Study of $W^\pm Z$ boson pair production in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector and extraction of the polarisation fractions

by

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Declaration of Authorship

I, Stergios Kazakos, declare that this thesis entitled:

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In this thesis are presented the results of a study on $W^\pm Z$ boson pair production in pp collisions at a center-of-mass energy of $\sqrt{s}=13$ TeV within the ATLAS experiment. The gauge bosons are expected to decay in the fully-leptonic mode, namely only to electrons and muons. The four decay channels of the $W^\pm Z$ boson pair are: $eee$, $e\mu\mu$, $\mu ee$ and $\mu\mu\mu$. The study is based on Monte Carlo signal simulations that simulate the data collected in 2015+2016 by the ATLAS detector at the LHC. The MC samples correspond to a luminosity of $26.65 \text{ fb}^{-1}$, while the data for the period 2015+2016 correspond to an integrated luminosity of $36.1 \text{ fb}^{-1}$. This study contains a detailed cutflow analysis in the inclusive fiducial phase-space region. The cutflow analysis consists of two parts: the object selection and the event selection. The $W^\pm$ and $Z$ bosons are reconstructed from their decay products, indicating the existence of a $W^\pm Z$ boson pair system. The analysis is performed in the EventLoop framework using the official ATLAS tools and recommendations for the cuts, provided by the associated groups. The interesting signal events are distinguished and the final results are similar to the ones of previous analyses. The signal events after the selection are used for control plots of the kinematic observables, for the calculation of the $W^+Z/W^-Z$ ratio, as well as in polarisation and truth association studies. In the $Z$ boson reconstruction, the leptons originating from a $W$ boson are sometimes wrongly attributed to a $Z$ boson. This lepton “miss-assignment” is observed in $eee$ and $\mu\mu\mu$ channels and the corresponding probability is calculated by accessing the truth information of the MC sample. In addition, the truth information is used to validate the agreement between the reconstructed variables and the variables at generated level.
A physics observable directly related to the boson polarisation is referred to as $\cos \theta^*_lV$, where V corresponds to the W and Z boson. The $\cos \theta^*_lV$ distribution is studied in the inclusive fiducial phase-space. In order to have a better understanding on boson polarisation, the $W^\pm Z$ polarisation fractions for each helicity state are extracted. This is performed with an analytical fit in the total phase-space using the truth information at generated level from the full MC signal sample.
Acknowledgements

This section is devoted to all the inspiring people that I had the chance to interact with and made this dissertation possible.

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A special thanks goes to close friends who supported me and insisted on completing this dissertation. Particularly, I would like to pay tribute to my friend and colleague Kostas Paraschou for his useful advice on programming and for amplifying my motivation in physics and my strive for success, by witnessing his own excellence in the field.

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<td>A Toroidal LHC Apparatus</td>
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<td>CSC</td>
<td>Cathode Strip Chambers</td>
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<td>EDM</td>
<td>Event Data Model</td>
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<td>Event Filter</td>
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<td>JVT</td>
<td>Jet Vertex Tagger</td>
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<td>LAr</td>
<td>Liquid Argon</td>
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<td>LH</td>
<td>Likelihood</td>
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<td>LHC</td>
<td>Large Hadron Collider</td>
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<td>LO</td>
<td>Leading Order</td>
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<td>MC</td>
<td>Monte Carlo</td>
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<td>MDT</td>
<td>Monitored Drift Tubes</td>
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<td>Missing Transverse Momentum</td>
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<td>Muon Spectrometer</td>
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<td>Abbreviation</td>
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<td>OR</td>
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<td>OQ</td>
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<td>Particle Data Group</td>
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<td>Quantum Electro-Dynamics</td>
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<td>RoI</td>
<td>Regions of Interest</td>
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<tr>
<td>RPC</td>
<td>Resistive Plate Chambers</td>
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<td>SCT</td>
<td>Semi-Conductor Tracker</td>
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<tr>
<td>SF</td>
<td>Scale Factors</td>
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<tr>
<td>SFOC</td>
<td>Same Flavour Opposite Charge</td>
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<td>SM</td>
<td>Standard Model</td>
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<tr>
<td>TGC</td>
<td>Triple Gauge Coupling</td>
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<td>TGC</td>
<td>Thin Gap Chambers</td>
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<td>TRT</td>
<td>Transition Radiation Tracker</td>
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<td>WP</td>
<td>Working Point</td>
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To the memory of my beloved grandmother Vassiliki
for her endless love and support . . .
Chapter 1

Introduction

Since its formulation the theory of the Standard Model (SM) has been tested with remarkable precision. The SM combines effectively the theories between the electroweak and strong interactions in the same mathematical framework, providing a detailed description of the fundamental particles and fields. The discovery of the Higgs boson in 2012 came to complement the observation of all the predicted SM constituents.

However, the success of the SM is disputed, as it still cannot support a complete theory of the physical universe. The reason is that the SM does not incorporate a theory of gravity. At the same time, it does not provide a certain explanation of the particular values of the masses of quarks, electrons and other elementary particles. Recently observed phenomena such as dark matter, matter-antimatter asymmetry, neutrino oscillations (verifying that neutrinos have mass) all indicate possible extensions to the current theory pointing to searches beyond the SM.

One of the strongest concerns for theorists is known as the hierarchy problem. The problem lies in the fact that is quite “unnatural” for physicists that the power of gravitational interactions is many orders of magnitude lower compared to the power of the other types of interactions. Much more to that, the observation of the Higgs boson at a mass of 125 GeV amplifies this problem in the sense that a “fine-tuning” technique is required for the cancellation of divergent terms in order to reproduce the observed mass value.

The experiments at the LHC have provided physicists the opportunity to test the SM and even search for phenomena beyond the standard model that originate
from deviations between the theoretical predictions and the experimental results. Many theoretical models were introduced for this task and the majority of them involve di-boson productions ($W^+W^-$, $W^+Z$, $ZZ$, $W^+\gamma$ and $Z\gamma$) at the LHC. The lowest-order diboson production at the LHC can be illustrated as $q\bar{q} \to VV$ (where $V$ stands for the vector boson), in which triple gauge couplings (TGCs) are mostly included in the s-channel diagram. In the electroweak theory of the SM, gauge boson couplings are precisely predicted by the non-Abelian SU(2)×U(1) gauge symmetry. Any deviation from the predictions on these couplings will be a sign of new physics. Many models beyond SM seem to be consistent with the SM at low energies, but deviate from the SM at the high energy scale. Therefore, the diboson physics at the high energies is the most stringent test of the SM electroweak theory and at the same time the tool to probe new physics. The diboson physics analyses were given some merit just recently and yet the $W^+Z$ production was the least one studied, due to the small cross-section and the fact that it can only be produced in hadron colliders.

Nevertheless, there is still a strong motivation in studying $W^+Z$ boson pair production, especially from its fully leptonic decays, as this channel gives a clean signature with three leptons and a neutrino in the final state. Additionally, $W^+Z$ production has a larger cross-section compared to $ZZ$ production and it also offers the chance for studying the W charge asymmetry or conducting some polarisation studies.

The physics results in this dissertation are based on MC samples that simulate the 36.1 fb$^{-1}$ collision data collected with the ATLAS detector during the years of 2015 and 2016. The major contents include the steps of the complete cutflow analysis concerning the $W^+Z$ boson pair production, some studies at the truth level and the extraction of the polarisation fractions in the total phase space using an analytical fit. For the cutflow analysis the name of the MC signal sample that was used was: DAOD_STS05.09046771_.000044.pool.root.1 and it was part of the full MC signal sample called: mc15_13TeV.361601.PowhegPy8EG_CT10nloME_AZNLOCTQ6L1_WZlvll_mll4.merge.DAOD_STS05.e4475_s2726_r7772_r7676_p2722. The extraction of the polarisation fractions is performed using the full MC signal sample with the tag: mc15_13TeV.361601.PowhegPy8EG_CT10nloME_AZNLOCTQ6L1_WZlvll_mll4.merge.DAOD_STS05.e4475_s2726_r7772_r7676_p3317. The dissertation is organized as following. Chapter 2 briefly describes the
theoretical overview, including the SM and the $W^\pm Z$ physics. The LHC and ATLAS detector are introduced in Chapter 3. Chapter 4 describes the ATLAS tools used in the analysis within the official ATLAS framework and provides a brief description of the MC sample properties. Chapter 5 lists the physics objects used in the analysis, explaining the object selection and reconstruction. Chapter 6 presents in detail the steps followed for the event selection and Chapter 7 contains the results of the cutflow analysis and the distributions of the kinematic observables. In addition, in Chapter 7 the lepton-to-boson “misassignment” probability is introduced and calculated, followed by further truth level studies used to check the agreement between the reconstructed variables and variables at generated level. In Chapter 8 the boson polarisation is presented and a method for the extraction of the polarisation fractions in the $W^\pm Z$ boson pair system is introduced. The conclusion and future prospects are given in the Chapter 9.
Chapter 2

Theoretical Overview

2.1 The Standard Model

Figure 2.1: The elementary particles of the Standard Model (SM): quarks and leptons together constitute all the matter particles, the gauge bosons mediate the electromagnetic, weak, and strong forces, and the Higgs boson generates the mass.
The Standard Model (SM) constitutes a theory that describes the fundamental particles and their interactions. It was developed in the early 1970s and it soon became a well-established physics theory that is based on our current understanding of how the universe works. Its structure is based on the statement that matter is composed of fundamental particles called fermions, all forces are mediated by force carrying gauge bosons, and all massive fundamental particles acquire their mass through interactions with the Higgs boson. Fermions have half spin and obey Pauli’s exclusion principle (or Fermi-Dirac statistics). Bosons have integer spin and obey Bose-Einstein statistics. Spin is the intrinsic property of the particles which stands for a different form of angular momentum.

Fermions constitute the building blocks of matter and are splitted in two main categories; quarks and leptons. Each of these groups consists of six particles which they are in turn divided into three subgroups, the three generations, according to their properties. There are some striking differences between quarks and leptons, despite they are both elementary particles. Starting from the former, the up (u) and down (d) quarks complete the first generation, the charm (c) and strange (s) quarks complete the second generation and the top (t) and bottom (b) quarks come to complement the third generation. Quarks cannot in principle exist freely in nature and they are subject to the four types of fundamental forces. Quarks carry a fraction of one fundamental charge unit. The upper half of each quark generation has an electric charge of +2/3 and is known as up-type quark. The lower half of each generation has an electric charge of -1/3 and is known as down-type quark. Quarks have also a color charge in addition to the electric one. Every quark appears in one of the three color states called red, green and blue. The color is associated with the way they interact through strong interaction, which binds them together inside colorless composite particles called hadrons. The most common hadron in particle physics is called proton (p) and is widely used in collisions at the LHC at CERN. On the leptons’ side, the six leptons are: electron (e), electron neutrino (ν_e), muon (μ), muon neutrino (ν_μ), tau (τ) and tau neutrino (ν_τ). Leptons can exist freely in nature and electron is the most common of them as a constituent of the atom’s structure. The heavier versions of the electron have a finite lifetime decaying to electrons, which are stable. Although they are not stable, they are still considered elementary particles due to the lack of inner structure. Muons (~200 times heavier than electrons) are mostly found in cosmic ray radiation and are characterized as highly penetrative particles. Neutrinos have a
small, finite, non-zero mass, and their oscillations were currently observed during their propagation through space. Leptons have integer charge of one charge unit in the case of electron, muon and tau and zero charge in the case of the corresponding neutrinos. Leptons also interact with all forces except for the strong force. Each quark and lepton has its corresponding antiparticle with the same properties.

The gauge bosons mediate the fundamental forces of nature: weak, strong and electromagnetic. The gauge bosons are exchanged between particles that interact via a certain type of force. The mediators of the weak force are $W^\pm$ and $Z^0$ bosons (massive spin-1 vector bosons), which can be also interpreted as resonances with a finite lifetime. $W$ boson is charged and changes the flavor of the quarks and leptons that interact with it, while $Z$ boson has no charge and leaves their flavor unchanged. The mediators of the strong force are the eight gluons ($g$) (massless), which have no electric charge, but instead they have a “color charge” that explains the strong interaction between color charged particles, or quarks. The interactions of gluons are described by the quantum chromodynamics (QCD). The mediator of the electromagnetic interaction is the photon (massless spin-0 vector boson). Photon ($\gamma$) is a stable particle with no electric charge. The behavior of the photon is properly described by the quantum electrodynamics (QED) with a twelve-decimal precision. Finally, the Higgs boson (massive spin-0 scalar) was recently discovered and it explains the mass acquisition of fermions, $W$ and $Z$ bosons (and maybe itself) through a process that is called the Higgs mechanism. The natural physics intuition suggests that another boson should exist that would be responsible for mediating gravitational force. Although not yet found, a spin-2 boson, the graviton, would be the perfect candidate for that completing our current understanding of gravity.

2.2 WZ Boson Pair Production

The production of the $W$ and $Z$ bosons was first discovered in Fermilab using a proton-antiproton collider. Today there is a large production at the LHC at CERN, a proton-proton collider. $W$ and $Z$ boson are produced in quark-antiquark annihilations at a hadron collider or in $e^+e^-$ annihilations at an electron-positron collider and decay shortly afterwards to smaller particles. Although they are highly unstable particles we are aware of their existence by measuring the properties of
the produced particles. The simultaneous production of these two weak gauge bosons is a physical process involved in a large range of measurements at the LHC and is called WZ boson pair production. The leading-order (LO) Feynman diagrams for the \( q\bar{q} \rightarrow W^\pm Z \) process are shown in Fig.2.2.

![Figure 2.2: The tree-level Feynman diagrams for W^±Z pair production.](image)

From left to right, the interactions follow the formations of the t-channel (annihilation), the u-channel and the s-channel (scattering), which is the only LO diagram that contains a TGC vertex (WWZ), where a \( q\bar{q} \) pair annihilates to a W boson (off-shell) which later decays to a W^±Z pair. There are also next-to-leading order (NLO) corrections from quark-gluon and antiquark-gluon processes, which result in the presence of an additional quark in the final state. Additional NLO contributions include \( q\bar{q} \) interactions with gluon bremsstrahlung in the final state and \( q\bar{q} \) interactions with virtual corrections. In some gluon-gluon processes the W^±Z boson pair is often accompanied with at least two jets leading to NNLO corrections with very small contribution (\( \sim 1\% \)).

![Figure 2.3: Schematic representation of the fully-leptonic final state of W^±Z decay.](image)

This thesis is dedicated to WZ boson pair production from the events that decay fully-leptonically. The W boson decays to an electron(positron) or a muon(antimuon) along with their associated neutrino (W → lν, \( l = e \) or \( \mu \)) and the Z boson decays
to an electron-positron or a muon-antimuon pair ($Z \rightarrow ll$, $l = e$ or $\mu$). The electron and muon will be referred to as leptons from now on, excluding neutrinos from the analysis.

### 2.2.1 W Boson Charge Assymetry

Normally, the cross-section of $W^+Z$ and $W^-Z$ production would be the same if the collision was about to take place between a proton and an antiproton. If that was the case the $W^+$ bosons would be produced in the same quantity as the $W^-$ bosons. However since the LHC is a proton-proton collider, the $W^+Z$ and $W^-Z$ cross sections are not equal and this difference is known as the W charge assymetry.

The preference in the production of positively charged leptons, originating from $W^+$, is attributed to the realisation that proton contains two valence $u$ quarks and only one valence $d$ quark. Particularly, $W^\pm$ bosons are produced mainly through the interaction $u\bar{d}(\bar{u}d) \rightarrow W^{+(−)}$, which is the annihilation of a $u$ or $d$ quark (sea or valence quark) of the first proton with a $\bar{d}$ and $\bar{u}$ quark (sea quark) of the second proton. Valence quarks carry larger fraction of the total momentum compared to sea quarks, namely $x(u) > x(\bar{d})$. $W^+$ bosons are being produced mostly in the direction of the $u$ quark, while $W^-$ bosons do so in the direction of the $d$ quark because $x(d) > x(\bar{u})$.

![Figure 2.4: Parton distribution functions (NLO) inside proton for different values of $Q^2$.](image)
Theoretical Overview

The ratio of the cross-sections of $W^\pm Z$ production at the LHC with the latest results at $\sqrt{s} = 14$ TeV is

$$\frac{\sigma^{NLO}(W^+Z)}{\sigma^{NLO}(W^-Z)} = 1.53$$ (2.1)

2.3 Phase-space Definition

The phase-space definition used in this study is based on final-state leptons ($e, \mu$) directly associated with the decays of the W and Z bosons. The WZ analysis is performed in the inclusive fiducial phase space. The polarisation measurements are performed in the total phase space.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Fiducial Inclusive PS</th>
<th>Total PS</th>
</tr>
</thead>
<tbody>
<tr>
<td>lepton $</td>
<td>\eta</td>
<td>$</td>
</tr>
<tr>
<td>$m_Z$ window [GeV]</td>
<td>$</td>
<td>m_Z - m_Z^{PDG}</td>
</tr>
<tr>
<td>$m_W^l$ [GeV]</td>
<td>$&gt; 30$</td>
<td>–</td>
</tr>
<tr>
<td>$\Delta R(l^Z_Z, l^Z_W), \Delta R(l_Z, l_W)$</td>
<td>$&gt; 0.2$, $&gt; 0.3$</td>
<td>–</td>
</tr>
</tbody>
</table>

Table 2.1: Demonstration of the criteria used for the phase-space definitions.

Inclusive Fiducial PS

The selected inclusive fiducial phase-space region is chosen to match the detector acceptance and the analysis selection, explained in Chapter 5. The phase space definition uses kinematics of dressed leptons in their final state. Dressed leptons are created using the information from bare leptons, i.e. after QED final state radiation (FSR), and summing the momenta of the radiated photons from charged leptons or weak bosons, in a cone of $\Delta R < 0.1$ around the direction of the bare lepton. Most of the QED FSR photons are close to the electromagnetic cluster or to the bare lepton’s track and the energies of the bare electrons and of the close-by photons are combined in the ATLAS cluster reconstruction. Dressed leptons have the advantage that their kinematics are closest to measurements in the electron channel reducing the amount of remaining QED FSR correction. Therefore, it makes possible the combination of leptonic channels with leptons radiating differently, namely electron and muon channels.
Total PS

The only requirement need for the total phase-space definition is that the Z boson has to be produced on-shell, particularly that the combined invariant mass of the two leptons originating from the Z boson is in the a window of $66 \text{ GeV} < m_{ll} < 116 \text{ GeV}$ around the Z mass.
Chapter 3

The ATLAS Detector

The ATLAS detector is a general purpose detector that is used in the ATLAS experiment as a probe for new physics by simultaneously checking the validity of the standard model by contacting precision tests at the TeV scale. The length of the detector reaches the 44m, while its diameter is estimated to 25m. It is designed to cover a solid angle of nearly $4\pi$ steradians around the interaction point (IP) and its weigh climbs to 7000 tonnes.

![3D side-view of the ATLAS detector and its sub-systems.](image)

**Figure 3.1:** A 3D side-view of the ATLAS detector and its sub-systems.

The sub-systems of the detector are labeled in Fig.3.1. The ATLAS detector is a cylindrical structure and consists of an outer solenoid magnet that surrounds the
inner detector. Several calorimeters are circled around the inner detector and three large superconducting toroids (one barrel-shaped and two end-caps) are located around the calorimeters.

3.1 ATLAS Coordinate System

The ATLAS experiment uses a right-handed coordinate system \((x,y,z)\) with respect to the interaction point in the centre of the detector. The \(x\) and \(y\) axes define the transverse plane and the \(z\)-axis goes along the beam direction. The positive \(x\)-axis points to the center of the accelerator ring and the \(y\)-axis points upwards. The positive \(z\)-axis points to the side \(A\) of the detector, while the side \(C\) lies in the opposite direction. ATLAS also uses frequently a polar system based on the angles \(\theta\) and \(\phi\). The azimuthal angle \(\phi\) is measured in the transverse plane from the positive \(x\)-axis to the positive \(y\)-axis ranging from \(-\pi\) to \(\pi\). On the experimental basis it is computed as

\[
\phi = \arctan \frac{p_y}{p_x}
\]

The polar angle \(\theta\) is the angle which is measured from the positive \(z\)-axis to the transverse plane with running values from 0 to \(\pi\). It is widely used to gain knowledge of transverse plane projections of the fragment trajectories and momentum after collision. Some of these projected quantities like transverse momentum \((p_T)\) and transverse energy are defined as:

\[
p_T = p \cdot \sin \theta = \sqrt{p_x^2 + p_y^2}
\]

\[
E_T = E \cdot \sin \theta = \sqrt{m^2 + p_T^2}
\]

and are preferred in particle physics experiments reflecting our lack of knowledge regarding momenta along the \(z\)-axis of the beam.

Another characteristic quantity is rapidity \(y\) which is defined as

\[
y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z}
\]

In a hadronic collider it is often more convenient to use the rapidity instead of the polar angle. The advantage of rapidity is that differences in rapidity are invariant under lorentz boosts. At the limit of relativistic energies, where the particle mass
can be neglected ($E \approx pc$), eq.3.4 simplifies to

$$\eta = \frac{1}{2} \ln \left| \frac{p}{p} + p_z \right| - \ln \left[ \tan \left( \frac{\theta}{2} \right) \right]$$  (3.5)

The quantity $\eta$ is called pseudorapidity and is just a special case of rapidity. Differences in pseudorapidity are also invariant under boosts along the $z$-axis and it can be defined in terms of $p$ and $p_z$ as

$$\eta = - \arctan \frac{p_z}{p}$$  (3.6)

**Figure 3.2:** (A) Schematic representation of the ATLAS coordinate system
(B) Correspondence between pseudorapidity $\eta$ and polar angle $\theta$.

The “forward” regions of the detector that are close to the beam axis are often described in terms of $\eta$ as high $\eta$ regions, while $\eta$ drops down to 0 around the transverse plane.

Distances between two particles in the detector region are described by the variable $\Delta R$:

$$\Delta R = \sqrt{(\Delta \phi)^2 + (\Delta \eta)^2}$$  (3.7)

One of the notable quantities used in the experiments is called transverse impact parameter $d_0$ and is defined as the smallest closing perpendicular distance between the trajectory of a track and its primary vertex in the transverse plane. A similar definition yields for the definition of the longitudinal impact parameter $z_0$. 
3.2 Inner Detector

The Inner Detector (ID) is the innermost subsystem of the detector that is closest to the interaction point. The central solenoid surrounding the ID generates a uniform axial magnetic field of 2 T which bends the trajectories of the charged particles. Due to the existence of the Lorentz force $v \times B$, the trajectory of the charged particle is a helix with a pitch angle $\lambda$ and a radius of curvature $R$ (shown in Fig.3.3). Hence for a singly charged particle ($|q| = e$) these quantities are related to its momentum by

$$p \cos \lambda = 0.3BR,$$

where $p$ is the momentum of the particle and $B$ is the magnetic flux density. By determining the parameters of the helical trajectory in the tracking detectors, $R$ and $\lambda$ can be obtained leading to the reconstruction of the particle’s momentum.

![Figure 3.3: Principles of tracking reconstruction using a silicon tracking detector. The curvature in the xy-plane determines the transverse momentum.](image)

The range of cover in pseudorapidity ($|\eta| < 2.5$) in addition to the high granularity and the strong bending power offers high precision tracking and excellent momentum resolution.

The precision tracking detectors are arranged in a formation of concentric cylinders around the beam axis in the barrel region. In the end-cap regions they appear as disks perpendicular to the direction of the beam axis (Fig.3.4).

The Inner Detector contains three main complementary subdetectors: the silicon Pixel Detector, the Semi-Conductor Tracker (SCT) and the Transition Radiation Tracker (TRT).
3.2.1 Pixel Detector

The Pixel Detector is the “heart” of the Inner Detector, as it is the closest part to the interaction point. Its function is based on semiconductor technology and recently introduced methods using silicon pixels and strips. When a charged particle traverses an appropriately doped silicon wafer and ionises it, electron-hole pairs are created, as shown in Fig.3.5. The potential difference is applied across the silicon and the holes will drift in the direction of the electric field where they can be collected by p-n junctions. Each time the amount of charge accumulated by the sensors surpasses a threshold a “hit” is registered.

![Illustration of the production of current in a silicon tracking sensor.](image)

The sensors are arranged in silicon strips, normally separated by $O(25 \text{ } \mu m)$, or in silicon pixels defining a precise 2D space point. The determination of the exact hit position is done through charge interpolation over adjacent pixels. The pixel
sensors have a resolution of 10 $\mu m$ in the transverse plane ($R-\phi$) and a resolution of 115 $\mu m$ in the longitudinal plane ($z$). This provides the required granularity for charged particles trajectories. The produced signals in a typical silicon wafer after the crossing of a charged particle are not small and with the appropriate amplification, the output is a clear signal associated with the strip/pixel on which the charge was collected. The most urgent issue that is associated with the Pixel Detector is the damage due to overheating and radiation. To avoid such incidents the detector is operated at very low temperatures ($\sim -5 ^\circ C$ to $-10 ^\circ C$). Pioneer cooling techniques are currently developed based on liquid nitrogen technology with the aim to be implemented in the upcoming upgrade.

![Figure 3.6: Overview of the Inner Detector subsystems (barrel region).](image)

### 3.2.2 Semi-Conductor Tracker

The complementary detector around the Pixel Detector is called Semi-Conductor Tracker (SCT). It is also a silicon based detector, which is made of thin layers of silicon “strips” and it is mainly responsible to guarantee excellent track reconstruction. It uses strips instead of pixels providing reliable information regarding the vertexing reconstruction, taking advantage of its structure. Particularly, the
SCT focuses on impact parameter measurements along with heavy flavor and tau-lepton tagging. Each track crosses four space points located on the four cylindrical double sensor layers (eight strips) of the SCT. In this way, there is access to the two-dimensional information taken from the grid that is created. The silicon strip detector attains a resolution of 17 $\mu$m in the transverse plane and 580 $\mu$m along the direction of the z-axis. The SCT suffers from the same weaknesses as the pixel and as a result they should operate at the same conditions, since they share the same thermal enclosure.

### 3.2.3 Transition Radiation Tracker

The outer part of the Inner Detector is called Transition Radiation Tracker (TRT). It is comprised of drift tubes which are located both in the barrel region and the end-cap regions. In the former the tubes are tangent to each other and parallel to the direction of the beam while in the latter the tubes are arranged radially on the caps and vertical to the beam axis. The tubes contain a certain mixture of gasses composed of 70% Xe, 27% CO$_2$ and 3% O$_2$. The length of the tubes in the end-cap regions reaches the 37 cm while in the barrel region the tubes are almost 4 times longer measuring 4 mm in diameter. The angular cover of TRT is restricted to $|\eta| < 2.0$ with a resolution of 130 $\mu$m in the tranverse (R - $\phi$) plane. Nevertheless, the notably large number of hits (36 hits on average per track) compensates for its low accuracy providing an optimal performance given its low price compared to the rest of the silicon subsystems. The straw-like structure of the TRT favors the discrimination between electrons and pions since the detection of transition-radiation photons contributes to the electron identification. The TRT is designed to measure the transition radiation which is produced when a charged particle passes through the straws. The gas inside the straws is ionised and the ions drift to the tube’s wall. The electrons are driven to a central wire in the centre of the tube and the generated current is measured. The amount of radiation is higher for lighter particles and in this way electrons are distinguished over heavier hadrons such as pions. In addition, the TRT cross-checks and complements the Electromagnetic Calorimeter at an energy window below 25 GeV, while contributing to the reconstruction of track segments from photon conversions.
3.3 ATLAS Calorimeters

The purpose of the calorimeter system is to deliver precise measurements of the particle energies while interrupting their course as they are passing through the detector. The ATLAS Calorimeters are located around the Inner Detector (ID) and they are arranged in a similar formation of two regions: the barrel region and the end-cap one.

![Diagram of ATLAS Calorimeters](image)

Figure 3.7: Inner structure of the ATLAS Calorimeters.

3.3.1 Electromagnetic Calorimeter

The Electromagnetic Calorimeter (EMCal) is designed to stop particles that produce EM showers such as electrons, positrons and photons and provide information about some of their properties. It has an angular cover of $|\eta| < 1.475$ in the barrel part and a cover of $1.375 < |\eta| < 3.2$ in the two end-cap parts. The detection medium of the EMCal is Liquid Argon (LAr) while there are also absorbing plates made of lead over its whole range. LAr shows remarkable radiation tolerance and it also provides a fine linear response.

The incident particles pass through the lead plates and create EM showers producing secondary particles of lower energies. Therefore, the depth and the material thickness of the EM calorimeter should be carefully considered in order to prevent
shower particles from reaching the muon system. The so-called “punch-through” of the Muon Spectrometer should be avoided as the EM particles can induce fake muon rates and they would disturb the precise measurement of the missing transverse energy (one of the objectives of the EM calo). The depth of the shower is given in terms of the critical energy $E_c$ and the radiation length $X_0$ as

$$X = X_0 \ln \left( \frac{E_0}{E_c} - 2 \right)$$

(3.9)

The traversing medium interacts with the incoming particles lowering their initial energy by a factor of $1/e$ for each radiation length. The material thickness of lead in the calorimeter is $\sim 22 X_0$ in the barrel part and $\sim 24 X_0$ in the end-caps. With this depth the EM calorimeter can accumulate almost all the showers initiated by particles of energies lower than 1 TeV. In fact, lead thickness is optimised as a function of pseudorapidity ($\eta$), thus it takes different values for different values of $\eta$.

The secondary low energy particles that survive from the showers, mostly electrons and positrons, ionise the liquid argon. The electrons after the ionisation are collected on electrodes made of cooper, generating a current that is measured. The energy of the initial particle is proportional to the number of particles ionising the LAr, and so is the measured charge and maximum current. The signal derived from the electron current is amplified, digitized and recorded. Owing to its accordion-like shape the EMCal presents fine azimuthal coverage over the full range of the $\phi$ angle without any gaps or cracks. Over the angular region that it has the same coverage with the ID ($|\eta| < 2.5$), the EMCal is divided into three sections or layers according to its purpose. The first layer has the finest granularity ($\Delta \eta \times \Delta \phi$) and it is designed to provide precise $\eta$ measurements determining the flight direction of the particles. Its sub-role is to distinguish photons from neutral pions that decay to two photons. The second layer focuses on the absorption of the radiation from EM showers, which justifies its larger depth compared to the other layers. The third layer attempts in principle to differentiate EM from hadronic objects by measuring the remaining energy of the incident particles. The granularity in the second and third layer, as well as the granularity in the end-caps is coarser complied with the purpose of each part.
3.3.2 Hadronic Calorimeters

Unlike electrons and photons, hadrons traverse the EMCal with no energy losses. The placement of the EM calorimeters prior to hadronic calorimeters is therefore justified since, in principle, hadronic showers penetrate deeper than EM showers. The Hadronic Calorimeter (HCal) is separated in different compartments: the Tile Calorimeter, the Forward Calorimeter and the Hadronic End-Cap Calorimeter. Its leading objectives are jet reconstruction, energy measurements, particle identification and determination of the $E_T^{\text{miss}}$.

Tile Calorimeter (TileCal)

The hadronic calorimeter that surrounds the EMCal is called Tile Calorimeter. It is segmented in two parts: the first one consists an extension to the EMCal in the barrel region with a coverage of $|\eta| < 1.0$ and the second is located around the end-cap wheels to provide additional coverage coping with the angular region of $0.8 < |\eta| < 1.7$. The development of the TileCal was based on scintillating tiles paneling absorbing steel plates. As the shower develops through the tiles, scintillation light is produced. The two sides of the scintillators communicate with...
fibers that shift the wavelength of the light to the visible region and transport the signal to photomultipliers.

**LAr Hadronic End-Cap Calorimeter (HECCal)**

The hadronic endcap calorimeter resembles the EMCal in the end-cap region, with the difference that it utilizes parallel copper plates as absorbers instead of lead. LAr is again the active material and flows between the two wheels from which the HECCal is comprised. It covers the angular region of $1.5 < |\eta| < 3.2$ it shares the same cryostat as the EMCal in the end-caps. For an optimal performance, the HECCal overlaps with the TileCal in the region $1.5 < |\eta| < 1.7$ and with the FCal in the range $3.1 < |\eta| < 3.2$. The front and back wheels are made up of copper plates that differ in number and thickness and LAr fills the gaps (8.5mm) between the plates.

**LAr Forward Calorimeter (FCal)**

The purpose of the forward calorimeter is to tackle the high particle flux and large energy densities in the forward region. Its coverage is restricted in the range of $3.1 < |\eta| < 4.9$ and its two hadronic components consist a follow-up to the forward part of the EMCal. The existence of the two hadronic parts is crucial since the majority of the incident particles that reach the FCal are hadrons. The active material is LAr and the absorber plates are made of cooper for the EM part, while for the two subsequent hadronic parts absorbers are made of tungsten. The plates are vertical to the beam direction and are held together by regularly spaced rods in a matrix formation. The gaps between the rods are filled with LAr and the ionization signal is measured from the rods. Overall, the depth of the FCal reaches about $10\lambda$\(^1\) and the FCal itself still suffers from pile-up issues which are expected to be amplified in the following runs.

---

\(^1\)The nuclear interaction length $\lambda$ is used in hadronic calorimeters and stands for the average distance traveled by a hadron before interacting with a nucleus.
3.4 Muon Spectometer

The outermost system of the ATLAS detector is called Muon Spectometer (MS). It is comprised of several subsystems in order to achieve optimal coverage and performance, while each subsystem is charged with a specific task. The outlying location of the MS is aptly justified since muons are highly penetrative particles and they traverse the calorimeters without being interrupted. It is designed to measure the momentum of muons and identify their charge in the region of $|\eta| < 2.7$ and it has also triggering capabilities in the region of $|\eta| < 2.4$. The MS is imposed with the requirement of precisely determining the muon kinematics up to the TeV scale achieving a resolution of 10% at 1 TeV. The momentum measurements in the GeV scale are considered more reliable with an average resolution of 30% at approximately 200 GeV. The MS performs stand-alone transverse momentum measurements owing to its separate magnetic field, combining the results with the track information that utilises from the ID. In principle, the determination of the momentum is based on the relation Eq.3.8, where $R$ is the radius of the sagitta formed by the curvature of the muon’s trajectory due to the presence of the magnetic field $B$.

![Figure 3.9: Cut-away 3-D layout of the ATLAS Muon Spectometer with its subsystems labelled.](image-url)
The subsystems of the MS which are shown in Fig.3.9 and the performed tasks are briefly described below:

**Monitored drift tubes (MDTs):** Chambers located both in the barrel and the end-cap regions. Typically, there are three to four layers of aluminium tubes filled with a gas mixture of Ar (93%) and CO$_2$ (7%). By the time a muon traverses the tubes a trail of electrons is created and drifted to a wire (anode). This constitutes the primary signal which is then amplified and digitised. The MDTs are responsible for muon tracking, while each chamber contains innovative sensors which monitor the temperature and the local magnetic field. The angular coverage of these chambers scales up to $|\eta| < 2.7$.

**Cathode Strip Chambers (CSCs):** Respecting the principles of energy and momentum conservation the muon flux is also expected to be larger in the kinematic region of $(2.0 < |\eta| < 2.7)$. In this forward region the CSCs replaced the MTDs due to their efficient handling of large fluxes, achieving satisfactory spatial and time resolutions. CSCs are chambers made of almost orthogonal strips and filled with a combination of Ar (80%) and CO$_2$ (20%). The CSCs are designed for muon tracking and their operation is similar to the MTDs. One main advantage of these chambers is that they combine four layers of anode/cathode wires, thus providing a four-point precision and four measurements of the $\phi$ coordinate per track. This feature is missing from MTDs, which cannot provide information about the second coordinate.

**Resistive Plate Chambers (RPCs):** Resistive Plate Chambers are designed in the barrel region to provide complementary measurements of the second coordinate $\phi$ while being engaged in the triggering procedure. RPCs are plate detectors placed in a parallel direction to the beam axis in altering distances. The 2 mm gap created by insulating spacers between the electrodes is filled with C$_2$H$_2$F$_4$ (gas), which is ionised. The strips on the two sides of the gap are perpendicular, providing information for $\eta$ and $\phi$ coordinates. The spatial resolution of RPCs is $\sim$10 mm for both coordinates and the timing resolution does not surpass the threshold of 7 ns, allowing for precise bunch crossing identification.

**Thin Gap Chambers (TGCs):** TGCs are introduced as another solution for triggering and determination of the $\phi$ coordinate. The coverage in terms of pseudorapidity is $1.05 < |\eta| < 2.7$ (for triggering it is $1.05 < |\eta| < 2.4$) and they are placed radially on the end-caps to account for the large muon flux there. The
chambers are filled with a combination of \( n\text{-C}_5\text{H}_{12} \) and \( \text{CO}_2 \) and provide fine time resolution for most of the tracks, which is 25 ns on average.

### 3.5 Trigger System

The trigger system at the ATLAS detector is designed to perform a primary event selection on-the-go and its development is itself a more challenging task. The system is responsible to record interesting events at a frequency of approximately 400 Hz while the nominal bunch crossing rate is estimated to a frequency of 40 MHz. The trigger’s combined efficiency is given by the complementary operation of a three-level system. The system at each level acts as an AND/OR gate making decisions that comply with the previous levels (if any). The trigger levels are: Level 1 (L1), Level 2 (L2) and event filter level (EF).

The L1 is the first trigger level and it is mostly hardware based. It employs the information from the calorimeters and the muon system to make a choice in less than 2.5 \( \mu \text{s} \). At this level the trigger focuses on high-\( p_T \) particles and jets, as well as on objects with large missing total and transverse energy. The L1 trigger also sets the Regions of Interest (RoI) which are passed to the next level for further use. The L2 trigger utilizes the previously identified RoIs and advanced reconstruction algorithms to provide decisions of higher precision. The current level is software-based and the event processing time at this level is only 40 ms. The triggering procedure is finalised in the Event Filter (also software-based), where there is complete event reconstruction incorporating sophisticated algorithms similar to the ones of the offline analysis.

The events are finally recorded upon passing the EF with an average registration size of 1.3 MB and are stored for further analysis. The decisions of the three trigger levels are organised in pre-selected trigger menus which determines the way the events are classified into physics channels for separated storage. Some menus require at least one lepton to satisfy certain criteria, while other menus contain additional selection criteria that are analysis dependent (e.g. increasing the momentum threshold for triggering). In the analysis of \( W^\pm Z \to l\bar{\nu}ll \) reported in this thesis, the processed events only need to comply to the muon and electron menus to be recorded. The criteria suggested in the menus are optimised as a function of luminosity aiming to meet the output rate limits.
Chapter 4

Monte-Carlo Samples and ATLAS Framework

4.1 Signal Simulation

The signal MC samples used in this analysis simulate proton-proton (pp) collisions at a centre-of-mass energy of $s = \sqrt{13} \text{ TeV}$, detected by the ATLAS detector in 2015 and 2016. The samples simulate data that were taken with a 25 ns bunch spacing between them. The data and MC samples are required to fulfil certain quality criteria. Some of the criteria apply only to data, based on data-quality flags, while others apply to both. The MC sample corresponds to a production cross-section of 4.5023 pb. The uncertainty in the integrated luminosity in the combined period of 2015+2016 is derived to be 2.1%.

Detailed information about the full MC signal sample is shown in Table 4.1. The samples are generated following the procedures of W and Z bosons decays into leptons (muons, electrons and taus), and these $\tau$ leptons decay to all known final states. The generators used to produce the primary sample used for $W^\pm Z$ simulation are PowHeg+Pythia8 with the option NLO QCD matrix elements to be matched to parton showers (PS). For the hard-scattering process, the CT10NLO PDF set is used, while the CTEQ6L1 PDF set is used for the PS.

The cross-section in Table 4.1 is used to normalise the sample, multiplied by filter efficiencies to account for any phase-space restrictions imposed when the sample
Table 4.1: Details of the MC signal simulation.

<table>
<thead>
<tr>
<th>DSID</th>
<th>Process</th>
<th>Generators</th>
<th>PDF</th>
<th>Events</th>
<th>Filter eff.</th>
<th>Cross-section [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>361601</td>
<td>$WZ \rightarrow \ell\nu\ell\nu$</td>
<td>Powheg+Pythia8</td>
<td>NLO CT10</td>
<td>~10M</td>
<td>1.00</td>
<td>4.5023</td>
</tr>
</tbody>
</table>

was first generated. The indicated branching ratio is also included in the cross-section.

### 4.2 Data Processing Chain

The procedure of data processing in the LHC consists of similar discrete stages between data and MC simulations.

![ATLAS data processing chain](image)

**Figure 4.1:** ATLAS data processing chain. The flow chart on the left describes data and the one on the right describes Monte-Carlo samples.

In the data scenario, a primary version of data (RAW data) is produced and triggered online (*Trigger*). In the MC scenario, the samples are generated through a process called *Event generation*. This is a simulation of the interaction between the quarks and gluons in the colliding protons, the subsequent parton showering and hadronization and decays into stable particles. In the following step, known as *Detector simulation*, it is calculated how the generated particles interact with the detector, how they shower into secondary particles and how much of their energy is deposited in each of the detector elements. The simulated energy deposits should be turned into a detector-like response that resembles the raw
data from the real experiment. This process is called **Digitisation** and from this step onwards similar processes are followed concerning the data and MC treatment. **Reconstruction** is the following processing stage, where event data/MC are stored in a Event Summary Data (ESD) format to reduce their size. ESD is an object-oriented representation and is stored in POOL ROOT files. It is designed to hold information of detector objects such as calorimetric cells and track hits, as well as of derived objects such as reconstructed clusters and tracks. ESD is used to store high-level physics objects (e.g. electrons, muons and jets). The Analysis Object Data (AOD) is the reduced event representation that is designed for analysis. The AOD retrieves the full information on high-level objects from the ESD, and only part of the information on detector objects. **Derivation** is called the procedure where reconstructed data/MC are significantly reduced in size in order to become suitable for physics analyses. After sophisticated data reduction and augmentation techniques the samples are segmented into smaller formats that are distributed to the associated analysis groups. Derivation allows reductions of a PB sized initial sample up to some TB, which can be further split in N-Tuples of some GB or even MB.

### 4.3 The xAOD Format

The ATLAS data and Monte Carlo samples are organised in a recently introduced Run 2 format called xAOD. This is a ROOT-readable format allowing the immediate browsing on the AODs produced in the Reconstruction or of the DAODs procuced in the Derivation. The xAOD format contains its own EDM, namely a set of objects that represent reconstructed physical objects, which can be accessed any time from reconstruction stage to final analysis. xAODs carry information related to the event itself (EventInfo) and the reconstructed objects of each event (muons, electrons, jets, etc.). Internally, the xAODs are split in the objects themselves and the numerical payload for each object, called **Auxiliary Store**. Normally, in a physics analysis there is no interaction with the auxiliary store. The xAOD is organised with the familiar structure of a TTree, which is called **Collection-Tree**. The TTree is organised in object container classes that inherit from the xAOD class. The main types of xAOD object containers are:

- **Electrons and Photons**
- **Muons**
Monte-Carlo Samples and ATLAS Framework

- Jets
- Taus
- Missing energy
- Truth Monte-Carlo
- Inner Detector tracks and vertices

Each event object in the container can be associated with spatial and kinematic properties (e.g. $p_T$, $\eta$, $\phi$, $E$). To enable an event-by-event processing of the object containers, the use of an analysis framework is required.

4.4 EventLoop

EventLoop is the most common ATLAS framework currently in use. It became popular for the quick and reliable analysis of the xAOD files in Run 2. EventLoop framework is designed to relieve the user of writing a code on his own to loop over the events. It is entirely ROOT-based and managed with the RootCore build system. The utilities of this framework allow the analysis of large files on lxplus, while being lightweight and flexible. It supports running on local machines, on ATLAS clusters and even on the grid, providing the ability of switching between them. EventLoop suppresses heavy crashes created by common individual job failures, especially when running on the grid. This time-saving solution is reinforced by messages, indicating the job that failed, thus assisting the user even more. Within this framework, can be performed simple tasks starting from creating and saving histograms and N-tuples to more composite tasks.

Technical details of setting up the environment are given in the following link:
https://twiki.cern.ch/twiki/bin/viewauth/AtlasComputing/SoftwareTutorialxAODAnalysisInROOT

The folder containing the RootCoreBin directory is named ROOTAnalysis-Tutorial and there the command

rc make_skeleton MyAnalysis

is executed. The contents of the ROOTAnalysisTutorial directory after the command are

- **cmt** directory: where the Makefile is located. This file is modified each time a
new dependency (package) needs to be added to the analysis

- **MyAnalysis** directory: where the C++ header files are located.
- **Root** directory: where the C++ source files are located. It also holds the LinkDef.h file that ROOT uses to build dictionaries.

A fourth directory called Run is created inside the RootCoreBin directory that is used to hold the running file or steering macro named ATestRun.cxx. This macro actually utilises an ASG tool called SampleHandler which allows for easy sample management. The xAOD file is used as input in the SampleHandler, the job is defined and it is then submitted to the driver (local/grid).

### 4.5 ATLAS Computing Tools

Standard analysis processes are performed in EventLoop with the use of pre-built tools (Release 20.7 for Run 2). Physics analysis groups are in charge of creating and validating these tools, which are in fact object classes containing a sequence of processes. The tools come in different versions and have to be explicitly set up in the main C++ analysis code. The inputs of the updated versions are sometimes altered, leading to changes in the results and cross-checking failures.

The C++ tools were configured in the cmt/Makefile.RootCore file and the objects were initiallised in the files named MyxAODAnalysis/MyxAODAnalysis.h and Root/MyxAODAnalysis.cxx. The tools are used in this study in order to reconstruct and perform the cutflow analysis on physics objects (electrons, muons, jets). These tools and the proper configuration recommendations are briefly described below:

**GoodRunsListSelectionTool**: A tool that uses a GRL xml file as an input, where good luminosity blocks from the data runs are listed. If the luminosity blocks of the analysis are not in this list, the quality of the data is considered “bad”. The tools returns a boolean as an output. The complete path of the GRL file in this study is: $ALRB_TutorialData/data15_13TeV.periodAllYear_DetStatus-v73-pro19-08_DQDefects-00-01-02_PHYS_StandardGRL_All_Good_25ns.xml

**JetCleaningTool**: A tool that removes “dirty” jets based on large beam backgrounds or detector inefficiencies. The selected cleaning level for the cuts is called LooseBad (loose criteria that fit most analyses), while a boolean (DoUgly) is also
activated for the removal of ugly jets (i.e. jets with most of their energy deposited on the TileGap3 layer). The activation is performed with the input value false in the tool. The tool in fact provides an automated way of removing jets falling in regions with hot noisy calorimeter cells, which is currently irrelevant for Run 2 (since no hot cells have been reported yet).

**IsolationSelectionTool**: A tool to select isolated objects. Its purpose is to distinguish muons, electrons and photons associated with jets, based on tracking and spatial information from the calorimeters. The tool is used in the muon and electron object selection in three levels with different input values and stricter cuts. The working point (WP) in baseline selection is LooseTrackOnly, the WP for Z selection is GradientLoose and the WP for W selection is Gradient. The third selection level applies only to electrons, while the rest apply both to electrons and muons.

**JetVertexTaggerTool**: A tool that uses tracking and vertex information to discriminate between pileup and hard scatter jets. Pileup jets in the central region (|\eta| < 2.4) are tagged and rejected afterwards with the JVT algorithm. The JVT value is recalculated using exclusively calibrated jets.

**JetJvtEfficiency**: A tool used to suppress the number of central jets originating from pile-up and hard scatter. In order to be consistent with how the JVT Scale Factors (SF) have been derived in release 20.7 the overlap removal (OR) should be performed with all jets (not just those that survived the JVT) and the JVT SF should be computed with the jets that survived the OR. A simple way of thinking about this: if a lepton overlaps with a pileup jet, this lepton probably should not be used in the analysis.

The configuration SFFile of the tools is: JetJvtEfficiency/Moriond2017/JvtSFFile_EM.root, which defines the “Medium” WP, which in turn corresponds to a threshold of JVT > 0.59 for jets with \( p_T < 60 \) GeV and \( |\eta| < 2.4 \).

**MuonCalibrationAndSmearingTool/ EgammaCalibrationAndSmearingTool/ JetCalibrationTool**: These tools are used to calibrate the MC objects (muons, electrons, and jets respectively) to ensure their agreement with data. The task is performed by recalculating
the energy and direction in the EM calorimeter with necessary corrections and then smearing the $p_T$ of the object. Default configuration is used in the MuonCalibrationAndSmearingTool. The recommendations for the EgammaCalibrationAndSmearingTool and JetCalibrationTool are given below:

<table>
<thead>
<tr>
<th>EgammaCalibrationAndSmearingTool</th>
<th>Property</th>
<th>Option</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESMModel</td>
<td>es2016data_mc15c</td>
<td></td>
</tr>
<tr>
<td>decorrelationModel</td>
<td>FULL_ETACORRELATED_v1</td>
<td></td>
</tr>
<tr>
<td>randomRunNumber</td>
<td>123456</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.2: Recommendations for EgammaCalibrationAndSmearingTool.

<table>
<thead>
<tr>
<th>JetCalibrationTool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Property</td>
</tr>
<tr>
<td>JetCollection</td>
</tr>
<tr>
<td>ConfigFile</td>
</tr>
<tr>
<td>CalibSequence</td>
</tr>
<tr>
<td>IsData</td>
</tr>
</tbody>
</table>

Table 4.3: Recommendations for JetCalibrationTool.

**MuonSelectionTool**: This tool selects good quality muons for physics analysis, based on eta cut, identification quality (i.e. Tight, Medium, Loose, VeryLoose corresponding to the values 0, 1, 2 and 3) and ID track requirements.

<table>
<thead>
<tr>
<th>MuonSelectionTool</th>
</tr>
</thead>
<tbody>
<tr>
<td>Property</td>
</tr>
<tr>
<td>MaxEta</td>
</tr>
<tr>
<td>MuQuality</td>
</tr>
</tbody>
</table>

Table 4.4: Recommendations for MuonSelectionTool.

**OverlapRemovalTool**: A tool that is in charge of discriminating between MC objects, when they can be mistakenly reconstructed as more than one type. The tool decides on which objects are best reconstructed and it removes the overlapping objects, to avoid their double counting. Since the object type is determined by reconstruction algorithms there is a small chance a jet to be identified as lepton, a muon to be identified as an electron and vice-versa.
**AsgElectronLikelihoodTool**: A tool used exclusively in electron object selection. It identifies the electrons depending on likelihood as loose, medium or tight and it is based on electromagnetic shower shapes, track qualities and track-cluster matching.

<table>
<thead>
<tr>
<th>Baseline</th>
<th>WorkingPoint</th>
<th>LooseBLLHElectron</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Z selection</th>
<th>WorkingPoint</th>
<th>MediumLHElectron</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>W selection</th>
<th>WorkingPoint</th>
<th>TightLHElectron</th>
</tr>
</thead>
<tbody>
<tr>
<td>ConfigFile</td>
<td>ElectronPhotonSelectorTools/offline/mc15_20160512/ ElectronLikelihoodTightOfflineConfig2016_Smooth.conf/</td>
<td></td>
</tr>
</tbody>
</table>

**Table 4.5**: Recommendations for AsgElectronLikelihoodTool.

**METMaker**: A tool to rebuild MET (Missing Transverse Momentum) based on the sum of the physics objects in the analysis.

<table>
<thead>
<tr>
<th>Property</th>
<th>Option</th>
</tr>
</thead>
<tbody>
<tr>
<td>DoMuonEloss</td>
<td>true</td>
</tr>
<tr>
<td>DoRemoveMuonJets</td>
<td>true</td>
</tr>
<tr>
<td>DoSetMuonJetEMScale</td>
<td>true</td>
</tr>
</tbody>
</table>

**Table 4.6**: Recommendations for METMaker tool.

**TrigDecisionTool**: A tool used to apply trigger selection criteria based on a user-defined chain group. The tool is used in the event selection and the trigger chain in this study is given in Table 6.1. Since TrigDecisionTool relies on meta-data (which is data about the data), another tool (xAODConfigTool) is declared on the “heap” to provide access to these meta-data.

**MCTruthClassifier**: A tool used subtly to classify the truth particles according with their origin. Based on the truth particle classification the tool provides classification of Inner Detector and combined muon tracks, egamma electrons (including forward electrons), egamma photons and jets. It provides access in truth information of Monte Carlo samples, allowing truth studies to check the efficiency rates of object reconstruction. The tool works with AOD or ESD formats.
Chapter 5

Object Selection and Reconstruction

This analysis is performed within the official ATLAS framework (Eventloop) using the release Analysis Base 2.4.29. The used calibration tools incorporate the latest scale factors for calibration, while correcting the MC selection efficiencies to match those in data, according to the recommendations of the ATLAS groups. The analysis uses STDM5 derivations of MC samples, where events with three leptons (e or \(\mu\)) are selected. In this section are described the selection criteria for all the physics objects used in the analysis, namely, electrons, muons, jets and \(E_T^{\text{miss}}\). The object selection procedure followed in this analysis is used to determine which objects make good candidates of particles originating from \(W^\pm Z\) boson pair production. It is possible, in addition to the standard object selection, that two or more reconstructed objects overlap in \(\eta - \phi\) space. In order address this problem only one object is considered real, while the other is rejected. The process is called overlap removal and is explained at the end of this section.

5.1 Lepton Selection

The lepton object selection is organised in three subsequent levels applied on top of each other. These levels are referred to as baseline selection, Z lepton selection and W lepton selection. Each stage is a tighter subset of the previous one, with stricter cuts applied. Therefore, all W leptons belong in the Z leptons subset, while both W and Z leptons are part of the baseline lepton subset. The only deviation
from that rule is noticed when electrons are reconstructed very close to muons and one of them should be removed in the overlap removal. In this case there are tighter requirements for baseline electrons than those for Z selected electrons. Since this only occurs in less than 0.5% of the total events, the rule that selections levels are strict subsets of each other will be assumed for simplicity.

The baseline selection criteria are optimised in order to support a fairly efficient veto to the events with four leptons. The majority of physics analyses suffer from fake-lepton background contamination, leading to tighter criteria for signal leptons defined by the Z and W lepton selections.

5.1.1 Muons

An essential role in muon reconstruction holds the combination of the information from the Inner Detector (ID) and Muon Spectrometer (MS). Muons also leave measurable energy deposits in the calorimeters, which are matched to the ID tracks. This matching can improve the detector’s acceptance for “blind” regions of the MS, namely for $|\eta| < 0.1$.

Muons are calibrated prior to the object selection. The three-level selection is summarised in Table 5.1. The exact selection criteria of each level are the optimised result from former analyses, which focused mostly on identification and isolation.

Muons in baseline selection have to surpass a $p_T$ threshold of $p_T > 7$ GeV, while remaining in the fiducial phase-space region of $|\eta| < 2.5$. Baseline muons should meet the Loose quality selection criteria, set by the MuonSelectionTool. At this level muons are associated with with the primary vertex, using ID tracks. The absolute value of transverse impact parameter significance has a threshold of $|d^{BL}_0/\sigma(d^{BL}_0)| < 3$, and the longitudinal impact parameter a threshold of $|\Delta z^{BL}_0 \sin \theta| < 0.5 \text{ mm}$. The calculation of the aforementioned impact parameters involves the information of the primary vertex and the track coordinates with respect to the positioning of the beam in the current event. Baseline muons should also satisfy the LooseTrackOnly isolation criteria, which corresponds to track isolation of $\text{ptvarcone20}/p_T < 0.15$ with 99% signal efficiency.

The Z selected muons have an increased $p_T$ threshold of $p_T > 15$ GeV, which is further increased to $p_T > 20$ GeV in the W selection. The Z selection also
requires Medium quality leptons and GradientLoose isolation, which combines calorimeter and track isolation information, namely topoetcone20 and $\frac{ptvarcone30}{p_T} < 0.1$, with an estimated signal efficiency of $\epsilon = (0.057 \cdot p_T \ [GeV] + 95.57)\%$, tuned for a targeted efficiency of 95% (99%) for $p_T = 25(60) \text{ GeV}$.

After the baseline selection a process called overlap removal is applied to Z and W selected muons. The OR provides a discrimination between prompt muons and those originating from hadronic decays in a jet. If a jet has more than or exactly 3 tracks and overlaps with a muon within an angular region of $\Delta R < 0.4$, the muon is removed.

<table>
<thead>
<tr>
<th>Selection</th>
<th>Baseline selection</th>
<th>Z selection</th>
<th>W selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T &gt; 7 \text{ GeV}$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>&lt; 2.5$</td>
<td>✓</td>
</tr>
<tr>
<td>Loose quality</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$</td>
<td>d_{0}^{BL}/\sigma(d_{0}^{BL})</td>
<td>&lt; 3$</td>
<td>✓</td>
</tr>
<tr>
<td>$</td>
<td>\Delta z_{0}^{BL} \sin \theta</td>
<td>&lt; 0.5 \text{ mm}$</td>
<td>✓</td>
</tr>
<tr>
<td>LooseTrackOnly isolation</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$p_T &gt; 15 \text{ GeV}$</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Medium quality</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>GradientLoose isolation</td>
<td>-</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$p_T &gt; 20 \text{ GeV}$</td>
<td>-</td>
<td>-</td>
<td>✓</td>
</tr>
</tbody>
</table>

Table 5.1: The three sequential levels of muon object selection.

### 5.1.2 Electrons

Electron reconstruction is based on the matching of ID tracks and significant energy deposits in the EC. Prior to ant object analysis the electrons are calibrated using the EgammaCalibrationAndSmearingTool, which applies corrections in electron $p_T$ as indicated by the associated ATLAS group. Three levels of electron object selection are applied and described in Table 5.2. The electron $p_T$ is calculated from the direction of ID tracks combined with the EC energy deposits, filling the missing coordinates of the electron four-vector.
Baseline electrons should have in principle a good object quality (OQ), meaning that electrons associated to clusters detected in malfunctioning high voltage regions are rejected from the analysis. Electrons at this level have a low $p_T$ threshold of $p_T > 7$ GeV and are reconstructed in the angular regions of $|\eta^{\text{cluster}}| < 2.47$ and $|\eta| < 2.5$. Baseline electrons should also satisfy the $\text{LooseLH+BLayer}$ identification criteria (require at least 1 hit in the IBL of the ID in addition to LH), with a targeted efficiency of 84 to 96% in the $p_T$ region of $10 < p_T < 80$ GeV. Another requirement for baseline selection is that electrons have to be associated with the originated vertex in order to allow the calculation of the transverse impact parameter and the longitudinal impact parameter. The significance of the former should satisfy the requirement $|d_{0}^{BL}/\sigma(d_{0}^{BL})| < 5$, while the latter is subjected to $|\Delta z_{0}^{BL} \sin \theta| < 0.5 \text{ mm}$. Both calculations are performed with respect to the beam position. The $\text{LooseTrackOnly}$ isolation WP is selected for baseline electron tracks, while an overlap removal procedure is performed for electron tracks that overlap with previously selected muon tracks.

<table>
<thead>
<tr>
<th>Electron Object Selection</th>
<th>Baseline selection</th>
<th>Z selection</th>
<th>W selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron object quality (OQ)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$p_T &gt; 7$ GeV</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$</td>
<td>\eta^{\text{cluster}}</td>
<td>&lt; 2.47,</td>
<td>\eta</td>
</tr>
<tr>
<td>LooseLH+BLayer identification</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$d_{0}^{BL}/\sigma(d_{0}^{BL}) &lt; 5$</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$</td>
<td>\Delta z_{0}^{BL} \sin \theta</td>
<td>&lt; 0.5 \text{ mm}$</td>
<td>✓</td>
</tr>
<tr>
<td>LooseTrackOnly isolation</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>e-to-µ Overlap Removal</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

| e-to-jets Overlap Removal | ✓ | ✓ | ✓ |
| $p_T > 15$ GeV | ✓ | ✓ | ✓ |
| Exclude 1.37 < $|\eta^{\text{cluster}}| < 1.52$ | ✓ | ✓ | ✓ |
| MediumLH identification | ✓ | ✓ | ✓ |
| GradientLoose isolation | ✓ | ✓ | ✓ |

| $p_T > 20$ GeV | ✓ | ✓ | ✓ |
| TightLH identification | ✓ | ✓ | ✓ |
| Gradient isolation | ✓ | ✓ | ✓ |

Table 5.2: The three sequential levels of electron object selection.

Z selection requires a threshold of $p_T > 15$ GeV for the $p_T$, which is applied to electrons that survive the e-to-jets OR (removes electrons within a cone of $0.2 < \Delta R < 0.4$ around the jet). Electrons in the EC crack region ($1.37 <$
$|\eta^{\text{cluster}}| < 1.52$) are removed, as the next step of Z selection. The exclusion is performed no earlier than Z selection, in order to increase ZZ background rejection that depends on the number of baseline electrons. MediumLH criteria are used for Z selection electron identification (efficiency: 72 to 93%), while GradientLoose WP is chosen for isolation, corresponding to $\epsilon = (0.057 \cdot p_T \ [GeV] + 95.57)\%$ for calo and track isolation, targeting an efficiency of 95% (99%) for $p_T = 25(60)$ GeV.

W selection for electrons is characterised by a requirement of $p_T > 20$ GeV. W electrons should satisfy the TightLH identification requirement (efficiency: 68 to 88%) and the Gradient isolation requirement, which corresponds to $\epsilon = (0.1143 \cdot p_T \ [GeV] + 92.14)\%$ for calo and track isolation, achieving efficiency of 90% (99%) for $p_T = 25(60)$ GeV.

5.2 Jets

Jet reconstruction is performed with the pre-defined anti-Kt algorithm from topological clusters (calorimeter) within a region of $\Delta R = 0.4$. Jets are required to pass the threshold of $p_T > 20$ GeV and $|\eta| < 4.5$. The pile-up and hard scatter jets are heavily suppressed by the JetJvtEfficiency tool by requiring the JVT output to be greater than 0.59 (Medium WP), for jets with $p_T < 60$ GeV and $|\eta| < 2.4$. The jets that survive are subjected to an OR, used to discard jets within $\Delta R < 0.2$ of a baseline electron. Jets are also removed when they consist of less than three tracks and are simulated within $\Delta R < 0.4$ of a baseline muon. Finally, the remaining jets should satisfy the requirement of $p_T > 25$ GeV.

<table>
<thead>
<tr>
<th>Jet Selection</th>
</tr>
</thead>
<tbody>
<tr>
<td>AntiKt4EMTopoJets</td>
</tr>
<tr>
<td>$p_T &gt; 20$ GeV</td>
</tr>
<tr>
<td>$</td>
</tr>
<tr>
<td>JVT &gt; 0.59 for jets with $p_T &lt; 60$ GeV, $</td>
</tr>
<tr>
<td>$p_T &gt; 25$ GeV</td>
</tr>
</tbody>
</table>

Table 5.3: Jet object selection.
5.3 Missing Transverse Energy

Missing transverse energy ($E_{\text{miss}}^T$), which is in fact missing transverse momentum, is a key observable used to reveal the presence of non-detectable physics objects. Large amounts of $E_{\text{miss}}^T$ are mostly attributed to the presence of neutrinos, while other complementary explanations suggest New Physics scenarios or the presence of particles falling outside the detector’s acceptance. In this study, the $E_{\text{miss}}^T$ amounts are most likely the outcome of $W$ boson decays, neglecting the number of neutrinos originating from $Z \rightarrow \nu \nu$ process due to the small cross-section.

Since the initial momentum of the colliding partons along the z direction is not known, momentum conservation can only be exploited using the projection of momentum to the transverse plane (x-y). This creates a momentum imbalance, thus $E_{\text{miss}}^T$ (or MET) is defined as the negative vector sum of the momentum of all the available objects in the event.

$$E_{\text{miss}}^T = - \sum_{\text{objects}} p_T$$  \hspace{1cm} (5.1)

The objects used are in principle calibrated electrons, muons, photons, taus, high-$p_T$ hadronic jets and soft-component particles, which are reconstructed from ID tracks starting from the primary vertex or clusters from the calorimeters that are not associated to previously reconstructed objects. $E_{\text{miss}}^T$ reconstruction is performed using the METMaker tool, with calibrated baseline leptons and jets. The calorimeter soft-term component suffers from large pile-up, leading to an extended use of track-based soft component that turned out to have a higher resolution. Muons have a special treatment in METMaker tool, as there is additional tracking information for them provided by Muon Spectrometer. The MET has already been reconstructed and stored in associated containers prior to this study. In fact, in the presented study, MET reconstruction corresponds to MET rebuilding, which is performed by accessing these containers.

Finally, the METMaker tool uses its own overlap removal, which is different from the one used in the object selection. This type of OR is set to prevent double counting of objects, since the information for MET reconstruction is provided from more than one parts of the detector (calorimeters, ID and MS). In order to perform
the OR more effectively, the tool requires only calibrated baseline electrons and muons as an input, along with calibrated jets prior to any selection.

Since the analysis is performed using copied objects (shallow copies of the original object containers), the object containers that are used by the METMaker tool should be linked to the original objects. This is performed by decorating the copy with an ElementLink, making the container available to the MissingETAssociationMap and enabling the proper use of the tool.

### 5.4 Summary of Overlap Removal

In this section is presented a brief synopsis of the ATLAS overlap removal procedure, which can be implemented either with the use of the AssociationUtils tool or using a standalone analysis code. The ATLAS OR is described below:

- A baseline electron is rejected if it shares the same ID track with a baseline muon.
- Jets are rejected if they are found in a region of $\Delta R < 0.2$ from a baseline electron and in a region of $\Delta R < 0.4$ from a baseline muon (only for jets with $<3$ tracks).
- A Z electron is rejected if its track is in a cone of $\Delta R < 0.4$ from a selected jet.
- A Z muon is rejected if its track is in a cone of $\Delta R < 0.4$ (only for jets with $\geq3$ tracks).

![Figure 5.1: A synopsis of the ATLAS overlap removal.](image-url)
Chapter 6

Event Selection

Event selection is the procedure after the object selection and is used to determine which are the interesting candidate events that involve $W^\pm Z$ boson pair production. Event selection is object selection dependent, since most of the decisions are based on the previously selected physics objects. It is performed in discrete steps that are summarised in Table 6.1.

The first task performed through the event selection is to ensure the correct operation of the detector during the recording of the events. This is done using the GoodRunsListSelectionTool and checking if the luminosity block of the events matches one from the Good Run List (GRL). Event cleaning is the following procedure, which is performed to ensure the correct recording of the data by requiring to pass the flags for LAr, Tile, SCT corrupted events and incomplete events. Events are then matched to a primary vertex that is associated with $\geq 2$ tracks. The three requirements explained above are applied both to data and simulated events. Nevertheless, these criteria should not affect the MC, since the majority of them is detector-based.

Events are required to pass certain trigger criteria that are topology dependent and slightly different for the years 2015 and 2016. In 2016, the increase in the instantaneous luminosity led to an increased threshold of 26 GeV for both electron and muon triggering. Events should fire at least one of the triggers from the menus described in Table 6.1. The lepton that passes the $Z$ selection and is reconstructed with the largest amount of transverse momentum compared to the other leptons in the container is known as the leading lepton. In order to satisfy the targeted trigger efficiency, the $p_T$ of leading lepton should surpass a threshold of 27 GeV.
The Z boson is reconstructed from Z lepton pair that is selected with the SFOC (Same Flavour Opposite Charge) algorithm, requiring the Z boson to be on-shell in a strict mass window of $|m_{ll} - m_Z| < 10$ GeV. In the case of more than one Z lepton pairs satisfying this requirement, the pair with combined mass $m_{ll}$ closest to the Z boson mass $M_Z$ is selected. Prior to the Z boson reconstruction it is required that the number of Z leptons should be equal to three.

<table>
<thead>
<tr>
<th>Event selection (inclusive PS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good Run List (GRL)\textsuperscript{t}</td>
</tr>
<tr>
<td>Event cleaning</td>
</tr>
<tr>
<td>Primary vertex</td>
</tr>
<tr>
<td>Jet cleaning</td>
</tr>
<tr>
<td>MC trigger (2015)</td>
</tr>
<tr>
<td>Data trigger (2015)</td>
</tr>
<tr>
<td>Trigger (2016)</td>
</tr>
<tr>
<td>Leading lepton $p_T$</td>
</tr>
<tr>
<td># of leptons</td>
</tr>
<tr>
<td>Z leptons</td>
</tr>
<tr>
<td>Mass window</td>
</tr>
<tr>
<td>W lepton</td>
</tr>
<tr>
<td>W transverse mass</td>
</tr>
<tr>
<td>ZZ veto</td>
</tr>
</tbody>
</table>

Table 6.1: Steps of the event selection in the inclusive PS.

If a W lepton exists in the event, W boson is reconstructed from this lepton and the corresponding neutrino, as explained in Section 7.1. Following W boson reconstruction, a threshold of $m^W_T > 30$ GeV is imposed for the W transverse mass. This requirement is the result of previous optimisation studies and is expected to provide better discrimination between signal and background events, while improving the agreement between data and MC simulations. The W transverse mass is defined according to the latest recommendations as

$$m^W_T = \sqrt{2p_T E_{Tmiss} (1 - \cos \Delta \phi)}$$  \hspace{1cm} (6.1)

Another event selection cut is required to restrict signal contamination from ZZ processes, one of the largest WZ backgrounds. This requirement is known as “ZZ veto” and is used to reject the events with $\geq 4$ baseline leptons. Providing that the above requirements are fulfilled, the WZ candidate events are determined and WZ reconstruction is performed from the selected leptons.
Chapter 7

W±Z Analysis Results

7.1 W Boson and W±Z Di-boson Reconstruction

W Boson is reconstructed from a charged lepton that passes the W selection and a corresponding neutrino. The x, y and E components of the neutrino four-vector are filled with the information of the $E_T^{miss}$ taken from the associated MET container, using the METMaker tool. This possible by exploiting the simplification that electroweak interaction is not affected by the virtual particle of the intermediate state. Since missing transverse momentum is measured only in transverse plane, there is still an ambiguity about the third component of the neutrino’s momentum. In order to resolve this ambiguity up to some point, one should solve the complete energy-momentum equation $E^2 = P^2 + M^2$ with respect to $p_z$. The solution is described below:

\[
m_W^2 = p_W^0 p_{\mu} = (p_l^0 + p_{\nu}) (p_l^\mu + p_{\nu}\mu) \\
m_W^2 = p_l^0 + p_{\nu}^0 + 2(E_l E_{\nu} - \vec{p}_l \cdot \vec{p}_\nu) \\
m_W^2 = 2 \left[ \sqrt{p_{T,l}^2 + p_{z,l}^2} \sqrt{p_{T,\nu}^2 + p_{z,\nu}^2} - \vec{p}_{T,l} \cdot \vec{p}_{T,\nu} - p_{z,l} p_{z,\nu} \right] \\
\left[ (m_W^2 + 2 \vec{p}_{T,l} \cdot \vec{p}_{T,\nu}) + 2p_{z,l} p_{z,\nu} \right]^2 = 4(p_{T,l}^2 + p_{z,l}^2)(p_{T,\nu}^2 + p_{z,\nu}^2) \\
X^2 + 4Xp_{z,l}p_{z,\nu} + 4p_{T,l}^2 p_{z,\nu}^2 = 4 \left[ p_{T,l}^2 p_{z,\nu}^2 + p_{T,\nu}^2 (p_{T,l}^2 + p_{z,l}^2) \right] + 4p_{z,l}^2 p_{z,\nu}^2 \\
4p_{T,l}^2 p_{z,\nu}^2 - 4Xp_{z,l}p_{z,\nu} + \left[ 4p_{T,\nu}^2 (p_{T,l}^2 + p_{z,l}^2) - X^2 \right] = 0 \\
p_{T,l}^2 p_{z,\nu}^2 - Xp_{z,l}p_{z,\nu} + \left[ p_{T,\nu}^2 (p_{T,l}^2 + p_{z,l}^2) - \frac{X^2}{4} \right] = 0
\]
The quadrature equation is solved with respect to the longitudinal component $p_{z,\nu}$ using the corresponding formula:

$$p_{z,\nu} = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \tag{7.2}$$

where

$$a = p_{T,l}^2$$

$$b = -X \ p_{z,l} = -2p_{z,l} \left( \vec{p}_{T,l} \cdot \vec{p}_{T,\nu} + \frac{m_W^2}{2} \right)$$

$$c = p_{T,\nu}^2 (p_{T,l}^2 + p_{z,l}^2) - \frac{X^2}{4}$$

$$= (p_{x,\nu}^2 + p_{y,\nu}^2) E_l^2 - \left( \frac{p_{x,l} \ p_{x,\nu} + p_{y,l} \ p_{y,\nu}}{2} \right)^2$$

$$p_{T,l} = \sqrt{p_{x,l}^2 + p_{y,l}^2}$$

$$E_l = \sqrt{p_{T,l}^2 + p_{z,l}^2}$$

The immediate conclusion from Eq. 7.1 is that two solutions exist for $p_{z,\nu}$. If $\Delta = b^2 - 4ac \geq 0$, the solutions are both real and the one with the smaller magnitude is selected. In the case of no real solutions, the imaginary part of the solution with the smaller (complex) magnitude is removed and only the real part is kept. In order to solve the equation, the mass of the W boson is kept constant and equal to the PDG value ($m_W^{PDG} = 80.385 \text{ GeV}$).

Previous studies searched for better options about choosing the right solution for $p_{z,\nu}$. One of these studies proposed that the two $p_{z,\nu}$ solutions should be selected randomly, with an equal probability, since the favoring of the solutions depending on the magnitude can distort the shape of the angular distributions. However, the selection of solutions with the smaller magnitude offers a better agreement with the truth MC in the analysis, thus the equal-probability approach is not followed in this study.

Other studies proposed replacing the PDG mass of W boson with other alternatives, such as the transverse mass $m_W^T$. The replacement led to some spikes in the shapes of the distribution and therefore, it was rejected.
Finally, in similar analysis the events are removed if there are complex solutions for the \( p_{z,\nu} \), namely if \( \Delta < 0 \). This approach would not be feasible in this study due to the frequent occurrence of such events. In fact, the percentage of the appearance of complex solutions for \( p_{z,\nu} \) is calculated to be 35.47\%, which justifies the need to keep the events.

The distribution of the reconstructed W boson mass is given in Fig. 7.1. The events in the large peak represent the events with real solutions \( p_{z,\nu} \), while in the rest of the events the solutions for \( p_{z,\nu} \) are complex.

![Figure 7.1: Distribution of the reconstructed W boson mass \( m_W \).](image)

Following the W boson reconstruction, the four-vector of the WZ system is created by the vector sum of the TLorentzVectors of the Z and W bosons. The WZ transverse mass is defined with respect to the final state W and Z leptons and the \( E_T^{\text{miss}} \), as shown below

\[
    m_T^{WZ} = \sqrt{\left( \sum_{l=1}^{3} p_T^l + E_T^{\text{miss}} \right)^2 - \left( \sum_{l=1}^{3} p_x^l + E_x^{\text{miss}} \right)^2 - \left( \sum_{l=1}^{3} p_y^l + E_y^{\text{miss}} \right)^2}
\]  

(7.4)


## 7.2 Cutflow Analysis

Starting from the analysis file in the EventLoop framework, the cutflow analysis for $W^\pm Z$ boson pair production is performed. In this section is described the decrease in the number of physics objects after being rejected for not passing the required selection criteria. The number shown in the following tables represents the physics objects that survived the selection.

### Table 7.1: Electron cutflow analysis.

<table>
<thead>
<tr>
<th>Selection</th>
<th>Number of electrons</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Baseline</strong></td>
<td></td>
</tr>
<tr>
<td>Electron OQ</td>
<td>310507</td>
</tr>
<tr>
<td>$p_T &gt; 7$ GeV</td>
<td>129645</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>Loose quality</td>
<td>62223</td>
</tr>
<tr>
<td>$</td>
<td>d_0^{BL}/\sigma(d_0^{BL})</td>
</tr>
<tr>
<td>$</td>
<td>\Delta z_0^{BL}\sin \theta</td>
</tr>
<tr>
<td>LooseTrackOnly isolation</td>
<td>57777</td>
</tr>
<tr>
<td><strong>Z Selection</strong></td>
<td></td>
</tr>
<tr>
<td>$p_T &gt; 15$ GeV</td>
<td>44933</td>
</tr>
<tr>
<td>Exclude 1.37 &lt; $</td>
<td>\eta</td>
</tr>
<tr>
<td>Medium quality</td>
<td>40813</td>
</tr>
<tr>
<td>GradientLoose isolation</td>
<td>39557</td>
</tr>
<tr>
<td><strong>W Selection</strong></td>
<td></td>
</tr>
<tr>
<td>$p_T &gt; 20$ GeV</td>
<td>34167</td>
</tr>
<tr>
<td>Tight quality</td>
<td>32035</td>
</tr>
<tr>
<td>Gradient isolation</td>
<td>31488</td>
</tr>
</tbody>
</table>

### Table 7.2: Muon cutflow analysis.

<table>
<thead>
<tr>
<th>Selection</th>
<th>Number of muons</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Baseline</strong></td>
<td></td>
</tr>
<tr>
<td>$p_T &gt; 7$ GeV</td>
<td>89552</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
</tr>
<tr>
<td>Loose quality</td>
<td>69567</td>
</tr>
<tr>
<td>$</td>
<td>d_0^{BL}/\sigma(d_0^{BL})</td>
</tr>
<tr>
<td>$</td>
<td>\Delta z_0^{BL}\sin \theta</td>
</tr>
<tr>
<td>LooseTrackOnly isolation</td>
<td>64280</td>
</tr>
<tr>
<td><strong>Z Selection</strong></td>
<td></td>
</tr>
<tr>
<td>$p_T &gt; 15$ GeV</td>
<td>48968</td>
</tr>
<tr>
<td>Medium quality</td>
<td>48201</td>
</tr>
<tr>
<td>GradientLoose isolation</td>
<td>45842</td>
</tr>
<tr>
<td><strong>W Selection</strong></td>
<td></td>
</tr>
<tr>
<td>$p_T &gt; 20$ GeV</td>
<td>39213</td>
</tr>
</tbody>
</table>


The sequential selections and the cutflow analysis results for leptons are shown in Tables 7.1 and 7.2, where good electron and muon candidates are selected respectively. In Table 7.3 is described the treatment of jets in the analysis, while all object selections are combined to be used in the event selection. The number of the selected \(W^\pm Z\) event candidates is presented in Table 7.4. The interesting events are divided in categories according to the topology, namely the leptonic channel in which the event is reconstructed. This type of categorisation is summarised in Table 7.5.

<table>
<thead>
<tr>
<th>Selection</th>
<th>Number of jets</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total jets</td>
<td>645622</td>
</tr>
<tr>
<td>(</td>
<td>\eta</td>
</tr>
<tr>
<td>(p_T &gt; 20 \text{ GeV})</td>
<td>439555</td>
</tr>
<tr>
<td>JVT &gt; 0.59 (for jets with (p_T &lt; 60 \text{ GeV}), (</td>
<td>\eta</td>
</tr>
<tr>
<td>Overlap Removal</td>
<td>212148</td>
</tr>
<tr>
<td>(p_T &gt; 25 \text{ GeV})</td>
<td>135640</td>
</tr>
</tbody>
</table>

**Table 7.3: Jet cutflow analysis.**

<table>
<thead>
<tr>
<th>Selection</th>
<th>Number of events</th>
</tr>
</thead>
<tbody>
<tr>
<td>Good Run List (GRL)</td>
<td>120000</td>
</tr>
<tr>
<td>Error flags (event cleaning, LAr, Tile, SCT, incomplete events)</td>
<td>120000</td>
</tr>
<tr>
<td>Primary vertex</td>
<td>120000</td>
</tr>
<tr>
<td>Jet cleaning (jets with (p_T &gt; 20 \text{ GeV}))</td>
<td>119512</td>
</tr>
<tr>
<td>Pass triggers</td>
<td>41082</td>
</tr>
<tr>
<td>At least one Z selected lepton</td>
<td>38858</td>
</tr>
<tr>
<td>(p_T^{\text{leading}} &gt; 27 \text{ GeV})</td>
<td>37009</td>
</tr>
<tr>
<td>(</td>
<td>m_{ll} - m_Z</td>
</tr>
<tr>
<td>(p_T^W &gt; 20 \text{ GeV})</td>
<td>4072</td>
</tr>
<tr>
<td>Tight and isolated W lepton</td>
<td>3921</td>
</tr>
<tr>
<td>(m_T^W &gt; 30 \text{ GeV})</td>
<td>3282</td>
</tr>
<tr>
<td>ZZ veto</td>
<td>3277</td>
</tr>
</tbody>
</table>

**Table 7.4: Event level cutflow analysis.**
7.3 Electron and Muon Distributions

Electrons and muons are studied in detail after the object selection. In general, the number of good reconstructed muon candidates is greater than the one for good electron candidates. In the ATLAS detector, tracking and ID efficiency is better for muons compared to electrons and that can explain the difference between the results. The difference in muon and electron number can be justified by taking into consideration the restrictions imposed from phase-space kinematic criteria.

<table>
<thead>
<tr>
<th>Channel</th>
<th>Events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$ee\mu$</td>
<td>658</td>
</tr>
<tr>
<td>$e\mu\mu$</td>
<td>782</td>
</tr>
<tr>
<td>$\mu ee$</td>
<td>815</td>
</tr>
<tr>
<td>$\mu\mu\mu$</td>
<td>1022</td>
</tr>
<tr>
<td>All</td>
<td>3277</td>
</tr>
</tbody>
</table>

Table 7.5: Summary of the event yields from the MC sample.

A comparison between electrons and positrons is performed in terms of their transverse momentum distributions. The same comparison is tried for muons and antimuons. Muon-antimuon $p_T$ distribution has a better-formed peak at approximately 25 GeV compared to electron peaks. In both electron and muon case, the
presence of positively charged leptons is stronger than the presence of negatively charged leptons, as expected (Section 2.2). The most significant discrepancy is observed in the number of events inhabiting the peak of the distribution at low energies, while the lepton numbers equalise at higher energies.

Figure 7.3: Distributions of the transverse momentum of positively and negatively charged muons after the object selection.

Figure 7.4: Distributions of the transverse momentum of electrons and positrons after the object selection.
### 7.4 Control Plots of Kinematic Observables

Figure 7.5: Plots of kinematic observables of Z and W bosons and $E_T^{\text{miss}}$ of the event.
In this section the distributions of several observables are studied in detail. The purpose of that is to ensure an agreement in the distribution shapes between the results of this study and the official published results. A good agreement is observed between the shapes of all the distributions, validating the results of this analysis. The distributions of each variable are shown in Fig.7.5. Most of the observables used in the analysis can be used to check the agreement between simulated events and data or even in optimisation studies for signal discrimination. Therefore, the variables can be referred to as “control variables”.

For the same reasons, the shapes of the distributions of the variables describing the $W^\pm Z$ boson pair are studied. The distributions of the most interesting observables are shown in Fig.7.6.

![Plots of transverse and invariant mass of the reconstructed $W^\pm Z$ boson pair.](image_url)

**Figure 7.6:** Plots of transverse and invariant mass of the reconstructed $W^\pm Z$ boson pair.

In this analysis, the invariant mass of the three-lepton system is studied. The system is reconstructed by the vector sum of the Z boson four-vector and the four-vector of the lepton, which is attributed to the W boson. The invariant mass distribution of the system peaks at $\sim 140$ GeV and is shown both for the total events and for each channel separately to account for possible topology-dependent changes in the shape of the distribution (Fig.7.7).
Figure 7.7: Invariant mass distributions of the three-lepton system.
The distributions of certain variables can be exploited to provide information about the W charge asymmetry observed in $W^{\pm}$ boson decays. The phenomenon is briefly described in Section 2.2.1. The dominance of positively charged leptons through $W^{\pm}Z$ boson pair production can be observed directly from the discrepancy in the number of muons-antimuons and electrons-positrons contained in the signal events. A similar observation is made through the comparison of the number of events containing a reconstructed positively charged W boson to the number of events containing a negatively charged W boson. The comparison is performed by using variables that either describe the reconstructed W boson or the $W^{\pm}Z$ system, which can unveil hidden correlations owning to the simultaneous Z boson production. However, such types of correlation have not been observed yet.

Since the number of events is proportional to the cross-section, considering equal luminosity, the $W^+/W^-$ ratio is a direct indicator of the $\sigma^{NLO}(W^+Z)/\sigma^{NLO}(W^-Z)$ ratio. This ratio seems to be in good agreement with the theoretical prediction, as shown in Fig. 7.8. The experimental value of $W^+/W^-$ ratio in this analysis is estimated to

$$\frac{N_{W^+Z}}{N_{W^-Z}} = 1.49 \pm 0.02$$

(7.5)

Figure 7.8: Distributions of observables describing the reconstructed W boson and the $W^{\pm}Z$ system. The $W^+/W^-$ ratio is shown.
7.6 Association to MC Truth

The truth information about the physics objects of the generated events is stored in containers of the class type xAOD::TruthParticleContainer. The containers can be accessed with ordinary C++ commands, making use of pre-defined variables, regarding kinematics and origin, provided by the MCTruthClassifier tool. In order to meet the needs of this study, truth leptons (electrons and muons) of the selected events are being retrieved.

7.6.1 Lepton Misassignment Probability

Following the object selection the selected leptons are attributed to Z or W bosons using the algorithms described in the event selection. The algorithms depend on the object selection kinematic and angular criteria combined with information from the Inner Detector, calorimeters, etc. In this way, the Z and W gauge bosons are reconstructed and are subjected to the event selection criteria, which consist of tighter cuts and restrictions. A direct impact of the sequential steps of the object selection is that Z selected leptons also contain all of the leptons, which will be attributed to a W boson candidate. Therefore, there is a probability to choose the “wrong” lepton, namely that leptons originating from a W boson are “mistakenly” attributed to a Z boson during the boson reconstruction. Lepton misassignment is observed in $e\!e\!e$ and $\mu\mu\mu$ channels. In the case of $e\!\mu\!\mu$ and $\mu\!e\!e$ channels there are only two same flavour leptons in the event and the lepton matching becomes a straightforward task.

In order to calculate the misassignment probability a link of the reconstructed leptons to the MC truth leptons is required. The link is settled during the object selection through the MET rebuilding procedure (Section 5.3). In the event selection and prior to the W boson reconstruction, a reconstructed Z lepton is required to match a physics object at truth level. An additional requirement is that the truth particle (to which the reco lepton is matched) should be a secondary particle originating from a decay and not directly from the primary vertex of the event. If the generated version of the lepton originates from a generated Z boson, the reconstructed lepton is counted as “correctly assigned”. In the opposite case the reconstructed lepton is counted as “misassigned”.

W$^\pm$Z Analysis Results
The total misassignment probability is calculated as the ratio of the misassigned Z leptons over the sum of the correctly assigned and misassigned Z leptons. The same calculation is performed in the $ee e$ and $\mu\mu\mu$ channels separately in order to extract the misassignment probability for each topology. The number of the correctly assigned and misassigned leptons, as well as the corresponding probabilities are summarised in Table 7.6.

It comes out that the misassignment probability is greater for the electron channel than for the muon channel, leading to a combined probability of 3.132 % for both channels. The discrepancy can be explained by considering the different energy-loss mechanisms of the two leptonic flavours. Electrons lose their energy faster and in many ways, reaching the EM calorimeter with only a fraction of their initial energy. Therefore, it is possible that a W lepton could lose larger amount of energy than the one expected, and be mistaken for a Z lepton, while at the same time a Z lepton of the event has enough energy left to surpass the W selection criteria.

<table>
<thead>
<tr>
<th>Channel</th>
<th>$ee e$</th>
<th>$\mu\mu\mu$</th>
<th>All</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z$ lepton type</td>
<td>$e_{misass}$</td>
<td>$\mu_{misass}$</td>
<td>$(e + \mu)_{misass}$</td>
</tr>
<tr>
<td># of leptons</td>
<td>53</td>
<td>1314</td>
<td>52</td>
</tr>
<tr>
<td>misassignment probability (%)</td>
<td>4.033</td>
<td>2.552</td>
<td>3.132</td>
</tr>
</tbody>
</table>

**Table 7.6:** Lepton-to-boson misassignment probability at the truth level for $ee e$ and $\mu\mu\mu$ channels separately, as well as for the combination of them.

The enumerator used to associate a particle to a $Z$ boson decay is named $\text{truthO-}\text{rigin}$ and is assigned with the value 13, as indicated in the corresponding h-file of the MCTruthClassifier class

```
https://svnweb.cern.ch/trac/atlasoff/browser/PhysicsAnalysis/MCTruthClassifier/trunk/MCTruthClassifier/MCTruthClassifierDefs.h
```

The reconstructed leptons are decorated with their $\text{truthO-}\text{rigin}$ through the object selection ($Z$ selection). However, reconstructed muons require a special treatment in order to be correctly matched to the generated particles and provide an acceptable value of their origin. This is achieved by imposing additional angular and tracking criteria using a function of the ATLAS WZ group, called $\text{getMuonTruth}$. One of the returning outputs of the function is the origin of the muon, which is used to discriminate between correctly and misassigned muons.
7.6.2 Distributions of $p_{T,\text{gen}}^l$ and $p_{T,\text{reco}}^l$

In this section the agreement between the kinematics of the generated and the reconstructed leptons is studied. The transverse momentum of the reconstructed leptons is in principle different from the transverse momentum of the leptons at generated level, since the calibration process intercedes between the two levels. Although not exactly equal, the two amounts of transverse momentum are in general close to each other within some limits. This agreement is shown in Fig. 7.9, where there is a comparison of the transverse momentum between reconstructed and simulated leptons, attributed to a Z or a W boson respectively. At low values of $p_T$ a better agreement is observed, while at high $p_T$ values there is a lack of statistics, as expected. Due to the small ambiguity in the transverse momentum of the electrons and muons, the kinematics of these particles are well-defined. The same assumption does not apply to neutrinos, where the ambiguity in the third component of the momentum greatly affects the agreement between the reconstructed and truth level particles.

![Figure 7.9: Comparison of transverse momentum distributions between reconstructed and MC truth leptons, attributed to a Z or a W boson respectively.](image)

For the above plots only calibrated reconstructed leptons (reco.) and dressed leptons at the truth level (gen.) are used. The number of events is summed in each row separately and the entries of each bin are normalised to the total number of events (per row). A color gradient and text values of the ratio are used for aesthetics and better understanding.
Chapter 8

W±Z Polarisation Measurements

The W± and Z0 bosons are the mediators of the weak interaction. These massive spin-1 vector bosons are allowed to have three polarisation states (-1, 0, +1). The zero state is longitudinal and the rest are transverse. The occurrence of three possible states is a result of imposing the Lorenz condition, which reduces the degrees of freedom of a vector from four to three. The condition is

\[ \epsilon^\mu p_\mu = 0 \quad (8.1) \]

where \( \epsilon^\mu \) is the polarisation vector and \( p^\mu \) is the momentum vector. Meanwhile, massless photons are allowed to have only two polarisation states, which are both transverse. In this case, Coulomb gauge

\[ \epsilon^0 = 0 \quad (8.2) \]

is imposed on top of the Lorenz gauge, further reducing the degrees of freedom from three to two, exhausting the longitudinal state.

Since the spin of W and Z bosons has a preferred direction, the concept of helicity is introduced to offer a physical meaning to that preference. Helicity \( h \) is defined as the projection of the spin \( S \) to the direction of the particle’s momentum \( \vec{p} \)

\[ h = \frac{\vec{S} \cdot \vec{p}}{|p|} \quad (8.3) \]

A first result of this definition is that helicity is not Lorentz-invariant. This conclusion can be reached either by considering Lorentz boosts along the direction
of the momentum or using an inertial frame that moves faster than the particle. However, the Lorentz invariance of the helicity holds for massless particles, since these particles move with the speed of light.

According to the helicity definition, in the case of the $h = 1$ state the helicity is called right-handed (RH) and the spin vector is parallel to the direction of the boson. In the case of $h = -1$ the spin vector is anti-parallel to the boson’s direction of motion and the state is called left-handed (LH). Finally, the characteristic of the $h = 0$ polarisation state is that the spin vector is vertical to the boson direction axis and the state is referred to as longitudinal.

A schematic representation of the polarisation for the $W^-$ boson is shown in Fig.8.1. Due to the chiral symmetry of the QED, a W boson couples only to LH particles and RH anti-particles. Therefore, a $W^-$ boson couples to a negatively charged LH lepton and a RH anti-neutrino. In the W boson’s rest frame, the produced lepton is most probable to escape in the direction of the spin for a $W^+$ boson and in the opposite direction for a $W^-$ boson. The spin of $W^-$ boson points along the z-axis in the RH helicity case, resulting in large $\theta_{l,W}^*$ decay angles. If the helicity is left-handed, small angles are expected. In the case of longitudinal polarisation, $\theta_{l,W}^*$ is expected to be $\theta_{l,W}^* \approx \pi/2$ rads.

In the diagrams of the $W^+$ boson case, the direction of the charged lepton is inverted, compared with the $W^-$ case, since a $W^+$ boson couples to a possitively charged RH lepton and a LH neutrino. A direct result is that the plots of the $(1 + \cos \theta)^2$ and $(1 - \cos \theta)^2$ distributions are also inverted between the two transverse polarisation states, along with the red arrows of the decay particles that denote the spin-alignment (for all the states).

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig8.1.png}
\caption{The three polarisation states of the $W^-$ boson and the $\cos \theta$ dependence for each state (explained in Eq.8.4.)}
\end{figure}
8.1 Polarisation Observables

An interesting observable directly related to the polarisation of the W and Z boson is known as $\cos \theta_{l,W(Z)}$. In order to make use of this variable, a definition of the angle $\theta_{l,W(Z)}$ should be sought. The angle $\theta_{l,W(Z)}$ is defined as the angle of negatively (positively for $W^+$) charged leptons produced in the decay of a W(Z) boson as seen in the W(Z) rest frame with respect to the direction of the WZ centre-of-mass frame [2]. The definition of these angles is presented in Fig.8.2. Therefore, the reconstruction of the $\cos \theta_{l,V}$ variable requires the reconstruction of the W and Z bosons, which is performed in the Event Selection. The charged leptons originating from boson decays are boosted back to the rest frame of W and Z boson. After that the reconstructed W and Z bosons are boosted back to the rest frame of the WZ boson pair. The $\theta_{l,V}$ angle is calculated as the angle between the boosted lepton and the boosted W or Z boson.

![Figure 8.2: Definitions of the $\theta_{l,V}$ angles, which are used in angular variables (e.g. $\cos \theta^*$). The particles shown in red (upper right side) are boosted along the direction of the $W^\pm$ boson, while the particles shown in blue (lower left side) are boosted along the direction of the $Z^\pm$ boson. The W and Z bosons are boosted back to the WZ centre-of-mass frame.](image)

The resolution on $\cos \theta_{l,V}$ variable suffers from the inability to measure the third component of the neutrino’s momentum $p_z$. The lack of this information negatively affects the resolution on $\cos \theta_{l,Z}$ in an indirect way, since it is associated to the initial direction of the WZ system. On the other hand, the resolution on $\cos \theta_{l,W}$ is directly affected as the reconstructed neutrino four-vector is used not only in the
W boson reconstruction, but also in the reconstructed WZ boson pair. As a result, the uncertainty is larger due to the use of both four-vectors in the Lorentz boosts. A solution to tackle the poor resolution on $\cos \theta_{l,W}^*$ is to introduce another variable that corresponds to the projection of the former variable to the transverse plane. This variable is referred to as $\cos \theta_{ZD}^*$ and is built by using only the transverse components of the charged lepton’s four-vector. It was first introduced for the W boson, though it can be used for the Z boson as well in order to protect against the bias originating from neutrino’s reconstruction.

The $\cos \theta^*$ distributions of this study are shown in Fig.8.3. Concerning the $\cos \theta_{l,Z}^*$ distributions, only the angle of the negatively charged lepton attributed to the Z boson is used.

**Figure 8.3:** Distributions of the angular observable $\cos \theta_{l,V}^*$ for the Z and W boson, using reconstructed MC signal events.
The distributions of $\cos \theta_{l,V}^*$ are dependent on the centre-of-mass energy $\sqrt{s}$ and can be distorted if stricter kinematic criteria are used in the selection process. Possible shape distortions can be avoided by studying the dependence of the $\cos \theta_{l,V}^*$ variable on the kinematic variables, starting from the transverse momentum of the lepton attributed to the W or Z boson. This dependence is depicted in Fig. 8.4, where the lepton’s $p_T$ is used in the laboratory frame. A strong dependence of the $\cos \theta_{l,V}^*$ variable on the transverse momentum of the charged lepton can be seen.

Figure 8.4: Correlation between transverse momentum and $\cos \theta^*$. The upper left plot corresponds to the lepton originating from a W boson. The upper right plot corresponds to the neutrino, associated with a W boson. The lower plot corresponds to negatively charged lepton, attributed to a Z boson. The $p_T$ is used in the laboratory frame, prior to any boost.

Particularly, in the Z boson case and for low $p_T$ values ($p_T^{l,Z} < 40$ GeV), large values of $|\cos \theta_{l,Z}^*|$ are observed. The region of $|\cos \theta_{l,Z}^*| = \pm 1$ is more populated and this is translated into a dominance of the transverse states for low $p_T$, since large values of $|\cos \theta_{l,Z}^*|$ correspond to decay angles close to $\theta_Z^* = 0$ or $\theta_Z^* = \pi$ rads. The decay angles close to $\theta_{l,Z}^* = \pi/2$ rads correspond to the longitudinal polarisation state, which seems to be suppressed for $15 < p_T^{l,Z} < 30$ GeV.
Similarly, in the W boson case the corresponding distributions indicate a strong dependence on the transverse momentum of the charged lepton. The \( \cos \theta_{l,W}^* \) distribution is not symmetrical around zero, in contrast to the \( \cos \theta_{l,Z}^* \) distribution. In the regions of low transverse momentum of the W-lepton (\( p_{T}^{l,W} < 30 \text{ GeV} \)), the distribution shows a peak close to \( \cos \theta_{l,W}^* = -1 \). Moving to higher \( p_T \) regions the maximum is shifted to larger values of \( \cos \theta_{l,W}^* \). If the \( p_T \) threshold is increased in the object selection, a reduction of events around \( \cos \theta_{l,W}^* = -1 \) is anticipated. The \( \cos \theta_{\nu,W}^* \) distribution shows a peak close to \( \cos \theta_{\nu,W}^* = +1 \), which is shifted to lower values of \( \cos \theta_{\nu,W}^* \) for higher \( p_T \) regions (\( p_{T}^{\nu,W} < 60 \text{ GeV} \)). As a result, it seems that applying further cuts at the \( p_{T}^{\nu,W} \) or the \( E_{T}^{miss} \) can distort the region around \( \cos \theta_{\nu,W}^* = +1 \) and it would be a good choice not to apply any of these cuts.

### 8.2 Polarisation Angular Distributions

The physical information on the boson production and decay is complemented by studying the differential distributions of the cross section. These relations of the differential distributions unveil the dependence of an initial particle’s helicity on the angular distributions of the produced particles after the decay. The differential cross sections for polarised Z and W boson production depend on the decay angle \( \theta_{l,V}^* \) and can be expressed in terms of the diagonal elements of the Spin Density Matrix (SDM).

The angular differential distribution with respect to \( \cos \theta_{l,V}^* \) for the \( W^\pm \) boson is

\[
\frac{1}{\sigma_{W^\pm Z}} \frac{d\sigma_{W^\pm Z}}{d\cos \theta_{l,W}^*} = \frac{3}{8}(1 \mp \cos \theta_{l,W}^*)^2 f_L + \frac{3}{8}(1 \pm \cos \theta_{l,W}^*)^2 f_R + \frac{3}{4} \sin^2 \theta_{l,W}^* f_0 \tag{8.4}
\]

where \( f_L, f_R \) and \( f_0 \) are the polarisation fractions that correspond to the helicity states of -1,+1 and 0 respectively. The RH and LH polarisation states are inverted for \( W^+ \) and \( W^- \) bosons and that also applies to the corresponding distributions of \( \cos \theta^* \).

The angular differential distribution for the Z boson is affected by its additional coupling to RH fermions and is given below
\[ \frac{1}{\sigma_{W^\pm Z}} \frac{d\sigma_{W^\pm Z}}{d\cos\theta_{l,Z}^*} = \frac{3}{8} (1 + 2A \cos \theta_{l,Z}^* + \cos^2 \theta_{l,Z}^*) f_L \\
+ \frac{3}{8} (1 - 2A \cos \theta_{l,Z}^* + \cos^2 \theta_{l,Z}^*) f_R + \frac{3}{4} \sin^2 \theta_{l,Z}^* f_0 \]  

(8.5)

where \( A = \frac{2c_v c_a}{c_v^2 + c_a^2} = 0.14885 \) and \( c_v, c_a \) are the vector-axial vector couplings of the \( Z \) boson to fermions. Assuming that the \( Z \) boson only couples to \( e \) and \( \mu \), the \( c_v \) and \( c_a \) couplings are given in terms of the weak mixing angle \( \theta_W \)

\[ c_v = -\frac{1}{2} + 2 \sin^2 \theta_W = -0.03742, \quad c_a = -\frac{1}{2} \]  

(8.6)

using \( \sin^2 \theta_W = 0.23146 \pm 0.00012 \), deduced from the latest measurements.

**Figure 8.5:** Cross-section differential distributions over \( \cos \theta^* \) for the three polarisation states of the \( W^\pm \) and \( Z \) boson.
If all $W^\pm$ and $Z$ bosons could be produced in a certain polarisation state, the shapes of the normalised distributions would resemble the ones shown in Fig.8.5.

In the case that the centre-of-mass energy is negligible ($\sqrt{s} \ll m_Z$) the couplings of the $Z$ boson to fermions would be the same for LH and RH polarisation states and the angular distribution would have the symmetric form of $(1 + \cos^2 \theta)$, which indicates a pure QED process with a photon propagator. At higher energies ($\sqrt{s} >> m_Z$) there is strong interference between QED and the weak interaction through the exchange of a $Z$ boson, as the strengths of the photon and $Z$ boson couplings become comparable. The V-A structure of the weak interaction manifests itself in an inequality between the couplings to left- and right-handed states ($c_L$ and $c_R$), resulting to differences in vector-axial vector couplings. The differences are interpreted as different probabilities for the four helicity combinations of the decay products, causing an asymmetry around zero in the $\cos \theta^*$ distribution.

### 8.3 Polarisation Fractions at Truth Level

The analytical expressions of the angular distributions of the boson production cross-section (Eq.8.4-8.5) suggest that the total differential distribution in the experiment is expected to be a mixture of the three possible polarisation states. A first glance at the differential $\cos \theta^*$ distributions is given in the associated MC simulations. In order to figure out to what extent each helicity combination is observed, an analytical fit is performed. The analytical expressions are fitted to the actual $\cos \theta^*$ distributions at the truth level in the total phase-space. The full MC signal sample is used for the fit, due to the great need for increased statistics and low uncertainties.

One of the fit requirements is that the three polarisation fractions should satisfy the relation $f_L + f_R + f_0 = 1$. Therefore, only two of these fractions are independent and the third one is calculated from the other two. The selected parameters for the fit are the longitudinal polarisation fraction $f_0$ and the combination of the transverse fractions $f_L - f_R$. Given that the theoretical distributions (Eq.8.4-8.5) are normalised to the total cross-section, the total number of events ($N_{tot}$) should be fitted as well. This is the last parameter of the fit.

Prior to the fit the equations 8.4 and 8.5 are parametrised with respect to the parameters of the fit. The parametrisation is described in detail in Appendix A,
resulting to the form

$$\frac{dN_{W^\pm Z}}{d \cos \theta^*_{l,W}} = \frac{3}{8} N_{tot} \left[ (1 - 3 \cos^2 \theta^*_{l,W}) f_0 + 2 \cos \theta^*_{l,W} (f_L - f_R) + 1 + \cos^2 \theta^*_{l,W} \right] \quad (8.7)$$

for the $W^\pm$ boson and the form

$$\frac{dN_{W^\pm Z}}{d \cos \theta^*_{l,Z}} = \frac{3}{8} N_{tot} \left[ (1 - 3 \cos^2 \theta^*_{l,Z}) f_0 + 0.2977 \cos \theta^*_{l,Z} (f_L - f_R) + 1 + \cos^2 \theta^*_{l,Z} \right] \quad (8.8)$$

for the $Z$ boson.

The $\cos \theta^*_{l,V}$ variables are reconstructed using the MC truth information of the full sample to fill the four-vectors of the boson decay products, in a way similar to the one described in Section 7.1. The bosons are reconstructed from their decay products and after reconstruction a series of boosts is performed, as explained in Section 8.1. The fit results and the corresponding distributions for the polarisation of the $W^\pm$ and $Z$ boson are shown in Fig.8.6.

**Figure 8.6**: Polarisation fractions at truth level in the total PS for the $W^\pm$ boson in association with a $Z$ boson (upper plots) and for the $Z$ boson in association with a $W^\pm$ boson (bottom plots), extracted using analytical fit.
Following the analytical fit, the fitted parameters \( f_0 \) and \( f_L - f_R \) are used to calculate the transverse polarisation fractions \( f_L \) and \( f_R \). The corresponding relations are

\[
f_L = \frac{1 - f_0 + (f_L - f_R)}{2}, \quad f_R = \frac{1 - f_0 - (f_L - f_R)}{2}
\] (8.9)

The uncertainty on \( f_0 \) is estimated by the fit, in contrast with the uncertainties on \( f_L \) and \( f_R \) that are calculated using error propagation. Therefore, the uncertainties on the transverse polarisation fractions are

\[
\delta f_L = \sqrt{\frac{\delta f_0^2 + \delta (f_L - f_R)^2 - \text{cov}(f_0, f_L - f_R)}{2}}, \quad \delta f_R = \sqrt{\frac{\delta f_0^2 + \delta (f_L - f_R)^2 + \text{cov}(f_0, f_L - f_R)}{2}}
\] (8.10)

The angular differential distributions shown in Fig.8.6 can be further analysed based on the shape and amplitude of each polarisation state. A notable observation on these distributions is that the longitudinal state is strongly suppressed, as the associated polarisation fraction \( f_0 \) takes low values in all cases. This is expected from the kinematics of the \( W^\pm Z \) boson production at very high energies. The majority of the bosons are produced in the high-\( \eta \) region, resulting in small decay angles \( \theta^*_V \) for their decay products. Consequently, the produced boson is less likely to be longitudinally polarised. Of course in lepton-\( p_T \) regions of \( 30 < p_T < 70 \) GeV, longitudinal polarisation dominates (Fig.8.4), since the quarks that actively participated in the interaction were carrying only a small fraction of the proton’s total energy. In particular, in the W boson case the longitudinal polarisation state is possible at regions of high transverse momentum, following a more complicated production mechanism that is also connected to the mass of the mediated gauge boson. The longitudinal polarisation although suppressed by the conservation of spin is conditionally allowed due to the non-zero mass of the decay products of the W boson.

Another notable comment on the amplitudes of the polarisation fractions is that \( W^- \) boson shows a slight preference for RH helicity, while \( W^+ \) boson seems to prefer LH helicity. This forward-backward asymmetry is greater in the \( W^+ \) boson case, owing to the W charge asymmetry that gives an edge to the production of antimatter over matter. The preference of the W boson concerning its polarisation state impacts the polarisation of the Z boson that is produced simultaneously to the W boson. Therefore, the Z bosons produced in association with a W boson show a tendency to the opposite transverse polarisation state of the W boson.
Particularly, a Z boson in a $W^−Z$ event prefers the LH polarisation and a Z boson in a $W^+Z$ event orients itself mostly to RH polarisation. Except of the shape of the distributions, this observation is supported by the extracted polarisation fractions themselves that are summarised in Table 8.1.

<table>
<thead>
<tr>
<th>Total PS</th>
<th>Analytical Fit</th>
<th>$W^±$ boson in $W^±Z$ events</th>
<th>$Z$ boson in $W^±Z$ events</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$W^−Z$</td>
<td>$W^+Z$</td>
</tr>
<tr>
<td>$f_0$</td>
<td></td>
<td>0.229 ± 0.0014</td>
<td>0.213 ± 0.0014</td>
</tr>
<tr>
<td>$f_L$</td>
<td></td>
<td>0.358 ± 0.0008</td>
<td>0.502 ± 0.0038</td>
</tr>
<tr>
<td>$f_R$</td>
<td></td>
<td>0.411 ± 0.0009</td>
<td>0.284 ± 0.0037</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.219 ± 0.0011</td>
<td>0.211 ± 0.0011</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.440 ± 0.0007</td>
<td>0.318 ± 0.0029</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.340 ± 0.0006</td>
<td>0.470 ± 0.0029</td>
</tr>
</tbody>
</table>

Table 8.1: Summary of $W^±$ and Z polarisation fractions extracted by performing an analytical fit on the angular distributions at truth level.

The polarisation fractions of the boson production are dependent to the energy $\sqrt{s}$ at the centre-of-mass. Taking a closer look at the corresponding total angular distributions of this analysis at $\sqrt{s} = 13$ TeV, we see a non-symmetrical “dip” forming around zero. The dip moves leftwards, as the centre-of-mass energy is increased, while it can also vanish or transformed into a peak for certain values of $\sqrt{s}$ (in the region $180 < \sqrt{s} < 300$ GeV, as described in [22]).

A further comment on the polarisation fractions and $\cos \theta^*$ distributions is that some discrepancies show up between inclusive fiducial PS and the total PS [5], owing to the increased sensitivity of $\cos \theta^*$ distribution on the kinematic variables. In the inclusive fiducial PS the measurement capabilities of the detector are restricted in the angular region $|\eta| < 2.5$, thus the events in the very forward region are not included. This explains the shape distortions around $\cos \theta_{l,V}^* = ±1$. Nevertheless, a fairly good agreement is observed between the fractions extracted from data and those extracted from MC simulated events.
Chapter 9

Conclusion

Since the circulation of the first beams inside the LHC, a large number of experiments has been designed to test the theory of Standard Model. In this dissertation, the $W^\pm Z$ boson pair production studied through its fully-leptonic $W^\pm Z \rightarrow l\nu ll$ final states, where $l$ refers to a positively or negatively charged electron ($e$) or muon ($\mu$) and $\nu$ refers to a neutrino (or antineutrino). Although neutrinos are also leptons, their orbit cannot be reconstructed and the decay channels are identified by the electrons and muons participating in the event, namely $eee$, $e\mu\mu$, $\mu ee$ and $\mu\mu\mu$. The study of the $W^\pm Z$ boson pair constitutes a fine test of the electroweak sector of the Standard Model. It is an excellent probe for New Physics, which could manifest as a modification of the known couplings between bosons (TGC and QGC). Furthermore, a wide range of conclusions can be extracted from the polarisation of the $W^\pm$ and $Z$ bosons regarding the gauge structure of the SM and the electroweak symmetry breaking mechanism.

The main analysis is based on a part of the full MC signal sample, produced with Powheg+Pythia8 to simulate the data taken at an integrated luminosity of 36.1 fb$^{-1}$ during the running period of 2015+2016 at a centre-of-mass energy of $\sqrt{s} = 13$ TeV with the ATLAS detector. The production of the simulated events corresponds to a cross-section of 4.5092 pb. Concerning the $W^\pm Z$ di-boson polarisation studies, the full MC signal sample is used. The analysis is performed in the EventLoop framework (RootCore), the official ATLAS framework on lxplus. The tools and the recommendations used in the study are provided by the associated groups and are described in detail in Chapter 4.
The leading purpose of this work is to “clean” the $W^\pm Z$ signal sample, in order to keep only the interesting events, namely the ones that are associated with a $W^\pm Z$ boson pair production. This task is achieved by implementing a number of angular and kinematic criteria to the products of the boson decay in the inclusive fiducial phase-space. The process is referred to as cutflow analysis and consists of two parts: the object selection and the event selection. In the object selection a series of sequential requirements are imposed to the analysis physics objects (electrons, muons, jets). The $W$- and $Z$-lepton candidates are selected with the intention to be used in the $W$ and $Z$ boson reconstruction. For the $W$ boson reconstruction, the information on the associated neutrino kinematics originates from the calculation of the event’s missing transverse momentum, and it is therefore restricted to the transverse plane (x-y). The ambiguity on the third component of the neutrino’s momentum is resolved at some point by requiring that the $W$ boson should be always produced on-shell with a mass equal to its PDG value ($m_{W}^{PDG} = 80.35$ GeV). The total ambiguity is reduced in a two-fold ambiguity as there are two possible solutions for $p_{T}^\nu$. Only one of the solutions is chosen and the neutrino four-vector is reconstructed. The $W$ and $Z$ boson reconstruction is performed from their decay products in the event selection, where additional quality and phase-space criteria are implemented. The $W^\pm Z$ boson event candidates are selected and the corresponding physics objects are stored. The cutflow procedure is explained in Chapters 5 and 6, and the results are presented in Chapter 7.

A special treatment is required regarding the $E_T^{miss}$ variable. The missing transverse momentum of each event is rebuilded by the associated MET containers, taking into consideration the physics objects that participate in the event in order to calculate the negative sum of the transverse momentum. The objects used in the MET rebuilding were calibrated baseline electrons and muons, and calibrated jets prior to any selection. Due the use of copied object in the analysis, a link to the original objects is required that allows the proper function of a separate overlap removal used in MET reconstruction.

The results of this analysis are validated through a series of control plots on kinematic and angular variables. From these plots, many conclusions can be drawn and an opportunity for further studies is given. Owing to the presence of the $W$ boson, the $W$ charge asymmetry can be studied. As shown in Fig.7.8, the production of $W^+ Z$ events is favored over $W^- Z$ events. The calculation of this ratio for the MC sample is rather trivial, involving a division of the integrals for the
corresponding distributions. The ratio is found to be: $N_{W^+Z}/N_{W^-Z} = 1.49\pm0.02$, a value that lies inside the uncertainty boundaries of the experimental result and is a direct indicator of the cross-section ratio $\sigma_{W^+Z}/\sigma_{W^-Z}$.

A wide range of equally important studies can come up, if a link is created between the reconstructed objects and their generated version at truth level. The truth information is accessed in this study using certain variables offered by the MCTruthClassifier tool. This information is provided only by some event generators and since POWHEG+PYTHIA8 is one of them, its MC samples contain a TruthParticleContainer with the kinematics of the generated particles.
Appendix A

Parametrisation of the Angular Differential Distributions

A parametrisation of the angular differential distribution of the cross-section is used in this study, in order to make the analytical fit possible.

The complete parametrisation for the W$^\pm$ boson is

$$
\frac{1}{\sigma_{W^\pm Z}} \frac{d\sigma_{W^\pm Z}}{d\cos \theta^*} = \frac{3}{8} (1 \pm \cos \theta^*)^2 f_L + \frac{3}{8} (1 \pm \cos \theta^*)^2 f_R + \frac{3}{4} \sin^2 \theta^* f_0 \\
= \frac{3}{8} [(1 + \cos^2 \theta^*) (f_L + f_R) \mp 2 \cos \theta^* (f_L - f_R) + 2 f_0 \sin^2 \theta^*] \\
= \frac{3}{8} [(1 + \cos^2 \theta^*) (1 - f_0) + \mp 2 \cos \theta^* (f_L - f_R) + 2 (1 - \cos^2 \theta^*) f_0] \\
= \frac{3}{8} [(1 + \cos^2 \theta^*) - (1 + \cos^2 \theta^*) f_0 \mp 2 \cos \theta^* (f_L - f_R) + (2 - 2 \cos^2 \theta^*) f_0] \\
= \frac{3}{8} [(1 + \cos^2 \theta^*) \mp 2 \cos \theta^* (f_L - f_R) + (2 - 2 \cos^2 \theta^* - 1 - \cos^2 \theta^*) f_0] \\
= \frac{3}{8} [(1 - 3 \cos^2 \theta^*) f_0 \mp 2 \cos \theta^* (f_L - f_R) + 1 + \cos^2 \theta^*] \\
$$

$$
\frac{dN_{W^\pm Z}}{d\cos \theta^*_{l,W}} = \frac{3}{8} N_{tot} [(1 - 3 \cos^2 \theta^*_{l,W}) f_0 \mp 2 \cos \theta^*_{l,W} (f_L - f_R) + 1 + \cos^2 \theta^*_{l,W}] \\
(A.1)
$$
Similarly, the parametrisation for the Z boson is

\[
\frac{1}{\sigma_{W^\pm Z}} \frac{d\sigma_{W^\pm Z}}{d\cos\theta^*} = \frac{3}{8}(1 + 2A \cos\theta^* + \cos^2\theta^*)f_L \\
+ \frac{3}{8}(1 - 2A \cos\theta^* + \cos^2\theta^*)f_R + \frac{3}{4}\sin^2\theta^*f_0
\]

\[
= \frac{3}{8}\left[(1 + \cos^2\theta^*)(f_L + f_R) + 2A \cos\theta^*(f_L - f_R) + 2f_0 \sin^2\theta^*\right]
\]

\[
= \frac{3}{8}\left[(1 + \cos^2\theta^*)(1 - f_0) + 2A \cos\theta^*(f_L - f_R) + 2(1 - \cos^2\theta^*)f_0\right]
\]

\[
= \frac{3}{8}\left[(1 + \cos^2\theta^*) - (1 + \cos^2\theta^*)f_0 + 2A \cos\theta^*(f_L - f_R) + (2 - 2 \cos^2\theta^*)f_0\right]
\]

\[
= \frac{3}{8}\left[(1 + \cos^2\theta^*) + 2A \cos\theta^*(f_L - f_R) + (2 - 2 \cos^2\theta^* - 1 - \cos^2\theta^*)f_0\right]
\]

\[
= \frac{3}{8}\left[(1 - 3 \cos^2\theta^*)f_0 + 2A \cos\theta^*(f_L - f_R) + 1 + \cos^2\theta^*\right]
\]

\[
\frac{dN_{W^\pm Z}}{d\cos\theta^*_{l,Z}} = \frac{3}{8}N_{tot}\left[(1 - 3 \cos^2\theta^*_{l,Z})f_0 + 0.2977 \cos\theta^*_{l,Z}(f_L - f_R) + 1 + \cos^2\theta^*_{l,Z}\right]
\]

(A.2)
Bibliography


