
The First Measurement of the Differential
Cross-Section of Electroweak $W^{\pm}W^{\pm}jj$ Production
at 13 TeV with the ATLAS Detector



SHALU SOLOMON

A dissertation submitted to

Albert-Ludwigs-Universität Freiburg

in partial fulfillment of the requirements for the degree of

Doctor rerum naturalium

October, 2022

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Dean

Prof. Dr. Michael Thoss

Supervisor

Prof. Dr. Beate Heinemann

Date of defense: 13.01.2023

Defense examiners

Prof. Dr. Beate Heinemann

Prof. Dr. Gregor Herten

JProf. Dr. Stefan Vogl

Dissertation examiners

Prof. Dr. Beate Heinemann

Prof. Dr. Karl Jakobs

Dekan

Prof. Dr. Michael Thoss

Betreuer der Arbeit

Prof. Dr. Beate Heinemann

Datum der mündlichen Prüfung: 13.01.2023

Prüfer

Prof. Dr. Beate Heinemann

Prof. Dr. Gregor Herten

JProf. Dr. Stefan Vogl

Gutachter

Prof. Dr. Beate Heinemann

Prof. Dr. Karl Jakobs

“It is the glory of God to conceal things but the glory of kings is to search things out.”

Proverbs 25:2

To my mother for always believing in me.

Acknowledgements

Completing this project has been an incredibly enriching endeavor, and it wouldn't have been possible without the help and support of many. Not all of you are listed here, but I am deeply grateful for each one of you.

First, I would like to express my sincere gratitude to my supervisor, Beate Heinemann, for being truly inspirational. Your drive and excitement for physics have certainly rubbed off on me. Thank you for giving me excellent supervision, teaching me how to think, providing me opportunities to grow both as a student and as a researcher, and always taking the time to simply chat with me about my future when I needed it. You have molded me in so many ways, and I cannot thank you enough!

Secondly, to my second supervisor, Christian Weiser, for regularly meeting with me, tracking the progress of my work until its completion, and making my teaching experience wonderful. To my technical supervisor on the New Small Wheel project, the late Stephanie Zimmermann, for giving me the first opportunity to work on a hardware task. You convinced me over a single coffee to work with you, and I am grateful for the great experience you gave me. You are very much missed.

A big thank you to my postdoctoral supervisor, Oleg Kuprash, without whom, I would not have made it this far. You have shown me an incredible amount of patience and kindness, which I am forever grateful for. Thank you for teaching me how to do data analysis, for all the long discussions, and for all your insights.

To the same-sign *WW* analysis group for being a wonderful team to work with. To the members of the Heinemann Freiburg-ATLAS group, especially José and Prasham, for making my time at the university memorable. Also, to the entire Herten's group for being simply great. I cannot forget you, Thorwald, for making the hardware experience a real fun one. Thank you for being so supportive even after leaving academia. Many thanks to Stathis for adopting me into the hardware work in Stephanie's absence, ensuring I had the supervision I needed, and always having my back!

To Mathieu Pellen for keeping the doors open anytime, I was puzzled by theory. To Valerie Lang for all the wonderful conversations, we shared over coffee and lunches. Thank you for helping me in so many ways and being there whenever I needed it. To Heather Russell for igniting my passion for particle physics and for all the great tips and advice that have helped me in the past years.

To my family, without whom, this thesis would clearly not have been possible. I am forever indebted to my mother, Jancy Solomon, for always believing in me and loving me immensely. I have a million reasons to thank you. Many thanks to my brother, Sharath Solomon, for coming to my rescue every time my code crashed when I did not know how to code. Our long phone calls about the usual sibling stuff certainly always cheered me up. My deep gratitude to Carlo Parisi and Mirella Facchini for giving me a home in Montreal. You have been my biggest encouragement and strength to keep moving forward. Thank you for making me feel loved even with the distance and paying attention to the slightest detail of my life.

To all my friends, special mention to Christeena, Anne, Nancy, Philipp, Steph, Pragya, and Shreya for all the laughter, fun, and memories we shared.

Lastly, to Julian Gronewald for your love and everything you mean in my life. You have given me an incredible amount of support and always made sure I was smiling at the end of a difficult day. Thank you for cooking almost all my meals while I was writing and for everything though words are not enough to express my gratitude. I look forward to our life together in Geneva.

The first measurement of the differential cross-section of electroweak $W^\pm W^\pm jj$ production at 13 TeV with the ATLAS detector

Shalu Solomon

Abstract

Vector boson scattering is one of the recent remarkable observations at the Large Hadron Collider. The longitudinal polarization modes of the massive vector bosons are strongly tied to the electroweak symmetry breaking mechanism. With the Standard Model predicted Higgs boson playing a crucial role in regularizing the scattering amplitude of these longitudinally polarized bosons, vector boson scattering is a pivotal process in experimentally probing the symmetry breaking mechanism. A golden channel for measuring vector boson scattering at the collider is the electroweak production of two W bosons with the same electric charges. Owing to its largest quark- to gluon-induced production ratio among other di-boson combinations, the process was also the first target of the ATLAS vector boson scattering program, with evidence made in 2014 and observation in 2019. This thesis presents the first measurement of the differential cross-section with the ATLAS experiment at $\sqrt{s} = 13$ TeV using 139 fb^{-1} datasets of proton-proton collisions.

The process is studied in the leptonic decay channels of the W bosons, effectively suppressing many Standard Model backgrounds. The process $pp \rightarrow l^\pm \nu l^\pm \nu jj$ is measured with the final state consisting of two leptons of like charges, two jets, and missing transverse energy. The characteristic vector boson scattering signature of two tagging jets, with a large di-jet invariant mass, separated by large angles, is used to tag electroweak-induced production. A combination of Monte Carlo-based predictions and data-driven approaches is used to estimate the various backgrounds. A statistical model of profile likelihood is used to constrain the background predictions and reduce the uncertainties following which the events are unfolded, and the cross-section is extracted. The fiducial differential cross-sections are measured in the leptonic channel as a function of several kinematic variables and are found to be consistent with the Standard Model predictions within uncertainties. An experimental precision of 10.2% is achieved for the fiducial cross-section, and the measurement is unprecedented in precision and granularity for the process. The integrated fiducial cross-section is $3.51 \pm 0.27 (\text{stat}) \pm 0.23 (\text{syst}) \text{ fb}$ and agrees with the leading order prediction of $2.97^{+0.28}_{-0.24} \text{ fb}$ simulated by MadGraph+Herwig7 within uncertainties.

Die erste Messung des differentiellen Wirkungsquerschnitts der elektroschwachen $W^\pm W^\pm jj$ -Produktion bei 13 TeV mit dem ATLAS-Detektor

Shalu Solomon

Zusammenfassung

Die Streuung von Vektorbosonen ist eine der jüngsten bemerkenswerten Beobachtungen am Large Hadron Collider. Die longitudinalen Polarisationsmodi der massiven Vektorbosonen sind eng mit dem Mechanismus der elektroschwachen Symmetriebrechung verknüpft. Da das im Standardmodell vorhergesagte Higgs-Boson eine entscheidende Rolle bei der Regulierung der Streuungsamplitude dieser longitudinal polarisierten Bosonen spielt, ist die Vektorboson-Streuung ein zentraler Prozess bei der experimentellen Untersuchung des Symmetriebrechungs-Mechanismus. Die elektroschwache Produktion von zwei W -Bosonen mit der gleichen elektrischen Ladung ist ein goldener Kanal für die Messung der Vektorboson-Streuung am Beschleuniger. Aufgrund seines größten Quark-zu-Gluon-induzierten Produktionsverhältnisses im Vergleich zu anderen Di-Boson-Kombinationen war dieser Prozess auch das erste Ziel des ATLAS-Vektorboson-Streuprogramms mit Nachweis im Jahr 2014 und Beobachtung im Jahr 2019. Diese Arbeit präsentiert die erste Messung des differentiellen Wirkungsquerschnitts mit dem ATLAS-Experiment bei $\sqrt{s} = 13 \text{ TeV}$ unter Verwendung von 139 fb^{-1} Datensätze von Proton-Proton-Kollisionen.

Der Prozess wird in den leptonischen Zerfallskanälen der W -Bosonen untersucht, wobei viele Standardmodell-Untergründe effektiv unterdrückt werden. Der Prozess $pp \rightarrow l^\pm \nu l^\pm \nu jj$ wird mit dem Endzustand gemessen, der aus zwei Leptonen gleicher Ladung, zwei Jets und fehlender transversaler Energie besteht. Die charakteristische Vektor-Bosonen-Streusignatur von zwei Jets mit großer invarianter Di-Jet-Masse, die durch große Winkel getrennt sind, wird verwendet, um die elektroschwach induzierte Produktion zu identifizieren. Eine Kombination aus Monte-Carlo-basierten Vorhersagen und datengesteuerten Ansätzen wird verwendet, um die verschiedenen Untergründe abzuschätzen. Eine Profile-Likelihood Methode wird verwendet, um die Hintergrundvorhersagen einzuschränken und die Unsicherheiten zu reduzieren, woraufhin die Ereignisse entgefaltet und die Wirkungsquerschnitte extrahiert werden. Die fiduziellen differentiellen Wirkungsquerschnitte werden im leptonischen Kanal als Funktion mehrerer kinematischer Variablen gemessen und stimmen mit den Vorhersagen des Standardmodells innerhalb der Unsicherheiten überein. Für den fiduziellen Wirkungsquerschnitt wird eine experimentelle Präzision von 10,2% erreicht, und die Messung ist in Bezug auf Präzision und Granularität für diesen Prozess innerhalb der Unsicherheiten beispiellos. Der integrierte Wirkungsquerschnitt beträgt $3.51 \pm 0.27 \text{ (stat)} \pm 0.23 \text{ (syst)} \text{ fb}$ und stimmt mit der Vorhersage führender Ordnung von $2.97^{+0.28}_{-0.24} \text{ fb}$ überein, die von MadGraph+Herwig7 berechnet wurde.

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Now I'm going to discuss how we would look for a new law. In general, we look for a new law by the following process. First, we guess it. No, don't laugh, that's the truth. Then we compute the consequences of the guess, to see what, if this is right, if this law we guess is right, to see what it would imply and then we compare the computation results to nature or we say compare to experiment or experience, compare it directly with observations to see if it works.

If it disagrees with experiment, it's wrong. In that simple statement is the key to science. It doesn't make any difference how beautiful your guess is, it doesn't matter how smart you are who made the guess, or what his name is . . . If it disagrees with experiment, it's wrong. That's all there is to it!

Richard Feynman

Preface

Experimentation is an objective way of exploring the universe with increasing detail every time. Knowingly or unknowingly, each time we are one step ahead in our experience, understanding, and perception. The job is rather simple. You take a theory and you test it. The theoretical reasonings shed light on what to look for in experiments. But without experimental results, one will never know the truth¹! In the course, new avenues, ideas, and questions are formed. And when you think you have found a solution, a door to a newer set of questions and perception of reality opens and the cycle continues resulting in more guided pathways. And the curiosity that drives you to still walk those paths is the very essence that makes us humans.

Though the task sounds rather easy, the journey isn't. This is one such journey spanning over three years where not all the days were "Eureka" moments but a constant process of experimenting and tweaking, experimenting and tweaking again. Sometimes the first trial turned out to be correct but sometimes the 50th trial was still wrong but not a failure for I learnt 50 ways of how not to do it.

The work in this thesis aims to present an advancement, however slight, in the scientific progress of understanding the genesis of the universe.

¹or what we perceive to be the truth.

Chapter 1

Introduction

About half a century ago, with tremendous collaborative efforts from both the theoretical and the experimental communities, a scientifically stunning piece of work known as the *Standard Model* (SM) was developed. It became so widely accepted that it was called “the standard model” and still is, and describes the fundamental structure and framework of the universe. The universe as we know it is governed by four forces namely gravity, strong force, weak force, and electromagnetic force. The Standard Model addresses all but gravity and their interactions with all the elementary particles discovered to date.

To better understand the bigger picture, let us start with the beginning of the universe. As best we can tell, the Big Bang marks the birth of the universe as an extremely hot and dense point in space about 13.7 billion years ago. In the evolution of the universe, the closest we reach in its chronology is the Planck epoch at 10^{-43} s since the origin with energies over $\mathcal{O}^{19}$ GeV. All the four forces are believed to be forged into a single unified force at this scale where the current known laws of physics do not apply. The end of the epoch is marked by a *phase transition* or *symmetry breaking* with gravity separating itself from the unified force as the universe cooled, and as it cooled further, the strong force separated, resulting in a unified electroweak force apart from the other two. Through a subsequent phase transition known as the electroweak symmetry breaking at $\mathcal{O}^2$ GeV, the electroweak force is realized as two separate forces, the weak force and the electromagnetic force, leaving the universe with the four fundamental forces we observe today. The weak force is mediated by the W and the Z bosons, which are massive in nature, while the electromagnetic force is mediated by the photons, which are massless. One of the key predictions of the Standard Model is that the weak gauge bosons acquire their mass through the process of symmetry breaking and if so, a scalar particle must accompany the mechanism.

The state-of-the-art technology facilitating the experimental reach of such energy scales to search for this particle is the Large Hadron Collider (LHC), located at the European Organization of Nuclear Research (CERN) in Geneva. Adorned as an engineering marvel, this hadron collider is the world’s largest and most powerful accelerator machine that smashes hadrons, mainly protons, at extremely high energies, re-creating the early conditions of the universe. The proton beams are accelerated to nearly the speed of light and are then collided at a center of mass energy of 13 TeV, which is the largest ever reached in a laboratory. The energy released in these collisions materializes in the form of new particles like quarks, leptons, gluons, or even massive bosons.

The LHC collides protons at four main points along its accelerator ring, where huge detectors are housed to detect the particles produced. The ATLAS and the CMS detectors are two such gigantic detectors that act like huge cameras capturing almost all the particles formed from the

high energy collisions. In 2012, the LHC culminated the 40 year long search for the elusive scalar particle with the discovery of the Higgs boson ($m_H = 125 \text{ GeV}$) in both ATLAS and CMS.

The discovery was momentous in the history of the LHC and confirmed the existence of the Higgs field in nature to which the particles couple and acquire mass. With the last piece of the puzzle found, the Standard Model is deemed complete but leaves no explanations for some of the observed phenomena, as a result of which many models beyond the Standard Model have been hypothesized, often generally referred to as new physics. New physics at the LHC is explored by searching for new particles or by rigorously testing the Standard Model to investigate any deviations of the parameters from the SM predictions. A promising subject in understanding the origin of the Higgs particle and probing hints for new physics is the self-interactions of the electroweak gauge bosons, also known as vector boson scattering (VBS). At the LHC, VBS occurs when the incoming quarks in the colliding protons radiate the gauge bosons, which subsequently interact leaving distinct experimental signatures. The process is marked by two jets separated by large angles in the detector and is one of the rarest, occurring once in hundreds of trillions of proton collisions. With the discovery of the Higgs boson, VBS has garnered much attention from the scientific community for several reasons. First, the nature of mass acquisition of the weak bosons is inextricably linked to the symmetry breaking mechanism. Second, the Higgs particle is pivotal to VBS as without it, unitarity is violated in the scattering amplitude of longitudinally polarized electroweak bosons. The SM predicts a light Higgs with mass less than 1 TeV for the exact cancellations of the divergences, thereby regularizing the scattering amplitude. If the mechanism of symmetry breaking differs even slightly from the SM predictions, the cross-sections of the VBS processes will be altered. Third, VBS can provide insight into gauge couplings. Prior to the LHC, only the triple gauge couplings and quartic gauge couplings involving photons were studied at the Large Electron Positron collider. But VBS at the LHC can throw light on quartic gauge interactions involving massive bosons and explore sensitivity to new physics by probing anomalous quartic gauge couplings. With all its prospects, VBS is undoubtedly of paramount importance to unravel the mysteries of nature in the LHC era.

A golden channel characterizing VBS is the scattering of two W bosons with the same electric charge in their lepton decay modes, $pp \rightarrow W^\pm W^\pm jj \rightarrow l^\pm \nu l^\pm \nu jj$. Apart from the clean experimental signatures of the leptons in the detector, the process is unique as the combination of the gauge bosons suppresses the several background processes with oppositely charged leptons which VBS typically suffers from otherwise. Furthermore, the production of the process from pure electroweak interactions is enhanced over strong interaction compared to any other di-boson combinations. Additionally, an excess with respect to SM predictions could suggest a new doubly charged resonance.

The process was the first target of the ATLAS Collaboration to study VBS with evidence reported in 2014 at 8 TeV. The observation of the process later in 2018 by CMS and in 2019 by ATLAS at 13 TeV was a milestone in the LHC physics program. This dissertation presents the first differential cross-section measurement of this process from the ATLAS Collaboration at 13 TeV. The contents of the document are structured as follows: A brief introduction to the theoretical foundations is given in Chapter 2, followed by a description of the experimental apparatus, the LHC and the ATLAS detector, in Chapter 3. In 2022, a new detector has been added to the ATLAS experiment, which is described briefly in Chapter 4. Chapter 5 presents an overview of vector boson scattering at the LHC, including a detailed explanation of the motivation to study the scattering of W bosons, and Chapter 6 discusses the experimental tools required for the same. The analysis methodology begins in Chapter 7 with the key objectives and workflow highlighted. In Chapters 8 and 9, the data and the simulated samples employed in the analysis and criteria for identifying the signal are detailed. Backgrounds are estimated in Chapters 10 and 11, and

in Chapter 12, the uncertainties associated with the measurement are discussed along with the methodology to extract the signal. Chapter 13 describes the unfolding procedure implemented for comparisons with the theory predictions. Finally, the results of the measurement are presented in Chapter 14, with a brief summary and outlook on future prospects in Chapter 15. The author's contributions to the measurement are clearly stated in the relevant chapters of this dissertation and are also summarized after the final chapter.

Chapter 2

Theory

This chapter introduces the theoretical foundation of the experimental measurement presented in this thesis. The chapter begins with a description of the Standard Model in Section 2.1 along with the particle content, mathematical formalism, and shortcomings of the model. The theory of proton-proton collisions relevant to LHC physics is explained in Section 2.2, and finally, vector boson scattering, the main topic covered in this thesis, is introduced briefly in Section 2.3.

2.1 The Standard Model of Particle Physics

The ordinary matter in the universe is made up of a small number of fundamental particles governed by the four forces of nature: gravitational, electromagnetic, weak, and strong forces. Our current best understanding of the phenomenology of particle physics is condensed into a theoretical framework called the *Standard Model* (SM) [1]–[3], which beautifully describes the fundamental constituents of matter and all the associated interactions except gravity¹. In the SM, the fundamental particles that make up the matter are *fermions*, with an intrinsic spin $\frac{1}{2}$. The *force carriers*, which mediate an interaction between the matter particles, are *bosons* with an intrinsic spin 1. Fermions can possess different *charge* quantum numbers which determine the type of their associated interactions (e.g color charge, hypercharge, weak isospin). A summary of the SM constituents is shown in Figure 2.1.

2.1.1 Introduction

The Standard Model is a renormalizable gauge quantum field theory. The underlying gauge symmetry of the SM is a product of three unitary Lie groups,

$$\underbrace{SU(3)_C}_{strong} \otimes \underbrace{SU(2)_L \otimes U(1)_Y}_{electroweak}. \quad (2.1)$$

The $SU(3)_C$ symmetry group describes the strong force, which acts on all particles that carry a color charge. The electroweak interaction described by $SU(2)_L \otimes U(1)_Y$ unifies the electromagnetic and the weak forces. The $SU(2)_L$ symmetry group acts only on left-handed particles with a weak isospin, while $U(1)_Y$ acts on particles carrying a weak hypercharge. The SM is a gauge theory, which means that the Lagrangian describing the physical state has to be invariant under local gauge transformations. To satisfy this gauge invariance, new vector fields or gauge fields have to be

¹Compared to the other forces, gravity is weaker by nearly 37 orders of magnitude. Hence, the effect of gravity on elementary particles is negligible.

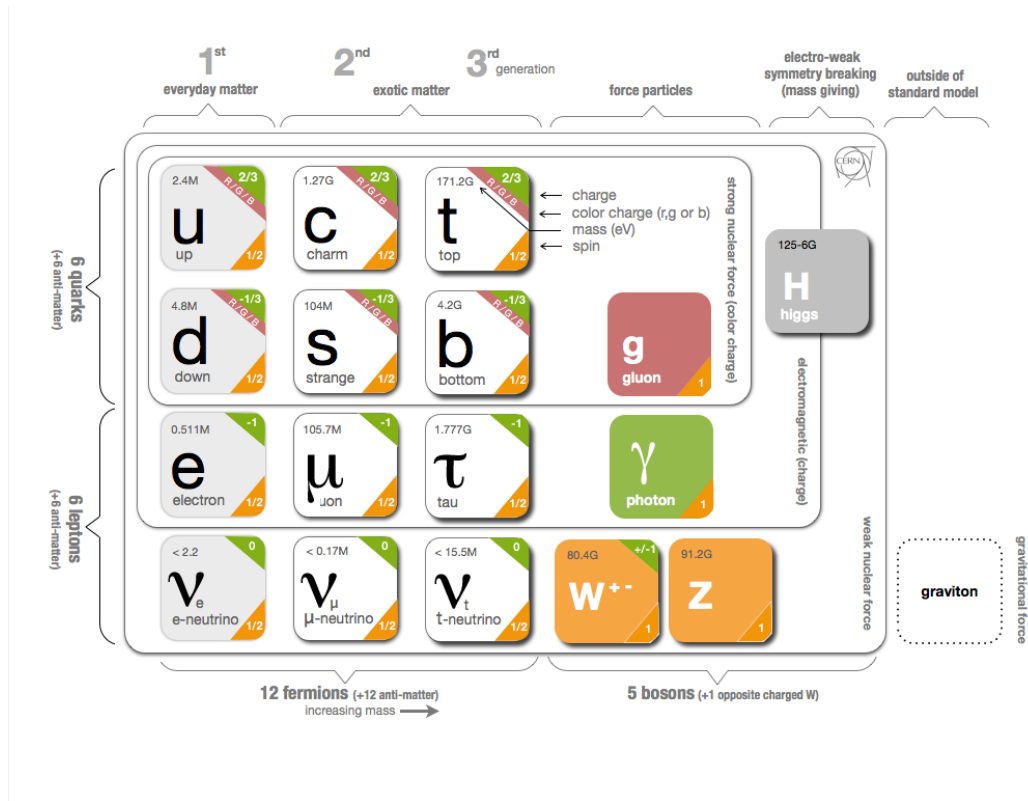


Figure 2.1: The fundamental particles in the Standard Model of particle physics. Image taken from [4].

introduced in the Lagrangian. The quanta of the gauge fields are called the *gauge* or *vector bosons* which mediate the interactions between the fermions. The electroweak symmetry is spontaneously broken through the Higgs mechanism, as a result of which the SM particles acquire mass. The Higgs mechanism also predicted a new particle called the *Higgs boson* having a spin 0, which was discovered in 2012 at the LHC [5], [6].

2.1.2 Particle Content in the Standard Model

Fermions

Fermions, or matter particles, are categorized into *quarks* and *leptons* depending on their interaction with the strong field. Quarks carry the color quantum number and can interact via the strong interaction while leptons cannot. All fermions, however, participate in the weak interaction. Quarks and leptons are classified into three generations in the order of increasing mass. Ordinary matter is built from the first generation fermions, while second and third generations are heavier cousins of the first. Quarks occur in six *flavors* each carrying a color and an electric charge, thus taking part in both strong and electromagnetic interactions. Each lepton generation consists of an electrically charged massive fermion along with an associated electrically neutral *neutrino*. Therefore, neutrinos can only interact via the weak force.

Bosons

The force carriers in the SM are vector bosons. The electromagnetic interaction is mediated by a massless, electrically neutral *photon* while the mediators of the strong force are eight massless *gluons*, which carry color charge. Gluons are electrically neutral as well. Unlike the electromagnetic and the strong interactions, the mediators of the weak force are the very massive *Z* and *W bosons*. The massive nature of these particles restricts the force range to short distances². The *Z* boson has an electric charge of 0, while the *W* bosons occur in two oppositely signed unit charges. In the SM, the fermions and the weak gauge bosons acquire mass as a consequence of the Higgs mechanism, described in detail in Section 2.1.3. The Higgs boson, which is a massive excitation of the Higgs field, is the only known fundamental scalar particle in the SM. The Higgs mechanism and the origin of the mass of the Higgs particle is currently at the forefront of research in particle physics.

2.1.3 Mathematical Formalism

The SM, like any other quantum field theory, integrates quantum mechanics with special relativity. Schrödinger's equation is a momentous contribution to the field of quantum mechanics but it fails to explain the creation and annihilation of particles. To consistently include both relativistic and quantum mechanical limits, one has to turn to the framework of quantum field theory. According to the theory, the equation for the free propagation of a fermion with mass m is given by:

$$(i\gamma^\mu \partial_\mu - m)\psi = 0, \quad (2.2)$$

and the corresponding Lagrangian density is:

$$\mathcal{L} = \bar{\psi}(i\gamma^\mu \partial_\mu - m)\psi. \quad (2.3)$$

The Lagrangian density is invariant under a global phase transformation of the form $\psi \rightarrow e^{iq\alpha}\psi$, where α is a constant and q is the fermion charge. This is the $U(1)$ symmetry group. But according to the SM requirements, the Lagrangian density must satisfy local gauge invariance as well, thus obeying transformations of the type $\psi \rightarrow e^{iq\alpha(x)}\psi$. The Lagrangian density given by Equation (2.3), is not invariant under the local phase transformation. To achieve this invariance, the derivative ∂_μ in the equation has to be replaced by a covariant derivative $\mathcal{D}_\mu = \partial_\mu - iqA_\mu$.

The covariant derivative introduces a new vector field A_μ called the electromagnetic vector field, and the Lagrangian density becomes:

$$\begin{aligned} \mathcal{L} &= \bar{\psi}(i\gamma^\mu \mathcal{D}_\mu - m)\psi \\ &= \bar{\psi}i\gamma^\mu \partial_\mu \psi - m\bar{\psi}\psi - q\bar{\psi}\gamma^\mu A_\mu \psi. \end{aligned} \quad (2.4)$$

The field theory that describes the interaction of a fermion with the electromagnetic field via the exchange of the respective gauge boson is called *Quantum Electrodynamics* (QED). In this theory, the mediating gauge boson is a massless photon. Taking into account the kinetic term of the gauge field as well in Equation (2.4), the QED Lagrangian density can be written as:

$$\mathcal{L}_{QED} = \underbrace{\bar{\psi}i\gamma^\mu \partial_\mu \psi}_{\text{fermion kinetic term}} - \underbrace{m\bar{\psi}\psi}_{\text{fermion mass term}} - \underbrace{\frac{1}{4}\mathcal{F}^{\mu\nu}\mathcal{F}_{\mu\nu}}_{\text{field kinetic term}} - \underbrace{q\bar{\psi}\gamma^\mu A_\mu \psi}_{\text{interaction term}}, \quad (2.5)$$

²Electromagnetic interaction is long-ranged due to the massless nature of photon. Even though gluons are massless, their self-interaction prevents them from propagating to long distances.

where $\mathcal{F}_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ is the electromagnetic field tensor. A mass term for the photon violates the gauge invariance, hence it cannot be included in the Lagrangian density. QED is an abelian gauge theory, therefore it disallows any photon self-interaction terms.

The strong interaction is described by a gauge theory called *Quantum Chromodynamics* (QCD) [7], [8], built on the $SU(3)_C$ symmetry group that conserves the color charge. Only quarks and gluons carry color charge and thus participate in strong interactions, while other bosons and leptons do not. The three color quantum numbers are r for red, g for green, and b for blue³. To achieve local gauge invariance, ∂_μ in Equation (2.3) is replaced by a covariant derivative $\mathcal{D}_\mu = \partial_\mu - ig_s T_a G_{a\mu}$, where T_a are the eight generators of $SU(3)$ that satisfy the commutation relation $[T_a, T_b] = if_{abc} T_c$ and G_a corresponds to each of the eight gluon fields ($a, b, c \in 1, \dots, 8$). f_{abc} are the structure constants of $SU(3)$ and g_s is the coupling strength of the gluon field. The QCD Lagrangian density is given by

$$\mathcal{L}_{QCD} = \underbrace{\bar{\psi}_f i \gamma^\mu \partial_\mu \psi_f}_{\text{quark kinetic term}} - \underbrace{m \bar{\psi}_f \psi_f}_{\text{quark mass term}} - \underbrace{\frac{1}{4} \mathcal{G}_a^{\mu\nu} \mathcal{G}_{a\mu\nu}}_{\text{field kinetic term}} - \underbrace{g_s \bar{\psi}_f \gamma^\mu T_a G_{a\mu} \psi_f}_{\text{interaction term}}, \quad (2.6)$$

where $\mathcal{G}_a^{\mu\nu} = \partial^\mu G_a^\nu - \partial^\nu G_a^\mu - g_s f_{abc} G_b^\mu G_c^\nu$ is the gluon field strength tensor. The subscript f on the field denotes the quark flavor, ($f \in 1, \dots, 6$), summed over all the colors. QCD is a non-abelian theory, thus allowing for gluon self-interactions.

In the context of cross-section measurement covered in this thesis, it is worth mentioning the two important properties characterizing QCD: *confinement* and *asymptotic freedom*. At energies lower than the QCD scale or confinement scale Λ_{QCD} , the strong coupling increases and ultimately diverges such that the quarks and gluons cannot be isolated. This property of color-charged particles is termed as color confinement. At energies above Λ_{QCD} , the strong interaction becomes asymptotically weaker and the quarks and gluons behave almost like free particles, exhibiting the property of asymptotic freedom.

Electroweak Interaction

The symmetry group underlying the electroweak interaction [9]–[11] is $SU(2)_L \otimes U(1)_Y$. $SU(2)_L$ conserves the weak isospin (I) and couples only to left-handed fermions as denoted by the index L . But $U(1)_Y$, the symmetry group of weak hypercharge (Y), couples to both left- and right-handed particles. The covariant derivative describing the electroweak force is given by:

$$\mathcal{D}_\mu = \partial_\mu - ig_2 \frac{\sigma^a}{2} W_\mu^a - ig_1 B_\mu. \quad (2.7)$$

Here, Pauli matrices denoted by $\frac{\sigma^a}{2}$ with $a \in 1, 2, 3$ are the three generators of the $SU(2)$ symmetry group. The three massless vector fields W_μ^a with the field tensor $\mathcal{W}_{\mu\nu}^a = \partial_\mu W_\nu^a - \partial_\nu W_\mu^a$ are introduced to preserve the local $SU(2)_L$ transformations. $U(1)_Y$ introduces an additional massless vector field B_μ and the field tensor $\mathcal{B}_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$. The physically observable fields of the gauge bosons mediating the electroweak force are superpositions of the four fields described by W_μ^a and B_μ . The mixing depends on the coupling strength of the fields and the mixing angle is called the Weinberg angle denoted by θ_W . Equation (2.8) gives the vector fields for W^+ and W^- bosons. The Z boson and the photon fields are given by Equations (2.9) and (2.10) respectively.

$$W_\mu^\pm = \frac{1}{\sqrt{2}} (W_\mu^1 \mp i W_\mu^2) \quad (2.8)$$

³The colors are just a naming convention with no physical meaning.

$$Z_\mu = W_\mu^3 \cos \theta_W - B_\mu \sin \theta_W \quad (2.9)$$

$$A_\mu = W_\mu^3 \sin \theta_W + B_\mu \cos \theta_W \quad (2.10)$$

$$\text{where} \quad \cos \theta_W = \frac{g_2}{\sqrt{g_1^2 + g_2^2}} \quad \text{and} \quad \sin \theta_W = \frac{g_1}{\sqrt{g_1^2 + g_2^2}}.$$

The Lagrangian density describing the electroweak interaction is written as:

$$\begin{aligned} \mathcal{L}_{\text{electroweak}} = & \underbrace{\bar{\psi}_L i \gamma^\mu \partial_\mu \psi_L}_{\text{left-handed}} + \underbrace{\bar{\psi}_R i \gamma^\mu \partial_\mu \psi_R}_{\text{right-handed}} && \text{fermion kinetic terms} \\ & - \underbrace{\frac{g_2}{2} \bar{\psi}_L \gamma^\mu \sigma^a W_\mu^a \psi_L}_{\text{left-handed}} - \underbrace{\frac{g_1}{2} \bar{\psi}_L \gamma^\mu \sigma^0 B_\mu \psi_L}_{\text{left-handed}} - \underbrace{\frac{g_1}{2} \bar{\psi}_R \gamma^\mu B_\mu \psi_R}_{\text{right-handed}} && \text{fermion interaction terms} \\ & - \frac{1}{4} \mathcal{W}^{a\mu\nu} \mathcal{W}_{\mu\nu}^a - \frac{1}{4} \mathcal{B}^{\mu\nu} \mathcal{B}_{\mu\nu}. && \text{gauge field kinetic and self-interaction terms} \end{aligned} \quad (2.11)$$

The non-abelian nature of the electroweak theory allows for the triple and the quartic self-interaction terms for W and Z bosons. It is evident that the gauge bosons emerging from the vector fields are massless, as constrained by the local gauge invariance. Today, it is a known fact that a photon is massless but W and Z bosons have exceptionally large masses. Even if the local gauge invariance is ignored, adding mass terms by hand for W and Z bosons results in non-renormalizable divergences, rendering the theory meaningless. This problem is solved by the Higgs mechanism [12], [13], as a consequence of which W and Z bosons acquire mass while photons remain massless. The W and Z bosons were discovered [14], [15] at CERN in the 1980s and the experimentally observed mass of these particles matched well with the predictions, which was one of the early achievements of the SM. A brief description of the Higgs mechanism and how particles acquire mass is given below.

Higgs Mechanism

A locally gauge invariant $SU(2)_L \otimes U(1)_Y$ symmetry forbids the existence of massive gauge bosons. To introduce the mass terms and to keep the theory renormalizable, the symmetry has to be spontaneously broken, which means that the Lagrangian is invariant under the electroweak transformation but the states are not. For this, a new complex scalar field φ with a specific potential is introduced. To keep the Lagrangian invariant, only $SU(2)_L \otimes U(1)_Y$ multiplets can be added and the simplest one is an isospin doublet as given in Equation (2.12), thus resulting in the name *minimalistic* Higgs mechanism.

$$\varphi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} \quad (2.12)$$

The electric charges of the two field components ensure a hypercharge $Y = +1$. This choice of the fields leaves the photon massless after the symmetry breaking, which will become clear from the discussion below.

The Lagrangian density for the scalar field is given by:

$$\mathcal{L} = (\mathcal{D}^\mu \varphi)^\dagger (\mathcal{D}_\mu \varphi) - V(\varphi), \quad (2.13)$$

where $\mathcal{D}_\mu$ is the covariant derivative of $SU(2)_L \otimes U(1)_Y$ symmetry group (see Equation (2.7)). The potential added to spontaneously break the symmetry is denoted by $V(\varphi)$, with $\mu^2 < 0$ and $\lambda > 0$, according to

$$V(\varphi) = \mu^2 \varphi^2 + \lambda \varphi^4, \quad (2.14)$$

also shown pictorially in Figure 2.2. From Equation (2.14), it is obvious that there is not a single

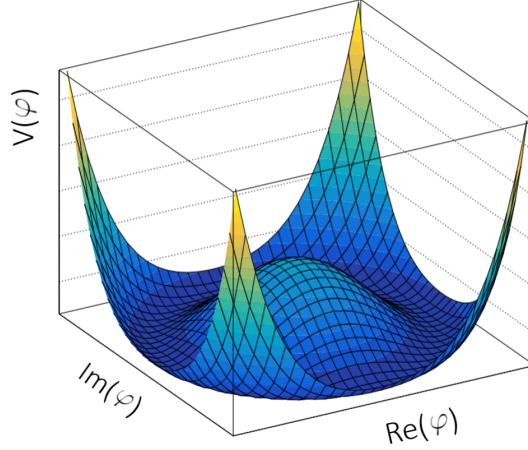


Figure 2.2: A pictorial representation of the potential $V(\varphi)$ of the complex scalar field. Image taken from [16].

vacuum but an infinite number of vacua located at:

$$\varphi_{min}^2 = (\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2)_{min} = -\frac{\mu^2}{2\lambda}, \quad (2.15)$$

on a four-dimensional hypersphere⁴, in the φ hyperplane⁵. One is free to choose any of the vacuum states and the chosen vacuum here is at:

$$\phi_{1,min}^2 = \phi_{2,min}^2 = \phi_{4,min}^2 = 0 \quad \text{and} \quad \phi_{3,min}^2 = -\frac{\mu^2}{2\lambda} = \nu^2, \quad (2.16)$$

where ν is the vacuum expectation value for which $V(\varphi)$ is minimized. The vacuum can be written as:

$$\varphi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu \end{pmatrix}, \quad \text{where } \nu = \sqrt{\frac{-\mu^2}{\lambda}}. \quad (2.17)$$

Currently, there are three massless degrees of freedom associated with the vacuum of the φ field. The Lagrangian is studied under small oscillations around the vacuum and within the freedom of gauge invariance, φ can be re-formulated. Perturbations around the vacuum in a direction away from the potential minimum correspond to a real massive scalar field called the Higgs field denoted by h , and the new vacuum can be written as:

$$\varphi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu + h \end{pmatrix}. \quad (2.18)$$

⁴A hypersphere is an n-dimensional sphere.

⁵A hyperplane is an n-dimensional plane.

One can notice that the vacuum defined is neutral. It is because, with hypercharge $Y = +1$, weak isospin $I = \frac{1}{2}$ and its third component $I_3 = -\frac{1}{2}$, the electric charge $Q = I_3 + \frac{1}{2}Y$ yields 0. This choice of vacuum breaks the $SU(2)_L \otimes U(1)_Y$ symmetry completely but leaves $U(1)_{EM}$ invariant, which is the reason photons are still massless after the symmetry breaking.

Using the new definition of φ , the Higgs sector of the Lagrangian density can be written as:

$$\begin{aligned}
\mathcal{L} = & \frac{1}{2} \partial_\mu h \partial^\mu h && \text{Kinetic and mass terms} \\
& - \lambda \nu^2 h^2 && \text{of the Higgs field} \\
& + \frac{1}{2} \left(\frac{g_2^2 \nu^2}{4} (|W_\mu^+|^2 + |W_\mu^-|^2) + \frac{\nu^2}{4} (g_1^2 + g_2^2) |Z_\mu|^2 \right) && \text{Mass terms of} \\
& && \text{W}^\pm \text{ and Z bosons} \\
& + \frac{g_2^2 \nu}{4} (|W_\mu^+|^2 + |W_\mu^-|^2) h + \frac{g_2^2}{8} (|W_\mu^+|^2 + |W_\mu^-|^2) h^2 && \text{Coupling of the W}^\pm \text{ boson} \\
& && \text{to the Higgs field} \\
& + \frac{\nu^2}{4} (g_1^2 + g_2^2) |Z_\mu|^2 h + \frac{1}{8} (g_1^2 + g_2^2) |Z_\mu|^2 h^2 && \text{Coupling of the Z boson} \\
& && \text{to the Higgs field} \\
& - \lambda \nu h^3 && \text{Self-interaction terms} \\
& - \frac{\lambda}{4} h^4 && \text{of the Higgs field} \\
& + \text{constant.}
\end{aligned} \tag{2.19}$$

From the above equation, masses of the electroweak gauge bosons can be identified as:

$$m_{W^\pm} = \frac{1}{2} \nu g_2, \quad m_Z = \frac{1}{2} \nu \sqrt{g_1^2 + g_2^2} = \frac{m_{W^\pm}}{\cos \theta_W}, \quad \text{and} \quad m_A = 0. \tag{2.20}$$

The massive excitation of the Higgs field gives rise to the scalar Higgs boson with mass $m_h = \nu \sqrt{2\lambda}$. The scalar doublet in Equation (2.12) has four degrees of freedom, out of which one degree of freedom generates the Higgs boson mass. The other three degrees of freedom, realized as the so-called *Goldstone modes* [17], [18], are absorbed by the massive gauge bosons as their longitudinal polarization modes.

It can be noted that Equation (2.19) does not describe the mass of fermions. The Higgs mechanism is extended further to the fermionic sector to generate masses for fermions by including additional Yukawa Lagrangian terms that describe the coupling of the Higgs field with the fermionic fields. The more the fermions interact with the Higgs field, the more mass they acquire. The fermion masses are then generated as $m_f = \frac{y_e \nu}{\sqrt{2}}$, where the Yukawa coupling, y_e , is a free parameter in the model.

2.1.4 Limitations of the Standard Model

The Standard Model of particle physics has stood the test of time. It is an experimentally well vetted theory and has repeatedly demonstrated remarkable accuracy in its predictions. However, despite its immense success, the theory has several shortcomings, including limitations inherent to the theoretical construct and inconsistencies with the experimental observations. A few of these shortcomings are summarized below:

- Gravity, one of the four fundamental forces, is entirely omitted in the theory. Moreover, attempts to integrate general relativity, the theory for gravitation, with quantum mechanics have failed continually. Therefore, the SM is valid only up to the Planck scale, $\mathcal{O}(10^{19} \text{ GeV})$, where the effects of gravity become prominent to be disregarded.

- According to the SM predictions, neutrinos are massless particles. However, experimental results on neutrino oscillations [19], [20] have shown that neutrinos indeed do have mass though the mechanism for the mass origin is still unknown.
- Most recently, there are solid experimental evidence suggesting new physics manifesting as deviations in the muon magnetic moment [21] and violations in lepton flavor universality [22].
- Matter and anti-matter are produced in equal quantities in the Standard Model. Nevertheless, from the smallest known life forms to the biggest galaxies, the observable universe is almost entirely made up of matter. The matter-antimatter asymmetry is still a mystery [23] and the SM fails to explain what tipped the balance and caused matter to take precedence over anti-matter in the early universe.
- The matter we know of, studied and addressed by the SM, is expected to constitute only 5% of the entire composition of the universe. Astronomical studies provide strong hints of hypothetical forms of matter and energy, known respectively as *dark matter* [24] and *dark energy* [25], filling up the rest of the universe. Neither dark matter nor dark energy are explained by the SM.
- The discovery of the Higgs boson, with mass as low as 125 GeV, brought with it a quandary of unnatural fine-tuning known as the *hierarchy problem* [26]. The Higgs mass is subjected to radiative corrections from all the energy scales up to the Planck scale, where SM remains valid. To explain the observed Higgs mass, the parameters in the Standard Model have to be incredibly fine-tuned, clearly speaking, precise to a large number of significant digits for cancellations over $\mathcal{O}(10^{17} \text{ GeV})$, which conflicts with the theoretical idea of naturalness. It is worth noting that the SM requires a very light Higgs boson to preserve unitarity in the scattering of longitudinally polarized vector bosons, which is one of the motivations for the study covered in this thesis.

Thus far, the theoretical description of the Standard Model and its limitations have been presented in a nutshell. The sparseness of the description should not be mistaken for simplicity. The underlying framework is mathematically complex and experimentally verified with much precision. Before one can further explore the scattering of vector bosons and how it is anchored to our very understanding of the Higgs mechanism in the SM, it is quite important to study proton physics to comprehend the experimental measurements.

2.2 Theory of Proton-Proton Collisions

The LHC collides protons at tremendously high energies, and to study the proton-proton collisions, it is essential to first understand the structure of a proton. In this section, a general idea of the proton structure at high energies and the structure of a typical proton-proton collision are presented. This is followed by a theoretical prescription of determining the cross-section without delving into the complexities of the calculations.

Proton Structure

A proton is a composite particle primarily made up of two *up* and one *down* quarks, which are called the *valence* quarks. In the high energy collider environment, this structure of the proton is too simple to explain the observed aftermath of the collision.

The proton structure at high energies is better explained by the Parton Model [27] proposed by Richard Feynman. According to this model, in addition to the valence quarks, a high energy proton consists of a sea of quarks, anti-quarks, and gluons, where each constituent particle is referred to as a *parton*. The momentum distribution of partons within the proton depends on the momentum carried by the proton. This information of the proton's deep structure is encoded as a probability density function known as the Parton Distribution Function (PDF), illustrated graphically in Figure 2.3. It defines the probability density of finding a parton of type i carrying a fraction x_i of the total momentum x of the proton when the proton is probed at a momentum transfer Q^2 .

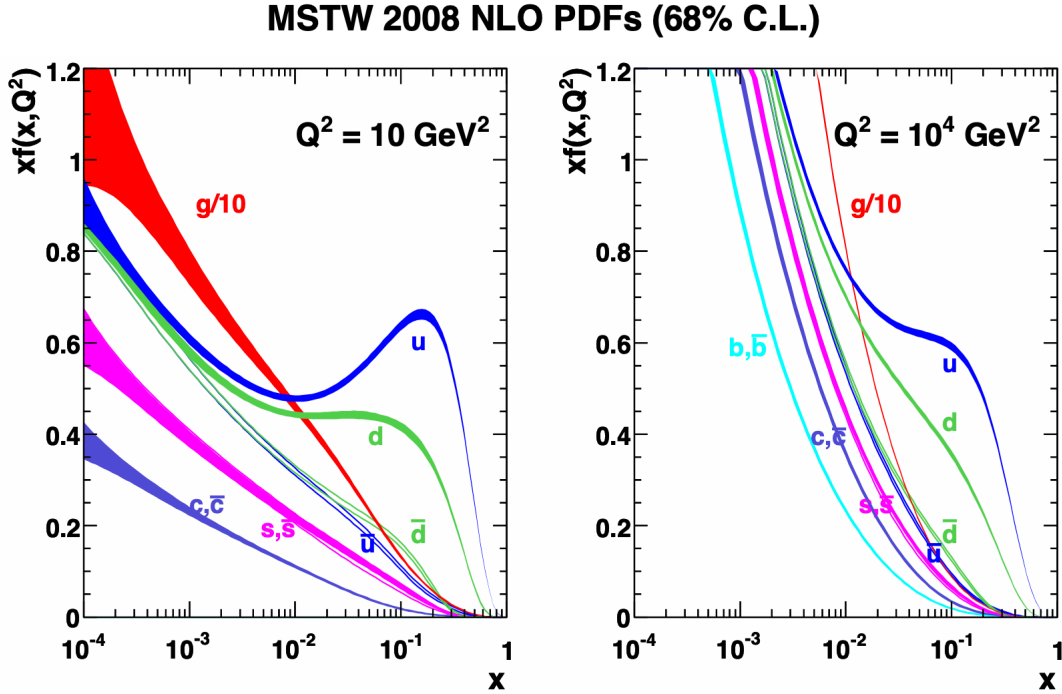


Figure 2.3: Martin-Stirling-Thorne-Watt Parton Distribution Functions at $Q^2 = 10 \text{ GeV}^2$ and $Q^2 = 10^4 \text{ GeV}^2$. Image taken from [28].

Event Structure

In a high energy proton, there is no relative motion between the partons inside. This is because, from the proton's reference frame, time is dilated according to the special theory of relativity and the partons are more or less "*frozen*". Proton-proton collision at the LHC is essentially a parton-parton collision where a parton from one proton hits another from the other proton.

If the colliding partons are energetic enough to cause an inelastic collision, then the process is termed a *hard scatter*. The incoming partons and the outgoing partons or particles of a hard scatter can emit soft radiation known as *Initial State Radiation* (ISR) and *Final State Radiation* (FSR) respectively. The radiations are soft because the energy of the emitted photons or gluons is small compared to the energy involved in the hard interaction. The final state parton remnant undergoes a process called *hadronization*, where the partons re-arrange themselves to form stable colorless hadrons. A sketch of a typical proton-proton collision at the LHC is shown in Figure 2.4.

The remaining partons not involved in the hard scatter along with the non-interacting protons in the beam (or the *beam remnant*) form the *underlying event*. Quite often, secondary hard inter-

actions with lower energy can occur from the underlying event. Such interactions are not used for the measurement covered in this thesis.

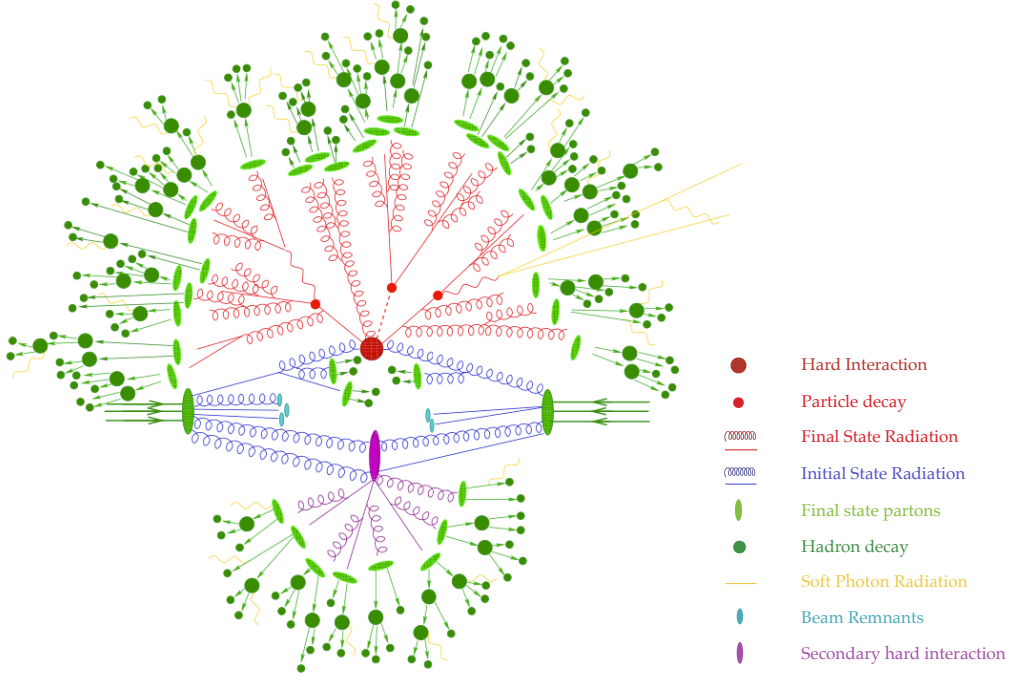


Figure 2.4: A schematic representation of a typical proton-proton collision at the LHC. Image taken from [29].

Cross-Section

In this chapter so far, the mathematical formalism of the physics model, as well as the structure of proton collisions have been discussed. But the mathematical description alone is insufficient to provide any direct means to make theoretical predictions that can be verified experimentally from the collisions. This necessitates translating the mathematical knowledge into physical observables which can be calculated theoretically as well as measured experimentally. One such example is the interaction cross-section which is also the subject of the measurement in this thesis.

One of the cardinal interests in particle physics is the particle interactions and decays, simply, the transition of initial state particles to final state particles. A cross-section is a physical quantity proportional to the probability for a given interaction to happen. It has the units of area and is usually expressed in *barns* ($1 \text{ barn} = 10^{-28} \text{ m}^2$).

The theoretical calculation of cross-section is built on the transition matrix element, $\mathcal{M}$, for the transition from an initial state to a final state of particles and the available phase space for such a transition. The matrix element gives the probability amplitude for the transition of states and it can be obtained by the perturbative evaluation of the quantum field theory. For the transition from one initial state to a final state of particles, the matrix element is obtained by summing over all the respective Feynman diagrams which contain the recipe for the particle interactions and

contributions from the Lagrangian densities discussed in Section 2.1.3. Finally, the kinematics of the particles are accounted for by integrating over the momentum phase space of the incoming and the outgoing particles. Then, cross-section is given by

$$\sigma = \int_{\text{phase space}} \frac{|\mathcal{M}^2|}{\text{incident particle flux}}. \quad (2.21)$$

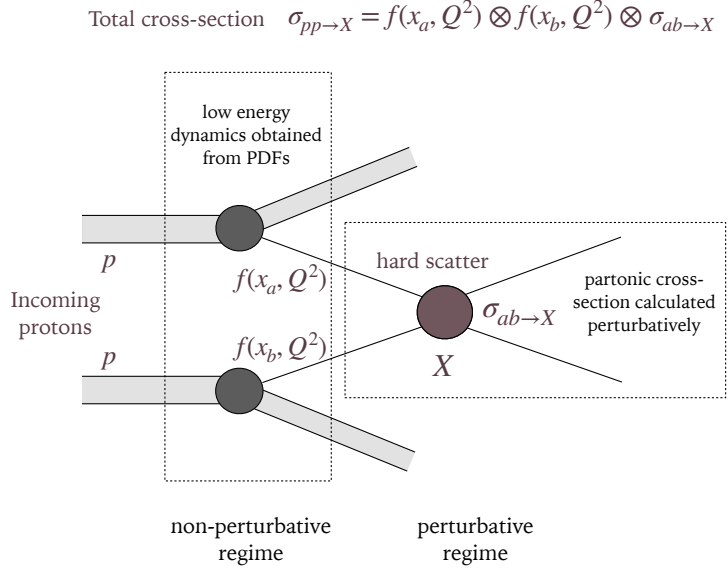


Figure 2.5: A simplified schematic representation of a proton-proton collision event showing the perturbative and the non-perturbative regimes in cross-section calculation.

Even though the proton collisions of interest are high energy interactions, the partons involved are governed by low energy QCD dynamics. And computing the integral in Equation (2.21) leads to divergences due to contributions from objects with very high energies, approaching infinity (ultraviolet divergence) as well as from objects with very small energies, approaching zero (infrared divergence). This compels the cross-section in hadron collisions to be computed using the QCD factorization theorem. It simply allows the cross-section to be factorized, that is, separated into perturbative (due to asymptotic freedom) and non-perturbative (due to color confinement) components at the limit of a factorization scale, μ_F . The partonic hard scattering cross-section parametrizes the perturbative component. It is process dependent, containing only the hard emissions above μ_F and is calculated using perturbative QCD. The non-perturbative component is encapsulated in the parton distribution functions, which is process independent and contains all the unresolved emissions below μ_F and is determined empirically. Figure 2.5 presents a simplified schematic representation showing the perturbative and non-perturbative regime in a proton-proton collision event. Factorization “fixes” the infrared divergences by “hiding” them in the PDFs. Since the factorization scale characterizes the boundary between the low energy and the high energy dynamics, it introduces a μ_F scale dependence on the partonic cross-section and the parton densities. The ultraviolet divergence, on the other hand, which appear due to the large momentum in the higher order loops, is cured by introducing a renormalization scale, μ_R . In simple terms, the strong coupling, α_s , is

made to absorb all the ultraviolet divergences through renormalization, thereby causing a μ_R scale dependency and ensuring that the theory is perturbatively well-defined in the regime under study.

The PDFs are obtained by performing global fits to the combined data from the early deep inelastic experiments, largely from HERA. The data included in the fit corresponds to measurements that probed the proton structure at a given Q^2 . The energy scales explored at the LHC are unprecedented and to predict the PDFs in the energy domain of the LHC, the known parton densities need to be dynamically evolved. The QCD evolution equations for parton densities are known as the Dokshitzer–Gribov–Lipatov–Altarelli–Parisi equations [30]–[32], which extrapolate the PDFs from one energy scale to another. Figure 2.6 shows the parton kinematics at the LHC in the (x, Q^2) kinematic plane.

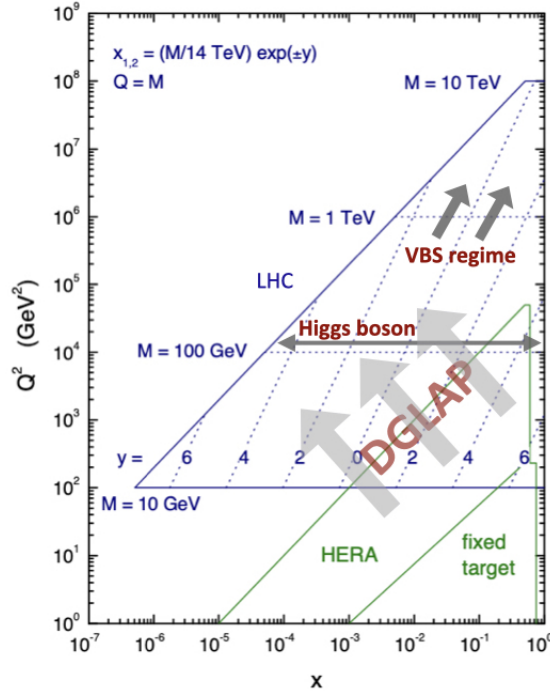


Figure 2.6: Parton kinematics covered by the LHC in the (x, Q^2) kinematic plane is shown. The particle mass is denoted by M at rapidity y . DGLAP evolution equations become essential to predict the PDFs at the energy scale probed by the LHC. The vector boson scattering regime covered in this thesis for a di-jet invariant mass above 500 GeV is also shown. Image taken from [33] and modified.

At this point, one has all the necessary ingredients to calculate the cross-section in the proton-proton collisions at the LHC. The total cross-section for any process $pp \rightarrow X$ can be expressed mathematically as:

$$\sigma_{pp \rightarrow X} = \sum_{a,b=q,\bar{q},g} \int_0^1 dx_a \int_0^1 dx_b f_a(x_a, \mu_F^2) f_b(x_b, \mu_F^2) \sigma_{ab \rightarrow X}(x_a, x_b, \mu_F^2, \mu_R^2, \alpha_s(\mu_R^2)), \quad (2.22)$$

where a and b denote the parton type in each of the colliding protons and $\sigma_{ab \rightarrow X}$ stands for the partonic cross-section of the process $ab \rightarrow X$. Partonic cross-section $\sigma_{ab \rightarrow X}$ can be expressed as the expansion in the strong coupling as:

$$\sigma_{ab \rightarrow X} = \sigma_0 + \alpha_s \sigma_1 + \alpha_s^2 \sigma_2 + \dots \quad (2.23)$$

The first term, σ_0 , is the tree-level or the leading order (LO) partonic cross-section, the second term corresponds to the next-to-leading order (NLO) correction and so on. These higher order terms in α_s are associated with radiative corrections as a result of gluon or quark emission.

It is important to note that the scale parameters are chosen arbitrarily and they are not intrinsic to QCD. The standard value is taken as $\mu_R = \mu_F = Q$. They simply imply how factorization and renormalization is performed. Therefore, ideally a physical observable should not depend on these scales and cross-section calculated for any values of the parameters should remain invariant. But this is only true if all the perturbative orders are included in the calculation which is theoretically as well as practically impossible. One can reduce the scale dependency by including more and more terms in the calculation. The scale dependence is usually assigned as an uncertainty in the theoretical calculations due to missing higher orders terms.

A fairly good agreement has been observed over the years between the experimental observations and the theoretical predictions from simulations implementing the above calculations. A summary of the production cross-section in proton-proton collisions for various processes is given in Figure 2.7 and the results show the agreement extending over 14 orders of magnitude.

Standard Model Production Cross Section Measurements

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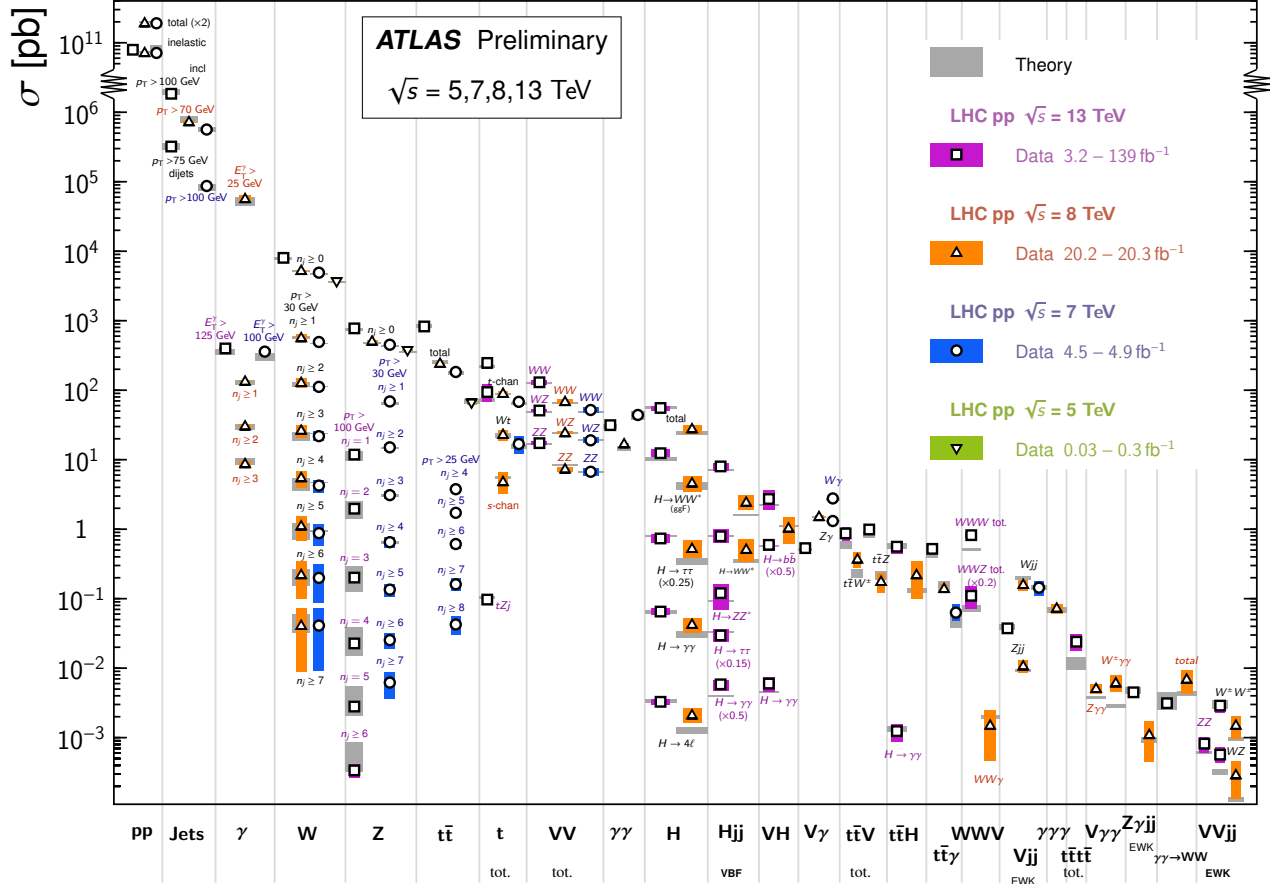


Figure 2.7: A summary of the production cross-sections in proton-proton collisions for various processes is shown. The theoretical predictions for cross-sections are simulated implementing the calculation method described in this section and compared with the experimental observations made by the ATLAS experiment. The results show a fairly good agreement extending over 14 orders of magnitude. Image taken from [34].

2.3 Vector Boson Scattering

Vector Boson Scattering (VBS) refers to the self-interactions of the electroweak vector bosons containing a three- or a four-boson vertex. The predictions for a triple or a quartic gauge vertex in the Standard Model are encapsulated in the non-abelian nature of the electroweak theory, described in Section 2.1.3. Vector boson scattering has garnered much attention from the scientific community with the recent discovery of the Higgs particle as the scattering of the massive electroweak gauge bosons is inextricably linked to the electroweak symmetry breaking mechanism. The three Goldstone modes of the broken symmetry translate to the longitudinal polarization modes of the W^+ , W^- , and Z bosons. Despite the fact that the mass of the observed Higgs particle poses the hierarchy problem, such a light scalar boson is indispensable to preserve the unitarity in the scattering cross-section of the longitudinally polarized gauge bosons.

2.3.1 Leading Order Diagrams

The probability amplitude for the transition of states is given by the matrix element, which is obtained by summing over all the possible Feynman diagrams, as discussed in Section 2.2. The diagrams of a $2 \rightarrow 2$ scattering are commonly represented by the Mandelstam variables, s , t , and u , which encapsulate energy, momentum, and scattering angles of the particles in a Lorentz invariant manner. The variables numerically represent the Feynman diagrams where the interaction involves the exchange of an intermediate particle, such that the square of its four-momentum is given by the Mandelstam variables, defined as:

$$s = (p_1 + p_2)^2 = (p_3 + p_4)^2 \quad (2.24)$$

$$t = (p_1 - p_3)^2 = (p_4 - p_2)^2 \quad (2.25)$$

$$u = (p_1 - p_4)^2 = (p_3 - p_2)^2 \quad (2.26)$$

where p_1 and p_2 are the four momenta of the two incoming particles and p_3 and p_4 are the four momenta of the two outgoing particles. The VBS processes involve several diagrams and the diagrams at leading order are shown in Figure 2.8 according to the corresponding Mandelstam variables.

2.3.2 Role of Higgs Boson in Vector Boson Scattering

The Higgs boson plays a crucial role in vector boson scattering. To understand its significance, one can take a look at the general expression of the polarization vector, ϵ^μ , of the gauge bosons. A massless gauge boson can exist in two transverse polarization modes,

$$\begin{aligned} \epsilon_+^\mu &= \frac{1}{\sqrt{2}}(0, 1, i, 0) \\ \epsilon_-^\mu &= \frac{1}{\sqrt{2}}(0, 1, -i, 0) \end{aligned} \quad (2.27)$$

while a massive gauge boson can exist in an additional longitudinal polarization mode,

$$\epsilon_L^\mu = \frac{1}{m}(p_z, 0, 0, E) \quad (2.28)$$

where m is the mass, E is the energy, and p_z is the longitudinal momentum of the particle. An important feature of the longitudinal polarization mode is its energy dependence. When longitudinally

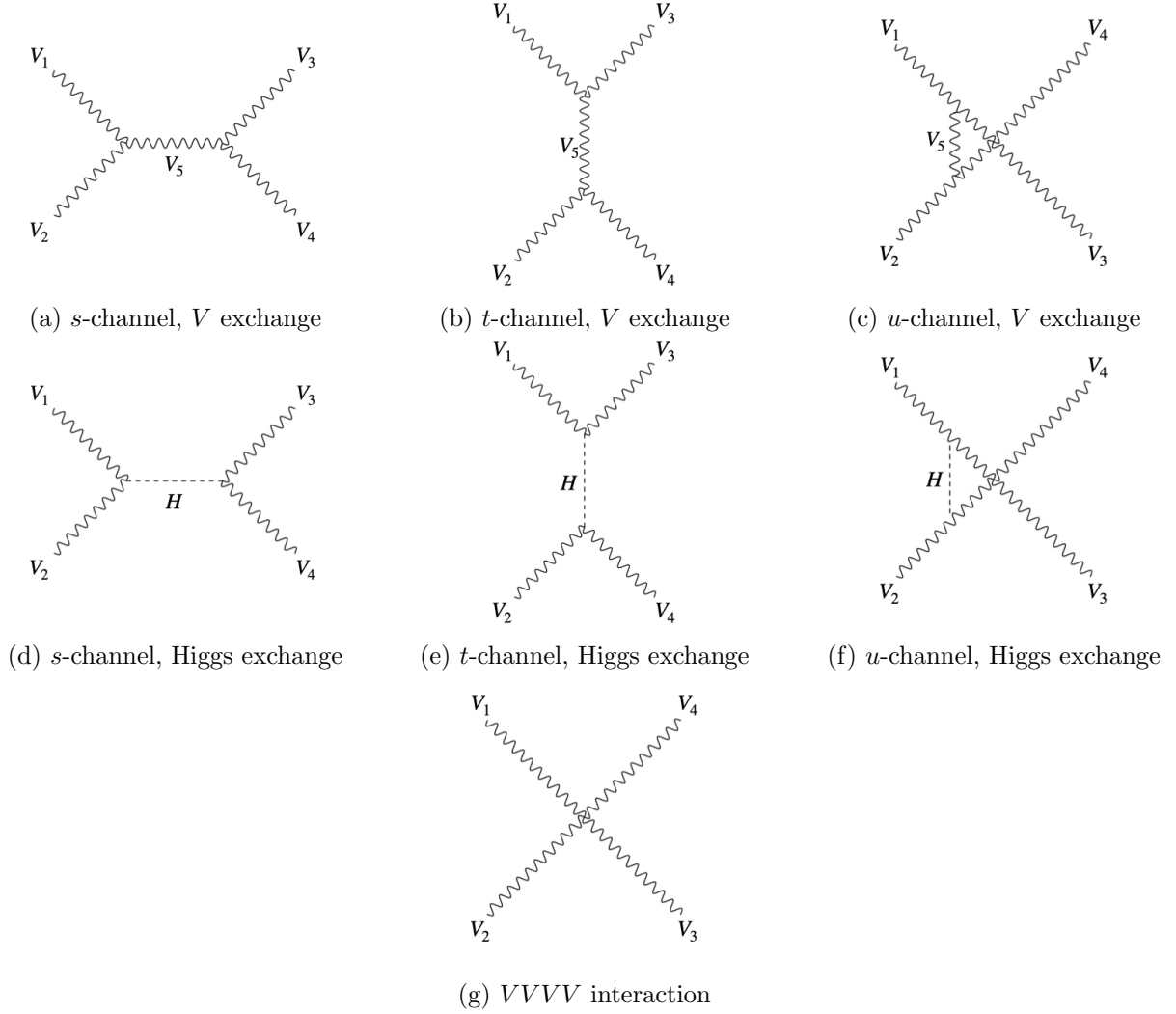


Figure 2.8: Feynman diagrams for the self-interactions of the electroweak gauge bosons at leading order are shown. In the diagrams, an electroweak gauge boson is denoted by V and a Higgs boson by H . Self-interactions through the exchange of an electroweak gauge boson are displayed in (a), (b), and (c). (d), (e), and (f) show the same but through the exchange of a Higgs boson. In (g), the interaction at a quartic gauge vertex is given.

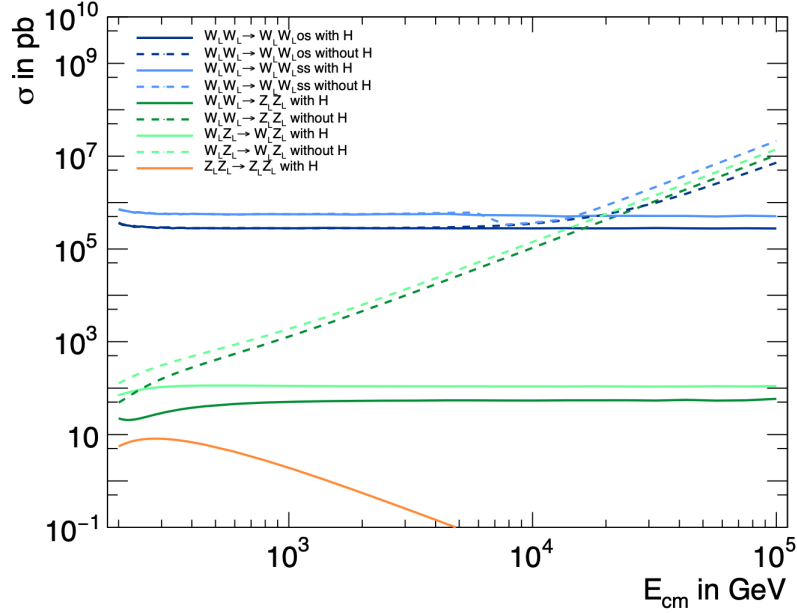


Figure 2.9: The dependence of the cross-section in $V_L V_L \rightarrow V_L V_L$ is shown for all combinations of the gauge bosons as a function of the centre of mass energy. The solid lines corresponds to the scenario with Higgs and dashed line corresponds to that without Higgs as simulated by the MADGRAPH generator. Image taken from [35].

polarized gauge bosons scatter at energies much larger the mass of the particle, the cross-section grows indefinitely with energy and violates the unitarity principle⁶. For increasing centre of mass energies, the cross-section diverges and the divergence is canceled *exactly* by the contributions of the Higgs boson, thus serving as the linchpin in vector boson scattering. Simply put, unitarity is preserved in $V_L V_L \rightarrow V_L V_L$ processes through diagrams like (d)-(f) in Figure 2.8. This can be seen graphically in Figure 2.9 where cross-section is plotted as a function of the centre of mass energy for scenarios with and without Higgs.

It is worth noting that the theoretical developments predicted early on that the Higgs mass must be less than 1 TeV to conserve unitarity in the scattering of longitudinally polarized gauge bosons which was why the scientific community knew if the Higgs boson exists, it would be discovered at the LHC!

⁶It requires that the sum of the probabilities of all the possible final states emerging from a given initial state must equal to one.

Chapter 3

The LHC and the ATLAS Experiment

Particle accelerators and colliders are instrumental in probing the sub-structure of particles, and they have always kept the scientific community on a cliffhanger because of the revolutionary changes they bring to the field of particle physics. By providing incredibly large amounts of energy, they make possible our access to distances even as small as 10^{-20} m. The underlying physics relating momentum, p (or energy), and wavelength, λ , is originally given by de Broglie according to $\lambda = h/p$, where h is the Planck's constant. Thus, larger momentum (or energy) corresponds to smaller wavelength or distance probed, which serves as the motivation for “*high energy*” experiments.

The highest energies, at present, are generated at CERN's accelerator complex by the Large Hadron Collider (LHC). This chapter focuses on the experimental setup for data collection from the LHC at the ATLAS detector. A brief introduction of the accelerator complex and the sub-systems of the LHC are given respectively in Sections 3.1.1 and 3.1.2. The principle of grouping the beam into bunches is summarized in 3.1.3, and the essential collider parameters relevant for physics analysis are discussed in Section 3.1.4. Finally, in Section 3.2, the ATLAS experiment and its sub-detectors are described.

3.1 The Large Hadron Collider

The LHC is the world's largest, most complex, and powerful particle accelerator. It is situated in a 27 km circular tunnel, 100 m underground at CERN near Geneva, Switzerland. Operational in 2008, it is the present final element in the accelerator complex at CERN. The LHC accelerates charged hadrons, mainly protons and lead ions, and collides them head-on at various points along the ring, where four main detectors are housed to record the collisions. The data used in this thesis are the proton-proton collisions taking place at one of the interaction points, located inside the ATLAS detector.

3.1.1 Accelerator Complex at CERN

Particle accelerators use electric fields to increase the energy of particles that are steered and held in trajectory by magnetic fields. CERN's accelerator complex is a sequence of such machines that raises the energy of the particles before injecting them into the next machine in the chain. The entire accelerator framework is shown in Figure 3.1. The protons for collisions are extracted from a small bottle of hydrogen gas from which electrons are stripped off under strong electric fields. The protons are then accelerated by LINAC 2, the first in the chain, to an energy of 50 MeV, followed by the Proton Synchrotron Booster (PBS) and the Proton Synchrotron (PS), which raise the energy

to 25 GeV. The next in line is the Super Proton Synchrotron (SPS) which delivers an energy of 450 GeV before injecting the beam to the LHC. The LHC splits the beam into two and circulates them in two separate rings in opposite directions, taking each beam to a record energy of 6.5 TeV before colliding them in the ATLAS detector at a center of mass energy of 13 TeV.

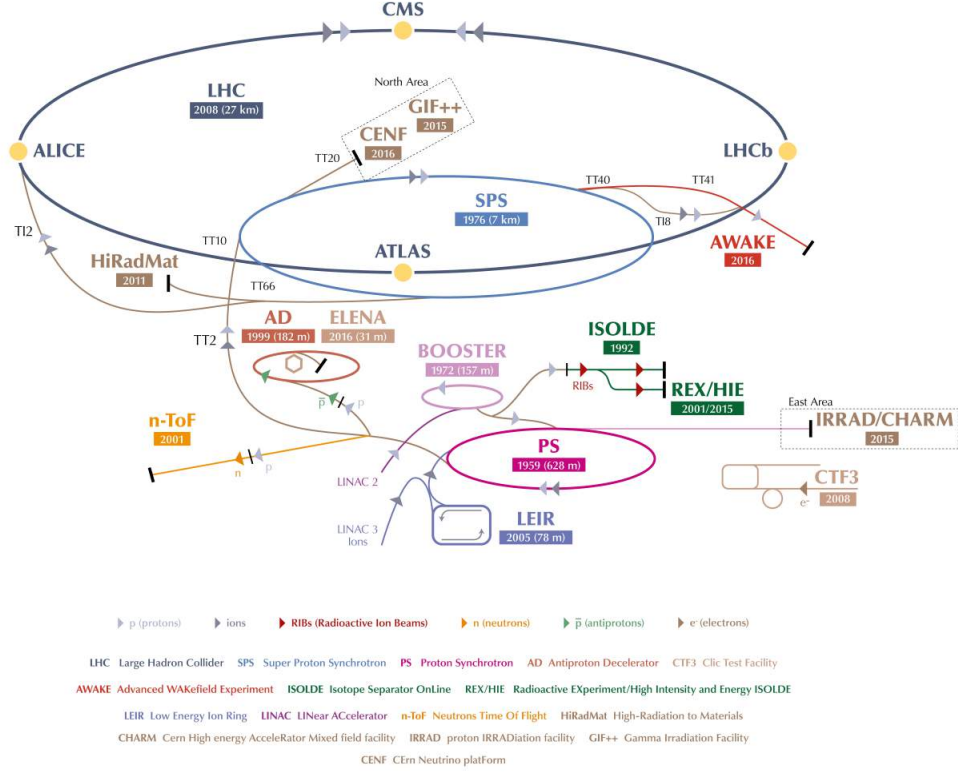


Figure 3.1: The accelerator complex at CERN. Image taken from [36].

3.1.2 Collider Sub-Systems

The controls and the instrumentation of the LHC are very complex and are beyond the scope of this thesis. For a detailed understanding of the technical design, refer to [37]. This section aims to present a simplified picture of the main sub-systems of the LHC, namely: 1. Magnet system 2. Cryogenic system and 3. Vacuum system.

Magnet System

The LHC magnetic system is designed to maintain narrow and focused beams along the quasi-circular orbit of the ring. To serve this purpose, the LHC employs magnetic dipoles and multipoles. The beam is guided in circular paths by the magnetic dipoles, whereas the beam is held in focus by the magnetic multipoles.

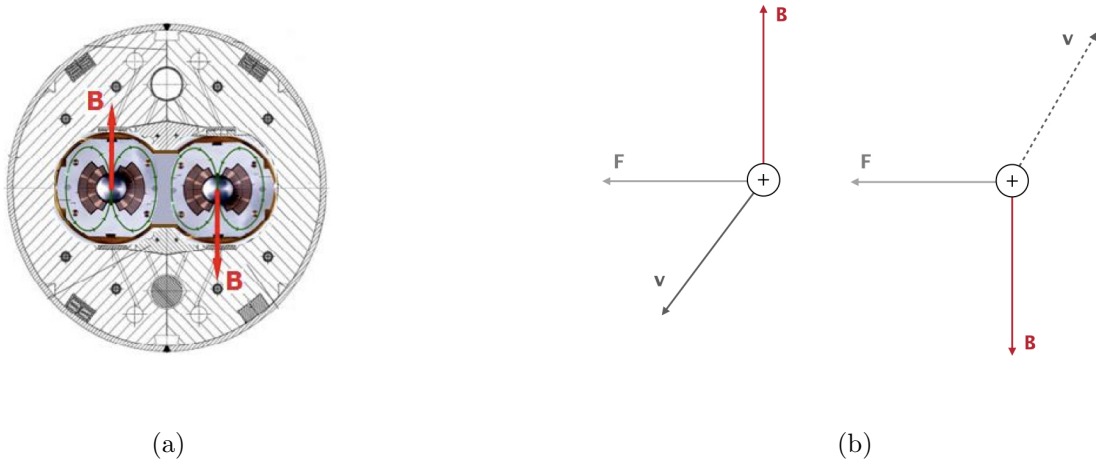


Figure 3.2: A cross-section of the LHC dipole magnet showing the directions of the magnetic field acting on the two beam pipes is given in (a). Image taken from [38]. (b) shows the directions of the magnetic field, the proton beams, and the Lorentz force acting on the beams. The force acting on the two beams is in the same direction, thus curving both the beams in that direction.

Nearly 1232 magnetic dipoles are stationed inside the collider to curve the beam. The dipole generates a magnetic field of 8 T in opposite vertical directions on the two beam pipes. As the two proton beams travel in opposing directions inside their respective beam pipes, the Lorentz force on the beams act is in the same direction, i.e., towards the center of the ring, thus maintaining the beam trajectory. Figure 3.2 shows the cross-sectional view of the dipole magnet and an illustration of the force acting on the beams.

There are 392 quadrupole magnets that work in pairs to focus the beam in two directions, one pair constricts the beam width, and the other constricts the beam height, thus delivering a narrow beam, as shown in Figure 3.3. The beams are further squeezed before they collide inside the various detectors. Additional beam focusing and corrections are facilitated by magnetic multipoles, as described in detail in [37].

The magnets at the LHC are superconducting electromagnets that operate from baths of superfluid¹ helium at 1.9 K. These electromagnets use a current of about 11,080 A, and their coils enter a superconducting state under very low temperatures and offer no resistance to the conduction of electric current, thus saving energy from being lost to electrical resistance.

Cryogenic System

To cool the magnets and to preserve the cryogenic temperatures, refrigerators and cold compression systems are installed at the different LHC segments. In addition to the collider ring in the tunnel, a second ring of the same length called the *cryogenic ring* is constructed to transmit the cold power to the superconducting magnets in the LHC ring. The cryogenic ring allows nearly 100 tons of liquid helium to run along its length.

¹Superfluidity is the property of remarkably high thermal conductivity.

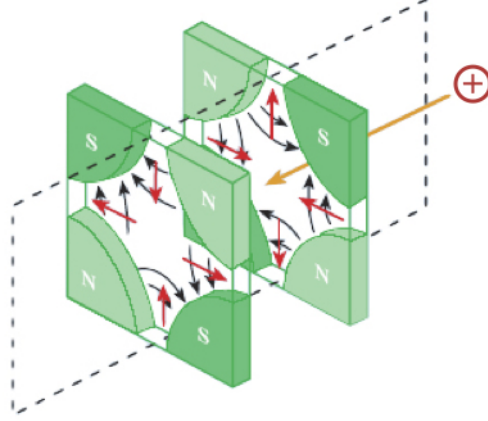


Figure 3.3: The operating principle of the quadrupole magnets is shown. The proton particles (positively charged) enter from the right. While one quadrupole constricts the beam width, the other quadrupole constricts the beam height. Image taken from [39] and modified.

Vacuum System

The vacuum systems play a significant role in operating the LHC at its full potential. The LHC vacuum system includes the insulation vacuum and the beam vacuum systems. The insulation vacuum system is used in the cryogenic ring and the magnet cryostats to reduce the heat exchange between the cryogenic fluids and the external envelopes. The beam vacuum system ensures a clean environment for the circulating protons as the machine's performance falls considerably if the protons in the beam pipe get a chance to interact with even some electrons from gas molecules. The ultrahigh vacuum systems installed render a vacuum pressure of nearly 10^{-7} Pa in the beam pipe and less than 10^{-9} Pa at the collision point.

3.1.3 Proton Bunching

Protons in their journey within the accelerator complex are grouped into *bunches* and are accelerated using a series of radio frequency (RF) cavities. The RF cavities are designed such that the electromagnetic radio waves become resonant and build up in the cavity. Electric fields in the LHC RF cavities are tuned to oscillate at 400 MHz. Depending on the energies carried by the particles, they arrive at the RF cavities at slightly different times. When the LHC is operating at its full energy, an ideally timed proton with the exact desired energy will experience zero accelerating voltage, but the protons arriving earlier or later will be decelerated or accelerated. Thus, the particles are sorted into tight and stable bunches of the same energy and are pushed forward. The LHC RF cavities raise the proton beam energy from 450 GeV to 6.5 TeV in nearly 15 minutes when the bunches have journeyed through them more than a million times.

Each bunch in the LHC has nearly 10^{11} protons and each beam, at its full intensity, has 2808 bunches in it with a spacing of 25 ns in between. Collisions take place when two bunches from the opposite beams inter-penetrate, which is termed as a *bunch crossing*. In the ATLAS detector, there are 40 million bunch crossings per second, but the probability of a proton in one bunch hitting another proton in the opposite bunch is very small, and most protons miss each other.

In the 2015-2018 collision data analyzed in this thesis, there occurs on average 34 proton-proton inelastic interactions for every bunch crossing. The collisions that occur in addition to an interesting collision in every bunch crossing are termed as *pile-up*. In other words, it is the total number of interactions per bunch crossing, and it represents one of the major backgrounds for any physics analysis. Figure 3.4 gives a summary of the pile-up interactions recorded by ATLAS in recent years.

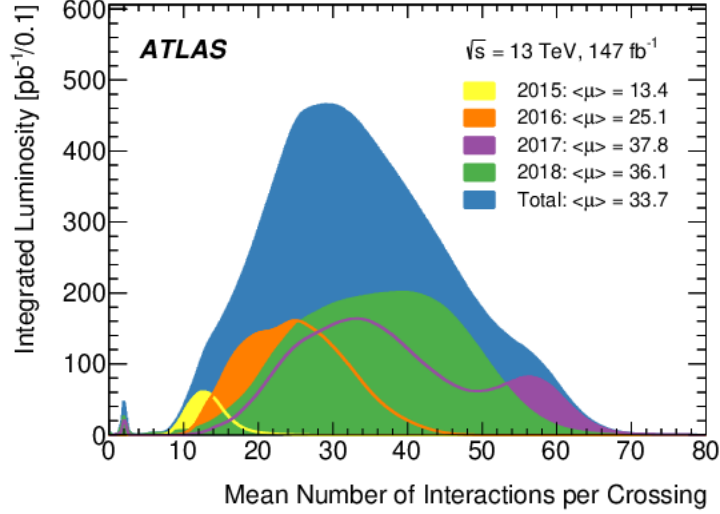


Figure 3.4: The number of pile-up interactions in the ATLAS detector in Run 2 (from 2015-2018) is shown. Image taken from [40].

3.1.4 Collider Parameters

The two important parameters that quantify the performance of a particle collider are its center of mass energy and luminosity.

Center of mass energy

The center of mass energy is a measure of the total energy delivered by the collider. It is the energy available for materialization, and it determines the energy threshold for particle production. The larger the center of mass energy, the greater the chance for the creation of massive particles. The LHC sets the world record, delivering an energy of 13 TeV, followed by Tevatron with 2 TeV.

Luminosity

The collider's capacity to produce the desired number of interactions is termed as its luminosity. If a physics process has a production cross-section σ and a rate of production R , then instantaneous luminosity, L , is the process independent proportionality factor between the two quantities, defined by $R(t) = L(t)\sigma$. Instantaneous luminosity is the number of collisions produced per cm^2 per second, calculated as

$$L = \frac{f N_1 N_2}{4\pi\sigma_x\sigma_y}. \quad (3.1)$$

Here, f is the frequency of bunch crossing, N_1 and N_2 are the number of protons in the two colliding bunches, σ_x and σ_y are the horizontal and vertical components respectively of the geometric

cross-section of the bunch at the interaction point. σ is rather the effective cross-section as the beam profile does not have a sharp edge².

As the collider's running conditions vary with time, a more interesting term useful for physics analysis is the integrated luminosity, $\mathcal{L}$, which is the instantaneous luminosity integrated over a period t defined as:

$$\mathcal{L} = \int_0^t L dt. \quad (3.2)$$

It determines the number of events produced in a given data taking period. For a given physics process, the total number of events produced is $N_{events} = \mathcal{L}\sigma$. While cross-section is a feature of the scattering process, luminosity characterizes the machine performance.

3.2 The ATLAS Experiment

The ATLAS (A Toroidal LHC ApparatuS) [41]–[44] experiment is one of the four main experiments at the LHC. Together with CMS [45], it serves as a general-purpose detector, operating at the LHC's highest luminosity conditions with a goal to record as many interesting physics events as possible. The ATLAS experiment is a long cylindrical barrel sandwiched between two end-cap regions, and it is the largest detector in volume ever built for particle detection. It has an overall length of 45 m with a diameter of 25 m and weighs 7000 tons. The detector has four major components:

1. The Inner Detector
2. The Calorimeter
3. The Muon Spectrometer
4. The Magnet System

These sub-detectors are stacked onto each other, along the beam axis, concentrically around the collision point. A schematic diagram of the longitudinal view of the detector can be seen in Figure 3.5.

The ATLAS experiment uses a right-handed Cartesian coordinate system. An illustration of the coordinate system is shown in Figure 3.6. The nominal interaction point, termed as IP, is taken as the origin with the $+x$ -axis pointing to the center of the LHC ring, the $+y$ -axis pointing upwards, and the $+z$ -axis along the beamline. The $x - y$ plane can be described equivalently using $r - \phi$ cylindrical coordinates. $r = \sqrt{x^2 + y^2}$ gives the displacement from the beam axis in the transverse plane (or the $x - y$ plane), and the azimuthal angle ϕ , measured anti-clockwise from the $+x$ -axis, gives the hermetic coverage around the beam axis. The angle from the $+z$ -axis in the $y - z$ plane is described by the polar angle denoted by θ .

In the collider environment, the laboratory frame is longitudinally Lorentz boosted as the relativistic incoming particles move along the z direction, but a difference in θ is not Lorentz invariant in the z direction. This makes the polar angle a less preferred variable as the momenta of the colliding particles differ from event to event. For this reason, the commonly used quantity is the pseudorapidity, η , defined as

$$\eta = -\ln \tan \left(\frac{\theta}{2} \right) = \frac{1}{2} \ln \left(\frac{|\vec{p}| + p_z}{|\vec{p}| - p_z} \right), \quad (3.3)$$

²The beam is assumed to have a Gaussian distribution in first approximation.

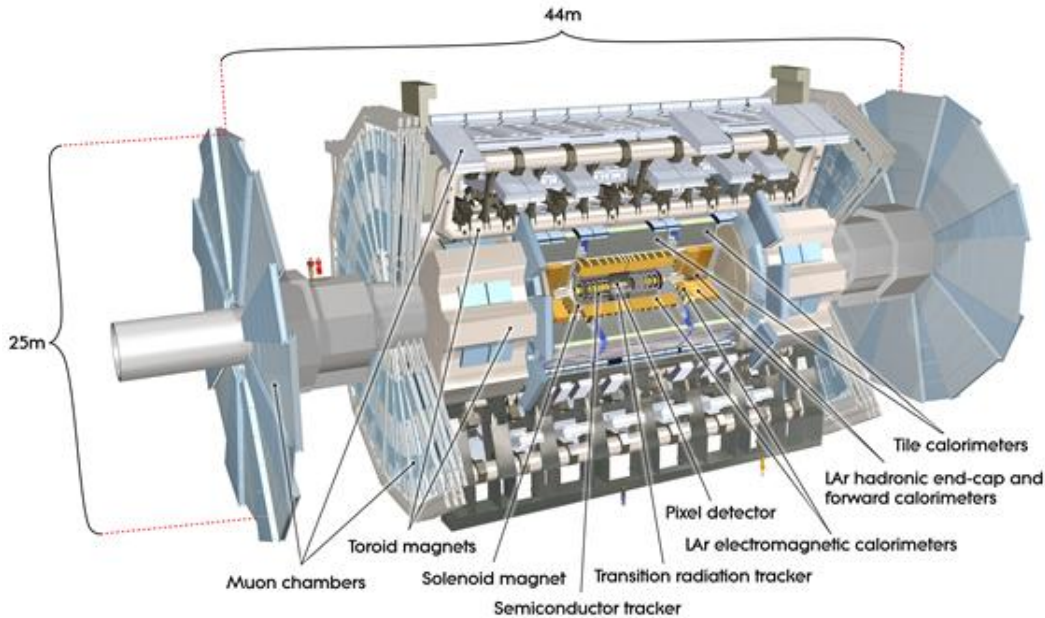


Figure 3.5: The ATLAS detector. Image taken from [44].

where $\vec{p}$ is the total three-vector momentum and p_z is the longitudinal momentum component of the particle. It is used when the mass of the particle is very small compared to its energy, and in relativistic cases when mass of the particle can be neglected. Pseudorapidity is an approximation of a more interesting quantity known as the rapidity, y ,

$$y = \frac{1}{2} \ln \left(\frac{E + p_z}{E - p_z} \right), \quad (3.4)$$

which takes into account the total energy, E , when the particle mass is significant. A difference in η and y is invariant under Lorentz boosts in the longitudinal direction which makes them the preferred geometric parameters used to describe events.

3.2.1 The Inner Detector

The Inner Detector (ID) is the first component of the multi-layered ATLAS detector, hence the layer closest to the beam pipe. It is 6.2 m long with a diameter of 2.1 m and immersed in an axial magnetic field of 2 T. Due to the high number density of particles emerging from the collision point, the ID is designed to be highly sensitive to the particle influx. Therefore, with high granularity, full ϕ coverage, and $|\eta| < 2.5$, the ID precisely locates the interaction vertex and reconstructs the trajectories of charged particles. This task is accomplished by the three main sub-systems of the ID: the Pixel Detector (PD), the Semiconductor Tracker (SCT), and the Transition Radiation Tracker (TRT). A detailed radial layout of the ID is shown in Figure 3.7.

The Pixel Detector [47], [48] is the first sub-system of the Inner Detector, consisting of 1,744 modules, each having 47,232 silicon pixels with an overall 46,080 readout channels per module. It is arranged in three barrels and three disk layers at each end-cap. When a particle deposits energy in a pixel, it is recorded as a *hit*. Each pixel has a size of $50 \times 400 \mu\text{m}^2$ in $\phi - z$, offering a spatial resolution of $10 \mu\text{m}$ in $r - \phi$ and $115 \mu\text{m}$ in z per hit in the barrel region. At the end-caps,

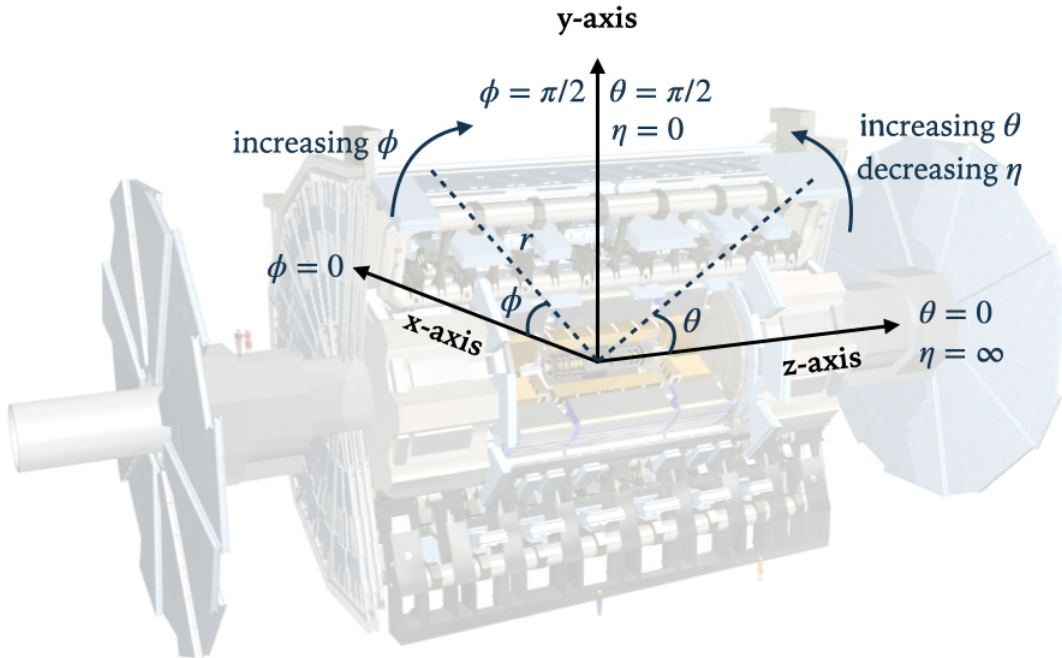


Figure 3.6: The ATLAS coordinate system. Base image taken from [44] and modified.

the resolution is $10\mu\text{m}$ in $r - \phi$ and $115\mu\text{m}$ in r per hit. When the hits are combined, the *track* of the particle trajectory can be determined. A minimum of three hits in the PD is required for track reconstruction. From the track information, the intersecting point from which all the tracks emerge can be found, which is identified as the interaction *vertex*. To ensure long-term physics performance coping with the increasing luminosities, the PD was upgraded in 2014 to install an additional layer called the insertable B-layer (IBL), which is now the closest layer to the beam pipe [49]. The insertion of this layer is to improve the tracking and the vertexing efficiencies, especially for b-quark initiated jets in the busy environment, and to protect the inner pixel layer from radiation damage.

Surrounding the PD lies the Semiconductor Tracker [50], [51] which is designed to provide precision measurements for track reconstruction. It consists of 4,088 modules of silicon-strip detectors arranged in four cylindrical layers in the barrel region and nine planar disks at the end-caps, with more than 6 million readout channels. Each module gives two strip measurements, corresponding to two hits, at a stereo angle which are combined to build a space-point. Typically, the SCT offers four space points for track reconstruction of particles originating from the interaction point. It provides a spatial resolution of $17\mu\text{m}$ in $r - \phi$ and $580\mu\text{m}$ in z (in r) in the barrel (at the end-cap) for each space-point.

The next layer encircling the SCT is the Transition Radiation Tracker [52], [53]. It consists of straw drift tubes with transition radiation material embedded in between. The straw tubes are filled with a gaseous mixture of 70% Xe, 27% CO_2 , and 3% O_2 , and polypropylene layers are used to stimulate transition radiation when the charged particle crosses the two media. There are 50,000 straw tubes in the barrel and 250,000 in the end-cap regions, with over 351,000 readout channels. It provides 36 (or 22) hits per track on average in the barrel (or end-cap), contributing

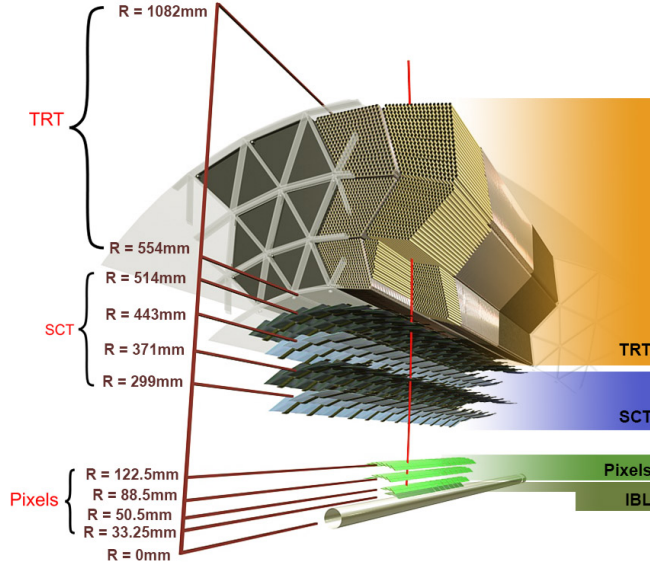


Figure 3.7: A schematic of the radial layout of the ATLAS Inner Detector showing the different detector layers. Image taken from [46].

to continuous tracking. Each straw in the TRT offers a precision of $130\text{ }\mu\text{m}$ in $r - \phi$ for a hit. In addition to tracking capabilities, the TRT can distinguish between electrons and pions due to the high efficiency of xenon to absorb transition radiation photons. When the charged particle crosses the polypropylene layer, it generates X-ray photons which are absorbed by xenon producing further ionization electrons. Pions radiate fewer transition radiation photons compared to electrons, thus enabling the TRT to discriminate between the two particles.

3.2.2 The Calorimeter

The ATLAS calorimeter system is designed to perform a disruptive measurement of the total energy carried by the incoming particles by bringing them to a halt. Depending on the type of interacting particles, the calorimeter system is classified as the Electromagnetic Calorimeter (ECal) and the Hadronic Calorimeter (HCal). An overview of the ATLAS calorimeters is shown in Figure 3.8. The ECal measures most of the energy of photons and electrons that interact electromagnetically, while the HCal measures most of the energy of hadrons through their strong and electromagnetic interactions. Both the calorimeters are of *sampling* type in construction, with alternating layers of absorber and active materials. When an incoming particle interacts with the absorber material, a shower of secondary particles is generated, and the energy deposited in the process is read out from the sampling layers. The measured signal, along with the shower development profile, provides an estimate of the energy of the incident particle.

The ECal [54] consists of a barrel and two end-cap calorimeters covering the region $|\eta| < 3.2$. The calorimeter utilizes liquid-argon as the readout material interleaved with lead absorber plates bent in an accordion shape, allowing for full coverage in ϕ . Figure 3.9 presents a sketch of the accordion geometry of ECal. The ECal measures energy in three layers. Layer 1 is finely segmented to provide an accurate measurement in η . Layer 2 collects most of the shower energy due to the large radiation lengths it covers, and layer 3 captures the tail of the shower that has leaked from layer 2. There is also has an additional layer called the presampler before layer 1, which corrects for any energy lost by the particles prior to reaching the ECal. $1.37 < |\eta| < 1.52$ corresponds to the barrel/end-cap

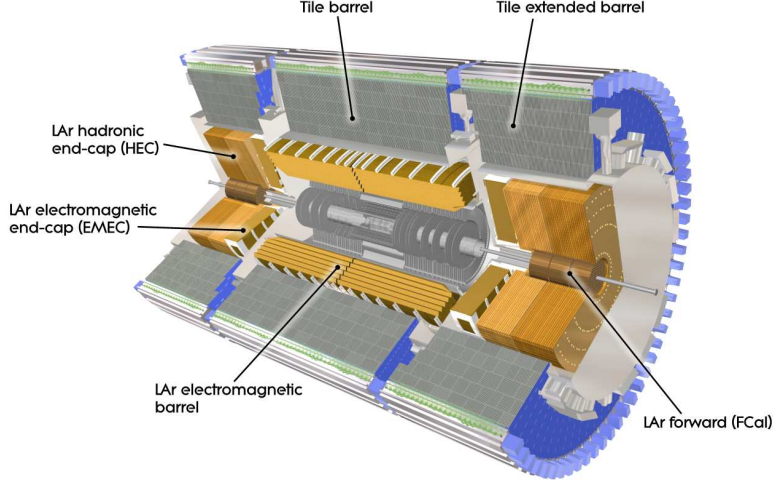


Figure 3.8: A cut-away view of the ATLAS Calorimeters. Image taken from [44].

transition region accommodating the service cables, and the calorimeter performance is not optimal in this region.

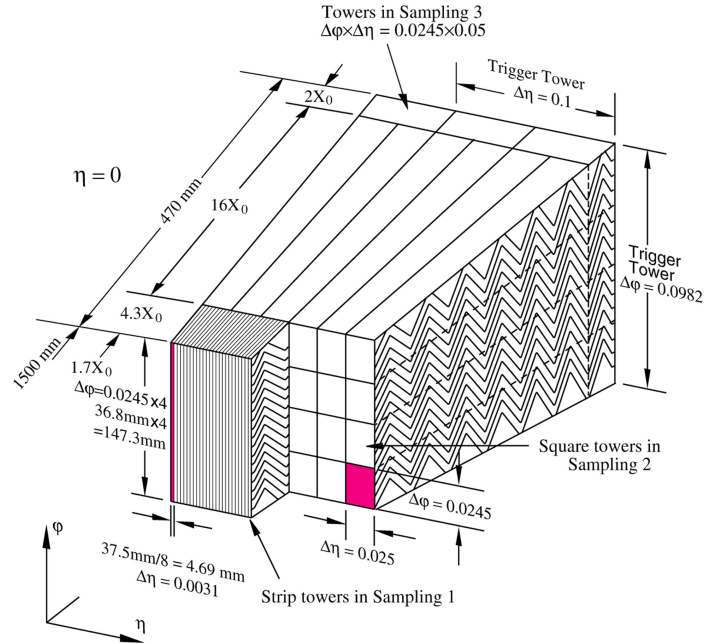


Figure 3.9: A schematic diagram of the barrel module of the ATLAS ECal showing different layers in $\eta - \phi$. Image taken from [44].

The HCal is purposed to measure the energy of jets and it consists of a barrel tile calorimeter (TileCal) and two hadronic end-cap calorimeters (HEC). The TileCal [55] uses iron as the *absorber* and plastic scintillating tiles as the *active medium* covering $|\eta| < 1.7$, while the HEC [56] is a copper/liquid-argon calorimeter located at $1.5 < |\eta| < 3.2$. To cover the forward regions, a liquid-argon based Forward Calorimeter (FCal) [57] is used. It consists of one electromagnetic and two hadronic layers. The electromagnetic FCal uses copper, and the hadronic layers use tungsten as

the absorbers. Located at $3.1 < |\eta| < 4.9$, the FCal is designed to reconstruct the energy of forward jets, and together with HCal, it serves to measure the missing transverse momentum.

The energy resolution offered by the ATLAS calorimeter system can be parametrized as:

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c, \quad (3.5)$$

where a is the stochastic term due to the intrinsic fluctuations in the shower development, b is the noise term due to the electronic noise of the readout chain, and c is the constant term due to instrumental effects. The symbol $\oplus$ indicates the quadratic sum. A summary of the energy resolution of the different calorimeter layers is given in Table 3.1. It is worth noting that the ATLAS detector is also equipped with cryostats where the calorimeters are housed to maintain low operating temperatures.

Calorimeter system	Resolution
ECal	$\sigma_E/E = 10\%/\sqrt{E} \oplus 0.7\%$
HCal	$\sigma_E/E = 50\%/\sqrt{E} \oplus 3\%$
FCal (electromagnetic)	$\sigma_E/E = 28.5\%/\sqrt{E} \oplus 3.5\%$
FCal (hadronic)	$\sigma_E/E = 94\%/\sqrt{E} \oplus 7.5\%$

Table 3.1: The energy resolution of the various ATLAS calorimeter systems is given. Noise term is not considered here. The electromagnetic layers are tested using electron beams. The HCal and the hadronic FCal are studied using pion beams [44], [57].

3.2.3 The Muon Spectrometer

The Muon Spectrometer (MS) [58] is the outermost layer of the detector surrounding the calorimeters. Muons are minimally ionizing and can easily pass through the calorimeters. Therefore, the MS is placed the furthest to provide high-resolution measurements of the position and the momentum of muons in $|\eta| < 2.7$. It provides a momentum resolution of 10% for 1 TeV [44]. The detector systems are arranged in three concentric layers along the beam axis in the barrel at $r = 5$ m, 7.5 m, and 10.5 m approximately from the beam pipe. At each end-cap, they take the form of wheels located at three different stations at $z = 7.4$ m, 14 m, and 21.5 m from the interaction point.

The MS has two types of detector chambers covering the barrel and the end-cap regions: trigger chambers and precision chambers. When the trigger chambers detect a muon, the detectors flag the respective event to determine whether to store the data of the event or not. The precision chambers, on the other hand, provide the track and the momentum measurements of the muon. The trigger chambers utilized in the MS are Resistive Plate Chambers (RPCs) and Thin Gap Chambers (TGCs) respectively in the barrel and at the end-caps. Monitored Drift Tubes (MDTs) are used for track reconstruction in the MS except in the innermost ring closest to the beam pipe in the inner wheel where the particle flux is higher. In this region, Cathode Strip Chambers (CSCs) are used due to their higher rate capacity. The schematic view of the Muon Spectrometer is shown in Figure 3.10 and the pseudorapidity coverages of the sub-detectors are detailed in Table 3.2.

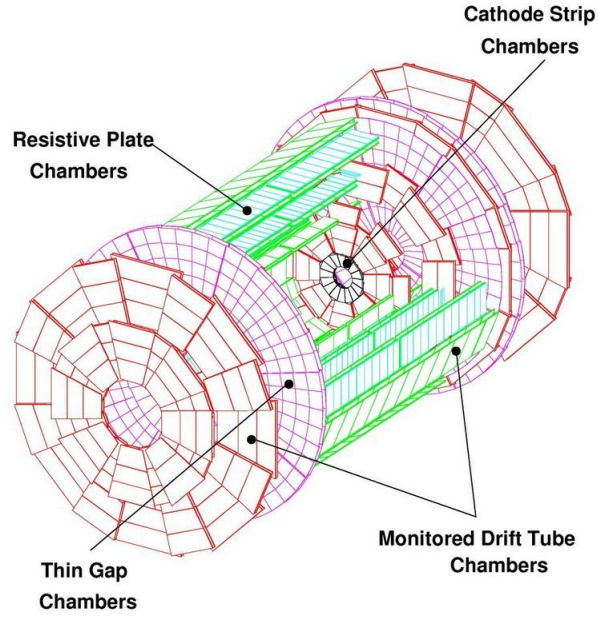


Figure 3.10: A schematic view of the Muon Spectrometer. Image taken from [58].

Barrel	
Detector Chamber	η Coverage
MDT	$ \eta < 1.05$
RPC	$ \eta < 1.05$
End-cap	
Detector Chamber	η Coverage
MDT	$1.0 < \eta < 2.7$
CSC	$2.0 < \eta < 2.7$
TGC	$1.05 < \eta < 2.4$

Table 3.2: The pseudorapidity coverage of the different detector chambers of the Muon Spectrometer.

3.2.4 The Magnet System

The ATLAS magnet system consists of four large superconducting magnets, with a central solenoid and three toroids (one barrel and two end-caps) [59], as shown in Figure 3.11, to bend the trajectory of charged particles for momentum measurement. The central solenoid provides a magnetic field of 2 T along the beam axis to the inner detector. The barrel toroid consists of eight coils, and another eight coils make up each of the end-cap toroids. The barrel and the end-cap toroids give a magnetic field of 0.5 T and 1 T respectively to the central and end-cap regions of

the muon spectrometer. The entire magnet system is 26 m in length and 22 m in diameter, and is maintained at cryogenic temperatures.

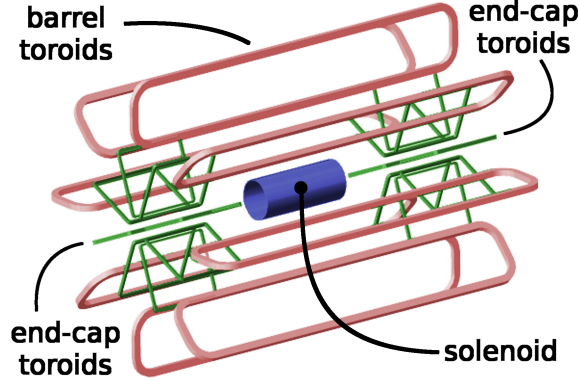


Figure 3.11: A schematic view of the ATLAS magnet system. Image taken from [60].

3.2.5 Luminosity Detectors

To measure the cross-section of any physics process in the ATLAS detector, it is necessary to determine the luminosity of the beams recorded by the detector³. The two main dedicated systems employed by ATLAS are LUMinosity measurement using Cerenkov Integrating Detector (LUCID) and Beam Conditions Monitor (BCM).

LUCID is purposed to detect inelastic proton-proton scattering in the forward direction to monitor the online beam conditions and measure the instantaneous and integrated luminosities. The detector is positioned symmetrically at a distance of 17 m from the IP. It consists of twenty polished aluminium tubes, and Cherenkov photons produced in the tubes undergo reflection which are then read out using photomultiplier tubes.

The main task of BCM is to monitor the beam conditions close to the interaction point and protect the ATLAS detector from any damage caused by beam losses. If several protons hit the beam pipe, it results in an enormous production rate of secondary particles that can cause damage to the main detector. Due to its fast readout, BCM is designed to identify collisions originating at the IP from background events and to determine luminosity. It consists of four diamond sensors located at 1.84 m on either side of the IP.

The primary bunch-by-bunch luminosity measurement is provided by LUCID complemented by BCM and other offline measurements. Recalling Equation (3.1), the only unknown parameter in luminosity determination is $\sigma_x \sigma_y$. It can be obtained experimentally from dedicated *van der Meer* scans where the location of one beam is varied with respect to the other, and studying the mean proton-proton interactions. Further details on the calculations can be found in [61]. In Run 2, ATLAS has measured the most precise luminosity estimate ever achieved with an uncertainty of 1.7% [62].

3.2.6 Trigger and Data Acquisition

The LHC delivers data at an astounding rate with millions of collisions per second, but the number of “interesting” events produced are not at all comparable with this rate. In fact, only

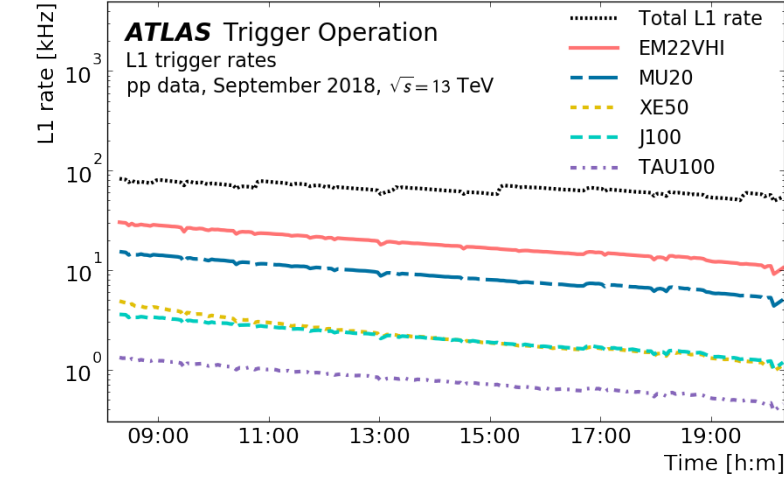
³Not all the luminosity delivered by the LHC is captured by the detector due to the limited geometrical acceptance and the detector conditions during data taking.

100 W bosons that decay into leptons are produced every second. Rare events like the electroweak $W^\pm W^\pm jj$, the signal studied in this thesis, occur only once every ten hours⁴!

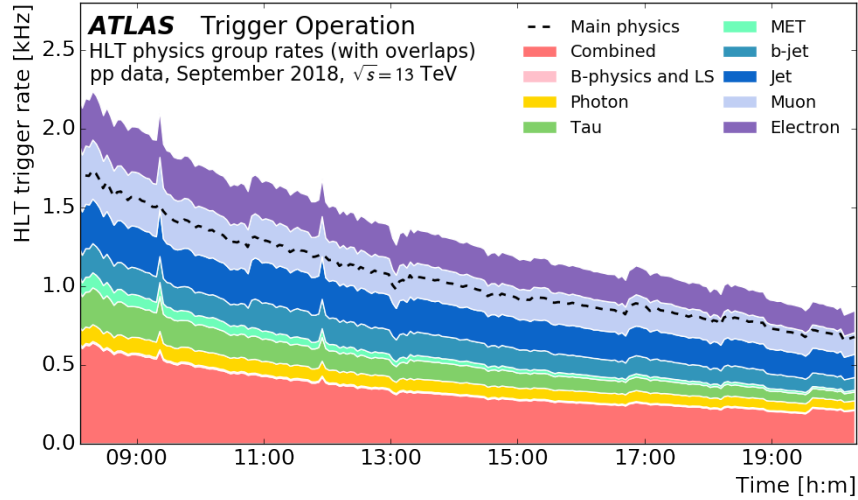
Since it is technically impossible to store all the collision data, ATLAS uses an extensive trigger system that saves only the interesting events and rejects the rest. This task is delegated between a hardware-based Level-1 (L1) trigger and a software-based high-level trigger (HLT). The L1 trigger receives the signal from the calorimeter and the muon detectors, selecting only objects⁵ with differentiating characteristics, thus reducing the event rate from the design bunch crossing rate of 40 MHz to 100 kHz. L1 trigger employs a generic object definition, and the objects meeting the selection criteria fire the trigger. The events passing the L1 trigger are directed to the HLT, which analyzes the selected events in greater detail, reducing the rate further down to 1 kHz. This can be better understood from Figure 3.12, which summarizes the ATLAS trigger rates in an LHC fill taken in July 2016. The Event Builder collects all the data fragments of the events selected by HLT and then assembles and builds the complete event. The Event Builder provides the fully assembled events to the Event Filter, the last element of the trigger system. The Event Filter accesses the fully built raw event, runs the offline algorithms, and writes the output to permanent mass storage. The Event Filter makes the final event selection and reduces the event rates to 100 Hz. In Run 2, the Event Builder and the Event Filter systems have been merged into the HLT farm, which reduces algorithm duplication and results in a more flexible HLT with better resourcing and an optimized workflow [63]. From the recorded data written to the storage, the particles and the various kinematic parameters are identified. The reconstructed data must pass certain quality conditions before being used for physics analyses.

⁴The rates mentioned are the predictions for a nominal luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$.

⁵An object is any physically detectable quantity in the detector like an energy deposit in the calorimeter or a reconstructed track.



(a) Level-1 trigger rate



(b) High-level trigger rate

Figure 3.12: The ATLAS trigger rates during an LHC fill is given. The L1 trigger rates are shown in (a). Events passing the L1 trigger are directed to the HLT which applies more stringent object definitions reducing the rate even further as given in (b). The sudden rises in the rates correspond to new triggers being enabled and the slow exponential falls are results of the decreasing luminosity during the fill. Images taken from [64].

Chapter 4

The New Small Wheel Upgrade

With the benchmark achievements and growing interest in the physics program at CERN, it becomes necessary to improve the performance of the LHC and churn out data at an even higher and astounding rate. The High-Luminosity Large Hadron Collider (HL-LHC) [65], a project led by CERN, aims to deliver luminosity 7.5 times larger than the current design luminosity. The project is one of the top priorities of the European Strategy for Particle Physics and requires several technological innovations and upgrades. Figure 4.1 shows the current schedule of the LHC/HL-LHC, and the project is expected to be installed before Run 4 during the third long shutdown.

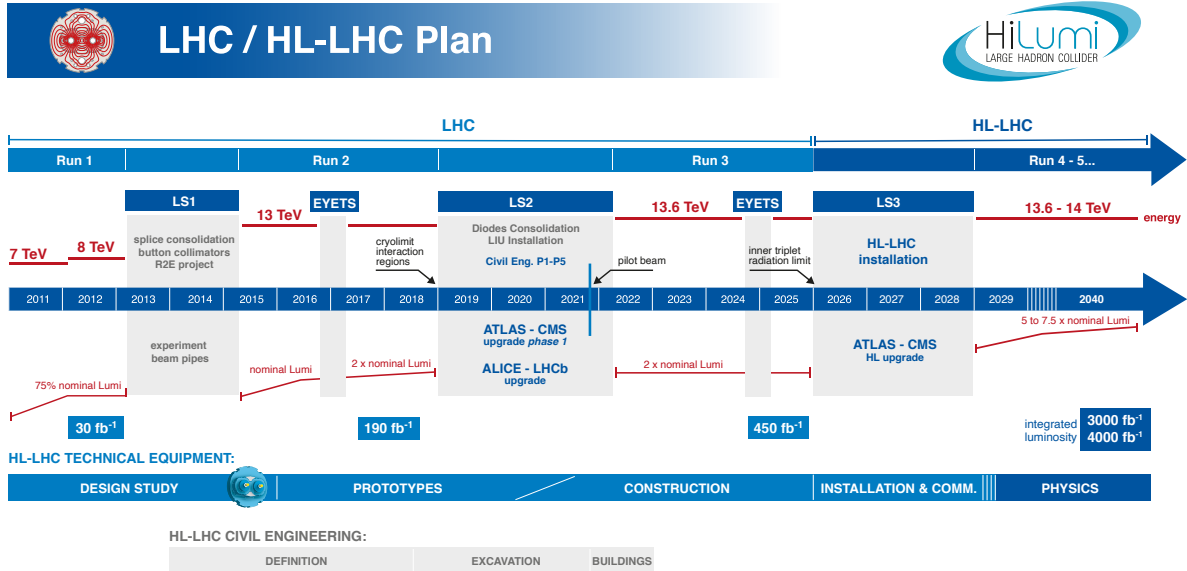


Figure 4.1: LHC schedule for the next years in preparation towards HL-LHC. Image taken from [66].

In order to cope with the extreme conditions of the HL-LHC environment, the experiments also require subsequent upgrades. The upgrades for the ATLAS detector are performed in two phases. Phase I upgrade spanned over the years 2019 to 2022, and Phase II upgrades are scheduled along with the installation of HL-LHC between 2026 and 2028.

During the Phase I upgrade, the innermost wheels at the end-cap region of the Muon Spectrometer are replaced by the *New Small Wheels* (NSW), and new detectors are added in the barrel region to improve the triggering and the tracking performance of the Muon Spectrometer. In addition, the electronics of the LAr calorimeter system (described in Chapter 3) have been upgraded to maintain good trigger performance, and the Trigger and Data Acquisition (TDAQ) system (described in Chapter 3) is also upgraded to keep the trigger rates at sustainable levels.

For the Phase II upgrade, the current Inner Detector will be replaced by an all-silicon tracking system known as the Inner Tracker (ITk). In addition, LAr and Tile calorimeters will be upgraded to meet the radiation hardness of the HL-LHC environment. Improvements are also planned for the muon and the TDAQ systems.

This chapter focuses on the New Small Wheel upgrade of the ATLAS detector. The details on the motivation for the upgrade are summarized in Section 4.1. Sections 4.2 and 4.3 describe the different detector technologies used and the layout of the New Small Wheel design. The high voltage power system is introduced in Section 4.4 where the author has made significant contributions. The author finalized the naming convention explained in Section 4.4.1 and devised the connection scheme discussed in Section 4.4.2. Finally, the author developed solely the project described in Section 4.5. It has to be noted that all the project details presented in this chapter reflect the developments at the time of writing this thesis.

4.1 Motivation for the New Small Wheel

Recalling the layout of the Muon Spectrometer presented in the previous chapter, the muon detectors are arranged in the form of wheels at the end-caps. The innermost wheel closest to the IP is known as the *Small Wheel* while the other wheels are called the *Big Wheels*. A longitudinal cross-sectional view of a quarter region of the ATLAS detector showing the location of the Small Wheels is shown in Figure 4.2. The Small Wheels are not compatible with the high particle rate conditions of the HL-LHC and would result in poor triggering and tracking performances. The “New” Small Wheels, replacing the Small Wheels, are designed to maintain excellent performance during the HL-LHC era. The motivation to improve the trigger and tracking capability that necessitated such an upgrade is discussed below.

4.1.1 Trigger Performance

The information to the L1 muon triggers at the end-cap region is provided solely by the three layers of TGCs mounted on the Big Wheel in the middle station, situated nearly 14 m along z from the IP. Any track traversing through the TGCs that points to the IP is a potential candidate to fire the L1 trigger. In this configuration, tracks that do not originate from the IP but journey through the TGCs as real muons from the IP can also fire the trigger. An abundant source of background that results in such false trigger decisions is the low energy particles produced due to the interactions with the end-cap toroid or any other material between the Small Wheel and the Big Wheel regions. In fact, performance studies have confirmed the unexpectedly high fake trigger rates at the end-caps. Figure 4.3 shows the η distribution of the muon candidates with at least 10 GeV that fired the L1.MU11 trigger. The distributions of those candidates that were reconstructed offline as muons and as muons with $p_T > 10$ GeV can also be seen in the figure. It is clear that 90% of the muon candidates that fired the trigger are fakes that are not reconstructed offline.

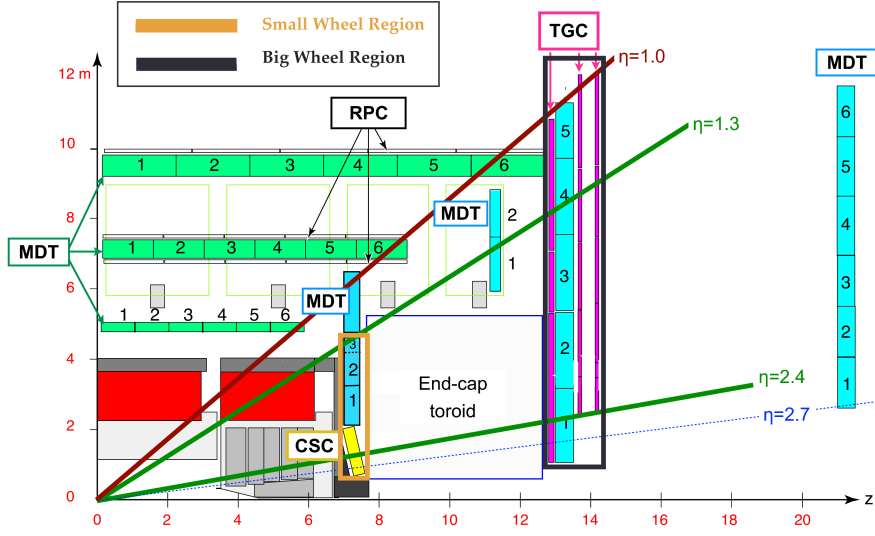


Figure 4.2: A view of a quarter region of the ATLAS detector in the $z - y$ plane is shown. Image is taken from [67] and modified. The green and the blue boxes show the MDTs in the barrel and the end-cap regions. CSCs are displayed as the yellow box in the Small Wheel region. RPCs and TGCs are indicated by the outlining white and magenta lines. The figure shows the Small Wheel along with the Big Wheel in the middle station. The Big Wheel in the outer station can be seen in the figure, but it is not explicitly marked.

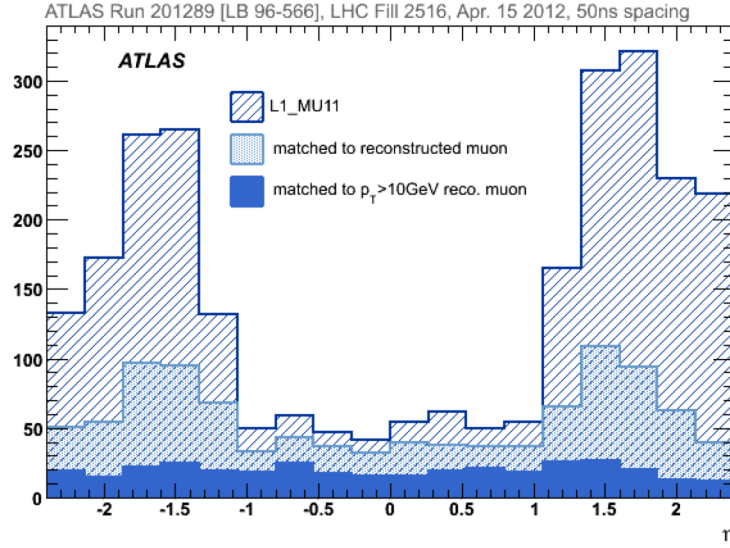


Figure 4.3: The η distribution of the muon candidates that fire the L1_MU11 trigger is shown. The subsets of muon candidates passing the offline reconstruction and matched to $p_T > 10 \text{ GeV}$ are also plotted. Image taken from [68].

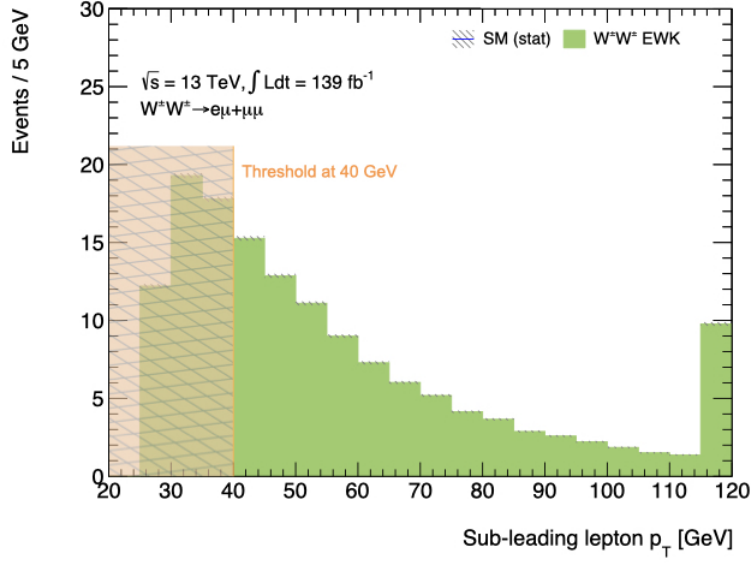


Figure 4.4: The p_T distribution of the (sub-leading) muons in the signal measured in this thesis as simulated by MADGRAPH for 139 fb^{-1} is shown. The hashed band indicates the signal events lost if the trigger threshold is raised to 40 GeV.

One can recall from the previous chapter that the current overall L1 trigger rate is 100 kHz. Even in a busy environment, only 20 kHz can possibly be allocated to single lepton muon L1 triggers. But for a p_T threshold of 20 GeV, the trigger rates are expected to be as high as 60 kHz, which is three times larger than the target rate. Therefore, to keep the trigger rates at sustainable levels, it becomes necessary to either apply prescales to the triggers or raise the p_T threshold in the trigger definition, both of which are undesirable for many physics analyses. Applying trigger prescales will save only one event out of every n events that fire the trigger where n is determined by the prescale chosen. Searches for exotic particles and rare events like Higgs production, vector boson scattering, etc., will suffer adversely from poor statistics if prescaled triggers are used for data taking. On the other hand, if the p_T threshold set in the trigger definition is raised, many analyses will have limited acceptance for measurements, which is detrimental to the scope of the ATLAS physics program. In the context of the measurement described in this dissertation, the impact of raising the muon trigger threshold to 40 GeV on the signal sought after is shown in Figure 4.4 as an example. But even for $p_T > 40 \text{ GeV}$, the L1 rate is expected to be 30 kHz which still exceed the target rate by 50%.

With the Phase I upgrade, the muon trigger performance can be substantially improved to meet the target rate by the New Small Wheels with its dedicated triggers. A schematic of the muon end-cap trigger with the expected improvement by the NSW is shown in Figure 4.5. The Big Wheel accepts muon candidates from tracks A, B, and C, all of which are directed to the IP. With the additional coordinate offered by the NSW to the track reconstruction, false muon candidates from tracks B and C can be rejected, and L1 triggers will be fired only by the genuine muon track A. Thus, the NSW reduces the fake trigger rates significantly and allows to maintain the low p_T threshold for the triggers. This is achieved by delivering the track information to the muon trigger electronics not later than the latency of ATLAS after a collision and providing an angular resolution of 1 mrad or better for the track segments.

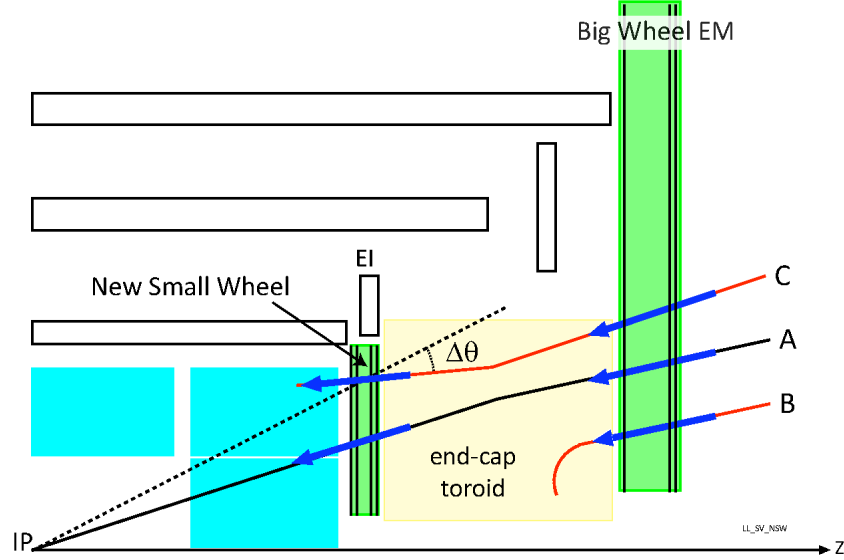


Figure 4.5: A schematic of the muon end-cap trigger with the intended improvement by the NSW. Image taken from [68]. Tracks A, B, and C correspond to the muon candidates accepted by the Big Wheel trigger systems. With the NSW, additional information of the particle trajectory is made available, and only track A from the genuine muon can fire the trigger. Track B and C, though pointing to the IP, will be rejected.

4.1.2 Tracking Performance

To precisely measure the p_T of muons, track information needs to be gathered from all the three wheels of the end-cap. Track segments are built from hits in each wheel, and then the segments are linked to form the particle track. The efficiency of the MDT¹ detectors as a function of the particle hit rate is shown in Figure 4.6. For a hit rate of 300 kHz (maximum rate expected for the design luminosity of the LHC), the efficiency of a single MDT is only 65% while the performance of an MDT chamber for this rate is still better as only a subset of the hits is required to build the track segments. In a high luminosity environment, the Small Wheel MDTs are required to operate at even higher rates and the efficiency of both the tube and the chamber drop drastically above 300 kHz. As the end-cap toroidal magnets are situated between the Small Wheel and the Big Wheel, tracking inefficiency of the Small Wheel would imply that the muon momentum cannot be measured accurately, which would significantly affect the physics performance. During the HL-LHC, the hit rate is expected to be at least five times larger, and the upgrade to NSW is essential for maintaining the excellent level of performance in the high rate environment. With the NSW, an efficiency of more than 97% can be achieved for muons with p_T greater than 10 GeV, and the muon p_T can be measured with a precision of 10% for 1 TeV.

¹An MDT is a pressurized aluminium tube with a diameter of 30 mm filled with Ar/CO₂ (93%:7%) gas held at 3 bar. The tube consists of a tungsten-rhenium anode wire of diameter of 50 μ m kept at a potential of 3 kV. When a muon traverses the volume, it ionizes the gas and the electrons produced drift towards the anode. From the drift time of the electrons, the location of the hit can be identified. Several MDTs form an MDT chamber. In general, an MDT chamber consists of two layers of four tubes each.

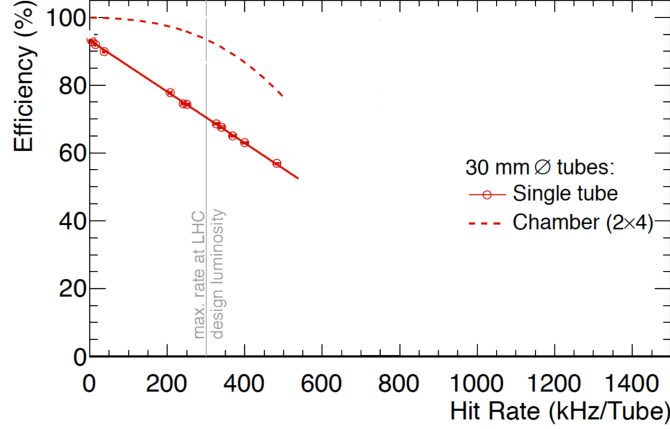


Figure 4.6: The efficiency of the MDT detectors as a function of the particle hit rate is shown. Image taken from [68]. The solid line corresponds to a single MDT, and the dashed line corresponds to an MDT chamber with 2×4 tube layers.

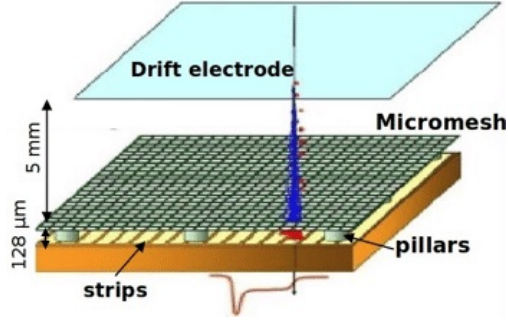
4.2 Detector Technologies

To furnish the colossal triggering and tracking demands in high particle flux conditions, the NSW employs two types of detector technologies, *Micro-mesh Gaseous Detector* (Micromegas) and *small-strip Thin Gap Chamber* (sTGC), both from the family of gaseous detectors. Due to its exceptional capabilities in precision tracking, the micromegas detector is chosen as the primary NSW tracker. The sTGC is the dedicated trigger detector of the NSW as it exhibits excellent bunch crossing identification capacity. The sTGC can also function as a tracker whereas the micromegas can also contribute to the trigger needs. The choice of the detectors builds the robust and redundant triggering and tracking systems of the NSW. The structure and operating principle of the two detectors are briefly described below.

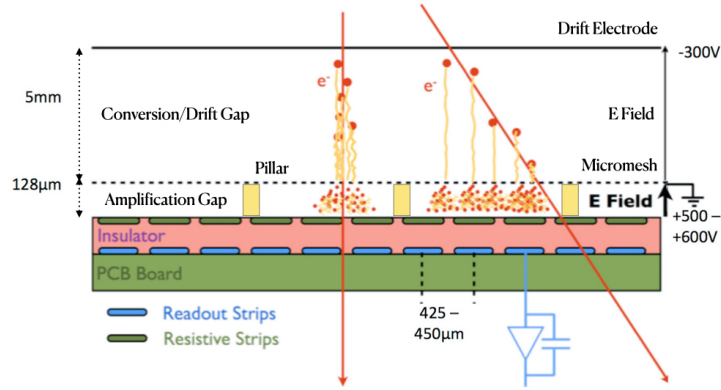
4.2.1 Micromegas

Micromegas (MM) detectors belong to the family of micro-pattern gaseous detectors, which are ionization detectors with microelectronic structures having a very thin region of high electric field for gas amplification.

A sketch of the design of the NSW MM detector is shown in Figure 4.7a. The micromegas detector consists of two parallel electrodes enclosing a volume of $\text{Ar}(93\%):\text{CO}_2(7\%)$ gas mixture. A metallic mesh separates the gas gap into a *drift gap* and an *amplification gap*. The mesh itself is made up of stainless steel wires, and it is placed at a distance of 5 mm from the drift cathode and 128 μm from the readout anode. To maintain the tiny and precise separation for the amplification gap, the mesh is supported on insulating spacers called pillars that are glued onto the readout anode. A positive voltage of +570 V is applied to the anode, whereas the drift cathode is held at a potential of -300 V, and the mesh is connected to the ground. The potentials are chosen such that there is an electric field of $\sim 600 \text{ V/cm}$ in the drift gap and $\sim 45 \text{ kV/cm}$ in the amplification gap. In addition, the anode is segmented into an upper layer of carbon resistive strips to mitigate any possible sparks and a lower layer of copper strips for readout. The readout plane is made up



(a)



(b)

Figure 4.7: A sketch of the layout of the MM detector is shown in (a). Image taken from [69]. The working principle of the detector is illustrated in (b). Image taken from [70] and modified.

of a printed circuit board (PCB) where the readout strips are printed on with a pitch² of $\sim 400 \mu\text{m}$. With the small pitch of the readout strips, a position resolution of $\sim 100 \mu\text{m}$ can be achieved.

The operating principle of the MM detector is depicted in Figure 4.7b. Muons traversing the drift gap ionize the gas, and the electrons produced in the process proceed towards the mesh. As the electric field in the amplification gap is nearly 75 times stronger than the drift field, almost all the electrons transit through the mesh and enter the amplification region, where they create avalanches. Due to the tiny amplification gap, fast pulses of electrons reach the readout strips in less than a nanosecond, whereas the ions generated in the avalanches migrate towards the mesh in about 100 ns. This drift time of the ions is very short compared to that in the drift tubes ($\sim 700 \text{ ns}$), and it is the fast evacuation of the ions which makes the detector particularly capable for high rates.

²The strip pitch is $425 \mu\text{m}$ for small sectors and $450 \mu\text{m}$ for large sectors. The concept of small and large sectors is discussed in Section 4.3.

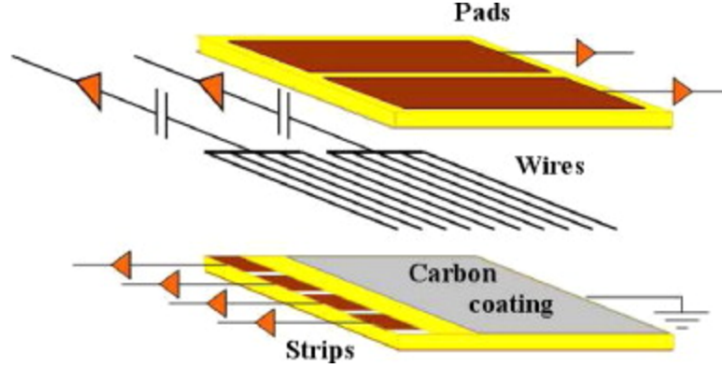


Figure 4.8: A schematic diagram of a small-strip TGC is presented. Image taken from [68].

4.2.2 small-strip Thin Gas Chamber

The small-strip Thin Gas Chamber is a multi-wire proportional chamber operating in a high rate environment, and it is the primary trigger detector for the NSW. Figure 4.8 shows a schematic diagram of a small-strip TGC. It consists of a plane of $50\text{ }\mu\text{m}$ thick gold-plated tungsten anode wires, immersed in a gas mixture, sandwiched between two cathode planes at a distance of 1.4 mm on each side. The anode wires³ have a pitch of 1.8 mm and are held at a potential of $+2.8\text{ kV}$. When a muon passes through the gas mixture, it ionizes the gas, and the ionization electrons drift towards the nearest anode under the influence of the electric field and generate a signal. The gas mixture chosen is $\text{CO}_2(55\%):\text{n-pentane}(45\%)$ to absorb any undesirable photons produced the ionization process that can initiate new avalanches. Due to the high electric field around the anode wires and the small distance between them, a time resolution of less than 25 ns is obtained, which helps in identifying muons originating from different bunch crossings.

The cathode takes the shape of large pads on one side and fine copper strips running perpendicular to the anode wires on the other. The pads cover large areas, identify muon tracks roughly pointing to the IP, and deliver fast trigger information to the L1 muon trigger. It also determines which subset of strips to be read out. The strips are separated by a distance of 3.2 mm and provide precise track information for reconstruction. It offers a position resolution ranging from $60\text{ }\mu\text{m}$ for perpendicular incidence to $150\text{ }\mu\text{m}$ for large angles. Due to the small strip pitch compared to the ATLAS TGC strip pitch of $150\text{--}490\text{ mm}$, this technology is known as the ‘small-strip TGC’.

The sTGCs and the micromegas detectors utilized in the NSW are planar in structure that perfectly fit the design needs of the NSW, which is described in the next section.

³The spacing between the anode wires and the gap between anode and cathode are chosen such that the best time resolution can be achieved for the lowest operating voltage.

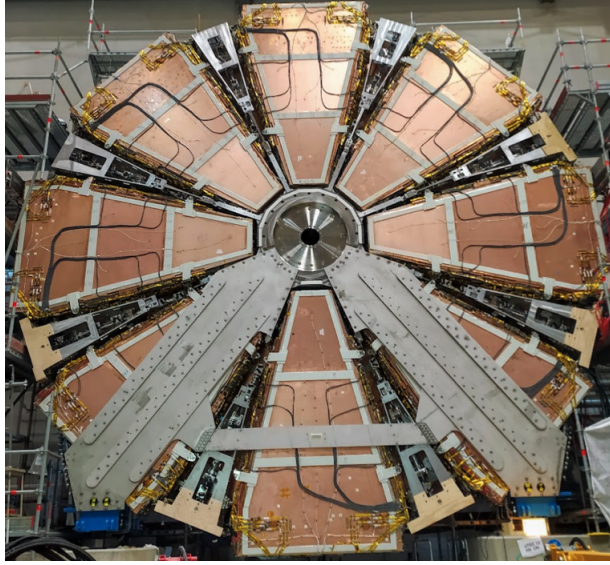


Figure 4.9: The New Small Wheel during surface commissioning with all the sectors assembled.

4.3 General Layout of the NSW Structure

As the name suggests, the New Small Wheel takes the shape of a wheel similar to the Small Wheel. It is 10 m in diameter and weighs about 100 tons. The wheel is sliced into 16 *sectors*, arranged alternately into large and small sectors⁴ such that every (large/small) sector slightly overlaps with two other (small/large) sectors. The small sectors are mounted on the side of the wheel closer to the IP, whereas the large sectors are installed on the other side. The physical dimensions of the wheel at each end-cap are carefully chosen not to exceed the dimensions of the Small Wheel. Figure 4.9 shows the New Small Wheel with all the 16 sectors assembled. Each sector is an assembly of the two detector technologies, stacked as sTGC - MM - MM - sTGC, along the z -direction in the form of four *wedges* as illustrated in Figure 4.10. A hit in one of the sTGC wedges prompts the search for a subsequent hit in the other sTGC wedge. If both the sTGC wedges confirm hits, then the L1 muon trigger is fired, and the precise track information is gathered from the MM detectors. Each wedge further consists of four layers of the respective detectors along the z -direction. Therefore, a muon passing through a sector in the NSW traverses through 16 detection layers: eight layers of sTGC and eight layers of MM. The choice of eight layers per detector type ensures a robust and prime performance of the NSW throughout the whole lifetime of the ATLAS experiment. Even if one of the layers fails to function, the tracks can still be reconstructed reliably with high precision, making them suitable for long-term operations. The NSW renders a trigger acceptance in $1.3 < |\eta| < 2.5$ and precision tracking acceptance in $1.3 < |\eta| < 2.7$.

4.4 The High Voltage Power Systems

The sTGC and the MM detector technologies of the NSW are both operated with high voltages, as discussed in Section 4.2. An sTGC detector is operated with a single high positive voltage of +2800 V, and the maximum current expected is 100 μA even in the highest luminosity conditions. Therefore, considering a safety factor of five, the HV power system should supply at least 500 μA

⁴The physical size of the large sector is bigger than the small sector as the names imply.

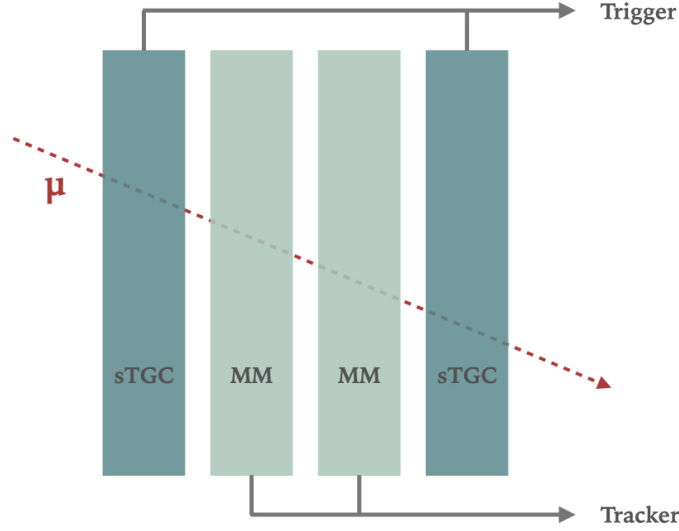


Figure 4.10: Arrangement of the wedges in a New Small Wheel sector.

and a maximum of 3200 V. A current resolution of 0.1 μA and a voltage resolution of 0.5 V are desirable for monitoring purposes to detect any leakage.

In the case of micromegas, the HV system is required to supply a positive voltage of 570 V for the amplification gap and a negative voltage of 300 V for the drift gap. Therefore, a power system delivering a maximum voltage of ± 1000 V should be optimal as a safety margin. Furthermore, as only the amplification gap needs to drive large currents to magnify the signal, the HV system should supply a maximum current of 10 μA (including a safety factor of five) in the amplification gap, whereas, in the drift gap, a supply of 1 μA is sufficient. A current resolution of 2 nA and a voltage resolution of 0.5 V are desirable for monitoring. A summary of the high voltage requirements of the power systems is given in Table 4.1 for sTGC and MM detectors.

HV Parameters	Value for sTGC	Value for MM
Max.output voltage (V)	+3200	+1000, −1000
Max.output current (μA)	500	10,1
Voltage resolution (V)	0.5	0.5
Current resolution (μA)	0.1	0.002

Table 4.1: The requirements of the high voltage power supply in sTGC and MM detectors.

For the ATLAS NSW, the high voltage power supplies are manufactured by *CAEN* [71]. The main high voltage power supply unit is CAEN’s *SY4527* mainframe. The mainframe supplies the high voltage directly to the HV boards for micromegas. In the case of sTGC, the high voltage is distributed from the mainframe to the HV boards using CAEN’s *EASY 3000* crates controlled by

A1676 branch controllers. The HV connections from the mainframe to the readout channels of the MM and sTGC detectors are described in detail later, in Section 4.4.2.

To ensure a smooth operation, the ATLAS experiment has a dedicated central *Detector Control System* (DCS) which checks the operational status of different sub-systems and enables the communication between them. All the DCS applications in ATLAS are based on *SIMATIC WinCC Open Architecture* (WinCC-OA), a *Supervisory Control And Data Acquisition* (SCADA) system from *Siemens*. The different high voltage units of the NSW are controlled by a dedicated HV DCS, which communicates with the NSW DCS, transmitting the information to the central ATLAS DCS. The control systems follow their own naming convention to address the different detector components and units. The following section discusses the naming convention used in the HV DCS.

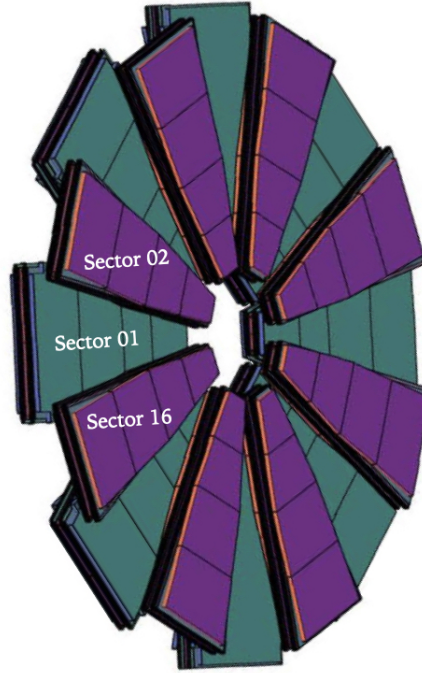


Figure 4.11: An illustration of the NSW sectors is shown. Image taken from [72] and modified. The large sectors are shown in dark green color, and the small sectors are shown in purple color. The numbering starts with 1 from the large sector on the left side of the wheel and follows clockwise. Both the wheels follow the same numbering pattern.

4.4.1 Naming Convention

The naming scheme used in HV DCS, summarized below, is adapted from [73] and is finalized by the author together with the NSW DCS team accommodating to the needs of the project during the final commissioning in 2019.

- **Wheel:** The two New Small Wheels are located at each end-cap of the ATLAS detector. The detector side in the positive z -direction is known as side A and the other side, in the negative z -direction, is known as side C. Therefore, the NSWs located at side A and side C of ATLAS are named respectively as NSW-A and NSW-C.

- **Sector:** In each wheel, the sectors are numbered clockwise, starting with 1 from the left large sector. Thus, all the large sectors have odd numbers (1,3,5,7,9,11,13,15) whereas all the small sectors are assigned even numbers (2,4,6,8,10,12,14,16). Figure 4.11 shows an illustration of the NSW with the sector numbering indicated.
- **Wedge:** The arrangement of the wedges in a sector is discussed already in Section 4.3 and the wedges are numbered, starting from 1, according to their position along the z -direction from IP. The wedge closest to the IP is indicated by Z1 and the farthest wedge by Z4 as depicted in Figure 4.12. The wedges are further segmented radially with two radial segments for MM and four radial segments for sTGC as shown in Figure 4.13.
- **Layer:** The four detector layers that make up a wedge, as mentioned in Section 4.3, are assigned numbers from 1 to 4 indicating its position from IP, with 1 given to the layer closest to IP.
- **PCB:** The layers of a micromegas wedge are further split into eight HV sections denoted by PCB numbers. The segmentation is depicted in Figure 4.14. The R1 segment is divided into five HV sections indicated by PCB1 to PCB5, and the R2 segment is split into three HV sections named as PCB6 to PCB8.

Finally, an HV unit in DCS can be addressed as:

$$\begin{aligned} & \text{EI Z}[1,4] \text{ R}[1-4] [\text{A,C}] [01-16] \text{ L}[1-4] \text{ for sTGC and} \\ & \text{EI Z}[2,3] \text{ R}[1,2] [\text{A,C}] [01-16] \text{ L}[1-4] \text{ PCB}[1-8] \text{ for MM,} \end{aligned}$$

where

- EI denotes Endcap Inner, the location with respect to the ATLAS geometry. It is a standard identifier complying with the ATLAS rules for naming convention.
- Z is the wedge position identifier. As the sTGs form the outer wedges in a sector, they are addressed as Z1 or Z4, whereas the micromegas that form the inner two wedges are identified by Z2 and Z3.
- R is the radial segment identifier within a given Z position. R takes values from 1 to 2 for MM and from 1 to 4 for sTGC.
- A, C indicate the side of the ATLAS detector to identify between NSW-A and NSW-C. The two-digit numbers that follow show the sector number.
- L stands for the layer position identifier.
- PCB represents the radial position of the HV section in micromegas.

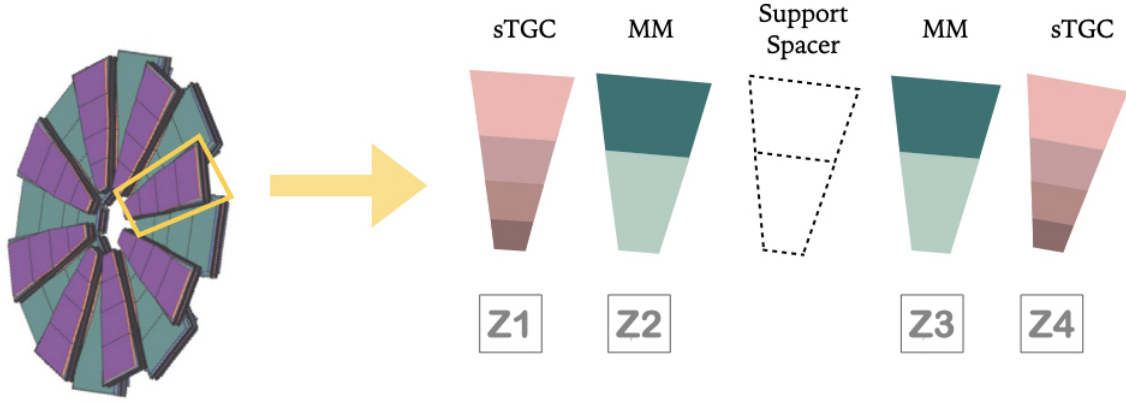


Figure 4.12: A diagrammatic depiction of the arrangement of the wedges in a New Small Wheel sector. The two sTGC wedges are mounted on the outer sides. The MM wedges, located on the inside, are separated by a metallic spacer for support. The wedges are numbered from 1 depending on their position along the z -direction from the IP.

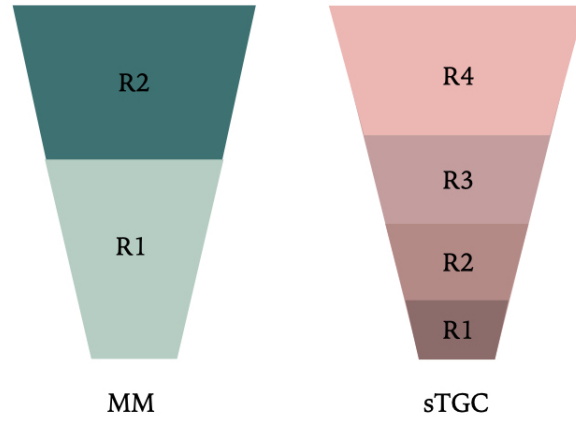


Figure 4.13: A schematic of the radial segmentation of the sTGC and the MM wedges is shown. MM is segmented into R1 and R2, whereas sTGC is divided into R1-R4.

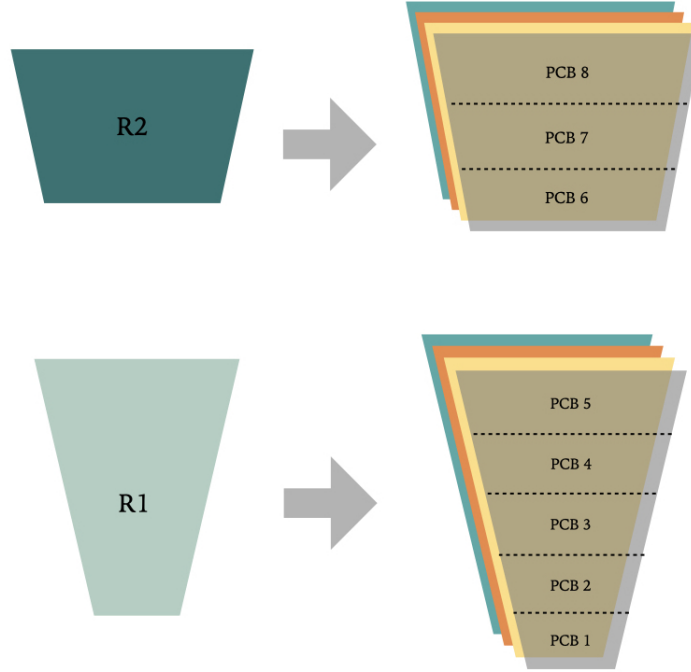


Figure 4.14: The segmentation of a micromegas radial segment into eight HV sections denoted by PCB numbers is shown. The numbers represent the radial position of the HV section. The R1 segment consists of five HV sections marked as PCB1 to PCB5. The R2 segment is divided into three HV sections indicated by PCB6 to PCB8. The arrangement of the four layers in a wedge can also be seen from the figure.

4.4.2 High Voltage Mapping

Ensuring maximum acceptance in the recorded data is of prime importance to the ATLAS physics program. In the New Small Wheels, this is guaranteed by strategically mapping the HV connections from the power supply all the way to the readout channels of the sTGC and the MM detectors mounted on the NSW sectors. The connections need to be made such that any failure in the HV would only have a minimal loss of phase space in the recorded data. Moreover, the connection scheme is carefully chosen by efficiently maximizing the existing resources. The HV mapping scheme for sTGC and MM detectors is developed by the author, and the scheme chosen is identical for both wheels, which is summarized below.

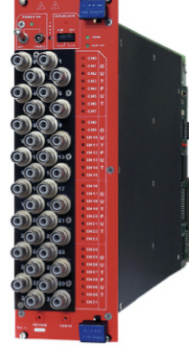
sTGC

In the sTGC wedges, the HV requirement of each radial segment of a layer is furnished by a single HV channel. Therefore, to supply one wheel ($16 \text{ sectors} \times 2 \text{ wedges} \times 4 \text{ layers} \times 4 \text{ radial segments}$), 512 HV channels are needed. This demand is met by CAEN's *A3535* and *A3540* boards. An *A3535* board contains 32 HV channels, and each of these channels supplies 3.2 kV and 0.5 mA in accordance with the HV requirements recorded in Table 4.1.

Due to the high particle influx encountered by the R1 segment, located close to the beam pipe, this segment has been discovered to draw higher currents, sometimes exceeding the current limits of 500 μA . Therefore, *A3540* boards consisting of 12 channels have been additionally chosen, which supply 4 kV and 1000 μA . Figure 4.15 shows the images of CAEN's *A3535* and *A3540* boards.



(a) CAEN's A3540 board



(b) CAEN's A3535 board

Figure 4.15: CAEN's A3540 and A3535 boards used in the high voltage connections for sTGC are shown. Images taken from [71].

Mapping scheme

The A3535 boards supply HV in R2, R3, and R4 segments layer-wise in all the sectors. The channels are first connected to the R2 segment, and after supplying R2 in all the four layers, the connections proceed to R3 until the 32 channels of each board are connected. In simple terms, the connection follows the pattern: $R2A01.L1 \rightarrow R2A01.L2 \rightarrow R2A01.L3 \rightarrow R2A01.L4 \rightarrow \mathbf{R3A01.L1} \rightarrow R3A01.L2 \dots \rightarrow R4A01.L4 \rightarrow \mathbf{R2A02.L1} \dots$. In this configuration, if one A3535 board fails, R2-R4 segments are affected in only three sTGC wedges of an entire wheel.

The A3540 boards supply HV in the R1 segment layer-wise in all the sectors similar to the A3535 board. After all the four layers are filled, the connection proceeds to the next sector, as $R1A01.L1 \rightarrow R1A01.L2 \rightarrow R1A01.L3 \rightarrow R1A01.L4 \rightarrow \mathbf{R1A02.L1} \dots$. With this arrangement, if one A3540 board fails, the R1 segment in only three sTGC wedges of an entire wheel is affected. It has to be noted that the A3535 and the A3540 boards supply HV to the two wedges interchangeably based on the cable length and available channels, which is not discussed here explicitly.

As mentioned earlier, the high voltage source that supplies power to the boards is the SY4527 mainframe. The mainframe is installed in *USA15*, the service cavern, whereas the HV boards are located in *UX15*, the experimental cavern. A graphic representation of the experimental areas is shown in Figure 4.16 to better understand the underground locations and connections. The mainframe houses four branch controllers (two for each wheel), which distribute power to eight EASY 3000 crates (four crates per wheel), built to operate in a magnetic field and a radioactive environment of *UX15*. The crates accommodate the HV boards and are situated in dedicated ATLAS electronic racks in the cavern. NSW-A occupies the racks Y.26-24.X1 and Y.29-24.X1 whereas NSW-C occupies Y.62-24.X1 and Y.58-23.X0. The branch controllers in *USA15* are connected to the crates in *UX15* with cables of length ~ 120 m. In total, to supply high voltage to the sTGC detectors in one NSW, ATLAS employs 2 branch controllers, 4 crates, 12 A3535 boards, and 12 A3540 boards. The crate and board arrangement in the cavern for NSW-A is tabulated in Table 4.2 and illustrated pictorially in Figure 4.17. Similar is the arrangement for NSW-C, except that the racks used are different.

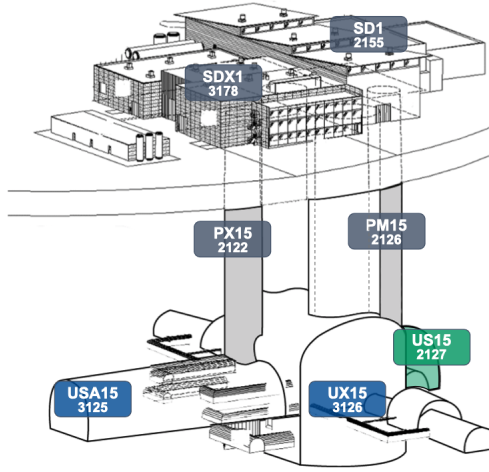
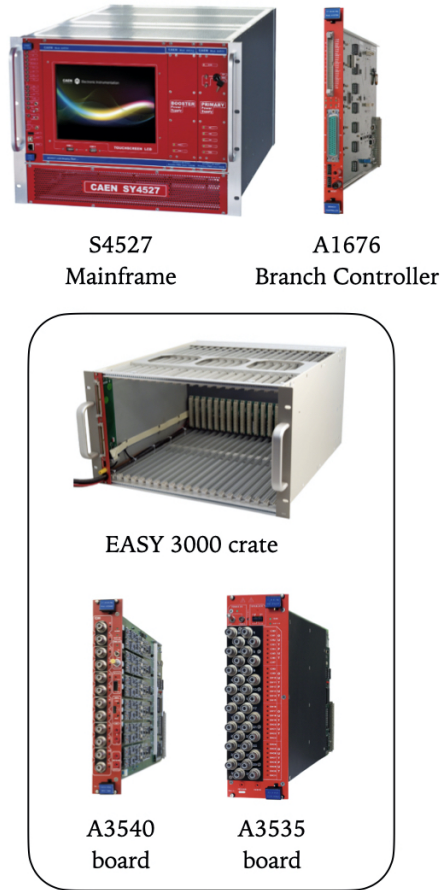


Figure 4.16: A schematic representation of the ATLAS experimental areas is shown. UX15 is the experimental cavern that hosts the ATLAS detector. USA15 is a service cavern shielded from radiation and can be accessed during LHC operations with beams. US15 is a non-shielded service cavern inaccessible during LHC operations with beams.

Crate	Boards
Lower in Y.26-24.X1	$3 \times \text{A3540}$
	$3 \times \text{A3535}$
Upper in Y.26-24.X1	$3 \times \text{A3540}$
	$3 \times \text{A3535}$
Lower in Y.29-24.X1	$3 \times \text{A3540}$
	$3 \times \text{A3535}$
Upper in Y.29-24.X1	$3 \times \text{A3540}$
	$3 \times \text{A3535}$

Table 4.2: The arrangement of crate and HV boards for sTGC detectors in the cavern for NSW-A is tabulated. Every crate houses three boards, each of A3540 and A3535. The crates themselves are located in the electronic racks in UX15. Upper and Lower stand for the location of the crate in the rack, which is graphically represented in Figure 4.17.



Arrangement of filled crates in the racks

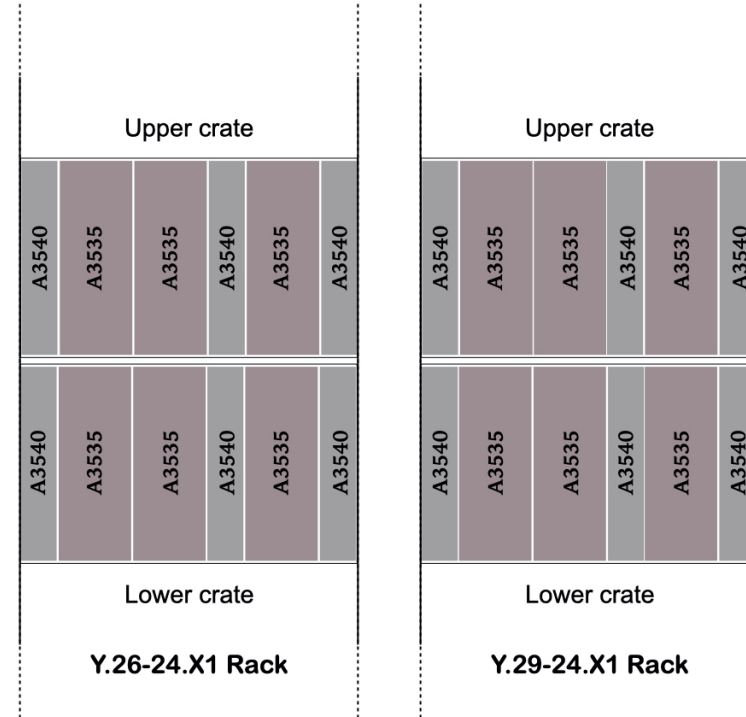


Figure 4.17: A graphical illustration of the arrangement of HV units for sTGC in the cavern for NSW-A is presented. The HV supplies (left) and arrangement of the HV boards in the crates (right) are shown. The two A1676 branch controllers are inserted into the S4527 mainframe. The branch controller distributes the power from the mainframe to the crates, which houses the A3540 and the A3535 HV boards. The mainframe and the branch controller are situated in USA15, whereas the crates and the HV boards are located in UX15. The branch controller in USA15 is connected to the crates in UX15 with the help of lengthy cables. Each crate hosts three boards, each of A3540 and A3535. A crate consists of 20 slots, and each A3540 board occupies two slots, and each A3535 board occupies four slots, leaving two slots free per crate. The HV boards are accommodated by four crates, arranged one on top of the other, named Upper and Lower, in two adjacent racks in the UX15 cavern.

Micromegas

A micromegas detector operates with high voltages of two different polarities: a negative high voltage for the drift gap and a positive high voltage to amplify the signal for readout. The high voltage for drift is supplied to each radial segment, and all four layers of the segment share the voltage. Altogether, 64 HV channels are required to provide drift voltage in one wheel ($16 \text{ sectors} \times 2 \text{ wedges} \times 2 \text{ radial segments}$). In the case of high voltage for readout, lowest HV unit is an HV channel supplied per radial segment similar to sTGC according to the initial NSW design proposal. But in early 2020, it was decided to increase the HV granularity by providing high voltage to every PCB within a radial segment rather than to every radial segment. Therefore, to supply readout HV to one wheel ($16 \text{ sectors} \times 2 \text{ wedges} \times 4 \text{ layers} \times 8 \text{ PCBs}$), 1024 HV channels are required.



(a) CAEN's A7038AP board



(b) CAEN's A7038ST(N/P) board

Figure 4.18: CAEN's A7038AP and A7038ST(N/P) boards used in the high voltage connections for MM are shown. Images taken from [71].

The HV needs of micromegas are fulfilled by CAEN's *A7038ST(N/P)* and *A7038AP* boards, shown in Figure 4.18, both supplying 1 kV and 100 μA . The A7038ST boards consist of 32 channels, and they come in two different polarities: A7038STN for negative and A7038STP for positive. The A7038AP board (purchased following the increased HV granularity needs) consists of 48 channels and provides only positive voltage.

Mapping scheme

The channels in A7038STN board are connected such that each board supplies the radial segments of both the wedges sector-wise as $R1A01 \rightarrow R2A01 \rightarrow \mathbf{R1A02} \rightarrow R2A02 \rightarrow \mathbf{R1A03} \dots$ Therefore, only two such boards are required to provide the 64 HV channels for drift in one wheel.

For the readout HV, each HV channel is connected to the PCBs radially and supplies all layers before proceeding to the next sector. An example for the connection scheme is $R1A01_L1_PCB1 \rightarrow R1A01_L1_PCB2 \dots R1A01_L1_PCB5 \rightarrow \mathbf{R2A01_L1_PCB6^5} \dots \rightarrow R2A01_L1_PCB8 \rightarrow \mathbf{R1A01_L2_PCB1} \dots \rightarrow R2A01_L4_PCB8 \rightarrow \mathbf{R1A02_L1_PCB1} \dots$ The HV connection scheme for MM readout channels is slightly more complicated than that for sTGC due to the large number of channels involved. The channels are assigned such that all the A7038AP boards are fully used first, and then the remaining supplies are provided by the A7038STP boards.

⁵PCB6 to PCB8 belong to the R2 segment.

Similar to sTGC, the HV power source for micromegas is also the SY4527 mainframe. But unlike sTGC, the HV supply for micromegas is not operated based on the branch controller-crate system. Instead, the HV boards are inserted directly into the mainframes, situated in the US15 service cavern⁶. Each wheel utilizes three mainframes, and the HV boards each mainframe houses are tabulated in Table 4.3. In total, to supply high voltage to the MM detectors in one NSW, ATLAS employs 3 mainframes, 16 A7038AP boards, 8 A7038STP boards, and 2 A7038STN boards. The mainframes are located in the Y.05-07.S2 rack for NSW-A and the Y.06-07.S2 rack for NSW-C. A summary of the mainframe and board arrangement in the cavern is illustrated graphically in Figure 4.19.

Mainframe	Boards
Mainframe 1 in Y.05-07.S2	16 $\times$ A7038AP
Mainframe 2 in Y.05-07.S2	4 $\times$ A7038STP 1 $\times$ A7038STN
Mainframe 3 in Y.05-07.S2	4 $\times$ A7038STP 1 $\times$ A7038STN

Table 4.3: Mainframe and HV boards arrangement for micromegas in the cavern for NSW-A is tabulated. The three mainframes are located in the Y.05-07.S2 rack (for NSW-A) in US15. Mainframe 1 hosts 16 A7038AP boards, whereas the other two mainframes house one A7038STN and four A7038STP boards each.

⁶For sTGCs, crates that are built to function in a magnetic field and a radioactive environment are used because the HV boards are operated from the racks in the experimental cavern. As the HV boards for micromegas are located in the service cavern of US15, crates are not necessary.

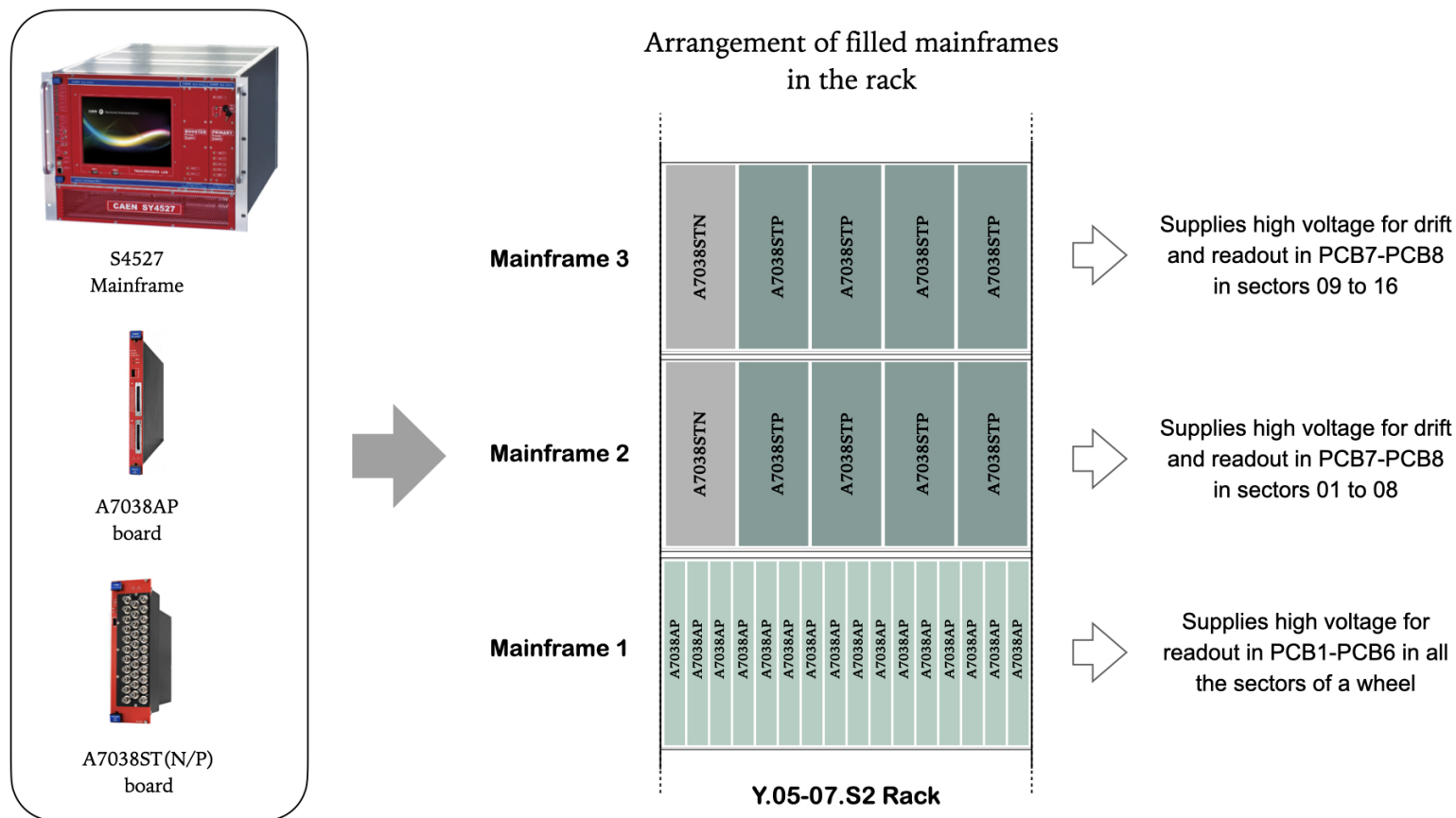


Figure 4.19: A graphical illustration of the arrangement of HV units for micromegas in the cavern for NSW-A is presented. The HV supplies (left) and arrangement of the HV boards in the mainframes (right) are shown. The boards are inserted directly into the three mainframes, arranged one on top of the other in the US15 racks. Each mainframe consists of 16 slots, and the first mainframe accommodates 16 A7038AP boards (each occupying one slot in the mainframe). The second and the third mainframes each hold one A7038STN and four A7038STP boards. The A7038ST boards occupy three slots in the mainframe, thus leaving one slot free each in Mainframe 2 and Mainframe 3.

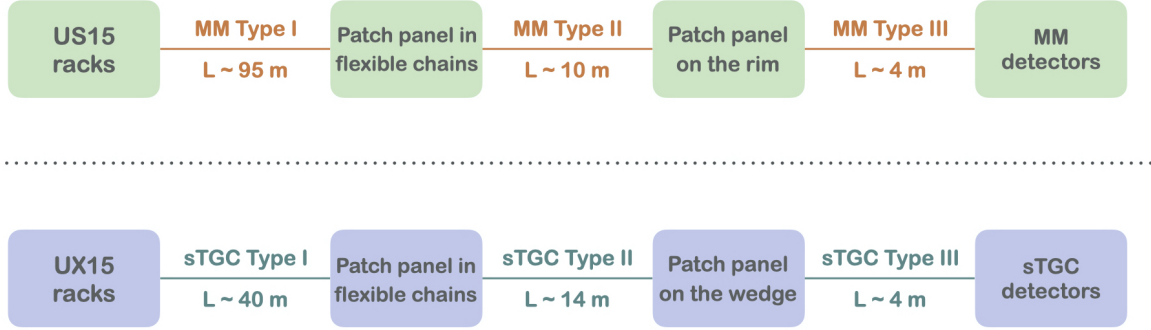


Figure 4.20: A schematic of the high voltage cable connections from the racks to the detectors is shown for micromegas (top) and for sTGC (bottom)

It is to be noted that the HV connections from the rack to the MM and the sTGC detectors mounted on the NSW sectors are not made by a single stretch of cables. Instead, a complex network of six sets (three sets for each detector technology) of cables with different lengths are involved. Figure 4.20 shows a schematic of the cable connections from the rack to the detector chambers. The current in the HV cables is conducted through copper wires that are surrounded by a protective film wrapped in an insulating sheath. The technical specifications of the different cable sets are beyond the scope of this chapter and are not described.

For MM, nearly 95 m long *Type I* cables are used to connect the HV boards in the US15 racks up to the patch panels located in the *flexible chains* in sector 09 of the NSW. From the flexible chains, *Type II* cables with 10 m are routed to the HV patch panel located in an accessible place on the outer rim of the wheel. The HV connection for drift and readout is then furnished by ~ 4 m long *Type III* cables. In the case of sTGC, Type I cables have a length of ~ 40 m and extend from the HV boards in the UX15 rack to the patch panel in the flexible chains of sector 09, similar to MM. Type II cables stretching over ~ 14 m continue the connections to the patch panel on the detector wedge and finally 4 m long Type III cables complete the supply to the sTGC detectors.

4.5 WinCC-OA Project for Leakage Current Measurement

For the MM and the sTGC detectors to render the expected performance, it is crucial to ensure that the power supplied from the HV boards in the racks reaches the detectors over the long stretch of the cables described above without any major leakages. Leakage current is the current that flows in alternative paths, apart from the designated path, usually the insulating sheaths, and it is quite common in electronics even when the power is off. It causes a constant wastage of energy, and excessive leakage adversely affects the performance of the detectors. Hence, it is essential to monitor the current carried by the cables before they can be used during the ATLAS operations. The leakage currents have been studied⁷, and the cables to be used in the cavern have been adequately chosen, passing specific quality requirements. But once the cables are transported to the underground cavern, it is necessary to measure the currents again to investigate any leakages due to cable damage that might have occurred during transportation. On that account, a WinCC-

⁷Results of the studies are in preparation for publication at the time of writing the thesis.

OA project is developed by the author in HV DCS that can be operated from the ATLAS Control Room to monitor the leakage current in the cables during the long-term operations of the New Small Wheel. The technical details associated with the WinCC project are not explained as it falls beyond the scope of this thesis.

The project is developed at the dedicated NSW laboratory of Albert-Ludwigs-Universität Freiburg and has been deployed at the NSW integration site. The goal of the project is to record the current conducted by the cables connected to the HV boards meeting the following requirements:

- For a given HV board, the current needs to be measured individually for each channel.
- The monitored current has to be displayed graphically on the WinCC-OA panel in real time.
- The monitored current values need to be saved into a text file which can later be used for offline studies.

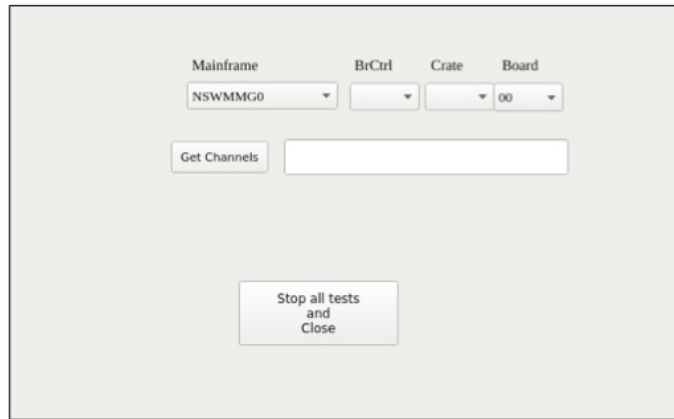


Figure 4.21: The main panel in the WinCC-OA project for leakage current measurement is shown. The panel is displayed for a micromegas HV board. As the project is developed at the Freiburg laboratory, the identifier names for the mainframes and boards in the images are slightly different from the nomenclature discussed in Section 4.4.1.

To perform the task, first of all, two panels are created in WinCC-OA: a *main panel* and a *channel view* panel. In the main panel, shown in Figure 4.21, drop-down menus are added to choose the respective HV supply units for MM and sTGC. For MM, the user is expected to provide the mainframe and the HV board location based on the connection scheme discussed in the previous section. For sTGC, branch controller and crate position information are needed in addition. Once the location of the HV board to be tested is entered, a *Get Channels* button is made functional that fetches the information of all the channels of the respective board. Each channel is addressed by a unique identifier based on the nomenclature explained in Section 4.4.1.



Figure 4.22: The channel view panel in the WinCC-OA project for leakage current measurement is presented. The panel is displayed for one of the channels, *Channel 0*, of a micromegas HV board. The channel is switched on, and the status is indicated by the green light.

The channel view panel, given in Figure 4.22, is used to interact directly with a given channel in a board and is placed in the main panel. The ON and OFF buttons are implemented to switch the channel on and off, and the status is displayed by a green (for ON) and a red light (for OFF) on the right side of the panel. If no colors are displayed, then the state is by default set to off. The channel view panels are created for every channel of a given board, and individual channels can be tested by pressing the T button, which stands for *testMe*, a variable introduced for the purpose. Thus, a channel can be tested in both the ON and the OFF configurations. When testMe is enabled, the background color of the T button turns green, and the monitored values, including current, voltage, and time, are written into a text file and saved. To stop the test run on a given channel, the T button can be clicked again, which then turns the background color to pink and immediately stops the test without changing the channel status. There is also a dedicated button introduced on the main panel, *Stop all tests and Close*, which, when clicked, stops all the running tests, turns off the power, and shuts down the project. Figure 4.23 shows the main panel for one of the A7038ST boards used for micromegas showing all the different testing instances discussed.

To test the working of the current measurement setup, a few seemingly good cables with no external damages and a few broken cables are connected to the HV channels and tested. One end of the cable is connected to the channel while the other is left open. The current monitored are displayed in real-time on the *trend view*, a graphic display object in WinCC-OA. Figures 4.24 and 4.25 show the trend views of the monitored current for a good and a broken cable with a possible short connected to an A7038ST board. The voltage is ramped up at a rate of 50 V per second from 0 V to 500 V, and after some time, the voltage is ramped down at the same rate. The good cable shows nearly no leakage overall, and during the stages of ramping up and down, the current reaches a maximum of 3-5 μA , which is very small compared to the operating currents of 100 μA ⁸. In the case of the broken cable, once the supply is turned on, the current shoots up drastically, and when it reaches the pre-set cut-off value of 95 μA , a *trip*⁹ is enforced, thus turning off the supply in that channel. Several cables are studied, with all of them resulting in negligible leakages that can be ignored. For graphical display in real-time, four trend views are implemented on the main panel to display currents in all the 32 channels of the board as shown in Figure 4.26.

It is worth noting that the working of the WinCC-OA project setup is tested only using an A7038ST board for micromegas available at the Freiburg laboratory. The channel information of the other HV boards is made available in the project, but no tests are run as the goal was to create a functioning framework to be used from the ATLAS Control Room. The project developed is approved by the (then) project leader to be integrated to the Control Room framework and for use in ATLAS to investigate any current leakage in the HV cables once the wheels are transported from the assembly location to the underground cavern.

⁸Ramping up the voltage to 1000 V still gave current values in the same order of magnitude.

⁹A trip is an interruption in the power supply used as a protective measure to safely turn off devices in cases of fault.

Channel	ON	OFF	T	Light	Mainframe	BrCtrl	Crate	Board
Channel: 0	☐	☐	☐	☒	NSWMMG0			00
Channel: 1	☐	☐	☒	☐				
Channel: 2	☐	☐	☒	☐				
Channel: 3	☐	☐	☐	☐				
Channel: 4	☐	☐	☐	☒	MMGHV:CAEN/NSWMMG0/board00/channel031.			
Channel: 5	☐	☐	☐	☐				
Channel: 6	☐	☐	☐	☐	Stop all tests and Close			
Channel: 7	☐	☐	☐	☐				
Channel: 8	☐	☐	☒	☒				
Channel: 9	☐	☐	☒	☒				
Channel: 10	☐	☐	☐	☐				
Channel: 11	☐	☐	☐	☐				
Channel: 12	☐	☐	☐	☐				
Channel: 13	☐	☐	☐	☐				
Channel: 14	☐	☐	☐	☐				
Channel: 15	☐	☐	☐	☐				
Channel: 16	☐	☐	☐	☐				
Channel: 17	☐	☐	☐	☐				
Channel: 18	☐	☐	☐	☐				
Channel: 19	☐	☐	☐	☐				
Channel: 20	☐	☐	☐	☐				
Channel: 21	☐	☐	☐	☐				
Channel: 22	☐	☐	☐	☐				
Channel: 23	☐	☐	☐	☐				
Channel: 24	☐	☐	☐	☐				
Channel: 25	☐	☐	☐	☐				
Channel: 26	☐	☐	☐	☐				
Channel: 27	☐	☐	☐	☐				
Channel: 28	☐	☐	☐	☐				
Channel: 29	☐	☐	☐	☐				
Channel: 30	☐	☐	☐	☐				
Channel: 31	☐	☐	☐	☐				

Figure 4.23: The main panel for one of the A7038ST boards used for micromegas is presented. The 32 channels of the boards are displayed by the 32 channel view panels. *Channel 0* shows an instance when the supply is on, whereas *Channel 4* indicates the off state. In both cases, no tests are run. *Channel 1* and *Channel 2* are off, but *Channel 1* shows an instance when a test is ongoing, and *Channel 2* shows the case when a test has been done and stopped. *Channel 8* and *Channel 9* show similar instances but with the channels in ON state. When the *Stop all tests and Close* button is clicked, all the tests are stopped, the channels are turned off, and the project is shut down.

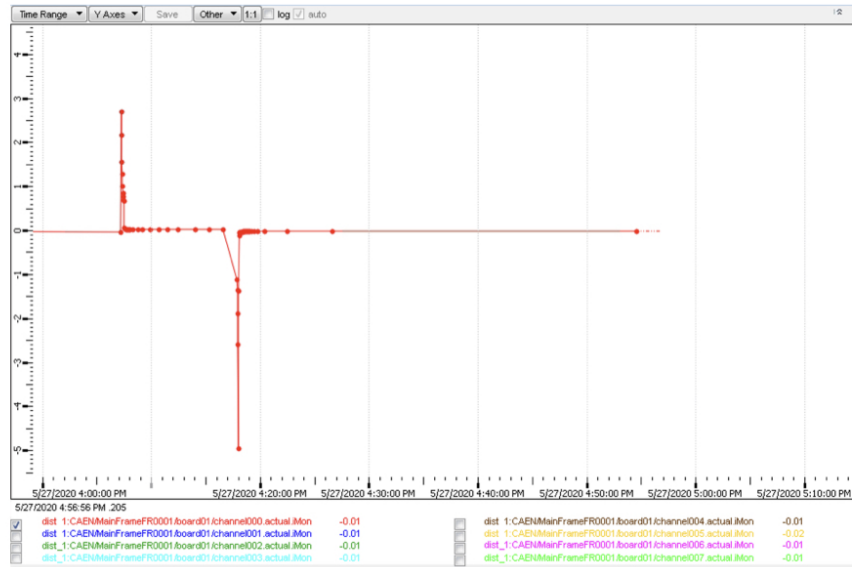


Figure 4.24: Trend view of the monitored current in a good cable connected to one of the channels of an A7038ST board.

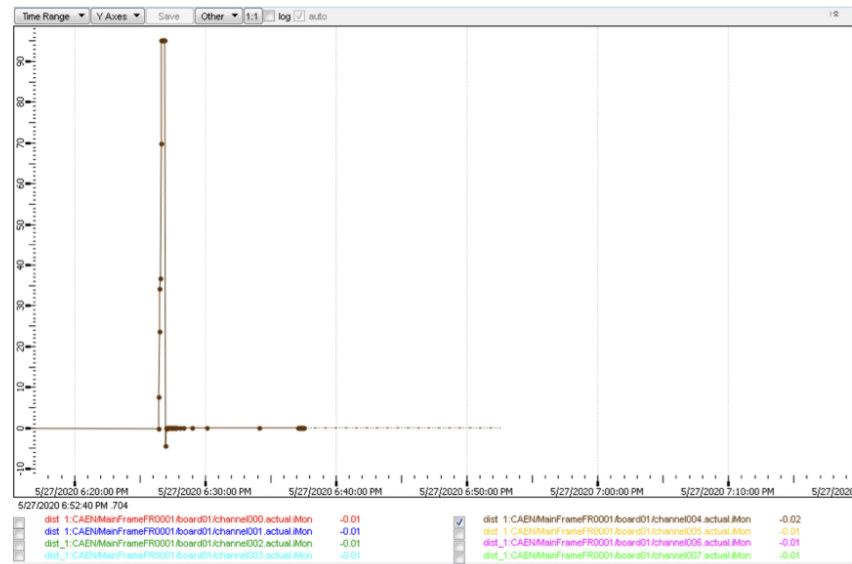


Figure 4.25: Trend view of the monitored current in a broken cable connected to one of the channels of an A7038ST board. When the supply is turned on, the current shoots up drastically due to a possible short in the cable. Once the current reaches the pre-set cut-off value of 95 μ A, the supply is forced to turn off automatically.

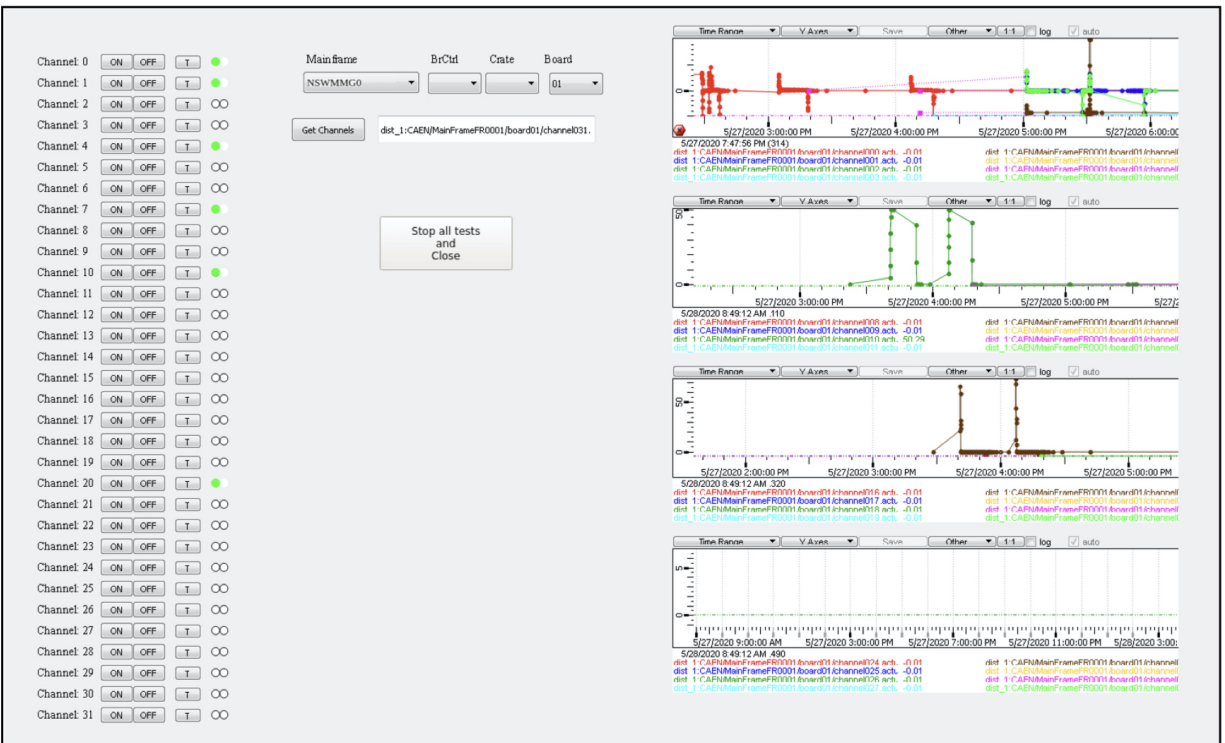


Figure 4.26: A display of the main panel with all the 32 channels of an A7038ST board shown along with their trend views.

Chapter 5

Vector Boson Scattering at the Large Hadron Collider

Vector boson scattering is one of the recent remarkable observations at the Large Hadron Collider. Due to the unique role played by the Higgs boson in regularizing the scattering amplitude of heavy gauge bosons, the scattering of W or Z bosons is of historic interest to validate the predictions of the Standard Model. This chapter aims to shed some light on the production of these phenomena in hadron collisions and the importance of the production of a pair of W bosons with the same electric charge, which is the main topic of this thesis. Henceforth, vector boson scattering is used synonymously with the scattering of heavy gauge bosons, and photon interactions are not considered unless explicitly mentioned.

Section 5.1 describes the typical signature of a heavy gauge boson scattering event in hadron collisions, including the representative Feynman diagrams for the various production modes. A comparison of the possible di-boson combinations and their final states are discussed briefly in Section 5.2, and Section 5.3 lays the foundation and the motivation for studying the production of $W^\pm W^\pm jj$.

5.1 Event Signature in Hadron Collisions

At the LHC, vector boson scattering occurs via the radiation of electroweak vector bosons from the incoming partons and their subsequent self-interaction as per Figure 2.8. In proton-proton collisions, vector boson scattering is initiated by electroweakly interacting partons, mainly quarks¹, and the process is therefore commonly addressed as electroweak induced production². The two vector bosons are accompanied by two quarks, a characteristic of hadron collisions. Due to color-confinement, the outgoing quarks hadronize into a spray of particles known as jets³, and the event is studied as $VVjj$ in the respective decay channels of the vector bosons. The representative Feynman diagrams for vector boson scattering at tree level are given in Figure 5.1. It includes diagrams with triple (5.1a, 5.1b) and quartic (5.1c) gauge interactions as well as diagrams with Higgs exchanges (5.1d, 5.1e).

The trajectory of the incoming quarks is altered only slightly when the gauge bosons are radiated. Consequently, the two associated jets, known as *tagging jets*, are typically seen in the forward

¹Gluons cannot radiate electroweak gauge bosons.

²Recently, $\gamma\gamma \rightarrow WW$ process has been observed in ATLAS [74]. As it does not entirely correspond to the scattering of heavy gauge bosons, such processes are not discussed in this thesis.

³A dedicated description of jets is given in Chapter 6.

regions close to the beam direction, at the opposite sides of the detector. Furthermore, the invariant mass of the two tagging jets has been observed to be rather large. Two tagging jets with a large di-jet invariant mass separated by large rapidities serve as the experimental signature of a VBS event. A mathematical justification for the observed signature is given in Appendix A.

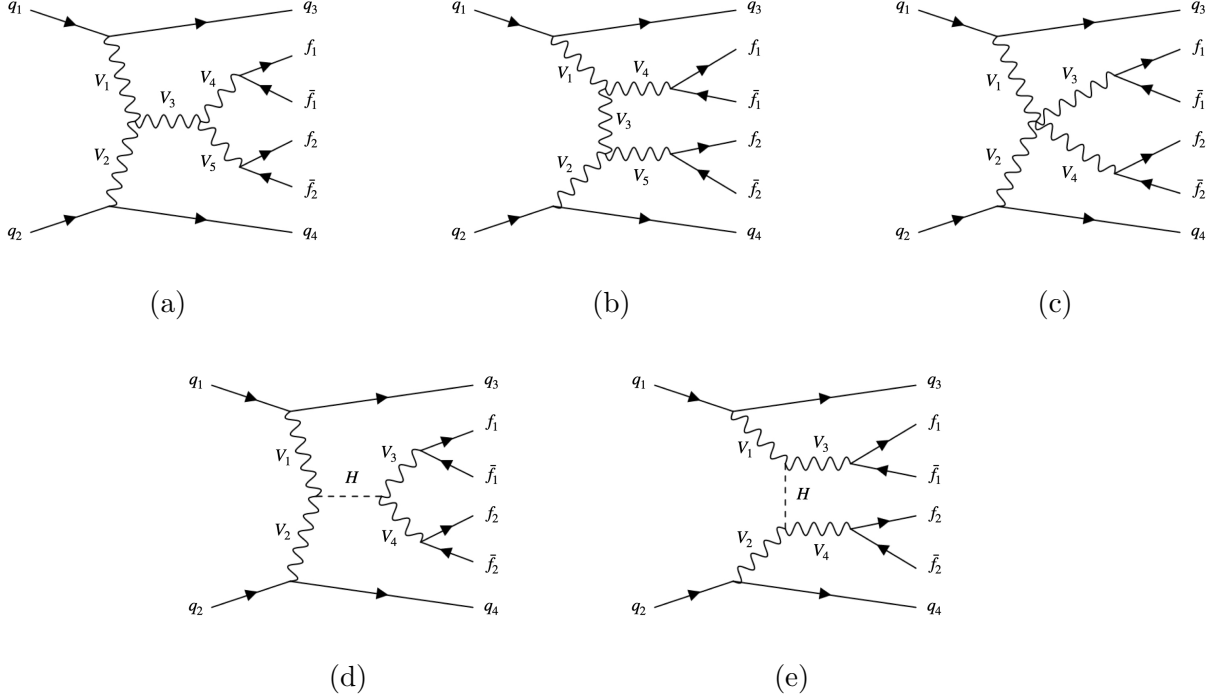


Figure 5.1: Representative Feynman diagrams for the electroweak $VVjj$ production through vector boson scattering at tree level are displayed. The labels on the lines correspond to quarks (q), vector bosons ($V = W, Z$), and fermions (f). (a) and (b) show triple gauge interactions while (c) has a quartic gauge interaction. Higgs exchanges are presented in (d) and (e).

In addition to the VBS mode of production, electroweak induced $VVjj$ can occur without the scattering of the two gauge bosons, as shown in Figure 5.2. However, the non-VBS component cannot be separated from the VBS component in a gauge invariant manner. Thus, the non-VBS component is an inevitable ingredient studied in conjunction with the VBS component as it cannot be distinguished from the latter. The third category of contributions, namely from tri-boson productions where one of the bosons decays hadronically, also yield the same final state. But such processes are gauge invariantly separable from the VBS contributions, and resonant decays of the boson into quarks in such events can be suppressed by requiring the VBS signature of the large invariant mass of the two jets. It is worthwhile to note that all the processes in electroweak $VVjj$ have purely electroweak vertices, $\mathcal{O}(\alpha^6)$, at tree level.

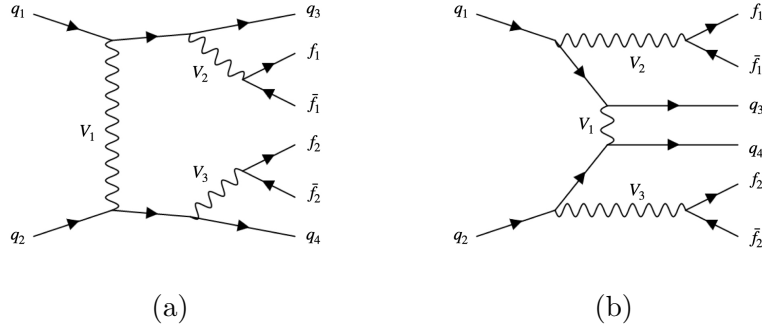


Figure 5.2: Representative Feynman diagrams for the electroweak $VVjj$ production without the scattering of the vector bosons at tree level are shown. The labels on the lines correspond to quarks (q), vector bosons ($V = W, Z$), and fermions (f).

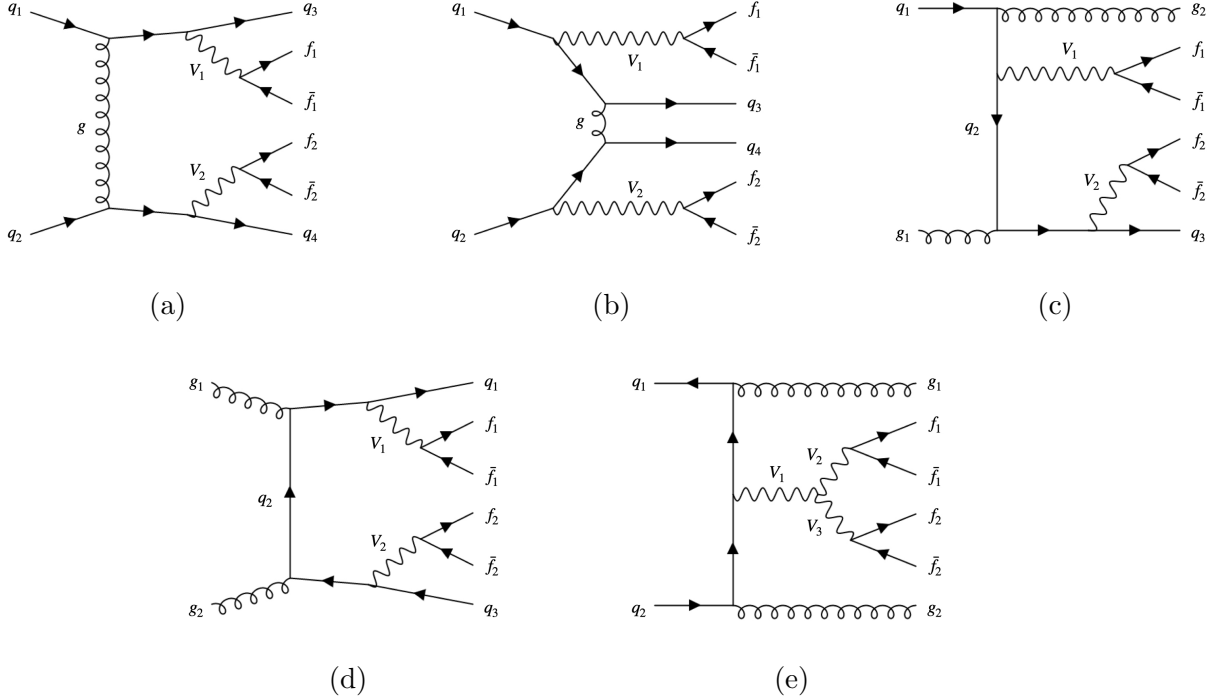


Figure 5.3: Representative Feynman diagrams for the strong $VVjj$ production at tree level are given. The labels on the lines correspond to quarks (q), gluons (g), vector bosons ($V = W, Z$), and fermions (f).

The electroweak $VVjj$ is accompanied by gluon-induced production of the order $\mathcal{O}(\alpha_s^2\alpha^4)$. Due to the relatively larger abundance of gluons in the colliding protons, as seen from Figure 2.3, the cross-section of the QCD or strong production of $VVjj$ is significant and can be even larger than the electroweak production depending on the combination of the gauge bosons produced. The representative Feynman diagrams for the strong production of $VVjj$ are displayed in Figure 5.3. Diagrams with multi-gauge interactions (5.3e) can also occur in the strong production mode, but such interactions are not sensitive to the electroweak symmetry breaking mechanism. On account

of the color connection between the gluons that pulls them closer together, the gluons (and quarks) in strong production scatter at large angles with respect to the colliding beams, unlike the small scattering angles in electroweak production.

While it is possible to categorize all the contributing diagrams to $VVjj$ into two production modes as introduced above, such a classification does not hold at the level of cross-section, which is the observable measured in this thesis. The total cross-section is computed by taking the phase space integral over the entire matrix element of $VVjj$ production. In addition to the pure electroweak and strong terms, it also has contributions resulting from the interference of electroweak and strong contributions seen numerically as

$$\begin{aligned}\sigma &\propto |\mathcal{M}_{\text{EWK}} + \mathcal{M}_{\text{QCD}}|^2, \\ &\propto |\mathcal{M}_{\text{EWK}}|^2 + |\mathcal{M}_{\text{QCD}}|^2 + 2\text{Re}(\mathcal{M}_{\text{EWK}}\overline{\mathcal{M}}_{\text{QCD}}), \\ &\equiv \sigma_{\text{EWK}} + \sigma_{\text{QCD}} + \sigma_{\text{INT}}.\end{aligned}\tag{5.1}$$

Thus, the total cross-section is the sum of the electroweak, strong, and interference cross-sections. While the electroweak and the strong production cross-sections are positive, the interference contribution can be positive or negative. The interference mode of production corresponds to a coupling order of $\mathcal{O}(\alpha_s\alpha^5)$ at leading order and cannot be assigned a single Feynman diagram. Early studies suggest that the contribution of interference effects to the total cross-section is quite small (up to 2-3%) in a typical VBS phase space [75], [76].

5.2 Final States and VV Combination

The heavy gauge bosons decay almost immediately into their preferred final states as soon as they are produced. The probability of decaying to a particular final state is given by its branching ratio. Table 5.1 lists the branching ratios for some of the commonly favored decay channels of W and Z bosons. On account of the poor resolution of the hadronic calorimeters, hadrons are identified with lower detector efficiency. Therefore, despite the large branching ratios in hadron decay modes, hadronic channels are more challenging for studies compared to leptonic channels from an experimental perspective. Neutrinos escape without leaving any signals for detection and are “invisible” to the detector. Among leptons, the tau lepton is exceptional with its relatively large mass and short lifetime and ability to decay into hadrons and lighter leptons. Hence, electron and muon decay modes of the gauge bosons are of particular interest for experimental measurements due to the relatively cleaner signatures they leave in the detector.

The cross-sections of some of the $VVjj$ processes in their leptonic final states according to the Standard Model expectations are displayed in Table 5.2. The results are computed in a VBS phase space⁴ designed to enhance the electroweak production over the strong production. With the largest electroweak to QCD production ratio, it is beyond doubt that the production of $W^\pm W^\pm jj$ serves as a golden channel to explore the scattering of heavy gauge bosons at the LHC. The process was also the first target of ATLAS, with evidence made in 2014 [77] and discovered later in 2019 [78].

5.3 Production of $W^\pm W^\pm jj$

The production of a pair of W bosons with the same electric charge is a rare process in the Standard Model, falling on the bottom right corner in Figure 2.7. Due to its large electroweak

⁴The selections defining this phase space differ only slightly from the selections of the fiducial region described in Chapter 12.

Decay Mode	Branching Ratio (%)
$W \rightarrow l^\pm \nu$	10.86 ± 0.09
$W \rightarrow \text{hadrons}$	67.41 ± 0.27
$Z \rightarrow l^\pm l^\mp$	3.3658 ± 0.0023
$Z \rightarrow \nu \bar{\nu}$	20.00 ± 0.06
$Z \rightarrow \text{hadrons}$	69.91 ± 0.06

Table 5.1: Branching ratios of some of the common decay modes of W and Z bosons are listed [1]. The branching ratios for $W \rightarrow l^\pm \nu$ and $Z \rightarrow l^\pm l^\mp$ are given for each lepton flavor and not their sum.

Final state	VV Combination	σ_{EWK} (fb)	σ_{QCD} (fb)	$\sigma_{EWK}/\sigma_{QCD}$
$l^+ l^- l^+ l^- jj$	ZZ	0.098	0.100	0.98
$l^\pm \nu l^\pm l^\mp jj$	$W^\pm Z$	2.34	4.38	0.53
$l^\pm \nu l^\mp \nu jj$	$W^\pm W^\mp, ZZ$	12.3	21.8	0.56
$l^\pm \nu l^\pm \nu jj$	$W^\pm W^\pm$	3.97	0.346	11.5
$l^\pm \nu \nu \nu jj$	$W^\pm Z$	7.64	15.5	0.49
$\nu \nu \nu \nu jj$	ZZ	1.68	1.38	1.22

Table 5.2: The comparison of the predicted cross-sections for various VV combinations in the leptonic final states is tabulated. The cross-sections are given for the leading order electroweak and strong production of $VVjj$ at $\sqrt{s} = 13$ TeV. The ratio of the electroweak to strong production cross-sections is also shown. The charged leptons are denoted by $l^\pm$, where $l^\pm \in e^\pm, \mu^\pm$, and (anti-) neutrinos are indicated by ν . The cross-sections are computed using simulations from SHERPA in a VBS phase space [79].

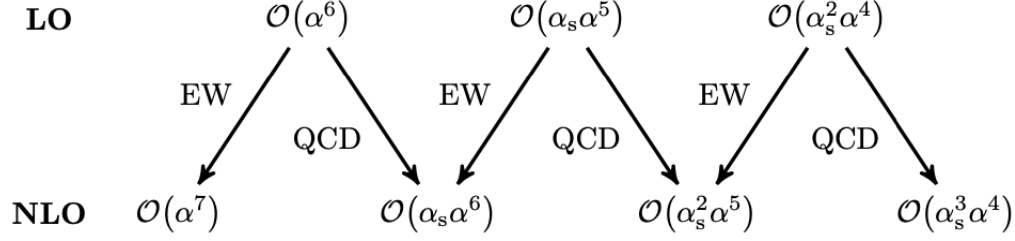


Figure 5.4: Contributions of coupling constants at LO and NLO in $W^\pm W^\pm jj$ production. Image taken from [80].

to strong production ratio, the process is an excellent candidate for investigating the scattering of heavy gauge bosons at the LHC. Table 5.3 shows some of the representative Feynman diagrams for $W^\pm W^\pm jj$ production, and the electroweak $W^\pm W^\pm jj$ is the signal considered for measurement in this thesis. Owing to electric charge conservation, the s -channel exchanges of a Higgs or a gauge boson are forbidden in the VBS mode. Additionally, gluon-induced strong production does not occur, resulting in the enhancement of the electroweak to strong production ratio of this process.

As the electric charge of the W bosons needs to be determined, only the leptonic decays of the W bosons ($W \rightarrow e/\mu + \nu$) are considered. Hence, the final state consists of two leptons with the same electric charge, two neutrinos, and two jets. Despite the smaller cross-section of this process compared to $W^\pm W^\mp jj$ production, the presence of two leptons in the final state with the same electric charge significantly reduces the many backgrounds from other Standard Model processes. Coupled with the relatively cleaner signature of electrons and muons in the detector, $pp \rightarrow W^\pm W^\pm jj \rightarrow l^\pm \nu l^\pm \nu jj$ is undoubtedly a golden channel to probe VBS at the LHC.

5.3.1 Characteristic Signature

The characteristic signature of $W^\pm W^\pm jj$ processes consists of two leptons with the same electric charge, two neutrinos, and two forward jets with large rapidity separation and large di-jet invariant mass. Figure 5.5 presents a simplified picture of the scattering of two W bosons and their subsequent decay in the leptonic modes. The two tagging jets in $W^\pm W^\pm jj$ production can be initiated by u -, d -, c -, and s -quarks whereas b -quarks in the final state are very rare. Furthermore, the two charged leptons originating from the W decay tend to lie between the two tagging jets while the neutrinos leave the detector undetected.

5.3.2 Higher Order Corrections

As discussed thus far, the different production modes of $W^\pm W^\pm jj$ process are differentiated by the choice of the phase space in the experimental selections whereas from a theoretical point of view, the production modes can be separated in a gauge invariant manner at leading order based on the different orders in the coupling constants. But this is no more the case at next-to-leading order. At NLO, the contributions involve four different orders: $\mathcal{O}(\alpha^7)$, $\mathcal{O}(\alpha_s \alpha^6)$, $\mathcal{O}(\alpha_s^2 \alpha^5)$, and $\mathcal{O}(\alpha_s^3 \alpha^4)$, also represented graphically in Figure 5.4. The contributions to order $\mathcal{O}(\alpha^7)$ are simply the electroweak corrections of the electroweak induced LO $W^\pm W^\pm jj$ production [81]. Similarly, $\mathcal{O}(\alpha_s^3 \alpha^4)$ correspond to the QCD corrections to the strong induced LO $W^\pm W^\pm jj$ production. But the orders $\mathcal{O}(\alpha_s \alpha^6)$ and $\mathcal{O}(\alpha_s^2 \alpha^5)$ involve electroweak and QCD corrections from more than one underlying process, making it challenging to distinguish the electroweak and strong induced

Electroweak Production			Strong Production
VBS	non-VBS	Tri-boson	
Diagram 1 (crossed out): $q_1, q_2 \rightarrow q_3, q_4$ via V_1, V_2 exchange, with $f_1, \bar{f}_1, f_2, \bar{f}_2$ production. Crossed out with a red line. Diagram 2 (valid): $q_1, q_2 \rightarrow q_3, q_4$ via V_1, V_2 exchange, with $f_1, \bar{f}_1, f_2, \bar{f}_2$ production. Diagram 3 (valid): $q_1, q_2 \rightarrow q_3, q_4$ via V_1, V_2 exchange, with $f_1, \bar{f}_1, f_2, \bar{f}_2$ production. Diagram 4 (crossed out): $q_1, q_2 \rightarrow q_3, q_4$ via V_1, V_2 exchange, with $f_1, \bar{f}_1, f_2, \bar{f}_2$ production. Crossed out with a red line. +	Diagram 1: $q_1, q_2 \rightarrow q_3, q_4$ via V_1 exchange, with $f_1, \bar{f}_1, f_2, \bar{f}_2$ production. Diagram 2: $q_1, q_2 \rightarrow q_3, q_4$ via V_2 exchange, with $f_1, \bar{f}_1, f_2, \bar{f}_2$ production. +	Diagram 1: $q_1, q_2 \rightarrow q_3, q_4$ via V_1 exchange, with $f_1, \bar{f}_1, f_2, \bar{f}_2$ production. Diagram 2: $q_1, q_2 \rightarrow q_3, q_4$ via V_2 exchange, with $f_1, \bar{f}_1, f_2, \bar{f}_2$ production. +	Diagram 1 (crossed out): $q_1, q_2 \rightarrow q_3, q_4$ via V_1, V_2 exchange, with $f_1, \bar{f}_1, f_2, \bar{f}_2$ production. Crossed out with a red line. Diagram 2 (valid): $q_1, q_2 \rightarrow q_3, q_4$ via V_1, V_2 exchange, with $f_1, \bar{f}_1, f_2, \bar{f}_2$ production. Diagram 3 (valid): $q_1, q_2 \rightarrow q_3, q_4$ via V_1, V_2 exchange, with $f_1, \bar{f}_1, f_2, \bar{f}_2$ production. Diagram 4 (crossed out): $q_1, q_2 \rightarrow q_3, q_4$ via V_1, V_2 exchange, with $f_1, \bar{f}_1, f_2, \bar{f}_2$ production. Crossed out with a red line. +

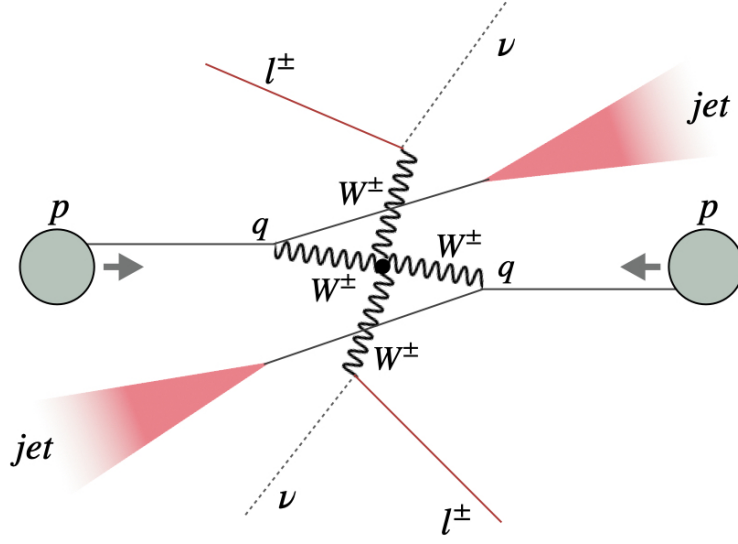
Table 5.3: Representative Feynman diagrams for $pp \rightarrow W^\pm W^\pm jj \rightarrow l^\pm \nu l^\pm \nu jj$ are shown. Electroweak and strong production are the two main production modes of this process. The process can also happen from the interference of the electroweak and strong processes, which is omitted in this table. Electroweak production is the signal used in the measurement, and it includes contributions from vector boson scattering, di-boson production without vector boson scattering, and tri-boson production where one of the gauge bosons decays hadronically. The non-VBS component is studied in conjunction with the VBS component as they are gauge invariantly inseparable. But the resonant production of tri-boson events can be suppressed with the VBS selection of the large di-jet invariant mass. The crossed-out diagrams indicate the $VVjj$ processes that do not happen in the case of $W^\pm W^\pm jj$ production.

production modes without ambiguity. Nevertheless, theoretical developments provide full NLO electroweak corrections and full NLO QCD corrections⁵ separately to the $W^\pm W^\pm jj$ production cross-section [80], and the electroweak corrections are estimated to be quite large, reaching up to -16%, which is one of the striking features of vector boson scattering.

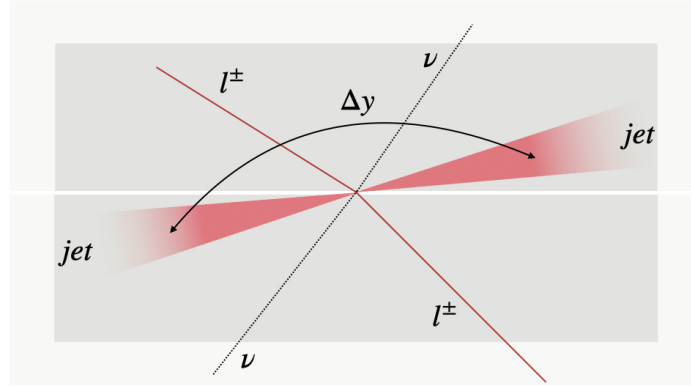
5.3.3 Measurements at the LHC

Following the Higgs discovery in 2012, the first evidence for electroweak $W^\pm W^\pm jj$ process was made in 2014 by ATLAS [77] $\sim 20 \text{ fb}^{-1}$ at 8 TeV recording a signal significance of 3.6 standard deviations. Using the same amount of data, CMS [82] observed 2.0 standard deviations in 2015. Later with $\sim 36 \text{ fb}^{-1}$ data recorded in 2015-2016 at 13 TeV, the process was observed with a signal significance of 5.5 and 6.5 standard deviations respectively by CMS [83] in 2018 and ATLAS [78] in 2019. In this dissertation, the first differential cross-section measurement of this process at 13 TeV with 139 fb^{-1} data collected in 2015-2018 is presented.

⁵No sample exists where electroweak and QCD corrections are implemented together until the time of this analysis.



(a)



(b)

Figure 5.5: A simplified picture of a proton-proton collision event resulting in the scattering of two W bosons with the same electric charge is shown in (a). The W bosons radiated from the incoming quarks scatter off each other and decay into a lepton and a neutrino. Since the W bosons are radiated from the quarks, the trajectories of the incoming quarks are altered only slightly. Therefore, the outgoing quarks lie close to the beam direction and manifest as jets as a result of hadronization. In (b), a schematic view of the event as seen in the ATLAS detector is displayed. The final state consists of two leptons with the same electric charge, two neutrinos, and two jets separated by large rapidities.

Chapter 6

Event Reconstruction

The final state particles produced in pp collisions traverse through the ATLAS detector and interact with it leaving measurable signals. The interaction of the particles with the various detector sub-systems is the key to their reconstruction and identification. ATLAS utilizes various reconstruction algorithms which transform the raw signal from the detector sub-systems into well-defined physics objects such as electrons, photons, etc., based on the characteristic signature laid by the corresponding particle. Reconstructing the relevant physics objects serves as the first step toward reconstructing a physics event of interest.

This chapter presents the various stages involved in reconstructing the final state physics objects of a $W^\pm W^\pm jj$ event. To carefully disentangle the $W^\pm W^\pm jj$ events amidst all the pp collisions, a hard scatter interaction vertex must be searched first. Once such a vertex is obtained, physics objects corresponding to the final state particles of the event that originate from the vertex of interest can be reconstructed and identified. In this chapter, the fundamental concepts behind reconstruction techniques are briefly outlined in Section 6.1. Section 6.2 describes how tracks and an interesting vertex of collision are reconstructed. Finally, in Section 6.3, the reconstruction of the physics objects relevant to identifying a $W^\pm W^\pm jj$ event is explained.

6.1 Reconstruction Techniques

Reconstruction in ATLAS relies on two main techniques: tracking and calorimetry. Tracking refers to tracing the trajectories of charged particles in a magnetic field, whereby the charged particle's momentum and electric charge can be identified. On the other hand, calorimetry measures the energies of neutral and charged particles by the complete absorption of the particle-induced showers in the calorimeters and the shower location in the calorimeter cells. The two methods are used complementarily for particle identification and event reconstruction in ATLAS. While the relative momentum resolution decreases with increasing momentum, the relative energy resolution improves with increasing energy. Thus, the interdependence of tracking and calorimetry in reconstruction is crucial for achieving the performance goals.

6.2 Tracks and Primary Vertices

When a charged particle traverses through the tracking detectors, it deposits energy which is recorded by the detector as an electronic signal or a hit. Based on their alignment, several hits are combined to trace the trajectory of the charged particle identified as its track. From the tracking information, the various proton-proton interaction points can be extrapolated. Tracks and

interaction vertices are reconstructed using the Inner Detector information in ATLAS [84]–[87]. To precisely identify the original trajectory of a charged particle, it is essential to reduce multiple scattering and energy losses resulting from interactions with the traversing material. Therefore, it is critical to minimize the tracker’s material and place the detectors close to the beamline.

The primary tracking algorithm uses the *inside-out* tracking sequence in which various hits are combined, beginning from the silicon detectors, PD and SCT, and then extending outward towards TRT. From the detector hits, a three-dimensional representation known as a space-point can be obtained. A seed is then formed by combining three space-points¹ in the silicon detectors. Next, a combinatorial Kalman filter is used to build track candidates from the seeds by including additional space-points from the remaining layers of the silicon detectors, which are compatible with the preliminary trajectory. In the numerous resulting track candidates, there are misidentified tracks and track segments with shared hits due to overlap. Such ambiguity in the identification of the original track is resolved by ranking the track candidates based on *track scores*. A track score is assigned based on how precisely the hits align with the chosen trajectory, and whether or not the tracks meet certain quality conditions. To the track candidates surviving this stage², compatible TRT hits are found to further extend the track to the TRT. A global χ^2 fit is then applied to estimate the track parameters precisely. The output of the tracking sequence is a collection of final tracks, where each track corresponds to the trajectory of a single particle pointing to the IP.

Following the inside-out tracking, a second tracking algorithm, *outside-in* tracking sequence, is executed. It employs a reverse tracking sequence beginning with the TRT and then extending inward to the silicon detectors. This reverse tracking allows to identify tracks mainly from secondary decays further away from the beamline or photon conversions which might not have enough hits in the silicon detectors necessary to be identified from the inside-out tracking sequence. It has to be kept in mind that if the silicon detector does not find a track candidate, the TRT track extension is automatically omitted. Therefore, the reverse tracking is crucial to identify particle tracks that might point to the IP without necessarily originating from there.

The fraction of tracks that are reconstructed correctly can be estimated using simulations and is quantified as the track reconstructed efficiency³. In Figure 6.1, the efficiency of track reconstruction in ATLAS is shown. The results exclude tracks from secondary decays.

The charged particles follow a helical trajectory in the ATLAS solenoidal magnetic field. A set of five parameters, $(d_0, z_0, \phi_0, \theta_0, q/p_T)$, are needed to fully represent a reconstructed track. The parameters are determined from the high-resolution final fit performed on the tracks and are defined in the global detector coordinates at the point of closest approach to the IP, also called the *perigee*. Figure 6.2 illustrates the definitions of the parameters graphically. d_0 is the distance of the closest approach of the track to the IP in the x - y plane, and z_0 gives the corresponding distance to the IP projected along the z -axis. d_0 and z_0 are known as the transverse and the longitudinal impact parameters respectively. ϕ_0 is the azimuthal angle, whereas θ_0 is the polar angle of the perigee. The fifth parameter, q/p_T , is a measure of the curvature⁴ of the track useful for determining the electric charge of the particle.

¹A set of three space-points in a seed maximizes the number of combinations for all the possible track candidates.

²At this point, the silicon track is not modified. The set of TRT hits is simply an extension of the selected silicon track.

³Precisely speaking, track reconstruction efficiency is defined as $\epsilon(p_T, \eta) = \frac{N_{\text{reco} \cap \text{truth}}(p_T, \eta)}{N_{\text{truth}}(p_T, \eta)}$. Here $N_{\text{reco} \cap \text{truth}}(p_T, \eta)$ is the number of reconstructed tracks matched to true charged particles and $N_{\text{truth}}(p_T, \eta)$ is the number of true charged particles generated.

⁴In first approximation, curvature, C , can be written as $C = 1/R = qB_z/p_T$.

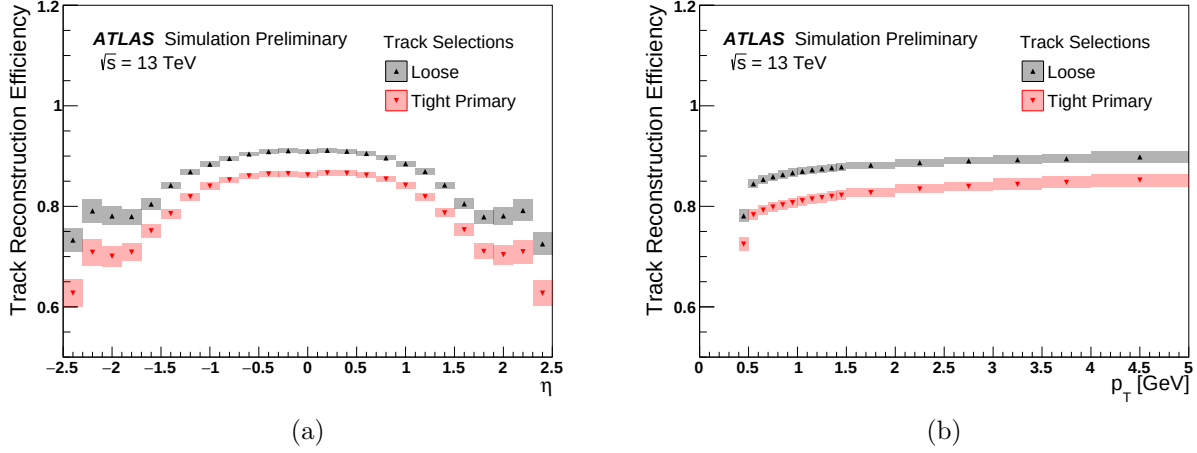


Figure 6.1: Track reconstruction efficiency is shown as a function of η in (a) and p_T in (b) [88]. The results are shown for *Loose* and *Tight Primary* track selections. The tracks passing a minimal set of quality selections fall into *Loose*, and those passing an additional set of stricter selections fall into *Tight Primary*. The drop in the reconstruction efficiencies at $|\eta| > 1$ results from the larger amount of material the particle traverses due to the cylindrical geometry of the detector. In the p_T spectrum, the track reconstruction efficiency reaches a plateau above 5 GeV.

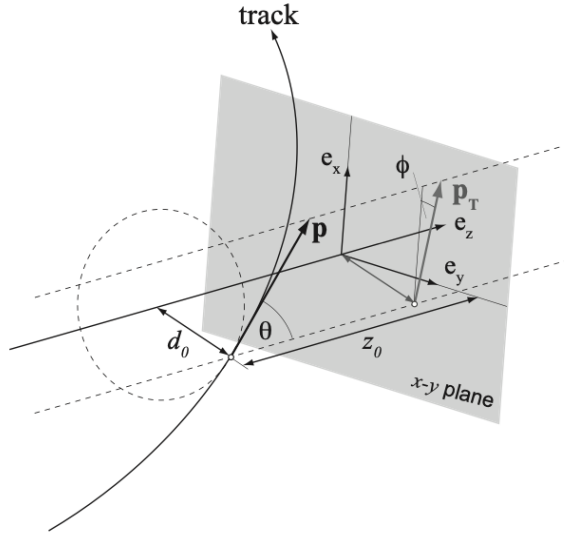


Figure 6.2: A graphic illustration of the definition of the tracking parameters needed to provide a complete and precise parametrization of a fully reconstructed track. Image taken from [89].

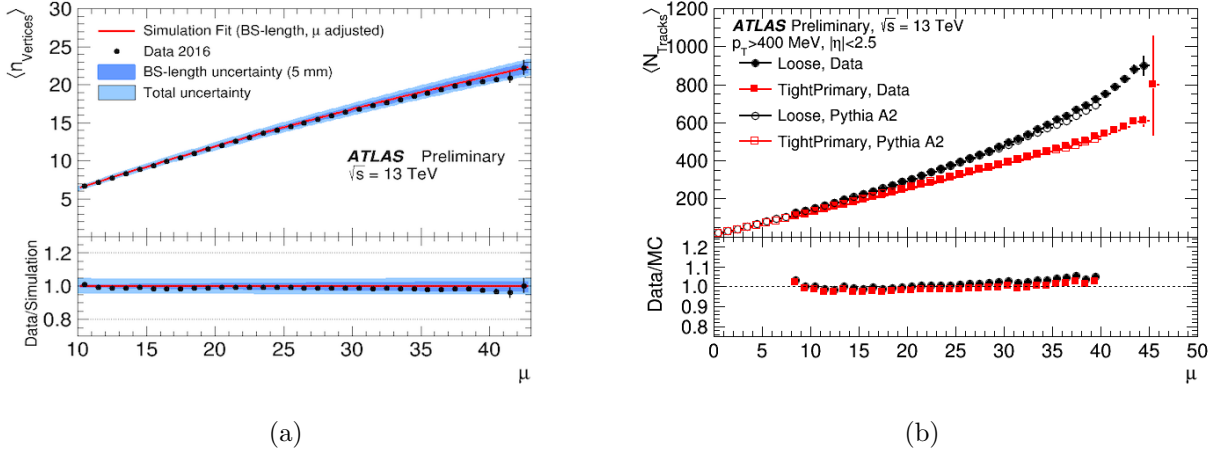


Figure 6.3: The number of reconstructed vertices and reconstructed tracks as a function of pile-up are shown respectively in (a) and (b). The plots show the results observed in data as well as the predictions from simulations [90], [91].

The typical size of the interaction region or beam spot⁵ in Run 2 is about 14 μm in the transverse plane and 45 mm along the beam direction. However, to accurately reconstruct a rare physics process like $W^\pm W^\pm jj$, a precise knowledge of the exact point of the hard scatter, referred to as the *primary vertex*, is crucial. Reconstructing the primary vertex involves vertex finding and vertex fitting. Firstly, the collection of the fully reconstructed tracks is extrapolated inwards to find a common unique origin in the beam spot. Once such a common vertex is found, the vertex position is precisely determined using an iterative χ^2 minimizing fit to find the optimal position. After determining the vertex position, all the tracks incompatible with the vertex are removed and used to determine another vertex. Finally, the vertex contributing to the highest $\sum p_T^2$ from its associated tracks is chosen as the primary vertex, and the rest of the reconstructed vertices are regarded as pile-up vertices. This criterion is based on the assumption that the charged particles produced in a hard scatter interaction have large transverse momenta on average compared to those produced in pile-up collisions. Figure 6.3 shows the number of reconstructed vertices and reconstructed tracks as a function of pile-up. In Run 2, considering a pile-up average of 34 according to Figure 3.4, nearly 19 vertices, 600 Loose tracks, and 400 Tight Primary tracks are reconstructed for every bunch crossing.

6.3 Physics Objects

In the measurement presented in this thesis, $W^\pm W^\pm jj$ events are reconstructed using electrons, muons, jets, and neutrinos in the final state as discussed previously in Chapter 5. The characteristic signatures of these objects in the detector are represented graphically in Figure 6.4. The four-momentum of all the final state objects can be reconstructed except neutrinos which escape the detector without any detection. As a result, neutrinos cannot be reconstructed directly but indirectly by measuring the momentum imbalance in an event. This section describes the reconstruction procedures for the various physics objects pertinent to $W^\pm W^\pm jj$ events.

⁵Beam spot is the spatial region surrounding the interaction point where the profiles of the two incoming proton beams overlap. It is described by a three-dimensional Gaussian.

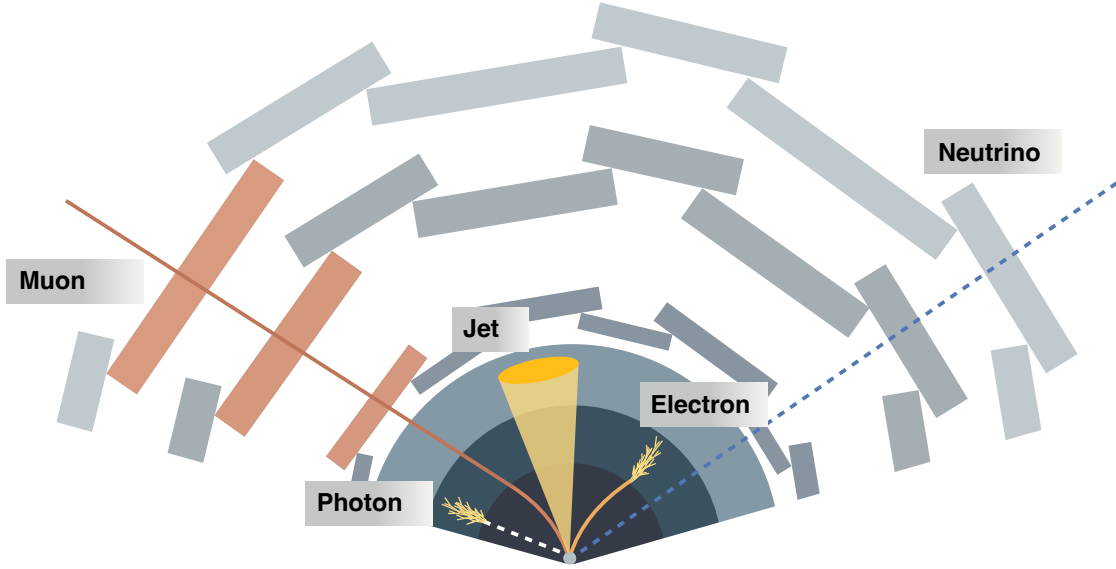


Figure 6.4: A section of the cross-sectional view of the ATLAS detector is sketched showing the characteristic signatures of the various physics objects.

6.3.1 Electrons

Reconstruction

Electrons are reconstructed in ATLAS from clusters of energy deposit in the ECal matched to an associated track in the ID [92], [93]. Owing to the geometric acceptance of the ID, the electrons are reconstructed only within $|\eta| < 2.5$ but with full ϕ coverage⁶. The trajectory of an electron passing through the various detector layers is shown schematically in Figure 6.5. Due to the low mass, an electron with high energy is subjected to Bremsstrahlung radiation, whereby it emits a photon. The emitted photon, in turn, produces an e^+e^- pair which then continues the cycle, creating a cascade of particles known as the electromagnetic shower. The development of the electromagnetic shower depends on the detector material. The ATLAS ECal is designed particularly to enhance the energy loss of the original electron by developing the shower and capturing the entire shower within the detector, minimizing any leakage into the HCal.

The reconstruction of an electron candidate begins, therefore, with the search of a localized energy cluster of at least 2.5 GeV in the ECal using a sliding window of size 3×5 cells in $\Delta\eta \times \Delta\phi$. The center of the cluster moves in steps of 0.025 in either the η or ϕ directions⁷. If two clusters are found in close vicinity, the cluster with the highest E_T is retained, and the other is removed. Following this, an attempt is made to match the cluster with the reconstructed tracks in the ID. As the electron's trajectory is affected by Bremsstrahlung, the tracks are re-fitted additionally with a Gaussian Sum Filter [94], to account for radiative losses for improved track parameter estimations⁸. Finally, the proximity of the track and the cluster is checked in the $\eta \times \phi$ space and the surviving candidates are reconstructed as electron candidates.

⁶Electrons can also be reconstructed in the forward region using the FCal information. Such forward electrons are not used in the measurement and therefore not discussed.

⁷0.025 $\times$ 0.025 in $\Delta\eta \times \Delta\phi$ is the granularity of Layer 2 in Figure 3.9, which absorbs most of the electron energy.

⁸Radiative energy loss leads to a decrease in the momentum, causing an increase in the track curvature in the ID. Therefore, re-fitting the tracks with Gaussian Sum Filter gives more precise track parameter estimations.

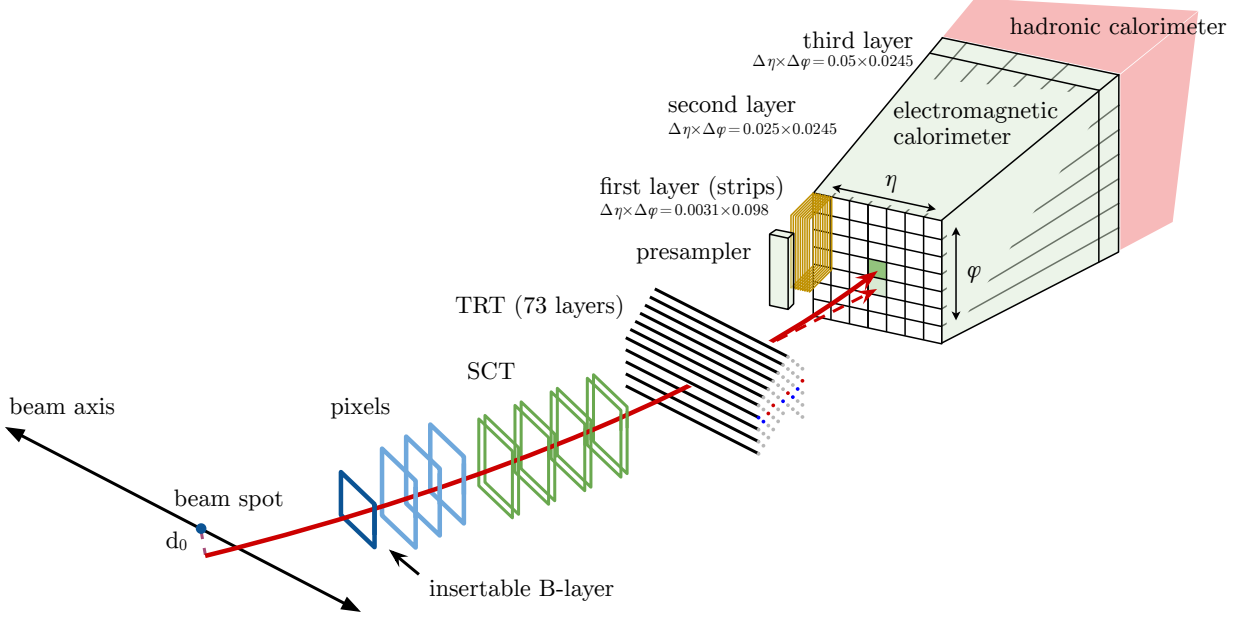


Figure 6.5: A schematic view of the passage of an electron through the various detector layers depicting the technique of electron reconstruction [92].

Calibration

For an accurate measurement of the electron's energy, the energy computed from the reconstructed cluster requires additional correction to account for the energy lost in the material upstream of the calorimeter, energy deposited in the calorimeter cells neighboring the selected cluster, and energy lost beyond the ECal. A multivariate boosted decision tree is trained on simulated electrons, and the energy of the electron is calibrated in both data and simulations, correcting for the losses [95], [96]. Any residual mis-calibration can be parametrized as

$$E_i^{data} = E_i^{MC} (1 + \alpha_i), \quad (6.1)$$

where E_i^{data} and E_i^{MC} are the electron energies in data and simulation, and α_i is the energy scale correction, representing the deviation from optimum calibration. Furthermore, the resolution in MC needs to be smeared to match the resolution in data. As the Z mass peak is experimentally well-determined, the calibration parameters are derived from $Z \rightarrow ee$ decays. The invariant mass of the two electrons in data is compared with different simulated templates differentially in η . Each simulated template has the corrections on energy scale and resolution applied, and the best estimates of the parameters are obtained by minimizing the χ^2 between the data and the template distributions. Any residual bias in the calibration procedure is assigned as an uncertainty which is typically smaller than 0.01% for energy scale and 0.1% for resolution, except in the calorimeter transition region where slightly larger effects are observed [95]. Figure 6.6 demonstrates that data and MC agree within uncertainties after the complete calibration. An agreement between data and simulations is crucial for a meaningful comparison between observation and theoretical predictions. Therefore, calibration is necessary for the accuracy and the repeatability of measurements.

At this stage, the reconstructed electron candidates are composed of the following:

- Prompt electron: An electron candidate with its track originating from the primary vertex. It is typically the electron from a hard scatter.

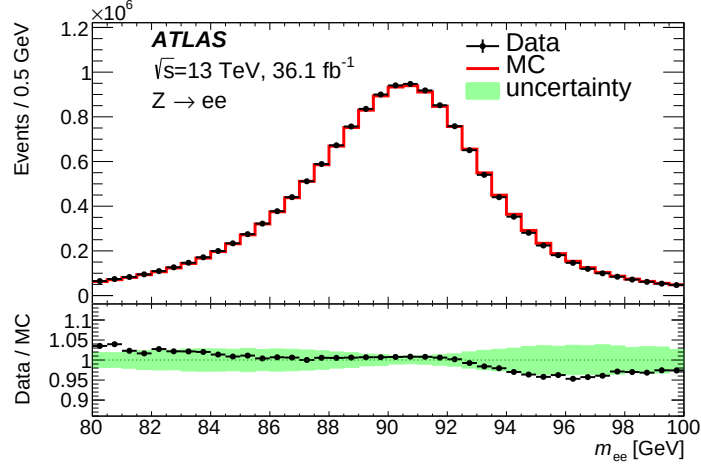


Figure 6.6: Invariant mass distribution of the two electrons in the selected $Z \rightarrow ee$ events are compared between data and MC. The result is shown after applying the energy scale and resolution corrections. The total number of simulated events is normalized to data, and the bottom plot presents the ratio of the agreement between the two distributions. The uncertainty shown represents the uncertainty in the energy scale and the resolution correction factors obtained [95].

- **Converted photon:** An electron candidate originating from a photon when it converts into an e^+e^- pair as it interacts with the traversing material.
- **Non-prompt electron:** An electron candidate originating from the decays of hadrons, commonly pions and heavy-flavor hadrons.
- **Fake electron:** A misidentified electron candidate, usually a jet wrongly reconstructed as an electron.

For the precise reconstruction of a hard interaction for the measurement aimed in this dissertation, it is crucial to distinguish the signal-like electrons originating from the interaction, clearly speaking, prompt electrons, from the remaining non-signal-like or background-like electrons. To extract the prompt electrons from all the reconstructed electron candidates, ATLAS has developed successful strategies, namely, *identification* and *isolation*, which are briefly described below.

Electron Identification

ATLAS employs dedicated identification algorithms to determine whether the reconstructed electron is signal-like or background-like. The algorithms use the principle of likelihood-ratio test based on Neyman-Pearson Lemma [97], which rejects the null hypothesis with the greatest statistical power when the alternate hypothesis is true. In other words, the likelihood-based (LH) method evaluates an overall efficiency to identify signal-like electrons and classifies the electrons into different *working points*. The working points are referred to as *VeryLoose*, *Loose*, *Medium*, and *Tight*, and correspond to increasing order of background rejection based on the LH discriminant.

Each working point uses the same set of variables for electron identification, but the requirements become rigorous with increasing “tightness” of the working point. For example, an electron passing the Medium likelihood-based identification selection will certainly pass the Loose and the VeryLoose selections but may or may not pass the Tight selections. Strictly speaking, an electron in a tight

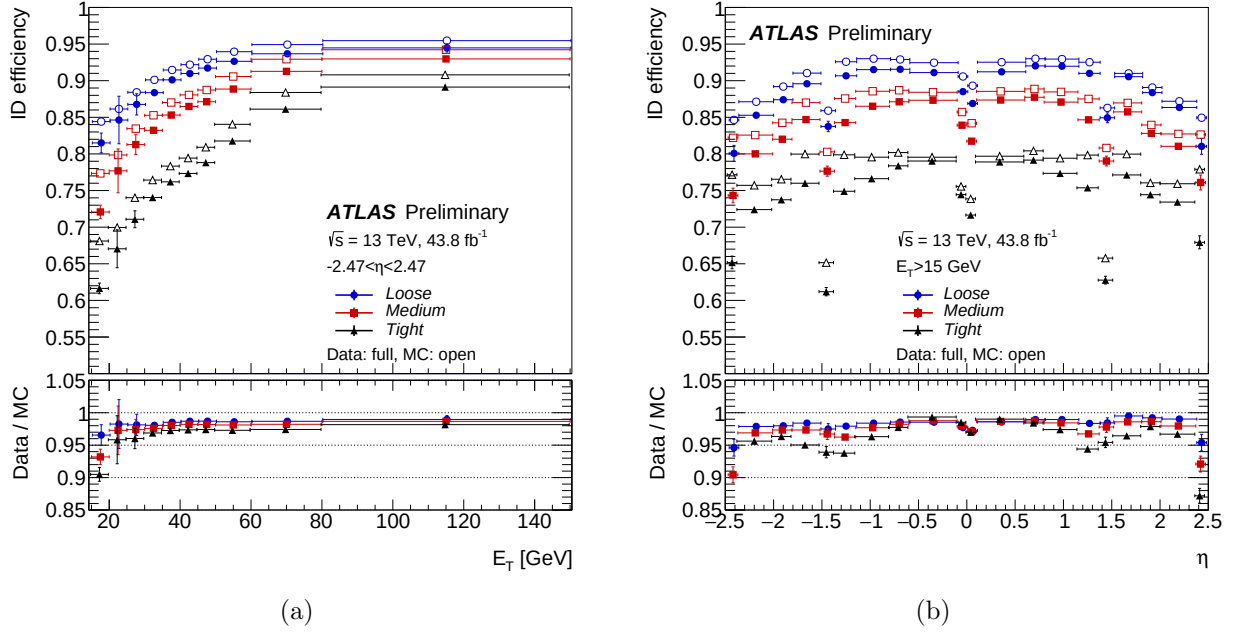


Figure 6.7: Electron identification efficiency as a function of E_T (left) and η (right). Plots taken from [98]. The identification efficiency, ϵ , is defined as the ratio of the number of identified and reconstructed electron candidates to the number of reconstructed electron candidates. The efficiencies are calculated from $Z \rightarrow ee$ events using a tag-and-probe method as described in [99]. Efficiencies are shown for Loose, Medium, and Tight working points.

menu will be a subset of a less tight menu, and the data quality or signal to background efficiency improves with increasing tightness. The details on the LH discriminant and the identification procedure are explained in [92].

Figure 6.7 shows the electron identification efficiency in data and MC simulations for the Loose, Medium, and Tight working points. The level of agreement of the identification efficiency between data and MC can be expressed as a ratio, known as the *efficiency scale factor* (SF),

$$SF = \frac{\epsilon_{\text{Data}}}{\epsilon_{\text{MC}}}. \quad (6.2)$$

Here, ϵ_{Data} is the measured efficiency for a given working point and ϵ_{MC} is the efficiency obtained for the same working point in simulations. The scale factor provides the deviation of the simulations from the actual detector behavior, and it is applied as a correction to simulations at the analysis level⁹.

Electron Isolation

Another way to suppress the contamination from the background-like electrons and identify prompt electrons is by estimating the activity in the vicinity of the reconstructed electron candidate. Isolation quantifies the amount of energy surrounding the candidate to determine whether the electron candidate is prompt or not. It can be measured independently using the track information

⁹Corrections through scale factors apply to all the objects, not just electrons, selected in the analysis based on the respective working points chosen.

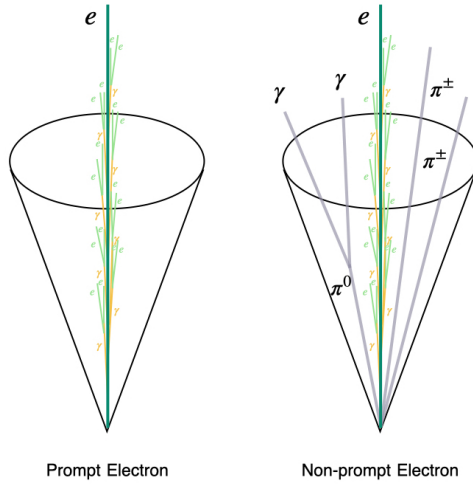


Figure 6.8: A simplified representation of the principle of isolation is shown. A cone of size ΔR is delineated around a prompt electron (left) and an electron from a hadron decay (right). The electron candidates are shown with Bremsstrahlung effects. The prompt electron has little activity surrounding it, whereas the non-prompt electron has significant activity due to other particles in its vicinity. In reality, the activity is more dense and complex.

from the ID, the energy information from the calorimeters, or even a combination of both measurements. Track-based isolation has lower pile-up dependence than calorimeter-based isolation due to the rejection of tracks originating from pile-up vertices. On the other hand, calorimeter-based isolation includes neutral particles, which are not considered in track-based isolation. Depending of the isolation criteria, various working points are defined such as *Gradient*, *Gradient (Loose)*, *FixedCut* etc. To estimate the surrounding activity, a cone of radius $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ is delineated around the electron candidate. Simply put, isolation can then be expressed as the sum of p_T (E_T) of the tracks (clusters) within the cone in the ID (ECal) surrounding the electron candidate¹⁰.

A prompt electron usually has little activity around it, whereas a background-like electron tends to have much activity around it. Figure 6.8 shows a simplified representation of the activity surrounding a prompt electron and a non-prompt electron.

Selecting Prompt Electrons

In the analysis, to extract the prompt electrons in the signal region, the reconstructed electrons are required to pass Tight identification and Gradient isolation working points. The Tight identification working point is chosen due to its large rejection power of background-like electrons. The Gradient isolation working point is built by combining both the track and calorimeter based isolations. It uses a narrow cone size of $\Delta R = 0.2$ in the ECal together with $\Delta R < 0.2$ in the ID, and selects “well-isolated” electrons. The efficiency of the Gradient isolation working point increases from 90% for $E_T = 25$ GeV to 99% for $E_T > 60$ GeV.

¹⁰It has to be noted that the isolation calculation excludes the p_T or the E_T of the interested electron candidate in the cone.

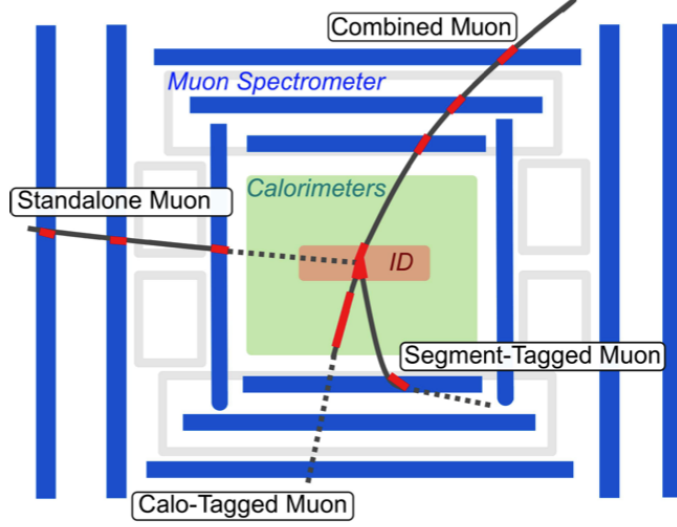


Figure 6.9: A graphic illustration summarizing the four algorithms for muon reconstruction. Image taken from [101].

6.3.2 Muons

Reconstruction

Muons are heavier counterparts of electrons and interact with matter primarily through ionization. Due to its heavy mass, the rate of Bremsstrahlung, which is proportional to $(m_\mu/m_e)^2$, is 40,000 times more suppressed in muons compared to electrons [100]. As a result, muons do not initiate electromagnetic showers but deposit only minimally ionizing energy in the calorimeters and proceed to the MS. Therefore, tracking is the chief mode of muon reconstruction, relying on the ID and the MS information. In the ID, muon tracks are reconstructed like any other charged particle tracks. Track reconstruction in the MS starts with the search for hit patterns in a well-aligned fashion to form a track segment. Various segments in the different detector layers are combined and fitted using a global χ^2 to reconstruct the muon track in the MS. Though combining the track measurements from the ID and the MS provides the best results, such a combination is not a strict requirement for muon reconstruction [102]. Depending on the sub-detectors involved, four different reconstruction strategies are used:

- Combined (CB) muon is reconstructed from a global refit combining the ID and the MS tracks.
- Segment-tagged (ST) muon has a definite track in the ID but crosses only one layer of the MS, either because of low p_T or because it falls in the MS regions with reduced acceptance.
- Standalone or Extrapolated (ME) muon has only a track in the MS and extends acceptance into the region, $2.5 < |\eta| < 2.7$, which is not covered by the ID.
- Calorimeter-tagged (CT) muon consists of a definite track in the ID matched to an energy deposit in the calorimeter compatible with a minimum ionizing particle. A CT muon has the lowest purity compared to all the muon types.

Figure 6.9 presents a graphic illustration summarizing the four reconstruction algorithms. Muons used in this measurement are CB muons reconstructed in $|\eta| < 2.5$.

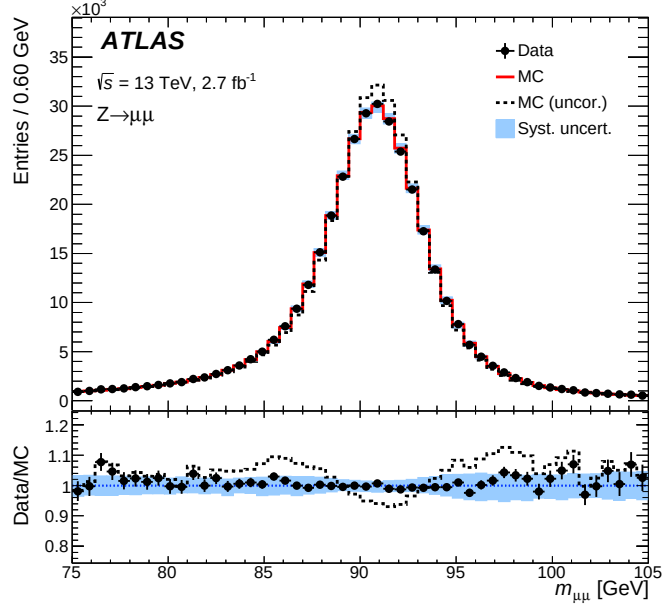


Figure 6.10: The invariant mass distribution of the di-muons in $Z \rightarrow \mu\mu$ decays are compared between data and MC simulations. The results show the MC distributions before and after corrections. The total number of simulated events is normalized to data, and the bottom plot presents the ratio of the agreement between data and MC. The systematic uncertainties associated with the calibration are also shown [103].

Calibration

After reconstruction, it is necessary to ensure that the muon performance is consistent between simulation and data. The transverse momenta of the reconstructed CB muons are compared between data and simulation in $\eta - \phi$ detector regions that are homogeneous in terms of detector technology and performance [103]. The simulation is corrected for any residual disagreement, including any inaccuracy in the magnetic field description and energy loss between the interaction point and the MS, to emulate the detector performance in data. Additionally, the momentum resolution in the simulations is smeared to describe the resolution in data. Figure 6.10 shows the invariant mass distribution of di-muons in $Z \rightarrow \mu\mu$ decays, demonstrating the effectiveness of the calibration.

Like electrons, the reconstructed muons are composed of prompt muons, non-prompt muons, and fake muons¹¹. To extract muons from prompt decays, identification and isolation selections are applied.

Identification

Prompt muons are identified by applying certain quality requirements on the CB muon tracks. The track of a muon originating from a secondary decay is more likely to yield a poorer quality in the final fit of the combined track. Additionally, such background-like muons exhibit incompatibility with the momentum measured in the ID and the MS. Based on the compatibility of track

¹¹Due to the massive nature of muons, the contribution of photon conversions is quite small.

information from the two detectors, various identification working points are defined such as *Loose*, *Medium*, and *Tight* in the increasing order of background rejection [102]. Similar to electrons, muons in a tight working point constitute a subset of a less tight working point. Medium identification is the default working point used in a wide range of analyses in ATLAS as it provides a fairly high efficiency for identifying prompt muons while keeping the associated systematic uncertainties small [102].

Isolation

In addition to identification, isolation criterion serves as a strong discriminator to extract prompt muons. The concept of isolation is already introduced for electrons and is not repeated here. The isolation working points for muons are defined for track-based isolation with or without calorimeter-based isolation. Based on the selections, a set of working points, *Loose*, *Tight*, *HighPtTrackOnly*, *PflowLoose*, *PflowTight*, etc., have been optimized. The *PFlow* working points are built using a novel particle-flow algorithm implemented since Run 2. In the *PFlow* isolation working points, the calorimeter information accounts for only neutral particles with a goal to remove the overlapping contributions from charged particles to both track and calorimeter based isolations.

Selecting Prompt Muons

In this analysis, muons in the signal region are CB muons that are required to pass Medium identification and *PFlowTight* working points. The Medium identification working point provides a prompt muon identification efficiency of 97% for $p_T > 5 \text{ GeV}$ and 70% for $3 < p_T \text{ (GeV)} < 5$. With the Medium identification working point, contamination from fake muons and muons from light hadron decays are already efficiently reduced. The *PFlow* working point uses both track measurement for charged particles and calorimeter measurement for neutral particles to estimate isolation. The *PFlowTight* working point is optimized to yield a fairly good efficiency for prompt muons while suppressing the efficiency for muons from heavy-flavor decays.

6.3.3 Jets

A jet is a collimated spray of particles produced as a result of the hadronization of quarks and gluons in the final state. Due to QCD color confinement, quarks and gluons, particles carrying color charge, cannot exist in free form. Instead, they hadronize immediately to build stable color-neutral hadrons travelling roughly in the same direction as the initial quark or gluon. An ensemble of these hadrons is known as a jet as it forms a narrow “jet” of particles. From the interactions of the hadrons with the detector material, a jet is reconstructed to closely reflect the kinematics of the initial parton.

Reconstruction

Jets typically traverse the entire ECal and are fully absorbed in the HCal. The reconstruction of jets is similar to that of the electromagnetic showers but more complex due to the different types of particles involved in the hadronic shower. Jets do not have a unique object definition. The definition depends on the algorithm which groups the particles into a jet and assigns a four-vector representing the energy and the direction of the parton from the hard scatter. There exist several jet finding algorithms, and two important conditions any jet algorithm should be wary of are *infrared safety* and *collinear safety*. An infrared-safe algorithm ensures that the jet configuration is insensitive to the effects of soft radiation, whereas a collinear-safe algorithm is insensitive to

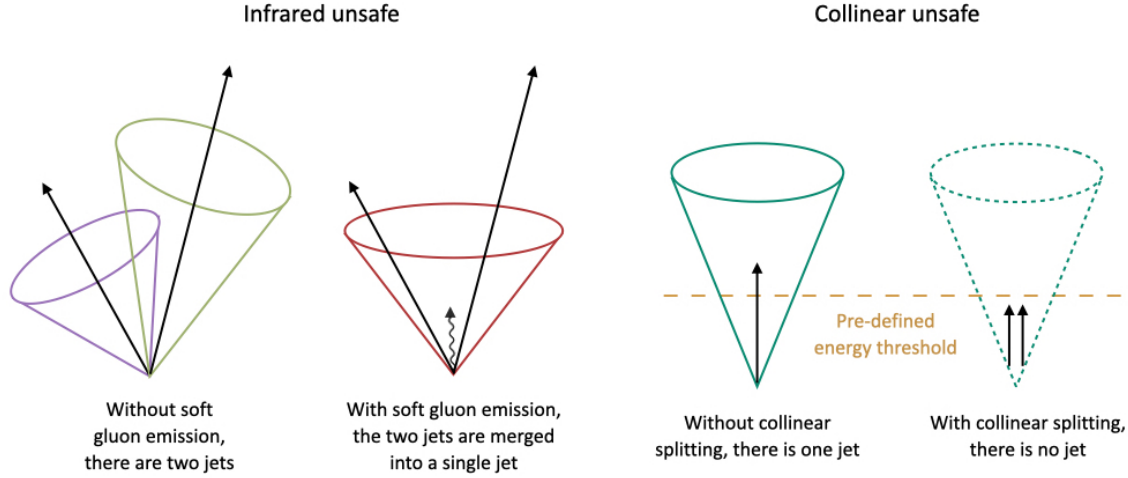


Figure 6.11: A graphic illustration of infrared unsafe and collinear unsafe scenarios is shown.

collinear splitting, i.e., the jet boundary is not affected by substituting one particle with two collinear particles with half the original energy. An illustration of infrared and collinear unsafe scenarios is shown in Figure 6.11. Soft emissions and collinear splittings are difficult to predict theoretically as they involve non-perturbative effects. Therefore, it is crucial for any algorithm to reconstruct jets in a manner insensitive to these effects for a meaningful comparison between data and theoretical predictions. The anti- k_t is one such algorithm satisfying these criteria, and it is the algorithm of choice at the LHC [104].

Clusters of energy deposit that are above a pre-defined signal-to-noise threshold in the nearby calorimeter cells are combined iteratively based on a distance metric to form topological clusters (topoclusters), defined at the electromagnetic (EM) scale¹². The procedure is repeated, and clusters are merged until the distance metric falls below a certain limit [105], [104]. At this point, the resulting object is deemed a jet and removed from further iterations. The anti- k_t algorithm uses a distance metric dependent on the transverse momentum of the particles and their angular separation [104]. The algorithm prefers to combine a low p_T topocluster with a high p_T topocluster before attempting to combine it with another low p_T cluster, thus resulting in almost a circular cone around the hardest particle. Finally, the four momentum assigned to the jet is the sum of the four momenta of all the topoclusters involved in reconstructing the jet.

This analysis uses jets with a radius parameter $R = 0.4$ reconstructed using the particle flow implementation of the anti- k_t algorithm [106]. The particle flow approach uses the combined information from the tracker and the calorimeters to reconstruct jets, exploiting the best of the resolutions of the two sub-systems. The algorithm uses a boolean decision to determine whether to use the tracker or the calorimeter measurement. If the particle's track measurement is used, the corresponding energy is subtracted from the calorimeter measurement to avoid double-counting. Finally, jets are reconstructed from the remaining calorimeter energy and the tracks matched to the primary vertex. The particle flow algorithm has been implemented since Run 2¹³ and offers some advantages. At low energies, the momentum resolution of the tracker is significantly better than

¹²It is the baseline calorimeter scale that correctly measures the energy of an electromagnetic shower. A dedicated calibration is performed later to correct for the calorimeter non-compensation.

¹³Until then, jets have been reconstructed purely from calorimeter measurements.

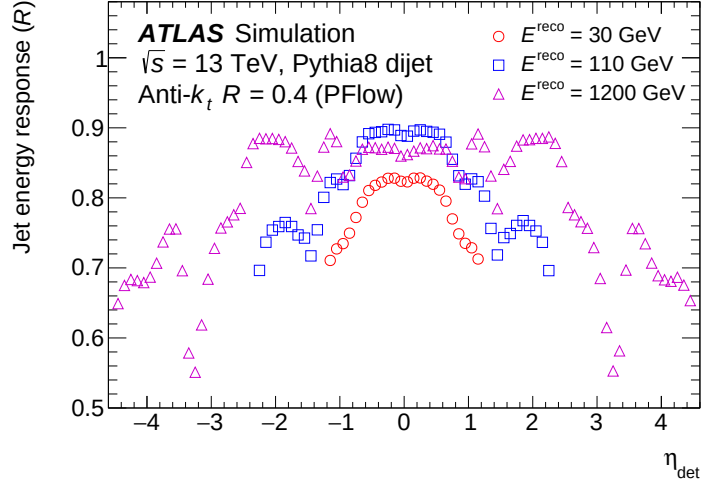


Figure 6.12: The average jet energy response as a function of the reconstructed jet η is shown. The distribution is obtained from the di-jet simulations of Pythia8 [107].

the calorimeter's energy resolution, allowing the reconstruction of softer particles that otherwise do not pass the signal-to-noise threshold required for building topoclusters. Under the influence of the magnetic field, low p_T charged particles originating from within a jet are swept out of the jet cone by the time the particles reach the calorimeters. Using the track measurement, such particles can be clustered into the same jet. The algorithm also provides better pile-up stability by removing undesired contributions in the energy clusters from pile-up interactions using a track-to-vertex association. Additional corrections are further applied to mitigate the effects of pile-up.

Calibration

After pile-up corrections are performed, the next step is calibration [107]. Due to the calorimeter non-compensation¹⁴, the jet energy measured at the EM scale tends to be lower than the true energy of the jet. The reconstructed energy is corrected to the true energy using simulations by determining the jet energy response $\mathcal{R} = E_{reco}/E_{true}$. The average energy response defined as the mean of a Gaussian fit applied to $\mathcal{R}$ is shown in Figure 6.12. The jet energy scale calibration factor is then derived as the inverse of the average response. Similarly, calibration is also applied to η to correct for the differences between η_{reco} and η_{true} , particularly in the transition regions of the calorimeter. Following the simulation-based calibration, any biases due to mismodeling effects are corrected using *in-situ* calibration. The in-situ calibration measures the jet response in data and simulation separately and applies the ratio as the correction to data as detailed in [107]. An astute reader may have noticed that the jets in the central region of the detector show a fairly good response while the jets in the forward regions vary in response. In the in-situ calibration, η inter-calibration is also performed where the jet response in the forward region, $0.8 < |\eta| < 4.5$, is calibrated to that in the central region, $|\eta| < 0.8$. The η inter-calibration is crucial to this analysis as the measurement of the $W^\pm W^\pm jj$ signal tags two jets in the forward regions of the detector.

The jet response can also vary from jet to jet depending on the initiating particles, most notably between quark- and gluon-initiated jets. A quark-initiated jet typically includes hadrons with a higher fraction of the jet p_T penetrating further into the calorimeter, while a gluon-initiated jet

¹⁴The calorimeter response is better for electromagnetic showers compared to hadronic showers.

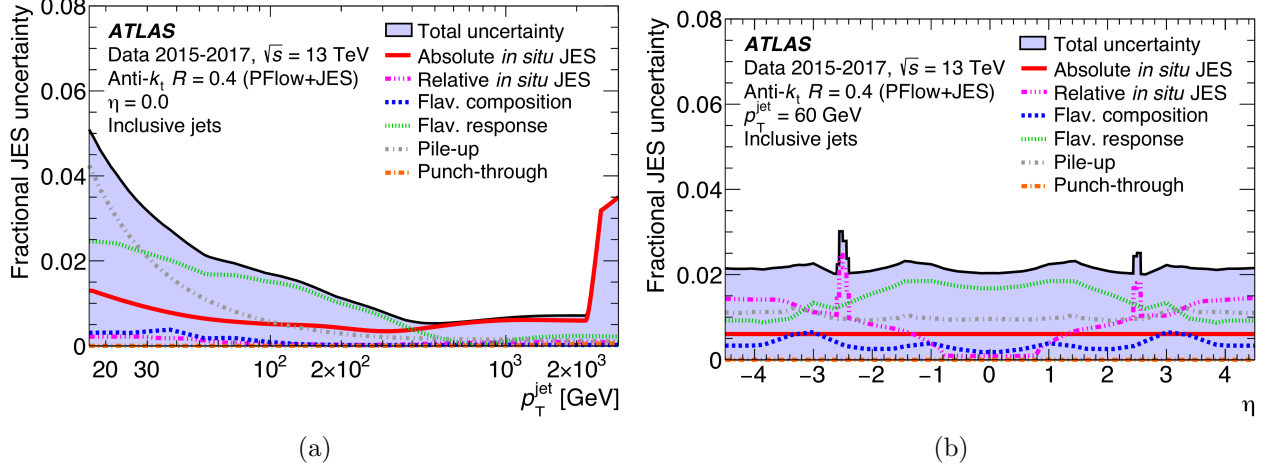


Figure 6.13: The total systematic uncertainty jet energy scale is shown as a function of p_T in (a) and η in (b). In the in-situ calibration, the uncertainty associated with η inter-calibration is given as the relative in-situ JES and the uncertainty in all other in-situ measurements are combined into the absolute in-situ JES on the plot [107].

often has more particles with softer p_T . Calibrations are also applied to reduce the jet response dependence on this jet flavor composition. The total systematic uncertainty computed on the jet energy scale is given in Figure 6.13, and the uncertainties due to the flavor dependence and η inter-calibration are two of the largest sources of uncertainties on the cross-section measured in this thesis, which can be seen later in Chapter 14.

Tagging b -jets

One of the major sources of non-prompt leptons is the jet initiated by a b -quark, known as b -tagged jet or b -jet. The hadronization of a b -quark produces a b -hadron, which has a high decay multiplicity of charged stable particles, as seen in Figure 6.14.

Non-prompt lepton is a dominant background in this analysis, and it becomes necessary to suppress their contribution by removing any b -jet in the measurement. A b -jet can be distinguished from other jets by exploiting the long lifetimes of b -hadrons. With an average lifetime of 1.5 ps, b -hadrons propagate measurable distances in the ID before decaying, thus resulting in a secondary vertex displaced from the hard scatter interaction point. Tracks originating from the secondary vertex of a b -hadron decay typically have large impact parameters allowing them to be separated from the tracks associated with a primary vertex.

Built on these distinguishing properties, several algorithms exist to identify b -jets, and the algorithm used to tag b -jets in this measurement is *DL1r* tagger. The *DL1r* tagger is based on a deep neural network optimized for PFlow jets and is currently the default tagger in ATLAS [109].

Like the b -hadrons, c -hadrons also have sufficiently long lifetimes leading to a reconstructible secondary vertex, making it difficult to distinguish the two kinds of jets. However, as the jets in $W^\pm W^\pm jj$ signal can be c -quark initiated, it is necessary that the *DL1r* tagger identifies a b -jet with maximum c -jet rejection, a desirable feature for many ATLAS analyses. Therefore, the neural network is trained with b -jets as signal and c -jets (jets containing a c -hadron and no b -hadron)¹⁵ and light-flavor jets (jets containing no b -hadron or c -hadron but initiated by a u -, d -, s -quark or

¹⁵A typical b -hadron decay chain contains a c -hadron but it falls under b -jet tagging.

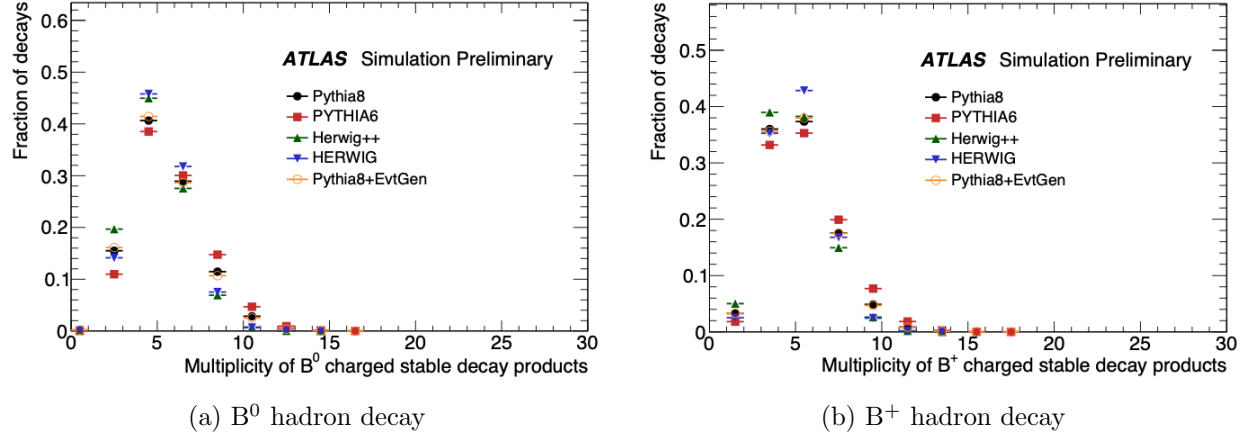


Figure 6.14: The decay of b -hadrons into charged stable decay products. The predicted results are compared between various generators [108].

a gluon) as background. Figure 6.15 shows the b -jet tagging efficiency of the DL1r tagger, and the working point with 85% identification efficiency is used to remove the contributions of b -jets in this analysis.

6.3.4 Missing Transverse Momentum

A neutrino is a weakly interacting stable particle, and indeed the only known particle which escapes the detector without leaving any signal. Nevertheless, the presence of neutrinos must be inferred and the experimental proxy to quantify the transverse momentum of undetected particles is the *missing transverse momentum* [111].

The momentum carried by the colliding partons follows a distribution according to Figure 2.3 and cannot be directly measured. As the incoming beams travel along the z -direction, one can say that the momentum of the interacting partons in the transverse plane is zero at the time of collision¹⁶. Conservation of momentum implies that if all the particles produced in an event are detected, then the vector sum of the transverse momenta of the particles should be zero. An imbalance in the sum of the visible transverse momenta equates to the transverse momenta carried by the undetected particles, numerically understood as

$$\mathbf{p}_T^{\text{miss}} = - \sum_{\text{detected particles}} \mathbf{p}_T = \sum_{\text{undetected particles}} \mathbf{p}_T. \quad (6.3)$$

Therefore, the reconstruction of missing transverse momentum involves all the sub-systems and relies entirely on the reconstruction of every other physics object in the event. The undetected particles correspond to neutrinos according to the Standard Model predictions, and E_T^{miss} , defined as the magnitude of the above vector¹⁷, is the observable used to confirm the presence of neutrinos in an event. E_T^{miss} can be written as

$$E_T^{\text{miss}} = |\mathbf{E}_T^{\text{miss}}| = \sqrt{(E_x^{\text{miss}})^2 + (E_y^{\text{miss}})^2}, \quad (6.4)$$

¹⁶Due to the effects of ISR, the incoming partons do have a net p_T , but it is negligible compared to the energy scale probed.

¹⁷Transverse momentum is synonymous with transverse energy for neutrinos.

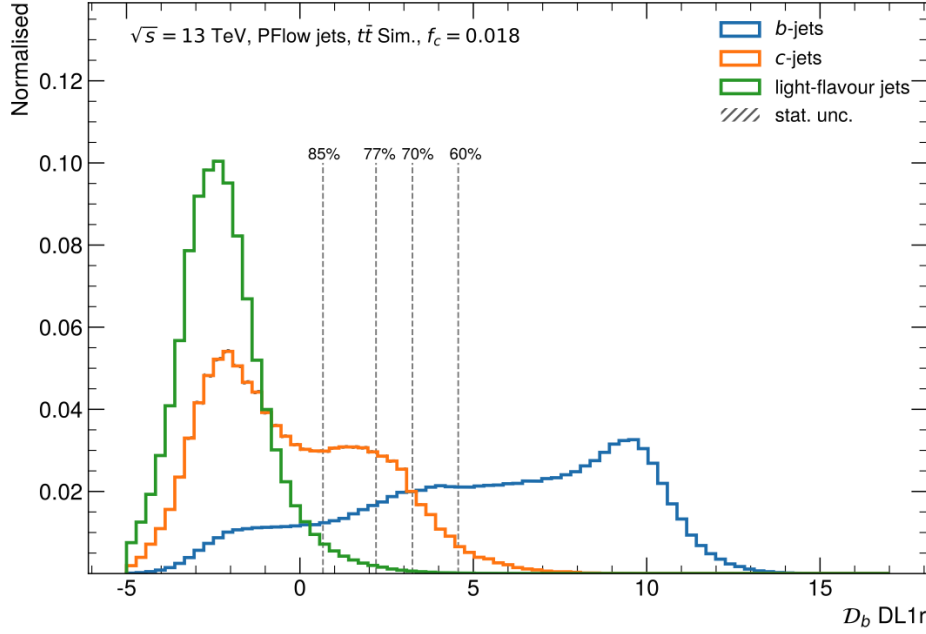


Figure 6.15: The DL1r b -jet tagging discriminant is shown for b -jets (blue), c -jets (orange), and light-flavor jets (green). f_c is a free parameter optimized for the best discrimination. The vertical dashed lines indicate the b -tagging efficiencies defining the different working points [110].

where

$$E_{x(y)}^{\text{miss}} = - \sum p_{x(y)}^e - \sum p_{x(y)}^\gamma - \sum p_{x(y)}^\tau - \sum p_{x(y)}^\mu - \sum p_{x(y)}^{\text{jet}} - \sum p_{x(y)}^{\text{unused tracks}}. \quad (6.5)$$

E_x^{miss} and E_y^{miss} are the x - and y - projections of $\mathbf{E}_T^{\text{miss}}$ computed from the contributions of fully reconstructed and calibrated electrons, photons, taus, muons, jets, and any unused tracks associated with the hard scatter vertex.

Chapter 7

Analysis Strategy

This chapter presents the main objectives of the measurement presented in this dissertation along with the methodologies implemented to achieve the same. Section 7.1 lays the key objectives of the measurement. An overview of the backgrounds encountered in the measurement is described in Section 7.2. This is followed by a brief outline of the workflow of the analysis in Section 7.3.

7.1 Key Objectives

The analysis described in this thesis aims to measure the total and the differential cross-sections of electroweak induced $W^\pm W^\pm jj$ ($W^\pm W^\pm jj$ -EWK) production which is crucial to validate the predictions of the Standard Model. Due to the presence of a quartic gauge vertex at tree level, the process is further interesting to search for anomalous quartic gauge couplings. Moreover, an enhancement in the measured signal is a direct hint to a doubly-charged resonance, and such deviations from the Standard Model expectations can provide sensitivities to new physics.

As discussed previously in Chapter 3, the cross-section of any physics process, $W^\pm W^\pm jj$ -EWK production in this case, can be measured as

$$\sigma = \frac{N^{\text{sig}}}{\mathcal{L}}, \quad (7.1)$$

where N^{sig} is the observed $W^\pm W^\pm jj$ -EWK events in data and $\mathcal{L}$ is the total integrated luminosity corresponding to the data. Besides the signal events, the observed events in data contain other Standard Model processes that mimic the $W^\pm W^\pm jj$ final state, which are considered as background events. To maximize N^{sig} , a set of selections are applied to define a fiducial phase space known as the signal region, where the contribution of $W^\pm W^\pm jj$ -EWK is enhanced while reducing the background. The observed signal events in data can now be written as $N^{\text{sig}} = N^{\text{data}} - N^{\text{bkg}}$, where N^{data} is the observed data events in the signal region and N^{bkg} is the sum of all the background events estimated in the signal region.

In addition to the measurement of the total cross-section, cross-section can also be determined differentially as a function of any given observable if the data sets are sufficiently large. Differential measurements of the cross-section give precise shape measurements of an observable, thus conveying more information than that obtained from total cross-section. One can define the differential cross-section ($d\sigma/dx$) as a function of an observable x as

$$\left(\frac{d\sigma}{dx}\right)_i = \frac{N_i^{\text{sig}}}{\Delta x_i \mathcal{L}}, \quad (7.2)$$

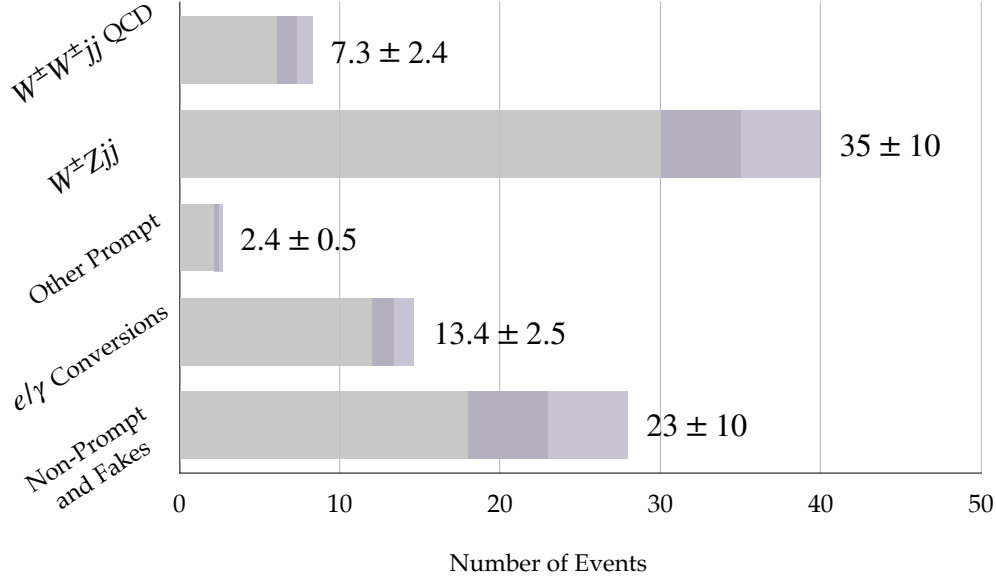


Figure 7.1: A bar chart showing the background yields in the previous iteration of this analysis using 2015-2016 data [78]. The nominal event yields are colored in gray and the total uncertainty (statistical and systematics) are colored in light purple. Other Prompt in the chart includes top, ZZ , and tri-boson processes. $W^\pm W^\pm jj$ -INT is not shown as it was not accounted for in the past measurement.

such that the total cross-section is

$$\sigma = \int \left(\frac{d\sigma}{dx} \right)_i \Delta x_i. \quad (7.3)$$

Here, Δx_i is the width of bin i , and the differential cross-section in i represented by $\left(\frac{d\sigma}{dx} \right)_i$ is the total cross-section in the kinematic range marked by that bin. This thesis presents the first measurement of the differential cross-section for $W^\pm W^\pm jj$ -EWK production from the ATLAS Collaboration.

7.2 Overview of Backgrounds

The background processes that mimics the $W^\pm W^\pm jj$ final state, thus gaining entry into the signal region of this measurement can be classified into three categories:

1. **Prompt leptons:** The prompt lepton background corresponds to the Standard Model processes where the final state consists of two prompt leptons with the same electric charge¹ imitating the final state of the signal. The sources of this background in the analysis are:
 - **$W^\pm W^\pm jj$ -QCD:** As described already in Chapter 5, this background arises from the strong production of $W^\pm W^\pm jj$ and has the same final state as the electroweak signal.

¹Henceforth, leptons with the same sign for the electric charge are referred to as same-sign leptons.

- **$W^\pm W^\pm jj$ -INT:** This background arises from the interference of the electroweak production and the strong production of the $W^\pm W^\pm jj$ process.
 - **$WZjj$:** The leptonic decay modes of the bosons, $W^\pm Zjj \rightarrow l^\pm \nu l^\pm jj$, results in a third lepton, originating from the Z boson, with a different charge in the final state. When this lepton is not reconstructed, for example, as a result of falling outside of the detector acceptance, the final state has two same-sign prompt leptons corresponding to the signal. $WZjj$ process is the largest source of prompt background in this analysis.
 - **Top:** The top background includes mainly $t\bar{t}Z$, $t\bar{t}W$, and tZ processes when some of the physics objects in the final state, particularly b -jets, are not reconstructed or correctly identified, thus mimicking the signal.
 - **$ZZjj$:** When both the Z bosons decay leptonically, the final state consists of two pairs of same-sign leptons. If two of the leptons with opposite charges happen to be missed, the process can imitate the signal topology.
 - **Tri-boson:** WWZ , WZZ , and ZZZ processes make up the tri-boson background. For example, if the oppositely charged lepton is not reconstructed in $W^+W^-Z \rightarrow l^+\nu jjl^+l^-$, the final state is same as that of the signal. But the tri-boson contributions are quite small in a typical VBS phase space due to the large di-jet invariant mass requirement.
2. **e/γ Conversions:** The e/γ conversions account for Bremsstrahlung effects and photon conversions and they contribute as the background in this analysis in events with electron candidates. This background is further realized as:
- **Charge misidentification:** It consists of Standard Model processes, such as Z +jets, $t\bar{t}$, etc., where the final state consists of two opposite-sign leptons where the electric charge of one of the leptons is incorrectly assigned, resulting in two same-sign leptons in the final state. Consider a prompt e^- candidate in an event which radiates a photon as it journeys through the detector. The emitted photon can convert into an e^+e^- pair and it is possible that the final reconstructed electron candidate can be the e^+ . If the final electron is reconstructed with a charge opposite to that of the initial prompt electron, the final state of the event consists of two same-sign electrons. Such a wrong assignment of charge can also occur in high p_T tracks when there is an ambiguity in determining the track curvature.
 - **$V\gamma jj$:** The $V\gamma jj$ background includes Standard Model processes with a heavy gauge boson and a prompt photon which result in a final state with two same-sign leptons through photon conversions. When the W/Z boson decays leptonically and the photon converts into an e^+e^- pair, the process can mimic the signal topology if the lepton objects are not reconstructed or properly identified. For example, $W^+\gamma jj \rightarrow l^+\nu e^+e^-jj$ process yields the same-sign lepton final state if e^- is not identified.
3. **Non-Prompt and Fake leptons:** This background comprises of leptons originating from secondary decays and jets that are misidentified as leptons, as discussed in the previous chapter. W +jets and $t\bar{t}$ processes constitute the major sources of the non-prompt and fake lepton background.

The charge misidentification background and non-prompt and fake lepton background are determined from data in this analysis. All the other background processes are estimated using Monte Carlo predictions. The simulations show mismodeling in the normalization of the $WZjj$ -QCD

background and the shape of its m_{jj} distribution. To correct for the mismodeling in the simulations, a data-driven normalization factor is derived for the background, and the shape of the m_{jj} distribution is re-weighted to emulate the shape observed in data. The background estimation strategies are explained in detail in the following chapters, and only the analysis workflow is outlined in this chapter.

A summary of the background yields obtained in the previous measurement using 2015-2016 data [78] is shown graphically in Figure 7.1. The $WZjj$ process was the dominant background whereas non-prompt and fake lepton background was estimated with the largest uncertainty.

7.3 Analysis Workflow

The measurement is performed using a “blind” analysis strategy² [112] and a simplified overview of the analysis chain is presented in Figure 7.2. As mentioned earlier, the first step in the workflow is to define a phase space with VBS topology as the signal region (Chapter 9). Without overlapping with the signal region definitions, multiple phase spaces are then selected that mark the validation and control regions to carefully study the backgrounds (Chapters 9-11). While the modeling of a given background is validated in the validation regions, the background parameters are extracted in the control regions. In this analysis, six different validation regions are used to validate the backgrounds and two control regions are adopted to parameterize the $WZjj$ -QCD background. Following a good data-background agreement in the validation regions, the shape of the m_{jj} distribution of $WZjj$ -QCD is re-weighted in its respective control region (Chapter 10) to match the shape observed in data. Thereafter, the (pre-fit) background event yields and the corresponding systematic uncertainties are estimated in the signal region. Next, a profile likelihood fit is performed in the signal region together with the two control regions to constrain the backgrounds and reduce the uncertainties. Here, the normalization factor of $WZjj$ -QCD and the post-fit results of the background estimates in the signal region that maximize the likelihood with the data are obtained³ (Chapter 12).

As the measurement of the differential cross-section for $W^\pm W^\pm jj$ -EWK production is performed for the first time, the binnings of the observable of interest need to be optimized to have a reasonable expected signal significance throughout the distribution. The bins are optimized for four different observables using the pre-fit background estimates and the MC predicted signal yields (Chapter 13).

At this point, one can measure the cross-section if the detector exhibits ideal performance but in reality the detector suffers from inefficiencies which a discerning reader will have noticed already in Chapter 6. As the observables are affected by detector effects, it is necessary to correct for the inefficiencies and extract the true physics distribution in data for a meaningful comparison with the theoretical predictions and other experiments. This is done through a method known as *unfolding* and the unfolding method chosen in this analysis is the iterative Bayesian unfolding (Chapter 13)⁴. To validate the unfolding method, unfolding is first performed on pseudo data. Once the unfolding method shows closure, the blinding procedure is removed and the real data of Run 2 is revealed in the signal region and the differential cross-sections in the data are measured (Chapter 14).

²Blind analysis is a measurement method where the entire data in the signal region is not revealed until the measurement procedures are optimized and finalized so as to eliminate or minimize the experimenter’s bias.

³It has to be noted that the fit is first performed on pseudo data for validation. The normalization factor of $WZjj$ -QCD and the post-fit results used in the final cross-section measurement are obtained by repeating the fitting procedure on the observed data after unblinding which is not explicitly shown on the figure.

⁴While it is possible to extract the cross-sections from the profile likelihood fit using a *bin-by-bin* unfolding approach, the method is not used as the nominal unfolding procedure for the various reasons described in Chapter 13.

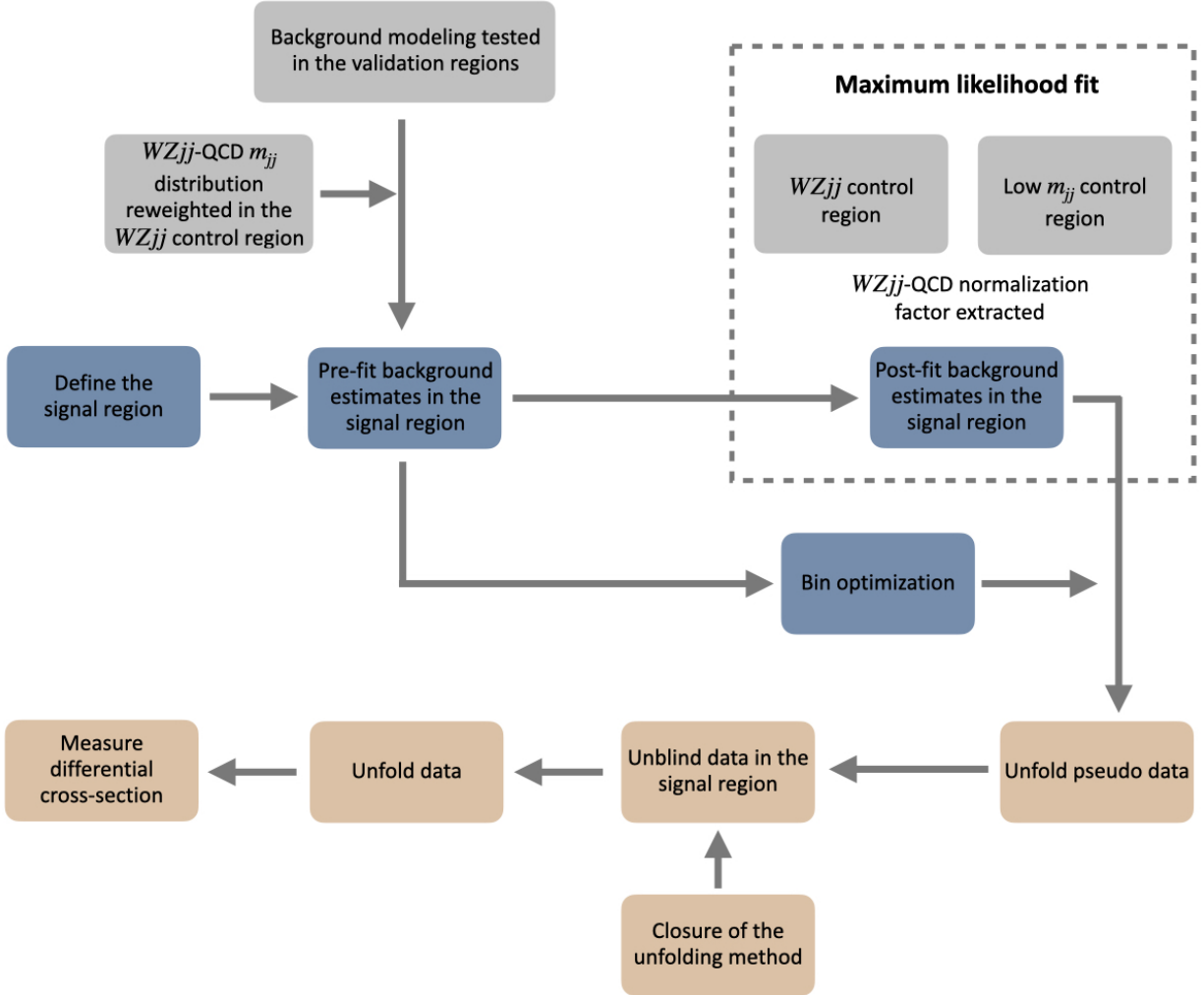


Figure 7.2: A flow chart showing a simplified overview of the analysis chain is given. Blue and light orange color denote the signal region among which the light orange color additionally represent the unfolding stages. Gray color indicates the validation and control regions.

Chapter 8

Analysis Samples

This chapter summarizes the particulars of the recorded datasets and the simulated samples used in the analysis. The chapter introduces the basic foundations of data processing and sample production, followed by the details regarding the analysis samples in the subsequent sections.

8.1 From Signal to Samples

The ATLAS data processing chain governs the transformation of the raw signals in the detector into an easily decipherable event format suitable for analyses. During the time of data taking, the trigger and data acquisition system saves the detector signals in a RAW data format. A RAW event contains all the information in great detail necessary for object reconstruction. The reconstruction algorithms, detailed in Chapter 6, then convert the RAW information into physics objects as Analysis Object Data (AOD). Due to the large $\mathcal{O}(\text{PB})$ size of the AODs, a derivation stage is executed which reduces the data size to $\mathcal{O}(\text{TB})$. The output of derivation is the derived AOD (DAOD). The DAODs are formatted in many derivation flavors, such as STDM3, HIGG3D3, etc., each of which represent different sub-sets of data meeting the needs of the various physics programs in ATLAS. As a final step, the data is often converted into flat n-tuples or physics AOD (PAOD) with smaller sizes, typically $\mathcal{O}(\text{GB})$, containing only the essential information relevant to the analysis. The measurement in this thesis uses PAODs as the final data format for analysis.

A similar chain is run in parallel for Monte Carlo (MC) simulations. The MC method is a mathematical technique of predicting a set of possible outcomes for an uncertain (stochastic) event based on probability distributions. In particle physics, the MC method simulates events preserving the intrinsic probabilistic nature of the physics processes. The MC simulations can generate a sample of events that follow a given theoretical model and all of its constraints, in a way that, the probability of generating such a simulated event matches with the probability of occurrence of an analogous actual event in Nature.

The ATLAS MC production chain begins with event generation. It includes simulating hard interactions followed by interfacing the output with generators that model the parton shower and hadronization into stable particles. The event stored in EVNT format is then subjected to a GEANT4 toolkit [113] that simulates the interactions of the particles with the ATLAS detector material including how much energy the particles deposit in the various detector elements. Next, a digitization stage converts the simulated signals into detector responses that resemble the raw data from the ATLAS detector. Thereafter, the subsequent stages are processed similar to the data chain which includes reconstruction, derivation, and skimming the events into PAOD samples with only analysis pertinent information. Finally, using the data and MC information from the

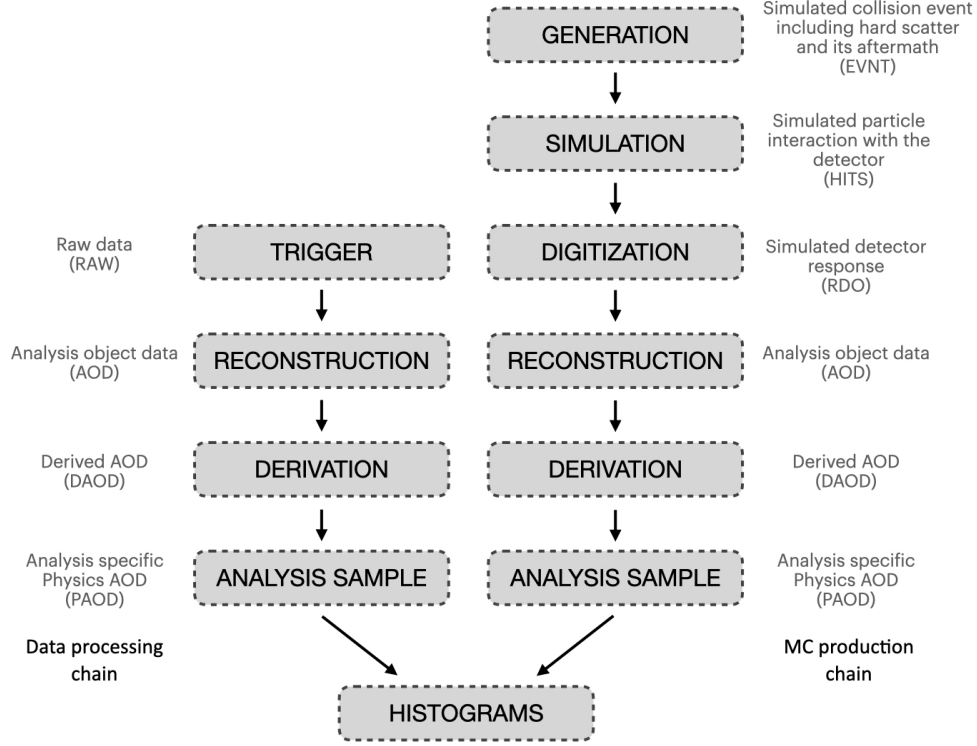


Figure 8.1: A flow chart depicting the various stages of data and MC processing in ATLAS is given. The data processing chain is shown on the left whereas the MC production chain is shown on the right. The information from data PAODs and MC PAODs are combined to perform the analysis.

respective samples, physics results are extracted and represented graphically as histograms. A flow chart summarizing the various stages of data and MC processing in ATLAS is given in Figure 8.1.

It has to be noted that any corrections applied to the simulated events to match the behavior in data such as the pile-up profile, scale factors, etc., are implemented as *weights* at the event level depending on the objects and selections used in the analysis.

8.2 Datasets

The data used in this analysis are the proton-proton collisions of the LHC at $\sqrt{s} = 13\text{ TeV}$ totaling an integrated luminosity of 139 fb^{-1} recorded by the ATLAS detector. The data are collected during the years 2015-2018 and are referred to as the ATLAS Run 2 data. During the data-taking period, the LHC operated with a constant bunch spacing of 25 ns but the instantaneous luminosity and pile-up varied with time (see Section 3.1.3). Overall, the LHC delivered stable beams amount to an integrated luminosity of 156 fb^{-1} , out of which the ATLAS experiment recorded 147 fb^{-1} [40], [114]. Among the recorded data, only events passing the standard detector conditions and data quality requirements, as defined by the Good Runs List (GRL), are considered suitable for physics analyses. The total integrated luminosity delivered, recorded, and suitable for physics are summarized in Table 8.1 and their time evolution is displayed in Figure 8.2. This analysis uses only events satisfying the relevant GRL, which correspond to an integrated luminosity of 139 fb^{-1} estimated with an uncertainty of 1.7% [62].

Data Period	Pile-up	Delivered	Recorded	Good for Physics
2015	13.4	4.2	3.9	3.2
2016	25.1	38.5	35.6	33
2017	37.8	50.2	46.9	44.3
2018	36.1	63.3	60.6	58.5
Run 2	33.7	156.2	147.0	139.0

Table 8.1: A summary of the data-taking periods in Run 2 and the corresponding pile-up and integrated luminosities (in units of fb^{-1}) of proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$ [40], [114]. The total integrated luminosity delivered by the LHC during stable beams is given as “Delivered” out of which the integrated luminosity recorded by ATLAS is indicated as “Recorded”. The total luminosity correspond to the recorded data enlisted in the GRL meeting the ATLAS data quality standards is tabulated as “Good for Physics”.

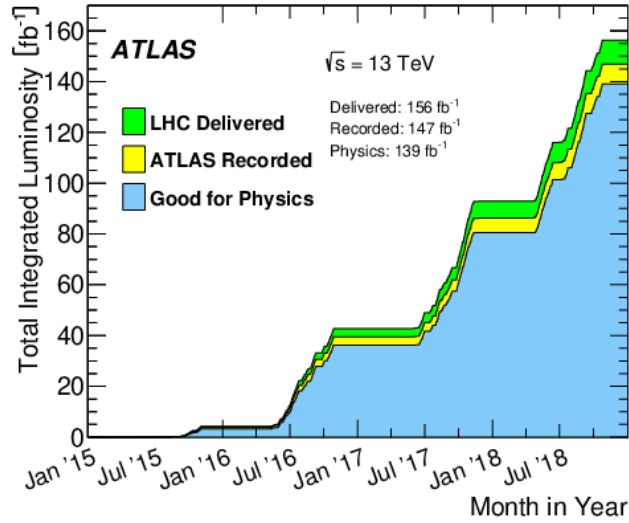


Figure 8.2: Time-evolution of the total integrated luminosities of proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$ in Run 2 is shown. The integrated luminosity delivered by the LHC during stable beams is marked in green and that recorded by ATLAS is given in yellow. The recorded data enlisted in the GRL meeting the ATLAS data quality standards is shown in blue. Plot taken from [40].

8.3 Monte Carlo Samples

8.3.1 Signal Samples

The $W^\pm W^\pm jj$ -EWK signal sample is generated for the $pp \rightarrow l^\pm \nu l^\pm \nu jj$ process by fixing the electroweak coupling to $\mathcal{O}(\alpha^6)$. The nominal signal sample is simulated using MADGRAPH5_aMC @NLO 2.6.7 [115] at leading order accuracy in perturbative QCD for the matrix element description. The output is interfaced with HERWIG 7 [116] for the modeling of parton shower, hadronization, and underlying event. A new dipole-recoil scheme [117]–[119] is adapted in parton showering, where

Process	Generator	PDF
$W^\pm W^\pm jj$ -EWK	MADGRAPH5_aMC@NLO+HERWIG 7	NNPDF3.0nlo
$W^\pm W^\pm jj$ -EWK	MADGRAPH5_aMC@NLO+PYTHIA 8	NNPDF3.0nlo
$W^\pm W^\pm jj$ -EWK	POWHEG-BOX+PYTHIA 8	CTEQ6L1
$W^\pm W^\pm jj$ -EWK	SHERPA 2.2.2, SHERPA 2.2.11	NNPDF3.0

Table 8.2: A summary of the Standard Model Monte Carlo samples used as signal in the analysis.

only one final state parton is subjected to the recoil of a W boson emission rather than the default scheme, where the whole final state suffers the emission recoil. The sample uses the NNPDF3.0nlo PDF set [120] implemented at NLO in QCD with $\alpha_s = 0.118$. The factorization and renormalization scales are chosen to be $\mu_F = \mu_R = \sqrt{p_T^{\text{jet1}} p_T^{\text{jet2}}}$, where p_T^{jet1} and p_T^{jet2} are the transverse momenta of the two jets in the event.

A mindful reader may have noticed that the sample neglects any higher order corrections. As some of the NLO contributions correspond to electroweak and QCD corrections from more than one underlying LO process, it is not possible to unambiguously distinguish the various production modes at NLO. The missing higher order corrections are accounted as theoretical uncertainties later in Chapter 12.

For studies and comparisons, additional samples have been simulated:

- **MADGRAPH + PYTHIA:** An alternate sample of MADGRAPH5_aMC@NLO with the PYTHIA 8 [121] parton shower modeling. The PDF set and the scales chosen are same as the nominal sample.
- **SHERPA:** Both the hard scatter and parton showering are modeled by SHERPA 2.2.2 [122]. NNPDF3.0 implemented at NNLO in QCD is the PDF set chosen. The sample suffers from an improper color flow setting resulting in lower predicted cross-sections. A new sample with improved modeling using SHERPA 2.2.11 provides a more accurate description of the cross-section which became available only at the time of writing this thesis. As a result, the sample is used only for the final cross-section comparisons in Chapter 14.
- **POWHEG-BOX + PYTHIA 8:** POWHEG-BOX [123] generates the signal events at NLO accuracy in perturbative QCD for the matrix element omitting the corrections on the interference component¹. The non-perturbative effects are modeled using the CTEQ6L1 PDF set and PYTHIA 8 simulates the parton shower and hadronization. The sample does not model resonant tri-boson contributions in the matrix element which becomes non-negligible at NLO in QCD [124].

Table 8.2 gives a summary of the Standard Model Monte Carlo samples used as signal in the analysis.

¹ $\mathcal{O}(\alpha_s \alpha^6)$ consists of QCD corrections to the electroweak component as well as electroweak corrections to the interference component (see Figure 5.4). The sample is generated such that the corrections on the interference component are neglected.

Process	Generator	PDF
$W^\pm W^\pm jj$ -QCD	MADGRAPH5_aMC@NLO+HERWIG 7	NNPDF3.0nlo
$W^\pm W^\pm jj$ -INT	MADGRAPH5_aMC@NLO+HERWIG 7	NNPDF3.0nlo
$WZjj$ -EWK	MADGRAPH5_aMC@NLO+PYTHIA 8	NNPDF3.0nlo
$WZjj$ -QCD	SHERPA 2.2.2	NNPDF3.0nnlo
$WZjj$ -INT	MADGRAPH5_aMC@NLO+PYTHIA 8	NNPDF3.0nlo
$W\gamma jj$	SHERPA 2.2.2	NNPDF3.0nnlo
$Z\gamma jj$	SHERPA 2.2.2	NNPDF3.0nnlo
W +jets	MADGRAPH5_aMC@NLO+PYTHIA 8	N30NLO
Z +jets	MADGRAPH5_aMC@NLO+PYTHIA 8	N30NLO A14NNPDF23LO
$t\bar{t}Z$	aMC@NLO+PYTHIA 8	MEN30NLO
$t\bar{t}W$	aMC@NLO+PYTHIA 8	MEN30NLO
tZ	MADGRAPH5_aMC@NLO+PYTHIA 8	NNPDF3.0
ZZ	SHERPA 2.2.2	NNPDF3.0nnlo

Table 8.3: A summary of the Standard Model Monte Carlo samples used as background in the analysis.

8.3.2 Background Samples

Among the backgrounds are the QCD and the interference production of $W^\pm W^\pm jj$. The backgrounds are simulated similarly to the electroweak sample but by changing the coupling to $\mathcal{O}(\alpha^4)$ and $\mathcal{O}(\alpha^5)$ respectively for the two samples. MADGRAPH5_aMC@NLO interfaced with HERWIG 7 is used for simulation with the same prescription employed for the nominal signal samples.

The dominant among the backgrounds is the $WZjj$ process, and its electroweak and interference production are simulated using MADGRAPH5_aMC@NLO at leading order interfaced with PYTHIA 8. The QCD induced production is simulated with SHERPA 2.2.2 as the MADGRAPH5_aMC@NLO sample was available only with the resonant contributions from the W and Z bosons at the time of the analysis. The sub-dominant MC modeled background process is $V\gamma jj$ and the samples are simulated with SHERPA 2.2.2. For small values of ΔR between the lepton and the photon, the background is modeled using V +jets simulated by MADGRAPH5_aMC@NLO interfaced with PYTHIA 8.

Table 8.3 summarizes all the background samples used in this analysis, including the marginally contributing prompt backgrounds such as top and other multi-boson processes.

It has to be noted that charge misidentification background and non-prompt and fake lepton background are determined from data, the details of which are already given in Table 8.1. But for the estimation of the latter background, MC samples with single lepton events are used and their particulars are provided separately in Table 8.4.

Process	Generator	PDF
W +jets	SHERPA 2.2.1	NNPDF3.0nnlo
Z +jets	POWHEG-BOX+PYTHIA 8	AZNLOCTEQ6L1
$t\bar{t}$	POWHEG-BOX+PYTHIA 8	NNPDF3.0nlo
Single top	POWHEG-BOX+PYTHIA 8	NNPDF3.0nlo
Single photon	SHERPA 2.2.2	NNPDF3.0nnlo

Table 8.4: A summary of the Standard Model Monte Carlo samples used as prompt lepton sources in the data-driven estimation of the non-prompt and fake background.

Chapter 9

Event Selection

To extract the signal of interest from the collision data, a set of selection criteria must be satisfied. The selections are applied at the object level to choose physics objects originating from a hard scatter vertex, and at the event level to choose events with the $W^\pm W^\pm jj$ signature. Likewise, certain requirements are also applied to define the various validation and control regions. The main goal of this chapter is to present all the selection criteria employed in the analysis. Sections 9.1-9.3 describe the different stages of selections applied at the object level, including the triggers fired. The selections in the analysis chain are explained in Section 9.4.

9.1 Baseline Selection

The events used for the measurement described are required to be recorded when the detector was in optimum function resulting in high data quality. Events with incomplete information are vetoed. Moreover, the events must have at least two leptons in them belonging to the STDM3 event data model, and only events containing a primary vertex with at least three associated tracks are considered for analysis.

9.1.1 Pre-selection

In the analysis, the objects used are electrons, muon, jets (and b -jets), and E_T^{miss} . But there occur situations where the same object is reconstructed by two or more reconstruction algorithms. For an unerring event selection, it is necessary to remove such possible duplication, and ATLAS utilizes an overlap removal procedure where a detector response is attributed to a single physics object. To perform the same, the objects are required to pass some baseline selection criteria known as *pre-selection*. The pre-selection requirements on the objects are discussed below.

Electrons

Electrons with $p_T > 4.5 \text{ GeV}$ are chosen passing the Loose likelihood identification and falling within $|\eta| < 2.47$. The track impact parameters must satisfy $|z_0 \times \sin \theta| < 0.5 \text{ mm}$ and $|\frac{d_0}{\sigma_{d_0}}| < 5$. No requirement on isolation is imposed.

Muons

Muons are required to have $p_T > 3 \text{ GeV}$ and $|\eta| < 2.7$. The impact parameters of the muon track must satisfy $|z_0 \times \sin \theta| < 1.5 \text{ mm}$ and $|\frac{d_0}{\sigma_{d_0}}| < 15$. The Loose working point is required for identification but no isolation selection is imposed.

Jets

Jets with $p_T > 20 \text{ GeV}$ and $|\eta| < 4.5$ are selected. They are required to be matched to the primary vertex using the jet-vertex-tagger (JVT) algorithm for jets with $p_T < 60 \text{ GeV}$ and $|\eta| < 2.47^1$ in its Tight working point. The b -jet tagging algorithm is run over the selected jet candidates and only jets identified with 85% efficiency from the DL1r tagger output are the b -jets considered.

9.1.2 Overlap Removal

The pre-selected objects are subjected to overlap removal, which prescribes the treatment procedure of overlapping objects to remove possible object duplication.

Lepton-Lepton Overlap

The different possibilities of lepton-lepton overlap removal are:

- **Electron-Electron:** Two electron candidates are said to be overlapping if they have an overlapping energy cluster in the ECal or share a track in the ID. In such a case, the electron with the highest p_T is retained while the other is removed.
- **Electron-Muon:** An electron and a muon candidate are considered to overlap when the two objects share the track in the ID. This can occur when the muon radiates a high energy photon as FSR as a result of Bremsstrahlung. The muon object is retained (and the electron is removed) if the MS tags the object as a muon. Otherwise, the electron is kept instead of the muon.
- **Muon-Muon:** Duplicate muons are removed at the time of reconstruction. Therefore, no muon-muon overlap removal procedure is applied.

Lepton-Jet Overlap

The overlap removal procedure chosen gives precedence to b -jets, saving it from removal in all cases of overlap. As the analysis requires all events with b -jets to be vetoed, such a selection is beneficial to reject the sources of non-prompt leptons. The two scenarios of overlap between leptons and light-flavor jets are treated in the following manner.

- **Electron-Jet:** An electron candidate is said to overlap with a jet when their separation is $\Delta R < 0.4$. If the electron is close to the center of the jet with $\Delta R < 0.2$, the jet is removed if it is not b -tagged. If the jet is b -tagged, then the electron is discarded and the jet is retained. For $0.2 < \Delta R < 0.4$ between the electron and the jet, the jet is kept and the electron is removed.

¹The analysis does not utilize the forward jet-vertex-tagger (fJVT) algorithm for forward jets with higher p_T as the samples were not ready during the time of measurement. However, the contribution of forward jets from pile-up was found to be negligible from studies.

- **Muon-Jet:** The muon-jet overlap removal is performed similar to that of the electron-jet overlap. But in addition to the above criteria, the jets are required to have more than two associated tracks.

9.2 Triggers

The $W^\pm W^\pm jj$ signal consists of two leptons and the analysis uses unscaled single electron and single muon triggers to select the events. The single lepton triggers are fired when there exists *at least* one lepton passing the requisites in the trigger definition. The trigger scheme utilized in the analysis is given in Table 9.1 and the trigger chain in 2015 is different from the rest. A logical OR of the electron triggers are used to identify events with electrons in a given data taking period and likewise for muons. Figures 9.1 and 9.2 show the efficiency of the muon and the electron triggers respectively in 2016. The trigger efficiency in MC is corrected to the efficiency in data using dedicated trigger scale factors [125]–[127].

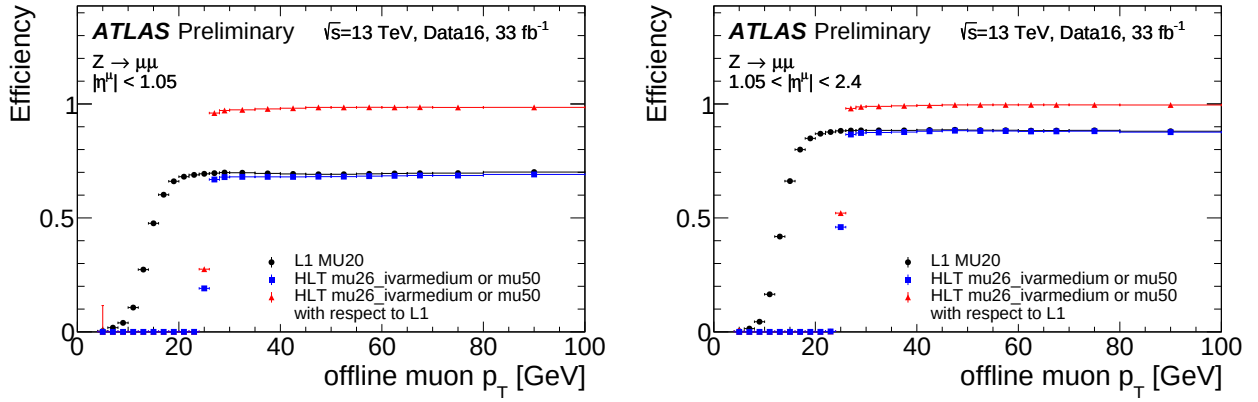


Figure 9.1: The efficiency of the logical OR of the muon triggers in 2016 is shown as a function of the muon’s transverse momentum reconstructed offline in the barrel (left) and at the end-caps (right). The absolute efficiency of the L1 MU20 trigger (black), and absolute (blue) and relative (red) efficiencies of the HLT scheme are plotted for data. The efficiencies are measured using a tag-and-probe method with $Z \rightarrow \mu\mu$ decays [125], [126].

Lepton	Trigger	Year(s)	E_T/p_T threshold	Identification	Isolation
Electron	HLT_e24_lhmedium_L1EM20VH	2015	24 GeV	Medium	-
	HLT_e60_lhmedium		60 GeV	Medium	-
	HLT_e120_lhloose		120 GeV	Loose	-
	HLT_e26_lhtight_nod0_ivarloose	2016 - 2018	26 GeV	Tight	ivarloose
	HLT_e60_lhmedium_nod0		60 GeV	Medium	-
	HLT_e140_lhloose_nod0		140 GeV	Loose	-
Muon	HLT_mu20_iloose_L1MU15	2015	20 GeV	-	iloose
	HLT_mu50		50 GeV	-	-
	HLT_mu26_ivarmedium	2016 - 2018	26 GeV	-	ivarmedium
	HLT_mu50		50 GeV	-	-

Table 9.1: The trigger scheme used in the analysis is tabulated. All the triggers shown are single lepton triggers and a logical OR of the triggers is used separately for electrons and muons in a given data taking period. The parameters in the HLT definition are also tabulated. The various E_T (for electrons) and p_T (for muons) thresholds cover a wide kinematic range, and different triggers use different set of identification and isolation selections.

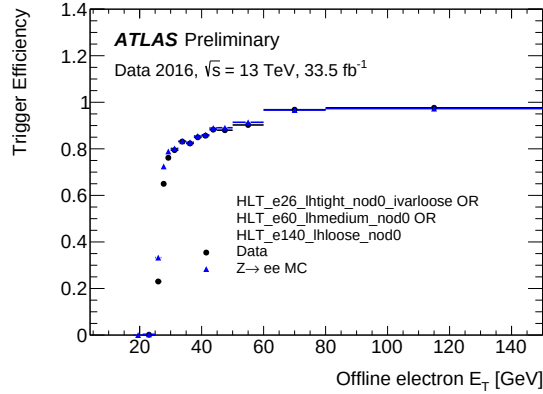


Figure 9.2: The efficiency of the logical OR of the electron triggers in 2016 is shown as a function of the electron’s transverse energy reconstructed offline. The efficiencies are measured using a tag-and-probe method with $Z \rightarrow ee$ decays in data (black) and Monte Carlo (blue) [127].

9.3 Object Selection

The pre-selected objects surviving overlap removal are the physics objects considered in the analysis, which are processed further by imposing various requisites.

9.3.1 Leptons

The leptons in the analysis are categorized into three groups with varying object selections. To identify the leptons from hard scatter, tight lepton selections are required and such signal-like leptons identified are commonly referred to as the *ID leptons*. For estimating the non-prompt and fake lepton background, a second category of leptons known as the *Anti-ID leptons* are used. An Anti-ID lepton is a lepton candidate that fails the ID lepton selection but still passes a set of looser selection requirements, and is usually a jet faking a lepton or a non-prompt lepton. The third lepton category is the *veto lepton* defined by adding selections on top of the lepton pre-selections and is used to study the modeling of the $WZjj$ background in events with three leptons. The selections defining the various lepton categories are recorded in Tables 9.2 and 9.3. In the case of electrons, a BDT based tool known as Electron Charge ID Selection (ECIDS) is utilized to suppress the contribution of charge misidentification, and only electrons surviving ECIDS are considered.

9.3.2 Jets

All jets (including b -jets) are processed further by raising the p_T threshold to 25 GeV.

ID Electron	Anti-ID Electron	Veto Electron
$p_T > 27 \text{ GeV}$ $ \eta < 2.47$ excluding $1.37 < \eta < 1.52$ $ z_0 \sin \theta < 0.5 \text{ mm}$ $ d_0/\sigma_{d_0} < 5$ pass ECIDS Tight Identification Gradient Isolation -	$p_T > 27 \text{ GeV}$ $ \eta < 2.47$ excluding $1.37 < \eta < 1.52$ $ z_0 \sin \theta < 0.5 \text{ mm}$ $ d_0/\sigma_{d_0} < 5$ pass ECIDS Medium Identification - Fail Tight Identification OR Fail Gradient Isolation	$p_T > 15 \text{ GeV}$ $ \eta < 2.47$ $ z_0 \sin \theta < 0.5 \text{ mm}$ $ d_0/\sigma_{d_0} < 5$ - Medium Identification Gradient Isolation -

Table 9.2: The selections defining ID electron, Anti-ID electron, and veto electron are tabulated.

ID Muon	Anti-ID Muon	Veto Muon
$p_T > 27 \text{ GeV}$ $ \eta < 2.5$ $ z_0 \sin \theta < 0.5 \text{ mm}$ $ d_0/\sigma_{d_0} < 3$ Medium Identification FixedCutPFlowTight Isolation -	$p_T > 27 \text{ GeV}$ $ \eta < 2.5$ $ z_0 \sin \theta < 0.5 \text{ mm}$ $ d_0/\sigma_{d_0} < 10$ Medium Identification FixedCutPFlowLoose Isolation Fail $ d_0/\sigma_{d_0} < 3$ OR Fail FixedCutPFlowTight Isolation	$p_T > 15 \text{ GeV}$ $ \eta < 2.7$ $ z_0 \sin \theta < 1.5 \text{ mm}$ $ d_0/\sigma_{d_0} < 10$ Loose Identification Gradient Isolation -

Table 9.3: The selections defining ID muon, Anti-ID muon, and veto muon are tabulated.

9.4 Event Selection

9.4.1 Signal Region

Selections for signal enhancement

All events in the signal region are required to fire one of the single lepton triggers given in Table 9.1. Events must have two leptons with the same electric charge passing the ID lepton criteria.

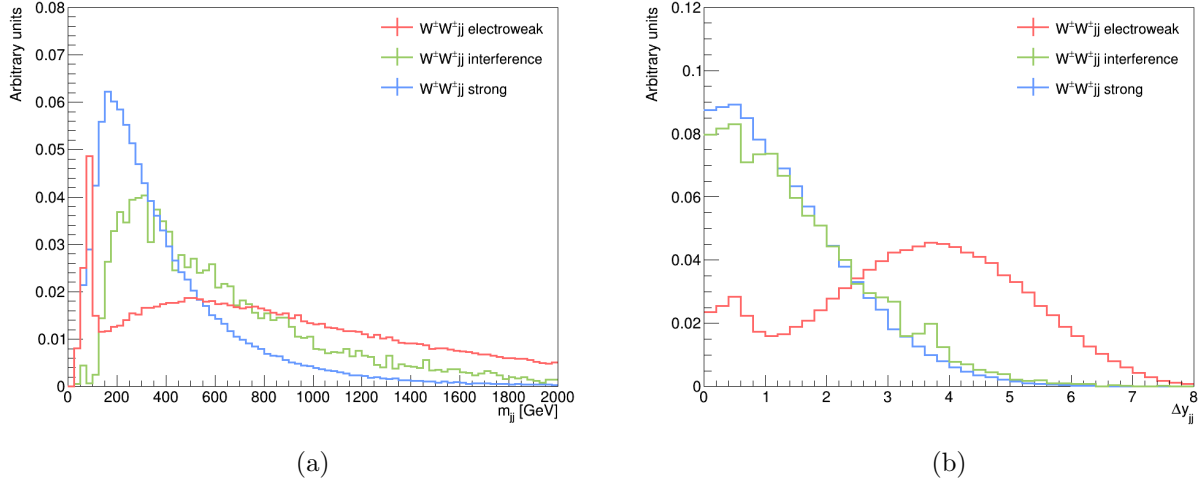


Figure 9.3: The predicted distributions of the invariant mass (m_{jj}) and the rapidity separation (Δy_{jj}) of the tagging jets from MADGRAPH+HERWIG7 are plotted for the electroweak, strong, and interference production modes of $W^\pm W^\pm jj$ in the $ee + \mu e + e\mu + \mu\mu$ channel.

The p_T threshold of the ID lepton is chosen to be above the p_T threshold of the trigger scheme to ensure that the trigger is fired by one of the ID leptons.

Due to the presence of two neutrinos in the final state, $E_T^{\text{miss}} > 30 \text{ GeV}$ is required. At least two jets must be present in each event within an acceptance of $|\eta| \leq 4.5$. The jets are p_T sorted and two jets with the highest p_T are selected as the tagging jets in the event. The leading (in p_T) jet in the event must have $p_T > 65 \text{ GeV}$ whereas the sub-leading one ought to have $p_T > 35 \text{ GeV}$.

To enhance the contribution of electroweak induced production of $W^\pm W^\pm jj$ over QCD-induced, the VBS signature of high di-jet invariant mass and large angular separation of the tagging jets are required. Figure 9.3 presents the distributions of m_{jj} and $|\Delta y_{jj}|$ for the various production modes of $W^\pm W^\pm jj$ according to the MC predictions. On account of the simulated results, $m_{jj} > 500 \text{ GeV}$ and $|\Delta y_{jj}| > 2$ are the selections applied to suppress $W^\pm W^\pm jj$ strong production efficiently.

Selections for background suppression

To suppress background from processes with more than two leptons in the final state (e.g. WZ and ZZ background), events containing a third pre-selected lepton, which survives the overlap removal, are rejected. In addition, events are also rejected if a third lepton which doesn't survive the nominal overlap removal, but together with one of the two ID leptons of the same flavor and opposite charge forms a di-lepton system with the invariant mass close to the Z boson mass, $|m_{ll} - m_Z| < 15 \text{ GeV}$.

Background contributions from non-prompt leptons and top processes are reduced by requiring the events to have no b -tagged jets. Furthermore, Drell-Yan contributions from Υ and J/ψ are suppressed with $m_{ll} > 20 \text{ GeV}$.

Due to a non-negligible charge misidentification rate of electrons, the ee channel is exceptionally required to have two additional selections to reduce the charge misidentification background. First, only the barrel electrons, in $|\eta| < 1.37$, are considered for measurement in the ee channel. Second, the peak of the m_{ee} distribution is removed by applying $|m_{ee} - m_Z| > 15 \text{ GeV}$, thereby reducing the contributions from $Z/\gamma^* \rightarrow ee$. The order in which the selection are applied in the signal region

are given in Table 9.4.

Signal Region Selection
Single lepton trigger fired
Two ID leptons
Electrons pass ECIDS
Only barrel electrons in ee channel
$m_{ll} > 20 \text{ GeV}$
Third lepton veto
Same-sign leptons
$n_{jet} \geq 2$
Leading (sub-leading) jet $p_T > 65(35) \text{ GeV}$
$m_{jj} > 200 \text{ GeV}$
$ m_{ee} - m_Z > 15 \text{ GeV}$
$E_T^{\text{miss}} > 30 \text{ GeV}$
$n_{b\text{-jet}} = 0$
$ \Delta y_{jj} > 2$
$m_{jj} > 500 \text{ GeV}$

Table 9.4: Event selections in the signal region.

9.4.2 Validation Regions

Six validation regions are considered to carefully study the modeling of the estimated backgrounds. The validation regions are defined in Table 9.5 and are listed below along with the backgrounds examined:

- **Inclusive:** $WZjj$ background, non-prompt and fake lepton background, and e/γ conversions
- **$Z(ee)$ Peak:** Charge misidentification background
- **Low N_{jet} :** $WZjj$ background and non-prompt and fake lepton background
- **Low m_{jj} :** $WZjj$ background and non-prompt and fake lepton background
- **One b -jet:** Non-prompt and fake lepton background
- **Tri-lepton:** $WZjj$ background

Some of the validation regions, such as Low m_{jj} , are used to test more than one background, and results obtained are shown when one of the corresponding backgrounds is discussed and not repeated for every background studied.

Inclusive	$Z(ee)$ Peak	Low m_{jj}	Low N_{jet}	One b -jet	Tri-lepton
Single lepton trigger fired Exactly two same-sign ID leptons	Single lepton trigger fired Exactly two same-sign ID leptons	Single lepton trigger fired Exactly two same-sign ID leptons	Single lepton trigger fired Exactly two same-sign ID leptons	Single lepton trigger fired Exactly two same-sign ID leptons	Single lepton trigger fired Exactly three leptons. Two same-sign ID leptons and a veto lepton of opposite charge
Only barrel electrons in ee channel $ m_{ee} - m_Z > 15 \text{ GeV}$ $m_{ll} > 20 \text{ GeV}$	Only barrel electrons in ee channel $ m_{ee} - m_Z < 15 \text{ GeV}$ $m_{ll} > 20 \text{ GeV}$	Only barrel electrons in ee channel $ m_{ee} - m_Z > 15 \text{ GeV}$ $m_{ll} > 20 \text{ GeV}$	Only barrel electrons in ee channel $ m_{ee} - m_Z > 15 \text{ GeV}$ $m_{ll} > 20 \text{ GeV}$	Only barrel electrons in ee channel $ m_{ee} - m_Z > 15 \text{ GeV}$ $m_{ll} > 20 \text{ GeV}$	$m_{ll} > 20 \text{ GeV}$
		$N_{\text{jet}} \geq 2$ jet $p_T > 65 \text{ GeV}$ (leading) jet $p_T > 35 \text{ GeV}$ (sub-leading)	$N_{\text{jet}} < 2$ OR jet $p_T < 65 \text{ GeV}$ (leading) OR jet $p_T > 35 \text{ GeV}$ (sub-leading)	$N_{\text{jet}} \geq 2$ jet $p_T > 65 \text{ GeV}$ (leading) jet $p_T > 35 \text{ GeV}$ (sub-leading)	
$N_{b\text{-jet}} = 0$	$N_{b\text{-jet}} = 0$	$N_{b\text{-jet}} = 0$	$N_{b\text{-jet}} = 0$	$N_{b\text{-jet}} = 1$ Leading jet is NOT a b -jet	$N_{b\text{-jet}} = 0$
		$E_T^{\text{miss}} > 30 \text{ GeV}$ $m_{jj} < 500 \text{ GeV}$	$E_T^{\text{miss}} > 30 \text{ GeV}$	$E_T^{\text{miss}} > 30 \text{ GeV}$	

Table 9.5: Event selections in the various validation regions. The characteristic selections of each validation region are given in blue color.

9.4.3 Control Regions

To perform the profile likelihood fit and to determine the normalization parameter of QCD-induced $WZjj$ process, two control regions are utilized in this analysis. The regions are defined in Table 9.6 and are listed below:

- **Low m_{jj} :** The Low m_{jj} control region has the same selections as the signal region but with the VBS m_{jj} selection² reversed to $m_{jj} < 500$ GeV. This region has the same signal region composition and the modeling of all the backgrounds can be evaluated in this region.
- **WZ :** The WZ control region is designed to extract a region pure in $WZjj$ events, and in addition to the fitting procedure, the region is used to re-weight the m_{jj} distribution of QCD-induced $WZjj$.

Low m_{jj}	WZ
Single lepton trigger fired Exactly two same-sign ID leptons	Single lepton trigger fired Two same-sign ID leptons and an additional veto lepton Opposite sign di-lepton pair forming a Z boson candidate
Only barrel electrons in ee channel $m_{ll} > 20$ GeV $ m_{ee} - m_Z > 15$ GeV	Only barrel electrons in eee and $ee\mu$ channels $m_{lll} > 106$ GeV
$N_{\text{jet}} \geq 2$ jet $p_T > 65$ GeV (leading) jet $p_T > 35$ GeV (sub-leading)	$N_{\text{jet}} \geq 2$ jet $p_T > 65$ GeV (leading) jet $p_T > 35$ GeV (sub-leading)
$N_{\text{b-jet}} = 0$ $E_T^{\text{miss}} > 30$ GeV $ \Delta y_{jj} > 2$ $200 \text{ GeV} < m_{jj} < 500 \text{ GeV}$	$N_{\text{b-jet}} = 0$ $E_T^{\text{miss}} > 30$ GeV $ \Delta y_{jj} > 2$ $m_{jj} > 200 \text{ GeV}$

Table 9.6: Event selections in the control regions. The characteristic selections of the control region are given in blue color.

²It has to be kept in mind that $m_{jj} > 200$ GeV in Table 9.4 still remains in this control region. The control region differs from the Low m_{jj} validation region in the selections of $|\Delta y_{jj}|$ and m_{jj} .

Chapter 10

Estimation of Prompt Lepton and e/γ Conversion Backgrounds

The major backgrounds encountered in this analysis are discussed in Chapter 7. To recap briefly, the backgrounds are classified into three groups: 1) prompt lepton background 2) e/γ conversions, and 3) non-prompt and fake lepton background. e/γ conversions are further categorized as charge misidentification and $V\gamma jj$. This chapter focuses on the estimation of prompt lepton and e/γ conversion backgrounds. The estimation of non-prompt and fake lepton background is explained in detail in the next chapter.

Among the prompt and e/γ conversion backgrounds, the charge misidentification background is estimated using a data-driven technique whereas the rest of the backgrounds are modeled using simulations. The estimation and modeling of the backgrounds in different validation and control regions, along with the strategy to extract some of the background parameters are presented in this chapter. The total event yields in the signal region are given in Chapter 12 (see Table 12.2) along with the general experimental uncertainties associated with the use of MC simulated backgrounds. Therefore, only the uncertainties associated with background parameter extraction and the data-driven estimation of charge misidentification background are described here.

10.1 Prompt Lepton Background

Prompt leptons are the largest sources of background in the analysis comprising 30% of the total yields in the signal region and 64% of the total background. All the prompt lepton backgrounds in this analysis are modeled using MC simulations and the samples used are stated in Chapter 8. The sources are discussed below in the decreasing order of their contributions in the signal region.

10.1.1 $WZjj$

The process $W^\pm Z jj \rightarrow l^\pm \nu l^\pm l^\mp jj$ is one of the dominant background sources after all the signal selection criteria are applied. When one of the leptons from the Z decay is out of the detector acceptance region or is not successfully identified, the event mimics the signal signature. The process accounts for 46% of the total background in the signal region, out of which QCD induced $WZjj$ production alone contributes to 40%.

To test the modeling of the WZ production, the Tri-lepton Inclusive validation region with three leptons, defined in Table 9.5, is used. Figure 10.1 shows the tri-lepton invariant mass and the jet multiplicity in the validation region for the combined lepton channels. Though the overall data-

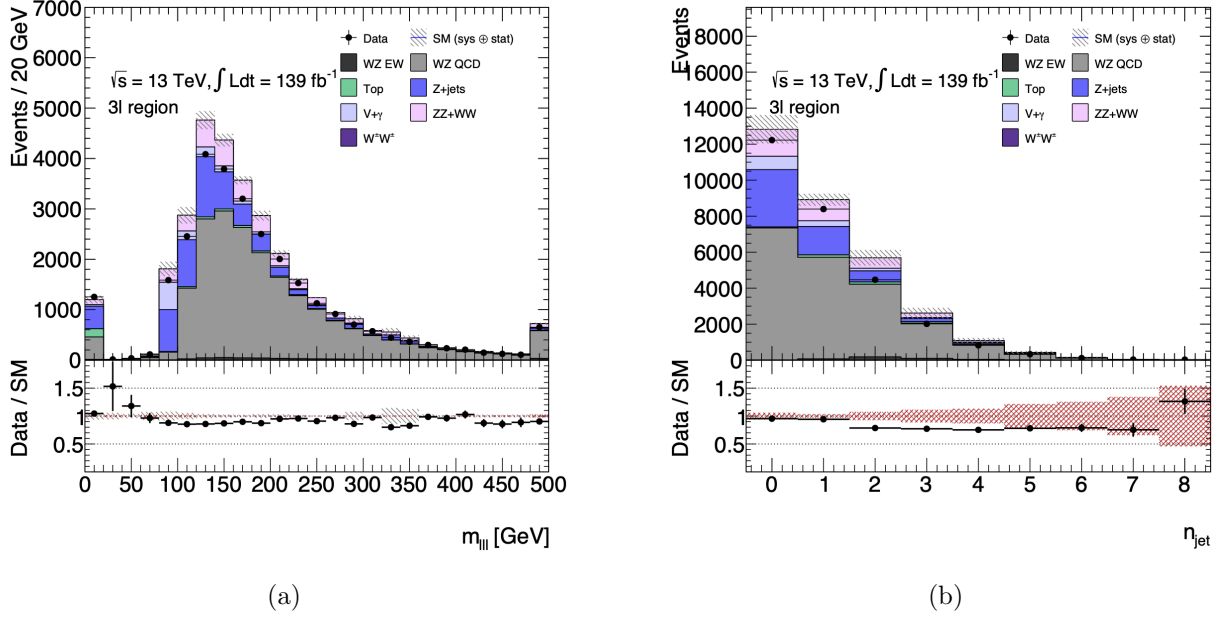


Figure 10.1: The distributions of the tri-lepton invariant mass (left) and number of jets (right) in the Tri-lepton Inclusive validation region is shown for the $e^{\pm}e^{\mp}e + e^{\pm}e^{\mp}\mu + \mu^{\pm}\mu^{\mp}e + \mu^{\pm}\mu^{\mp}\mu$ channel. The red band denotes the systematic uncertainties and the gray band indicates the combined systematic and statistical uncertainties on the backgrounds.

background agreement is reasonable, the total background is slightly over-estimated (about 20%) in bins with a minimum of two jets owing to the poorly described normalization of $WZjj$ -QCD¹ in VBS-like regions, which is corrected later in Chapter 14. Additionally, the background is also validated in two lepton Inclusive and Low N_{jet} regions. The distributions of E_T^{miss} in the Inclusive validation and sub-leading lepton p_T in Low N_{jet} validation region are plotted in Figure 10.2.

m_{jj} re-weighting of the $WZjj$ -QCD model

The modeling of the shape of the m_{jj} distribution is known to be challenging for QCD-induced processes in VBS phase spaces [128]. The QCD-induced $WZjj$ process is the leading background in the analysis and its mismodeling can affect the fitted signal significantly as m_{jj} is the variable used in the fitting procedure. In order to check and correct for the potential mismodeling of the m_{jj} shape in $WZjj$ -QCD, the WZ control region with high purity $WZjj$ events is chosen. The control region is defined according to the selections in Table 9.6 and the expected event yields in this region are listed in Table 10.1.

¹As mentioned already in Chapter 7, the normalization factor is obtained from the final fit.

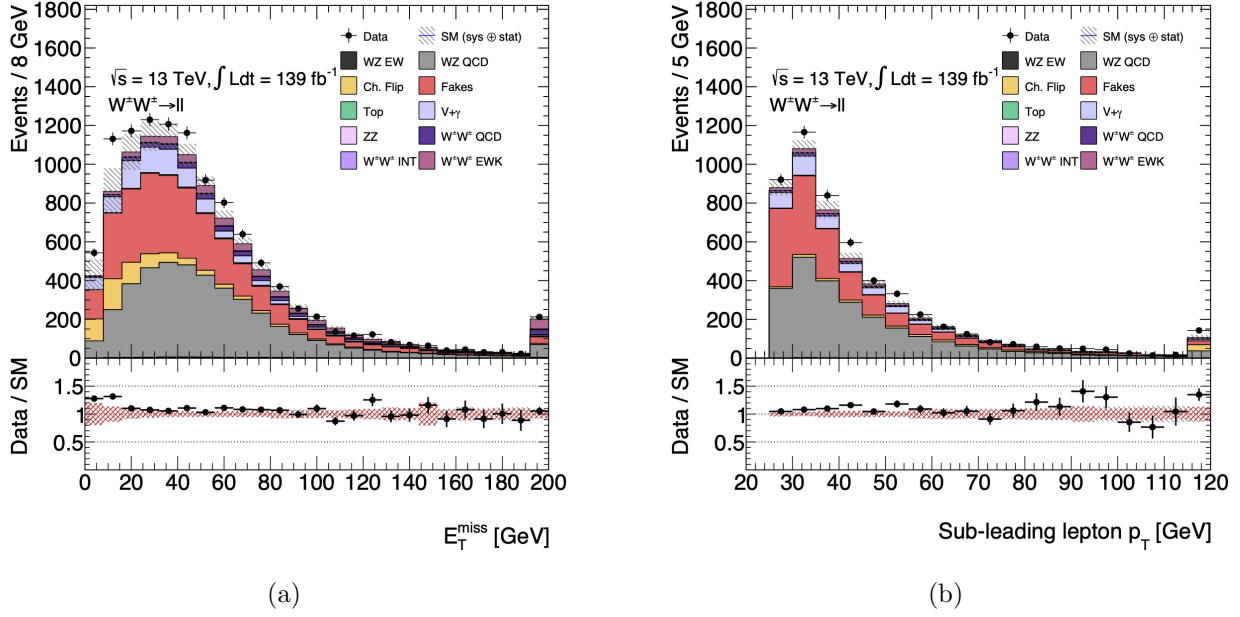


Figure 10.2: The E_T^{miss} distribution in the Inclusive validation region (left) and the sub-leading lepton p_T distribution in the Low N_{jet} validation region (right) are shown in the $ee + \mu e + e\mu + \mu\mu$ channel. The red band denotes the systematic uncertainties and the gray band indicates the combined systematic and statistical uncertainties on the backgrounds.

Sample	Yields
$WZjj$ -QCD	821.2 ± 2.6
$WZjj$ -EWK	141.4 ± 0.5
$WZjj$ -INT	2.34 ± 0.07
$ZZjj$	60.6 ± 0.4
Z +jets	27.7 ± 3.5
$t\bar{t}V$	30.7 ± 0.5
$t\bar{t}$	11.0 ± 0.7
$Z\gamma$	5.4 ± 2.6
Total Prediction	1100 ± 5
Data	832 ± 29

Table 10.1: Event yields in the WZ control region are given for the $e^\pm e^\mp e + e^\pm e^\mp \mu + \mu^\pm \mu^\mp e + \mu^\pm \mu^\mp \mu$ channel. The unmodified $WZjj$ MC prediction is used. Only statistical uncertainties on the MC estimations are included.

Although the control region is largely populated by QCD production of $WZjj$, the electroweak induced production amounts to nearly 15% of the total $WZjj$ yields. In order to suppress $WZjj$ -EWK and re-weight the QCD events with minimum bias, several variables sensitive to the difference between $WZjj$ -QCD and $WZjj$ -EWK topologies are studied, such as:

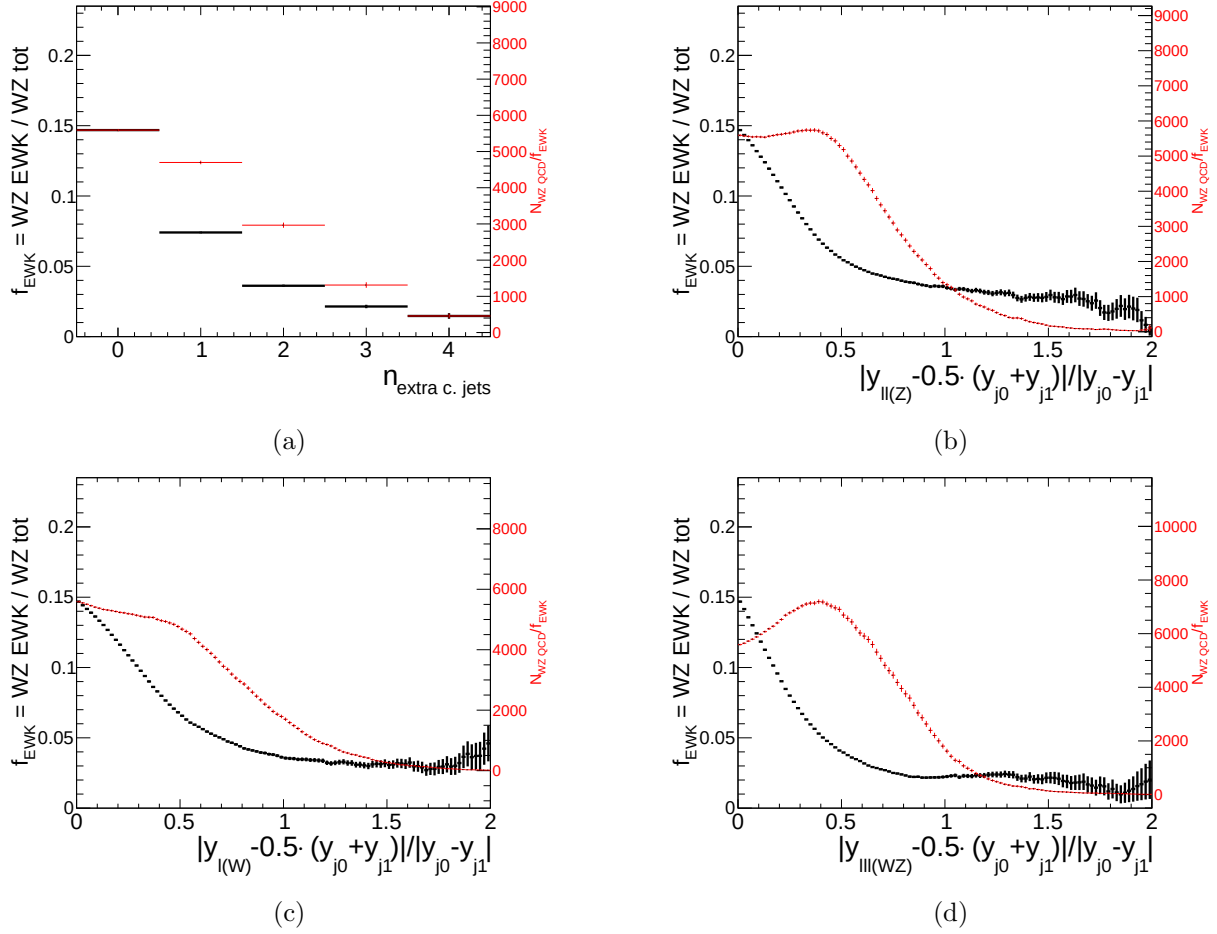


Figure 10.3: Dependence of f_{EWK} and $N_{WZjj\text{-}QCD}/f_{\text{EWK}}$ on the lower bounds are given for $n_{\text{extra central jets}}$ in (a), Z boson centrality in (b), W boson centrality in (c), and WZ system centrality in (d).

- Number of jets between the two forward tagging jets, $n_{\text{extra central jets}}$, which is expected to be zero for the electroweak component and non-zero for the QCD component.

As the weak bosons are expected to be located close to the middle (in rapidity) between the tagging jets in electroweak processes, several variants of the centrality of W and/or Z bosons are also considered:

- Z boson centrality defined as $\left| \frac{y_{||Z)} - 0.5(y_{j0} + y_{j1})}{y_{j0} - y_{j1}} \right|$, where $y_{j0(1)}$ is the rapidity of the (sub)leading- p_T jet, and $y_{||Z)}$ is the rapidity of the Z boson candidate constructed from two same-flavor opposite-sign leptons, forming the di-lepton with invariant mass closest to the Z boson mass, if multiple pairings are possible.
- W boson centrality given by $\left| \frac{y_{l(W)} - 0.5(y_{j0} + y_{j1})}{y_{j0} - y_{j1}} \right|$.
- WZ system centrality defined as $\left| \frac{y_{||WZ)} - 0.5(y_{j0} + y_{j1})}{y_{j0} - y_{j1}} \right|$, where $y_{||WZ)} = (y_{l(W)} + y_{||Z)})/2$ is the average of the rapidities of the charged leptons coming from the W and the Z candidates.

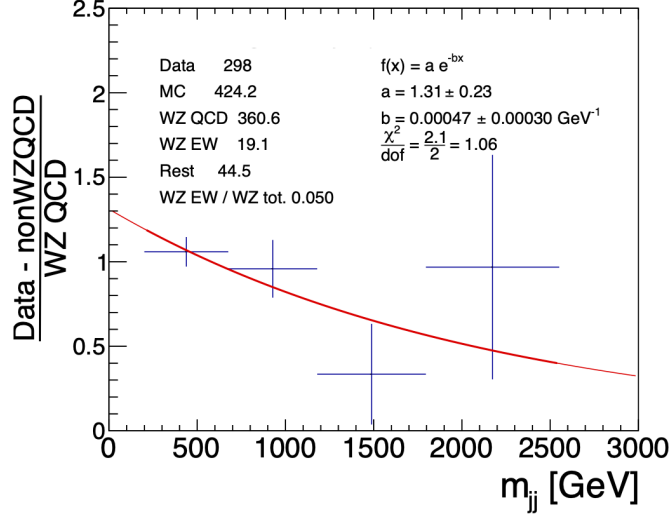


Figure 10.4: Ratio of the $WZjj$ -QCD in data and MC is plotted (in blue) for the m_{jj} distribution in the WZ control region with high centrality. The expected $WZjj$ -QCD events in data is the difference between the total data yields and the sum of all non- $WZjj$ -QCD events. Both the numerator and denominator are normalized to unity before plotting the ratio to correct only the shape mismodeling in m_{jj} . The ratios are fitted with an exponential function (in red) in $200 \text{ GeV} < m_{jj} < 2500 \text{ GeV}$ and the fit parameters are given. The m_{jj} distribution in $WZjj$ -QCD is re-weighted by the fitting function.

To select the best suited discriminating variable for constructing a $WZjj$ -EWK suppressed region, while keeping sufficient statistics for $WZjj$ -QCD events, two metrics are constructed: f_{EWK} and $N_{WZjj\text{-QCD}}/f_{\text{EWK}}$. The former is the ratio of the $WZjj$ -EWK to the total $WZjj$ yields and the latter is the ratio of the $WZjj$ -QCD yields to f_{EWK} . The dependence of these two metric on the lower bounds of the discriminating variables studied are plotted in Figure 10.3. The position of the maximum of $N_{WZjj\text{-QCD}}/f_{\text{EWK}}$ is designed to achieve a trade-off between the suppression of $WZjj$ -EWK and the enhancement of $WZjj$ -QCD events. The optimal suppression of $WZjj$ -EWK is achieved for the WZ centrality value above 0.4 where $N_{WZjj\text{-QCD}}/f_{\text{EWK}}$ exhibits a pronounced peak. As a result, WZ control region with the additional high centrality selection on the WZ system applied is used to perform the re-weighting.

In order to perform the m_{jj} shape comparison between data and simulations, a histogram equal to the difference between the m_{jj} distributions in data and non- $WZjj$ -QCD contributions is constructed². The obtained distribution is then divided by the m_{jj} distribution as predicted by the $WZjj$ -QCD model. Both the numerator and the denominator are normalized to unity to cancel the effect of the $WZjj$ -QCD normalization mismodeling. The obtained ratios are plotted in Figure 10.4, and an exponential fit is applied to the distribution in the $200 \text{ GeV} < m_{jj} < 2500 \text{ GeV}$ range, following which the shape of the $WZjj$ -QCD m_{jj} distribution is re-weighted to the fitted function.

Systematic uncertainties in the re-weighting procedure

To quantify the systematic uncertainties associated with the re-weighting procedure, following are the sources considered:

²Having observed a reasonable data-background agreement in the WZ control region, the aforementioned difference between data and non- $WZjj$ -QCD events is expected to be the $WZjj$ -QCD events in data.

- The largest source of uncertainty on the m_{jj} re-weighting procedure is the limited statistics in the data and the MC samples in the region from where the re-weighting function is derived. Therefore, the re-weighting function is varied up and down according to the statistical uncertainty on the fit.
- The re-weighting function obtained depends on the $WZjj$ -QCD model. To account for the theoretical uncertainty due to the PDF and α_s choice, the re-weighting procedure is repeated for various PDF sets and α_s , and the envelope of the fit functions is assigned as the systematic uncertainty.
- Likewise, theoretical uncertainty also results from the renormalization and factorization scales chosen. Similar to the previous case, the envelope of the fit functions obtained for different scale variations are accounted as the systematic uncertainty on the re-weighting method.

The impact of the systematic uncertainties associated with m_{jj} re-weighting procedure on the $WZjj$ -QCD background yields in the signal region are listed in Table 10.2. Finally, a comparison of the m_{jj} distribution in the WZ control region before and after correction is given in Figure 10.5, showing the improvement achieved through the re-weighting procedure.

Systematic Uncertainty	%
Limited Statistics	9%
Choice of Scales	0.8%
Choice of PDF and α_s	0.2%

Table 10.2: Breakdown of the systematic uncertainties due to m_{jj} re-weighting on the $WZjj$ -QCD yields in the signal region for the $ee + \mu e + e\mu + \mu\mu$ channel.

10.1.2 $W^\pm W^\pm jj$ -QCD

The QCD induced production of $W^\pm W^\pm jj$ is suppressed in the signal region by the m_{jj} and Δy_{jj} selections, described already in the previous chapter. Any residual contribution of this background is modeled using simulations. This process is the third dominant background in the analysis totaling to 11% of the total background and 18% of the total prompt lepton background in the signal region.

10.1.3 $W^\pm W^\pm jj$ -INT

The contribution of the interference of the electroweak and QCD induced production of $W^\pm W^\pm jj$ is quite negligible amounting to only 3.5% of the total background.

10.1.4 Other Prompt

The other prompt lepton backgrounds imitating the $W^\pm W^\pm jj$ final state include top, $ZZjj$, and tri-boson events constituting less than 3% of the total background in the signal region, and their contributions are taken directly from the corresponding MC samples.

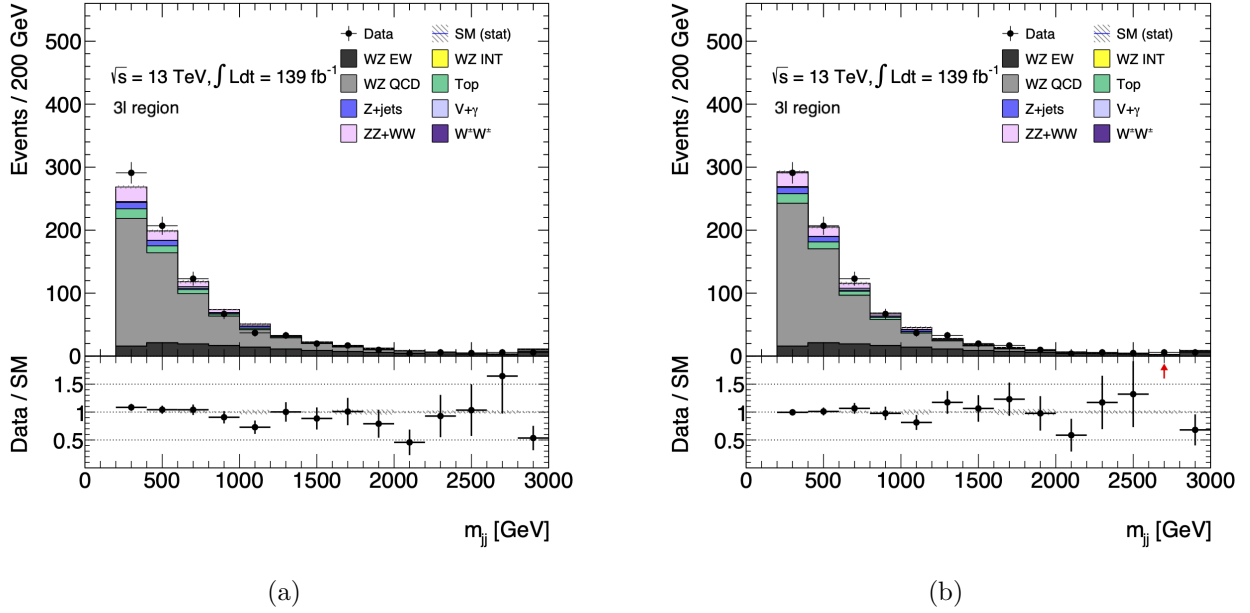


Figure 10.5: The m_{jj} distributions before and after re-weighting the m_{jj} shape in $WZjj$ -QCD are plotted respectively in (a) and (b) in the WZ control region. The total yield of the $WZjj$ -QCD is scaled by a factor of 0.67 for the sole purpose of visualizing the effect of the shape correction. Only statistical uncertainties are shown.

10.2 e/γ Conversions

Processes with e/γ conversions amount to 10% of the background yields. It is composed of $V\gamma jj$ and charge misidentification backgrounds contributing about 7% and 5% respectively in the signal region affecting only channels with electrons. Among e/γ conversions, the $V\gamma jj$ process is simulated using MC, whereas the charge misidentification background is estimated from data. The estimation of the $V\gamma jj$ background is described below, followed by the charge misidentification background.

10.2.1 $V\gamma jj$

The Standard Model processes with an electroweak heavy gauge boson and a prompt photon can gain entry into the signal region in electron channels through photon conversions. The background is modeled by the $V\gamma jj$ samples ($W\gamma jj$ and $Z\gamma jj$) and the V +jets (W +jets and Z +jets) samples mentioned in Table 8.3. The $V\gamma jj$ samples typically include parton level selections on the angular separation between the lepton and the photon and the samples used in this analysis contain only events with $\Delta R(l, \gamma) > 0.1$. In order to cover the full phase space, V +jets samples are additionally used which employ no such parton level selections on the photon. However, events in the V +jets sample that pass the $V\gamma jj$ parton selections overlap with the $V\gamma jj$ events. Such events are removed using a dedicated overlap removal tool to avoid double counting before estimating the final background. The $V\gamma jj$ process is the fourth largest background source in the analysis, arising mainly from $W\gamma jj$, and a flat cross-section uncertainty of 40% is applied on the $V\gamma jj$ background. The uncertainty applied is a conservative choice driven by the scale factor uncertainty of electron

charge identification for wrongly identified charges, which is better understood from the following section.

10.2.2 Charge misidentification

The charge misidentification background consists of all Standard Model processes with the final state consisting of two opposite-sign prompt leptons, such as $Z(\rightarrow e^+e^-)+\text{jets}$, $t\bar{t}$, where the charge of the electron has been wrongly identified and mimics the same-sign $W^\pm W^\pm jj$ signal. As the electron is reconstructed with its charge *flipped*, the background is also referred to as the charge-flip background.

The electric charge of an electron is inferred from the Inner Detector based on the curvature of the reconstructed track and a misidentification of the charge can occur mainly due to two reasons:

- *Incorrect track-to-electron association:* Due to the geometrical design of the detector, an electron traverses more material with increasing η , and the probability of Bremsstrahlung emission and subsequent pair production depends significantly on the amount of material traversed. As a result, the final electron may be reconstructed with a charge opposite to that of the initial electron, as illustrated graphically in Figure 10.6a, and is the chief mechanism for charge misidentification.
- *Incorrect track curvature measurement:* As an electron traverses through the detector, it is subjected to the magnetic field, whereby the track curves. The direction of the track curvature is utilized in identifying the charge, and a wrong measurement of the curvature can result in electron charge misidentification. This effect is predominant in high p_T tracks, which are typically rather straight making it difficult to determine the track curvature correctly, such as that in Figure 10.6b.

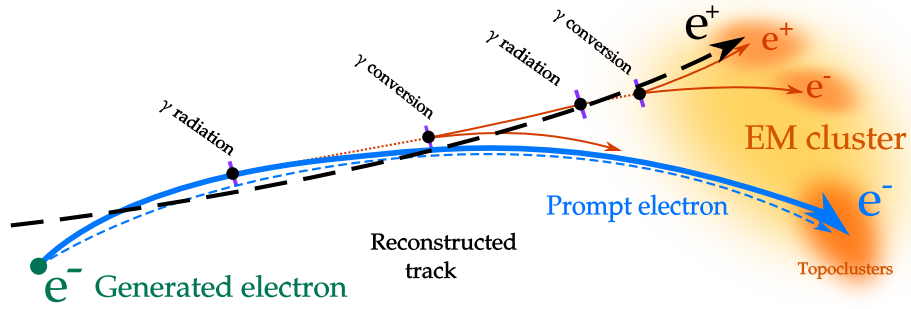
In this analysis, the background emerging from electron charge misidentification is estimated using a data driven approach. First of all, a BDT based ECIDS discriminator is used to reject electrons passing the isolation and identification requirements of the signal electron but reconstructed with a wrong charge (see Table 9.2). The ECIDS selection has shown to suppress the background by a factor of four compared to the previous iteration of the analysis [78]. To evaluate the background, data events passing the signal region³ selections but with opposite-sign leptons (instead of same-sign leptons) are taken and weighted by a measure of the probability for one of the electrons to flip the charge. The resulting events consists of two same-sign leptons that originate from opposite-sign events, which constitute the charge-flip background.

Measurement of the charge misidentification probabilities

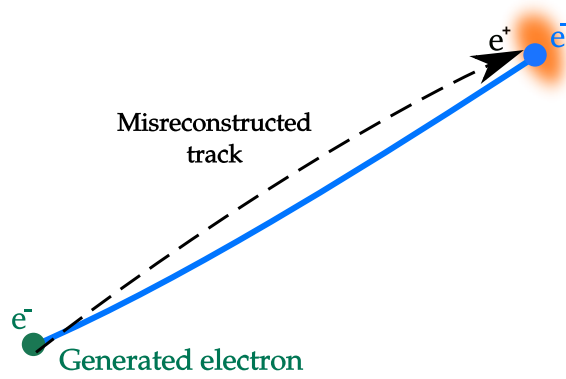
The charge misidentification probabilities are computed using simulated $Z(\rightarrow e^+e^-)+\text{jets}$ events exploiting the truth level information. Only events having two opposite-sign electrons originating from a Z boson at the truth level are considered. Events are required to fire the single lepton trigger in Table 9.1, and must contain two ID electrons surviving ECIDS but with p_T threshold lowered to 20 GeV. Further $m_{ee} > 20 \text{ GeV}$ is applied as in the signal region. Finally, the events are corrected using dedicated scale factors to emulate the charge misidentification rate in data. The misidentification rate is computed differentially in p_T (in bins of i) and η (in bins of j) as:

$$\epsilon_{\text{misid},ij} = \frac{N_{\text{misid},ij}}{N_{\text{all},ij}}, \quad (10.1)$$

³Or validation region selections depending on where the background is estimated.



(a) Incorrect track-to-electron association



(b) Incorrect track curvature measurement

Figure 10.6: A simplified graphic representation of the two main mechanisms for the misidentification of the electron charge. Charge misidentification due to incorrect track-to-electron association is illustrated in (a) and incorrect track curvature measurement is shown in (b). Images taken from [129].

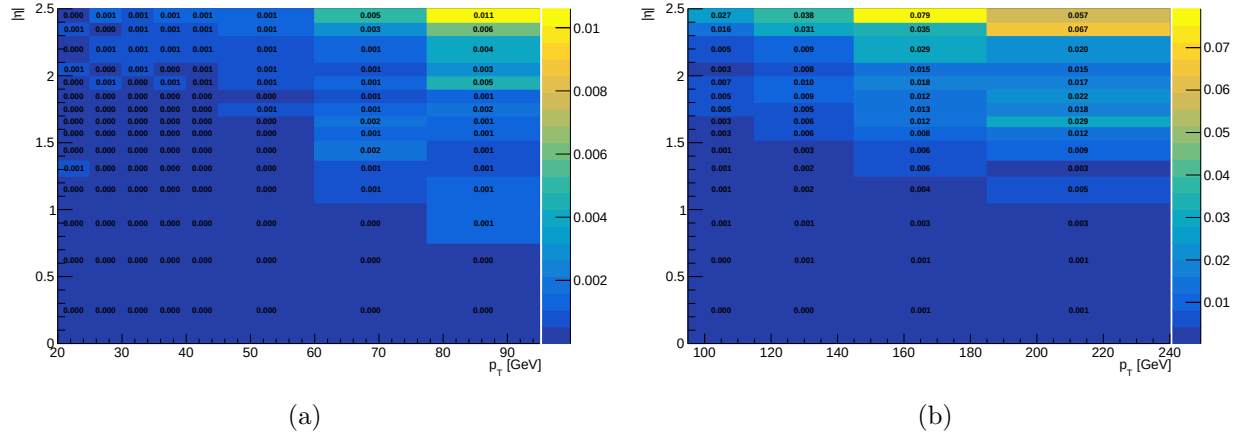


Figure 10.7: The charge misidentification rates are shown for electrons with $20 < p_T < 95$ GeV (left) and $95 < p_T < 240$ GeV (right).

where $\epsilon_{\text{misid},ij}$ is the ratio of the number of electrons with a wrong charge in a given p_T and η bin to the total number of electrons in the same bin. The results obtained are plotted in Figure 10.7 and the rates are seen to vary by a few orders of magnitude depending on p_T and η .

Estimation of charge misidentification background

Having determined the probabilities for charge-flip, the number of events with two same-sign leptons originating from events with two opposite-sign leptons can be determined by applying weights to the opposite-sign events that correspond to the probability for one of the opposite-sign leptons to flip the charge. In the ee channel, the weight is computed as:

$$w = \frac{\epsilon_1(1 - \epsilon_2) + \epsilon_2(1 - \epsilon_1)}{(1 - \epsilon_1)(1 - \epsilon_2) + \epsilon_1\epsilon_2}, \quad (10.2)$$

where ϵ_1 and ϵ_2 are the charge-flip rates for the leading and the sub-leading electrons respectively. The numerator corresponds to the probability for a same-sign event to originate from an opposite-sign event due to one of the electrons flipping charge while the denominator corresponds to the probability of an opposite-sign event to stay the same as a result of either both or none of the electrons flipping charge. In the case of single electron channels such as $e\mu$ or μe , the charge-flip rate of the muon is assumed to be zero and above equation simplifies to

$$w = \frac{\epsilon}{1 - \epsilon}. \quad (10.3)$$

Systematic uncertainties

The systematic uncertainty in the estimation of charge-flip background comes from the uncertainty in the scale factors applied to the simulated Z +jets sample for wrongly charged electrons surviving ECIDS. The $p_T - |\eta|$ distribution of the systematic uncertainties on the scale factors provided by the ATLAS EGamma group is plotted in Figure 10.8. While the scale factors are obtained with a rather good precision at high $|\eta|$, the systematic uncertainty in the centrally lying low p_T electrons peaks to about 70%. To estimate the uncertainty on the charge-flip background due to the uncertainty on the scale factors, the scale factors are varied up and down corresponding

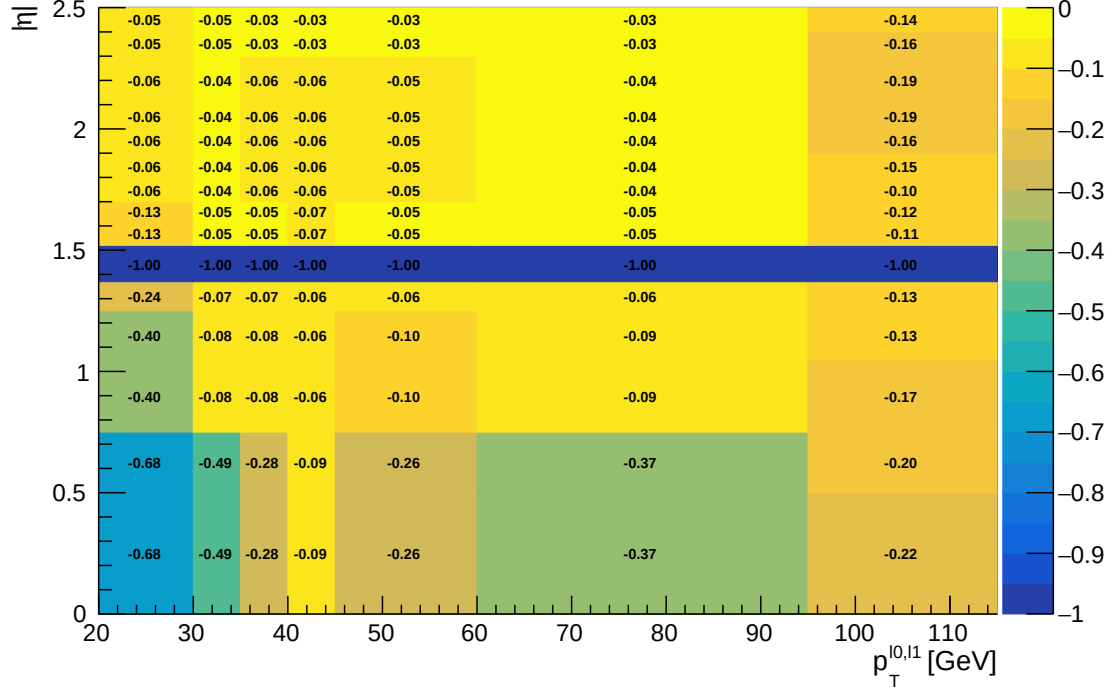


Figure 10.8: The systematic uncertainties on the scale factors for wrongly charged electrons surviving ECIDS and passing Tight identification and Gradient isolation are given as provided by the ATLAS EGamma group. Plots taken from [129].

to the systematic uncertainties, and charge-flip probabilities⁴ are re-estimated separately for each of the variations. The charge-flip background is computed for each of the variation and the average of the differences of the variations with respect to the nominal yields is assigned as the systematic uncertainty on the background due to the uncertainty on the scale factors.

Finally, the background is validated in the $Z(ee)$ Peak validation region, and the distribution of m_{ee} , where the same-sign electrons are the result of charge-flip, is shown in Figure 10.9. The large uncertainties seen are consistent with the uncertainties on the ECIDS scale factors. As an electron misidentified through Bremsstrahlung effects is typically reconstructed with lower energy with respect to the original electron, energy corrections are additionally applied, which is discussed in Appendix B. The m_{ee} distribution is plotted after applying the energy corrections. The breakdown of the total uncertainties associated with charge-flip background in the signal region is listed in Table 10.3.

⁴including the respective energy corrections.

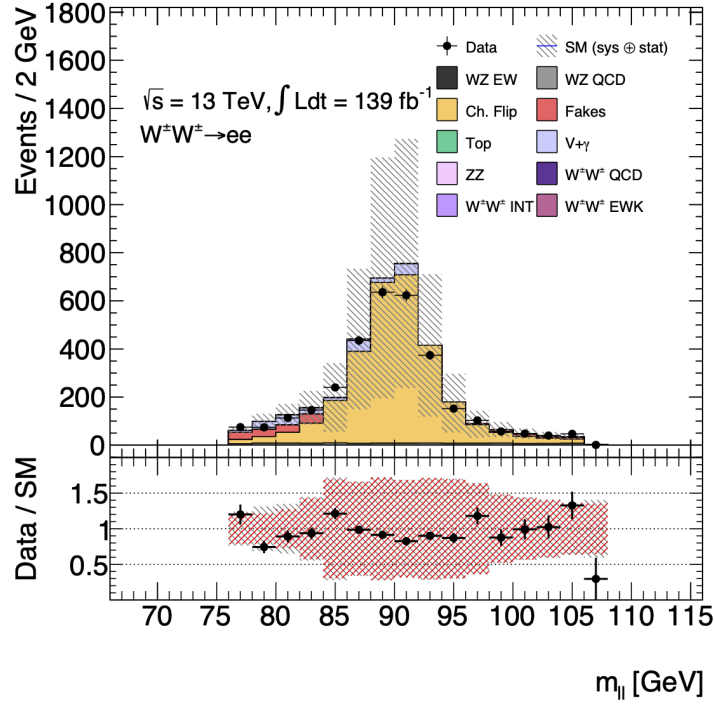


Figure 10.9: The distribution of the di-lepton invariant mass is shown in the Z(ee) Peak validation region for the $e^\pm e^\pm$ channel. The red band denotes the systematic uncertainties and the gray band indicates the combined systematic and statistical uncertainties on the backgrounds.

Lepton channel	% of nominal yields to ll	% of stat. uncert. to channel yields	% of syst. uncert. to channel yields
ee	39%	3%	48%
$e\mu + \mu e$	61%	5%	26%
ll	-	4%	35%

Table 10.3: Breakdown of the uncertainties associated with charge-flip background estimation.

Chapter 11

Estimation of Non-Prompt and Fake Lepton Backgrounds

The correct identification of prompt leptons is crucial to isolate hard scatter events. Despite the identification and isolation selections, misidentification of the reconstructed leptons can still occur resulting in non-prompt and fake lepton background. This chapter presents the estimation of this background which is one of the largest backgrounds in the analysis.

First, the definition and the sources of the background are introduced in Sections 11.1-11.2 followed by a briefing of the estimation strategy in Section 11.3. The method is then described in detail with the relevant results in Section 11.4 along with the uncertainty calculation in Section 11.5. Section 11.6 and 11.7 present the additional cross-checks and closure tests performed. Finally, the background is estimated in Section 11.8, and the results obtained in the validation regions and the signal region are shown.

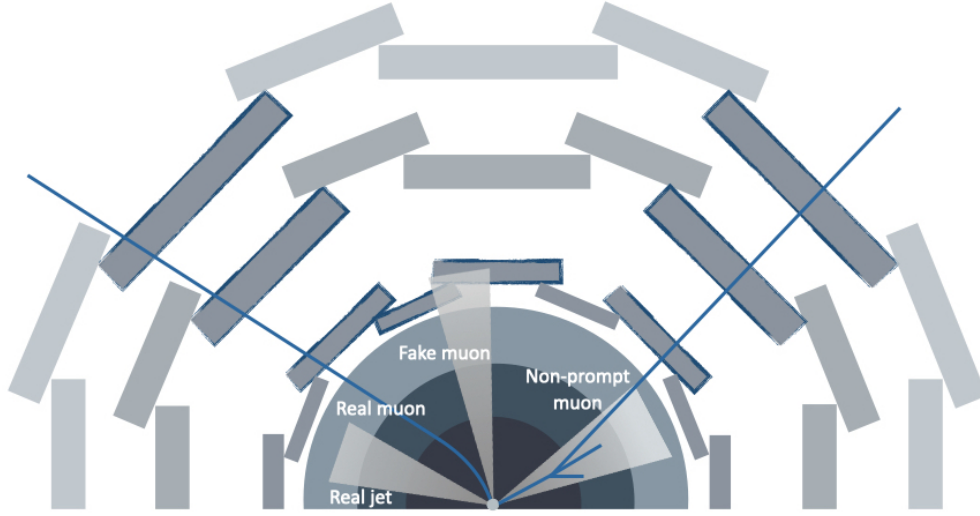
The estimation of the non-prompt and fake lepton background detailed in this chapter is the sole work of the author, which relies greatly on the complementary contributions made by the author in the estimation of this background in three other ATLAS analyses: differential $W^\pm W^\mp + \geq 1$ jet production [130], differential $W^\pm W^\mp + \geq 0$ jet, and production of $WZ\gamma$. The results presented in this chapter are further used in three additional ATLAS analyses: polarization measurement of W bosons in $W^\pm W^\pm jj$ production, production of $W^\pm W^\pm$ through double parton scattering, and search for heavy Majorana neutrinos in $W^\pm W^\pm jj$ production.

11.1 Definition

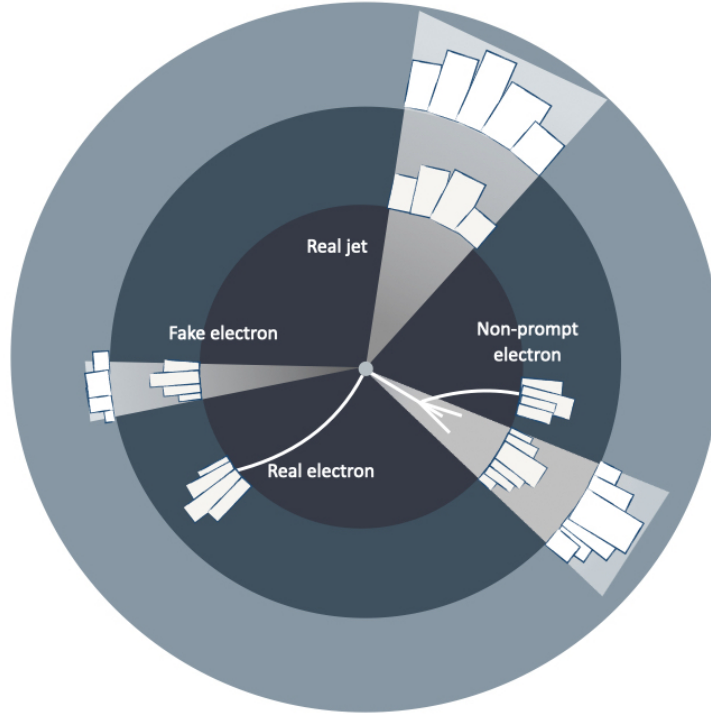
Non-prompt and fake lepton background consists of Standard Model processes where one of the leptons in the final state is a non-prompt or a fake lepton (see Chapter 6 for details), defined as:

- **Non-prompt lepton:** A lepton originating from a secondary decay that is incorrectly associated with a primary vertex.
- **Fake lepton:** Any object, commonly a jet, incorrectly reconstructed as a lepton where no lepton existed previously.

A simplified graphical illustration differentiating a real lepton from non-prompt and fake leptons is presented in Figure 11.1. Fake muons arise as a result of misidentification, such as from *punch-through* jets where high energy jets punch through the calorimeter and leave energy in the MS. Fake electrons are jets mis-reconstructed as electrons due to the energy deposits in the ECal. Non-prompt leptons are genuine leptons but originating from a displaced vertex.



(a) Muon Fakes



(b) Electron Fakes

Figure 11.1: A simplified graphic illustration is shown for muon fakes in (a) and electron fakes in (b). In (a), a partial cross-sectional view of the ATLAS detector is displayed where a fake muon and a non-prompt muon are seen to leave signals similar to a real muon, thus resulting in misidentification. In (b), the cross-sectional view of the detector excluding the MS is given. The two outer filled concentric circles represent the ECAL and the HCAL, and the white blocks depict the energy deposits in them. A fake and a non-prompt electron leave real lepton-like signals and are misidentified.

11.2 Sources

The dominant sources of non-prompt and fake leptons in the signal region are the leptonic decays of W +jets followed by the semi-leptonic decays of $t\bar{t}$ such as those illustrated in Figure 11.2. Both of these processes produce one prompt lepton and one non-prompt or fake lepton in association with jets and E_T^{miss} , thus imitating the signal final state. With a production cross-section thousands of times larger than $W^\pm W^\pm jj$, W +jets processes amount to nearly 70% of this background in signal region and the rest is $t\bar{t}$. Single top and di-boson processes also contribute but their overall yields are rather small.

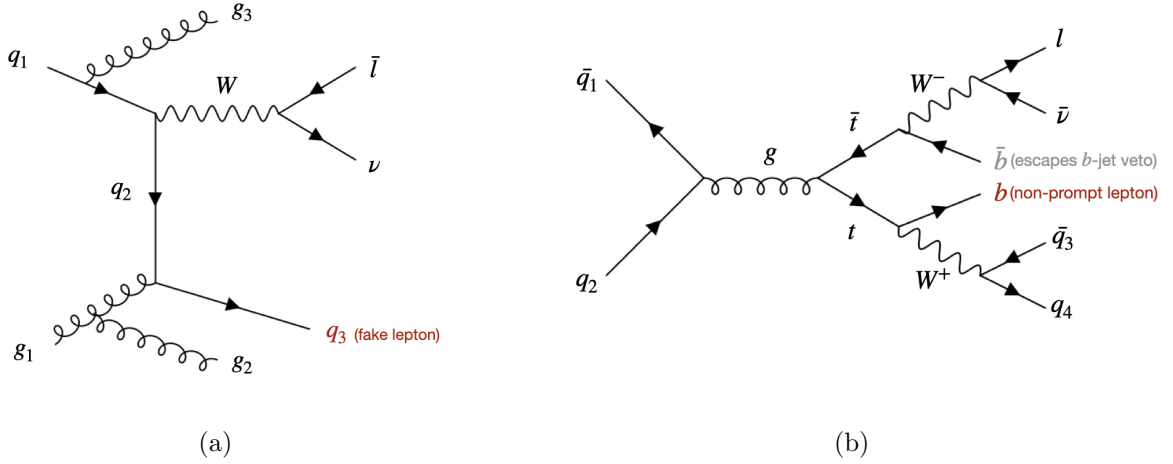


Figure 11.2: Feynman diagrams of W +jets in (a) and $t\bar{t}$ processes in (b) that contribute to the major sources of non-prompt and fake leptons in the analysis.

Unlike the fake leptons, the non-prompt leptons originate from definite particle sources, which vary depending on the lepton type. One of the predominant sources is the heavy-flavor decay, discussed already in Chapter 6. Tau leptons and light mesons like pions also yield non-prompt leptons. For electrons, Dalitz decays of $\pi^0 \rightarrow e^+e^-\gamma$ and photon conversions are other common sources. To obtain a rough estimate of the origin of these background leptons in the signal region, simulations are used. Figure 11.3 shows the origin composition in the signal region derived from W +jets simulated with MADGRAPH5_aMC@NLO+PYTHIA 8. The results are obtained from two separate tools that exploit generator level information to assign particle origin. Non-prompt electrons originate mostly from light-flavor sources whereas non-prompt muons originate from heavy-flavor sources despite the b -jet veto applied in the signal region.

For simplicity, the terms fakes and non-prompt are used interchangeably for the sum of fake leptons and non-prompt leptons in the remainder of this thesis.

11.3 Estimation Strategy

For the estimation of fake lepton background, data driven methods are preferred over Monte Carlo simulations for two main reasons. First, sufficient events are required to examine a specific phase space enriched in fake leptons, which is often limited in simulations resulting in large statistical uncertainties. Second, although simulations model leptons from hard scatter well, the modeling

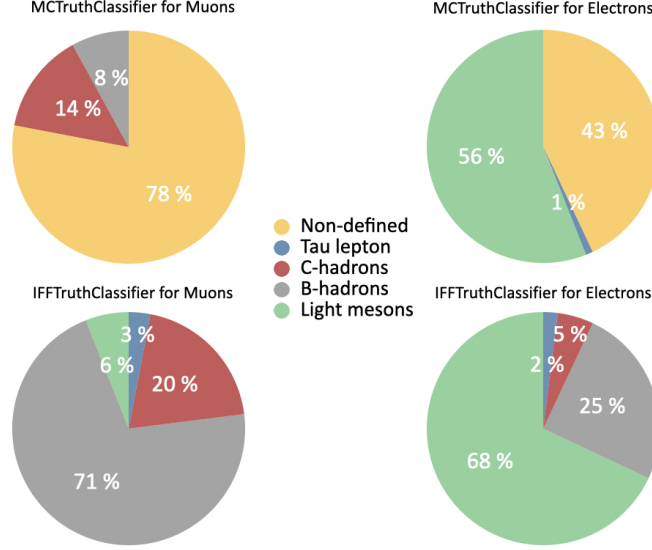


Figure 11.3: A pie-chart representation of the predicted origin composition of the lepton, which does not originate from the hard scatter vertex of the event, is given. The results are shown for muons (left) and electrons (right) in the signal region from simulated W +jets events using the MCTruthClassifier (top) and IFFTruthClassifier (bottom) tools. Non-defined (yellow) correspond to cases where there is no particle production vertex or when the algorithm fails to assign a source. Heavy-flavor decays dominate the muon channels whereas light-flavor decays dominate the electron channels. The IFFTruthClassifier results are taken from [131].

is worse for leptons from secondary decays and even more so for jet misidentification. Considering that only a small fraction of jets are identified as leptons, correctly modeling the misidentification rate requires an accurate description of the non-Gaussian tails of the detector response to jets. As the MC samples do not provide such level of detail, the background is estimated directly from the data.

In this analysis, a data driven technique called *fake factor* method is used to estimate the background. The fake factor method is an approximation of the matrix method [132], and its mathematical description is given below.

11.3.1 Mathematical Description

Two parameters fundamental to the method are the real efficiency (ε_r) and the fake efficiency (ε_f) determined from respective phase spaces rich in real and fake leptons. ε_r is the fraction of real leptons satisfying some baseline selections that further passes the signal or the ID lepton selections, and is given by $\varepsilon_r = N_r^{\text{ID}}/N_r^{\text{B}}$. ε_f , on the other hand, is the fraction of fake leptons satisfying the baseline selections that passes the ID lepton criteria given by $\varepsilon_f = N_f^{\text{ID}}/N_f^{\text{B}}$. If Anti-ID leptons represent another set of leptons that pass the baseline selections but fail the ID lepton requirements, then for single lepton events:

$$\begin{aligned}
 N^{\text{ID}} &= \varepsilon_r N_r^{\text{B}} + \varepsilon_f N_f^{\text{B}}, \\
 N^{\text{Anti-ID}} &= (1 - \varepsilon_r) N_r^{\text{B}} + (1 - \varepsilon_f) N_f^{\text{B}},
 \end{aligned} \tag{11.1}$$

where $(1-\varepsilon_r)$ represent the efficiency for a real lepton to fail ID (or pass Anti-ID) and $(1-\varepsilon_f)$ is the efficiency for a fake lepton to be Anti-ID. The above equation can be written in matrix form as

$$\begin{pmatrix} N^{\text{ID}} \\ N^{\text{Anti-ID}} \end{pmatrix} = \begin{pmatrix} \varepsilon_r & \varepsilon_f \\ 1 - \varepsilon_r & 1 - \varepsilon_f \end{pmatrix} \begin{pmatrix} N_r^{\text{B}} \\ N_f^{\text{B}} \end{pmatrix}, \quad (11.2)$$

where the quantity of interest is the number of fake leptons passing ID lepton selections, N_f^{ID} , which can also be identified as

$$N_f^{\text{ID}} = \varepsilon_f N_f^{\text{B}}. \quad (11.3)$$

Simplifying Equation (11.2), one gets

$$\begin{pmatrix} N_r^{\text{B}} \\ N_f^{\text{B}} \end{pmatrix} = \begin{pmatrix} \varepsilon_r & \varepsilon_f \\ 1 - \varepsilon_r & 1 - \varepsilon_f \end{pmatrix}^{-1} \begin{pmatrix} N^{\text{ID}} \\ N^{\text{Anti-ID}} \end{pmatrix}, \quad (11.4)$$

$$\begin{pmatrix} N_r^{\text{B}} \\ N_f^{\text{B}} \end{pmatrix} = \frac{1}{\varepsilon_r - \varepsilon_f} \begin{pmatrix} (1 - \varepsilon_f)N^{\text{ID}} - \varepsilon_f N^{\text{Anti-ID}} \\ (\varepsilon_r - 1)N^{\text{ID}} + \varepsilon_r N^{\text{Anti-ID}} \end{pmatrix}. \quad (11.5)$$

It follows that

$$N_f^{\text{B}} = \frac{1}{\varepsilon_r - \varepsilon_f} (\varepsilon_r N^{\text{Anti-ID}} + (\varepsilon_r - 1)N^{\text{ID}}). \quad (11.6)$$

The fake factor method approximates $\varepsilon_r \rightarrow 1$ resulting in $N^{\text{Anti-ID}}$ in Equation (11.1) to be populated with $N_f^{\text{Anti-ID}}$. Equation (11.6) now simplifies as

$$N_f^{\text{B}} = \frac{1}{1 - \varepsilon_f} N_f^{\text{Anti-ID}}, \quad (11.7)$$

and finally, using Equation (11.3), one gets

$$N_f^{\text{ID}} = \frac{\varepsilon_f}{1 - \varepsilon_f} N_f^{\text{Anti-ID}}. \quad (11.8)$$

The fake factor, F , is the coefficient in Equation (11.8), which is the ratio of the efficiency of a fake lepton to be identified as an ID lepton to the efficiency to be an Anti-ID lepton extracted from data in a region rich in fake leptons. In reality, the real efficiency in any analysis is less than unity and contributions of real leptons are subtracted from data according to Equation (11.9) to correctly estimate fake factors. As the real leptons are modeled quite well in simulations, their contributions are taken from the MC samples.

$$F = \frac{N_f^{\text{ID}}}{N_f^{\text{Anti-ID}}} = \frac{N^{\text{ID}} - N_r^{\text{ID}}}{N^{\text{Anti-ID}} - N_r^{\text{Anti-ID}}} \quad (11.9)$$

11.3.2 Fake Factors to Fake Lepton Background

In this measurement, fake factors are determined from single lepton events in a fake lepton enriched phase space. But the signal region has two lepton events, among which events consisting of a fake lepton are to be extracted that form the fake lepton background. To achieve this, two lepton events with one ID lepton and one Anti-ID lepton entering the signal region are selected and weighted by the fake factors to obtain the fake lepton background, shown schematically as per Figure 11.4. As the prompt leptons contaminate the fake lepton background estimation region, prompt lepton contributions are subtracted using MC expectations and the fake lepton background estimated can be expressed as

$$N_f^{\text{ID+ID}} = F \cdot (N^{\text{ID+Anti-ID}} - N_r^{\text{ID+Anti-ID}}). \quad (11.10)$$

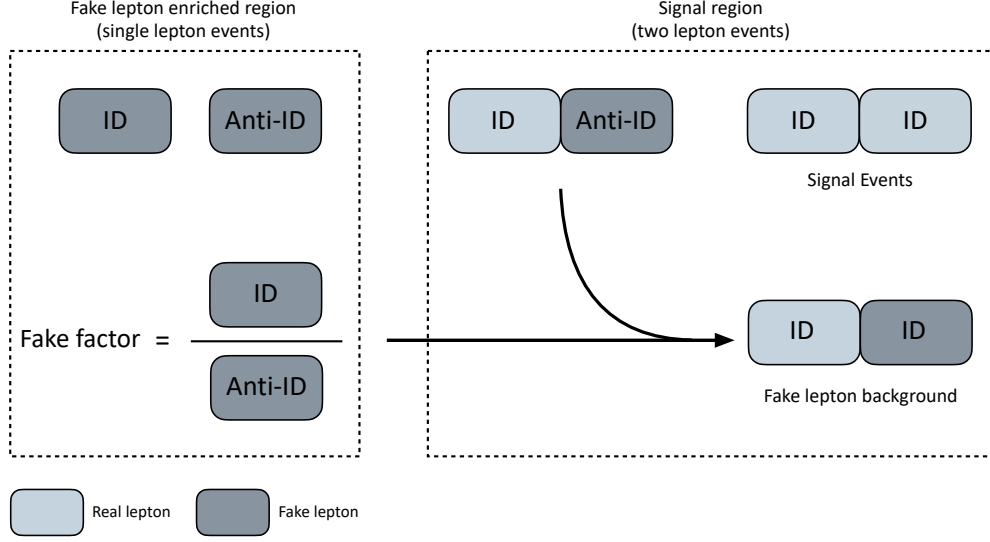


Figure 11.4: A schematic representation depicting the estimation of fake lepton background using the fake factor method.

11.4 Fake Factor Determination

11.4.1 Di-jet Region

To extract fake factors, the analysis uses di-jet events in data passing single lepton selections. To enhance the contribution of fakes, a configuration is chosen where the lepton candidate in the event is balanced by a jet. This follows the idea that the two underlying jets are balanced in p_T and if the sole lepton candidate in the event lies back-to-back with a jet, then the lepton candidate examined is ultimately a fake lepton.

To define the di-jet phase space, certain selections are applied which are summarized in Table 11.1. The events are collected with prescaled single lepton triggers `HLT_mu14` for muons and `HLT_e12_lhvloose_nod0_L1EM10VH` for electrons. The trigger prescales are applied as an additional weight to unprescale the data. The events require a single lepton with $p_T > 27$ GeV that passes either the ID or the Anti-ID lepton selections given in Tables 9.2-9.3. There has to be at least one jet and the leading jet must satisfy $p_T > 25(30)$ GeV for $|\eta| < 2.5(2.5 < |\eta| < 4.5)$. The lepton candidate is required to be back-to-back with the leading jet in the azimuthal plane with $|\Delta\phi| > 2.8$.

To suppress the prompt lepton contamination from W +jets events, the dominant source of prompt leptons in the phase space considered, the sum of E_T^{miss} and the transverse mass of the lepton and the missing energy system is required to be smaller than 50 GeV. Finally, the selected events are further divided into two phase spaces based on the b -jet multiplicity: heavy-flavor di-jets and light-flavor di-jets. The former is required to have at least one b -jet and the latter is populated with events without a b -jet.

Fake factors are evaluated separately in these two regions for electrons and muons in bins of the lepton p_T . As the fake leptons in the signal region originate from a combination of both light- and heavy-flavor decays despite the b -jet veto (see Figure 11.3), the nominal fake factors are taken to be the average of the fake factors estimated from the heavy-flavor and the light-flavor di-jet regions.

Di-jet Region Selection	
Light-flavor	Heavy-flavor
$n_{b-jet} = 0$	$n_{b-jet} \geq 1$
Single lepton trigger fired Single lepton with $p_T > 27$ GeV ID or Anti-ID lepton $n_{jet} \geq 1$ Leading jet $p_T > 25(30)$ GeV Leading jet $ \eta < 2.5(2.5 < \eta < 4.5)$ $ \Delta\phi > 2.8$ $E_T^{\text{miss}} + m_T < 50$ GeV	

Table 11.1: Event selection in the fake factor derivation region.

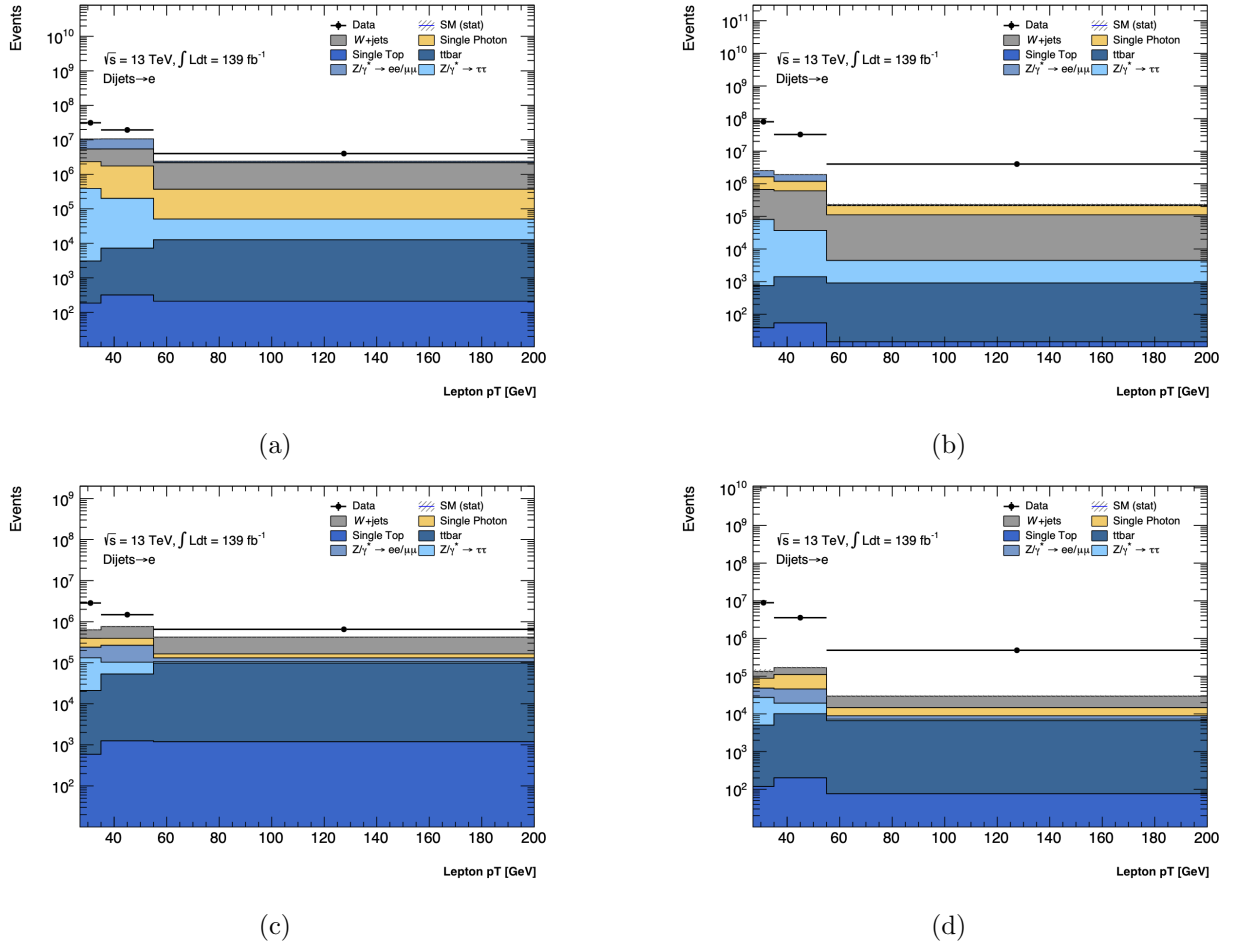
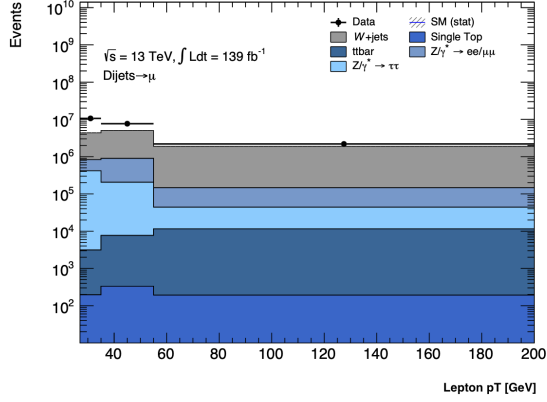
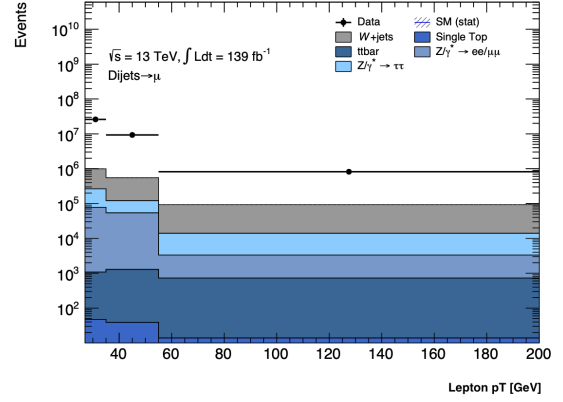


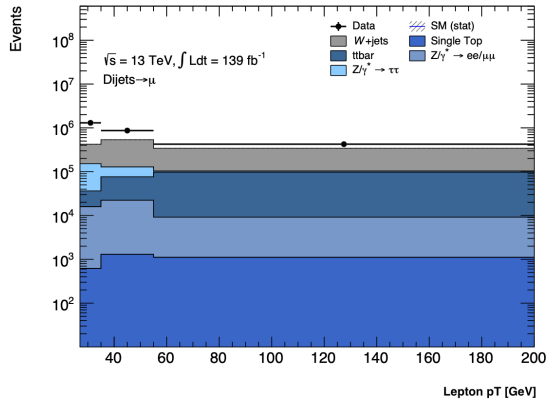
Figure 11.5: Distributions of the ID (left) and the Anti-ID (right) electron p_T in events with $n_{b-jet} = 0$ (top) and $n_{b-jet} \geq 1$ (bottom).



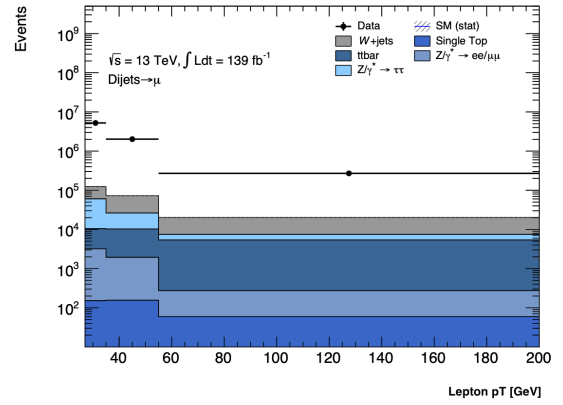
(a)



(b)

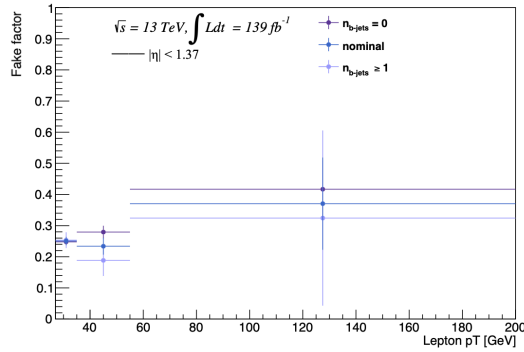


(c)

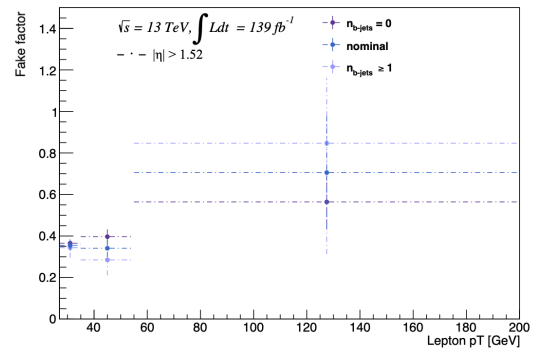


(d)

Figure 11.6: Distributions of the ID (left) and the Anti-ID (right) muon p_T in events with $n_{b-jet} = 0$ (top) and $n_{b-jet} \geq 1$ (bottom).



(a)



(b)

Figure 11.7: Electron fake factors in the light- and the heavy-flavor di-jet regions are plotted in $|\eta| < 1.37$ (left) and $|\eta| > 1.52$ (right). The average of the fake factors obtained from the two di-jet regions with differing source compositions is taken as the nominal fake factors.

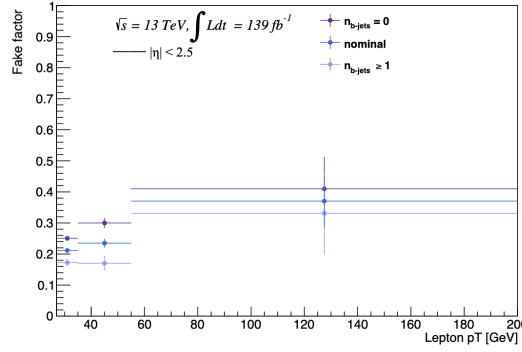


Figure 11.8: Muon fake factors in the light-flavor and the heavy-flavor di-jet regions are plotted in $|\eta| < 2.5$. The nominal muon fake factors are taken to be the average of the fake factors estimated from the two di-jet regions with differing source compositions.

The input for calculating fake factors according to Equation (11.9) are the p_T distributions of the ID and the Anti-ID leptons in the light-flavor and the heavy-flavor di-jet regions plotted in Figures 11.5 and 11.6. The contamination from prompt leptons is simulated using the samples recorded in Table 8.4. The prompt processes considered are W +jets, Z +jets, $t\bar{t}$, single top, and single photon, and their contributions are found to be small except in the high p_T regions. In the electron channel, fakes from photon conversions¹ are removed using the single photon events. Finally, the electron and muon fake factors obtained from the light-flavor and heavy-flavor di-jet regions are plotted in Figures 11.7 and 11.8 along with their averaged (nominal) fake factors.

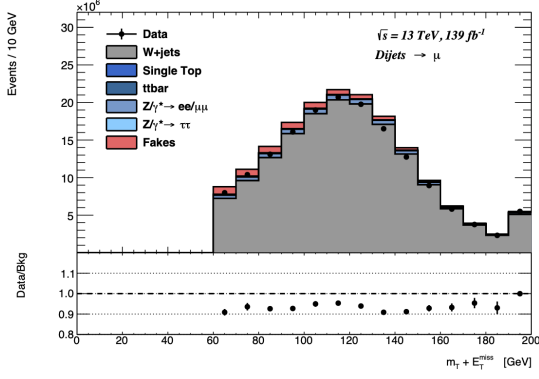
Despite the $E_T^{\text{miss}} + m_T$ selection applied, the W +jets process is still the largest prompt lepton source for both the electron and the muon channels in the di-jet events. As the fake factors are affected by the amount of prompt leptons, it is necessary to test the modeling of the prompt lepton backgrounds. Therefore, a control region dominated by W +jets is defined which serves two purposes:

1. *Correction for mismodeled normalization:* The W +jets sample generated with SHERPA exhibits mismodeling in normalization in both light-flavor and heavy-flavor events. The $E_T^{\text{miss}} + m_T$ distribution for muons and electrons in light- and heavy-flavor events are shown in Figure 11.9 in a W +jets enriched control region. Therefore, normalization factors are extracted for W +jets in the control region before using the process in the di-jet region to estimate fake factors.
2. *Correction for missing trigger scale factors:* The single lepton events used are collected with prescaled triggers for which the trigger scale factors are not available to correct the MC events to match data. As a result, a mismodeling in all the prompt lepton backgrounds used is expected. Corrections in the form of scale factors are also determined from the W +jets control region.

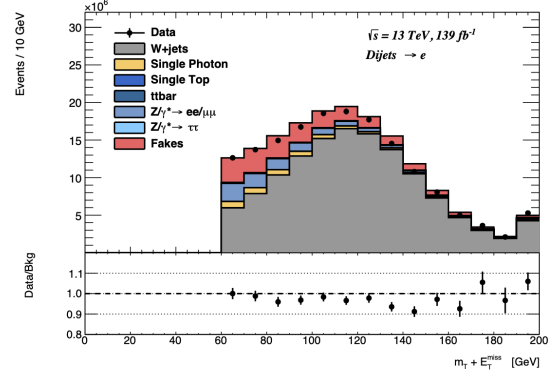
11.4.2 W +jets Control Region

The W +jets control region is a phase space orthogonal to the fake factor derivation region, defined according to Table 11.2, requiring $E_T^{\text{miss}} + m_T > 60$ GeV to isolate the W +jets process. The

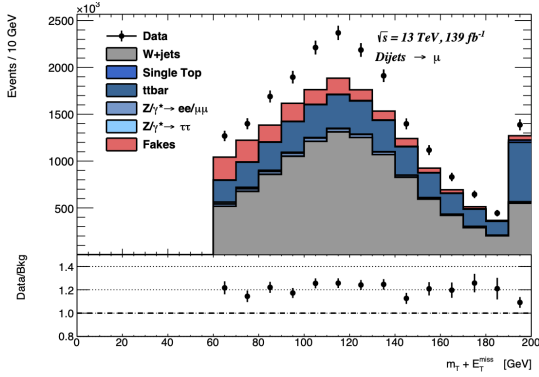
¹Photon conversions are already estimated as e/γ conversion background in Chapter 10.



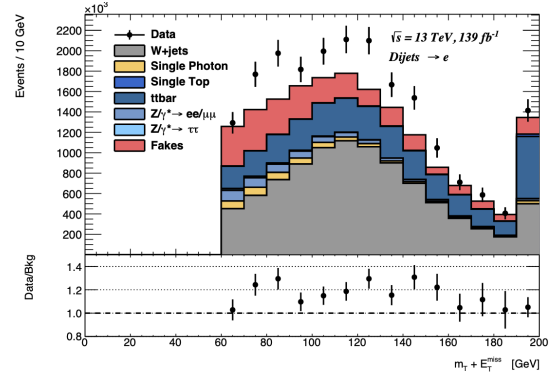
(a)



(b)



(c)



(d)

Figure 11.9: The $E_T^{\text{miss}} + m_T$ distribution is given for muons (left) and electrons (right) in light- (top) and heavy- (bottom) flavor events showing the mismodeling of prompt leptons with respect to data in a W +jets enriched control region.

back-to-back configuration of the lepton and the leading jet is not required in this region. The control region is investigated in both $n_{b-jet} = 0$ and $n_{b-jet} \geq 1$ events, similar to the di-jet region.

W+jets Control Region Selection	
Light-flavor	Heavy-flavor
$n_{b-jet} = 0$	$n_{b-jet} \geq 1$
Single lepton trigger fired Single lepton with $p_T > 35$ GeV ID lepton $n_{jet} \geq 1$ Leading jet $p_T > 25(30)$ GeV Leading jet $ \eta < 2.5(2.5 < \eta < 4.5)$ $E_T^{\text{miss}} + m_T > 60$ GeV	

Table 11.2: Event selection in the W +jets control region.

Correction parameter extraction strategy

A template fit is performed in the di-jet and the W +jets control regions separately for light- and heavy-flavor events to extract the correction parameters. First, with the existing knowledge of the scale factors of the HLT_2mu14 trigger, the scale factor for HLT_mu14 is obtained. The estimated trigger scale factor is then applied to all the MC prompt backgrounds in the di-jet and the W +jets control region for muon events. The W +jets control region also has a small contribution of fake lepton background which is estimated using the fake factors from the di-jet region. A χ^2 fit then performed on the agreement of the $E_T^{\text{miss}} + m_T$ distribution between data and the total background in the W +jets control region with the normalization on W +jets kept as a floating parameter. The fit tries different values for the normalization factor, and for every normalization factor, fake factors are evaluated in the di-jet region which are used in the W +jets control region to estimate the fake lepton background. The data-background agreement is checked until the χ^2 is minimized and the value for which the χ^2 minimization converges is the normalization factor used to scale the W +jets events in the muon channel. The resulting fake factors (with the scale factor and the normalization factor applied) are the muon fake factors used for the respective flavor type.

As the branching ratio for the W boson is the same for electrons and muons, see Table 5.1, W +jets normalization factor determined from the muon channel must be the same for the electron channel as well. Finally, using the normalization factor, the same method is repeated in the electron channel but in the reverse order to extract the scale factor for the electron trigger. The strategy to extract the correction parameters, including the mathematical implementations is summarized in Figure 11.10. The methodology and results obtained for the light- and the heavy-flavor events are discussed in detail in the following.

It has to be noted that the correction parameter obtained for the missing electron trigger scale factor should not be mistaken for the trigger scale factor. Typically, trigger scale factors are estimated using high purity ID leptons whereas in this estimation, fake leptons in the simulations are also applied the correction parameter as shown in the figure.

Di-jet Region

$$F = \frac{N_{data}^{ID} - N_{MC}^{ID}}{N_{data}^{Anti-ID} - N_{MC}^{Anti-ID}}$$

$$F = \frac{N_{data}^{ID} - \text{SF} \left(N_{prompt\ except}^{ID} + \text{NF} \cdot N_{W+jets}^{ID} \right)}{N_{data}^{Anti-ID} - \text{SF} \left(N_{prompt\ except}^{Anti-ID} + \text{NF} \cdot N_{W+jets}^{Anti-ID} \right)}$$

W +jets Control Region

χ^2 fit between data and total background where,

$$\text{total background} = \text{SF} \left(N_{prompt\ except}^{ID} + \text{NF} \cdot N_{W+jets}^{ID} \right) + F \cdot N_{data}^{Anti-ID}$$

Figure 11.10: A summary of the strategy used to extract the correction parameters is shown along with the mathematical implementations. The fake factors, F , are obtained in the di-jet region whereas the χ^2 fit is performed in the W +jets control region. The correction parameters are first extracted in the muon channel and then in the electron channel. To begin with, the trigger scale factor (SF) is fixed for the muon channel to obtain the normalization factor (NF) for W +jets. The normalization factor is estimated by minimizing the χ^2 between the data and the total background in the W +jets control region, which depends on the fake factors determined in the di-jet region. Once NF is obtained from the muon channel, it is fixed in the electron channel keeping its trigger scale factor floating. The same method is repeated and the SF is obtained. The method is followed independently in both light- and heavy-flavor regions to obtain the final fake factors for $n_{b-jet} = 0$ and $n_{b-jet} \geq 1$ events.

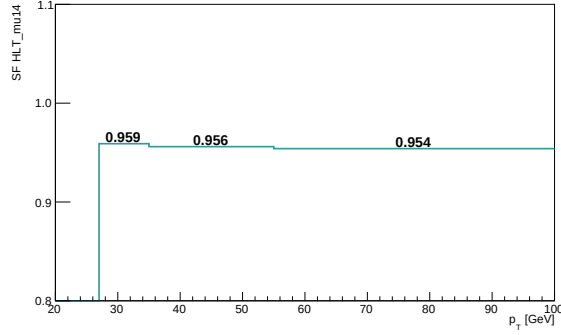


Figure 11.11: The scale factor of HLT_mu14 plotted as a function of the muon transverse momentum. The uncertainties are typically less than 1% and are not plotted. Only the central values shown are used in the correction methodology described.

Correction in light-flavor events

The trigger scale factors are typically provided by the ATLAS trigger groups for use in analyses. Prescaled triggers² are not commonly used for physics measurements but mainly for background studies, and their scale factors are not provided at large. While the scale factor for the electron trigger is not computed in ATLAS, information regarding the scale factor of the muon trigger is available indirectly³.

HLT_2mu14 is an unprescaled trigger⁴ and being a symmetric trigger, its scale factor is computed as

$$\text{SF}(2\text{mu}14) = \frac{\epsilon_{\text{data}}(\text{mu}14) \cdot \epsilon_{\text{data}}(\text{mu}14)}{\epsilon_{\text{MC}}(\text{mu}14) \cdot \epsilon_{\text{MC}}(\text{mu}14)}, \quad (11.11)$$

where $\epsilon_{\text{data}}(\text{mu}14)$ and $\epsilon_{\text{MC}}(\text{mu}14)$ are the trigger efficiencies of HLT_mu14 in data and MC respectively. From the trigger scale factor of HLT_2mu14, the scale factor of HLT_mu14 can be obtained according to

$$\text{SF}(\text{mu}14) = \frac{\epsilon_{\text{data}}(\text{mu}14)}{\epsilon_{\text{MC}}(\text{mu}14)} = \sqrt{\text{SF}(2\text{mu}14)}, \quad (11.12)$$

and the values are plotted in Figure 11.11 as a function of the muon p_T . With this knowledge, the corrections are first applied in the muon channel. As the trigger scale factors do not exhibit a strong dependence on p_T , all the MC prompt backgrounds in $n_{b\text{-jet}} = 0$ events are scaled down by 4% in the di-jet and the W +jets control regions. Keeping the normalization factor of W +jets floating, the χ^2 between the data and the total background of the $E_T^{\text{miss}} + m_T$ distribution in the control region is minimized, which converges for 0.959 ± 0.005 as seen from Figure 11.12a, following which the W +jets contribution is further scaled down by 4% in the di-jet and the control regions. The muon fake factors thus obtained for $n_{b\text{-jet}} = 0$ events are shown in Figure 11.12b and the data-background agreement in the W +jets control region before and after applying the corrections are plotted in Figure 11.13. After applying the muon trigger scale factor and the W +jets normalization factor, the data to background ratio is 0.998 ± 0.004 , which agrees well with unity.

²Prescaled triggers save only one event out of every n events that fire the trigger where n is determined by the prescale chosen.

³The muon trigger efficiency is provided by the MUONEFFICIENCYCORRECTIONS TOOL, which does not support prescaled triggers. HLT_2mu14 is an unprescaled trigger and its scale factors are provided by the tool from which the scale factors for HLT_mu14 can be derived.

⁴HLT_2mu14 is not used in this analysis. It is used solely for the purpose of estimating the scale factor of HLT_mu14.

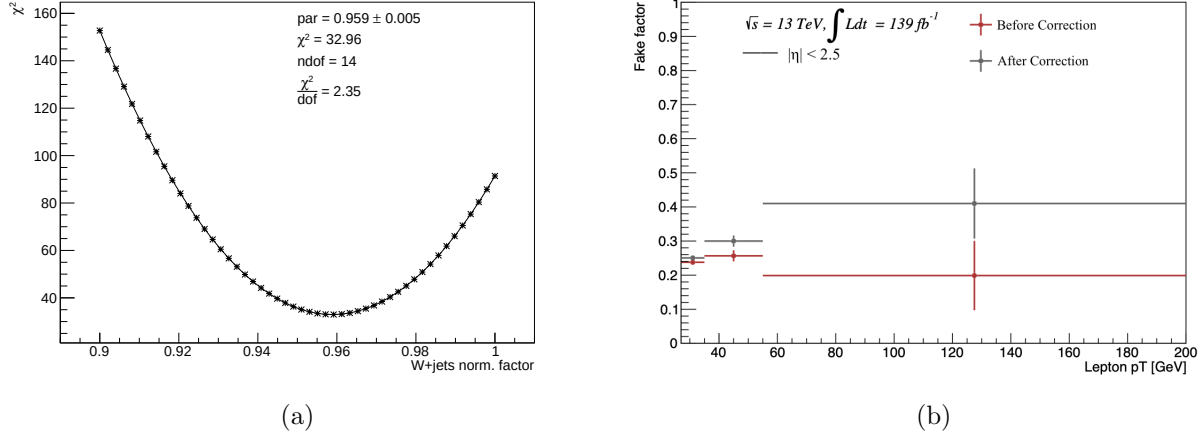


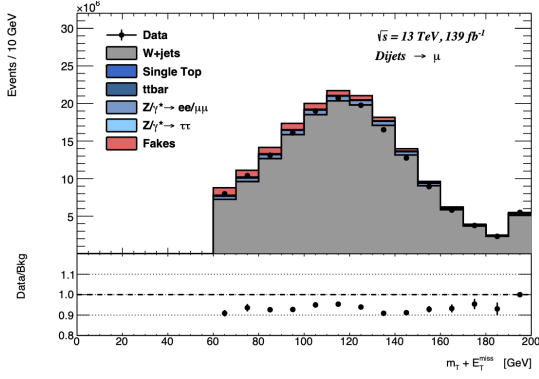
Figure 11.12: The χ^2 of the $E_T^{\text{miss}} + m_T$ distribution between data and simulations in the light-flavor W +jets control region is plotted in (a) to extract the normalization factor of W +jets. The distribution is given for the muon channel in $n_{b\text{-jet}} = 0$ events, and the χ^2 is minimized for a value of 0.959. In (b), a comparison of muon fake factors obtained in the light-flavor di-jet region before and after applying the corrections are given. Muon trigger scale factor and W +jets normalization factor for $n_{b\text{-jet}} = 0$ events are the corrections applied.

In the electron channel, the estimation strategy is reversed. Keeping the correction on W +jets fixed, the electron trigger scale factor is floated and the χ^2 is checked in the W +jets control region for various values of the scale factor. Finally, the χ^2 is minimized for a scale factor of 0.996 ± 0.011 according to Figure 11.14a, and the electron fake factors estimated are plotted in Figure 11.14b. The data-background agreement in the W +jets control region before and after applying the corrections are plotted in Figure 11.15. After applying the electron trigger scale factor and the W +jets normalization factor, the data-background agreement is 0.999 ± 0.008 .

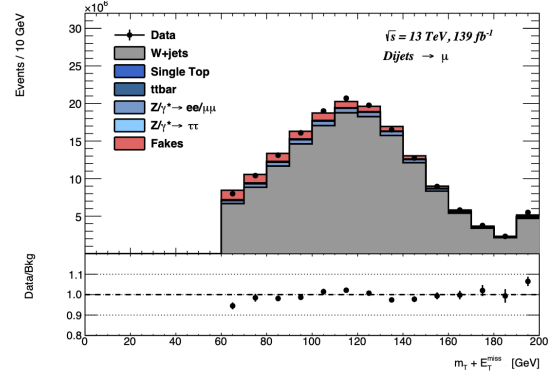
Correction in heavy-flavor events

Similar to light-flavor events, the normalization factor for heavy-flavor W +jets is extracted in the muon channel based on the aforementioned method after applying the muon trigger scale factor. The χ^2 between data and simulations in the $E_T^{\text{miss}} + m_T$ distribution is minimized for a value of 1.445 ± 0.003 and is plotted in Figure 11.16. It suggests that the W +jets contribution in simulations has to be raised by 45% to match the distribution in data. The agreement before and after corrections in the muon channel is compared in Figure 11.17 for $E_T^{\text{miss}} + m_T$ and b -jet multiplicity distributions. An agreement of 0.978 ± 0.021 is observed between the data and the total backgrounds after applying the corrections. The distribution of the b -jet multiplicity confirms that the apparent discrepancy exists in bins where the W +jets yields dominate. The correction is also applied in the electron channel, and the agreement observed between data and simulations after the correction, in Figure 11.18, is 1.002 ± 0.011 , which serve as an additional validation of the normalization parameter applied. The muon and the electron fake factors thus obtained in the fitting procedure are plotted in Figure 11.19 for $n_{b\text{-jet}} \geq 1$ events.

It has to be noted that the plots in Figures 11.5-11.8 are shown after the application of the corrections discussed above. The heavy-flavor di-jet region has also been analyzed using an alternate W +jets sample and the results are given in Appendix C.1.

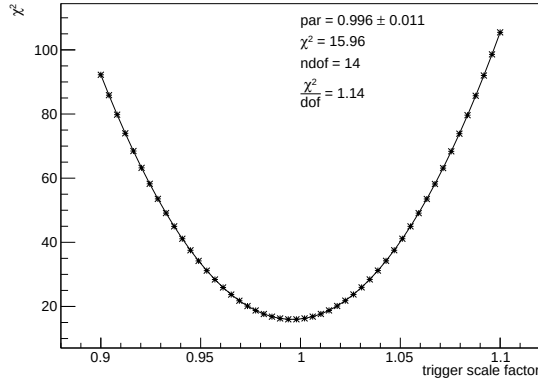


(a)

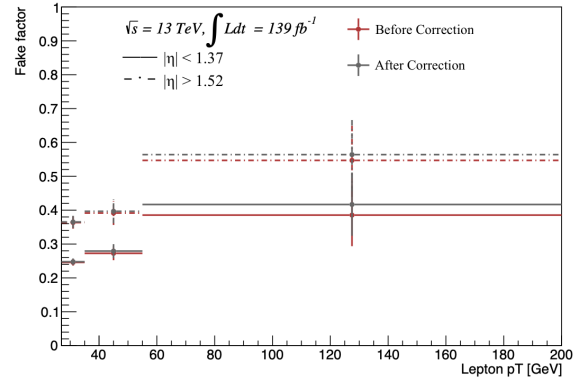


(b)

Figure 11.13: Comparison of the $E_T^{\text{miss}} + m_T$ distribution in W +jets control region for $n_{b\text{-jet}} = 0$ events before (left) and after (right) applying the corrections are shown for the muon channel. Figure 11.9a (before correction) is repeated here only for comparison. In Figure 11.13b (after correction), all the MC backgrounds are scaled down by 4% and the W +jets background is further scaled down by 4% according to the method shown in Figure 11.10.

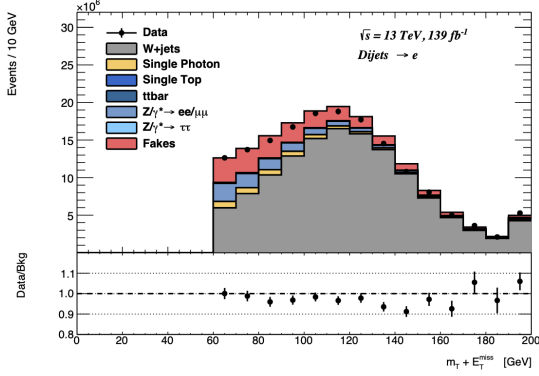


(a)

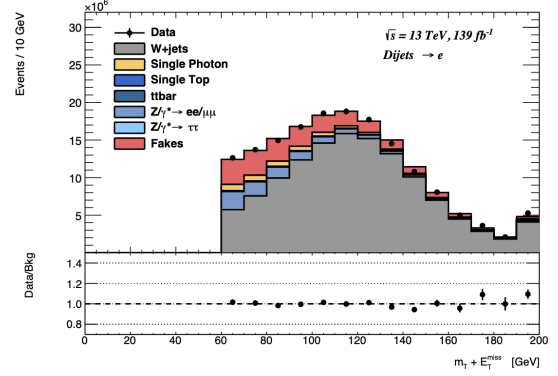


(b)

Figure 11.14: The χ^2 of the $E_T^{\text{miss}} + m_T$ distribution between data and simulations in the light-flavor W +jets control region is plotted in (a) to extract the scale factor of the electron trigger. The distribution is given for $n_{b\text{-jet}} = 0$ events, and the χ^2 is minimized for a value of 0.996. In (b), a comparison of the electron fake factors obtained in the light-flavor di-jet region before and after applying the corrections are given. Electron trigger scale factor and W +jets normalization factor for $n_{b\text{-jet}} = 0$ events are the corrections applied.



(a)



(b)

Figure 11.15: Comparison of the $E_T^{\text{miss}} + m_T$ distribution in W +jets control region for $n_{b\text{-jet}} = 0$ events is shown before (left) and after (right) applying the corrections in the electron channel. Figure 11.9b (before correction) is repeated here only for comparison. In Figure 11.15b (after correction), W +jets background is scaled down by 4% according to the method shown in Figure 11.10.

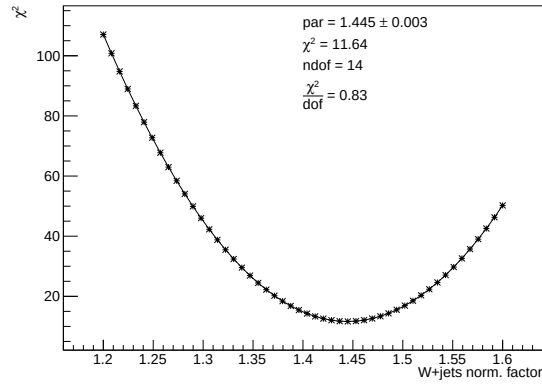
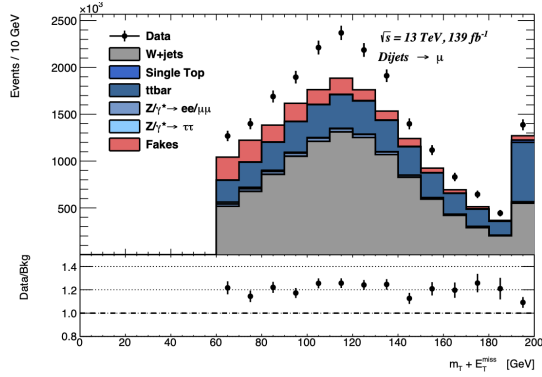
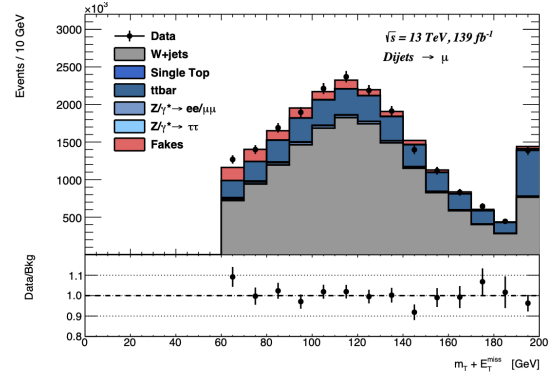


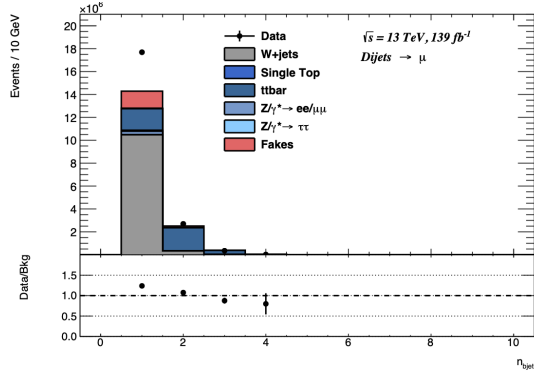
Figure 11.16: The χ^2 of the $E_T^{\text{miss}} + m_T$ distribution between data and simulations in the W +jets control region is plotted to extract the normalization factor of W +jets. The distribution is given for the muon channel in $n_{b\text{-jet}} \geq 1$ events, and the χ^2 is minimized for a value of 1.445.



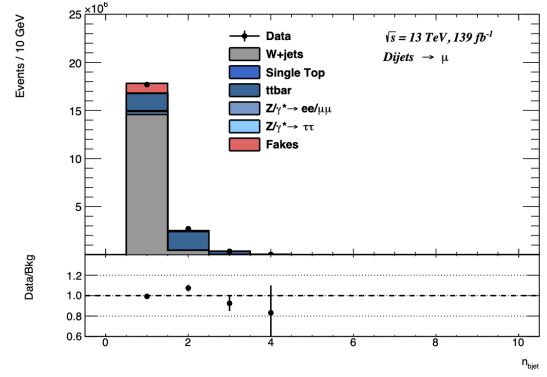
(a)



(b)

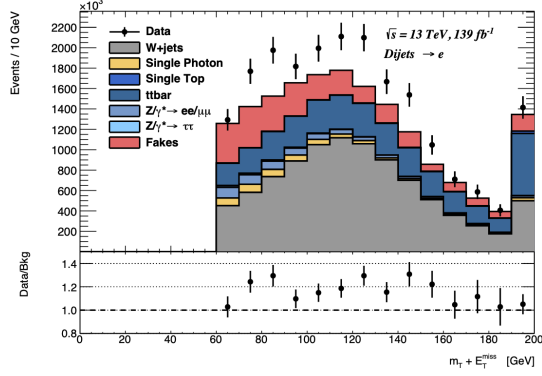


(c)

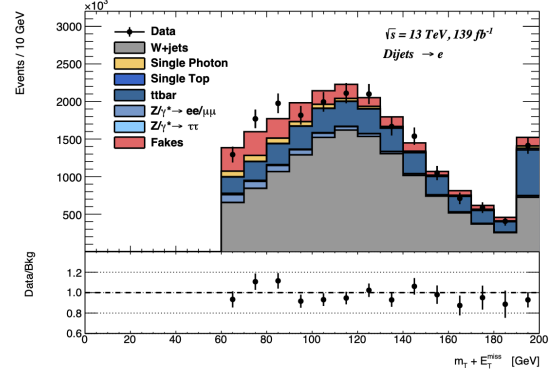


(d)

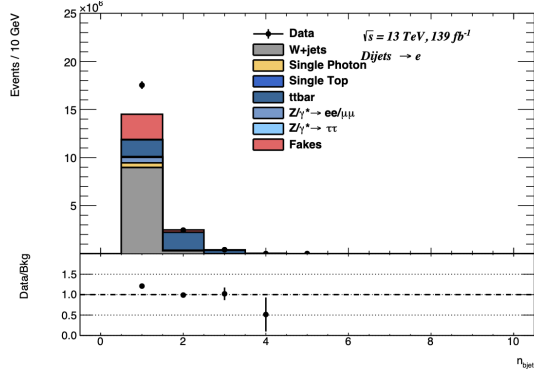
Figure 11.17: Comparison of the $E_T^{\text{miss}} + m_T$ (top) and b -jet multiplicity (bottom) distributions in W +jets control region for $n_{b\text{-jet}} \geq 1$ events before (left) and after (right) applying the corrections are shown for the muon channel. Figure 11.9c (before correction) is repeated here only for comparison. In Figures 11.17b and 11.17d (after correction), all the MC backgrounds are scaled down by 4% and the W +jets background is additionally scaled up by 45% according to the method shown in Figure 11.10.



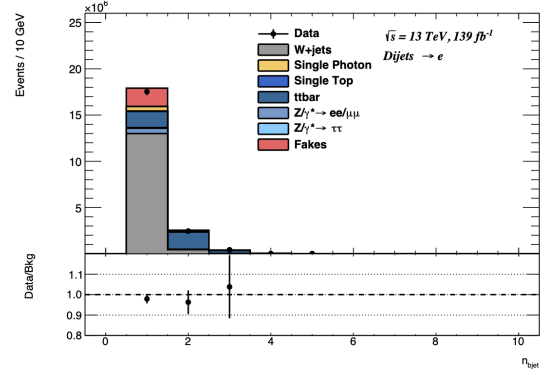
(a)



(b)

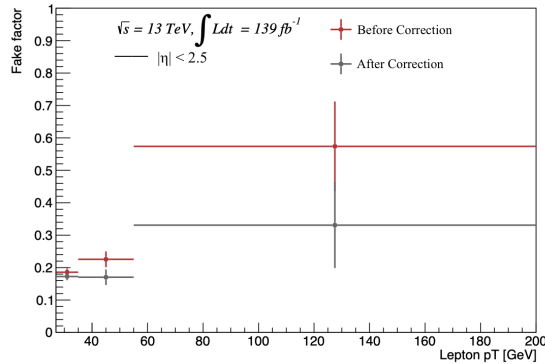


(c)

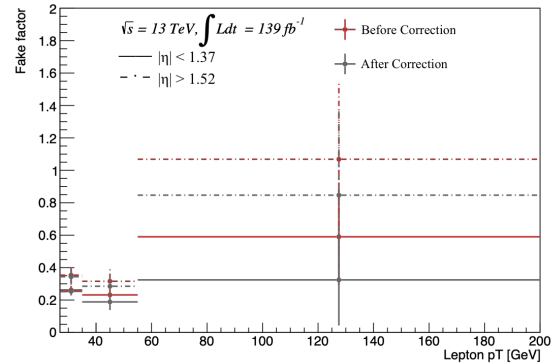


(d)

Figure 11.18: Comparison of the $E_T^{\text{miss}} + m_T$ (top) and b -jet multiplicity (bottom) distributions in W +jets control region for $n_{b\text{-jet}} \geq 1$ events before (left) and after (right) applying the corrections are shown for the electron channel. Figure 11.9d (before correction) is repeated here only for comparison. In Figures 11.18b and 11.18d (after correction), the W +jets background is scaled up by 45% according to the method shown in Figure 11.10.

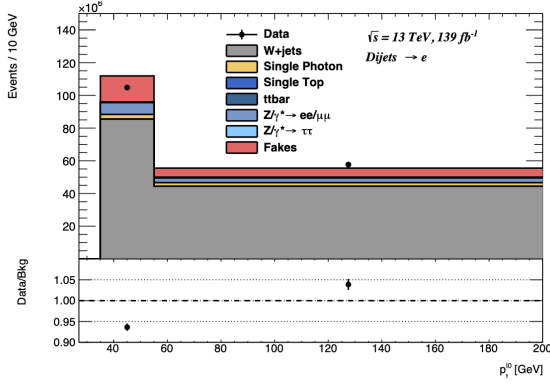


(a)

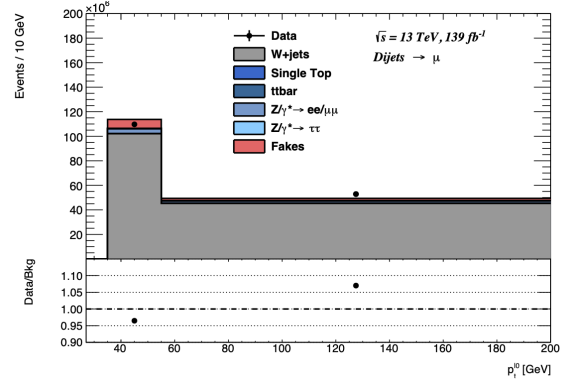


(b)

Figure 11.19: Comparison of the muon (left) and the electron (right) fake factors derived from the heavy-flavor di-jet region before and after applying the corrections is shown.



(a)



(b)

Figure 11.20: The lepton p_T distributions in W +jets control region for $n_{b-jet} = 0$ events after applying the corrections are shown for the electron (left) and muon (right) channels.

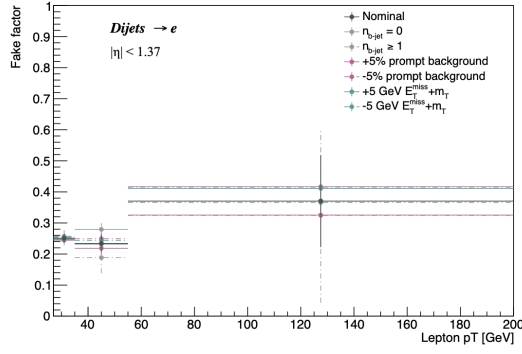
11.5 Systematic Uncertainties

11.5.1 $E_T^{\text{miss}} + m_T$ variation

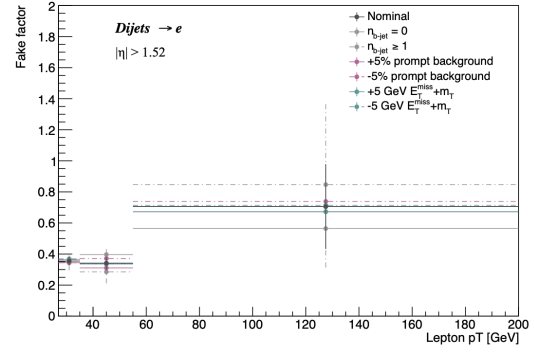
For the determination of fake factors, the contamination from W +jets is suppressed by applying a definite selection on $E_T^{\text{miss}} + m_T$. The jets underlying the fake leptons affect the calculation of E_T^{miss} , and to account for the impact on fake factors due to the selection applied on $E_T^{\text{miss}} + m_T$, the $E_T^{\text{miss}} + m_T$ selection is varied by 5 GeV and fake factors are re-estimated. As the signal region of the analysis rejects events with b -jets, the varied fake factors are determined from the light-flavor di-jet region. The differences in the obtained varied fake factors and fake factors extracted previously from the di-jet light-flavor region are systematically applied to the nominal fake factors preserving the value of the absolute variation, which are treated as the systematic uncertainties due to the selection variation on $E_T^{\text{miss}} + m_T$.

11.5.2 Prompt background subtraction

In the derivation of fake factors, prompt lepton contamination is subtracted using simulations. A dedicated control region has been defined to check the modeling of W +jets, the largest prompt lepton source, and corrections have been applied to the simulated prompt sources to agree with data as described in Section 11.4.2. However, in the lepton p_T distribution, a residual difference of 5% is observed between data and simulations according to Figure 11.20. To estimate the systematic uncertainty on the fake factors measured as a result of the modeling uncertainties, the total prompt lepton contribution subtracted while extracting fake factors is increased or decreased by 5%, and fake factors are re-estimated in the light-flavor di-jet region. The difference in the obtained varied fake factors and the fake factors estimated from the di-jet light-flavor region are systematically applied to the nominal fake factors preserving the value of the absolute variation. The differences between the nominal and the varied fake factors are then taken as the systematic uncertainties due to the modeling uncertainty of the prompt lepton sources.



(a)



(b)

Figure 11.21: The systematic uncertainties on electron fake factors are plotted in $|\eta| < 1.37$ (left) and $|\eta| > 1.52$ (right).

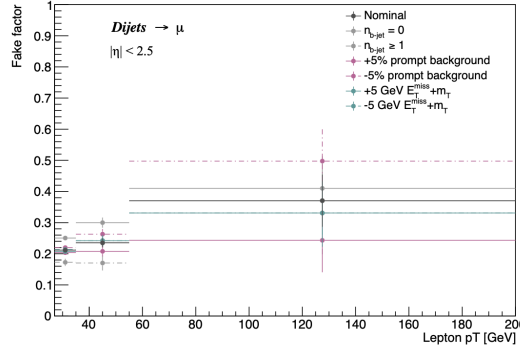


Figure 11.22: The systematic uncertainties on muon fake factors are plotted in $|\eta| < 2.5$.

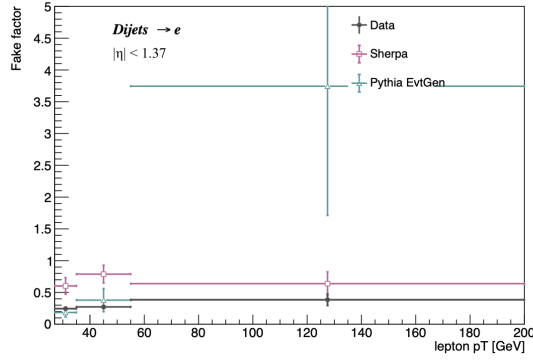
11.5.3 Sample composition difference

The di-jet region where the fake factors are estimated from has to have the same composition as the region where the fake factors are applied to, i.e., the signal region. As the nominal fake factors are computed as the average of the fake factors estimated from $n_{b-jet} = 0$ and $n_{b-jet} \geq 1$ events, the fake factors from $n_{b-jet} = 0$ and $n_{b-jet} \geq 1$ are taken as the systematic uncertainty due to the difference in the sample composition. The two sets of fake factors correspond to the extreme cases of the composition difference, and additional studies performed on the choice of $n_{b-jet} \geq 1$ events are given in Appendix C.2.

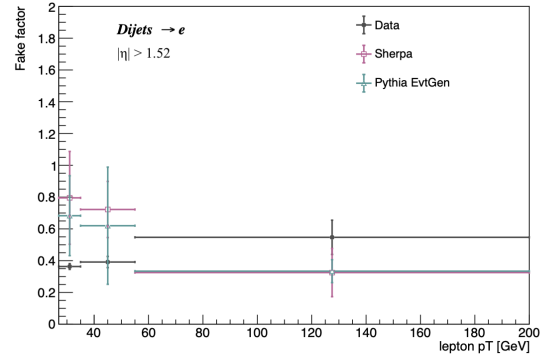
11.5.4 Statistical uncertainty

In addition to the uncertainties considered above, systematic uncertainties also occur due to the limited statistics in the di-jet region, which appear as the statistical uncertainties on the fake factors. Fake factors are varied according to their statistical uncertainties, and the differences with respect to the nominal fake factors are taken as the systematic uncertainties due to the statistical uncertainties on the fake factors.

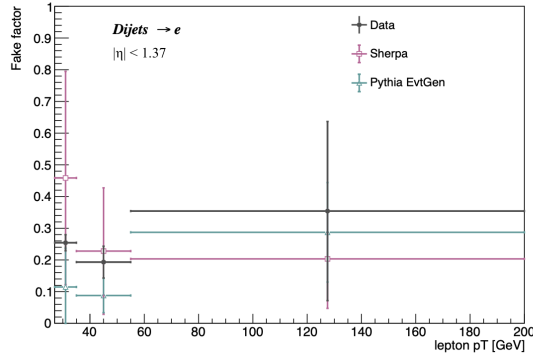
Finally, the fake factors determined for all the systematic variations considered above are shown in Figure 11.21 for electrons and in Figure 11.22 for muons.



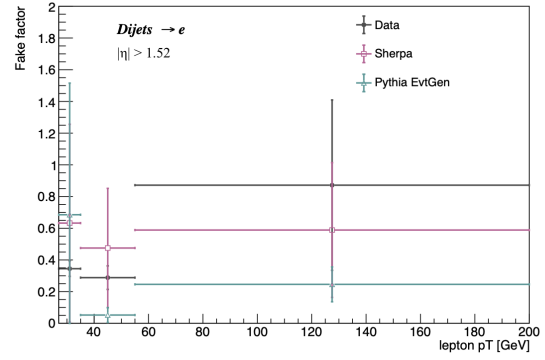
(a)



(b)

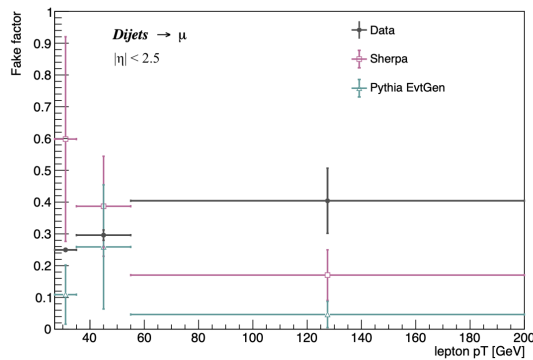


(c)

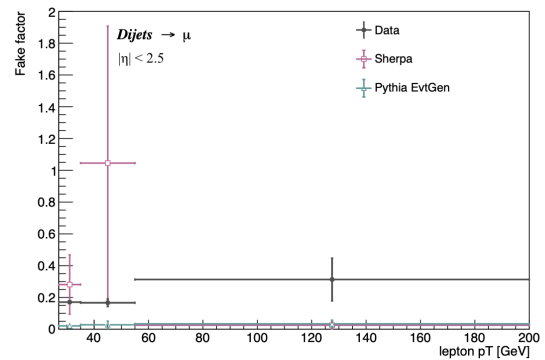


(d)

Figure 11.23: The fake factors estimated from di-jet samples simulated by SHERPA and EVT-GEN+PYTHIA are compared with the fake factors derived from data. The results are given for the electron channel in the light-flavor (top) and heavy-flavor (bottom) di-jet regions. Only statistical uncertainties are shown.



(a)



(b)

Figure 11.24: The fake factors estimated from di-jet samples simulated by SHERPA and EVT-GEN+PYTHIA are compared with the fake factors derived from data. The results are given for the muon channel in the light-flavor (left) and heavy-flavor (right) di-jet regions. Only statistical uncertainties are shown.

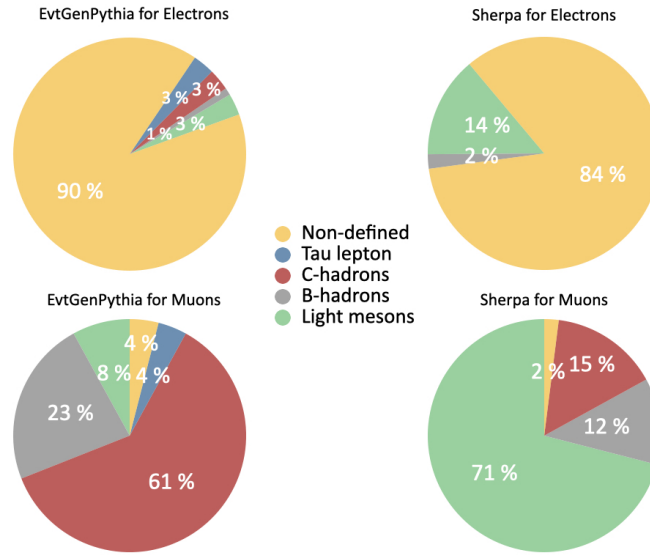


Figure 11.25: A pie-chart representation of the predicted origin composition of the fake lepton in the light-flavor di-jet region using the MCTruthClassifier.

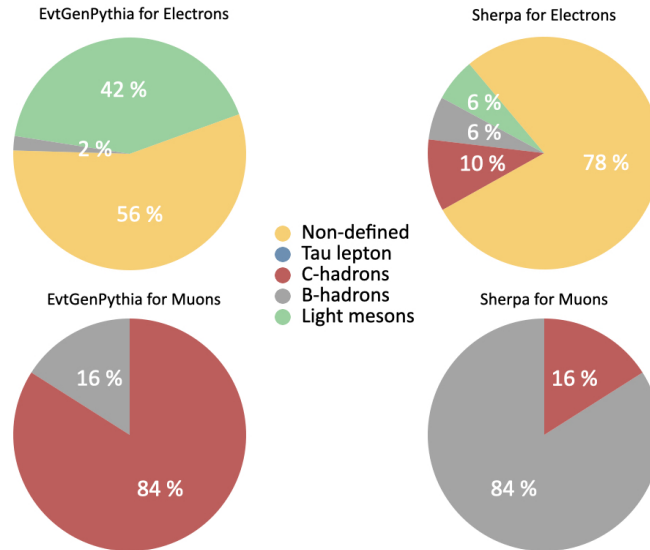


Figure 11.26: A pie-chart representation of the predicted origin composition of the fake lepton in the heavy-flavor di-jet region using the MCTruthClassifier.

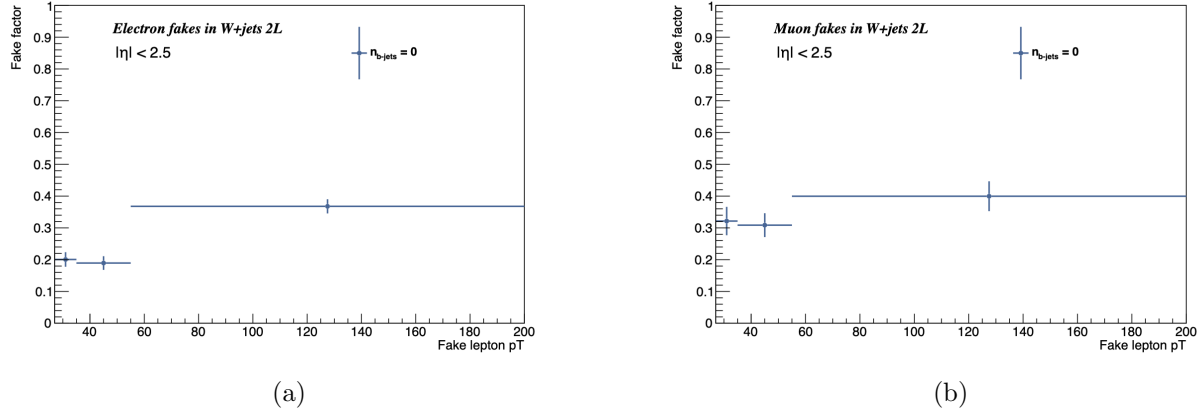


Figure 11.27: Fake factors estimated from di-lepton W +jets sample are plotted for electrons (left) and muons (right).

11.6 MC-Driven Cross-Check

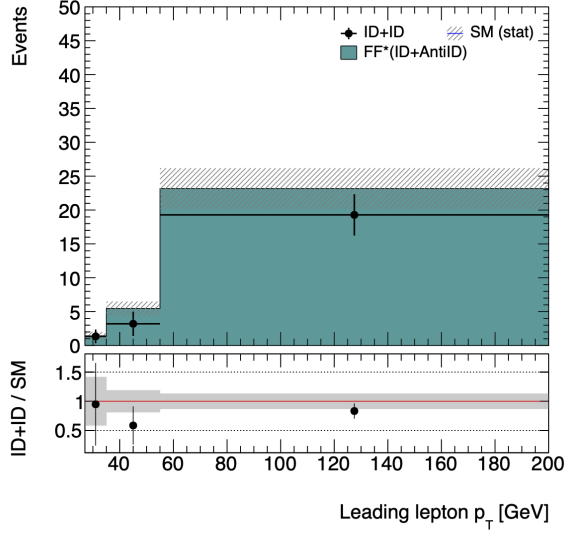
To cross-check the agreement of the data-driven fake factor estimate with simulations, fake factors have also been derived from dedicated di-jet MC samples following the event selection in Table 11.1. Samples from SHERPA and EVTGEN+PYTHIA are considered, and the fake factors derived are compared with that from data in Figures 11.23-11.24 for electrons and muons. In the low p_T bins, where the fake background is the largest in the signal region, the fake factors from data tend to lie between the two predicted fake factors. Although the data-driven estimates are not expected to align with the predicted results, the results are found to be of the same order overall. The two simulated samples vary in their predictions due to the different composition of the origin of the fake leptons. The sample composition of the two MC samples considered as estimated by the MCTruthClassifier are given in Figures 11.25-11.26.

11.7 MC-Driven Closure Test

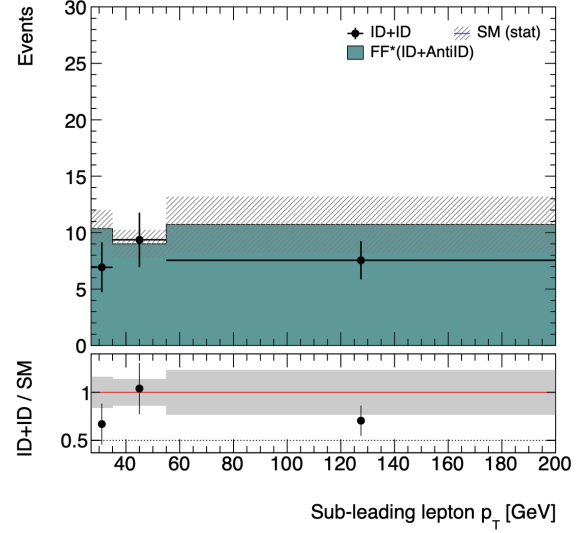
Before applying the fake factors in the di-lepton nominal analysis, the closure of the fake factor method is tested in the corresponding di-lepton events using a simulation based non-prompt background estimate. For this MC-driven closure test, a W +jets sample simulated with MADGRAPH+PYTHIA8 is used. The event must pass the two lepton selection in Table 9.4 but is required to have only one lepton at the truth level. The same-sign selection on the lepton charge is not applied to preserve statistics. Finally, only events without any b -jets similar to the signal region selection are considered.

Events surviving the selection are separated as: 1) ID and ID leptons 2) ID and Anti-ID leptons, and one ID lepton in each event is required to have its origin from a W boson. Fake factor is then determined as the ratio of the number of ID and ID lepton events to the number of ID and Anti-ID lepton events as a function of the lepton p_T , and the results are plotted in Figure 11.27a for electron fakes and 11.27b for muon fakes.

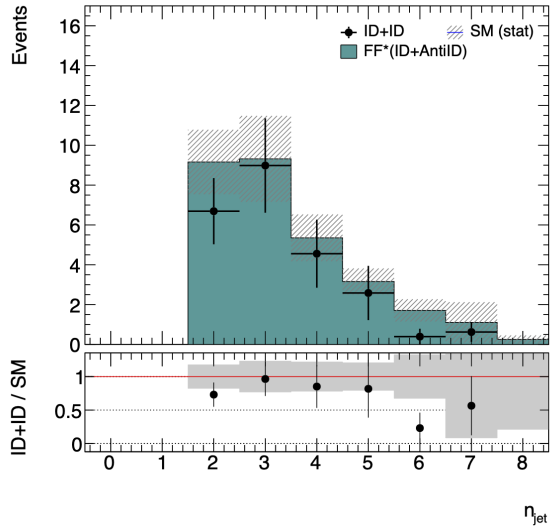
The fake factors derived are applied to the ID and Anti-ID lepton events in the signal region, and the agreement of the MC-driven fake estimate with the ID and ID lepton events is then checked. The signal region distributions for leading and sub-leading lepton p_T , jet multiplicity, and m_{jj} are given in Figures 11.28a -11.28d, and overall a fairly good closure is observed.



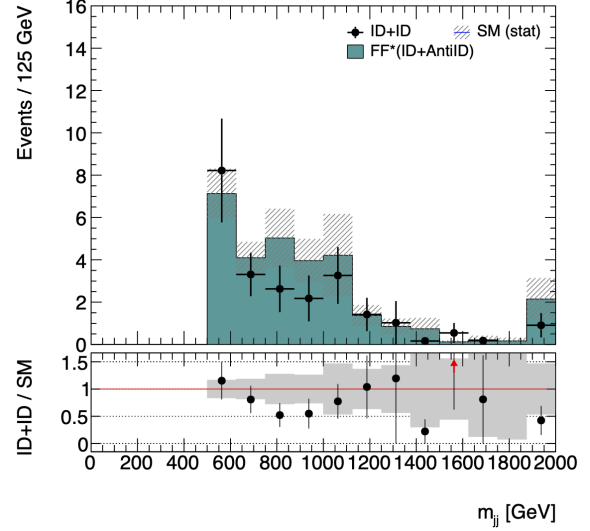
(a)



(b)



(c)



(d)

Figure 11.28: The non-prompt lepton background estimated from di-lepton W +jets in the MC-driven closure test is given for the signal region. The figure shows the leading lepton p_T in (a), sub-leading lepton p_T in (b), jet multiplicity in (c), and m_{jj} distribution in (d). Only statistical uncertainties are shown. The black lines denote the distribution of the events with two ID leptons whereas the green color denote the fake background estimated.

11.8 Fake Lepton Background Estimation

To estimate the non-prompt lepton background, events with an ID lepton and an Anti-ID lepton having the same-sign are selected from data, and the contribution from same-sign prompt lepton sources in the analysis are subtracted using MC expectations as per Equation (11.10). From the previous chapter, it is clear that the charge misidentification rate is not negligible in ID leptons. Anti-ID leptons are no exemption to the incorrect charge identification, and the ID and Anti-ID events can additionally be contaminated by the charge misidentified prompt leptons. Therefore, the charge misidentification probabilities for the Anti-ID leptons are computed similar to the ID leptons, and the contamination from opposite-sign leptons passing same-sign ID and Anti-ID lepton selections due to incorrect charge is further subtracted. The residual two-lepton ID and Anti-ID events weighted by the fake factors constitute the non-prompt lepton background in the analysis. The expression for the computation of the background is given in Equation (11.13) for the $e\mu$ channel as an example.

$$N_{\text{non-prompt}(\text{data})}^{\text{ID}(e)+\text{ID}(\mu)} = F_e \cdot \left(N_{\text{all}(\text{data})}^{\text{ID}(\mu)+\text{Anti-ID}(e)} - N_{\text{prompt}(\text{MC})}^{\text{ID}(\mu)+\text{Anti-ID}(e)} - N_{\text{chFlip}(\text{data})}^{\text{ID}(\mu)+\text{Anti-ID}(e)} \right) + F_\mu \cdot \left(N_{\text{all}(\text{data})}^{\text{ID}(e)+\text{Anti-ID}(\mu)} - N_{\text{prompt}(\text{MC})}^{\text{ID}(e)+\text{Anti-ID}(\mu)} - N_{\text{chFlip}(\text{data})}^{\text{ID}(e)+\text{Anti-ID}(\mu)} \right). \quad (11.13)$$

The estimated background is validated in two different regions before computing the yields in the signal region. But the triggers used to select the di-lepton events are different from the triggers used to select the single lepton events from which fake factors are estimated, thereby introducing a bias which needs to be corrected beforehand. The correction of the observed trigger bias is discussed next.

Region	Triggered only by	ee	$e\mu + \mu e$	$\mu\mu$	ll
One b -jet	Anti-ID lepton	-	6.5%	14%	8.6%
	Anti-ID electron	-	3.5%	-	1.9%
	Anti-ID muon	-	3.0%	14%	6.7%
Low m_{jj}	Anti-ID lepton	4%	6.5%	18%	10%
	Anti-ID electron	4%	3.8%	-	2.6%
	Anti-ID muon	-	2.7%	18%	7.4%
Signal	Anti-ID lepton	-	5.4%	9.4%	6%
	Anti-ID electron	-	3.1%	-	1.5%
	Anti-ID muon	-	2.3%	9.4%	4.5%

Table 11.3: Yields of ID and Anti-ID events in data triggered only by the Anti-ID lepton. The contributions are given for One b -jet validation region, Low m_{jj} validation region, and signal region.

11.8.1 Trigger bias correction

According to the event selection criteria described in Chapter 9, among the two leptons, at least one of them is required to fire the trigger. In the case of ID and Anti-ID di-lepton events, the trigger can be fired by either of the two leptons. If the trigger is fired only by the Anti-ID lepton, a bias is introduced due to the different choice of the triggers in the one-lepton and two-lepton events.

The prescaled triggers used to define the di-jet region have relaxed definitions of isolation and identification compared to the Anti-ID lepton selection. However, the definitions of the analysis triggers, given in Table 9.1, are tighter than the Anti-ID requirements. The Tight identification in HLT_e26_lhtight_nod0_ivarloose definition being tighter than the Medium identification requirement of Anti-ID electron is one such example. As a result, the HLT definition itself acts as an additional selection on the Anti-ID leptons when the lepton firing the trigger is solely the Anti-ID lepton. Clearly speaking, a lepton passing Anti-ID requirements is used for the fake factor determination in the one-lepton events but a similar lepton passing the same selections can be rejected in the di-lepton events at the HLT stage itself, resulting in an underestimation of fake lepton background. Therefore, fake factors in Figures 11.21-11.22 cannot be applied in such events as the Anti-ID lepton passes additional selections. To correct the bias introduced by the HLT, fake factors are re-estimated with the nominal analysis triggers in the exact same way as the prescaled triggers and applied to events triggered only by the Anti-ID leptons while estimating the fake background. The electron and muon fake factors estimated along with the associated systematic uncertainties using the analysis triggers are given in Figures 11.29-11.32, and Table 11.3 gives the fraction of ID and Anti-ID events in data triggered only by the Anti-ID leptons in the signal and the validation regions where these fake factors are utilized.

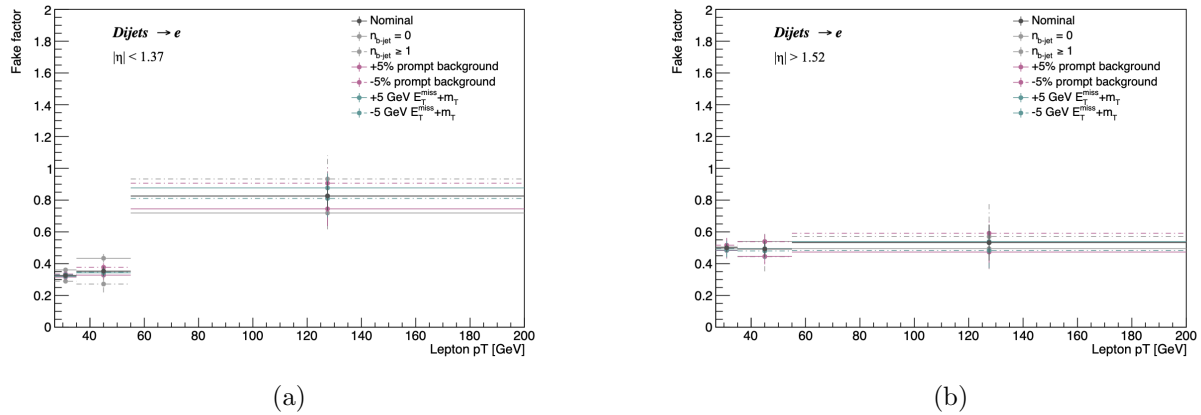


Figure 11.29: Electron fake factors estimated using the 2015 analysis triggers along with the systematic uncertainties are plotted in $|\eta| < 1.37$ (left) and $|\eta| > 1.52$ (right).

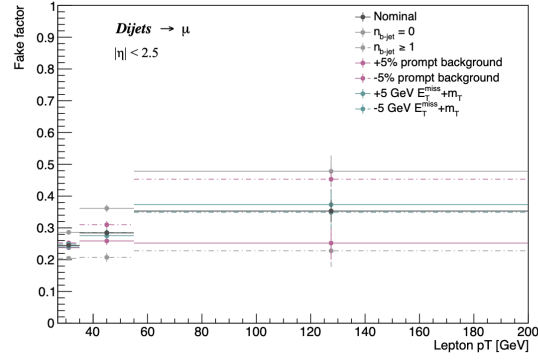
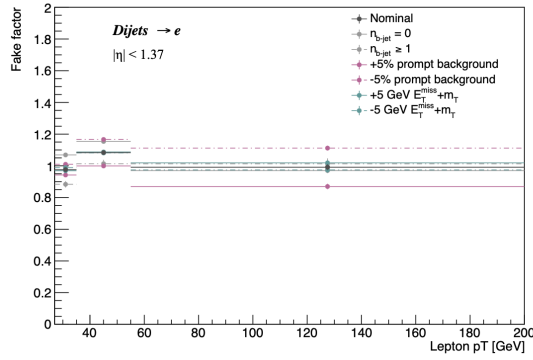
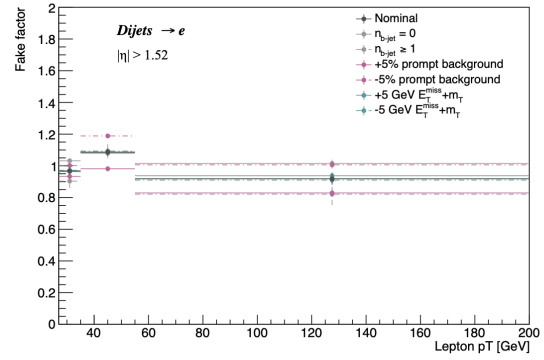


Figure 11.30: Muon fake factors estimated using the 2015 analysis triggers along with the systematic uncertainties are plotted in $|\eta| < 2.5$.



(a)



(b)

Figure 11.31: Electron fake factors estimated using the 2016-2018 analysis triggers along with the systematic uncertainties are plotted in $|\eta| < 1.37$ (left) and $|\eta| > 1.52$ (right).

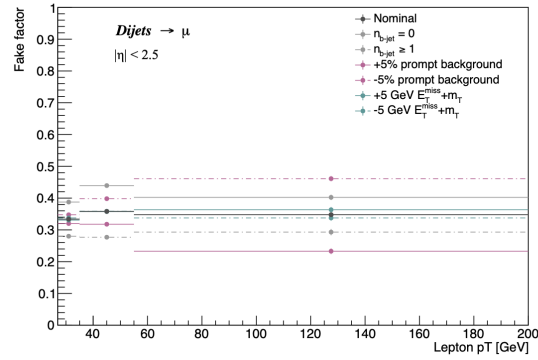
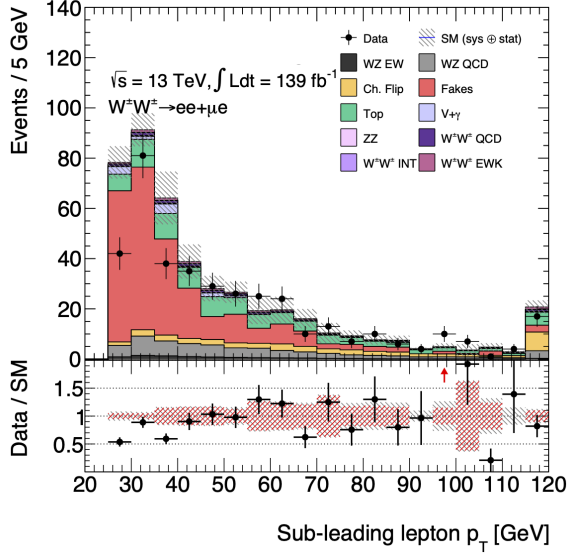
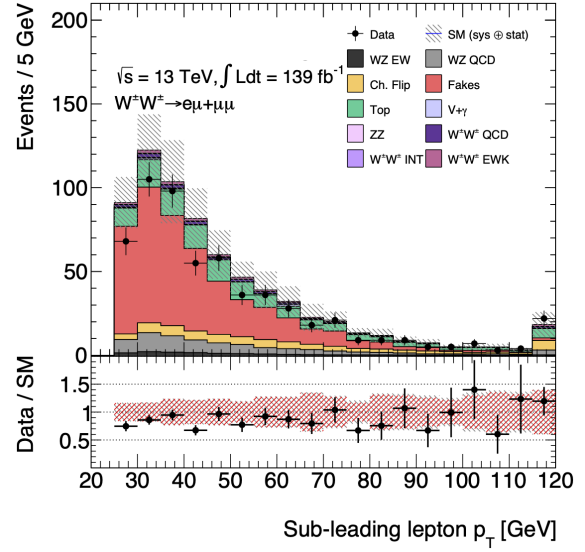


Figure 11.32: Muon fake factors estimated using the 2016-2018 analysis triggers along with the systematic uncertainties are plotted in $|\eta| < 2.5$.

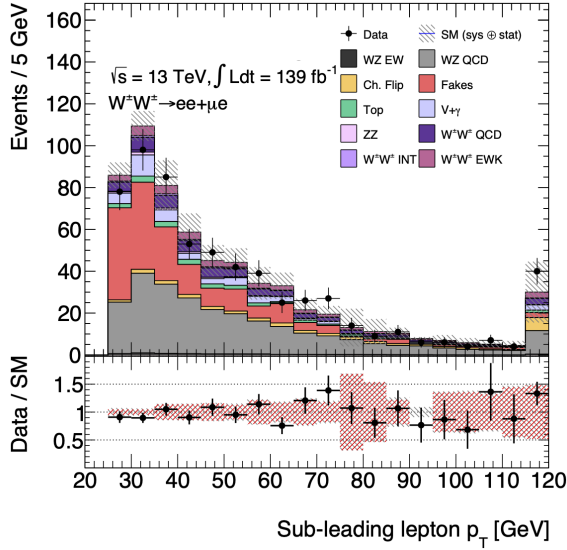


(a)

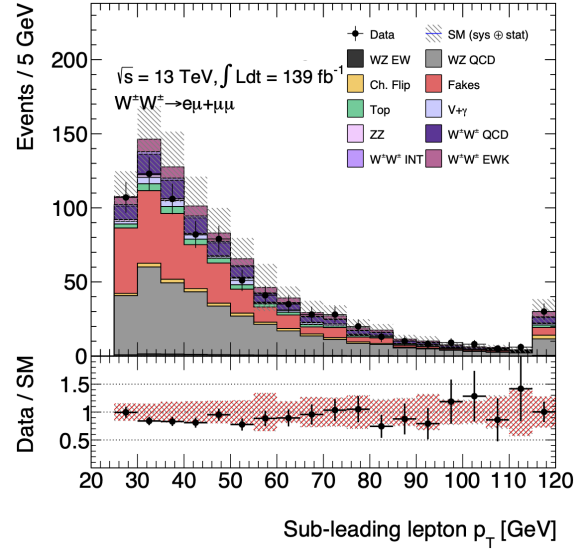


(b)

Figure 11.33: The p_T distributions in the One b -jet validation region are shown for the sub-leading electron (left) and the sub-leading muon (right). The red band denotes the systematic uncertainties and the gray band indicates the combined systematic and statistical uncertainties on the backgrounds.



(a)



(b)

Figure 11.34: The p_T distributions in the Low m_{jj} validation region are shown for the sub-leading electron (left) and the sub-leading muon (right). The red band denotes the systematic uncertainties and the gray band indicates the combined systematic and statistical uncertainties on the backgrounds.

11.8.2 Validation Region Yields

The fake lepton background estimated according to Equation (11.13) is validated in the One b -jet and Low m_{jj} regions defined in Table 9.5. The p_T distributions of the sub-leading lepton (usually the fake lepton) are given in Figures 11.33 and 11.34 for the two validation regions. The estimated backgrounds agree with data in the overall distribution within the uncertainties. Though the purity of the fake lepton background is high in the One b -jet validation region, the composition of the fake lepton source in the Low m_{jj} validation region is seen to be similar to that of the signal region according to MC predictions.

11.8.3 Signal Region Yields

Having observed a fairly good agreement between data and backgrounds in the validation regions, the non-prompt lepton background is estimated in the signal region and the yields are tabulated in Table 11.4 along with the statistical uncertainties. The statistical uncertainties correspond to the uncertainty resulting from the limited statistics in the ID and Anti-ID di-lepton events. The systematic uncertainties on the fake background are computed according to the prescription discussed already in Section 11.5. The uncertainties are uncorrelated and are added in quadrature to obtain the total systematic uncertainties in the ee , $e\mu$, μe , and $\mu\mu$ channels. Except for the statistical uncertainties (including the systematic uncertainties due to the statistical uncertainty on the fake factors), the uncertainties are treated correlated when combining channels into $ee + \mu e$, $e\mu + \mu\mu$, and $ee + \mu e + e\mu + \mu\mu$. The event yields including the total uncertainties are recorded in Table 11.5, and the breakdown of the largest uncertainties on the total yields are given in Table 11.6. The largest systematic uncertainties originate from the muon fake factors due to the sample composition difference and uncertainty in the prompt lepton modeling.

The non-prompt lepton background is the second largest background estimated with a statistical uncertainty of 9% and systematic uncertainty of 20%, amounting to a total uncertainty of 22% when added in quadrature. Compared to the previous iteration of the analysis, the total systematic uncertainty on the estimated background is reduced by 55%, which is one of the largest improvements in the analysis.

Sample	ee	$e\mu$	μe	$\mu\mu$	ll
Data	11.83 ± 1.87	23.30 ± 3.14	18.38 ± 2.60	26.73 ± 2.81	80.25 ± 5.29
$W^\pm W^\pm jj$	1.42 ± 0.03	3.85 ± 0.05	3.93 ± 0.05	3.52 ± 0.04	12.72 ± 0.09
$WZjj$	0.61 ± 0.04	2.26 ± 0.10	2.12 ± 0.11	1.84 ± 0.07	6.83 ± 0.17
$V\gamma jj$	0.26 ± 0.11	0.91 ± 0.32	1.60 ± 0.94	—	2.78 ± 1.00
Charge-flip	0.61 ± 0.03	0.78 ± 0.12	0.28 ± 0.03	—	1.68 ± 0.13
Top	0.06 ± 0.02	0.15 ± 0.03	0.09 ± 0.02	0.10 ± 0.02	0.40 ± 0.05
ZZ	0.02 ± 0.00	0.09 ± 0.01	0.09 ± 0.01	0.04 ± 0.01	0.25 ± 0.02
Tri-boson	0.00 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.00	0.03 ± 0.00
Non-prompt	8.84 ± 1.87	15.20 ± 3.16	10.23 ± 2.77	21.21 ± 2.81	55.49 ± 5.39

Table 11.4: Yields of the compositions of ID and Anti-ID events. Non-prompt events calculated are the data events after subtracting the prompt and the charge-flip contributions. Only statistical uncertainties are shown.

Lepton channel	Total event yields in the channel ($\pm$ stat. $\pm$ syst.)	% of nominal yields to ll	% of stat. uncert. to channel yields	% of syst. uncert. to channel yields
ee	$8.8 \pm 1.9 \pm 2.3$	16%	22%	26%
$e\mu$	$15.2 \pm 3.2 \pm 2.8$	28%	21%	18%
μe	$10.2 \pm 2.8 \pm 1.7$	19%	27%	17%
$\mu\mu$	$21 \pm 3 \pm 7$	38%	14%	32%
$ee + \mu e$	$19.1 \pm 3.3 \pm 3.3$	34%	18%	17%
$e\mu + \mu\mu$	$36 \pm 4 \pm 9$	66%	11%	24%
ll	$55 \pm 5 \pm 11$	—	9%	20%

Table 11.5: Yields of the non-prompt lepton background in the signal region including the total uncertainties are given.

Systematic Uncertainty	%
Muon Sample Composition	10.8%
Muon Prompt Modeling	10.5%
Muon Statistical Uncertainty	6.7%
Electron Statistical Uncertainty	5.5%
Electron Prompt Modeling	3.0%
Electron Sample Composition	2.3%
Muon $E_T^{\text{miss}} + m_T$ Variation	1.3%
Electron $E_T^{\text{miss}} + m_T$ Variation	0.5%

Table 11.6: Breakdown of the systematic uncertainties of the non-prompt lepton background in the $ee + \mu e + e\mu + \mu\mu$ channels is given.

Chapter 12

Signal Extraction

This chapter details the methodologies implemented in this analysis to extract the signal process. In Chapters 10 and 11, the measurement techniques of the major backgrounds are discussed but the background determination is only deemed complete when the uncertainties are estimated. In Section 12.1, an overview of all the uncertainties considered in this measurement is presented. This is followed by a summary of the expected yields in the signal region in Section 12.2, and the strategies adopted for the statistical inference of the measured signal in Section 12.3. Finally, Section 12.4 gives a brief description of how experimental observations are compared with theoretical predictions. The results presented in this chapter are the work of the author.

12.1 Uncertainties

One may have noticed in Chapter 7 that the total number of signal events is the background subtracted data events. As the backgrounds are determined with a certain degree of inaccuracy, the uncertainties on the estimated backgrounds translate as the uncertainties on the measured signal events. This section details the statistical and the systematic uncertainties involved in the estimation of the total number of signal events. Unless stated explicitly, all the uncertainties considered are two-sided, corresponding to a positive variation known as *up* and a negative variation known as *down* around the nominal values.

12.1.1 Statistical Uncertainties

The statistical uncertainty quantifies the uncertainty stemming from the finite size of the samples used in the measurement. Due to the probabilistic nature of events, the events observed vary from measurement to measurement, and statistical uncertainty is a measure of the range of that variation. The uncertainties taken are the Poisson errors on the data and simulated event counts. As the events observed in a measurement do not depend on the events observed in an identical measurement of the same process, statistical uncertainties are uncorrelated.

12.1.2 Systematic Uncertainties

The systematic uncertainties arise as a result of the limitations in our understanding, which includes uncertainties associated with the experimental apparatus, assumptions made, theoretical model, etc. The effect is systematic and does not vary randomly from data point to data point. The systematic uncertainties can be classified as experimental and theoretical uncertainties. Experimental uncertainties reflect how well we understand a measurement whereas theoretical uncertainty ties

to our understanding of the underlying theoretical model being tested. Depending on the source, the uncertainties can be correlated or uncorrelated with each other.

Experimental Systematic Uncertainties due to Detector Effects

All the MC-based predictions are subjected to inherent systematic uncertainties that assess the degree to which MC can model event properties and object selections with respect to data. The uncertainties are provided by the ATLAS performance groups and the precision achieved is after understanding the detector for over a decade. The computations involve numerous components taking into account the various correlations and the final uncertainties provided by the performance groups are categorized into sources, which can be treated as uncorrelated in the analysis. The individual sources of the uncertainties are tabulated in Appendix D, which fall into the following broad categories:

- **Leptons:** Uncertainties associated with electrons and muons include several sources which are estimated and treated separately for the two lepton types as the detectors and algorithms involved are different. The lepton uncertainty sources consider the uncertainties in efficiency measurements of single lepton triggers and lepton reconstruction. Muons are subjected to an additional uncertainty in track-to-vertex association. Uncertainties on lepton identification and isolation are included, which parametrize the uncertainties in the efficiencies of the chosen working points for identification and isolation. Apart from the uncertainties in lepton efficiencies, the scale and resolution uncertainty of electron energy and muon momentum are also reckoned. However, the overall impact of the lepton uncertainties in the analysis is minimal.
- **Jets:** Uncertainties affecting jets originate mainly from Jet Energy Scale (JES) and Jet Energy Resolution (JER) uncertainties associated with jet energy calibration described in Chapter 6. The uncertainty in JES describes the accuracy to which the jet p_T is understood, which depends on pile-up, jet flavor composition, jet η inter-calibration, etc., and is one of the largest sources of systematic uncertainty in the analysis. The uncertainty is roughly 4% for jet with p_T of 30 GeV and decreases to 1% at 200 GeV [107]. As the modeling of the jet energy resolution can be quite optimistic in simulations, the resolution in MC is smeared to match the resolution in data. JER uncertainty accounts for the uncertainty in jet energy resolution associated with this smearing procedure. In addition, uncertainty associated with the efficiency of the JVT working point (see Chapter 9) chosen for jets is considered, affecting the analysis only minimally.

Furthermore, although b -jets are vetoed in the analysis, uncertainties still arise due to b -tagging. As the efficiency of b -jet veto can be different between data and MC, scale factors are applied on MC backgrounds to match the tagging efficiency in data. The efficiencies are different for b -, c -, and light-jets, and uncertainties on the efficiencies assess the accuracy of b -jet veto.

- **E_T^{miss} :** As the uncertainties on all the physics objects are propagated in the calculation of E_T^{miss} , only the uncertainty associated with the unused tracks (soft term) are considered as the uncertainty related to E_T^{miss} , which includes both one-sided and two-sided variations.
- **Pile-up re-weighting:** In order to correctly model the pile-up profile in data, the MC events are re-weighted to match the observed profile in data, and the uncertainty associated with the re-weighting procedure is considered.

Experimental Systematic Uncertainties due to Background Estimation

In addition to the above sources, experimental uncertainties can also stem from background estimation techniques such as,

- **m_{jj} re-weighting:** The systematic uncertainties due to the m_{jj} shape re-weighting in $WZjj$ -QCD events are discussed already in Chapter 10 and are applied to all the $WZjj$ -QCD events in addition to the above experimental uncertainties.
- **Fake factors:** The uncertainties associated with fake factor determination are explained in Chapter 11 and are applied to all the fake lepton background events.
- **Charge misidentification probability:** The uncertainty on charge misidentified lepton background comes from the uncertainty on the scale factors used to correct the simulated $Z(\rightarrow ee)$ +jets events to emulate the charge misidentification probabilities in data (see Chapter 10 for details).

The uncertainty sources are independent from one another, and the largest uncertainties due to background estimation methods emerge from m_{jj} re-weighting and fake factors.

Theoretical Uncertainties

Simulations are used to model many backgrounds in this analysis and also the signal which is used in the fitting procedure, explained later in this chapter. Therefore, it becomes necessary to parametrize the extent to which we understand the underlying model before extracting the VBS cross-section. As $W^\pm W^\pm jj$ and $WZjj$ make up nearly 80% of the total expected event yields in the signal region, the theoretical uncertainties are applied only on their predictions unless stated otherwise, and the sources considered are listed below.

- **PDF and α_s :** The uncertainty due to the nominal choice of PDF and α_s is estimated following the prescription for NNPDF3.0nlo [133], which is the PDF set used in the matrix element calculation. The PDF set consists of 100 PDF variations from which the internal PDF uncertainty is estimated as the standard deviation of the variations. In addition, the difference in the nominal predictions between NNPDF3.0nlo and two alternative PDF sets, namely CT14 and MMHT2014, are considered. The total PDF uncertainty is then computed as the absolute envelope of the internal PDF uncertainty and the differences between the nominal and the alternative PDF sets as:

$$\Delta\sigma_{\text{PDF}} = \max(\Delta\sigma_{\text{internal}}, \Delta\sigma_{\text{CT14}}, \Delta\sigma_{\text{MMHT2014}}). \quad (12.1)$$

The uncertainty due to the choice of the strong coupling is evaluated using the nominal PDF but varying α_s by ± 0.001 to 0.117 and 0.119. The α_s uncertainty is then computed as the average of the absolute differences of the variations as

$$\Delta\sigma_{\alpha_s} = \frac{|\Delta\sigma_{\alpha_s+0.001}| + |\Delta\sigma_{\alpha_s-0.001}|}{2}. \quad (12.2)$$

Finally, the PDF uncertainty and the α_s uncertainty are added in quadrature to obtain the uncertainty on the nominal NNPDF3.0nlo PDF:

$$\Delta\sigma_{\text{NNPDF3.0nlo}} = \sqrt{(\Delta\sigma_{\text{PDF}})^2 + (\Delta\sigma_{\alpha_s})^2}. \quad (12.3)$$

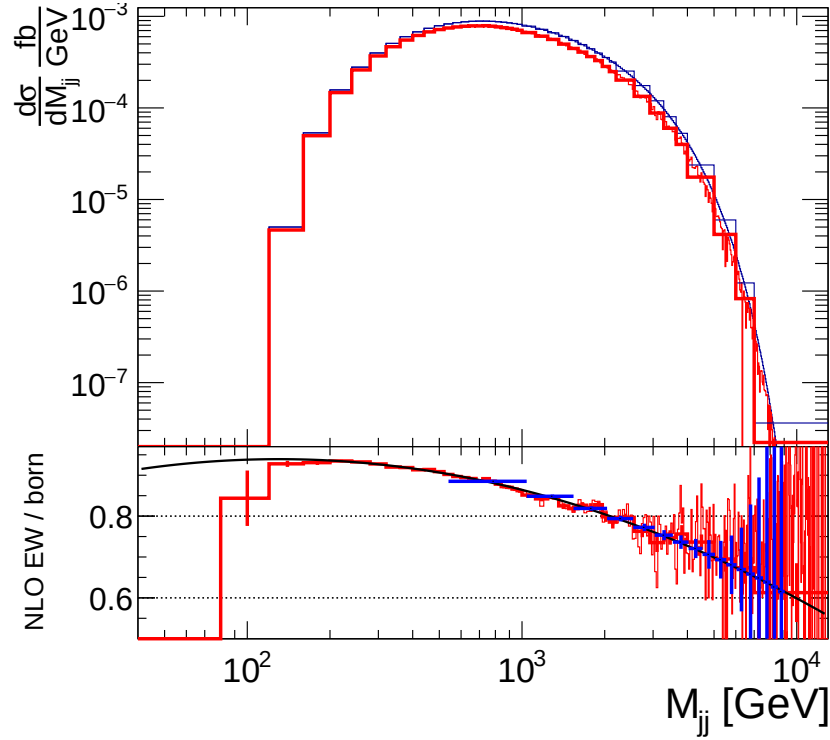


Figure 12.1: Differential cross-sections of $W^\pm W^\pm jj$ -EWK production as a function of m_{jj} at LO (or Born level) (in blue) and with NLO electroweak corrections included (in red), as provided by the authors of [81] are shown in the upper panel. In the lower panel, ratio of the NLO electroweak to Born cross-sections (in red), fit result of the ratio (in black), and ratio of the re-weighted model to the non-re-weighted nominal LO predictions (in blue) are given.

- **Scale:** The nominal signal sample used in the analysis neglects higher order QCD corrections (refer to Chapter 8 for sample details). The variations of the renormalization and the factorization scales are used to estimate the uncertainty due to missing higher order corrections of the perturbative expansion of the partonic cross-section. A 7-point scale variation method is used to access the scale uncertainty by varying μ_F and μ_R pair-wise but independently by -50% and +100% excluding maximal variations in opposite directions. The combinations of the scale variations considered in this approach are $(0.5 \times \mu_R, 0.5 \times \mu_F)$, $(1.0 \times \mu_R, 0.5 \times \mu_F)$, $(0.5 \times \mu_R, 1.0 \times \mu_F)$, $(2.0 \times \mu_R, 1.0 \times \mu_F)$, $(1.0 \times \mu_R, 2.0 \times \mu_F)$, and $(2.0 \times \mu_R, 2.0 \times \mu_F)$. Together with the nominal setting $(1.0 \times \mu_R, 1.0 \times \mu_F)$, there are altogether seven predictions, and the total uncertainty considered is the envelope of all the variations taken as

$$\Delta\sigma_{\text{scale}} = \max[(\mu_R, \mu_F)_i - (\mu_R, \mu_F)_0], \quad (12.4)$$

where 0 denotes the nominal setting and i is the variation following one of the other six combinations.

- **Shower:** To estimate the uncertainty associated with the chosen parton shower model, signal predictions are obtained with an alternative PYTHIA8 parton shower, and the difference between the two shower predictions is symmetrized and taken as a two-sided uncertainty.
- **NLO electroweak corrections:** The nominal signal sample used in the analysis neglects higher order electroweak corrections (refer to Chapter 8 for sample details). The NLO electroweak corrections of $\mathcal{O}(\alpha^7)$ are provided by the theoretical community [81] in the form of differential cross-sections of the electroweak induced $W^\pm W^\pm jj$ production as a function of m_{jj} . The ratio of the cross-sections (with and without the NLO electroweak corrections) is fitted with a function of the form $f(m_{jj}) = p_0 + p_1 \ln \frac{m_{jj}}{\text{GeV}} + p_2 \ln^2 \frac{m_{jj}}{\text{GeV}}$, where $p_0 = 0.511$, $p_1 = 0.176$, and $p_2 = -0.0181$ are parameter values extracted from the fit. The signal sample is re-weighted to the functional fit and the re-weighted model with effectively NLO electroweak corrections included is used as a systematic variation on the electroweak $W^\pm W^\pm jj$ signal. Figure 12.1 presents the distributions showing the cross-sections at LO and the cross-sections with the NLO electroweak corrections in the upper panel. In the lower panel, the ratio of the cross-sections are shown along with the fit result.
- **Background cross-sections:** Ideally, the theoretical uncertainties applied to $W^\pm W^\pm jj$ and $WZjj$ are also required to be applied on other MC modeled processes. As the computing resources required to generate these samples with sufficient statistics are restrained, a flat uncertainty on the cross-section is applied. A cross-section uncertainty of 20% is applied to $ZZjj$, 30% to both top and tri-boson processes. The values are conservative choices and are based on the previous iteration of the analysis. Furthermore, a cross-section uncertainty of 40% is applied on $V\gamma jj$ processes driven by the scale factor uncertainty of electron charge identification for wrongly identified charges (see Chapter 10).

A summary of the experimental and the theoretical systematic uncertainties applied on the various processes in the analysis is given in Table 12.1.

Process	Experimental Uncertainty	Theoretical Uncertainty
$W^\pm W^\pm jj$ -EWK	Detector effects due to leptons Detector effects due to jets Detector effects due to E_T^{miss} Pile-up re-weighting	PDF and α_s Scale Shower NLO electroweak corrections
$W^\pm W^\pm jj$ -QCD,INT	Detector effects due to leptons Detector effects due to jets Detector effects due to E_T^{miss} Pile-up re-weighting	PDF and α_s Scale Shower
$WZjj$	Detector effects due to leptons Detector effects due to jets Detector effects due to E_T^{miss} Pile-up re-weighting m_{jj} re-weighting	PDF and α_s Scale
Non-prompt leptons	Fake factors	
Charge-flip leptons	Charge misidentification probability	
$V\gamma jj$	Detector effects due to leptons Detector effects due to jets Detector effects due to E_T^{miss} Pile-up re-weighting	Cross-section
$ZZjj$	Detector effects due to leptons Detector effects due to jets Detector effects due to E_T^{miss} Pile-up re-weighting	Cross-section
Top	Detector effects due to leptons Detector effects due to jets Detector effects due to E_T^{miss} Pile-up re-weighting	Cross-section
Tri-boson	Detector effects due to leptons Detector effects due to jets Detector effects due to E_T^{miss} Pile-up re-weighting	Cross-section

Table 12.1: Summary of the systematic uncertainties applied on the various processes.

12.2 Expected Signal Region Yields

Taking into account all the uncertainties, the expected yields of the background processes and the signal can be computed. Table 12.2 lists the expected event yields in the signal region along with the observed data¹ for each lepton channel and all lepton channels combined. Additionally, the m_{jj} distribution of all the expected events and the observed data are plotted in Figure 12.2. The leading background is the $WZjj$ process followed by the non-prompt background and QCD induced production of $W^\pm W^\pm jj$.

Signal	ee	$e\mu$	$\mu\mu$	μe	ll
$W^\pm W^\pm jj$ -EWK	27.6 ± 1.1	68.2 ± 2.1	77.8 ± 1.9	61.3 ± 1.9	235 ± 7
Background	ee	$e\mu$	$\mu\mu$	μe	ll
$WZjj$	10.1 ± 1.0	31.8 ± 2.9	25.0 ± 2.2	30.8 ± 2.9	98 ± 9
Non-prompt	8.8 ± 2.9	15 ± 4	21 ± 7	10.2 ± 3.2	55 ± 12
$W^\pm W^\pm jj$ -QCD	1.55 ± 0.07	7.26 ± 0.24	8.82 ± 0.27	6.41 ± 0.18	24.0 ± 0.7
Conversions	5.1 ± 2.2	10.1 ± 2.5	0.003 ± 0.005	5.8 ± 2.5	21 ± 6
$W^\pm W^\pm jj$ -INT	0.93 ± 0.09	2.19 ± 0.14	2.51 ± 0.14	1.96 ± 0.11	7.6 ± 0.5
Other Prompt	1.01 ± 0.22	2.5 ± 0.5	1.7 ± 2.1	1.8 ± 0.4	7.0 ± 1.4
Total Expected	55 ± 4	137 ± 6	137 ± 8	118 ± 5	448 ± 17
Data	52	149	147	127	475

Table 12.2: Signal region (pre-fit) yields are shown along with the total uncertainties.

¹The blinding strategy is removed only later in the analysis workflow after validating the unfolding procedure. The observed (unblinded) data yields are quoted here for the sole purpose of comparison.

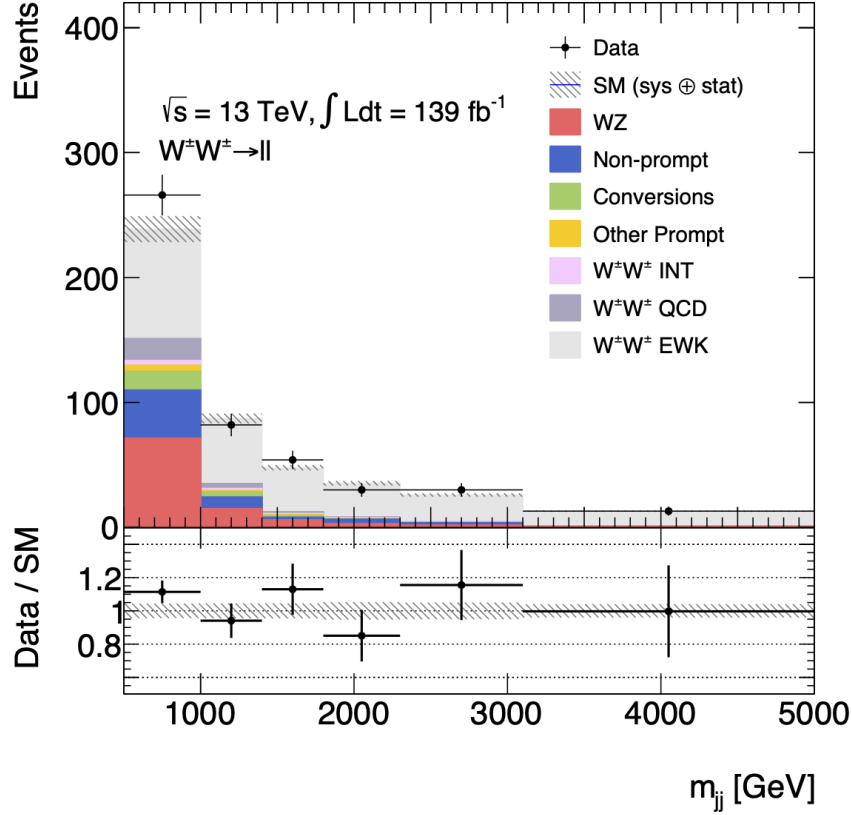


Figure 12.2: The (pre-fit) distributions of the estimated backgrounds, expected signal, and observed data are plotted as a function of m_{jj} in the signal region. The hashed band represents the statistical and experimental uncertainties on the Standard Model predictions.

12.3 Statistical Analysis

With all the signal region expectations at hand, the next step is to perform a statistical analysis to interpret the results. As famously written by Werner Heisenberg²: “*What we observe is not nature in itself, but nature exposed to our method of questioning*”, the method of questioning adopted in particle physics is hypothesis testing. In hypothesis testing, the background-only hypothesis or null hypothesis is tested against an alternative hypothesis, which includes both the background and the sought-after signal. The level of agreement of the observed data with the null hypothesis is quantified by the p -value, which gives the probability of observing the data with equal or greater incompatibility with the predictions of the null hypothesis. Simply put, the smaller the p -value, the less likely the observed data events to be background-only. The background-only hypothesis is rejected if the observed p -value falls below a certain threshold which is set prior to the tests. In particle physics, the p -value is typically converted into an equivalent quantity known as significance defined as,

$$Z = \phi^{-1}(1 - p), \quad (12.5)$$

²in Physics and Philosophy.

where ϕ^{-1} is the quantile of a standard Gaussian distribution. The LHC experiments use three standard deviations to claim evidence and five standard deviations to confirm observation of a physics process. For a process like $W^\pm W^\pm jj$ -EWK, which has been observed in the previous iteration of the analysis, the aim of the differential measurements is to extract the cross-section in several kinematic ranges with a significance of at least five standard deviations, and test if the cross-section agrees with the Standard Model predictions in each range (identified as bins). In the following, a brief discussion of only the pertinent points of statistical treatment is given, with more detailed description in [134].

12.3.1 Profile Likelihood Fit

A commonly used approach for statistical inference is the profile likelihood fit performed to data, which relies on a test statistic defined as the ratio of likelihood functions. If s is the MC predicted signal and b represent the measured backgrounds, then the total expected events v can be written as

$$v = \mu s + b \quad (12.6)$$

where the parameter μ is known as *signal strength* which takes the value unity for Standard Model predictions and zero for background-only hypothesis. The parameter μ is considered as the only parameter of interest and all the other parameters, such as uncertainties, normalizations, etc., are known as *nuisance parameters*. The nuisance parameters can be classified into three groups, $\theta_\alpha = (\theta_{\alpha_1}, \theta_{\alpha_2}, \dots)$ that corresponds to the experimental and theoretical uncertainties, $\theta_\gamma = (\theta_{\gamma_1}, \theta_{\gamma_2}, \dots)$ that represents the background statistical uncertainties, and $\theta_\tau = (\theta_{\tau_1}, \theta_{\tau_2}, \dots)$ that gives the background normalizations. Combining all the nuisance parameters together into θ , the above equation can be realized as $v(\mu, \theta) = \mu s(\theta) + b(\theta)$. In the light of n observed events, the likelihood function for a binned distribution is defined as the product of the Poisson probabilities in all bins to observe n events for v expected events, given by

$$\mathcal{L}(\mu, \theta_{\alpha, \gamma, \tau} | n) = \prod_{\substack{\text{all} \\ \text{bins}}} \mathcal{P}(n | v(\mu, \theta_{\alpha, \gamma, \tau})). \quad (12.7)$$

The parameter of interest is determined by varying all the nuisance parameters and the likelihood function provides a profile of the parameter of interest, hence known as the *profile likelihood*.

In order to discourage the fit from taking any arbitrary values for the nuisance parameters, one can add the pre-existing knowledge into the above likelihood function as *constraint terms*. The constraints are added only on the uncertainties and not on the background normalizations, which are allowed to freely float in the fit. The information regarding the experimental and theoretical systematic uncertainties, estimated a priori in auxiliary measurements, is incorporated into the likelihood function by a Gaussian approximation of each uncertainty denoted by $\mathcal{G}(\theta_\alpha | 0, 1)$. Each Gaussian distribution has a mean of zero with $\pm 1\sigma$ as the values of the uncertainty variations (up and down). Adding them to Equation (12.7) penalizes the likelihood function as θ_α moves away from zero³. Therefore, the function tries to keep θ_α close to the auxiliary measurements unless the observed data, which encode the absolute truth of a measurement, exhibit a different behavior. The statistical uncertainties on the background predictions are also accounted for in the likelihood function by assigning θ_γ to each bin modeled using Poisson distributions⁴ denoted by $\mathcal{P}(\theta_\gamma | b)$.

³In terms of fit implementation, it implies that the fit prefers zero shift or *pull*.

⁴As the expected background events can be non-integer, Gamma function is used to replace the usual integer factorial.

The final expression for the likelihood function can be written as

$$\mathcal{L}(\mu, \theta|n) = \prod_{\substack{\text{all} \\ \text{bins}}} \mathcal{P}(n|v(\mu, \theta_{\alpha, \gamma, \tau})) \cdot \prod_{\substack{\text{all} \\ \text{bins}}} \mathcal{P}(\theta_{\gamma}|b) \cdot \prod_{\substack{\text{syst.} \\ \text{uncert}}} \mathcal{G}(\theta_{\alpha}|0, 1), \quad (12.8)$$

and the best fit value of the parameter of interest is taken as the one that maximizes the likelihood function. The expected signal and background yields are modified by the corresponding nuisance parameters for which the best value of μ is obtained and the yields after the fit (also known as *post-fit* yields) represent the values that best describe the observed data.

It has to be noted that in some cases, the nuisance parameters associated with systematic uncertainties can be largely constrained better than the auxiliary measurements. To check and quantify the deviations of the nuisance parameters before and after the fit, the *pull* of the nuisance parameter is computed. The pull of a nuisance parameter θ can be defined as the difference between the post-fit and the pre-fit nuisance parameter in units of the pre-fit uncertainty, written as

$$\text{pull}(\theta) = \frac{\hat{\theta} - \theta_0}{\Delta\theta}, \quad (12.9)$$

where $\hat{\theta}$ is the post-fit nuisance parameter obtained from the maximized likelihood fit, θ_0 and $\Delta\theta$ are the pre-fit nuisance parameter and its uncertainty. It shows the degree to which the data “pulls” the nuisance parameter from its expected value. If the uncertainty on a nuisance parameter is highly reduced compared to the pre-fit uncertainty of $\pm 1\sigma$, the nuisance parameter is said to be overconstrained by the data. It suggests that the performed measurement is more accurate than the auxiliary measurement which then requires additional investigations.

The impact of a nuisance parameter on the parameter of interest maximizing the likelihood, $\hat{\mu}$, can be studied as,

$$\text{impact}(\theta) = \Delta\mu = \hat{\mu}_{\hat{\theta} \pm \Delta\theta, \Delta\hat{\theta}} - \hat{\mu}. \quad (12.10)$$

Here, $\hat{\mu}$ is the value of parameter of interest obtained by fixing θ to its post-fit value, varied by the (pre-fit) post-fit uncertainties for the (pre-fit) post-fit impacts.

In this analysis, the likelihood fit is applied simultaneously to the signal region, $WZjj$, and Low m_{jj} control regions in two-dimensional slices of m_{jj} and any observable of interest. The $WZjj$ -QCD normalization is the only θ_{τ} considered, which is kept floating along with the parameter of interest. Before applying the fit to the data, the fit method is first validated on an *Asimov* dataset, using the sum of predicted signal and estimated backgrounds as data. As the predictions are used as the signal in the dataset, the pulls of all the nuisance parameters are expected to be zero, and the signal strength must be one. The obtained results of the signal strength and the $WZjj$ normalization parameter are plotted in Figure 12.3. The nuisance parameters are sorted according to their impact on the signal strength into a ranking plot as seen from Figure 12.4, which presents the nuisance parameters with the largest impacts along with their pulls. The results do not exhibit any suspicious behavior, following which the fit is applied to the observed data in Chapter 14.

12.3.2 Hypothesis Testing

To test if the observed data are compatible with a background-only hypothesis ($\mu = 0$), the profile likelihood ratio, given by

$$t_{\mu} = -2 \ln \frac{\mathcal{L}(\mu|\hat{\theta}_{\mu})}{\mathcal{L}(\hat{\mu}|\hat{\theta})}, \quad (12.11)$$

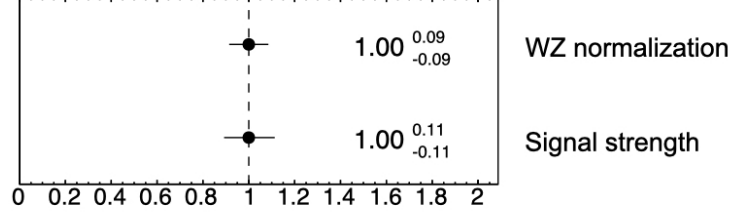


Figure 12.3: The signal strength of $W^\pm W^\pm jj$ -EWK and the normalization factor of $WZjj$ obtained from the maximized likelihood function using Asimov data are shown.

is typically used as the test statistic. Here, $\mu = 0$ represents the tested hypothesis, and $\hat{\theta}_\mu$ denotes the values of θ that maximizes the likelihood for the tested hypothesis, whereas $\hat{\mu}$ and $\hat{\theta}$ are the estimated signal strength and θ that globally maximizes the likelihood. According to Wilk's theorem [135], the distribution of the test statistic asymptotically approaches the χ^2 distribution with one degree of freedom. Higher values of t_μ signify increasing incompatibility between the observed data and the background-only hypothesis. The level of disagreement is quantified as the significance, introduced earlier in this section, and is evaluated as $Z = \sqrt{t_\mu}$. Dedicated calculations compute the significance numerically according to Equation (12.12),

$$Z = \begin{cases} +\sqrt{2 \left(n \ln \left[\frac{n(b+\sigma^2)}{b^2+n\sigma^2} \right] - \frac{b^2}{\sigma^2} \ln \left[1 + \frac{\sigma^2(n-b)}{b(b+\sigma^2)} \right] \right)} & \text{if } n \geq b \\ -\sqrt{2 \left(n \ln \left[\frac{n(b+\sigma^2)}{b^2+n\sigma^2} \right] - \frac{b^2}{\sigma^2} \ln \left[1 + \frac{\sigma^2(n-b)}{b(b+\sigma^2)} \right] \right)} & \text{if } n < b, \end{cases} \quad (12.12)$$

for n observed events and b background events estimated with an uncertainty of σ , with details on the numerical implementations described in [136].

12.4 Theory-Experiment Comparison

All the results presented so far in this thesis are obtained at the detector level where the true particles are examined at their reconstructed stages as physics objects in ATLAS. Simply put, to reproduce these physics results, one needs the ATLAS detector. The observable of interest in this analysis is the production cross-section. In order to compare the experimentally observed cross-section with the theoretical predictions in a meaningful manner, the dependency of the observed result on the experimental apparatus used must be rectified. Two factors contributing to such a dependency on the measured cross-section are the event selections and the non-ideal nature of the detector.

1. **Event Selections:** From Chapter 2, one can recall that the cross-section is computed in the total phase space in simulations. However, due to the detector design and data collection strategy, the theoretical phase space is not accessible in experiments. As a result, all the $W^\pm W^\pm jj$ -EWK events produced are not necessarily counted. Only the events in the signal region, where the contribution of signal is enhanced over the backgrounds, are considered

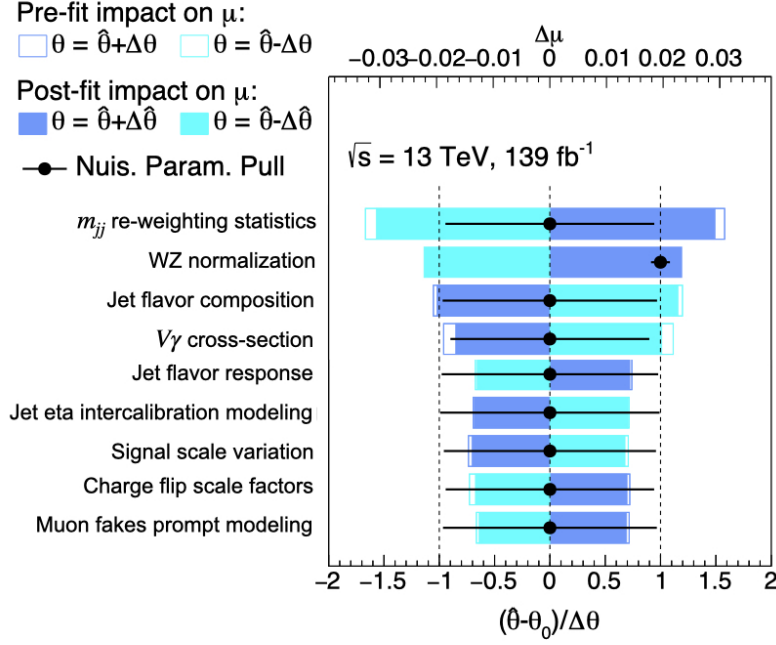


Figure 12.4: Ranking plot showing the nuisance parameters according to their impact on the measured signal strength from Asimov data is given. Only the top nine parameters are shown. The hollow rectangles correspond to the pre-fit impact and the filled ones correspond to the post-fit impact, both referring to the upper scale. The impact of each nuisance parameter, $\Delta\mu$, is computed by comparing the nominal best-fit μ with the result of the fit when fixing the considered nuisance parameter to its best-fit value, $\hat{\theta}$, shifted by its pre-fit (post-fit) uncertainties $\pm\Delta\theta$ ($\pm\Delta\hat{\theta}$). The black points show the pulls of the nuisance parameters with respect to their nominal values, θ_0 . The pulls and their relative post-fit errors, $\Delta\hat{\theta}/\Delta\theta$, refer to the lower scale.

in the measurement. For example, a signal event with $m_{jj} = 200$ GeV can be present in the predictions but not in the data. As the experimentally available phase space cannot be extended, it is convenient to reduce the theoretical phase space to a *fiducial* region defined at the particle level that matches reasonably closely with the signal region. In other words, the number of simulated signal events in the fiducial region should match the number of observed signal events in the signal region in data if the detector is ideal. The set of selections marking the fiducial phase space are given below:

- Two same-sign leptons (e or μ) with $p_T > 27$ GeV and $|\eta| < 2.5$.
 - Di-lepton invariant mass must be above 20 GeV.
 - At least two jets with $p_T > 65(35)$ GeV for leading(sub-leading) in $|\eta| < 4.5$.
 - Di-electron events with invariant mass in the range $|m_{ee} - m_Z| < 15$ GeV are removed.
 - The negative vectorial sum of the transverse momenta of the leptons and the jets above 30 GeV is considered to account for neutrinos.
 - The leading and the sub-leading jets must satisfy $m_{jj} > 500$ GeV and $|\Delta y_{jj}| > 2$.
2. **Non-Ideal Detector:** Due to the detector inefficiencies and limited resolution, the reconstructed objects do not reflect the accurate kinematics of the underlying true particles (more details in the next chapter). The detector effects can be stripped off from the observed events through *unfolding*, and the unfolded cross-section is our best understanding of the underlying true cross-section in data.

At this stage, one can finally assess the validity of the Standard Model predictions by testing the unfolded cross-section against the cross-section in the fiducial region ⁵. The integrated fiducial cross-section as predicted by MADGRAPH5_aMC@NLO+HERWIG 7, the nominal signal sample, is

$$\sigma_{\text{MG,LO}}^{\text{fid}} = 2.972 \pm 0.005 (\text{stat}) \pm \frac{0.092}{0.090} (\text{PDF and } \alpha_s) \pm \frac{0.262}{0.225} (\text{scale}) \text{ fb.} \quad (12.13)$$

The unfolding procedure implemented in this analysis is described in the next chapter and the unfolded cross-sections observed in data are presented in Chapter 14.

⁵The unfolded cross-section can also be extrapolated to the total phase space to obtain the absolute cross-section by relying entirely on the generator-level MC predictions. The fraction of the total generated events that pass the fiducial selections is known as the *acceptance factor* (should not be confused with the detector acceptance mentioned so far in this thesis). Fiducial cross-section divided by the acceptance factor yields the total cross-section. Such an extrapolation is not performed in this analysis.

Chapter 13

Unfolding

When the ATLAS detector records a collision event, the measured spectrum of an observable differs from its original true spectrum as the measured data necessarily suffers from detector-specific effects. The reverse method whereby the true spectrum is obtained from the observed spectrum is known as unfolding. Through unfolding, a measurement is made independent of the experimental details and lets one compare the results with theoretical predictions and other experimental observations.

This chapter explains the unfolding procedure utilized in the analysis to extract the underlying cross-section from the data observed in ATLAS. The discussion begins with a conceptual overview in Section 13.1 followed by a brief description of the inputs required to perform unfolding in Section 13.2, and the variables unfolded in Section 13.3. The different unfolding methods considered in the analysis are outlined in Section 13.4 and the nominal method chosen is the Bayesian unfolding using an iterative approach. Section 13.5 summarizes the various tests the method is subjected to and the results obtained. Finally, in Section 13.6, the procedure of uncertainty propagation through the unfolding procedure is explained, thus completing the recipe for cross-section extraction. The unfolding implementation and the results presented in this chapter are the sole work of the author.

13.1 Overview

For a given physics process $ab \rightarrow X$, the number of observed signal events is given by

$$N_{ab \rightarrow X}^{\text{meas}} = \varepsilon \times \sigma_{ab \rightarrow X}^{\text{true}} \times \mathcal{L}, \quad (13.1)$$

where $\sigma_{ab \rightarrow X}^{\text{true}}$ is the true cross-section in the fiducial region, $\mathcal{L}$ corresponds to the total integrated luminosity delivered, and ε is the efficiency of the detector. Dividing by the total integrated luminosity, one gets

$$\sigma_{ab \rightarrow X}^{\text{meas}} = \varepsilon \times \sigma_{ab \rightarrow X}^{\text{true}}, \quad (13.2)$$

where the measured cross-section is same as the true cross-section with ε applied. ε takes the value of unity for an ideal detector.

In the case of the ATLAS detector, with $\varepsilon \neq 1$, the inefficiencies affect the object yields¹. The picture gets a lot more complicated in the case of differential cross-section, where the limited

¹For example, due to the reconstruction inefficiencies, not at all the objects produced are reconstructed. Electrons falling in the ECal crack are more likely to be missed than the electrons falling in the more active regions of the detector. Similarly, a lepton trigger with a p_T threshold of 26 GeV is not necessarily fired by all the 26 GeV leptons due to the trigger inefficiencies.

detector resolution causes migration of events between neighboring bins. However, unfolding offers to remedy the detector effects and render the underlying true distribution in data. The procedure relies on deriving *unfolding inputs* based on the simulated behavior of the detector, and therefore, unfolding cannot provide exact conclusions of the true spectrum of an observable in data but only an estimate of the likely true spectrum.

13.2 Unfolding Inputs

If n is the observed number of events in data and b is the estimated background, then for a binned distribution, one can write

$$n_i = \sum_j R_{ij} \mu_j + b_i, \quad (13.3)$$

where i indicates reconstructed level bins and j denotes particle level bins also known as truth level bins. μ is the underlying true signal distribution of interest in data, and R , known as the response matrix, is the detector's response to the true distribution. μ together with R forms the observed signal events. The equivalent quantity in MC is the reconstructed level signal (details in Table 8.2) simulated by *folding* the generated signal with an ATLAS model from which the expected response of the detector to the signal can be determined. The unfolding technique determines the various components of the response matrix from simulations, known as unfolding inputs, which are obtained using the nominal signal sample in this analysis. The unfolding inputs that form the response matrix are:

- **Fiducial correction:** Fiducial correction, f , corresponds to the ratio of events in MC that pass both the reconstructed and fiducial level selections to all those that pass only the reconstructed level selections. It is obtained in bins of the reconstructed level observable and corrects for the events that are outside of the fiducial region, which satisfy the reconstructed level selections due to smearing effects arising from limited detector resolution.
- **Efficiency correction:** Efficiency correction, ϵ , is the ratio of events in MC that pass both the reconstructed and fiducial level selections to all those that pass only the fiducial level selections, and is determined in bins of the particle level observable. It accounts for the reconstruction inefficiencies of the detector.
- **Migration matrix:** Migration matrix, M , is a two-dimensional distribution obtained by comparing the particle and reconstructed level distributions of an observable, and encode the migrations of events between bins at the reconstructed level due to resolution effects with respect to the particle level. In simple terms, it corresponds to the probability that an event in a particle level bin j will be reconstructed in a detector level bin i . Two quantities often used when referring to the migration matrix are purity and stability. The fraction of events in a true bin that get reconstructed in the same bin at the detector level is known as purity. Stability is the fraction of reconstructed events that originate from the same bin at the truth level. Both of these quantities are derived from the migration matrix and are defined, therefore, in the joint reconstructed-truth phase space.

A simplified representation of the definitions of the unfolding inputs is shown in Figure 13.1. Finally, the response matrix is constructed as

$$R_{ij} = \frac{1}{f_i} \cdot M_{ij} \cdot \epsilon_j. \quad (13.4)$$

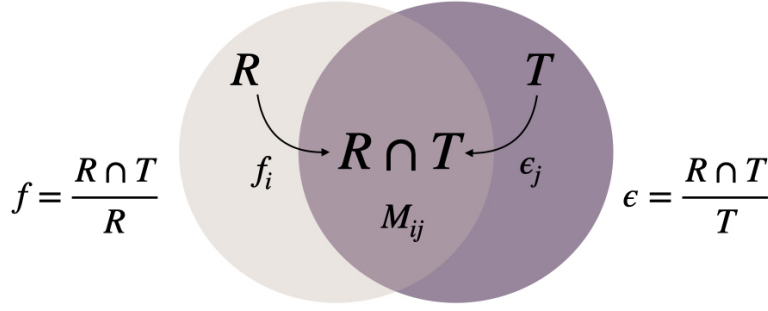


Figure 13.1: A simplified graphical representation of the definitions of the unfolding inputs is shown. The fiducial correction, f , and the efficiency correction, ϵ , provide respectively the corrections for the reconstructed level and the truth level phase spaces to the joint reconstructed-truth phase space. Migration matrix, M , is defined in the joint reconstructed-truth phase space and encodes the bin migrations in this region.

The numerical implementations of all the variables discussed are given in Equations (13.5) to (13.9).

Fiducial correction:

$$f_i = \frac{N_{\text{reco},i}^{\text{pass reco \& truth}}}{N_{\text{reco},i}^{\text{pass reco}}} \quad (13.5)$$

Efficiency correction:

$$\epsilon_j = \frac{N_{\text{truth},j}^{\text{pass reco \& truth}}}{N_{\text{truth},j}^{\text{pass truth}}} \quad (13.6)$$

Migration matrix:

$$M_{ij} = \frac{N_{\text{truth},j\&\text{reco},i}^{\text{pass reco \& truth}}}{N_{\text{truth},j}^{\text{pass reco \& truth}}} \quad (13.7)$$

Purity:

$$p_j = \frac{N_{\text{truth},j\&\text{reco},j}^{\text{pass reco \& truth}}}{N_{\text{truth},j}^{\text{pass reco \& truth}}} \quad (13.8)$$

Stability:

$$s_i = \frac{N_{\text{truth},i\&\text{reco},i}^{\text{pass reco \& truth}}}{N_{\text{reco},i}^{\text{pass reco \& truth}}} \quad (13.9)$$

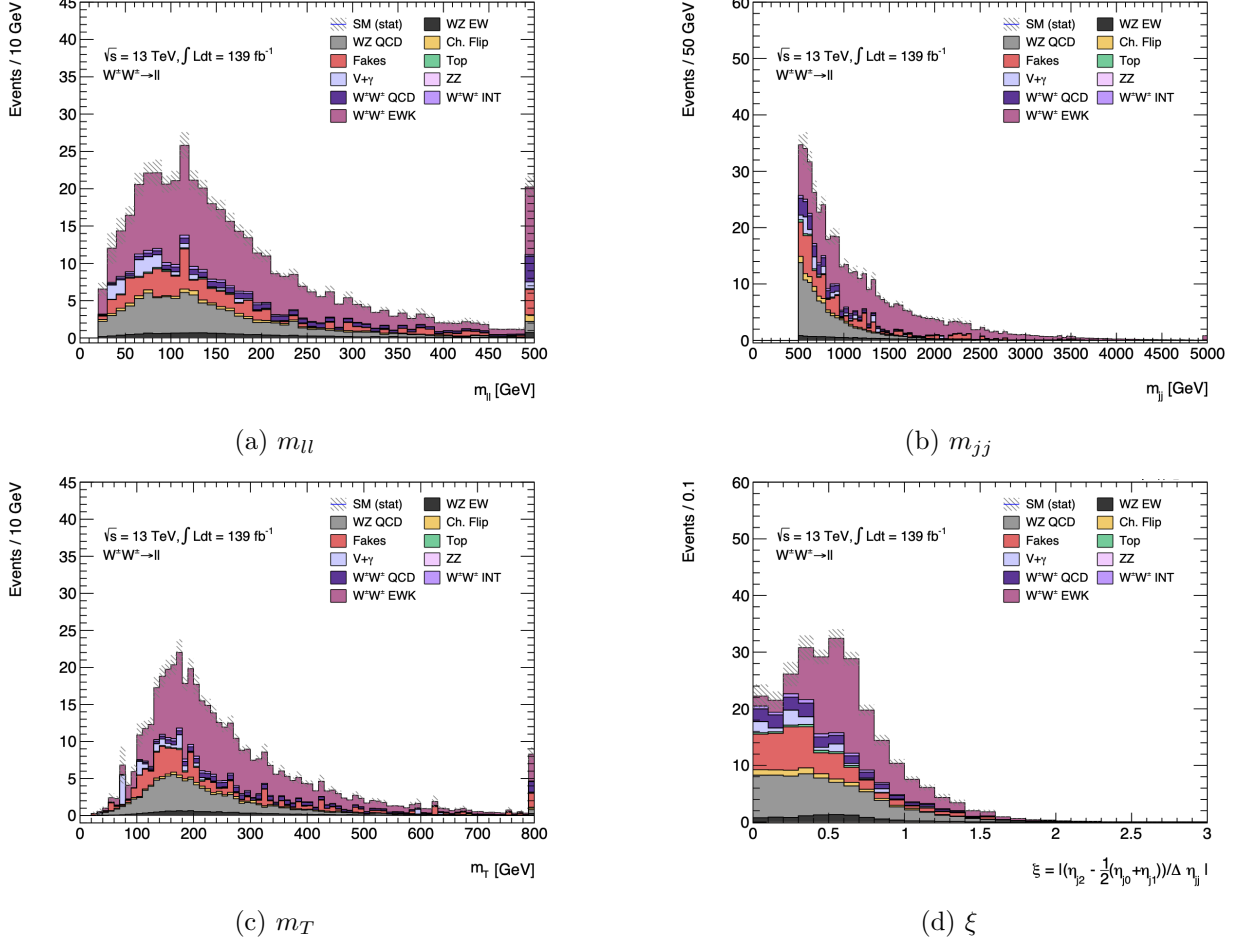


Figure 13.2: The distributions of the unfolding observables before optimizing the bin edges.

13.3 Observables and Binning

In this analysis, the cross-section is extracted differentially in four different observables, namely,

- m_{ll} , the invariant mass of the two same-sign leptons,
- m_{jj} , the invariant mass of the two tagging jets,
- m_T , the transverse mass of the WW system calculated as $m_T = \sqrt{(E_T^{ll} + E_T^{miss})^2 - (p_T^{ll} + E_T^{miss})^2}$ and finally,
- ξ , the Zeppenfeld variable defined as $\xi = |(\eta_{j_2} - \frac{1}{2}(\eta_{j_0} + \eta_{j_1}))/\Delta\eta_{j_0j_1}|$. It represents the centrality of the third jet and is estimated exceptionally from the signal region with ≥ 3 jets instead of ≥ 2 jets.

An important aspect to be considered in differential cross-section measurements is the binning of the unfolded observables. The bins of a given observable must be selected such that the underlying shape of the observable is preserved with sufficient statistics without being plagued by huge event migrations between neighboring bins. As the analysis performs the first attempt in measuring the differential cross-section, the bin edges are chosen such that the signal can be observed with

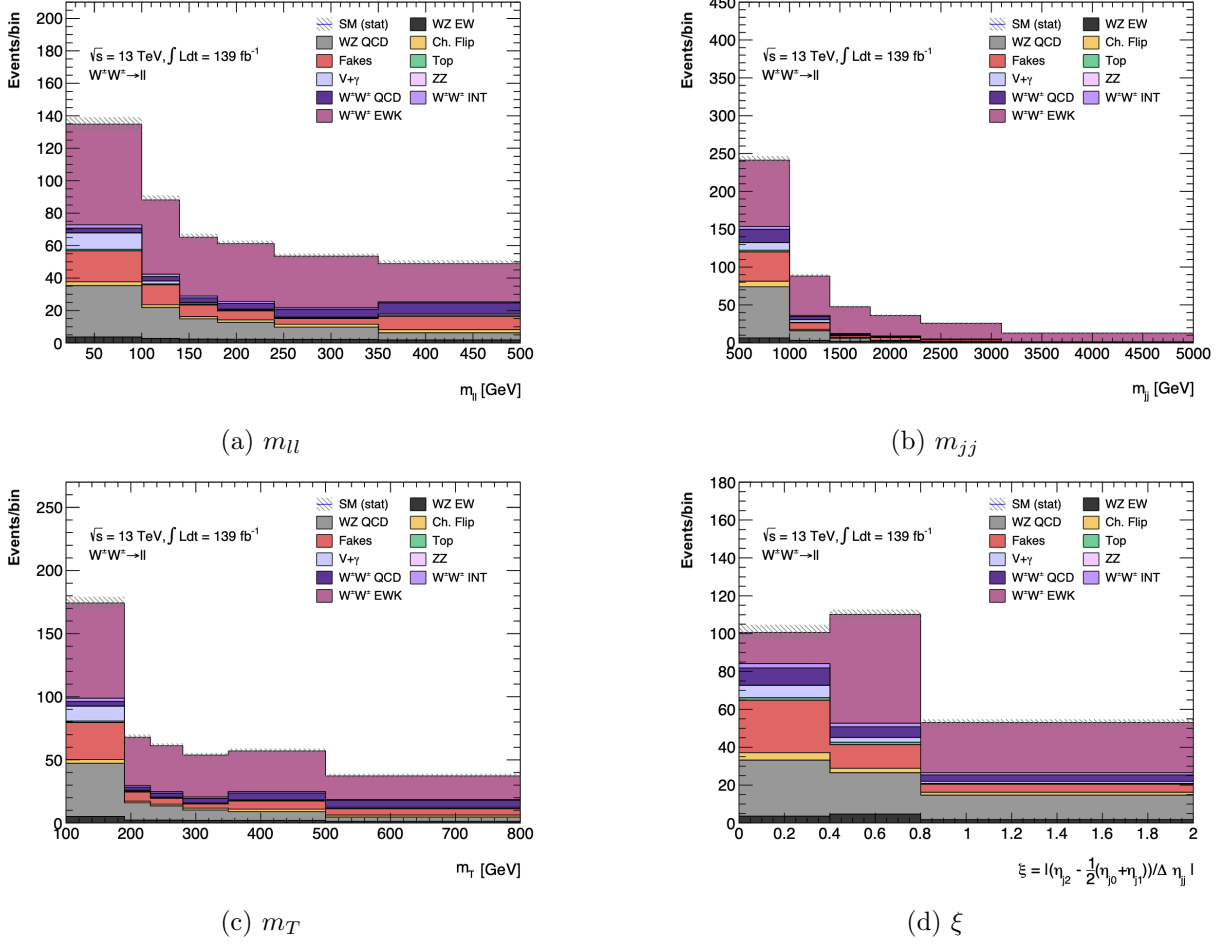
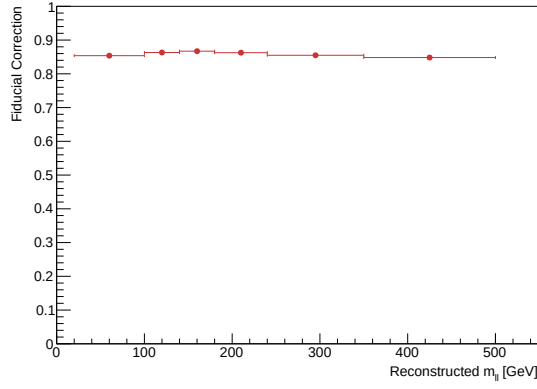


Figure 13.3: The distributions of the unfolding observables after optimizing the bin edges.

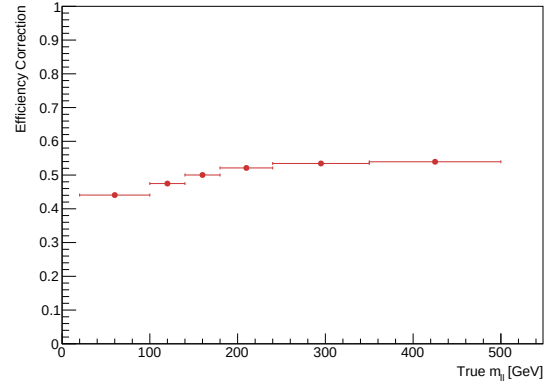
roughly five standard deviations in each bin. Using Equation (12.12), the bins are optimized using the expected event yields in the signal region for the four unfolding variables. In addition, each bin must have at least ten expected signal events. Finally, to reduce the migrations in neighboring bins, the bin sizes are kept coarse enough by requiring a minimum fiducial purity of 60%. Inspecting the three factors simultaneously, the bin edges chosen for the four observables are

- m_{ll} : [20, 100, 140, 180, 240, 350, 500] in GeV,
- m_{jj} : [500, 1000, 1400, 1800, 2300, 3100, 5000] in GeV,
- m_T : [100, 180, 230, 280, 350, 500, 800] in GeV,
- ξ : [0, 0.4, 0.8, 2.0].

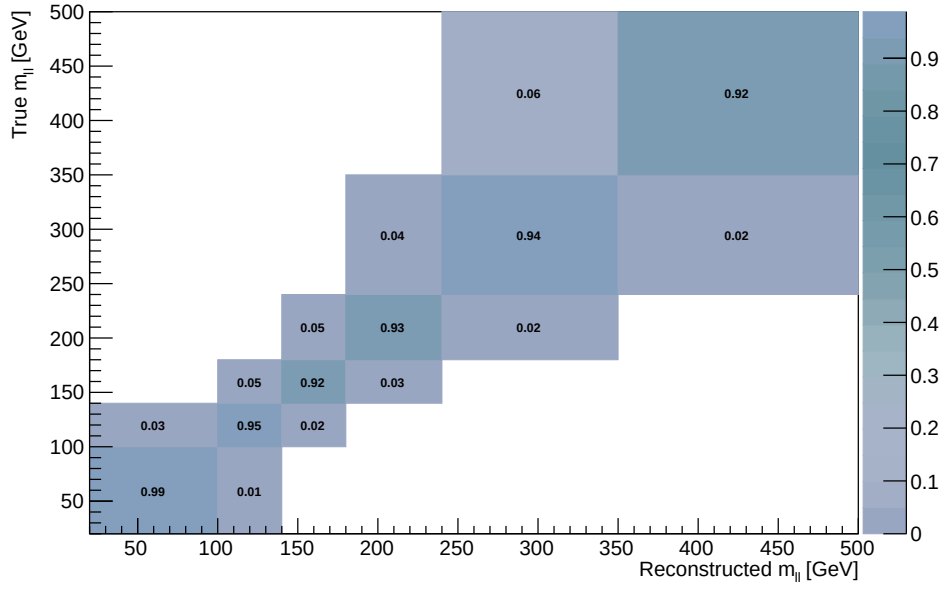
The distributions of the observables before and after applying the optimized bin edges are shown in Figures 13.2 and 13.3 respectively. With the optimized bin edges of the observables, the unfolding inputs for the differential cross-section measurement are obtained and are plotted in Figures 13.4-13.7. The distributions for purity and stability are also included, and the nearly diagonal behavior of the migration matrix seen ensures that the bin migrations are kept low.



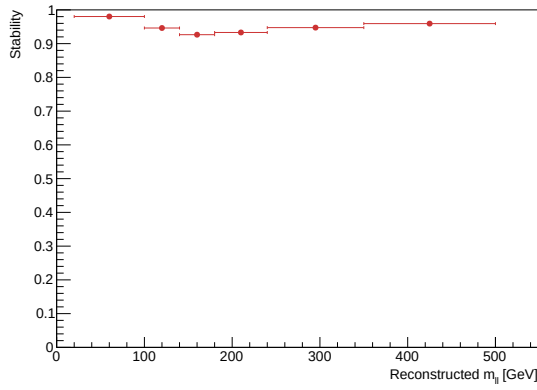
(a) Fiducial Correction



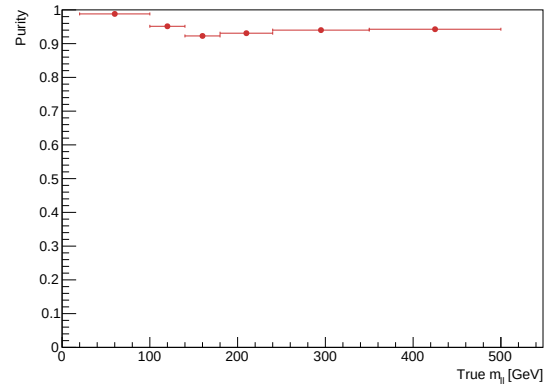
(b) Efficiency Correction



(c) Migration Matrix

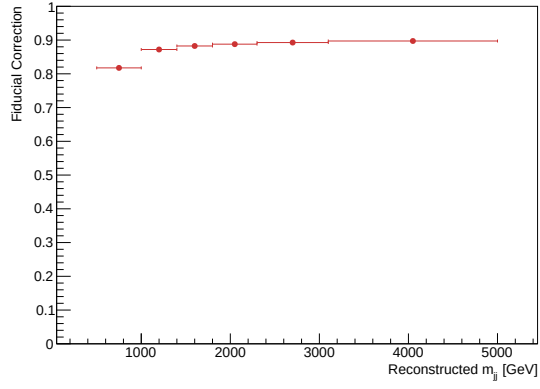


(d) Stability

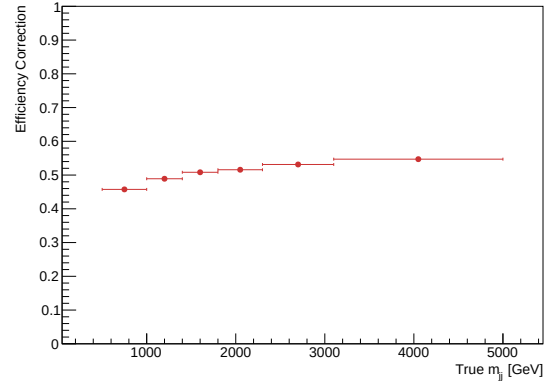


(e) Purity

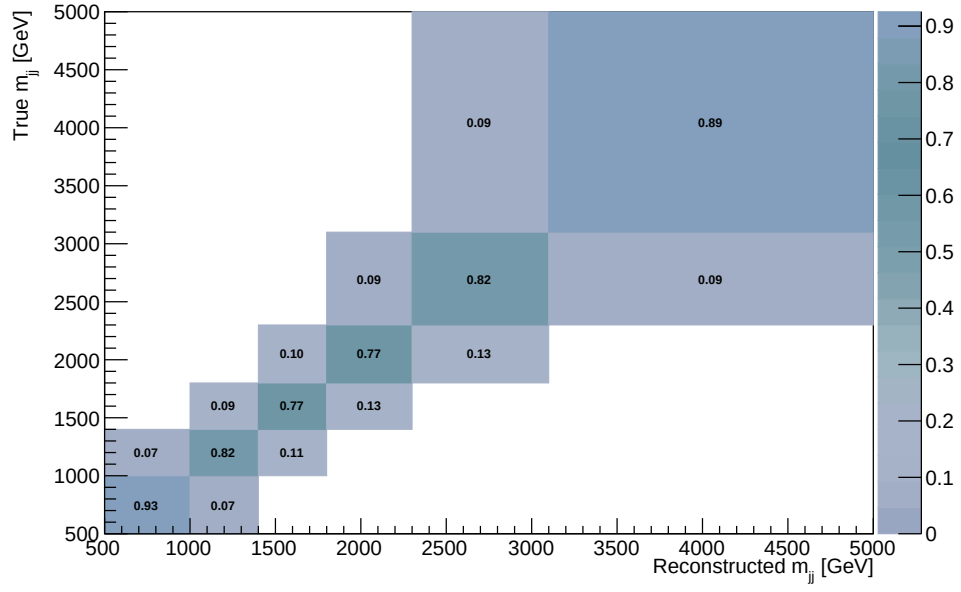
Figure 13.4: Unfolding inputs for m_{ll} are shown.



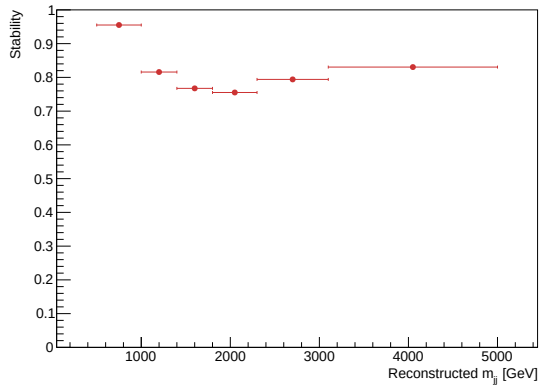
(a) Fiducial Correction



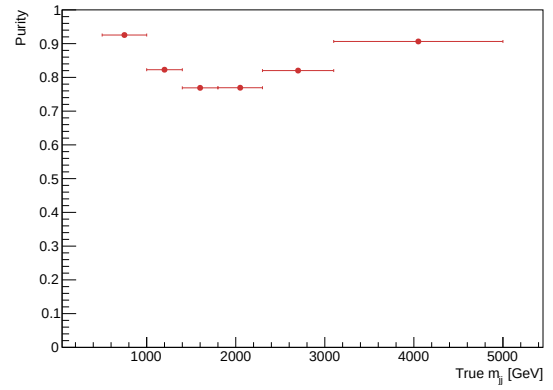
(b) Efficiency Correction



(c) Migration Matrix

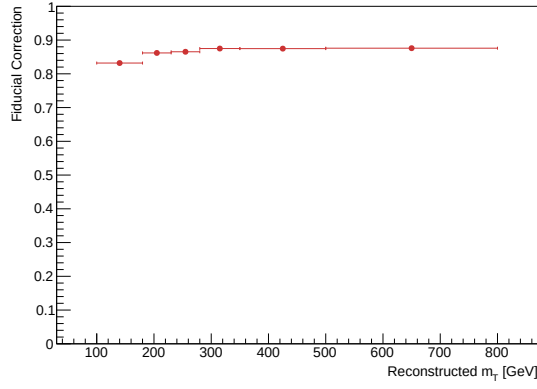


(d) Stability

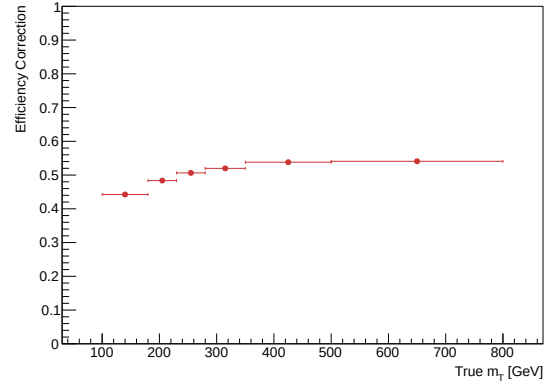


(e) Purity

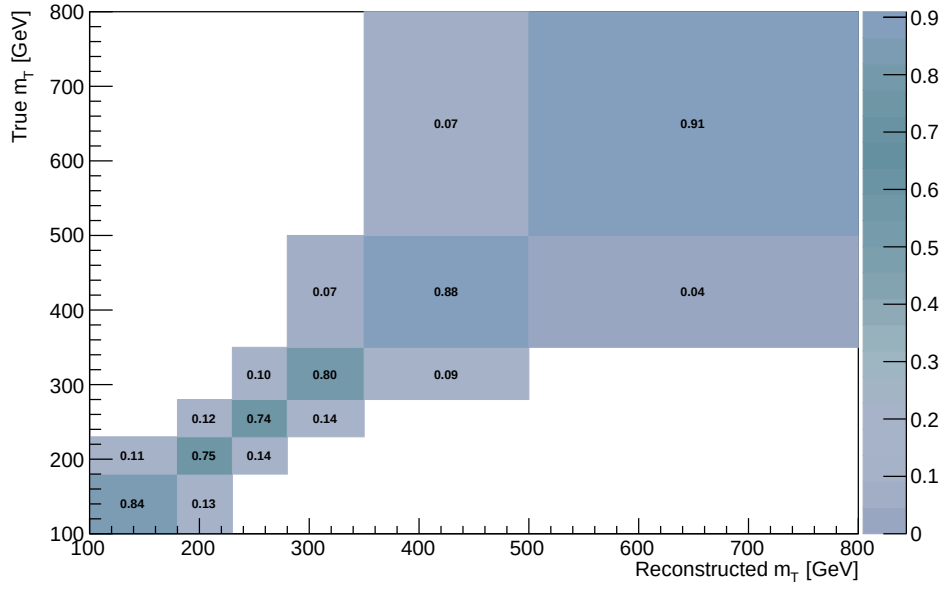
Figure 13.5: Unfolding inputs for m_{jj} are shown.



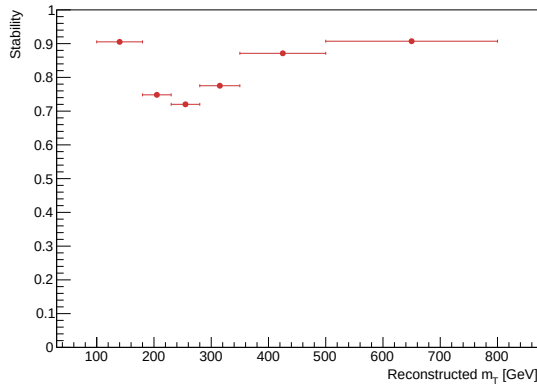
(a) Fiducial Correction



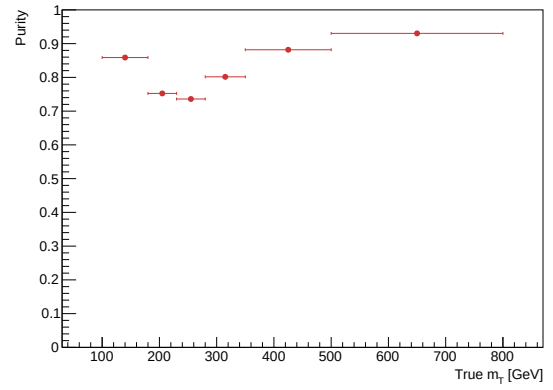
(b) Efficiency Correction



(c) Migration Matrix

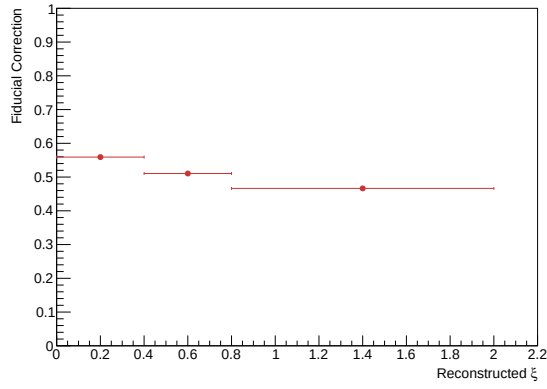


(d) Stability

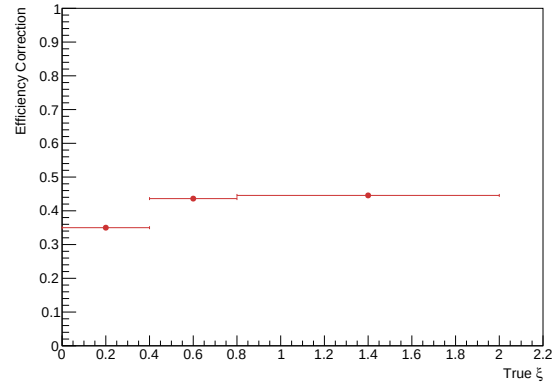


(e) Purity

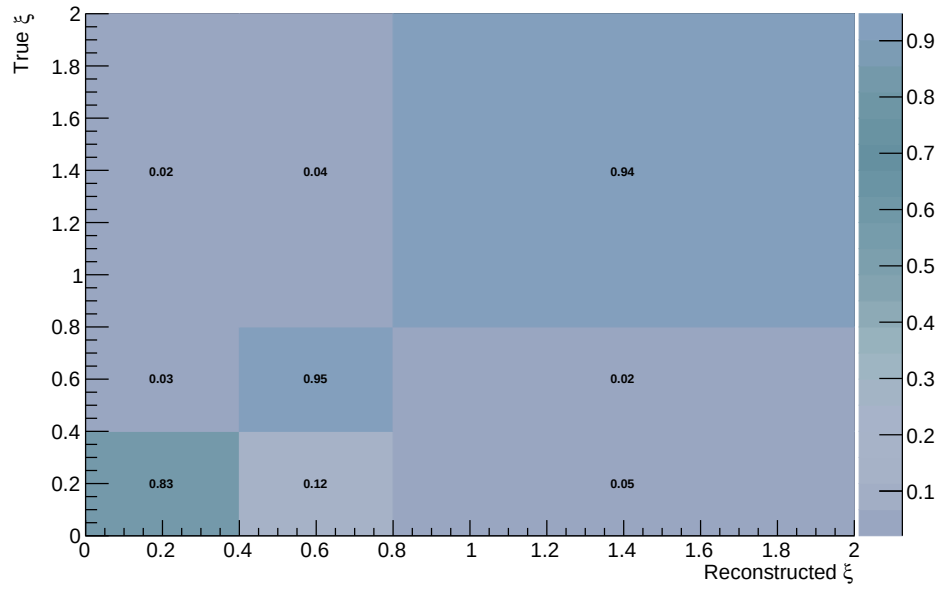
Figure 13.6: Unfolding inputs for m_T are shown.



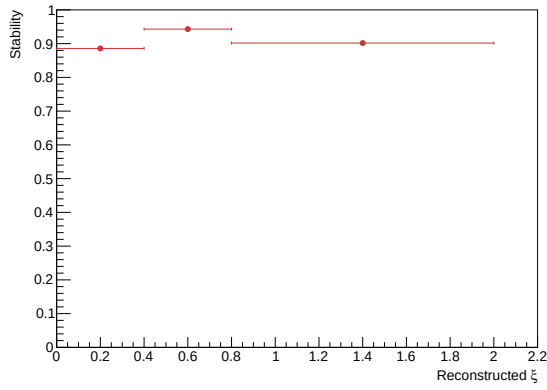
(a) Fiducial Correction



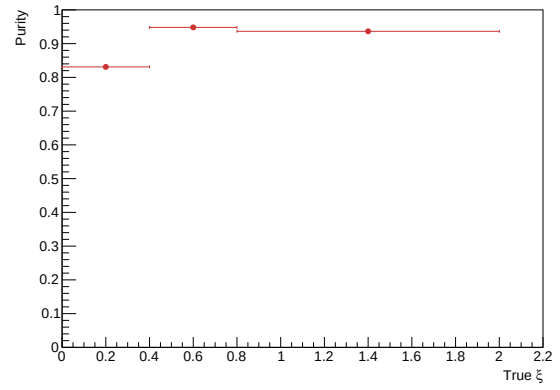
(b) Efficiency Correction



(c) Migration Matrix



(d) Stability



(e) Purity

Figure 13.7: Unfolding inputs for ξ are shown.

13.4 Unfolding Methods

Several methods exist to perform unfolding, and this thesis considers three unfolding algorithms, namely, bin-by-bin, matrix inversion, and iterative Bayesian, implemented in the ROOUNFOLD package [137]. The iterative Bayesian method is the nominal unfolding algorithm, while bin-by-bin and migration inversion are used as cross-check methods. In the following, the three algorithms are briefly discussed.

13.4.1 Bin-By-Bin Unfolding

Bin-by-bin unfolding is a simple unfolding technique that scales the observed signal events in data by correction factors determined from the MC expectations of the signal. The correction factors describe the ratio of the truth to the reconstructed level events, and are obtained for each bin according to

$$c_k = \frac{s_k^{truth}}{s_k^{reco}}, \quad (13.10)$$

where s denote the simulated signal events. The unfolded events are then computed as

$$\mu_k = c_k \cdot (n_k - b_k). \quad (13.11)$$

Though the method is conceptually very simple and requires less computation power, it has the disadvantage of omitting bin migrations by definition. As the name suggests, the correction factors are obtained *bin-by-bin* but bin-to-bin corrections are not accounted for. Thus, unless the bin purities are high, the unfolded result will be biased towards the MC signal sample from which the correction factors are derived.

13.4.2 Matrix Inversion

Matrix inversion follows the mathematically intuitive method of simply inverting the response matrix in Equation (13.4), resulting in the unfolded distribution as

$$\mu = R^{-1}(n - b). \quad (13.12)$$

But the method results in large statistical uncertainties due to correlations between bins when the migrations are not small.

13.4.3 Iterative Bayesian Unfolding

The default unfolding technique employed is the iterative Bayesian unfolding [138], [139]. It is an iterative approach that repeatedly solves the Bayes theorem with the output of the previous iteration serving as the prior probability and the migration matrix providing the probability of observing the reconstructed distribution given the true distribution. The first iteration uses fiducial level predictions as the prior², and the output of the iteration is fed as the prior of the subsequent iteration.

The picture can be better understood in terms of causes and effects. Due to the probabilistic nature, a cause can result in many effects, but for a given effect, the exact cause is unknown. As one cannot attribute a set of effect events to a particular cause bin with certainty, the realistic goal becomes the determination of the probability to obtain the observed spectrum given the true

²The choice is the default selection of the ROOUNFOLD framework.

spectrum, which is obtained from Bayes theorem³. In a measurement, effect can be realized as the observed reconstructed distribution, while the cause is the true distribution. The unfolded events of an observable x in a given particle level bin j is then computed according to

$$x_j = \frac{1}{\epsilon_j} \sum_i^{\text{reco}} f_i x_i P(x_j | x_i). \quad (13.14)$$

The equation can be expanded for a single iteration as

$$x_j = \frac{1}{\epsilon_j} \sum_i^{\text{reco}} \left(f_i (n_i - b_i) \frac{M_{ij} x_j^{n-1}}{\sum_k^{\text{truth}} M_{ik} x_k^{n-1}} \right). \quad (13.15)$$

One may notice that the unfolded distribution is influenced by the prior distribution, and the choice of the fiducial distribution as the prior for the first iteration introduces an undesirable bias towards the MC predictions. An important parameter that optimizes the Bayesian unfolding method is the number of iterations. The more the number of iterations run, the less the bias from the fiducial level MC expectations. However, increasing the number of iterations poses the caveat of amplifying the statistical uncertainties due to the feedback nature of the algorithm. The number of iterations determine the trade-off between reducing the bias (increasing the number of iterations) without blowing up the statistical uncertainties (decreasing the number of iterations). To perform the optimization, pseudo data made with alternative signal samples (sample details in Table 8.2) are unfolded and the iterations are stopped when the solutions become roughly stable. In general, the impact of the initial prior diminishes after two or three iterations, and this analysis chooses two iterations as the unfolded distributions differ only slightly after the second iteration. The agreement with the previous iteration is quantified by means of χ^2 , and the results are plotted in Figure 13.8 for the MADGRAPH sample and in Figure 13.9 for the POWHEG sample, together with the statistical uncertainties for each iteration.

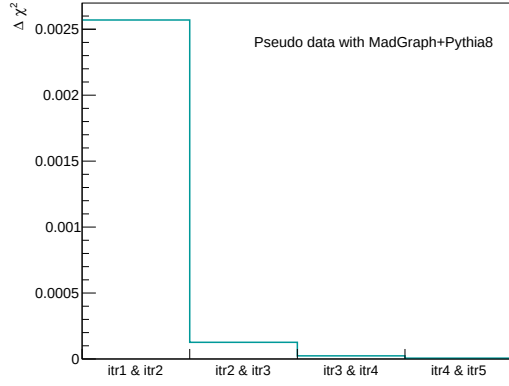
13.5 Tests on the Unfolding Method

Several tests are carried out to examine if the nominal unfolding method performs as expected, including the validity of the unfolding inputs and the unfolded output. First, a technical closure test is performed to identify any problems associated with the technical implementation of the unfolding procedure. Background subtracted pseudo data, with the nominal signal sample used to derive the response matrix utilized as the signal, are unfolded. The output spectrum is expected to be the exact same as the truth spectrum. In Figure 13.10, the unfolded distribution overlaid with the true distribution is plotted for the m_{jj} observable, and a perfect closure is seen.

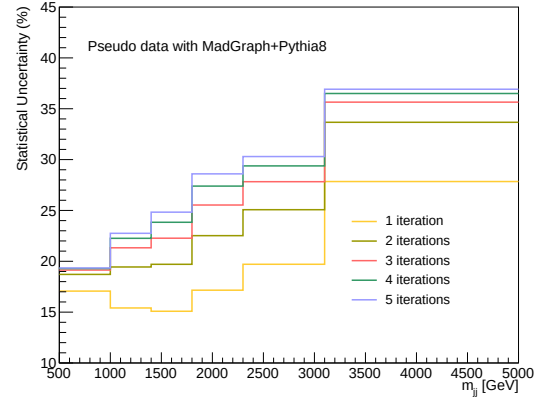
Following the technical closure, the nominal unfolding method of Bayesian unfolding with two iterations is cross-checked with Bayesian unfolding with one and three iterations, bin-by-bin, and matrix inversion method, and the unfolded results obtained for the m_{jj} distribution are shown in

³If several independent causes C_j ($C_j = C_1, C_2, \dots, C_n$) produce an effect E and the effect is observed, Bayes theorem formulates how the probability that the effect occurred due to the i th cause should be updated based on the probability of the cause to produce the effect and the prior probability of the cause. Mathematically, the formula can be written as

$$P(C_j | E) = \frac{P(E | C_j) P(C_j)}{\sum_k^n P(E | C_k) P(C_k)}. \quad (13.13)$$

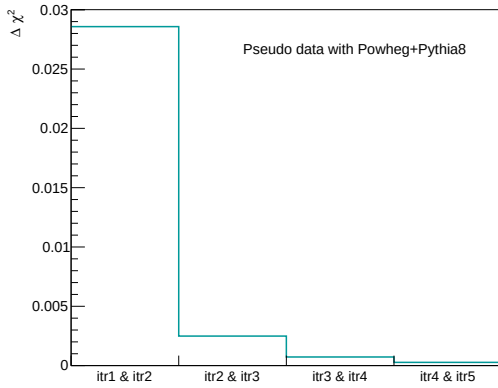


(a)

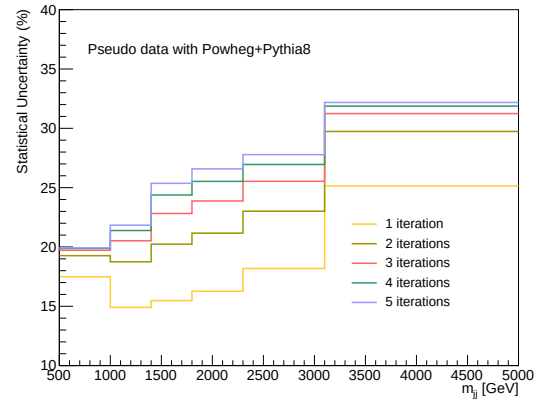


(b)

Figure 13.8: The change in χ^2 of the unfolded distributions between iterations is plotted in (a), and the statistical uncertainties of the unfolded distributions are plotted in (b). The pseudo data, with MADGRAPH+PYTHIA8 signal and measured backgrounds, are unfolded with inputs made from MADGRAPH+HERWIG7 for the m_{jj} observable.



(a)



(b)

Figure 13.9: The change in χ^2 of the unfolded distributions between iterations is plotted in (a), and the statistical uncertainties of the unfolded distributions are plotted in (b). The pseudo data, with POWHEG+PYTHIA8 signal and measured backgrounds, are unfolded with inputs made from MADGRAPH+HERWIG7 for the m_{jj} observable.

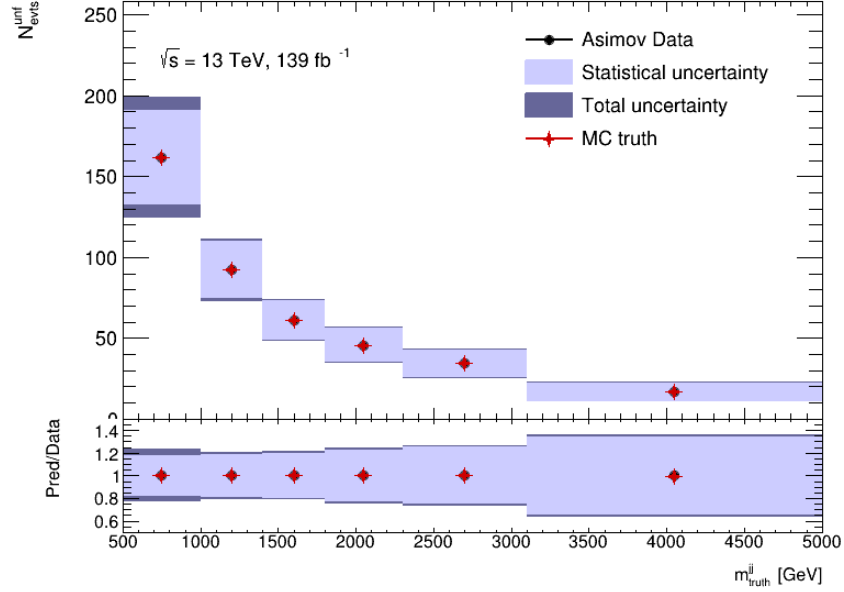


Figure 13.10: Comparison of the unfolded (in black) and the true simulated spectra (in red) of the m_{jj} observable in the technical closure test of the unfolding method is shown. The uncertainties on the unfolded distribution are also plotted, and the computation of the uncertainties is detailed later in Section 13.6.

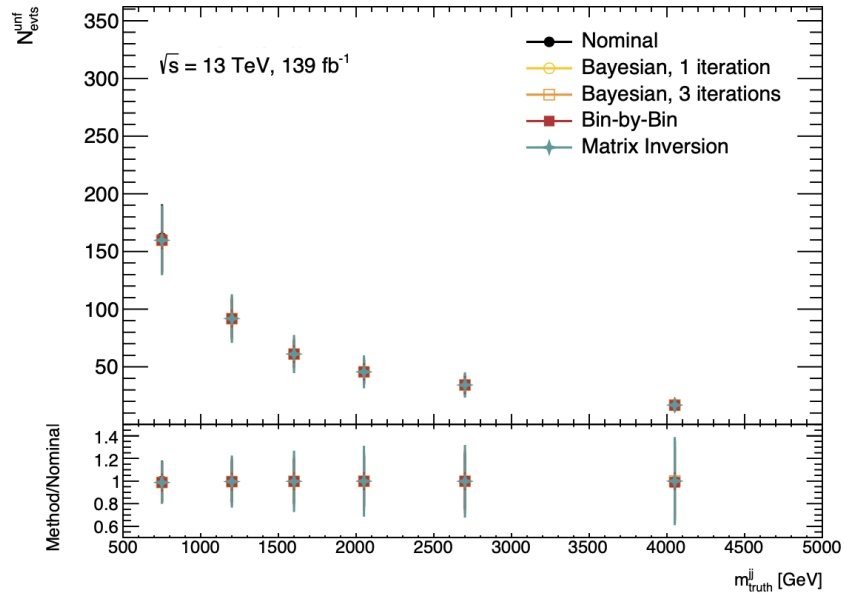
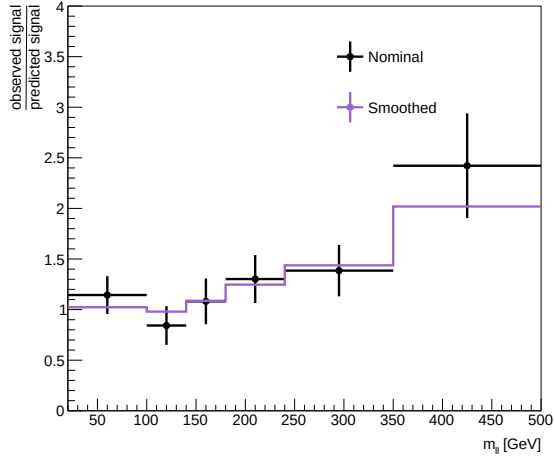


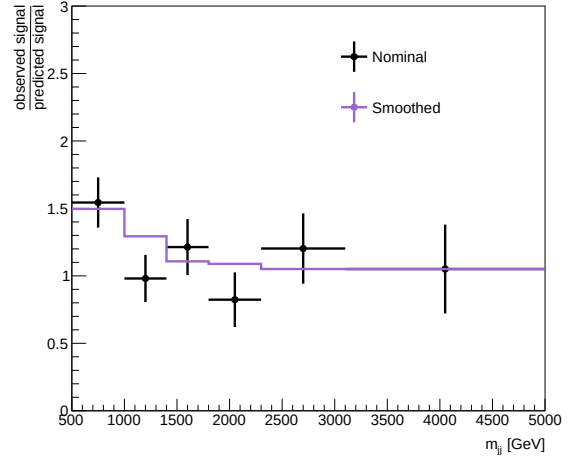
Figure 13.11: Comparison of the unfolded m_{jj} distributions from the various unfolding methods.

Figure 13.11. The central values of the unfolded yields are seen to be in good agreement between all the methods.

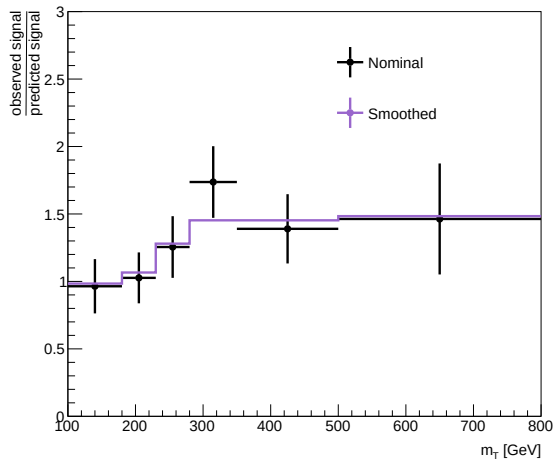
Finally, a data-driven closure test is performed where the truth spectrum of the nominal signal sample generated by MADGRAPH+HERWIG7 is re-weighted using a smooth function such that the reconstructed level distribution agrees closely with the observed data. The truth re-weighted reconstructed signal distribution is unfolded using the nominal unfolding method and compared with the re-weighted truth spectrum. Any non-closure seen is assigned as a systematic uncertainty arising from the unfolding procedure. Figures 13.12-13.14 present the results of the data-driven closure, and the unfolding uncertainties are obtained differentially for each of the unfolding observables. The smooth re-weighting function is plotted in Figure 13.12, and the truth re-weighted reconstructed signal distribution is compared with data in Figure 13.13. The unfolded result is found to agree well with the re-weighted truth spectrum in all the bins from Figure 13.14 with the largest deviation of 3% seen in the first bin of ξ . The numerical values of the unfolding uncertainty computed are presented in the next chapter (see Figure 14.9) for each of the observable unfolded.



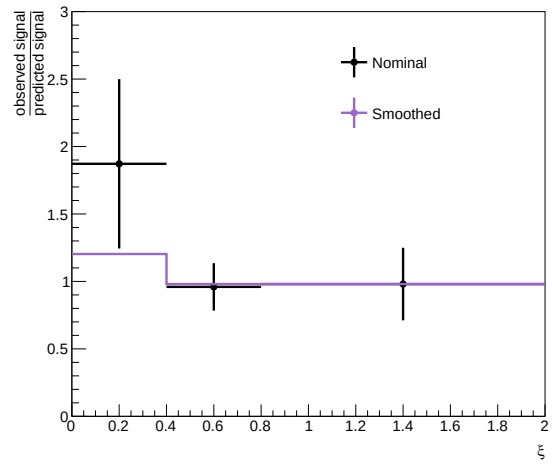
(a) m_l



(b) m_{jj}

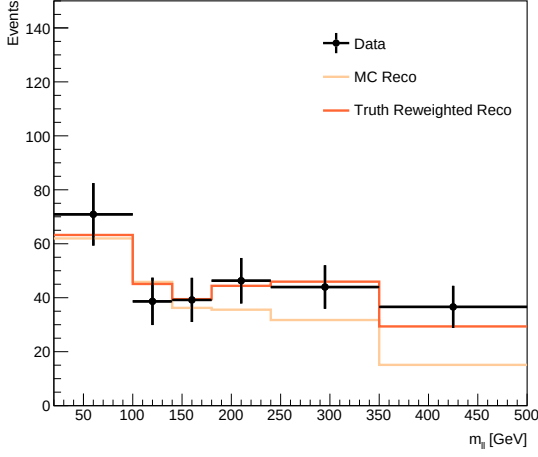


(c) m_T

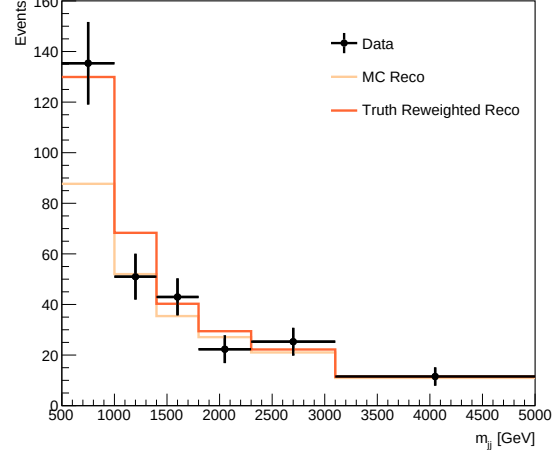


(d) ξ

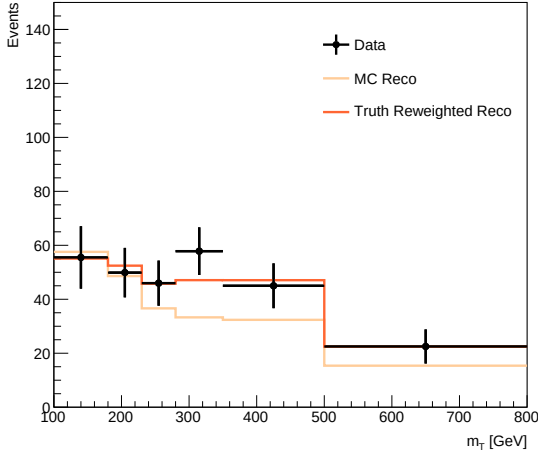
Figure 13.12: The ratio of the observed background-subtracted data to the expected signal is plotted in black for the various unfolding observables. The smoothed weights to be applied on the truth spectrum of the predicted signal are shown in purple.



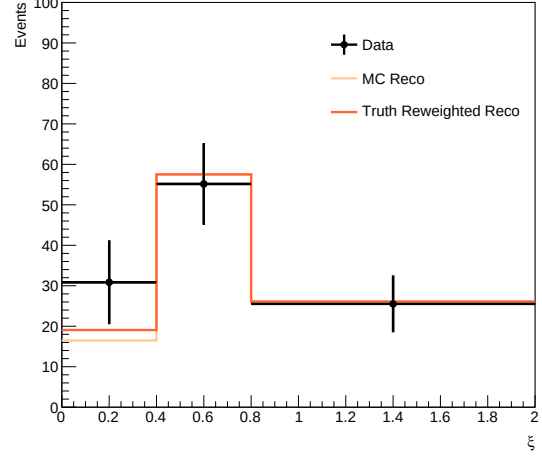
(a) m_{ll}



(b) m_{jj}

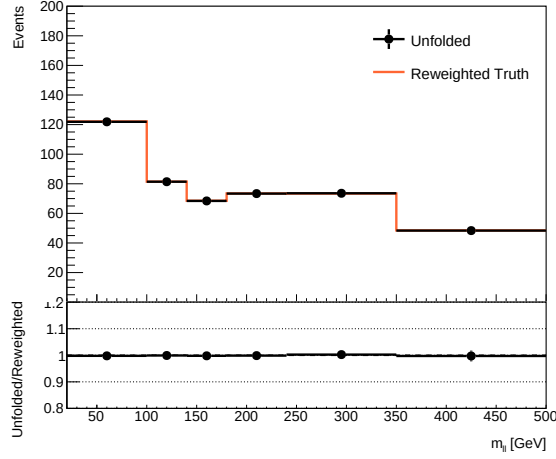


(c) m_T

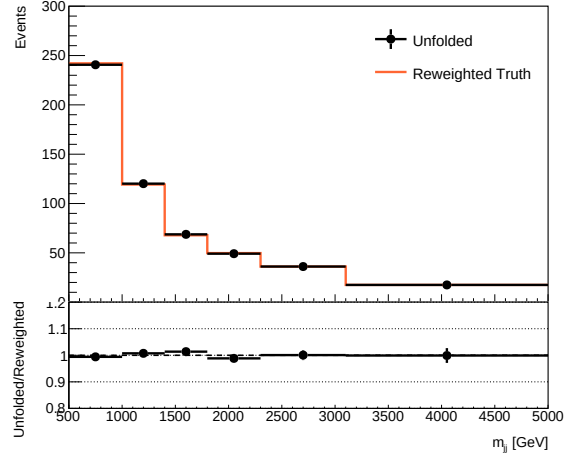


(d) ξ

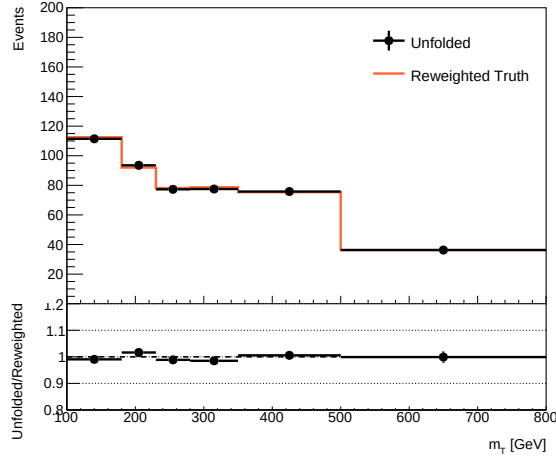
Figure 13.13: The reconstructed level distribution of the predicted signal that has been re-weighted at the truth level (in orange) using the smoothed weights, obtained from Figure 13.12, is compared with data (in black). The distributions depict a reasonable agreement for all the unfolding variables. The default reconstructed level distribution of the predicted signal is also plotted (in light orange) for comparison.



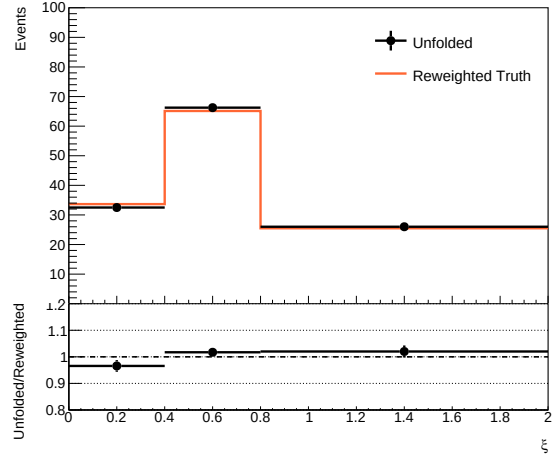
(a) m_{ll}



(b) m_{jj}



(c) m_T



(d) ξ

Figure 13.14: The truth re-weighted reconstructed signal is unfolded using the nominal unfolding method (in black) and compared with the re-weighted truth spectrum (in orange). The difference of the unfolded distribution with respect to the re-weighted true distribution is assigned as the unfolding uncertainty. The uncertainty differs for each bin and is propagated to the unfolded cross-sections.

13.6 Uncertainty Propagation through Unfolding

13.6.1 General Treatment

If N denotes the nominal distribution of an observable and $\hat{N}$ is the varied distribution corresponding to an uncertainty source, then the uncertainty on N due to the source is parametrized as

$$\sigma_s = \hat{N} - N, \quad (13.16)$$

with

$$\frac{\sigma_s}{N} = \frac{\hat{N} - N}{N} \quad (13.17)$$

being the relative uncertainty on N due to the source. For sources with two-sided uncertainties, where *up* and *down* variations are available, the uncertainty due to each of the variation is computed as

$$\sigma_{up} = \hat{N} - N \quad \text{and} \quad \sigma_{down} = N - \hat{N}, \quad (13.18)$$

which are averaged to obtain the total uncertainty due to the source,

$$\sigma_s = \frac{\sigma_{up} + \sigma_{down}}{2}. \quad (13.19)$$

For S number of uncorrelated uncertainty sources, the total uncertainty is evaluated as their quadrature sum,

$$\sigma_S = \sqrt{\sum_{s=1}^S \sigma_s^2}. \quad (13.20)$$

In binned distributions, there can be correlations between bins for a given uncertainty source. The covariance between the entries in i^{th} and j^{th} bins is given by the two-dimensional matrix,

$$\text{cov}_s^{ij} = (\hat{N} - N)_i (\hat{N} - N)_j, \quad (13.21)$$

in which the diagonal entries correspond to the variances (i.e., the covariance of the each element with itself). The correlation is then computed as

$$\text{corr}_s^{ij} = \frac{\text{cov}(ij)}{\sqrt{\text{cov}(ii)}\sqrt{\text{cov}(jj)}} = \frac{\text{cov}(ij)}{\sigma_s(i)\sigma_s(j)}. \quad (13.22)$$

The correlation matrix has diagonal entries of 1 and off-diagonal entries between -1 and +1. Correlations close to +1 imply that the entries vary in the same direction, whereas correlations close to -1 imply that they vary in opposite directions. Correlations near 0 indicate that the entries are independent. If the correlations between bins are ignored, then the square root of the sum of the diagonal entries of the covariance matrix represents the uncertainty due to a given source. This also means that for S uncorrelated uncertainty sources, adding the covariance matrices is equivalent to the square of their quadrature sum,

$$\sigma_S^2 = \sum_{s=1}^S \text{cov}_s^{ij}. \quad (13.23)$$

13.6.2 Uncertainty Estimation

Following the above treatment, the uncertainties can be propagated to the final cross-section through the unfolding procedure. The exact methodology used in the estimation of statistical and systematic uncertainties on the measured events is detailed below.

Statistical Uncertainty

The statistical uncertainties on the unfolded signal events in data are estimated from Monte Carlo modeled pseudo experiments. First, the total number of observed data events is varied by a random number following a Poisson distribution with background subtracted data as the mean. Next, the distribution is unfolded, and the process is repeated 2000 times, each time filling a covariance matrix with deviations from the nominal unfolded result. Finally, the statistical uncertainty is taken as the square root of the diagonal entries in the final covariance matrix averaged over the total number of iterations.

Systematic Uncertainty

The unfolding procedure propagates all the uncertainties⁴ described in Chapter 12 to the final unfolded events as systematic uncertainties. Depending on whether an uncertainty affects just the background estimate only or the background estimate as well as the simulated signal used to produce the response matrix, the propagation of systematic uncertainties can be distinguished as *Background-only* and *Model and Background*.

In *Background-only*, every uncertainty modifies the background estimate, and the unfolding method is repeated for each of the background-subtracted data estimates to measure the uncertainty on the unfolded events. Let us take a two-sided uncertainty as an example, say from charge-flip background estimation. The uncertainty modifies the total background measured, and the systematically varied total unfolded events for the *up* and *down* variations of the uncertainty can be evaluated. Their differences with the nominal unfolded result is symmetrized according to Equation (13.19) and is taken as the systematic uncertainty on the unfolded events due to the background source. The experimental uncertainties arising from background estimation techniques and theoretical uncertainties on the backgrounds are propagated in this manner. Furthermore, the statistical uncertainty on the total background estimates is also added to this category. The background yields are Gaussian fluctuated in Monte Carlo 2000 times, and the uncertainty is computed from the final covariance matrix similar to the statistical uncertainty described above.

In *Model and Background*, the systematic uncertainties, such as the experimental uncertainties due to detector effects, affect the background estimate and also the simulated signal used to produce the response matrix. In such cases, instead of using the nominal response matrix, the unfolding is performed using the corresponding response matrix obtained with the respective systematic variation, and the symmetrization procedure is repeated.

Apart from the above, the uncertainties stemming from the unfolding procedure itself, discussed in the previous section, are also propagated. To this category, a second uncertainty source, originating from the uncertainty in the unfolding inputs due to the limited statistics in the signal sample, is considered. Unfolding is performed bin-by-bin 200 times by Gaussian fluctuating the correction factors, and the uncertainty is obtained from the covariance matrix.

Finally, at the level of cross-section measurement, an uncertainty of 1.7% on the luminosity is further included.

The contribution of each uncertainty source to the cross-section is described in the next chapter, which presents the results of the unfolded cross-sections obtained from the data.

⁴The theoretical uncertainties on the signal are not propagated to the unfolded result, but the uncertainties affect the signal strength, which influences the post-fit background estimates propagated.

Chapter 14

Results

This chapter presents the measurement results of the differential cross-section of the $W^\pm W^\pm jj$ -EWK process from the ATLAS experiment. The data are unblinded, and the statistical treatment and the unfolding procedure described in Chapters 12-13 are repeated but this time with the real data. From a profile likelihood, the reconstructed level background yields and uncertainties that maximize the likelihood with the observed data are determined. The results are then unfolded with the Bayesian method using two iterations and the cross-sections are extracted at the particle level. The cross-section is computed differentially for the $W^\pm W^\pm jj$ -EWK process and four observables are considered for measurement. All the results presented in this chapter are the work of the author.

14.1 Fit Results

According to the treatment described in Chapter 12, a profile likelihood fit is implemented to derive the background yields and uncertainties, that provide the maximum likelihood with the observed data, to be used in the unfolding procedure. The fit is performed on the (pre-fit) estimated signal and background yields in the Low m_{jj} control region, the WZ control region, and the signal region using the observed data. From the maximum likelihood fit, the signal strength (μ) of the $W^\pm W^\pm jj$ -EWK process and all the nuisance parameters including the normalization factor of the $WZjj$ -QCD process are determined. The signal strength provides a measure by which the nominal signal predictions (Equation (12.13) in Chapter 12 as predicted by MADGRAPH) are to be scaled to agree with the data. The parameter is additionally used to normalize the interference of the electroweak and the QCD induced contributions by $\sqrt{\mu}$. The fitted signal strength of the $W^\pm W^\pm jj$ -EWK process using the full Run 2 datasets is

$$\mu = 1.14 \pm 0.11, \quad (14.1)$$

observed with a significance of 12.4 standard deviations over the background-only hypothesis. Figure 14.1 presents the overall agreement between the data and the expectations in the three regions included in the fit, which shows that the composition of the data is understood in all the regions. The normalization factor of the $WZjj$ -QCD process extracted from the fit is

$$\theta_{WZ} = 0.72 \pm 0.07, \quad (14.2)$$

and is found to be consistent with the measurements in [78], [140]. Figure 14.2 summarizes the results of signal strength and the normalization parameter obtained from the maximized likelihood fit. The nuisance parameters with the largest impact on the obtained signal strength are ranked

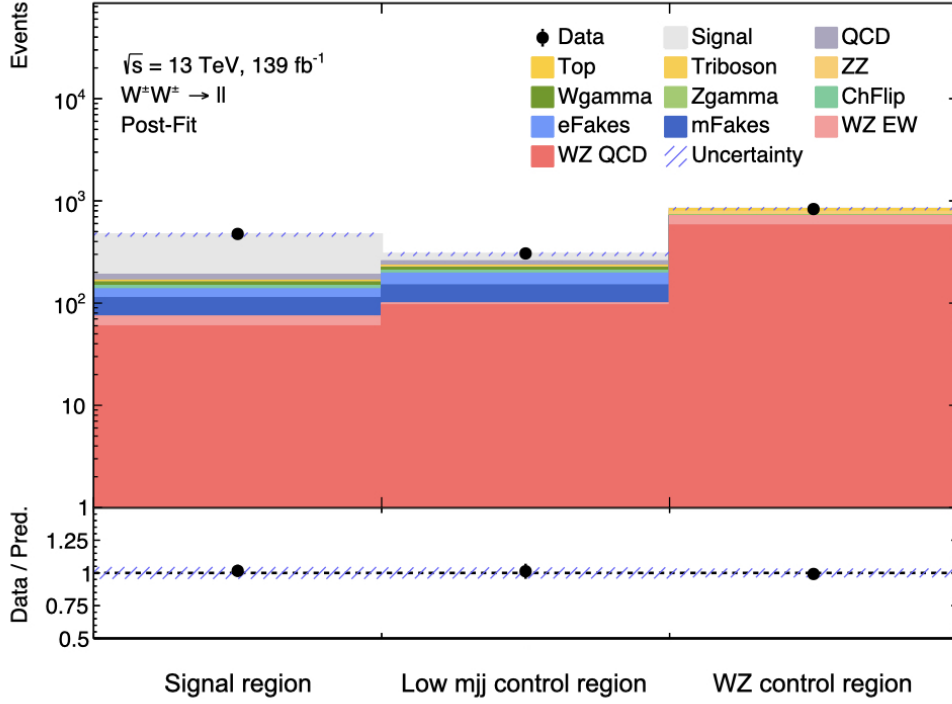


Figure 14.1: A summary of the post-fit yields in the signal region, the Low m_{jj} , and the WZ control regions are shown. The electroweak and the interference contributions of $W^\pm W^\pm jj$ are combined as signal, and the strong contribution is given by QCD. The $WZjj$ process is shown in shades of red, fake leptons in shades of blue, e/γ conversions in shades of green, and finally other prompt leptons in shades of yellow. The total expectations are seen to agree with the observed data in the three regions.

in Figure 14.3, which also displays their respective pulls. The modeling of prompt leptons in fake factor estimation is ranked to have the largest impact on the fitted signal strength followed by the statistical uncertainty on the m_{jj} shape re-weighting factors of the $WZjj$ -QCD process. The post-fit yields of the various processes in the signal region are summarized in Table 14.1 in all the lepton channels. Compared to the pre-fit results (see Table 12.2 in Chapter 12), there is a significant reduction in the contribution of the $WZjj$ background due to the corrected normalization of the process while the changes in all the other backgrounds are within one standard deviation. $WZjj$ process is still the leading background in the measurement, followed by non-prompt leptons.

The pre-fit and the post-fit contributions of the various processes in the signal region are compared in Figures 14.4-14.7 for the distributions of the four observables, m_{ll} , m_{jj} , m_T , and ξ , considered for the differential cross-section measurements. The modified yields after the fit match with the data within uncertainties and the post-fit results are used to extract the unfolded differential cross-sections at the particle level. While it is possible to extract the cross-section from the profile likelihood fit in a bin-by-bin approach, the cross-sections are unfolded in this measurement using the Bayesian method for the various reasons described in Chapter 13.

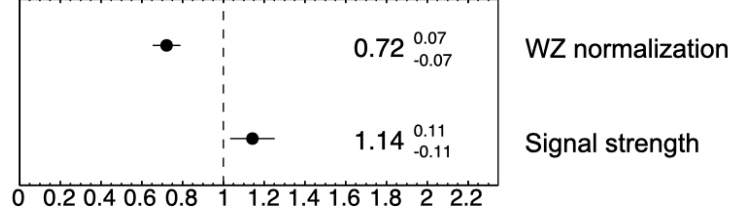


Figure 14.2: The signal strength of $W^\pm W^\pm jj$ -EWK and the normalization factor of $WZjj$ obtained from the maximized likelihood fit on observed data are shown.

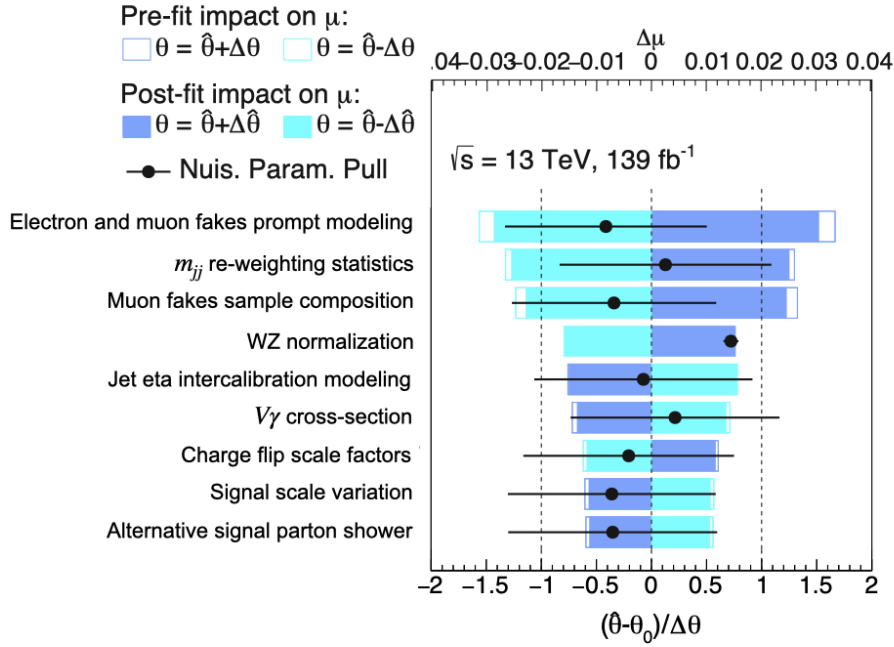
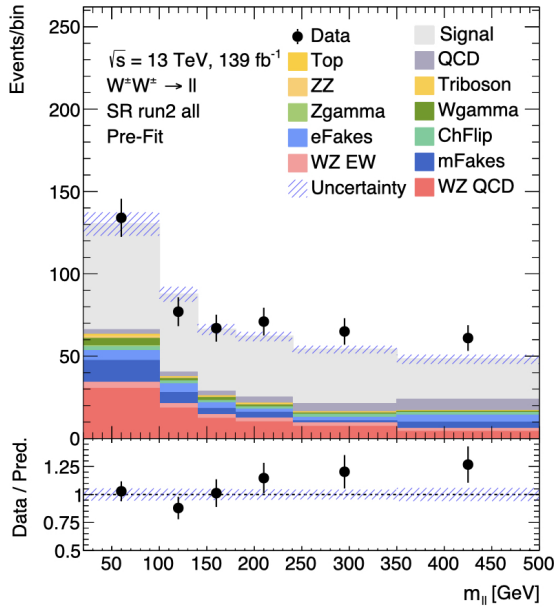


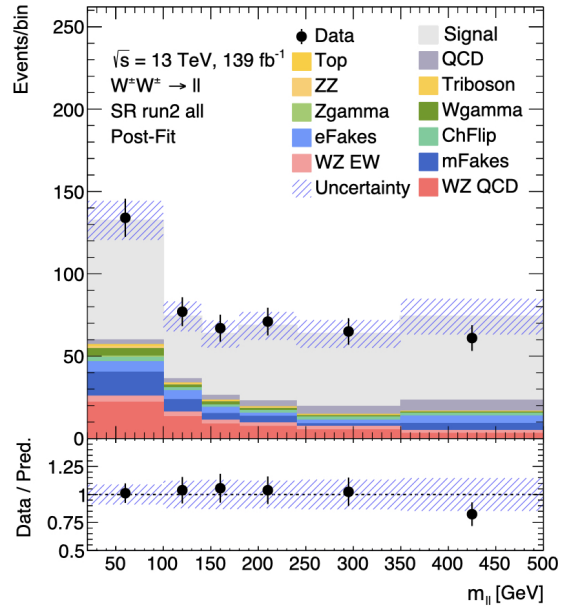
Figure 14.3: Ranking plot showing the nuisance parameters according to their impact on the measured signal strength from the observed data is given. Only the top nine parameters are shown. The hollow rectangles correspond to the pre-fit impact and the filled ones correspond to the post-fit impact, both referring to the upper scale. The impact of each nuisance parameter, $\Delta\mu$, is computed by comparing the nominal best-fit μ with the result of the fit when fixing the considered nuisance parameter to its best-fit value, $\hat{\theta}$, shifted by its pre-fit (post-fit) uncertainties $\pm\Delta\theta$ ($\pm\Delta\hat{\theta}$). The black points show the pulls of the nuisance parameters with respect to their nominal values, θ_0 . The pulls and their relative post-fit errors, $\Delta\hat{\theta}/\Delta\theta$, refer to the lower scale.

Signal	ee	$e\mu$	$\mu\mu$	μe	ll
$W^\pm W^\pm jj$ -EWK	31.5 ± 3.0	78 ± 7	88 ± 9	70 ± 7	268 ± 26
Background	ee	$e\mu$	$\mu\mu$	μe	ll
$WZjj$	7.7 ± 0.7	24.0 ± 2.0	19.0 ± 1.6	19.4 ± 2.1	74 ± 6
Non-prompt	9.4 ± 1.8	16.8 ± 2.5	25 ± 6	11.2 ± 1.5	62 ± 10
$W^\pm W^\pm jj$ -QCD	1.55 ± 0.05	7.25 ± 0.22	8.80 ± 0.25	6.40 ± 0.16	24.0 ± 0.7
Conversions	5.7 ± 2.1	10.8 ± 2.3	0.003 ± 0.004	6.3 ± 2.4	22 ± 6
$W^\pm W^\pm jj$ -INT	0.99 ± 0.11	2.35 ± 0.20	2.69 ± 0.20	2.11 ± 0.16	8.1 ± 0.7
Other Prompt	1.00 ± 0.19	2.4 ± 0.5	1.8 ± 2.2	1.81 ± 0.33	6.9 ± 1.4
Total Expected	58 ± 4	141 ± 7	146 ± 9	121 ± 7	466 ± 23
Data	52	149	147	127	475

Table 14.1: The post-fit yields in the signal region are shown along with the total uncertainties.

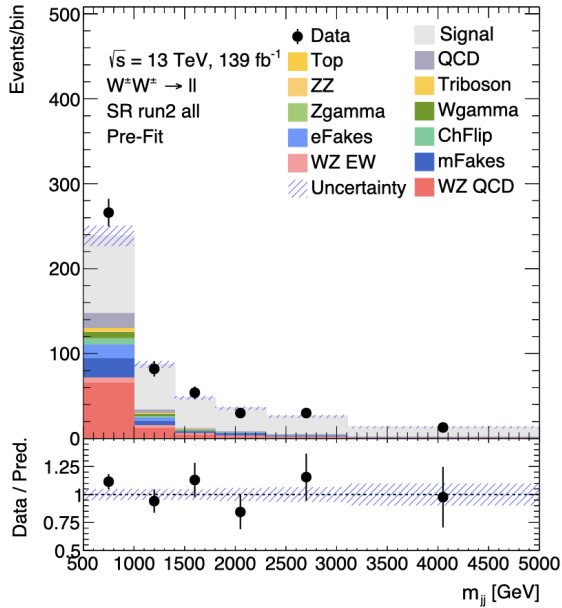


(a)

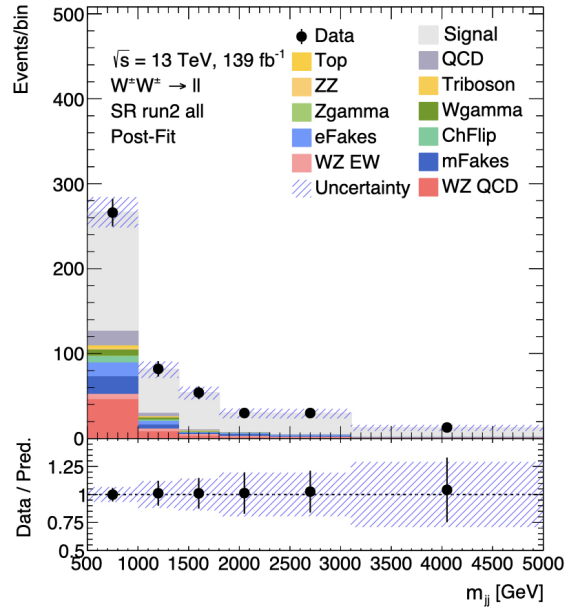


(b)

Figure 14.4: The pre-fit (left) and the post-fit (right) distributions of m_{ll} in the signal region are shown.

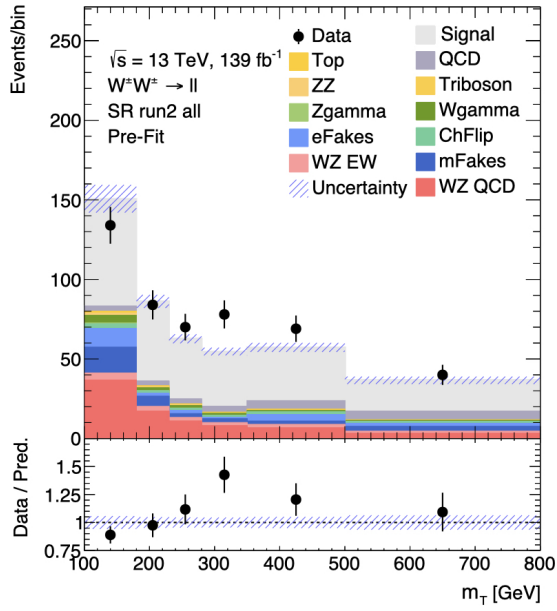


(a)

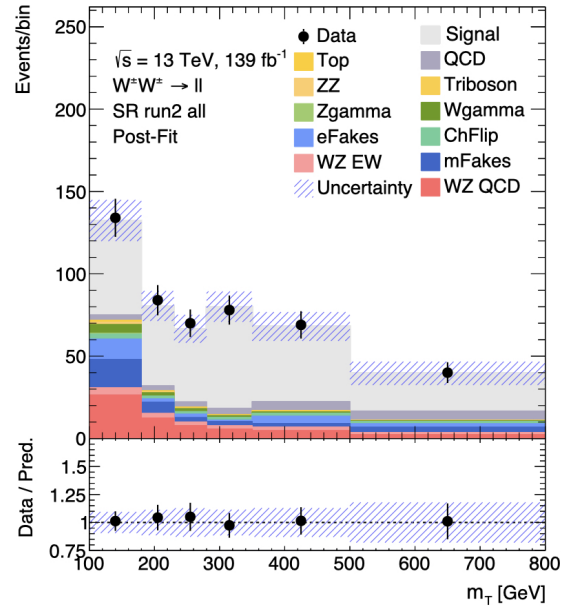


(b)

Figure 14.5: The pre-fit (left) and the post-fit (right) distributions of m_{jj} in the signal region are shown.

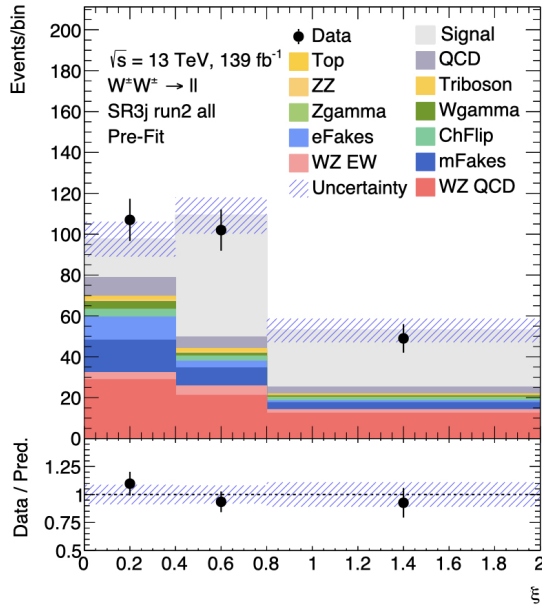


(a)

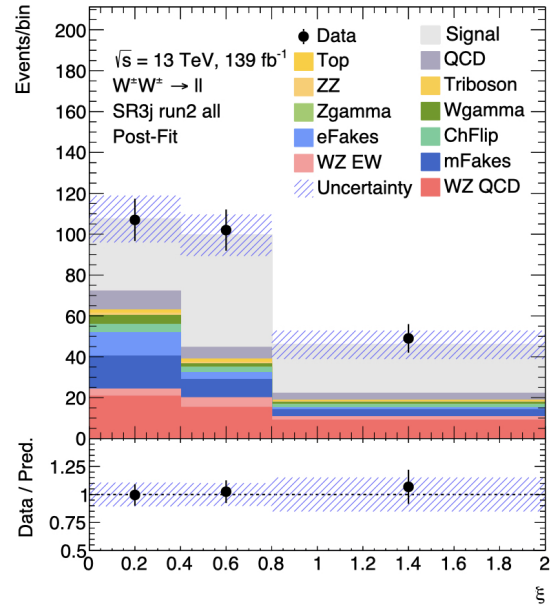


(b)

Figure 14.6: The pre-fit (left) and the post-fit (right) distributions of m_T in the signal region are shown.



(a)



(b)

Figure 14.7: The pre-fit (left) and the post-fit (right) distributions of ξ in the signal region are shown.

14.2 Unfolded Cross-Sections

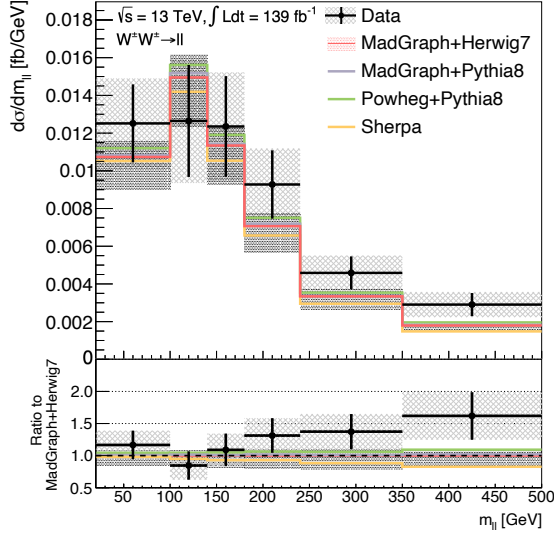
The reconstructed level post-fit distributions of the four observables are extrapolated to the particle level using the Bayesian unfolding method iterated two times. The differential cross-sections are obtained using Equation (7.2), and the uncertainties are propagated to the cross-sections according to the prescription described in Chapter 13. Figure 14.8 presents the differential cross-sections extracted for the observables using the full Run 2 datasets. The results are compared with the leading order predictions from MADGRAPH+HERWIG7, MADGRAPH+PYTHIA8, and SHERPA, and next-to-leading order QCD predictions from POWHEG+PYTHIA8. Overall, the measured cross-sections agree reasonably well with the Standard Model predictions within the uncertainties. Nevertheless, the data show an upward deviation with respect to the Standard Model expectations in certain bins with the most significant deviation seen in the fourth bin of the m_T distribution, which is addressed in Section 14.3. These results are the most precise measurements to date of this process. In Figure 14.9, the contribution of each uncertainty source can be seen for the differential measurements, and the uncertainty sources are summarized below for completeness:

1. Statistical uncertainty

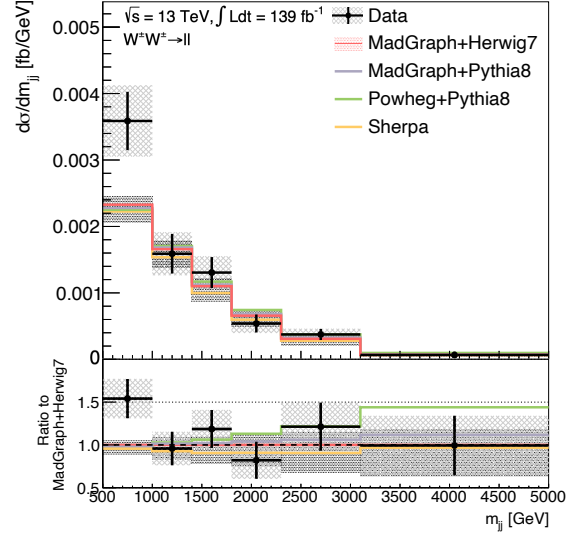
- Limited data statistics: The statistical uncertainty on the unfolded data events is computed from Poisson modeled pseudo experiments (see Section 13.6.2).

2. Systematic uncertainty

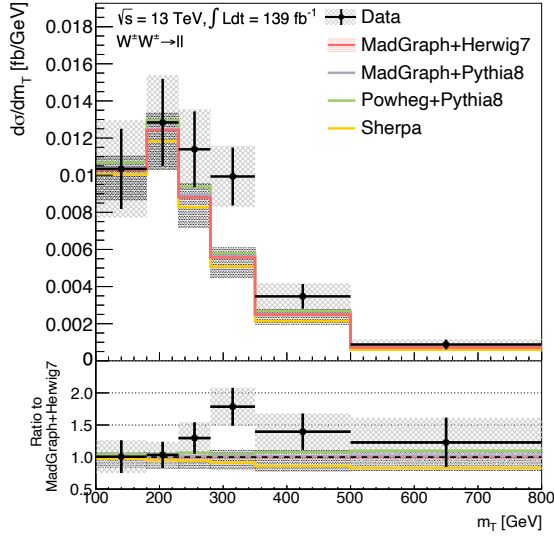
- Model and background: The model and background systematic uncertainty includes all uncertainty sources that affect the backgrounds as well as the signal model used in the unfolding inputs, such as the experimental uncertainty due to detector effects (see Section 13.6.2).
- Background-only: The background-only systematic uncertainty includes all uncertainty sources that affect only the background and not the signal, such as the experimental uncertainty due to data-driven background estimates (see Section 13.6.2).
- Unfolding: The uncertainty associated with the unfolding procedure account for the uncertainty due to the non-closure in the data-driven closure test (see Section 13.5) and the uncertainty in the unfolding inputs due to limited statistics in the signal sample (see Section 13.6.2).
- Luminosity: A flat uncertainty of 1.7% is used as the luminosity uncertainty (see Section 3.2.5).



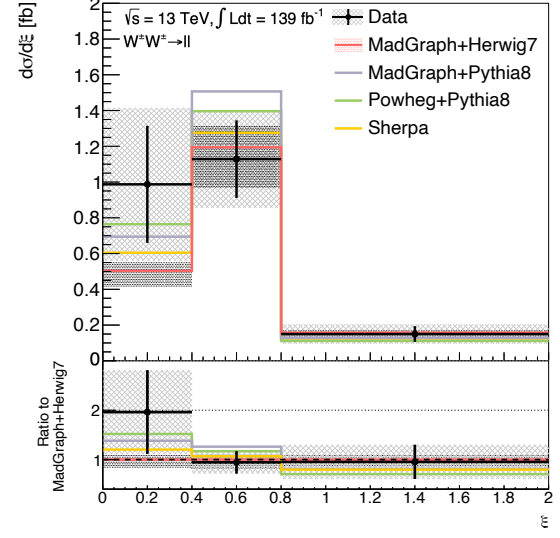
(a) $m_{\ell\ell}$



(b) m_{jj}

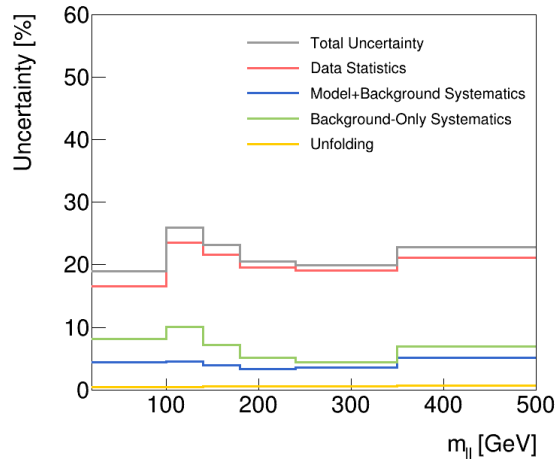


(c) m_T

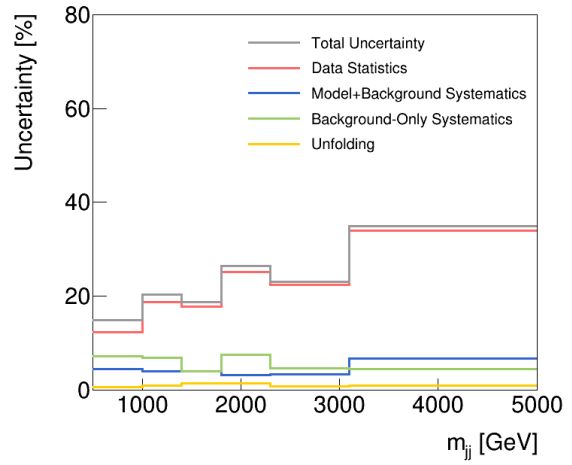


(d) ξ

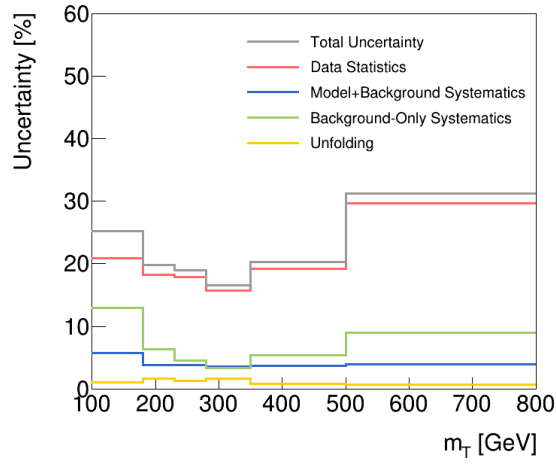
Figure 14.8: The unfolded differential cross-sections of $W^\pm W^\pm jj$ -EWK production in the lepton channel using the full Run 2 datasets compared against the Standard Model predictions are shown. The statistical uncertainty on the measured cross-section is indicated by the error bars (in black), whereas the total uncertainty is shown by the grey hashed band. The theoretical distributions given are predicted by MADGRAPH+HERWIG7 (in red) along with the uncertainties (in red band), MADGRAPH+PYTHIA8 (in purple), POWHEG+PYTHIA8 (in green), and SHERPA (in yellow). The theoretical uncertainties shown include the statistical, scale, PDF and α_s uncertainties.



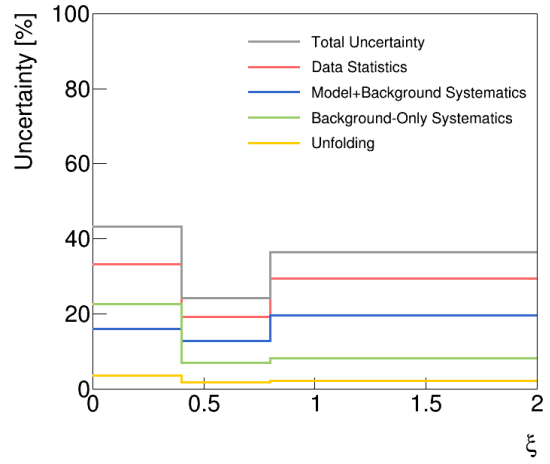
(a) m_{II}



(b) m_{jj}



(c) m_T



(d) ξ

Figure 14.9: The contribution of the various uncertainty sources on the unfolded events are plotted for the four observables. The luminosity uncertainty is not shown as it applies only at the level of cross-section measurements.

The total uncertainty on the measured cross-section is dominated by the uncertainty due to the limited data statistics. Integrating the distributions, the fiducial cross-section measured by the ATLAS experiment is found to be

$$\sigma_{\text{fid}} = 3.51 \pm 0.27 (\text{stat}) \pm 0.23 (\text{syst}) \text{ fb}. \quad (14.3)$$

The overall uncertainty of 10% on the measurement includes a statistical uncertainty of 7.8% and a systematic uncertainty of 6.6%. The contributions of the individual sources of the systematic uncertainty to the total uncertainty are detailed in Table 14.2. Non-prompt leptons and jets are the dominant sources of the systematic uncertainty, and the leading uncertainties of these two sources are given in Table 14.3. The description of the leading uncertainties are provided already in Chapters 6 and 11. Finally, the result in Equation (14.3) is additionally cross-checked with the signal strength obtained from the maximum likelihood fit (see Section 14.1) and is found to agree within the uncertainties¹.

The measured cross-section is consistent with the predictions of the Standard Model from MADGRAPH+HERWIG²,

$$\sigma_{\text{pred}} = 2.97^{+0.28}_{-0.24} \text{ fb}. \quad (14.5)$$

The result also agrees with the experimental result from the previous iteration of the analysis³ using partial Run 2 data [78] shown in Figure 14.10. Table 14.4 provides a summary of the observed results and the predictions using the partial and the full Run 2 datasets at $\sqrt{s} = 13 \text{ TeV}$. The measurements from the CMS experiment [83], [141] are also added for comparison, but it has to be noted that the CMS experiment uses a slightly different fiducial phase space, and the result cannot be compared directly with the ATLAS measurement.

14.3 The m_T Distribution

In the fourth bin⁴ of the m_T distribution, a notable excess of events is observed in the data with respect to the predictions of the Standard Model as can be seen from Figures 14.6 and 14.8c. This can suggest either a manifestation of new physics or a mere statistical fluctuation. The significance of the excess is quantified in terms of the local p-value, which gives the probability to produce an excess at least as large as the one observed. The local p-value is obtained as 2.9×10^{-4} equivalent to a local significance of 3.4 standard deviations. The probability of the excess with the calculated local p-value as the most significant excess to be observed anywhere in the distribution is known as the global p-value. The global p-value is determined using the Look Elsewhere Effect as detailed in Appendix E and is found to be 1.7×10^{-3} , corresponding to a global significance of 2.9 standard deviations, resulting in no evidence for deviations from the Standard Model predictions.

¹From the fitted signal strength in Equation (14.1), the cross-section can be computed as

$$\sigma_{\text{fid}}^{\text{LH}} = \mu \times \sigma_{\text{pred}} = 3.39 \pm 0.33 \text{ fb}, \quad (14.4)$$

where σ_{pred} corresponds to the predicted cross-section taken from Equation (12.13) in Chapter 12. The cross-section determined is consistent with the result in Equation (14.3) within the uncertainties. During the fitting procedure, the signal MC is re-weighted to match the data distribution of a given variable, which changes the correction for the detector inefficiency. This results in a slightly different central value for the cross section in the fit method compared to the background-subtracted data method used in Bayesian unfolding.

²same as Equation (12.13) in Chapter 12.

³The SHERPA 2.2.2 sample predicts a lower cross-section due to an improper color flow setting (see Chapter 8).

⁴The excess of the observed data events in the m_T distribution corresponds to the excess observed in the high m_{ll} and low m_{jj} bins in Figures 14.8a-14.8b.

Uncertainty Source	%
Data statistics	7.8%
Non-prompt leptons	4.0%
Jets	3.4%
Background statistics	2.0%
m_{jj} shape re-weighting	1.8%
Luminosity	1.7%
Theory [*]	1.6%
Charge flipped electrons	1.3%
b -jets	1.0%
Muons	0.68%
Electrons	0.50%
E_T^{miss}	0.50%
Pile-up	0.29%
Unfolding	0.21%
Total systematics	6.6%
Total uncertainty	10.2%

^{*} Theoretical uncertainties on background modeling (see Chapter 12).

Table 14.2: The contribution of the various uncertainty sources to the integrated fiducial cross-section.

Uncertainty Source	Systematic Uncertainty	%
Non-prompt leptons	Prompt modeling in electron and muon fakes	2.7%
	Sample composition difference in muon fakes	2.3%
Jets	η inter-calibration modeling	1.7%
	Flavor response	1.4%
	Pile-up modeling	1.3%

Table 14.3: The contribution of the leading uncertainties of the dominant systematic uncertainty sources on the measured cross-section.

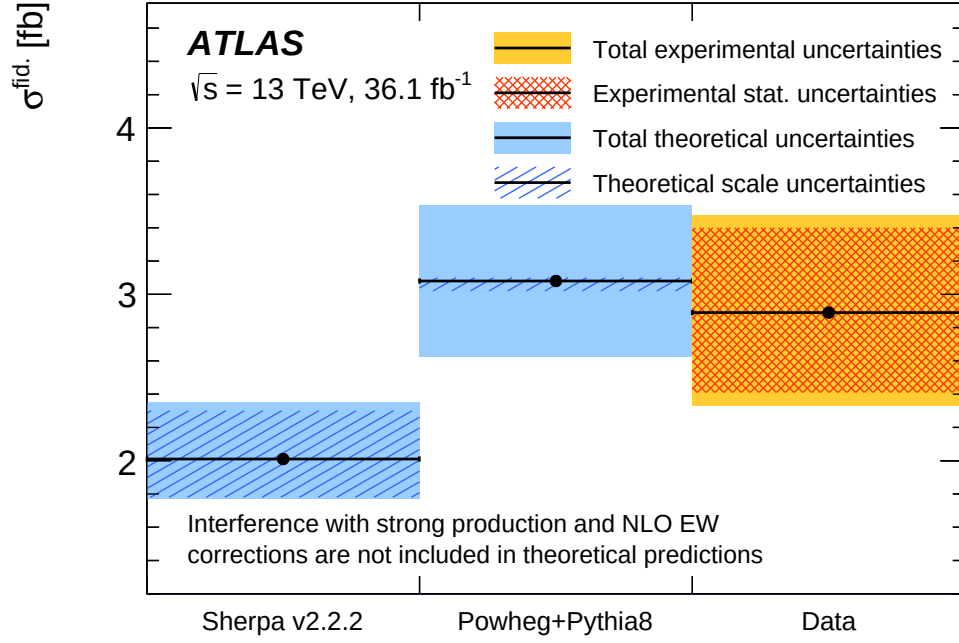


Figure 14.10: The comparison of the measured fiducial cross-section and theoretical predictions during the previous iteration of the analysis at $\sqrt{s} = 13 \text{ TeV}$ using 36.1 fb^{-1} datasets.

Integrated Luminosity	Experimental Result	Theoretical Prediction
139 fb^{-1}	ATLAS $3.51 \pm 0.36 \text{ fb}$	MADGRAPH+HERWIG7 (LO) $2.97^{+0.28}_{-0.24} \text{ fb}$
36.1 fb^{-1}	ATLAS $2.89^{+0.58}_{-0.56} \text{ fb}$	POWHEG+PYTHIA8 (NLO) $3.08^{+0.45}_{-0.46} \text{ fb}$
137 fb^{-1}	CMS $3.98 \pm 0.45 \text{ fb}$	MADGRAPH+PYTHIA8 (LO) $3.93 \pm 0.57 \text{ fb}$
35.9 fb^{-1}	CMS $3.83 \pm 0.75 \text{ fb}$	MADGRAPH+PYTHIA8 (LO) $4.25 \pm 0.27 \text{ fb}$

Table 14.4: A comparison of the experimental measurement and the theoretical prediction of the $W^{\pm}W^{\pm}jj$ -EWK cross-sections for $\sqrt{s} = 13 \text{ TeV}$ are shown.

14.4 Potential Areas of Improvements

The result from the ATLAS Collaboration is measured with the highest precision achievable for the process, but the analysis has got areas where improvements are still possible. The current measurement is limited by the statistics of the LHC Run 2, but this will not remain the same for long. With the onset of Run 3, the collider is expected to deliver two times more data than in Run 2, with which a greater precision can be achieved. The uncertainty on the fake leptons can be reduced if the W +jets control region is studied further especially with another W +jets MC sample⁵. Furthermore, using an alternative $WZjj$ -QCD MC sample⁶ can eliminate the m_{jj} re-weighting procedure and reduce the uncertainty on the $WZjj$ -QCD background. The theory uncertainty is dominated by the cross-section uncertainty applied on $V\gamma$ samples. With more statistics at hand, the background can be better understood in a VBS phase space, and the uncertainty can be reduced.

⁵SHERPA and POWHEG simulated samples (see Chapter 11 and Appendix C) have already been used in the current analysis. An alternative sample simulated with a different generator is preferred.

⁶MADGRAPH simulated sample is available, but the sample is only at the stage of validation at the time of writing this thesis.

Chapter 15

Conclusion and Outlook

The discovery of the Higgs boson is the highlight in the history of the LHC. Due to the unique role the particle plays in the scattering of the gauge bosons, vector boson scattering has become a very exciting phenomenon in unraveling the electroweak sector. A golden channel characterizing VBS is the scattering of two W bosons with the same electric charge in their lepton decay modes, $pp \rightarrow W^\pm W^\pm jj \rightarrow l^\pm \nu l^\pm \nu jj$, with observation claimed in 2018 by the CMS experiment and in 2019 by the ATLAS experiment. This thesis presents the first measurement of the differential cross-section of the electroweak induced production of $W^\pm W^\pm jj$ from the ATLAS experiment. The data from the LHC proton-proton collisions at $\sqrt{s} = 13$ TeV from 2015-2018 totaling to 139 fb^{-1} are used. The measured cross-sections are unprecedented in precision and granularity ever achieved for the process.

Events with two leptons of the same electric charge, missing transverse energy, and two jets in the forward direction separated by large angles are used to identify the signal sought after. The leading background originates from the $WZjj$ process, followed by the non-prompt and fake leptons. The latter is estimated with a systematic uncertainty of 20%, which is a 55% reduction compared to the previous iteration of the analysis and is one of the largest improvements achieved in the measurement. A profile likelihood fit is performed to constrain the background predictions and reduce the uncertainties, and the post-fit results are used to unfold the cross-section. Using an iterative Bayesian unfolding procedure, the fiducial differential cross-section is extracted for four observables, and the results are found to be consistent with the predictions of the Standard Model within uncertainties.

The measurement of the differential cross-section for the process is just the beginning of probing the electroweak sector. Extracting the polarization fractions of the gauge bosons is of extreme importance to understand the nature of electroweak symmetry breaking and the role of the Higgs boson. Studies have shown that the purely longitudinal scattering of $W^\pm W^\pm jj$ can be obtained at the HL-LHC, with a significance of 3 standard deviations (considering only the statistical uncertainties) [142]. In addition to validating the predictions of the Standard Model, the process serves as a promising avenue to explore the sensitivities to new physics by searching for anomalous quartic gauge couplings using the Effective Field Theory interpretations [143] or for a doubly charged Higgs boson produced through vector boson fusion. The onset of Run 3 marks the beginning of a new era of precision electroweak measurements with a wealth of exciting results awaiting us!

Appendix A

Mathematical Justification for the Observed VBS Event Signature

Consider the scattering of two W bosons, as given in Figure A.1. The squared matrix element [144] can be written as

$$|\mathcal{M}|^2 \propto \frac{p_1 \cdot p_2 \, p_3 \cdot p_4}{(q_1^2 - M_W^2)^2 (q_2^2 - M_W^2)^2}, \quad (\text{A.1})$$

where $q_1 = p_1 - p_3$ and $q_2 = p_2 - p_4$ denote the four momenta of the two W bosons. The partonic centre of mass energy can be written as $\sqrt{s} = 2 p_1 \cdot p_2$. To maximize the probability amplitude for a fixed partonic centre of mass energy, there are two possibilities: increasing the numerator or decreasing the denominator.

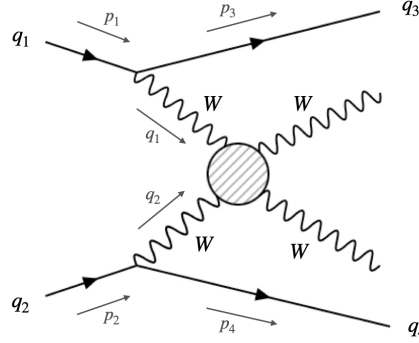


Figure A.1: The scattering of two W bosons.

Large di-jet invariant mass:

The invariant mass of the two tagging jets, m_{jj} , can be written as $m_{jj} = \sqrt{(p_3 + p_4)^2} = \sqrt{2 p_3 \cdot p_4}$. Increasing the numerator in Equation A.1 implies that $p_3 \cdot p_4$ should be high. This is manifested as the large invariant mass of the di-jets.

Small scattering angles:

For smaller denominator, one can take a look at:

$$\begin{aligned} q_1^2 &= (p_1 - p_3)^2 \\ &= -2 p_1 \cdot p_3 \\ &= -2 (E_1 E_3 - E_1 E_3 \cos \theta_1) \\ &= \frac{-2 E_1 E_3 (1 - \cos \theta_1)(1 + \cos \theta_1)}{(1 + \cos \theta_1)} \\ &= \frac{-2 E_1 E_3 \sin^2 \theta_1}{(1 + \cos \theta_1)} \cdot \frac{E_3}{E_3} \\ &= \frac{-2 E_1 p_{T,3}^2}{E_3 (1 + \cos \theta_1)}. \end{aligned} \tag{A.2}$$

The upper bound on q_1^2 is zero and $\frac{1}{q_1^2 - M_W^2}$ gets smaller for small values of θ_1 . Small scattering angles imply large rapidity separation between the two jets.

Appendix B

Energy Corrections in Charge Misidentification Background

In the course of Bremsstrahlung and subsequent pair production, the electron loses some of its energy as it interacts with the detector material, leading to leakage of energy outside the EM cluster and worsening of the resolution. The effect is visible in Figure B.1 which shows the di-electron invariant mass dominated by $Z \rightarrow ee$ events where the same-sign electrons are largely the result of charge-flip. The same-sign events show a wider distribution shifted towards lower energies in both data (in black) and MC (in green). The widening of the distribution is a result of the poorer resolution and the difference with respect to opposite sign events is the energy loss of the wrongly reconstructed electrons. Therefore, to describe the kinematics of the charge-flip background correctly, the momentum of the wrongly reconstructed electrons needs to be corrected. The corrections applied are based on the energy response, $\mathcal{R}$, defined as $\mathcal{R} = p_T^{\text{reco}}/p_T^{\text{true}} - 1$, which characterizes the difference in the original and the reconstructed p_T . Two correction terms are derived from MC and applied to the momentum as

$$p_T^{\text{corrected}} = \frac{p_T^{\text{orig}}}{1 + \alpha} + dE, \quad (\text{B.1})$$

where p_T^{orig} is the original p_T of the electron, $(1 + \alpha)$ is the correction in energy loss, and dE is the smearing term used to widen the distribution. The term α is derived in bins of $|\eta|$ as

$$\alpha = \frac{\mathcal{R}^{\text{correct}}}{\mathcal{R}^{\text{wrong}}}. \quad (\text{B.2})$$

dE is chosen randomly from a Gaussian distribution centered at zero and having a width equal to the difference in the relative variances of $\mathcal{R}^{\text{wrong}}$ and $\mathcal{R}^{\text{correct}}$ in the corresponding η bin. The di-electron invariant mass distribution obtained after applying the energy corrections are plotted (in orange) in Figure B.1. An overcorrection of the energy loss is seen resulting in a residual mis-modeling of the background estimate. To account for the uncertainties due to the energy correction technique, the background is re-estimated with a 100% uncertainty on the correction parameters. The effect was found to be negligible compared to the uncertainties on the scale factors and is therefore omitted.

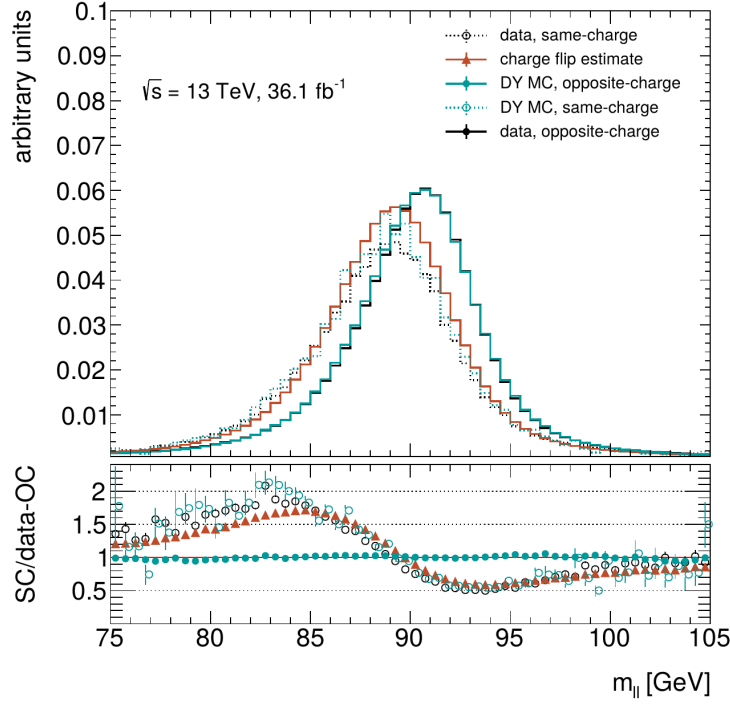


Figure B.1: Invariant mass of the two electrons in $Z \rightarrow ee$ events are plotted for data (in black) and MC (in green). The distributions in same-sign events (dashed lines) are shifted towards lower energies and are found to be wider compared to opposite-sign events (solid lines). The charge-flip background estimated from opposite-sign events according to the procedure mentioned in Section 10.2.2 is plotted in orange. The lower pad presents the ratio of the same-sign distributions to the opposite-sign distribution in data. Image taken from [145].

Appendix C

Additional Studies on Fake Factors

C.1 Alternative W +jets Sample

On account of the large normalization factor obtained for the SHERPA W +jets sample in $n_{b-jet} \geq 1$ events, fake factors have also been derived with an alternative sample simulated using POWHEG interfaced with PYTHIA. The fake factors obtained are plotted in Figure C.1, which agree with the SHERPA results within statistical uncertainties. But the shape of the distributions in the POWHEG sample differs from that in data in the W +jets control region. Therefore, the SHERPA sample is continued as the W +jets sample used in fake factor estimation.

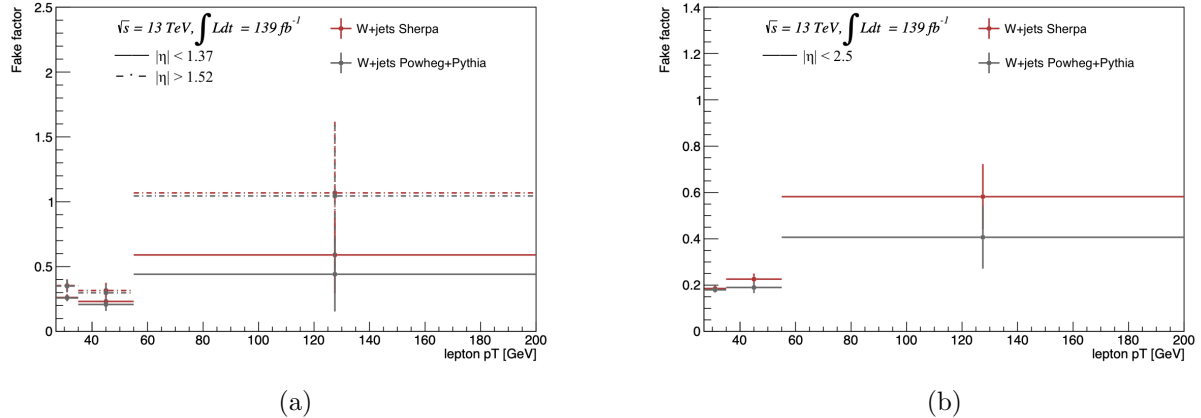


Figure C.1: Comparison of the fake factors obtained in $n_{b-jet} \geq 1$ events using different W +jets samples. The fake factors are obtained in the di-jet region as usual and only the W +jets prompt lepton source is simulated using different generators. The results obtained using the nominal SHERPA sample are plotted in red and the results obtained with an alternative POWHEG sample are plotted in gray. Only statistical uncertainties are shown. The results are shown before applying the corrections discussed in Section 11.4.2.

C.2 Heavy-Flavor Di-jet Region Selection

C.2.1 Jet Selection

To determine a suitable heavy-flavor di-jet region, several sample composition choices are considered such as:

- $n_{\text{jet}} \geq 1$: Baseline di-jet selection without applying any selections on b -jets
- $n_{b\text{-jet}} \geq 1$: At least one b -jet
- lead b -jet: Leading jet is b -tagged

The heavy-flavor di-jet region is then chosen as the one that varies maximally from the light-flavor di-jet region. Figure C.2 shows the fake factors obtained in the various regions. In the low p_T bins, where the fake lepton background is the largest, fake factors obtained from $n_{b\text{-jet}} \geq 1$ have the largest absolute difference from $n_{b\text{-jet}} = 0$. Hence, $n_{b\text{-jet}} \geq 1$ is taken as the heavy-flavor di-jet region.

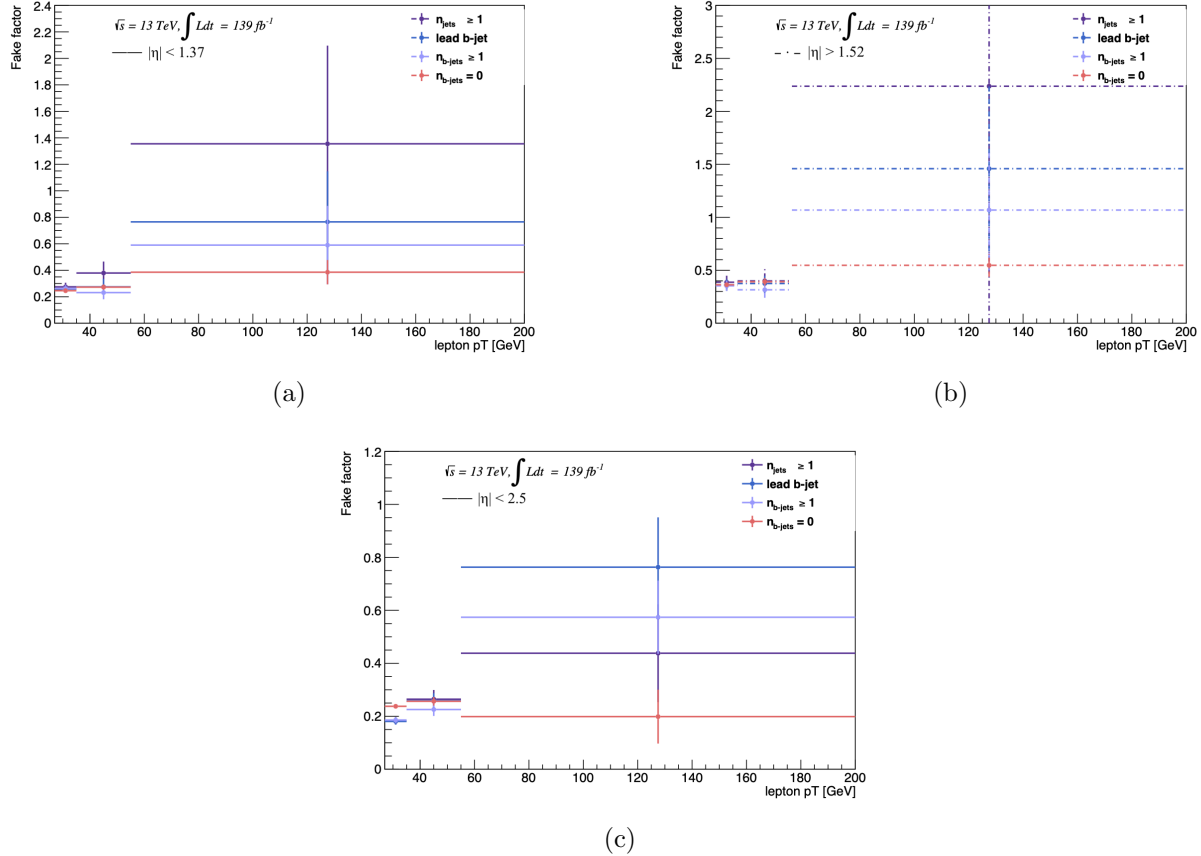


Figure C.2: Fake factors obtained in the various choices of jet selections are given for the electron channel (top) and the muon channel (bottom). Only statistical uncertainties are shown. The results are shown before applying the corrections discussed in Section 11.4.2.

C.2.2 Selection of b -Tagging Working Points in $n_{b\text{-jet}} \geq 1$

The various b -tagging working points have also been considered in the selection of $n_{b\text{-jet}} \geq 1$ events. The fake factors obtained for the different b -tagging efficiencies are plotted in Figure C.3 and 85% efficiency is chosen to tag b -jets in $n_{b\text{-jet}} \geq 1$ events due to the largest values of the fake factors estimated.

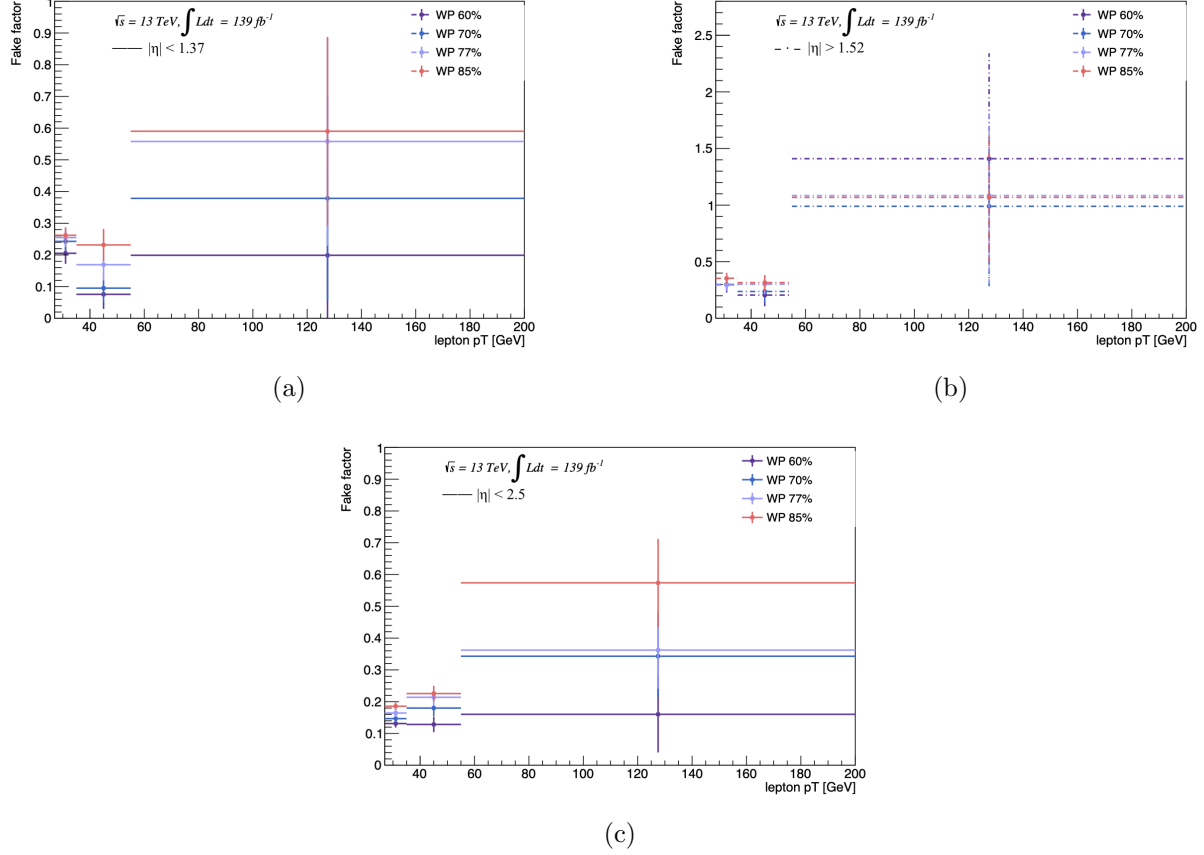


Figure C.3: Fake factors obtained for various b -tagging working points in $n_{b\text{-jet}} \geq 1$ events are given for the electron channel (top) and the muon channel (bottom). Only statistical uncertainties are shown. The results are shown before applying the corrections discussed in Section 11.4.2.

Appendix D

Experimental Systematic Uncertainties due to Detector Effects

A total of 128 sources of experimental systematic uncertainties due to detector effects are considered in the analysis. The uncertainties are provided by the ATLAS performance groups such that they can be applied at the event-level and object-level. At the event-level, a pile-up re-weighting uncertainty is included, which accounts for the uncertainty associated with re-weighting the MC events to emulate the pile-up profile in data. At the object-level, 127 sources associated with the physics objects used in the analysis are considered. The uncertainty sources of each object are detailed in Tables D.1-D.4.

Electrons:

Systematic uncertainty	Number of components
Energy scale	2
Energy resolution	1
Trigger efficiency	2
Reconstruction efficiency	1
Identification efficiency	34
Isolation efficiency	1

Table D.1: Systematic uncertainty associated with electrons due to detector effects.

Muons:

Systematic uncertainty	Number of components
Momentum scale	3
Momentum resolution	2
Trigger efficiency	2
Reconstruction efficiency	4
Track-to-vertex association efficiency	2
Isolation efficiency	2

Table D.2: Systematic uncertainty associated with muons due to detector effects.

Jets:

Systematic uncertainty	Number of components
Energy scale due to in-situ calibration	15
Energy scale due to η inter-calibration	5
Energy scale due to flavor response	1
Energy scale due to flavor composition	1
Energy scale due to pile-up modeling	4
Energy scale due to punch-through jets	1
Energy scale due to high p_T jets	1
Energy scale due to b -jets	1
Energy resolution	26
Jet-to-vertex tagging	1
Flavor tagging	12

Table D.3: Systematic uncertainty associated with jets due to detector effects.

E_T^{miss} :

Systematic uncertainty	Number of components
Soft term	3

Table D.4: Systematic uncertainty associated with E_T^{miss} due to detector effects.

Appendix E

Local Excess and Calculation of Global Significance

In chapter 14, the observed data distributions are found to agree with the Standard Model predictions largely but leaving some noticeable excess of events particularly in the fourth bin of the m_T distribution. The next natural step is to quantify the statistical significance of such an excess for which a likelihood scan is performed. If one recalls from chapter 12, the significance, Z , can be derived directly from the profile likelihood using the test statistic, t_μ (see Equation (12.11)), as $Z = \sqrt{t_\mu}$. But instead of using the background-only hypothesis ($\mu = 0$), the Standard Model prediction ($\mu = 1$) must be used as the null hypothesis to compute the significance with respect to the Standard Model expectations. The likelihood scan is plotted in Figure E.1 which shows the test statistic with the log likelihood for the best fitted value subtracted on the y -axis and the various μ values on the x -axis. The significance is calculated as

$$\begin{aligned} Z &= \sqrt{-2[\ln \mathcal{L}(\mu = 1|\hat{\theta}_{\mu=1}) - \ln \mathcal{L}(\hat{\mu}|\hat{\theta})]} \\ &= \sqrt{2 \cdot 6} \\ &= 3.4 \end{aligned} \tag{E.1}$$

The result has been additionally verified by performing a profile likelihood fit with the $W^\pm W^\pm jj$ -EWK signal considered among the backgrounds and computing the significance with respect to the background-only hypothesis. The observed significance is 3.4 standard deviations, consistent with Equation (E.1), equivalent to a p-value of 2.9×10^{-4} . The significances and the p-values computed thus far are *local*, in the sense that they account for the possibility of a background fluctuation occurring in this particular bin. It is plausible that a statistically significant observation may have indeed occurred by chance purely due to the size of the range considered, also known as the *Look Elsewhere Effect*. Therefore, instead of the local p-values, the relevant quantities to be quantified are the global p-values and significances that account for the possibility of a background fluctuation, as extreme as the one observed, occurring anywhere in the distribution.

To compute the global p-value, consider the probability to have a less extreme result than what is observed in the fourth bin, which is $1 - p_{local}$. As the m_T distribution is not steeply falling in nature, it is safe to assume that the fluctuations in a bin is independent from one another. Therefore, the probability that all the six bins of the m_T distribution have a less extreme result than what is observed in the fourth bin is $(1 - p_{local})^N$ where N is the number of bins. Finally, the probability that at least one of the six bins has a result at least as extreme as the one observed in

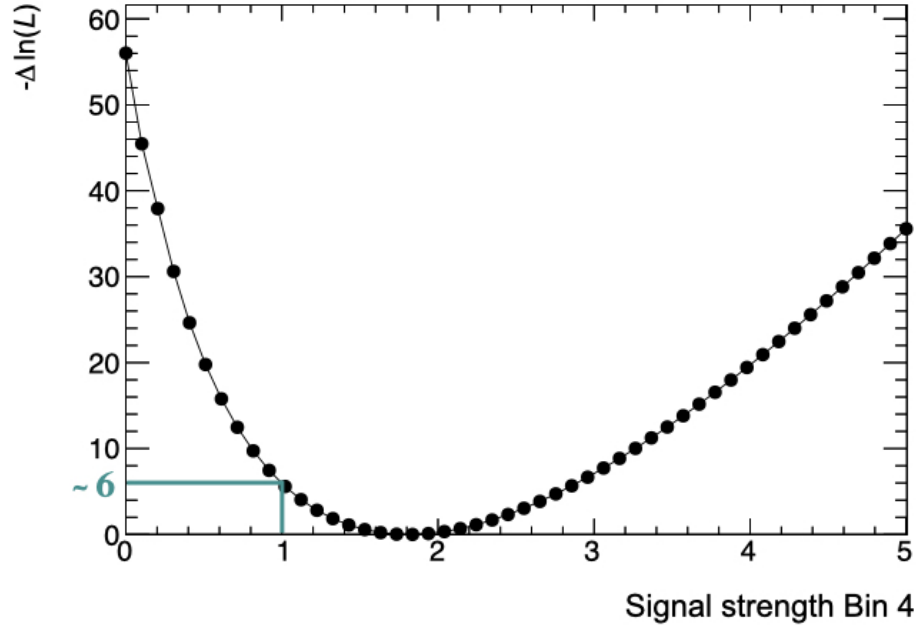


Figure E.1: The likelihood scan is plotted in the fourth bin of the m_T distribution. On the y -axis, $-\Delta \ln \mathcal{L}$ is plotted for the various μ values shown on the x -axis.

the fourth bin is given by

$$p_{\text{global}} = 1 - (1 - p_{\text{local}})^N. \quad (\text{E.2})$$

The above equation yields a global p-value of 1.7×10^{-3} , resulting in a corresponding global significance of 2.9 standard deviations. The global values are consistent with the results from Davies formula [146], used in the search for the Higgs boson [147]. Alternatively, one can also compute the global significance from toy experiments (number of toys of $\mathcal{O}(10^5)$). As the method is highly CPU-intensive and time consuming, it is not considered in this thesis due to the limited time available for the completion of the same.

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Author's Contributions

In the past three years of my doctoral studies, I have taken responsibilities in physics analyses, detector operations, detector upgrade, tutoring at the university, and also taken leadership roles all of which have shaped the successful completion of this dissertation. But for the sake of brevity, only the contributions in the context of the same-sign WW analysis have been primarily focused here.

Physics Analyses

The work presented in this thesis, associated with $W^\pm W^\pm$ scattering, is expected to result in seven ATLAS publications¹, where I am one of the authors. None of this would have been possible without the help of my supervisor, Beate Heinemann, and my postdoctoral supervisor, Oleg Kuprash, whose influence and inputs are absolutely unparalleled.

Having enrolled in the Ph.D. program at Freiburg in 2019, I was fortunate to join the same-sign WW analysis group at the right time to be one of the main analyzers. My first task was to reproduce the results from the previous iteration of the measurement, and migrate the technical framework to a multi-analyses compatible version of the HWWANALYSIS framework. This was accompanied by necessary changes to use the updated release required for analyzing the full Run 2 datasets. To perform a differential cross-section measurement with sufficient statistical significance, the backgrounds must be estimated precisely. As the previous iteration of the analysis suffered from large uncertainties of 43% (pre-fit) on the non-prompt lepton background, the second largest background, I led the effort to re-consider its estimation strategy and make a precise measurement of the background. This began with the technical implementation for producing PAOD samples with single leptons events, followed by the validation of the samples and optimization of the isolation working points.

In the same year, I joined the $W^\pm W^\mp + \geq 1$ jet measurement and derived fake factors for the analysis, which resulted in an uncertainty of 35% on the non-prompt lepton background. Working on this second analysis boosted my knowledge which has undoubtedly contributed to the convergence of the non-prompt background estimation to the method described in Chapter 11, estimated with an uncertainty of 20%. The method and results presented are utilized (partially or fully) for this background estimation in W boson polarization measurement in $W^\pm W^\pm$ scattering, $W^\pm W^\pm$ production through double parton scattering and search for heavy Majorana neutrinos in $W^\pm W^\pm$ scattering. Finally, the strategy has also been adapted in $W^\pm W^\mp + \geq 0$ jet and $WZ\gamma$ analyses.

¹1) Differential $W^\pm W^\pm$ scattering (thesis topic, not yet published),

2) W boson polarization in $W^\pm W^\pm$ scattering (not yet published),

3) Study of $W^\pm W^\pm$ production through double parton scattering (expecting observation, not yet published),

4) Differential $W^\pm W^\mp + \geq 1$ jet production [130],

5) Differential $W^\pm W^\mp + \geq 0$ jet production (not yet published),

6) Study of $WZ\gamma$ production (expecting observation, not yet published), and

7) Search for heavy Majorana neutrinos in $W^\pm W^\pm$ scattering (not yet published).

Apart from the estimation of non-prompt lepton background, I have made substantial contributions in testing the overall modeling of the various backgrounds in four out of the six validation regions presented, performing statistical analysis, optimizing the bin edges of the unfolding observables, unfolding, and extracting the cross-sections, all of which have been covered in this dissertation. All the results in these topics given in Chapters 11-14 are my own work.

Detector Operations and Upgrade

As part of the ATLAS service task, I joined the New Small Wheel project in 2019 under the supervision of the late Stephanie Zimmermann. After qualifying in 2020, I continued my contributions for another year until the installation of the detector at P1. Together with my local technical supervisors, Thorwald Kleingrothaus (until mid-2020) and Efstathios Karentzos (since mid-2020), I finalized the naming convention utilized for the high voltage systems and led the efforts in developing a mapping strategy to connect the high voltage cables from the detector chamber readout channels all the way to the underground rack maximizing the geometric coverage in the physics data. Additionally, I was the sole developer of a WinCC-OA project that can be operated from the ATLAS Control Room to test the current leakage in these cables.

Furthermore, I was also the ATLAS Control Room shifter at the Run Control desk during the machine development weeks prior to Run 3 when the ATLAS sub-detectors were being continuously and rigorously tested to ensure successful long-term operations of the detector during Run 3.

Laboratory Course on the ATLAS Experiment

Three out of the five teaching semesters at the university, I was the tutor in charge of data analysis with the ATLAS experiment, one of the experiments of the advanced laboratory courses for master's students. The experiment involved identifying physics processes using ATLANTIS event display, calibrating the electron energies using $Z \rightarrow ee$ decays, measuring the W boson mass using a simple likelihood fit, and finally searching for the Higgs boson, all of which have resulted in an increment in my overall understanding of data analysis in ATLAS.

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