W^-Z normalized differential cross sections. This measurement helps in probing in more details the kinematics difference between the W^+Z and W^-Z productions.

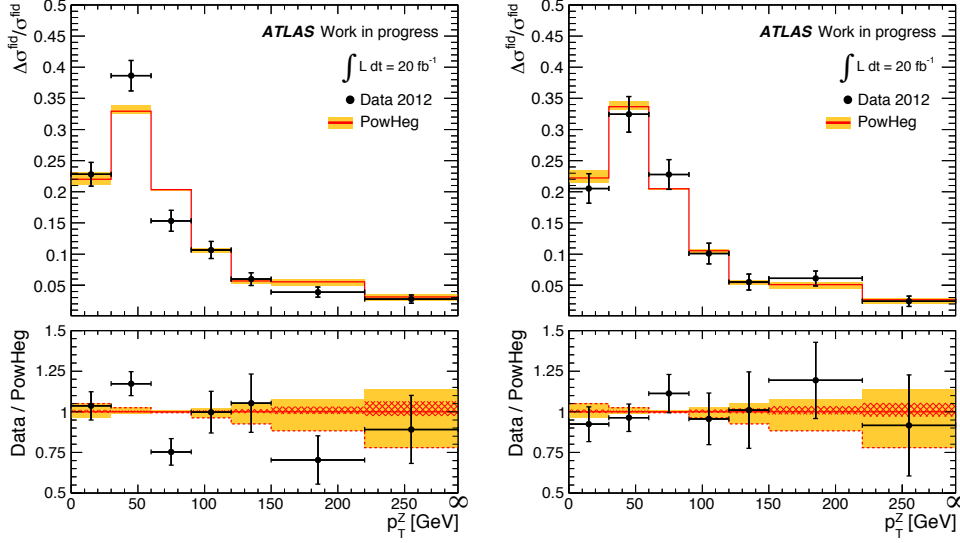


Figure 6.5: The normalized differential fiducial cross section, as a function of p_T^Z , for all W^+Z (left) and W^-Z (right) decay channels. The error bars on the data points represent the total uncertainties. The prediction from POWHEGPYTHIA using fixed renormalization and factorization scale $(M_W + M_Z)/2$ is presented by the red histogram. The red band presents the statistical and PDF uncertainties added quadratically. The orange band represents the quadratic sum of the statistical, PDF, and scale uncertainties. The red dashed histogram in the ratio plot represents the prediction from POWHEGPYTHIA using dynamic renormalization and factorization scale M_{WZ} .

6.3.2 Differential measurement of the $\frac{\sigma_{W+Z}}{\sigma_{W-Z}}$ ratio

The ratio of both distributions on figure 6.5 for data and MC is presented in figure 6.6. The propagation of the other uncertainties on this measurement is done by considering the numerator and denominator of this ratio as two uncorrelated quantities. The uncertainties were considered uncorrelated since the statistical uncertainty is dominating the ratio calculation of the differential cross section.

This ratio R_{fid} measurement shows a good agreement with the MC predictions except in the two bins where the measured W^+Z normalized differential cross section shown also a disagreement with the MC predictions. This shows that there might also be a shape related problem between data and MC, mainly coming from the W^+Z channel.

6.4 Conclusion on normalized differential cross sections measurement

In this chapter, the normalized differential cross section of the WZ , W^+Z , and W^-Z have been presented. The measurements have shown a good agreement between data measurement and MC prediction for all of the WZ channels. In case of splitting the channels with respect to positive or negative W bosons, the W^+Z channels normalized differential cross section has shown some fluctuations between data measurement and MC predictions in two bins of p_T^Z between the 60 and 120 GeV. These fluctuations seems to also appear in the ratio of the normalized differential cross section between the W^+Z and W^-Z channels. However, the provided statistics is not enough to point significantly to a possible problem in the description of the shape of the kinematic variables

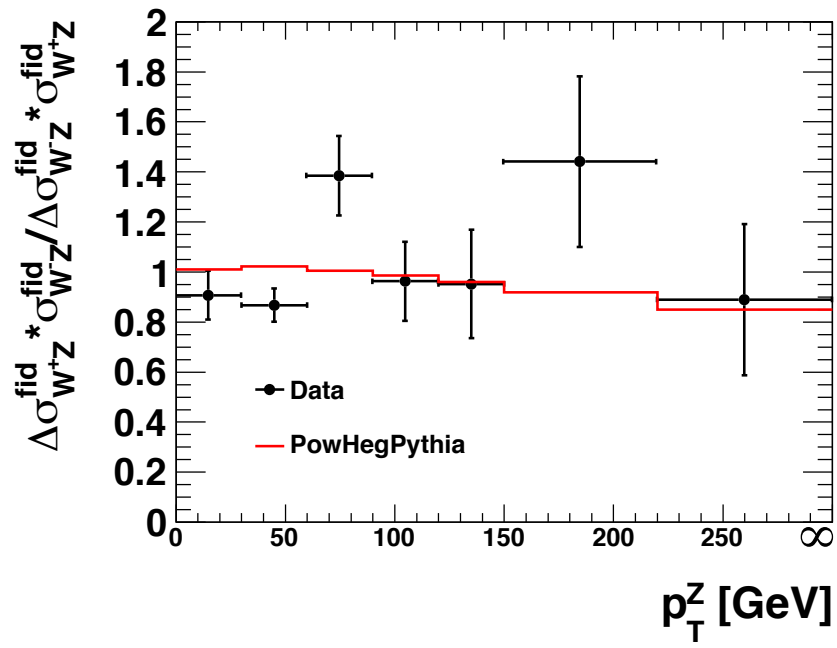


Figure 6.6: The W^+Z and W^-Z normalized differential fiducial cross section, as a function of p_T^Z , for all the W^+Z and W^-Z decay channels.

in differential distributions in the MC.

Chapter 7

Performance of Third Chain muons within the ATLAS experiment

As explained in section 2.3.2.2, a new algorithm has been developed in ATLAS in order to unify the STACO and MUID muon reconstruction chains. This was called Third Chain (TC) and it is the only reconstruction chain that will be used at the restart of the LHC in 2015. Testing the performance of these new muon reconstruction algorithm in physics analyses is crucial. It has to be verified that TC muons perform similarly and even better than STACO or MUID muons.

In this chapter the performance of the TC muons in terms of background rejection will be studied within the context of the WZ analysis and a comparison of results obtained using STACO muons will be shown. The performance of the TC muons will be presented using the 2012 data collected by the ATLAS detector. The impact of using TC muon on the background will also be studied using MC based and data based methods.

7.1 Reconstruction of non-isolated muons in jets

This section presents the impact using TC muons in a data selection enriched with $Z + jets$ events. In that aim, a special selection is developed to build a data sample enriched with a real Z boson and a non-isolated muon in a jet. Both STACO and TC Muons performances are tested.

7.1.1 Event selection

The event selection is applied in channels where the Z can decay to both electrons and muons. A data sample that is enriched with a Z and a non-isolated muon in a jet is built using the following selection criteria.

1. **Z candidate:** The event must contain two selected same flavored leptons with opposite charge, and an invariant mass that is consistent with the Z mass peak so that: $|M_{ll} - 91.1876| < 10$ GeV. If more than one pair of leptons build a Z candidate in one event, the candidate with the invariant mass closest to the PDG Z mass, is considered.
2. **exactly 3 leptons:** The event must contain exactly 2 leptons passing the selection criteria as in Section 2.3.3 that will be associated to the Z candidate. An additional muon is required in the event that should not be isolated. Hence, no isolation cut is required to increase the probability that the muon is in a jet. Also a low $|d_0|/\sigma d_0 < 3$ is put on the selected muon candidate to enhance the heavy flavored jets contribution in the event.

3. **Transverse mass:** The transverse mass of the muon in a jet and E_T^{miss} system should be greater than 30 GeV.

Using these selection criteria, TC muon objects are selected but the same analysis is repeated using also STACO muons for comparison purposes. This selection will lead to a sample that is enriched with $Z + jets$ events, however we also want to reduce all other processes containing a Z and an isolated muon as events. Figure 7.1 shows the distribution of the distance ΔR between the selected muon and the closest jet to the muon in the event. The figure shows that it is possible to remove almost 50 % of the WZ events by requiring a $\Delta R_{\mu-jet}$ less than 1. After this cut, the event sample is dominated by the $Z + jets$ events.

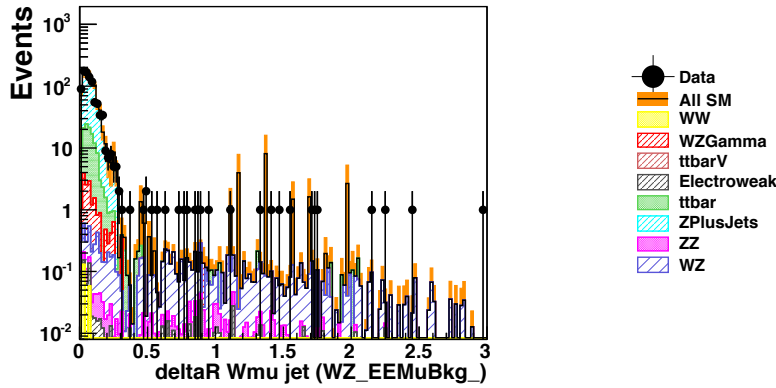


Figure 7.1: The $\Delta R_{\mu-jet}$ distribution between the muon associated to the $\mu_{jet} - E_T^{miss}$ system and the closest jet to that muon in the event.

7.1.2 Data and MC comparison

The resulting data distributions in the control region are compared to MC predictions. For the $Z + jets$ prediction, SHERPA and ALPGENPYTHIA MC event samples can be used to model it and the results are compared to each other. In Figure 7.2 (a) the invariant mass of the Z boson shows a good agreement between data and MC, when TC muons are used. In this figure, the SHERPA $Z + jets$ sample is used. The Figure also shows that this data sample is dominated with events that contain a fake muon in a jet. Figure 7.2 (b) shows the same distribution but using $Z + jets$ ALPGENPYTHIA sample. In this plot we can see that the sample is dominated with heavy flavor jets. This is normal and it is due to the inversion of the d_0 significance cut. However, the agreement between data and MC is not as much as good than the agreement shown by the SHERPA sample. Therefore, in the remaining part of the analysis, the SHERPA $Z + jets$ MC sample will be used.

The channels under study are the $(Z \rightarrow \mu\mu) + \mu_{jet}$ and $(Z \rightarrow ee) + \mu_{jet}$ channels. In Figure 7.3, we can see a comparison of the invariant mass distribution of the Z boson in these channels using both STACO and TC muons. A fair data to MC agreement is seen in both channels with both types of muons. To be able to see if there is a significant increase in this fake muon in a jet dominated data sample using the TC muons, Figure 7.4 shows for the $ee\mu$ and $\mu\mu\mu$ channels, the ratio of the M_Z distribution of data events when using STACO muons to that using TC muons. The data distribution subtracted from all the non $Z + jets$ MC is used to make these ratios. In the $\mu\mu\mu$ channel no significant difference is seen using STACO or TC muons. In the $ee\mu$ channel however, an increase of $\sim 5\%$ is seen using TC muons. Therefore, the TC muon reconstruction

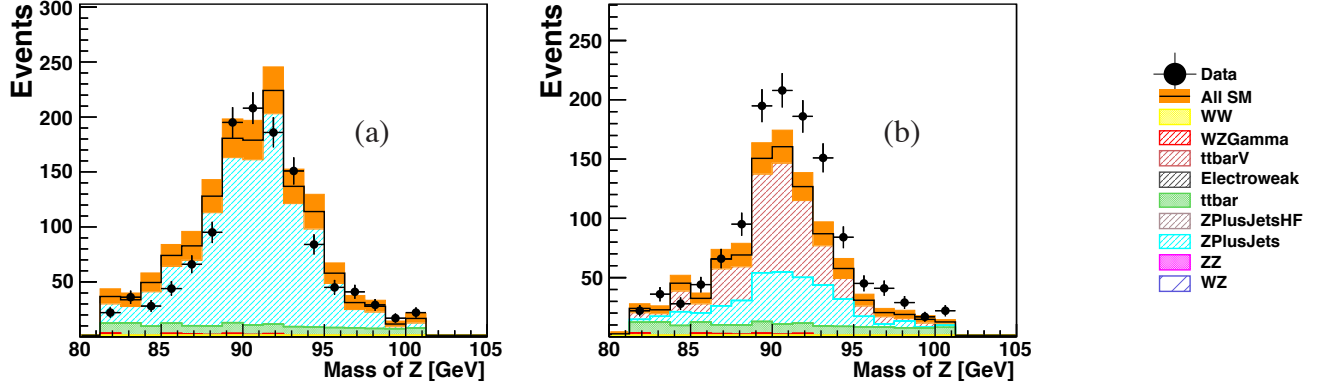


Figure 7.2: Data and MC comparison of the invariant mass distribution of the Z boson in the $(Z \rightarrow \mu\mu) + \mu_{jet}$ channel. TC muons are used. In Figure (a) the $Z + jets$ MC used is SHERPA. In Figure (b) the $Z + jets$ MC used is ALPGENPYTHIA decomposed in two components corresponding to light or heavy flavour jets.

seems to contain more non-isolated muons in jets than the STACO reconstruction. This behavior is fairly well described by the MC simulation. Further comparisons of TC and STACO muon reconstruction will now be performed in a more restrictive event selection corresponding to the one used for the WZ analysis.

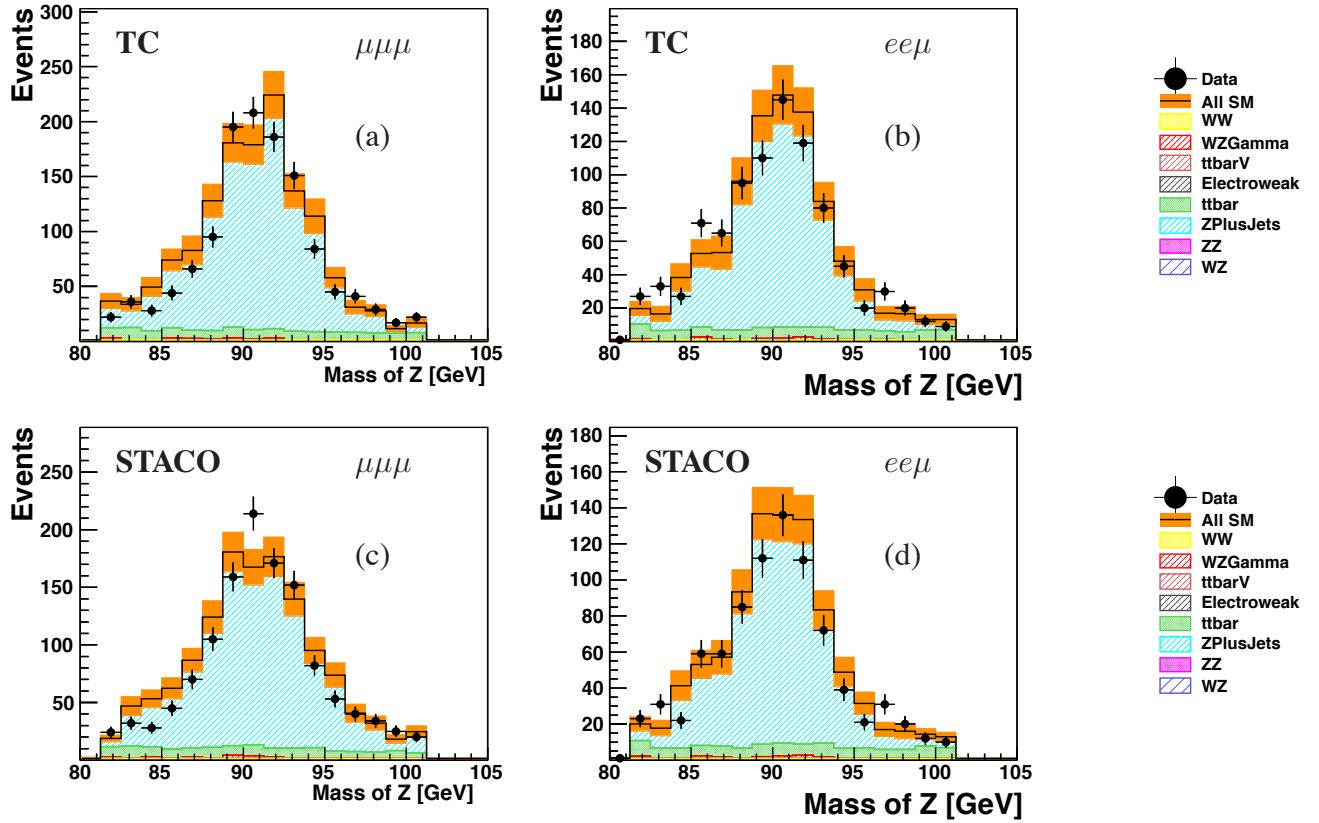


Figure 7.3: Data and MC comparison of the invariant mass distribution of the Z boson. In Figures (a) and (c) TC muons are used and distributions in the $(Z \rightarrow \mu\mu) + \mu_{jet}$ and $(Z \rightarrow ee) + \mu_{jet}$ channels are shown in (a) and (b) respectively. In Figures (b) and (d) STACO muons are used and distributions in the $(Z \rightarrow \mu\mu) + \mu_{jet}$ and $(Z \rightarrow ee) + \mu_{jet}$ channels are shown in (c) and (d) respectively.

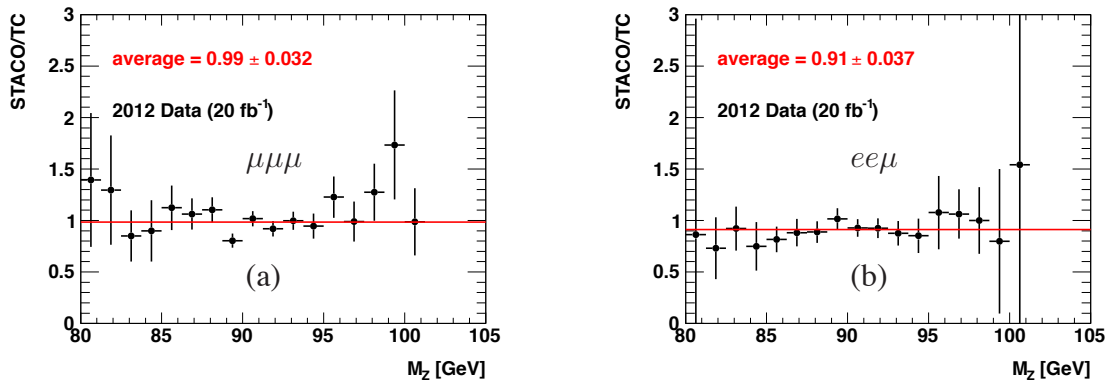


Figure 7.4: Ratio of M_Z data distributions using STACO and TC muons in the $\mu\mu\mu$ (Figure (a)) and $ee\mu$ (Figure (b)) channels. All non $Z + jets$ MC contributions are subtracted from data.

7.2 Performance of Third chain muons in the WZ analysis

To study the performance of the TC muons, the WZ analysis was repeated using all 2012 ATLAS data. The MC sample used for the WZ processes is the SHERPA sample. As for the backgrounds they are all the same as used for the original analysis except that for the $Z + jets$ background both SHERPA and ALPGEN interfaced with PYTHIA samples will be used. The use of two different generators for this background is done to compare their behaviors and study their differences.

In this study WZ events are selected using TC muons instead of STACO. The TC muons reconstruction is not as “tight” as the STACO reconstruction, it can contain more fake muons. Therefore additional requirements on the quality of these muons should be applied within physics analyses. These additional criteria were defined by the ATLAS muon combined performance working group after studying closely the efficiencies and background rejection capacities of TC muons (detailed records can be found in internal communications).

The muon identification requirements are the same as the WZ analysis. The muons that are the decay product of the Z boson are identified as combined or segment tagged. Whereas the muons decaying from a W are identified as combined only.

The event selection is exactly the same as the original analysis, the different steps of which are presented in section 4.1.7, except that the 30 GeV threshold on the M_T^W is removed. This was done because the missing transverse energy computation was not yet finalized for TC muons. The choice of dropping the M_T^W requirement was taken in order to avoid interplays between the muon reconstruction and the computation of the E_T^{miss} . In addition, removing this M_T^W cut allows to enrich the event selection in background events with non-isolated muon associated to a W candidate.

The processes under study to understand the TC muons performance are only processes containing muons which means $WZ \rightarrow ee\mu$, $WZ \rightarrow \mu\mu e$, $WZ \rightarrow \mu\mu\mu$.

7.2.1 Data and MC comparison using STACO and TC muons

The same event selection is performed using both TC and STACO muons. Data and MC are treated the same way except that additional scale factors are applied to the MC, such as the muon efficiency scale factors, the trigger scale factors, and pile-up reweighting (see section 4.1.7).

The data results are compared to the MC prediction. For the $Z + jets$ background, the SHERPA sample is used in a first place. Figure 7.5 shows a comparison of the distributions of the invariant mass of the Z boson produced using STACO muons (figure (a)) and TC muons (figure (b)) in the channel where both W and Z decay to muons. Both distributions show a reasonable data to MC agreement, with a slightly better resolution when using the TC muons. Figure (b) also shows that using the TC muons, the total background contribution is increasing. Using STACO muons the dominant background in the $WZ \rightarrow \mu\mu\mu$ channel is the ZZ background, however when TC muons are used the $Z + jets$ background becomes the dominant one. Therefore, the $Z + jets$ background is the one that is mainly increased when TC muons are used.

A data to MC comparison was also done using the ALPGEN interfaced with PYTHIA generator for the $Z + jets$ background. In this sample the contribution of heavy flavor quarks (ex: b and c quarks) are missing. Therefore, a separate sample is added to it to recover for the missing events. It is possible that events are counted twice using these two samples. In this case, overlapping events are removed using an official ATLAS tool. Figure 7.6 shows the final results. Using this $Z + jets$ sample the conclusion is always the same as using the SHERPA sample. When TC muons are used the data and MC agreement is slightly improved, however the total background contribution, mainly the $Z + jets$ events, is increased.

It is important to check if the shape of the $Z + jets$ background changes significantly When

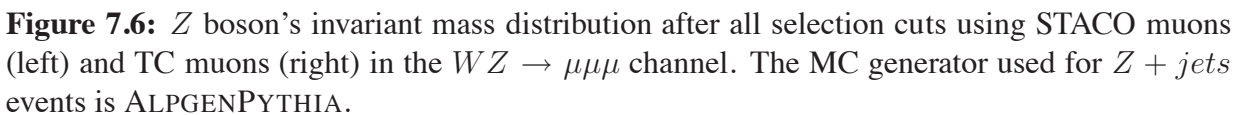
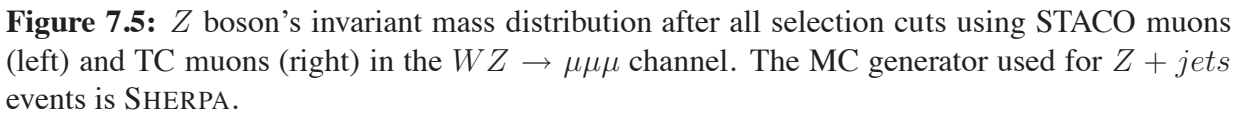


Table 7.1 shows the data and each of the signal and background MC yields in the tree channels that contain muons. In the $WZ \rightarrow \mu\mu e$ channel, the use of STACO or TC muons does not change

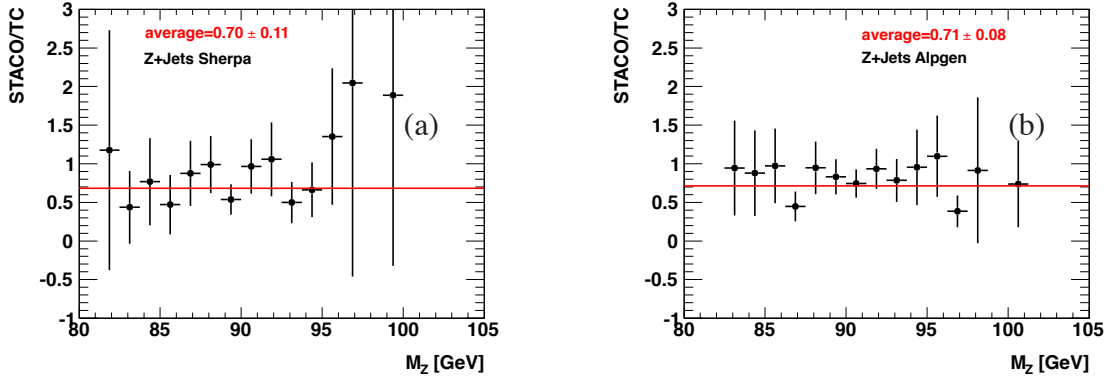


Figure 7.7: The ratio between the Z boson's invariant mass distributions using Staco muons to that using TC muons in $Z + jets$ events. Error bars represent the statistical errors. In Figure (a) the SHERPA MC generator is used. In Figure (b) the ALPGENPYTHIA MC is used.

the total yields. However in the $WZ \rightarrow ee\mu$ and $WZ \rightarrow \mu\mu\mu$ channels the total yields for data, Signal MC, and backgrounds are increased in general. The average increase in data is about 6%, the signal efficiency increases only by $\sim 2\%$. Looking at the event yields for each individual background, we can see that the only background that is increasing with the use of TC muons is the $Z + jets$ background. In this case the SHERPA sample is used for this background. Since the total event yield is increasing only in channels where the muon is associated to a W candidate, and since the only background increasing is the $Z + jets$ background, we can deduce that using TC muons leads to the reconstruction of more fake muons in jets associated to the W candidate and that will slightly increase the rate of the $Z + jets$ background in the WZ analysis.

Muon Chain	STACO	TC	STACO	TC	STACO	TC
Yields	$\mu\mu\mu$	$\mu\mu\mu$	$ee\mu$	$ee\mu$	$\mu\mu e$	$\mu\mu e$
Data	860 ± 29	917 ± 30	615 ± 25	642 ± 25	700 ± 26	699 ± 26
Total Expected	799 ± 11	840 ± 14	582 ± 12	607 ± 14	716 ± 13	713 ± 13
WZ	623 ± 5	638 ± 5	433 ± 4	443 ± 4	477 ± 4	474 ± 4
ZZ	79.4 ± 0.4	82 ± 0.4	54 ± 0.4	56 ± 0.4	76 ± 0.5	76 ± 0.5
$Z + jets$	69 ± 10	92 ± 13	77 ± 12	88 ± 13	67 ± 12	67 ± 12
$t\bar{t}$	14 ± 2	14 ± 1	8 ± 1	9 ± 1	9 ± 1	8 ± 1
$t\bar{t} + V$	13 ± 0.3	13 ± 0.4	9 ± 0.3	10 ± 0.3	10 ± 0.3	10 ± 0.3
$W/Z\gamma$	1.2 ± 0.6	1.3 ± 0.6	0.9 ± 0.5	0.9 ± 0.5	76 ± 5	78 ± 5
WW	0 ± 0	0 ± 0	0.23 ± 0.1	0.2 ± 0.1	0.07 ± 0.07	0.07 ± 0.07

Table 7.1: Comparison of data and all MC total yields obtained using STACO or TC muons. Yields for all of the $\mu\mu\mu$, $ee\mu$, and $\mu\mu e$ channels are presented. The MC generator used for $Z + jets$ events is SHERPA.

To cross check the consistency of the results, the ALPGENPYTHIA generator for the $Z + jets$ sample accompanied with its heavy flavor sub-sample were used instead of SHERPA. Table 7.2 shows the total yields obtained. Since the heavy flavor jets are separated from light jets, we can see in this table the total yields in each channel for each of the light and heavy flavored jets samples. Interestingly, using TC muons, there is no change in the $Z + (heavy\ flavor\ jet)$ sample, but the increase of the $Z + jets$ is significant when the muon is inside a light jet. The Signal To Background (S/B) ratio is used to compare the global performances of TC and STACO

Muon Chain	STACO	TC	STACO	TC	STACO	TC
Yields	$\mu\mu\mu$	$\mu\mu\mu$	$ee\mu$	$ee\mu$	$\mu\mu e$	$\mu\mu e$
$Z + jets$ ALPGENPYTHIA	65 ± 8	84 ± 9	35 ± 6	45 ± 6	99 ± 11	100 ± 11
$Z + jets$ ALPGENPYTHIA HF	29 ± 5	33 ± 6	37 ± 7	40 ± 7	11 ± 4	11 ± 4
$Z + jets$ SHERPA	69 ± 10	92 ± 13	77 ± 12	88 ± 13	67 ± 12	67 ± 12

Table 7.2: Total yields comparison with STACO and TC muons using ALPGENPYTHIA and SHERPA MC generators for $Z + jets$ events. Yields for all of the $\mu\mu\mu$, $ee\mu$, and $\mu\mu e$ channels are presented.

muons on the background rejection in each channel. Table 7.3 shows this ratio for all the three channels under study. In this table, the SHERPA sample is used for the $Z + jets$ background. In the $\mu\mu e$ channel no change is seen in the S/B ratio, meaning that the efficiency to reconstruct good and isolated muons, associated to a Z candidate in this channel, is the same for STACO and TC muons. However, in the $\mu\mu\mu$ and $ee\mu$ channels a decrease of about 10% and 7% respectively is seen after using TC muons in the analysis. The uncertainties presented in the table are only statistical. Since the same analysis is repeated twice using the same samples and only changing the type of muons, these two results are strongly correlated. The statistical uncertainties on the S/B ratio can be counted only once because of the correlation between the two results. Based on this, the difference in the S/B ratio seen in the $\mu\mu\mu$ channel is significant. In the $ee\mu$ channel, the difference seen is within the statistical uncertainties.

channels			
S/B	$\mu\mu\mu$	$ee\mu$	$\mu\mu e$
STACO	3.53 ± 0.21	2.90 ± 0.23	2.00 ± 0.11
TC	3.16 ± 0.20	2.70 ± 0.21	1.98 ± 0.11

Table 7.3: Signal to background ratios using STACO and TC muons. The uncertainties are only statistical. Ratios for all of the $\mu\mu\mu$, $ee\mu$, and $\mu\mu e$ channels are presented. The $Z + jets$ MC used is SHERPA.

As a cross check to these results, the S/B ratio is also calculated using the ALPGENPYTHIA sample for the $Z + jets$ background. Table 7.4 shows the results. The picture is the same as using the SHERPA sample for this background. A $\sim 10\%$ increase of the background in the $\mu\mu\mu$ channel and about 7% of increase in the $ee\mu$ channel. We can conclude that both MC give consistent results.

channels			
S/B	$\mu\mu\mu$	$ee\mu$	$\mu\mu e$
STACO	3.10 ± 0.15	3.00 ± 0.19	1.70 ± 0.08
TC	2.80 ± 0.14	2.80 ± 0.17	1.70 ± 0.08

Table 7.4: Signal to background ratios using STACO and TC muons. The uncertainties are only statistical. Ratios for all of the $\mu\mu\mu$, $ee\mu$, and $\mu\mu e$ channels are presented. The $Z + jets$ MC used is ALPGENPYTHIA.

7.2.2 Composition of the $Z + jets$ background

In order to further understand the origin of the excess in the $Z + jets$ background when TC muons are used instead of STACO, studies at the MC truth level are shown in this section. In the $WZ \rightarrow \mu\mu\mu$ and $WZ \rightarrow ee\mu$ channels, the muon that is associated to the W candidate is matched to the true MC particle. The aim is to check if these muons are real muons inside jets or if they are fake particles that are reconstructed as muons. Both SHERPA and ALPGENPYTHIA $Z + jets$ samples are used for this study. Reconstructed particles are matched to their true MC particles and a search for the origin of these muons is performed.

In the $WZ \rightarrow \mu\mu\mu$ and $WZ \rightarrow ee\mu$ channels the muons associated to the W candidate is matched to its truth particle. Figure 7.8 shows a comparison between the distributions obtained using TC and STACO muons. The results from two different MC generators, SHERPA and ALPGENPYTHIA, are presented. In the case of both generators, we can see that the reconstructed particles match mostly to true muons when using TC and STACO muons. However, there is a fraction of event where pions or kaons can be fakely reconstructed as muons. In these cases, the reconstruction of these fake muons is enhanced using the TC muons. Using SHERPA MC, the reconstruction of fake muons increases by a factor of about three. However, using ALPGENPYTHIA fake reconstructed muons are only doubled. The global picture using both generators is the same, leading to the conclusion that, TC muons give a higher rate of fake reconstructed particles. However, this increase is not the same in the two generators. Using the ALPGENPYTHIA generator, we reconstruct more fake muons in STACO and TC. Using SHERPA, the rate of fake particles is lower. However using SHERPA, the increase of fakely reconstructed muons using TC muons is more than when using ALPGENPYTHIA. It is important to understand if this difference is statistically significant. In Figure 7.9 (a) the ratios of the associated true particles using TC and Staco muons for each of the ALPGENPYTHIA and SHERPA generators, show that for both generators the increase of fakely reconstructed muons using TC muons instead of STACO muons, is significant. The Figure 7.9 shows that for pions and kaons reconstructed as muons, the ratios obtained are different than one and the difference is not covered by the statistical errors. To see if the difference seen between these ratios is significant, Figure 7.9(b) shows the ratio between the ratios of Figure 7.9(a). The figure shows that these differences can be explained by statistical fluctuations and both generators show a consistent agreement as far as the increase of the fakely reconstructed muons in the $Z + jets$ events.

To understand the origin of these associated true particles, Figure 7.10 shows for both ALPGENPYTHIA and SHERPA MC generators, a map of the associated true particles to their origin mother particle. The figures show that most of the reconstructed true muons are the decay product of $D^\pm$ mesons. Whereas charged pions are the decay products of ρ^+ mesons. Finally, kaons are mostly disintegrated from K^* particles. Both generators show the same picture in terms of the origin of muons reconstructed as fake particles.

7.3 Conclusion about the TC muons performance in the WZ analysis

Testing the performance of TC muons within a physics analysis was an important task. The next software release for run-2 will no longer contain STACO nor MUID muons but only TC muons. The performance of TC muon reconstruction was verified using a data driven method. A control sample enriched with real Z and a muon in a jet was built. The reconstructed events as $Z + jets$ have shown an enhancement when TC muons are used. Therefore, in the WZ analysis performed with the 2012 data only STACO muons were being used.

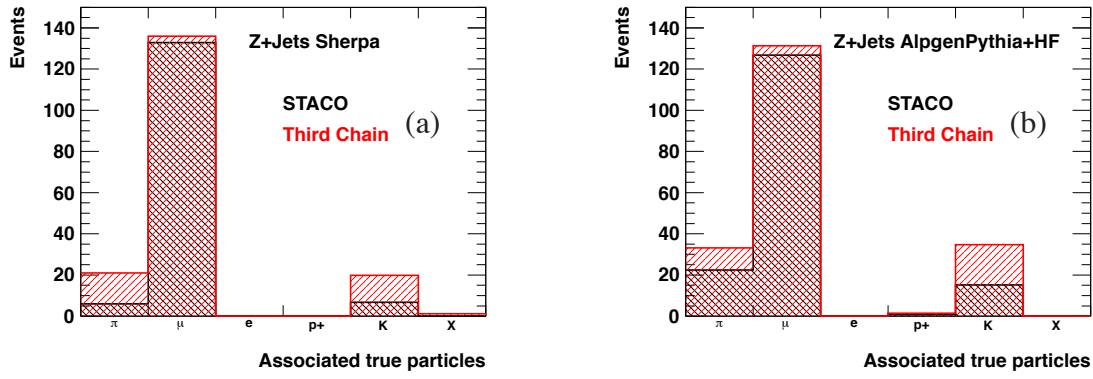


Figure 7.8: The associated true particles to the reconstructed W muon. The $ee\mu$ and $\mu\mu\mu$ channels are merged in these histograms. In Figure (a), the $Z + jets$ MC used is SHERPA. In Figure (b), ALPGENPYTHIA MC together with its heavy flavor sample is used. The distribution in red corresponds to when TC muons are used. The distribution in black corresponds to when STACO muons are used.

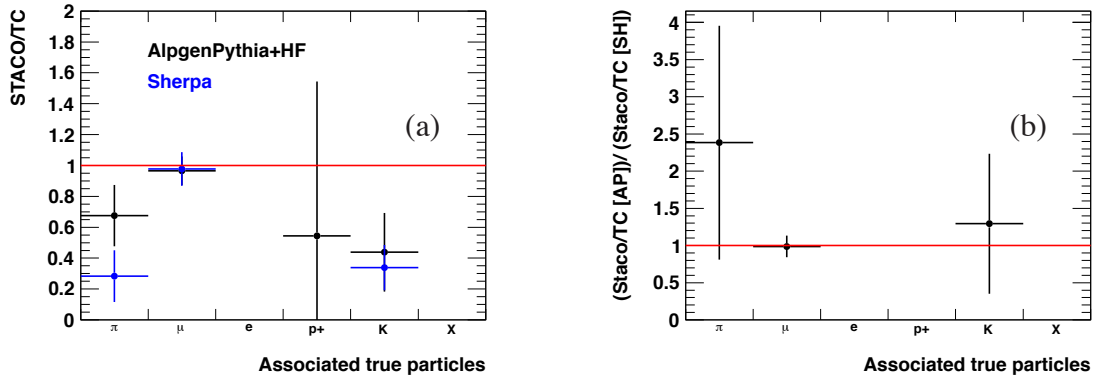


Figure 7.9: Figure (a) presents the ratio of the associated true particles to the W muon in $Z+jets$ events with SHERPA MC generator to that with ALPGENPYTHIA MC generator when STACO (black) and TC (red) muons are used. Figure (b) shows the ratio of the two distributions of Figure (a).

Another MC based approach within the WZ analysis frame, has shown that using TC muons will increase the $Z + jets$ processes. This means that the number of muons in jets or fake particles reconstructed as muons will slightly increase when using TC muons. However, even though the background will be increasing, the data and MC agreement will slightly improve when TC muons are used. Also in this study, the MC truth information was used to investigate the origin of increase of the $Z + jets$ processes. We have shown that the number of real reconstructed muons is not changing using the TC, but there are more particles such as pions and kaons that are reconstructed as muons. It is possible that these pions are particles that will decay to muons after traversing the inner detector but this is not possible to know within the frame of this physics analysis. If these pions and kaons disintegrate to muons, this means that using TC muons the muon reconstruction efficiency increases. However resistance against the $Z + jets$ processes seems worse than when using STACO muons.

The inputs of this study on the TC muons performance was handed to the official ATLAS muon

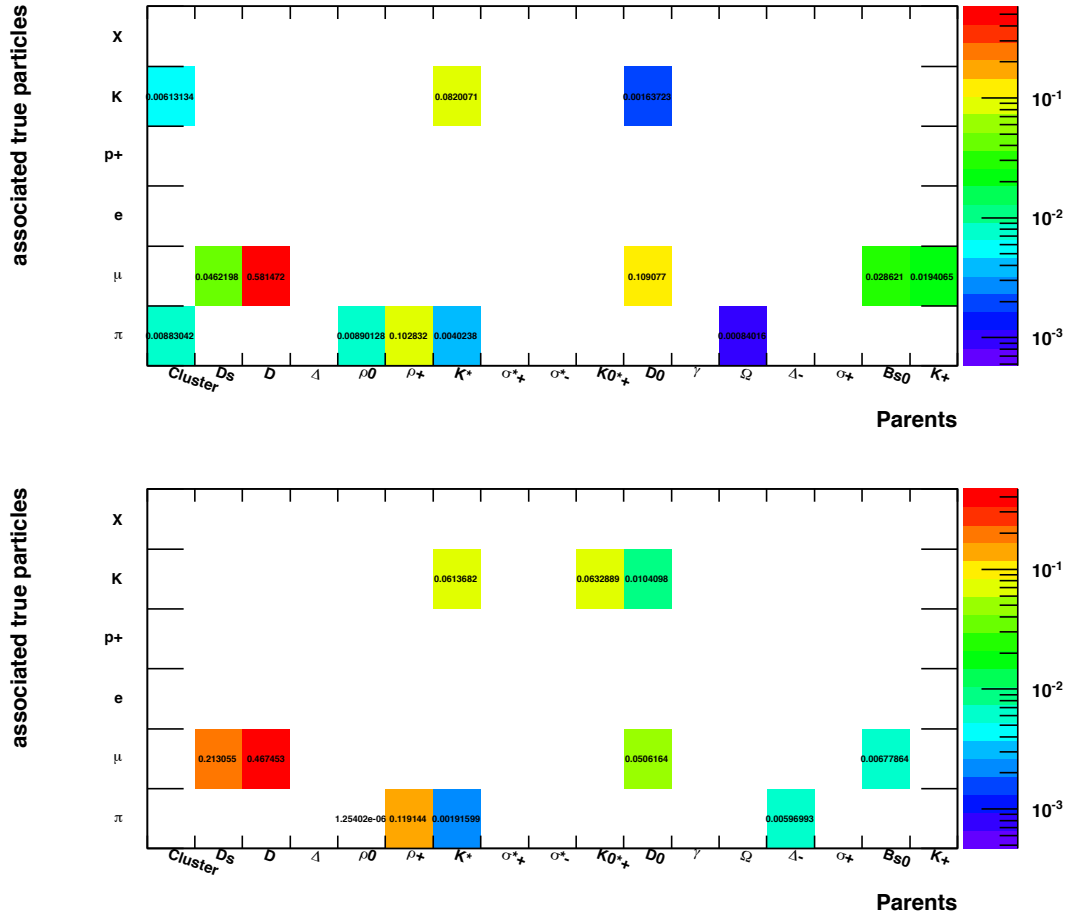


Figure 7.10: Associated true particles to the muon associated to the W candidate as a function of their parent true particle using TC muons for ALPGENPYTHIA (top) and SHERPA (bottom) $Z + jets$ MC generators.

working group. The results served to study more deeply the performance of the TC muons and to improve them further.

Conclusion

The first part of this thesis presented the time alignment of the ATLAS LAr Calorimeter. During the 2012 data taking, the timing of the LAr Calorimeter was monitored on a run-by-run basis. Then two sets of corrections were introduced to align the LAr Calorimeter in time. First, on-line time corrections were applied to align the FEBs in time. The effect of these corrections was a reduction of the spread of the FEB time to ~ 150 ps. Then more precise corrections extracted for each LAr calorimeter cell and these were applied offline. The effect of the cell time corrections was an improvement of the time resolution by ~ 200 ps.

The second part of this thesis consisted on selecting events with WZ diboson pairs. Each of the main background sources mimicking the WZ final states were controlled using special data selections. Global normalizations of 1.16, 1.11 and 0.96 have been defined for each of the $t\bar{t}$, $Z + e$, and $Z + \mu$ backgrounds, respectively. Otherwise, the MC predictions for each of these backgrounds have shown to describe the data with a good accuracy. This is the result of a good simulation of the detector response, convoluted with a good description of parton showering and jet sub-structures by the actual MC generators and parton shower algorithms.

In the final part of this thesis, the measurements of the $W^\pm Z$, $W^+ Z$, and $W^- Z$ production cross section were presented using the 2012 data collected by the ATLAS detector at a center-of-mass energy of 8 TeV during proton-proton collisions at the LHC. The integrated luminosity of the data used for the presented measurement corresponds to $\mathcal{L} = 20 \text{ fb}^{-1}$.

First, the measurement of the integrated cross section in the total and fiducial phase spaces were shown. This measurement improved with respect to the previous ATLAS measurement [27] especially in terms of statistical uncertainty. As the collected data in 2012 was five times that collected in 2011, the statistical uncertainty on this measurement improved by 60% compared to the previous ATLAS measurement.

The measurement in the total phase space can be compared to that obtained by the CMS experiment. Table 7.5 shows this comparison of the total cross sections obtained in this thesis using the ATLAS data and that obtained by the CMS experiment [28]. The results are very compatible with slightly better uncertainty level for the results of ATLAS due to the enlarged fiducial phase space definition.

Experiment	$\sigma(pp \rightarrow WZ; \sqrt{s} = 8 \text{ TeV}) [\text{pb}]$
ATLAS	$24.54 \pm 0.65 \text{ (stat.)} \pm 0.91 \text{ (sys.)} \pm 0.76 \text{ (lumi.)}$
CMS	$24.61 \pm 0.76 \text{ (stat.)} \pm 1.13 \text{ (sys.)} \pm 1.08 \text{ (lumi.)}$

Table 7.5: The total cross section in the total phase space in pb for the combination of all the WZ channels for ATLAS and CMS experiment.

The measurements in each individual WZ channel and for their combination have also been compared to theory predictions by both experiments. The CMS experiment compares the measurement to the predictions of MCFM 6.6 using factorization and normalization scales of $\mu_R = \mu_F = (M_W + M_Z)/2$. The predictions used to compare by the ATLAS experiment is POWHEGPYTHIA with the same normalization and factorization scale and which was shown to be in agreement with the predictions of MCFM. For both of the experiments the combination results have shown a limited agreement within 5% with the predictions.

This thesis also presented a measurement of the W^+Z and W^-Z cross sections ratio in the fiducial phase space. This measurement was not possible to be performed with the 2011 ATLAS data collected at 7 TeV due to the lack of statistics. Therefore, in this thesis a first measurement with the 8 TeV ATLAS data of the ratio $\frac{\sigma_{W^+Z}}{\sigma_{W^-Z}}$ was measured in the fiducial phase space. Table 7.6 presents the comparison of this ratio measurement to the theoretical prediction obtained by POWHEGPYTHIA using the CT10 PDF. The measured ratio by ATLAS is slightly lower than the theory prediction ($\sim 10\%$). The ratio $\frac{\sigma_{W^+Z}}{\sigma_{W^-Z}}$ was also measured by CMS in the total phase space so that $R_{tot} = 1.81 \pm 0.12(stat.) \pm 0.03(sys.)$ and this result is in agreement within 2% with the theory predictions [28].

	$R_{fid} = \frac{\sigma_{W^+Z}}{\sigma_{W^-Z}}$
Measurement	$1.50 \pm 0.08 (stat.) \pm 0.02 (sys.)$
POWHEGPYTHIA	$1.69 \pm 0.01 (stat.) \pm 0.07 (sys.)$

Table 7.6: The ratio $R_{fid} = \frac{\sigma_{W^+Z}}{\sigma_{W^-Z}}$ of W^+Z and W^-Z cross sections in the fiducial phase space for the combination of all the WZ channels measured in this thesis.

Finally, normalized differential cross section measurements as a function of four kinematic variables, p_T^Z , p_T^W , M_{WZ} , and $y_Z - y_{W,l}$ have been performed. They were found to be in good agreement with the predictions from POWHEGPYTHIA. No difference, between measurement and predictions, in the shape of differential distributions have been yet observed. The ratio of the normalized differential cross section between the W^+Z and W^-Z as a function of the Z boson's transverse momentum has also shown a fair agreement between data and MC predictions with some fluctuations in a few bins.

Outlook

The measurement presented in this thesis can be used further to constrain potential anomalous Triple Gauge Couplings affecting the WWZ vertex. As no deviations were observed in the WZ kinematic spectra, a fit can be applied to these to set limits on the aTGCs for the WWZ vertex. Angular variables can also be used to study the differential distributions and set better constraints on aTGCs as they have a higher experimental resolution than the kinematic variables. Results using the ATLAS 7 TeV data have set limits on the aTGCs, however because of the increased statistics improved constraints are expected with the 8 TeV ATLAS data.

All of these measurement will be repeated with the new data that will be collected in 2015 at a center-of-mass energy of 13 TeV. After 3 years of running with the total data collected of hundreds of fb^{-1} in the future, measurements will allow a significant decrease of the statistical

uncertainty on the measurement. This will show if the small deviation of $\sim 10\%$ of the observed total WZ production cross section with respect to the theory predictions remains. Additionally, the limits that will be set on the aTGCs will be improved by at least one order of magnitude. Finally, in a longer term in the future with the high statistics data from high luminosity LHC machine, as currently under study, the WZ and WW scattering predicted by the SM could be studied precisely as a demonstration to the Higgs mechanism.

The work presented in this thesis is going to be included in a future publication by the ATLAS collaboration, that is currently under preparation.

Appendix A

LAr Time Definitions

A.1 FEB time estimation method

- Individual times of all events within a FEB are used through a single distribution.
- In building the distribution of the time of all events in one FEB, a weighting of each event by its energy is introduced.
- The core of each FEB time distribution is adjusted with a Gaussian function, using a double iterative fit procedure. The first fit is performed in the range of $[-5, 5]$ ns. This fit allows to have a global idea about the aspect of the distribution and of its spread. The second fit is performed in the range $[t_{max} - \delta t_1 \times \sigma_t, t_{max} + \delta t_2 \times \sigma_t]$, where t_{max} is the time value of the bin containing the maximum number events, σ_t is the standard deviation of the first fit, finally δt_1 and δt_2 are optimized factors to make symmetric or asymmetric fits based on the shape of the distributions in different FEBs.

Table A.1 gives the values of δt_1 and δt_2 estimated for groups of specific FEBs defined by conditions on their position (slot or FT) or on the width (RMS) of their time distribution. Figure A.1 shows an example of the $\langle t \rangle_{FEB}$ computation in one FEB in the EMEC, using a single fit and a double iterative fit. The mean of the single fit is biased towards higher time values by the presence of a tail in the time distribution. Therefore, the average FEB time is not estimated correctly in this case. However, we observe that using the double iterative fit procedure, the core of the FEB time distribution is well fitted and the mean is correctly estimated.

This means that in many cases where the FEB time distributions are not completely Gaussian a single fit in a given fixed range is not enough to correctly estimate the average FEB time. The error $\delta \langle t \rangle_{FEB}$ is defined as the statistical error on the mean value obtained from the Gaussian fit used to determine the $\langle t \rangle_{FEB}$. In cases for which the result of the fit is not used, the error corresponds to the statistical error on the median.

- Finally, if the fit converges, the time $\langle t \rangle_{FEB}$ is defined as the mean value of the final fit. If the fit did not converge or if the error on the fit was larger than the fit mean value or the σ of the fit was larger than 1.5 times the RMS of the corresponding FEB time distribution, the weighted median of the distribution is used instead. The median of weighted events is defined as the value, in this case the time, for which the sum of weights of all events before and after it is 50%.

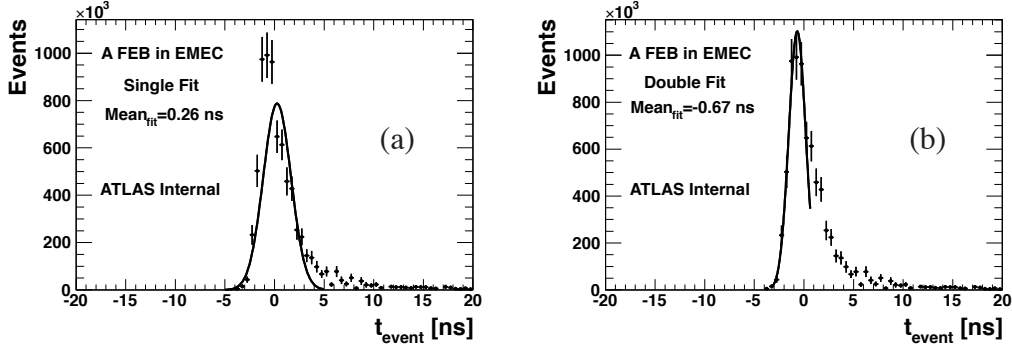


Figure A.1: Examples of the estimation of the average FEB time $\langle t \rangle_{\text{FEB}}$ in a given FEB, using a single fit in the range $[-5, 5]$ ns (a) and a double iterative fit (b).

Partition	Condition on FEBs	Values of δt_1 and δt_2
EMB	if slot=9 or 10	$\delta t_1=3, \delta t_2=2$
EMB	if $2 \leq \text{slot} \leq 5$	$\delta t_1=1.5, \delta t_2=2.5$
EMB	if slot=14	$\delta t_1=2, \delta t_2=1$
EMB	everything else	$\delta t_1=\delta t_2=1.8$
EMEC	if slot=13 and $\text{RMS} > 3$ ns	$\delta t_1=1.5, \delta t_2=1$
EMEC	if $\text{slot} \geq 14$ and $\text{RMS} > 3$ ns	$\delta t_1=1.5, \delta t_2=0.3$
EMEC	if slot=9 and FT=2, 9, 15, 21	$\delta t_1=\delta t_2=3$
EMEC	if slot=8 or slot=9 and $\text{RMS} > 3$ ns	$\delta t_1=\delta t_2=2$
EMEC	if slot=8 and FT=13	$\delta t_1=\delta t_2=3$
EMEC	everything else	$\delta t_1=\delta t_2=1.8$
HEC	all	$\delta t_1=\delta t_2=1.5$
FCAL	all	$\delta t_1=\delta t_2=0.8$

Table A.1: Optimized Values of δt_1 and δt_2 used for the different groups of channels in each partition (see text for details).

A.2 Cell time determination

- The distribution of the energy weighted times of all events is constructed for each cell.
- A double iterative fit, for each channel time distribution, is done using a Gaussian function. The first fit is done in the range $[-5, 5]$ ns and the second fit is done in the range $[t_{\text{max}} - \delta t_1 \times \sigma, t_{\text{max}} + \delta t_2 \times \sigma]$. For the determination of each channel time, it is possible to use symmetric fit ranges, since the statistics in each channel remains relatively low and the spread is small most of the time. For the FCAL, a narrow fit with $\delta t_1=\delta t_2=0.8$ is used. For the HEC, $\delta t_1=\delta t_2=1.5$. Otherwise, $\delta t_1=\delta t_2=2$ for all remaining distributions except for wide ones which have an $\text{RMS} > 4$ ns. In this case $\delta t_1=\delta t_2=0.5$ values are used. For the slot 1 in the EMB, corresponding to the presampler, $\delta t_1=\delta t_2=1$ is used since these distributions contain more background events than others due to their location. A narrower fit will therefore help to better estimate the mean value of the distribution.

A.3 Self consistency of the cell time alignment corrections

In order to verify the self-consistency of the method used to extract and apply the cell time alignment corrections, the corrections have been applied to the same data set as used for their determination (see section 3.3.4.2).

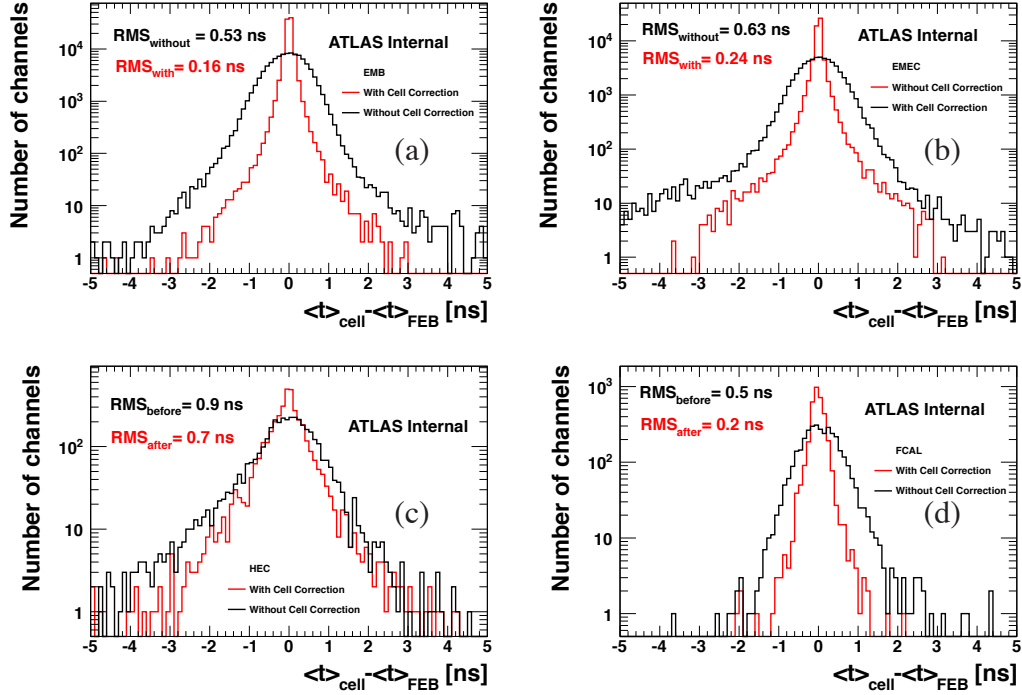


Figure A.2: Distributions of $\langle t \rangle_{\text{cell}} - \langle t \rangle_{\text{FEB}}$ values for each of the four LAr calorimeter partitions before (black) and after (red) applying the cell time corrections. These results are obtained using 2 fb^{-1} of data.

The results are presented in Figure A.2 which shows, for all the four LAr Calorimeter partitions, the values of $\langle t \rangle_{\text{cell}} - \langle t \rangle_{\text{FEB}}$ for all cells before and after implementing the cell time corrections. A large improvement in the resolution, of the order of 75 %, is seen after applying the corrections. This demonstrates the technical validity of the corrections procedure.

A.4 Effect of the cell time corrections on the average FEB time

The effect of the cell time corrections on the average FEB time is checked. The cell corrections are applied locally in the analysis framework and the $\langle t \rangle_{\text{FEB}}$ is recomputed. The results are presented in Figure A.3 where the $\langle t \rangle_{\text{FEB}}$ distribution obtained with and without cell corrections is shown. We observe that the cell time corrections have no effect on the global FEB time average. Therefore, they do not create time offsets in FEBs and can be determined and applied independantly of the FEB timing adjustment.

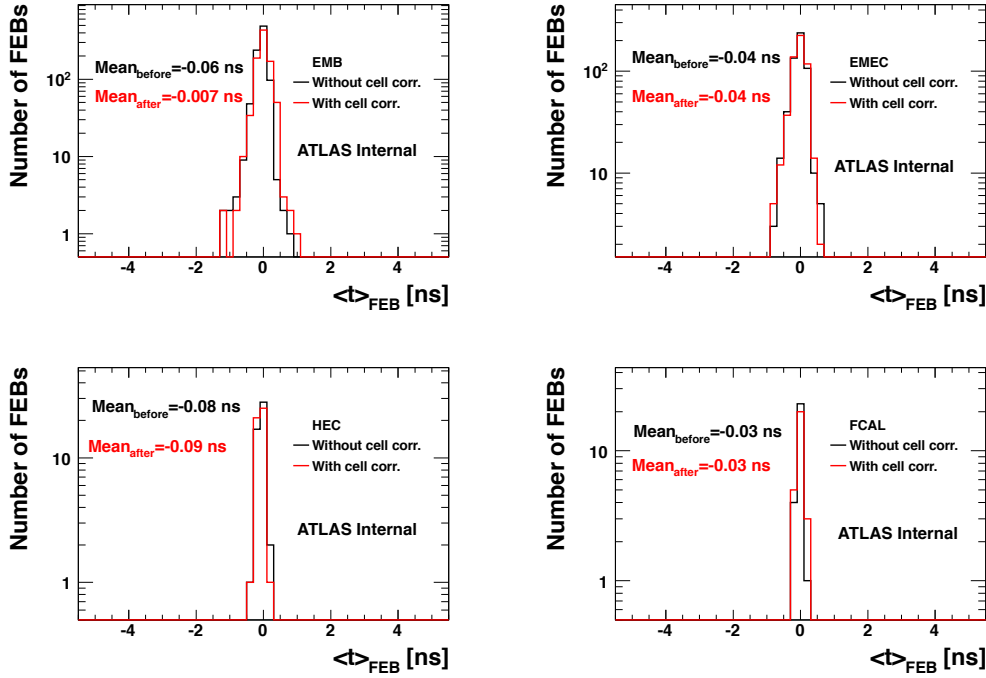


Figure A.3: Distributions of the average FEB time, $\langle t \rangle_{FEB}$, for the four LAr calorimeter partitions, before (black) and after (red) applying cell time corrections. The data used correspond to an integrated luminosity of 2 fb^{-1} .

A.5 FEB time after cell time corrections

At the beginning of the 2012 data taking, no new FEB time corrections were applied. Even with the FEB time corrections determined with the 2011 data, some FEBs were not properly aligned at 0. The new 2012 analysis FEB time computing method was finalized in May 2012 and new FEB time corrections were applied on May 16th. Therefore the average time of the FEBs was not completely stable during the beginning of the 2012 data taking. Figure A.4 shows the $\langle t_{FEB} \rangle$ as a function of the run number, for all four LAr calorimeter partitions along the 2012 data taking.

On this figure, we can observe four different periods in terms of FEB time stability. The first period corresponds to runs for which no FEB corrections were applied. The second and third periods correspond to runs for which FEB corrections were applied using the old computation method used for the 2011 data. Finally the fourth period corresponds to runs for which the FEB corrections were computed and applied using the new calculation method introduced for the 2012 data. We observe that the FEB time became very stable after that. For the last period which represents the main part of the 2012 data, the cell time corrections are defined according to equation 3.4. For the three other periods, three different sets of cell by cell time corrections are extracted in a way to absorb also FEB time deviations. These corrections were defined as:

$$C_{cell_{p1,p2,p3}} = C_{cell} + \langle t \rangle_{FEB_{p1,p2,p3}}, \quad (\text{A.1})$$

where p_1, p_2, p_3 are the three run periods, C_{cell} is the cell time correction computed for the last period using the 2 fb^{-1} data set, and $\langle t \rangle_{FEB_{p1,p2,p3}}$ is the average FEB time computed for each of the three periods. After applying the new cell by cell corrections for each period, and recomputing the $\langle t \rangle_{FEB}$, it is expected to see a timing stability along 2012 as shown in the Figure 3.14.

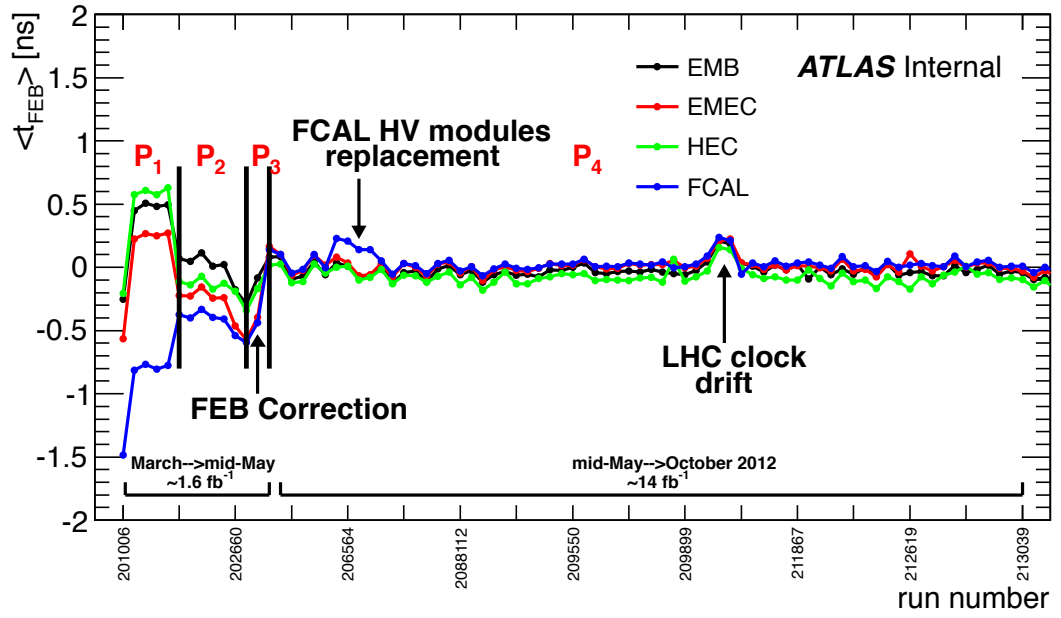


Figure A.4: The average FEB time, $\langle t_{FEB} \rangle$, per partition, as a function of the run number before applying cell time corrections at the data reprocessing.

Résumé

La compréhension de l'origine des constituants fondamentaux de la matière a changé au fil du temps dans l'histoire humaine. Le concept des éléments classiques a commencé autour du sixième siècle avant JC avec Thales et ses successeurs Anaximandre et Anaximène. L'idée de l'atome a été proposée au cinquième siècle avant J.-C. par le philosophe grec Démocrite, qui a introduit l'idée de constituants indivisibles de la matière. Dans le quatrième siècle, la première proposition des éléments fondamentaux de la matière avait été proposée avec la théorie d'Empédocle où il a déclaré que tout ce qui nous entoure est composé de quatre éléments, l'air, le feu, la terre et l'eau. Il a fallu ensuite à l'humanité plus d'un millénaire et demi pour mettre en place une première théorie scientifique pour la définition d'un élément. En 1789, Antoine Lavoisier a défini un élément comme une substance qui ne peut pas être divisée en d'autres morceaux. En 1869, le chimiste russe Dimitri Mendeleïev a classé ces éléments en fonction de leurs propriétés atomiques dans un tableau que nous connaissons aujourd'hui sous le nom de tableau périodique.

Avec cette révolution et l'évolution continue de la science, aujourd'hui, au XXI^e siècle, nous avons été capable de classer les éléments constituant la matière d'une manière différente. Avec des instruments comme le Grand Collisionneur de Hadrons (LHC), nous explorons l'«infiniment petit» et regardons à travers ce que l'on appelle les particules élémentaires d'aujourd'hui. Après une longue chaîne d'études étendue sur plusieurs dizaines d'années, la science a convergé au regroupement des particules élémentaires en construisant un modèle mathématique décrivant de leurs propriétés, le Modèle Standard (MS). Le Modèle Standard de la physique des particules contient les quarks, les leptons et enfin les bosons. Les quarks interagissent à travers des interactions électromagnétique, faible et forte. Les leptons interagissent via les interactions électromagnétique et faible. Finalement, Les bosons médient les interactions entre les quarks et les leptons.

Parmi les particules prédites par le MS, cette thèse présentera des mesures concernant la production en paires des deux bosons W et Z . Les bosons W et Z sont les médiateurs de l'interaction faible. Leur production par paires est prédite par le MS. Cette thèse décrit la mesure de la section efficace de la production de paires WZ réalisée avec les dernières données expérimentales de l'expérience ATLAS. La grande quantité de données enregistrée a permis une amélioration notable de ces mesures.

Le chapitre 1 présente une introduction théorique au Modèle Standard de la physique des particules. Il présentera également la phénoménologie des collisions proton-proton au LHC ainsi que les mécanismes de production des dibosons WZ . Enfin, une perspective théorique de la physique au-delà du MS avec les dibosons sera expliquée, à travers d'une théorie effective des champs.

Le chapitre 2 décrit le Grand Collisionneur de Hadrons et son fonctionnement au cours des années 2011 et 2012. Il donne des détails techniques sur le détecteur ATLAS et ses sous-

composants. Toujours dans ce chapitre, la reconstruction des particules à l'intérieur du détecteur, utilisées pour identifier les désintégrations leptoniques du système WZ , comme les électrons, les muons, neutrinos, sera expliqué.

Une partie du travail de cette thèse a été consacré à l'alignement en temps du calorimètre à Argon Liquide (LAr) du détecteur ATLAS. Ce travail a contribué à l'amélioration de la qualité des données recueillies au cours de l'année 2012. La procédure et la mise en œuvre de cet alignement en temps du calorimètre sont présentés dans le chapitre 3.

Le chapitre 4 présente les étapes de la sélection des événements WZ . Il présente les critères de sélection et la motivation derrière eux. Toujours dans ce chapitre, la description et l'extraction des événements de bruit de fond contribuant à cette sélection seront détaillées. Enfin, le nombre des événements obtenus et les distributions des variables cinématiques seront présentés afin de contrôler l'accord entre les données et les prédictions de la simulation Monte Carlo.

Le chapitre 5 détaille la mesure de la section efficace de production des $W^\pm Z$ dans les espaces de phase fiduciel et total. La mesure commence dans l'espace de phase fiduciel, correspondant à une région restreinte de l'espace de phase et très proche de celle où les événements sont reconstruit dans le détecteur. Cette mesure est alors extrapolée à l'espace de phase total dans le but de faciliter la comparaison des résultats avec ceux d'autres expériences. Enfin, une première mesure, en utilisant les données 2012 d'ATLAS, du rapport des sections efficaces des événements W^+Z et W^-Z sera présentée.

Le chapitre 6 présente les mesures de la section efficace différentielle normalisée de la production des WZ dans l'espace de phase fiduciel en fonction de quatre variables cinématiques différentes, p_T^Z , p_T^W , M_{WZ} et $y_Z - y_{W,l}$ comme la présence de nouvelle physique peut affecter la forme de ces spectres. Le but est de comparer en détail les spectres mesurés de ces variables cinématiques à ceux prédits par le MS.

Enfin, cette thèse sera conclue avec un résumé de tous les résultats présentés et des perspectives pour les futures attentes du LHC et l'expérience ATLAS.

I. Le Modèle Standard

Le MS de la physique des particules est un modèle mathématique qui permet de regrouper les particules élémentaires observées expérimentalement et de décrire leurs comportements et leurs interactions. Dans ce modèle les «particules de matière», soit les fermions, interagissent via les médiateurs, les bosons, qui sont les «particules de force». Les fermions ont un spin qui est un multiple impair de $\hbar$. Les quarks et les leptons sont classés comme des fermions. Contrairement aux quarks, les leptons comme les électrons, ne subissent pas l'interaction forte. Ils peuvent toutefois faire l'objet d'interactions gravitationnelles, électromagnétiques et faibles. Les leptons peuvent transporter une charge électrique et les quarks portent en plus de la charge électrique, une charge de couleur. Les bosons sont des particules de spin multiple de $\hbar$ et ils sont les médiateurs des interactions faibles, fortes, et électromagnétiques. Le photon est un boson de masse nulle qui médie l'interaction électromagnétique. Le gluon, également sans masse, est responsable de l'interaction forte, et les porteurs de l'interaction faible sont les bosons de jauge massifs $W^\pm$ et Z^0 . La dernière particule qui complète le modèle standard est le boson de Higgs, qui résulte du mécanisme par lequel les bosons $W^\pm$ et Z^0 sont devenus massifs.

Le MS est une théorie quantique des champs qui est invariante sous le groupe de symétrie

$SU(3) \times SU(2)_L \times U(1)_Y$. Chacun de ces groupes représente le groupe de symétrie de l'interaction forte, faible et électromagnétique respectivement avec le groupe $SU(2)_L \times U(1)_Y$ ayant associé à l'invariance de la force électrofaible. L'invariance de la Lagrangien, décrivant la propagation du champ électrofaible et ses interactions, ne produit pas des bosons de jauge massifs. Or les deux bosons de jauge W et Z sont massifs, la symétrie $SU(2)_L \times U(1)_Y$ doit être brisée. Cette brisure de la symétrie impose l'existence d'une nouvelle particule ayant aussi une masse, le boson de Higgs.

Le boson de Higgs était une pièce manquante du MS pour longtemps après sa prédiction en 1964 simultanément par Peter Higgs, François Englert et Robert Brout. Le 4 juillet 2012, les expériences ATLAS et CMS du LHC ont observé une nouvelle résonance autour d'une énergie de 125 GeV. Cette résonance est cohérente avec la masse prédite du boson Higgs du MS. Après avoir mesuré les propriétés de cette particule, il a été déduit que les propriétés de cette nouvelle particule correspondent à celles du boson Higgs du MS. Par conséquent, le MS est maintenant une théorie complète avec son dernier pièce trouvé.

II. La production des événements WZ

Lors des collisions proton-proton au LHC, les dibosons peuvent être produit à partir d'une interaction quark anti-quark. La Figure 1.9 montre les diagrammes possibles à l'ordre dominant pour la production de dibosons. La production par l'intermédiaire des voies t et u domine la section efficace. La production de dibosons par la voie s correspondante à la production d'un W virtuel qui se désintègre en un W et Z réel, via un vertex d'interaction appelé vertex de couplage de jauge triple. Ce type de vertex est sensible aux interactions de bosons de jauge entre eux. Dans le MS les couplages de jauge triple incluant un boson chargé sont prévus. Par contre les couplages entre les bosons neutres sont interdits. Les mesures présentées dans cette thèse concernent les couplages de jauge triple chargés. Toute anomalie qui peut être mesuré dans la section efficace des événements $W^\pm Z$, $W^+ Z$, ou $W^- Z$ est un signe pour une nouvelle physique au-delà du MS qui pourra être associé aux couplages anomaux chargés.

Notons que le taux de production des événements $W^+ Z$ est différent de celui du $W^- Z$ au LHC. Les événements $W^+ Z$ sont principalement produits par de l'interaction d'un quark u avec un quark $\bar{d}$ et les événements $W^- Z$ sont produits la plupart du temps quand un quark $\bar{u}$ interagit avec un quark d . En raison de la prédominance de quarks de valence u dans le proton, la production de $W^+ Z$ est plus importante par rapport à la production de $W^- Z$. La cinématique de production de ces deux processus est aussi différente.

III. Le LHC et la description du détecteur ATLAS

Le LHC est le plus grand accélérateur de particules au monde. Le LHC est installé dans un grand tunnel circulaire d'une circonférence de 27 km et il est installé à 175 m de profondeur dans les montagnes du Jura, à la frontière Franco-Suisse. Le LHC est un collisionneur de protons et peut également être utilisé pour accélérer des ions lourds comme le plomb. Il est utilisé pour sonder les constituants fondamentaux de la matière de l'échelle électrofaible (quelques centaines de GeV) à quelques TeV. La première opération réussie du LHC était le 20 Novembre 2009, avec des collisions d'une énergie dans le centre de masse de 900 GeV. L'énergie dans le centre de masse a ensuite progressivement augmentée pour atteindre 7 TeV en 2010 et 2011, puis 8 TeV en 2012. Ensuite, il s'en est suivi à un long arrêt pour redémarrer en 2015 avec des collisions

$p - p$ à une énergie dans le centre de masse de ~ 13 TeV.

ATLAS est l'acronyme de "A Toroidal LHC Apparatus". Le détecteur se trouve dans une cavité du LHC où les collisions ont lieu. ATLAS est un détecteur polyvalent, conçu pour identifier et mesurer les énergies et les directions des particules élémentaires chargées et neutres créés lors des collisions.

ATLAS a une géométrie cylindrique avec 44 m de long et 25 m de haut. Il pèse environ 7000 tonnes et couvre environ 4π de l'acceptance géométrique. Il est composé d'un détecteur interne qui est utilisé pour mesurer la courbure des particules chargées et en déduire leur quantité de mouvement. Le détecteur interne est immergé dans un champ magnétique de 2 T délivré par un aimant solénoïde. Il est construit sur la base de trois types de technologies : la technologie des micro-pistes, la technologie des semi-conducteurs, et une technologie utilisant des pailles de dérive avec un détecteur à rayonnement de transition pour aider à l'identification des électrons. Sur la partie extérieure du détecteur de traces interne, les calorimètres sont placés pour mesurer l'énergie des particules neutres et chargées. Les calorimètres d'ATLAS sont composés d'une partie électromagnétique, basé sur la technologie Argon Liquide et utilisés pour mesurer l'énergie des photons et des électrons et une partie hadronique soit le calorimètre à tuiles, utilisant la technologie de scintillateur à tuile pour mesurer l'énergie des jets hadroniques. Le calorimètre électromagnétique possède une très grande granularité, par conséquent, il fournit des mesures de très haute résolution. Enfin, le spectromètre à muons, situé sur le bord du détecteur ATLAS, est immergé dans un champ magnétique variable fourni par un système d'aimants toroïdaux. Ce spectromètre, est utilisé spécifiquement pour détecter les muons qui interagissent d'abord dans le détecteur interne et contrairement à toutes les autres particules, ils passent à travers les calorimètres en perdant seulement une très petite quantité de leur énergie et laissant finalement des traces dans le spectromètre à muons. Finalement, ATLAS a besoin d'un système de déclenchement pour filtrer les données initialement collectées avec une fréquence de 20 MHz puis enregistrer seulement à un taux de 40 Hz. Le système de déclenchement d'ATLAS possède trois composantes, le niveau-1 de déclenchement (L1), le niveau-2 de déclenchement (L2), et le filtre d'événements (EF). Les systèmes L2 et EF forment un système combiné appelé déclencheur de haut niveau. Des algorithmes complexes sont utilisés dans chacun de ces systèmes pour reconnaître les événements d'intérêts et les conserver pour les analyses physiques.

IV. L'alignement en temps du calorimètre Argon Liquide

Le calorimètre à Argon Liquide d'ATLAS est utilisé pour mesurer l'énergie des particules comme les électrons et les photons. Lorsque des particules telles que les électrons traversent le calorimètre LAr, ils déposent une certaine quantité d'énergie à un instant donné t . En raison de nombreuses imperfections dans le système électronique, la différence de temps δt entre le dépôt de l'énergie et la détection d'un signal par le système électronique du calorimètre n'est pas toujours égale à zéro. Le calcul de δt et de l'énergie d'un dépôt dans le calorimètre sont complémentaires dans ATLAS. Si δt n'est pas autour de zéro, un biais est introduit dans la reconstruction de l'énergie. Cela affecte la qualité des données et toutes les mesures effectuées dans les analyses de physique.

Un alignement précis en temps du calorimètre est alors nécessaire pour assurer une mesure correcte de l'énergie. Des analyses pourraient aussi utiliser l'information du temps des dépôts d'énergie dans le calorimètre pour identifier de possible particules exotiques. Par exemple, l'information du temps des dépôts d'énergie pourrait aider à la recherche des particules exotiques hautement ionisantes ou des particules avec un long temps de vie, demeurant longtemps à l'intérieur du calorimètre. Sinon, pour de très hautes luminosités, les informations de temps

pourraient être utilisées pour rejeter les événements d'empilement produits par des collisions voisines de la collision $p - p$ étudiée. Afin d'être sensible à ce genre d'analyses, il est très important d'avoir une inter-calibration en temps correcte entre les différentes voies de lecture du calorimètre Argon Liquide.

L'alignement en temps du calorimètre Argon Liquid d'ATLAS, a tout d'abord été effectué au niveau des FEBs (Front End Board). Les FEBs appartiennent à la partie frontale du système de lecture électronique du calorimètre. Un second alignement en temps, plus précise a ensuite été réalisé au niveau de chaque cellule du calorimètre. Les corrections en temps au niveau des FEBs ont réduit la déviation standard des distributions du temps moyen des dépôts d'énergies dans les FEBs à 150 ps, ce qui est équivalent à une amélioration de 30% par rapport aux résultats obtenus avec les données 2011. Les corrections en temps au niveau des cellules calorimétriques ont permis une amélioration de la résolution en temps par 200 ps par rapport aux résultats obtenus avant l'introduction de ces corrections. Cette réduction est aussi équivalent à une amélioration de 30% de la résolution temporelle.

V. Mesure de la section efficace de production du WZ

Dans l'analyse présenté dans cette thèse, les données utilisées sont celles provenant des collisions proton-proton au LHC collectées entre avril et décembre 2012 à une énergie au centre de masse de 8 TeV. Seules les données enregistrées lorsque tous les sous-détecteurs et les systèmes de déclenchement sont en bon état de fonctionnement sont utilisées. En 2012, la luminosité intégrée de ces données qualifiée comme "bonne", était de 20.3 fb^{-1} avec une incertitude de 2.8%.

Au niveau de l'analyse, les événements de données sont soumis à des procédures de nettoyage additionnelles afin de réduire le bruit provenant des dépôts d'énergie parasites ou des événements corrompus dans le calorimètre ou des sources non attribuées à la collision $p - p$. Or, on cherche à étudier les états finaux leptonique, les événements WZ sont sélectionnés de sorte que l'événement contienne trois "bon" leptons et de l'impulsion transverse manquante. Des coupures additionnelles sur l'isolation de ces leptons sont demandées aussi qu'une coupure sur la masse transverse du candidat W . Ces coupures sont optimisées afin de minimiser le taux des événements de bruit de fond tout en gardant une efficacité importante sur la sélection de vrai événements WZ .

Les principaux événements de fond imitant le signal de WZ proviennent des processus ZZ , $Z\gamma$, $Z + jets$, $t\bar{t}$ et $t\bar{t} + V$ où V est un boson vecteur W ou Z . L'accord entre les données et les simulations Monte Carlo des processus ZZ , $Z\gamma$, $Z + jets$ et $t\bar{t}$ est contrôlé en utilisant des régions de contrôles spécifiques pour chacun de ces processus. L'accord observé entre les données et les prédictions MC est en général bien pour les processus ZZ et $Z\gamma$. Les événements de $Z + jets$ et $t\bar{t}$ ont montré une différence dans la normalisation entre les données et les Monte Carlos tel que une normalisation de 1.16 ± 0.02 est trouvée pour le $t\bar{t}$, une normalisation de 1.1 ± 0.03 pour les $Z + jets$ dans les canaux eee et $\mu\mu e$ et une normalisation de 0.96 ± 0.06 pour les $Z + jets$ dans les canaux $\mu\mu\mu$ et $ee\mu$.

Les résultats finaux en combinant tous les canaux correspondent à 2091 événements WZ observés dans les données pour 1856 événements prédits par le Monte Carlo, incluant la contribution estimés des événements de bruit de fond.

Les mesures de la section efficace WZ sont effectuées dans deux espaces de phase, total et fiduciel. L'espace de phase fiduciel définit une région restreinte de l'espace de phase, très proche à l'acceptance de la mesure expérimentale. Ceci permet de faire une mesure qui est moins sen-

sible aux incertitudes théoriques telles que celles résultant de la connaissance des Fonctions de Distributions des Partons (PDF) dans le proton. En effet, ces incertitudes théoriques deviennent plus importantes lorsque la mesure est extrapolée à l'espace de phase total. Cette extrapolation repose uniquement sur la précision de la prédiction théorique. D'un autre côté, l'avantage de l'extrapolation à l'espace de phase totale est que les résultats seront indépendants des critères de sélection et ceci permet de comparer facilement aux résultats obtenus par différentes expériences.

En physique des particules, une section efficace est la probabilité pour que deux ou plusieurs particules entrent en collision et réagissent d'une certaine manière. Experimentalement, la mesure d'une section efficace s'effectue en comptant le nombre d'événements observés pour un processus donné par rapport au nombre total d'événements créés au cours des collisions $p - p$. Techniquement, la section efficace de production de WZ est le rapport des événements de données totaux WZ soustraits par le nombre d'événements de fond estimées divisé par la luminosité intégrée des collisions $p - p$. Ce rapport est ensuite corrigé par des facteurs représentant l'efficacité et l'acceptance du détecteur.

En utilisant cette définition, on calcule une section efficace fiducielle égale à :

$$\sigma_{fid}^{comb} = 35.11 \pm 0.93 \text{ (stat.)} \pm 1.31 \text{ (sys.)} \pm 1.08 \text{ (lumi.) fb}, \quad (\text{A.2})$$

et une section efficace totale égale à :

$$\sigma_{tot}^{comb} = 24.54 \pm 0.65 \text{ (stat.)} \pm 0.91 \text{ (sys.)} \pm 0.76 \text{ (lumi.) pb}, \quad (\text{A.3})$$

Cette mesure peut être comparée à la prédiction théorique de :

$$\sigma_{th} = 21.68 \pm 0.02 \text{ (stat.)} \pm 0.75 \text{ (PDF)} \pm 1.39 \text{ (QCDScale) pb}, \quad (\text{A.4})$$

où les incertitudes sont dues à la statistique de l'échantillon utilisée pour la prédiction, cette incertitude est négligeable. L'incertitude des PDF provenant des 52 vecteurs propres du CT10 et d'une comparaison des résultats à ATLAS PDF. Finalement, l'incertitude de l'échelle QCD provient de la variation de l'échelle de renormalisation et de factorisation entre une échelle M_{WZ} dynamique et $(M_W + M_Z)/2$ fixe.

La différence entre les mesures et la prédiction est de l'ordre de 10% avec une section efficace mesurée plus haute que la prédiction théorique.

Dans cette thèse, la mesure du rapport des sections efficaces de production des événements W^+Z et W^-Z dans l'espace de phase fiduciel a également été effectué. La mesure de ce rapport est de :

$$R_{fid} = \frac{\sigma_{W^+Z}}{\sigma_{W^-Z}}|_{fid} = 1.50 \pm 0.08 \text{ (stat.)} \pm 0.02 \text{ (sys.)} \pm 0.002 \text{ (lumi.)}, \quad (\text{A.5})$$

qui est $\sim 10\%$ inférieure à la prédiction théorique calculé comme :

$$R_{fid,th} = \frac{\sigma_{W^+Z}}{\sigma_{W^-Z}}|_{fid,th} = 1.69 \pm 0.01 \text{ (stat.)} \pm 0.07 \text{ (PDF)}. \quad (\text{A.6})$$

Des mesures des sections efficaces fiducielles et totales ont été présentées. Des mesures du rapport des sections efficaces de production d'événements W^+Z et W^-Z ont été effectuées. Les résultats ont été comparés aux prédictions théoriques. La combinaison finale montre un accord raisonnable entre les mesures et la prédiction théorique. L'incertitude totale sur la mesure de la section efficace intégrée est de 5.5%, atteinte en réduisant l'incertitude statistique de 55% par rapport aux précédents résultats d'ATLAS.

VI. Mesure de la section efficace différentielle normalisée des événements WZ

Les mesures de la section efficace différentielle normalisée en fonction de différentes variables cinématiques sont aussi présentées dans cette thèse. Ces mesures sont les premières avec l'ensemble des données d'ATLAS 2012 à $\sqrt{s} = 8$ TeV. Il a été démontré que des couplages de jauge triples anomaux pourraient créer une augmentation de la section efficace sur les queues de certaines distributions différentielles liées aux énergies des particules produites, comme le p_T^Z , le p_T^W ou le M_{WZ} . Ces couplages affectent également des distributions angulaires comme le $y_Z - y_{l,W}$. Par conséquent, la mesure de ces distributions différentielles est importante pour contrôler leurs accord avec la prédiction théorique du MS et l'absence de déviation à celui-ci.

La section efficace différentielle normalisée dans l'espace de phase fiduciel peut être mesurée en calculant dans chaque *bin* d'une distribution cinématique, la section efficace fiducielle comme définit auparavant, puis en normalisant cette quantité avec la section efficace fiducielle totale mesurée sur tous les *bins*. Cette procédure de normalisation permet d'être indépendant de toute différence globale entre la mesure et la prédiction et permet de pouvoir ainsi comparer uniquement les formes des spectres mesurés et prédits. Cette normalisation des mesures différentielles permet également de réduire l'effet des incertitudes systématiques expérimentales (par exemple l'incertitude liée à la luminosité enregistrée).

La section efficace différentielle normalisée est corrigée par des facteurs liés aux différents effets comme l'efficacité du détecteur et les effets de sa résolution. Le processus de correction des données de ces effets est appelée déconvolution. Dans cette thèse, nous avons étudié deux façons différentes de déconvolution. La première est la méthode dite *bin par bin* qui est appliquée en utilisant des facteurs correctifs calculés indépendamment par *bin* des distributions différentielles. L'autre est la méthode "Bayésien itérative" appliquée en utilisant le théorème de Bayes pour calculer des probabilités telles que plusieurs causes créent différents effets, puis en itérant plusieurs fois jusqu'à ce qu'un accord entre les prédictions reconstruites et générées soit atteint.

Les résultats obtenus sont montrés dans le tableau ci-dessous :

p_T^Z bins	σ_{Norm}^{fid}		$\delta\sigma_{Norm}^{fid}(stat)$ [%]		$\delta\sigma_{Norm}^{fid}(sys)$ [%]	
	bin-by-bin	iterative	bin-by-bin	iterative	bin-by-bin	iterative
0–30	0.221	0.219	5.14	5.81	1.61	1.81
30–60	0.358	0.363	3.64	4.11	0.92	1.19
60–90	0.186	0.184	5.72	6.88	1.38	1.62
90–120	0.104	0.104	8.02	9.61	2.04	2.27
120–150	0.057	0.058	11.08	12.99	2.59	2.95
150–180	0.048	0.048	12.04	10.51	2.43	2.33
180– ∞	0.026	0.026	16.38	24.42	3.77	5.35

Table A.2: Section efficace différentielle normalisée avec les incertitudes statistiques et systématique par bin de p_T^Z en utilisant les déconvolution "bin par bin" et "Bayésien itérative".

Dans ce tableau, les deux premières colonnes montrent les valeurs centrales de la section efficace différentielle normalisée pour chaque *bin* de p_T^Z avec les deux méthodes de déconvolution. Les troisième et quatrième colonnes montrent les incertitudes statistiques sur la mesure par *bin*. Finalement, les deux dernières colonnes montrent l'incertitude systématique par *bin*. Comme

montré dans le tableau, les résultats obtenus avec les deux méthodes de déconvolution sont en très bon accord. Finalement, la comparaison de ces résultats aux prédictions théoriques a montré que la forme des sections efficaces différentielles normalisées est en accord avec les prédictions du MS.

VII. Conclusion

Dans la première partie de cette thèse l'alignement en temps du calorimètre Argon Liquide d'ATLAS a été présenté. Lors de la prise de données 2012, le temps des dépôts d'énergie dans le calorimètre a été suivie. Ensuite, deux séries de corrections ont été introduites pour aligner le calorimètre en temps. Tout d'abord, des corrections temporelles ont été appliqués pour aligner les *Front End Boards* (FEB) en temps. Ces corrections ont permis de réduire la dispersion de la réponse en temps des différents FEBs du calorimètre à ~ 150 ps. Puis des corrections plus précises ont été extraites pour chaque cellule du calorimètre. Avec ces corrections une amélioration de la résolution temporelle des dépôts d'énergie dans le calorimètre par ~ 200 ps a pu être atteint.

Dans la deuxième partie de cette thèse, des mesures de section efficace de production des événements $W^\pm Z$, $W^+ Z$, et $W^- Z$ ont été présentés en utilisant les données 2012 d'ATLAS provenant des collisions proton-proton à une énergie dans le centre de masse de 8 TeV au LHC. Le tableau ci-dessous compare la section efficace mesurée dans l'espace de phase totale aux mesures préliminaire obtenus par l'expérience CMS. Les deux résultats sont en très bon accord.

Experiment	$\sigma(pp \rightarrow WZ; \sqrt{s} = 8 \text{ TeV}) [\text{pb}]$
ATLAS	$24.54 \pm 0.65 \text{ (stat.)} \pm 0.91 \text{ (sys.)} \pm 0.76 \text{ (lumi.)}$
CMS	$24.61 \pm 0.76 \text{ (stat.)} \pm 1.13 \text{ (sys.)} \pm 1.08 \text{ (lumi.)}$

Table A.3: Section efficace totale intégrée de production de WZ en pb pour les expériences ATLAS et CMS.

Cette mesure a permis d'améliorer l'incertitude statistique expérimentale par 55% par rapport aux mesures obtenues précédemment avec les données 2011.

Nous avons également présenté dans cette thèse la mesure des rapports des sections efficaces $W^+ Z$ et $W^- Z$. Cette mesure n'était pas possible auparavant avec les données enregistrées en 2011, par manque de statistique.

Enfin, des mesures de la section efficace différentielle normalisée en fonction de quatre variables cinématiques, p_T^Z , p_T^W , M_{WZ} , et $y_Z - y_{W,l}$ ont montré un bon accord avec les prédictions du Modèle Standard. Aucune différence entre la mesure et les prédictions sur la forme des distributions différentielles n'a été observé.

Le travail présenté dans cette thèse sera inclus dans une éventuelle publication de la collaboration ATLAS, qui est en cours de préparation.

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Résumé: Ce travail de thèse se situe dans le cadre de l'expérience ATLAS au LHC. Une première partie du travail présenté dans ce document porte sur l'étalonnage temporel du calorimètre à argon liquide d'ATLAS (LAr). Le control de l'alignement temporel du calorimètre est important pour la bonne qualité de l'énergie reconstruite dans le calorimètre. Les résultats présentés dans cette thèse ont permis une amélioration de 30% de la résolution temporelle globale du calorimètre LAr.

Le Modèle Standard de la physique des particules prédit, lors des collisions de protons, la production de bosons faibles W et Z par paire via l'interaction d'un quark et d'un anti-quark. La production de dibosons peut être sensible aux couplages des bosons vecteurs entre eux. Une déviation anormale de ces couplages par rapport aux valeurs prédites par le MS pourrait signer la présence de nouvelle physique. L'exploitation de toute la statistique des données 2012 d'ATLAS nous a permis d'accroître la précision de la mesure de ces couplages par rapport aux précédents résultats basés sur des lots de données moindres. Cette thèse présente donc la mesure de la section efficace de production des dibosons WZ utilisant l'ensemble de données collectées par ATLAS en 2012 lors de collisions $p-p$ au LHC à une énergie de 8 TeV au centre de masse. Avec la statistique disponible, le rapport des sections efficaces de production des événements W^+Z et W^-Z a pu être aussi mesuré. Cette dernière mesure n'avait pu être effectuée jusqu'alors en utilisant les données 2011 en raison du manque de statistique. Enfin, des mesures de section efficaces différentielles normalisées en fonction de quatre variables cinématiques ont aussi été effectuées. La précision sur la section efficace intégrée mesurée est de 5.5%, ce qui est atteint en réduisant l'incertitude statistique par 55% par rapport aux précédents résultats d'ATLAS. Ainsi, les incertitudes expérimentales des mesures ont commencé à se rapprocher des incertitudes des prédictions théoriques. Ceci est prometteur pour les futures mesures au LHC avec beaucoup plus de statistique où l'on s'attend alors à une augmentation significative de la précision expérimentale.

Abstract: This thesis is performed in the frame of the ATLAS experiment at the LHC. A first part of the work presented in this document consists on the time calibration of the ATLAS Liquid Argon (LAr) calorimeter. The control of the time alignment of the calorimeter is important for the goodness of the quality of the energy reconstructed in the calorimeter. The results presented in this thesis have allowed an improvement of 30% of the global time resolution of the LAr calorimeter.

The Standard model of particle physics predicts, during proton collisions, the production of the W and Z weak bosons as a pair due to the interaction of a quark with an anti-quark. The diboson production can be sensitive to the couplings between vector bosons. An anomalous deviation of these couplings from the prediction of the SM would point to the presence of new physics. The use of the full statistics of the 2012 ATLAS data allowed us to increase the precision of the measurement of these couplings compared to previous results based on smaller datasets. This thesis presents therefore the measurement of the WZ dibosons production cross section using the full 2012 data collected by the ATLAS experiment from the $p-p$ collisions at the LHC at a center-of-mass energy of 8 TeV. Also, with the available statistics the ratio of the production cross sections of W^+Z and W^-Z events were measured. This measurement was not performed previously using the 2011 data due to a lack of statistics. Finally, measurements of the normalized differential cross section as a function of four kinematic variables were also performed. The precision on the measured integrated cross section is 5.5% which is reached mainly by the reduction of the statistical uncertainty by 55% with respect to the previous ATLAS results. Therefore, the order of magnitude of the experimental uncertainties on the measurement started to approach that of the theoretical predictions. This is promising for future measurements at the LHC as with higher statistics the experimental precision is expected to overcome the theoretical one.