

Associated production of weak bosons at the LHC with the ATLAS detector

Marius Groll (*on behalf of the ATLAS Collaboration*)

Institute of Physics, Johannes-Gutenberg University of Mainz, Germany

E-mail: groll@uni-mainz.de

Abstract. The study of the associated production of weak vector bosons at the LHC allows to search for New Physics through the measurement of possible deviations of the weak boson self-couplings from the expectation within the Standard Model. The sensitivity of the ATLAS experiment to Standard Model diboson ($W^+ W^-$, $W^\pm Z^0$, $Z^0 Z^0$, $W^\pm \gamma$, and $Z^0 \gamma$) production in pp collisions at $\sqrt{s} = 14$ TeV, using final states containing electrons, muons and photons, is presented. These studies use Monte Carlo data sets with full detector simulation from the ATLAS Computer System Commissioning, which furthermore include detailed trigger information as well as effects of detector calibration and alignment corrections. The influence of backgrounds on diboson detection is assessed using large samples of fully simulated background events. The sensitivity of the ATLAS experiment to anomalous triple gauge boson couplings is determined. Even for small integrated luminosities (about 0.1 fb^{-1}) the sensitivity to anomalous triple gauge boson couplings can be significantly improved by ATLAS, when comparing to results from the Tevatron that use 1.0 fb^{-1} of data.

1. Introduction

Studies of the ATLAS experiment's sensitivity to diboson ($W^+ W^-$, $W^\pm Z^0$, $Z^0 Z^0$, $W^\pm \gamma$, and $Z^0 \gamma$) production using lepton and photon final states, and the corresponding ability to set limits on triple gauge boson couplings (TGC) are discussed. Results are based on Monte Carlo datasets produced in the ATLAS Computing System Commissioning (CSC) program. The analysis of diboson production at the LHC provides an important test of the high energy behavior of electroweak interactions. Many models predict deviations of vector boson self-couplings from the Standard Model at the $10^{-3} - 10^{-4}$ level [1]. Experiments that can reach this sensitivity could provide powerful constraints on these models.

The signature for anomalous couplings is an enhanced diboson production cross-section, particularly at high transverse momentum (p_T) of the bosons. Experimental limits on non-Standard Model TGC's can be obtained by comparing the shape of the measured p_T or mass distributions (or transverse mass, M_T , for final states involving $W^\pm$ -bosons) with predictions, provided that the signal is not overwhelmed by background. Furthermore, the diboson signal is also an important background for many searches beyond the SM like Higgs and SUSY and therefore it is important to understand these signals.

The analysis uses over 30 million fully simulated and reconstructed events, with a detector layout and trigger system that reflects the ATLAS experiment [2] as it will operate at LHC turn-on, thus providing a realistic understanding of the detection of these diboson final states. A Boosted Decision Tree (BDT) [3] technique is applied to selected channels, significantly

enhancing measurement sensitivities. These are among the ways this study improves on the understanding and the results of the previous ATLAS diboson studies [4]-[5].

Tree-level Feynman diagrams for electroweak diboson production at hadron colliders, where V_1 , V_2 stand for W, Z or γ are shown in Figure 1. The s -channel diagram contains the vector-boson self-interaction vertices of interest here. These diboson final states have predictable cross-sections and manifest the gauge boson coupling. The pure neutral ZZZ and $ZZ\gamma$ are forbidden in the SM and therefore only the charged vertices $WW\gamma$ and WWZ define the TGC.

The cross-sections are calculated to next-to-leading-order (NLO) in [6]-[8]. The LHC diboson production rates will exceed those of the Tevatron by at least a factor 100 (10 times higher cross-sections and at least 10 times higher luminosity). Furthermore, because the energy reach at the LHC will be 7 times higher than at the Tevatron, the LHC sensitivity to anomalous TGC's is expected to be improved by orders of magnitude over that which can be reached at the Tevatron or LEP. The Standard Model diboson production cross-sections are listed in detail in [9]. For example, the cross section for $W^\pm Z$ [10] with the $W^\pm$ -boson and Z -boson on mass shell is 3.7 pb at the Tevatron and 47.8 pb at the LHC. The theoretical uncertainty from the Parton Distribution Functions (PDF) and the QCD scale factor is typically of the order of 5%.

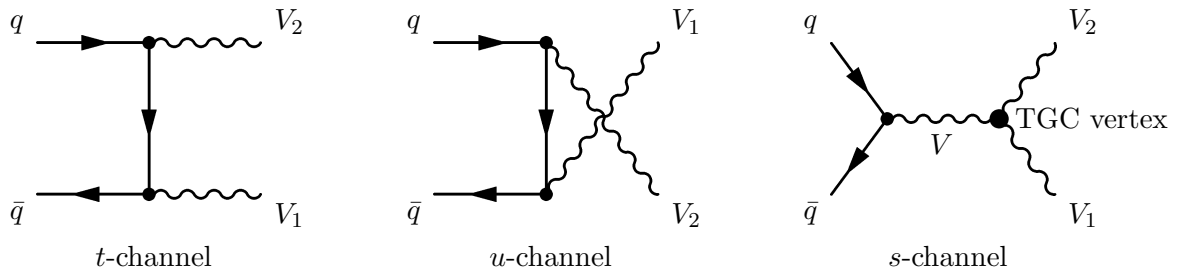


Figure 1. The generic Standard Model tree-level Feynman diagrams for diboson production at hadron colliders; $V, V_1, V_2 = \{W, Z, \gamma\}$. The s -channel diagram contains the trilinear gauge boson vertex. In the Standard Model, only $WW\gamma$ and WWZ vertices are allowed.

2. Event selection

The event selection follows two general approaches: One cut-based approach based on kinematic variables and a second approach using Boosted-Decision-Trees. Both strategies have profited by the clean signal of the leptonic final state particles and by the experimentally well established identification of $W^\pm$ -bosons and Z -bosons. Furthermore, the known masses of these bosons give additional constraints and their decay leads to a certain number of high- p_T leptons depending on the final state, which can be well observed due to low background contributions and high efficiencies at already low trigger thresholds.

As an example the event selection of WZ events is described. In total three high- p_T leptons are required, each having a p_T higher than 25 GeV. Due to the non-detectable ν a high missing transverse energy of at least 25 GeV is required. The separation of the leptons is achieved by requesting a minimal opening angle between the two leptons of $\Delta R(l^+l^-) > 0.2$. Since two leptons originate from the Z -boson, the invariant mass of two leptons should fit into the Z -boson mass window. A powerful cut to reduce especially background from $t\bar{t}$ events is to limit the hadronic activity in the event. Therefore, only one jet with transverse energy larger than 30 GeV is allowed and the total hadronic transverse energy is limited to be below 200 GeV. The resulting background contributions for example in the BDT analysis are $pp \rightarrow t\bar{t}$ contributing with 17.4 %, $pp \rightarrow Z + jets$ and $pp \rightarrow Z/\gamma^* \rightarrow ee/\mu\mu$, where the final state leptons are produced via τ -lepton decays. These channels are sources for fake missing E_T and a fake third lepton

signal due to a jet. The dominant background contribution with a fraction of 47.8 % originates from $pp \rightarrow ZZ \rightarrow 4$ leptons, where one lepton is lost in the reconstruction.

The trigger is a combination of single and dilepton triggers, which leads to an efficiency of $(98.9 \pm 0.1)\%$. The signal efficiency is 8.7% for W^-Z and 7.1% for W^+Z events. In the cut-based event selection this leads to the results listed in Table 1, where a signal to background ratio of around 7 is achieved. For 0.1 fb^{-1} of integrated luminosity, only 5 signal events (N_S) with 0.7

Table 1. Number of expected $W^\pm Z^0$ signal (N_{WZ}) and background (N_B) events for 1 fb^{-1} with cut-based analysis and with BDT analysis using the cut $\text{BDT} > 200$.

cut-based	WZ	$Z^0 Z^0$	$t\bar{t}$	$Z + \text{jet}$	$Z + \gamma$	Drell-Yan	Total bkg	N_{WZ}/N_B
N events	53	2.7	.023	1.9	0.18	2.5	7.3	7.3
% of background	-	37	.32	26	2.5	35	-	-
BDT								
N events	128	7.7	2.8	2.5	2.0	1.1	16	7.9
% of background		48	17	16	12	7.0	-	-

background event (N_B) contamination are expected. The $W^\pm Z^0$ detection significance, defined as the probability from Poisson distribution with a mean of N_B to observe equal or greater than $N_S + N_B$ events, converted in equivalent number of sigmas (standard deviations) of a Gaussian distribution, will be 3.6σ only. To improve the detection sensitivity, the BDT analysis technique is employed. Based on the variables used in the cut-based analysis, a total of 22 kinematic and topological variables are selected for the BDT training. The outcome is shown in Table 1. The detailed description including efficiencies of the event selection for the other channels is described in [9]. In principle the same quantities and selection strategy are used. However, the general statement that the BDT selection has a higher detection sensitivity can be e.g. shown for the $W^+ W^- \rightarrow l^+ \nu l^- \nu$ channel. The cut based analysis achieves an efficiency of only 2 % where the BDT selection depending on the lepton flavour has an efficiency between 6 and 15 %. The cross-section measurement uncertainties are estimated for various event selection cuts and integrated luminosities e.g. in the $W^\pm Z^0$ BDT based analysis. The BDT output spectra are used to build a log-likelihood distribution by using ‘mock data’, which is a sample of simulated events with appropriate statistics according to the luminosity and the Standard Model. To understand the optimal cut on the BDT spectra for cross-section measurements, the cuts on the BDT spectra are varied and the cross-section measurements are repeated. Figure 2 (left) shows the cross-section measurement uncertainty as a function of the BDT cut for different integrated luminosities from the $W^\pm Z^0$ analysis. Figure 2 (right) shows the relative cross-section uncertainties as a function of integrated luminosity (with BDT spectrum cut at 200) for the $W^\pm Z^0$ cross-section measurements. A total of 9.2% systematic uncertainty is included, where the luminosity uncertainty contributes with 6.5% and starts to dominate after 10 fb^{-1} of integrated luminosity.

3. Sensitivity to anomalous couplings

The signature of anomalous couplings in diboson production is an increase in the cross-section at high values of gauge boson transverse momentum (p_T) and diboson transverse mass (M_T). The ATLAS sensitivity to anomalous TGC’s is investigated by comparing the ‘measured’ diboson production cross-sections and the vector boson p_T or diboson M_T distributions to models with anomalous TGC’s. A binned likelihood fitting procedure for each channel is performed to extract

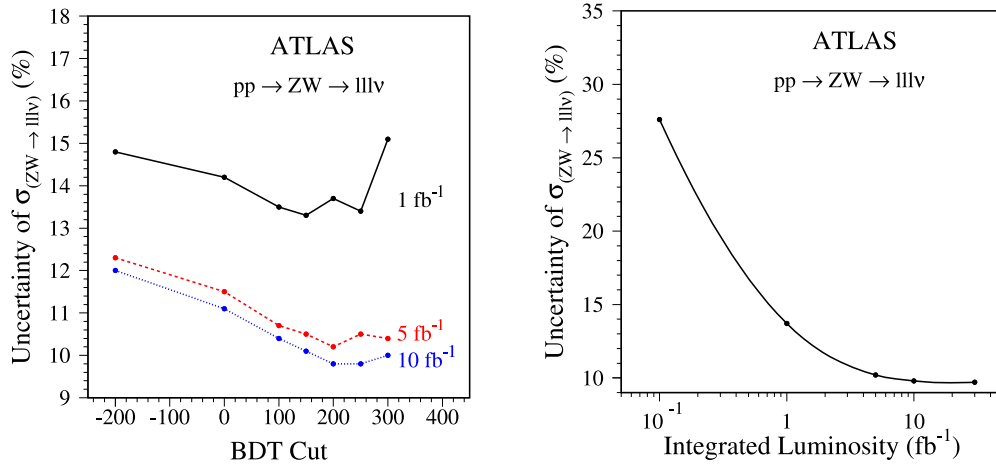


Figure 2. The total relative uncertainties for $W^\pm Z^0$ production (left) cross section measurements as the BDT cut is varied for different luminosities. The optimal BDT cut is between 200 and 300. The $W^\pm Z^0$ production (right) cross-section measurement uncertainties as a function of integrated luminosity (with BDT spectrum cut at 200). An overall 9.2% systematical uncertainty was included in the fitting process in both studies.

the 95% C.L. intervals of anomalous coupling parameters. The most general effective Lagrangian for charged triple gauge boson interactions [11], that conserves C and P separately, introduces three coupling parameters g_1^V, κ_V and λ_V . The Standard Model triple gauge boson vertices are created by letting $g_1^V = \kappa_V = 1$ and $\lambda_V = 0$. Experimentally, deviations from the Standard Model couplings is searched for; thus the anomalous coupling parameters are defined as

$$\Delta g_1^Z \equiv g_1^Z - 1, \quad \Delta \kappa_\gamma \equiv \kappa_\gamma - 1, \quad \Delta \kappa_Z \equiv \kappa_Z - 1, \quad \lambda_\gamma, \quad \text{and} \quad \lambda_Z.$$

Note that electromagnetic gauge invariance requires $g_1^\gamma = 1$ or $\Delta g_1^\gamma = 0$. With non-Standard Model coupling parameters, the amplitudes for gauge boson pair production grow with energy, eventually violating tree-level unitarity. The unitarity violation is avoided by introducing an effective cutoff scale, Λ [12]. The sensitivities are expressed in terms of constraints on the anomalous triple gauge boson couplings in the effective Lagrangian. The effective Lagrangian for neutral TGC's is different and introduces the following four parameters $f_4^Z, f_5^Z, f_4^\gamma, f_5^\gamma$.

One- and two-dimensional limits are set on the charged CP-conserving coupling parameters from the W^+W^- , $W^\pm Z^0$, and $W^\pm \gamma$ final states. For this study, with 0.1-30 fb⁻¹ of integrated luminosity, Λ values of 2-3 TeV are used. To avoid producing an impractically large number of fully simulated events in the non-Standard Model anomalous coupling parameter space, a re-weighting method was invoked to study the ATLAS detector sensitivities to anomalous coupling parameters. The BHO [13] and the BosoMC [14] calculations are used with different anomalous coupling parameters to re-weight the fully simulated events generated by MC@NLO [10]. The fully simulated events with the Standard Model couplings are required to pass the event selection cuts, and then reweighted according to the parton level kinematics.

The $W^\pm Z^0$ diboson production involves exclusively the WWZ coupling, in contrast to the W^+W^- diboson final state which contains both WWZ and $WW\gamma$ couplings. To extract the 95% C.L. sensitivity intervals on the anomalous parameters, $\Delta \kappa_Z, \Delta g_1^Z$, and λ_Z , from the $W^\pm Z^0$ diboson final state, both the transverse mass of $W^\pm Z^0$ ($M_T(W^\pm Z^0)$) and the transverse momentum of Z ($p_T(Z^0)$) spectra are used to fit the anomalous couplings. This study has been performed for 0.1, 1, 10, and 30 fb⁻¹ of integrated luminosity to study the anomalous

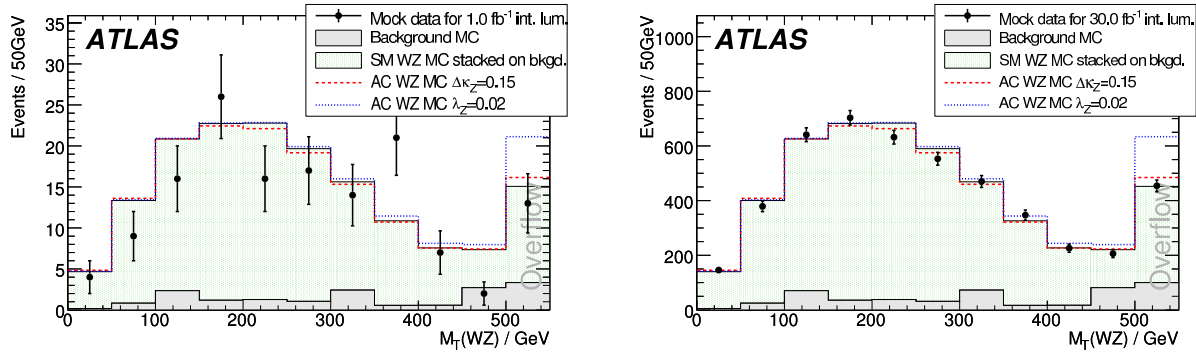


Figure 3. The expected signal+background of the Standard Model, superimposed with ‘mock data’ (points with error bars showing statistical uncertainty), and the non-Standard Model (anomalous couplings) predicted signal+background histograms (dashed and dotted histograms). The last bins in the plots are overflow-bins. The left plot is for 1 fb^{-1} and the right plot is for 30 fb^{-1} of integrated luminosity.

coupling sensitivities. Figure 3 shows the expected signal+background of the Standard Model, superimposed with the ‘mock data’ (points with error bars), and the non-Standard Model (anomalous couplings) predicted signal+background distributions. Table 2 shows the summary

Table 2. Summary of WWZ one-dimensional anomalous coupling parameter 95% CL sensitivities using the $M_T(W^\pm Z^0)$ fitting for $\Lambda = 2 \text{ TeV}$ and $\Lambda = 3 \text{ TeV}$ for integrated luminosities of 0.1 and 30 fb^{-1} .

Int. Lumi (fb^{-1})	Cutoff Λ (TeV)	$\Delta\kappa_Z$	λ_Z	Δg_1^Z
1	2.0	[-0.203, 0.339]	[-0.028, 0.024]	[-0.021, 0.054]
30	2.0	[-0.080, 0.169]	[-0.012, 0.008]	[-0.005, 0.023]
1	3.0	[-0.178, 0.281]	[-0.020, 0.018]	[-0.017, 0.038]
30	3.0	[-0.069, 0.131]	[-0.008, 0.005]	[-0.003, 0.016]

of 1-dimensional 95% C.L. anomalous coupling parameter intervals based on the $M_T(W^\pm Z^0)$ spectra fitting. Results corresponding to 1 and 30 fb^{-1} of integrated luminosity for cutoff values of $\Lambda = 2 \text{ TeV}$ and $\Lambda = 3 \text{ TeV}$ are listed. It should be noted that even for 0.1 fb^{-1} of integrated luminosity, the ATLAS sensitivity to WWZ anomalous couplings could be much better than the Tevatron limits based on 1 fb^{-1} of $p\bar{p}$ collision data.

To understand the systematic uncertainty effects on the TGC sensitivity, different systematic uncertainty assumptions are considered. Starting with the ideal case with no systematic uncertainties: $\sigma_S = 0$, and $\sigma_B = 0$ going to a conservative situation where the systematic uncertainty of 9.2% for signal, and 18.3% for background is considered. This study shows that the systematic uncertainties become significant enough to affect the TGC sensitivities only when reaching 30 fb^{-1} of integrated luminosity. The studies on the WWZ anomalous couplings in two-dimensional space are also based on the $p_T(Z)$ fits for different integrated luminosities and for the two cutoff values. The anomalous coupling limit contours are not very sensitive to these cutoff values. The effects of different systematic uncertainties on the 2-dimensional TGC sensitivity contour have been investigated as well. Again, the systematic uncertainties become

significant when the integrated luminosity reaches 30 fb^{-1} .

4. Summary

This note presents studies of the production of diboson pairs from pp collisions at the LHC, using leptonic decays of $W^\pm$ -bosons and Z -bosons. The simulated measurements are done using the ATLAS detector with full detector simulation and event reconstruction, and the statistics expected in the initial data taking periods. The advanced analysis technique BDT is used in analysis of most of the final states, which improves the sensitivities significantly. This study concludes that with 0.1 fb^{-1} of integrated luminosity the Standard Model signals of W^+W^- , $W^\pm Z$, $W^\pm \gamma$ and $Z\gamma$ can be established with significance better than 5σ assuming 20% systematic uncertainties. ZZ production can be established with 1 fb^{-1} of data using the four-lepton decay channels.

Any significant deviation from the Standard Model prediction for these final states can lead to indications of new physics phenomena. The sensitivities to anomalous TGCs are presented. Table 3 compares the 95% confidence level sensitivity interval for charged anomalous TGC's using observables from different diboson final states with 10 fb^{-1} of integrated luminosity. Compared to recent published limits from the Tevatron [15]-[18] and LEP [19] it can be stated that the sensitivity increases by an order of magnitude.

Table 3. 95% C.L. interval of the anomalous coupling sensitivities from W^+W^- , $W^\pm Z$, $W^\pm \gamma$ final states with 10 fb^{-1} of integrated luminosity and the cutoff $\Lambda = 2 \text{ TeV}$. The table also indicates the variables used in the fit to set the AC sensitivity interval.

Diboson,	λ_Z	$\Delta\kappa_Z$	Δg_1^Z	$\Delta\kappa_\gamma$	λ_γ
$WZ, (M_T)$	[-0.015, 0.013]	[-0.095, 0.222]	[-0.011, 0.034]		
$W\gamma, (p_T^\gamma)$				[-0.26, 0.07]	[-0.05, 0.02]
$WW, (M_T)$	[-0.040, 0.038]	[-0.035, 0.073]	[-0.149, 0.309]	[-0.088, 0.089]	[-0.074, 0.165]

The neutral anomalous TGC's can be explored with the $Z^0\gamma$ and Z^0Z^0 final states. The Z^0Z^0 final state is used to probe the neutral anomalous TGC sensitivity. Both the $ZZ \rightarrow \ell^+\ell^-\ell^+\ell^-$ and $ZZ \rightarrow \ell^+\ell^-\nu\bar{\nu}$ final states are used to constrain the neutral anomalous TGC parameters ($f_4^Z, f_5^Z, f_4^\gamma, f_5^\gamma$). The 95% C.L. intervals on the anomalous couplings for 10 fb^{-1} of integrated luminosity are listed in Table 4. The 95% C.L. limits on neutral TGC from LEP Z^0Z^0 detection are reviewed in [19]. Compared to published limits from LEP it can be observed that the combined sensitivity increases by an order of magnitude.

Table 4. Expected 95% C.L. intervals on anomalous couplings from fits to the $ZZ \rightarrow \ell\ell\ell\ell$ channel, the $ZZ \rightarrow \ell\ell\nu\nu$ channel and both channels together for 10 fb^{-1} of integrated luminosity, with $\Lambda = 2 \text{ TeV}$. In each case, other anomalous couplings are assumed to be zero.

	f_4^Z	f_5^Z	f_4^γ	f_5^γ
$ZZ \rightarrow \ell\ell\ell\ell$	[-0.010, 0.010]	[-0.010, 0.010]	[-0.012, 0.012]	[-0.013, 0.012]
$ZZ \rightarrow \ell\ell\nu\nu$	[-0.012, 0.012]	[-0.012, 0.012]	[-0.014, 0.014]	[-0.015, 0.014]
Combined	[-0.009, 0.009]	[-0.009, 0.009]	[-0.010, 0.010]	[-0.011, 0.010]

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