



UNIVERSITÀ DEGLI STUDI DI ROMA
TOR VERGATA

FACOLTÀ DI SCIENZE MATEMATICHE, FISICHE E NATURALI
LAUREA SPECIALISTICA IN FISICA
anno accademico 2010/2011

Measurement of $Z/\gamma^* \rightarrow \mu\mu$ differential cross section with the ATLAS experiment at LHC

Author:
Francesco GUESCINI

Supervisor:
Prof. Anna DI CIACCIO

September 30, 2011

Francesco.Guescini@cern.ch

*There is a theory which states that if ever anyone discovers exactly what the Universe is for and why it is here, it will instantly disappear and be replaced by something even more bizarre and inexplicable.
There is another theory which states that this has already happened.*

The Restaurant at the End of the Universe, Douglas Adams

Contents

Contents	i
List of Figures	v
List of Tables	vii
Introduction	1
1 The Large Hadron Collider	3
1.0.1 Design and performances	3
1.0.2 Physics at the LHC	6
1.0.3 Acceleration chain	6
1.0.4 History	7
1.0.5 LHC as an ion collider	8
1.1 Other main LHC experiments	9
1.1.1 ALICE	9
1.1.2 CMS	9
1.1.3 LHCb	9
2 The ATLAS experiment	11
2.1 Coordinate system	11
2.2 Track parametrization	13
2.3 Inner Detector	13
2.3.1 The Pixel detector	14
2.3.2 The SemiConductor Tracker	15
2.3.3 The Transition Radiation Tracker	15
2.4 Calorimeters	17
2.4.1 The Electromagnetic Calorimeter	18
2.4.2 The Hadronic Calorimeters	19
2.5 The Muon Spectrometer	20
2.5.1 Monitored Drift Tube chambers	21
2.5.2 Cathode Strip Chambers	21
2.5.3 Resistive Plate Chambers	22
2.5.4 Thin Gap Chambers	23

2.6	Magnet system	23
2.7	Trigger and Data AcQuisition	24
2.7.1	Level 1 trigger	25
2.7.2	Level 2 trigger	26
2.7.3	Event Filter	26
2.8	Athena	26
2.9	Simulation	27
2.10	Tracking	27
2.10.1	Inner Detector tracking	27
2.10.2	Muon Spectrometer tracking	28
3	The Standard Model	31
3.1	The electro-weak interaction	32
3.2	The Glashow-Wienberg-Salam model	34
3.3	The Higgs hunt	37
3.3.1	Theoretical constraints	37
3.3.2	Production processes	39
3.3.3	Branching ratios	41
3.3.4	Direct searches	43
4	$Z/\gamma^* \rightarrow \mu\mu$ cross section measurement	47
4.1	Proton-proton collisions	48
4.2	Drell-Yan process	50
4.3	Analysis procedure	52
4.4	Data	53
4.4.1	Muon trigger	53
4.5	Simulation	53
4.5.1	MC generators	54
4.5.2	MC samples	56
4.5.3	MC corrections	56
4.5.4	Theoretical calculations	57
4.6	Event selection	58
4.6.1	Muon selection	58
4.6.2	Z selection	58
4.7	Background	59
4.7.1	QCD background	59
4.7.2	Electro-weak background	62
4.7.3	Total background	62
4.8	Muon performance	62
4.8.1	Tag'n'probe method	63
4.8.2	Background contamination	66
4.9	C_Z factor	66
4.10	Scale Factor	67

5	Acceptance and extrapolation factors	71
5.1	Acceptance factor	71
5.2	Extrapolation factors	72
5.3	Systematic uncertainties	73
5.3.1	Parton Distribution Functions	74
5.3.2	CTEQ	76
5.3.3	NNPDF	79
5.3.4	PDF reweighting	80
5.3.5	PDF error set uncertainty	82
5.3.6	PDF choice uncertainty	82
5.3.7	MC generator uncertainty	83
5.3.8	Parton shower generator uncertainty	84
5.4	Results	85
6	Results	91
6.1	$Z/\gamma^* \rightarrow \mu\mu$ cross section	91
6.2	$Z/\gamma^* \rightarrow ll$ cross section	93
6.3	Muon-electron universality	95
6.4	W/Z ratio	95
	Conclusions	97
	Bibliography	99

List of Figures

1.1	LHC	4
1.2	CERN acceleration complex	7
1.3	ATLAS integrated luminosity as a function of time	8
2.1	The ATLAS experiment	12
2.2	Inner Detector	14
2.3	Inner Detector barrel region	16
2.4	Inner Detector end-cap region	17
2.5	Calorimeters	18
2.6	Muon Spectrometer	21
2.7	MDT chamber	23
2.8	Muon Spectrometer cross section	24
2.9	Geometry of the magnet system end calorimeter steel	25
3.1	Standard Model particles	32
3.2	SM Higgs boson main production processes at LHC	40
3.3	SM Higgs boson production cross section	41
3.4	SM Higgs boson branching ratios	42
3.5	Tevatron Higgs boson exclusion plot	45
3.6	ATLAS Higgs boson exclusion plot	46
4.1	Representation of a pp collision	49
4.2	Feynman diagram for LO Drell-Yan process	52
4.3	QCD template fit of the dimuon invariant mass	61
5.1	LHC parton kinematics	75
5.2	NNPDF gluon distribution	80
5.3	Gluon distributions comparison	81
5.4	Acceptance factor for CTEQ6.6 error set	83
5.5	Extrapolation factor for CTEQ6.6 error set	84
5.6	Differential extrapolation factors for CTEQ6.6 error set	87
5.7	Acceptance and extrapolation factors for different PDFs	88
5.8	Differential extrapolation factors for different PDFs	89

6.1	Measured $Z/\gamma^* \rightarrow ll$ differential cross section compared with muon and electron channels	94
6.2	Measured $Z/\gamma^* \rightarrow ll$ differential cross section compared with theoretical calculations	95
6.3	Experimental $Z/\gamma^* \rightarrow ll$ cross section values compared with NNLO QCD calculations as a function of $\sqrt{s}$	96

List of Tables

2.1	ID dimensions	15
2.2	MS parameters	22
3.1	$SU(2)_L \times U(1)_Y$ quantum numbers for the electron family. . .	34
4.1	y_Z binning	53
4.2	Total integrated luminosity	53
4.3	C_Z systematic uncertainties	57
4.4	Event selection cuts	59
4.5	Cutflow for the Z selection	59
4.6	Z candidate events per rapidity bin	60
4.7	QCD background from template fit	60
4.8	QCD background from ABCD method	62
4.9	Electro-weak background	62
4.10	Total background	62
4.11	Total background per Z rapidity bin	63
4.12	Tag selection cuts	63
4.13	MS probes selection cuts	64
4.14	ID efficiency and total SF	64
4.15	ID probes selection cuts	65
4.16	MS+CB efficiency and total SF	65
4.17	CB probes selection cuts	65
4.18	isolation efficiency and total SF	66
4.19	isolated probes selection cuts	66
4.20	trigger efficiency and total SF	66
4.21	C_Z for the integrated cross section measurement	67
4.22	C_Z in bins of Z rapidity	67
4.23	SF for the integrated cross section measurement	68
4.24	SF in bins of Z rapidity	69
5.1	A_Z value	72
5.2	E_Z value	73
5.3	$E_Z(y_Z)$ values	74
5.4	Acceptance factor and systematic uncertainty contributions. .	84

5.5	Extrapolation factor and systematic uncertainty contributions.	85
5.6	Differential extrapolation factors and systematic uncertainty contributions.	85
6.1	Uncertainties on the $Z/\gamma^* \rightarrow \mu\mu$ integrated cross section . . .	92
6.2	Uncertainties on the fiducial $Z/\gamma^* \rightarrow \mu\mu$ differential cross section	92

Introduction

Since its first evidence back in 1983, long after its introduction in the theoretical frame of the Standard Model of particle physics in the 1960s, the Z weak vector boson has played a main role in the physics of particle accelerators. Its existence, together with neutral currents and the W boson, decided the success of the Glashow-Weinberg-Salam model. Since then the Z particle is a fundamental object of measurement at any high energy physics experiment. Its mass, adopted as a parameter of the Standard Model, and all of its properties have been widely and thoroughly investigated at LEP and Tevatron. Our present knowledge on its production and decay mechanisms makes it the perfect standard candle for any particle physics measurement. The $Z/\gamma^* \rightarrow \mu\mu$ channel in particular, besides a small contribution from the γ^* and its small branching ratio (3%), is ideal for its clear signature: two high p_T muons which can be easily identified with a minimal background contamination.

The main goal of the ATLAS experiment is the search of the Higgs bosons and of any possible scenario beyond the current picture of particle physics that may manifest at the TeV scale. Both these topics have in common the Z and μ physics. $H \rightarrow ZZ^* \rightarrow 4\mu$ is indeed the channel with the highest possibilities to precisely measure the characteristics of the Higgs boson for large m_H values while high p_T leptons are a recurrent signature in theories beyond the Standard Model.

The Drell-Yan process involved with the Z production is an excellent test of our knowledge on Quantum Chromodynamics. The parton-antiparton annihilation allows the investigation of Parton Distribution Functions in otherwise never probed before regions of transferred momentum and parton momentum fraction.

This thesis presents the measurement of the Drell-Yan inclusive $pp \rightarrow Z/\gamma^* \rightarrow \mu\mu + X$ cross section with the ATLAS experiment on 36.2 pb^{-1} of data collected during 2010 at an energy in the center of mass of $\sqrt{s} = 7 \text{ TeV}$. As the measurement accuracy reaches a few percent and the simulations at NNLO are calculated with a precision of no more than 1%, particular attention is paid to the estimation of the uncertainties. Within the W/Z group responsible for the analysis, my task has been to calculate the acceptance and extrapolation factors adopted to extend the cross section measurements

obtained in the fiducial volume to the total phase space and to a larger combination volume. An exhaustive coverage of the associated systematic uncertainties is provided as integral part of my work. These uncertainties are in fact expected to become the largest ones affecting the experimental measure since those arising from luminosity and statistics will gradually decrease with the increase of the available amount of data.

The first chapter introduces the Large Hadron Collider, giving a brief description of the machine, its performances, its goals and its history. The second chapter is centered on the description of the ATLAS experiment. Chapter number three gives a quick introduction to the Standard Model of particle physics, from the electro-weak unification to the introduction of the Higgs boson. The final section is dedicated to the Higgs quest, with a glance at past and recent experimental results. In chapter 4 the $Z/\gamma^* \rightarrow \mu\mu$ analysis is presented. A rapid description of pp collisions and of the Drell-Yan process is provided at first. The analysis procedure is then described in all its aspects: data, simulations, event selection, background, muon efficiencies and correction factors. The fifth chapter is focused on my contribution to the $Z/\gamma^* \rightarrow \mu\mu$ analysis, providing the acceptance and extrapolation factors calculation from Monte Carlo simulations together with a detailed description of the uncertainties. The role played by Parton Distribution Functions in the estimation of the errors is explained. Finally in chapter 6 the results of the $Z/\gamma^* \rightarrow \mu\mu$ cross section measurement are presented. Conclusions are drawn in a dedicated closing chapter.

Chapter 1

The Large Hadron Collider

The Large hadron Collider, LHC, is a proton-proton collider situated at CERN, in Geneva, Switzerland [1][2][3][4]. It is designed to achieve energies in the center of mass up to $\sqrt{s} = 14$ TeV, which makes it the most powerful accelerator ever built. It was conceived to investigate the accuracy and the limits of the predictions given by the Standard Model, SM, up to the TeV scale and in particular to search for the Higgs boson. Its high energy in the center of mass makes it suitable to shed light on the existence of physics beyond the Standard Model.

LHC lies ~ 100 m underground in the same 26.7 km long tunnel that was drilled for LEP, Large Electron Positron collider. Contrary to particle-antiparticle accelerators, such as Tevatron (proton-antiproton), that may use a single beampipe to circulate the two beams to collide, LHC has two different pipes for the two counter rotating proton beams. In four different points around the ring the two beams cross (see figure 1). These locations are occupied by the LHC experiments: ATLAS at point 1, ALICE at point 2, CMS at point 5 and LHCb at point 8. Of the remaining four sections of LHC, two are occupied by collimations systems (octant 3 and octant 7), one by radio frequency systems (octant 4) and one by the beam dump insertion (octant 6), which separately extracts the beams from the machine.

1.0.1 Design and performances

LHC is composed of 1232 superconducting dipole magnets providing a field of 8.33 T at an operating temperature of 1.9 K reached by using superfluid helium. Each proton beam allows up to 2808 bunches of around 10^{11} protons separated by 25 ns. The total beam current of 0.584 A corresponds to a stored beam energy of 362 MJ.

LHC has an unprecedented design luminosity of $L = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. Such a high luminosity is needed in order to investigate rare events with cross sections of a few pb. In a year of data taking at high luminosity LHC will

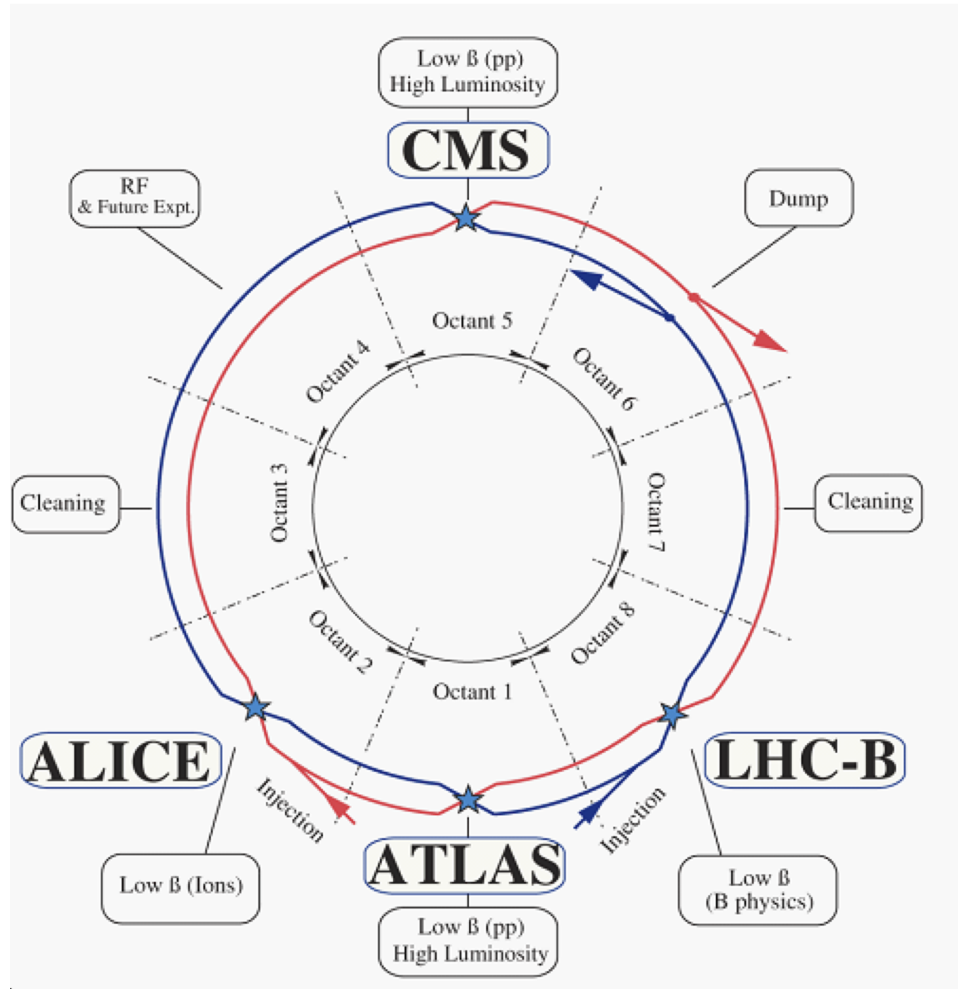


Figure 1.1: schematic representation of the Large Hadron Collider. In evidence are the four intersecting points where the two proton beams cross and which host the four main LHC experiments: ATLAS, ALICE, CMS and LHCb.

provide experiments with an integrated luminosity of:

$$\int_{10^7 s} L dt \sim 10 \text{ fb}^{-1} \quad (1.1)$$

When each bucket of the beams is filled, the expected collision rate is:

$$R = \sigma_{pp}^{\text{tot}} \times L = 80 \text{ mb} \times 10^{34} \text{ cm}^{-2}\text{s}^{-1} \sim 10^9 \text{ Hz} \quad (1.2)$$

where 80 mb is the proton-proton total cross section at $\sqrt{s} = 14 \text{ TeV}$. On average 22 collisions happen per bunch crossing. Such a high rate contributes to the overlap in time of collisions coming from different bunch crossings. This time overlap goes by the name of *pile-up*. Most of these events are dominated by soft QCD interactions, with a consequent generation of low p_T particles. These so called *Minimum Bias* events are a huge background to more interesting and high p_T physics and have been widely studied with data from the very first runs [5].

The machine luminosity strictly depends on some beam parameters and can be written as:

$$L = \frac{N_b^2 n_b f_{\text{rev}} \gamma_r}{4\pi \epsilon_n \beta^*} F \quad (1.3)$$

where the beam distribution is supposed to be gaussian in the transverse plane. N_b indicates the number of protons per bunch, n_b the number of bunches per beam, f_{rev} the revolution frequency, γ_r the relativistic gamma factor, ϵ_n is the normalized transverse beam emittance, β^* the beta function at the interaction point and F is the luminosity reduction factor due to the crossing angle between the beams at the interaction point.

Other factors contribute to set a limit on the maximum reachable luminosity. A limit to the maximum particle density per bunch is set by the beam-beam interactions experienced by the particles when traversing the interaction region and by the particles interactions within the same bunch. The safety of the machine plays an important role on the limits of the machine too. The total energy stored in the beam and in the LHC magnets is around 1 GJ. This huge amount of energy needs to be dissipated as safely and quickly as possible in case of a malfunction. The beam dumping system therefore introduces additional limits to the performances of the machine. The synchrotron radiation emitted by the beam, although small compared to LEP, imposes limits on the beam intensity due to the radiation absorbed by the cryogenic system.

Beam loss due to collisions, degradation of the beam intensity and beam emittance constantly contribute to the decay of the luminosity. The decay time is given by:

$$\tau = \frac{N_0^{\text{tot}}}{L_0 \sigma_{\text{tot}} n_{\text{IP}}} \simeq 45 \text{ h} \quad (1.4)$$

where N_0^{tot} is the initial beam intensity, L_0 is the initial luminosity, σ_{tot} the total cross section and n_{IP} the number of interaction points. This results in:

$$N_{\text{tot}}(t) = \frac{N_0^{\text{tot}}}{1 + t/\tau} \quad (1.5)$$

$$L(t) = \frac{L_0}{(1 + t/\tau)^2} \quad (1.6)$$

Further effects like Touschek scattering and emittance blow-up, contribute to the limited lifetime of the beam, reducing the previous estimation to approximately $\tau \simeq 15\text{h}$.

1.0.2 Physics at the LHC

The possibilities offered by the LHC are countless. The high luminosity and center of mass energy provide an enormous potential which goes well beyond the Higgs search. The Standard Model is the current picture in particle physics and LHC experiments may extend the precision of our knowledge but also prove the existence of new features that do not fit in the present model. The main goal is certainly to explore the origin of the masses in particle physics, which are supposed to be given through the BEHHGK mechanism by the Higgs boson. The LHC is able to discover the Higgs boson in the mass range $114 \text{ GeV} < m_{\text{H}} < 1 \text{ TeV}$. Anyways the potentials of LHC exceed the Higgs hunt. The high luminosity lets a large sample of data to be collected in a rather short time, allowing a rapid, as well as accurate, test of our knowledge on QCD, electro-weak interactions and flavor physics. In particular top quark is produced with a rate of a few Hz allowing a precise measurement of its mass and interactions. B physics will be significantly improved, especially the study of CP violation and of the processes which may involve new physics. W and Z precision measurements will be boosted too. Last but not least, physics beyond the SM is a crucial goal of the LHC program, for example the discovery of new gauge bosons W' and Z' as well as supersymmetry, which predicts new particles to be found in the TeV scale and which LHC will test in the 0.1 - 5 TeV mass range.

1.0.3 Acceleration chain

Protons circulating in LHC are accelerated in five steps (see figure 1.2). At the beginning protons are given an energy of 50 MeV by a small linear accelerator, Linac2. They are then accelerated to an energy of 1.4 GeV by the BOOSTER. Subsequently the Proton Synchrotron, PS, increases the energy of the beam up to 26 GeV before injecting the protons into the Super Proton Synchrotron, SPS, which boosts the protons to 450 GeV. The protons are now ready to be injected into LHC. The Large Hadron Collider finally accelerates

the beams to the maximum energy of 7 TeV. However since March 2010 and until the end of 2012 the maximum beam energy is set to 3.5 TeV.

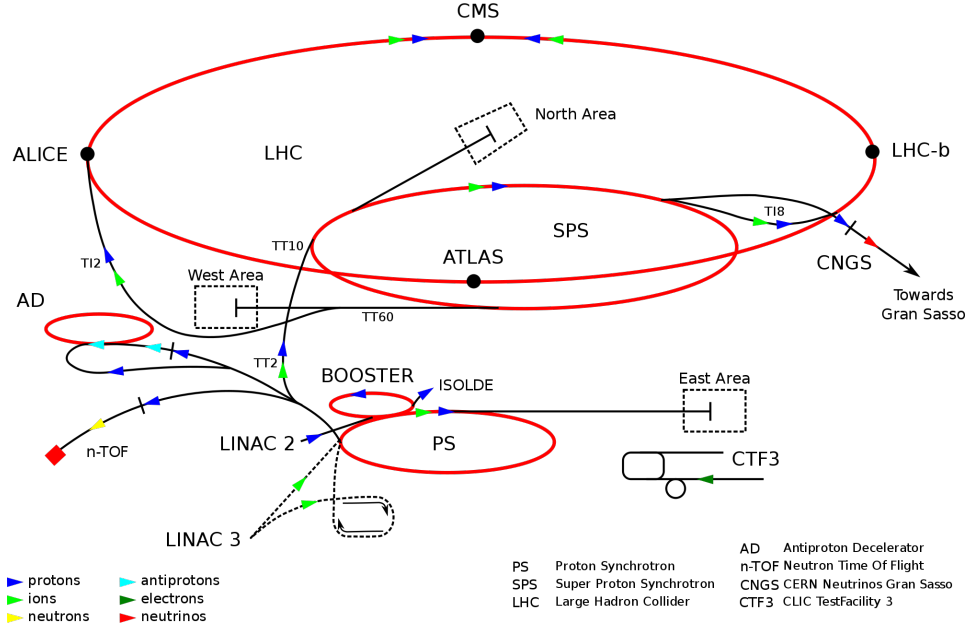


Figure 1.2: schematic representation of CERN acceleration complex.

1.0.4 History

The two proton beams were first successfully circulated in LHC on September 10th, 2008. On September 19th, 2008 a faulty electrical connection between two superconducting dipoles caused a large helium leak, resulting in a serious mechanical damage of the LHC. 53 dipoles had to be replaced. The repair and installation of new safety devices took more than one year. On November 23th, 2009 the two proton beams were circulated again in LHC. Three days later, on November 26th, 2009 the beams were collided at the injection energy of 450 GeV. On December 8th, 2009 LHC achieved the title of world most powerful collider by smashing protons at $\sqrt{s} = 2.36$ TeV, higher than Fermilab's Tevatron $\sqrt{s} = 1.96$ TeV. After winter technical stop, LHC activities were resumed in February 2010. On March 30th, 2010 LHC set today's $\sqrt{s}$ world record by colliding protons at $\sqrt{s} = 7$ TeV. LHC collided protons until November 4th, 2010, delivering the experiments an integrated luminosity of around 45 pb⁻¹. From November 4th, till December 6th, 2010 LHC moved to heavy ion collisions. After resuming operations in 2011, on June 17th, 2011 LHC achieved its 2011 goal of delivering 1 fb⁻¹ of data to the experiments. At the present time LHC is delivering its fourth fb⁻¹. On September 15th LHC set new world record luminosity, reaching an instan-

taneous luminosity peak of $3.30 \cdot 10^{33} \text{cm}^{-2}\text{s}^{-1}$, exceeding previous Tevatron record.

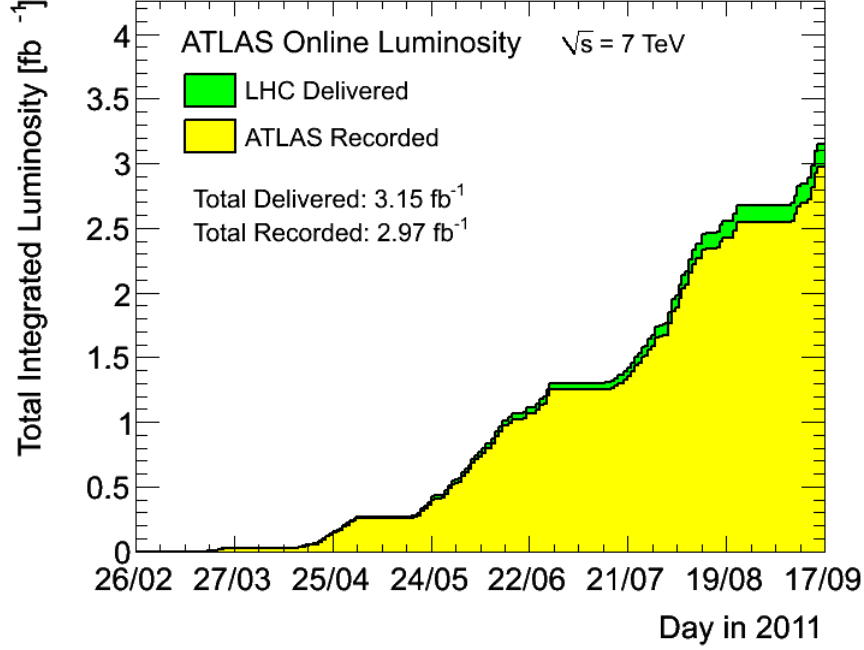


Figure 1.3: ATLAS integrated luminosity as a function of time.

Future plans

LHC will keep colliding protons at $\sqrt{s} = 7 \text{ TeV}$ till the end of 2012. After a long technical stop due to machine upgrade, the Large Hadron Collider will resume operations in 2014 at its design energy of $\sqrt{s} = 14 \text{ TeV}$.

1.0.5 LHC as an ion collider

Since the early stages of LHC design, the possibility of colliding heavy ions was included in the project. The Large hadron Collider is capable of colliding fully stripped lead ions, $^{282}\text{Pb}^{82+}$, with a beam energy of 2.76 TeV/nucleon , $\sqrt{s} = 1.15 \text{ PeV}$, and a design luminosity of $10^{27} \text{ cm}^{-2}\text{s}^{-1}$. Even though ALICE is a heavy ion dedicated experiment, ATLAS and CMS have plans to observe and study this kind of collisions too. Heavy ion physics has quite different parameters than proton physics. When colliding heavy ions a new set of secondary interactions appear in the beam dynamics. These effects are dominated by electromagnetic interactions and contribute to the total loss rate and beam lifetime. The most important sources of loss are the intra-

beam scattering and the synchrotron radiation, which play a less relevant role in proton collisions.

1.1 Other main LHC experiments

Besides ATLAS, three other main experiments are installed on LHC.

1.1.1 ALICE

ALICE, A Large Ion Collider Experiment, is a heavy ion dedicated experiment. It is designed to investigate quark-gluon plasma at high energy densities in Pb-Pb collisions. The vertex reconstruction is obtained using Pixel and Silicon Drift Chambers as inner tracker while the main tracking system is the Time Projection Chamber. Other elements of the ALICE detector are a Time of Flight system, a Ring Image Cherenkov detector, a proton spectrometer and a muon arm.

1.1.2 CMS

CMS, Compact Muon Solenoid, is a general purpose experiment. Its goal is to verify the existence of the Higgs boson and to test the limits of the SM. CMS is 21.5 m long and 15 m in diameter, weighting 12500 tons. The inner volume is occupied by the Silicon Pixel and the Silicon Microstrip detectors. Outside are the scintillating crystal Electromagnetic Calorimeter and the sampling Hadronic Calorimeter. These detectors are surrounded by a superconducting solenoid, which provides a magnetic field of 3.8 T. Outside of the magnet, but within the return yoke, is the muon detector, composed of Drift Tubes, Cathod Strip Chambers and Resistive Plate Chambers.

1.1.3 LHCb

LHCb, LHC beauty, is an experiment designed to study B hadrons and CP violation. Since most of the B hadrons are produced in the forward direction, it is designed as a single arm detector covering a relative small angle. LHCb consists of a Vertex Locator, two Ring Image Cherenkov detectors and a tracker. Far from the IP are located the electromagnetic and hadronic calorimeters and the muon spectrometer, composed of Resistive Plate Chambers and Multi-Wire Proportional Chambers.

Chapter 2

The ATLAS experiment

ATLAS, A Toroidal LHC ApparatuS, is a multi-purpose particle experiment designed for high energy and luminosity proton-proton collisions with an almost complete 4π coverage [6][2][3][4]. ATLAS is 46 m long and 25 m high, which makes it world's largest volume particle experiment, and weights 7000 tons. It is installed in a cavern underground on the LHC at CERN. It has a cylindrical symmetry, with the barrel region sub-detectors coaxially oriented with respect to the beam and the end-cap sub-detectors perpendicularly oriented to the beam. The structure of the sub-detectors is organized in layers in the barrel region and in disks in the end-caps. ATLAS is composed of three main sub-systems:

- **Inner Detector**, ID, is the innermost tracking system. It is immersed in a 2 T strong magnetic field.
- **Calorimeters**, placed outside of the ID solenoid, are responsible for the measurement of the energy of the particles.
- **Muon Spectrometer**, MS, is the outermost tracking device, dedicated to the measurement of muons tracks.

2.1 Coordinate system

The origin of the ATLAS coordinate system is defined as the nominal interaction point. The reference system is right-handed with the beam direction defining the z -axis and the x - y perpendicular plane. The x -axis points to the center of LHC while the y -axis points upwards. The A side of the experiment is the one with positive z (Geneva Airport side) while the C side is the one with z negative values. Instead of (x, y, z) , a (R, ϕ, z) coordinate system is preferred due to the symmetry of the experiment.

- R is the distance from the z -axis in the transverse plane:

$$R = \sqrt{x^2 + y^2}$$

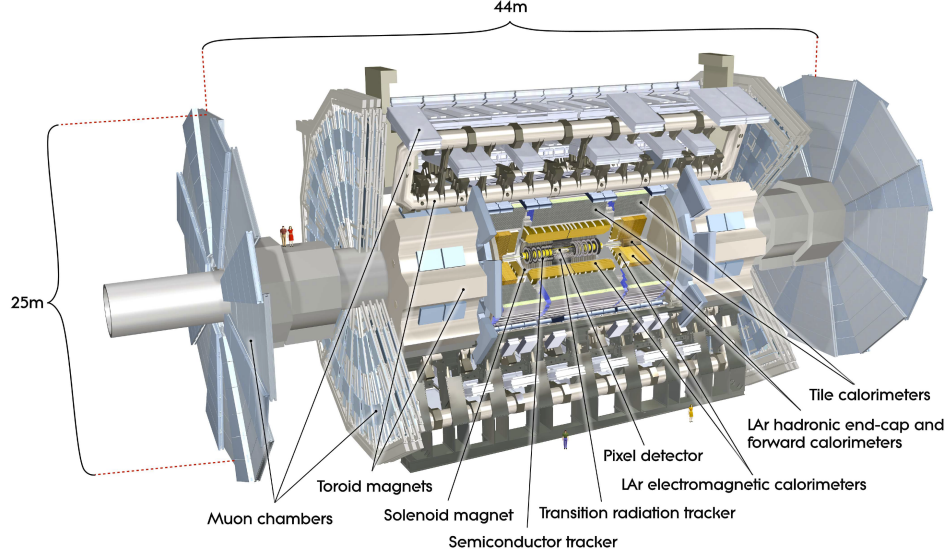


Figure 2.1: cut-away view of the ATLAS experiment.

- ϕ is the azimuthal angle measured from the x -axis in the transverse plane.
- z is the z -axis coordinate.

The relation between R and z is given by:

$$\theta = \arccos \frac{z}{\sqrt{R^2 + z^2}} \quad (2.1)$$

θ is the polar angle measured with respect to the beam axis in the longitudinal plane. The pseudorapidity, η , is frequently used in collider experiments instead of the θ polar angle. It is defined as:

$$\eta = -\ln \left(\tan \frac{\theta}{2} \right) \quad (2.2)$$

The pseudorapidity is an ultrarelativistic approximation of the rapidity, y :

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

The convenience of using the pseudorapidity lies in the fact that, given the high p_T of most of the particles produced, it is a good approximation of the rapidity, which in turn is a Lorentz invariant. The distance in the pseudorapidity-azimuthal space is defined as:

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} \quad (2.4)$$

2.2 Track parametrization

Particle four-vectors are indicated using the parameters: p_T , η , ϕ . For completeness two more parameters are needed in order to describe track trajectories inside the experimental volume. ATLAS uses the d_0 and z_0 parameters at track perigee, the point of closest approach to the z -axis. d_0 is the distance of the track to the z -axis in the transverse plane, defined positive when the particle trajectory is clockwise. Similarly, z_0 is the z coordinate of the track at perigee.

2.3 Inner Detector

The Inner Detector, ID, is ATLAS closest sub-detector to the IP. It is designed to provide pattern recognition and momentum resolution for charged particles. Its high granularity and proximity to the IP are fundamental for the reconstruction of particles trajectories and of primary and secondary vertices. It has a η coverage up to $|\eta| < 2.5$ and complete ϕ coverage in order to prevent as much as possible particles to escape undetected from the interaction region. As regards the transverse momentum measurement, the ID can go as low as 0.1 GeV. The ID closeness to the IP requires strong resistance of its components to the hard radiation it is constantly exposed during machine operation. To reduce the background noise the detector needs to be continuously cooled down. The ID is 7.024 m long and has a radius of 1.150 m. It is surrounded by a superconducting solenoid providing a magnetic field of 2 T.

The ID consists of three independent sub-detectors:

- **Pixel detector**, the closest device to the IP and with the highest granularity. It is a silicon detector with 3 barrel layers and 3 disks per end-cap. Provides 3 dimensional space points.
- **SemiConductor Tracker**, SCT, is a silicon detector outside of the Pixel detector. It has 4 layers and 9 disks per end-cap. Provides 3 dimensional space points from pairs of hits on stereo layers.
- **Transition Radiation Tracker**, TRT, surrounding the SCT, is made of 73 layers of gaseous straws in the barrels and 160 in the end-cap regions.

The combination of the three different detectors together with the use of barrel and end-caps results in a thorough tracking, with high precision track measurements both in R - ϕ and in η - z coordinates.

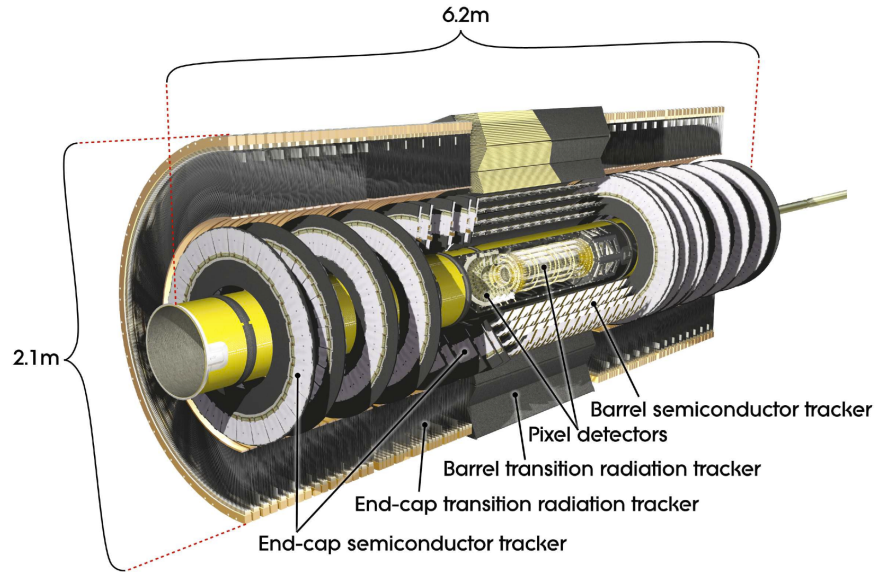


Figure 2.2: cut-away view of the Inner Detector.

2.3.1 The Pixel detector

The Pixel detector is the closest device to the beam pipe. Its purpose is to provide robust pattern recognition and reconstruction of primary and secondary vertices. It is fundamental to determine the impact parameters of the tracks for the identification of B hadrons and their decays. The Pixel detector has three barrel layers, at distances of 50.5, 88.5 and 122.5 mm from the beam pipe, and three disks per end-cap, at distances of 495, 580 and 650 mm from the IP. The coverage extends up to $|\eta| < 2.5$. Its high precision measurements are granted by the high granularity close to the IP. The silicon sensors are in fact segmented into rectangles in the R - ϕ and longitudinal planes, the *pixels*, providing three-dimensional space points. The size of these pixels ranges from $50 \times 400 \mu\text{m}^2$ to $50 \times 600 \mu\text{m}^2$. A module of the Pixel detector has a sensible area of $63.4 \times 24.4 \text{ mm}^2$, thickness of $250 \mu\text{m}$ and is read by 16 front-end electronics chips, each with 2880 channels. 1744 modules compose the Pixel detector, giving a total of 80.4 million readout channels. The overall precision of the detector is of $10 \mu\text{m}$ in the R - ϕ plane and $115 \mu\text{m}$ in the longitudinal plane, both in the barrels and in the end-caps. Due the high radiation damage it is exposed, the inner barrel layer, the *B-layer*, is designed to be replaced every few years. This exposure, together with the need of suppressing noise signals, requires the Pixel detector to be constantly cooled down to a temperature between -5 and -10°C .

		radial extension [mm]	length [mm]
ID	overall envelope	$0 < R < 1150$	$0 < z < 3512$
beam pipe		$29 < R < 36$	
Pixel	overall envelope	$45.5 < R < 242$	$0 < z < 3092$
	3 barrel layers	$50.5 < R < 122.5$	$0 < z < 400.5$
	2×3 end-cap disks	$88.8 < R < 149.6$	$495 < z < 650$
SCT	overall envelope (barrel)	$255 < R < 594$	$0 < z < 805$
	overall envelope (end-cap)	$251 < R < 610$	$810 < z < 2797$
	4 barrel layers	$299 < R < 514$	$0 < z < 749$
	2×9 end-cap disks	$275 < R < 560$	$839 < z < 2735$
TRT	overall envelope (barrel)	$554 < R < 1082$	$0 < z < 780$
	overall envelope (end-caps)	$617 < R < 1106$	$827 < z < 2744$
	73 straws barrel planes	$563 < R < 1066$	$0 < z < 712$
	160 straw end-caps planes	$644 < R < 1004$	$848 < z < 2710$

Table 2.1: Inner Detector dimensions.

2.3.2 The SemiConductor Tracker

The SemiConductor Tracker, SCT, uses silicon microstrips to track charged particles and it is composed of four barrel layers and nine end-cap disks. Each SCT module is made of two silicon strips sensors attached back to back with a relative angle of 40 mrad. In this way each particle traversing a module has two stereo hits allowing three-dimensional reconstruction of the trajectory space points. Barrel modules are rectangular and have 64 mm long sensors directed along the z axis with $80 \mu\text{m}$ strip pitch, while end-cap modules, wedge shaped, are oriented perpendicularly to the z -axis and are 60 or 120 mm long with an average strip pitch of $80 \mu\text{m}$. There are 2112 modules in the barrels and 988 modules in the end-caps, each one with 768 strips, yielding a total of 6.3 million readout channels. The accuracy of the measurements in the SCT is of $17 \mu\text{m}$ in the R - ϕ plane and $580 \mu\text{m}$ in the longitudinal plane, both in the barrels and in the end-caps. Together with the Pixel detector, the SCT plays a fundamental role in high precision pattern recognition and measurement of vertices and impact parameters.

2.3.3 The Transition Radiation Tracker

The Transition Radiation Tracker, TRT, is a drift tube tracking system located in the outermost part of the ID. It uses 4 mm diameter straws, filled with 70:27:3 Xe:CO₂:O₂ gas mixture, with a gold plated tungsten wire inside. A particle traversing a straw causes the ionization of the gas, whose charges are then collected by applying a strong potential difference between the wall of the straw and the wire. The distance of a particle from the wire, the *drift radius*, can be determined by measuring the time it takes to the wire to collect

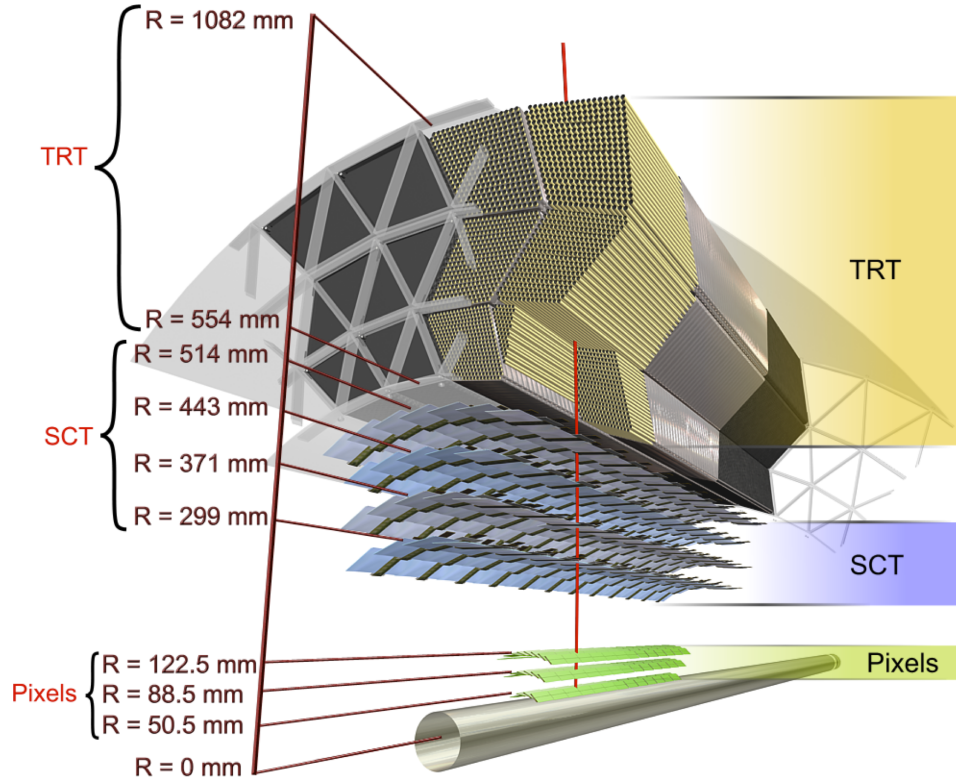


Figure 2.3: representation of the Inner Detector barrel region with a 10 GeV p_T track.

the ionization charges. The resolution on the drift radius is $170 \mu\text{m}$. The gas mixture is sensitive to the radiation photons produced in the material between the straws. The number of photons produced is proportional to the relativistic $\gamma = E/m$ factor of the incoming particle. For any given track it is therefore possible to discriminate, to some extent, the nature of the particle, in particular it is possible to determine whether it is an electron or a much heavier hadron. For energies higher than 1 GeV an electron identification efficiency of 99% can be achieved with a pion rejection factor of 100. In the barrel region the TRT has 73 layers of 144 cm long straws oriented along the beam axis and divided in two at $\eta = 0$, while each TRT end-cap has 18 disks of 37 cm long straws radially arranged. The Transition Radiation Tracker offers a total of 372032 readout channels from 52544 straws in the barrels and 319488 in the end-caps. Since the straws have a much bigger dimension than the silicon strips and pixels, the occupancy level of the TRT is higher, reaching a value close to 50% at LHC design luminosity. The TRT can only provide measurements in the R - ϕ plane with an accuracy of $130 \mu\text{m}$. Despite its limited space precision, the use of the TRT in pattern recognition improves the momentum resolution by a factor of two for muons with a p_T

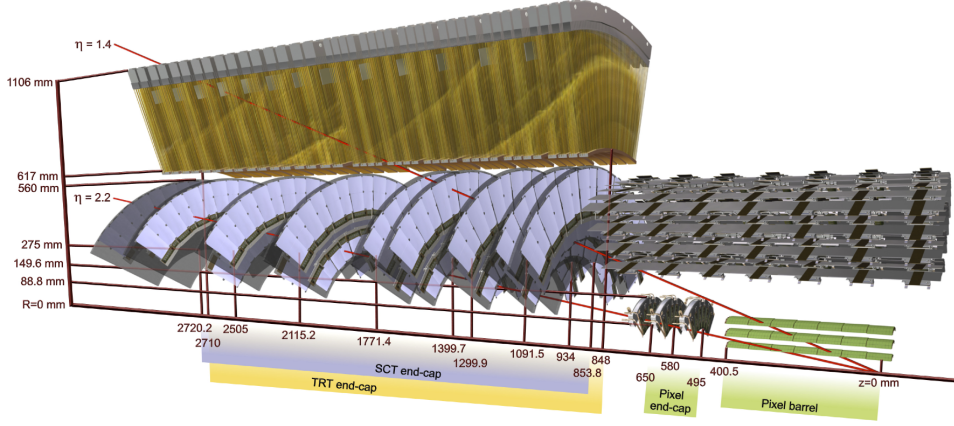


Figure 2.4: representation of the Inner Detector end-cap region with two 10 GeV p_T tracks.

of 500 MeV, thanks to its long lever arm.

2.4 Calorimeters

Calorimeters measure the energy deposited by charged and neutral particles, interacting electromagnetically or strongly, in the calorimeter active volume. High energy particles traversing the calorimeters produce a cascade of secondary particles, the *shower*. Secondary particles, in turn, contribute to the development of the shower until they have enough energy or, in the worst scenario, until they have completely traversed the calorimeter. The energy loss in the calorimeters can be estimated by the amount of light, charge or heat produced. The purpose of the calorimeters is to provide the experiment with the measurement of particle direction, jet energy, missing transverse energy, E_T^{miss} , and particle identification. ATLAS calorimeters are *sampling calorimeters*, which means they are made of a passive material, or absorber, and an active material interleaved in layers. The passive material is a high dense material, typically lead, since it has to produce the shower and make it evolve in a limited space. Active material layers are in turn used to measure the energy deposited by the shower. The advantage of this strategy is that showers can be produced, measured and fully contained in a rather limited space. The down side is that part of the shower energy is absorbed by the passive material, therefore the total energy shower has to be estimated from the fraction effectively measured. The depth of the calorimeter is a fundamental parameter in the design. Showers must be in fact completely contained in order to be able to measure their energy. Moreover there is the need to limit as much as possible punch-through particles reaching the Muon Spectrometer placed outside of the calorimeters.

ATLAS has two calorimeters for the identification of differently interacting particles: the Electromagnetic Calorimeter and the Hadronic Calorimeters.

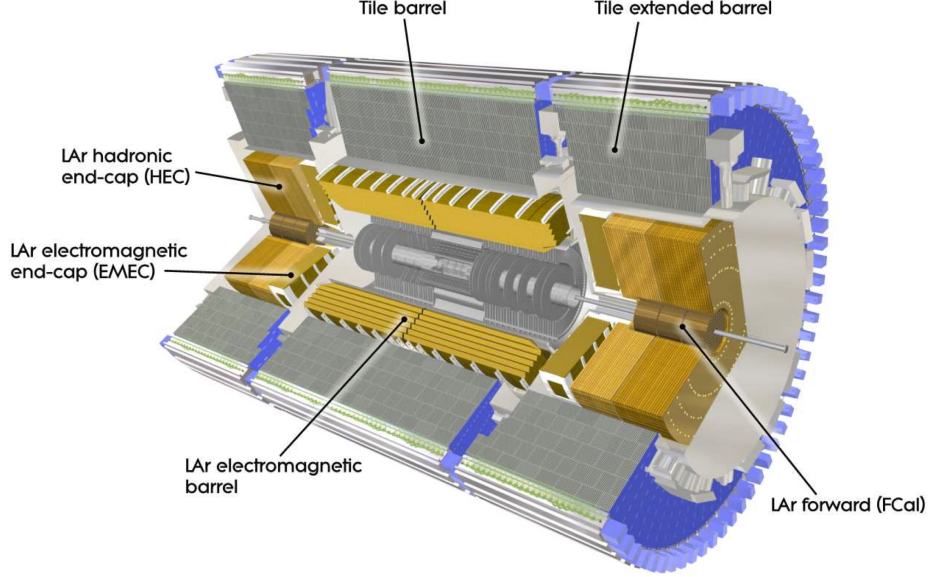


Figure 2.5: cut-away view of ATLAS calorimeters.

2.4.1 The Electromagnetic Calorimeter

The Electromagnetic Calorimeter, EM, is intended to measure electron and photon showers. Showers by muons, produced by bremsstrahlung, are usually negligible up to a muon energy of ~ 500 GeV. Electrons and positrons lose energy mainly by ionization and bremsstrahlung, while high energy photons mostly interact via pair production. High energy electrons and photons are signatures of important processes at LHC. Their identification plays thus a crucial role in ATLAS physics analyses. The design of the EM calorimeter required strong electron and photon identification against QCD background and high energy and spatial resolutions (both in η and ϕ), with minimal acceptance loss. The search of the Higgs boson in channels such as $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ^* \rightarrow 4e$ imposes in fact a good spatial resolution for the calculation of invariant masses.

The EM sampling calorimeter uses lead as absorber material and liquid Argon, LAr, as active material due to its tolerance to radiations. The internal layers are designed with an accordion shape which provides a complete ϕ coverage without any crack region. The EM calorimeter is divided in a barrel and two end-caps, each one housed in a different cryostat. The barrel is 6.8 m long with an inner radius of 1.15m and an outer radius of 2.25 m,

it covers up to $|\eta| < 1.475$. Its thickness varies in η from 22 to 33 radiation lengths, X_0 . The end-caps cover the region $1.375 < |\eta| < 3.2$, they go as close to the beam as 0.3 m and have an outer radius of 2 m. Each end-cap is divided in two wheels along the $|\eta| = 2.5$ cone. The thickness varies as a function of η from 24 to 38 X_0 .

In the $|\eta| < 2.5$ region the EM calorimeter is divided in three longitudinal layers with a presampler placed in the front for $|\eta| < 1.8$. The purpose of the presampler, which does not have any absorber material, is to give a correction for any energy loss before the calorimeter. The inner layer, 6 X_0 deep, has the highest granularity, allowing e and γ to be separated from π . The second layer is 16 X_0 deep and collects most of the deposited energy. The last layer has the coarser granularity and is 2-12 X_0 deep. It is used to discern the high energy electromagnetic showers.

The resolution of the EM calorimeter can be parametrized as:

$$\frac{\sigma(E)}{E} = \sqrt{\left(\frac{a}{\sqrt{E}}\right)^2 + \left(\frac{b}{E}\right)^2 + c^2} \quad (2.5)$$

where a is the stochastic term, b accounts for electronic noise and c accounts for local non-uniformities in the response of the calorimeter [7]. For ATLAS the values are: $a = 10\%$, $b = 0.5\%$ and $c = 0.7\%$. In the 15 - 180 GeV energy range the response of the EM calorimeter is linear to within 0.1%.

2.4.2 The Hadronic Calorimeters

ATLAS Hadronic Calorimeters are placed right outside of the EM calorimeter. They are designed to measure the energy and the direction of jets. Since hadronic showers are much deeper than the electromagnetic ones, the Hadronic Calorimeter must be thick enough to fully contain such energetic showers and prevent punch-through hadrons from reaching the Muon Spectrometer. ATLAS Hadronic Calorimeters are up to 10 interaction lengths, λ , long and divided into three sub-systems: the Hadronic Tile Calorimeter, the Hadronic End-cap Calorimeter and the Forward Calorimeter.

Depending on the η region covered, ATLAS Hadronic Calorimeters have two different resolutions [7]:

$$\frac{\sigma(E)}{E} = \frac{50\%}{\sqrt{E}} \oplus 3\% \quad |\eta| < 3 \quad (2.6)$$

$$\frac{\sigma(E)}{E} = \frac{100\%}{\sqrt{E}} \oplus 10\% \quad 3 < |\eta| < 5 \quad (2.7)$$

The Hadronic Tile Calorimeter

The Hadronic Tile Calorimeter is a sampling calorimeter that uses steel plates as absorber and plastic scintillators as active material. It is divided

into one central barrel and two lateral extended barrels. The central barrel is 5.8 m long and the extended barrels are 2.6 m long. Both barrels have an inner radius of 2.28 m and an outer one of 4.25 m. The total coverage extends up to $|\eta| < 1.7$, where the central element covers up to $|\eta| < 1.0$ and the lateral ones cover the $0.8 < |\eta| < 1.7$ volume. The depth of the Hadronic Tile Calorimeter ranges from 7.4λ at $|\eta| = 0$ to 9.7λ in the lateral barrels.

The Hadronic End-cap Calorimeter

The Hadronic End-cap Calorimeter, HEC, is a sampling calorimeter with copper plates as absorbers and LAr as active material. It is placed behind the EM calorimeter wheels, inside the Hadronic Tile Calorimeter extended barrels, and covers the $1.5 < |\eta| < 3.2$ region. Each HEC is divided into two identical wheels, longitudinally aligned, with an outer radius of 2.03 m.

The Hadronic Forward Calorimeter

The hadronic Forward Calorimeter, FCal, is a sampling calorimeter covering the very forward regions, $3.1 < |\eta| < 4.9$, placed inside the HEC. The FCal has three different longitudinal layers. The first layer, designed for electromagnetic measurements, uses copper as passive material. The other two layers use tungsten and are meant for hadronic showers measurements. In both cases LAr is used as active material since the forward regions are subject to high radiation doses.

2.5 The Muon Spectrometer

The Muon Spectrometer, MS, is ATLAS outermost sub-detector, designed to track high p_T muons independently from the ID and to provide muon trigger. Momentum measurements are allowed by the ATLAS superconducting air-core toroid magnetic system. The MS has by design 10% p_T resolution at 1 TeV and $50 \mu\text{m}$ spatial resolution. It covers the pseudorapidity region $|\eta| < 2.7$. The MS is composed of a barrel and two end-caps, each one composed of three layers: inner, middle and outer layers. The barrel layers are placed at distances of 5, 7.5 and 10 m from the beam pipe and divided into 16 azimuthal sections providing a full ϕ coverage. The three end-caps wheels have the same ϕ symmetry of the barrels and are positioned at 7.4, 14 and 21.5 m from the IP. An extra wheel is arranged in the barrel-end-cap transition region at 10.4 m from the IP.

The MS employs Monitored Drift Tube chambers and Cathode Strip Chambers for high precision muon tracking and Resistive Plate Chambers and Thin Gap Chambers for muon trigger.

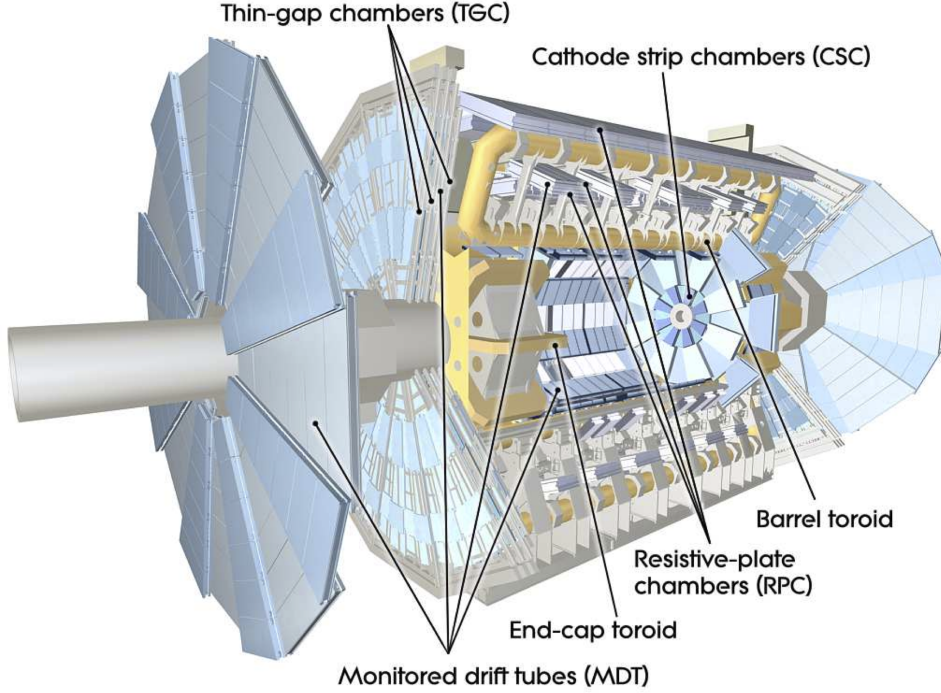


Figure 2.6: cut-away view of the Muon Spectrometer.

2.5.1 Monitored Drift Tube chambers

Monitored Drift Tube chambers, MDT chambers, provide ATLAS with high precision muon tracking in the barrel region. MDT stations are composed of two multi-layers of MDTs divided by a spacer. Each multi-layer has three or four MDT layers, depending on the region covered. An MDT is made of a 30 mm diameter aluminium tube filled with 93:7 Ar:CO₂ gas mixture at 3 bar pressure. A gold plated tungsten anode wire is placed inside each tube with a voltage difference of 3040 V between the walls and the wire. When a track traverses a tube, its position is inferred from the arrival time of the charge clusters collected by the wire. A single MDT has a resolution of 80 μm but in a chamber it goes down to 35 μm . Track position is measured only in the chamber transverse plane, i.e. ATLAS longitudinal plane, where tracks are bent by the toroidal magnetic field. The MDT chamber frame houses an alignment system deploying four optical rays (see figure 2.7) to constantly monitor any possible deformation and displacement.

2.5.2 Cathode Strip Chambers

Cathode Strip Chambers, CSCs, offer high precision muon measurements in the end-cap regions. Unlike MDT chambers, CSCs can manage the high

MDT	coverage	$ \eta < 2.7$
	number of chambers	1150
	number of channels	354000
	function	precision tracking
CSC	coverage	$2.0 < \eta < 2.7$
	number of chambers	32
	number of channels	31000
	function	precision tracking
RPC	coverage	$ \eta < 1.05$
	number of chambers	606
	number of channels	373000
	function	triggering, second coordinate
TGC	coverage	$1.05 < \eta < 2.7$ (2.4 for triggering)
	number of chambers	3588
	number of channels	318000
	function	triggering, second coordinate

Table 2.2: Muon Spectrometer parameters.

particle rates typical of the forward regions without suffering for the high occupancy. CSCs are multi-wire proportional chambers with anode wires oriented radially and cathode strip oriented perpendicularly to the wires. From the measurement of the charge collected by the segmented cathode strips it is possible to resolve the position of the hit. CSCs have a precision of $40\ \mu\text{m}$ in the bending plane and $5\ \text{mm}$ in the non-bending plane. The small volume of the chambers allows small drift times and a time resolution of $7\ \text{ns}$.

2.5.3 Resistive Plate Chambers

Resistive Plate Chambers, RPCs, provide muon trigger in the barrel region. An RPC is a gaseous detector with parallel electrode plates. Two parallel resistive plates, made of phenolic-melaminic plastic laminate, at a distance of $2\ \text{mm}$ are immersed in a $4.9\ \text{kV/mm}$ electric field provided by graphite electrodes at a voltage of $9.8\ \text{kV}$. The gap is filled with $\text{C}_2\text{H}_2\text{F}_4$: Iso – C_4H_{10} : SF_6 94.7:5:0.3 gas mixture. Traversing muons generate, along their tracks, avalanches that are read by capacitive coupling to metallic strips on the outer sides of the resistive plates. RPCs have a spatial resolution of $10\ \text{mm}$ in both longitudinal and transverse planes. The ϕ coordinate from the RPCs is used together with precise η coordinate from the MDTs to track the muons. The $\sim 1.5\ \text{ns}$ time resolution of the RPCs justifies their adoption for muon triggering. Each RPC station is composed of two RPCs. Two RPC stations are mounted on each MDT middle layer and only one RPC station

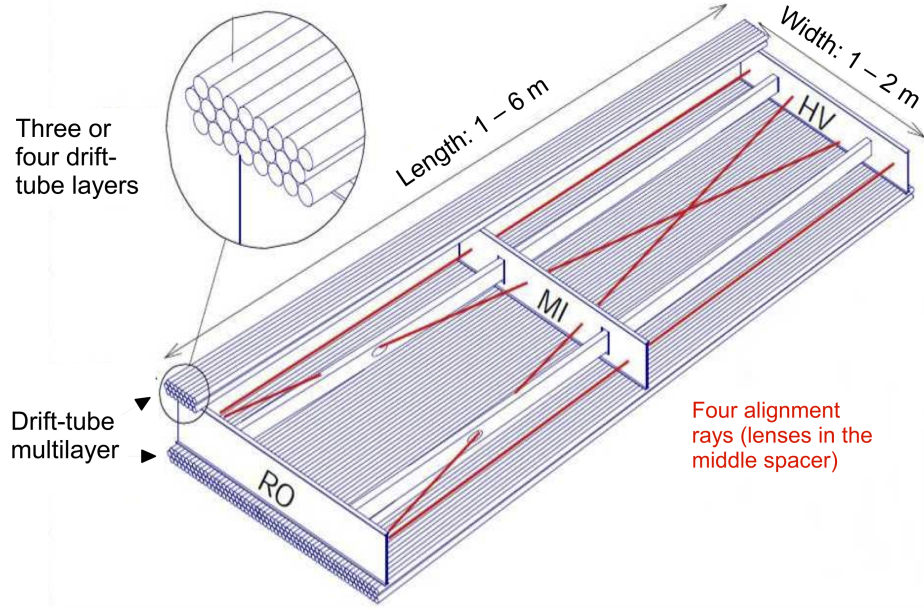


Figure 2.7: structure of a Monitored Drift Tube chamber.

is mounted on the outer MDT layer.

2.5.4 Thin Gap Chambers

Thin Gap Chambers, TGCs, are multi-wire proportional chambers providing muon tracking and triggering in the end-caps. TGCs are operated at a voltage of 2.9 kV and use a gas mixture of $\text{CO}_2 : n - \text{C}_5\text{H}_{12}$ 55:45. The radial coordinate is measured by gold-coated anode wires and the azimuthal coordinate is measured by pick-up strips. Four TGC wheels are mounted per end-cap.

2.6 Magnet system

ATLAS magnet system is composed of four superconducting magnets working at a temperature of 4.6 K: the Central Solenoid, the Barrel Toroid and the two End-Cap Toroids. The Barrel Toroid and the the End-Cap Toroids together form ATLAS air-core superconducting magnetic system. The choice of an air-core magnet, instead of a stronger iron-core, was driven by the request of minimizing multiple scattering in the Muon Spectrometer.

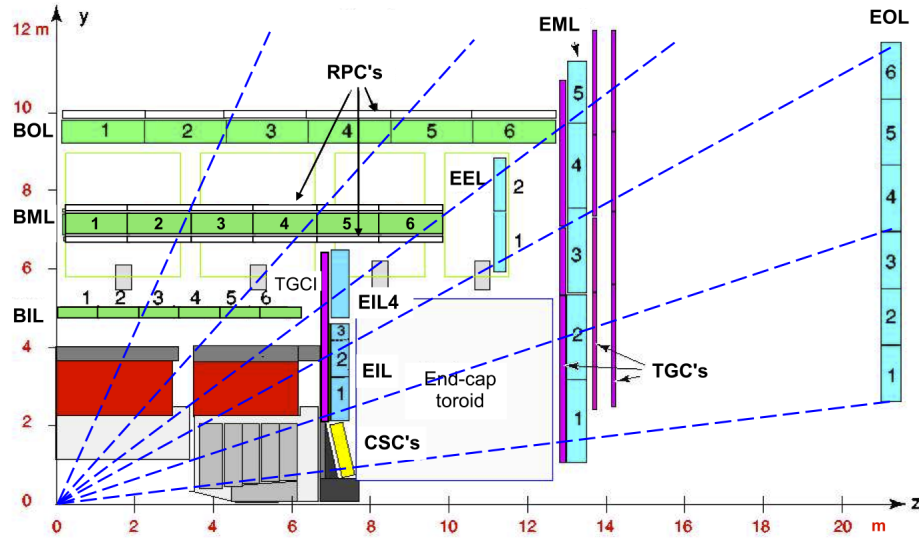


Figure 2.8: Muon Spectrometer cross section.

Central Solenoid

The Central Solenoid, CS, provides a 2 T strong axial magnetic field for the Inner Detector. Its flux is returned by the hadronic calorimeter. The CS has an inner radius of 2.46 m, an outer one of 2.56 m and it is 5.8 m long.

Barrel Toroid

The Barrel Toroid, BT, provides a 0.5 T toroidal magnetic field to the Muon Spectrometer barrel volume. It is composed of eight coils surrounding the calorimeters. The BT has an inner diameter of 9.4 m and an outer diameter of 20.1 and is 25.3 m long.

End-Cap Toroids

The End-Cap Toroids, ECT, provide a 1.0 T magnetic field in the end-cap volumes. The ECT is formed by eight small superconducting coils.

2.7 Trigger and Data Acquisition

The average size of an ATLAS event is about 1.3 MB. Multiplying by the LHC average bunch crossing rate of 40 MHz we get a rather unmanageable data stream of 52 TB/s. To reduce the data stream to a sustainable output bandwidth of 300 MB/s, corresponding to an event rate of 200 Hz, ATLAS

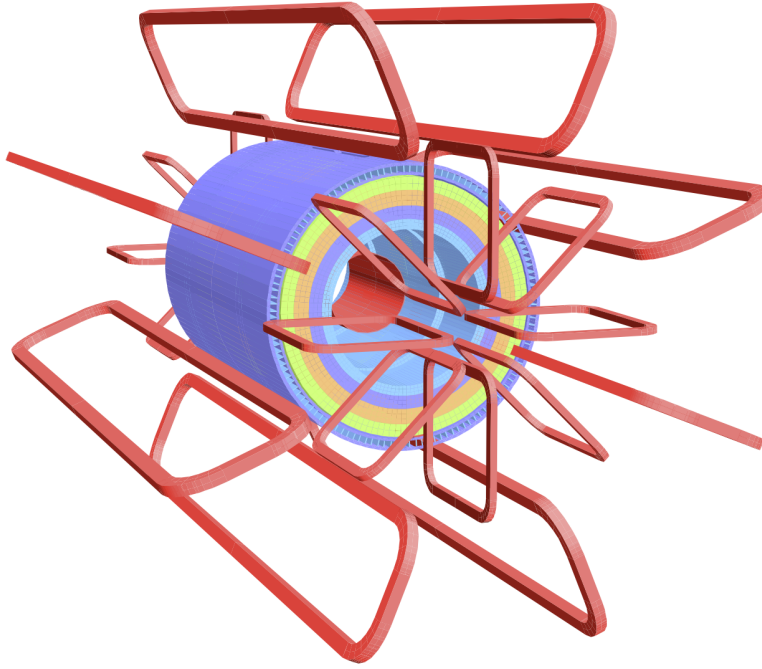


Figure 2.9: geometry of the magnet system end calorimeter steel.

uses a Trigger and Data Acquisition system, TDAQ. The purpose of the TDAQ is to reduce the amount of data to store by selecting only interesting events, removing those not containing hard scattering processes such as Minimum Bias soft collisions. Operation of the trigger system is defined by *trigger menus*, specifying thresholds, trigger items and selection criteria to be adopted at each stage of the trigger chain. Data streams are tagged accordingly to the adopted trigger menu. ATLAS TDAQ is organized in three distinct levels: a Level 1 trigger, a Level 2 trigger and an Event Filter. Level 2 and Event Filter together constitute the High Level Trigger, HLT. Trigger levels work in chain, each one refining the selection operated by the previous.

2.7.1 Level 1 trigger

Level 1 trigger, L1, is hardware-based and uses limited information from the detectors to reduce the event rate down to 75 kHz. L1 trigger uses informations from the coarser sections of the calorimeters and Muon Spectrometer trigger chambers. It searches for high p_T muons, electrons, photons, jets, τ leptons decaying into hadrons and E_T^{miss} . L1 trigger defines Regions of Interest, RoIs, in the η - ϕ plane in correspondence of identified trigger features. L1 has a latency of 2.5 μs .

2.7.2 Level 2 trigger

Level 2 trigger, L2, is software based and is seeded by the RoIs from L1. L2 uses dedicated software to reconstruct physics objects, such as muons, photons and jets within the RoIs, using the full information from the detector. The event stream is reduced to 3.5 kHz with a decision time of about 40 ms.

2.7.3 Event Filter

The Event Filter, EF, exploits the offline analysis procedure on fully reconstructed events, reducing the event rate to 200 Hz. The processing time is around 4 s. Events succeeding the EF are written to mass storage.

2.8 Athena

The complexity of the ATLAS experiment imposes the use of a modular software framework to manage the reconstruction, the analysis and also the event simulation. The advantage of a modular framework lies in its intrinsic flexibility and ease of development and maintenance. Athena is ATLAS software framework. The purpose of Athena is to provide users with a common software skeleton into which developers can plug their code. Extendability and flexibility allow common functions to be implemented into the framework for re-use, encouraging a common approach and granting a robust coding and debugging. Athena is designed to handle both simulation and reconstruction of events, thanks to its modularity. Common interfaces and data objects are implemented into ATLAS software framework to ensure communication between different algorithmic modules.

The definition within Athena of an Event Data Model, EDM, for data classes ensures commonality across experiment sub-systems, allowing the use of common software between different processes and the interchangeability of software modules. For example, data from ATLAS is converted from a byte stream to Raw Data Objects, RDOs; simulated data is converted too into RDOs. The module responsible for producing Prepared Raw Data, PRD, from RDOs takes as input any RDO, enabling the use of the same algorithms for data and simulation. As a consequence, the reconstruction module producing Event Summary Data, ESD, and Analysis Object Data, AOD, takes as input any PRD, prescindig from its source. ESDs are the output of the reconstruction process and contain all of the event information, making the files too cumbersome to be adopted in most of the analyses. On the other hand, AODs contain only physics objects, such as particle four vectors, and are therefore much more manageable.

2.9 Simulation

Simulated data is of fundamental importance in the software validation process and in the understanding process of the detectors. The simulation begins with the generation of the physics process using an event generator. At this stage the hard scattering process, the initial and final state radiation, the quark hadronization and the decay of particles are generated at physics level¹. In a second step particles are propagated through the detectors, simulating the interactions with the active and passive materials of the experiment. An algorithm based on the GEANT4 software and customized with the ATLAS geometry, G4ATLAS, takes care of propagating the particles. At last the response of the ATLAS experiment to the passage of the particles is translated into signals. The simulated hits, SIM, are then translated into RDOs. This stage is called *digitization*.

2.10 Tracking

ATLAS is designed to provide high precision particle detection over a wide momentum range. The tracking is accomplished by the Inner Detector, the Muon Spectrometer and in part by the calorimeter system. Track parameters such as momentum, charge and impact parameters are measured, thanks also to the magnet system. The modularity of the ATLAS software allows the use of common tracking software for the two main tracking devices, ID and MS.

2.10.1 Inner Detector tracking

Tracking inside the ID is achieved in two steps: pattern recognition and track fitting. Pattern recognition identifies hits belonging to the same particle trajectory. Subsequently a track is fitted to the identified pattern, returning the best estimation of the track parameters. Two reconstruction approaches are adopted in sequence in the ID: inside-out and outside-in tracking. More sophisticated algorithms are adopted in addition when interested in recovering very low p_T tracks, like in the Minimum Bias analysis.

Inside-out

The reconstruction starts with the creation of three dimensional Space Points out of Pixel detector hits and SCT hits from stereo layers. Track seeds are then created out of three silicon space points and are used to define roads to find other points to include in the track candidate. Afterwards, shared hits between different tracks, the so called *ambiguities*, are resolved by assigning the hit to the track with the lowest χ^2 fit value. The other tracks are then

¹A more detailed description of the simulation process at physics level is given in chapter 4.

refitted. Tracks with χ^2 values beyond a certain value are rejected. Silicon seeded tracks are then used to find roads in the TRT for a possible extension. If the TRT hits improve the quality of the fit, they are included in the track.

Outside-in

The outside-in method, on the other hand, uses TRT seeded tracks to find extensions in the silicon detector. Due to the limited tracking capabilities of the TRT, track seeds are created in the two-dimensional transverse plane. A Hough transform strategy is adopted to find TRT track segments which are then extrapolated to the SCT and Pixel detectors, adding successively silicon hits. After solving any ambiguity, a track refitting is operated as in the inside-out process. Outside-in tracking brings the possibility of recovering particles coming from secondary vertices due to long-lived particles, such as $D^0 \rightarrow K^- \pi^+$, or conversion electrons, which have too few hits in the silicon detectors to be efficiently identified by the inside-out algorithm. TRT segments with no silicon extension are stored anyways as *TRT-only* tracks.

2.10.2 Muon Spectrometer tracking

ATLAS employs a variety of different strategies to reconstruct muons [6][8]. The direct approach is given by the *standalone* reconstruction, which uses the MS alone. Anyways, the most robust technique is the *combined* reconstruction, which combines MS and ID tracks. The last strategy is the *tagging*, which adopts information from the MS to tag ID tracks as muons. Two families of algorithms, both covering all these three strategies, are adopted in ATLAS: STACO and MUID, named after their algorithms for combined muon reconstruction. In this section more focus will be put on STACO².

Standalone muons

Within the STACO family the algorithm responsible for the reconstruction of standalone muons is Muonboy. The reconstruction process starts by looking for patterns in the outermost muon chambers. Close hits in the same chamber are fitted into segments which are then extrapolated inward adding segments from the middle and inner chambers. Muons are extrapolated to the IP taking into account multiple scattering effects due to interactions with detector material, parametrized energy loss and the map of the inhomogeneous magnetic field. No use is made of the energy loss measured in the calorimeters. Standalone tracking has the advantage of an extended tracking

²The analysis presented in this thesis uses STACO muons. However results were found to be consistent with MUID.

volume, $|\eta| < 2.7$, compared to the ID, $|\eta| < 2.5$, and ensures the reconstruction of muons from K and π decays in the calorimeters. Low energy muons, $E \lesssim 2$ GeV, produced in the inner volume are likely to be stopped inside the calorimeter.

Combined muons

The quality of standalone muons is significantly improved when they are combined with ID tracks. Standalone muons suffer badly from the back extrapolation to the IP due to material effects. The problem is solved by combining MS and ID tracks together into a single muon track. Combined muons benefit greatly from the high precision of the ID although the tracking volume is reduced to $|\eta| < 2.5$. The STACO algorithm performs a statistical combination of the two muon tracks to obtain the combined muon track vector. The χ^2 returned by the matching is used to decide whether or not the combination is successful.

Muon tagging

Additional muon candidates are provided by the muon tagging algorithm: MuTag for the STACO family. This algorithm tags ID tracks as muons based on the available informations from the MS. In contrast to the muon combining method, muon tagging does not require a complete standalone muon but just muon segments. Tracks from the ID are extrapolated to the inner chambers of the MS, looking for available Muonboy segments. If a segment is close enough to the extrapolated ID track then the track is tagged as muon. Tagged muons are an extension to the muon collection since segments already included into combined muons are not used by MuTag. Muon tagging is particularly helpful in recovering low p_T muons and muons from areas with limited MS coverage.

Chapter 3

The Standard Model

The Standard Model is the current picture of elementary particles physics and by all means may be regarded as the state of the art of human thought.

The SM describes in a rather simple and elegant way fundamental particles and their behavior under the action of the electromagnetic, weak and strong interactions¹ [9][10][11]. It provides a perturbative and renormalizable theoretical framework suitable for the calculation of cross sections and the prediction of experimentally observable phenomena. The SM was originally developed in the 1960s by Glashow, Weinberg and Salam and finalized in the following years when confirmations from a variety of different experiments decided the success of the theory. Within the SM particles are identified as being either *fermions* or *bosons*. Fermions, by definition, have half-integer spin values and are regarded as the ultimate constituents of matter. They can be divided into families of quarks and leptons: the quarks interacting via electromagnetic, strong and weak forces while the leptons interacting only electromagnetically and weakly. Both quarks and leptons have six members that can be arranged in three families of two quarks or two leptons. As a distinction between the two classes of fermions, quarks are said to have a *flavor* while leptons have a *leptonic number* defined by their family. The masses of the fermions extend up to a few hundreds GeV. On the other hand bosons have integer spin values and are identified as the carriers of the fundamental interactions. The photon is the carrier of the electromagnetic interaction and it is massless. The $W^\pm$ bosons together with Z are the carriers of the weak force and have masses of 80.40 GeV and 91.19 GeV respectively [12]. Gluons mediate the strong interaction between color charged particles, i.e. quarks. The Higgs boson, although it hasn't been observed yet, is the key-stone of the SM. It is a scalar boson which doesn't carry any force but it is the responsible for the mass of all the particles within the SM.

On a mathematical point of view, the SM is a gauge field theory based

¹Gravitational interaction is not included since there is no coherent description of such force to be used together with the other three.

Three Generations of Matter (Fermions)				
	I	II	III	
mass→	2.4 MeV	1.27 GeV	171.2 GeV	0
charge→	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$	0
spin→	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$	1
name→	u up	c charm	t top	γ photon
Quarks	4.8 MeV $-\frac{1}{3}$ $\frac{1}{2}$ d down	104 MeV $-\frac{1}{3}$ $\frac{1}{2}$ s strange	4.2 GeV $-\frac{1}{3}$ $\frac{1}{2}$ b bottom	0 0 1 g gluon
	<2.2 eV 0 $\frac{1}{2}$ ν_e electron neutrino	<0.17 MeV 0 $\frac{1}{2}$ ν_μ muon neutrino	<15.5 MeV 0 $\frac{1}{2}$ ν_τ tau neutrino	91.2 GeV 0 1 Z weak force
	0.511 MeV -1 $\frac{1}{2}$ e electron	105.7 MeV -1 $\frac{1}{2}$ μ muon	1.777 GeV -1 $\frac{1}{2}$ τ tau	80.4 GeV ± 1 1 W weak force
Leptons				Bosons (Forces)

Figure 3.1: Standard Model particles. In purple are the quarks while in green are the leptons. On the right column, in light blue, are the gauge bosons. The Higgs boson is not included in this figure.

on the symmetries of the $SU(3)_C \times SU(2)_L \times U(1)_Y$ group, where the interactions are generated from the requirement of local gauge invariance. The subgroup $SU(2)_L \times U(1)_Y$ is the core of the SM, describing QED and weak interactions as a whole. On the other side, the $SU(3)$ block is an almost straight forward extension for QCD interactions of the QED formalism given by the $U(1)_{em}$ group and is beyond the purpose of this thesis².

Despite its strong experimental confirmations the SM is nevertheless far from being a complete theory. Physics subjects like general relativity, dark matter, dark energy and neutrino oscillations do not fit inside the SM frame and constitute a motivation for a theory beyond the SM.

3.1 The electro-weak interaction

The electro-weak interaction unification is the heart of the Standard Model and was formalized in the 1960s by Glashow, Weinberg and Salam. Before its unification with the electromagnetic interaction, the weak inter-

²A description of proton-proton interactions can be found in chapter 4.

action was described by Fermi's theory, assuming a point-like interaction coupling between the four fermions involved. Anyhow the theory reveals its limits when applied at high energies, where divergencies arise. This behavior can be avoided by the introduction of weak vector bosons. The first attempt to frame the weak interaction into a gauge theory was with the $SU(2)_L$ group. The idea was based on the observation that weak Charged Current, CC, interactions associate pair of particles like $e \leftrightarrow \nu_e$ and $\mu \leftrightarrow \nu_\mu$ in interactions like β decay, $p \rightarrow n \bar{\nu}_e e$, and neutrino scattering, $\nu_\mu N \rightarrow \mu X$. The subscript “ L ” came from the observation that only left-handed particles are coupled to CC. In terms of particle fields, weak CC are formalized as:

$$j_\mu^+ = \bar{\nu} \gamma_\mu \frac{1}{2} (1 - \gamma^5) e = \bar{\nu}_L \gamma_\mu e_L \quad (3.1)$$

$$j_\mu^- = \bar{e} \gamma_\mu \frac{1}{2} (1 - \gamma^5) \nu = \bar{e}_L \gamma_\mu \nu_L \quad (3.2)$$

where $\frac{1}{2}(1 - \gamma^5)$ is the chiral left projector which introduces the coupling to only left-handed particles and thus parity violation in weak interactions. A left-handed doublet can be arranged from e and ν , together with a right-handed e singlet:

$$\chi_L = \begin{pmatrix} \nu \\ e \end{pmatrix}_L \quad \chi_R = e_R \quad (3.3)$$

usually called *weak isospin doublet* and *singlet*. A right-handed neutrino singlet is not introduced since there is no observation of such particle, although there exist evidence of non-vanishing neutrino mass³. Making use of Pauli 2×2 matrices, σ_i , which are a fundamental representation of $SU(2)$, we may rewrite CCs as:

$$j_\mu^\pm = \bar{\chi}_L \gamma_\mu \sigma_\pm \chi_L \quad (3.4)$$

$$\sigma_\pm = \frac{1}{2}(\sigma_1 \pm \sigma_2) \quad (3.5)$$

The effect of the $\sigma_\pm$ operators is that of changing one state of the $SU(2)_L$ doublet to the other. σ_+ transforms the electron into a neutrino while σ_- transforms the neutrino into an electron. σ_+ and σ_- are identified as generators of the weak isospin. The third component of the chosen $SU(2)_L$ representation, namely σ_3 , can be used to define a new current, orthogonal to the previous two:

$$\begin{aligned} j_\mu^3 &= \bar{\chi}_L \gamma_\mu \frac{1}{2} \sigma_3 \chi_L = \\ &= \bar{\nu}_L \gamma_\mu \frac{1}{2} \sigma_3 \nu_L - \bar{e}_L \gamma_\mu \frac{1}{2} \sigma_3 e_L \end{aligned} \quad (3.6)$$

$\frac{1}{2}\sigma_3$ defines the third generator of the weak isospin. Anyhow this charge-preserving current cannot be identified with the weak Neutral Current, NC,

³The inclusion of neutrino mass into the SM picture is still an open issue. According to certain models the introduction of neutrino mass is foreseen in a theory beyond the SM. For a comprehensive description of the introduction of neutrino mass within the SM through the Majorana mass mechanism refer to [11].

since this is experimentally observed to have both left and right-handed terms while j_μ^3 couples only to left-handed particles. Nonetheless the identification of a triplet of currents is remarkable since it forms the basis for a gauge theory of weak interactions.

The breakthrough idea came to Glashow in 1961 [13]. He proposed to combine $SU(2)_L$ weak isospin group with $U(1)_{em}$ electromagnetic group into a unified $SU(2)_L \times U(1)$ group. Since $U(1)_{em}$ doesn't have any defined transformation property under $SU(2)_L$, a new $U(1)$ symmetry group with singlet properties under $SU(2)_L$ has to be defined. This is achieved by defining the *weak hypercharge*, Y , as the generator of the new $U(1)_Y$ symmetry:

$$Y = 2(-T_3 + Q) \quad (3.7)$$

$$T_3 = \frac{1}{2}\sigma_3 \quad (3.8)$$

where T_3 is the third component of the weak isospin. The associated current is:

$$j_\mu^Y = \bar{\psi}\gamma_\mu Y\psi \quad (3.9)$$

The electromagnetic current, in turn, can be written as:

$$j_\mu^{em} = j_\mu^3 + \frac{1}{2}j_\mu^Y \quad (3.10)$$

	T	T_3	Q	Y
ν_L	1/2	+1/2	0	-1
e_L	1/2	-1/2	-1	-1
e_R	0	0	-1	-2

Table 3.1: $SU(2)_L \times U(1)_Y$ quantum numbers for the electron family.

Numbers in table 3.1 clearly show the commutation properties between $SU(2)_L$ and $U(1)_Y$. $SU(2)_L$ doublets have the same $U(1)_Y$ value, while this is not true for $U(1)_{em}$. j_μ^Y is invariant under $SU(2)_L$ transformations:

$$j_\mu^Y = -\bar{e}_R\gamma_\mu 2e_R - \bar{e}_L\gamma_\mu 1e_L - \bar{\nu}_L\gamma_\mu 1\nu_L \quad (3.11)$$

The $SU(2)_L \times U(1)_Y$ symmetry provides two weak CCs and two NCs. Of the two NCs, one violates the parity while the other couples to both left and right-handed particles. It is important to underline that all these ideas were formalized well before the discovery of NCs in 1973 at CERN and Fermilab.

3.2 The Glashow-Wienberg-Salam model

Weinberg [14] and Salam [15] contributed to the development of the Standard Model by extending the BEHHGK mechanism⁴ to the non-abelian

⁴This mechanism usually takes the name of *Higgs mechanism*, even though it was independently developed by Englert and Brout [16], Higgs [17] and Guralnik, Hagen and

$SU(2)_L \times U(1)_Y$ group, giving mass to all the gauge bosons while retaining the photon massless.

The locally gauge invariant electro-weak Lagrangian is:

$$\begin{aligned} \mathcal{L} = & \bar{\psi}_L \gamma^\mu [i\partial_\mu - g\mathbf{T} \cdot \mathbf{W}_\mu - \frac{1}{2}g'YB_\mu] \psi_L + \\ & + \bar{\psi}_R \gamma^\mu [i\partial_\mu - \frac{1}{2}g'YB_\mu] \psi_R + \\ & - \frac{1}{4} \mathbf{W}_{\mu\nu} \cdot \mathbf{W}^{\mu\nu} + \\ & - \frac{1}{4} B_{\mu\nu} \cdot B^{\mu\nu} \end{aligned} \quad (3.12)$$

where, in order to preserve the $SU(2)_L \times U(1)_Y$ invariance, fermion and boson mass terms cannot be inserted. The BEHHGK mechanism is introduced by adding a $SU(2)_L \times U(1)_Y$ invariant Lagrangian for the Higgs scalar field, ϕ , to the electro-weak Lagrangian:

$$\mathcal{L}_\phi = (D_\mu \phi)^\dagger (D^\mu \phi) - \mu^2 \phi^\dagger \phi - \lambda \phi^\dagger \phi \quad (3.13)$$

where D_μ is the covariant derivative for the $SU(2)_L \times U(1)_Y$ symmetry:

$$D_\mu \equiv i\partial_\mu - g\mathbf{T} \cdot \mathbf{W}_\mu - \frac{i}{2}g'YB_\mu \quad (3.14)$$

and $\mu^2 < 0$ and $\lambda > 0$. The ϕ_i fields can be arranged as a weak isospin doublet with hypercharge $Y = -1$:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} \quad (3.15)$$

in order to be $SU(2)_L$ invariant. As a consequence of choosing $Y = -1$ for the doublet, it follows from $Q = T_3 + \frac{1}{2}Y$ that ϕ^+ is positively charged while ϕ^0 is neutral. The symmetry may be broken and ϕ may be expanded around the vacuum state as:

$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix} \quad (3.16)$$

Upon substitution of the last expression for $\phi(x)$ into the Lagrangian and retaining all the terms up to second order:

$$\begin{aligned} \mathcal{L}_\phi = & [\frac{1}{2}(\partial_\mu H)^2 - \lambda v^2 H^2] + \\ & + \frac{1}{8}g^2 v^2 (W_\mu^1 W^{1\mu} + W_\mu^2 W^{2\mu}) + \\ & + \frac{1}{8}(gW_\mu^3 - g'B_\mu)(gW^{3\mu} - g'B^\mu) + \\ & + \text{kinetic terms for } \mathbf{W} \text{ and } B + \\ & + \text{higher order terms} \end{aligned} \quad (3.17)$$

The first term of the Lagrangian describes the massive scalar field H , $m_H = \sqrt{2\lambda}v = \sqrt{-2\mu^2}$. The second term collects the mass terms for the W^1 and

Kibble [18] in 1964 and is therefore sometimes called *BEHHGK mechanism*.

W^2 gauge fields. According to the definition given in section 3.1 the two fields may be combined to give the $W^\pm$ bosons. The mass of these bosons is found to be $m_W = \frac{1}{2}gv$. As regards the third term we observe that, due to the structure of the third $SU(2)_L$ generator, the gauge boson fields W_μ^3 and B_μ are mixed into one mass term. From the linear combination of W_μ^3 and B_μ two new vector gauge bosons may be defined. In addition, since only one combination of W_μ^3 and B_μ has a mass term, the other one, orthogonal to the first, will be necessarily massless. Therefore the vector gauge fields Z_μ and A_μ may be introduced:

$$Z_\mu = -B_\mu \sin \theta_W + W_\mu^3 \cos \theta_W \quad (3.18)$$

$$A_\mu = B_\mu \cos \theta_W + W_\mu^3 \sin \theta_W \quad (3.19)$$

defining the Z boson and the photon respectively. θ_W is identified as the *Weinberg angle* and it is a parameter of the SM whose value is not predicted and needs to be measured experimentally. On comparison of equations 3.17 and 3.18 it is straightforward to see that:

$$\sin \theta_W = g' \quad (3.20)$$

$$\cos \theta_W = g \quad (3.21)$$

Equations 3.18 and 3.19 may be inverted:

$$W_\mu^3 = A_\mu \sin \theta_W + Z_\mu \cos \theta_W \quad (3.22)$$

$$B_\mu = A_\mu \cos \theta_W - Z_\mu \sin \theta_W \quad (3.23)$$

Therefore, going back to the electro-weak locally gauge invariant Lagrangian, see equation 3.12, the Neutral Current interaction term may be extracted. Upon substitution:

$$\begin{aligned} gj_\mu^3 W^{3\mu} + \frac{1}{2}g' j_\mu^Y B^\mu &= (g \sin \theta_W j_\mu^3 + \frac{1}{2}g' \cos \theta_W j_\mu^Y) A^\mu + \\ &+ (g \cos \theta_W j_\mu^3 - \frac{1}{2}g' \sin \theta_W j_\mu^Y) Z^\mu \end{aligned} \quad (3.24)$$

The first term on the right is clearly the electromagnetic interaction, $ej_\mu^{em} A^\mu$, therefore, recalling equation 3.10:

$$g \sin \theta_W = g' \cos \theta_W = e \quad (3.25)$$

The Weinberg angle is defined by the weak isospin and weak hypercharge interaction coupling constants:

$$\tan \theta_W = \frac{g'}{g} \quad (3.26)$$

The particular choice we operated for the ϕ isospin doublet and its ground state granted the null mass of the photon. The vacuum state, ϕ_0 , was chosen to break the $SU(2)_L \times U(1)_Y$ symmetry but not the $U(1)_{em}$ symmetry

generated by $Q = T_3 + \frac{1}{2}Y$ so that ϕ_0 is a singlet under any $U(1)_{em}$ rotation:

$$\phi_0 \rightarrow [1 + i\Lambda(x)Q]\phi_0 = \phi_0 \quad (3.27)$$

$$Q\phi_0 = (T_3 + \frac{1}{2}Y)\phi_0 = 0 \quad (3.28)$$

and the electro-magnetic gauge boson is therefore massless. The bosons mass spectrum can be summarized as:

$$\begin{aligned} m_{W^\pm} &= \frac{1}{2}gv \\ m_Z &= \frac{1}{2}v\sqrt{g^2 + g'^2} = \frac{1}{2}v = \frac{m_{W^\pm}}{\cos\theta_W} \\ m_\gamma &= 0 \\ m_H &= \sqrt{2\lambda v^2} = \sqrt{-2\mu^2} \end{aligned} \quad (3.29)$$

The parameters introduced by the Glashow-Weinberg-Salam model are just four: the coupling constants g and g' and the Higgs potential parameters λ and v , where $v^2 = -\mu^2/\lambda$. Rather than these theoretical values, for convenience, other four values, associated with experimental observables, are commonly used as parameters of the Standard Model: the fine-structure constant α , the Fermi constant G_F , the Z boson mass m_Z and the Higgs boson mass m_H :

$$\begin{aligned} \alpha &= \frac{1}{4\pi}g^2g'^2 \\ G_F &= \frac{1}{v^2\sqrt{2}} \\ m_Z &= \frac{1}{2}v \\ m_H &= \sqrt{2\lambda v^2} \end{aligned} \quad (3.30)$$

The first three parameters are measured with great precision and represent the basic test measurements of any physics experiment. The only parameter left to be measured within the Standard Model is the mass of the Higgs boson, which is the only term related to λ and it is indeed one of the most challenging goals of the ATLAS experiment.

3.3 The Higgs hunt

3.3.1 Theoretical constraints

The Higgs mass value is the last SM parameter yet to be determined [19][20]. This almost completeness of the theory allows us to put some upper and lower constraints on the value of m_H from theoretical argumentations. While reading, the reasons behind the design $\sqrt{s}$ values of Tevatron and LHC will become more and more clear.

Unitarity

A restriction comes from the violation of unitarity in the scattering of weak gauge bosons. The calculation of the scattering cross section for longitudinally polarized $W^\pm$ and Z bosons yields a value proportional to the center of mass energy. Therefore as $\sqrt{s}$ increases so does σ and the probability of occurring becomes greater than one. Depending on the value of the Higgs mass this can lead to two different scenarios:

- if the Higgs boson exists and $m_H \ll \sqrt{s}$, then the amplitude grows as m_H^2 and $m_H \leq 1$ TeV.
- if the Higgs boson doesn't exist or $m_H \gg \sqrt{s}$, then there must be an energy scale to the validity of the SM above which new physics is expected. This scale is estimated to be around 1-2 TeV.

Therefore by exploring energies up to 2 TeV we should be able to either discover the Higgs boson or exclude it and find new physics.

Triviality

The running of the Higgs self-coupling constant λ imposes more stringent bounds. λ runs accordingly to:

$$\lambda(Q) = \frac{\lambda(Q_0)}{1 - \frac{3}{4\pi^2} \lambda(Q_0) \ln \left(\frac{Q^2}{Q_0^2} \right)} \quad (3.31)$$

For large values of Q , λ is not asymptotically free and approaches the Landau pole. Since $m_H = v\sqrt{2\lambda}$ we have to introduce a cut-off energy, Λ , to limit the validity of the SM. We therefore set $Q = \Lambda$ and $Q_0 = v$ and obtain that for λ to be finite:

$$m_H^2 < \frac{8\pi^2 v^2}{3 \log \left(\frac{\Lambda^2}{v^2} \right)} \quad (3.32)$$

If the SM scale energy is given by the Plank scale at 10^{16} GeV then the limit on the Higgs mass is really stringent:

$$m_H < 160 \text{ GeV} \quad (3.33)$$

In general the higher the cut-off energy the tighter is the constraint on the Higgs mass boson.

Vacuum stability

On the other hand, for small values of Q the coupling λ runs accordingly to:

$$\lambda(Q) = \lambda(Q_0) - \frac{3}{4\pi^2} y_t^2 \log \left(\frac{Q^2}{Q_0^2} \right) \quad (3.34)$$

where $y_t = \frac{\sqrt{2}}{v}m_t$ is the top quark Yukawa coupling. Recalling the requirements previously introduced for the Higgs potential, we have to make sure that $\lambda > 0$, which leads us to:

$$m_H > \frac{3}{2\pi^2} y_t^2 \log \left(\frac{Q^2}{Q_0^2} \right) \quad (3.35)$$

By setting the cut-off energy at the Plank scale we get the lower limit for the Higgs boson mass:

$$m_H > [130.5 + 2.1(m_t - 174)] \text{ GeV} \quad (3.36)$$

depending on the mass of the top quark.

Electro-weak measurements

Effects related to the existence of the Higgs boson arise from virtual corrections in SM calculations. For example Higgs loop corrections enter in the W mass calculation and although the Higgs contribution is just logarithmic, while the top quark contributes quadratically, the measurements from data are precise enough to constraint the Higgs mass. A global fit of Standard Model precision measurements yields [21]:

$$m_H = 80_{-23}^{+30[+75]} \text{ GeV} \quad (3.37)$$

including direct searches at LEP and Tevatron:

$$m_H = 116.4_{-1.3}^{+18.3[+28.4]} \text{ GeV} \quad (3.38)$$

with errors expressed at 1σ [2σ].

3.3.2 Production processes

There are four main production processes at hadron colliders, such as Tevatron and LHC, for the Higgs boson [22]: the Gluon Fusion, the Vector Boson Fusion, the associated production with a vector boson and the associated production with $t\bar{t}$. A summary of the SM Higgs boson production cross section contributions at LHC as function of m_H is presented in figure 3.3.

Gluon Fusion

The Gluon Fusion, GF, is the dominant production process at the LHC. As can be observed in figure 3.2, the process is mediated by a heavy quark loop, since the coupling of the Higgs to quarks is proportional to their mass. The process is enhanced by higher order QCD corrections and the cross section is slowly converging, with 70% and 30% contributions to LO coming from NLO and NNLO corrections.

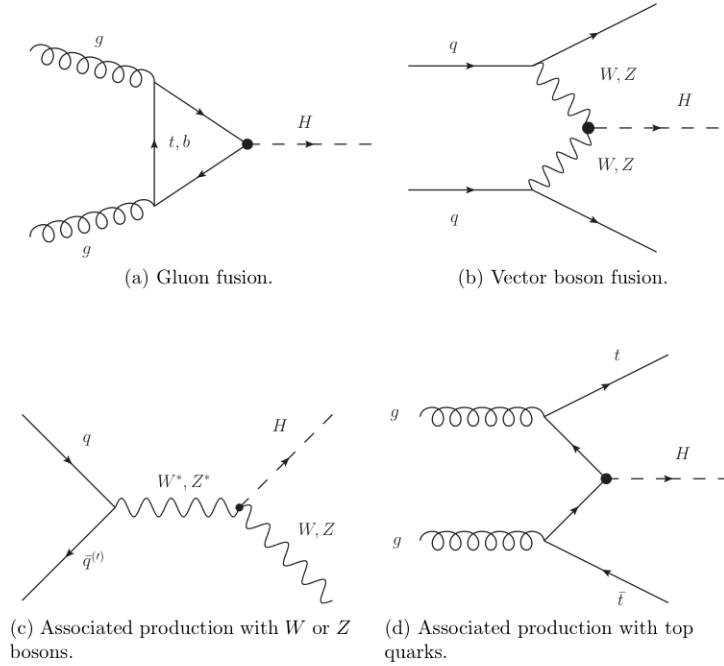


Figure 3.2: Standard Model Higgs boson main production processes at LHC.

Vector Boson Fusion

Vector Boson Fusion, VBF, is the sub-leading Higgs production process. In this reaction two interacting quarks radiate two weak vector bosons which in turn produce a Higgs boson from their annihilation. In the final state the quarks hadronize in two jets in the forward regions of the experiment with a large rapidity gap, providing a peculiar signature of the process. The Higgs boson, on its side, decays in the central rapidity region. Moreover, since the two quarks are not connected by color interactions, no gluon is emitted in the central region, therefore a central jet veto may be applied in order to reject background events. Higher order contribution do not have any significant influence on the cross section. A detailed study of the VBF production process is complementary to that of the GF since they exploit the couplings of the Higgs boson to weak vector bosons and quarks respectively.

Associated production with a weak vector boson

The associated production with a weak vector boson, often called *Higgs-strahlung*, is not one of the predominant processes but it is quite easy to experimentally tag it. The decay products of W or Z in fact help trigger the event and reduce the QCD background. In the process a pair of $q\bar{q}$ annihilates into a weak vector boson which then radiates a H . This was the

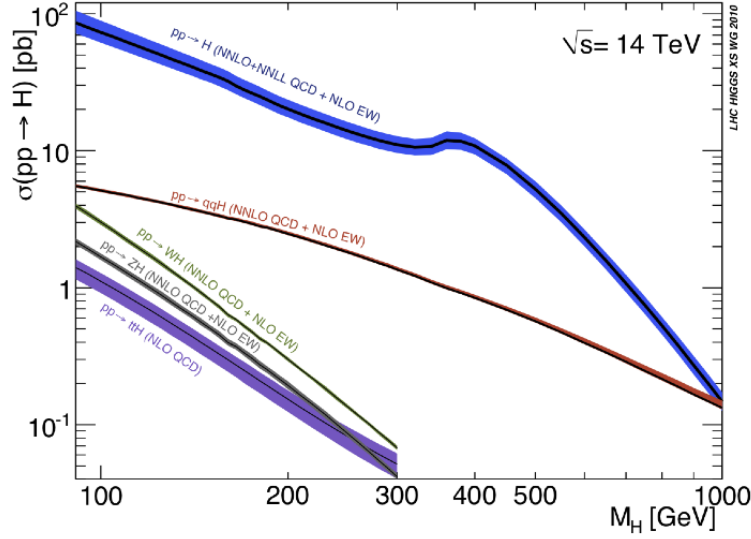


Figure 3.3: Standard Model Higgs boson production cross section in pp collisions at $\sqrt{s} = 14$ TeV as a function of the Higgs boson mass.

main production channel at LEP since direct production of the Higgs was unlikely to happen due to the small coupling of the boson to the electrons, while Higgs-strahlung has the advantage of coupling proportionally to the square of the weak boson mass. The associated production with a weak vector boson is also the sub-leading production channel at Tevatron, since it collides $p\bar{p}$.

Associated production with $t\bar{t}$ pair

Associated production with $t\bar{t}$ pair has a relevance in the low mass region search. The process is initiated by two gluons that produce two pairs of $t\bar{t}$ quarks. Two of these quarks in turn annihilate and produce the Higgs boson. This channel suffers mostly from $pp \rightarrow t\bar{t}b\bar{b}$ events.

3.3.3 Branching ratios

Besides the production processes, which are fixed by the nature of the collider, the most important feature in the quest to the Higgs boson is the choice of the decay channel in which search for the evidence of its existence. This choice is limited by the effective ability of the experiment to discern from interesting events and background. For LHC experiments an important constraint comes from the overwhelming QCD background produced in pp interactions. This reduces the possibilities to only those channels that provide clear signatures for the trigger, such as leptons, photons, jets and

large E_T^{miss} . Furthermore the choice of the decay channel must be operated accordingly to the mass range of interest, as can be observed in figure 3.4.

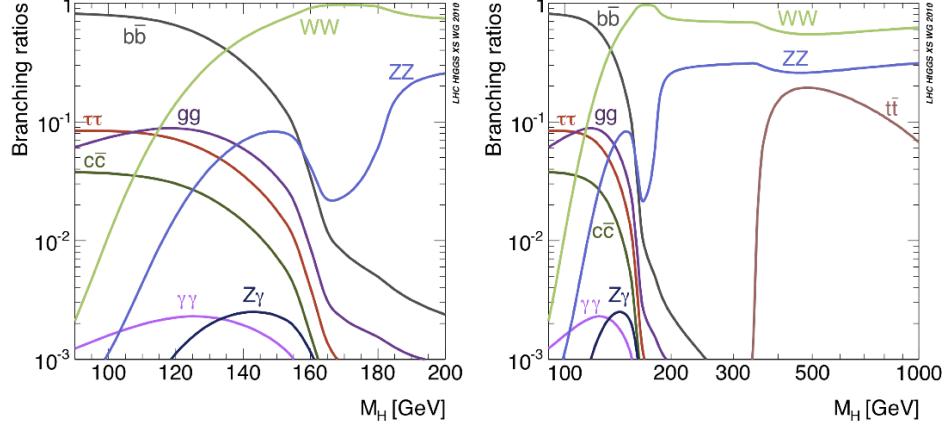


Figure 3.4: Standard Model Higgs boson branching ratios as a function of the Higgs boson mass in the low mass range and up to 1 TeV.

$H \rightarrow b\bar{b}$

At low Higgs mass values $H \rightarrow b\bar{b}$ has the largest branching ratio but suffers badly from QCD background. The b -tagging algorithms help in rejecting light jets but there is no efficient trigger on this channel regardless of the Higgs production process. Similar channels such as $c\bar{c}$ and gg are not considered since there is no way to identify these final states.

$H \rightarrow \gamma\gamma$

Despite its really small branching ratio $H \rightarrow \gamma\gamma$ is one of the only feasible search channels at low m_H values, thanks to the clear signature of the two gammas. Although irreducible, the QCD background to this decay has the advantage of being well known and simulated and a narrow Higgs mass peak might be observed. All of the production processes contribute to this channel.

$H \rightarrow \tau^-\tau^+$

Together with $H \rightarrow \gamma\gamma$, $H \rightarrow \tau\tau$ is one of the only channels to access the very low Higgs mass region. Although τ leptons decay predominantly hadronically, the semi-leptonic (46%) and leptonic decays (12%) provide a decent signature to be identified. The biggest background contribution comes from $Z \rightarrow \tau\tau$.

$H \rightarrow W^\pm W^\mp$

As soon as the kinematic of the process is allowed, the Higgs branching ratio into weak vector bosons increases steeply, thanks to the Higgs coupling being proportional to the W and Z square masses. $H \rightarrow WW$ is the dominant channel all over the high m_H region. The clear signature of the two $W \rightarrow l\nu$ decays, given by the leptons and the E_T^{miss} , together with the high BR makes $H \rightarrow WW$ the channel with the highest potential in discovering the Higgs boson. All the production processes can be explored with this channel but the VBF provides even more constraints on the rejection of the background. The dependence of the Higgs width on its mass makes it impossible to identify a narrow peak in the mass spectrum for large m_H values.

$H \rightarrow ZZ$

The $H \rightarrow ZZ$ channel has the second largest BR for high mass values, with an important dip in the region where the Higgs decay in WW turns on shell and the ZZ channel is thus suppressed. This channel has the advantage of providing final states with four isolated high p_T leptons, which makes it the *golden channel* in the Higgs boson search, thanks to its clear signature. The rather smooth background to this channel allows the identification of an Higgs mass peak given by the invariant mass of the four leptons produced in the final state. Although the Higgs boson may be discovered most likely in the $H \rightarrow WW$ channel, the measurement of its properties, such as mass, couplings and quantum numbers, will be obtained from the $H \rightarrow ZZ \rightarrow llll$ golden channel.

3.3.4 Direct searches

LEP-II

The four experiments installed on the Large Electron Positron collider, LEP, namely ALEPH, DELPHI, L3 and OPAL, where the first to perform a direct search for the Higgs boson. LEP was a e^-e^+ collider located in the same 27 km long tunnel where now lies the LHC. In its first run, from 1989 till 1995, LEP had a center of mass energy of $\sqrt{s} = 90$ GeV allowing important electro-weak measurements around the Z peak. After the upgrade in 1996, LEP-II started smashing e^-e^+ pairs with an energy that reached 209 GeV. Since the dominant production process was the Higgs-strahlung, $e^-e^+ \rightarrow Z^* \rightarrow ZH$, the accessible m_H range extended up to $m_H < \sqrt{s} - m_Z \simeq 118$ GeV. The main decay channels available to the Higgs were the low mass region ones: $b\bar{b}$ (BR = 74%), $\tau\tau$ (BR = 7%), WW (BR = 7%), gg (BR = 7%) and $c\bar{c}$ (BR = 4%). In contrast to Tevatron and LHC, the $H \rightarrow b\bar{b}$ channel was of extreme importance because of the lack of an overwhelming

QCD background. Anyways the LEP experiments, combining together their analyses, were only able to set a lower limit to the Higgs boson mass of $m_H > 114.4$ GeV, based on a total integrated luminosity of 2.5 fb^{-1} [23]. It must be added however that ALEPH claimed an excess beyond 95% C.L. compatible with a 115 GeV Higgs boson, while DELPHI reported a lack of events in that same region.

Tevatron

Tevatron is a $p\bar{p}$ collider at Fermi National Accelerator Laboratory running since 1989. During its first run Tevatron was operating at $\sqrt{s} = 1.8$ TeV. After a five year shutdown between 1996 and 2001, Tevatron resumed colliding $p\bar{p}$ at an increased energy of 1.96 TeV. Two experiments are installed on the collider: CDF and D0. At Tevatron, in the low Higgs mass region, the most important production process is the Higgs-strahlung, since pairs of $p\bar{p}$ are collided and the presence of the vector boson makes it easier to tag the events. The GF on the other hand is subject to a heavy jet background and is therefore less significant to the analysis. The most sensitive decay channel in this mass region is $H \rightarrow b\bar{b}$. In the high m_H range the focus is on the $H \rightarrow WW$ decay channel, regardless of the production process. In 2010 CDF and D0 presented the outcome of their combined analyses based on integrated luminosities between $5.4 - 6.7 \text{ fb}^{-1}$ [24]. The results, see figure 3.5, combine all the Higgs analyses and are presented as the ratio of the measured upper limit to the Higgs boson cross section with 95% C.L. to the expected SM cross section. A value of the ratio below 1.0 indicates an exclusion of the Higgs boson at 95% C.L. With this combination CDF and D0 were able to exclude the Higgs in the mass window 158 - 175 GeV. No improvements were obtained on the lower limit set by LEP-II. Tevatron will run until September 2011, providing the experiments with a total integrated luminosity of around 10 fb^{-1} . Future improvements to the analysis with the full luminosity are expected in the 100 - 185 GeV mass range with a sensitivity expected to be at least 2.4σ .

ATLAS

In ATLAS the Higgs hunt is at the very beginning. As previously explained, ATLAS has its best chances to find the Higgs boson in the low mass region, $m_H < 140$ GeV, by studying the $H \rightarrow \gamma\gamma$ and $H \rightarrow \tau\tau$ decays. However this mass range remains really tough for the analysis as a result of the overwhelming QCD background. For a Higgs mass heavier than 140 GeV, the most sensible channel is given by $H \rightarrow WW$, thanks to the strong coupling of the vector bosons to the Higgs and the consequent high BR. Due to the decay of the W into $l\nu$ this channel is helpful only to set an exclusion limit on the Higgs, for the precise measurement of m_H other decays must

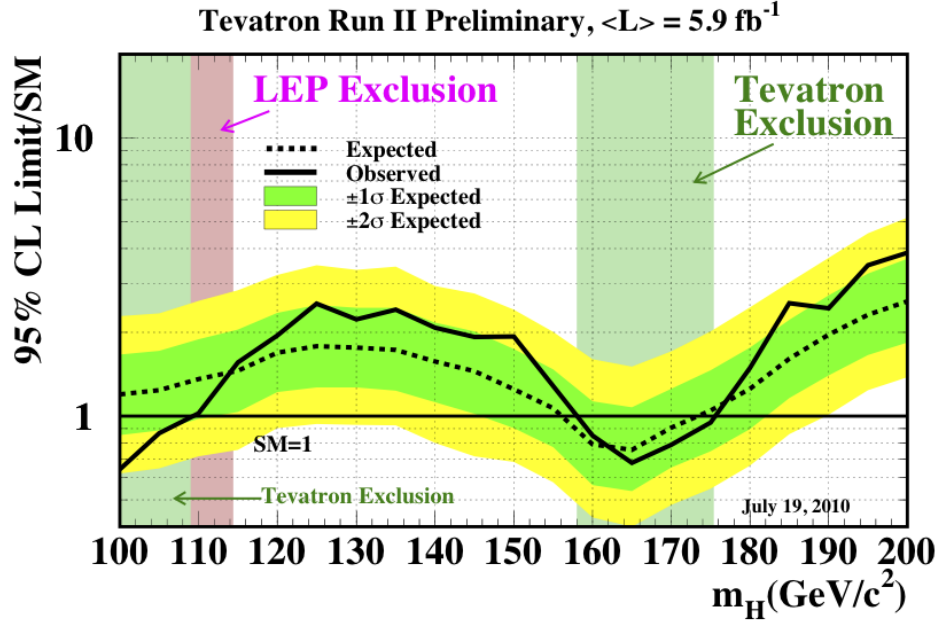


Figure 3.5: Tevatron Higgs boson exclusion plot. The histogram shows the ratio of the measured upper limit to the Higgs boson cross section with 95% C.L. to the expected SM cross section. A value of the ratio below 1.0 indicates an exclusion of the Higgs boson at 95% C.L. The results are presented as a combination of all Higgs channels from both CDF and D0 analyses. The Higgs boson is excluded in the 158 -175 GeV mass window.

be investigated. Here comes into play the golden channel: $H \rightarrow ZZ \rightarrow llll$. Despite its low BR this channel provides a clear signature and, most importantly, all of its decay products can be precisely measured, providing an excellent mass resolution.

The most recent public results from ATLAS [25] are based on 1.0 - 2.3 fb^{-1} of data, depending on the channel, collected at $\sqrt{s} = 7$ TeV between March 2010 and summer 2011, thanks to the excellent performances of LHC. The combined analysis is obtained from the merger of the $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow llll$, $H \rightarrow ZZ \rightarrow ll\nu\nu$, $H \rightarrow ZZ \rightarrow llqq$, $H \rightarrow WW \rightarrow l\nu l\nu$, $H \rightarrow WW \rightarrow l\nu qq$ and $H \rightarrow \tau\tau$ channels in the 110 - 600 GeV Higgs mass window. No evidence of the Higgs boson has been found. The Standard Model Higgs boson is excluded by the ATLAS experiment at 95% C.L. in an unprecedentedly wide mass window extending from 146 GeV to 232 GeV, from 256 GeV to 282 GeV and from 296 GeV to 466 GeV. Similar exclusions have been simultaneously set by CMS.

Comparing ATLAS results with those from CDF and D0, the different behavior of the two colliders, LHC and Tevatron, it's explicit below 140 GeV.

In contrast to Tevatron, LHC collides pairs of pp and has therefore GF and VBF as the main production processes, which suffer from QCD backgrounds. Tevatron on the other hand adopts $p\bar{p}$ pairs and its sub-leading production channel is Higgs-strahlung, which makes much easier the identification of Higgs events and results in an improved sensibility in those regions where the QCD background overcomes the signal.

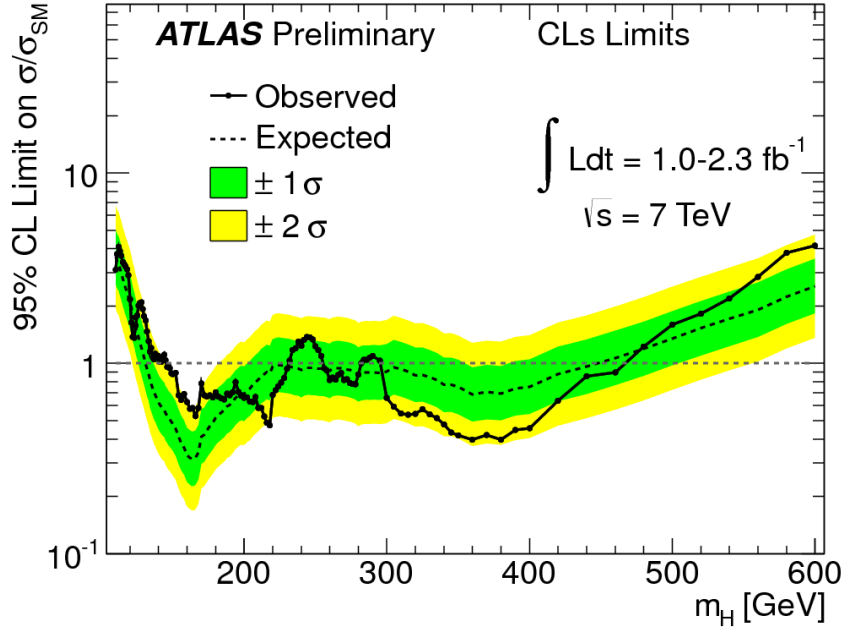


Figure 3.6: ATLAS Higgs boson exclusion plot obtained using 1.0 to 2.3 fb^{-1} of data [25]. The histogram shows the ratio of the measured upper limit to the Higgs boson cross section with 95% C.L. to the expected SM cross section. A value of the ratio below 1.0 indicates an exclusion of the Higgs boson at 95% C.L. The results are presented as a combination of all Higgs channels from ATLAS analyses. The Higgs boson is excluded in the regions extending from 146 GeV to 232 GeV, from 256 GeV to 282 GeV and from 296 GeV to 466 GeV. No evidence of the the Higgs boson is observed.

Chapter 4

$Z/\gamma^* \rightarrow \mu\mu$ cross section measurement

The measurement of the inclusive Drell-Yan production cross section of the Z vector boson is one of the primary goals of every collider experiment since the evidence of its existence was found back in 1983 by the UA1 [26] and UA2 [27] experiments. The analysis of the Z decay in two muons is a fundamental step in ATLAS plans. The high production rate supplied by the LHC allows precision measurements at the early stages of data taking, providing a deeper insight of the experiment and impacting the whole ATLAS physics program.

The Z cross section is calculated theoretically at NNLO with a precision at the level of a few percent, making the experimental measurement a stringent test on our knowledge of the processes involved. The rapidity, y , distribution in particular is a direct probe of the PDF, since it is related to the momentum fractions, x_1 and x_2 , of the two partons involved:

$$y = \frac{1}{2} \ln \frac{x_1}{x_2} \quad (4.1)$$

A stronger precision on the Parton Distribution Functions can be achieved thanks to the expansion of the available experimental data to an unprecedented wide region of momentum fraction and transferred momentum, which in addition allows also an extended test of the DGLAP evolution equations.

$$\begin{aligned} x_{1,2} &= \frac{Q}{\sqrt{s}} e^{\pm y} \sim 1 - 10^{-6} \\ Q^2 &\sim 10^2 - 10^8 \text{ GeV}^2 \end{aligned} \quad (4.2)$$

The production of the Z vector boson, and in general of all the weak vector bosons, is rather important in LHC physics since it is widely involved in the most interesting processes, such as the Higgs production and decay and the search for the Z' . High p_T leptons play a fundamental role too. Besides

being the decay products of the W and Z bosons, leptons are signatures of great value in SM and beyond SM analyses. Therefore the W and Z analyses constitute a valuable test towards the understanding of the ATLAS experiment and the performance of its components, affecting also the tuning of MC simulations. The event selection criteria optimized for the selection of the vector bosons are subsequently applied to all the analyses relying on the W and Z . The deep knowledge on the Z vector boson decay in two muons from LEP and Tevatron and on the experimental topology of the decay makes this process a *standard candle* for the measurement of the luminosity and the calibration of the experiment. However it should not be forgotten that the determination of the Z cross section itself is a compelling test of the validity of the Standard Model.

It must be stressed that since there is no way to discern a Drell-Yan process mediated by a virtual photon or a Z vector boson, the measurement of the cross section is referred to $Z/\gamma^* \rightarrow \mu\mu$. The only way to limit the γ^* contribution, although minimal, is to narrow down the analysis to a tight di-lepton invariant mass window around the mass value of the vector boson. A multiplicative factor F is calculated from simulations in order to go from $Z/\gamma^* \rightarrow \mu\mu$ to $Z \rightarrow \mu\mu$ as:

$$F = \int_0^\infty \sigma_Z \, d\sqrt{\hat{s}} / \int_{66 \text{ GeV}}^{116 \text{ GeV}} (\sigma_Z + \sigma_{Z\gamma^*} + \sigma_{\gamma^*}) \, d\sqrt{\hat{s}} = 1.0064 \quad (4.3)$$

This factor takes into account the γ^* contribution as well as the $Z\gamma^*$ interference and extends the cross section measure to the whole dilepton mass spectrum. A similar value, $F = 1.004$, was obtained for Tevatron in [28] and [29]. We therefore conclude that the γ^* contribution to the $Z/\gamma^* \rightarrow \mu\mu$ process is small.

Hereafter a description of the inclusive Drell-Yan $Z/\gamma^* \rightarrow \mu\mu$ cross section measurement with the ATLAS experiment is given [30]. The terms entering the calculations are described along with their uncertainties. The acceptance and extrapolation factors, which represent my contribution to ATLAS W/Z analysis, are postponed to the next chapter. Results are given in chapter 6.

4.1 Proton-proton collisions

The characterization of pp pairs collisions is not an easy task [31][32]. Protons are not elementary particles and consequently the internal structure of the incoming hadrons may give rise to multiple parton interactions within the same collision. The partons, either incoming or outgoing, can produce initial as well as final state radiation before finally hadronising into observable particles. Hadronic collisions therefore are extremely complex since they

involve both perturbative and non-perturbative QCD in the calculation of the processes. Luckily they can be divided into a *hard scattering process* plus an *underlying event*. The most interesting processes in particle physics involve high momentum transfer, producing high p_T particles, and are therefore identified as being hard scattering processes. On the other hand lots of soft collisions between partons take place alongside any hard scattering process. These constitute the underlying event, or Minimum Bias, which accounts for the largest fraction of the total pp cross section, 60.3 mb at $\sqrt{s} = 7$ TeV [33]. Minimum Bias events are a mixture of Single Diffractive (SD), Double Diffractive (DD) and Non-Diffractive (ND) events. In the case of diffractive events, a color neutral object is exchanged between the interacting protons, giving a spray of particles with a flat distribution in $|\eta|$. In the ND events the interaction between two quarks of the colliding protons happens through the exchange of a colored object. An abundance of particles with higher p_T is produced in this case in the $\eta \simeq 0$ region. These events represent the major source of background to low cross section, but much more interesting, processes, such as the Z or the Higgs boson production. Six orders of magnitude actually separate the total pp cross section at $\sqrt{s} = 7$ TeV from the Z boson production cross section, ~ 30 nb.

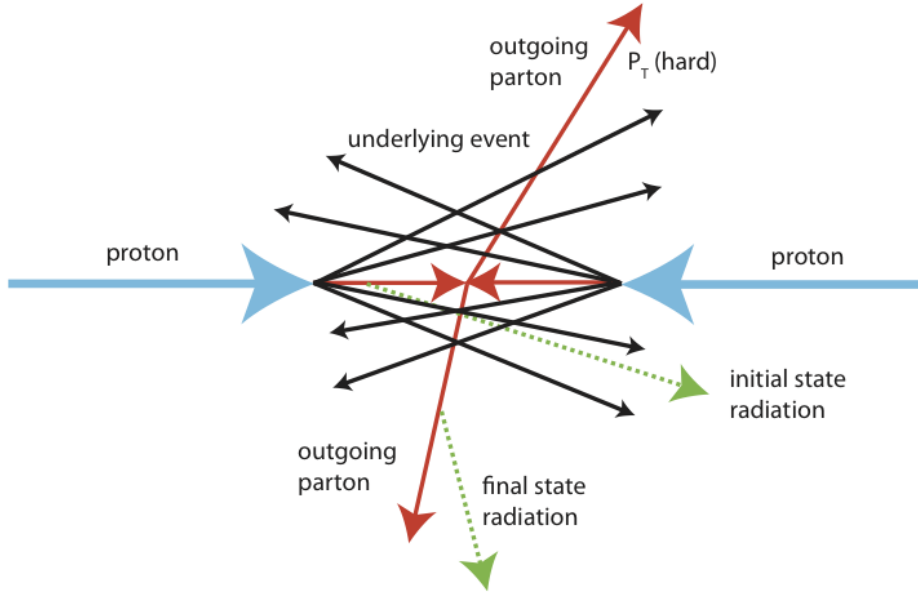


Figure 4.1: representation of a pp collision. The incoming protons are pictured in light blue, the partons involved in the hard scattering are red, the partons participating to the underlying event are black while initial and final state radiation is green.

At sufficiently high energies, $\Lambda_{QCD} \simeq 200$ MeV, the strong coupling con-

stant, $\alpha_s(Q^2)$, allows a perturbative approach to quark interactions. This property has a great value in QCD calculations and is called *asymptotic freedom*. In this limit the hadron can be considered as an ensemble of partons, each one carrying a fraction x of the hadron momentum with a probability given by the *Parton Distribution Functions*, PDFs:

$$f(x)dx \equiv P(x' \in [x, x+dx]) \quad f = q, \bar{q}, g \quad (4.4)$$

As a consequence, the *factorization theorem* allows us to write the generic hadron-hadron cross section as an incoherent sum of the independent parton subprocesses:

$$\begin{aligned} \sigma(h_1 h_2 \rightarrow cd)(Q^2) &= \\ &= \sum_{a,b=q,\bar{q},g} \int_0^1 dx_1 dx_2 f_{a,h_1}(x_1, \mu_F^2) f_{b,h_2}(x_2, \mu_F^2) \hat{\sigma}^{(ab \rightarrow cd)}(Q^2, \mu_F^2) \end{aligned} \quad (4.5)$$

The hadronic cross section is given by the convolution of the parton cross section, $\hat{\sigma}$, together with the PDFs, $f_{a,h_1}(x_1, \mu_F^2)$ and $f_{b,h_2}(x_2, \mu_F^2)$. h_1 and h_2 represent the incoming hadrons and Q^2 is the momentum transferred in the hard scattering. The sum is extended to all the quarks and gluons in the hadrons that may contribute to the process. The integral is over the fraction of momentum carried by the two interacting partons, x_1 and x_2 , identified as a and b from h_1 and h_2 respectively. μ_F is the factorization scale, an arbitrary energy scale introduced to discern between short and long distance physics. A parton emitted with momentum larger than μ_F is regarded as contributing to short distance physics and is therefore included in the short distance parton cross section, $\hat{\sigma}$. Partons with lower momenta belong to hadron structure and are absorbed in the PDFs. The scale μ_F is usually chosen to be of the order of Q^2 . It is worth stressing here that although PDFs and $\hat{\sigma}$ depend on the factorization scale, the total cross section does not. Since α_s is small at high energies, the short distance cross section can be calculated as a perturbation serie, where each term corresponds to a higher order contribution to the total cross section. At Leading Order, LO, the cross section is given by the parton scattering cross section at tree level. The factorization theorem rests upon the assumptions of the PDFs being universal and of the interactions being fast enough not to alter the distributions within the hadrons.

4.2 Drell-Yan process

The Drell-Yan process [34], DY:

$$pp \rightarrow \gamma^* \rightarrow ll + X \quad (4.6)$$

is the process involved with the production of lepton pairs in hadron-hadron interactions. The fundamental process associated to DY is the annihilation of a quark-antiquark pair of the same flavor, $q_i\bar{q}_i$, into a virtual photon of mass M producing a lepton pair:

$$q_i\bar{q}_i \rightarrow \gamma^* \rightarrow l^-l^+ \quad (4.7)$$

At large Q^2 values we may apply perturbative QCD in the calculation of the cross section. The final state with two high p_T leptons grants an easy experimental identification of the event. In the limit of negligible quark masses, the center of mass energy of the DY process, $\hat{s}$, is:

$$\hat{s} = (x_1p_1 + x_2p_2)^2 \simeq sx_1x_2 \quad (4.8)$$

From the QED process $e^-e^+ \rightarrow \mu^-\mu^+$ we may obtain the cross section for the DY process:

$$\hat{\sigma}(q\bar{q} \rightarrow l^-l^+) = \frac{4\pi\alpha_s^2}{3\hat{s}} \frac{1}{N_c} Q_q^2 \quad (4.9)$$

where we divided by the number of colors, N_c , since we require a pair of quarks of the same and opposite color, and multiplied by the square of the charge of the quarks, Q_q^2 . For a lepton pair of mass M we get:

$$\frac{d\hat{\sigma}}{dM^2}(q\bar{q} \rightarrow l^-l^+) = \frac{4\pi\alpha_s^2}{3M^2} \frac{1}{N_c} Q_q^2 \delta(\hat{s} - M^2) \quad (4.10)$$

The hadronic cross section for DY may now be derived by substituting the last expression into equation 4.5:

$$\begin{aligned} \frac{d\hat{\sigma}}{dM^2}(h_1h_2 \rightarrow l^-l^+) &= \frac{4\pi\alpha_s^2}{3M^2} \frac{1}{N_c} \int_0^1 dx_1 dx_2 \delta(\hat{s} - M^2) \times \\ &\times \left[\sum_i Q_i^2 (q_i(x_1, Q^2) \bar{q}_i(x_2, Q^2) + \bar{q}_i(x_1, Q^2) q_i(x_2, Q^2)) \right] \end{aligned} \quad (4.11)$$

The cross section for the $pp \rightarrow Z \rightarrow \mu\mu$ process can be obtained by introducing:

$$\hat{\sigma}(q\bar{q} \rightarrow Z) = \frac{8\pi}{\sqrt{2}} G_F [c_v^2 + c_a^2] M_Z^2 \delta(\hat{s} - M_Z^2) \quad (4.12)$$

conveniently convoluted with the desired branching ratio, into equation 4.5. In the last formula G_F is Fermi's coupling constant while c_v and c_a are the vector and axial couplings of the weak interaction.

NLO perturbative corrections introduce the emission of real and virtual gluons by the partons, giving rise to a set of divergencies: ultraviolet divergencies related to loops, infrared divergencies related to the emission of soft gluons and infrared collinear divergencies related to the splittings $q \rightarrow qg$ and $g \rightarrow q\bar{q}$. These divergencies are logarithmic and can be reabsorbed into the definition of PDF. The introduction of NLO corrections increases significantly the LO cross section of around 30%.

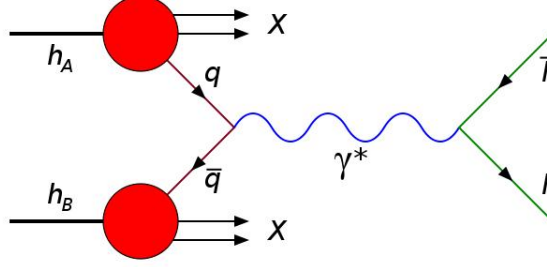


Figure 4.2: Feynman diagram for LO Drell-Yan process.

4.3 Analysis procedure

The $pp \rightarrow Z/\gamma^* \rightarrow \mu\mu + X$ cross section is measured in the fiducial volume according to:

$$\sigma_{\text{fiducial}} = \sigma_{pp \rightarrow Z/\gamma^*}^{\text{fiducial}} \times BR(Z/\gamma^* \rightarrow \mu\mu) = \frac{N - B}{C_Z \cdot \mathcal{L}} \quad (4.13)$$

where N is the number of selected candidates, B is the number of background events, C_Z is the efficiency factor and $\mathcal{L}$ is the integrated luminosity. The fiducial volume for the $Z/\gamma^* \rightarrow \mu\mu$ analysis is defined as:

$$\begin{aligned} p_T^\mu &> 20 \text{ GeV} \\ |\eta_\mu| &< 2.4 \\ 66 \text{ GeV} &< m_{\mu\mu} < 116 \text{ GeV} \end{aligned} \quad (4.14)$$

where the η cut is introduced to limit the event selection only to the Muon Spectrometer trigger volume while the requirement of high p_T leptons is motivated by the kinematic of the process investigated.

The cross section measurement can be further extrapolated to the whole kinematic region by the introduction of the acceptance factor, A_Z , which accounts for the fraction of the events produced that falls within the geometrical and kinematical fiducial cuts:

$$\sigma_{\text{total}} = \frac{\sigma_{\text{fiducial}}}{A_Z} \quad (4.15)$$

Similarly to A_Z , another factor is defined: E_Z . The extrapolation factor, E_Z , is adopted to extend the $Z/\gamma^* \rightarrow \mu\mu$ fiducial volume to a slightly large combination volume common to the $Z/\gamma^* \rightarrow ee$ channel, so that a direct comparison of the two cross sections is allowed with minimal use of MC simulation. A thorough investigation of the A_Z and E_Z factors and their uncertainties is given in chapter 5.

The differential measurement of the cross section is given in bins of absolute Z rapidity, $|y_Z|$, listed in table 4.1.

$0.0 < y_Z < 0.4$
$0.4 < y_Z < 0.8$
$0.8 < y_Z < 1.2$
$1.2 < y_Z < 1.6$
$1.6 < y_Z < 2.0$
$2.0 < y_Z < 2.4$

Table 4.1: y_Z binning for the differential cross section measurement.

4.4 Data

The analysis is based on the data collected by the ATLAS experiment during 2010. The first runs at 7 TeV have been discarded since the trigger configuration was steadily modified, affecting the muon selection performances. The data samples employed for the measurement span from period G2 to I2, roughly corresponding to a month of data taking between September 25th and October 29th, and is processed using release 16 of the Athena software. During this time the performances of the LHC have greatly improved, moving from an instantaneous luminosity of $1.93 \cdot 10^{31} \text{ cm}^{-2}\text{s}^{-1}$ with 47 colliding bunches to $1.64 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ with 348 colliding bunches. The total integrated luminosity is 32.6 pb^{-1} with a systematic uncertainty on the measurement of 3.4%.

	value	syst [%]
$\mathcal{L}$	32.6 pb^{-1}	3.4

Table 4.2: total integrated luminosity.

4.4.1 Muon trigger

Two triggers have been used between periods G2 and I1: EF_mu13_MG and EF_mu13_MG_tight. Both triggers are based on the MuonGirl algorithm, which uses combined muons, and apply a muon p_T threshold of 13 GeV. The only difference between the two is that EF_mu13_MG is seeded at Level 1 by L1_MU0, which doesn't apply any threshold to the muon p_T , while EF_mu13_MG_tight is seeded by L1_MU10, which has a threshold of 10 GeV.

4.5 Simulation

Simulations are employed in the analysis to calculate C_Z , acceptance and extrapolation factors and to evaluate the background contamination in the signal.

4.5.1 MC generators

Monte Carlo, MC, generators are tools adopted to simulate the physics involved in particle collisions. They play a fundamental role in the evaluation of the expected experimental performances and in the validation of the reconstruction software. They combine rigorous calculations from perturbative QCD and QED together with phenomenological descriptions of the interactions from PDFs. A generic hard scattering process can be resolved into four stages, organized in space and time: the hard scattering interaction, the Initial and Final State Radiation, ISR and FSR, the hadronization and decay, the underlying event. The hard scattering process, describing the interaction of the incoming partons, is the heart of any collision. The transferred momentum, Q^2 , between the partons defines the scale of the interaction. For large Q^2 values, perturbative QCD calculations can be performed. The incoming partons are colored objects and may therefore radiate gluons in the interaction, producing ISR and FSR. The radiated objects, in turn, may continue the radiation cascade. This process takes the name of *parton showering*. The momenta involved in the process are generally low and a phenomenological approach is applied to model this stage. When a certain cut off threshold in the transferred momentum is reached, the parton showering is terminated and the color connected partons are recombined into color singlets hadrons. This stage goes by the name of *hadronization* and does not depend on the hard process. Afterwards, the produced unstable hadrons, together with heavy objects like top quarks, vector gauge bosons and Higgs bosons (if any), decay accordingly to their BR until they reach a stable configuration. Finally the interaction of the partons not participating to the hard process is simulated. Underlying events are dominated by low Q^2 QCD interactions, thus requiring the adoption of model dependent descriptions.

Once the event is fully simulated at the physics level, it undergoes three more stages of detector simulation, digitization and reconstruction in order to be ready for a comparison with data. These steps do not enter in the MC generation. Other softwares tools, specifically tuned on the experiment and its geometry, take care of these last stages.

MC@NLO

MC@NLO [35] is a MC generator providing QCD calculations at Next to Leading Order, NLO. The adoption of NLO computations has the benefit of yielding accurate total cross sections and, most importantly, of providing a treatment for hard emissions. Soft and collinear emissions on the other hand are managed by the MC generator through the showering process. The matching between the hard and soft emission processes needs to be carefully handled in order to avoid the double counting of common kinematical con-

figurations and to ensure the cancellation of infrared divergencies. MC@NLO adopts the subtraction method to get rid of the duplicates and for this reason a small fraction of the events is generated with a negative weight. Due to the high number of diagrams involved in NLO corrections, a limited number of final states are implemented in MC@NLO, these interactions include in the final states W and Z vector bosons, b and t quarks and the Higgs boson. MC@NLO is combined with HERWIG for the conversion of the partonic final states into hadrons.

POWHEG

POWHEG¹ [36] is a MC generator interfacing NLO QCD calculations with parton showering. Unlike MC@NLO, events generated by POWHEG have weights greater than zero, thanks to a completely different approach to the treatment of the parton emissions. The generator can be adopted for a number of different processes such as Z pair production, heavy quark production, single top, lepton collisions, Drell-Yan vector boson production, W production and Higgs production. POWHEG can be interfaced to HERWIG and PYTHIA for the shower generation.

PYTHIA

PYTHIA is a multipurpose MC event generator for hadronic interactions at colliders which combines perturbative QCD at Leading Order, LO, with phenomenological models. The PYTHIA generator contains also libraries for ISR, FSR, hadronization, decays, underlying events, SM and SUSY. The transition between perturbative and non-perturbative QCD is governed by a parameter, $p_T^{\min}$, corresponding to the minimum momentum transfer in the hard scattering. This parameter determines the number of multiple parton-parton interactions within the same proton-proton collision and regulates the divergences of the cross section at low momenta. After the parton interaction is calculated, the partons are fragmented into hadrons. PYTHIA adopts a *string hadronization model* based on the linearity of the colour potential at large distances. PYTHIA can be interfaced with other MC generators to take care of the parton showering process.

HERWIG

HERWIG is a MC generator at LO for lepton and hadron collisions. HERWIG simulates hard scattering processes together with ISR and FSR and adopts a *cluster based model* in the parton showering process. As PYTHIA, HERWIG can be configured to provide parton showering within other MC generators.

¹POsitive Weight Hardest Emission Generator.

PHOTOS

PHOTOS is a tool employed to simulated QED radiative corrections at order $\mathcal{O}(\alpha)$ in particle decays and resonances. PHOTOS can be interfaced with any MC generator to add FSR bremsstrahlung photons to the generated events, independently of the physics process.

4.5.2 MC samples

$Z/\gamma^* \rightarrow \mu\mu$ signal events have been generated by MC@NLO, with parton showers provided by HERWIG. Crosschecks are performed with signal samples produced by POWHEG interfaced with either HERWIG or PYTHIA for the showering process. In both cases the CTEQ6.6 NLO PDF have been adopted. Further checks are made with PYTHIA samples produced with MRST LO PDF. All of the generators are interfaced with PHOTOS to simulate QED FSR effects. The interaction of the particles with the detectors is simulated by GEANT4. The MC samples belong to the MC10 production, which makes use of the latest information available from 2010 data on the experiment alignment, material and Minimum Bias.

4.5.3 MC corrections

In order to cancel discrepancies between data and simulation distributions, corrections factors are applied on the MC samples. All the systematic uncertainties from these corrections add up to the uncertainty on C_Z (see table 4.3).

Z p_T

The Z boson p_T distribution produced by the NLO generators, namely MC@NLO and POWHEG, was found to be inadequate when compared to data. Therefore it was decided to reweight the MC samples to the p_T spectrum provided by the LO generator PYTHIA, which has a better agreement thanks to its fine tuning on Tevatron data. Anyways the effect of the p_T reweight is found to affect the cross section measurement for less than 0.3%. The systematic uncertainty for the adoption of the boson p_T reweight is estimated to be negligible.

Pile-up

In order to model the pile-up present in data, Minimum Bias events have been added on top of the hard scattering processes in the MC samples. Further discrepancies between data and MC distributions of the number of vertices per event have been corrected by reweighting the MC samples to data. The systematic uncertainty introduced by the method is evaluated

from data and MC by studying the effects of the variation of the weights on the measure. The systematic is found to be 0.30%.

Primary vertex position

The position of the primary vertex is slightly shifted between data and MC. For this reason a reweight is applied on MC to match data. A systematic uncertainty of 0.08% is evaluated by comparing the results obtained when the vertex reweight is removed.

Muon momentum scale and resolution

The muon momentum resolution is defined by a set of factors like the detector hit resolution, the misalignment and the multiple scattering. These effects are modeled by parameters within the MC simulation and provide slightly different results from data. In order to account for the discrepancies, the MC momentum is corrected, or *smeared*, to reflect the actual resolution of the experiment. This result is achieved by introducing correction factors to match the dimuon invariant mass and the MS to ID p_T difference distributions of the MC to those of data. Also the momentum scale of the muons is corrected to match the expected Z boson mass value. The systematic uncertainty on the muon momentum scale is obtained by studying the variation of the C_Z factor when the scale correction parameters are varied within their errors. The muon momentum scale uncertainty on the other hand is evaluated from the comparison of the C_Z values when the correction is not applied. The systematics are given in table 4.3.

	syst [%]
Z p_T	0.00
pile-up	0.30
primary vertex position	0.08
muon momentum scale	0.20
muon momentum resolution	0.02
total	0.37

Table 4.3: C_Z systematic uncertainties from MC samples corrections.

4.5.4 Theoretical calculations

QCD calculations at NNLO order are adopted as terms of comparison for the final $Z/\gamma^* \rightarrow \mu\mu$ cross section measurements. The calculations have been obtained from FEWZ and DYNLO programs using the most recent PDF sets available. The predictions provided by the softwares agree to within 1% for the fiducial cross sections and 0.5% for the total cross sections.

4.6 Event selection

The event selection aims to refine the quality of the samples employed in the analysis. It is mainly based on the quality of the muons and on the kinematics of the $Z/\gamma^* \rightarrow \mu\mu$ process. The ATLAS experiment is required to be fully operational during the data taking. This is ensured by the adoption of the Good Runs Lists, GRLs. The event selection cuts are reported in table 4.4.

4.6.1 Muon selection

In order to reduce as much as possible the background from fake muons, only combined muons are selected, thus narrowing the experimental volume to the coverage of the ID, $|\eta| < 2.5$. This volume is further reduced by the MS trigger, which limits the analysis to $|\eta| < 2.4$. A set of quality cuts is applied to the ID hits of the muons to ensure an accurate reconstruction. The background from cosmic muons is suppressed by requiring the muons to be geometrically compatible with Z bosons produced in the primary vertex. In addition a cut on the *isolation* of the muons is applied. Muons from a Z decay are in fact expected to be isolated from other tracks, in particular from jets, since the process investigated doesn't involve the production of any other particle beyond the muon pair. The isolation is defined at ID level as the sum of the p_T of all the particles in a cone of radius 0.2 around the muon over the p_T of the muon:

$$I = \frac{\sum_{\Delta R < 0.2} p_T}{p_T^\mu} < 0.1 \quad (4.16)$$

This cut is particularly efficient in rejecting muons from in flight decay of pions and other light mesons. In this analysis muons were reconstructed using STACO algorithm but compatible results were found when using MUID.

4.6.2 Z selection

Depending on the run, events must be triggered by either EF_mu13_MG or EF_mu13_MG_tight. Events must also fulfill the requirement of a vertex with at least three tracks in order to be selected. Two muons with opposite charge are required, both with p_T greater than 20 GeV and $|\eta| < 2.4$. In addition the invariant mass of the lepton pair must lie in the $66 \text{ GeV} < m_{\mu\mu} < 116 \text{ GeV}$ mass window.

A total of 11709 $Z/\gamma^* \rightarrow \mu\mu$ candidates are found in the data sample. The number of events passing each step of the selection and the efficiencies of the cuts are reported in table 4.5. The number of Z candidates per rapidity bin is given in table 4.6.

GRL	
trigger	EF_mu13_MG or EF_mu13_MG_tight
primary vertex	$n_{VTX} \geq 1$ with $n_{\text{tracks}} \geq 3$ and $ z_{PV} < 200$ mm
muons	$n_{\text{combined}} \geq 2$
muon kinematic	$p_T > 20$ GeV and $ \eta < 2.4$
muon quality	ID quality cuts
z_0	$ z_0 - z_{PV} < 10$ mm
isolation	$I < 0.1$
charge	$c_1 \cdot c_2 < 0$
invariant mass	$66 \text{ GeV} < m_{\mu\mu} < 116 \text{ GeV}$

Table 4.4: event selection cuts.

selection	events	$\epsilon_{\text{abs}}[\%]$	$\epsilon_{\text{rel}}[\%]$
	62086344		
skim	10830624	17.444	17.444
GRL	9070423	14.609	83.75
trigger	4628930	7.456	51.03
primary vertex	4625532	7.450	99.927
$n_{\text{combined muons}} \geq 2$	319287	0.514	6.90
$ \eta_\mu < 2.4$	299523	0.4824	93.81
$p_T^\mu > 20$ GeV	14931	0.0240	4.98
muon quality	14593	0.0235	97.7
z_0	14558	0.0234	99.76
isolation	12571	0.0202	86.4
charge	12562	0.0202	99.93
invariant mass	11709	0.0189	93.2

Table 4.5: cutflow for the Z selection. For each selection cut the absolute and the relative efficiencies are given.

4.7 Background

The QCD and electro-weak sources of background are investigated separately.

4.7.1 QCD background

Although the Z selection cuts previously presented are highly efficient in rejecting the background, the cross section for QCD processes is really large, therefore the background contamination can still be significative. The QCD background is mainly formed by heavy flavor production and in flight decay of light mesons, both providing non-isolated muons. Two different method are adopted to estimate the QCD background: the $ABCD$ method and the

N ($0.0 < y_Z < 0.4$)	2441
N ($0.4 < y_Z < 0.8$)	2607
N ($0.8 < y_Z < 1.2$)	2528
N ($1.2 < y_Z < 1.6$)	2166
N ($1.6 < y_Z < 2.0$)	1455
N ($2.0 < y_Z < 2.4$)	512

Table 4.6: Z candidate events per rapidity bin.

template fit. The background estimation from the ABCD method is the one employed in the calculation of the cross section. The template fit value on the other hand is used for the evaluation of the systematic uncertainty. Both methods are data driven.

Template fit

The number of QCD background events is measured from data with a two component fit of the dimuon invariant mass spectrum. One component for the fit is given by the electro-weak channels, signal and background together, from MC simulation while the other component is the QCD background. The shape of the QCD background is taken from data by reverting the isolation cut applied for the signal selection. This background control sample is found to be in good agreement with MC QCD but suffers from electro-weak contamination, which is thus subtracted using simulation. The invariant mass fit, shown in figure 4.3, performs very well, providing a χ^2 value close to unity. The number of QCD background events yielded is given in table 4.7. It is remarkable that the background level is three orders of magnitude smaller than the signal.

	value	stat
$B_{QCD}^{\text{template fit}}$	56.5	18.3

Table 4.7: QCD background from template fit. Only the statistical uncertainty is reported.

ABCD method

The ABCD method is based on the idea that the invariant mass of the muon pair and the isolation of the muons are uncorrelated quantities and can thus be factorized. The $(m_{\mu\mu}, \text{isolation})$ plane is divided in four domains:

- A: isolated muons with $66 \text{ GeV} < m_{\mu\mu} < 116 \text{ GeV}$
- B: isolated muons with $25 \text{ GeV} < m_{\mu\mu} < 55 \text{ GeV}$

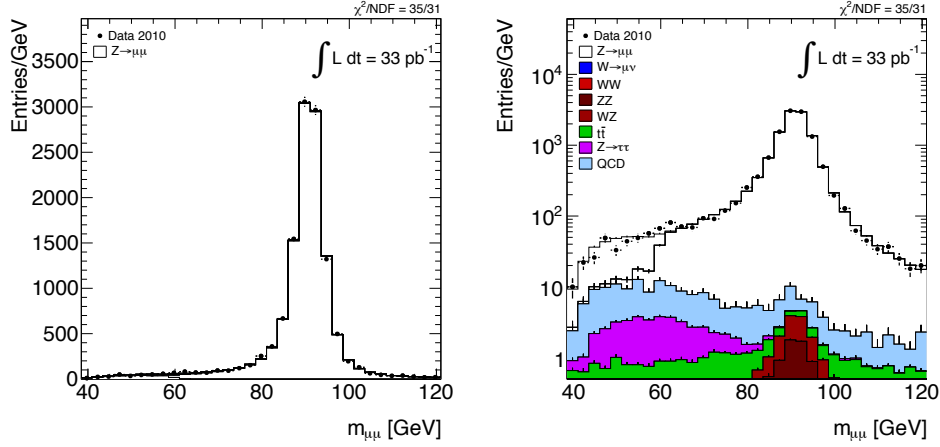


Figure 4.3: QCD template fit of the dimuon invariant mass in linear and logarithmic scales, on the left and on the right respectively. The electro-weak component, signal plus background, is taken from simulation, while the QCD shape is taken from data by inverting the isolation cut of the signal selection. The background is three orders of magnitude smaller than the signal.

- C: non isolated muons with $66 \text{ GeV} < m_{\mu\mu} < 116 \text{ GeV}$
- D: non isolated muons with $25 \text{ GeV} < m_{\mu\mu} < 55 \text{ GeV}$

where A corresponds to the signal region. Since the four domains are uncorrelated and the ratio of the isolated and non-isolated regions are independent from $m_{\mu\mu}$:

$$\frac{A}{C} \simeq \frac{B}{D} \quad (4.17)$$

the number of QCD events in A can be estimated from the other three domains:

$$A = \frac{B \cdot C}{D} \quad (4.18)$$

Since the method does not hold for electro-weak events, these are subtracted using MC simulations. The result of the QCD background measurement is reported in table 4.8. The systematic uncertainty is evaluated from the effects of the variation of the ABCD regions, from the normalization of the electro-weak background and from the isolation cut definition. An additional term, summed in quadrature, is given by the difference between the ABCD and the template fit background values.

	value	stat	syst
B_{QCD}^{ABCD}	45.46	18.19	25.55

Table 4.8: QCD background from ABCD method. The statistical and systematic uncertainties are reported.

4.7.2 Electro-weak background

The electro-weak background is produced mostly by W or Z decays, $t\bar{t}$ decays and diboson decays. The last two sources in particular introduce a subtle background of muon pairs. The overall contribution is anyways expected to be lower than 1%. The number of background events is estimated from MC simulations and the systematic uncertainty comes from the theoretical uncertainty on the cross section of the processes. The total electro-weak background is reported in table 4.9.

	value	stat	syst
$B_{\text{electro-weak}}$	40.77	0.57	2.35

Table 4.9: Electro-weak background. The statistical and systematic uncertainties are reported.

4.7.3 Total background

The total background is calculated as the sum of the QCD and electro-weak components. The value, reported in table 4.10, represents about 0.7% of the selected $Z/\gamma^* \rightarrow \mu\mu$ candidate events. Table 4.11 reports the background values for each Z rapidity bin.

	value	stat	syst
B	86.23	18.20	25.66

Table 4.10: total background calculated as the sum of the QCD and electro-weak components. The statistical and systematic uncertainties are reported.

4.8 Muon performance

The calculation of muon efficiencies, ϵ , is the key step to the evaluation of data-MC differences that are still present after the corrections introduced in subsection 4.5.3. These efficiencies are employed to evaluate Scale Factors, SF , to correct C_Z :

$$SF = \frac{\epsilon_{\text{data}}}{\epsilon_{\text{MC}}} \quad (4.19)$$

	value	stat	syst
B ($0.0 < y_Z < 0.4$)	24.2	1.8	6.1
B ($0.4 < y_Z < 0.8$)	21.9	1.7	5.3
B ($0.8 < y_Z < 1.2$)	19.7	1.7	5.1
B ($1.2 < y_Z < 1.6$)	12.2	1.3	2.4
B ($1.6 < y_Z < 2.0$)	6.3	1.0	0.8
B ($2.0 < y_Z < 2.4$)	1.6	0.5	0.1

Table 4.11: total background per Z rapidity bin. The numbers are calculated as the sum of the QCD and electro-weak components. The statistical and the systematic uncertainties are reported.

4.8.1 Tag'n'probe method

Muon trigger, reconstruction and isolation efficiencies of the ATLAS experiment are measured with the *tag'n'probe* method, a robust data driven technique which takes advantage of the strong dynamic and kinematic correlations between the muons coming from a Z decay. The method has a high background rejection but on the other hand it suffers from the small statistic of the data sample. The tag'n'probe method is based on the idea of *tagging* a muon with tight selection criteria and use it to identify its partner from a Z decay to *probe* the efficiency. The Z mass constraint on the invariant mass of the muon pair ensures the selection of a pure sample of muons. The selection of the probe is loose and operated without the adoption of the cut we want to test, so that the efficiency, ϵ , can be calculated as the number of probes that successfully makes the cut, x , over the total number of selected probes, n :

$$\epsilon = \frac{x}{n} \quad (4.20)$$

The efficiencies are computed as functions of muon η and p_T and divided per charge.

Tag selection

Tag selection cuts are made in conformity with those introduced for the analysis and are reported in table 4.12.

trigger	EF_mu13_MG or EF_mu13_MG_tight
muon kinematic	$p_T > 20$ GeV and $ \eta < 2.4$
muon quality	ID quality cuts
z_0	$ z_0 - z_{PV} < 10\text{mm}$
isolation	$I < 0.1$

Table 4.12: tag selection cuts.

ID efficiency

The ID efficiency is evaluated through the use of MS probes. Muon Spectrometer tracks are selected applying the cuts listed in table 4.13 and subsequently matched to ID tracks using a cone of radius $\Delta R = 0.01$. A total of 14454 MS probes are selected from the data set, whose distribution in η and p_T is observed to be in good agreement with MC. The overall efficiencies from data and MC are reported in table 4.14. The SF value compatible with 1.0 shows that there is no need to apply it in the analysis.

muon kinematic	$p_T > 20 \text{ GeV and } \eta < 2.4$
z_0	$ z_0 < 10 \text{ mm}$
isolation	$I_{MS} < 0.1$
charge	$q_{\text{tag}} \cdot q_{\text{probe}} < 0$
$\Delta\phi$	$ \phi_{\text{tag}} - \phi_{\text{probe}} > 2.0$
Δz_0	$ z_0^{\text{tag}} - z_0^{\text{probe}} < 3.0 \text{ mm}$
Δd_0	$ d_0^{\text{tag}} - d_0^{\text{probe}} < 2.0 \text{ mm}$
invariant mass	$ m_{\text{tag-probe}} - m_Z < 10 \text{ GeV}$

Table 4.13: MS probes selection cuts.

	data	MC	SF
ϵ_{ID}	0.9967 ± 0.0005	0.9963 ± 0.0000	1.0004 ± 0.0005

Table 4.14: ID efficiency and total SF . Only statistical uncertainties are reported.

MS and combined muon efficiency

The calculation of the MS plus ID-MS combination efficiency, MS+CB, makes use of ID probes, which are selected according to the cuts listed in table 4.15 and matched to combined muons within a cone of radius $\Delta R = 0.01$. The MS+CB efficiency is relative to that of the ID. 16660 ID probes have been found in the data sample. An overall good agreement between data and MC is observed and proved by a SF close to unity. The results are reported in table 4.16.

Isolation efficiency

The calculation of the isolation efficiency employs combined muons as probes and is thus relative to the MS+CB efficiency. Probes are selected by applying the cuts listed in table 4.17. A total of 15360 CB probes is selected from data. A good agreement is observed between data and MC. Results are presented in table 4.18.

muon kinematic	$p_T > 20 \text{ GeV and } \eta < 2.4$
z_0	$ z_0 < 10 \text{ mm}$
isolation	$I_{ID} < 0.1$
charge	$q_{\text{tag}} \cdot q_{\text{probe}} < 0$
$\Delta\phi$	$ \phi_{\text{tag}} - \phi_{\text{probe}} > 2.0$
Δz_0	$ z_0^{\text{tag}} - z_0^{\text{probe}} < 3.0 \text{ mm}$
Δd_0	$ d_0^{\text{tag}} - d_0^{\text{probe}} < 2.0 \text{ mm}$
invariant mass	$ m_{\text{tag-probe}} - m_Z < 10 \text{ GeV}$
quality	$n_{\text{Pixel hits}} + n_{\text{Pixel holes}} + n_{\text{SCT hits}} + n_{\text{SCT holes}} > 4$

Table 4.15: ID probes selection cuts.

	data	MC	SF
$\epsilon_{\text{MS+CB ID}}$	0.9177 ± 0.0021	0.9243 ± 0.0002	0.9929 ± 0.0023

Table 4.16: MS+CB efficiency and total SF . Only statistical uncertainties are reported.

Trigger efficiency

Isolated muons are adopted as probes for the measurement of the trigger efficiency, which is therefore relative to the isolation efficiency. The match of the isolated probe muons with trigger objects is operated adopting a cone of radius $\Delta R = 0.2$. In order to avoid a bias, tag muons are required to match a trigger object, in addition to the selection cuts of table 4.12. The data sample provides 8223 probes to test the efficiency of the EF_mu13_MG trigger plus other 9239 probes to test EF_mu13_MG_tight. The overall agreement between data and MC is good. The results are presented in table 4.20.

muon kinematic	$p_T > 20 \text{ GeV and } \eta < 2.4$
z_0	$ z_0 < 10 \text{ mm}$
muon quality	ID quality cuts
charge	$q_{\text{tag}} \cdot q_{\text{probe}} < 0$
$\Delta\phi$	$ \phi_{\text{tag}} - \phi_{\text{probe}} > 2.0$
Δz_0	$ z_0^{\text{tag}} - z_0^{\text{probe}} < 3.0 \text{ mm}$
Δd_0	$ d_0^{\text{tag}} - d_0^{\text{probe}} < 2.0 \text{ mm}$
invariant mass	$ m_{\text{tag-probe}} - m_Z < 10 \text{ GeV}$

Table 4.17: CB probes selection cuts.

	data	MC	SF
$\epsilon_{\text{isolation} \text{MS+CB}}$	0.9947 ± 0.0006	0.9952 ± 0.0000	0.9995 ± 0.0006

Table 4.18: isolation efficiency and total SF . Only statistical uncertainties are reported.

muon kinematic	$p_T > 20 \text{ GeV}$ and $ \eta < 2.4$
z_0	$ z_0 < 10 \text{ mm}$
isolation	$I_{ID} < 0.1$
muon quality	ID quality cuts
charge	$q_{\text{tag}} \cdot q_{\text{probe}} < 0$
$\Delta\phi$	$ \phi_{\text{tag}} - \phi_{\text{probe}} > 2.0$
Δz_0	$ z_0^{\text{tag}} - z_0^{\text{probe}} < 3.0 \text{ mm}$
Δd_0	$ d_0^{\text{tag}} - d_0^{\text{probe}} < 2.0 \text{ mm}$
invariant mass	$ m_{\text{tag-probe}} - m_Z < 10 \text{ GeV}$

Table 4.19: isolated probes selection cuts.

4.8.2 Background contamination

In order not to bias the efficiency measurements, the background contamination has been subtracted from the numerator and denominator of equation 4.20. The QED component of the background is estimated from MC while the shape and the normalization of the QCD background are taken from data control samples. The contamination for the MS+CB efficiency is found to be 1.0%, while that for the ID efficiency is less than 0.1% and that for the isolation efficiency is 0.2%. The contamination for the trigger efficiency is negligible.

4.9 C_Z factor

The C_Z factor accounts for the efficiency of the experiment within the fiducial volume. It is calculated from MC simulations and is defined as:

$$C_Z \equiv \frac{N_{\text{acc}}^{\text{reco}}}{N_{\text{acc}}^{\text{gen}}} \quad (4.21)$$

	data	MC	SF
$\epsilon_{\text{trigger} \text{isolation}}$	0.9947 ± 0.0006	0.9952 ± 0.0000	0.9995 ± 0.0006

Table 4.20: trigger efficiency and total SF . Only statistical uncertainties are reported.

where $N_{\text{acc}}^{\text{reco}}$ is the number of simulated events within the fiducial volume that are reconstructed while $N_{\text{acc}}^{\text{gen}}$ is the total number of simulated events within the fiducial volume. A multiplicative Scale Factor, SF , is adopted in order to correct for any discrepancy between data and MC efficiencies:

$$C_Z \rightarrow C_Z \cdot SF \quad (4.22)$$

The theoretical systematic uncertainties are calculated similarly to those for the acceptance and extrapolation factors in section 5.3. The difference between MC@NLO and POWHEG C_Z values is taken as systematic on the simulation of the hard process while the difference between the values obtained from POWHEG interfaced with either HERWIG or PYTHIA is taken as systematic on the shower modeling. An additional term is obtained from the PDF error set. The values of C_Z calculated with MC@NLO samples are reported in table 4.21 for the integrated cross section and in table 4.22 for the differential measurement. Further sources of C_Z systematic uncertainties from MC corrections are reported in subsection 4.5.3.

	value	stat	syst
C_Z	0.7946	0.0003	0.0020

Table 4.21: C_Z for the integrated cross section measurement. Statistical and systematic uncertainties are reported.

	value	stat	syst
C_Z ($0.0 < y_Z < 0.4$)	0.7440	0.0006	0.0023
C_Z ($0.4 < y_Z < 0.8$)	0.7621	0.0006	0.0021
C_Z ($0.8 < y_Z < 1.2$)	0.7935	0.0006	0.0021
C_Z ($1.2 < y_Z < 1.6$)	0.8368	0.0006	0.0019
C_Z ($1.6 < y_Z < 2.0$)	0.8651	0.0007	0.0029
C_Z ($2.0 < y_Z < 2.4$)	0.8820	0.0011	0.0026

Table 4.22: C_Z in bins of Z rapidity. Statistical and systematic uncertainties are reported.

4.10 Scale Factor

The Scale Factor introduced in section 4.9 is employed to take care of the differences between data and MC efficiencies that are still present after the reweights listed in section 4.5.3. The SF s entering the cross section measurement are calculated as the average SF values of the MC events

passing the analysis selection cuts:

$$SF = \frac{1}{N_{\text{events}}} \sum_{\text{events}} \frac{\epsilon_{\text{data}}}{\epsilon_{\text{MC}}} \quad (4.23)$$

yielding SF s slightly different from those reported in tables 4.14, 4.16, 4.18 and 4.20. The reconstruction, isolation and trigger SF s are calculated separately and then multiplied to provide the final SF .

The statistical uncertainty on the SF accounts for the limited number of MC events available to compute the average and the finite statistics of the data sample employed for the calculation of the efficiency maps. The latter source of uncertainty is the dominant one and its contribution is investigated by varying the data efficiency values. As regards the systematic uncertainty, this is obtained by varying the tag'n'probe selection criteria adopted to compute the efficiencies. Since reconstruction, isolation and trigger efficiencies share most of the cuts, the variations are applied simultaneously to all three scale factors, yielding the total SF uncertainty. For completeness the SF systematic uncertainties are calculated also separately for each term but they are not involved in any measurement. The results are reported in tables 4.23 and 4.24.

	value	stat [%]	syst [%]
$SF_{\text{MS+CB}}$	0.9828	0.44	0.43
$SF_{\text{isolation}}$	0.9974	0.14	0.25
SF_{trigger}	1.0043	0.13	0.05
SF	0.9845	0.49	0.58

Table 4.23: SF for the integrated cross section measurement. The statistical and systematic uncertainties are reported. The total Scale Factor is obtained from the product of the first three SF . However the total systematic uncertainty is not given by the sum in quadrature of the first three uncertainties. It is instead obtained by varying simultaneously the tag selection cuts for the reconstruction, isolation and trigger efficiencies.

	value	stat [%]	syst [%]
SF ($0.0 < y_Z < 0.4$)	0.983	0.9	1.1
SF ($0.4 < y_Z < 0.8$)	0.980	0.7	1.1
SF ($0.8 < y_Z < 1.2$)	0.984	0.7	0.6
SF ($1.2 < y_Z < 1.6$)	0.985	0.6	0.6
SF ($1.6 < y_Z < 2.0$)	0.994	0.6	0.6
SF ($2.0 < y_Z < 2.4$)	0.991	1.2	1.3

Table 4.24: SF in bins of Z rapidity. Statistical and systematic uncertainties are reported.

Chapter 5

Acceptance and extrapolation factors

The results obtained in the previous chapter allow the measurement of the $Z/\gamma^* \rightarrow \mu\mu$ cross section in the fiducial volume defined by the selection cuts as in equation 4.13. It will be shown in the next chapter that this measure is indeed accurate and only slightly affected by MC uncertainties, thanks to its minimal dependence on simulations. Nevertheless the fiducial cross section is impractical to compare to results from other experiments and theoretical calculations since it depends on the specific ATLAS fiducial volume. Therefore the acceptance and extrapolation factors are introduced to extrapolate the fiducial measurement to different volumes. As will be more clear in the next sections, these factors introduce a strong MC dependence on the cross section measure, severely affecting the uncertainty. An exhaustive coverage of the error is therefore required and is hereby presented.

Besides the intrinsic crucial role of the acceptance and extrapolation factors within the context of the $Z/\gamma^* \rightarrow \mu\mu$ cross section, a particular focus is put on the subject as this constitutes my personal contribution to ATLAS W/Z analysis.

5.1 Acceptance factor

The geometrical acceptance factor, A_Z , is derived from MC simulation and enters the calculation of the cross section in order to go from the fiducial cross section, i.e. calculated in the fiducial volume of the phase space defined by the selection cuts on the Z decay leptons, to the total cross section:

$$\sigma_{\text{total}} = \frac{\sigma_{\text{fiducial}}}{A_Z} \quad (5.1)$$

A_Z is defined as the ratio of the events satisfying the geometrical and kinematical cuts at the generator level over the total number of generated

events, both lying in the $66 \text{ GeV} < m_{\mu\mu} < 116 \text{ GeV}$ dilepton mass window:

$$A_Z \equiv \frac{N(p_T^\mu > 20 \text{ GeV}, |\eta_\mu| < 2.4, 66 \text{ GeV} < m_{\mu\mu} < 116 \text{ GeV})}{N(66 \text{ GeV} < m_{\mu\mu} < 116 \text{ GeV})} \quad (5.2)$$

The kinematical cuts are applied on the leptons at *born* level, i.e. before Final State Radiation, since the cross section is always measured before FSR. The result is reported in table 5.1.

	value
A_Z	0.4874

Table 5.1: A_Z value.

For sake of completeness the acceptance factor has been studied also for *bare* muons, i.e. after FSR, and *dressed* muons, i.e. bare muons whose fourvector is summed with that of the closest photons (within $\Delta R < 0.1$). A comparison of the values is shown in figure 5.4. The FSR is observed to significantly alter the acceptance values of almost 1%. As expected the acceptance for dressed muons is closer to that for born muons than that for bare muons.

The muon p_T reweight, introduced in subsection 4.5.3 in order to correct for momentum discrepancies between data and MC distributions, is observed to increase the A_Z value of as much as 0.5%. Pile-up reweight on the other hand has a small effect as it lowers the acceptance of 0.05%.

5.2 Extrapolation factors

In addition to the geometrical acceptance, two more factors are estimated from MC simulation at generator level: the integrated and the differential extrapolation factors, E_Z and $E_Z(y_Z)$. The purpose of this two factors is to extrapolate the fiducial cross section measurement to a combination volume, common to Z muon and electron channels, with minimal use of the MC simulation, so that the extrapolation uncertainty does not significantly affect the cross section measurement.

Integrated extrapolation factor

The integrated extrapolation factor extends the fiducial volume up to $|y_Z| < 2.5$. It is defined as:

$$E_Z \equiv \frac{N(p_T^\mu > 20 \text{ GeV}, 66 \text{ GeV} < m_{\mu\mu} < 116 \text{ GeV}, |\eta_\mu| < 2.4)}{N(p_T^\mu > 20 \text{ GeV}, 66 \text{ GeV} < m_{\mu\mu} < 116 \text{ GeV}, |\eta_\mu| < 2.5)} \quad (5.3)$$

and is applied as:

$$\sigma_{\text{combination}} = \frac{\sigma_{\text{fiducial}}}{E_Z} \quad (5.4)$$

The measured E_Z value for born muons is reported in table 5.2. By definition the extrapolation value is closed to unity, since the volume is broaden just from 2.4 to 2.5 in rapidity while the bulk of the Z production is around $y_Z = 0$. This reflects also in closer extrapolation factors for born, bare and dressed muons, as can be observed in figure 5.5.

	value
E_Z	0.9534

Table 5.2: E_Z value.

The MC corrections reported in subsection 4.5.3 have irrelevant consequences on the extrapolation. The p_T reweight increases E_Z of just 0.04% and the pile-up reweight correction is expected to be even smaller.

Differential extrapolation factors

The $E_Z(y_Z)$ factors play a role in the measurement of the $Z/\gamma^* \rightarrow \mu\mu$ differential cross section. They are meant to extrapolate the fiducial measurement to a phase space volume without any η cut on the muons. The differential extrapolation factors are divided in bins of y_Z and are defined as:

$$E_Z(y_Z) \equiv \frac{\frac{dN}{dy}(p_T^\mu > 20 \text{ GeV}, 66 \text{ GeV} < m_{\mu\mu} < 116 \text{ GeV}, |\eta_\mu| < 2.4)}{\frac{dN}{dy}(p_T^\mu > 20 \text{ GeV}, 66 \text{ GeV} < m_{\mu\mu} < 116 \text{ GeV})} \quad (5.5)$$

They are applied bin per bin on the differential cross section as the integral extrapolation factor.

The measured differential extrapolation factors are presented in table 5.3. $E_Z(y_Z)$ values for central rapidities are either one or close to one, proving that almost all of the muon pairs from Z candidates belonging to this region fall within $|\eta_\mu| < 2.4$. Conversely, only a small fraction of high rapidity Z bosons ($|y_Z| \gtrsim 1.6$) survives the analysis selection cuts, since in this case the muons are expected to be boosted in the forward directions. Small $E_Z(y_Z)$ values imply larger extrapolations and therefore important MC-dependent corrections on the measured cross sections, leading to higher $E_Z(y_Z)$ uncertainties. The impact of p_T reweight is also found to be important on the last bins, reaching a correction of as much as 1.6% for the last y_Z bin.

5.3 Systematic uncertainties

Since A_Z and E_Z are completely determined from MC, the systematics affecting the factors are evaluated from the uncertainties on the simulation of the $Z/\gamma^* \rightarrow \mu\mu$ process. Three main sources may therefore be taken in consideration: the hard scattering process, the parton showering and the PDF.

	value
E_Z ($0.0 < y_Z < 0.4$)	1.0000
E_Z ($0.4 < y_Z < 0.8$)	1.0000
E_Z ($0.8 < y_Z < 1.2$)	0.9837
E_Z ($1.2 < y_Z < 1.6$)	0.8494
E_Z ($1.6 < y_Z < 2.0$)	0.5778
E_Z ($2.0 < y_Z < 2.4$)	0.2076

Table 5.3: $E_Z(y_Z)$ values.

The uncertainties from the first two sources depend on the accuracy and on the modeling applied by the respective generators. For this reason they are evaluated by comparing acceptance and extrapolation factors from different generators. As regards PDF uncertainties, the investigation of systematics may be break down in two contributions: the choice of the PDF and the error determined from the quality of the data fit performed to obtain the PDF. An additional PDF-related uncertainty, namely the PDF reweighting uncertainty, arises from the method adopted to evaluate the previous two contributions.

In conclusion, the systematic uncertainties on the acceptance and extrapolation factors are estimated accounting for five possible sources of error: the PDF error set, the PDF choice, the PDF reweighting method, the MC generator and the parton shower generator. Since this five uncertainties are independent, they are added in quadrature to provide the total systematic uncertainty. The contribution from the statistical uncertainty of the MC samples employed is negligible when compared to the other sources. The results are presented in tables 5.4, 5.5 and 5.6.

5.3.1 Parton Distribution Functions

As previously stated in section 4.1, PDFs describe the parton momentum distribution within hadrons and are expressed as functions of the momentum fraction carried by the parton, x , and of the factorization scale, μ_F . The introduction of PDFs in hadron processes allows the calculation of long distance and soft interactions. In doing so we must bear in mind that PDFs do not stem from perturbative, therefore analytical, QCD calculations. They can only be determined from experimental data and they thus offer a mere phenomenological description of soft QCD interactions. In the following sections it will emerge indeed that the uncertainty on the knowledge of PDFs gives one of the main contributions to the error on the measurement of the Z boson cross section.

Deep Inelastic Scattering, DIS, experiments together with DY and jet studies provide data to fit PDFs over a wide range in the (x, Q^2) phase

space. DIS experiments mostly cover the regions at high x and low Q^2 values, as a consequence of the low center of mass energies accessible to these experiments. On the other hand, powerful hadron colliders, such as Tevatron and LHC, can explore higher Q^2 regions, thanks to the large $\sqrt{s}$, and lower x values, since a lower momentum fraction is needed in order to produce high p_T lepton pairs. Moreover the analysis of jet distributions allows the gluon distribution to be determined.

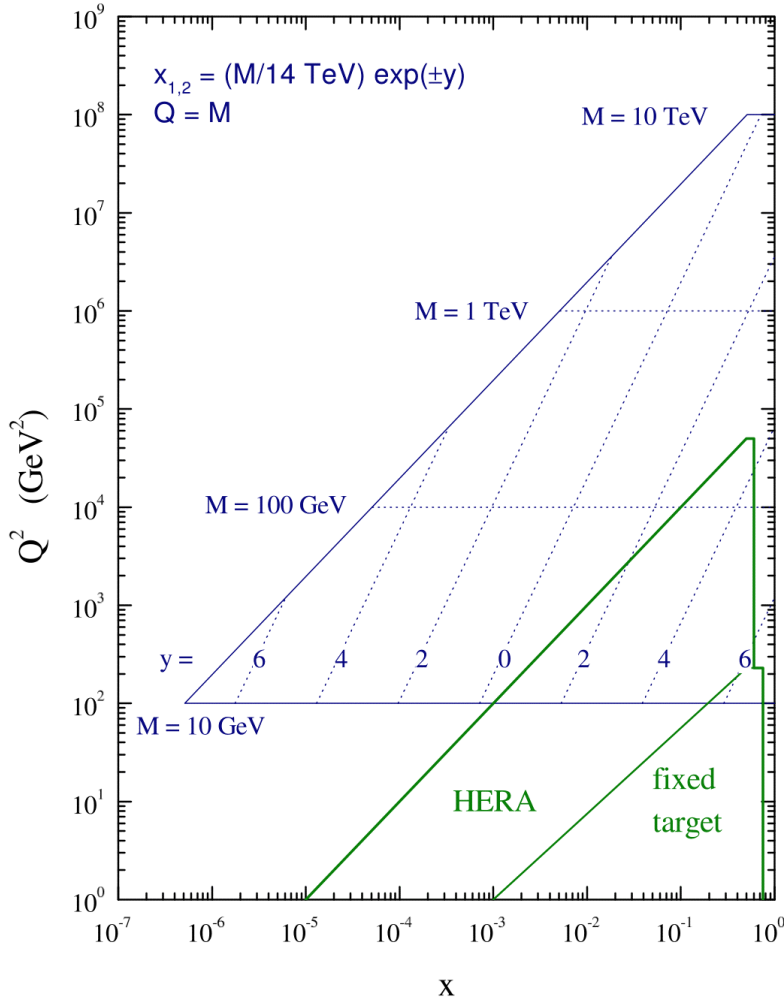


Figure 5.1: LHC parton kinematics. The blue line delimits the kinematic region accessible to LHC while the green line identifies the area probed by HERA and other fixed target experiments. The PDFs currently available are extracted from this last region and then extrapolated to LHC values.

It's interesting to note that even though PDFs cannot be analytically determined, their dependence on Q^2 can be calculated in a perturbative

manner. The so called *evolution* of the PDFs is described by a set of integro-differential equations which go by the name of *DGLAP* equations, from the names of the authors: Dokshitzer, Gribov, Lipatov, Alterelli and Parisi. This scale violation of PDFs has a logarithmic dependence and is tested over five orders of magnitude in x , $10^{-5} < x < 0.65$, and Q^2 , $1 \text{ GeV}^2 < Q^2 < 10^5 \text{ GeV}^2$. Data and theory are observed to agree to a very large extent. The possibility of evolving PDFs at higher energies is at same time a useful tool and an optimal test bench for PDF universality. The PDFs available today are largely based on data from DIS experiments, such as those at HERA, but are fundamental for any QCD calculation at LHC experiments, where they must be evolved to the much higher Q^2 values accessible, $Q^2 \gtrsim 10^2 \text{ GeV}^2$. For these reasons LHC will be able to probe the reliability of the evolution mechanism given by the DGLAP equations and provide new experimental constraints to the Parton Distribution Functions.

5.3.2 CTEQ

The CTEQ¹ [37] collaboration is strongly involved in PDF fitting since the beginning of the '90s. The method developed through the years by the team is one of the most valid available nowadays and provides measurements with an accurate coverage on the estimation of the uncertainties and their correlations.

Before the CTEQ analysis, most of the PDF fit were based on a simple data best fit estimation made on a set of parameters. However this technique doesn't allow a clear estimation of the uncertainties on the PDF-derived calculations. Moreover such method presents significant issues when it comes to the combination of datasets, since each experiment presents its own results on different kinematic ranges and with different sets of parameters, without providing any possibility of estimation of the correlations.

The CTEQ method starts from the minimization of the n data samples χ_n^2 fit values, which are then used for the combination through a weighted sum. For any given data set, the χ_n^2 value is estimated from the difference between data, D_{ni} , and theoretical values, T_{ni} , normalized to the uncertainty, σ_{ni} :

$$\chi_n^2 = \sum_{i=1}^{N_e} \left(\frac{D_{ni} - T_{ni}}{\sigma_{ni}} \right)^2 \quad (5.6)$$

where N_e is the number of experimental points. By means of the Hessian method it is possible to investigate the behavior of the χ^2 in the neighborhood of its minimum, $\chi_0^2 \equiv \chi^2(S_0)$, where S_0 identifies the set of best PDF fit parameters, namely $\{a_i^0\}$, provided that the variations fall within the tolerance, T :

$$\Delta\chi^2 \leq T^2 \quad (5.7)$$

¹Coordinated Theoretical/Experimental project on QCD.

determined so that PDF measurements are compatible to data within 90% of Confidence Level, CL. The χ^2 may be expanded around its minimum in Taylor series at second order as:

$$\Delta\chi^2 = \chi^2 - \chi_0^2 = \sum_{i,j}^d H_{i,j} (a_i - a_i^0) (a_j - a_j^0) \quad (5.8)$$

where d is the size of $\{a_i\}$ and $H_{i,j}$ is the Hessian matrix of second derivatives. The Hessian matrix may be diagonalized, providing a new basis of orthonormal eigenvectors, $\{z_i\}$. Therefore the variation of the χ^2 value around the minimum becomes:

$$\Delta\chi^2 = \sum_{i=1}^d z_i^2 \leq T^2 \quad (5.9)$$

or in other words we can say that it is now limited in a hypersphere of radius T in the $\{z_i\}$ space. By probing the variations of the χ^2 along each $\{z_i\}$ direction it is thus possible to obtain an estimation of the uncertainty on the fit.

For these reasons, along with the PDF central value of the fit, $S_0 \equiv \{z_i^0\}$, a set of $2d$ PDF *error vectors*, $S_i^\pm$, may be introduced. Each error vector is defined as the vector obtained from the central value when moving of a distance t in the positive or negative direction defined by one of the d parameters:

$$z_i(S_j^\pm) = \pm t \delta_{ij} \quad (5.10)$$

Let now X be a variable that depends on the PDF. $X = X(\vec{z})$ is a function of the d parameters entering the PDF fit and its central value can be calculated using $\{z_i^0\} \equiv \vec{z}_0$. The first order variation of $X(\vec{z})$ in the neighborhood of $\vec{z}_0$ is:

$$\Delta X(\vec{z}) = X(\vec{z}) - X(\vec{z}_0) = \vec{\nabla} X \Big|_{\vec{z}_0} \cdot \Delta \vec{z} \quad (5.11)$$

where $\Delta \vec{z} = \vec{z} - \vec{z}_0$. The i th component of the X gradient can be approximated as:

$$\frac{\partial X}{\partial z_i} = \frac{1}{2t} \left(X_i^{(+)} - X_i^{(-)} \right) \quad (5.12)$$

where $X_i^{(+)}$ and $X_i^{(-)}$ are the X values along the $\pm$ directions of the i th error vector. Therefore the uncertainty on X due to the PDF is:

$$\Delta X = \frac{1}{2} \sqrt{\sum_{i=1}^d \left(X_i^{(+)} - X_i^{(-)} \right)^2} \quad (5.13)$$

which is the *master formula* provided by the CTEQ collaboration for the uncertainty calculation of any PDF-related quantity.

The power of the method adopted is that it allows an easy estimation of the correlations too. Let $Y = Y(\vec{z})$ be a new variable, we now may calculate the correlation between $X(\vec{z})$ and $Y(\vec{z})$. The tolerance hypersphere previously introduced can be projected into an ellipse in the (X, Y) plane, parametrized by Lissajous equations:

$$\begin{aligned} X &= X_0 + \Delta X \cos \theta \\ Y &= Y_0 + \Delta Y \cos(\theta + \phi) \end{aligned} \quad (5.14)$$

where $0 \leq \theta < 2\pi$, $X_0 \equiv X(\vec{z}_0)$, $Y_0 \equiv Y(\vec{z}_0)$ and ΔX and ΔY are evaluated according to equation 5.13. ϕ is the angle defining the correlation, or anti-correlation, between X and Y :

$$\cos \phi = \frac{\vec{\nabla} X \cdot \vec{\nabla} Y}{\Delta X \Delta Y} = \frac{1}{4\Delta X \Delta Y} \sum_{i=1}^d \left(X_i^{(+)} - X_i^{(-)} \right) \left(Y_i^{(+)} - Y_i^{(-)} \right) \quad (5.15)$$

for $\cos \phi = 1$ $\vec{\nabla} X$ and $\vec{\nabla} Y$ are parallel to each other, therefore any shift in $\vec{z}$ has the same effect on $X(\vec{z})$ and $Y(\vec{z})$ and the correlation is maximal. Conversely, for $\cos \phi = -1$ the anti-correlation is maximal. On the other hand for $\cos \phi = 0$ the ellipse has its axes oriented along X and Y , therefore $X(\vec{z})$ and $Y(\vec{z})$ are completely uncorrelated since any measurement of $X(\vec{z})$ does not constrain $Y(\vec{z})$ and vice versa. The method illustrated for the evaluation of uncertainties and correlations extends also to any function of X and Y , $f = f(X, Y)$.

CTEQ6.6, CT10 and CT10w

The CTEQ6.6 [37] PDFs have been widely adopted in the analysis described in this thesis. CTEQ6.6 were first introduced in 2008 as the latest result on PDF fitting from the CTEQ collaboration and are composed of 44 eigenvectors, given by the 22 free parameters used for the fit, plus a central value for the best fit.

Recently, in 2010, the collaboration released two new sets of PDFs including an improved theoretical treatment of the fit and the most recent data on Deep Inelastic Scattering, vector boson production and single jet inclusive production: CT10 and CT10w [38]. These two PDFs are based on 26 free parameters providing a total of 52 error sets in addition to the central fit value. Recent data from DIS experiments at HERA together with Tevatron single jet production and Z rapidity distribution were exploited. However D0 Run-II results on W lepton asymmetry clashed with previous data sets. Because of this disagreement two different PDFs were presented: CT10 and CT10w. The first one, CT10, does not make any use of D0 results on the W lepton asymmetry. CT10w on the other hand includes the W results in the fit but applies a lower weight to reduce the impact on the global fit.

5.3.3 NNPDF

The NNPDF² [39][40] collaboration adopts a PDF fitting approach which is completely different from the more conventional Hessian method. Common PDF fits are all based on the same scheme: the choice of a functional form for the PDF, the search for the best fit by minimization of the χ^2 , the estimation of the uncertainties through the Hessian matrix method and the production of a central value fit with its corresponding error sets. This approach suffers from two main problems: the theoretical bias introduced by the choice of certain functions and parametrization for the PDF and the need to introduce more and more parameters in the fit in order to get a better agreement between data and theory. The NNPDF collaboration exploits artificial Neural Networks, NN, to get an unbiased PDF fit instead.

A NN is a non-linear computational model of parallel processing based on interconnected nodes, the neurons. Each neuron in a NN receives inputs from the neighbors, implements simple calculations and passes the output to the neurons of the following level. NNs are adaptive systems that change their structure based on the inputs received and they therefore need to be trained before any analysis. The training procedure determines the strength of the interconnections between the neurons.

The NNPDF team includes in the analysis data from the DIS experiments at HERA together with vector boson and inclusive jet production from Tevatron experiments. Out of the available experimental data sets, N_{rep} separate data sets are produced. Each of these is subsequently divided in two halves: a NN training set and a validation set. After the NN has been trained, the validation set is fitted by the NN through the minimization of a χ^2 , finally yielding a PDF fit. A total of N_{rep} equiprobable PDF replicas is therefore extracted from data. None of these replicas is an eigenvector, they all are equally valid PDF fits. The collaboration usually provides two PDF sets: one composed of 100 replicas and a larger one with 1000 entries. This method of PDF fitting has the advantage of adopting an unbiased functional form for the fit, since it lets the NN fit the PDF without any superimposed constraint. Moreover the NNPDF technique does not have the need to add any new parameter to the fit in order to get a better data-theory agreement.

Although for convenience a central value PDF, $q^{(0)}$, is provided as the average of all the replicas in the set, $\{q\}$:

$$q^{(0)} \equiv \langle q \rangle = \frac{1}{N_{\text{rep}}} \sum_{k=1}^{N_{\text{rep}}} q^{(k)} \quad (5.16)$$

any PDF-related function, F , can be calculated as the average of its values

²Neural Network PDF.

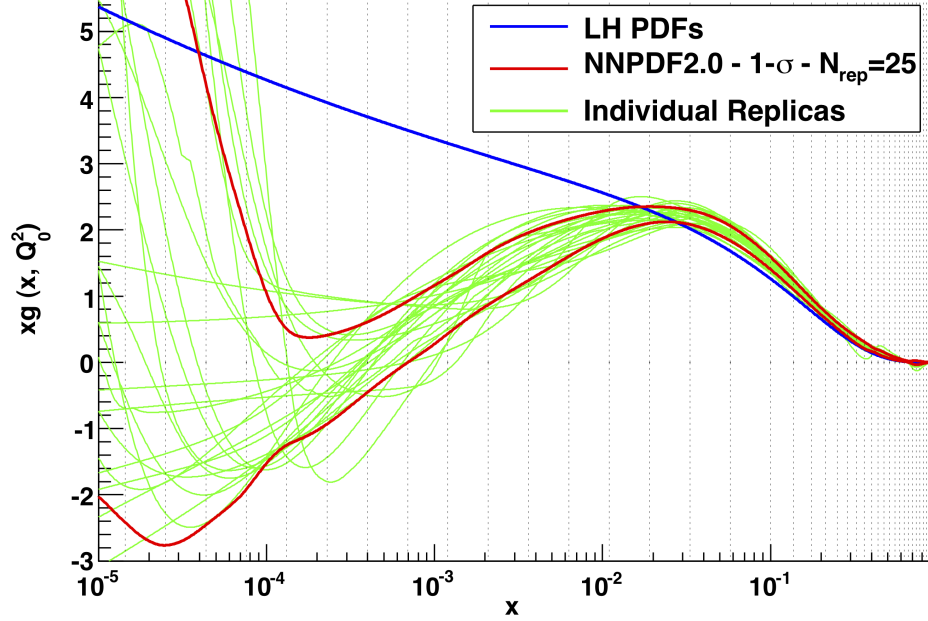


Figure 5.2: NNPdf gluon distribution. In green are 25 replicas of the gluon distribution from NNPdf2.0 while in red is the 1σ interval given from the replicas. In blu is the Les Houches gluon distribution.

calculated with the replicas in the set:

$$\langle F[\{q\}] \rangle = \frac{1}{N_{\text{rep}}} \sum_{k=1}^{N_{\text{rep}}} F[\{q^{(k)}\}] \quad (5.17)$$

Unless $F[\{q\}]$ has a linear dependence on q , in general it is true that:

$$\langle F[\{q\}] \rangle \neq F[\{q^{(0)}\}] \quad (5.18)$$

It is quite straightforward to understand that the standard deviation on $F[\{q\}]$ is given by:

$$\sigma_F = \sqrt{\frac{1}{N_{\text{rep}}} \sum_{k=1}^{N_{\text{rep}}} (F[\{q^{(k)}\}] - \langle F[\{q\}] \rangle)^2} \quad (5.19)$$

The precision on any measure obtained with NNPdf PDF scales as $1/\sqrt{N_{\text{rep}}}$.

The latest NNPdf distributions, NNPdf2.1, have been adopted in the analysis here described.

5.3.4 PDF reweighting

The adoption of PDF error sets for the estimation of uncertainties introduces a significative increase in the need of computing resources, since statis-

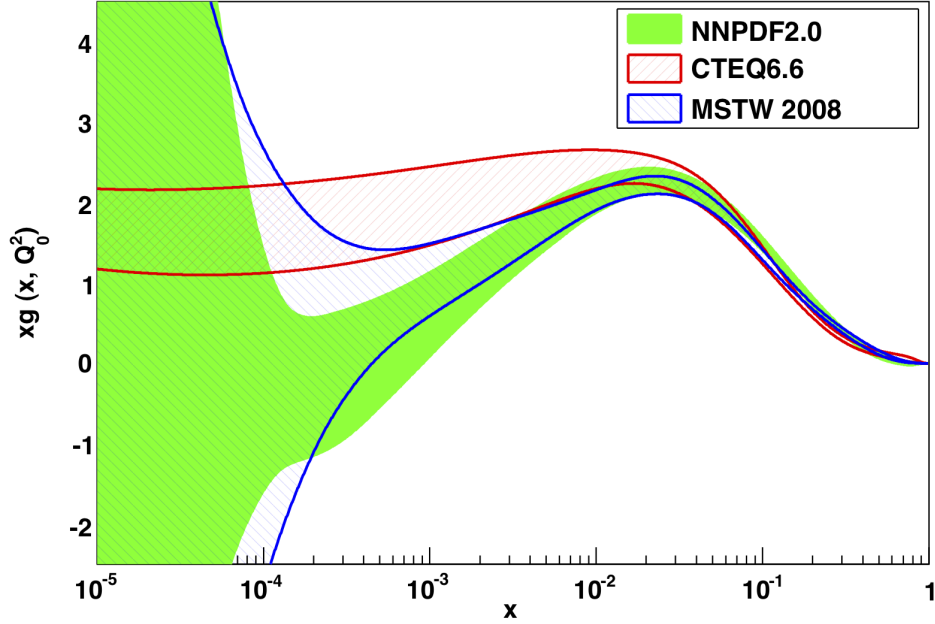


Figure 5.3: gluon distributions comparison between NNPDF2.0, CTEQ6.6 and MSTW2008. The large uncertainties at small x are symptoms of the lack of data to constrain the PDF distributions in this region.

tically large samples are required to be generated for each PDF eigenvector in order to evaluate the uncertainty associated to the employed PDF. This *brute force* method is indeed robust and theoretically accurate but rather lengthy and *CPU-time-consuming* and is thus commonly replaced by the less accurate, but anyways proved to be valid, PDF reweighting method [41]. The idea behind the reweight is that the PDF contribution to the calculation of the cross section, see equation 4.5, may be factored out. In other words, for every single event generated adopting the PDF central value a weight, w , may be defined to account for the employment of a different eigenvector:

$$w = \frac{f'(x_1, Q^2) \cdot f'(x_2, Q^2)}{f(x_1, Q^2) \cdot f(x_2, Q^2)} \quad (5.20)$$

where $f(x_i, Q^2)$ is the PDF adopted in the generated MC sample while $f'(x_i, Q^2)$ is the new PDF.

The ultimate advantage of PDF reweighting is that it requires the production of just one MC sample, saving disk space and CPU-time, thus allowing the generation of a single large sample, whose statistical uncertainty is negligible. On the other hand, it is understandable that the reweighting procedure is not as precise as the direct generation and for this reason it comes with a few *caveat*. The method does not account for variations in the

non perturbative QCD process of showering. However it was shown that the deviations are negligible and thus the shower generated for the central value PDF is accurate enough also for any other PDF eigenvector. Moreover the reweighting method procedure is accurate only as long as statistically large samples are employed, so that the whole phase space is explored, since we are interested in total distributions. It must be underlined that the PDF reweighting assumes that exactly the same events, with the same kinematics, are generated by the MC for any PDF eigenvector. The only difference between PDF eigenvectors is the weight that is associated to each event.

The efficiency of the method is investigated in [42], where the kinematic distributions of a sample produced with a certain PDF and those of another sample produced with a different PDF but reweighted to the PDF of the previous sample are compared, yielding an excellent agreement.

A *conservative* systematic uncertainty of 1% is added to the acceptance factor for the adoption of the PDF reweighting method on the MC samples. This contribution is not considered for the extrapolation factor since E_Z is close to unity and therefore the effects of the PDF reweighting method alone is expected to be negligible.

5.3.5 PDF error set uncertainty

The most significant source of uncertainty is due to our limited knowledge on the PDFs. The sample adopted for the estimation of the acceptance and extrapolation factors was generated by MC@NLO together with the CTEQ6.6 PDF. The PDF uncertainty within the set is thus calculated using the 44 PDF eigenvectors provided by the CTEQ collaboration. The standard prescription for the calculation of the error is adopted (see section 5.3.2):

$$\Delta A = \frac{1}{2} \sqrt{\sum_{i=1}^N \left(A_i^{(+)} - A_i^{(-)} \right)^2} \quad (5.21)$$

Although the master formula has the limit of providing a symmetric error, it can be observed in figures 5.4, 5.5 and 5.6 that the variations of the acceptance and extrapolation factors of nearly all the pairs of eigenvectors related to the same parameter are indeed symmetric. Therefore we can safely adopt the standard prescription without any worry of underestimating the uncertainty. Given the results of subsection 5.3.4, each acceptance and extrapolation value entering the master formula is not calculated from a MC sample generated with the specified PDF eigenvector but is instead obtained from the PDF reweighting of the CTEQ6.6 central value sample.

5.3.6 PDF choice uncertainty

There is no a priori reason to choose a certain PDF over another. It is therefore imperative to estimate the uncertainty coming from the possible

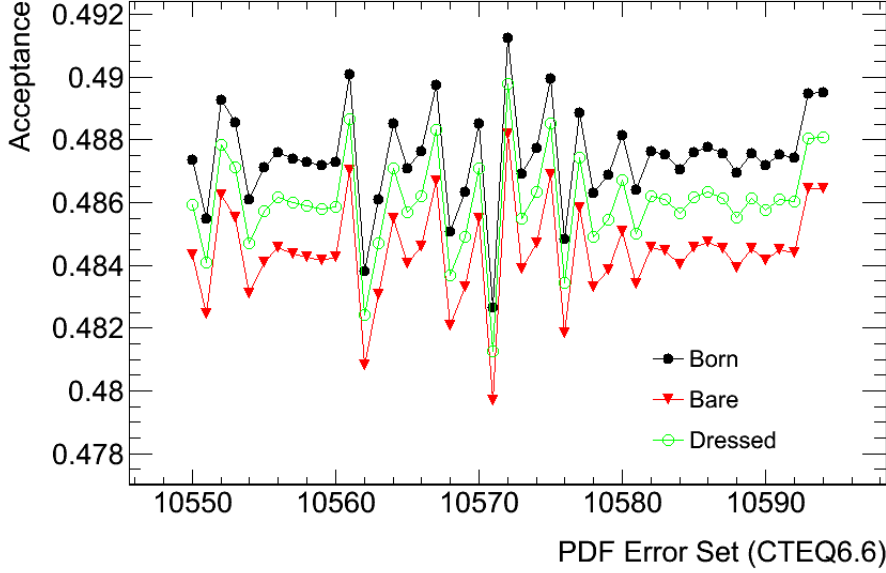


Figure 5.4: acceptance factor, A_Z , for CTEQ6.6 error set. The acceptance for born muons is compared to that of bare and dressed muons. Each acceptance value is obtained from the PDF reweighting of the PDF central value (10550). It can be observed that almost each pair of values belonging to the variation of the same parameter oscillates symmetrically around the central value.

use of a different PDF, obtained through a distinct fitting technique. The uncertainty here is taken as the maximum deviation between the factors evaluated using the PDF central value of CTEQ6.6 and those calculated with ABKM095fl, HERAPDF10, MSTW2008, CT10, CT10w and NNPDF2.1. Again, the results obtained for all these PDFs are obtained from the PDF reweight of the CTEQ6.6 sample.

5.3.7 MC generator uncertainty

The uncertainty arising from the simulation of the hard scattering process strictly depends on the MC generator employed. Therefore the choice of the MC generator is source of uncertainty too. This contribution is estimated as the difference between the acceptance and extrapolation factors calculated using MC@NLO and those calculated using the POWHEG generator. Both generators work at NLO in QCD calculations and are interfaced with the CTEQ6.6 PDF.

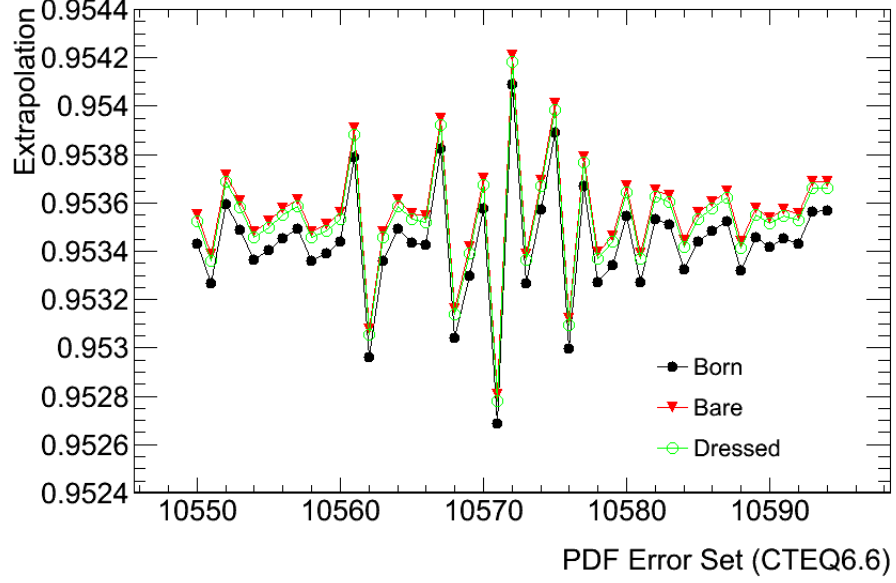


Figure 5.5: extrapolation factor, E_Z , for CTEQ6.6 error set. The extrapolation for born muons is compared to that of bare and dressed muons. Each extrapolation value is obtained from the PDF reweighting of the PDF central value (10550). It can be observed that almost each pair of values belonging to the variation of the same parameter oscillates symmetrically around the central value.

5.3.8 Parton shower generator uncertainty

An additional uncertainty contribution comes from the modeling of the parton showering process. As for the hard scattering process, the uncertainty is taken as the difference between the factors calculated using two different shower generators interfaced with the same MC generator. In this analysis a POWHEG sample interfaced with HERWIG as parton shower generator and another POWHEG sample interfaced with PYTHIA are employed for the estimation of the parton showering uncertainty.

	value	error set [%]	maximum PDF difference [%]	MC@NLO - POWHEG HERWIG [%]	POWHEG HERWIG - POWHEG PYTHIA [%]	PDF reweight [%]	total [%]
A_Z	0.4874	1.5	0.6	0.2	0.7	1.0	2.0

Table 5.4: acceptance factor and systematic uncertainty contributions. All the uncertainties are in percent. The statistical uncertainty is negligible.

	value	error set [%]	maximum PDF difference [%]	MC@NLO - POWHEG HERWIG [%]	POWHEG HERWIG - POWHEG PYTHIA [%]	total [%]
E_Z	0.9534	0.11	0.05	0.03	0.02	0.13

Table 5.5: extrapolation factor and systematic uncertainty contributions. All the uncertainties are in percent. The statistical uncertainty is negligible.

	value	error set [%]	maximum PDF difference [%]	MC@NLO - POWHEG HERWIG [%]	POWHEG HERWIG - POWHEG PYTHIA [%]	total [%]
$E_Z(0.0 < y_Z < 0.4)$	1.0000	0.00	0.00	0.00	0.00	0.00
$E_Z(0.4 < y_Z < 0.8)$	1.0000	0.00	0.00	0.00	0.00	0.00
$E_Z(0.8 < y_Z < 1.2)$	0.9837	0.01	0.01	0.00	0.01	0.02
$E_Z(1.2 < y_Z < 1.6)$	0.8494	0.03	0.03	0.23	0.04	0.24
$E_Z(1.6 < y_Z < 2.0)$	0.5778	0.06	0.04	0.77	0.17	0.79
$E_Z(2.0 < y_Z < 2.4)$	0.2076	0.17	0.12	2.49	0.18	2.51

Table 5.6: differential extrapolation factors and systematic uncertainty contributions. All the uncertainties are in percent. The statistical uncertainty is negligible.

5.4 Results

Observing the results in tables 5.4 and 5.5 we may notice that the acceptance and the extrapolation uncertainties, 2.0% and 0.13% respectively, are separated by an order of magnitude. This does not come as a surprise and is somehow expected since, as we already commented for the A_Z and E_Z values, the extrapolation expands the phase space volume of a minimal quantity while the acceptance expands it to the whole volume. For this reason the differences between MC and shower generators and, most importantly, the uncertainties on the PDFs at very low x values, intimately related to Z bosons produced in the forward regions (see equation 4.1), affect predominantly the A_Z factor measure rather than E_Z . This is confirmed in table 5.6. In this case we observe that the agreement between different PDF sets, PDF eigenvectors and generators is striking in the very first bins, $|y_Z| < 1.2$. As we move to the forward regions anyways all of the uncertainties increase significantly. Although the errors from PDFs and showering remain of the order of 0.1%, the hard scattering contribution gets as large as 2.5%, due to the lack of experimental constraints to tune the generators in these regions of the phase space.

Figure 5.7 shows that the CTEQ6.6 PDF error set uncertainty for both A_Z and E_Z factors is dominant over the PDF choice uncertainty, as all the values calculated for ABKM095fl, CT10, CT10w, HERAPDF10, MSTW2008 and NNPDF2.1 lie comfortably within the CTEQ6.6 error band.

The differential extrapolation factors for the CTEQ6.6, ABKM095fl, CT10, CT10w, HERAPDF10, MSTW2008 and NNPDF2.1 PDFs are illustrated to-

gether in figure 5.8. The remarkable superposition is proved in the bottom plot by the representation of the differences from the CTEQ6.6 distribution. For each bin, the biggest difference in absolute value is taken as the PDF choice uncertainty for $E_Z(y_Z)$ (see table 5.6).

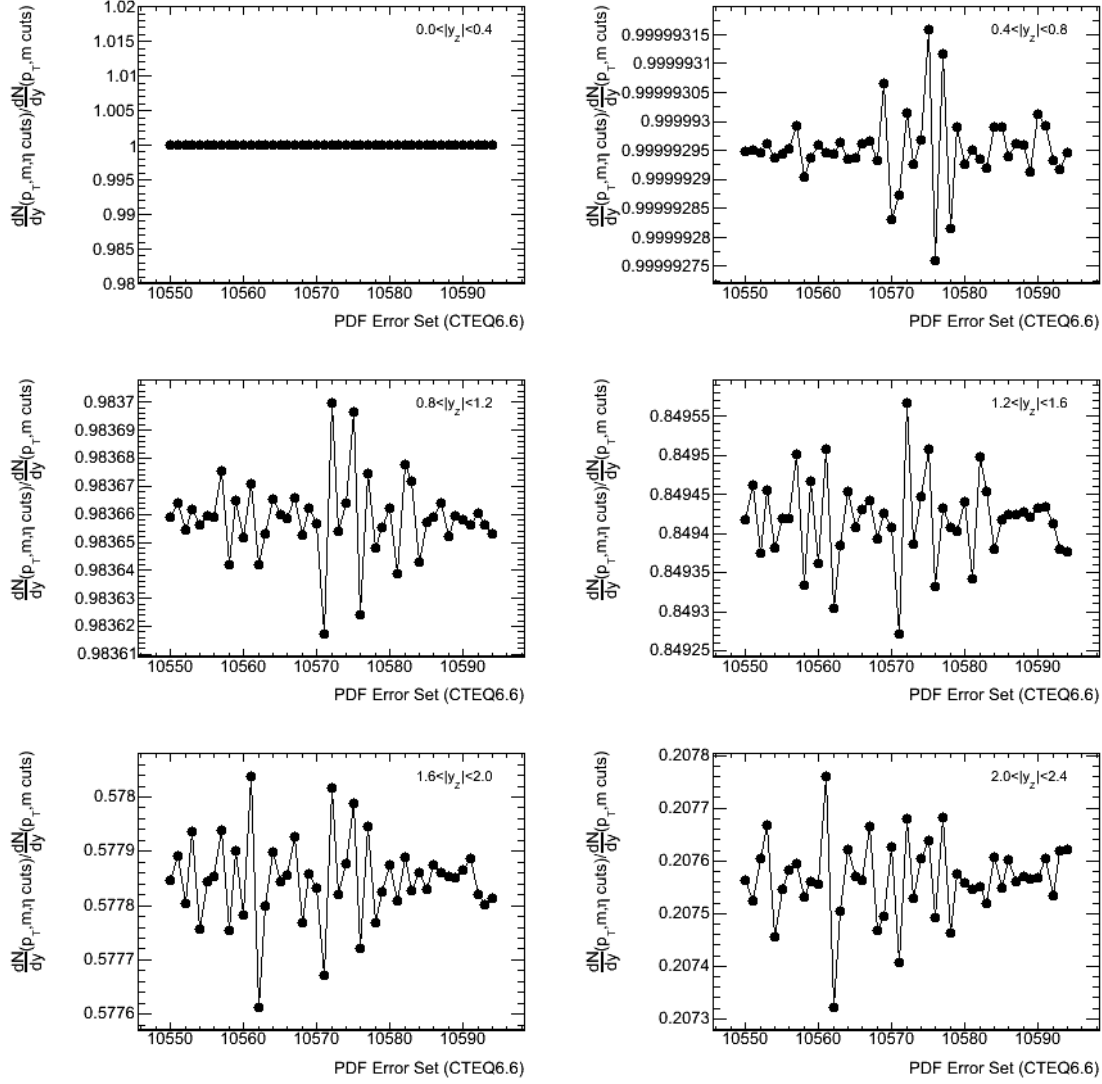


Figure 5.6: differential extrapolation factors, $E_Z(y_Z)$, for CTEQ6.6 error set. The six bins chosen for the $Z/\gamma^* \rightarrow \mu\mu$ differential cross section measurement are represented separately. Each extrapolation value is obtained from the PDF reweighting of the PDF central value (10550). It can be observed that almost each pair of values belonging to the variation of the same parameter oscillates symmetrically around the central value.

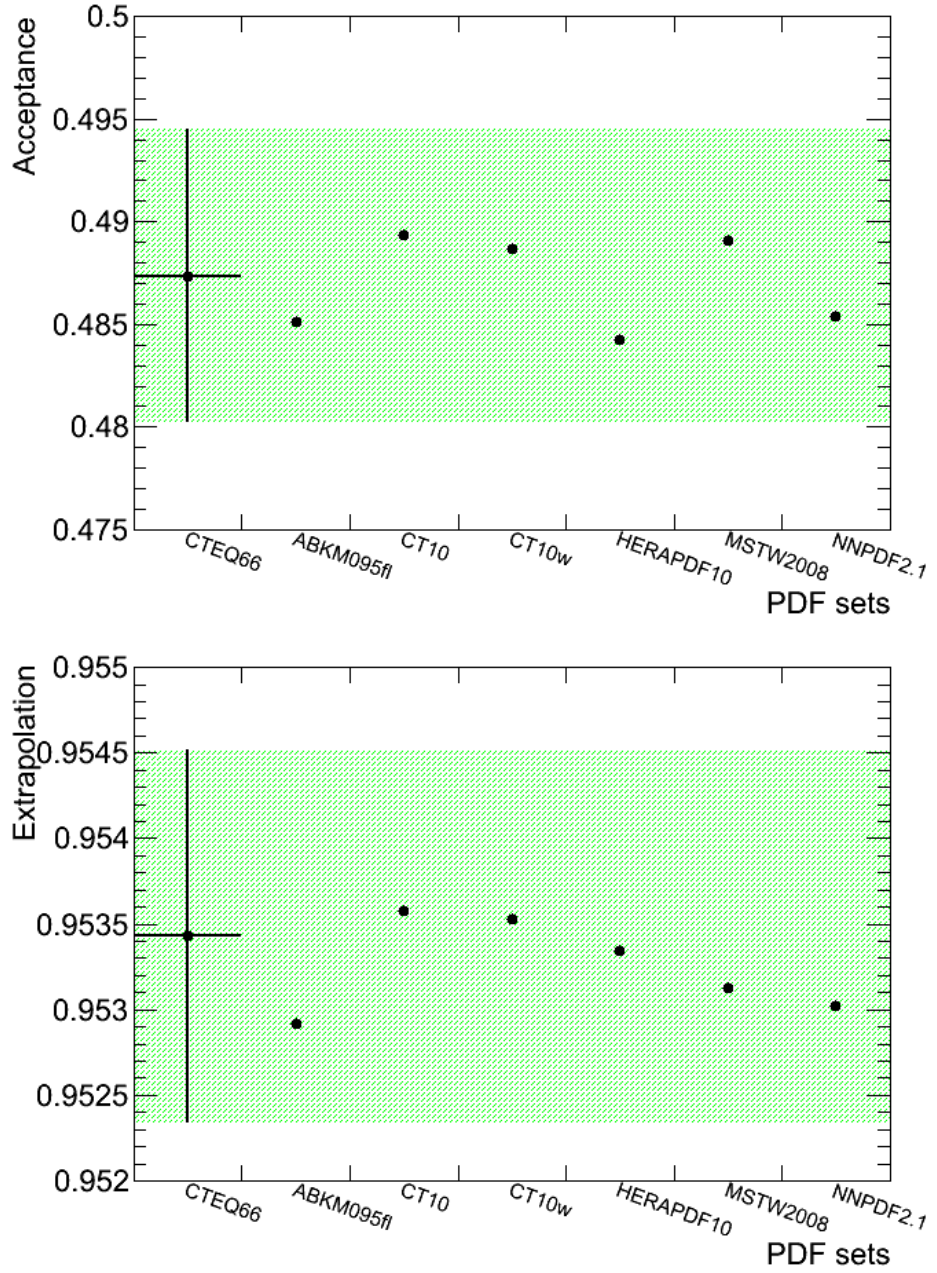


Figure 5.7: acceptance and extrapolation factors, A_Z and E_Z , for different PDFs. The A_Z and E_Z CTEQ6.6 values are pictured along with the values obtained for ABKM095fl, CT10, CT10w, HERAPDF10, MSTW2008 and NNPDF Parton Distribution Functions. It is graphically explicit how the different values are well within the CTEQ6.6 error set uncertainties, represented by the green shaded areas. The PDF error set uncertainty bar is represented only for CTEQ6.6.

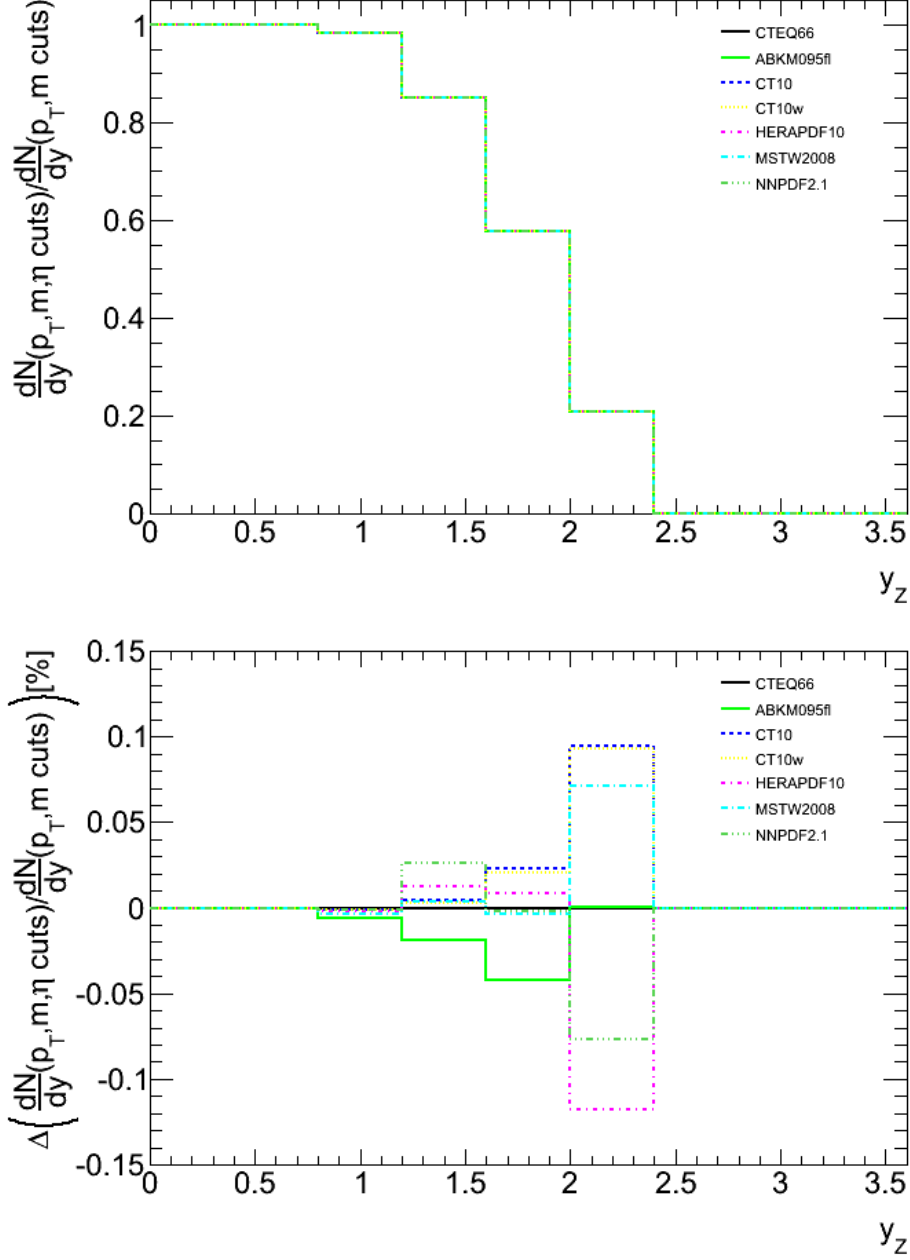


Figure 5.8: differential extrapolation factor, $E_Z(y_Z)$, for CTEQ6.6, ABKM095f, CT10, CT10w, HERAPDF10, MSTW2008 and NNPDF PDFs. The excellent $E_Z(y_Z)$ agreement between Parton Distribution Functions in the top plot is proved in the bottom plot by the PDF differences with respect to CTEQ6.6, all of the order of 0.1% or less.

Chapter 6

Results

Out of 32.6 pb^{-1} of integrated luminosity collected in 2010, 11709 $Z/\gamma^* \rightarrow \mu\mu$ candidate events have been found (table 4.5), 86.23 of these events are estimated to be background (tables 4.10 and 4.11). The luminosity is given in table 4.2, the C_Z factors in tables 4.21 and 4.22, the Scale Factors in tables 4.23 and 4.24, the acceptance factor in table 5.4 and the extrapolation factors in tables 5.5 and 5.6.

6.1 $Z/\gamma^* \rightarrow \mu\mu$ cross section

The statistical and systematic uncertainties of each term entering the calculations are propagated to the cross section. The statistical uncertainty on the cross section measurement is taken as the Poisson variance of the number of background subtracted events:

$$\frac{\delta\sigma}{\sigma} = \frac{\sqrt{N - B}}{N - B} \quad (6.1)$$

All the uncertainties on the cross sections are summarized in tables 6.1 and 6.2.

The statistical and systematic uncertainties provide comparable contributions to the integrated cross section measurement. Nevertheless the statistical contribution is expected to decrease with the increase of the amount of data collected, as well as the luminosity uncertainty itself, which is the dominant term. The A_Z error however will remain of the same order and become the dominant term.

The fiducial, combined and total $pp \rightarrow Z/\gamma^* \rightarrow \mu\mu + X$ inclusive cross

	$\delta\sigma$ [%]
statistical	0.93
pile-up	0.30
primary vertex position	0.08
muon p_T scale	0.20
muon p_T resolution	0.02
QCD background	0.22
electro-weak background	0.02
SF	0.76
C_Z theoretical	0.25
total systematic	0.91
A_Z	2.0
E_Z	0.13
luminosity	3.4

Table 6.1: uncertainties on the $Z/\gamma^* \rightarrow \mu\mu$ integrated cross section.

	stat [%]	syst [%]	lumi [%]
$\sigma_{\text{fiducial}} (0.0 < y_Z < 0.4)$	2.04	1.52	3.4
$\sigma_{\text{fiducial}} (0.4 < y_Z < 0.8)$	1.98	1.42	3.4
$\sigma_{\text{fiducial}} (0.8 < y_Z < 1.2)$	2.00	1.09	3.4
$\sigma_{\text{fiducial}} (1.2 < y_Z < 1.6)$	2.16	0.98	3.4
$\sigma_{\text{fiducial}} (1.6 < y_Z < 2.0)$	2.63	0.95	3.4
$\sigma_{\text{fiducial}} (2.0 < y_Z < 2.4)$	4.43	1.89	3.4

Table 6.2: uncertainties on the fiducial $Z/\gamma^* \rightarrow \mu\mu$ differential cross section.

sections are calculated as:

$$\sigma_{\text{fiducial}} = \sigma_{pp \rightarrow Z/\gamma^*}^{\text{fiducial}} \times \text{BR}(Z/\gamma^* \rightarrow \mu\mu) = \frac{N - B}{C_Z \cdot SF \cdot \mathcal{L}} \quad (6.2)$$

$$\sigma_{\text{combination}} = \sigma_{pp \rightarrow Z/\gamma^*}^{\text{combination}} \times \text{BR}(Z/\gamma^* \rightarrow \mu\mu) = \frac{N - B}{E_Z \cdot C_Z \cdot SF \cdot \mathcal{L}} \quad (6.3)$$

$$\sigma_{\text{total}} = \sigma_{pp \rightarrow Z/\gamma^*}^{\text{total}} \times \text{BR}(Z/\gamma^* \rightarrow \mu\mu) = \frac{N - B}{A_Z \cdot C_Z \cdot SF \cdot \mathcal{L}} \quad (6.4)$$

The measured fiducial, combination and total cross sections are:

$$\sigma_{\text{fiducial}} = 0.456 \pm 0.004(\text{stat}) \pm 0.004(\text{syst}) \pm 0.015(\text{lumi}) \text{ nb}$$

$$\sigma_{\text{combination}} = 0.478 \pm 0.004(\text{stat}) \pm 0.004(\text{syst}) \pm 0.016(\text{lumi}) \pm 0.001(\text{extrap}) \text{ nb}$$

$$\sigma_{\text{total}} = 0.935 \pm 0.009(\text{stat}) \pm 0.009(\text{syst}) \pm 0.032(\text{lumi}) \pm 0.019(\text{acc}) \text{ nb}$$

The differential cross section measured in the fiducial volume in units of Z rapidity is:

$$\begin{aligned}
\sigma_{\text{fiducial}}(0.0 < y_Z < 0.4) &= 0.1267 \pm 0.0026(\text{stat}) \pm 0.0019(\text{syst}) \pm 0.0043(\text{lumi}) \text{ nb} \\
\sigma_{\text{fiducial}}(0.4 < y_Z < 0.8) &= 0.1327 \pm 0.0026(\text{stat}) \pm 0.0019(\text{syst}) \pm 0.0045(\text{lumi}) \text{ nb} \\
\sigma_{\text{fiducial}}(0.8 < y_Z < 1.2) &= 0.1232 \pm 0.0025(\text{stat}) \pm 0.0013(\text{syst}) \pm 0.0042(\text{lumi}) \text{ nb} \\
\sigma_{\text{fiducial}}(1.2 < y_Z < 1.6) &= 0.1002 \pm 0.0022(\text{stat}) \pm 0.0010(\text{syst}) \pm 0.0034(\text{lumi}) \text{ nb} \\
\sigma_{\text{fiducial}}(1.6 < y_Z < 2.0) &= 0.0646 \pm 0.0017(\text{stat}) \pm 0.0006(\text{syst}) \pm 0.0022(\text{lumi}) \text{ nb} \\
\sigma_{\text{fiducial}}(2.0 < y_Z < 2.4) &= 0.0224 \pm 0.0010(\text{stat}) \pm 0.0004(\text{syst}) \pm 0.0008(\text{lumi}) \text{ nb}
\end{aligned}$$

6.2 $Z/\gamma^* \rightarrow ll$ cross section

Assuming lepton universality, the measured $Z/\gamma^* \rightarrow \mu\mu$ cross section can be combined with that of the electron channel, $Z/\gamma^* \rightarrow ee$, from [30], to provide a $Z/\gamma^* \rightarrow ll$ cross section measurement with lower statistical uncertainty. Since the muon and electron channel analyses have two different fiducial volumes, defined by the different performances of the ATLAS experiment for the two leptons, they must be first extrapolated to a common fiducial volume. Here come into play the E_Z and $E_Z(y_Z)$ factors, for an extrapolation with minimal use of the simulation, as well as the acceptance factor, A_Z , for the total cross section calculation. The combination procedure adopted accounts for the correlations and anticorrelations between the uncertainties of the two decay channels arising from MC re-weighting, background, extrapolations, C_Z factors and luminosity.

The measured fiducial and total cross sections for the $Z/\gamma^* \rightarrow ll$ process are:

$$\begin{aligned}
\sigma_{\text{fiducial}} &= 0.479 \pm 0.003(\text{stat}) \pm 0.005(\text{syst}) \pm 0.016(\text{lumi}) \pm 0.001(\text{extrap}) \text{ nb} \\
\sigma_{\text{total}} &= 0.937 \pm 0.006(\text{stat}) \pm 0.009(\text{syst}) \pm 0.032(\text{lumi}) \pm 0.016(\text{acc}) \text{ nb}
\end{aligned}$$

The combined cross sections are observed to be very close to those measured for the muon channel alone. The systematic uncertainties are significantly smaller, thanks to the increased statistics given by the combination. The contribution of the error from the extrapolation to the common fiducial volume is negligible.

The differential combined cross section measured in the fiducial volume

common to muons and electrons in units of Z rapidity bins is:

$$\begin{aligned}
\sigma_{\text{fiducial}}(0.0 < y_Z < 0.4) &= 0.1293 \pm 0.0025(\text{tot}) \pm 0.0044(\text{lumi}) \text{ nb} \\
\sigma_{\text{fiducial}}(0.4 < y_Z < 0.8) &= 0.1294 \pm 0.0024(\text{tot}) \pm 0.0044(\text{lumi}) \text{ nb} \\
\sigma_{\text{fiducial}}(0.8 < y_Z < 1.2) &= 0.1258 \pm 0.0023(\text{tot}) \pm 0.0043(\text{lumi}) \text{ nb} \\
\sigma_{\text{fiducial}}(1.2 < y_Z < 1.6) &= 0.1182 \pm 0.0023(\text{tot}) \pm 0.0040(\text{lumi}) \text{ nb} \\
\sigma_{\text{fiducial}}(1.6 < y_Z < 2.0) &= 0.1134 \pm 0.0026(\text{tot}) \pm 0.0039(\text{lumi}) \text{ nb} \\
\sigma_{\text{fiducial}}(2.0 < y_Z < 2.4) &= 0.1053 \pm 0.0038(\text{tot}) \pm 0.0036(\text{lumi}) \text{ nb} \\
\sigma_{\text{fiducial}}(2.4 < y_Z < 2.8) &= 0.0922 \pm 0.0038(\text{tot}) \pm 0.0031(\text{lumi}) \text{ nb} \\
\sigma_{\text{fiducial}}(2.8 < y_Z < 3.6) &= 0.0534 \pm 0.0054(\text{tot}) \pm 0.0018(\text{lumi}) \text{ nb}
\end{aligned}$$

where the statistical, correlated and uncorrelated systematic uncertainties are given together as total uncertainty. The Z rapidity range is extended to $|y_Z| < 3.6$ by the electron channel measurement.

As shown in figure 6.1, the muon and electron channels are in good agreement with each other, as well as with theoretical calculations (figure 6.2) although small deviations are observed for some PDFs. The total $Z/\gamma^* \rightarrow ll$ cross section measured by the ATLAS collaboration is compatible with that from CMS [43] and is in line with those from previous experiments (figure 6.3).

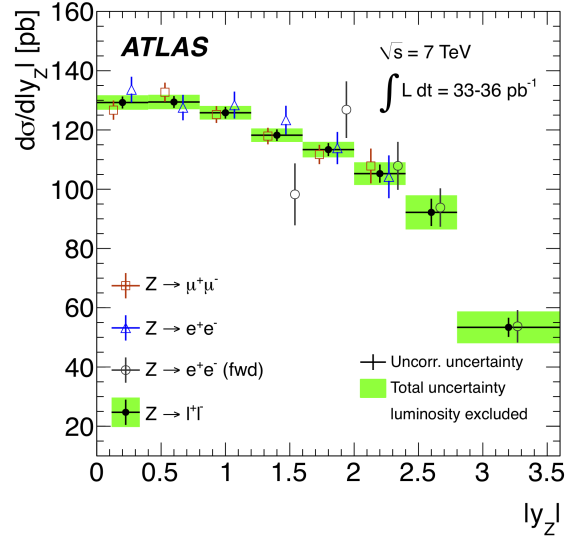


Figure 6.1: measured $Z/\gamma^* \rightarrow ll$ differential cross section compared with muon and electron channels.

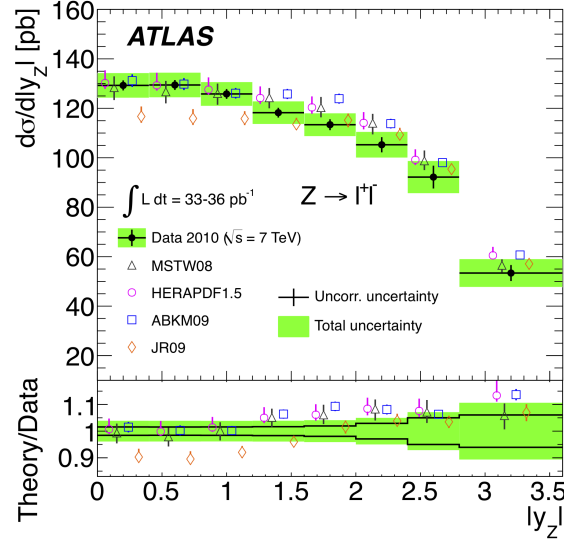


Figure 6.2: measured $Z/\gamma^* \rightarrow ll$ differential cross section compared with theoretical calculations. Small deviations are observed for JR09 and ABKM09.

6.3 Muon-electron universality

The ratio of electron to muon fiducial cross sections may be taken as a check on the lepton universality:

$$R_{Z/\gamma^*} = \frac{\sigma_{Z/\gamma^* \rightarrow ee}}{\sigma_{Z/\gamma^* \rightarrow \mu\mu}} = \frac{\text{BR}(Z/\gamma^* \rightarrow ee)}{\text{BR}(Z/\gamma^* \rightarrow \mu\mu)} = 1.018 \pm 0.031$$

The measured value, compatible with one, confirms the independence of the Z decay from the flavor of the lepton pair.

6.4 W/Z ratio

The W/Z cross section ratio is a standard electro-weak precision measurement, taken as a test on the validity of the Standard Model. Using the W cross section from [30]:

$$\begin{aligned} \frac{\sigma_W^{\text{fiducial}}}{\sigma_{Z/\gamma^*}^{\text{fiducial}}} &= 10.703 \pm 0.078(\text{stat}) \pm 0.110(\text{syst}) \pm 0.008(\text{extrap}) \\ \frac{\sigma_W^{\text{total}}}{\sigma_{Z/\gamma^*}^{\text{total}}} &= 10.893 \pm 0.079(\text{stat}) \pm 0.110(\text{syst}) \pm 0.116(\text{acc}) \end{aligned}$$

Where the uncertainties are computed taking into account the correlations between W and Z measurements. The systematic error from the acceptance

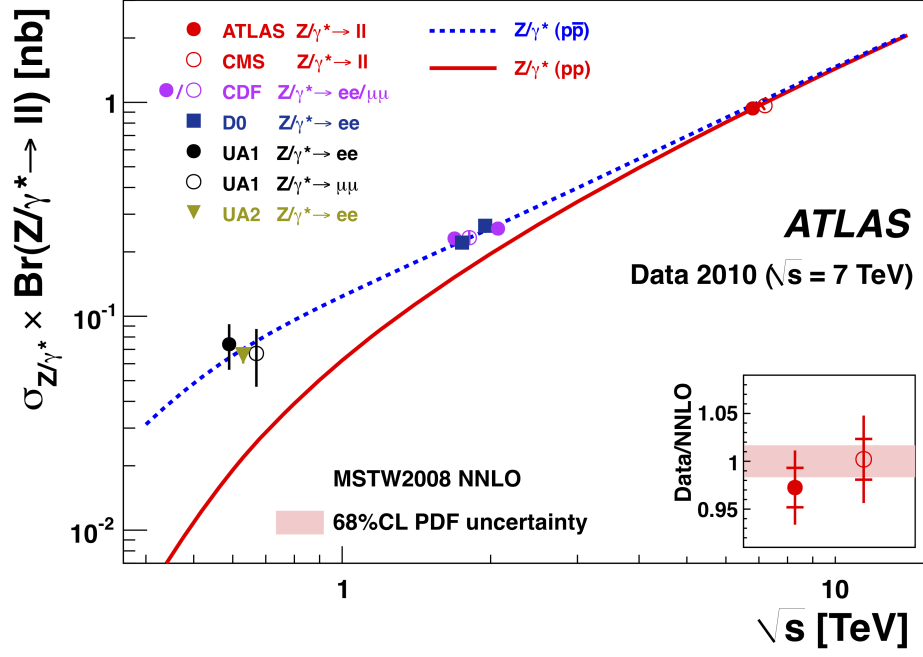


Figure 6.3: experimental $Z/\gamma^* \rightarrow ll$ cross section values compared with NNLO QCD calculations as a function of $\sqrt{s}$. Data points are represented with total uncertainties. The insert shows the comparison of ATLAS and CMS values normalized to the NNLO calculations.

is dominant on the total cross section ratio, yielding a total uncertainty of 1.6%, significantly larger than the 1.3% of the fiducial cross section ratio. The measure is free from the luminosity uncertainty since the term is common to numerator and denominator.

Conclusions

For my thesis I have contributed to the most recent measurement of the total and differential Drell-Yan $Z/\gamma^* \rightarrow \mu\mu$ inclusive cross sections with the ATLAS experiment at the LHC at CERN. The measurement is based on 36.2 pb^{-1} of data collected in 2010 at an energy in the center of mass of $\sqrt{s} = 7 \text{ TeV}$, providing a total of 11709 candidate events. The measurement of the acceptance and extrapolation factors, A_Z and E_Z , adopted to extend the fiducial cross section measurement to the total and combination volumes, represents my personal contribution to the analysis and is given in chapter 5. In addition the uncertainties from these factors have been thoroughly investigated as part of my thesis work. As presented in section 5.4, the uncertainty is found to be minimal for E_Z , $\Delta E_Z = 0.13\%$, due to the small extrapolation, and around 2.0% for A_Z . The differential extrapolation factors, $E_Z(y_Z)$, have higher uncertainties in the forward bins, due to the lack of experimental constraints in these regions to tune the MC simulations.

As illustrated in chapter 4, the measurement of the Z vector boson Drell-Yan production at LHC represents a crucial test bench of our knowledge on Quantum ChromoDynamics. The parton annihilation involved in the process allows indeed the investigation of Parton Distribution Functions for both valence and sea quarks, most importantly for quarks and antiquarks, over an unprecedentedly wide range in momentum transfer, Q^2 , and momentum fraction, x , thanks to the elevated $\sqrt{s}$.

The fiducial and total cross section measurements have been calculated in chapter 6 for the $Z/\gamma^* \rightarrow \mu\mu$ process together with their combination with the electron channel, providing the experimental measure of the $Z/\gamma^* \rightarrow ll$ cross section. The accuracy reached is of 1% and 2% for the fiducial and total cross section values respectively, excluding the luminosity uncertainty contribution, 3.4% , which is dominant over the statistical and systematic errors, both 0.9% . However the luminosity uncertainty is foreseen to become less incisive on the accuracy of the cross section as the integrated luminosity grows. The same holds for the statistical and systematic uncertainties. The latter in particular will benefit from better tunings of the MC simulations and from a higher statistics to calculate the efficiency maps. The acceptance uncertainty on the other hand will remain of the order of a few per cent, thus becoming the dominant contribution until a higher accuracy on the PDFs

will be reached, thanks also to the ATLAS measurements.

In chapter 6 the integrated and differential cross sections for $Z/\gamma^* \rightarrow ll$ have been compared with success to QCD calculations at NNLO. Some small deviations are observed in the central Z rapidity region for the JR09 PDF set and at large y_Z for ABKM09. The ATLAS measurement of the $Z/\gamma^* \rightarrow \mu\mu$ cross section therefore reveals to be a sensitive test of perturbative QCD and of the phenomenological descriptions adopted to model the Parton Distribution Functions. Given the overall broad compatibility of the results obtained with the Monte Carlo simulations, it is expected that when a higher statistics will be employed these measurements will contribute to reduce the uncertainties on the PDF sets. Moreover this is an evidence of the universality of PDFs and of the validity of the DGLAP equations to evolve the PDFs measured with Deep Inelastic Scattering experiments up to the kinematic range probed by LHC.

Compared to the Z cross section measured by the ATLAS collaboration with the first 2010 data (roughly 320 nb^{-1}) [44], the $Z/\gamma^* \rightarrow ll$ measurement presented here improves the statistical uncertainty by more than a factor of ten, from 7.2% to 0.6%, the systematic plus acceptance uncertainty by a factor of 2, from 4.8% to 2%, and the luminosity uncertainty by a factor of three, from 11% to 3.4%.

Bibliography

- [1] Lyndon Evans (ed.) and Philip Bryant (ed.). LHC machine. *JINST*, 3:S08001, 2008.
- [2] M. Leyton and J. Siegrist. *Minimum Bias measurements with the ATLAS detector at the CERN Large Hadron Collider*. PhD thesis, University of California, Berkeley, CA, 2009. Presented on August 13, 2009.
- [3] Hyeon Jin Kim and J. Yu. *Search for Standard Model Higgs in two photon final state at ATLAS*. PhD thesis, University of Texas at Arlington, Arlington, TX, 2010. Presented on June 25, 2010.
- [4] Zdenko van Kesteren. *Identification of muons in ATLAS*. PhD thesis, Amsterdam U., Amsterdam, NL, 2010. Presented on March 12, 2010.
- [5] The ATLAS Collaboration. Charged-particle multiplicities in pp interactions measured with the ATLAS detector at the LHC. *New J. Phys.*, 13(5):053033, May 2011.
- [6] The ATLAS collaboration. The ATLAS experiment at the CERN Large Hadron Collider. *JINST*, 3:S08003, 2008.
- [7] Roberto Di Nardo. *Minimum Bias Measurements with the ATLAS experiment at LHC: strangeness production and $\overline{\Lambda}^0$ to Λ^0 particle ratio*. PhD thesis, Università degli Studi di Roma Tor Vergata, Roma, IT, 2011.
- [8] B. Resende. Muon identification algorithms in ATLAS. *ATL-PHYS-PROC-2009-113*, September 2009.
- [9] Francis Halzen and Alan Douglas Martin. *Quarks and leptons: an introductory course in modern particle physics*. John Wiley & sons, New York, NY, 1984.
- [10] W. E. Burcham and M. Jobes. *Nuclear and particle physics*. Longman, Essex, UK, 1995.

- [11] Michele Maggiore. *A modern introduction to quantum field theory*. Oxford Master Series in Statistical, Computational and Theoretical Physics. Oxford University, Oxford, UK, 2005.
- [12] K. Nakamura et al. (Particle Data Group). Review of Particle Physics. *Journal of Physics G*, 37:075021, 2010 and 2011 partial update for the 2012 edition.
- [13] Sheldon Lee Glashow. Partial-symmetries of weak interactions. *Nuclear Physics*, 22(4):579 – 588, 1961.
- [14] Steven Weinberg. A model of leptons. *Phys. Rev. Lett.*, 19(21):1264–1266, November 1967.
- [15] Abdus Salam. Weak and Electromagnetic Interactions. *Elementary Particle Theory, Proceedings of the 8th Nobel Symposium*, pages 367–377, 1968.
- [16] F. Englert and R. Brout. Broken symmetry and the mass of gauge vector mesons. *Phys. Rev. Lett.*, 13(9):321–323, August 1964.
- [17] Peter W. Higgs. Broken symmetries and the masses of gauge bosons. *Phys. Rev. Lett.*, 13(16):508–509, October 1964.
- [18] G. S. Guralnik, C. R. Hagen, and T. W. B. Kibble. Global conservation laws and massless particles. *Phys. Rev. Lett.*, 13(20):585–587, November 1964.
- [19] Daniele Zanzi and Stefania Xella. *Search for the Standard Model Higgs boson in the ATLAS Experiment*. PhD thesis, University of Copenhagen, Copenhagen, DK, 2011. Presented on February 4, 2011.
- [20] Bruno Lenzi, Claude Guyot, and Rosy Nicolaidou. *Search for the Higgs boson decaying to four leptons in the ATLAS detector at LHC and studies of muon isolation and energy loss*. PhD thesis, Université Paris Sud Orsay, Paris, FR, 2010. Presented on September 17, 2010.
- [21] H. Flücher, M. Goebel, J. Haller, A. Hoecker, K. Mönig, and J. Stelzer. Revisiting the global electroweak fit of the Standard Model and beyond with Gfitter. *The European Physical Journal C - Particles and Fields*, 60:543–583, 2009.
- [22] The ATLAS Collaboration. Limits on the production of the Standard Model Higgs boson in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector. *arXiv:1106.2748 [hep-ex]*, June 2011.
- [23] ALEPH Collaboration, DELPHI Collaboration, L3 Collaboration, OPAL Collaboration, and The LEP Working Group For Higgs Boson

- Searches. Search for the Standard Model Higgs boson at LEP. *Physics Letters B*, 565:61 – 75, July 2003.
- [24] B. Penning. High Mass Higgs Boson Searches at the Tevatron. *arXiv:1011.6307 [hep-ex]*, November 2010.
- [25] The ATLAS Collaboration. Update of the Combination of Higgs Boson Searches in 1.0 to 2.3 fb⁻¹ of pp Collisions Data Taken at $\sqrt{s} = 7$ TeV with the ATLAS Experiment at the LHC. *ATLAS-CONF-2011-135*, August 2011.
- [26] The UA1 Collaboration. Experimental observation of lepton pairs of invariant mass around 95 GeV/c² at the CERN SPS collider. *Physics Letters B*, 126(5):398 – 410, 1983.
- [27] The UA2 Collaboration. Evidence for $Z^0 \rightarrow e^+e^-$ at the CERN $\bar{p}p$ collider. *Physics Letters B*, 129(1-2):130 – 140, 1983.
- [28] A. V. Varganov. *The Production Cross Sections of the Weak Vector Bosons in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV and a Measurement of the W Boson Decay Width*. PhD thesis, University of Michigan, Ann Arbor, MI, 2004.
- [29] A. Abulencia and others. CDF. Measurements of Inclusive W and Z Cross Sections in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV. *J. Phys.*, G34:2457–2544, 2007.
- [30] M. Aharrouche, G. Artoni, J. Barreiro Guimaraes da Costa, M. Bellomo, A. Belloni, E. F. Berglund, C. Bini, S. Borroni, R. Di Nardo, F. Ellinghaus, J. Ferrando, D. Froidevaux, C. Gatti, S. Giagu, M. Giunta, A. Glazov, F. Guescini, J. Hartert, V. Ippolito, F. Lo Sterzo, P. Mastandrea, P. Onyisi, A. Kapliy, M. Karnevskiy, M. Klein, U. Klein, J. Kretzschmar, R. Poettgen, S. Prasad, M. Rescigno, E. Richter-Was, S. Rosati, A. Salvucci, A. Sapronov, M. Schott, M. Shochet, and E. Solfaroli Camillocci. Total and differential $W \rightarrow l\nu$ and $Z \rightarrow ll$ cross-sections measurements in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS Detector. *ATL-COM-PHYS-2011-751*, June 2011.
- [31] Manuela Venturi. *Studio dell'accettazione geometrica nei decadimenti leptonici dei bosoni vettori intermedi W e Z per l'esperimento ATLAS ad LHC*. Master's thesis, Università degli studi di Roma Tor Vergata, Roma, IT, 2008.
- [32] Heather M. Gray and Emlyn W. Hughes. *The Charged Particle Multiplicity at Center of Mass Energies from 900 GeV to 7 TeV measured with the ATLAS Experiment at the Large Hadron Collider*. PhD thesis, California Institute of Technology, Pasadena, CA, 2010. Presented on November 9, 2010.

- [33] The ATLAS Collaboration. Measurement of the inelastic proton-proton cross-section at $\sqrt{s} = 7$ TeV with the ATLAS detector. *Nat Commun*, 2, September 2011.
- [34] Sidney D. Drell and Tung-Mow Yan. Massive lepton-pair production in hadron-hadron collisions at high energies. *Phys. Rev. Lett.*, 25:316–320, August 1970.
- [35] Stefano Frixione and Bryan R. Webber. Matching NLO QCD computations and parton shower simulations. *JHEP*, 6:29, June 2002.
- [36] P. Nason. Recent developments in POWHEG. *PoS, RADCOR2009*:18, January 2010.
- [37] P. M. Nadolsky, H.-L. Lai, Q.-H. Cao, J. Huston, J. Pumplin, D. Stump, W.-K. Tung, and C.-P. Yuan. Implications of CTEQ global analysis for collider observables. *Phys. Rev.*, D78(1):013004, July 2008.
- [38] H.-L. Lai, M. Guzzi, J. Huston, Z. Li, P. M. Nadolsky, J. Pumplin, and C.-P. Yuan. New parton distributions for collider physics. *Phys. Rev.*, D82(7):074024, October 2010.
- [39] R. D. Ball, L. Del Debbio, S. Forte, A. Guffanti, J. I. Latorre, J. Rojo, M. Ubiali, and NNPDF Collaboration. A first unbiased global NLO determination of parton distributions and their uncertainties. *Nucl. Phys.*, B838:136–206, October 2010.
- [40] NNPDF Collaboration, R. D. Ball, V. Bertone, F. Cerutti, L. Del Debbio, S. Forte, A. Guffanti, J. I. Latorre, J. Rojo, and M. Ubiali. Impact of Heavy Quark Masses on Parton Distributions and LHC Phenomenology. *Nucl. Phys.*, B849:296–363, August 2011.
- [41] D. Bourilkov, R. C. Group, and M. R. Whalley. LHAPDF: PDF use from the Tevatron to the LHC. *arXiv:hep-ph/0605240*, May 2006.
- [42] O. Gonzalez and C. Root. Uncertainties due to the PDFs for the gluino-sbottom search. *CDF note 7051*.
- [43] The CMS Collaboration. Measurement of the Inclusive W and Z Production Cross Sections in pp Collisions at $\sqrt{s} = 7$ TeV. *CERN-PH-EP/2011-107, CMS-EWK-10-005*, July 2011.
- [44] The ATLAS Collaboration. Measurement of the $W \rightarrow l\nu$ and $Z/\gamma^* \rightarrow ll$ production cross sections in proton-proton collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector. *J. High Energy Phys.*, *arXiv:1010.2130 [hep-ex]*, *CERN-PH-EP-2010-037*, 12, October 2010.