

# Introduction to LHC physics

**Giacomo Polesello**

INFN, Sezione di Pavia, via Bassi 6, 27100 Pavia Italy

**Abstract.** An elementary introduction to the basic features of experimentation at the LHC is given, with some emphasis on the detector requirements and on some basic experimental techniques. The experimental program is briefly introduced, and bibliographical indications are provided for a detailed study of the key physics topics.

## 1. Introduction

The two lectures delivered in Corfu in 2005 included a general introduction to experimentation at the LHC, a review of the key measurements in Standard Model physics which will be performed by the ATLAS and CMS experiments, and a description of the strategy developed by the experiments to search for the Higgs boson.

In these proceedings, a detailed write-up only of the general introductory part is given, also to serve as introduction to the lectures on physics beyond the Standard Model given by Frank Paige at the same school. For the discussion of physics topics, for which excellent material is existing, I will limit myself to give some bibliographical indication to guide the student through the latest key developments.

While most of the issues are common for the ATLAS and CMS experiments, the detailed discussions on specific topics will be mainly based on ATLAS material, with which, as a member of the Collaboration, I have a better familiarity.

Finally, the basic reference for all physics studies at the LHC are Technical Design Reports (TDR) for physics of the two experiments [1]-[3]. The size of the multi-volume documents is daunting, but the physics topics are organised in chapters, and the introductory part of each chapter normally provides a useful basic introduction to the topic. For CMS the TDR is very recent, as it was published during 2006, whereas for ATLAS it dates back to 1999. I will therefore, when relevant cite internal notes which provide an update on the ATLAS TDR studies.

## 2. The LHC and its experimental environment

The LHC is a proton proton Collider with  $\sqrt{s}=14$  TeV in construction at CERN in Geneva. The start-up is programmed for the second half of 2007.

Two main luminosity scenarios are foreseen for the LHC:

- An initial “low luminosity” scenario with peak luminosity  $\sim 10^{33}$  cm<sup>-2</sup>s<sup>-1</sup>, corresponding to an integrated luminosity:

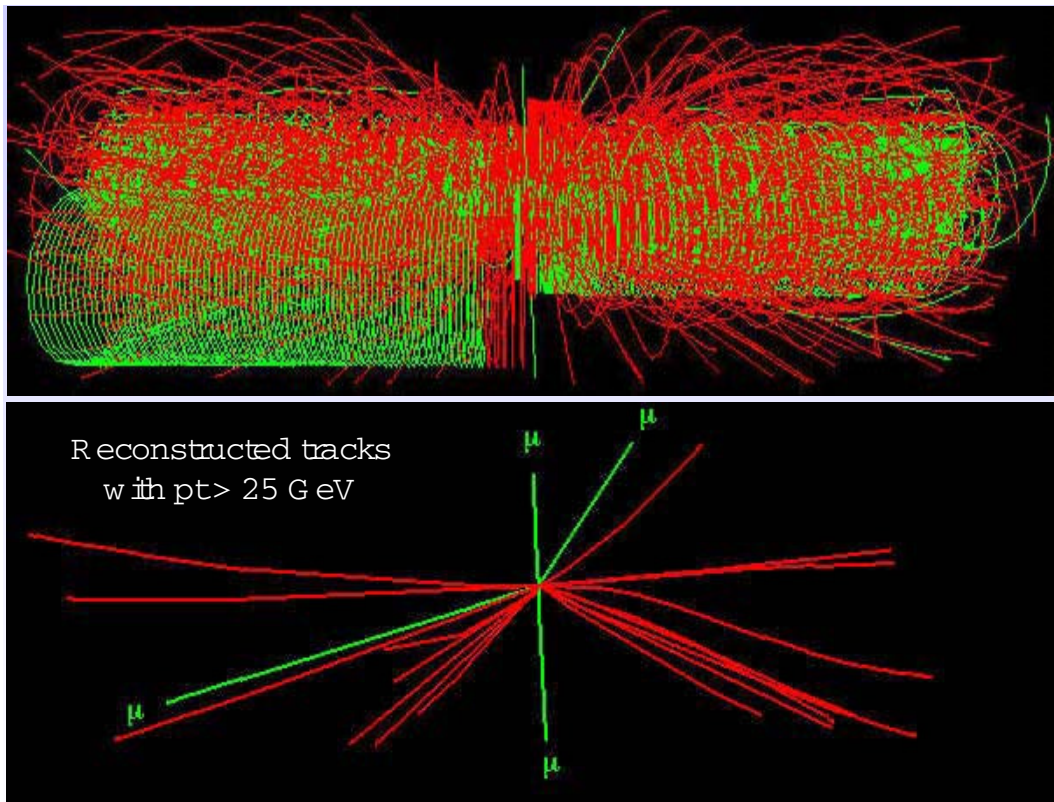
$$\int \mathcal{L} dt = 10 \text{ fb}^{-1} \text{ per year}$$

- A design “high luminosity” to be reached approximately 3 years after startup, with a peak value of  $\sim 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ , corresponding to an integrated luminosity:

$$\int \mathcal{L} dt = 100 \text{ fb}^{-1} \text{ per year}$$

The accelerator is built in the LEP tunnel with a circumference of  $\sim 27 \text{ Km}$ , and the beam is distributed in  $\sim 2800$  bunches of  $\sim 10^{11}$  proton per bunch. The resulting time between two bunch crossings is 25 ns. Given an inelastic cross section of  $\sim 100 \text{ mb}$ , this will result in  $\sim 20$  interactions per crossing at high luminosity. A total of  $\sim 700$  charged particles with  $P_T > 150 \text{ MeV}$  per crossing will traverse the detector.

We show in Fig. 1 the tracks in CMS for a  $H \rightarrow 4\mu$  event with 20 interactions superimposed.



**Figure 1.** Above: image of a  $H \rightarrow 4\mu$  event with 20 soft interaction superimposed (CMS). Below: the same event when only tracks with transverse momentum in excess of 25 GeV are shown.

In the upper figure no cut is applied on the track transverse momentum. In the lower figure only tracks with  $p_T > 25 \text{ GeV}$  are shown. It can be seen that most of the additional tracks are soft and the interesting event can be disentangled from the superimposed interactions.

Such an experimental environment is however very harsh on detectors, and poses severe requirements in terms of:

- Speed, to avoid integrating over too many bunch crossings;
- Granularity, in order to facilitate the reconstruction of the interesting events, one needs to avoid as much as possible that the same detector element is traversed by particles from different interactions;

**Table 1.** Typical values of number of expected events for physics processes of interest at the LHC.

Process	$\sigma$	Events/s	Events/year (low L)
$W \rightarrow e\nu$	15 nb	15	$10^8$
$Z \rightarrow ee$	1.5 nb	1.5	$10^7$
$t\bar{t}$	800 pb	0.8	$10^7$
$b\bar{b}$	500 $\mu b$	$10^5$	$10^{12}$
$\tilde{q}\tilde{q}$ ( $m_{\tilde{q}} = 1$ TeV)	1 pb	0.001	$10^4$
Higgs ( $m_H = 0.8$ TeV)	1 pb	0.001	$10^4$

- Radiation hardness: the high flux of particles deposits as significant amount of energy in the detector elements and thence induces radiation damage.

The high value of the design luminosity, combined with the center-of-mass energy implies that heavy particles are produced with high statistics, as shown by the event rate for some key processes reported in Table 1. A large statistics for discovery physics is available up to the TeV scale.

The Standard Model processes which constituted the discovery physics of the last decades will be abundantly produced at the LHC. This has a twofold impact on searches for new physics:

- Large backgrounds to discovery, in particular from top events that due to their complex topology can mimic many of the signatures for new physics;
- Availability of large control samples to calibrate backgrounds, helping to reduce the systematics of background evaluation.

Given the large statistics available, the precision measurements will be dominated by systematic effects, thus calling for a very good control of the detector performance.

### 3. The LHC detectors

We do not know how new physics will manifest itself. Detectors must therefore be sensitive to all the particles and signatures  $e$ ,  $\mu$ ,  $\tau$ ,  $\nu$ ,  $\gamma$ , jets,  $b$  – quarks which will be produced in the interactions. The two large detectors which will take data at the LHC, ATLAS and CMS are therefore “general purpose”. They are composed of many sub-detectors, each of which has a specific task in the reconstruction of the events, which dictates the corresponding requirements. Although ATLAS and CMS are very different and complementary in conception, the basic detection structure is similar. Proceeding outwards from the beam:

- The momentum/charge of tracks and secondary vertexes (e.g. from  $b$ -quark decays) are measured in the central tracker. Excellent momentum and position resolution are required.
- Energy and position of electrons and photons are measured in electromagnetic calorimeters. Excellent position and energy resolution are required.
- Energy and position of hadrons and jets are measured mainly in the hadronic calorimeters. Good coverage and granularity are required.
- The muons are identified and their momentum is measured in the external muon spectrometer (+ central tracker). Excellent momentum resolution required.
- Neutrinos are “detected and measured” through measurement of missing transverse energy  $\cancel{E}_T$ . A calorimeter coverage over a pseudorapidity  $|\eta| < 5$  needed.

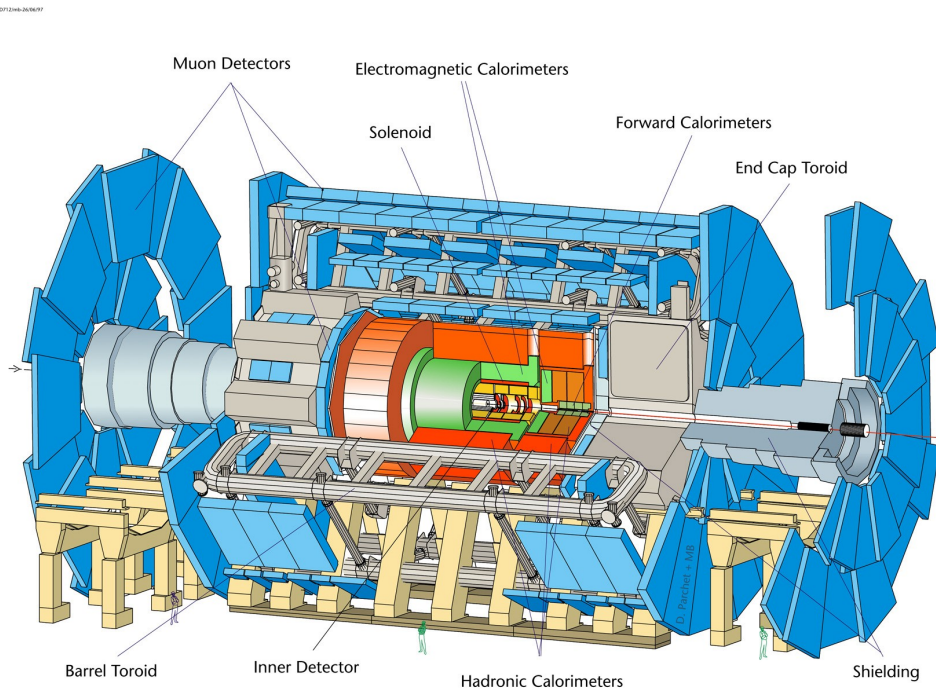


Figure 2. Exploded view of the ATLAS detector.

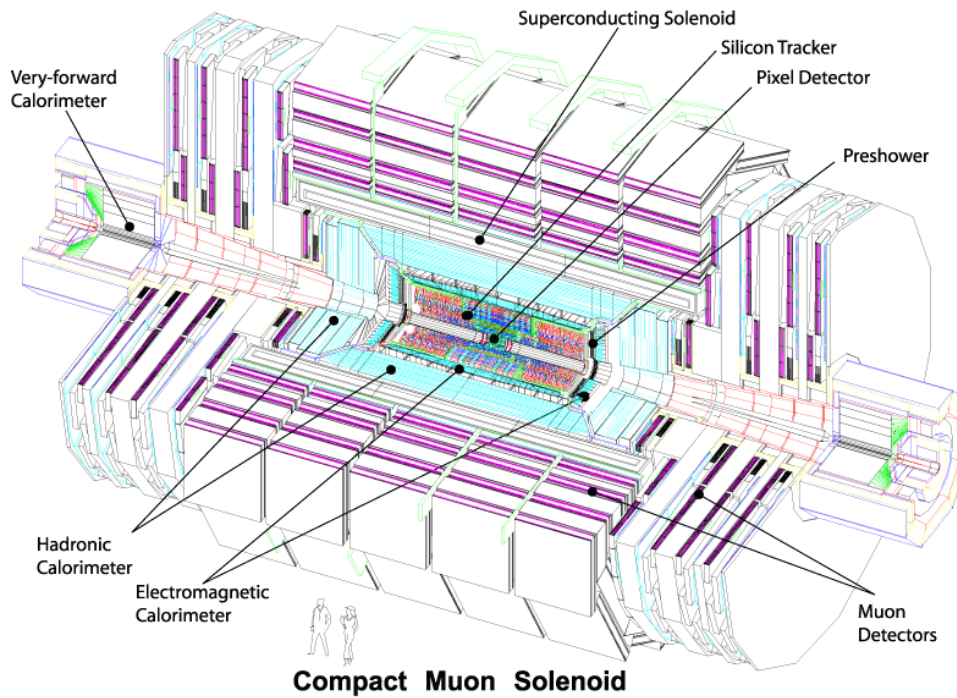


Figure 3. Exploded view of the CMS detector.

**Table 2.** Synoptic table comparing the ATLAS and CMS detectors

	ATLAS	CMS
MAGNET(S)	Air core toroids+solenoid in inner cavity Calorimeters outside field 4 magnets	solenoid Calorimeters inside field 1 magnet
TRACKER	Si pixel+strips TRD $\rightarrow$ particle identification B=2T $\sigma/p_T \sim 5 \times 10^{-4} p_T \oplus 0.01$	Si pixel + strips No particle identification B=4T $\sigma/p_T \sim 1.5 \times 10^{-4} p_T \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ uniform longitudinal segmentation	PbWO <sub>4</sub> crystals $\sigma/E \sim 3 - 4\%/\sqrt{E}$ no longitudinal segmentation
HAD CALO	Fe-scintillator + Cu-Liquid argon (10 $\lambda$ ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Cu-scint. (> 5.8 $\lambda$ +catcher ) $\sigma/E \sim 65\%/\sqrt{E} \oplus 0.05$
MUON	Air $\rightarrow \sigma/p_T \sim 7\%$ at 1 TeV standalone	Fe $\rightarrow \sigma/p_T \sim 5\%$ at 1 TeV combining with tracker

We show in Figs 2 and 3 an exploded view of the ATLAS and CMS detectors.

For ATLAS the tracking section is built of silicon pixel and strip detectors, followed by a Transition Radiation Tracker made with straw drift tubes. It is immersed in a solenoidal field of 2 T. Behind the solenoid is a high granularity liquid argon calorimeter, followed by an iron-scintillator hadronic calorimeter. Outside of the calorimeter is a gigantic muon detector system made of gas detectors arranged inside a toroidal magnetic field in air.

For the CMS detector the tracking detector is built exclusively of silicon detectors. The high resolution electromagnetic calorimeter is built of PbWO<sub>4</sub> crystals, and the hadronic calorimeter is copper with scintillator readout. All of these detector are inserted in a large solenoid providing a field of 4 T. Outside of the solenoid the muon chambers are inserted in the iron which acts as a return yoke for the solenoidal field.

A schematic comparison of the performance figures for the two detectors is shown in Table 2 [4]. Both detectors are designed to achieve similar performance goals for the detection of physics objects, dictated by the benchmark physics processes which will be studied at the LHC. A few examples, with the corresponding benchmark physics processes in parenthesis are:

- Lepton measurement: the experiments should be able to measure the lepton  $p_T$  in the range between  $\sim 1$  GeV and 5 TeV ( $b \rightarrow lX$ ,  $W'$ ,  $Z'$ )
- Mass Resolution: for  $m \sim 100$  GeV, the required resolution is:
  - $\sim 1\%$  for leptonic peaks ( $H \rightarrow \gamma\gamma, 4l$ )
  - $\sim 10\%$  for jet-jet peaks ( $W \rightarrow jj$ ,  $H \rightarrow bb$ )
- Calorimeter coverage:  $|\eta| < 5$  ( $E_T^{miss}$ , forward jet tag)
- Particle identification :
  - $\epsilon_b \sim 50\%$   $R_j \sim 100$  ( $H \rightarrow bb$ , SUSY)
  - $\epsilon_\tau \sim 50\%$   $R_j \sim 100$  ( $A/H \rightarrow \tau\tau$ )
  - $\epsilon_\gamma \sim 80\%$   $R_j \sim 10^3$  ( $H \rightarrow \gamma\gamma$ )
  - $\epsilon_e > 50\%$   $R_j \sim 10^5$

Where  $\epsilon$  is the detection efficiency for the desired object, and  $R_j$  is the required rejection on jets from the fragmentation of light quarks.

- Trigger: the beam crossing rate will be of 40 MHz. Due to limitation of the number of

events which can be stored the output rate is limited to  $\sim 100$  Hz. The detectors are therefore equipped with an on-line multi-stage selection system which must achieve the required rejection maintaining a high efficiency for the interesting events.

The issue of jet identification is particularly important, as the high  $p_T$  events at the LHC will be dominated by the production of QCD jets. It is worth briefly explaining the experimental techniques used to reject QCD jets.

### 3.1. Electron-photon identification

The issue is the separation of electrons/photons directly produced in the hard interaction or from the decay of a heavy particle from the overwhelming background of QCD jets

We describe here the approach adopted by the ATLAS Collaboration, which is described in detail in Chapter 7 of [3]. The corresponding CMS work is discussed in Chapter 10 of [1].

The charged hadron component in jets is rejected through the study of longitudinal and lateral energy deposition pattern. A fine lateral and longitudinal segmentation of the calorimeters is necessary to achieve an adequate rejection. After this step, the candidate sample is dominantly constituted of electromagnetic (EM) objects. These include the electrons and photons and a residual large jet background from the fragmentation of quarks/gluons where a  $\pi^0$  carries away most of the momentum and thence decays  $\pi^0 \rightarrow \gamma\gamma$ .

Additional rejection against  $\pi^0$  decays can be achieved through a detailed study of the pattern of the energy deposition of the EM shower in the calorimeter in order to distinguish the two photons from  $\pi^0$  decay from a single photon. A high granularity of the electromagnetic calorimeter is a key factor for the rejection of two-photon configurations.

For the electrons, a track from  $\pi^\pm$  superimposed to an electromagnetic cluster can fake an electron signature. The request of a match between position/momentum of track and position/energy of the electromagnetic cluster is used to reject fake electrons. An excellent resolution in EM energy measurement and in the determination of the position of the EM cluster are required to achieve an adequate rejection.

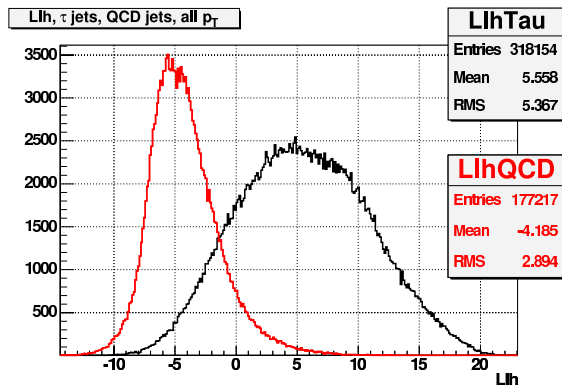
### 3.2. Tagging of $\tau$ hadronic decays

The identification technique is described in detail in the ATLAS Internal Note [5], from which the material in this section is extracted. The corresponding CMS studies are documented in Chapter 12 of [1].

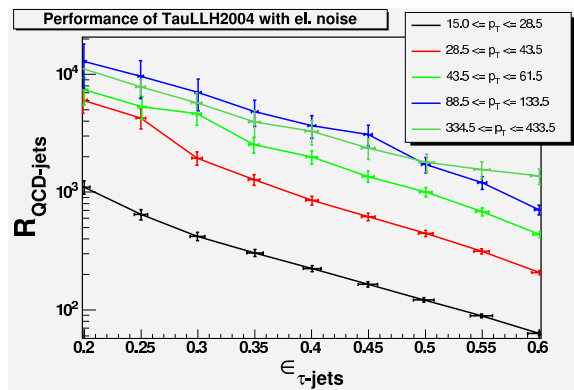
The dominant hadronic decay of the  $\tau$  is into one or three charged particles plus additional  $\pi^0$ s. Since the mass of the  $\tau$  is  $\sim 1.7$  GeV, already for a  $\tau$  energy of a few GeV the high momentum tracks from the decay are well collimated. Finally, the  $\tau$  has long lifetime ( $c\tau = 87 \mu\text{m}$ ), so that the tracks from its decay do not point directly to the interaction vertex, but have a non-zero impact parameters. The main features of a  $\tau$  hadronic decay will therefore be:

- Low track multiplicity ( $1 < N_{tr} < 3$ );
- A narrow jet in the calorimeter, measured through the shower radius in the EM calorimeter, and the number of hit strips in the presampler;
- Non-zero impact parameter;

Based on these discriminating variables, from a full simulation study of the ATLAS detector, a likelihood function in bins of jet  $p_T$  ( $15 < p_T < 600$  GeV) is built. The shape of the function is shown in Fig. 4 for  $\tau$  hadronic decays and jets from light quarks respectively. By selecting jets with a value of the likelihood variable in excess of a given value,  $\tau$  jets are selected with an efficiency  $\epsilon_\tau$ , while light jets are rejected with a rejection factor  $R_j$ . In Fig. 5, the achieved  $R_j$  is shown as a function of  $\epsilon_\tau$  for different ranges in jet  $p_T$ . The performance of the algorithm increases with increasing  $p_T$ , as the  $\tau$  jets become narrower. A canonical performance figure



**Figure 4.** Shape of the likelihood variable for  $\tau$  hadronic decays (black) and light quark jets (red or gray) respectively.



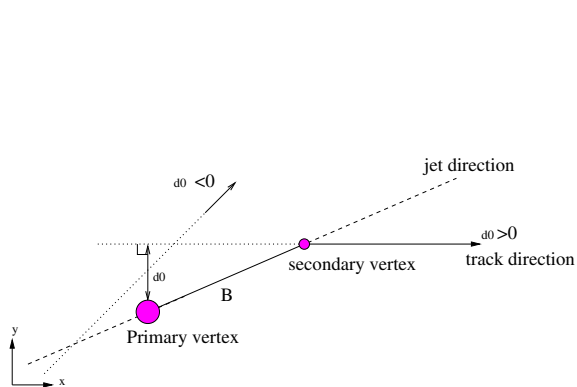
**Figure 5.** Rejection on light jets  $R_j$  versus efficiency for  $\tau$  selection  $\epsilon_\tau$  for different ranges in  $p_T$  of the jet.

used in many simplified simulation studies is a rejection factor 100 on jets for a  $\tau$  efficiency of 50%

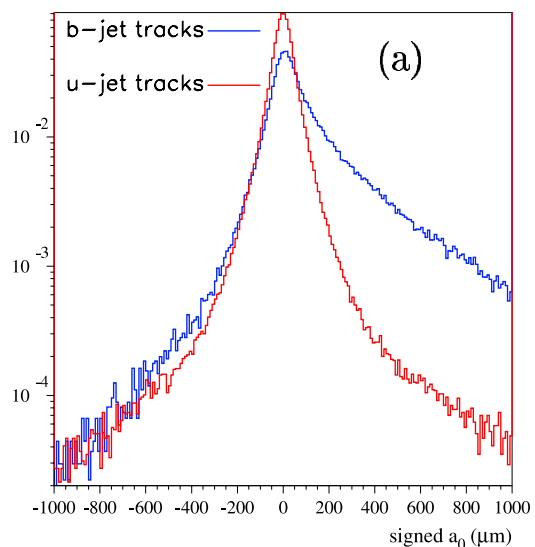
### 3.3. Tagging of $b$ -jets

In order to distinguish between the jets from the fragmentation of light quarks and of  $b$  quarks, we exploit the fact that  $b$ -hadrons decay a few mm away from the interaction vertex. A detailed discussion of the topic is given in the TDRs and in an ATLAS internal note [6].

The decay path of the  $b$ -hadrons is measured through the impact parameter of the tracks coming from the decay, defined as the minimum distance of a given track from the primary vertex, as shown in the graph in Fig. 6. The distributions of the impact parameter in the plane transverse



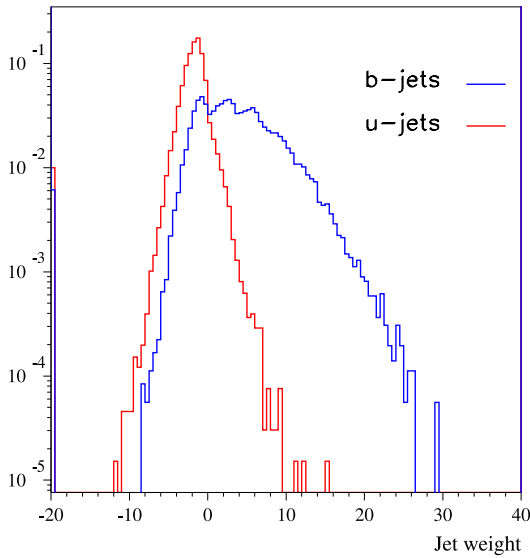
**Figure 6.** Definition of the transverse impact parameter  $|a_0|$  and its sign



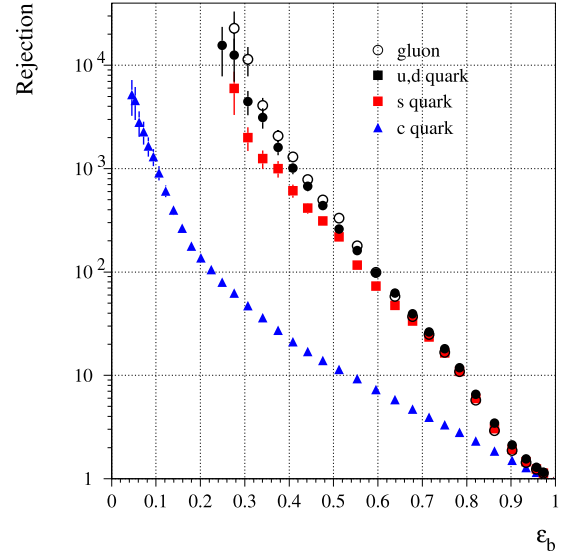
**Figure 7.** Transverse impact parameter distribution for tracks from  $b$ -jets (blue) and light jets (red).

to the beam for tracks coming from the fragmentation of light and  $b$ -quarks respectively are

shown in Fig. 7. Whereas the distribution for light quarks is symmetric, the one for tracks from  $b$ -hadron decays has a tail towards positive values of the impact parameter. It can also be



**Figure 8.** Distribution of the jet weight function for light jets (red) and  $b$  jets (blue).



**Figure 9.** Comparison of the rejections for the different jet flavours, as a function of the  $b$ -jet identification efficiency  $\epsilon_b$ .

observed that the discrimination power of this variable depends on the width of the distribution for light quarks, which is determined by the resolution of the layers of pixel detectors near the beam line. The simplest tagging algorithm for a jet is built by assigning to each track in a jet a weight based on the value of its transverse impact parameter scaled by the intrinsic resolution, and by building a jet weight function out of the product of these variables. The resulting weight function (ATLAS) is shown in Fig. 8 for light jets and  $b$ -jets respectively based study of samples of fully simulated  $WH$ ,  $ttH$ ,  $\bar{t}t$  events which have a large number of  $b$ -jets in the final state. The achieved rejection on QCD jets as a function of tagging efficiency for the algorithm based on the transverse impact parameter is shown in Fig: 9. The canonical performance value is a rejection factor of 100 on light jets for  $\epsilon_b = 60\%$ .

Significant improvements in performance can be achieved by an improved algorithm which also exploits the impact parameter in the direction along the beam and by searching for secondary vertexes inside the candidate  $b$ -jet.

#### 4. Physics program of the LHC experiments

The LHC will explore a new energy regime in the center of mass energy of the elementary constituents. It will therefore be able to provide essential information on a large spectrum of physics topics:

- Standard Model:
  - W mass measurement (goal 15 MeV), triple Gauge Couplings ( to  $10^{-3}$ )
  - Top physics: measure  $m_t$ ,  $\sigma_{\bar{t}t}$ , polarisation, rare decays, single top....
  - Soft interactions, QCD, B-physics, .....
- Higgs searches, both SM and SUSY
- New physics:

- SUSY
- Extra Dimensions
- Leptoquarks, extra gauge bosons, technicolor, compositeness, ....

The searches for physics beyond the Standard Model are the subject of the lectures by Frank Paige, I will give in the following some brief indications about Standard Model and Higgs physics.

#### 4.1. Standard Model physics

A large amount of work has been devoted to the exploration of the potential of the LHC for Standard Model studies. Important references, besides the relevant chapters of the two TDR, are the proceedings of a workshop organised in CERN in 1999 [7]-[9]. The lectures at Corfu concentrated on three main lines, focusing on physics topics which can be studied with the early LHC data, and/or, because of the high precision required, challenge the performances of the LHC detectors.

- *Measurement of Minimum Bias and Underlying Event.* The bulk of the proton-proton interactions at the LHC will be “soft” interactions, without high  $q^2$  interaction between partons. Events of this type, normally called “minimum bias”, correspond to non single-diffractive events. The study of the track multiplicity and kinematic distributions of these events will be the first physics accessible at the LHC. Detailed measurements in this field are moreover necessary because at high luminosity  $\sim 20$  of these events will be superimposed in each beam crossing, thus distorting the measurements of high  $p_T$  events. A separate, but equally important issue is the underlying event, i.e. the low  $p_T$  particles from the fragmentation of non-interacting partons in the protons. A detailed investigation on these issues performed in ATLAS is documented in [10].
- *Precision measurement of the  $W$  mass.* The  $W$  mass is one of the fundamental parameters of the Standard Model. By 2007 it will be measured with a precision of 25 MeV from the results of LEP and of the Tevatron Run II. Given the very high statistics of  $W$  and  $Z$  at the LHC it is worth investigating whether the LHC experiments will be able to improve on this precision. A careful study of the possible systematic uncertainties, documented in [11] and [7], and in the TDRs concludes that the most difficult experimental challenge will be the control on the systematic uncertainty on the lepton energy scale at the 0.003 % level.
- *Top mass measurement.* This is another fundamental measurement for which the LHC should be able to exploit the very large event statistics. In this case the precision of the Tevatron measurement by the time of the LHC startup will be of  $\sim 2.5$  GeV, and the goal of the LHC experiments is to measure the top mass with an error of  $\sim 1.5$  GeV. The main experimental issue involved will be the control of the energy scale of the b-jet from the top decay to 1%. This issue is investigated in great detail in both TDRs, and the ATLAS work has been recently updated in a Scientific Note [12]. Besides the issue of precision measurements, the top quark will be one of the main tools for the understanding of the detector performance in the early stages of the experiment, thanks to its complex decay topology involving b-jets, leptons,  $\cancel{E}_T$ , and a jet-jet peak from the hadronic decay of the  $W$ . The pioneering work in [13] investigates the potential of the ATLAS detector for the detection of a top signal with low statistics and a detector not perfectly calibrated.

#### 4.2. Higgs physics

The search for the Higgs boson, the missing building block of the Standard Model is one of the main motivations for the LHC. As such, it has been intensely studied from the inception of the LHC physics studies at the beginning of the 90’s.

Therefore it is the subject of very comprehensive chapters in the two TDR documents, where the ATLAS write-up should be complemented by a Scientific Note [14] which addresses the

searches for Higgs in production channels where the Higgs is produced through the fusion of two vector bosons radiated from the initial state quarks.

A very recent and excellent summary is also available [15], also addressing Higgs searches at the Tevatron. The terseness and clarity of the style make this review the ideal starting point for the study of Higgs searches at the LHC.

### Acknowledgments

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