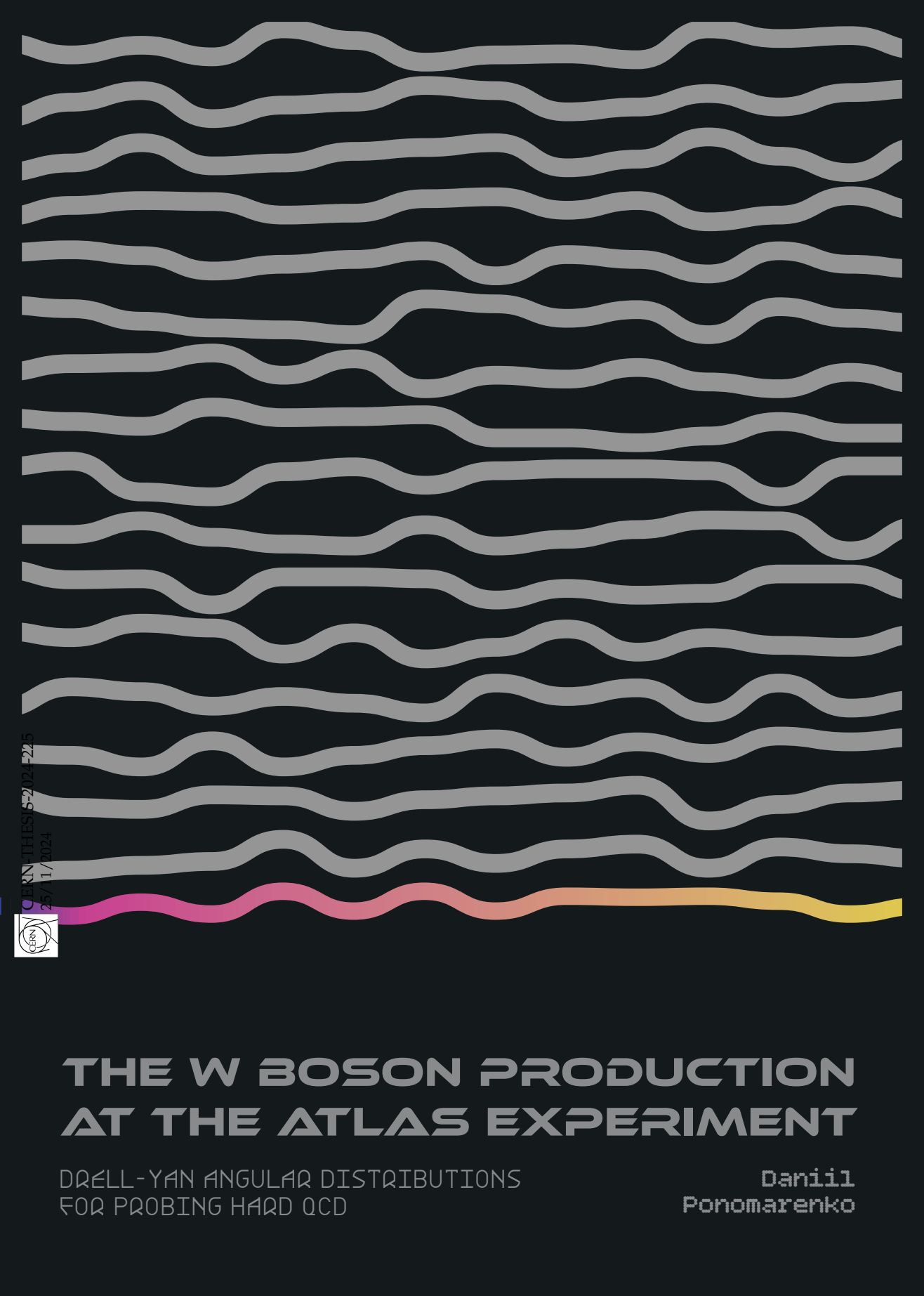




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THE W BOSON PRODUCTION AT THE ATLAS EXPERIMENT

DRELL-YAN ANGULAR DISTRIBUTIONS
FOR PROBING HARD QCD

Daniil
Ponomarenko

THE W BOSON PRODUCTION AT THE ATLAS EXPERIMENT

DRELL-YAN ANGULAR DISTRIBUTIONS FOR PROBING HARD
QCD

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QCD**

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volgens besluit van het college voor promoties
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Daniil PONOMARENKO

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te Vladivostok, Rusland

Promotoren:

prof. dr. N. De Groot
prof. dr. A. Romaniouk (Universiteit van Innsbruck, Oostenrijk)

Manuscriptcommissie:

prof. dr. C.W.J.P. Timmermans (voorzitter)
dr. S. Caron
dr. H. Schoorlemmer
prof. dr. J. Rojo (Vrije Universiteit Amsterdam)
prof. dr. M. Vreeswijk (Universiteit van Amsterdam)

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Dissertation

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from Radboud University Nijmegen,
on the authority of the Rector Magnificus prof. dr. J.M. Sanders,
according to the decision of the Doctorate Board
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at 2.30 pm

by

Daniil PONOMARENKO

born on March 27, 1992
in Vladivostok, Russia

Supervisors:

prof. dr. N. De Groot
prof. dr. A. Romaniouk (University of Innsbruck, Austria)

Manuscript Committee:

prof. dr. C.W.J.P. Timmermans (chair)
dr. S. Caron
dr. H. Schoorlemmer
prof. dr. J. Rojo (Free University Amsterdam)
prof. dr. M. Vreeswijk (University of Amsterdam)

*Nobody ever figures out what life is all about, and it doesn't matter. Explore the world.
Nearly everything is really interesting if you go into it deeply enough.*

—Richard P. Feynman

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INTRODUCTION

High-energy physics studies elementary particles and their interactions, evolving through experimental discoveries and theoretical developments. The Standard Model (SM) is a central concept in this field, a fundamental theory from the 20th century that describes the electromagnetic, weak, and strong forces.

The W boson, an intermediate particle in the weak force, is a key element of the SM. As an elementary gauge boson, its properties are significant for exploring deeper symmetries and possible new physics beyond the SM. The decay process of the W boson into a lepton and a neutrino ($W \rightarrow \ell \nu$) is one of the channels used to detect the W boson, offering insights into the physics of fundamental particles.

However, a detailed and comprehensive understanding of W boson production requires studies beyond superficial observables. In this context, the coefficients A_i , known as *Drell-Yan angular coefficients*, become particularly relevant. These coefficients are essential for quantifying the polarization states of the W boson and analyzing its decay dynamics. They characterize the angular distribution of decay products in the process $W \rightarrow \ell \nu$ in hadronic collisions. The analysis of these angular distributions through the A_i coefficients allows researchers to test the predictions of the SM and probe potential new physics phenomena. While individual A_i coefficients have been probed in various contexts, a holistic measurement of the entire set in W events represents a significant leap in the field.

The production process $pp \rightarrow W \rightarrow \ell \nu$ is a complex phenomenon that requires in-depth analysis under the principles of both quantum chromodynamics (QCD) and the electroweak interaction. This complexity arises because QCD drives the behavior of parton distribution functions and the dynamics of initial state interactions in proton-proton collisions, which are fundamental to the production mechanism. Concurrently, the electroweak interaction describes the subsequent production and decay of the W boson. A comprehensive representation of its differential cross-section is captured in Equation 1, which employs Drell-Yan angular coefficients (A_i). Here, the variables p_T^W , m_W , and y^W represent the transverse momentum, mass, and rapidity of the W boson in the laboratory frame, respectively. The angles θ and ϕ represent the polar and azimuthal angles of the lepton in the rest frame of the W boson. The rapidity is computed using the following equation: $y = \frac{1}{2} \ln \left[\frac{E+p_z}{E-p_z} \right]$ where E is the energy of the W boson, and p_z is the momentum of the W boson along the z-axis.

$$\begin{aligned}
\frac{d\sigma}{dp_T^W dm^W dy^W d\cos\theta d\phi} = \frac{3}{16\pi} \frac{d\sigma^{U+L}}{dp_T^W dm^W dy^W} & \left\{ (1 + \cos^2\theta) + \frac{1}{2}A_0(1 - 3\cos^2\theta) \right. \\
& + A_1 \sin 2\theta \cos\phi + \frac{1}{2}A_2 \sin^2\theta \cos 2\phi \\
& + A_3 \sin\theta \cos\phi + A_4 \cos\theta + A_5 \sin^2\theta \sin 2\phi \\
& \left. + A_6 \sin 2\theta \sin\phi + A_7 \sin\theta \sin\phi \right\} \quad (1)
\end{aligned}$$

The Equation 1 above illustrates the dynamics of the decay process and underscores the role of [QCD](#) in these interactions. Further details and a comprehensive derivation of this equation can be found in seminal works by Mirkes et al. [1], [2]. This thesis will examine the practical challenges and methods for measuring the A_i coefficients and their implications for particle physics.

Several implications arise from this investigation for both theoretical and experimental high-energy physics:

- Quantum Chromodynamics (QCD) Verification:** Quantum Chromodynamics ([QCD](#)) is the theoretical foundation of strong interactions in the [SM](#). Ensuring its consistency and applicability across different processes is important. The measurement of Drell-Yan angular coefficients (A_i) in the decay $W \rightarrow \ell\nu$ provides a means of testing the theoretical framework of [QCD](#). Discrepancies between these measurements and [QCD](#) predictions may indicate new phenomena or require further refinement of the theoretical framework. Moreover, focusing on the W boson's transverse momentum, p_T^W , may reveal effects of [QCD](#) that remain unnoticed in other analyses.
- Refinement of W -Mass Measurement:** The mass of the W boson's, m_W , is the key parameter in the [SM](#). Its precise determination is important for checking internal consistency and for investigating potential new physics. Data on the A_i coefficients can directly affect the accuracy of W -mass measurements. An improved understanding of the polarizations and asymmetries of the W boson's can enhance the methodologies employed to derive m_W from the lepton p_T spectrum. Such improvements could affect global fits and the [SM](#)'s precision tests by reducing systematic uncertainties.
- Enhancements in Parton Distribution Functions (PDFs):** [PDFs](#) represent the probability distribution of quarks and gluons within protons and play a core role in predicting cross-sections for various processes at hadron colliders. The analysis of the A_i coefficients can substantially refine current [PDF](#) models. Charge asymmetry measurements, in particular, can provide insights into flavor differentiation within protons. The measurement of asymmetry based on boson rapidity, in addition to lepton rapidity, provides a more comprehensive understanding, which may refine predictions for processes at colliders like the [LHC](#).

Among the various A_i coefficients, some are of particular significance in terms of their potential impact:

- **A_4 - Forward-Backward Asymmetry and Polarisation:** The A_4 coefficient allows the observation of the W boson asymmetry in the forward-backward direction. Polarization measurements provide detailed insight into the production and decay mechanisms of the W boson, including the dynamics of the involved interactions. The measurement of the A_4 coefficient can refine the modelling of the W boson transverse momentum (p_T^W) spectra and help reduce systematic uncertainties in it. Consequently, it improves the accuracy with which the W boson mass can be extracted from p_T lepton spectra in subsequent analyses.
- **Lam-Tung Relation ($A_0 - A_2$):** The Lam-Tung relation, predicting $A_0 - A_2 = 0$, arises due to the spin-1 nature of gluons. This relation is known to hold at the order of $\mathcal{O}(\alpha_S)$. However, deviations are theorized to occur at the order of $\mathcal{O}(\alpha_S^2)$. For the Z boson, such deviations were observed, approximately twice as large as the predictions. For the W boson, it remains an intriguing question as to whether such violations will manifest.

The subsequent chapters will address the methods for measuring the A_i coefficients and discuss their implications in particle physics.

Outline

In Chapter 1, an overview of the Standard Model is provided, focusing on weak boson production at hadron colliders, and discussing the significance of Drell-Yan angular coefficients, particularly concerning Z and W bosons. This chapter sets the stage for the subsequent detailed analyses and measurements of Drell-Yan angular distributions. Chapter 2 describes the operational sequence of the Large Hadron Collider (LHC) and highlights the special low-pileup run during LHC Run 2, which is essential for precise W boson physics measurements. Chapter 3 outlines the architecture and functionalities of the ATLAS detector, covering the basic principles of particle registration crucial for data collection in this analysis. Chapter 4 discusses the enhancements in the ATLAS Transition Radiation Tracker (TRT), including modifications to the trigger and data acquisition systems for efficient operation under high luminosity and elevated trigger rates. In Chapter 5, object and event reconstruction techniques used in W boson event analysis are explored, with detailed methods for charged particle track reconstruction and solving neutrino momenta equations. Chapter 6 focuses on signal and background estimation techniques, emphasizing the challenges posed by multijet (MJ) background estimation in W boson analysis. It also presents control plots to validate the estimation techniques used. Chapter 7 discusses the measurement methodology for this analysis, including the Moments Method, the construction of the Likelihood Method, and the Template Folding procedure. Chapter 8 examines the uncertainties covering statistical, experimental, and theoretical aspects of the measurements and analyses conducted. Chapter 9 emphasizes the quality of the fit and the challenges encountered during the real data fitting process, focusing on strategies to investigate and address these complications. Lastly, Chapter 10 encapsulates the research summary, conclusions, and potential future advancements and explorations within this domain.

Personal contributions

In high-energy physics, discovery and progress almost always result from the collective work and collaboration of numerous dedicated individuals. The research presented in this thesis is a reflection of the joint effort of the [ATLAS](#) collaboration, where a multitude of skilled individuals come together to contribute to a common goal. The following section is intended to illustrate the specific contributions made by the author to various sections of this thesis, demonstrating the individual efforts within the broader collaborative framework.

Drell-Yan angular coefficients measurement in W boson decays (Chapters 6-9). As the primary contributor, the author has completed a wide range of critical tasks for the analysis. All of the author's contributions to the analyses were conducted across all four channels: $W^- \rightarrow e^- \bar{\nu}$, $W^+ \rightarrow e^+ \nu$, $W^- \rightarrow \mu^- \bar{\nu}$, and $W^+ \rightarrow \mu^+ \nu$.

1. The author performed efforts to reproduce and adapt the [MJ](#) estimation algorithm, originally developed for the p_T^W -analysis, to a new signal region with relaxed $m_T^{\ell, \nu}$ and E_T^{miss} criteria (Section 6.5). The author undertook the complete [MJ](#) background estimation, which involved fraction fits, anti-isolation scans, and closure tests (Section 6.5.6).
2. The author recognized that estimation of the [MJ](#) for an inclusive signal region was insufficient for fine binning based on $[\cos \theta_{CS}, \phi_{CS}]$ distributions within the p_T^W and y^W bins. Therefore, the author developed and validated a novel method. For extrapolating multijet background templates across different $W A_i$ measurement bins, the author employed multijet acceptance corrections through [MJ](#) modelling [MC](#) samples (Section 6.6).
3. The author generated control plots for both the inclusive signal region and the analysis' fine bins across all four leptonic channels, as detailed in Section 6.7. The electroweak and top backgrounds estimations presented in Section 6.4 are performed by the author.
4. The author undertook thorough cross-validation of the analysis fit quality through the use of a simplified fit model, and investigated potential solutions to address the observed pulls (see Section 9).
5. The author was responsible for adopting and enhancing the NTuples generation software based on the p_T^W -analysis framework, incorporating new variables and systematics. The author served as the principal person for analysis specific NTuples production, processing both data and [MC](#) samples as detailed in Sections 6.1 and 6.2. Furthermore, the integration of additional lepton scale factors, precalculated by the analysis team, was executed by the author (Section 6.3.2).
6. The author also contributed to the analysis supporting note [3] as one of the editors and served as the contact person for the analysis.

Lepton flavour universality test in W boson decays in Run 2 (Appendix A). The full responsibility for the development and management of this analysis, focusing on leptonic decay channels of the W boson, lay with the author. The study involved two distinct datasets

from Run 2, categorized by high- μ and low- μ conditions. This necessitated comprehensive analyses for each. The author oversaw the entire data workflow, from initial preparation and processing to the optimization of signal region selection. A significant contribution was the development of a software package for modeling [MJ](#) backgrounds, which was later enhanced and applied in the W boson angular analysis ($W A_t$). Further, the work entailed detailed examination of track impact parameter (d_0) corrections and the implementation of a multivariate analysis technique to discriminate between prompt leptons and those arising from tau decays. The execution of Asimov data fits was also a key task undertaken by the author. Detailed documentation of this analysis can be found in [Appendix A](#).

The ATLAS Transition Radiation Tracker (Chapter 4). Due to space constraints, this thesis does not cover all of the author's [TRT](#)-related activities. This chapter primarily highlights the [TRT](#) readout upgrade and resynchronization challenges in Run 3. However, the author has made substantial contributions to the [TRT](#) detector operations, which are summarized as follows:

1. The author has performed two [ATLAS](#) qualification tasks. These tasks included upgrading the dE/dx tool for new gas mixtures and higher occupancies and enhancing [TRT](#) test stands. The first contribution established the foundation for the author's involvement in the analysis search for heavy long-lived multicharged particles [\[4\]](#). The author was particularly responsible for all studies and control plots related to $Z \rightarrow \mu\mu$. (Refer to [\[5\]](#), [\[6\]](#))
2. The author participated in the [TRT](#) readout upgrade for operation at high-pileup and high trigger rate conditions.¹. This involved optimizing the readout driver performance, increasing [TRT](#) data flow bandwidth, and addressing hardware issues at high luminosity runs. The author contributed to the refactoring of [TRT TDAQ](#) software and to the implementation of new [ATLAS TDAQ](#) releases. (Refer to [Chapter 4.2](#)) Notably, the author assumed key roles as a [TRT DAQ](#) expert and run coordinator, specifically addressing [TRT](#) resynchronization issues in high-pileup conditions at the onset of Run 3 (refer to [Section 4.2.3](#)).
3. Significant contributions were made in the development of [TRD](#) prototypes for [TRT](#) test beams in [CERN](#)'s north area. These contributions included the refinement of the data acquisition systems for test beam experiments, which are critical for advancing understanding of transition radiation. (Refer to publications [\[7\]](#)–[\[16\]](#))

Additionally, this thesis has been subject to extensive grammatical refinement using [Grammarly](#) and [ChatGPT-4](#) to assure clarity and precision in its language and structure, further highlighting data and outcomes derived either by the author or by the physicists group the author is part of.

¹These contributions were recognized with the [ATLAS](#) Outstanding Achievement Award in 2020.

1

THEORETICAL CONSIDERATIONS

This chapter introduces the fundamentals of the Standard Model (SM), which serves as the central theoretical framework for defining the A_i coefficients. It also justifies the use of the Collins-Soper rest frame for vector boson analysis and reviews recent advancements in Drell-Yan angular coefficient measurements for both Z and W bosons. Finally, it discusses future prospects for measuring angular distributions in W boson studies.

1.1 Standard Model

In the 20th century, advancements in particle physics, particularly during the 1960s and 1970s, led to the development of the Standard Model (SM) [17]–[22], which unified existing knowledge and accurately predicted new particles. Three of the four known fundamental forces find a detailed formulation in the SM:

- **Electromagnetic Force:** Governed by Quantum Electrodynamics (QED), this force is mediated by photons and is responsible for interactions between charged particles. It is the very force that underpins the stability of atoms, the phenomena of electricity, magnetism, and much of the daily observed macroscopic interactions.
- **Weak Nuclear Force:** The force behind radioactive decay and other subatomic processes and is also a consequence of QED. It operates over short distances and is mediated by W and Z bosons. Their discovery in 1983 [23]–[26] established the SM's as the fundamental theory.
- **Strong Nuclear Force:** Governed by Quantum Chromodynamics (QCD), this force binds quarks to form protons, neutrons, and other hadrons. It is the strongest of the three forces at subatomic distances and is mediated by gluons.

The fourth force, gravity, remains elusive within the framework of the SM. Due to its significantly weaker magnitude at microscopic scales, its effects in the majority of collider studies are minimal. Despite the SM's success in explaining electromagnetic, weak, and

strong interactions, the quest for a quantum description of gravity remains one of the most significant challenges in theoretical physics.

The **SM** is characterised by 18 free physical constants, which are fundamental parameters that are not derived from the theory itself but rather measured experimentally¹. The degree of precision with which these constants are known directly impacts the accuracy of predictions made using the **SM**. As the constants become more precisely determined through experiments, the predictions become increasingly refined.

The predictive power of **SM** has been demonstrated through a series of groundbreaking discoveries, including the W and Z bosons, the top quark, the τ neutrino, and most notably, the Higgs Boson [27]–[31].

1.1.1 Elementary particles and their interactions

The **SM** describes a universe of fundamental particles, which are divided into two categories: fermions and bosons. Fermions are particles that represent matter and comply with Fermi-Dirac statistics. They have half-integer spin. Bosons are particles that mediate interactions and follow Bose-Einstein statistics. They have integer spin. An overview of these particles is presented in Figure 1.1.

In the fermion sector, these particles are further classified into quarks and leptons based on their response to the strong force. Leptons, which are not affected by the strong force, are colourless. Among leptons, the charged types include the electron (e), muon (μ), and tau (τ), while their neutral counterparts are the neutrinos (ν_e , ν_μ , ν_τ).

In contrast, quarks engage in strong interactions and are colour-charged. With six distinct types (u , d , c , s , t , b), they possess either an electric charge of $-\frac{1}{3}$ or $+\frac{2}{3}$. These variations in quarks and leptons underlie the diversity of fermionic properties, which are termed as ‘flavours’.

The differentiation of fermions into three generations is reflective of their varying masses and degrees of stability. The lightest and most stable fermions are those belonging to the first generation, while the heavier and less stable ones are found in the second and third generations. The observation of higher-generation fermions is predominantly limited to particle accelerators and cosmic rays. The majority of observable matter is constituted by first-generation fermions, as illustrated in the first column of Figure 1.1.

In contrast to fermions, bosons facilitate interactions between fermions. These particles represent vector fields with an inherent integer spin. The photon (γ) mediates electromagnetic interactions while the trio of W^+ , W^- , and Z^0 bosons govern weak interactions. Simultaneously, eight massless gluons navigate the domain of strong interactions, described by quantum chromodynamics (**QCD**).

The scalar Higgs boson (H) represents a unique category of particles. Rather than mediating interactions, it signifies the excitation of the Higgs field, which gives mass to other fundamental particles.

While all quarks and charged leptons have observed anti-particles, with identical mass and spin but inverse electric charges, bosons without electric charge, such as the γ , Z , and gluons, mirror their anti-particles.

¹The extensions of the **SM** that account for non-zero neutrino masses include up to 25 parameters. However, this document, considers the conventional **SM** with massless neutrinos.

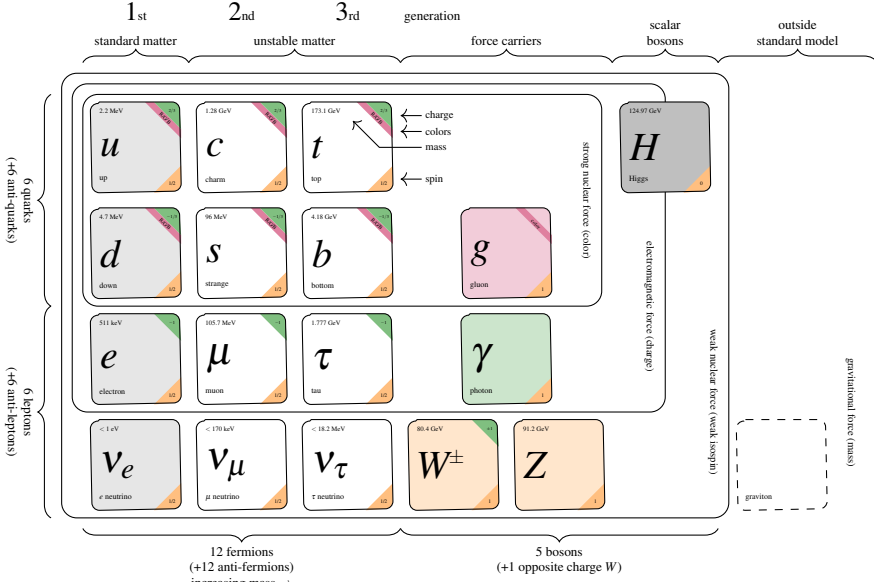


Figure 1.1: Schematic view of the Standard Model (SM) with the tree generations of fermions, the gauge bosons and the Higgs boson [34].

In terms of mass, only the Higgs boson, the W boson, and the Z boson are among the bosons with a non-zero mass. The masses constitute 12 of the 18 free parameters¹ in the SM. Two additional parameters emerge from the strong and electromagnetic coupling constants, which define interaction scales contingent on interaction types and particle charges. The remaining four parameters can be attributed to the Cabibbo-Kobayashi-Maskawa (CKM) matrix [33]. This encompasses three generation-mixing angles and a unique CP -violating complex phase.

Quarks and leptons are the fundamental building blocks of matter. Hadrons, which are composed of quarks, can be classified into two categories: baryons, which are three-quark combinations with half-integer spin, and mesons, which are quark and anti-quark pairs with integer spin.

The weak interaction, which is mediated by the W -boson and Z -boson, plays a central role within the leptonic sector. It facilitates transitions between different leptonic generations and is necessary for processes such as beta decay (shown in Figure 1.2).

1.1.2 Lagrangian

This section sets out the theoretical foundations of the Standard Model (SM). While a comprehensive treatment of quantum field theory is beyond the scope of this discussion, detailed analyses can be found in references such as [35], [36].

¹All 18 free parameters are determined by experiment and recent values and world averages can be found in Ref. [32].

In particle physics, the identification of symmetries plays a crucial role, particularly when formulating physical theories through differential equations. Symmetries often correspond to conserved quantities, as elucidated by E. Noether's theorem, which establishes a connection between symmetries and conservation laws [37]. Building upon the framework of symmetries, H. Weyl introduced the gauge principle in 1927 [38], which later became instrumental in the formulation of the electroweak sector of the **SM** by S. Glashow, S. Weinberg, and A. Salam [18], [39], [40]. This gauge principle was subsequently extended to the strong interaction sector through the pioneering work of M. Gell-Mann and G. Zweig [41], [42].

One of the fundamental elements of the **SM** is the Lagrangian, which represents the state of a system:

$$\mathcal{L}_{SM} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + i\bar{\psi}D\psi + \psi_i y_{ij} \psi_j \phi + |D_\mu \phi|^2 - V(\phi) \quad (1.1)$$

It is presented here in the compact form. The gauge kinetic term is characterized by $-\frac{1}{4}F_{\mu\nu}F^{\mu\nu}$, which represents the kinetic energy of the gauge bosons. The field strength tensor, $F_{\mu\nu}$, varies depending on the gauge boson under consideration, including the photon for electromagnetism, the W and Z bosons for the weak interaction, and the gluons for the strong force. The fermionic sector is described by $i\bar{\psi}D\psi$, which accounts for the propagation of fermions, such as quarks and leptons, through spacetime and their interactions with the gauge bosons. The covariant derivative D ensures the proper coupling of fermions with the corresponding gauge fields. Fermion interactions with the Higgs field are governed by the Yukawa term $\psi_i y_{ij} \psi_j \phi$. In this expression, the Yukawa couplings y_{ij} determine the interaction strength, resulting in fermions acquiring mass when the Higgs field develops a vacuum expectation value (**VEV**). The Higgs field, central to the mechanism of electroweak symmetry breaking, is governed by two key terms: $|D_\mu \phi|^2$ and $-V(\phi)$. The former term describes the Higgs field's kinetic energy and its interaction with the gauge fields. The latter, the Higgs potential, is of central importance in ensuring that the Higgs field obtains a non-zero **VEV**. This spontaneous symmetry breaking results in the mass to the W and Z bosons, leaving the photon massless and accounts for the existence of the Higgs boson.

Central to the **SM** Lagrangian is the group's gauge symmetry:

$$G_{SM} = SU(3)_C \oplus SU(2)_L \oplus U(1)_Y \quad (1.2)$$

Each generator of this group corresponds to a specific gauge boson. In this context, the interactions are identified by color charges (C), left-handed fields (L), and the weak hypercharge ($Y \equiv 2(Q - T_3)$) where Q represents the field's electric charge, and T_3 indicates the weak isospin's z -axis projection. $SU(3)_C$ symbolises the non-Abelian color symmetry of **QCD**. The combinations $SU(2)_L \oplus U(1)_Y$ reflect the symmetries of the weak isospin and hypercharge. While both $SU(3)$ and $SU(2)$ are non-Abelian¹, $U(1)$ remains Abelian. These symmetries are fundamental for the existence and properties of gauge particles, such as gluons, the Z^0 and $W^\pm$ bosons, and the photon.

The compact formulation of the **SM** Lagrangian provides a succinct representation of nearly all quantum processes in the known universe, with the exception of gravity. Its predictive accuracy, confirmed by numerous experimental results, has established the **SM** as

¹In non-Abelian groups, the operations don't commute: $ab \neq ba$, where a, b are group elements.

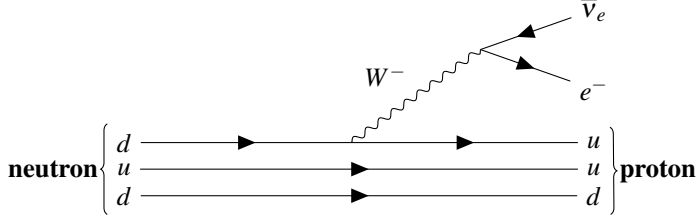


Figure 1.2: Feynman diagram of nuclear beta decay where a down quark in a neutron emits a W boson to change flavour into an up quark. The W boson then decays into an electron and an anti-neutrino. This W boson emission is an example of one of the weak charged currents.

the foundation of contemporary particle physics. However, like any theoretical framework, it has limitations and fails to account for certain phenomena, such as dark matter and neutrino masses. These gaps motivate ongoing research efforts to achieve a more fundamental understanding beyond the current paradigm.

1.1.3 Electroweak theory

The electroweak theory, originally postulated by Glashow, Salam, and Weinberg [18], [39], [40], provides a compelling description of how the electromagnetic force (mediated by the photon in QED) and the weak nuclear force (mediated by the W^+ , W^- , and Z bosons) were unified as a single force in the early universe when temperatures were extraordinarily high.

The weak interaction, unlike its electromagnetic counterpart, has a preference in its interactions. For instance, the Z boson, which is electrically neutral, discriminates between particles based on their chirality. The term chirality refers to the handedness of particles, which can be categorised as either left-handed or right-handed. It is notable that while the Z boson is capable of interacting with both, the W bosons, selectively interact only with left-handed fermions or their right-handed antiparticle counterparts.

The concept of chirality becomes particularly important when discussing massless particles. In this context, chirality and helicity (the alignment of a particle's spin with its momentum) are considered to be synonymous. Consequently, for particles where the mass is negligible in comparison to their energy, as is the case in this thesis, the helicity provides a straightforward means of determining their chirality.

The formal representation of these interactions is captured by the electroweak interaction Lagrangian, as detailed in Eq. 1.3. This equation captures the nature of how fermions participate in electroweak processes. The terms in the Lagrangian introduce the weak isospin and hypercharge, which are two crucial quantum numbers in the context of electroweak theory.

$$\mathcal{L}_{EW}^{int} = g \vec{J}_\mu \cdot \vec{W}^\mu + g' J_\mu^Y B^\mu \quad (1.3)$$

The Einstein summation convention is used here, whereby the contracted indices are summed over in the range $\mu = 0, 1, 2, 3$. In Eq. 1.3, the constants g and g' are gauge coupling constants associated with the $SU(2)_L$ and $U(1)_Y$, respectively, and give the strengths of the interaction. The interaction mediated by the weak isospin bosons (W_1^μ , W_2^μ , W_3^μ), collectively denoted

by the symbol W^μ , and the hypercharge boson represented by B^μ . The weak isospin, T , is a quantum number with three components. The third component, T^3 , and the quantum number hypercharge, Y , combine to give the electric charge through the relation $Q = T^3 + \frac{Y}{2}$.

A more detailed insight into these interactions is provided by the isospin currents, as set out in Eq. 1.4. These currents represent the rules by which fermions, like electrons (e) and neutrinos (ν_e), participate in weak processes. While these are only illustrated here just for electrons and electron neutrinos, similar currents can be formulated for other fermions such as quarks. The main difference for quarks is due to the phenomenon known as flavour mixing. However, the fundamental structure of the currents remains the same.

$$\begin{aligned} J_\mu^+ &= \frac{1}{2} \bar{\nu}_e \gamma^\mu (1 - \gamma^5) e \\ J_\mu^- &= \frac{1}{2} \bar{e} \gamma^\mu (1 - \gamma^5) \nu_e \\ J_\mu^3 &= \frac{1}{2} \bar{e} \gamma^\mu (\nu - \gamma^5) e + \frac{1}{2} \bar{\nu} \gamma^\mu (\nu - a \gamma^5) \nu \end{aligned} \quad (1.4)$$

In order to mathematically represent particles and their interactions, the Dirac matrices (commonly referred to as gamma matrices, γ) and Pauli matrices (commonly referred to as tau matrices, τ) are employed in Eqs. 1.5 and 1.6 respectively. These matrices are fundamental tools in the realm of quantum mechanics, helping define the behaviour and properties of fermions in various interactions. In particular, the Pauli matrices, are central to the understanding of spin in quantum systems, as they are related to the behaviour of spin- $\frac{1}{2}$ particles.

$$\gamma^0 = \begin{pmatrix} \mathbb{1} & 0 \\ 0 & -\mathbb{1} \end{pmatrix}; \gamma^i = \begin{pmatrix} 0 & \tau_i \\ -\tau_i & 0 \end{pmatrix}; \gamma^5 = \begin{pmatrix} 0 & \mathbb{1} \\ \mathbb{1} & 0 \end{pmatrix}. \quad (1.5)$$

$$\tau_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}; \tau_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}; \tau_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}. \quad (1.6)$$

The physical bosons W^+ , W^- , Z , and the photon, are composite entities that originate from combinations of weak isospin and hypercharge gauge bosons. This relationship is governed by the following equations:

$$\begin{aligned} W^{\pm, \mu} &= \frac{1}{\sqrt{2}} (W_1^\mu \mp i W_2^\mu), \\ Z^\mu &= W_3^\mu \cos \theta_W - B^\mu \sin \theta_W, \\ A^\mu &= W_3^\mu \sin \theta_W + B^\mu \cos \theta_W, \end{aligned} \quad (1.7)$$

where, A^μ represents the field associated with the photon, which remains massless after symmetry breaking. The parameter θ_W denotes the weak mixing angle, an integral yet unconstrained parameter within the Standard Model (SM).

Another noteworthy aspect of this domain is how the strengths of QED and the electroweak theory intertwine. They can be connected through the equation:

$$g \sin \theta_W = g' \cos \theta_W = e. \quad (1.8)$$

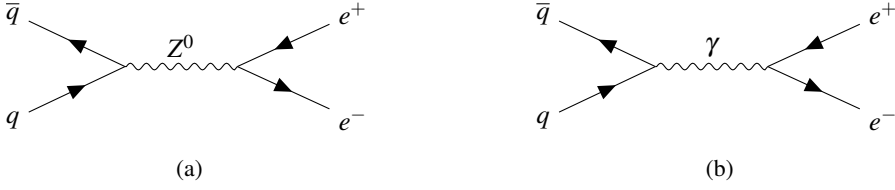


Figure 1.3: Feynman diagrams representing quark-antiquark pair annihilation into a Z boson (left) and a photon (right), followed by their subsequent decay into an electron-positron pair.

which relates the gauge coupling constants of the $SU(2)_L$ and $U(1)_Y$ groups, g and g' , to the electromagnetic coupling constant $e = \frac{1}{137}$ through the weak mixing angle θ_W . This relationship is of great significance, as it serves to connect our understanding of the weak force (W and Z interactions) with the well-established electromagnetic interactions (photon).

The Lagrangian which describes fermionic interactions, as stated in Eq. 1.3, can be reformulated in the context of these physical bosons. This redefined interaction Lagrangian is given by:

$$\mathcal{L}_{EW}^{int} = \frac{g}{\sqrt{2}}(J_\mu^+ W^{-,\mu} + J_\mu^- W^{+,\mu}) + \frac{g}{\cos \theta_W}(J_\mu^3 - \sin^2 \theta_W J_\mu^{EM})Z^\mu + eJ_\mu^{EM}A^\mu. \quad (1.9)$$

The term $\frac{g}{\sqrt{2}}(J_\mu^+ W^{-,\mu} + J_\mu^- W^{+,\mu})$ is responsible for the charged current interactions involving the W bosons. In this expression, J_μ^+ represents the charged current that couples with the negatively charged W^- boson, enabling processes in which a W^- is emitted or absorbed. On the other hand, J_μ^- corresponds to the charged current associated with the positively charged W^+ boson, mediating processes in which a W^+ is emitted or absorbed. This current has contributions from leptons and quarks and is responsible for processes such as beta decay. The term $\frac{g}{\cos \theta_W}(J_\mu^3 - \sin^2 \theta_W J_\mu^{EM})Z^\mu$ is used to describe interactions involving the neutral Z boson. In particular, J_μ^3 represents the neutral current associated with the third component of isospin. The correction term, $\sin^2 \theta_W J_\mu^{EM}$, encapsulates the mixing between the W^3 boson from the $SU(2)_L$ group and the B boson of the $U(1)_Y$ group, which leads to the formation of the Z boson and photon. θ_W is the Weinberg angle, reflecting the electroweak mixing mentioned previously. The term $eJ_\mu^{EM}A^\mu$ encapsulates the classical electromagnetic interactions, where e is the electromagnetic coupling constant and J_μ^{EM} is the electromagnetic current, which describes the motion of electrically charged particles.

In the expression of the electroweak interaction Lagrangian presented in Eq. 1.9, the middle term, $\frac{g}{\cos \theta_W}(J_\mu^3 - \sin^2 \theta_W J_\mu^{EM})Z^\mu$, represents the currents J_μ^3 and J_μ^{EM} from Eq. 1.4, which illustrate the decay of the Z boson into an electron-positron pair e^+e^- . This is exemplified by the Feynman diagram shown in Figure 1.3 (a), which describes the transformation $q\bar{q} \rightarrow Z \rightarrow e^+e^-$. A key feature of this interaction is the conjunction of weak and electromagnetic currents in the middle term for the Z boson, as outlined in Eq. 1.9. This combination allows for coupling with both left-handed and right-handed fermions, in contrast to the W bosons, which couple exclusively with left-handed fermions. The Z boson has different coupling strengths between the left and right-handed fermions, which can be expressed using

the following equations:

$$\begin{aligned} g_L &= T^3 - Q \sin^2 \theta_W, \\ g_R &= -Q \sin^2 \theta_W. \end{aligned} \quad (1.10)$$

Often, for clarity, these are represented in terms of vector and axial-vector couplings, v and a respectively, for the Z boson:

$$\begin{aligned} v &= g_L + g_R = T^3 - 2Q \sin^2 \theta_W, \\ a &= g_L - g_R = T^3. \end{aligned} \quad (1.11)$$

For the $W^\pm$ bosons, the coupling of fermions is more direct compared to other interactions in the electroweak sector. The left-handed fermions couple to $W^\pm$ bosons with a strength given by $\frac{g}{\sqrt{2}}$. In contrast, the right-handed fermions do not couple to $W^\pm$ bosons:

$$g_L = \frac{g}{\sqrt{2}}, \quad (1.12)$$

where g is the gauge coupling constant of the $SU(2)_L$ group. The $W^\pm$ bosons exclusively interact with left-handed fermions. Specifically, the W^+ and W^- bosons enable transitions between different members of weak isospin doublets. Due to this exclusive left-handed interaction, the Weinberg angle (often associated with the mixing of weak and electromagnetic interactions) doesn't affect the coupling of $W^\pm$ bosons to fermions, unlike its role in the coupling of the Z boson. Consequently, for the $W^\pm$ bosons, both the vector and axial-vector couplings are identical:

$$v = a = \frac{g}{\sqrt{2}}. \quad (1.13)$$

The differences in left and right-handed couplings for the W and Z bosons across various fermions, are concisely presented in Table 1.1.

Fermion	T^3	Charge (Q)	Z boson		$W^\pm$ boson	
			g_L	g_R	g_L	g_R
e, μ, τ	$-1/2$	-1	$-1/2 + \sin^2 \theta_W$	$\sin^2 \theta_W$	$\frac{g}{\sqrt{2}}$	0
ν_e, ν_μ, ν_τ	$1/2$	0	$1/2$	0	$\frac{g}{\sqrt{2}}$	0
u, c, t	$1/2$	$2/3$	$1/2 - 2/3 \sin^2 \theta_W$	$-2/3 \sin^2 \theta_W$	$\frac{g}{\sqrt{2}}$	0
d, s, b	$-1/2$	$-1/3$	$-1/2 + 1/3 \sin^2 \theta_W$	$1/3 \sin^2 \theta_W$	$\frac{g}{\sqrt{2}}$	0

Table 1.1: List of all fermions along with their respective third component of weak isospin T^3 and electric charge Q . A comparison of the left and right-handed coupling strengths for $W^\pm$ and Z^0 bosons is provided.

1.1.4 Mass generation for fermions and gauge bosons

The Higgs mechanism [20], a central concept in the Standard Model, offers a consistent way to mass generation for elementary particles, without violating the gauge invariance

principle. This mass generation method revolves around the spontaneous breaking of the $SU(2)_L \times U(1)_Y$ electroweak symmetry, facilitated by the Higgs field.

The Higgs field is represented by a complex scalar doublet field, $\Phi(x)$, comprised of four components. Within the framework of the $SU(2)_L \times U(1)_Y$ symmetry, the Higgs mechanism introduces an isospin doublet of $SU(2)_L$. This doublet is made up of complex scalar fields, each possessing a hypercharge $Y = 1$:

$$\Phi(x) = \begin{pmatrix} \phi^+(x) \\ \phi^0(x) \end{pmatrix}. \quad (1.14)$$

The Higgs field's role in the electroweak Lagrangian can be expressed by:

$$\mathcal{L}_H = (D_\mu \phi)^\dagger (D^\mu \phi) - V(\phi) \quad (1.15)$$

Here, $V(\phi)$ represents the Higgs potential, parameterised by λ (a dimensionless coupling constant) and μ (a mass parameter):

$$V(\phi) = \mu^2 |\phi|^2 + \lambda |\phi|^4. \quad (1.16)$$

The morphology of the potential hinges heavily on the specific values of these parameters. To deduce the base state expectation, ϕ_0 , one must seek the potential's minima:

$$\frac{\partial V}{\partial \phi} = 2\phi(\mu^2 + 2\lambda \phi^2) = 0, \quad (1.17)$$

where λ characterises the strength of the scalar field's self-interaction, as evidenced by the $|\phi|^4$ term. In contrast, the parameter μ is directly tied to the scalar field's mass. For stability reasons, it is necessary that λ is positive, thereby ensuring that the energy is bounded from below.

The sign of μ^2 is determinative of the vacuum behavior of the Higgs field:

- $\mu^2 > 0$: Under these circumstances, the Higgs potential has a singular minimum at $\phi = 0$. This corresponds to a scenario where the vacuum expectation value (VEV) of the ϕ field is null, leaving the gauge bosons without mass and retaining the $SU(2)_L \times U(1)_Y$ symmetry intact.
- $\mu^2 < 0$: In contrast, a negative μ^2 ensures that the VEV of ϕ^2 isn't zero. The resulting Higgs potential adopts a "Mexican hat" topology, demonstrating a local maximum at $\phi = 0$. This spontaneous symmetry breaking allows for the generation of mass for the gauge bosons.

The morphology of the potential, for both scenarios, is illustrated in Figure 1.4. The potential parameters can be either $\mu^2 < 0$ or $\mu^2 > 0$. The ground state expectation value is:

$$\phi_0^2 = -\frac{\mu^2}{\lambda} = \frac{v^2}{2}. \quad (1.18)$$

When a non-zero ground state is chosen, the symmetry of $SU(2)_L \times U(1)_Y$ is spontaneously broken. This is due to the fact that the ground state is no longer invariant under the mentioned

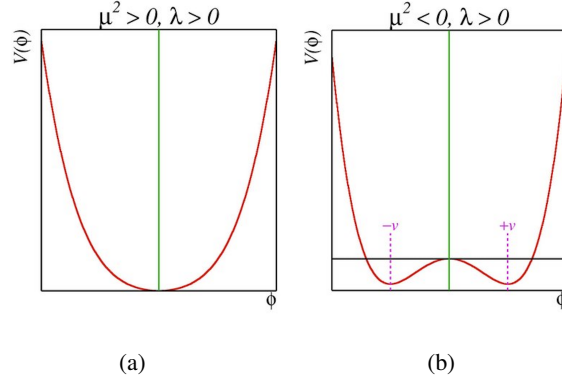


Figure 1.4: Forms of the Higgs potential due to the sign of μ^2 : (a) $\mu^2 > 0$ and (b) $\mu^2 < 0$. The degeneracy of the vacuum state in this 2-dimensional graph is represented by $+v$ and $-v$, which correspond to the states of minimum energy for the Higgs potential, with $v = v/\sqrt{2}$.

symmetry. Consequently, the potential's minimum is not unique to a singular value of ϕ , but is linked to a plethora of states. Upon introducing quantum fluctuations around this minimum, the scalar doublet ϕ is represented as follows:

$$\phi(x) = e^{\frac{i\xi_i(x)\tau^i}{2v}} \begin{pmatrix} 0 \\ \frac{v+H(x)}{\sqrt{2}} \end{pmatrix}. \quad (1.19)$$

In this representation, $\xi_i(x)$ (for i spanning from 1 to 3) represents the massless real fields, which are known as the Goldstone bosons. Concurrently, the symbol $H(x)$ represents the massive scalar Higgs field. The scalar field, $H(x)$, corresponds to radial oscillations about the ground state that influence potential energy. In contrast, the Goldstone bosons represent angular oscillations that do not affect the potential energy. These three massless scalar bosons are associated with the trio of broken symmetry generators.

By maintaining local $SU(2)_L$ invariance in the Lagrangian, gauge transformations can be used to remove the term $\xi_i(x)$, thereby simplifying the expression of ϕ .

$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v+H(x) \end{pmatrix}. \quad (1.20)$$

With the covariant derivative defined as:

$$D_\mu = \partial_\mu = ig \frac{\tau^i}{2} W_\mu^i + ig' \frac{1}{2} B^\mu, \quad (1.21)$$

the kinetic term of the Lagrangian, $\mathcal{L}_H$, specifically from Equation 1.15, evolves to:

$$\frac{1}{2} \partial^\mu H \partial_\mu H + \frac{1}{8} g^2 (v+H)^2 |W_1^\mu + iW_2^\mu|^2 + \frac{1}{8} (v+H)^2 |g'W_3^\mu - gB^\mu|^2. \quad (1.22)$$

From this, four distinct physical fields can be identified. The charged fields, $W^{\pm,\mu}$ (which correlate with the $W^\pm$ bosons), are derived from the fields W_1^μ and W_2^μ :

$$W_\mu^\pm = \frac{1}{\sqrt{2}}(W_1^\mu \mp W_2^\mu), \quad (1.23)$$

Two neutral fields, namely Z^μ and A^μ , are associated with the Z boson and photon, respectively. They emerge as orthogonal combinations of the fields B^μ and W_3^μ :

$$\begin{aligned} Z^\mu &= -B^\mu \sin \theta_W + W_3^\mu \cos \theta_W \\ A^\mu &= B^\mu \cos \theta_W + W_3^\mu \sin \theta_W. \end{aligned} \quad (1.24)$$

Analysing the kinetic part of the Lagrangian from Equation 1.22, the masses of the bosons can be extracted. The charged W bosons possess a mass:

$$m_W = \frac{g\nu}{2}, \quad (1.25)$$

In contrast, the mass of the Z boson is:

$$m_Z = \frac{\nu}{2} \sqrt{g^2 + g'^2} \quad (1.26)$$

It is noteworthy that the photon remains massless, expressed as $m_\gamma = 0$.

The mass of the Higgs boson is not invariant; it fluctuates in accordance with the value of the free parameter, λ . This parameter encapsulates the self-coupling nature of the Higgs, whereas the vector bosons' masses remain fixed once both g^2 and ν are defined.

It is possible to establish an relationship between the boson masses and Weinberg's angle:

$$m_W = m_Z \cos \theta_W. \quad (1.27)$$

Consequently, the SM's fundamental parameters can be reduced to four distinct elements: the coupling constants g and g' , in conjunction with the Higgs potential parameters λ and μ .

The Yukawa coupling

In the SM the masses of fermions are generated through their interactions with the Higgs field. Nevertheless, the introduction of direct mass terms into the Lagrangian would violate the $SU(2)_L$ gauge invariance. Therefore, an invariant coupling term introduction, known as the Yukawa coupling, was introduced in order to ensure the consistent allocation of mass to fermions. The Yukawa coupling describes the interactions between fermions and the Higgs field, utilising a coupling constants, which are represented by terms such as g_f and y_f .

For a typical fermion f , the Yukawa Lagrangian is:

$$\mathcal{L}_{\text{Yukawa}} = -y_f \bar{f}_L \Phi f_R + h.c., \quad (1.28)$$

When the Higgs field VEV achieving a non-zero value, a mass term for fermions is generated:

$$m_f = \frac{y_f \nu}{\sqrt{2}}. \quad (1.29)$$

Hence, the fermion's mass, m_f , is proportional to its Yukawa coupling, y_f . Larger Yukawa couplings correspond to heavier fermions, with the top quark being the heaviest due to its near-unity Yukawa coupling. In contrast, the electron, with a much smaller Yukawa coupling, is one of the lightest fermions.

The Yukawa interactions and the Higgs mechanism collectively form the origin of mass for both gauge bosons and fermions in the [SM](#), marking a significant milestone in our understanding of particle physics.

1.1.5 Quantum Chromodynamics

The fundamental constituents of hadronic matter, quarks, carry a fundamental quantum number, called "colour" [\[43\]](#). These are classified into three distinct categories: red, green, and blue. These categorisations arise from the $SU(3)$ gauge symmetry of Quantum Chromodynamics (QCD). The symmetry has eight generators, which correspond to the eight different gluons. The [QCD](#) provides the theoretical framework for the dynamics of these coloured charges, which are mediated by gauge bosons known as gluons. In contrast to quarks, gluons are characterised by the possession of both a colour and an anticolour.

A particular characteristic of [QCD](#) is the confinement phenomenon [\[44\]](#). This phenomenon ensures that quarks and gluons only appear within colour-neutral bound states, which are termed hadrons. These hadrons can be composed of either quark-antiquark pairs, known as mesons, or tri-quark configurations, which are known as baryons. For instance, protons (with quark content uud) and neutrons (udd) are baryons, while the π^+ meson ($u\bar{d}$) demonstrates a quark-antiquark configuration¹.

The primary quarks within hadrons, which are responsible for the quantum numbers of the latter, are termed valence quarks. However, hadrons also host a complex environment of transient quark-antiquark pairs and gluons, collectively referred to as partons. The valence quarks are continually interacting via gluon exchange, which ensures the confinement of quarks within the hadron.

A central aspect of [QCD](#) is the momentum-dependent strong coupling constant, $\alpha_s(Q^2)$. In the context of short distances or high momentum transfers² (Q^2), the behaviour of quarks is characterised by a notable degree of freedom, a phenomenon known as asymptotic freedom [\[47\]](#), [\[48\]](#). However, as the distance between quarks increases, leading to a reduction in the value of Q^2 , the strength of the coupling increases, resulting in the confinement property. The variation of α_s with momentum transfer is illustrated in [Figure 1.5](#). Soft processes, characterised by a low value of Q^2 , include phenomena such as diffraction, as well as the processes of [ISR](#) and [FSR](#) and the remnants of beam-beam interactions. In contrast, processes that can be classified as hard, such as those involving the production of vector bosons resulting from quark-antiquark annihilations, demonstrate high values of Q^2 . A key distinction lies in their computational approach: hard processes can be calculated using perturbative calculations within [QCD](#), while soft processes are non-perturbative and therefore resist a straightforward analytical treatment. In the context of a given collision event, the

¹It is noteworthy that the [LHCb](#) experiment at [CERN](#) has reported evidence for exotic hadronic states, such as pentaquarks [\[45\]](#), [\[46\]](#), containing at least four quarks and one antiquark, e.g., $uudc\bar{c}$.

²This shouldn't be mistaken for the electric charge, Q .

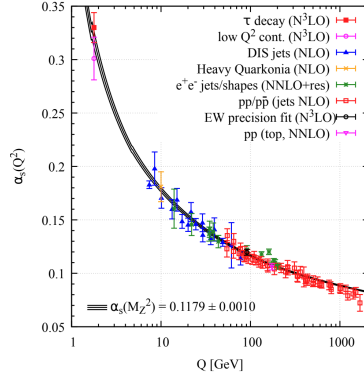


Figure 1.5: The evolving strong coupling constant α_s decreases with increasing momentum transfer Q^2 . Sourced from PDG [32].

collective result of soft processes is referred to as the “underlying event”. This term is used to describe the background against which the primary hard processes of interest unfold.

The dynamics of QCD also intersect with the electroweak sector. In particular, the production of W and Z bosons in high-energy collisions at the LHC provides an indirect means of investigating QCD phenomena. The rate and kinematic distributions of W and Z production are influenced by the internal structure of protons, which is encoded in the Parton Distribution Functions (PDFs). These functions describe the momentum distribution of partons within a proton.

One of the fundamental principles that allow for precision calculations in the context of weak boson production is the QCD factorisation theorem¹. This theorem enables the separation of the cross section into two parts: one that is calculable using perturbation theory, corresponding to short-distance interactions, and another that encapsulates the non-perturbative nature of long-distance interactions, which are represented by PDFs. This separation is fundamental when analysing scenarios such as those occurring at the LHC, where the complex and non-perturbative internal dynamics of colliding hadrons significantly affect observables.

Applying this factorisation concept to the Drell-Yan process, the cross section emerges from a convolution of the PDFs of the colliding hadrons and the partonic cross sections for the production of the weak bosons. This convolution can be mathematically captured by the following equation:

$$\sigma = \sum_{i,j} \int dx_a dx_b f_i(x_a; \mu_F^2) f_j(x_b; \mu_F^2) [\hat{\sigma}_0 + \alpha_s(\mu_R^2) \hat{\sigma}_1 + \alpha_s^2(\mu_R^2) \hat{\sigma}_2 \dots]_{ab \rightarrow V}. \quad (1.30)$$

Here, $f_i(x_a; \mu_F^2)$ and $f_j(x_b; \mu_F^2)$ represent the PDFs of the colliding partons, while $\hat{\sigma}$ terms correspond to the partonic cross sections, expanded perturbatively in the strong coupling constant α_s . Within this formulation:

¹Developed by Drell and Yan [49], hence the term “Drell-Yan process” for this W and Z production process.

- μ_F defines the factorisation scale, a important boundary separating the long-distance, non-perturbative details from the high-energy, short-distance interactions.
- μ_R , termed as the renormalisation scale, plays a role in modulating the strength of the strong interaction. A widely accepted criterion for these scales in Drell-Yan processes is that they are equivalent to the invariant mass of the produced lepton pair, encapsulated as $\mu_F = \mu_R = m^{\ell\ell}$.
- Encapsulated within the brackets is a series, represents an expansion in a perturbation theory that mirrors the effects of the strong coupling constant, α_S . Each term is associated with a specific level in QCD. In this context, $\mathcal{O}_0$ represents the leading order (LO), while the $\alpha_S(\mu_R^2)\mathcal{O}_1$ represents the next-to-leading order (NLO). As one progresses to higher levels of theoretical precision, the computational resources required to obtain accurate predictions increase. A visual representation of each order in the perturbative series can be found in Figure 1.6. Currently the accurate theoretical prediction is available up to NNLO and NNLL (next-to-next-to leading logarithms).

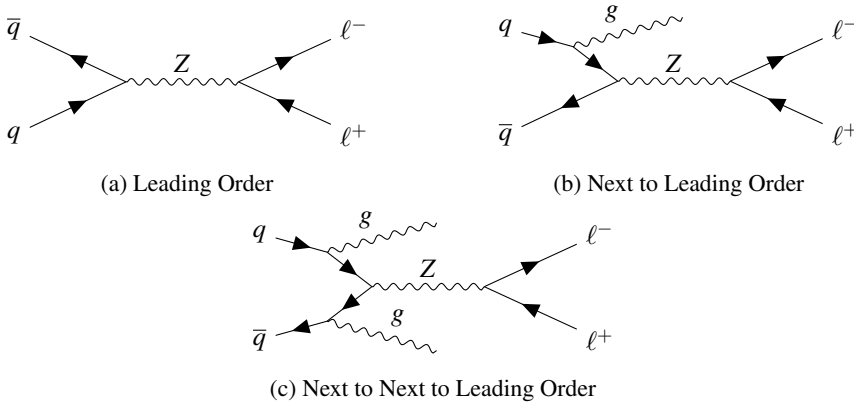


Figure 1.6: Examples of a LO (a), NLO (b) and NNLO (c) Feynman diagrams for the Drell-Yan process. The order is determined by the number of QCD vertices on the left. With increased order, the number of Feynman diagrams increases.

The composite nature of hadrons requires an understanding of the momentum fractions borne by their constituent partons. These probabilities are encapsulated within the Parton Distribution Functions (PDF), which are represented by the functions $f_i(x)$. The derivation of a comprehensive theoretical framework for PDFs remains an ongoing challenge. However, empirical methodologies have yielded detailed insights. The convolution of individual parton cross-sections, when interplayed with the corresponding PDFs, serves to complicate the task of determining net cross-sections for specific processes in hadron collisions.

1.2 Drell-Yan angular coefficients

In high-energy physics, the angular distribution of leptons resulting from the decay of gauge bosons offers key insights into the underlying fundamental interactions that give rise to these particles. In the gauge boson's rest frame, the lepton distribution is strongly influenced by the gauge boson's polarization.

The framework for analyzing this angular distribution is based on nine helicity cross-sections, which correspond to the gauge boson's helicity density matrix elements as outlined in reference [1]. In the leading order (LO) of parton subprocesses, $q\bar{q} \rightarrow V \rightarrow \ell\ell'$, only the transversely polarized gauge boson contributes to the helicity density matrix. However, at higher orders, all three possible polarizations of the gauge boson contribute.

At the order $\mathcal{O}(\alpha_S)$ within perturbative QCD, the lepton's angular distribution is characterized by six distinct helicity cross-sections. These functions depend on both the gauge boson's transverse momentum and its rapidity. At the subsequent order, $\mathcal{O}(\alpha_S^2)$, an additional three helicity cross-sections contribute, reflecting the increased complexity of the interactions.

Following the conventions and notations established in [50], it is important to note that the correlations between leptons and hadrons are conceptualized through the interaction of the lepton tensor $L_{\mu\nu}$ with the hadron tensor at the parton level, $H^{\mu\nu}$. Here, $L_{\mu\nu}$ acts as an analyzer, extracting the structure of $H^{\mu\nu}$ and separating production dynamics from decay kinematics. This analytical framework is instrumental for understanding the nuances of gauge boson polarization in subsequent interactions.

The overarching structure of angular dependence becomes discernible upon introducing helicity cross-sections, which correspond to the non-vanishing combinations of the polarization density matrix elements. These elements are represented by:

$$H_{mm'} = \varepsilon_\mu^*(m) H^{\mu\nu} \varepsilon_\nu(m') \quad (1.31)$$

Here, the indices m and m' can take on the values of $+1$, 0 , or -1 . These values correspond to different polarisation states of the boson. Specifically, $+1$ and -1 represent transversely polarized bosons with their spins oriented perpendicular to the direction of motion, while 0 corresponds to a longitudinally polarized boson with its spin aligned along the direction of motion.

The polarisation vectors for the gauge boson, represented by

$$\varepsilon_\mu(\pm 1) = \frac{1}{\sqrt{2}}(0, \pm 1, -i, 0), \quad \varepsilon_\mu(0) = \frac{1}{\sqrt{2}}(0, 0, 0, 1) \quad (1.32)$$

are explicitly defined with respect to the selected gauge boson rest frame. Here, $\varepsilon_\mu(\pm 1)$ corresponds to the transverse polarisation, with the ± 1 values indicating the two possible orientations (in the plane perpendicular to the direction of motion) and $\varepsilon_\mu(0)$ represents the longitudinal polarisation.

The angular dependence observed in the differential cross-section can be neatly represented as:

$$\frac{d\sigma}{dp_T^W dm^W dy^W d\cos\theta d\phi} = \frac{3}{16\pi} \sum_{\alpha \in M} g_\alpha(\theta, \phi) \frac{d\sigma^\alpha}{dp_T^W dm^W dy^W}, \quad M = \{U+L, L, T, I, P, A, 7, 8, 9\} \quad (1.33)$$

In this context, the symbol g_α represents the second-order harmonic polynomials, which have been scaled by the appropriate normalization constants. The angles $\cos\theta$ and ϕ represent the polar and azimuthal angles of lepton decay within the reference frame of the gauge boson. Meanwhile, the quantity $d\sigma^\alpha$ represents the helicity cross-sections, which are subsequently mapped to the nine established helicity matrix elements, as illustrated in Equation 1.34. They encapsulate the frequency with which a specific helicity state is produced, given the specified kinematic conditions (p_T^W , m^W and y^W). The set M represents the different potential contributions to this distribution, originating from various polarisation transitions and interferences. Each of these terms corresponds to distinct combinations of polarisation states and their potential interferences.

$$\begin{aligned} \sigma^{U+L} &\sim H_{00} + H_{++} + H_{--} \\ \sigma^L &\sim H_{00} \\ \sigma^T &\sim 1/2 (H_{+-} + H_{-+}) \\ \sigma^I &\sim 1/4 (H_{+0} + H_{0+} - H_{-0} - H_{0-}) \\ \sigma^P &\sim H_{++} + H_{--} \\ \sigma^A &\sim 1/4 (H_{+0} + H_{0+} + H_{-0} + H_{0-}) \\ \sigma^7 &\sim -i/2 (H_{+-} - H_{-+}) \\ \sigma^8 &\sim -i/4 (H_{+0} - H_{0+} + H_{-0} - H_{0-}) \\ \sigma^9 &\sim -i/4 (H_{+0} - H_{0+} - H_{-0} + H_{0-}) \end{aligned} \quad (1.34)$$

The unpolarised differential cross-section, denoted by σ^{U+L} , represents a combination of unpolarised and longitudinally polarised contributions. Various differential cross-sections, such as σ^L , σ^T , σ^I , σ^P , and σ^A characterise different polarisation states and interference effects of the produced gauge boson. In particular, σ^L corresponds to the cross-section for a longitudinally polarised gauge boson, σ^T captures the transverse polarisations where helicity flips, σ^I refers to an interference term between longitudinal and transverse polarisations, σ^P is the purely transversely polarised cross-section, and σ^A gives a measure of the combined contribution of longitudinal and transverse states. Additionally, terms like σ^7 , σ^8 , and σ^9 are associated with CP-violating phases or other interference effects between helicity states [1].

The cross-sections for different helicity states and interference terms are connected to the vector v_x and axial-vector a_x coupling coefficients. Here, x represents either the lepton (l) or quark (q) couplings to the W boson, as defined by the relations:

$$\begin{aligned}
\sigma^{U+L,L,T,I} &\sim (v_\ell^2 + a_\ell^2) (v_q^2 + a_q^2). \\
\sigma^{P,A} &\sim v_\ell a_\ell v_q a_q. \\
\sigma^{7,8} &\sim (v_\ell^2 + a_\ell^2) (v_q a_q). \\
\sigma^9 &\sim (v_\ell a_\ell) (v_q^2 + a_q^2).
\end{aligned} \tag{1.35}$$

The terms $\sigma^{U+L,L,T,I}$ encapsulate contributions originating from the parity-conserving (p.c.) component of the hadron tensors. This reflects the symmetric aspects of the interaction under parity transformation, where the physics remains unchanged if spatial coordinates are inverted. In contrast, the quintet $\sigma^{P,A,7,8,9}$ is governed by the parity-violating (p.v.) sector of $H^{\mu\nu}$. A key feature of these terms is their inversion under a parity (P) transformation, underlining the breaking of this symmetry in the weak interactions mediated by the W boson. The associated angular polynomials $g_{P,A,9}(\theta, \phi)$ also undergo a sign change under the parity operation. As a result, angular distributions associated with $\sigma^{U+L,L,T,I,P,A,9}$ reflect the balance between the parity-preserving and parity-violating sectors in the Drell-Yan process involving W bosons, underscoring the nuanced interplay of symmetry and symmetry-breaking in these interactions.

To fully characterise the angular distributions resulting from particle decays, which have spin-1, a complete and complex representation up to all orders in QCD can be achieved by using the standard polynomials, $g_\alpha(\theta, \phi)$:

$$\begin{aligned}
g_{U+L} &= 1 + \cos^2 \theta; & g_L &= 1 - 3 \cos^2 \theta; & g_T &= 2 \sin^2 \theta \cos 2\phi; \\
g_I &= 2 \sqrt{2} \sin 2\theta \cos \phi; & g_P &= 2 \cos \theta; & g_A &= 4 \sqrt{2} \sin \theta \cos \phi; \\
g_7 &= 2 \sin^2 \theta \sin 2\phi; & g_8 &= 2 \sqrt{2} \sin 2\theta \sin \phi; & g_9 &= 4 \sqrt{2} \sin \theta \sin \phi.
\end{aligned} \tag{1.36}$$

The standard notation is then to factorise out unpolarised cross-section and present formula of Equation 1.33 as expansion into standard polynomials, where the dimensionless angular coefficients serve as representations of the relative contributions of different helicity cross-sections:

$$\begin{aligned}
A_0 &= 2d\sigma^L/d\sigma^{U+L}; & A_1 &= 2\sqrt{2}d\sigma^I/d\sigma^{U+L}; & A_2 &= 4d\sigma^T/d\sigma^{U+L}; \\
A_3 &= 4\sqrt{2}d\sigma^A/d\sigma^{U+L}; & A_4 &= 2d\sigma^P/d\sigma^{U+L}; & A_5 &= 2d\sigma^7/d\sigma^{U+L}; \\
A_6 &= 2\sqrt{2}d\sigma^8/d\sigma^{U+L}; & A_7 &= 4\sqrt{2}d\sigma^9/d\sigma^{U+L}.
\end{aligned} \tag{1.37}$$

The advantage of this approach is that it allows the complex expression for the differential cross-section to be simplified, making it more tractable and transparent. The differential cross-section can then be represented in terms of the Drell-Yan angular coefficients, A_i , and the corresponding polynomials, P_i , as shown in Table 1.2:

$$\frac{d\sigma}{dp_T^W dm^W dy^W d\cos\theta d\phi} = \frac{3}{16\pi} \frac{d\sigma^{U+L}}{dp_T^W dm^W dy^W} \left\{ (1 + \cos^2 \theta) + \sum_{i=0}^7 A_i (p_T^W, y^W, m^W) P_i(\cos \theta, \phi) \right\}. \tag{1.38}$$

P_i	$Y_l^m(\theta, \varphi)$	A_i	Coupling	Non-Zero
$1/2(1 - 3\cos^2\theta)$	Y_2^0	A_0		$\mathcal{O}(\alpha_S^1)$
$\sin\theta\cos\varphi$	$(Y_2^{-1} - Y_2^1)$	A_1	$(v_\ell^2 + a_\ell^2)(v_q^2 + a_q^2)$	$\mathcal{O}(\alpha_S^1)$
$1/2\sin^2\theta\cos 2\varphi$	$(Y_2^{-2} + Y_2^2)$	A_2		$\mathcal{O}(\alpha_S^1)$
$\sin\theta\cos\varphi$	$(Y_1^{-1} - Y_1^1)$	A_3	$v_\ell a_\ell v_q a_q$	$\mathcal{O}(\alpha_S^1)$
$\cos\theta$	Y_1^0	A_4	$\sim \sin^2\theta_W$	$\mathcal{O}(\alpha_S^0)$
$\sin^2\theta\sin 2\varphi$	$(Y_2^{-2} - Y_2^2)$	A_5	$(v_\ell^2 + a_\ell^2)(v_q a_q)$	$\mathcal{O}(\alpha_S^2)$
$\sin 2\theta\sin\varphi$	$(Y_2^{-1} + Y_2^1)$	A_6		$\mathcal{O}(\alpha_S^2)$
$\sin\theta\sin\varphi$	$(Y_1^{-1} + Y_1^1)$	A_7	$(v_\ell a_\ell)(v_q^2 + a_q^2)$	$\mathcal{O}(\alpha_S^2)$

Table 1.2: Overview of polynomials related to spherical harmonics, Drell-Yan angle coefficients, vector and axial-vector couplings, and the order in which they take non-zero values.

The differential cross-section given by Eq. 1.38 expresses its dependency on the lepton angular variables solely through the harmonic polynomials $P_i(\cos\theta, \phi)$. The relevant kinematic variables for the production of W bosons, namely p_T^W , y^W , and m^W , are encapsulated within the angular coefficients A_i . This encapsulation indicates that the hadronic mechanism responsible for W boson production is embedded within the structure of the A_i coefficients. As a result, this mechanism is factorised from the electroweak decay processes of the W boson into leptons, which are responsible for determining the decay kinematics of the W boson in its rest frame.

An inherent advantage of this formulation is the minimal theoretical uncertainties associated with the choice of factorisation and renormalisation scales when considering the cross-section ratios A_i . Moreover, the uncertainties that arise from the structure functions and the selected factorisation scheme are significantly reduced, as they largely cancel out within these ratios.

In the limit of zero transverse momenta all coefficients except A_4 vanish due to the conservation of angular momentum. The orientation of the spin of the gauge boson determines the angular distribution of the decay leptons. In the Drell-Yan process, if the gauge boson is produced at rest, the leptons will be emitted in a back-to-back configuration in the boson's rest frame, with an angular distribution that depends on the boson's polarisation. It is also important to note that the dependence of the (p_T^W, y^W) on the A_i coefficients is strongly influenced on the choice of the z -axis. The choice of the rest frame for this analysis is discussed in Section 1.3.

The angular coefficients A_0 , A_2 , and A_3 display an increasing trend as a function of p_T^W . Remarkably, their deviations from the lowest-order expectation, where $A_0 = A_2 = 0$, are considerable within a moderate range of p_T^W , specifically between 20 to 50 GeV. While these coefficients are perfectly aligned at LO [51], this equivalence is no longer valid at NLO. The resulting corrections at this order induce deviations, but these are smaller than 10% [50]. In contrast, the deviation of A_1 from zero remains relatively minor, even at heightened p_T^W values. The contribution of A_4 is pronounced at smaller p_T^W values and fades away as p_T^W increases. Interestingly, both A_3 and A_4 show a larger contribution for the W boson compared to the Z boson. This difference is due to the fact that the ratio of A_3 and A_4 is proportional to $v_\ell a_\ell v_q a_q$. Consequently, in the scenario of the Z boson, they are influenced

by the weak mixing angle, leading to their suppression.

Upon integrating Eq. 1.38 over θ , we derive:

$$\frac{d\sigma}{dp_T^W dm^W dy^W d\phi} = \frac{1}{2\pi} \frac{d\sigma^{U+L}}{dp_T^W dm^W dy^W} \left\{ 1 + \frac{1}{4} A_2 \cos 2\phi + \frac{3\pi}{16} A_3 \cos \phi + \frac{1}{2} A_5 \sin 2\phi + \frac{3\pi}{16} A_7 \sin \phi \right\}, \quad (1.39)$$

while integration over ϕ yields:

$$\frac{d\sigma}{dp_T^W dm^W dy^W d\cos\theta} = \frac{3}{8} \frac{d\sigma^{U+L}}{dp_T^W dm^W dy^W} \left\{ (1 + \cos^2\theta) + \frac{1}{2} A_0 (1 - 3\cos^2\theta) + A_4 \cos\theta \right\}. \quad (1.40)$$

As evidenced by Eq. 1.39 and Eq. 1.40, the act of integrating over polar or azimuthal angles leads to the loss of data concerning the angular coefficients A_1 and A_6 . This phenomenon arises due to the respective integrals of the polynomials corresponding to these coefficients equating to zero. It is therefore essential to use the full two-dimensional phase space defined by the variables $(\cos\theta, \phi)$ in order to accurately capture all the A_i coefficients, including in particular A_1 and A_6 .

1.3 The Collins-Soper frame

The study of the angular distributions of dileptons in Drell-Yan processes offers a unique probe into the dynamics of the strong and electroweak interactions. The angular coefficients in these distributions are, however, dependent on the choice of the reference frame due to their reliance on the kinematics of the produced W or Z bosons. Several reference frames have been proposed in the literature, each with its own advantages and pitfalls. Notable among these are the Collins-Soper frame [52], the Mustraal frame [53], and the Helicity frame.

For the purpose of this analysis, the Collins-Soper (CS) frame is adopted. This choice is primarily motivated by its robustness against higher-order QCD effects and the direct analogy it offers when comparing the angular coefficients of the W boson with those of the Z boson. The CS frame was introduced by John Collins and Davison Soper in 1977 as an intermediate frame that smoothly interpolates between the target and projectile rest frames.

The definition of the CS frame is firmly established within the context of the W boson rest frame. The z -axis bisects the angle between the direction of the incoming hadron and the opposite of the direction of the other incoming hadron, all within the W boson rest frame. This is graphically illustrated with the angle α in Figure 1.7. The direction of the z -axis is further constrained to align with the W boson's momentum in the laboratory frame. To complete the right-handed Cartesian system, the y -axis is chosen perpendicular to the plane defined by the two incoming protons, while the x -axis is set orthogonal to both the z and y axes.

The orientation of the produced leptons in the CS frame is characterised by the polar and azimuthal angles, θ_{CS} and ϕ_{CS} respectively. The polar angle, θ_{CS} , measures the angle between the negatively charged lepton's momentum and the z -axis. For W^+ production, due

to the absence of a negatively charged lepton, the neutrino direction is utilised instead. The kinematics of the leptons in the laboratory frame offers a convenient pathway to calculate $\cos \theta_{CS}$ as presented in [54]:

$$\cos \theta_{CS} = \frac{P_W^{\ell\bar{\ell}}}{|P_W^{\ell\bar{\ell}}| m^{\ell\bar{\ell}} \sqrt{m^{\ell\bar{\ell}2} + p_T^{\ell\bar{\ell}2}} (P_1^+ P_2^- - P_1^- P_2^+) \quad (1.41)$$

where,

$$P_i^\pm = \frac{1}{\sqrt{2}} (E_i \pm p_{z,i}). \quad (1.42)$$

Here, E_i represents the energy and $p_{z,i}$ the longitudinal momentum of the lepton, where the indices $i = 1$ for the lepton and $i = 2$ for the anti-lepton. $p_W^{\ell\bar{\ell}}$ represents the longitudinal momentum of the dilepton system. The azimuthal angle, ϕ_{CS} , measures the angle between the lepton plane and the xz -plane, and it is necessary to evaluate it within the confines of the CS frame to ensure accuracy.

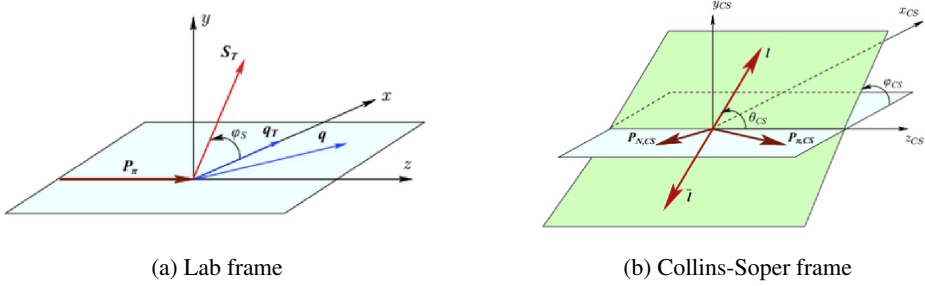


Figure 1.7: Left: Laboratory frame showing protons with momentum P_π approaching from opposite directions, producing a W boson with four-momentum q travelling in an arbitrary direction. Metrics such as the transverse momentum imbalance S_T , azimuthal angle ϕ_S , and the boson's transverse momentum q_T are also shown. Right: The Collins-Soper frame representation.

1.4 Experimental measurements of Drell-Yan angular coefficients

Drell-Yan angular coefficients offer insightful probes into the dynamics of the underlying quark and anti-quark annihilation into a virtual Z boson, which subsequently decays into lepton pairs. Over time, the measurement of these coefficients has played a key role in validating theoretical frameworks and enhancing the understanding of these processes. This section provides an overview of the experimental investigations related to the Drell-Yan angular coefficients, with a particular focus on measurements involving the Z and W bosons.

1.4.1 Measurements with Z bosons

The neutral Z boson, which is characterised by its well-defined mass resonance, plays a central probe in the investigation of the Drell-Yan mechanism. A multitude of experiments have been conducted with the objective of studying the angular distributions of lepton pairs resulting from the decays of the Z boson decays. Such investigations facilitate the extraction of angular coefficients while also providing crucial tests of the theoretical predictions made by the SM.

The team at the CDF Collaboration at the Tevatron has published its findings on angular coefficient measurements for lepton pairs in the region of the Z boson mass resonance [55]. The research made use of 2.1 fb^{-1} of proton-antiproton collision data at a center-of-mass energy of $\sqrt{s} = 1.96 \text{ TeV}$. As a consequence of the methodological constraints of their measurement technique, which were limited to the projections of $\cos \theta$ and ϕ , the coefficients A_1 and A_6 remained unprobed. In the case of the coefficients A_5 and A_7 , it was assumed that their values were not zero, given the limitations of the experimental precision. The coefficients $A_{0,2,3,4}$ were determined as functions of the transverse momentum p_T^Z . In subsequent studies conducted by the same research group [56], these measurements were used to estimate $\sin^2 \theta_W$, thereby establishing a link to the on-shell scheme of the W boson mass via the average value of the A_4 coefficient. This research illuminated the significant potential of this approach in exploring detailed aspects of both the hard QCD and electroweak sectors.

Subsequently, the CMS experiment presented their analyses concerning the angular coefficients of the Z boson in the context of the $Z \rightarrow \mu\mu$ decay channels, as detailed in reference [57]. In this study, the collaboration employed 19.7 fb^{-1} of proton-proton collision data at a center-of-mass energy of $\sqrt{s} = 8 \text{ TeV}$. The examination was divided into two rapidity (y^Z) bins and further segmented into eight regions based on the transverse momentum (p_T^Z), with a maximum threshold of 300 GeV. This comprehensive analysis revealed a notable deviation from the established Lam-Tung relation [58]–[60], an observation that concurred with predictions based on QCD formalisms extending beyond NLO.

Lastly, the ATLAS collaboration conducted a detailed examination of the angular coefficients associated with Z boson events, with a particular focus on electron and muon pair production. The analysis was based on data from proton-proton collisions at a center-of-mass energy of $\sqrt{s} = 8 \text{ TeV}$, totaling an integrated luminosity of 20.3 fb^{-1} [61]. This comprehensive study included the full range of eight A_i coefficients. Methodologically, the research was carried out within the Z -boson invariant mass window, ranging 80 to 100 GeV, and detailed as a function of the transverse momentum p_T^Z , while being classified into three distinct rapidity y^Z segments. Significant deviations from the $\mathcal{O}(\alpha_s^2)$ theoretical predictions were observed, particularly with respect to the Lam-Tung relation, as demonstrated by $A_0 - A_2$. Additionally, the results showed notable appearances of the coefficients $A_{5,6,7}$, consistent with established theoretical frameworks. For a detailed visual analysis of these distributions in the domain of the Drell-Yan angular coefficients for Z -boson decays, the reader is referred to Figure 1.8.

Table 1.2 shows that at the LO level of QCD, the predominant process is the $q\bar{q}$ -annihilation, resulting in a non-zero value exclusively for the coefficient A_4 . As one progresses to NLO within QCD, additional diagrammatic contributions emerge, notably from gq , $g\bar{q}$, and gg interactions. This inclusion results in non-zero values for the coefficients

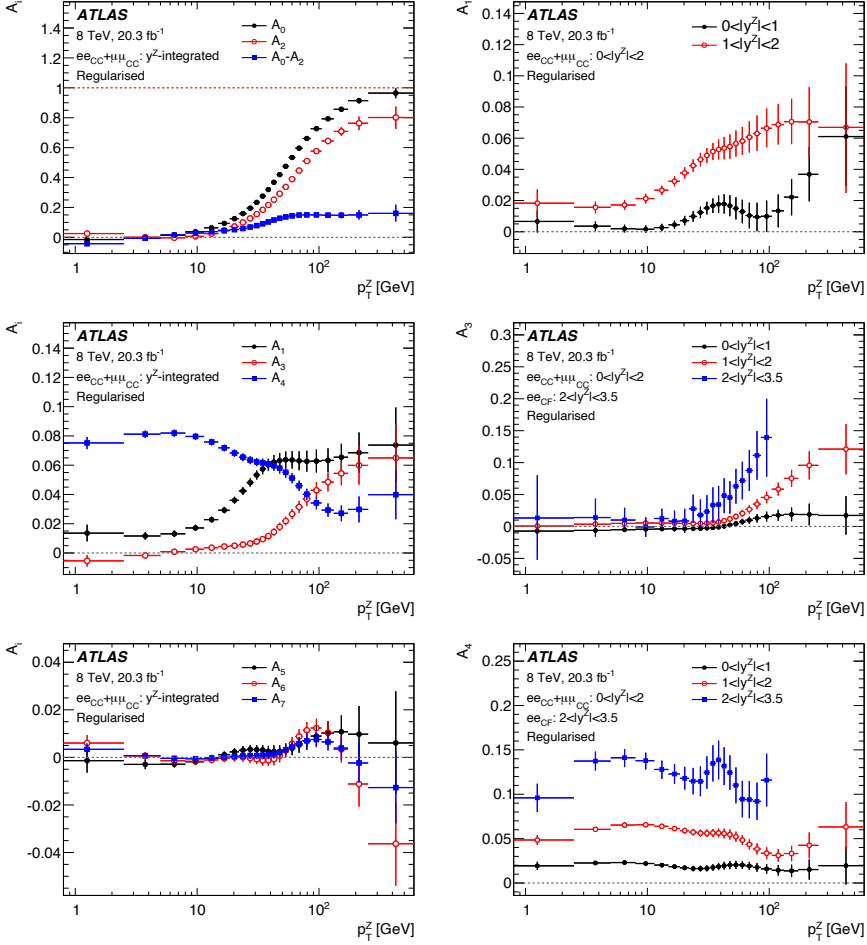


Figure 1.8: Angular coefficient measurements as functions of p_T^Z in both y^Z -integrated and y^Z -binned configurations. For the y^Z -integrated configurations, the top left panel displays $A_{0,2}$ alongside the difference $A_0 - A_2$; the middle left panel represents $A_{1,3,4}$; and the bottom left panel illustrates the coefficients $A_{5,6,7}$. Correspondingly, the y^Z -binned coefficients, A_i , are overlaid over all relevant y^Z bins: A_1 (top right), A_3 (middle right), and A_4 (bottom right). The accompanying error bars represent the total uncertainty in the measurements. Data sourced from Ref. [61].

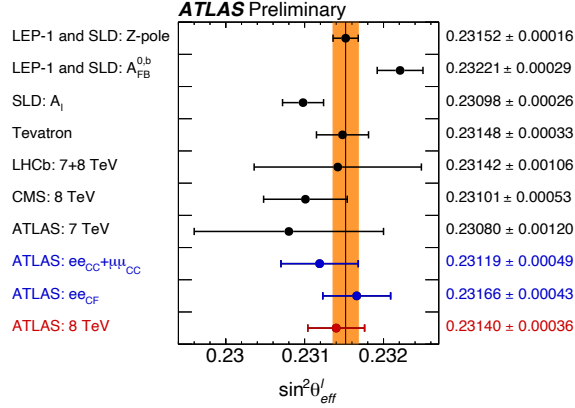


Figure 1.9: Comparison of the effective lepton weak mixing angle, $\sin^2 \theta_{eff}^{ell}$, from the [ATLAS](#) $\sqrt{s} = 8$ TeV measurement to previous measurements [62]. The [ATLAS](#) results at the bottom are in agreement to the vertical band corresponding to the [LEP-1/SLD](#) average.

A_{0-3} . In the [NNLO](#) regime and beyond, gluonic loops become a significant factor, indicating that while A_{5-7} are expected to retain relatively small values, they should deviate from zero.

Upon examination of Figure 1.8 (top left), it becomes clear that the Drell-Yan angular coefficients, particularly A_0 and A_2 , display an increasing trend with the rise in p_T^Z . Additionally, a noticeable deviation is observed between A_0 and A_2 . This deviation, known as the Lam-Tung relation, is of considerable interest as it is expected to be negligible at [NLO](#) within the framework of perturbative [QCD](#) theory. This expectation is based on the spin-1 nature of gluons in interactions such as $qg \rightarrow Zq$ and $q\bar{q} \rightarrow Zqg$. However, with the inclusion of higher-order diagrams, particularly at [NNLO](#), allows this difference to deviate from zero, indicating the complex nature of [QCD](#) processes at higher orders. A closer examination of Figure 1.8 (middle left) reveals the behaviour of the Drell-Yan angular coefficients A_1 , A_3 , and A_4 when integrated in rapidity for the combined electron and muon channels. Both A_1 and A_3 exhibit an increase with p_T^Z , similar to A_0 and A_2 , but with distinctive magnitudes. In contrast, A_4 demonstrates a diminishing trend with increasing transverse momentum, p_T^Z . It is noteworthy that coefficients A_{5-7} , which have a significance of 3.0 standard deviations, are shown in Figure 1.8 (bottom left). These coefficients, in particular $A_{5,6,7}$, consistently orient towards positive non-zero values, especially in regions where p_T^Z approximates 100 GeV.

With regard to the weak mixing angle, Table 1.2 shows a linear association between coefficients A_3 and A_4 and the vector and axial-vector couplings of quarks and leptons. This enables the extraction of the weak mixing angle, $\sin^2 \theta_W$, through the measurement of these coefficients. In accordance with this understanding, the [ATLAS](#) experiment conducted a measurement, leveraging the A_4 coefficient, with data at $\sqrt{s} = 8$ TeV, yielding a result of $\sin^2 \theta_{eff}^{ell} = 0.23140 \pm 0.00036$ [62]. This outcome is in accordance with the sensitivity and agreement observed with the [LEP-1](#) and [SLD](#) Z-pole average [33], as represented by the vertical band on Figure 1.9.

1.4.2 Measurements with W bosons

In contrast to its neutral counterpart, the Z boson, the charged W boson presents a complex challenge in the analysis of the Drell-Yan process involving it. A significant challenge in the measurement of W boson A_i coefficients is the inclusion of a neutrino in the final state, which complicates the reconstruction of the W boson's rest frame. Notwithstanding these difficulties, a considerable number of experimental studies have been conducted with the objective of investigating the angular distributions that arise from the decays of W bosons into lepton-neutrino pairs.

Since the discovery of the W boson, its hadronic production in $p\bar{p}$ and pp collisions, mass, and width have been measured with precision [32]. The focus then shifted to understanding the boson's differential distribution, which relies heavily on the leptons originating from $W \rightarrow \ell\nu$ decays in the boson's rest frame. With the electroweak interaction at the decay vertex known precisely, these measurements primarily test the dynamics of the strong interaction present in the angular distributions of the outgoing leptons.

For a comprehensive review of the experimental measurements and methodologies involved in these studies, the reader is encouraged to refer to [63]. At present, the evaluation of the A_i coefficients for $W \rightarrow \ell\nu$ in hadronic collisions is not yet fully satisfactory. A limited number of coefficients, such as A_2 and A_3 [64], or specific combinations like α_1 , α_2 in the CS frame [65], [66] or f_L , f_R , f_0 in the helicity frame [67], [68], fails to provide a comprehensive insight into the QCD dynamics underlying the production process. The initial studies [2], [69] have argued that it is unfeasible to capture the entire coefficient set, primarily due to the challenges associated with reconstructing lepton neutrino momenta. This results in an inherent ambiguity when determining the sign of $\cos\theta$.

However, this thesis adopts a more refined measurement strategy, accordance with the methodologies outlined in Ref. [61]. It is of particular importance to note that the methodology incorporates solutions designed to resolve the ambiguity surrounding the sign of $\cos\theta$. These techniques have been both introduced and tested in Ref. [63]. By employing this approach, it becomes feasible to perform a holistic measurement of all coefficient sets. With a substantial quantity of statistical data, even the $W \rightarrow \ell\nu$ process in pp collisions can be subjected to a comprehensive examination.

1.5 Prospect of W boson angular distributions measurements

The angular distribution coefficients A_i of the W boson have historically been a relatively unexplored area of research, with only two measurements, A_2 and A_3 , having been conducted by the CDF experiment [64]. The introduction of a complete set of measurements for the angular distribution coefficients of the W boson represents a significant advancement in the field. Such comprehensive measurements permit an in-depth investigation of the QCD and electroweak structures of angular correlations. This paves the way for a more precise test of QCD and allows for greater precision in physics modelling.

A comparison of the angular distribution coefficients (A_i) of the W boson with those of the Z boson can provide valuable insights. Such a comparison has the potential to highlight both the differences and similarities in their production and decay mechanisms,

thereby deepening our understanding of weak interaction processes and the nuances of gauge theories.

This research represents a departure from tradition, marking the first instance where the W boson cross-section is measured as a function of the rapidity (Y) at the [LHC](#). Previous efforts have concentrated on the lepton's pseudorapidity (η), making this new approach particularly groundbreaking. The rapidity (Y) of a produced W boson provides direct information about the longitudinal momentum fractions of the interacting quarks, offering a pathway to disentangle contributions from valence quarks and the more elusive sea quarks.

The Lam-Tung relation, given by $A_0 - A_2 = 0$, while being a cornerstone of [QCD](#) for other particles. However, it remains unexplored territory for the W boson. This study aims to determine whether the W boson follows this relation or if it diverges, as seen with the Z boson.

Moreover, the distinctive dependencies of the W^+ and W^- bosons on quark-antiquark interactions provide a unique point of view. The production of a positively charged W^+ boson primarily relies on u and $\bar{d}$ quarks, whereas a negatively charged W^- boson is contingent on a d and an $\bar{u}$ quarks. An investigation of these nuances can provide insights into parton distribution functions, thereby enhancing our understanding of their behaviours.

Another avenue of interest is the charge asymmetry extracted from the $W A_i$ measurements. Such data represents an important input for [PDF](#) fits, potentially enhancing the accuracy and consistency of these fits. Notably, these measurements also promise to reduce the systematic uncertainties linked with [PDF](#) in the ongoing W mass determinations, thereby establishing a solid foundation for future endeavours in particle physics.

1.5.1 Limitations in m_W measurement

The W boson mass (m_W) holds a significant place in the [SM](#), particularly in the context of spontaneous symmetry breaking. Its importance can be understood by examining its relationship with the electroweak parameters. In leading-order perturbation theory, the W mass is closely linked to various electroweak parameters. This relationship is captured by the following equation:

$$m_W = \sqrt{\frac{\pi\alpha_{EM}}{\sqrt{2}G_F}} \frac{1}{\sin\theta_W}, \quad (1.43)$$

wherein G_F is the Fermi constant, representing the strength of weak interactions, $\alpha_{EM} \approx \frac{1}{137}$ is the electromagnetic coupling constant, characterising the strength of electromagnetic interactions, and $\sin\theta_W$, known as the Weinberg angle, is a parameter in the [SM](#) that relates the masses of the W and Z bosons to the electroweak gauge coupling constants (refer to Eqs. 1.27). From this relationship, the factor $\sqrt{\frac{\pi\alpha_{EM}}{\sqrt{2}G_F}} \approx 40$ GeV can be seen as setting a fundamental lower limit for the W mass. Incorporating higher order corrections to the above relationship yields:

$$m_W = \sqrt{\frac{\pi\alpha}{\sqrt{2}G_F}} \frac{1}{\sin\theta_W} (1 + \Delta r) \quad (1.44)$$

where Δr aggregates the spectrum of possible radiative corrections. It is noteworthy that this correction is sensitive to other [SM](#) parameters, in particular the masses of the top quark and

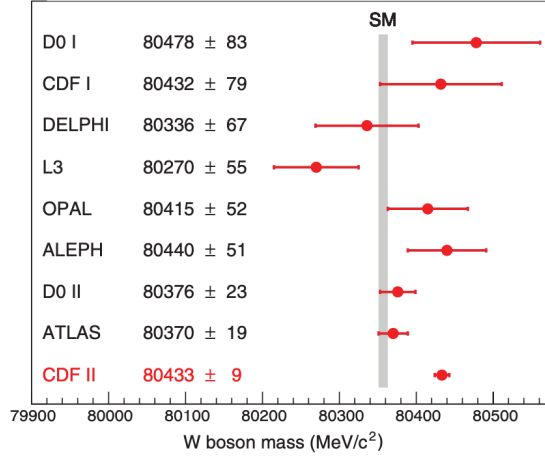


Figure 1.10: An comparative overview of available measurements for the W boson mass [71].

the Higgs boson. Moreover, the potential impact of the physics Beyond the Standard Model (BSM) on this term represents a significant prospects for future research.

The direct measurements of the Higgs and top quark masses have reached a precision that surpasses their indirect determinations from global fits of electroweak observables. It can therefore be concluded that the refinement of the accuracy of these specific measurements is unlikely to significantly enhance sensitivity to potential new physics. Conversely, the indirect determination of the W boson mass, m_W , currently stands at approximately ± 7 MeV, which represents a higher precision than that achieved by direct experimental methods [70]. This discrepancy highlights the necessity for the experimental uncertainty of the W boson mass, denoted as δm_W^{exp} , to be approximately of 5 MeV. Given that current theoretical estimates showcasing uncertainties that are nearly half as much as the best available experimental measurements (as shown in Figure 1.10), there exists a pressing need to refine experimental methodologies with the aim of reducing the systematic uncertainties associated with m_W measurements. In light of these observations, it becomes evident that the improvement of the precision of the W boson mass measurement is not just a merely an endeavour to enhance the accuracy of a single parameter. Instead, it represents a cornerstone measurement, potentially capable of significantly increasing the sensitivity of the global electroweak fits, thereby enhancing our prospects of uncovering potential new physics.

The W boson's mass has been a topic of significant investigation at the LHC. Notably, a milestone was achieved with the measurement of the W boson mass using the Run-I data at $\sqrt{s} = 7$ TeV collected by the ATLAS detector [72]:

$$\begin{aligned}
 m_W &= 80369.5 \pm 6.8 \text{ MeV (stat.)} \pm 10.6 \text{ MeV (exp. syst.)} \pm 13.6 \text{ MeV (mod. syst.)} \\
 &= 80369.5 \pm 18.5 \text{ MeV.}
 \end{aligned}
 \tag{1.45}$$

Incorporation of novel theoretical corrections stemming from analytical calculations enhances the competitiveness of this measurement. Nevertheless, the achieved precision

indicates the limitations of the [ATLAS](#) detector's capabilities for W boson mass measurements under its typical operational settings. Given the 19 MeV uncertainty, there remains a challenge in achieving a required precision of 8 MeV for comparisons with indirect predictions from [EW](#) observables (see Figure 1.10). A detailed breakdown of uncertainties is provided in Tab. 1.3.

The measurement of m_W is influenced by the choice of observable, be it p_T^ℓ or m_T^W . Thus, uncertainties related to leptons form a substantial component of the overall experimental uncertainty. On the theoretical front, the corrections include contributions from [QED](#), vector-boson-polarization (notably [QCD](#) (A_i)), W boson's transverse momentum due to [NNLO](#) effects in [pQCD](#), and [PDFs](#). Several enhancements are anticipated for the upcoming W boson mass measurements at [ATLAS](#):

- The measurement of Z boson polarisation and its angular coefficients A_i at $\sqrt{s} = 8$ TeV is already published [61], as discussed in Section 1.4.1.
- The [EM](#) correction precision has transitioned from [LO](#) to [NLO](#) predictions.
- Recent analyses have improved the modeling of p_T^W , particularly in the low p_T^W region that holds the highest sensitivity to m_W ; in this region, [pQCD](#) predictions are not applicable [73].
- This research aims to refine the measurements of A_i coefficients for the W boson, which, when used with the latest [PDF](#) sets, may reduce uncertainties from both [PDF](#) and vector-boson-polarization corrections.

With the recent achievements of the [CDF II](#) collaboration in m_W measurements, the situation becomes increasingly interesting. Utilising data corresponding to 8.8 fb^{-1} of integrated luminosity collected from proton-antiproton collisions at a 1.96 TeV center-of-mass energy with the [CDF II](#) detector at the Fermilab Tevatron collider, the m_W value was measured with the highest precision ever achieved [71]:

$$m_W = 80433.5 \pm 6.4 \text{ MeV (stat.)} \pm 6.9 \text{ MeV (syst.)} = 80433.5 \pm 9.4 \text{ MeV.} \quad (1.46)$$

The precision of this measurement surpasses that of all previous measurements combined. This significant deviation from the [SM](#) expectation necessitates validation from other experimental collaboration groups. The [ATLAS](#) collaboration stands as a strong candidate to achieve this validation.

Experement	ATLAS	CDF II	ATLAS	ATLAS
Year	2018	2022	ongoing	ongoing
Data sample	7 TeV, $\mu \sim 9$	1.96 TeV	13 TeV, $\mu \sim 1$	5 TeV, $\mu \sim 2$
Luminosity	4.5 fb^{-1}	8.8 fb^{-1}	$\sim 335 \text{ pb}^{-1}$	$\sim 258 \text{ pb}^{-1}$
Nb. of candidates	$\sim 15 \times 10^6$	$\sim 4 \times 10^6$	$\sim 2 \times 10^6$	$\sim 0.7 \times 10^6$
Value [MeV]	80369.5	80433.5	-	-
Stat.	6.8	6.4	9	15
Lepton calibration	7	3.4	3	3
Lepton efficiencies	7	0.4	7	7
Recoil calibration	2.9	2.2	6	10
Backgrounds	4.5	3.3	2	2
EW	5.5	2.2	2	2
QCD (p_T^W)	6	1.9	< 3	< 3
QCD (A_i)	6	1.9	< 3	< 3
PDFs	9.2	3.9	6	6
Total	19	9.4	15	23

Table 1.3: Breakdown of uncertainty estimates for the latest m_W measurement by [ATLAS \[72\]](#) and [CDF II \[71\]](#) collaborations. Preliminary estimates for the uncertainty of future [ATLAS](#) m_W measurements are also provided. Uncertainties targeted for reduction by results of this thesis analysis are highlighted in red.

2

THE LARGE HADRON COLLIDER

This chapter provides a general overview of the operational principles of the Large Hadron Collider (LHC) at CERN. In addition, this chapter discusses the special low-pileup runs performed during Run 2. With a reduced number of simultaneous proton-proton collisions, these runs provide clearer data, which is essential for precision analysis such as the measurement of W boson angular coefficients.

2.1 Introduction

The development of particle accelerators in the late 20th century has played a central role in advancing the Standard Model (SM) of particle physics. A prime example of these advancements is the Large Hadron Collider (LHC), launched in 2008 as the world's largest and most powerful particle accelerator [74]. Located in a 27 km tunnel below the French-Swiss border near Geneva, the LHC conducts particle collisions at unprecedented energies across four beam collision sites, each equipped with a large particle detector—ATLAS [75], CMS [76], ALICE [77], and LHCb [78]. These detectors are integral to exploring fundamental particles and forces, supporting various physics programs tailored to their design. The ATLAS and CMS detectors are multipurpose detectors that are instrumental in conducting a wide range of SM measurements and in searching for new physics phenomena. In contrast, the LHCb experiment is specifically designed to investigate the physics of b -hadrons². Although these three experiments utilize proton-proton (pp) collisions, the ALICE experiment is distinct in its focus on studying heavy ion collisions.

The operational principles of the LHC utilize circular accelerator technologies. Particles are initially boosted to 450 GeV by the pre-acceleration complex, then directed to circulate in opposite directions within separate beam pipes that maintain an ultra-high vacuum to reduce unwanted interactions. This setup leverages powerful superconducting magnets to generate a strong 8.3 T magnetic field, guiding the particle beams along the LHC ring. The magnets

²A b -hadron is a type of hadron containing a bottom quark (b -quark). These particles are crucial for studying weak interactions and CP -violation.

are kept at a temperature of 2 K using superfluid helium, which is required to maintain their superconducting properties.

2.2 The LHC running sequence

The LHC at CERN employs a sophisticated multi-stage process for accelerating protons, key for high-energy collisions and particle physics experiments. The initial stage of proton acceleration begins with the extraction of protons from hydrogen gas. Using an electric field, electrons are stripped from hydrogen atoms in a hydrogen tank, isolating protons which are then accelerated by the Linear Accelerator 2 (Linac2) to 50 MeV. Following this, protons are advanced through a series of synchrotron accelerators. The Proton Synchrotron Booster (PSB) increases their energy to 1.4 GeV, and then the protons are further accelerated in the Proton Synchrotron (PS), an accelerator with a legacy of continuous upgrades since its inception in 1959, to 25 GeV. The final pre-LHC acceleration occurs in the Super Proton Synchrotron (SPS), where protons reach 450 GeV before injection into the LHC (see Fig. 2.1a).

Operating within a 27-kilometer tunnel, originally constructed for the Large Electron-Positron (LEP) Collider, the LHC ring is equipped with dipole magnets responsible for maintaining the protons' trajectory. These superconducting magnets generate a powerful magnetic field of 8.3 T, which is needed for steering the protons along the ring. The LHC also utilizes quadrupole magnets to focus the proton beams, reducing their cross-sectional area to as small as $16 \mu\text{m}^2$ at the collision points. This beam squeezing significantly increases the likelihood of proton-proton collisions.

Radio-frequency (RF) cavities play a dual role within the LHC. They not only accelerate the protons by boosting their energy to achieve a center-of-mass collisions energy of $\sqrt{s} = 13 \text{ TeV}$, but also pack them into tightly bunched groups, optimizing the collision rates. During LHC Run 2, the beams consisted of proton bunches spaced 7 meters apart¹, allowing up to 2556 bunches to circulate simultaneously within the collider, enhancing the intensity of the proton beams at the collision points.

Luminosity ($\mathcal{L}$) is a fundamental parameter in particle physics, defining the intensity and effectiveness of particle beam collisions within accelerators like the LHC. It quantifies the expected number of interactions per unit time and area, providing a basis for calculating the potential for particle interactions and experimental results.

The initial expression to calculate luminosity for head-on collisions is given by [79]:

$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y} \quad (2.1)$$

where N_1 and N_2 represent the intensities of the two colliding beams, f denotes the revolution frequency, N_b is the number of bunches per beam, and σ_x and σ_y are the horizontal and vertical root-mean-square (r.m.s.) widths of the beams, assuming Gaussian profiles.

¹The bunches are spaced by 25 ns, which corresponds to a maximum collision frequency of 40 MHz.

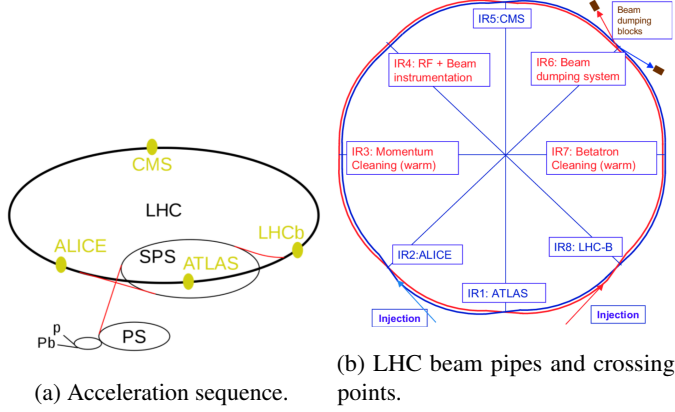


Figure 2.1: Schematic of the LHC ring.

However, real collision conditions often deviate from the ideal due to factors like the crossing angle (θ_c)¹ and bunch length (σ_s)², necessitating a correction factor $\mathcal{F}$. This factor adjusts the theoretical luminosity to reflect actual conditions, calculated as:

$$\mathcal{F} = \frac{1}{\sqrt{1 + \left(\frac{\sigma_s}{\sigma_x} \frac{\theta_c}{2}\right)^2}} \quad (2.2)$$

The integrated luminosity ($\mathcal{L}_{int}$), essential for evaluating the total interaction potential over time, is determined by integrating the instantaneous luminosity as follows:

$$\mathcal{L}_{int} = \int_0^T \mathcal{L}(t) dt \quad (2.3)$$

This integration directly determines the total number of detectable events (N_{events}), which can be calculated using the equation:

$$N_{events} = \mathcal{L}_{int} \cdot \sigma, \quad (2.4)$$

where σ represents the cross section of the process being studied.

High integrated luminosity increases the likelihood of observing rare processes, while precision in measuring luminosity is crucial due to its significant impact on the uncertainty in cross-section measurements. The predominant method for achieving precise absolute luminosity measurements at the LHC is the van der Meer (vdM) scan method, which involves varying the spatial overlap of the intersecting beams and measuring the interaction rate, allowing for direct calibration of beam sizes and positions. For a comprehensive understanding of luminosity determination at proton colliders, further reading can be found in [80], along with seminal works [81], [82].

¹Beams at colliders often intersect at a defined angle rather than colliding head-on. This crossing angle reduces the overlap between the beams, diminishing the effective luminosity.

²The longitudinal length of the particle bunches affects collision dynamics, where longer bunches may decrease particle density at the collision point, thus reducing interaction probability.

2.3 Special low-pileup run during LHC Run 2

The [ATLAS](#) experiment at the [LHC](#) underwent Run 2 from 2015 to 2018, during which it collected a substantial 146.9 fb^{-1} of data under varying bunch crossing conditions. This period is shown in Figure 2.2. Notably, precise measurements of processes involving the W boson necessitate special experimental conditions due to the challenges posed by high proton-proton collision rates per bunch crossing. Big number of interactions per bunch crossing often lead to the contamination of the final state signal with products from soft collisions, a phenomenon known as *pileup*. Pile-up can significantly complicate the reconstruction of objects and lead to an increase in systematic uncertainties.

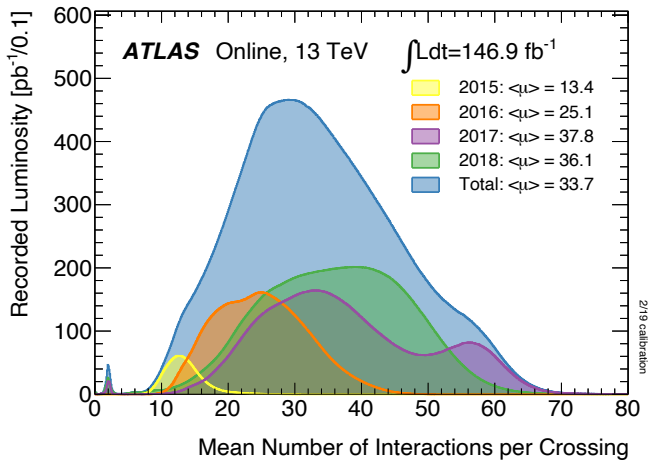


Figure 2.2: Number of interactions per bunch crossing in [ATLAS](#) during Run 2. The little bump around $\mu \approx 2$ corresponds to special low-pileup runs.

To address these challenges, the [LHC](#) conducted two special low- μ pileup runs in 2017 and 2018, with energies set at 5 and 13 TeV, respectively, aimed at reducing the number of interactions per bunch crossing. The [ATLAS](#) experiment leveraged on these runs to gather data in a cleaner environment for a number of pileup sensitive analyses. This includes measurements of W and Z boson's transverse momentum (p_T^W and p_T^Z) and precision mass measurement of the W boson. Information regarding the data collected during these special runs is detailed in Table 2.1. For the analysis discussed in this thesis, only low-pileup data from the 13 TeV run was used.

Collision energy	Year	Integrated luminosity, pb^{-1}	Total uncertainty, %
5 TeV	2017	258	1.6
13 TeV	2017	148	2.1
13 TeV	2018	193	1.5

Table 2.1: Energy and luminosity of the special low- μ runs.

3

THE ATLAS DETECTOR

The **ATLAS** (A Toroidal LHC ApparatuS) detector [75], located at Point-1 (P1) of the **LHC** [83] at **CERN**, is one of the four major experiments designed to explore a wide range of particle physics phenomena. This multi-purpose detector, the largest in terms of size but not weight, operates under full **LHC** luminosity to probe proton-proton (p-p), proton-ion (p-A), and ion-ion (A-A) collisions. The **ATLAS** detector, located in an underground cavern 95 meters deep, spans 46 meters in length and 25 meters in diameter, with a total mass of approximately 7000 tonnes.

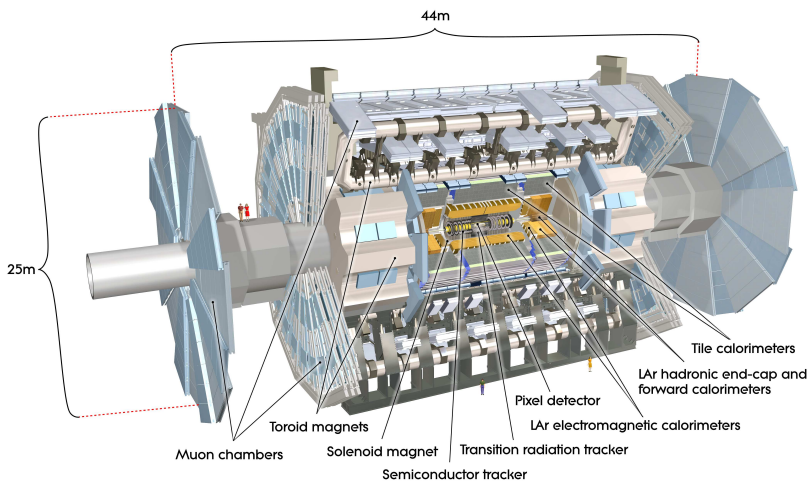


Figure 3.1: The **ATLAS** detector general layout.

ATLAS's cylindrical structure contains three primary sub-detector systems symmetrically arranged around the interaction point, covering nearly the entire solid angle of 4π (see Figure 3.1). These include the Inner Detector (**ID**), which tracks charged particles; the calorimeters, which measure the energy of electrons, photons, and hadrons; and the Muon

Spectrometer (**MS**), which detects muon hits and trajectories. The detailed sub-systems of the **ID** include the Pixel detector (**PIX**), the Semiconductor Tracker (**SCT**), and the Transition Radiation Tracker (**TRT**). In addition, the calorimetry system consists of the Electromagnetic Calorimeter (**EMC**), the Hadronic Calorimeter (**HC**), and the Forward Calorimeter (**FCal**). These systems are important for distinguishing different particle types produced in collisions, such as electrons, muons, photons, and jets. The detector operates within the magnetic fields generated by solenoid and toroid magnets, crucial for bending the trajectories of charged particles to determine their charge and momentum. The Trigger and Data Acquisition (**TDAQ**) system plays a key role in managing the data flow, selectively recording events to maintain a manageable rate for storage and further analysis.

The passage of various particle types through the subsystems of the **ATLAS** detector in the transverse plane is shown in Figure 3.2. Charged particles are identified by the curvature of their paths in a magnetic field, which allows for the determination of their charge and momentum. Photons and electrons release their energy in the electromagnetic calorimeter, whereas hadrons deposit their energy in the hadron calorimeter. The distinction between charged and neutral particles is that the latter do not leave tracks in the inner detector. Muons and neutrinos are unique in that they can traverse the entire detector. However, unlike muons, which leave tracks in the muon spectrometer, neutrinos pass through undetected, leaving no trace. Although neutrinos are not directly observable, their presence is inferred from missing energy in the detector. This missing energy is subject of studies of some particles outside the **SM** (for example as candidates for a dark matter). The measurement of this missing energy relies solely on the energy balance across the transverse plane, using the assumption that the total transverse energy in the collision should be zero.

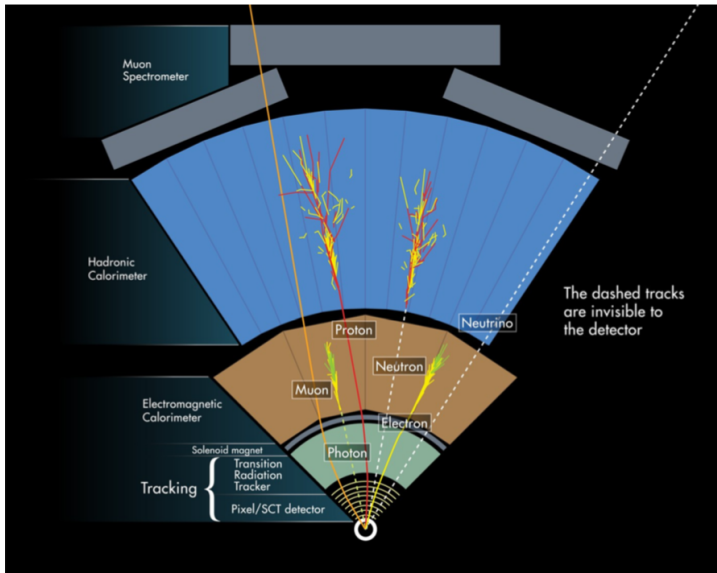


Figure 3.2: The principle of various particle types detection in the transverse plane of the **ATLAS** detector.

3.1 Coordinate system

The **ATLAS** experiment uses a right-handed Cartesian coordinate system with its origin at the nominal interaction point (**IP**) in the center of the detector, specified by coordinates $(x, y, z) = (0, 0, 0)$. The z -axis aligns with the beam pipe, extending along the beamline, while the x -axis extends from the **IP** towards the center of the **LHC** ring, and the y -axis points vertically upwards. This configuration places the x - y plane perpendicular to the beam direction.

For more detailed analysis, **ATLAS** also utilizes cylindrical coordinates (θ, ϕ, z) , where the azimuthal angle ϕ ranges from $[-\pi, \pi]$ and the polar angle θ from $[0, \pi]$. Pseudorapidity, defined as:

$$\eta = -\ln \tan(\theta/2), \quad (3.1)$$

is commonly used in particle physics to describe angular separation because it remains invariant under boosts in the longitudinal (z) direction. An η value of 0 corresponds to an angle perpendicular (90°) to the beamline, with values increasing towards infinity along the beam direction. Rapidity is defined as:

$$y = \frac{1}{2} \ln \frac{E + p_z}{E - p_z} \quad (3.2)$$

where E represents the total energy and p_z the momentum component along the beam axis.

Key metrics calculated within this coordinate framework include:

- **Transverse Momentum** (p_T): the magnitude of the momentum vector of a particle in the x - y plane, calculated as $p_T = \sqrt{p_x^2 + p_y^2}$.
- **Transverse Energy** (E_T): derived from the transverse momentum, given by $E_T^2 = p_T^2 + m^2$, where m is the particle's mass.
- **Transverse Impact Parameter** (d_0): representing the shortest distance in the transverse plane between a particle track and the beam spot, or alternatively, the primary proton-proton interaction point.
- **Longitudinal Impact Parameter** (z_0): the closest approach of a particle track to the primary interaction along the z -axis.

Additionally, the metric used to assess the separation between two particles over angular distances in the pseudorapidity-azimuthal angle space is defined by:

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} \quad (3.3)$$

This metric becomes particularly useful for studies of particle isolation, as it facilitates the summation of energy deposits or tracking activities within a ΔR cone.

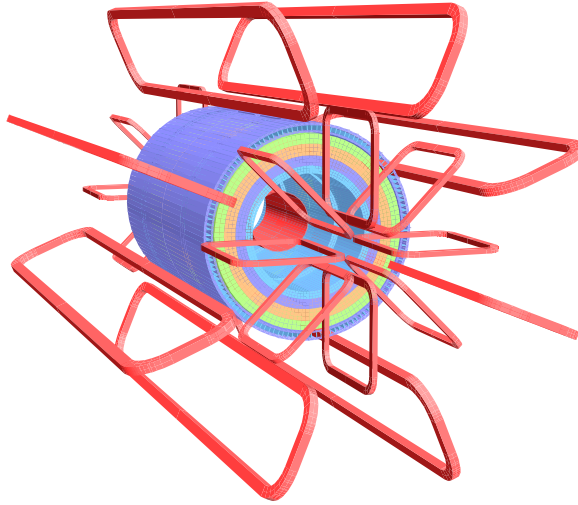


Figure 3.3: Geometry of [ATLAS](#) magnet windings and tile calorimeter steel [84]. The eight barrel toroid coils, with the end-cap coils interleaved are visible. The solenoid winding lies inside the calorimeter volume. The tile calorimeter is modelled by four layers with different magnetic properties, plus an outside return yoke. For the sake of clarity the forward shielding disk is not displayed.

3.2 Magnet system and magnetic field

The [ATLAS](#) experiment has a sophisticated magnet system that is important for directing particle beams and for the precise measurement of the momenta of particles resulting from collisions. This system integrates both solenoidal and toroidal magnets, as shown in Figure 3.3.

At the core of this system lies a central solenoid magnet, which is 4.5-cm thick, 5.8-m long, and 2.4-m in diameter. It surrounds the inner detector and generates a strong 2 Tesla magnetic field aligned with the beam axis. This solenoid is instrumental in bending the paths of the charged particles coming from the collision points, allowing precise momentum estimates to be made by analyzing the curvature of their trajectories in the inner layers of the detector.

Additionally, the system includes toroidal magnets, which are indispensable for optimizing the performance of the muon spectrometer. These magnets consist of a barrel toroid and end-cap toroids that generate magnetic fields up to 0.5 Tesla in the barrel and 1 Tesla in the end-caps. These fields are bending the trajectories of muons orthogonally to the beam axis, thus allowing for muon momentum measurements. The barrel toroid is 25.3 m long and with 9.4 m and 20.1 m inner and outer diameters. The end-cap toroids have an axial length of 5.0 m and an outer diameter of 10.7 m.

3.3 Inner detector

The Inner Detector (ID) [85], [86] of the ATLAS experiment is the first detector from the interaction point and is instrumental in achieving high precision in the tracking and identification of charged particles. The ID operates within a 2 Tesla solenoidal magnetic field and is designed to provide high-resolution tracking of charged particles, precise reconstruction of both primary and secondary vertices, measurement of particles momenta. It handles charged tracks with transverse momentum above $p_T > 0.5$ GeV (in some cases being capable of going as low as 0.1 GeV) and covers pseudorapidity range of $|\eta| < 2.5$. To fulfill the requirements of high granularity and performance even under extreme luminosity conditions at the LHC, the ID comprises three complementary sub-detectors: a pixel detector (PIX), a semiconductor tracker (SCT) and a transition radiation tracker (TRT). These sub-detectors are integrated within a cylindrical envelope that extends ± 3512 mm in length and 1150 mm in radius. Representation of the ID's layout is shown in Figure 3.4. Notably, the detector layers in the barrel are arranged as concentric cylindrical layers around the beam axis. In the end-caps the layers consist of disks positioned perpendicularly to the beam axis.

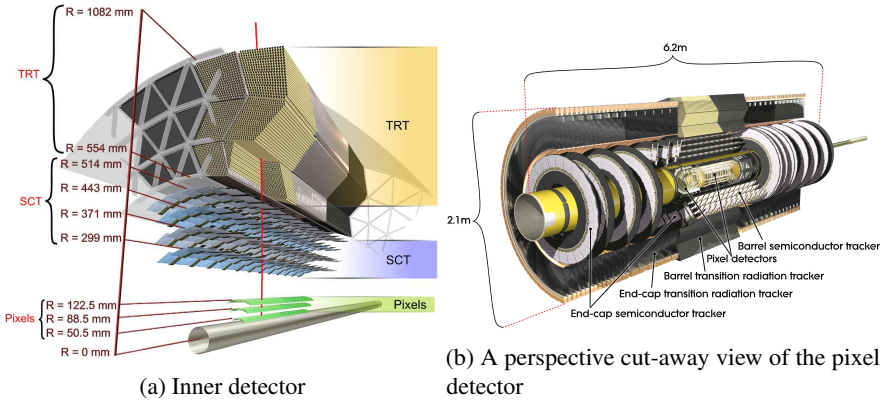


Figure 3.4: The ATLAS ID general layout.

- The **silicon Pixel (PIX)** [87], [88] is providing high granularity measurements around the vertex region of the detector. The PIX is structured into three cylindrical layers in the barrel, positioned at radii of $R = 50.5$, 88.5 , and 122.5 mm, and three disks on each side for the end-caps, located at $|z| = 495$, 580 , and 650 mm. This layout is designed to ensure that, on average, each charged track intersects three pixel layers, significantly enhancing the detector's tracking and vertex measurement capabilities. Approximately 90% of the pixels in the PIX measure $50 \times 400 \mu\text{m}^2$, matching the readout pitch of the front-end electronics. The other pixels, located near the front-end chips on the modules, are slightly larger, measuring $50 \times 600 \mu\text{m}^2$. The PIX comprises 1744 pixel modules, each outfitted with 16 front-end electronic chips that feature 2880 electronic channels per chip, enabling the efficient processing and transmission 80.4 million readout channels signals to the trigger and data acquisition system.

The innermost component of the **PIX, Insertable B-Layer (IBL)** [89], [90] was installed between Run 1 and Run 2 to enhance the measurement of the tracks and secondary vertices. It compensates for the increased radiation exposure that affected the original innermost layer, which has a radius of 50.5 mm. The **IBL** is positioned closer to the beam line, at a radius of 31 mm, ensuring improved tracking robustness and precision in the event of failures in the original first layer, as well as to cope with the higher luminosity levels that were not anticipated in the original design.

With the highest granularity and of radius 31 mm, together with **PIX** it provides an accuracy at $10\mu\text{m}$ in $R - \phi$ and $115\mu\text{m}$ in z .

- The **Silicon Microstrip Tracker (SCT)** [91]–[93] is the next layer after **PIX**, ranged from $R = 275$ mm to 560 mm. It has 4 cylindrical layers and 9 discs on each side for the end-cap. On average each charged track crosses the strip layers in four space points, providing four two-dimensional space points thus essential to the momentum and vertex position measurements. The **SCT** consists of 15912 sensors which result in approximately 6.3 million readout channels. Each sensor contains 768 active strips of 12 cm length and $80\mu\text{m}$ width plus two bias potential strips on the sensor edges. The accuracy of **SCT** is $17\mu\text{m}$ in $R - \phi$ and $580\mu\text{m}$ in z , coarser than **PIX** due to larger radius.
- The **Transition Radiation Tracker (TRT)** [94]–[96] is the outermost inner detector provides tracking as well as electron identification. Based on polyamide drift tubes (straws) of 4 mm diameter and 144 cm (37 cm for end-cap) length with the layers of polyamide films reinforced with carbon fibres. They are grouped in 73 straw planes in the barrel and 160 straw planes in the end-cap. This results in around 351000 readout channels which provide the ability to detect on average 36 hits per track in **TRT**. The straws are filled with a gas mixture of 70% Xe, 27% CO_2 and 3% O_2 . However, channels that are affected by irreparable gas leaks now use a much cheaper argon-based mixture [97]. Transition radiation photons from electrons are absorbed by Xe-based gas mixture, yielding larger signal amplitudes compared to minimum-ionising charged particles. The **TRT** provides space information only on $R - \phi$ and $z - \phi$, both of an accuracy approximating $130\mu\text{m}$. For a thorough exploration of the **TRT**, including details on detector upgrades for Run 2 and Run 3, please refer to Chapter 4.

The **TRT** operates at room temperature, whereas the pixel and **SCT** sensors, which are highly resistant to radiation, are maintained within a temperature range of -5°C to -10°C to minimize radiation damage. The combined operation of these three independent sub-detectors enables high-precision momentum measurements and excellent vertex determination.

3.4 Calorimeters

The **ATLAS** calorimeter system is located between the internal detector and the muon system and is intended for accurate measurement of the energy of charged and neutral particles in

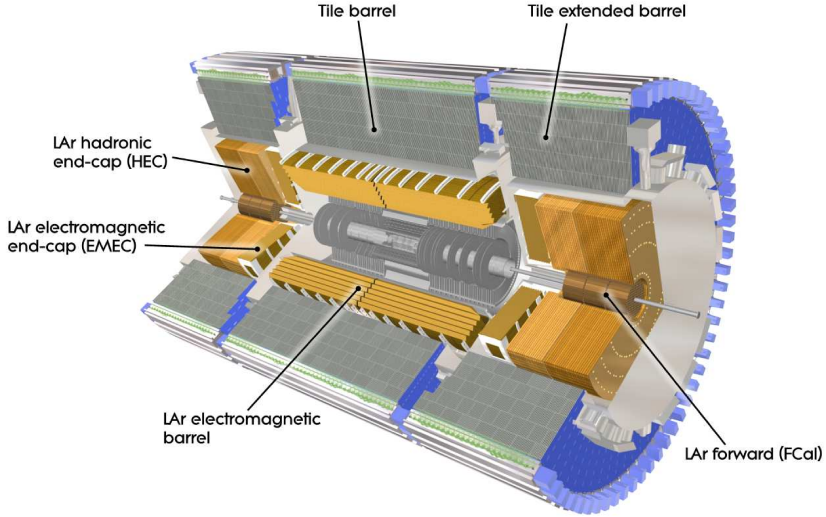


Figure 3.5: [ATLAS](#) calorimeter general layout [101].

the pseudorapidity region $|\eta| < 4.9$. To provide good measurement accuracy for a missing energy and jets reconstruction, the calorimeter system covers as much volume as possible and has no gaps. The view of the [ATLAS](#) calorimeter is presented on Figure 3.5. The calorimeter system consists of two calorimeter sections:

- the electromagnetic calorimeter (EMC) [98], that covers the region of $|\eta| < 3.2$ and measures the energy of electrons and photons;
- the hadronic calorimeter (HC) [99], [100], which measures the energy of hadrons within $|\eta| < 4.9$, using different type of calorimeters.

Both sections are made up of alternating layers of passive absorbent material, which causes showers, and active measurement volumes, which measure the energy of the particles in the shower. An electromagnetic shower is generated from the processes like bremsstrahlung and pair-antipair production, while the main contribution to a hadronic shower comes from nuclear interactions. The length of the calorimeters must be large enough to absorb all electromagnetic and hadron showers before they reach the muon system.

The characteristic value of the length of an electromagnetic calorimeter is the radiation length X_0 , which corresponds to the average distance passed by the particle in the calorimeter before it loses $1/e$ of its initial energy (where $e = 2.718$). In the case of hadron showers, the absorption length (λ_0) is used for this purpose with a similar definition. Hadron calorimeters are larger and wider than electromagnetic calorimeters, and due to the fact that they are designed to completely extinguish the energy of a particle, they are placed after electromagnetic calorimeters.

3.4.1 LAr electromagnetic calorimeter

The electromagnetic calorimeter [98] is a sampling calorimeter designed for precision measurement of the energy of particles interacting through an electromagnetic channel. It uses liquid argon as the active material and lead as the absorbent to induce showers. Liquid argon (LAr) was chosen due to its linear response and resistance to radiation. The electromagnetic calorimeter consists of two parts:

- EMC barrel detector, which covers $|\eta| < 1.475$
- two EMC end-cap detectors, which covers $1.375 < |\eta| < 3.2$ correspondingly.

The half-barrels are 3.2 m long and with inner and outer radii of 1.4 m and 2 m. The EMC end-cap detectors comprise two pairs of coaxial wheels of 63 cm thickness having inner and outer radii of 330 mm and 2098 mm respectively. The accordion geometry provides symmetry and full coverage in ϕ and fast readout, while there are cracks along η , at $|\eta| = 0$ (the boundary of two half-barrels), $1.37 < |\eta| < 1.52$ (between barrel and end-cap), and at $|\eta| = 2.5$ (the boundary of inner and outer end-cap wheel). The orientation of the accordion waves is axial in the barrel and radial in the end-caps.

There are three different sections of the EMC, with differing granularity depending on radial depth. By varying the amount of absorber material as a function of $|\eta|$ good energy resolution is ensured over the range of coverage. The layers have the following properties (see Figure 3.6):

- **Layer 1:** $4.4 X_0$, 0.0031×0.0245 in $\Delta\eta \times \Delta\phi$
- **Layer 2:** $16 X_0$, 0.025×0.245 in $\Delta\eta \times \Delta\phi$
- **Layer 3:** $2 X_0$, 0.05×0.245 in $\Delta\eta \times \Delta\phi$

The total thickness of the EMC are 22 radiation length (X_0), increasing from $22 X_0$ to $33 X_0$ in the barrel and varying from $24 X_0$ to $38 X_0$ in the end-cap. The EMCs has longitudinal samplings, three in the precision-measurement region ($0 < |\eta| < 2.5$) and two in the forward region ($2.5 < |\eta| < 3.2$). In addition, there is an individual LAr layer without absorber before EMC covering $|\eta| < 1.8$ region to recover the energy lost in the upstream material (cryostat, superconducting coil, inner detector, etc.) called presampler.

The EMC presampler has 7808 readout channels in the barrel and 1536 channels on both sides of the end-cap. The EMC itself has 101760 readout channels in the barrel and 62208 channels on both sides of the end-cap.

3.4.2 Hadronic calorimeters

The hadron calorimeter (HC) [99], [100] measures the energy of particles that interact via strong force using other detection technologies. It is composed of three submodules:

- the scintillating tile calorimeter in $|\eta| < 1.7$;
- two LAr calorimeters that uses different absorbers, named the Hadronic endcap calorimeter (HEC), covering $1.5 < |\eta| < 3.2$ region;

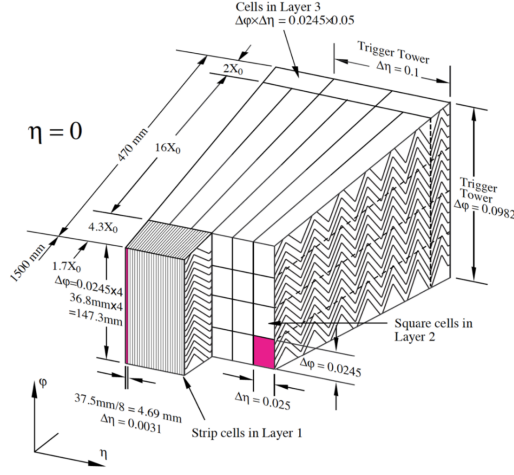


Figure 3.6: ATLAS EMC layout.

- forward calorimeter (FCal), covering $3.1 < |\eta| < 4.9$ region.

The HC's scintillating tile calorimeter is a steel sampled detector divided in turn into a central barrel having 5.8 m in length and two extended barrels of 2.6 m in length each. The extended barrels have inner radii of 2.28 m and outer radii of 4.25 m. It's a longitudinally sampling calorimeter with polystyrene scintillating tile as the active material and steel as the absorber. Three samplings with corresponding granularity $\Delta\eta \times \Delta\phi$ equal to 0.1×0.1 , 0.1×0.1 and 0.2×0.1 . The interaction lengths λ_0 in the barrel are about 1.5, 4.1 and 1.8 correspondingly. In the extended barrel it is 1.5, 2.6 and 3.3 λ_0 s. The total thickness is about 7.4 interaction length. Ionising particles crossing the tiles induce the production of ultraviolet scintillation light, which is captured and converted to visible light by the wavelength-shifting fibres placed next to the tile edges. The read-out is performed by the photomultiplier tubes (PMT's). There are 5760 readout channels in the barrel and 4092 in both end-caps.

The hadronic end-cap calorimeter (HEC) detector is a LAr calorimeter sampled with copper. It is composed of two pairs of independent wheels symmetrically located behind the end-cap EMC called the front and the rear wheels. Their thickness is 0.8 m and 1.0 m with a radius of 2.09 m. The front wheel (HEC1) is made of 25 mm thick copper plates. The rear wheel (HEC2) is made of 50 mm thick copper plates. Each wheel contains two longitudinal sections. The granularity of the HEC cells is in $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ in the $|\eta| < 2.5$ region and 0.2×0.2 for larger value of $|\eta|$. The HEC has 5632 readout channels in both end-caps.

The forward calorimeter (FCal) detector is a longitudinal sampling calorimeter located at high η and its modules are located about 4.7 m from the IP. It is designed for very high particle flux and radiation in the forward region. Each out of 3 FCal's wheels is 45 cm deep and has naming FCal1, FCal2 and FCal3. They are covering $3.1 < |\eta| < 4.9$. The first one is sampled with copper and used for the measurement of electromagnetic processes. The two other wheels are sampled with tungsten and designed for the hadronic showers measurement. The interaction lengths λ_0 is about 9.5 λ long. There HEC has 3524 readout channels in

both end-caps.

3.5 Muon spectrometer

As muons are minimum ionizing particles, they interact little with the detector material and do not form showers in the calorimeters. This allows muons to pass through the calorimeters and make them reach the muon detectors where their tracks are measured, while other particles (except neutrinos) are absorbed by other sub-detectors. Thus the outermost and largest part of **ATLAS** detector is the muon spectrometer (**MS**) [102], [103]. A schematic layout is shown in Figure 3.7. The **ATLAS MS** has two purposes:

- provides a fast trigger for muons which are achieved by using two types of fast triggering detectors;
- measures tracks of muons. This is achieved by precision-tracking chambers.

The muon spectrometer covers a range of $|\eta| < 2.7$. While in the barrel the muon chambers are arranged cylindrically around the calorimetry system, the end-caps **MS** has large wheels that are orthogonal to the beamline. The **MS** end-caps wheels have a radius of from 4.25 to 11 m.

The fast triggering muon system is composed of two types of detectors:

- The Resistive Plate Chambers (**RPCs**) [105] is a electrode-plate gaseous detector used in the barrel region covering $|\eta| < 1.05$. It uses $C_2H_2F_4/Iso - C_4H_{10}/SF_6$ gas mixture (94.7/5/0.3). Two parallel resistive plates with sandwich-like orientation produce an electric field of 4.5 kV/mm. That allows ionisation from muons to produce electrons which are accelerated towards the anode, producing electron avalanches on route. The **RPCs** provide a great time resolution of a few ns with a 1 cm spatial resolution and supported local rate capability of 1000 Hz/cm². There are 606 **RPCs** chambers resulting in 373000 readout channels.
- The Thin Gap Chambers (**TGCs**) [106] are a type of multi-wire proportional chambers that cover the pseudorapidity region $1.05 < |\eta| < 2.7$. They are designed with a wire-to-cathode distance of 1.4 mm and a wire-to-wire distance of 1.8 mm, operating at a wire potential of 2900 V. The chambers are filled with a gas mixture consisting of 55% CO_2 and 45% n-pentane (C_5H_{12}), enhancing their quenching ability and stability in operation. The **TGCs** offer a high time resolution of less than 25 ns, allowing them to effectively resolve events within the duration of less than one bunch crossing. They also achieve a spatial resolution between 2 and 7 mm due to the narrow gap between the cathode planes. This configuration enables the **TGCs** to operate in a saturated mode, where their response is largely independent of the amount of charge deposited by the particles or their angle of impact. A total of 3588 **TGCs** chambers, incorporating approximately 318000 readout channels.

The precision muon tracking chambers are composed of the following subsystems:

- The Monitored Drift Tubes (**MDTs**) [107] covers the region $|\eta| < 2.7$, except for the innermost layer in the forward region $2.0 < |\eta| < 2.7$. The **MDTs** is composed of

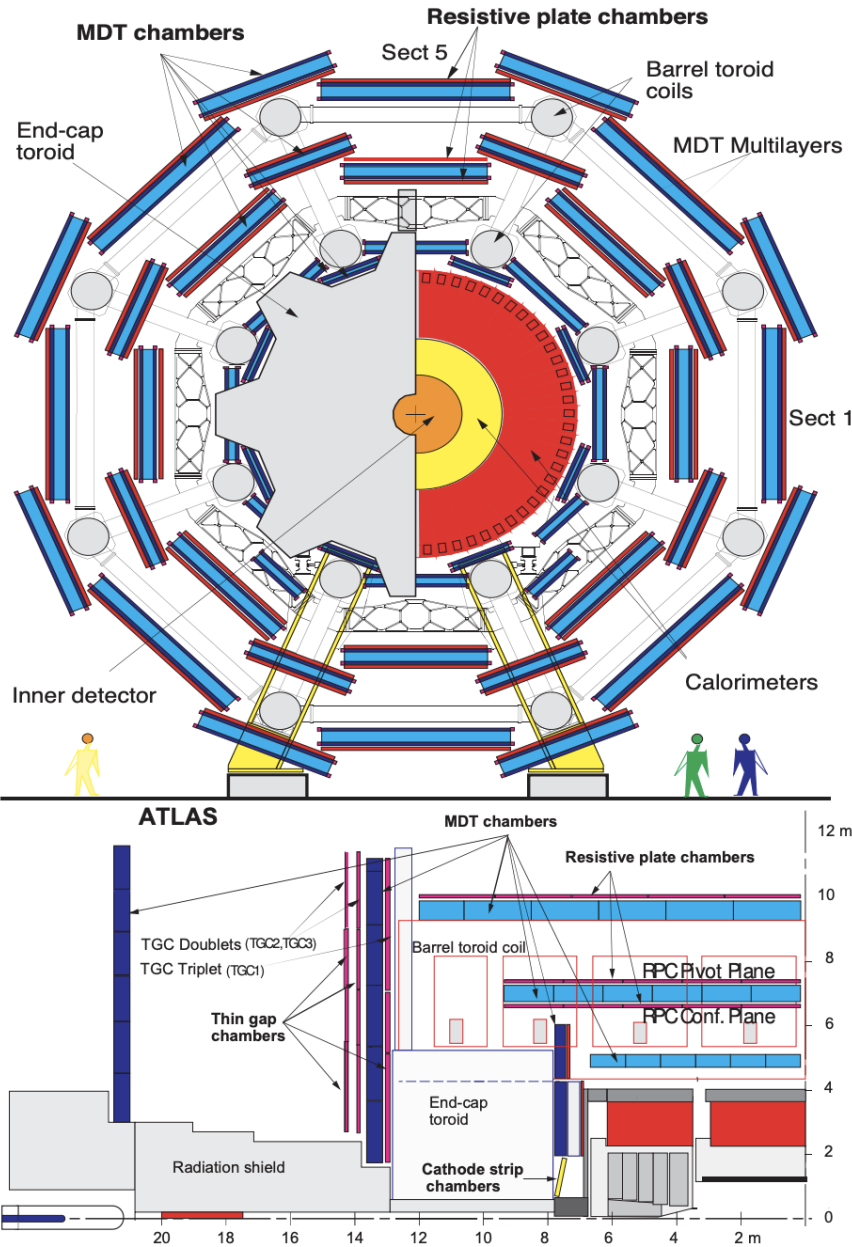


Figure 3.7: Schematic view of the muon spectrometer in the $x-y$ (top) and $z-y$ (bottom) projections [104].

three to eight layers of 30 mm drift tubes filled with Ar and CO₂ gas at 3 bar. Muons passing the tube ionises the gas and produce free electrons that are later collected at the central tungsten-rhenium wire of 50 μm in diameter with a voltage of 3080 V. The counting rate of **MDTs** is limited by 150 Hz/cm², what is not sufficient for the innermost layer in the forward region of $2.0 < |\eta| < 2.7$ where **CSCs** are used.

- The Cathode Strip Chambers (**CSCs**) [108] are gas detector that has higher rate capability and time resolution. The **CSCs** contain multi-wire proportional chambers filled with Ar/CO₂ (80/20) gas mixture with quenching agents CO₂ and CF₄ and operate at a potential of 1900 V. Planes of cathodes are segmented into strips and anode wires are placed perpendicular to the cathodes. Due to the orthogonal layout of anodes and cathodes, a measurement of two coordinates is obtained for each traversing muon. On each **ATLAS** side there are 16 **CSCs** installed on the so-called Small Wheels.

3.6 Forward detectors

The **ATLAS** forward detectors are responsible for the measurement of luminosity during **ATLAS** data taking and for forward neutron detection at $|\eta| > 8.3$ in heavy-ion collisions. The measurement of luminosity is the main goal for LUMinosity measurement using Cherenkov Integrating Detector (**LUCID**) and Absolute Luminosity for ATLAS detector (**ALFA**), while Zero-Degree Calorimeter (**ZDC**) detects forward neutrons.

The **LUCID** [109] plays important role of the main **ATLAS** relative luminosity monitor. It measures the integrated luminosity and performs online monitoring of the instantaneous luminosity and beam conditions by detecting elastic p-p scattering processes in the forward region. It is installed at ± 17 m distance on both sides from **IP** and at a distance about 10 cm perpendicular from the beam, at position $|\eta| \approx 5.8$ of the **ATLAS** detector. To produce Cherenkov radiation in the detector four bundles of quartz fibres are used on each side. The Cherenkov light is directed to the 16 **PMT**'s located in the safe space outside the radiation shielding.

The **ALFA** [110] consists of scintillating fibre trackers located in Roman pots¹ at ± 240 m from the **IP**. It is designed to approach as close as 1 mm to the beam to precisely measure the track of scattered protons at a millimetre distance from the beams. The **ALFA** provides a resolution of 30 μm

During Run 2 **LUCID** provided to **ATLAS** the absolute luminosity measurements on an uncertainty level of 1.7% [111].

3.7 Trigger system and data acquisition

Each recorded collision at a single bunch-crossing in **ATLAS** provides 1 MB of data from all **ATLAS** sub-detectors in total (over one million read-out channels). Considering that the bunch crossing rate at **LHC** is about 40 MHz, collisions at **P1** happen every 25 ns. For the

¹A “Roman pot” (where “pot” stands for proton-on-target) is the name of the technique and hardware solution used to localise the trajectories of protons in a beam.

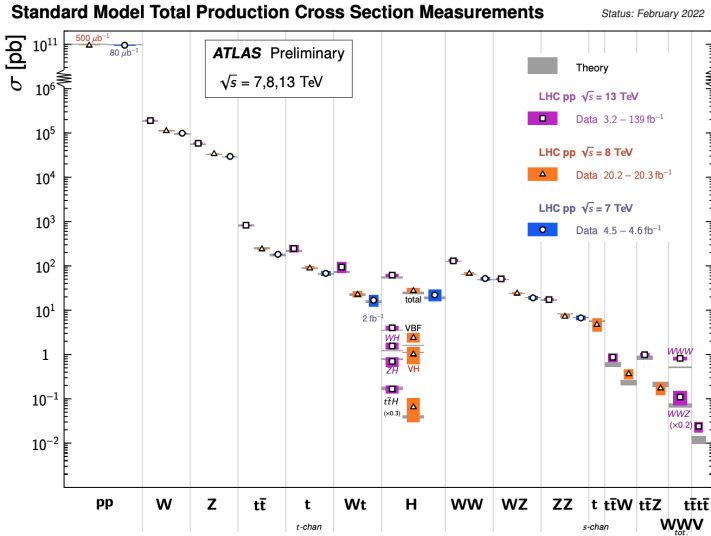


Figure 3.8: A summary of Standard Model measurements taken by the [ATLAS](#) collaboration, ordered by production rate [112]. Each process is labelled on the x -axis.

perfect and ideal detector's readout system this would result in 40 TB of data every second. However, with current technology, storing all this raw data is impractical without substantial preselection. Additionally, the readout system faces constraints in terms of how quickly it must be ready to handle data from subsequent collisions.

Using the fact that even the most frequent physics processes in the [ATLAS](#) measurements, such as W and Z production, occur at rates more than five orders of magnitude lower than the total proton-proton collision cross-section (see Figure 3.8), and that for rare processes this difference can easily reach 12 orders of magnitude, special selection criteria might be applied to retain and store only interesting events and to decrease the data rate. For this purpose, the [ATLAS](#) uses *trigger* system, designed significantly reduce data flow to the order of MB/s.

There are three levels of the trigger system: a hardware-based trigger (called **L1** or Level-1), a software-based L2 (Level-2) and the event filter. The last two levels are called High-Level Trigger (**HLT**). Every next level refines and applies additional selection, further lowering the event rate. The **L1** trigger accept rate for Run 2 was 100 kHz [113]. After **HLT** the rate was down to 1.5 kHz which is stored in the offline analysis.

For the **L1** to determine whether the event should be kept or not, the calorimeters or muon spectrometer are used. Events only proceed to further processing if there is a hit in these subsystems, indicating the production of muons, electrons, photons and hadrons from τ -lepton decays with high transverse momentum, large missing and total transverse energy. The **L1** trigger decision which events to keep must be within $2.5 \mu\text{s}$ after the corresponding bunch-crossing.

The region close to the hit in the **L1** is called as a Region of Interest (**ROI**). The **ROI** are seeded to **HLT** which uses full granularity and precision along with other available

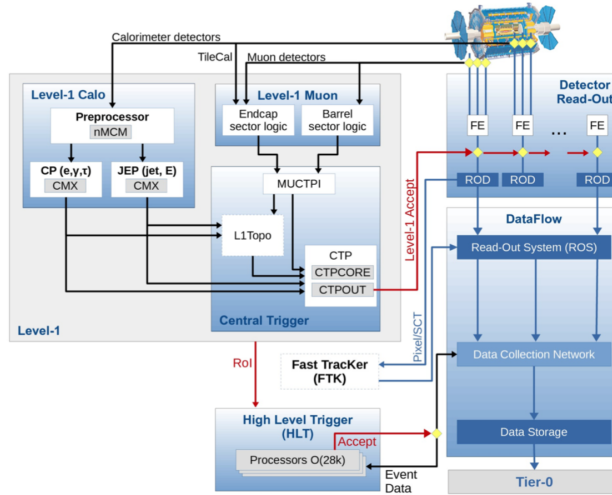


Figure 3.9: The scheme of **ATLAS** trigger systems and detector read-out.

subdetectors data that is not available at **L1**. The **HLT** can reconstruct the full detector or only **ROI** as defined by the **L1** trigger, depending on what is required. The Trigger and Data Acquisition (**TDAQ**) scheme is presented on Figure 3.9. All events passing both the **L1** and **HLT** triggers are further stored for offline processing using the ATLAS software framework (**ATHENA**) [114].

4

THE ATLAS TRANSITION RADIATION TRACKER

This thesis primarily focuses on the measurement of W boson decays into muon and electron channels, which depends on the precise measurement of numerous parameters. These parameters require the exceptional performance of all sub-detector systems within the [ATLAS](#) detector and accurate representation in software. In particular, this chapter discusses authors contributions to enhancements in the [ATLAS](#) experiment's performance, focusing on the [ATLAS](#) Transition Radiation Tracker operation, Trigger and Data Acquisition upgrades.

The Transition Radiation Tracker ([TRT](#)) serves as the outer tracking system, uniquely integrating both tracking and particle identification functionalities within a single detector. It utilizes a continuous tracking method, enabling the acquisition of over 30 precise measurement points along a particle's trajectory, complemented by particle type information through transition radiation detection. This is achieved by uniformly distributing small-diameter, thin-wall proportional tubes within or between layers of radiator material. This design significantly enhances particle momentum measurement accuracy, reduces the likelihood of false track detection, and aids in electron identification.

This chapter is structured as follows: Section [4.1](#) provides a concise overview of the [TRT](#), including its electronics, Trigger and Data Acquisition ([TDAQ](#)) system. Section [4.2](#) emphasizes the specific upgrades made to the [TRT](#) for the [TDAQ](#), aimed at enabling the [TRT](#) to operate efficiently under conditions of high occupancy and trigger rates in Runs 2 and 3.

4.1 The TRT detector overview

The [ATLAS TRT](#) consists of a barrel and endcap structure. The barrel consists of 52544 straws, each 144 cm long and aligned parallel to the beam axis. In contrast, the endcap comprises 122880 straws, each 37 cm long and radially aligned to the axis [\[92\]](#), [\[94\]](#), [\[96\]](#), [\[115\]](#), [\[116\]](#). These straws, with a diameter of 4 mm, are constructed from a 35 μm thick kapton film, coated with aluminum for electrical conductivity and a graphite-polyamide layer for protection against gas discharge evaporation. Additionally, carbon fiber bundles reinforce

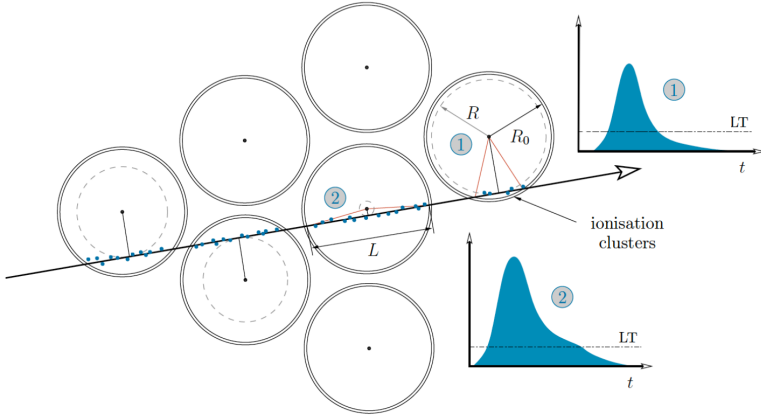


Figure 4.1: Schematic representation of a particle's passage through the TRT detector. As the particle travels through the gas, it ionizes the medium. The resulting ionization electrons drift towards the anode wire, where a signal proportional to the level of ionization is induced.

the structure. Inside each straw is a gold-tungsten anode wire, $30\ \mu\text{m}$ in diameter. A high voltage potential of 1530 V is applied between this wire and the cathode of the straw tube, achieving an amplification gain of 2.5×10^4 with a gas mixture of Xenon (70%), carbon dioxide (27%), and oxygen (3%). Xenon is specifically chosen for its efficiency in absorbing Transition Radiation (TR) photons with energies between 6-15 keV. When charged particles traverse the straw (see Figure 4.1), they ionize the gas, causing electrons to drift towards the anode wire and ions towards the straw walls. Approaching the wire, these electrons induce an electron avalanche, amplifying the signal by a factor of 25000. The amplified signal undergoes discrimination at two thresholds: a low threshold (LT) set at 300 eV, and a high threshold (HT) ranging from 6-7 keV. These thresholds provide critical tracking information and aid in identifying the energy absorbed by TR photons. Timing information derived from the straw hits offers a resolution of approximately $130\ \mu\text{m}$ for charged tracks with $|\eta| < 2$ and $p_T > 0.5\ \text{GeV}/c$.

In the ATLAS TRT, the barrel and end-cap structures are distinct in design and material arrangement. The Barrel TRT, comprising 52544 axial straws, utilizes a matrix of $19\ \mu\text{m}$ thick polypropylene/polyethylene fibers as transition radiation material, with an average straw separation of 6.8 mm. On the other hand, the TRT End-Cap (EC) consists of two identical parts, each with 122880 straws. The EC uses radially arranged straws in layers, with varying spacing and different types of wheels for optimized particle detection. The straw layers in the EC are separated by 15.5 micron thick polypropylene foils, acting as transition radiation material, with a spacing between straw centers in the $R - \phi$ plane ranging from approximately 5.2 mm to 8.4 mm.

As charged particles traverse these mats, they have a certain probability of emitting transition radiation, a phenomenon resulting from the particle moving between media of differing refractive indices. This radiation is particularly associated with the interaction of the

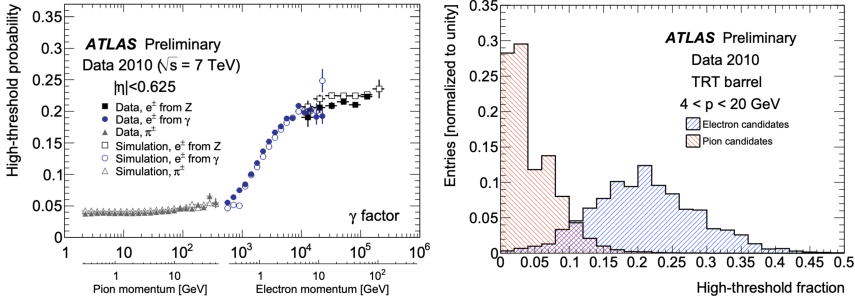


Figure 4.2: Illustration of the TRT barrel's response characteristics: (Left) Probability of straw signal exceeding the high threshold plotted against the Lorentz γ -factor of the passing particle; (Right) Percentage of straws along a particle's path that surpass the high threshold [117].

charged particle with the plasma frequency, ω_p , as described by the following formula [33]:

$$I = \frac{\alpha z^2 \gamma \hbar \omega_p}{3} \quad (4.1)$$

Here, α is the fine-structure constant, z represents the atomic charge, and the value of $\hbar \omega_p$ in the TRT context is 21 eV. The intensity of the transition radiation, I , is directly proportional to the Lorentz factor, γ , indicating that electrons, owing to their lower mass and consequently higher Lorentz factors compared to pions or muons, will emit more transition radiation. For multiple boundary crossings, interference leads to saturation above a Lorentz factor γ_{sat} . A charged particle typically intersects around 30 straws in the TRT, surpassing the high threshold (HT) in about six of these encounters. The correlation between a straw signal meeting the high threshold and the Lorentz γ -factor of the particle in transit is illustrated in Figure 4.2. Additionally, this figure illustrates the proportion of straws along a particle's trajectory that exceed the high threshold.

The ability to distinguish pions from electrons in the TRT primarily hinges on the absorption characteristics of TR photons by Xenon. However, prior to Run 2, gas leaks were identified within the TRT, leading to a significant change. Considering budgetary constraints, the original Xenon gas was substituted with Argon. Although Argon gas has comparable tracking performance, it lacks the efficiency of Xenon in absorbing TR photons. Consequently, straws filled with Argon gas have a diminished role in electron identification. Despite these changes in gas composition, the accuracy of track position measurement in the straws remained unaffected [118].

Particle identification using the TRT [116] involves evaluating the energy deposited in the straws, which is calculated as the sum of energy deposits from transition radiation (TR) and ionization losses as the charged particle passes through the straw. The distinction between electrons and pions, particularly at low momenta (below $p \leq 10$ GeV), is significantly enhanced by measuring specific energy losses (dE/dx) of charged particles in addition to TR. This method not only improves electron-pion separation but is also effective in identifying highly ionizing particles, such as protons at low momenta, and potentially exotic objects like

highly ionizing stable massive particles [119]. Combining TR and dE/dx measurements within a unified likelihood function achieves the optimal separation of electrons and pions.

At the time of drafting the Technical Design Report [120], [121], it was projected that the accelerator ring would operate with a full complement of colliding bunches, and the number of interactions per bunch crossing (BX) could reach up to 27 at the LHC's peak luminosity. The anticipated straw occupancy rate (the likelihood of detecting a hit in a straw) was estimated at around 30%. However, with the commencement of LHC operations, it became evident that significantly higher luminosities were achievable. Yet, due to technical constraints, the number of colliding bunches was limited to approximately 2500. This limitation necessitated an increase in the number of interactions per BX to boost luminosity. In Run 3, the luminosity was expected to reach $2.2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, with about 70 interactions per BX. As a result, the straw occupancy rates increased to as high as 80%, which is 2.6 times higher than the maximum design value. These demanding operational conditions necessitated comprehensive studies and the optimization of various characteristics and reconstruction algorithms to maintain the detector's effective contribution to the ATLAS experiment's physics program.

4.1.1 TRT electronics and data acquisition

The functioning and the development improvements of the TRT are deeply connected with its read-out electronics system. This part of the document gives a necessary basic overview about the TRT electronics, including both the main architecture and a brief explanation of the TRT's Trigger and Data Acquisition (TDAQ) system. For more deep and full details about these electronics, the readers can look at [122].

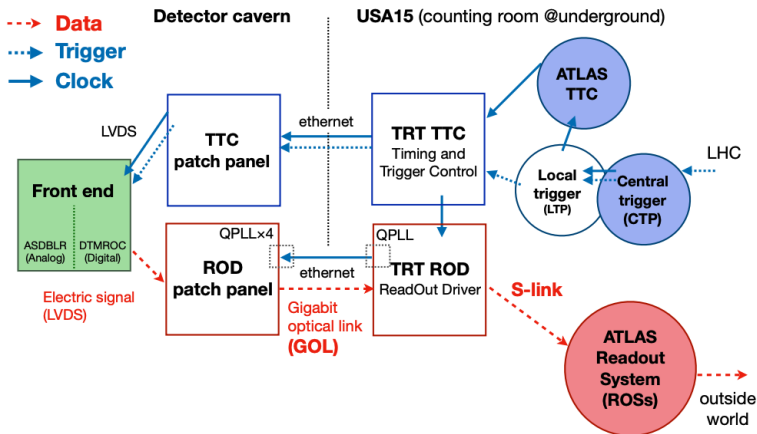


Figure 4.3: Overview of the TRT TDAQ system.

The TRT's signal processing from the straws utilizes a specialized Application-Specific Integrated Circuit (ASIC), designed for Amplification, Shaping, Discrimination, and Base-Line Restoration (ASDBLR). This signal is subsequently sampled by another ASIC, known

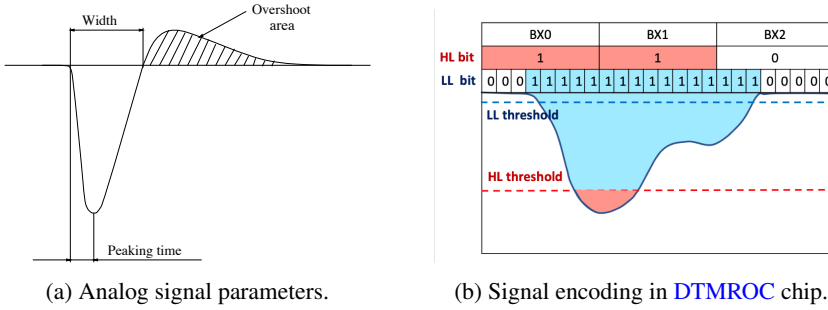


Figure 4.4: (Left) Shaping parameters for the analog signal in the [ASDBLR](#) chip; (Right) Encoding scheme utilized by the [DTMROC](#).

as the Drift Time Measuring Read-Out Chip ([DTMROC](#)), which is responsible for timing analysis and digitizing the data from up to 16 straws. The coordination and control of these 480 [DTMROC](#)s are handled by Timing, Trigger, and Control ([TRT-TTC](#)) modules. The data readout process is executed by the Read Out Drivers ([TRT-ROD](#)). The [TRT](#) system includes 96 [ROD](#) modules and 48 [TTC](#) modules, distributed across 10 [VME](#) crates, each operated by a computer running a Linux-based operating system. The layout and functionality of the [TRT](#) electronics dedicated to readout are shown in Figure 4.3.

The [ASDBLR](#) is responsible for the analog signal processing of eight straws. It amplifies and shapes the signals, concurrently eliminating the long ion tail and performing baseline restoration, see Figure 4.4a. The output from the [ASDBLR](#) is a ternary (three-level differential) current signal, subsequently relayed to a custom receiver on its companion chip, the [DTMROC](#). This ternary signal encodes the time-over-threshold ([ToT](#)) data for two separate discriminators in the [ASDBLR](#) – the low threshold ([LT](#)), set at 300 eV, and the high threshold ([HT](#)), calibrated at 6-7 keV. The [LT](#) discriminator is critical in distinguishing the signal from noise, facilitating tracking and dE/dx measurements. The [HT](#) discriminator, on the other hand, is tuned to detect the presence of a [TR](#) signal. For a more comprehensive exposition of the [ASDBLR](#), readers are referred to [123].

The complementary digital readout chip for the [TRT](#) is the [DTMROC](#). The [DTMROC](#) accepts 16 ternary inputs from two [ASDBLR](#)s. The ternary signal encodes [ToT](#) for the two separate discriminators on the [ASDBLR](#). The [DTMROC](#) records the low level ([LL](#)) threshold signal in 3.12 ns bins. The high level ([HL](#)) discriminator is sensitive to the presence of a [TR](#) signal and the output of that [HL](#) discriminator is latched as a single bit during each 25 ns clock cycle that it is active. The [DTMROC](#) contains a programmable depth [L1](#) pipeline to hold the [FE](#) data until the Level-1 ([L1](#)) trigger arrives. In total, 24 [LL](#) bits and 3 [HL](#) bits representing the information over 3 bunch crossings at nominal [LHC](#) operating conditions (75 ns) are stored in this pipeline for each readout channel. These 27 bits of information form a “straw word” which is the basic block of data from a readout¹. The [DTMROC](#) signal encoding is shown schematically in Figure 4.4b. When a trigger arrives as a serial string the data for three successive bunch crossings are transferred to a derandomizing buffer. From

¹These units of data are of major importance, especially in the context of the forthcoming discussion on the [TRT](#) upgrades described in Section 4.2.

the derandomizing buffer those 27 bits of data per channel are serialized and sent off chip over a low voltage differential signal (LVDS) twisted pair copper connection to the back-end electronics (ROD) via patch panel boards.

The primary function of the **TRT Patch Panels (PP)** is to receive and repeat signals between the **TTC**, **ROD** and the **FE** boards. There are two types of **TRT PPs**: **ROD PP** and **TTC PP**.

The TTC PP handles 20 **TTC** lines, each consisting of one group of Clock, Command In, Command Out, and Reset signals. The clock signal can also be independently delayed for each line in increments of 0.5 ns allowing to compensate for differences in cable length, as well as differences in particle flight time, so that the rising edge of the clock is synchronous with the earliest arrival of particles at every part of the detector. The **TTC PP** is also responsible for driving temperature read-out of the detector and front-end boards.

The data PP board associated with the **TRT ROD** receives data over copper lines from a set of **FE** boards and passes that data to a **ROD** over optical fibers. The inputs to the **ROD PP** from the **FE** boards consist of up to 120 LVDS signals (one per **DTMROC**). That data is sent out to the **TRT ROD** via four 1.6 Gb/s optical links using an 850 nm **VCSEL** from Honeywell which has been radiation qualified. The data are serialized by the Gigabit Optical Link (**GOL**) chip which was developed by the **CERN** microelectronics group [124] specifically for high radiation **LHC** applications. Serialized data are then driven over each optical link to the **ROD**.

The TRT-TTC module is used to implement **TTC** [125] and **TRT** specific command functions and parameter loading for **FE** electronics. It receives one encoded **TTC** signal over an optical line from the **TTC** modules [126] and a **TTCrx** chip [127] decodes this signal. It extracts the clock (**BC**), the **L1** Accept (**L1A**), the bunch counter reset (**BCR**) and the event counter reset (**ECR**) commands and receives trigger type information. Through the custom lines over **TTC PPs** it downloads parameters to the front-end electronics. There are 40 **TTC** links arranged on 4 connectors served by the module in total. It distributes the clock and commands both to the **FE** electronics and the **ROD** modules. All lines to the **FE** electronics have adjustable delay. For dead time monitoring purposes it measures the duration of the **BUSY** signals generated by the **TRT-ROD**'s **S-Link** and the **ROD**'s on-board buffers control. A combined **BUSY** signal is sent to the Central Trigger Processor (**CTP**) through a **Busy** module [126].

The main function of the **TRT-ROD** is to receive data from the **FE** boards via the data **PP**, check the validity of the data, compress the data, format and build the data into mini event fragments and output the event to the Read Out System (**ROS**) via the **S-Link** transmitters. The **RODs** also send clock and control information to the data **PP**, receive trigger information from local **TRT-TTCs** and assert **BUSY** when the readout system cannot accept any more data.

Each **ROD** is connected to two identical **PPs**, and every **ROD** is divided into two logical sections, one for each data source. The **ROD** interfaces to each **PP** via four 1.6 Gb/s optical transceivers (**RocketIO**¹ blocks) and two **Cat5** ethernet cables containing Clock and control information, for a total of eight optical links and four ethernet cables per physical **TRT-ROD**.

¹Xilinx Inc., proprietary transceiver logic blocks embedded in Virtex II and 4 **FPGA** parts, capable of 622 Mbps to 6.25 Gbps rates.

Most of the **ROD** functionality is implemented within five Xilinx **FPGAs**. Most important is terms of upcoming discussions are:

- A Virtex II Pro XC2VP7 (referred as **V2** chip) is responsible for decoding the eight optical input data streams, providing test data for checking the data processing and interfacing to the output **S-Link** daughtercards.
- Two Virtex 4 XC4VLX40 chips (referred as **V4** chips) each handle one half of the data processing (one for each data **PP** connected), control the data buffering and compression, check for errors and build the data into formatted event fragments.

To accommodate the bandwidth requirements of subsequent parts of the **DAQ** system and the storage system, a data compression/zero suppression scheme is implemented on the **ROD** side. This design employs Huffman encoding, a lossless, entropy-based method. The principle of this compression is based on the fact that, although each straw outputs 27 bits of data, resulting in 2^{27} potential bit patterns, only a fraction of these patterns are physically significant. Huffman's encoding algorithm efficiently assigns shorter codes to more common patterns, while rare patterns receive longer codes. This method approximates the theoretical minimum number of bits needed to represent the data stream's information, as dictated by its entropy. The scheme's practical implementation relies on a specialized Network Search Engine (**NSE**) **ASIC**, originally developed for internet routers. In the **ROD**'s Virtex 4 **FPGAs**, these **NSE** chips operate with custom firmware to enable deadtime-less, lossless compression of the **TRT** data. This setup is specifically optimized for the anticipated trigger rates and occupancy levels.

4.2 The TRT operation and TDAQ commissioning

With the onset of Run 2, the **TRT** component of the **ATLAS** experiment embarked on a series of significant upgrades to its **TDAQ** system. These enhancements were crucial for accommodating the increased trigger rate of 100 kHz and the average pileup of $\langle \mu \rangle = 60$, as projected for the **LHC** in 2017 (see Figure 2.2). The **TRT** have culminated in three primary advancements:

- Firstly, the integration of a validity gate alongside modifications in straw word processing was implemented. This strategy was primarily aimed at eliminating non-essential data bits that do not contribute to physics analyses.
- Secondly, a more efficient Huffman compression table was developed, specifically optimized for high occupancy levels in high-pileup runs.
- Lastly, a comprehensive overhaul of the High-speed Optical Link for **ATLAS** (**HOLA**) cards was undertaken on the **TRT RODs**. This replacement has effectively enhanced the **S-Link** readout speed by 20%.

These strategic enhancements have led to a significant enhancement in the read-out capabilities of the **TRT TDAQ** system, achieving a 25% improvement over the performance during Run 1. These advancements have been of great importance in ensuring the efficient

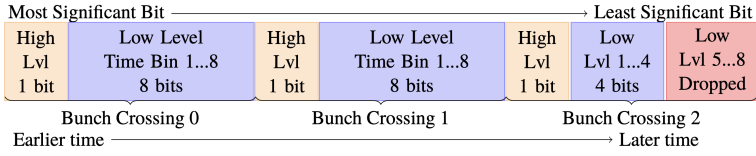


Figure 4.5: The 23-bit straw word structure for Run 2, illustrating the omission of the last four low threshold bits [128].

operation of the **TRT** at an average pileup of $\langle \mu \rangle = 60$ and a trigger rate of 100 kHz in Run 2, maintaining high levels of efficiency. For a comprehensive overview of these upgrades, readers are encouraged to reference this detailed analysis, which can be found in [128].

4.2.1 TRT data structure optimization

The development of a straw word transformation algorithm and the introduction of a validity gate are examples of solutions that rely solely on software and firmware. Their primary purpose is to increase data processing efficiency and minimize the volume of data transfer:

- **Bit Pattern reduction.** Each **DTMROC** transmits data fragments to the **ROD** patch panels using twisted-pair cables, employing low-voltage differential signaling at a rate of 40 Mbit/s. The inherent limitation of the **TRT** to operate at a maximum **L1** rate is due to the length of the **DTMROC** data fragments, which was 444 bits. This constrains the maximum **L1** rate to around 90 kHz, as calculated by the formula $40 \text{ Mbps} / 444 \text{ bits}$. However, for Run 2, where a 100 kHz **L1** rate was desired, strategic modifications were implemented. A key change involved omitting the last four bits from the third bunch crossing (**BC**) in the **DTMROC** data fragments, as shown in Figure 4.5. This selective exclusion of non-essential timing data has the effect of streamlining the readout process through a reduction in size, amounting to 368 bits for each straw word.
- **TRT ROD data compression.** Once the data reaches the **ROD**, it is assembled into a unified output buffer. This assembly process for the straw data includes three potential methods: *uncompressed*, *zero-suppression*, or *fully compressed*¹.

For *fully compressed* data, Huffman encoding is employed for lossless compression. To accommodate the 100 kHz **L1** rate, encoding is executed post-validity gate in the **ROD** using a hash table that catalogues 4096 of the most frequent patterns. Should a pattern be absent, a Network Search Engine (**NSE**) chip, containing the next 131071 common patterns, is utilized for encoding. In cases where the pattern remains unidentified, an escape sequence of `0b000000` is added, followed by the 23-bit “raw” pattern. To further enhance the efficiency of compression under conditions of high-pileup, the catalogues of patterns have been optimized for higher occupancy levels. This optimization leads

¹For a detailed technical understanding of the compression scheme, refer to [122].

to a more effective compression, consequently reducing the size of the serialized straw word.

- **Validity Gate in ROD.** The validity gate functions precisely as its name suggests: as a selective barrier that only permits valid straw patterns to pass through. In the hardware, this gate is a 13-bit window, equivalent to 40.625 ns, which corresponds to the green-highlighted bits in Figure 4.6. Should a low-level threshold hit occur within this designated time window, the event is retained; otherwise, it is nullified. Most non-zero events which have hits outside this gate are from out of time pileup so this helps keep only “interesting” straw words.
- **Middle High Threshold Bit.** During the initial data-taking period of 2016, a V4 chips firmware update was implemented to decrease the number of patterns, thereby enhancing the data’s compressibility [128]. Instead of retaining the three high threshold bits corresponding to the three bunch crossings (BCs), the system was modified to only preserve the high threshold bit of the middle BC. The first and last high-level threshold bits were set to zero. Although this adjustment may appear minor, it effectively facilitated a reduction of approximately 4% in the event size.
- **Suppress Error Block.** The error block, whose length is not fixed, encapsulates any anomalies in headers that deviate from the ROD’s expectations. This includes verifying the Bunch Crossing ID (BCID) and Level-1 ID (L1ID) against the ROD’s header values and monitoring the general error bit for activation. Should there be a discrepancy in the BCID or L1ID, or if the general error bit is engaged, the DTMROC’s 9-bit header is coupled with a 7-bit address and inserted into the error block as half of a 32 bit word.

Historically, the general error bit was frequently set. These common errors were attributed to front-end issues, including:

- Full derandomizer buffers occurring before the initiation of data taking.
- Detection of Single Event Upsets (SEUs) in various chip segments.

Although these errors are not critical, they can be flagged in advance as anticipated. To streamline error reporting, the TRT TDAQ software underwent modifications. The TRT-TTC system was programmed to identify chips that were known to produce errors during the configuration and to exclude these from triggering the general error bit. Consequently, while L1ID/BCID discrepancies continued to be reported, the general error bit remained inactive.

This software update led to a reduction in event size by approximately 10%, a significant efficiency gain that was incorporated into the V4 chip firmware in the early data-taking phase of 2016.

4.2.2 HOLA card upgrade

The S-Link, a high-performance data acquisition interface developed at CERN, plays a crucial role in the ATLAS experiment. It serves as the standard interface for data communi-

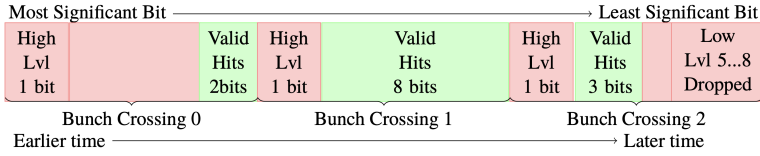


Figure 4.6: The TRT-ROD validity gate schema [128].

cation between the ROD and ROS. Within the TRT of ATLAS, the S-Link is integral to the operation of two HOLA interface cards mounted on the ROD.

Initially, the HOLA was designed for data transfer using a duplex fiber at the full S-Link bandwidth of 200 MB/s, operating with an internal clock speed of 40 MHz/32bits. During the early phases of Run 2, this clock was overclocked to 50 MHz/32bits. However, the increased Level-1 (L1) trigger rate and TRT occupancy during Run 2 presented a bandwidth bottleneck for the S-Link.

Consequently, an upgrade was implemented to enhance the clock speed. Although the target was 62.5 MHz/32bits offering a theoretical bandwidth improvement of over 50%, limitations in the V2 chip firmware necessitated capping the clock speed at 60 MHz/32bits. Alongside, the FPGA on the HOLA card was upgraded to manage data at a rate of 2.5 Gbps.

To enhance the S-Link bandwidth, a substantial upgrade and mass production of the new HOLA cards were undertaken. In total, 240 HOLA cards were manufactured and subjected to comprehensive testing. Subsequently, 192 of these cards, accounting for two cards per physical ROD, were installed in the USA15 area of the ATLAS detector.

Table 4.1 presents a comparative comparison of the performance between the upgraded and the previous versions of the HOLA card, specifically focusing on the 40 MHz clocking scenario. A key parameter for evaluation is the upper limit of the event fragment size that the ROD can handle without inducing back-pressure in the S-Link, which could lead to system busy states. This event fragment size is quantified in terms of 32-bit words. The maximum allowed size is a function of the trigger rate, calculated as the ratio of the S-Link's speed to the L1 trigger rate. For instance, at an L1 rate of 90 kHz, the maximum allowable number of 32-bit words per event is determined by dividing 60×10^6 words/s by 90 kHz, resulting in a threshold of 667 words. The old HOLA cards could only handle a maximum event size of 400 words at 100 kHz trigger rate, but the new HOLA cards increase the maximum allowed event size to 600 words. The techniques used to achieve an event size less than 600 words are explained in the previous Section 4.2.1.

4.2.3 TRT synchronization

The synchronization of the TRT-TTC systems with the primary 40 MHz beam clock from the ATLAS TTC, which in turn is synchronized with the LHC, is a critical aspect of data integrity. Each chipset on the front-end boards requires the ability to fine-tune the timing of the incoming clock signal to compensate for varying cable lengths and ensure data is accurately recorded by the front-end chips. This synchronization is achieved through the use of Delay25 chips [129], which offer a range of delay adjustments from 0 to 24.5 ns with 0.5 ns step.

Period	Run 1 (old HOLA)	Since 2017 (new HOLA)
Internal clock	40 MHz/32bits	60 MHz/32bits
Total 32-bit words at L1 =100 kHz	400 32-bit words/s	600 32-bit words/s
Header and footer size	20 words	
Available bits for data+error	12160 (380×32)	18560 (580×32)
Number of straws to handle per ROD	1920 ($120 \text{ DTMROC} \times 16 \text{ straws}$)	
Average bits/straw	6.44 bits/straw	9.66 bits/straw

Table 4.1: Comparison of the expected performance of the old and new [HOLA](#) cards [128].

The calibration process begins with clock delay (“bx”) scans to establish the optimal moment for the clock signal to be captured by the [DTMROC](#). Subsequently, with the clock delay set, fine delay (“dx”) scans are conducted to pinpoint the precise timing configurations across the “bx-dx” phase space that result in accurate data read-back from all chips within a [GOL](#) group—which includes 30 chips. It is worth noting that during these scans, regions of instability often emerge adjacent to the clock signal’s rising edge. For an in-depth exploration of the [TRT](#)’s timings and the methodologies employed to maintain them, please see [130].

Following the establishment of precise timings, the [ATLAS](#) detector’s stable beam operations may still encounter timing discrepancies. Such errors are typically linked to the Quartz Phase Locked Loop ([QPLL](#)) chip [131], which can struggle to stabilize the incoming clock signal. The root causes of these discrepancies are either issues with the [QPLL](#) chip or the Quartz crystal, or they can stem from significant jitters in the [LHC](#) clock signal — a phenomenon that is occasionally observed.

The critical components, including the [QPLL](#) chips and Quartz crystals, are installed within the back-end electronics of the [TRT-TTC](#), the [TRT-ROD](#), the [TTC](#) [PPs](#), and on the [ROD](#) [PPs](#). Each [ROD](#) is equipped with a singular [QPLL](#) and associated crystal, while each [ROD](#) patch panel houses four sets of [QPLLs](#) and crystals. These sets are tasked with ensuring the clock’s stability after it is divided into four separate streams to accommodate the four [GOLs](#) present on the [PP](#) (see Figure 4.7).

Due to [TRT](#) electronics architecture, the most sensitive device for timing issues is [RocketIO](#) block. Each [RocketIO](#) block is responsible for independently aligning, decoding, and performing a serial to parallel conversion on its data stream received from the data [PP](#)’s [GOLs](#). There are two different types of errors possible here: “lock resync errors” and “buffer resync errors”. Both types of errors significantly impact data-taking efficiency since they require a 30-second resynchronization of the entire [TRT](#) detector, causing a temporary halt in the [ATLAS](#) experiment’s data collection during this period.

- Initially, **buffer errors** were associated with [LHC](#) clock jitter and are typically observed across the detector in random patterns. This implies that the [RocketIO](#) operates at a frequency marginally different from that of the incoming data clock, leading to serializer buffers becoming either full or empty intermittently. Consequently, [RocketIO](#) reports these discrepancies to the [ROD](#), necessitating a [TRT](#) resynchronization.
- Lock errors**, on the other hand, are usually indicative of a malfunctioning [QPLL](#),

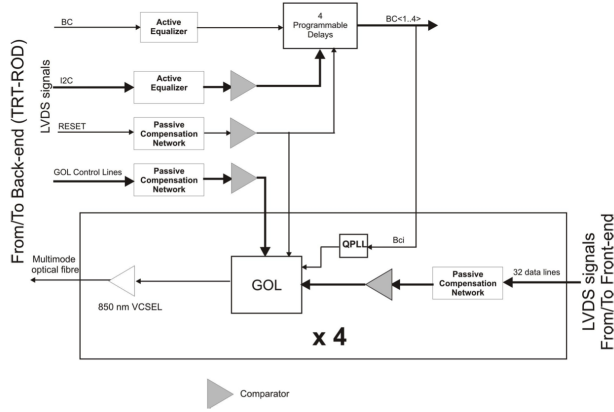


Figure 4.7: Block diagram of the ROD Patch Panel showing connections to and from the back-end (the TRT-ROD) on the left and the Front End electronics on the right [122].

either on the TRT-ROD or the ROD PP side, and show consistent error patterns. These errors signify that the RocketIO is unable to lock onto the incoming signal clock, potentially affecting the synchronization process.

The sensitivity of the RocketIO device is fundamentally influenced by the design of the TRT clock distribution system. The RocketIO buffers reader is synchronized directly with the reference clock, which is provided by the QPLL chip located on the TRT-ROD. Meanwhile, the clock for the incoming data signal travels approximately 100 meters from USA15 to the ROD-PP via a Cat5 cable and is re-emitted by the QPLL chips on the ROD-PP side to make a path of other 100 meters back to the same ROD. The complex routing process, along with the amplification of the clock signal on the ROD side, leads to significant amplification of any fluctuations or jitters in the clock signal. As a result, this section of the clock distribution becomes highly sensitive to clock disturbances.

Lock errors contribute a smaller fraction to the overall TRT dead time and are therefore outside the scope of this thesis. The primary focus of this section is on buffer errors, which play a more significant role in the context of TRT efficiency and reliability.

Buffer errors in Run 2 and Run 3

During data acquisition, it is considered acceptable to have one TRT resynchronization every 30 minutes of stable beams. A higher frequency of resynchronizations may indicate underlying issues with the electronics, warranting expert intervention. Historically, there have been situations where buffer errors triggered what is known as a TRT “resync storm”: a series of continuous TRT resynchronizations caused by buffer errors. These incidents were predominantly localized in the two VME crates, which house a significant portion of the TRT back-end electronics.

At the start of Run 3, after 3.5 years of CERN LHC Long Shutdown 2 (LS2), the TRT experienced another set of resync storms. These events were initiated when ATLAS reached

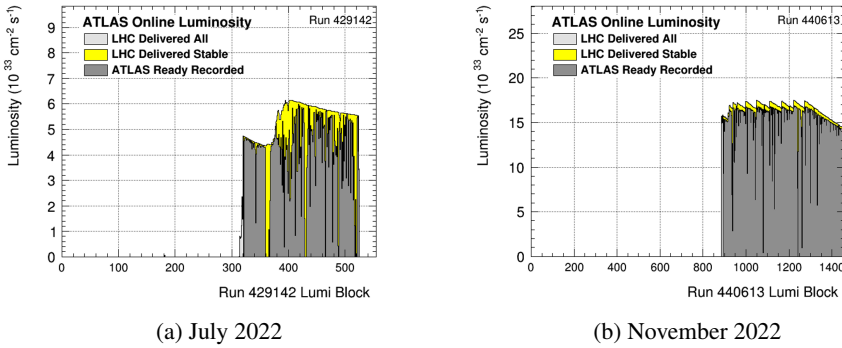


Figure 4.8: Online luminosity plots from [ATLAS](#) illustrating two distinct runs: (a) Run 429142, which experienced significant impact from [TRT](#) resynchronizations, resulting in reduced data-taking efficiency (81.9%); and (b) Run 440613, following the replacement of capacitors in [RODs](#), showing improved nominal data-taking efficiency (95.6%).

an average interaction rate ($\langle \mu \rangle$) of 50. The [TRT](#) system stabilized once $\langle \mu \rangle$ decreased to below 43. The storms mainly involved [RocketIO](#) buffer errors in the Endcap A and C regions, consistently affecting the same seven [RODs](#) across two different [VME](#) crates, and occasionally impacting other [RODs](#), including those in the Barrel region crates.

In an effort to identify the problem's source, hardware near the most affected [ROD](#) in Endcap C was systematically replaced, which included replacing the [ROD](#) and [TTC](#), as well as swapping cables to assess any correlation with the patch panels. The challenge was that these type of resync storms could not be reproduced without a beam, requiring that all tests be conducted during [ATLAS](#) data-taking sessions. This required extensive run coordination planning involving both the [ATLAS](#) and [LHC](#) operational teams. Despite various hardware replacements, a partial solution was found by replacing the power supply for that particular crate.

At the same time, the [ATLAS HLT](#) farm was operating under less-than-ideal conditions, which led to trigger back pressure. This mirrored past experiences where micro BUSY signals from other subsystems induced [TRT-ROD](#) instabilities. During certain operational conditions in [ATLAS](#), the [TRT](#) experienced a sudden spike in event processing demand on the [RODs](#). This increased demand led to a significant current draw, which the weak power supplies struggled to meet promptly, resulting in a voltage drop and subsequent [QPLL](#) unlock from the clock in the [RODs](#). However, this time, the reasons for a large portion of the [TRT](#) being affected remained unclear. It was particularly puzzling that the [VME](#) crates in the Barrel, which houses fewer [FE](#) electronics compared to the Endcap crates, also experienced a considerable impact. Extensive testing of the power supply under dynamic load conditions in the laboratory stand failed to reveal any overt issues, yet the incident underscored their varying characteristics.

Implementing debugging register dumps from the [RODs](#) helped to gather more data. Analysis of these logs suggested that the issues were not related to the [PP](#) or [GOL](#), but were common across all [ROD](#)'s optical lines. This finding pointed to a potential issue with noise on one power rail of the [ROD](#). Further investigations revealed that several low [ESR](#) tantalum

capacitors, connected to the DC-DC converters and regulators, were known to degrade over time. Measurements of capacitance and ESR on one of the most affected RODs indicated that, while capacitance levels were within acceptable ranges, there was a notable degradation in noise performance – about three times worse than for other, less affected RODs.

As a result, the 15-year-old capacitors were replaced with new ones, offering substantially better performance (approximately five times better ESR). Subsequent tests conducted in the cavern during data-taking sessions revealed significant improvements in TRT operational stability. The number of resynchronizations caused by buffer errors in areas with upgraded capacitors was drastically reduced, almost to zero. Figure 4.8b presents the luminosity plots for two separate runs: one severely affected by TRT resynchronizations and the other conducted after replacing capacitors in the most affected RODs.

4.3 Summary

The TRT was initially designed for data taking conditions that differed significantly from the current environment. While the original straw occupancy rate was anticipated to be around 30%, the TRT now operates at straw occupancy rates as high as 80%, far exceeding its initial design parameters (by factor of 2.6!). To adapt to the demands of high luminosity operation and achieve the targeted 100 kHz trigger rate, substantial upgrades were implemented in the TRT data acquisition system, in which the author actively participated. Key among these were the upgrades to the S-Link and HOLA cards, which resulted in a 50% increase in data throughput, elevating the S-Link speed from 160 MB/s to 240 MB/s (Section 4.2.2).

Despite this advancement, the challenges posed by increased pileup and the consequent higher occupancy of hits in the TRT required further measures (Section 4.2.1). The denser tracking environment led to a reduced occurrence of zero words from the straws and a greater diversity in straw words, diminishing the efficiency of Huffman encoding. A critical solution was the introduction of a reduced readout mode, which shortened the straw word length from 27 to 23 bits prior to compression, achieving a 15% reduction in straw word size. Additionally, strategies such as the implementation of a validity gate and error block suppression were employed. These techniques effectively minimized the size of the data fragment by converting non-essential words to 0x0, thereby reducing both detector occupancy and the ROD event fragment size. Tests [128] demonstrated that setting the validity gate to a 37.5 ns width at an average pileup of $\langle \mu \rangle = 60$ increased the proportion of 0x0 straw words in an endcap ROD from 25% to 45%. The presence of more 0x0 words in an event significantly enhances the effectiveness of Huffman table compression. The author played a key role in refactoring of TRT TDAQ software and integrating new releases of ATLAS TDAQ system.

Additionally, the author's efforts in diagnosing and localizing the sources of buffer errors were central in identifying necessary maintenance actions, including the replacement of aging capacitors in the RODs by technical teams. These actions have significantly reduced the need for resynchronizations at high $\langle \mu \rangle$, thus enhancing the overall operational efficiency of the ATLAS detector, as discussed in Section 4.2.3.

These upgrades have been instrumental in enabling the TRT to handle high-pileup up to $\langle \mu \rangle = 66$ with L1 the trigger rate 100 kHz during the Run 3 data taking.

5

EVENT RECONSTRUCTION

The successful reconstruction of various physics objects from detector signals is a fundamental aspect of any [ATLAS](#) analysis. Particle identification in the [ATLAS](#) detector exploits the unique signatures left by different types of particles in various detector subsystems, enabling their accurate identification. [Figure 3.2](#) provides an overview of the characteristic signatures observed in the detector. The interpretation of detector signals and the reconstruction of events and associated objects rely on advanced algorithms known as event reconstruction. These algorithms are specifically designed to reconstruct objects from raw detector data and facilitate the precise measurement of their kinematic properties. This chapter presents a concise overview of these algorithms and their performance, which play a crucial role in reconstructing particles such as photons, electrons, muons and neutrinos used by this analysis. All algorithms are implemented in the framework [ATHENA](#)[\[114\]](#), based on [GAUDI](#) [\[132\]](#).

5.1 Charged particles track and vertex reconstruction

The reconstruction process for both lepton and charged hadron candidates follows the same procedure. It involves the formation of a track, q , using information from the Inner Detector ([ID](#)). The track is represented by five parameters:

$$q = (d_0, z_0, \phi, \theta, \frac{q}{p}). \quad (5.1)$$

These parameters include the transverse impact parameter d_0 , which indicates the distance from the track to the z -axis, and the longitudinal impact parameter z_0 , which represents the z coordinate of the perpendicular dropped from the track onto the z -axis. The remaining parameters are the azimuthal angle ϕ , the polar angle θ , and the charge-to-momentum ratio q/p .

To reconstruct tracks from the detector's response data, the [NEWT](#) tracking algorithm is employed [\[133\]](#). This algorithm facilitates the formation of several track collections, which are subsequently utilized in physics analyses. There are two primary methods employed: *inside-out* tracking and *outside-in* tracking.

- **The inside-out** tracking approach is primarily used for reconstructing primary charged particles originating from the proton-proton interaction and from the decay of particles with lifetimes shorter than 3×10^{-11} s. This method initiates with the formation of track seeds using three-point seeds from the silicon detectors, specifically in the **IBL**, pixel detector and the first layer of the **SCT**. These seeds are extrapolated using a Kalman Filter based algorithm [134]. The tracks are required to have a transverse momentum (p_T) greater than 400 MeV and are extended to the outer layers of the **SCT**, adding new track points as they move away from the interaction point.
- **Outside-in** tracking, also known as back-tracking, complements inside-out tracking by focusing on secondary particles, which are particles resulting from the decay of primary particles. This method starts with segments in the **TRT** and extends them towards the interaction point by incorporating silicon hits. This method, particularly needed when dealing with tracks that may not have silicon hits, such as those resulting from photon conversion. When tracks share a common hit, the hit is preferentially assigned to the track that best fits according to the **NEWT** algorithm. Tracks not receiving the hit are then refitted without it.

To minimize the selection of fake tracks number of constraints is applied. This is accomplished through applying quality criteria based on the number of hits, holes, and outliers¹, combined with specific constraints. The constraints include requirements such as a transverse momentum (p_T) greater than 400 MeV, a pseudorapidity ($|\eta|$) less than 2.5, and a specific minimum number of silicon hits, which varies with $|\eta|$. Additionally, tracks must have at least one hit in the first two layers of the pixel detector and the **IBL**, and are limited to a maximum number of shared hits and holes in the pixel and **SCT** detectors. Track overlap is resolved by scoring tracks based on their hits and holes, with ambiguous hits assigned to the highest-scoring track. This process is repeated until no overlaps remain, and the tracks are extended and refitted in the **TRT**. Tracks that satisfy these criteria are stored as a track parameter helix vector $\vec{q}$ for further analysis, such as vertex reconstruction.

5.1.1 Vertex reconstruction

After the reconstruction of individual particle tracks, the next step is to reconstruct the Primary Vertex (**PV**) of the event [135]. Accurate determination of the **PV** is crucial for various aspects of physics analyses. It serves as a means to distinguish particles originating from hard events from those arising due to pileup interactions, enabling the separation of relevant physics processes. Additionally, **PV** determination allows for the identification and tracking of long-lived decay chains, aiding in the differentiation between prompt and non-prompt particles. This information plays a important role in tasks such as flavour tagging, background suppression, and decay reconstruction.

The procedure for **PV** reconstruction relies on the information obtained from the reconstructed tracks by the **NEWT** algorithm and follows an iterative approach to accurately determine the **PV**. Initially, a seed for the first vertex is selected by identifying the peak of the z_0 distribution of the tracks, with the transverse position of the seed taken as the center of

¹A hit is a detected particle interaction point, an outlier negatively impacts the fit quality, and a hole is where a hit was expected but not found.

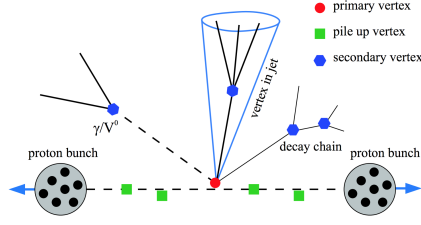


Figure 5.1: Primary, secondary and pileup vertices [137].

the beam spot. The adaptive vertex fitting (AVF) algorithm [136], which employs a Kalman Filter based approach, is then applied to these tracks to fit the vertex. During the fitting process, tracks less compatible with the current vertex hypothesis are systematically down-weighted, reducing their influence on the vertex position calculation. This iterative fitting allows for the refinement of the PV position by progressively assigning more weight to the tracks that are more compatible with the vertex hypothesis. As the iterations progress, tracks incompatible with the vertex are used as new seeds for subsequent iterations. The vertex fitting and track assignment process is repeated, with each iteration refining the position and the associated tracks of the vertex. The iterative vertex finding algorithm terminates when all tracks are associated with vertices or when no additional vertices can be found.

The PV is identified as the vertex that lies within the beamspot with the highest sum of the squared transverse momenta (p_T^2) of its associated tracks. This criterion ensures that the PV corresponds to the location with the majority of high- p_T tracks, typically indicative of the hard scattering process.

In addition to the primary vertex, events can also contain secondary and pileup vertices [137], as illustrated in Figure 5.1. Secondary vertices are identified where particles, originating from the primary vertex, decay after a measurable distance. Pileup vertices are additional interaction points occurring within the same bunch crossing as the primary event.

5.2 Electrons

The process of electron reconstruction has two main stages: the track reconstruction within the ID and cluster reconstruction in the calorimeter. These components are matched to form a complete electron candidate [138]. A crucial step following this reconstruction is the identification of the electron candidate as a prompt electron, signifying its direct origination from the PV. Furthermore, electron isolation is performed, which involves an examination of surrounding activity in both the calorimeter and ID, to effectively discriminate prompt electrons from those embedded within jets.

5.2.1 Electron reconstruction

The initial phase of the electron reconstruction process involves precise extrapolation of tracks from the ID to the EMC, employing a Gaussian Sum Filter [139]. This is followed by aligning these tracks with EM clusters, detected through a topo-cluster reconstruction

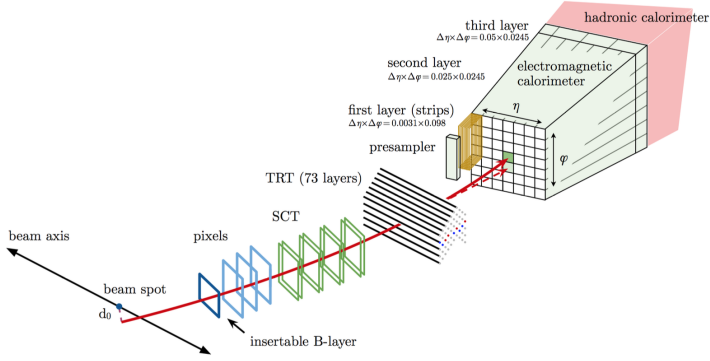


Figure 5.2: The path of an electron through the detector is shown by solid red line. The dashed red line represents the trajectory of a photon, produced as a Bremsstrahlung radiation in the TRT [138].

algorithm [140], [141]. This approach is particularly proficient at accounting for energy loss mechanisms, such as Bremsstrahlung, crucial for differentiating electron from photon interactions (refer to Figure 5.2). In scenarios where multiple tracks correlate with an electron candidate's energy cluster in the EMC, a singular track is selected based on criteria including momentum disparity, spatial proximity, and the number of hits in the pixel detector [142].

5.2.2 Electron identification

Once an electron candidate is reconstructed, the ensuing step involves its identification as a prompt electron, which originates from the PV. Other electron sources, such as photon conversions or those within hadronic jets, are considered backgrounds. The identification utilizes a multivariate likelihood (LH) discriminant, integrating parameters like shower shape, track properties, and track-to-cluster matching. Detailed information about the inputs used in the LH identification can be found in Table 1 of the cited publication [138]. This identification method is structured across three defined working points: LooseLH, MediumLH, and TightLH, each offering higher degrees of background discrimination. The TightLH working point ensures the strictest selection for optimal background distinction, while LooseLH offers the most inclusive criteria. Notably, these working points are inclusive, with LooseLH subsuming MediumLH and MediumLH, in turn, also including TightLH.

5.2.3 Electron isolation

In the final step, different isolation variables are employed. Usually prompt electrons are well isolated. There are two ways of calculating the energies and momenta produced in a cone around the electron candidate, what leads to the existence of two isolation definitions: track-based isolation ($p_T^{varcone}$) and calorimeter-based isolation (E_T^{cone}). The E_T^{cone} is defined as the sum of transverse energies of topological clusters within a cone of $R = 0.2$ around the candidate electron cluster [143]. The $p_T^{varcone}$ is defined as the sum of transverse momenta

of all tracks originating from the **PV** within a cone of $\Delta R = \min\left(\frac{10 \text{ GeV}}{p_T [\text{GeV}]}, R_{\text{max}}\right)$ around the candidate electron track, where R_{max} represents the maximum cone size and can vary depending on the specific requirements of the analysis, typically ranging between 0.2 and 0.4.

5.2.4 Electron efficiency and scale factors

Event efficiency refers to the proportion of events that are successfully reconstructed and meet the selection criteria out of the total number of true events produced in collisions. For low pileup data it is estimated using a tag-and-probe method [144] using $Z \rightarrow ee$ and $J/\psi \rightarrow ee$ generally follow what is done for the standard EGamma tag-and-probe method [143], [145]. It can be factorised in four terms:

$$\epsilon_{\text{total}} = \epsilon_{\text{reco}} \times \epsilon_{\text{id}} \times \epsilon_{\text{iso}} \times \epsilon_{\text{trig}} \quad (5.2)$$

where the reconstruction efficiency (ϵ_{reco}) covers the efficiency to reconstruct an electron from its energy deposits in the electromagnetic calorimeter and match a track in the inner detector. The identification (ϵ_{id}) and isolation (ϵ_{iso}) criteria use the shapes of **EM** showers in the calorimeter and track-related quantities to separate prompt, isolated electrons from photons and jet. Finally, the trigger efficiency ($\epsilon_{\text{Trigger}}$) relates to the fact events are recorded online only if they pass the selection imposed by the `HLT_e15_lhloose_nod0_L1EM12` algorithm. The combination of these four selections significantly improves the purity of electrons selected as $W \rightarrow \ell\nu$ candidates for the analysis and rejects most of the backgrounds. The efficiency of the process is observed to improve with an increase in the transverse energy (E_T), attributable to enhanced **EM** cluster formation at higher E_T levels and improved track extrapolation. However, the resulting efficiencies measured on real data and **MC** simulation are different, due to flaws e.g. in the description of detector imperfections or the **GEANT4** simulation.

To account for differences in detector response and selection efficiency compared to real-world observations the scale factors (**SFs**) are applied to simulated data. In this analysis **SFs** for reconstruction are derived by extending the standard high-pileup **SFs** into the low-mu region. Identification **SFs** are determined in-situ. In-situ measurements are also performed for isolation and trigger efficiencies and **SFs**.

Examples of electron reconstruction, identification, trigger and isolation efficiencies and **SFs** for **MediumLH** working point and $p_T^{\text{varcone20}}/p_T < 0.1$ isolation selection are shown on Figures 5.3 to 5.6. For a more in-depth details, readers are directed to the reference [144]. Although the analysis in this thesis is rely on low-pileup calibrations provided by the p_T^W analysis group, the application of additional isolation and identification **SFs** was required. This is due to the use of **TightLH** identification criteria and an extra signal region selection of $E_T^{\text{cone20}} < 0.05$. A detailed discussion on these additional **SFs** is presented in Section 6.3.2.

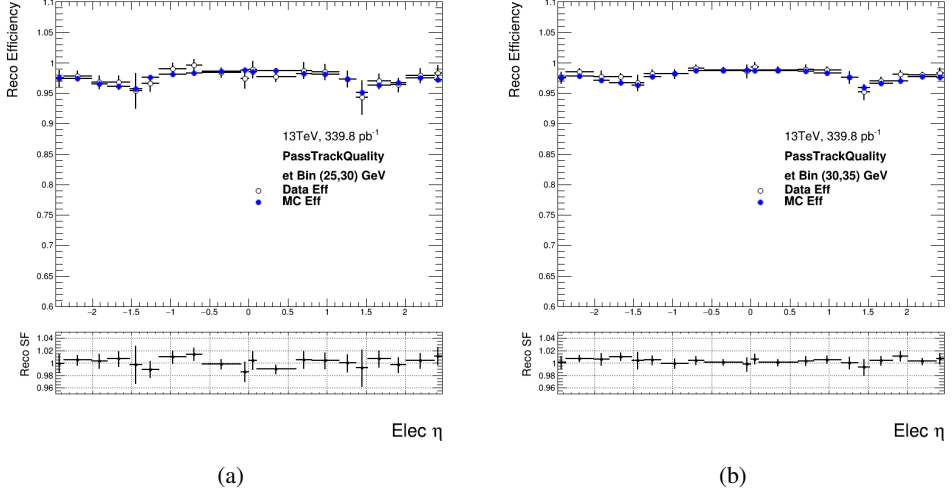


Figure 5.3: Electron reconstruction efficiencies and scale factor for 13 TeV low-pileup dataset in E_T range $25 < |E_T| < 30$ GeV (left) and $30 < |E_T| < 35$ GeV (right). The total uncertainties are included. Sourced from [144].

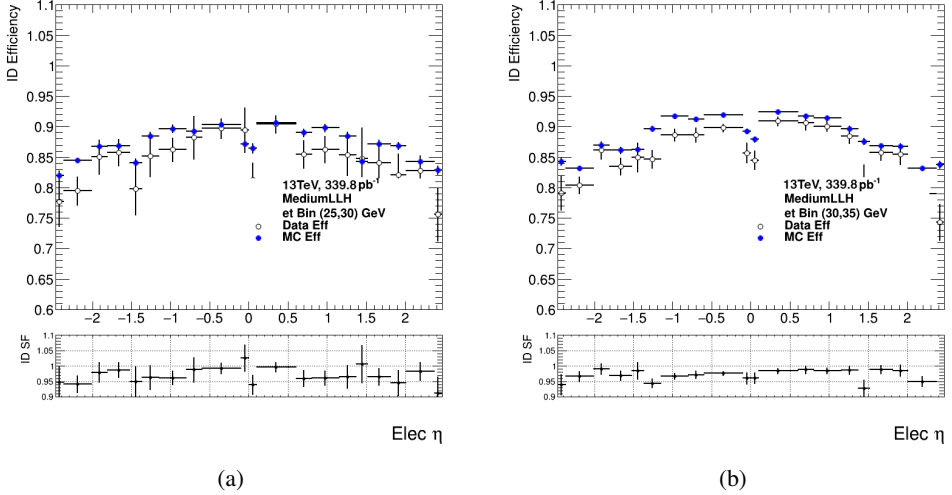


Figure 5.4: Electron identification efficiencies and scale factor for 13 TeV low-pileup dataset in E_T range $25 < |E_T| < 30$ GeV (left) and $30 < |E_T| < 35$ GeV (right). The total uncertainties are included. Sourced from [144].

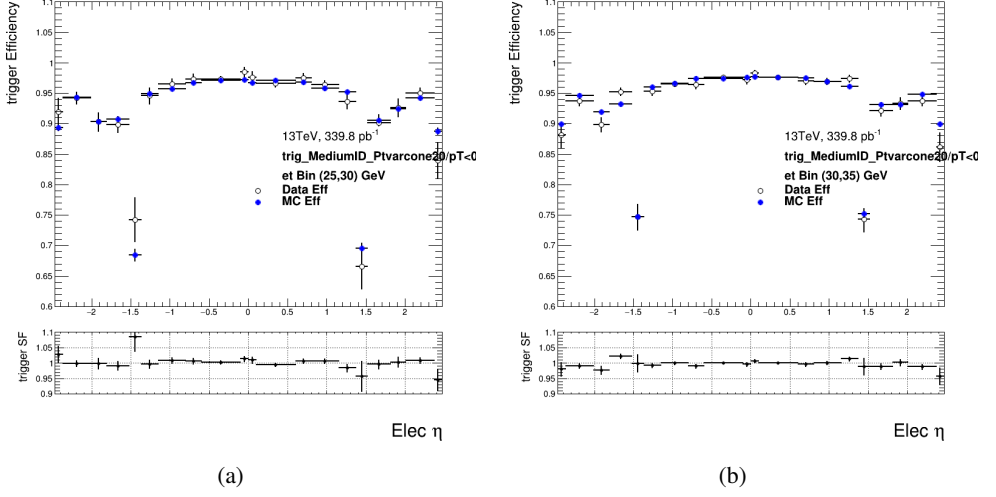


Figure 5.5: Electron trigger efficiencies and scale factor for 13 TeV low-pileup dataset in E_T range $25 < |E_T| < 30$ GeV (left) and $30 < |E_T| < 35$ GeV (right). The total uncertainties are included. Sourced from [144].

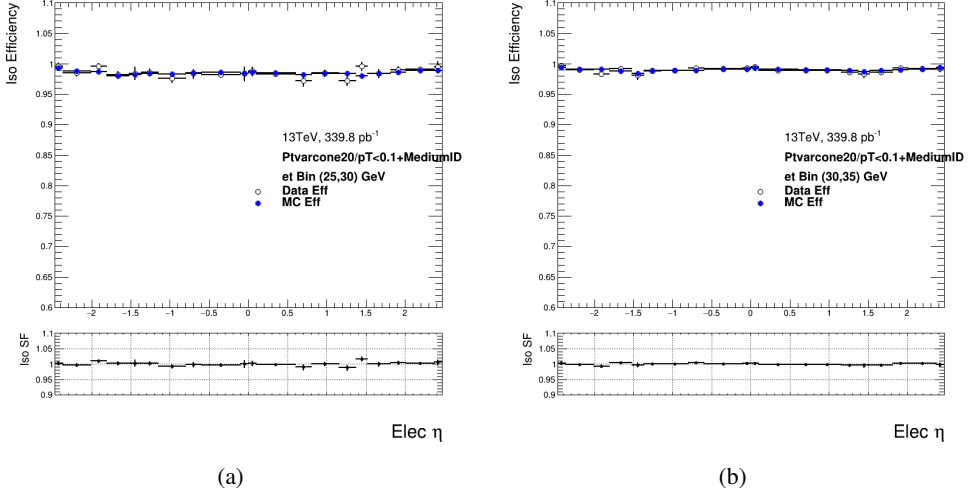


Figure 5.6: Electron isolation efficiencies and scale factor for 13 TeV low-pileup dataset in E_T range $25 < |E_T| < 30$ GeV (left) and $30 < |E_T| < 35$ GeV (right). The total uncertainties are included. Sourced from [144].

5.3 Muons

Muon reconstruction is a multi-step process that utilises information from both the **ID** and the Muon Spectrometer (**MS**), with additional input from the calorimeter in some cases. The reconstruction begins with the independent reconstruction of muon tracks in the **ID** and the **MS**. These tracks are then combined to form an unified muon track, which is used in physics analyses. For more detailed information, refer to the reference [146].

5.3.1 Muon reconstruction

Muon reconstruction in the **MS** starts with the identification of hit patterns in each muon chamber and the formation of segments. The hits in the Monitored Drift Tube (**MDTs**) chambers and nearby trigger chambers are aligned along trajectories in the bending plane using the Hough transform [147]. The orthogonal coordinate is measured using the Resistive Plate Chambers (**RPCs**) and Thin Gap Chambers (**TGCs**) detectors. In the Cathode Strip Chambers (**CSCs**) detectors, a separate combinatorial search is performed in the ϕ and η detector planes to reconstruct the muon tracks.

After reconstructing the muon tracks in each detector system separately, the information is combined to form a reconstructed muon object. Based on the detectors used for the combined reconstruction, four types of muons are defined [148]:

- **Combined (CB) muon:** It is formed by globally refitting the tracks reconstructed independently in the **ID** and the **MS**. This refit uses hits from both detectors, and new hits may be added. Typically, an outside-in pattern is used, where the **MS** track is extrapolated inwards to match the **ID** track. The inverse inside-out procedure is used as a complementary approach.
- **Segment-tagged (ST) muon:** It is a muon with an **ID** track that has been extrapolated to the **MS** and associated with at least one local track segment in the **MDTs** or **CSCs** chambers. ST muons are typically low- p_T muons or muons whose trajectory crosses regions with reduced **MS** acceptance.
- **Calorimeter-tagged (CT) muon:** It has a valid **ID** track that can be associated with an energy deposit in the calorimeter compatible with a minimum-ionizing particle. CT muons have the lowest purity among the muon types, but they provide acceptance in regions where the **MS** coverage may be absent, such as the very central region with $|\eta| \geq 0.1$ for $15 < p_T < 100$ GeV.
- **Extrapolated (ME) muon (standalone muon):** Its trajectory is reconstructed based only on the **MS** track and a loose requirement to match the interaction point (**IP**). The ME muons extend the muon acceptance to regions not covered by the **ID**, specifically $2.5 < |\eta| < 2.7$.

In this analysis, combined (CB) muons are generally utilized within the range of $|\eta| < 2.47$.

5.3.2 Muon identification

Muon identification is a important step in the analysis to confirm that the detected particle indeed possesses the properties of a muon and to determine its production mechanism. Muons that are produced directly in the decay of short-lived particles, such as massive bosons, are referred to as prompt muons, while those originating from the decays of hadrons or taus are known as non-prompt muons. Accurate muon identification is essential for effectively suppressing background contributions and ensuring reliable momentum measurements.

In order to suppress the background from non-prompt muons, which are predominantly produced within hadronic jets, the Muon Combined Performance group deploys an multivariate analysis (MVA) methodology [146]. The MVA leverages a CB muons, utilizing discriminating variables such as:

- q/p significance: This variable is defined as $\frac{|(q/p)_{ID} - (q/p)_{MS}|}{\sqrt{\sigma^2(q/p)_{ID} + \sigma^2(q/p)_{MS}}}$ - an absolute difference between q/p measured in the ID and MS detectors over the combined uncertainty.
- Relative transverse momentum difference $\rho = \frac{|p_T^{ID} - p_T^{MS}|}{p_T^{combined}}$.
- Normalised χ^2 fit of the combined track: This variable represents the goodness-of-fit measure for the combined track, normalised by the number of degrees of freedom.

Reflecting the diverse needs of various analysis strategies, three muon identification working points are used, as follows: Loose ID, Medium ID, and Tight ID. As for electrons the Loose, Medium and Tight working points are inclusive. For the analysis at hand, only muons that pass the Medium ID selection are considered.

5.3.3 Muon isolation

Similarly to electrons isolation, to quantify the degree of isolation of a muon candidate and to effectively suppress background, the detector activity around the muon is measured using two observables: one based on the muon's track ($p_T^{varcone}$) and another based on the calorimeter (E_T^{cone}).

The track-based observable $p_T^{varcone20}$ is defined as a scalar sum of all the particles with $p_T > 1$ GeV in a cone $\Delta R = \min(10\text{GeV}/p_T^\mu, 0.2)$ around the muon, excluding the muon's own track. This definition takes into account the muons p_T^μ dependence, making it more effective for muons originating from the decay of particles with high transverse momentum.

The calorimeter-based isolation observable $E_T^{topocone20}$ measures the sum of transverse energy from all topological clusters within a cone of size $\Delta R = 0.2$ around the muon. It accounts for the energy contributions of nearby particles, excluding the energy deposited by the muon itself. Additionally, corrections are applied to account for pileup effects caused by overlapping proton-proton collisions in the same event.

The size of the isolation cone can be adjusted based on the specific requirements of the analysis, typically ranging from 0.2 to 0.4.

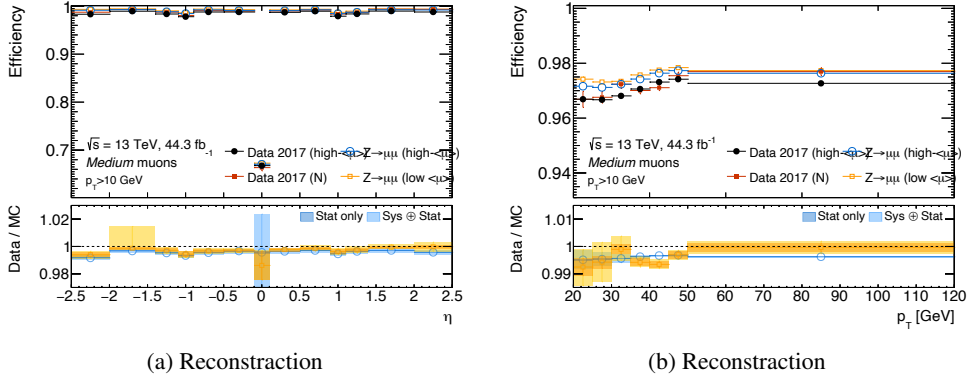


Figure 5.7: Reconstruction efficiencies and scale factors for low-pileup datasets in 2017 at $\sqrt{s} = 13$ TeV, shown as functions of leptons' η (left) and p_T (right). Sourced from [149].

5.3.4 Muon efficiency and scale factors

The determination of the muon reconstruction, identification, trigger and isolation efficiencies in data and MC simulations for low-pileup datasets taken in 2017 and 2018 required dedicated studies of the muon performance, since the standard efficiency scale factors and calibration constants determined for high-pileup datasets might not be appropriate. Details on this studies are in [149].

Similarly to electrons, efficiencies are measured with the tag-and-probe method in both the data and simulation. It can be also factorised in four terms:

$$\epsilon_{\text{total}} = \epsilon_{\text{reco/id}} \times \epsilon_{\text{TTVA}} \times \epsilon_{\text{iso}} \times \epsilon_{\text{trig}} \quad (5.3)$$

The trigger and isolation efficiency studies and correction factors were derived using low-pileup data, while the reconstruction and track-to-vertex-association (TTVA) scaling factors were provided by the same Muon Combined performance group analysis that does the full Run 2 muon efficiency studies [150]. Figures 5.7 to 5.10 illustrate the measured muon efficiencies and SFs with 2017 13 TeV low-pileup samples.

Similar to the approach for electrons, this thesis adopts a distinct isolation selection for muons, differing from the one utilized in [149]. As will be shown in Section 6.3.1, which is dedicated to sensitivity studies, the implementation of an additional calorimeter-based isolation cut of $E_T^{\text{cone20}} < 0.05$ in the signal regions was important for muon channel analysis. Section 6.3.2 provides an in-depth discussion on the additional SFs required to accommodate these changes in selection criteria.

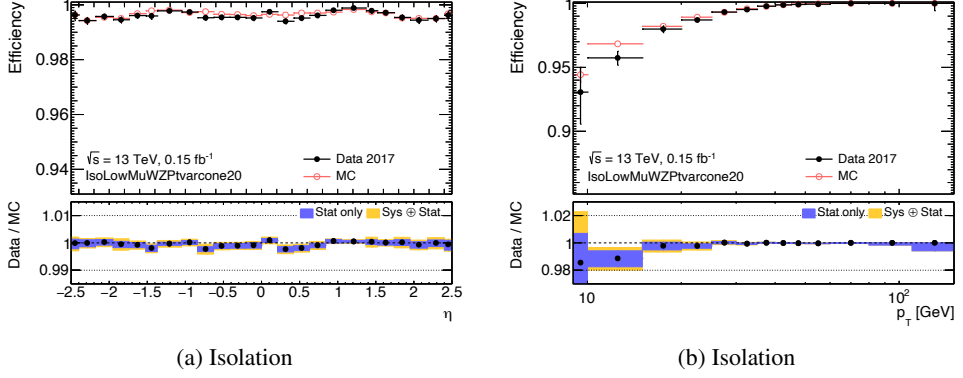


Figure 5.8: Isolation efficiencies and scale factors for low-pileup datasets in 2017 at $\sqrt{s} = 13$ TeV, shown as functions of leptons' η (left) and p_T (right). Sourced from [149].

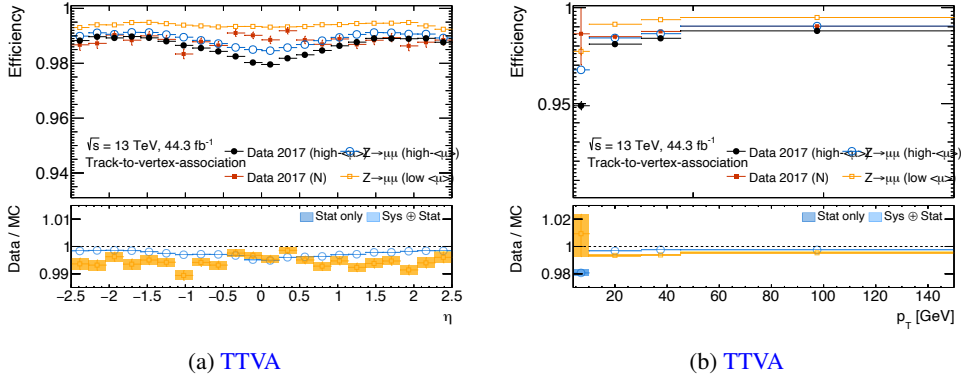


Figure 5.9: TTVA efficiencies and scale factors for low-pileup datasets in 2017 at $\sqrt{s} = 13$ TeV, shown as functions of leptons' η (left) and p_T (right). Sourced from [149].

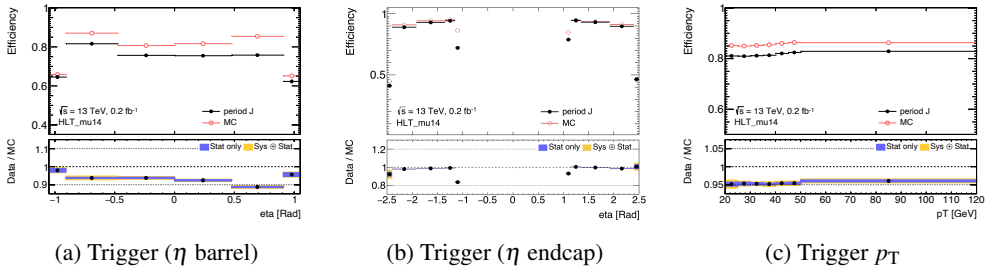


Figure 5.10: Trigger efficiencies and scale factors for low-pileup datasets in 2017 at $\sqrt{s} = 13$ TeV, shown as functions of leptons' η for barrel (a) and endcap (b) regions and p_T (c). Sourced from [149].

5.4 Particle flow objects

The measurement of hadronic objects and particle showers poses challenges due to the diverse properties and energy/momentum range of the particles involved. The Inner Detector (ID) provides better momentum and angular resolution for low-energy charged particles, while the calorimeter performs better at higher energies and can detect neutral particles. The Particle Flow (PF) algorithm aims to combine the information from both detectors to achieve the best possible result [151]. One of the significant advantages of Particle Flow Objects (PFO) technique is its ability to suppress the contribution of pileup events, which can introduce additional tracks and energy deposits in the calorimeter, complicating the reconstruction and identification of particles from the primary interaction.

The first step is obtaining *tight* tracks from the ID, which refers to tracks with a minimum of nine hits in the silicon detectors and no holes in the pixel detector. These tracks are required to have $|\eta| < 2.5$ and $0.5 < p_T < 40$ GeV, corresponding to the kinematic region where the tracks offer better resolution compared to the calorimeter. Tracks associated with leptons are removed from further consideration. The matching process performed by associating the calorimeter topoclusters, which have been reconstructed and calibrated using the electromagnetic scale as described in [140], with the corresponding tracks based on their spatial position and measured momentum. To determine the compatibility between a topocluster and a track, a distance metric, $\Delta R'$, is calculated. This metric is defined as:

$$\Delta R' = \sqrt{\left(\frac{\Delta\phi}{\sigma_\phi}\right)^2 + \left(\frac{\Delta\eta}{\sigma_\eta}\right)^2}, \quad (5.4)$$

where $\Delta\phi$ and $\Delta\eta$ represent the angular distances between the barycentres of the topoclusters and the tracks, and σ_ϕ and σ_η correspond to the width of the topoclusters. The preliminary matching is established by applying a criterion that ensures the compatibility of the topocluster and track in terms of their energy and momentum measurements. Specifically, a requirement of $E^{clus}/p^{trk} > 0.1$ is imposed, where E^{clus} represents the energy of the cluster and p^{trk} corresponds to the momentum of the track.

In situations where the energy deposit of a particle is split between multiple clusters, a split shower recovery procedure is initiated. This procedure involves searching for matching clusters in a radius of $\Delta R = 0.2$ around the track that is extrapolated to the second layer of the electromagnetic calorimeter. During the split shower recovery, an estimation is made to determine if the energy associated with the track and the energy of the corresponding topocluster are consistent. If they are found to be consistent, the topoclusters that are matched to the tracks are removed. As a result of this procedure, two separate collections of particle flow objects are obtained. The first collection consists of charged particle flow objects (cPFOs), each of which is associated with a track. These cPFOs are required to match the primary vertex, satisfying the condition of $|z_0 \times \sin \theta| < 2$ mm. The second collection consists of neutral particle flow objects (nPFOs), which are characterised by their calorimeter deposits.

In essence, the Particle Flow Object (PFO) formula is expressed as:

$$PFO = (E_{\text{calo}} - E_{\text{tracks}}^{\text{all}})^{\text{Neutral}} + (E_{\text{tracks}}^{\text{PV}})^{\text{Charged}} \quad (5.5)$$

Here, E_{calo} represents the total energy captured by the calorimeter. The term $(E_{\text{calo}} - E_{\text{tracks}}^{\text{all}})$ isolates the component of energy attributable to neutral particles by deducting their aggregate energy from the total calorimeter energy. Lastly, $E_{\text{tracks}}^{\text{PV}}$ reflects the energy associated with charged particles emanating from the **PV**, thereby providing a detailed representation of the various energy contributions in particle collisions.

The complete procedure for particle flow object reconstruction, including the split shower recovery, is described in detail in the reference [151].

5.5 Hadronic recoil

The analysis of the W boson kinematics through its leptonic decay products $W^\pm \rightarrow \ell^\pm \nu$ presents challenges primarily due to the presence of the undetected neutrino, which carries away significant information. However, it is still possible to measure the transverse momentum of the W boson. The majority of the W boson's transverse momentum arises from the initial state radiation (**ISR**). The energy of the generated parton shower can be expressed as follows:

$$\vec{p}_T^V = \vec{p}_T^\ell + \vec{p}_T^\nu = - \sum_{i=\text{ISR}, q, g} \vec{p}_{Ti} = -\vec{u}_T, \quad (5.6)$$

where the transverse momenta of the vector boson, lepton, and neutrino are denoted by $\vec{p}_T^V$, $\vec{p}_T^\ell$, and $\vec{p}_T^\nu$, respectively. The combined transverse momenta of all partons originating from the initial state radiation (**ISR**) is referred to as the Hadronic Recoil (**HR**), represented by the vector sum $\sum_{i=\text{ISR}, q, g} \vec{p}_{Ti} = \vec{u}_T$. This term accounts for the transverse momenta of any partons recoiling from the color-neutral boson. Furthermore, the missing transverse momentum $\vec{E}_T^{\text{miss}}$ associated with the escaping neutrino can be defined as follows:

$$\vec{E}_T^{\text{miss}} := \vec{p}_T^\nu = -(\vec{u}_T + \vec{p}_T^\ell). \quad (5.7)$$

The reconstruction of the **HR** relies on the use of Particle Flow Objects (**PFO**), which were previously defined and described in Section 5.4. In the specific context of low-pileup precision W boson analysis, employing **PFO**s as the input constituents for constructing the

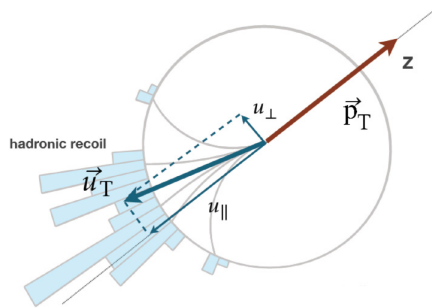


Figure 5.11: The hadronic recoil vector in the transverse plane and its components with respect to vector boson p_T [152].

vector quantity $\vec{u}_T$ results in a notable enhancement. This approach allows for the utilization of the complete information available from both topo-clusters and tracks.

The [HR](#) in the transverse plane, $\vec{u}_T$, is computed by summing the vector momenta of all charged and neutral [PFOs](#). The magnitude of this two-dimensional vector is referred to as u_T . To avoid double counting, it is important to exclude the leptons from the calculation of the [HR](#) in a W event. To achieve this, a cone with a radius of $\Delta R < 0.2$ is removed around each lepton, and instead, a cone of the same size is considered in the same η and ϕ region but at a distance of $\Delta R > 0.4$ away from any lepton. By applying this procedure, an unbiased estimate of the pileup and underlying event can be obtained. Only leptons with transverse momentum above $p_T > 10$ GeV, and that satisfy fiducial cuts in η and identification requirements, are removed from the calculation of the [HR](#).

In addition to the [HR](#), the scalar sum of transverse energies of all the [PFOs](#), known as ΣE_T , plays a crucial role. This quantity provides an estimate of the total event activity. The magnitude of ΣE_T is closely related to the resolution of u_T . As the transverse momentum of the vector boson (p_T^V) increases, ΣE_T also tends to increase due to the enhanced dynamics of the boson. However, it is important to separate the contributions from the underlying event activity, pileup, and soft emissions. To achieve this, the quantity $\Sigma \bar{E}_T = \Sigma E_T - u_T$ is introduced, representing ΣE_T with the hard activity subtracted. This allows for a better characterisation of the additional activity beyond the vector boson in the event.

For the calibration of the [HR](#), it is advantageous to introduce quantities that have a natural physical interpretation. In this context, the transverse momentum of the vector boson (p_T^V) serves as a natural axis, making it convenient to perform a 2-component decomposition of the u_T vector. One of these components is the u_T component parallel to the vector boson p_T :

$$u_{\parallel} = \frac{\vec{p}_T^V \cdot \vec{u}_T}{p_T^V}, \quad (5.8)$$

and a perpendicular component:

$$u_{\perp} = \frac{|\vec{p}_T^V \times \vec{u}_T|}{p_T^V}. \quad (5.9)$$

Ideally, it would be preferable the parallel component $u_{\parallel}$ of the [HR](#) to be equal to the transverse momentum of the vector boson (p_T^V), and the perpendicular component $u_{\perp}$ to be zero. However, due to detector effects, this is typically not the case. The perpendicular component $u_{\perp}$ can be seen as a measure of the resolution of the [HR](#), while the parallel component $u_{\parallel}$ carries information about the scale of the recoil. Another important quantity in this context is the bias:

$$b = u_{\parallel} - p_T^V, \quad (5.10)$$

which is expected to be centred around zero, indicating that the average value of the parallel component $u_{\parallel}$ should be close to the transverse momentum of the boson (p_T^V). However, in experimental data, the true p_T^V is not known. In the case of Z decay events, the transverse momentum of the dilepton system ($p_T^{\ell\ell}$) can be used as an axis for the decomposition of $u_{\perp}$ and $u_{\parallel}$. This is possible because the difference in $u_{\perp}$ resolution between p_T^V and $p_T^{\ell\ell}$ is

negligible. On the other hand, in W data events, only the transverse momentum of the lepton (p_T^ℓ) can be used for the decomposition of $u_\perp$.

The definition and calibration of the [HR](#) are described in detail in reference [152] and are summarised briefly here. The calibration procedure is performed as a function of $\Sigma \vec{E}_T$ (the event activity corrected for the directed recoil) and the transverse momentum of the boson (p_T^V), as these quantities have the most significant impact on the [HR](#). The calibration is obtained using Z events and then extrapolated to W events.

The calibration procedure consists of three main steps:

- **Modeling the $\Sigma \vec{E}_T$ distribution:** The goal is to ensure that the $\Sigma \vec{E}_T$ distribution in the [MC](#) simulation accurately matches that of the data. This is achieved through a 2-dimensional reweighting procedure in Z events, where the correlation between $\Sigma \vec{E}_T$ and p_T^V is correctly modeled. In simulated W events, an additional reweighting of $\Sigma \vec{E}_T$ in bins of u_T is applied. Furthermore, a 1-dimensional reweighting is performed for each process (W^- , W^+ , and Z) to recover the initial underlying p_T^{true} spectrum.
- **Correction of recoil direction:** The direction of the recoil is corrected by considering the projections of the recoil vector onto the x and y axes in Z events. Any differences between data and [MC](#) are accounted for and corrected to ensure consistent recoil direction estimation.
- **Response and resolution corrections:** Response and resolution corrections are obtained in-situ using Z data events. The parallel and perpendicular components of the recoil are extracted from the data as a function of $\Sigma \vec{E}_T$ and $p_T^{\ell\ell}$. These components are compared to the [MC](#) simulation to determine corrective coefficients that account for any discrepancies and ensure accurate response and resolution modeling.

The Z -based calibration is extended to W events by applying the calibration derived from Z events. However, this extrapolation introduces uncertainties, which are taken into account in the analysis. These uncertainties capture the potential differences between Z and W events and account for any limitations in the extrapolation procedure. A comprehensive overview of these uncertainties, along with a detailed summary, can be found in reference [152].

The transverse components of the neutrino's momentum, p_x^V and p_y^V , can be approximated from the missing transverse momentum, which balances the event. On the other hand, the longitudinal component p_z^V can only be determined up to a twofold ambiguity when solving the quadratic equation involving the invariant mass of the lepton-neutrino system m_W , assuming the value of m_W is known. The determination of the neutrino's momenta in the [CS](#) frame, including the twofold ambiguity will be discussed in the following section.

5.6 Solving equation for neutrino momenta

Once the computation of the [HR](#) is complete, it becomes possible to indirectly determine the transverse momentum of the neutrino, denoted as $\vec{p}_T^V$, using the Formula 5.7, where E_T^{miss} is the missing transverse energy. To incorporate the transverse momenta of additional muons in the calculation of missing transverse energy (E_T^{miss}), muons with $p_T > 5$ GeV and satisfying medium identification criteria are included. These muons transverse momenta are added to

the definition of E_T^{miss} . However, since muons also deposit energy in the calorimeter, their calorimeter energy deposits are subtracted from the event to avoid double counting. This ensures an accurate and comprehensive calculation of E_T^{miss} , accounting for the contributions of these additional muons.

Thanks to the clean environment provided by the low-pileup dataset, this analysis was able to maximize sensitivity and extend acceptance at high p_T^W without imposing any requirements on m_T^W ¹. Similarly, no requirements were placed on E_T^{miss} in order to fully exploit the available information and enhance the sensitivity of the analysis. This approach allows for a broader exploration of the phase space.

In order to infer the unmeasured longitudinal momentum of the neutrino, an assumption is made based on the Drell-Yan process. It is assumed that the dilepton pair produced in this process has an invariant mass equal to m_W . This assumption allows for the determination of the neutrino's longitudinal momentum. In the laboratory frame, let's consider a massless charged lepton with four-momentum p^μ and a massless neutrino with four-momentum q^μ :

$$p^\mu = \begin{pmatrix} \vec{p} \\ |p| \end{pmatrix} \quad q^\mu = \begin{pmatrix} \vec{q} \\ |q| \end{pmatrix} \quad (5.11)$$

$$\vec{p} = \begin{pmatrix} p_x \\ p_y \\ p_z \end{pmatrix} \quad \vec{q} = \begin{pmatrix} q_x \\ q_y \\ q_z \end{pmatrix} \quad (5.12)$$

By imposing the m_W constrain:

$$(p+q)^\mu (p+q)_\mu = m_W^2 \quad (5.13)$$

and using the relations:

$$|p| = \sqrt{p_x^2 + p_y^2 + p_z^2} \quad |q| = \sqrt{q_x^2 + q_y^2 + q_z^2} \quad (5.14)$$

and factorizing the expression in powers of q_z , leads to:

$$aq_z^2 + bq_z + c = 0 \quad (5.15)$$

with

$$a = (p_x^2 + p_y^2) \quad (5.16)$$

$$b = -p_z[2(p_x q_x + p_y q_y) + m_W^2] \quad (5.17)$$

$$c = |p|^2(q_x^2 + q_y^2) - [2(p_x q_x + p_y q_y) + \frac{m_W^2}{2}]^2 \quad (5.18)$$

¹ m_T^W is defined as the transverse mass given by $\sqrt{2p_T^V p_T^l (1 - \cos \Delta\phi^V)}$, where p_T^V and ϕ^V are estimated using the corresponding E_T^{miss} quantities as described in Eq. (5.7).

Finally, the two solutions for the longitudinal momentum of the neutrino can be expressed as follows:

$$q_z(1,2) = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a} \quad (5.19)$$

The momentum of the lepton in the **CS** frame can be expressed as [1]:

$$p_x^{CS} = \frac{1}{2} \frac{m_W}{m_W^2 + p_{T,W}^2} (2p_x - p_{T,W}^2) \quad (5.20)$$

$$p_y^{CS} = p_y \quad (5.21)$$

$$p_z^{CS} = \pm \frac{m_W}{2} \sqrt{1 - \frac{(p_x^{CS})^2 + (p_y^{CS})^2}{m_W^2/4}} \quad (5.22)$$

The azimuthal and polar angles in the **CS** frame are given by:

$$\phi_{CS} = \arctan p_y^{CS} / p_x^{CS} \quad (5.23)$$

$$\theta_{CS} = \arctan \sqrt{(p_x^{CS})^2 + (p_y^{CS})^2} / p_z^{CS} \quad (5.24)$$

It is important to note that in the **CS** frame, the transverse components p_x^{CS} and p_y^{CS} can be uniquely determined from measurable laboratory frame quantities. However, the longitudinal component p_z^{CS} is only determined up to a sign, resulting in a twofold ambiguity. This ambiguity results as an uncertainty in the sign of $\cos \theta_{CS}$, while ϕ_{CS} remains determined. Consequently, the unmeasured longitudinal momentum of the neutrino introduces two possible solutions for the rapidity of the W boson, y_W , and two solutions for $\cos \theta_{CS}$, differing by a sign. Nevertheless, the transverse momentum $p_{T,W}$ and azimuthal angle ϕ_{CS} are uniquely determined in this frame.

The assumption of collinearity between the z axis and one of the collider beams is not applicable in proton-proton collisions. Instead, in these collisions, the sign of the z axis in the **CS** frame is aligned with the direction of the longitudinal momentum of the W boson. Consequently, the expression for $\cos \theta_{CS}$ becomes $\cos \theta_{CS} \cdot \text{sign}(y_W)$, as shown in Equation 1.41. With this definition, there are events in which the two solutions have opposite signs for y_W , allowing for the unambiguous determination of $\cos \theta_{CS}$. These events, typically occurring at central rapidities, provide an opportunity to measure the forward-backward asymmetry (the A_4 coefficient) in W boson production.

To understand the sign ambiguity in $\cos \theta_{CS}$, one can analyse Equation 1.41, which consists of two parts contributing to this ambiguity. The first part, $p_z^{\ell\nu} / |p_z^{\ell\nu}|$, can be rewritten as the sign of $y_{\ell\nu}$. The second part is $\Delta P_\ell = (P_1^+ P_2^- - P_1^- P_2^+)$. The primary source of ambiguity resolution in $\cos \theta_{CS}$, occurring approximately 25% of the time, arises when the two solutions have opposite signs in $y_{\ell\nu}$. This also leads to a sign flip in ΔP_ℓ , resulting in both solutions of $\cos \theta_{CS}$ being equal. This situation is more prevalent for bosons with central rapidity, as illustrated in Figure 5.12 (shown in red).

This sign flip can be understood by examining the $W^- \rightarrow e^- \bar{\nu}$ case, where P_1 is fixed since the lepton is measured. As a result, ΔP_ℓ simplifies to:

$$\Delta P_\ell = P_1^+ (E_v - p_z^v) - P_1^- (E_v + p_z^v). \quad (5.25)$$

If ΔP_ℓ flips sign then

$$\begin{aligned} E_v - p_z^v > E_v + p_z^v &\Rightarrow p_z^v < 0 \quad \text{for solution 1,} \\ E_v - p_z^v < E_v + p_z^v &\Rightarrow p_z^v > 0 \quad \text{for solution 2.} \end{aligned} \quad (5.26)$$

The sign flip of $y^{\ell v}$ can be understood by examining the definition of rapidity, which is given by:

$$y = \frac{1}{2} \ln \left(\frac{E + p_z c}{E - p_z c} \right), \quad (5.27)$$

where E and p_z are the energy and longitudinal momentum of the particle, respectively. If $y^{\ell v}$ flips sign, it implies that the following inequalities hold:

$$\begin{aligned} E^{\ell v} + p_z^{\ell v} c &> E^{\ell v} - p_z^{\ell v} c \quad \text{for solution 1,} \\ E^{\ell v} + p_z^{\ell v} c &< E^{\ell v} - p_z^{\ell v} c \quad \text{for solution 2.} \end{aligned} \quad (5.28)$$

The sign flip predominantly occurs for central $y^{\ell v}$ because the sign flip of p_z^v is more likely to happen when $p_z^\ell + p_z^v$ is close to zero. This can be observed by substituting $p_z^{\ell v} = p_z^\ell + p_z^v$ into Equation 5.28, which can be rearranged as:

$$\begin{aligned} p_z^\ell + p_z^v &> 0 \quad \text{for solution 1,} \\ p_z^\ell + p_z^v &< 0 \quad \text{for solution 2.} \end{aligned} \quad (5.29)$$

Thus, when $p_z^\ell + p_z^v$ is close to zero, there is a higher probability of encountering a sign flip in p_z^v , resulting in the twofold ambiguity in the sign of $y^{\ell v}$.

The other time when the sign ambiguity in $y^{\ell v}$ can also be resolved is when one of the solutions violates the Bjorken condition, which states that $x < 1$. This occurs when either $|p_z^v| > \sqrt{s}/2$ or $|p_z^v + p_z^\ell| > \sqrt{s}/2$, where $\sqrt{s}$ is the center-of-mass energy of the collision. In these cases, the solution leads to longitudinal momenta for the neutrino or the W boson that exceed the beam energy, which is unphysical. These events, where the solution violates the Bjorken condition, are not very common, as can be observed by the blue region in Figure 5.12. Thus, the majority of events fall into the category where the sign ambiguity is resolved based on the sign of $y^{\ell v}$.

In order to gain a deeper understanding of the sensitivity, it is important to examine the consequences of selecting both the correct and incorrect solutions for p_z^v . Here, the “correct” p_z^v solution refers to the one that is closest to the true value of p_z^v . Interestingly, both the correct and incorrect solutions occur with equal frequency, as shown in Figure 5.13. In the figure, the distribution of the incorrect solution (shown in blue) covers the distribution of the correct solution (shown in red).

There are four possible combinations when selecting the correct solution for p_z^v and obtaining the correct sign of $\cos \theta_{CS}$. The first combination corresponds to events where the correct p_z^v solution is chosen and the correct sign of $\cos \theta_{CS}$ is obtained. These events are shown in red in Figure 5.14. They are particularly important for achieving sensitivity

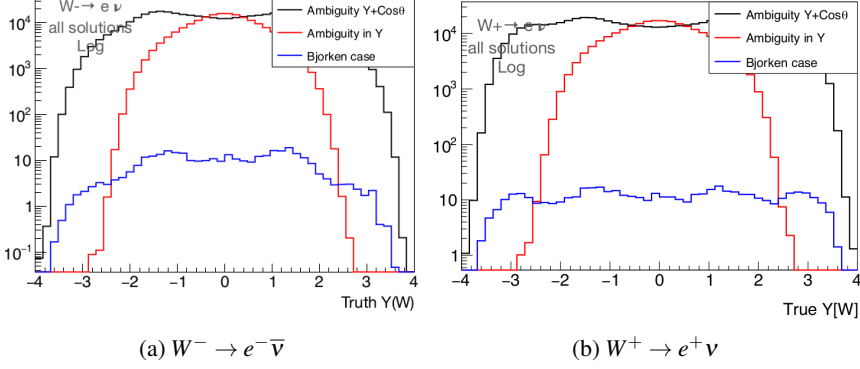


Figure 5.12: The distribution of events categorised based on their ability to resolve the sign ambiguity. The black category represents events with a sign ambiguity in both $\cos \theta_{CS}$ and $y^{\ell\nu}$. The red category consists of events where the sign ambiguity in $\cos \theta_{CS}$ is resolved by sign flipping, but there is still an ambiguity in the sign of $y^{\ell\nu}$. The blue category corresponds to events where one solution violates the condition of Bjorken $x < 1$, resulting in only one valid solution.

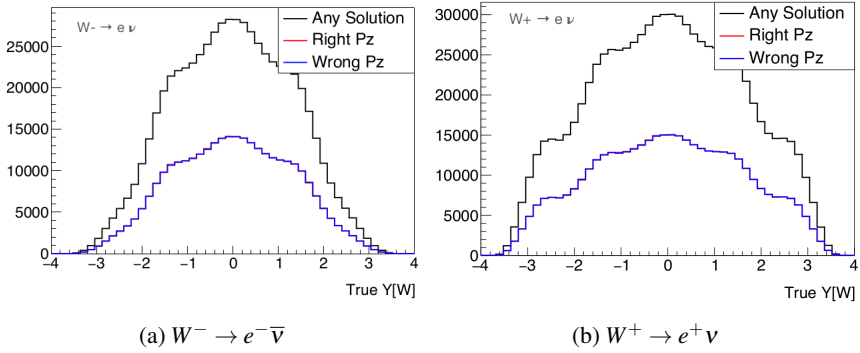


Figure 5.13: The distribution of events with the right (red) and wrong (blue) choice of p_z^ν , which are equally distributed in $y^{W, \text{Truth}}$.

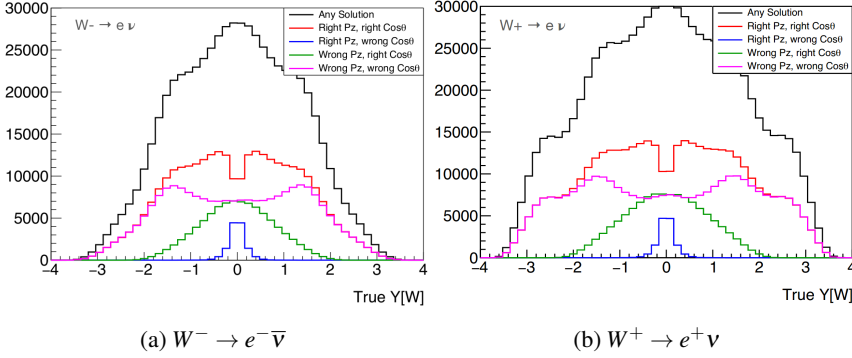


Figure 5.14: Distribution of events based for the four combinations of the choice of p_z^v solution and the correct sign of $\cos \theta_{CS}$.

at large rapidities. In the more central region, the correct sign of $\cos \theta_{CS}$ can be obtained regardless of the p_z^v choice. The second combination involves events where the correct p_z^v solution is chosen, but due to limited resolution, the sign of $\cos \theta_{CS}$ is flipped. These events are shown in blue in Figure 5.14. The third combination corresponds to events where the wrong p_z^v solution is chosen, but the sign of $\cos \theta_{CS}$ flips, resulting in the correct sign of $y^{\ell\nu}$. These events, shown in green in Figure 5.14, yield enhanced sensitivity to A_4 . They are primarily observed in the more central region. The fourth and final combination consists of events where the wrong p_z^v solution is chosen, leading to the wrong sign of $\cos \theta_{CS}$. These events, shown in pink in Figure 5.14, have the effect of diluting the sensitivity, particularly at high $y^{\ell\nu}$.

The sensitivity to A_4 was assessed by examining the impact of the sign ambiguity on the measurement. The analysis was performed by categorizing events based on the ambiguity level, as shown in Figure 5.12. Events where both the sign of $\cos \theta_{CS}$ and the sign $y^{\ell\nu}$ are ambiguous, with the correct sign being determined with a 50% chance, do not contribute to the sensitivity to A_4 . These events are represented by the black points in Figures 5.15. By combining these events with the ones that only have a sign ambiguity in $y^{\ell\nu}$, where the correct sign is obtained every time, a significant sensitivity gain to A_4 is achieved. This can be observed by the blue points in Figures 5.15. Events that violate the Bjorken $x < 1$ condition contribute a small increase in sensitivity, as shown by the red points in Figures 5.15. In Figures 5.15 (bottom), it is evident that the majority of the sensitivity gain is observed in the central region of $y^{\ell\nu}$, which is in line with expectations.

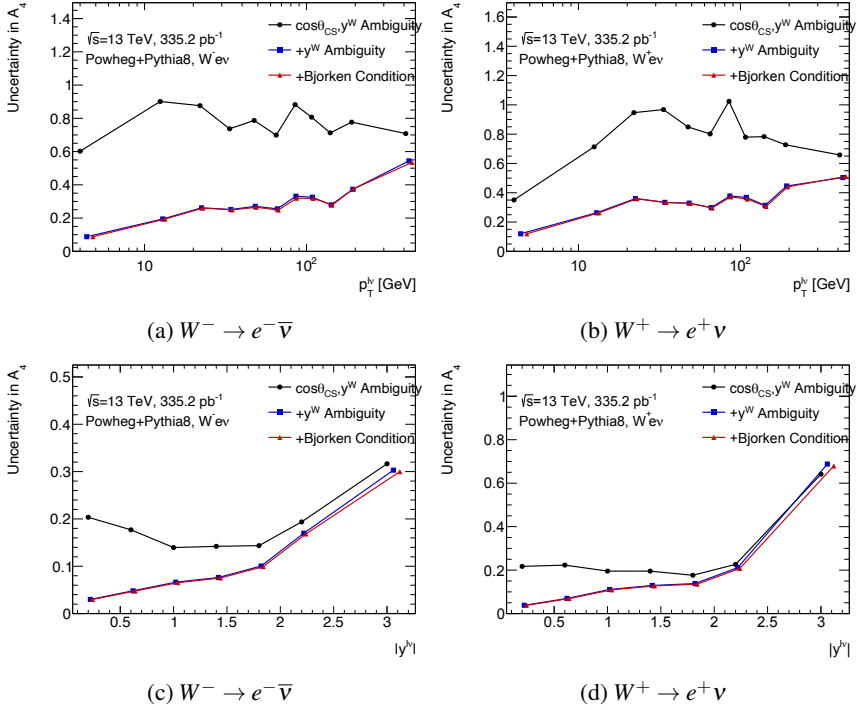


Figure 5.15: Comparison of the total statistical uncertainty for A_4 when including events based on the ambiguity in the sign of $\cos \theta_{CS}$ and y^W in the $p_T^{\ell\nu}$ binning (top) and $y^{\ell\nu}$ binning (bottom) for $W^- \rightarrow e^- \bar{\nu}$ and $W^+ \rightarrow e^+ \nu$. Event selection for this studies will be covered in Section 6.

5.7 Summary

This chapter has presented an overview of the methodologies and techniques employed by the analysis team in the reconstruction of events within the ATLAS experiment.

The reconstruction of charged particle tracks and vertices forms the foundation of event analysis (Section 5.1). Track reconstruction involves identifying the paths taken by charged particles as they traverse the detector, while vertex reconstruction focuses on determining the points at which particles originate or interact. Key techniques include the fitting of tracks to hits in the detector and the clustering of tracks to identify primary and secondary vertices, crucial for studying particle interactions and decay mechanisms.

Electrons are reconstructed by combining information from the tracking system and the electromagnetic calorimeter (Section 5.2). The identification of electrons is based on a set of criteria, including the shape of the energy deposit in the calorimeter and the matching of tracks to calorimeter clusters. Electron isolation, which distinguishes prompt electrons from those originating from hadron decays, along with the determination of electron efficiency and scale factors, are important for accurate electron measurement.

Muon reconstruction involves tracking muons through the inner detector and into the muon chambers, allowing for high-precision measurements of their momentum (Section 5.3). Identification criteria for muons include the quality of the track fit and the level of activity in the calorimeters surrounding the track. Muon isolation is employed to distinguish signal muons from background, and efficiency and scale factors are calculated to correct for detector effects.

In Section 5.4 the concept of particle flow objects is presented, that integrates information from all sub-detectors to build a comprehensive picture of each event. This approach enhances the precision of particle identification and measurement, crucial for reconstructing complex events like W decays. The discussion progresses to Section 5.5, where the concept of hadronic recoil is explored. This quantity is essential for accurately measuring the transverse momentum of the W boson and is calculated as the vector sum of the transverse momenta of all detected particles, excluding the decay lepton from the W .

Finally, Section 5.6 demonstrates that the longitudinal component of the neutrino's momentum, p_z^{ν} , for a fraction of events can only be estimated with a twofold ambiguity when solving the quadratic equation involving the invariant mass of the lepton-neutrino system, m_W , assuming m_W 's value is known. Sensitivity studies for A_4 are conducted to assess the impact of this sign ambiguity on the measurement. It was found that incorporating events with sign ambiguity in $y^{\ell\nu}$, where the correct sign is consistently determined, significantly enhances the sensitivity to A_4 .

6

SIGNAL AND BACKGROUND ESTIMATION

In this chapter, the procedures and findings associated with the measurement of the angular coefficients of the W boson are outlined. The reconstruction of W boson events involves identifying a prompt lepton and measuring missing transverse energy, employing the hadronic recoil technique.

A critical aspect of this analysis lies in achieving agreement between the experimental data and the Monte Carlo (MC) simulations, with particular emphasis on the W boson angular coefficient measurements. The application of the hadronic recoil method confers the capability to reconstruct the W boson's center-of-mass frame, significantly improving the study's accuracy. One of the most substantial challenges encountered in this analysis is the presence of considerable number of fake leptons in the background. These fake leptons can arise from various sources, such as misidentified hadrons or leptons, and they can significantly impact the accuracy of the measurements.

6.1 Data sample

This analysis makes use of special runs conducted at the [ATLAS](#) experiment with a center-of-mass energy of 13 TeV. These runs were carried out during Fall 2017 and July 2018 and were carefully selected to ensure low-pileup conditions, with an average number of interactions per bunch crossing $\langle\mu\rangle$ of approximately 2. The specific purpose of these special conditions is to optimise the measurement resolution of the hadronic system that recoils against the bosons. This recoil system provides a direct measurement of the transverse momentum of the W -boson, which is a key aspect of this analysis.

The analysis considers two sets of data runs for examination:

- Data taken in November 2017 at a center-of-mass energy of $\sqrt{s} = 13$ TeV, during ATLAS data period N. The preliminary calibrated luminosity for this dataset is 147.061 pb^{-1} , with an uncertainty of $\pm 1.15\%$.

- Data taken in June 2018 at a center-of-mass energy of $\sqrt{s} = 13$ TeV, during ATLAS data period G4+J. The preliminary calibrated luminosity for this dataset is 191.085 pb^{-1} , with an uncertainty of $\pm 1.08\%$.

The total luminosity of the 13 TeV data used in the analysis is $338.1 \pm 3.1 \text{ pb}^{-1}$ with an uncertainty of $\pm 0.92\%$. The 13 TeV data was collected with a fixed levelled luminosity at an average number of interactions per bunch crossing $\langle \mu \rangle = 2$, with minor exceptions (see Figure 6.1). The runs of November 2017 and June 2018 had the same bunch spacing of 25 ns. However, they had different filling schemes.

In addition to the lower pileup conditions, there are several notable differences in the low μ data taking compared to the standard high μ data taking:

- The reconstruction uses lower topo-cluster thresholds to optimise the response of topo-clusters for the hadronic recoil, which also affects the electron response.
- Single e and μ triggers are employed with significantly lower thresholds and looser identification criteria, and these triggers are run without prescale. Two examples of such triggers are HLT_e15_lhloose_nod0_L1EM12 and HLT_mu14.

For a more detailed description of the low- μ data conditions, please refer to [153].

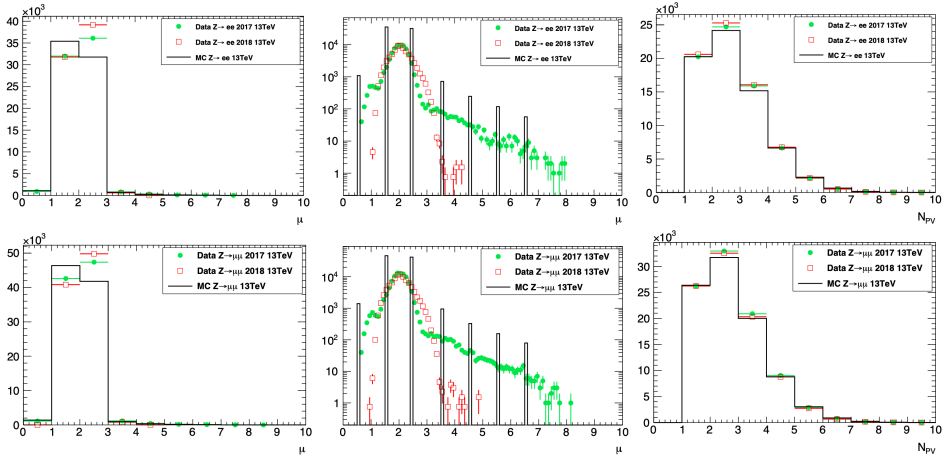


Figure 6.1: Comparison plots show distributions from the 13 TeV low μ datasets in 2017 and 2018, for the $Z/\gamma \rightarrow ee$ (top row) and $Z/\gamma \rightarrow \mu\mu$ (bottom row) selections. Data points are compared to the corresponding signals MC. Distributions are roughly normalised to the same number of events in the 2017 dataset. The left and middle plots show the actual μ (for a particular event) in a coarsely-binned and a finely-binned version. The right plot shows the number of reconstructed primary vertices N_{PV} . Results are from [153].

Process	Data set	Generator	$\sigma \cdot \text{BR} \cdot \varepsilon_{\text{filter}}$ [nb] (th. unc.)	$N_{\text{evt}}^{\text{skim}} [10^6]$	$N_{\text{evt}}^{\text{unskim}} [10^6]$
$W^+ \rightarrow e^+ \nu$	361100	POWHEG+PYTHIA8	11.61 (5%)	40	40
$W^+ \rightarrow \mu^+ \nu$	361101	POWHEG+PYTHIA8	11.61 (5%)	40	40
$W^+ \rightarrow \tau^+ \nu$	361102	POWHEG+PYTHIA8	11.61 (5%)	0.28	5.0
$W^- \rightarrow e^- \bar{\nu}$	361103	POWHEG+PYTHIA8	8.630 (5%)	30	30
$W^- \rightarrow \mu^- \bar{\nu}$	361104	POWHEG+PYTHIA8	8.630 (5%)	29	29
$W^- \rightarrow \tau^- \bar{\nu}$	361105	POWHEG+PYTHIA8	8.630 (5%)	0.24	4.0
$Z \rightarrow ee$	361106	POWHEG+PYTHIA8	1.910×1.025 (5%)	10	10
$Z \rightarrow \mu\mu$	361107	POWHEG+PYTHIA8	1.910×1.025 (5%)	10	10
$Z \rightarrow \tau\tau$	361108	POWHEG+PYTHIA8	1.910×1.025 (5%)	0.12	1.0
$ZZ(q\bar{q}\ell\ell)$	363356	SHERPA 2.2.1	0.01556×0.141 (10%)	0.0064	0.010
$WZ(q\bar{q}\ell\ell)$	363358	SHERPA 2.2.1	0.003433 (10%)	0.0063	0.010
$WW(q\bar{q}\ell\nu)$	363359	SHERPA 2.2.1	0.02472 (10%)	0.0093	0.020
$WW(\ell\nu q\bar{q})$	363360	SHERPA 2.2.1	0.02472 (10%)	0.0093	0.020
$WZ(\ell\nu q\bar{q})$	363489	SHERPA 2.2.1	0.01142 (10%)	0.0047	0.010
$ZZ(4\ell)$	364250	SHERPA 2.2.2	0.001252 (10%)	0.0057	0.010
$WZ(3\ell\nu)$	364253	SHERPA 2.2.2	0.004583 (10%)	0.0062	0.010
$WW(2\ell 2\nu)$	364254	SHERPA 2.2.2	0.01250 (10%)	0.0073	0.010
$WZ(\ell 3\nu)$	364255	SHERPA 2.2.2	0.003235 (10%)	0.0050	0.010
Wt	410013	POWHEG+PYTHIA8	0.03582 (10%)	0.0037	0.010
$W\bar{t}$	410014	POWHEG+PYTHIA8	0.03399 (10%)	0.0037	0.010
$t\bar{t}$ (nominal)	410470	POWHEG+PYTHIA8	0.8318×0.544 (7%)	1.2	2.0
$t(t - \text{chan. } t)$	410642	POWHEG+PYTHIA8	0.03699 (10%)	0.016	0.030
$t(t - \text{chan. } \bar{t})$	410643	POWHEG+PYTHIA8	0.02217 (10%)	0.011	0.020
$t(s - \text{chan. } t)$	410644	POWHEG+PYTHIA8	0.002027 (10%)	0.0050	0.010
$t(s - \text{chan. } \bar{t})$	410645	POWHEG+PYTHIA8	0.001268 (10%)	0.0052	0.010
$t\bar{t}$ (syst.)	410480	POWHEG+HERWIG 7	0.8318×0.438 (7%)	0.85	1.5
$t\bar{t}$ (syst.)	410482	POWHEG+HERWIG 7	0.8318×0.105 (7%)	0.40	0.50
$t\bar{t}$ (syst.)	410557	POWHEG+HERWIG 7	0.8318×0.438 (7%)	0.85	1.5
$t\bar{t}$ (syst.)	410558	POWHEG+HERWIG 7	0.8318×0.105 (7%)	0.40	0.50

Table 6.1: Monte Carlo samples at $\sqrt{s} = 13\text{TeV}$. Given is a short description of the process, the [ATLAS MC](#) data set number (**DSID**), the names and version numbers of the **MC** generator(s), the used value of the higher order cross section times any branching and filter efficiencies ($\sigma \cdot \text{BR} \cdot \varepsilon_{\text{filter}}$) with the theoretical uncertainty in percent (“th. unc.”), and finally the number of events analysed after skimming at derivation production ($N_{\text{evt}}^{\text{skim}}$) as well as the number of events originally processed and simulated ($N_{\text{evt}}^{\text{unskim}}$). In the case of $Z \rightarrow \ell\ell$ samples, the given $\varepsilon_{\text{filter}} > 1$ is related to the fact, that the cross sections were calculated for $66 < m_{\ell\ell} < 116\text{GeV}$, but the generated mass range is larger. The last section of $t\bar{t}$ samples refers to variation samples for systematics studies. The **MC** equivalent luminosity $N_{\text{evt}}^{\text{unskim}} / (\sigma \cdot \text{BR} \cdot \varepsilon_{\text{filter}})$ is generally above 3 pb^{-1} for signal and significant backgrounds, the exception are POWHEG $W \rightarrow \tau\nu$ and $Z \rightarrow \tau\tau$ samples, that have about 0.45 pb^{-1} only. For more details please see [153].

6.2 Monte Carlo simulated samples

The analysis utilises fully simulated and reconstructed Monte Carlo samples to model both the signal and background processes. The GEANT4-based simulation [154] provides a comprehensive representation of the ATLAS detector. Specifically, the analysis uses fully simulated and reconstructed ATLAS Monte Carlo samples (referred to as MC) obtained from the MC16 production campaigns. These MC samples are tailored to the special data run conditions, incorporating adjustments for pileup overlay, topo-cluster noise thresholds, and trigger menu settings. As the pileup distribution is already adapted to the dataset, no further pileup reweighting is performed.

Table 6.1 presents a summary of the MC samples utilised in this analysis for signal templates and EW+top background modelling. The cross-sections provided in the table are used to normalise the predicted event counts for each sample, and the corresponding uncertainties are also listed.

The primary signal event samples for W production are generated using the POWHEG event generator [155]–[158] with CT10 [159] PDF, interfaced to PYTHIA8 [160] with the AZNLO tune [161]. To simulate the effect of final state QED radiation, these POWHEG+PYTHIA8 samples are further interfaced to Photos++ [162].

The effect of multiple interactions per bunch crossing (pileup) is accounted for by overlaying simulated minimum bias events on top of the original hard-scattering event. The minimum bias events were generated using PYTHIA8 with the NNPDF2.3LO set of PDFs [163] and the A3 tune [164]. This A3 tune improves on the previous A2 tune [165] by incorporating some Run2 results at $\sqrt{s} = 13\text{TeV}$ and the Donnachie–Landshoff diffractive model, which provides a better description of the “visible” inelastic cross section compared to the default Schuler–Sjöstrand model.

For W and Z processes, the samples are normalized to NNLO+NNLL calculations performed using the DYTURBO program, which is an optimised version of DYNNLO [166], [167] using the MMHT2014nnlo PDF set [168]. The numerical values are extracted from the corresponding ATLAS ongoing analysis of low-pileup data at 13 TeV [169]. The uncertainties on these cross-sections arise from the choice of PDF set and PDF set internal uncertainties (approximately 3-4%), factorisation and renormalisation scale dependence (less than 1%), and the strong coupling constant α_s (around 1-2%). A conservative total uncertainty of 5% is considered for any event count predictions normalised using these cross-sections, for instance, for the subtraction of electroweak backgrounds. Further p_T^W -reweighting

Backgrounds from top-quark pair-production ($t\bar{t}$) as well as single-top production (Wt , t -channel, s -channel) are generated using POWHEG+PYTHIA8. For $\sqrt{s} = 13\text{TeV}$, samples were produced to derive systematics on the $t\bar{t}$ background. Various combinations of dibosons (VV , where $V = W, Z$) are generated with SHERPA in all decay channels with at least one real lepton in the final state. For more details, refer to Table 6.1.

6.3 Event selection

In this analysis, electrons and muons are classified as leptons. Electrons are reconstructed using energy clusters in the calorimeter that are associated with a track, while muons are

reconstructed based on tracks that traverse both the inner detector and the muon chambers. Detailed procedures can be found in Chapter 5.

The object selection for this analysis follows the selection used for p_T^W and W mass analysis [169]. However, to increase sensitivity to the angular coefficients additional studies were conducted. This studies are discussed later in this section.

The selection criteria for $W \rightarrow \ell \nu$ candidate events are as follows:

- Single electron (HLT_e15_lhloose_nod0_L1EM12) and muon (HLT_mu14) triggers were used for the electron and muon channels, with trigger matching requirement applied.
- Exactly one lepton in the event.
- Both electrons and muons are required to have $p_T > 25$ GeV.
- Electrons should have $|\eta| < 2.47$, and candidates in the crack region $1.37 < |\eta| < 1.52$ are excluded. Muons candidates are required to be within $|\eta| < 2.4$.
- The electron candidates must satisfy the **TightLH** identification criteria, and the muon candidates must satisfy the **MediumLH** identification criteria.
- All leptons are required to be isolated. Leptons are considered isolated if they satisfy both isolation criteria: $p_T^{\text{varcone20}}/p_T < 0.1$ and $E_T^{\text{cone20}}/p_T < 0.05$.
- Leptons are required to originate from the primary vertex. The longitudinal impact parameter of each lepton track is required to be less than 0.5 mm ($\Delta z_0 \times \sin \theta < 0.5$ mm). Additionally, the significance of the transverse impact parameter divided by its estimated uncertainty is required to be $|\frac{d_0}{\sigma(d_0)}| < 5$ for electrons and $|\frac{d_0}{\sigma(d_0)}| < 3$ for muons.
- To enhance the analysis sensitivity in the signal region, no cuts on E_T^{miss} and m_T were applied.

These criteria ensure that only relevant events with desired characteristics are included in the analysis. The selections are carefully chosen to maximise sensitivity to the W boson process while minimising background contributions from various sources. Table 6.2 provides an overview of all the selection criteria applied to objects and W boson events, defining the inclusive signal region.

Dedicated lepton calibrations and efficiency corrections, specifically tailored for the low- μ conditions, are applied to both data and MC. Detailed descriptions of these corrections for electrons and muons can be found in References [144] and [149], respectively.

The electron reconstruction scale factors (SFs) are derived by extrapolating the standard high-pileup SFs to the low- μ regime and are applied to both the 13 TeV datasets. The identification SFs are measured in-situ separately for the 13 TeV data. Isolation and trigger efficiencies and SFs are also measured in-situ separately for the 13 TeV datasets.

For the electron energy calibration, the global strategy follows the methodology used in the high- μ standard calibration, as described in Ref. [143]. Electron energy scale and

Preselection		
GRL	Pass Good Run List	
Vertex	Primary Vertex Number ζ 1	
Object selection		
Channel	$e^\pm$	$\mu^\pm$
Trigger	HLT_e15_lhloose_nod0_L1EM12	HLT_mu14
p_T^ℓ	> 25 GeV	
η^ℓ	$ \eta < 1.37$ or $1.52 < \eta < 2.47$	$ \eta < 2.4$
Identification	Tight LH	Medium LH
Isolation	$p_T^{varcone20}/p_T < 0.1$ & $E_T^{cone20}/p_T < 0.05$	
Vertex z_0	$\Delta z_0 \times \sin \theta < 0.5$ mm	
Vertex d_0	$ d_0/\sigma(d_0) < 5$	$ d_0/\sigma(d_0) < 3$
Event selection		
N_{leptons}	Exactly 1 lepton	
m_T, E_T^{miss}	No cuts on E_T^{miss} and m_T	

Table 6.2: Overview of the W boson event selection at the detector level used in low-pileup measurements.

resolution corrections are determined in-situ using $Z \rightarrow ee$ events from the low-pileup dataset.

Muon reconstruction and *track-to-vertex association* efficiencies, measured in-situ with $Z \rightarrow \mu\mu$ events, are found to be compatible with the corresponding high- μ measurements and have been determined with precision at the permille level. Similarly, the muon trigger and isolation efficiencies are measured in-situ in the low- μ data, for each dataset, with a precision typically better than $< 1\%$, limited by the size of the $Z \rightarrow \mu\mu$ data samples. The muon calibration, derived from the high- μ data, has been cross-checked using both $Z \rightarrow \mu\mu$ and $J/\psi \rightarrow \mu^+\mu^-$ events in the low- μ datasets and has been found to be sufficient at the current level of systematics. Additionally, a dedicated correction for charge-dependent momentum biases, referred to as sagitta correction, has been derived using a combination of different methods based on the 13 TeV low- μ dataset.

Additional efficiency corrections were calculated specifically for this analysis as discussed in Section 6.3.2 for the TightLH identification criteria applied to the electrons candidates and the additional isolation requirement ($E_T^{cone20}/p_T < 0.05$) for both electrons and muons.

6.3.1 Sensitivity studies

Given the limited luminosity recorded by ATLAS under low-pileup conditions during the Run 2 data acquisition (338.1 pb^{-1} at 13 TeV), a suite of sensitivity studies were conducted to enhance the analysis sensitivity and maximise the statistical significance of the measurement.

The primary kinematic variables examined were p_T^ℓ , E_T^{miss} , and m_T , with intervals spanning from 20 to 25 GeV for p_T^ℓ , 0 to 50 GeV for m_T , and 0 to 25 GeV for E_T^{miss} . The predominant background in this analysis emanates from MJ, and the modulation of kinematic cuts serves as an effective means to diminish its contribution, particularly given its concentration at lower E_T^{miss} and m_T values. By reducing both of these cuts to 0, the

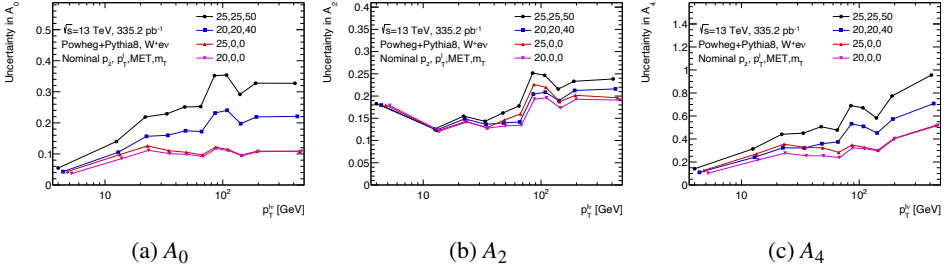


Figure 6.2: The graphs compares the total statistical uncertainty for the coefficients A_0 , A_2 , A_4 , with different selection criteria in $p_T^{\ell\nu}$ binning for $W^+ \rightarrow e^+ \nu$. The legend indicates the various selection criteria in GeV for p_T^ℓ , E_T^{miss} , and m_T , respectively. For example, the black line corresponds to the case when $p_T^\ell > 25\text{ GeV}$, $E_T^{\text{miss}} > 25\text{ GeV}$, and $m_T > 50\text{ GeV}$.

statistical sensitivity is significantly augmented, especially at higher $p_T^{\ell\nu}$, where the analysis is constrained. Since the **MJ** background is chiefly concentrated at lower $p_T^{\ell\nu}$, the statistical gain from the relaxed cuts remains unaffected (see Figure 6.2). However, the study discerned that there was not a significant enough enhancement in statistical sensitivity by including events with $20 \leq p_T^\ell \leq 25\text{ GeV}$ to justify the increase in **MJ** background.

Relaxing kinematic cuts makes a larger contribution of the **MJ** background possible, which can be mitigated by implementing stricter identification and/or isolation requirements. In the electron channel, where the **MJ** background is more dominant, a tighter identification requirement is employed, while both electron and muon channels utilise the isolation requirement. The inclusion of these identification and isolation cuts does not significantly compromise the statistical sensitivity. Consequently, a net gain in statistical significance is attained through the combination of relaxed kinematic cuts (as outlined in Section 6.3) and the additional identification and isolation requirements.

As expounded in Section 5.6, the mass constraint can lead to an imaginary solution when $\Delta < 0$, which occurs when $m_T > m^W$. In such instances, events cannot be fully reconstructed. However, the value of ϕ_{CS} can still be calculated normally for these events. To leverage this information, the templates were expanded to include an additional 8×8 phase space, ensuring that the ϕ_{CS} shape information is retained without interfering with the real solutions. However, the choice of what to use for the $\cos \theta_{\text{CS}}$ value had to be determined, and four approaches were tested:

- **Nominal:** The nominal approach abstains from assigning any $\cos \theta_{\text{CS}}$ information to these events. They are stored within the same bin, and only the ϕ_{CS} information is utilised. In this case, $\cos \theta_{\text{CS}}$ is set to 0, and no solution for p_z^y is sought when $\Delta < 0$. A disadvantage of this approach is that no effort is made to determine the sign of $\cos \theta_{\text{CS}}$, so the W is always presumed to be traveling perpendicular to the negatively charged lepton (or neutrino in the W^+ case) in the **CS** frame. The subsequent methods listed below intended to recover some of this $\cos \theta_{\text{CS}}$ information.
- **VH style:** The second method, designated as VH style, drew inspiration from a VH measurement and involves removing the imaginary part of the solution to $p_z^y =$

$-b/2a$ [170]. This method permitted some solutions to have a negatively signed $\cos \theta_{\text{CS}}$ value, but overall, it only heightened the sensitivity to A_1 compared to the other methods.

- **Shifted m_T** : The Shifted m_T method tested leverages the fact that a solution is unattainable when $m_T > m^W$. For the events that do not obtain an initial solution using the PDG m^W , the solution is recalculated using $m_T + 100$ MeV for the mass constraint. The 100 MeV shift ensures that $\Delta \neq 0$ for all events, similar to the VH style, and this applied shift is well within the resolution of m_T . One downside to this method is that, even with this shift, there are still events with $\Delta < 0$ depending on the rest of the parameters used in the calculation.
- **Rotation p_z^V** : The final method derives its name from rotating the E_T^{miss} by the minimum amount needed for a solution. This rotation alters the values of the neutrino p_T and ϕ , resulting in a different ϕ_{CS} value for these events. It was observed to provide the best overall increment in sensitivity, displaying a noticeable difference for low $p_T^{\ell V}$ bins for A_0, A_2, A_3, A_5 , and A_7 , along with a slight increase in sensitivity over the nominal method.

6.3.2 Identification and isolation scale factors

The decision to relax the kinematic selection requirements by not including both for E_T^{miss} and m_T was made to increase the signal acceptance at high p_T^W . However, this also allowed for more background from MJ events, which required additional selection requirements to be introduced. Specifically, a TightLH identification requirement was introduced into the electron channels, and a calorimeter isolation requirement of $E_T^{\text{cone20}}/p_T^\ell < 0.05$ was applied to all channels.

To ensure consistency between data and MC samples, SFs were derived for these additional selection requirements. These SFs account for the differences in efficiencies between data and MC simulations. This section provides details on the process of deriving these scale factors.

To produce these SFs, events are pre-selected to have leptons that already pass all the other selection requirements used in the analysis. These SFs are then applied in addition to the SFs already used for identification, isolation, and calibration. During the selection process, events are weighted with the existing SFs. The tag and probe method is then employed using Z kinematic selection, and events are categorised into two groups:

- Leading lepton as tag, subleading lepton as probe
- Subleading lepton as tag, leading lepton as probe

These categories are combined into one sample before calculating the efficiency, $\varepsilon = N_{\text{probes}}^{\text{passed}}/N_{\text{probes}}$, for both data and MC using Bayesian statistics. The SF is then calculated by taking the ratio of the data efficiency over the MC efficiency. This process is carried out as a function of p_T^ℓ and η^ℓ for various quantities, such as electron TightLH identification, electron calorimeter isolation, and muon isolation, as shown in Figures 6.3.

To estimate the systematic uncertainty, the tag and probe categories were processed separately to produce scale factors. Subsequently, a weighted average is calculated between these separate scale factors. The systematic uncertainty is then determined as the difference between the **SF** obtained from combining the samples and the weighted average between them. This uncertainty is illustrated as errors in Figure 6.3.

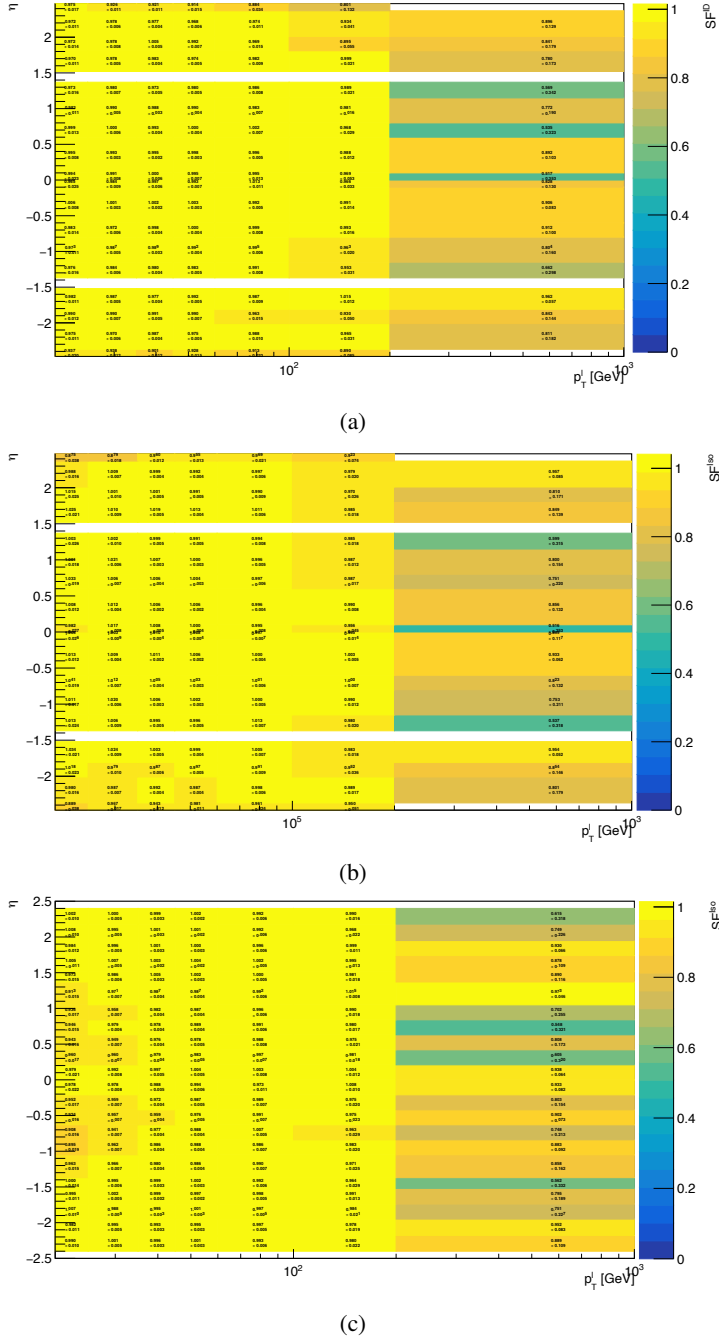


Figure 6.3: Scale Factors (SF) for selection criteria: (a) SF for TightLH ID for electrons versus p_T^e and η^e ; (b) SF for calorimetric isolation $E_T^{cone20}/p_T^e < 0.05$ for electrons versus p_T^e and η^e ; (c) SF for muon isolation versus p_T^μ and η^μ .

6.4 Electroweak and top backgrounds

Previous W boson experiments and analyses have extensively investigated and understood the sources of backgrounds. The backgrounds that contaminate the W events with leptonic decay can be classified into two categories: electroweak processes (single and di-boson processes) and top-quark backgrounds, which are derived from the corresponding [MC](#) simulated samples. Additionally, the multijet ([MJ](#)) background is estimated using a data-driven method.

The electroweak ([EW](#)) backgrounds consist of single boson productions, including $W^\pm \rightarrow \tau^\pm \nu$ and $Z \rightarrow ee, \mu\mu, \tau\tau$, as well as di-boson productions like WW , WZ , and ZZ . Specifically, the Z boson background arises from events where one good lepton is detected, and another lepton fails the selection requirement, resulting in the reconstruction of missing energy. This background can be mitigated by relaxing the lepton selection criteria and utilising forward muons when reconstructing the hadronic recoil.

Events involving top quarks can have similar signatures to W events, particularly in the decay process $t \rightarrow Wb$. However, the contribution of top-quark backgrounds to the analysis is relatively small due to their low production cross-section.

Table 6.3 displays the event yields for the $W^\pm \rightarrow \ell^\pm \nu$ signal selection in the 13 TeV dataset. Among the [EW](#) backgrounds, the most significant contributions come from the decay of Z bosons and $W \rightarrow \tau \nu$.

Channel	$W \rightarrow e^- \nu$	$W \rightarrow e^+ \nu$	$W \rightarrow \mu^- \nu$	$W \rightarrow \mu^+ \nu$
Wenu	855521.75 ± 264.71 (stat)	1102521.18 ± 301.22 (stat)	3.17 ± 0.52 (stat)	4.51 ± 0.63 (stat)
Wmunu	66.76 ± 2.56 (stat)	74.80 ± 2.88 (stat)	941053.04 ± 277.65 (stat)	1238279.66 ± 315.78 (stat)
Wtaunu	26380.62 ± 146.61 (stat)	31644.84 ± 167.00 (stat)	24924.76 ± 140.57 (stat)	30790.71 ± 163.09 (stat)
Zee	82901.64 ± 66.54 (stat)	86974.52 ± 67.97 (stat)	0.67 ± 0.22 (stat)	0.36 ± 0.19 (stat)
Zmumu	26.96 ± 1.69 (stat)	23.16 ± 1.30 (stat)	68548.85 ± 58.83 (stat)	73407.01 ± 60.76 (stat)
Ztautau	6936.33 ± 77.79 (stat)	7070.46 ± 78.26 (stat)	7472.29 ± 85.76 (stat)	7553.81 ± 86.22 (stat)
Top	16581.90 ± 55.33 (stat)	17278.30 ± 57.85 (stat)	16048.35 ± 53.79 (stat)	16765.29 ± 57.34 (stat)
Diboson	2170.16 ± 48.59 (stat)	2187.45 ± 51.63 (stat)	2170.41 ± 48.91 (stat)	2289.27 ± 51.46 (stat)
Data	1259751.00 ± 1122.39 (stat)	1531246.00 ± 1237.44 (stat)	1206859.00 ± 1098.57 (stat)	1533100.00 ± 1238.18 (stat)

Table 6.3: Expected number of contributions from the [MC](#) process in the inclusive signal region. Errors are statistical uncertainties evaluated as $\sqrt{N}$ for both [MC](#) and data statistics.

6.5 Multijet background in inclusive signal region

Two main categories of backgrounds affect single W boson final states: the electroweak (single and diboson) and top backgrounds, which are obtained from the appropriate MC samples. Additionally, there is the so-called multijet (MJ) background, which cannot be reliably simulated and must be derived from data. The MJ background has significant contributions from real leptons produced in semi-leptonic decays of heavy quarks, pion decays, or photon conversions, depending on the lepton flavor.

As mentioned in Section 6.1, the data sample used in this analysis has a pileup of $\mu \sim 2$, which is about 15–20 times smaller than the standard 13 TeV running conditions. The lower pileup conditions result in a reduction of the MJ background yield for several reasons:

- There is a reduced pileup contribution to the isolation distributions, leading to improved discriminating power of the isolation cuts.
- The E_T^{miss} and m_T resolution is better, resulting in improved discriminating power of the event selection cuts.
- The contribution from pileup jets themselves to the contamination of the sample is reduced.

The fake lepton background, commonly referred to as the multijet background or MJ, is more prominent at lower values of p_T^ℓ , E_T^{miss} , and m_T . By relaxing the kinematic cuts in the signal region definition, a significant amount of multijet background is introduced. The general estimation method for this background follows a similar approach as described in Reference [171]. However, certain W-Ai analysis-specific details need to be considered, which will be discussed in the following sections.

6.5.1 General procedure

The estimation of the multijet background is based on the assumption that the kinematic characteristics of multijet events remain consistent, regardless of lepton isolation. By relaxing or inverting the lepton isolation selection, a control region (CR) is formed, enriching the signal phase space with multijet backgrounds. In this CR, the kinematic spectra of multijet events are derived, and it is expected that these spectra will have a similar profile to those in the signal region, assuming the stability of multijet kinematics.

The procedure aims to estimate the multijet background yield and shape in the signal region (SR) using a data-driven method. This estimation relies on fitting the data distributions of p_T^ℓ , E_T^{miss} , m_T , and $|\Delta\phi(\ell, E_T^{\text{miss}})|$ with signal and MJ templates. The signal, electroweak (EW), and top backgrounds are obtained from simulation, which includes calibration corrections. On the other hand, the MJ background templates are obtained from the data in a separate control region (CR1) where the same kinematic selections are applied, but the isolation cuts are inverted.

The choice of lepton isolation definition to define the SR and CR1 for the electron and muon channels is illustrated in Figure 6.4 and is explained in Section 6.5.5. The data-driven method allows for a more accurate estimation of the MJ background, accounting for specific data characteristics and reducing the dependence on simulation.

The event categories used for extracting the MJ background follow the naming convention described in Ref. [172] and are defined as follows:

- Fit Region (FR): This corresponds to the analysis signal region (SR), and includes events with one isolated lepton ($p_T^{\text{varcone20}}/p_T < 0.1$ and $E_T^{\text{cone20}}/p_T < 0.05$). All distributions include overflow bins.
- Control Region 1 (CR1): This is a multijet enriched control region where the lepton is required to be anti-isolated ($E_T^{\text{cone20}}/p_T < 0.05$ and $p_T^{\text{varcone20}}/p_T > 0.1$ for muons or $p_T^{\text{varcone20}}/p_T < 0.1$ and $E_T^{\text{cone20}}/p_T > 0.05$ for electrons). All distributions include overflow bins.

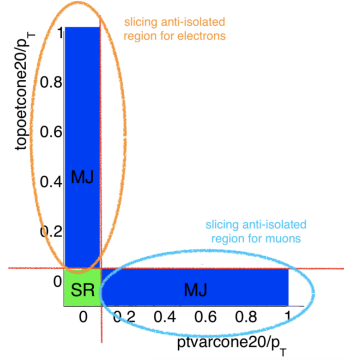


Figure 6.4: Sketch of the definition of the signal region (SR) and control region 1 (CR1) for the multijet background estimation.

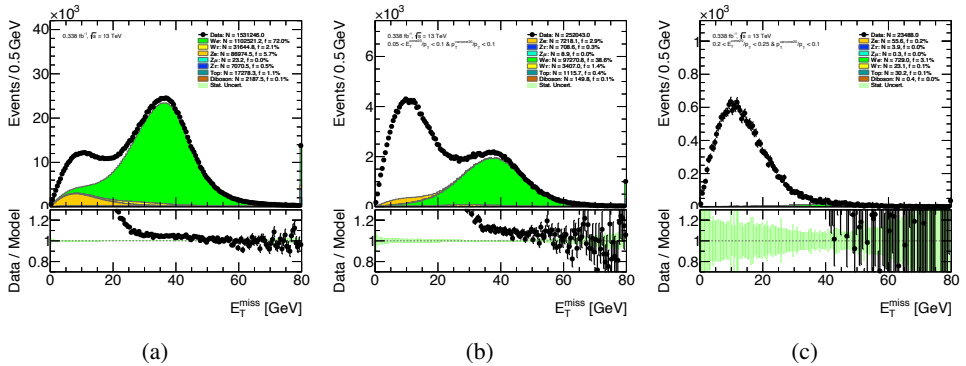


Figure 6.5: The E_T^{miss} distribution for $W^+ \rightarrow e^+ \nu$ candidates in the fit region (a) and in control region 1 (CR1) for the first anti-isolated slice $0.05 < E_T^{\text{cone20}}/p_T < 0.1$ (b) and anti-isolated slice $0.2 < E_T^{\text{cone20}}/p_T < 0.25$ (c). The discrepancy between data and simulation in the fit region is attributed to the missing multijet contribution.

As example, in Figure 6.5a, the E_T^{miss} distribution for data in the fit region (FR) is compared with the expected contributions from signal and electroweak and top backgrounds obtained from MC simulations. The discrepancy between data and the MC simulation in the fit region is attributed to the multijet background contribution. The control region 1 (CR1) is designed to be enriched with non-isolated objects, which are characteristic of multijet production. It is used to determine the multijet template distribution that is applied in the fit region (FR) for multijet background estimation. Details of the correction applied to the recoil reconstruction in CR1 can be found in Section 6.5.4, which is also described in Ref. [172]. In this analysis, CR1 is constructed by scanning only one isolation requirement at a time. For $\mu^\pm$ channels, only track-based isolation is relaxed and sliced, while for $e^\pm$ channels, only calo-based isolation is relaxed and sliced, as displayed in Figure 6.4.

The MJ template used in the fit region (FR) is extracted from control region 1 (CR1) while subtracting the contribution of signal, electroweak, and top processes as simulated by MC. Figure 6.5b shows the E_T^{miss} distribution for data and MC in CR1, where the lepton is required to have $0.05 < E_T^{cone20}/p_T < 0.1$. Figure 6.5c shows the E_T^{miss} distribution for data and MC in CR1, defined with a lepton having $0.2 < E_T^{cone20}/p_T < 0.25$. In Figure 6.5b, the fraction of electroweak and top-related process contributions is 44.6%, and this fraction is drastically reduced in Figure 6.5c. However, in this slice, the data statistics are much lower.

To investigate the variation of the multijet templates with different anti-isolation criteria used to define CR1, the CR1 is divided into successive intervals (slices) of the isolation variable, instead of having a single, integrated anti-isolated region. The isolation slices used to define $CR1(i)$ to extract the MJ templates are defined as the following intervals of lepton isolation :

- For $W \rightarrow \mu\nu$ channels $p_T^{varcone20}/p_T$ in $[0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.45, 0.5]$ and $E_T^{cone20}/p_T < 0.05$
- For $W \rightarrow e\nu$ channels E_T^{cone20}/p_T in $[0.05, 0.1, 0.15, 0.2, 0.25, 0.3, 0.35, 0.4, 0.45]$ and $p_T^{varcone20}/p_T < 0.1$

The extraction of the number of multijet background events in the FR is carried out by following these steps for each isolation slice $CR1(i)$:

- The multijet background template in each anti-isolation slice (also called bin), denoted as $N_{MJ}^{CR1(i)}$, is obtained through the following procedure:

$$N_{MJ}^{CR1(i)} = N_{data}^{CR1(i)} - N_{EW}^{CR1(i)} \quad (6.1)$$

where the template $N_{MJ}^{CR1(i)}$ is derived for each of the kinematic distributions used in the fit, including p_T^ℓ , E_T^{miss} , m_T , and $|\Delta\phi(\ell, E_T^{miss})|$.

- The fraction fit is performed for the distributions of p_T^ℓ , E_T^{miss} , m_T , and $|\Delta\phi(\ell, E_T^{miss})|$ in the FR, using each multijet template $N_{MJ}^{CR1(i)}$ obtained from different anti-isolation slices in $CR1(i)$. An example of this procedure is shown in Figure 6.6, which displays the E_T^{miss} distribution in the FR after fitting the multijet templates from different anti-isolation slices in $CR1(i)$. It's written as:

$$N_{data}^{FR} = \alpha \cdot N_{MC}^{FR} + T(i) \cdot N_{MJ}^{CR1(i)}. \quad (6.2)$$

The fitting parameter $T(i)$ provides the estimated number of multijet events in the signal region (SR), which can be approximated as $N_{MJ}^{SR} \approx T(i) \cdot N_{MJ}^{CR1(i)}$. In this analysis, an overall normalisation factor, α , is applied to the signal and electroweak + top contributions (N_{MC}^{FR}) during the fit. The value of α is limited to be around 1 in the fit, considering the uncertainty in the MC cross-section.

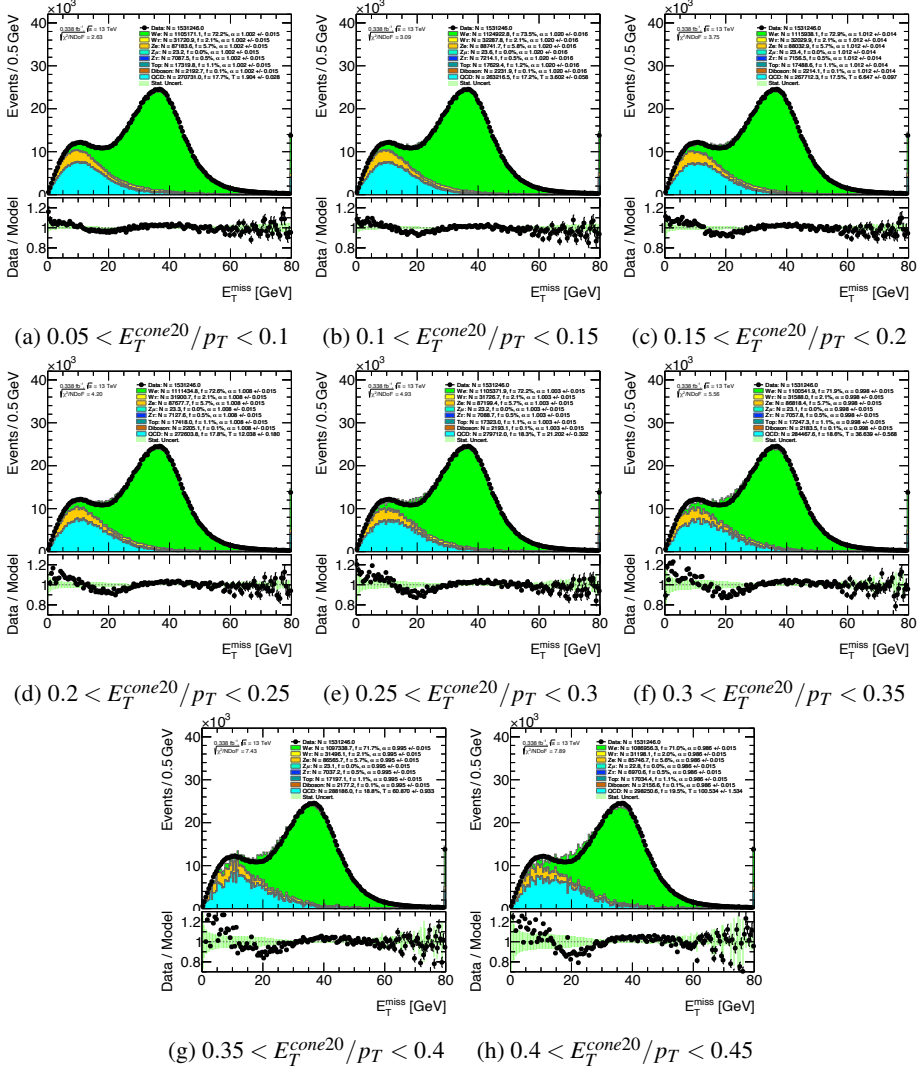


Figure 6.6: The multijet template distributions used in the fraction fit for the $W^+ \rightarrow e^+ \nu$ channel are shown in the plots. The MJ distributions are derived in the control region CR1 and fitted to the data in the fit region FR, indicated by the light-blue color. The plots show 8 control region slices with different E_T^{cone20}/p_T cuts, ranging from 0.05 to 0.45.

In Equation 6.2, the multijet distributions in the fitting region are approximated by their anti-isolated counterparts from CR1(i). However, this introduces a systematic effect in the procedure due to the residual dependence on the anti-isolation criteria used to build the template. To mitigate this dependence, the MJ yields extracted in the FR using the different anti-isolation slices are used to extrapolate the final MJ yields in the signal region at very low isolation values. The final MJ background estimation is extrapolated toward the SR for both the total yield and the template shape. Section 6.5.2 covers the final extraction of the MJ yield for the inclusive signal region, while Section 6.5.3 discusses the extrapolation of the MJ template shape for the same inclusive signal region. To predict MJ shape and yields within fine $|Y|$ and $p_T^{\ell\nu}$ bins (as used in this analysis), a more complex approach has been employed and is covered in Section 6.6.

6.5.2 Multijet yield normalisation

The total MJ yield in the analysis SR is evaluated by extrapolating the number of MJ events extracted from the fraction fit using different MJ template build from different anti-isolated bin towards the isolated regions. To achieve this, the MJ yield is first extracted in the fit region (FR) by performing the fraction fit using Equation 6.2 for each anti-isolation template $N_{MJ}^{CR1(i)}$ in different discriminating distributions (p_T , m_T , E_T^{miss} , and $|\Delta\phi(\ell, E_T^{miss})|$). The MJ yields obtained from different anti-isolation slices for all discriminating variables are shown in Figure 6.7. To account for any potential mismodeling in the templates of the considered variables, the error on each measured MJ yield is multiplied by $\sqrt{\chi^2/NDoF}$ resulting from the fraction fit.

To extrapolate the MJ yield extracted using different anti-isolation slices to the analysis signal region (SR), a linear fit is employed separately for each discriminative variable: p_T , m_T , E_T^{miss} , and $|\Delta\phi(\ell, E_T^{miss})|$. The average isolation value for the final extrapolation of the MJ background, denoted as X , is set to 0.025 based on studies from $b\bar{b}$ and $c\bar{c}$ samples [172]. The final central value of the MJ yield in the signal region is obtained as the average of the linear extrapolations at $X = 0.025$ for the four observables. Figure 6.7 displays the linear fits used for the yield extrapolation to the signal region for each channel. Ideally, all four observables should converge at $X = 0.025$.

The final yield estimation and the breakdown of uncertainties for the $W^- \rightarrow e^- \bar{\nu}$, $W^+ \rightarrow e^+ \nu$, $W^- \rightarrow \mu^- \bar{\nu}$, and $W^+ \rightarrow \mu^+ \nu$ channels are summarised in Table 6.6. For more detailed information, including all numbers and plots related to this estimation method, please refer to Ref. [3].

6.5.3 Correction of the multijet background shapes in the signal region

To address the discrepancy between the MJ templates obtained from anti-isolated control regions and the MJ shape in the isolated regions, a shape correction is applied to all MJ templates in CR1. This correction aims to bring the MJ templates closer to the true shape in the inclusive signal region. The MJ shape is defined as:

$$H_{MJ}^{[0.A,0.B]}[X] = H_{data}^{[0.A,0.B]}[X] - H_{EW+Top}^{[0.A,0.B]}[X] \quad (6.3)$$

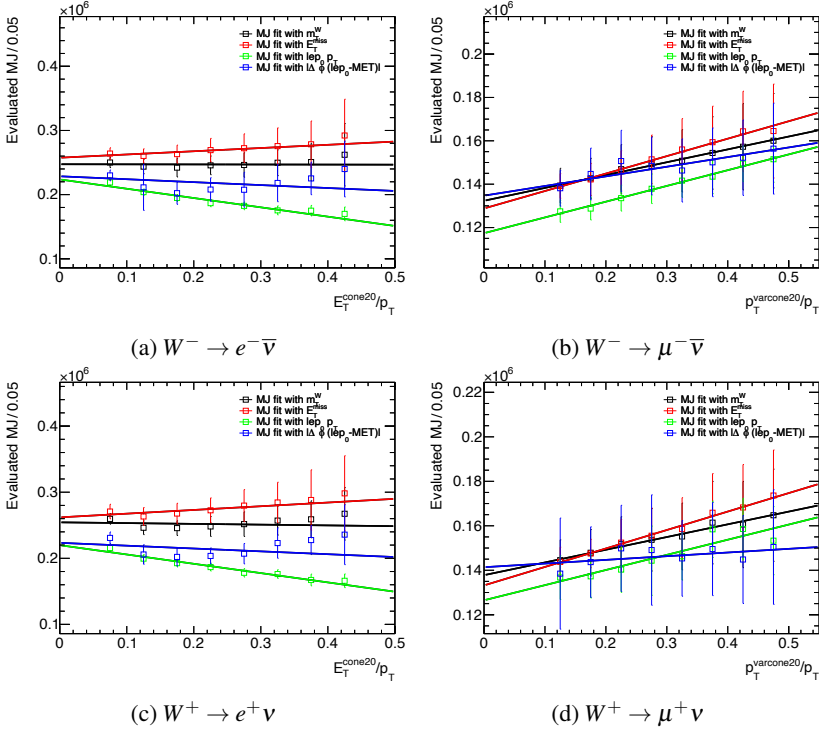


Figure 6.7: The estimated total number of the multijet background in SR scanned as a function of the isolation slice. Isolation scans in the $W^- \rightarrow e^- \bar{\nu}$, $W^- \rightarrow \mu^- \bar{\nu}$, $W^+ \rightarrow e^+ \nu$ and $W^+ \rightarrow \mu^+ \nu$ with recoil correction. Each point is plotted as the central of each isolation slice and correspond to the result of Eq. 6.2. Every set of points corresponds to the one of four multijet discriminative variables m_T , E_T^{miss} , p_T , and $|\Delta\phi(\ell, E_T^{miss})|$.

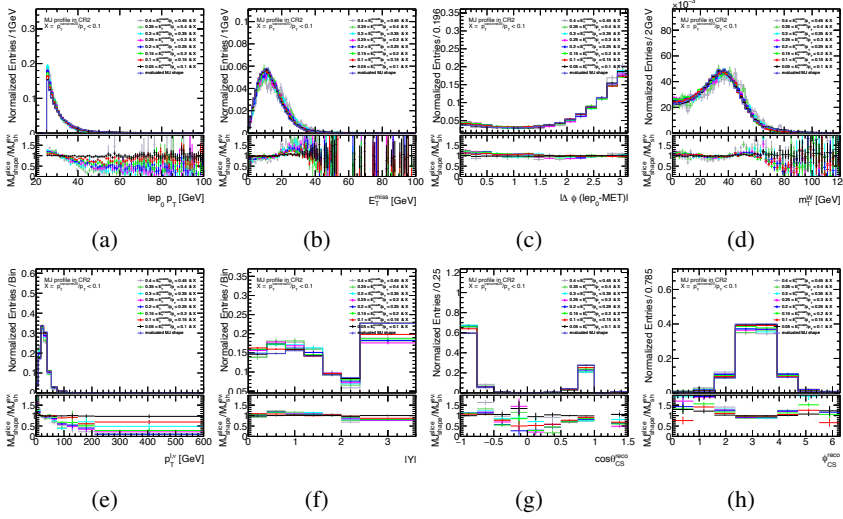


Figure 6.8: Normalised **MJ** shapes in anti-isolated slices of CR1 for the $W^- \rightarrow e^- \bar{\nu}$ channel, along with the shape corrected for the inclusive signal region.

Here, $H_{MJ}^{[0,A,0,B]}[X]$ represents the normalised distribution of each kinematic variable X in CR1 after the subtraction of the contributions from **EW** and top processes. These distributions are selected from the control region CR1, with the requirement that $A < \text{isoCone}/pT < B$, where isoCone is $p_T^{\text{varcone20}}$ for $W^- \rightarrow \mu^- \bar{\nu}$ and $W^+ \rightarrow \mu^+ \nu$, and E_T^{cone20} for $W^- \rightarrow e^- \bar{\nu}$ and $W^+ \rightarrow e^+ \nu$. The shape correction, which represents the dependence on the isolation variable (e.g., when isoCone is $p_T^{\text{varcone20}}$), is calculated as follows:

$$\Delta^{CR1}[X] = \frac{1}{4} \left\{ \frac{H_{MJ}^{0.1,0.15} - H_{MJ}^{0.3,0.35}}{4} + \frac{H_{MJ}^{0.15,0.2} - H_{MJ}^{0.35,0.4}}{4} + \frac{H_{MJ}^{0.2,0.25} - H_{MJ}^{0.4,0.45}}{4} + \frac{H_{MJ}^{0.25,0.3} - H_{MJ}^{0.45,0.5}}{4} \right\} \quad (6.4)$$

which aids in estimating the **MJ** shape in the signal region (SR):

$$H_{MJ}^{SR}[X] = H_{MJ}^{0.1,0.15}[X] + 2 \cdot \Delta^{CR1}[X] \quad (6.5)$$

The correction term $\Delta[X]$ is constructed exclusively based on the **MJ** shape in the 8 anti-isolated slices of CR1. By applying this correction, the shapes of **MJ** templates in each CR1(i) are extrapolated to a unique shape in the signal region (SR), as illustrated in Figure 6.8 to 6.11. Accordingly, the fraction fit needs to be performed only once for a given kinematic distribution, simplifying the estimation process.

The same strategy is employed when isoCone corresponds to E_T^{cone20} for the $W^- \rightarrow e^- \bar{\nu}$ and $W^+ \rightarrow e^+ \nu$ channels, but with different binning.

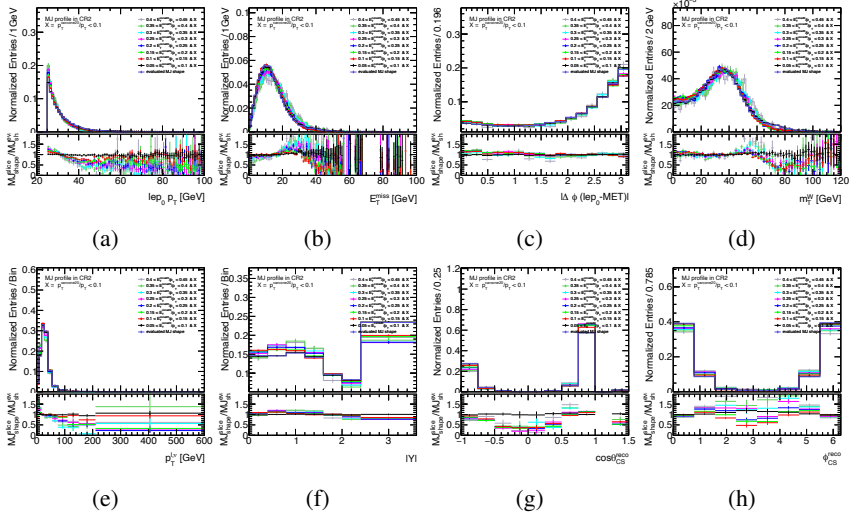


Figure 6.9: Normalised **MJ** shapes in anti-isolated slices of CR1 for the $W^+ \rightarrow e^+ \nu$ channel, along with the shape corrected for the inclusive signal region.

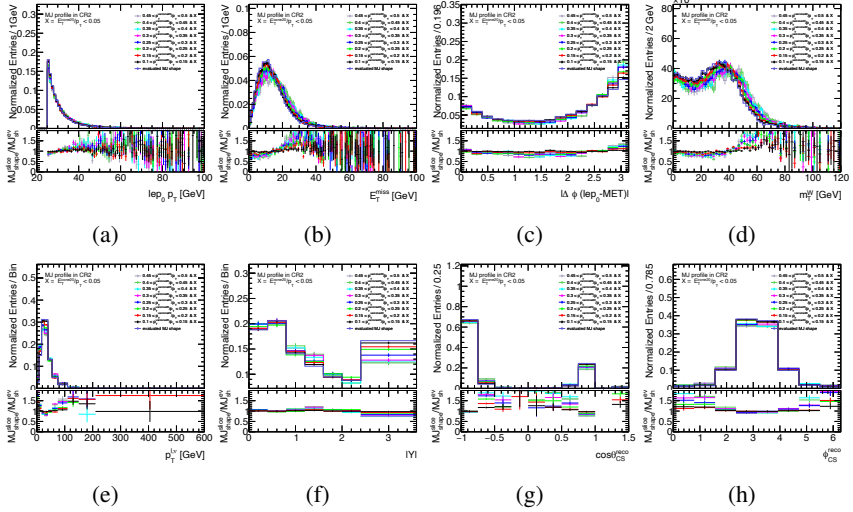


Figure 6.10: Normalised **MJ** shapes in anti-isolated slices of CR1 for the $W^- \rightarrow \mu^- \bar{\nu}$ channel, along with the shape corrected for the inclusive signal region.

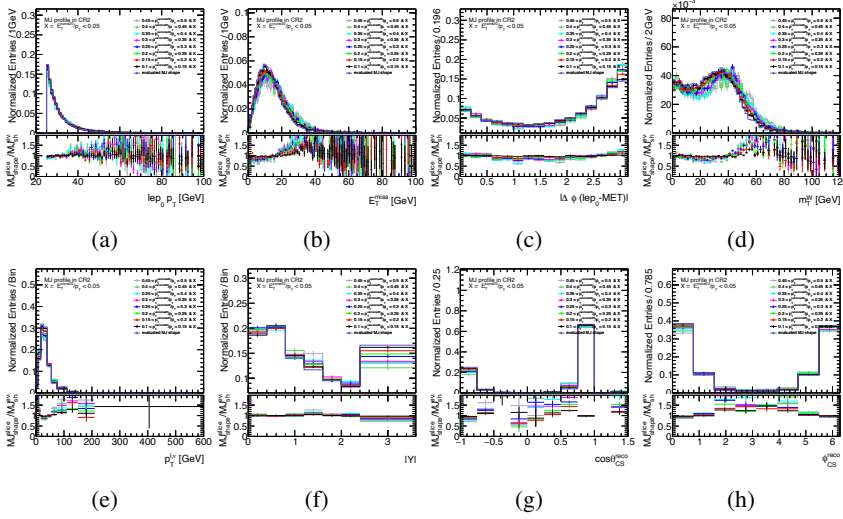


Figure 6.11: Normalised **MJ** shapes in anti-isolated slices of CR1 for the $W^+ \rightarrow \mu^+ \nu$ channel, along with the shape corrected for the inclusive signal region.

6.5.4 Hadronic recoil correction

The recoil reconstruction, as discussed in Section 5.5, involves excluding a cone of $\Delta R = 0.2$ around the selected leptons and using the remaining particles in the event to reconstruct the recoil. However, this process removes some of the underlying event and pileup energy activity. To account for this, a cone of the same size is selected in the event, centred at the same η but away in azimuth from any lepton and hard activity. The energy observed in this cone is used to construct a vector, oriented along the removed lepton and with a magnitude equal to the energy in the cone. This vector is then added to the recoil. This approach works well in the signal region, where the leptons are typically isolated and surrounded by soft activity.

In anti-isolated regions, the selected lepton is, on average, closer to a jet, making the cone replacement procedure less effective. For background events where the selected lepton has $p_T^\ell > 30$ GeV and $p_T^{cone20}/p_T > 0.1$, the total track energy around the lepton is at least $0.1 \times p_T^\ell \sim 3$ GeV. When this energy is removed in the recoil reconstruction, it is replaced by an inappropriately soft contribution, which biases the recoil, and consequently E_T^{miss} , m_T , and $|\Delta\phi(\ell, E_T^{miss})|$. This effect becomes more pronounced for higher isolation values.

The component of the recoil along the lepton momentum direction, denoted as $u_\parallel^\ell$, is the most affected by the cone replacement procedure. This projection is crucial for reconstructing the missing transverse energy, E_T^{miss} , and the transverse mass of the W boson.

As a result, the recoil reconstruction becomes less accurate for anti-isolated events, impacting the precision of the analysis in regions with higher isolation requirements. To mitigate this effect, additional corrections are applied to improve the recoil reconstruction in anti-isolated regions. These corrections aim to reduce the bias introduced by the cone replacement procedure and enhance the overall accuracy of the hadronic recoil reconstruction

in the analysis.

To address this issue, a specialised hadronic recoil reconstruction is utilised in the **MJ** background analysis. This reconstruction involves defining the **isocone20** (p_T^{cone20} or E_T^{cone20}) for each lepton, which represents the sum of transverse momenta of tracks (or calorimeter deposits) within a cone of $\Delta R = 0.2$ around the lepton. This quantity is then used to correct for the energy that was removed around the lepton during the recoil reconstruction process. The proposed correction can be expressed as follows:

$$\vec{u}^{corr} = \vec{u}^{baseline} + \vec{u}^{iso}, \quad (6.6)$$

where:

$$\vec{u}^{iso} \equiv k_{iso} \times isocone20 \cdot \vec{u}_\ell \quad (6.7)$$

Here, $\vec{u}^{baseline}$ represents the standard recoil reconstruction, $\vec{u}^{iso}$ is the present correction, and $\vec{u}_\ell$ is the unit vector aligned with the lepton direction. The parameter k_{iso} accounts for a possible difference in scale between the **isocone20** energy and the energy removed around the lepton. The correlation coefficient, k_{iso} , between **isocone20** and the energy of removed hard activities is measured with data, making the correction data-driven. Importantly, the effect of this correction is designed to be negligible as one approaches the signal region, ensuring that it does not significantly impact the signal templates used in the fraction fits.

To determine the value of k_{iso} , it is assumed that the average value of $u_{||}^\ell$ should be independent of the anti-isolation value. Therefore, after the correction, $\langle u_{||}^{corr} \rangle$ should be a constant denoted as b_{iso} :

$$\begin{aligned} \langle u_{||}^{corr} \rangle &= \langle u_{||}^{baseline} \rangle + \langle u_{||}^{iso} \rangle \equiv b_{iso} \\ \langle u_{||}^{corr} \rangle &= \langle u_{||}^{baseline} \rangle + k_{iso} \langle isocone20 \rangle \equiv b_{iso} \\ \langle u_{||}^{baseline} \rangle &= -k_{iso} \langle isocone20 \rangle + b_{iso} \end{aligned} \quad (6.8)$$

Although the assumption of independence between $\langle u_{||}^{baseline} \rangle$ and **isocone20** may not be perfectly accurate due to different properties of isolation slices in terms of jet structure, it is justified to apply a correction to account for the mismatch in the energy replacement procedure for anti-isolated leptons. The correction factor k_{iso} is determined by fitting the linear relationship between $\langle u_{||}^{baseline} \rangle$ and **isocone20**. The effect of this correction is illustrated in Figure 6.12, which show a significant reduction in the dependence of $\langle u_{||}^\ell \rangle$ on the value of **isocone20** after the correction is applied. The k_{iso} value fitted for a given channel is obtained from the opposite of the slope obtained from the linear fit between [5, 25] GeV, and the resulting values are listed in Table 6.4.

The impact of the correction is illustrated through example fraction fits for the $W^- \rightarrow e^- \bar{\nu}$ channel with the first and third anti-isolation slices shown in Figure 6.13 and Figure 6.14, respectively. The fits for m_T , E_T^{miss} , and $|\Delta\phi(\ell, E_T^{miss})|$ are visibly improved after the correction since these variables directly benefit from the improved recoil definition. The p_T^ℓ distribution is not affected by the recoil reconstruction and shows satisfactory agreement even before the correction.

Figures 6.15 demonstrate the impact of the absence of this correction on the $p_T^{varcone20}/p_T$ (for $\mu^\pm$) and E_T^{cone20}/p_T (for $e^\pm$) scans in both the electron and muon channels. The

k_{iso} parameter	$W^- \rightarrow e^- \bar{\nu}$	$W^+ \rightarrow e^+ \nu$	$W^- \rightarrow \mu^- \bar{\nu}$	$W^+ \rightarrow \mu^+ \nu$
p_T^{cone20}	0.72 ± 0.02	0.70 ± 0.02	1.51 ± 0.02	1.50 ± 0.02
E_T^{cone20}	1.38 ± 0.02	1.41 ± 0.02	1.54 ± 0.02	1.54 ± 0.02

Table 6.4: Fitted values of k_{iso} and their corresponding statistical uncertainties from the fitting procedure.

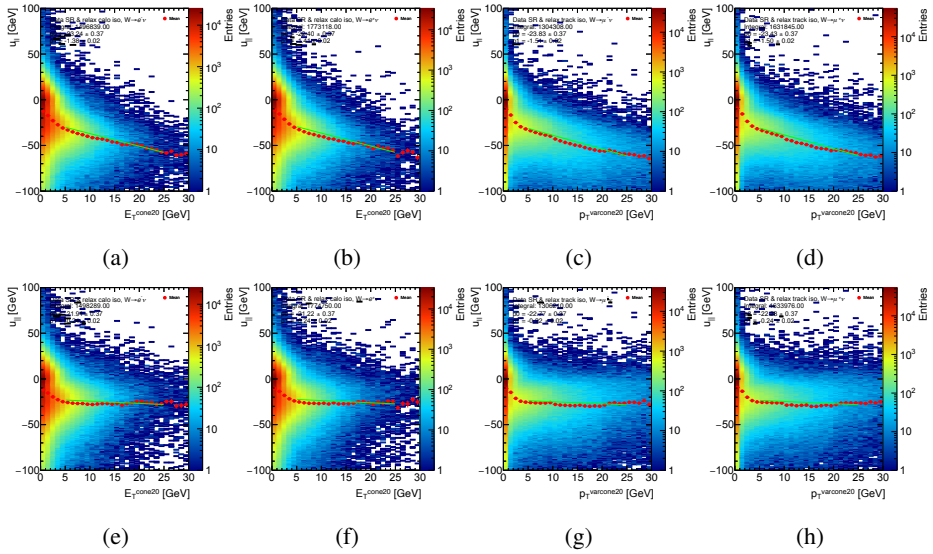


Figure 6.12: $\langle u_{\parallel}^{\ell} \rangle$ as a function of E_T^{cone20} (a, b, e, f) and as a function of $p_T^{varcone20}$ (c, d, g, h) before (top) and after (bottom) correction in the FR + CR1 for the $W^- \rightarrow e^- \bar{\nu}$ channel (a, e), the $W^+ \rightarrow e^+ \nu$ channel (b, f), the $W^- \rightarrow \mu^- \bar{\nu}$ channel (c, g), and the $W^+ \rightarrow \mu^+ \nu$ channel (d, h).

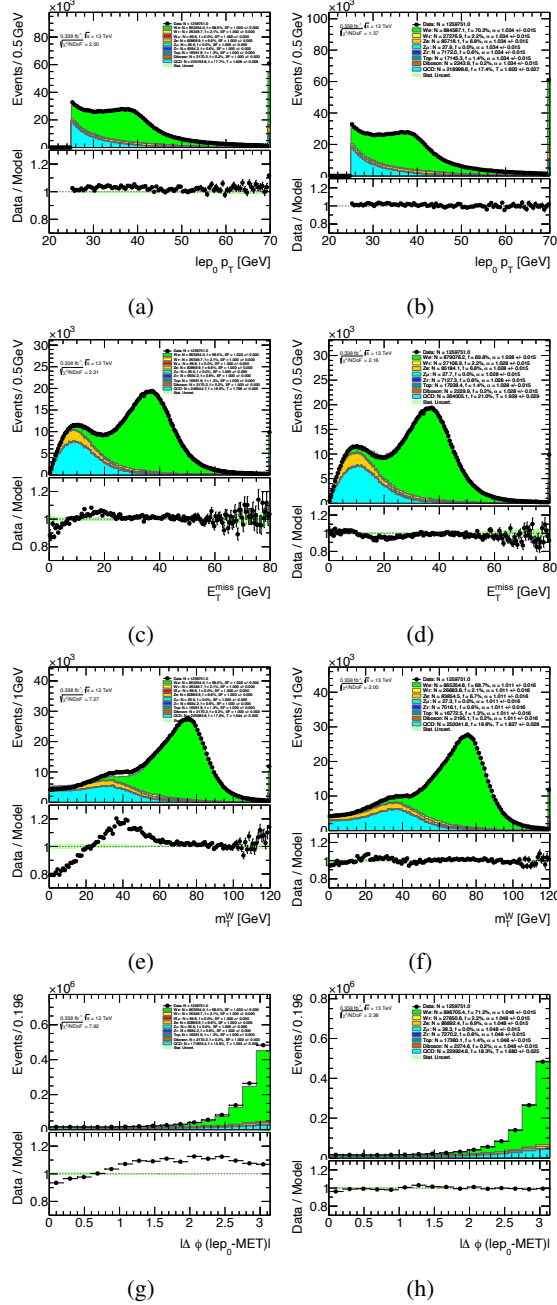


Figure 6.13: Multijet background template fits performed in the distributions of $p_T^{e^-}$ (top), E_T^{miss} (middle), and m_T (bottom) with the MJ template obtained from the isolation slice $0.05 < E_T^{cone20}/p_T < 0.1$. The fits are presented in the $W^- \rightarrow e^- \bar{\nu}$ channel before (left) and after (right) recoil correction.

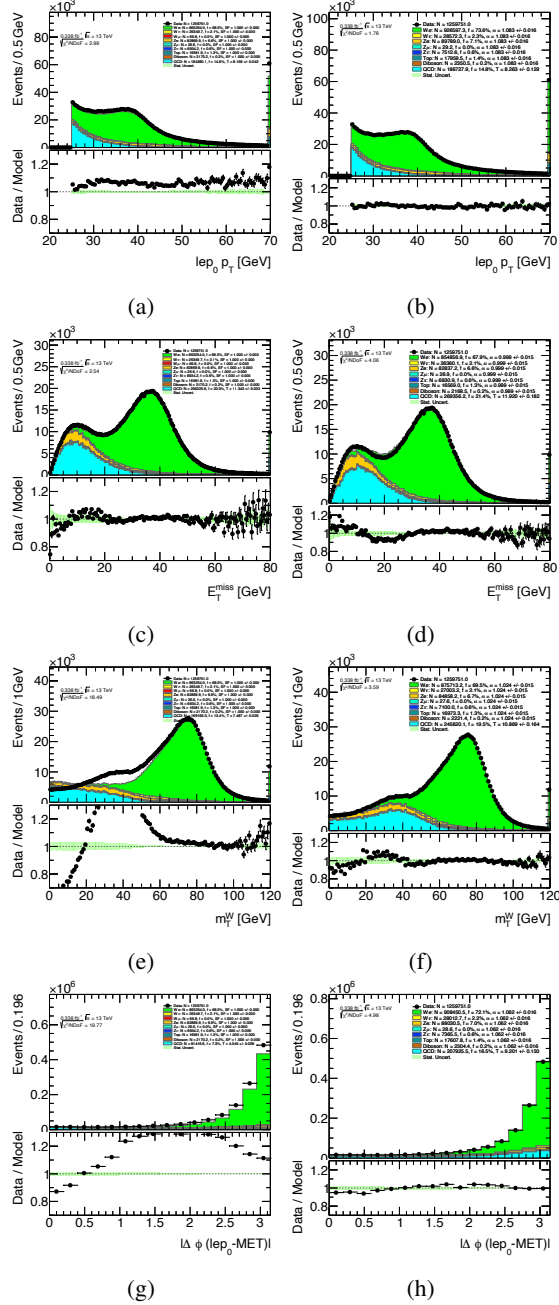


Figure 6.14: Multijet background template fits performed in the distributions of $p_T^{e^-}$ (top), E_T^{miss} (middle), and m_T (bottom) with the MJ template obtained from the isolation slice $0.2 < E_T^{cone20}/p_T < 0.25$. The fits are presented in the $W^- \rightarrow e^- \bar{\nu}_e$ channel before (left) and after (right) recoil correction.

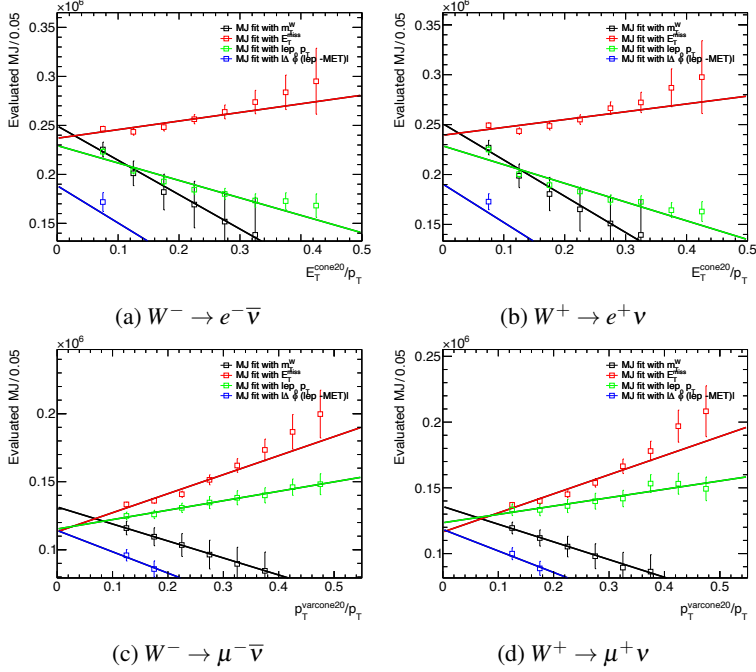


Figure 6.15: The estimated total number of the multijet background in SR is scanned as a function of the isolation slice. Isolation scan in the $W^- \rightarrow e^- \bar{\nu}$ channel (a), $W^+ \rightarrow e^+ \nu$ channel (b), $W^- \rightarrow \mu^- \bar{\nu}$ channel (c), and $W^+ \rightarrow \mu^+ \nu$ channel (d) is shown without recoil correction. Each point is plotted as the average $isocone20/p_T$ of each slice in CR1.

correction has an influence on the dependence of the fitted yield on the isolation range, except for the $p_T^{\ell, \nu}$ discriminative variable.

6.5.5 Decision of isolation variables

This analysis uses different isolation variables for the $e^\pm$ and $\mu^\pm$ channels:

- Slicing $p_T^{varcone20}/p_T$ for $W^- \rightarrow \mu^- \bar{\nu}$ and $W^+ \rightarrow \mu^+ \nu$: 8 slicing bins from 0.1 to 0.5.
- Slicing in E_T^{cone20}/p_T for $W^- \rightarrow e^- \bar{\nu}$ and $W^+ \rightarrow e^+ \nu$: 8 slicing bins from 0.05 to 0.45.

This chapter highlights the reasons for making this asynchronous decision.

Initial MJ studies primarily focused on the track-based isolation variable. However, discrepancies between Data and MC simulations in the $\cos \theta_{CS}$ distributions for the $W^- \rightarrow e^- \bar{\nu}$ and $W^+ \rightarrow e^+ \nu$ channels were observed. These discrepancies pointed to potential issues in the tails of the lepton η distributions, as shown in Figure 6.16a for electrons. No such Data / MC discrepancies were observed in the $W^- \rightarrow \mu^- \bar{\nu}$ and $W^+ \rightarrow \mu^+ \nu$ channels, as demonstrated in Figure 6.16b for the muon channel.

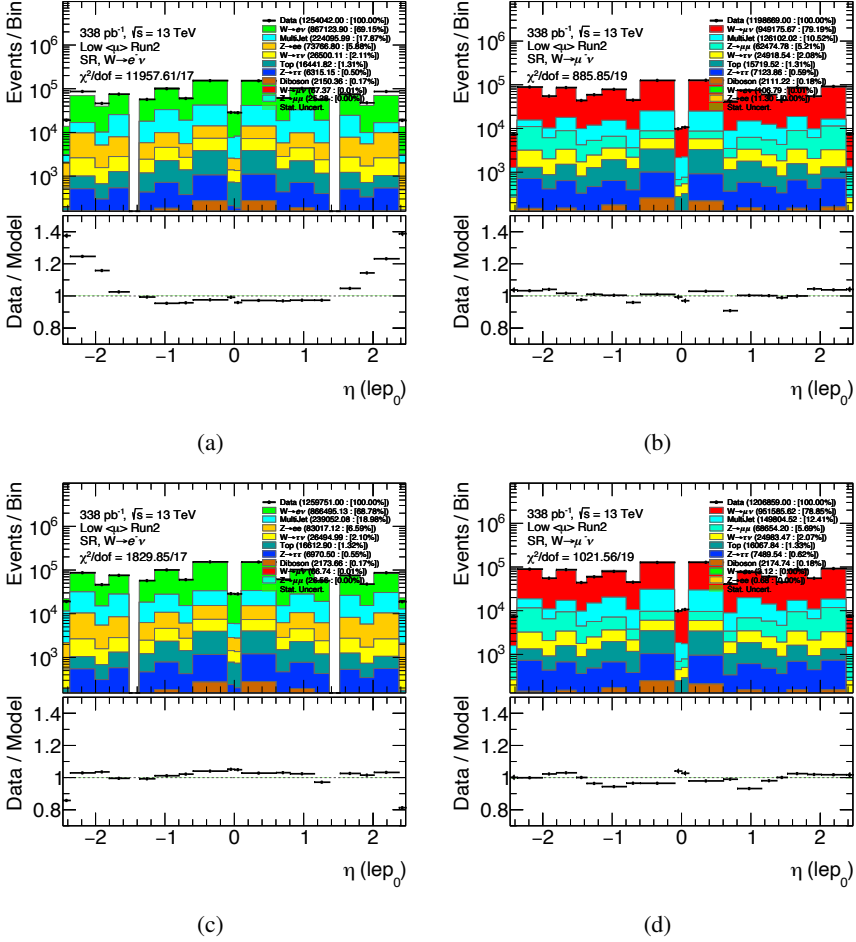


Figure 6.16: The η distributions for $W^- \rightarrow e^- \bar{\nu}$ (left) and $W^- \rightarrow \mu^- \bar{\nu}$ (right) channels using multijet estimation slicing over $p_T^{\text{varcone20}}/p_T$ (top) and E_T^{cone20}/p_T (bottom).

The issue arises from the estimation of the **MJ** template shape. Replacing the track-based isolation variable ($p_T^{\text{varcone20}}/p_T$) with the calo-based isolation variable (E_T^{cone20}/p_T) of the same cone size resolves the discrepancies. The results are shown in Figures 6.16c and 6.16d for the $W^- \rightarrow e^- \bar{\nu}$ and $W^- \rightarrow \mu^- \bar{\nu}$ channels, respectively.

The impact of using track-based and calo-based isolation variables on the normalized **MJ** shapes in anti-isolated slices of CR1 for the η distribution in the $W^- \rightarrow e^- \bar{\nu}$ channel is shown in Figure 6.17. This discrepancy may arise from the tight cut on E_T^{cone20}/p_T during the $p_T^{\text{varcone20}}/p_T$ anti-isolation slice scan.

Using the same E_T^{cone20}/p_T isolation variable for all channels would be a natural approach. However, it was found that E_T^{cone20} is not properly modelled in the signal samples for the $W^- \rightarrow \mu^- \bar{\nu}$ and $W^+ \rightarrow \mu^+ \nu$ channels. Figure 6.18 shows the E_T^{cone20}/p_T distributions for the $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ selections. In the $Z \rightarrow \mu\mu$ channel, there is a 20% discrepancy between data and background in the central rapidity region, while no such discrepancy is observed in the $Z \rightarrow ee$ channel.

The same effect of the E_T^{cone20} mis-modeling is observed in the first anti-isolated slice for the $W^- \rightarrow \mu^- \bar{\nu}$ and $W^+ \rightarrow \mu^+ \nu$ channels. Figure 6.19 shows the evaluation of the multijet background template fit in the $W^- \rightarrow \mu^- \bar{\nu}$ channel for the first two anti-isolated slices: $0.05 < E_T^{\text{cone20}}/p_T < 0.1$ and $0.1 < E_T^{\text{cone20}}/p_T < 0.15$. The absence of signal **MC** to subtract in the first anti-isolation slice results in the same 20% discrepancy as observed in the $Z \rightarrow \mu\mu$ channel. The impact on other anti-isolated slices is not as significant since the signal contribution to CR1 decreases. Linear extrapolations from the anti-isolated slices for the $W^- \rightarrow \mu^- \bar{\nu}$ channel are shown in Figure 6.20a.

Applying an overall 20% scaling of signal contamination helps to improve the linear extrapolations, as shown in Figure 6.20b. However, this is not the ideal solution as it leads to a negative shape in m_T^W , as shown in Figure 6.21b.

To address the issue with the **MC** mismodelling of E_T^{cone20} , the decision was made to use $p_T^{\text{varcone20}}/p_T$ anti-isolation for muon channels. This choice helps avoid the problem with the linear extrapolations that arise when using E_T^{cone20}/p_T .

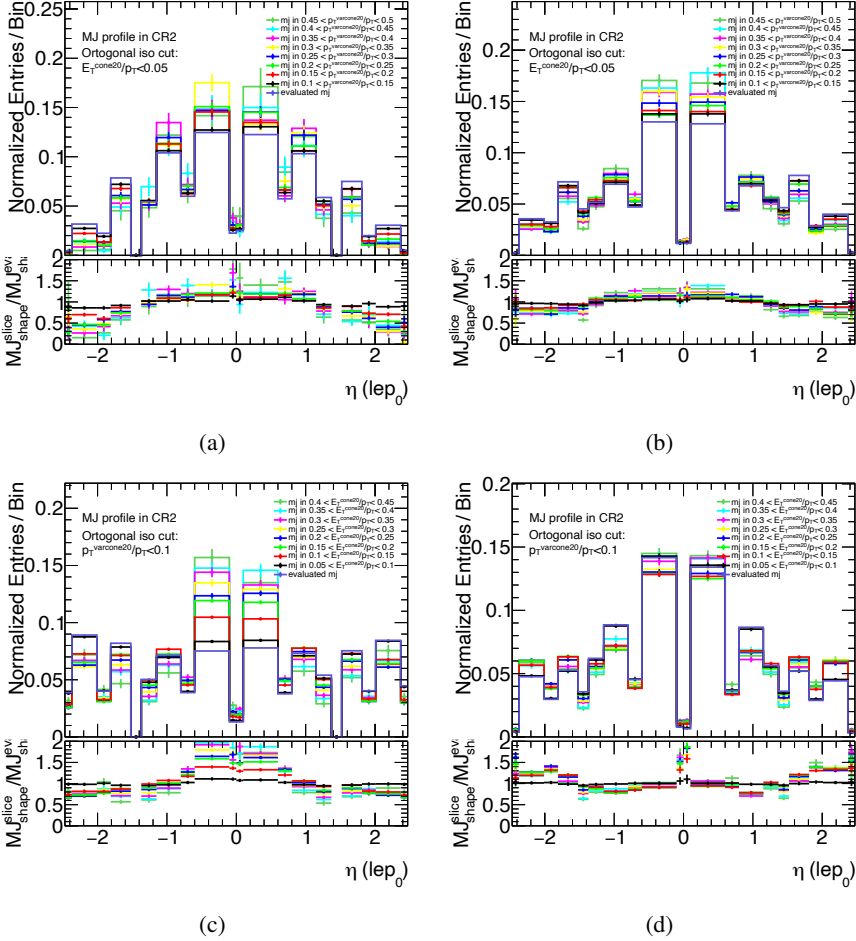


Figure 6.17: Normalised MJ shapes in anti-isolated slices of CR1 for η distribution for $W^- \rightarrow e^- \bar{\nu}$ (left) and $W^- \rightarrow \mu^- \bar{\nu}$ (right) channels using multijet estimation slicing over $p_T^{\text{varcone20}}/p_T$ (top) and E_T^{cone20}/p_T (bottom).

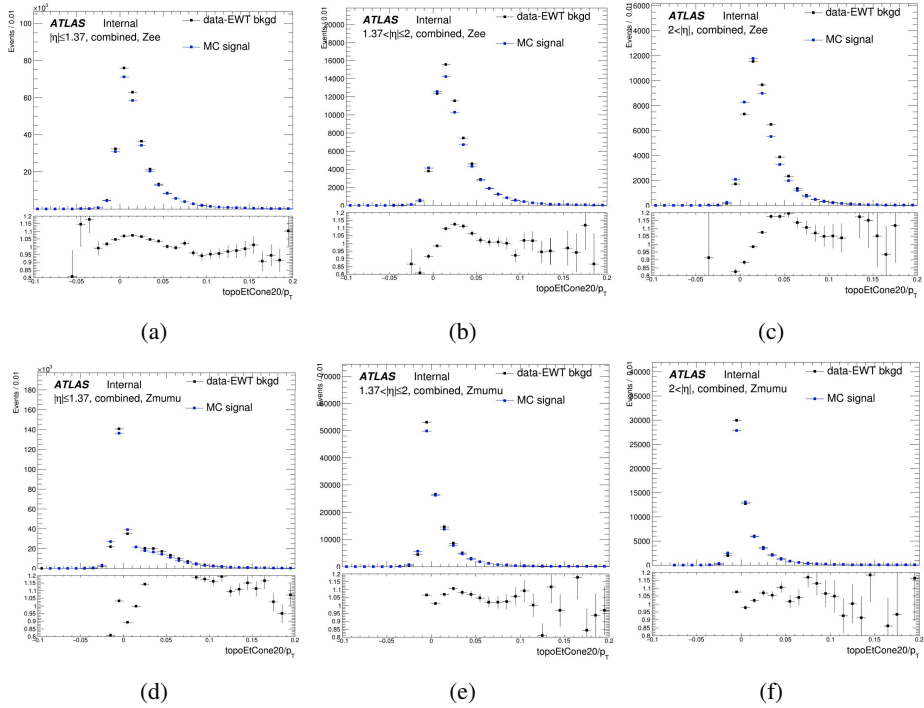


Figure 6.18: The relative E_T^{cone20}/p_T distributions for $Z \rightarrow ee$ (top) and $Z \rightarrow \mu\mu$ (bottom) selections for probe leptons in central (left), medium (center), and forward (right) detector locations.

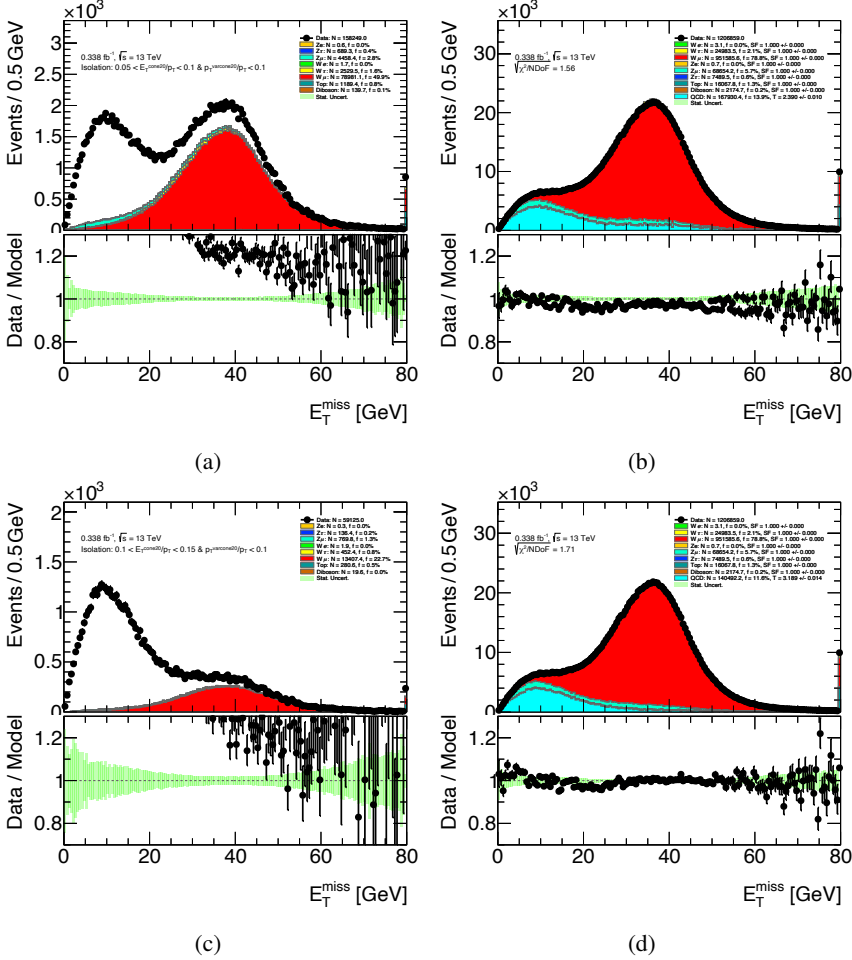


Figure 6.19: The **MJ** background template fit in the $W^- \rightarrow \mu^- \bar{\nu}$ for the anti-isolated slices $0.05 < E_T^{\text{cone}20}/p_T < 0.1$ (top) and $0.1 < E_T^{\text{cone}20}/p_T < 0.15$ (bottom). The plots on the left show the control region 1 (CR1) and on the right show the fit region.

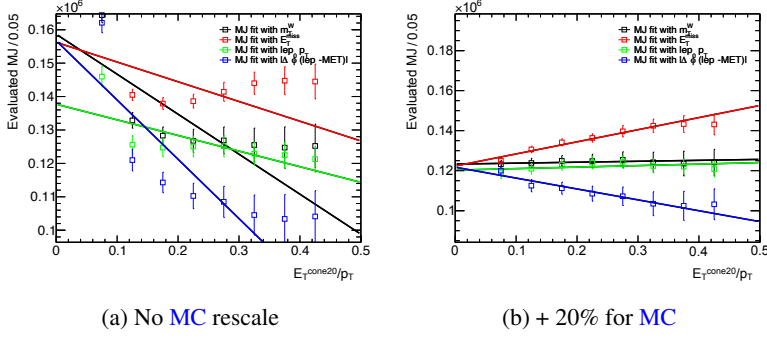


Figure 6.20: Linear extrapolations from anti-isolated slices for the $W^- \rightarrow \mu^- \bar{\nu}$ channel before (left) and after (right) the 20% rescale of the MC contribution to the CR1.

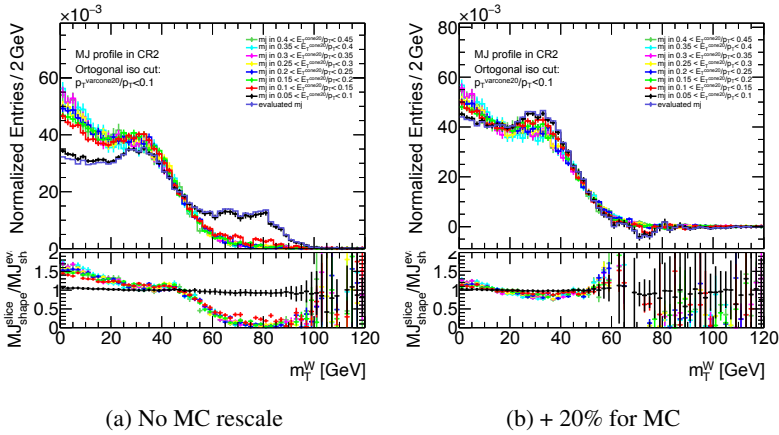


Figure 6.21: Normalised MJ shapes in anti-isolated slices of CR1 for the $W^- \rightarrow \mu^- \bar{\nu}$ channel before (left) and after (right) the 20% rescale of the MC contribution to the CR1.

6.5.6 Closure test for data-driven multijet estimation algorithm

To validate the performance of the anti-isolated slices extrapolation method, a series of closure tests were conducted. For these tests, $b\bar{b} + c\bar{c}$ MC samples were used for the $W^- \rightarrow \mu^- \bar{\nu}$ and $W^+ \rightarrow \mu^+ \nu$ channels. The closure tests involve comparing the data-driven multijet background estimation obtained from anti-isolated slices with the multijet background from the $b\bar{b} + c\bar{c}$ MC samples to assess the agreement and accuracy of the method.

The properties of the $b\bar{b}$ and $c\bar{c}$ samples at $\sqrt{s} = 13$ TeV are provided in Table 6.5. The cross sections for heavy-flavour production are higher than those for the signal and other backgrounds. However, the calculation of these cross sections carries significant uncertainties, mainly arising from the dijet production cross section (calculated at leading order) and the decay fractions and fragmentation functions for b and c quarks to muons.

Process	Data set	Generator	$\sigma \cdot \text{BR} \cdot \varepsilon_{\text{filter}}$ [nb]
$b\bar{b} \rightarrow \mu$	361250	Pythia8B+A14+NNPDF23LO	186
$c\bar{c} \rightarrow \mu$	361251	Pythia8B+A14+NNPDF23LO	58

Table 6.5: The MC simulation of $b\bar{b}$ and $c\bar{c}$ decay to muons performed at $\sqrt{s} = 13$ TeV.

The $b\bar{b}$ and $c\bar{c}$ MC samples were utilised to obtain MJ templates in the anti-isolated slices CR1 (for $W^- \rightarrow e^- \bar{\nu}$ and $W^+ \rightarrow e^+ \nu$) and CR2 (for $W^+ \rightarrow \mu^+ \nu$ and $W^- \rightarrow \mu^- \bar{\nu}$) channels. The linear extrapolations from the anti-isolated slices are shown in Figure 6.22 and listed in Ref. [3]. The impact of limited MC sample statistics on the anti-isolated templates is evident.

The results are consistent with the linear extrapolations shown in Figure 6.7, which were derived using the data-driven method.

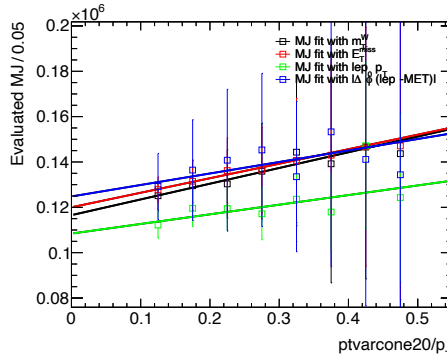


Figure 6.22: Linear extrapolations from anti-isolated slices for $W^- \rightarrow \mu^- \bar{\nu}$ channels using $b\bar{b} + c\bar{c}$ MC samples as a source of templates in anti-isolated region.

6.5.7 Sources of uncertainty in the multijet background estimation

The **MJ** background estimation is subject to uncertainties originating from three main sources: total yield, shape, and statistics. These uncertainties have different correlation patterns: the total yield and shape uncertainties are fully correlated across the measurement bins, while the statistical uncertainty is uncorrelated due to its statistical nature.

Table 6.6 presents the breakdown of uncertainties for the final **MJ** estimation in the inclusive signal region for the $W^- \rightarrow e^- \bar{\nu}$, $W^+ \rightarrow e^+ \nu$, $W^- \rightarrow \mu^- \bar{\nu}$, and $W^+ \rightarrow \mu^+ \nu$ channels. The following section provides a detailed breakdown of the various sources of uncertainty investigated in this analysis for the inclusive signal region.

Channel	$W^- \rightarrow e^- \bar{\nu}$	$W^+ \rightarrow e^+ \nu$	$W^- \rightarrow \mu^- \bar{\nu}$	$W^+ \rightarrow \mu^+ \nu$
Total Number of MJ bkg	238399	239696	129755	136412
Luminosity and cross section	± 6890 (2.89%)	± 8183 (3.41%)	± 721 (0.56%)	± 917 (0.67%)
Intersection point	± 20401 (8.56%)	± 23612 (9.85%)	± 10520 (8.11%)	± 8110 (5.95%)
Extrapolation target	± 887 (0.37%)	± 939 (0.39%)	± 1619 (1.25%)	± 1382 (1.01%)
Choice of hists	± 6800 (2.85%)	± 7871 (3.28%)	± 3507 (2.70%)	± 2703 (1.98%)
Isolation correction	± 2393 (1.00%)	± 3624 (1.51%)	± 1081 (0.83%)	± 1084 (0.79%)
Correlated Uncertainty	± 22567 (9.47%)	± 26191 (10.93%)	± 10528 (8.11%)	± 8233 (6.04%)
Data Stat.	± 519 (0.21%)	± 499 (0.20%)	± 807 (0.63%)	± 818 (0.61%)
MC Stat.	± 277 (0.11%)	± 248 (0.10%)	± 1003 (0.78%)	± 894 (0.67%)
Shape Correction	± 3241 (1.32%)	± 3296 (1.32%)	± 1157 (0.90%)	± 908 (0.68%)
Uncorrelated Uncertainty	± 3294 (1.35%)	± 3343 (1.33%)	± 1731 (1.34%)	± 1514 (1.13%)

Table 6.6: Multijet background yield and the impact on the uncertainty on the yield due to shape uncertainty breakdown for inclusive signal region in the $W^- \rightarrow e^- \bar{\nu}$, $W^+ \rightarrow e^+ \nu$, $W^- \rightarrow \mu^- \bar{\nu}$ and $W^+ \rightarrow \mu^+ \nu$ channels.

The **MJ** background yield extraction described in Section 6.5.2 is subject to evaluation for the following sources of uncertainty:

- Uncertainty related to the luminosity and the cross section of the simulated samples. In certain anti-isolated slices in CR1, the contribution from the **MC** backgrounds dominates. This source of uncertainty is accounted for in the overall uncertainty of the **MJ** background estimation.
- Intersection Point: This uncertainty arises from the spread of the linear extrapolation as a function of isolation $k^i X + b^i$ using different discriminating variables i (p_T , m_T , E_T^{miss} , and $|\Delta\phi(\ell, E_T^{miss})|$). It mainly affects the total number of the **MJ** background, which is estimated by considering the maximum and minimum $k^i X + b^i$ values. Here, X represents the isolation value for the central value, which is 0.025. These 4 lines used in the uncertainty sources which could lead to an bad intersection point. To avoid double counting, the statistical uncertainty is excluded from the uncertainty of the extrapolation.
- Uncertainty from the choice of the extrapolation target is estimated by varying the isolation target from 0.025 to 0.
- The uncertainty arising from the choice of the discriminating variable used to extract the **MJ** background in the FR (e.g., p_T , m_T , E_T^{miss} , and $|\Delta\phi(\ell, E_T^{miss})|$) is estimated by

excluding one of the results from the MJ yield extraction using a specific discriminative variable from the linear extrapolation. The maximum difference observed is quoted as the uncertainty.

- The uncertainty arising from the isolation correction is evaluated by varying the isolation correction by 10%. However, this uncertainty is found to be negligible compared to the statistical uncertainty of the first slice of CR1. As a result, only the contribution to the total MJ background yield is considered.

The shape of the MJ background is subject to the following sources of uncertainty:

- Bin-by-bin uncorrelated data and MC statistics: The uncertainty arises from limited data and MC samples and is propagated to the results of the shape extrapolation based on Eq. 6.5.
- Uncertainty due to the shape correction (as described in detail in Section 6.5.3): This primarily affects the shape of the MJ background estimation. The shape uncertainty is quantified as the difference between the extrapolated shape in the SR and the MJ shape of the first slice in CR1 (Eq. 6.4).

The final MJ estimation output includes three sources of uncertainty, which are combined and propagated to the measurement for inclusive signal region. The uncertainties related to the MJ yield extraction and the shape of the MJ background are considered to be fully correlated across the measurement bin.

On the other hand, this analysis requires estimating the MJ yield and predicting its shape for two-dimensional distributions within fine $p_T^{\ell,v}$ and $|Y|$ bins, rather than considering the inclusive signal region. The next section will focus on this estimation and shape prediction using the acceptance correction method. Additionally, the section will discuss the systematic uncertainty arising from this acceptance correction.

6.6 Multijet background in analysis fine bins

The methodology outlined in Section 6.5 can be readily extended to predict 2D distributions instead of 1D histograms, using the same approach. Figure 6.23 displays the final 2D multijet templates as a function of the $\cos\theta_{CS}$ and ϕ_{CS} distributions, normalised to the total multijet yield for the inclusive signal region.

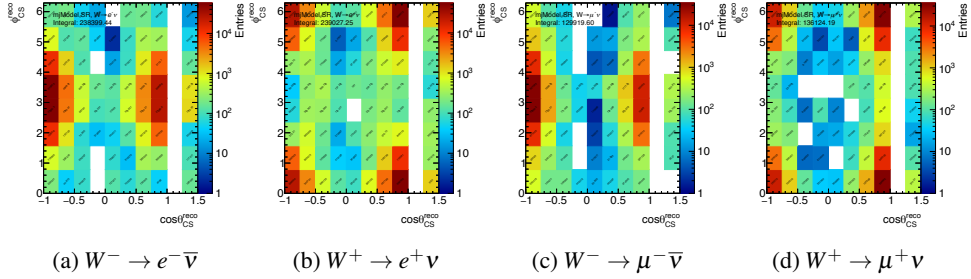


Figure 6.23: The multijet templates for the $\cos\theta_{CS}$ vs. ϕ_{CS} distributions in the $W^- \rightarrow e^- \bar{\nu}$, $W^+ \rightarrow e^+ \nu$, $W^- \rightarrow \mu^- \bar{\nu}$, and $W^+ \rightarrow \mu^+ \nu$ channels for the inclusive signal region.

In this analysis, the **MJ** templates need to be provided as functions of $\cos\theta_{CS}$ and ϕ_{CS} for each $p_T^{\ell,\nu}$ and $|Y|$ measurement bin. This introduces additional complexity and requires further studies on the **MJ** template and yield predictions within each $p_T^{\ell,\nu}$ and $|Y|$ bin.

As a reminder, the extraction of the angular coefficient is performed in $p_T^{\ell,\nu}$ and $|Y|$ bins, as defined below:

$$\begin{aligned} p_T^{\ell,\nu} &: [0, 8, 17, 27, 40, 55, 75, 110, 150, 210, 600]; \\ |Y| &: [0, 0.4, 0.8, 1.2, 1.6, 2.0, 2.4, 3.6] \end{aligned} \quad (6.9)$$

Running the data-driven method directly to provide **MJ** shape and yield estimation for each $p_T^{\ell,\nu}$ or $|Y|$ bin individually would not be feasible due to the significant statistics drop in the CR1 regions used to extract **MJ** templates. On the other hand, using a single 2D **MJ** template ($\cos\theta_{CS}^{reco}$ vs. ϕ_{CS}^{reco}) derived from the inclusive SR for all $p_T^{\ell,\nu}$ and $|Y|$ bins is not suitable because there are strong dependencies of the $\cos\theta_{CS}$ **MJ** shape on $|Y|$ and ϕ_{CS} as a function of $p_T^{\ell,\nu}$, as shown in Figure 6.24.

6.6.1 Multijet shape acceptance correction

To overcome these challenges, the 2D $\cos\theta_{CS}$ vs. ϕ_{CS} **MJ** distribution extracted in the inclusive signal region (Figure 6.23 shows this distribution for $W^- \rightarrow e^- \bar{\nu}$, $W^+ \rightarrow e^+ \nu$, $W^- \rightarrow \mu^- \bar{\nu}$, and $W^+ \rightarrow \mu^+ \nu$ channels) can be extrapolated to each $p_T^{\ell,\nu}$ and $|Y|$ bin using so-called *acceptance correction functions* to account for the kinematic changes in the different $p_T^{\ell,\nu}$ and $|Y|$ bins: $A_j = h_{MC}^{bin_j} / h_{MC}^{inc}$.

To construct the *acceptance correction*, special background **MC** samples that are expected to have kinematics similar to the **MJ** kinematics are used. The $b\bar{b}+c\bar{c}$ **MC** samples for

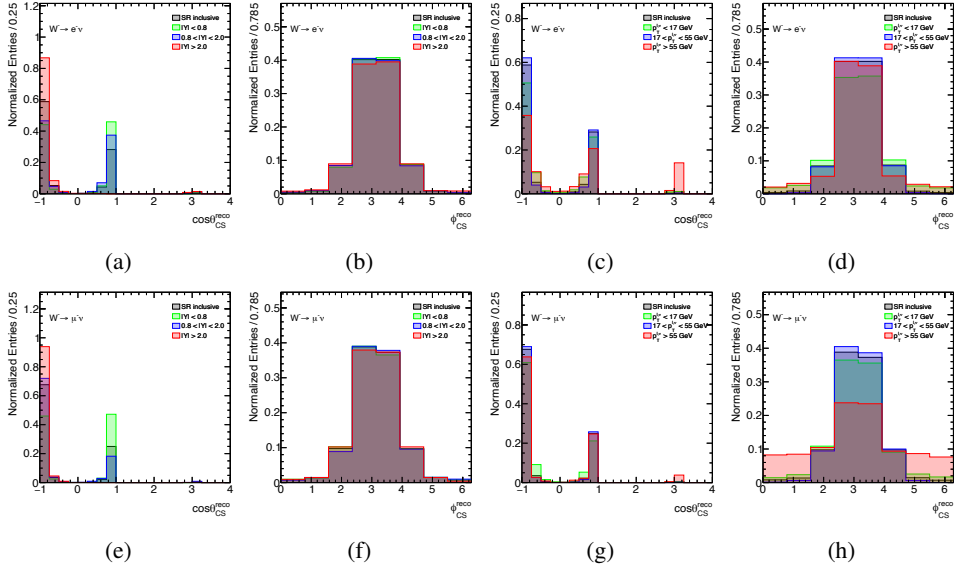


Figure 6.24: Projections of data-driven **MJ** templates derived for the inclusive signal region compared with three different $p_T^{\ell,v}$ or $|Y|$ bins for $W^- \rightarrow e^- \bar{\nu}$ (top) and $W^- \rightarrow \mu^- \bar{\nu}$ (bottom) channels.

$W^\pm \rightarrow \mu^\pm \nu$ channels and *JF17* **MC** samples for $W^\pm \rightarrow e^\pm \nu$ channels are used for this purpose.

The properties of the $b\bar{b}$ and $c\bar{c}$ samples at $\sqrt{s} = 13$ TeV are provided in Table 6.5 for muon channel. In the electron channel, the multijet production was simulated using PYTHIA [8.2] [173] with leading-order matrix elements for dijet production, and these were subsequently matched to the parton shower. Additional information about the properties of the *JF17* samples used can be found in Table 6.7.

Process	Data set	Generator	$\sigma \cdot \text{BR} \cdot \epsilon_{\text{filter}}$ [nb]
<i>JF17</i>	423300	Pythia8B+A14+NNPDF23LO	180×10^3

Table 6.7: The **MC** simulation of the **MJ** *JF17* sample for electrons performed at $\sqrt{s} = 13$ TeV.

To validate this procedure, the full **MJ** extraction was also performed directly from data in three coarse $p_T^{\ell,v}$ and $|Y|$ regions defined as follows:

$$\begin{aligned}
 p_T^{\ell,v} &: [0, 17, 40, 600]; \\
 |Y| &: [0, 0.8, 2.0, 3.6]
 \end{aligned}
 \tag{6.10}$$

In the coarse regions defined by $p_T^{\ell,v}$ and $|Y|$, the entire data-driven multijet estimation

procedure described in Section 6.5.1 was repeated to estimate the MJ yield and shape. The 2D MJ templates extracted from data in these coarse regions were then compared with the 2D MJ templates extracted from the data inclusive region and corrected with the corresponding acceptance correction factors ($B_k = h_{MC}^{bin_k} / h_{MC}^{Inc.}$, where the index k runs over the coarse regions defined in Formula 6.10). The closure test results are shown in Figure 6.25 for both the $W^- \rightarrow e^- \bar{\nu}$ and $W^- \rightarrow \mu^- \bar{\nu}$ channels. The test verified that directly extrapolating the data-driven inclusive MJ 2D template might lead to suboptimal results. Similar tests were conducted using $\cos \theta_{CS}$ vs. ϕ_{CS} 2D distributions, and their results are presented in the flattened histograms in Ref. [3].

Therefore to obtain the final 2D multijet background template for a specific $p_T^{\ell, \nu}$ or $|Y|$ bin j (as defined in Eq. 6.9), the following procedure is followed:

- The shape of multijet background events as a function of $\cos \theta_{CS}^{reco}$ and ϕ_{CS}^{reco} distributions is derived from data in three coarse bins, k , as defined in Equation 6.10 (denoted as $h_{MJ,data}^{bin_k}$). The corrections on the multijet background shapes, as described in Section 6.5.3, are then applied to these distributions.
- Using the dedicated MC samples, a multijet template is constructed for each coarse bin k in $|Y|$ or $p_T^{\ell, \nu}$ (referred to as $h_{MC}^{bin_k}$). Additionally, a separate multijet template is built for the fine j -bin (referred to as $h_{MC}^{bin_j}$, bins defined in Equation 6.9).
- The acceptance correction for each $p_T^{\ell, \nu}$ or $|Y|$ measurement bin is computed in MC as the difference in multijet templates between the coarse bin k and the shape of the given j -bin:

$$A_j = h_{MC}^{bin_j} / h_{MC}^{bin_k} \quad (6.11)$$

- The acceptance correction is applied to the data-driven template from the coarse bin k to extrapolate and obtain the template shape for a given j -bin:

$$h_{MJ}^{bin_j} = h_{MJ,data}^{bin_k} \times A_j \quad (6.12)$$

The procedure is demonstrated for a selected number of $|Y|$ and $p_T^{\ell, \nu}$ bins, presented in Figures 6.26. These figures display the flattened 2D distributions of $\cos \theta_{CS}^{reco}$ vs ϕ_{CS}^{reco} for the $W^- \rightarrow e^- \bar{\nu}$ channel. For a comprehensive list of acceptance corrections applied to the 2D distributions across all four channels, please refer to Ref. [3].

An observation was made that the acceptance correction function predicts overly sharp MJ background shapes for the highest $p_T^{\ell, \nu}$ bins. This behavior is attributed to the limited statistical power of the MC multijet template constructed for these fine bins, resulting in such pronounced shapes. Consequently, this sharp MJ shape introduced notable tension between the data and the model in the fitting process, leading to unexpected shifts in the nuisance parameters. To mitigate this issue, a solution was implemented by grouping the last three bins within the $110 < p_T^{\ell, \nu} < 600$ GeV range. These bins were assigned a shared acceptance correction function, effectively utilising the same shape within the width of this broader bin.

Two sources of uncertainty are considered for this acceptance correction. One source of systematic uncertainty is defined as the relative difference between $h_{MC}^{bin_k}$ and $h_{MJ,data}^{bin_k}$ and is

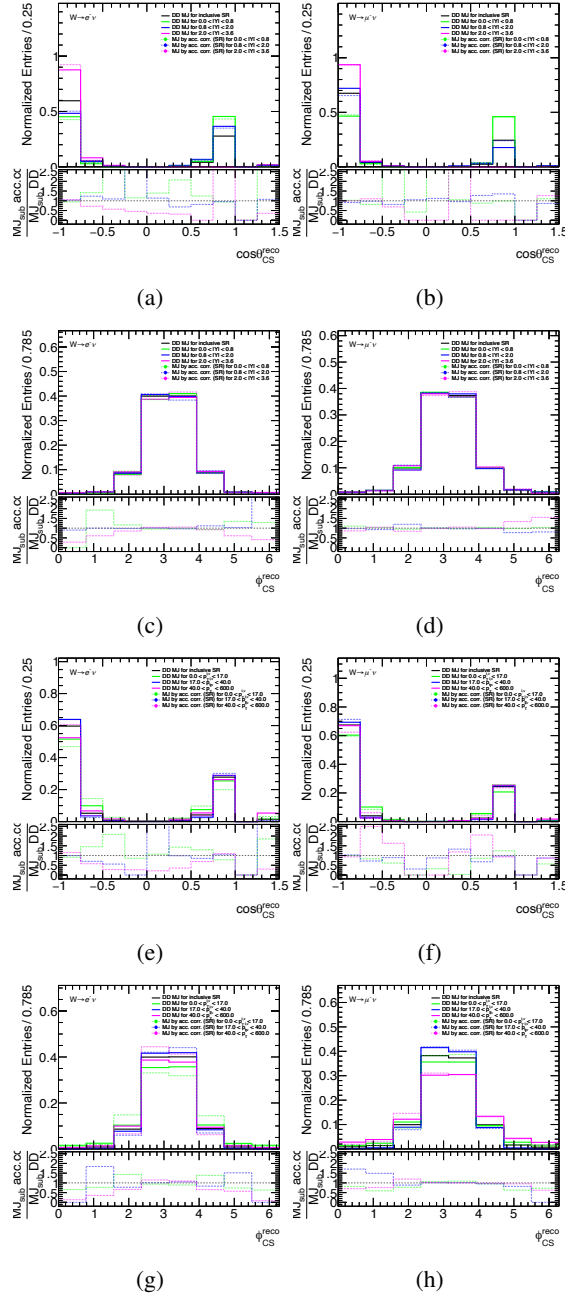


Figure 6.25: Projections for data-driven multijet templates (solid lines) and templates provided by the acceptance correction method (dashed lines) derived for three individual subregions for $W^- \rightarrow e^- \bar{\nu}$ (left) and $W^- \rightarrow \mu^- \bar{\nu}$ (right) channels. The ratios between the data-driven multijet templates and the templates provided by the acceptance correction method for each individual coarse subregion are presented in the ratio parts of the figures.

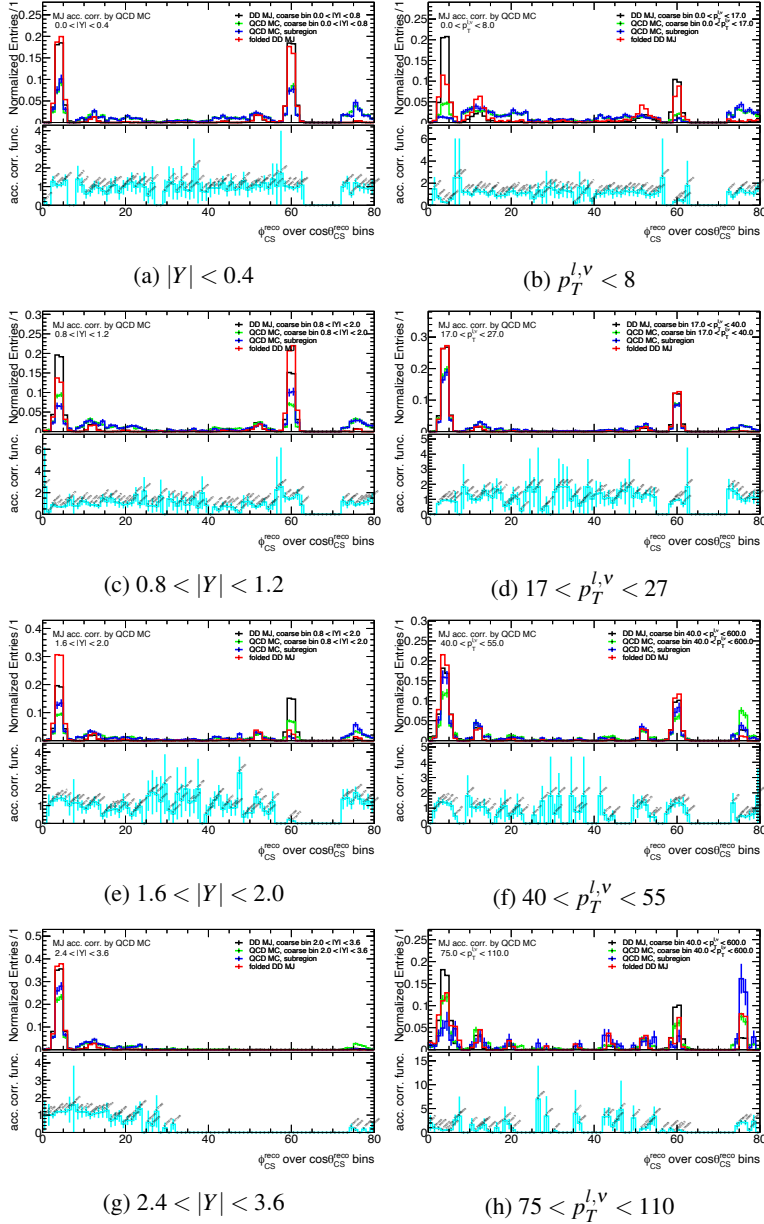


Figure 6.26: Normalised multijet background templates for flattened 2D distributions of $\cos \theta_{CS}^{reco}$ vs. ϕ_{CS}^{reco} in the $W^- \rightarrow e^- \bar{\nu}$ channel. The templates are derived using acceptance correction functions (shown in red) for specific $|Y|$ bins (left) and $p_T^{l,v}$ bins (right), while data-driven multijet templates (shown in black) were obtained using corresponding coarse bins according to Eq. 6.10. The bottom segments of the figures display the multijet acceptance correction functions, with error bars denoting the binomial statistical uncertainty.

taken to be correlated within the coarse bin k . The other source is the statistical uncertainty of the **MC** samples template derived for j bins, h_{MC}^{binj} , which is included in the analysis as a fully uncorrelated uncertainty on the acceptance correction functions. Further details on systematic uncertainties in the **MJ** background estimation for fine bins will be presented in Section 6.6.3.

6.6.2 Multijet yield normalisation in the analysis fine bins

The expected multijet yield for a given $p_T^{\ell,v}$ or $|Y|$ bin can be directly derived from the corresponding number of multijet events in each $p_T^{\ell,v}$ or $|Y|$ distribution, obtained inclusively in the signal region following the methodology described in Section 6.5.2. In this scenario, all predictions for **MJ** yields share a correlated uncertainty in yield, as discussed in Section 6.5.7. Nonetheless, the presence of the three coarse $p_T^{\ell,v}$ and $|Y|$ regions defined in Equation 6.10 provides an opportunity to explore alternative approach for estimating the **MJ** yield within these coarse bins. These estimates can serve as initial values to derive the count of multijet events in each corresponding fine bin of the $p_T^{\ell,v}$ or $|Y|$ distributions following almost same original methodology. This strategy permits the decoupling of **MJ** yield uncertainties within the coarse bins during the fitting process.

$W \rightarrow e^- \bar{\nu}$	$ Y < 0.8$	$0.8 < Y < 2.0$	$2.0 < Y < 3.6$	$0 < p_T^{\ell,v} < 17 \text{ GeV}$	$17 < p_T^{\ell,v} < 40 \text{ GeV}$	$40 < p_T^{\ell,v} < 600 \text{ GeV}$
Total Number of MJ bkg	69631	95987	73405	40969	162492	35610
Luminosity and cross section	± 2327 (3.34%)	± 2886 (3.01%)	± 1441 (1.96%)	± 2934 (7.16%)	± 2517 (1.55%)	± 523 (1.47%)
Intersection point	± 8429 (12.10%)	± 8099 (8.44%)	± 8892 (12.11%)	± 4195 (10.24%)	± 6314 (3.89%)	± 14100 (39.59%)
Extrapolation target	± 41 (0.06%)	± 723 (0.75%)	± 604 (0.82%)	± 52 (0.13%)	± 1278 (0.79%)	± 918 (2.58%)
Choice of histos	± 2810 (4.03%)	± 2700 (2.81%)	± 2964 (4.04%)	± 1398 (3.41%)	± 2105 (1.30%)	± 4700 (13.20%)
Isolation correction	± 557 (0.80%)	± 1119 (1.17%)	± 743 (1.01%)	± 577 (1.41%)	± 1689 (1.04%)	± 825 (2.32%)
Correlated Uncertainty	± 8718 (12.52%)	± 9109 (9.49%)	± 9032 (12.30%)	± 5129 (12.52%)	± 7097 (4.37%)	± 14921 (41.90%)

Table 6.8: Multijet background yield and uncertainty breakdown for coarse $p_T^{\ell,v}$ and $|Y|$ bins in the $W^- \rightarrow e^- \bar{\nu}$ channel.

$W \rightarrow e^+ \nu$	$ Y < 0.8$	$0.8 < Y < 2.0$	$2.0 < Y < 3.6$	$0 < p_T^{\ell,v} < 17 \text{ GeV}$	$17 < p_T^{\ell,v} < 40 \text{ GeV}$	$40 < p_T^{\ell,v} < 600 \text{ GeV}$
Total Number of MJ bkg	69675	94698	77374	43646	164736	36708
Luminosity and cross section	± 2672 (3.84%)	± 3480 (3.67%)	± 2086 (2.70%)	± 3507 (8.03%)	± 2795 (1.70%)	± 639 (1.74%)
Intersection point	± 10090 (14.48%)	± 11420 (12.06%)	± 9492 (12.27%)	± 4709 (10.79%)	± 9237 (5.61%)	± 14048 (38.27%)
Extrapolation target	± 64 (0.09%)	± 737 (0.78%)	± 781 (1.01%)	± 327 (0.75%)	± 1127 (0.68%)	± 941 (2.56%)
Choice of histos	± 3363 (4.83%)	± 3807 (4.02%)	± 3164 (4.09%)	± 1570 (3.60%)	± 3079 (1.87%)	± 4683 (12.76%)
Isolation correction	± 934 (1.34%)	± 1185 (1.25%)	± 2176 (2.81%)	± 1372 (3.14%)	± 1989 (1.21%)	± 782 (2.13%)
Correlated Uncertainty	± 10479 (15.04%)	± 12537 (13.24%)	± 9959 (12.87%)	± 6029 (13.81%)	± 9994 (6.07%)	± 14864 (40.49%)

Table 6.9: Multijet background yield and uncertainty breakdown for coarse $p_T^{\ell,v}$ and $|Y|$ bins in the $W^+ \rightarrow e^+ \nu$ channel.

Tables 6.8 through 6.11 present the **MJ** yields derived for each individual coarse bin for the $W^- \rightarrow e^- \bar{\nu}$, $W^+ \rightarrow e^+ \nu$, $W^- \rightarrow \mu^- \bar{\nu}$, and $W^+ \rightarrow \mu^+ \nu$ channels. The correlated systematic uncertainty within the $|Y|$ coarse bins remains relatively stable. However, it is evident that the systematic uncertainty of the **MJ** yield undergoes substantial changes across the $p_T^{\ell,v}$ coarse bins, with variations up to 31% for the outermost $p_T^{\ell,v}$ coarse bin. All linear extrapolations from the anti-isolated slices for these coarse bins can be found in Ref. [3].

The aggregated **MJ** yield across the coarse $p_T^{\ell,v}$ or $|Y|$ bins demonstrates a coherent alignment with the outcomes obtained for the inclusive signal region, as illustrated in

$W \rightarrow \mu^- \bar{\nu}$	$ Y < 0.8$	$0.8 < Y < 2.0$	$2.0 < Y < 3.6$	$0 < p_T^{\ell, \nu} < 17 \text{ GeV}$	$17 < p_T^{\ell, \nu} < 40 \text{ GeV}$	$40 < p_T^{\ell, \nu} < 600 \text{ GeV}$
Total Number of MJ bkg	47029	46423	36686	16971	84798	29947
Luminosity and cross section	± 162 (0.34%)	± 273 (0.59%)	± 137 (0.37%)	± 230 (1.35%)	± 184 (0.22%)	± 55 (0.18%)
Intersection point	± 3305 (7.03%)	± 3570 (7.69%)	± 3408 (9.29%)	± 1533 (9.03%)	± 2952 (3.48%)	± 3167 (10.57%)
Extrapolation target	± 663 (1.41%)	± 502 (1.08%)	± 281 (0.76%)	± 366 (2.16%)	± 859 (1.01%)	± 67 (0.22%)
Choice of histograms	± 1102 (2.34%)	± 1190 (2.56%)	± 1136 (3.10%)	± 511 (3.01%)	± 984 (1.16%)	± 1056 (3.52%)
Isolation correction	± 239 (0.51%)	± 147 (0.32%)	± 187 (0.51%)	± 205 (1.21%)	± 356 (0.42%)	± 170 (0.57%)
Correlated Uncertainty	± 3318 (7.05%)	± 3584 (7.72%)	± 3538 (9.64%)	± 1665 (9.81%)	± 3238 (3.82%)	± 3344 (11.16%)

Table 6.10: Multijet background yield and uncertainty breakdown for coarse $p_T^{\ell, \nu}$ and $|Y|$ bins in the $W^- \rightarrow \mu^- \bar{\nu}$ channel.

$W \rightarrow \mu^+ \nu$	$ Y < 0.8$	$0.8 < Y < 2.0$	$2.0 < Y < 3.6$	$0 < p_T^{\ell, \nu} < 17 \text{ GeV}$	$17 < p_T^{\ell, \nu} < 40 \text{ GeV}$	$40 < p_T^{\ell, \nu} < 600 \text{ GeV}$
Total Number of MJ bkg	49249	48872	38112	14888	89938	32661
Luminosity and cross section	± 200 (0.41%)	± 348 (0.71%)	± 188 (0.49%)	± 232 (1.56%)	± 262 (0.29%)	± 68 (0.21%)
Intersection point	± 1919 (3.90%)	± 3194 (6.54%)	± 1759 (4.62%)	± 5978 (40.16%)	± 2632 (2.93%)	± 434 (1.33%)
Extrapolation target	± 650 (1.32%)	± 360 (0.74%)	± 228 (0.60%)	± 311 (2.09%)	± 837 (0.93%)	± 11 (0.03%)
Choice of histograms	± 640 (1.30%)	± 1065 (2.18%)	± 586 (1.54%)	± 1993 (13.39%)	± 877 (0.98%)	± 145 (0.44%)
Isolation correction	± 166 (0.34%)	± 312 (0.64%)	± 265 (0.69%)	± 53 (0.35%)	± 270 (0.30%)	± 339 (1.04%)
Correlated Uncertainty	± 1937 (3.93%)	± 3228 (6.60%)	± 1878 (4.93%)	± 5983 (40.18%)	± 2922 (3.25%)	± 573 (1.75%)

Table 6.11: Multijet background yield and uncertainty breakdown for coarse $p_T^{\ell, \nu}$ and $|Y|$ bins in the $W^+ \rightarrow \mu^+ \nu$ channel.

Table 6.6. However, an additional cross-check was undertaken. The yields for the coarse bins were directly determined based on the respective multijet event counts in each $p_T^{\ell, \nu}$ or $|Y|$ distribution. The MJ shapes anticipated for the coarse $p_T^{\ell, \nu}$ or $|Y|$ bins are shown in Figure 6.27. Utilising these normalisation plots, the MJ yields in the coarse bins were computed, and the outcomes are presented in Table 6.12. The level of agreement between these results and those obtained for individual coarse bins was found to be excellent.

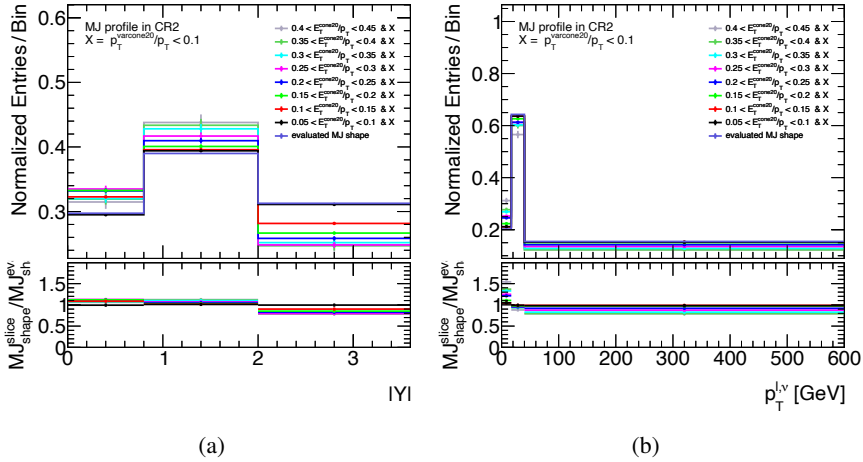


Figure 6.27: Normalised multijet background templates for coarse $p_T^{\ell, \nu}$ and $|Y|$ bins in the $W^- \rightarrow e^- \bar{\nu}$ channel.

$W \rightarrow e^- \nu$	$ Y < 0.8$	$0.8 < Y < 2.0$	$2.0 < Y < 3.6$	$0 < p_T^{\ell, \nu} < 17 \text{ GeV}$	$17 < p_T^{\ell, \nu} < 40 \text{ GeV}$	$40 < p_T^{\ell, \nu} < 600 \text{ GeV}$
Total Number of MJ bkg	70991	95388	78128	49453	157260	37795
Yield normalisation from SR	± 4472 (6.3%)	± 6009 (6.3%)	± 4922 (6.3%)	± 3115 (6.3%)	± 9907 (6.3%)	± 2381 (6.3%)
Shape Correction	± 2535 (3.57%)	± 2008 (2.1%)	± 2441 (3.12%)	± 2527 (5.11%)	± 2457 (1.56%)	± 1181 (3.12%)
Total uncertainty	± 5140 (7.2%)	± 6335 (6.6%)	± 5494 (7.03%)	± 4011 (8.11%)	± 10207 (6.49%)	± 2657 (7.03%)

Table 6.12: Multijet background yield and uncertainty breakdown for coarse $p_T^{\ell, \nu}$ and $|Y|$ bins derived from inclusive signal region distributions in the $W^- \rightarrow e^- \bar{\nu}$ channel.

6.6.3 Sources of uncertainty in the MJ background estimation for fine bins

Similar to the inclusive signal region, the MJ background estimation in the fine analysis bins is subject to uncertainties originating from the following sources: total yield, shape, statistics, and acceptance correction. However, due to the methodology employed to derive MJ yield and shape in fine bins using coarse bins, the sources of uncertainties related to total yield, shape, and statistics are somewhat more complex compared to those used in the inclusive signal region MJ estimation.

Figures 6.28 and 6.29 illustrate the breakdown of MJ background systematic uncertainties for flattened 2D distributions of $\cos \theta_{CS}^{reco}$ vs. ϕ_{CS}^{reco} in the $W^- \rightarrow e^- \bar{\nu}$ and $W^- \rightarrow \mu^- \bar{\nu}$ channels across selected $p_T^{\ell, \nu}$ and $|Y|$ bins. A comprehensive list of figures for all fine $p_T^{\ell, \nu}$ and $|Y|$ bins is provided in Ref. [3]. A detailed description of each uncertainty component is presented below:

- The “yield coarse bin” uncertainty represents the yield systematic uncertainty, following the same systematic uncertainty estimation approach as outlined in Section 6.5.7, but derived for each coarse $p_T^{\ell, \nu}$ and $|Y|$ bin individually. The results are presented in Tables 6.8–6.11, with these uncertainties considered fully correlated across the coarse bins.
- The “total shape” uncertainty is similar to the shape systematic uncertainty described in Section 6.5.7. Derived for each coarse $p_T^{\ell, \nu}$ and $|Y|$ bin, it is thus considered fully correlated across the coarse bins. Its components, including Data and MC statistics (Data stat. and MC stat.), as well as the uncertainty due to shape correction (ΔH), are also illustrated. The bins with the highest total shape systematic uncertainty are those with a small fraction of MJ background, driven by the lack of Data or MC statistics in those bins.
- The “acc.corr.closure” uncertainty arises from the acceptance correction, driven by discrepancies between MJ template predictions in the coarse bin by MJ acceptance correction and by a purely data-driven method. As this estimation is at the coarse bin level, this uncertainty is considered fully correlated for fine bins across the coarse bin.

The remaining sources of systematic uncertainties were provided but were not used in the $W A_i$ fit as they were considered too conservative:

- The “acc.corr. (QCD MC stat)” uncertainty represents the MJ systematic uncertainty due to limited MC statistics in the $b\bar{b} + c\bar{c}$ and $JF17$ samples, considered as a fully uncorrelated systematic uncertainty.

- The “acc. corr. itself” uncertainty is associated with the **MJ** acceptance correction function applied to the given fine bin, also considered as a fully uncorrelated systematic uncertainty.

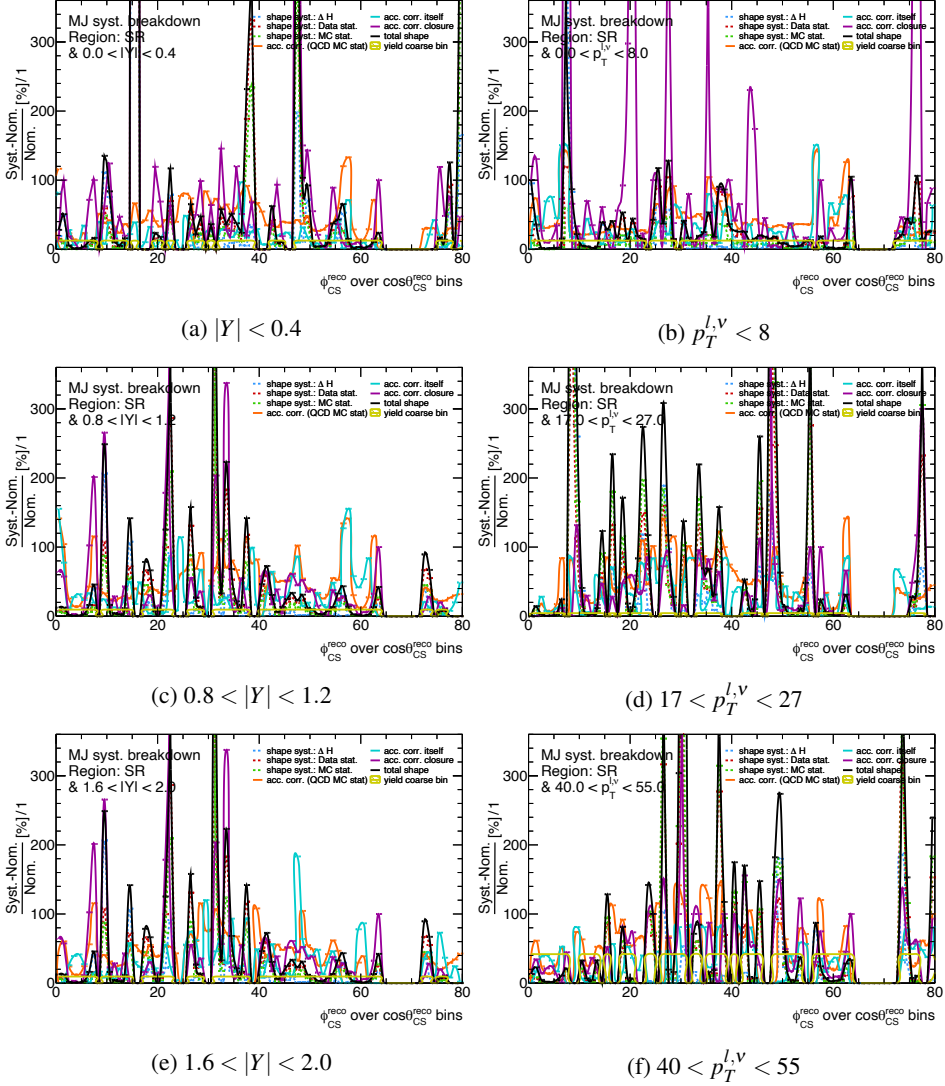


Figure 6.28: Multijet background systematic uncertainties breakdown for flattened 2D distributions of $\cos \theta_{CS}^{reco}$ vs. ϕ_{CS}^{reco} in the $W^- \rightarrow e^- \bar{\nu}$ channel. The uncertainties are shown for specific $|Y|$ bins (left) and $p_T^{l,\nu}$ bins (right).

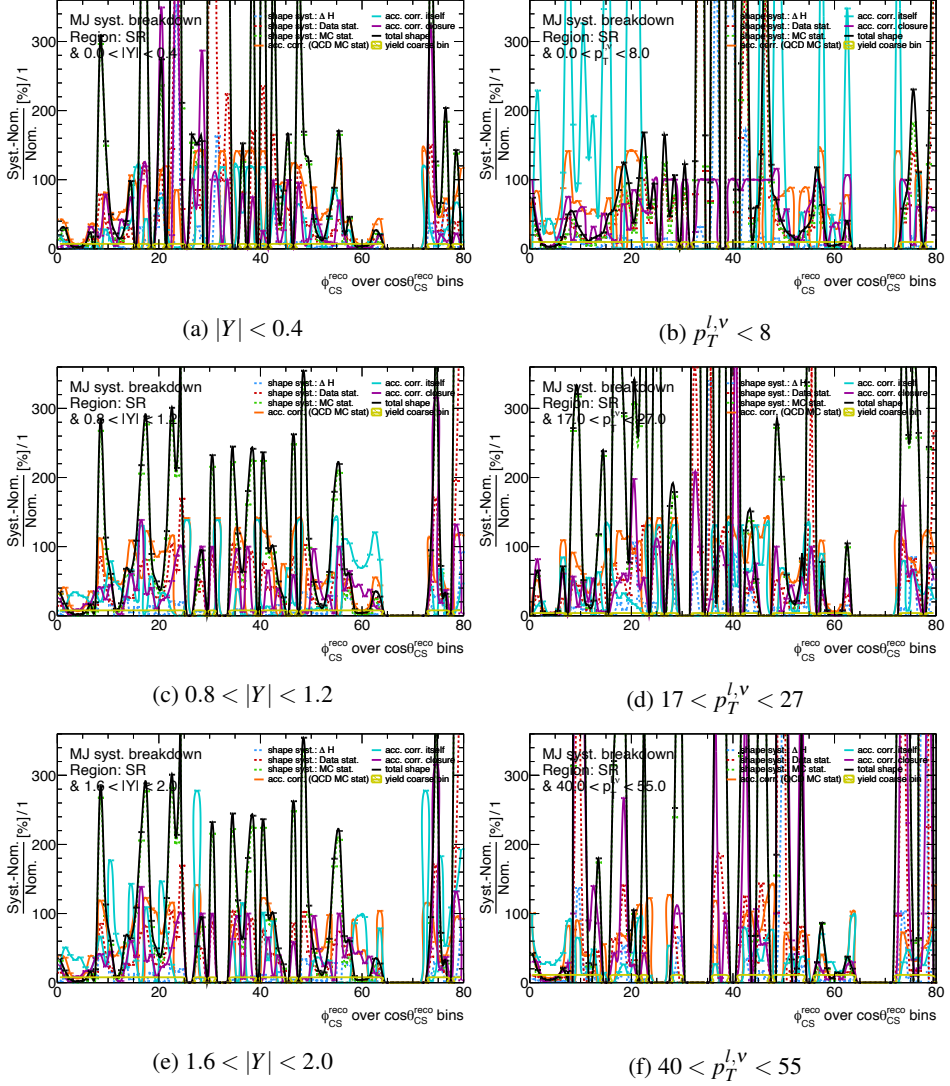


Figure 6.29: Multijet background systematic uncertainties breakdown for flattened 2D distributions of $\cos \theta_{CS}^{reco}$ vs. ϕ_{CS}^{reco} in the $W^- \rightarrow \mu^- \bar{\nu}$ channel. The uncertainties are shown for specific $|Y|$ bins (left) and $p_T^{l,\nu}$ bins (right).

Discussion

The examination of Figures 6.28 and 6.29 reveals distinct characteristics of the MJ systematic uncertainties. Specifically, within the less populated bins of the MJ distribution, the uncertainty increases, sometimes exceeding 300%. These are primarily associated with the `total_shape` and `acc.corr.closure` systematic uncertainties. Nevertheless, these fluctuations in uncertainty do not substantially affect the W - A_i analysis. Their main effect lies in the constraints of the MJ background nuisance parameters during the W - A_i fit, as will be shown in Section 8.2.

The `total_shape` uncertainty, which includes statistics from both data (`Data_stat.`) and MC simulations (`MC_stat.`) in the first anti-isolated slice of the control region 1 (CR1), along with the uncertainty due to shape correction (ΔH), predominantly arises from insufficient data statistics. In order to reduce these sources of systematic uncertainty, increasing the dataset to improve data statistics, as well as generating additional MC simulations, is advisable. The shape correction term (ΔH), representing the discrepancy between the extrapolated shape in the signal region (SR) and the MJ shape of the first slice in CR1, highlights the challenges in MJ shape extrapolation to the SR. Employing a larger number of anti-isolated slices in CR1 will not contribute to a reduction in uncertainty, as the effectiveness of a straightforward increase in anti-isolated slices for enhancing bin-by-bin extrapolation across isolation slices is limited. A more sophisticated method for bin-by-bin extrapolation to the signal region might offer improvement, yet it also runs the risk of revealing potential inaccuracies in the core assumption that the extrapolation across isolation slices is linear. Regardless of the chosen extrapolation technique, augmenting the data volume in CR1 is important to facilitate any prospective improvements.

Upon analysis of the `acc.corr.closure` systematic uncertainty, it is noted that this uncertainty presents less contribution for muons. This increased clarity is attributed to the superior modeling of MJ kinematics by the $b\bar{b} + c\bar{c}$ MC samples for muons MJ acceptance correction, in contrast to the $JF17$ MC sample utilized for electrons acceptance correction. This difference becomes especially pronounced across $p_T^{\ell\nu}$ measurement bins. However, while in bins characterized by a low MJ background population, the `acc.corr.closure` uncertainty remains significant, its impact is considerably reduced in bins with a higher MJ background presence.

In the analysis of bins with a predominant MJ background, it is critical to note that the systematic uncertainties related to MJ shape and acceptance corrections are both manageable and comparable to those linked to MJ yield. Systematic uncertainty related to MJ yield is illustrated in chartreuse green within the systematic breakdown plots, offering a detailed view as outlined in Tables 6.8 to 6.11. To identify the bins significantly impacted by MJ background, please consult the detailed analysis of control plots for fine bins in Section 6.7.2. Moreover, as detailed in Chapter 8, the occurrence of substantial systematic uncertainties in bins with minimal MJ background does not compromise the overall W - A_i fit's sensitivity.

6.7 Control plots

This section presents analysis control plots, showcasing various distributions necessary for evaluating data quality, comprehending background process behaviors, and validating the analysis methodology. Section 6.7.1 introduces control plots for scrutinising kinematic distributions tailored for MJ background estimation, such as p_T^ℓ , E_T^{miss} , m_T^W , and $\Delta\phi(\ell, E_T^{\text{miss}})$. Subsequently, distributions like $p_T^{\ell, \nu}$, $|Y|$, $\cos\theta_{\text{CS}}^{\text{reco}}$, and $\phi_{\text{CS}}^{\text{reco}}$ are displayed to assess data-to-model agreement for significant analysis variables. While these distributions are not directly employed in the analysis fit, they provide insights into detector reconstruction-level agreement between data and simulation. In Section 6.7.2, a collection of plots illustrates flattened 2D $\phi_{\text{CS}}^{\text{reco}}$ vs. $\cos\theta_{\text{CS}}^{\text{reco}}$ distributions across $p_T^{\ell, \nu}$ and $|Y|$ bins, offering a means to examine data-to-model agreement that directly influences the analysis fit.

6.7.1 Inclusive signal region

Control plots for the $W^- \rightarrow e^- \bar{\nu}$ and $W^+ \rightarrow e^+ \nu$ channels (Figures 6.30-6.31) and the $W^- \rightarrow \mu^- \bar{\nu}$ and $W^+ \rightarrow \mu^+ \nu$ channels (Figures 6.32-6.33) at 13 TeV are presented here. These plots are obtained for inclusive signal region after applying the event selection and all the necessary corrections as described in Section 6.3. The ratio plots illustrate only the systematic uncertainty associated with the MJ background, a 0.92% uncertainty due to luminosity, and assumed cross-section uncertainties for MC samples: 5% for single boson samples, 10% for diboson samples, and variable uncertainties for top backgrounds, ranging between 7% and 10%.

Discussion

The overall agreement between Data and Model is satisfactory, falling within the boundaries of systematic uncertainties. Consistency is observed across all four analysis channels, underscoring the robustness of the results. An average discrepancy of approximately 12% in the lower range of the E_T^{miss} distributions, as seen in Figures 6.30-6.33 (b), is attributed to the factors elaborated in the section on hadronic recoil correction (refer to Section 6.5.4). This discrepancy significantly influences the $|\Delta\phi(\ell, E_T^{\text{miss}})|$ and m_T distributions. Nonetheless, the correspondence for key analysis variables ($p_T^{\ell, \nu}$, $y^{\ell, \nu}$, $\cos\theta_{\text{CS}}$, and ϕ_{CS}) remains good.

In the electron and positron channels, the multijet MJ background predominates, constituting 18.9% and 15.6% of the background, respectively. The Z boson decay stands as the secondary source of background, contributing 7.1% and 6.1%, respectively. In contrast, the muon and antimuon channels demonstrate a reduction in the background contributions of the MJ and Z boson, highlighting the inherently cleaner nature of the muon channels. Therefore, notable contamination in the signal region is observed, presenting challenges to the Drell-Yan angular coefficients analysis. However, considering that the control plots presented here are connected to the inclusive signal region, it's necessary to also review the control plots for the more detailed analysis bins used in the actual W - A_i measurements and this will be addressed in the next Section 6.7.2.

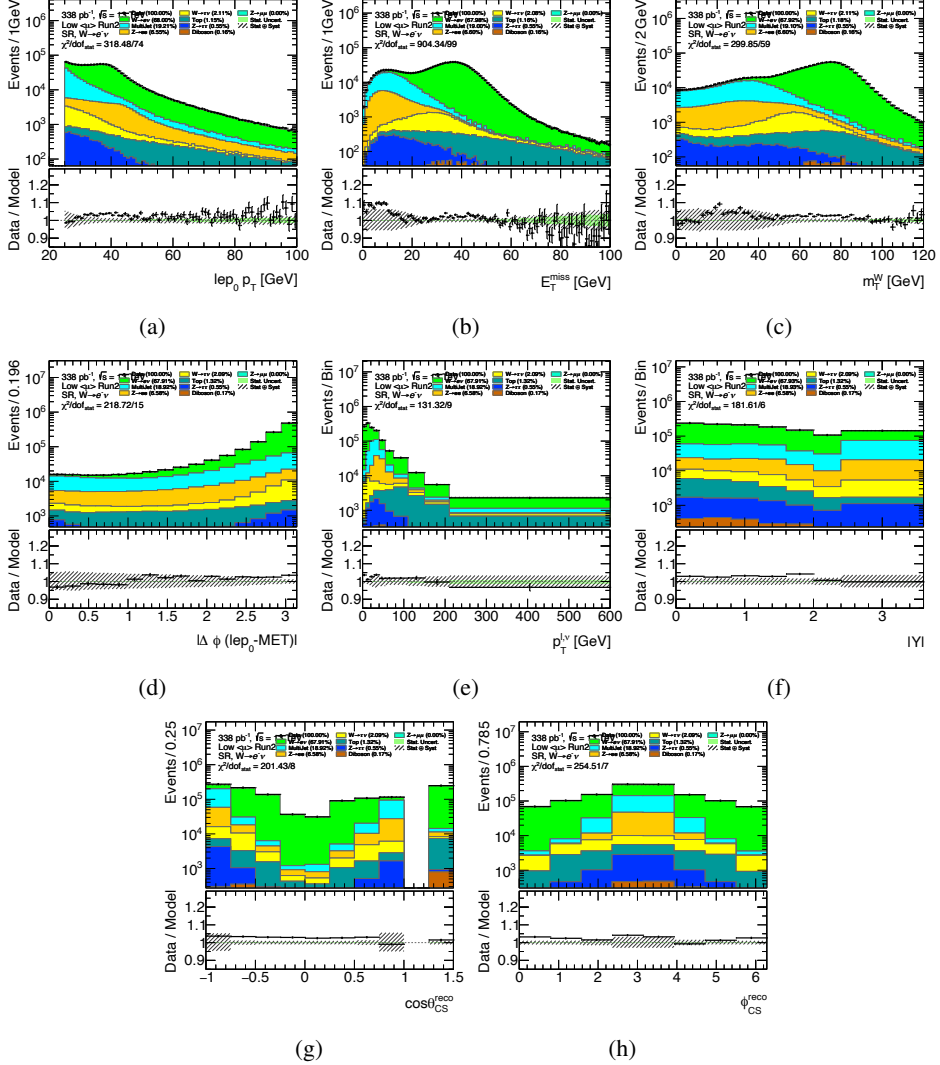


Figure 6.30: Control plots for inclusive signal region for $W^- \rightarrow e^- \bar{\nu}$ channel. The ratio plots illustrate only the systematic uncertainty associated with the **MJ** background, a 0.92% uncertainty due to luminosity, and assumed cross-section uncertainties for **MC** samples: 5% for single boson samples, 10% for diboson samples, and variable uncertainties for top backgrounds.

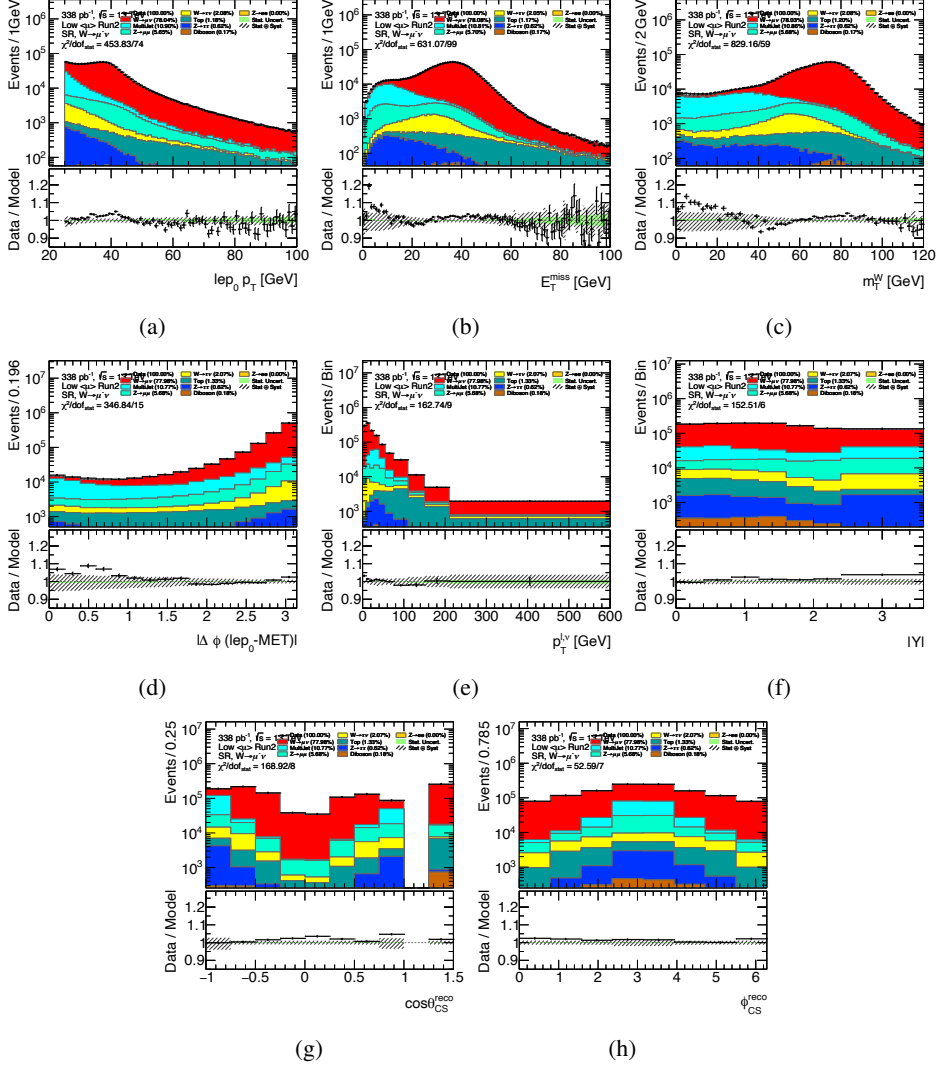


Figure 6.32: Control plots for inclusive signal region for $W^- \rightarrow \mu^- \bar{\nu}$ channel. The ratio plots illustrate only the systematic uncertainty associated with the **MJ** background, a 0.92% uncertainty due to luminosity, and assumed cross-section uncertainties for **MC** samples: 5% for single boson samples, 10% for diboson samples, and variable uncertainties for top backgrounds.

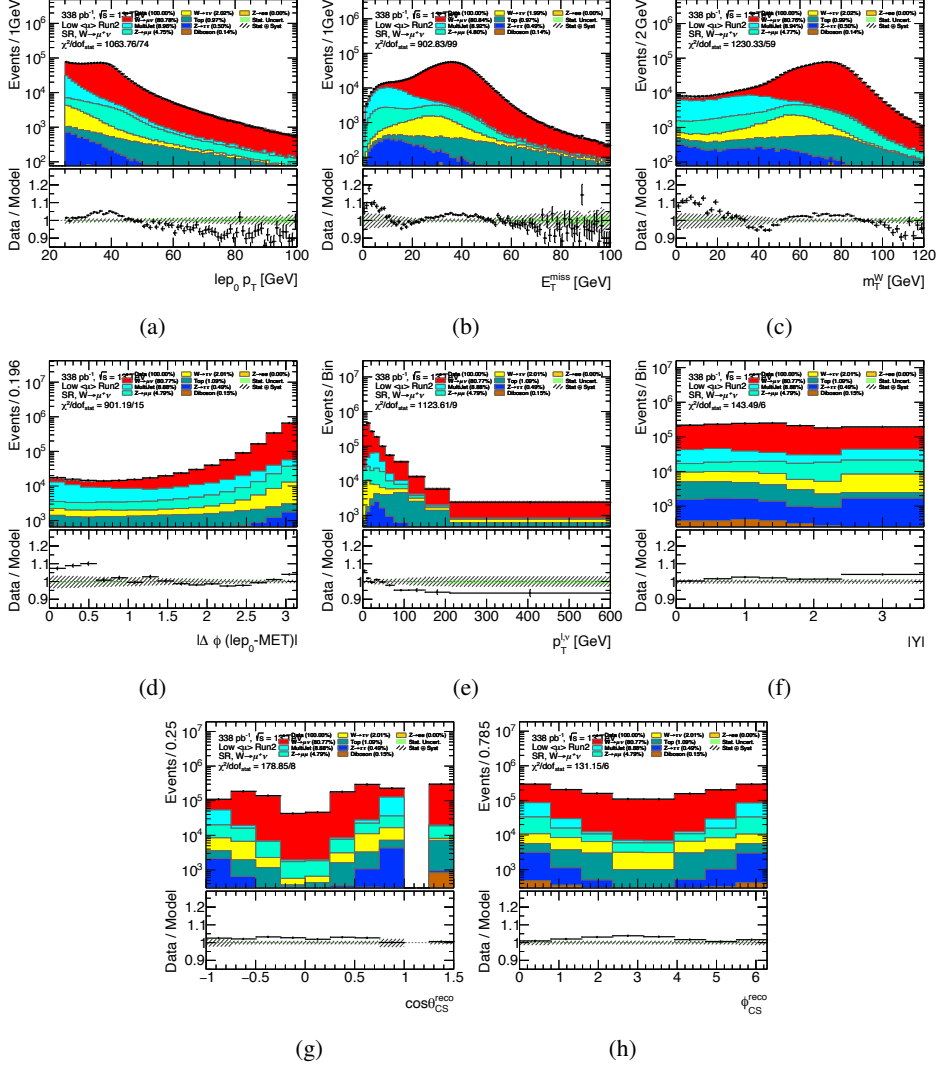


Figure 6.33: Control plots for inclusive signal region for $W^+ \rightarrow \mu^+ \nu$ channel. The ratio plots illustrate only the systematic uncertainty associated with the **MJ** background, a 0.92% uncertainty due to luminosity, and assumed cross-section uncertainties for **MC** samples: 5% for single boson samples, 10% for diboson samples, and variable uncertainties for top backgrounds.

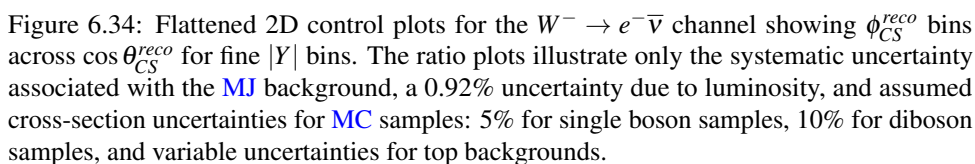
6.7.2 Analysis fine bins

Flattened 2D control plots illustrating the ϕ_{CS}^{reco} vs. $\cos\theta_{CS}^{reco}$ distributions are provided for both the $W^- \rightarrow e^- \bar{\nu}$ and $W^+ \rightarrow e^+ \nu$ channels (Figures 6.34-6.37) and the $W^- \rightarrow \mu^- \bar{\nu}$ and $W^+ \rightarrow \mu^+ \nu$ channels (Figures 6.38-6.41). These plots correspond to different $p_T^{\ell,\nu}$ and $|Y|$ bins, as defined in Equation 6.9. These plots have undergone the necessary event selection and corrections for the fine analysis bins, as detailed in Section 6.6 specifically for **MJ** background estimation. The ratio plots illustrate only the systematic uncertainty associated with the **MJ** background, a 0.92% uncertainty due to luminosity, and assumed cross-section uncertainties for **MC** samples: 5% for single boson samples, 10% for diboson samples, and variable uncertainties for top backgrounds.

Discussion

The control plots of the fine bins also demonstrate a high degree of agreement between the data and the model, with the data aligning well within the presented margins of systematic uncertainty. The first $p_T^{\ell,\nu}$ bin (Figures 6.34-6.41 (a)) among all channels reveals few percents normalisation discrepancies between the data and model predictions, particularly due to the sensitivity of the distribution to the modeling of the W boson's transverse momentum. This $p_T^{\ell,\nu}$ bin highlights the deviation between data and **MC** simulations for both electron and muon channels. Despite this discrepancy, it is important to note that the Drell-Yan W - A_i measurement should remain unaffected, as the analysis is conducted within distinct $p_T^{\ell,\nu}$ bins (more details on W boson- A_i measurement methodology is in Chapter 7).

Given that the **MJ** is the dominant source of background and there was a specific focus on accurate **MJ** background estimation within the finer analysis $p_T^{\ell,\nu}$ and $|Y|$ bins, it's worth noting that the overall **MJ** background estimation across all four analysis channels is considered to be satisfactory. The systematic uncertainties, as illustrated in the ratio plots from Figures 6.34-6.41, are largely influenced by **MJ** systematic uncertainties, which are discussed in Section 6.6.2 for yield systematic uncertainties and in Section 6.6.3 for shape systematic uncertainties. A significant concern was the considerable shape systematic uncertainties (order of 300%) for bins with low **MJ** population, as demonstrated in Figures 6.28 and 6.29 for the $W^- \rightarrow e^- \bar{\nu}$ and $W^- \rightarrow \mu^- \bar{\nu}$ channels. Nonetheless, considering the overall minor contribution of such **MJ**-populated bins, the **MJ** shape systematic uncertainties for bins with low **MJ** contribution are on par or lesser than other systematic uncertainties (like cross-section uncertainties for **MC** samples). In bins predominantly influenced by **MJ** (such as bins 3-6 and 57-62 in Figure 6.34 (a)), the systematic uncertainty is mainly driven by **MJ** yield systematic uncertainty determined in the coarser bins (for given example illustrated in Figure 6.28 (a)).



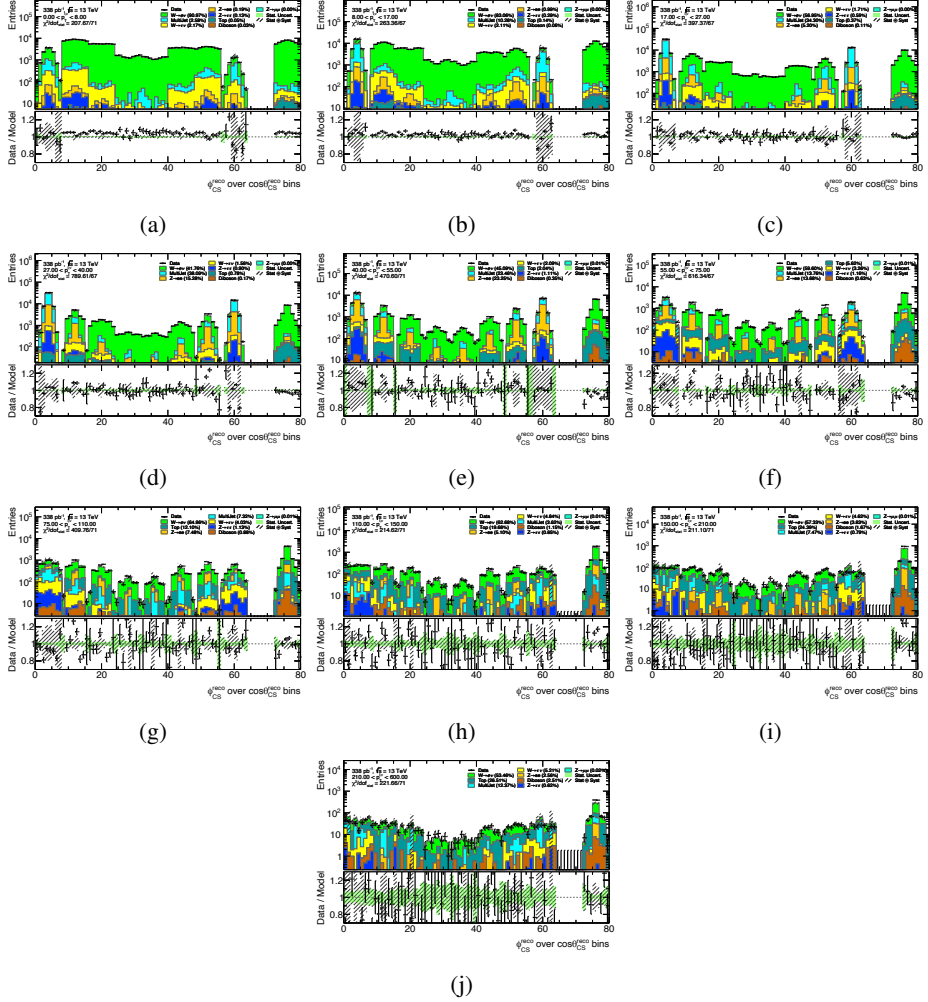


Figure 6.35: Flattened 2D control plots for the $W^- \rightarrow e^- \bar{\nu}$ channel showing ϕ_{CS}^{reco} bins across $\cos\theta_{CS}^{reco}$ for fine $p_T^{\ell,\nu}$ bins. The ratio plots illustrate only the systematic uncertainty associated with the **MJ** background, a 0.92% uncertainty due to luminosity, and assumed cross-section uncertainties for **MC** samples: 5% for single boson samples, 10% for diboson samples, and variable uncertainties for top backgrounds.

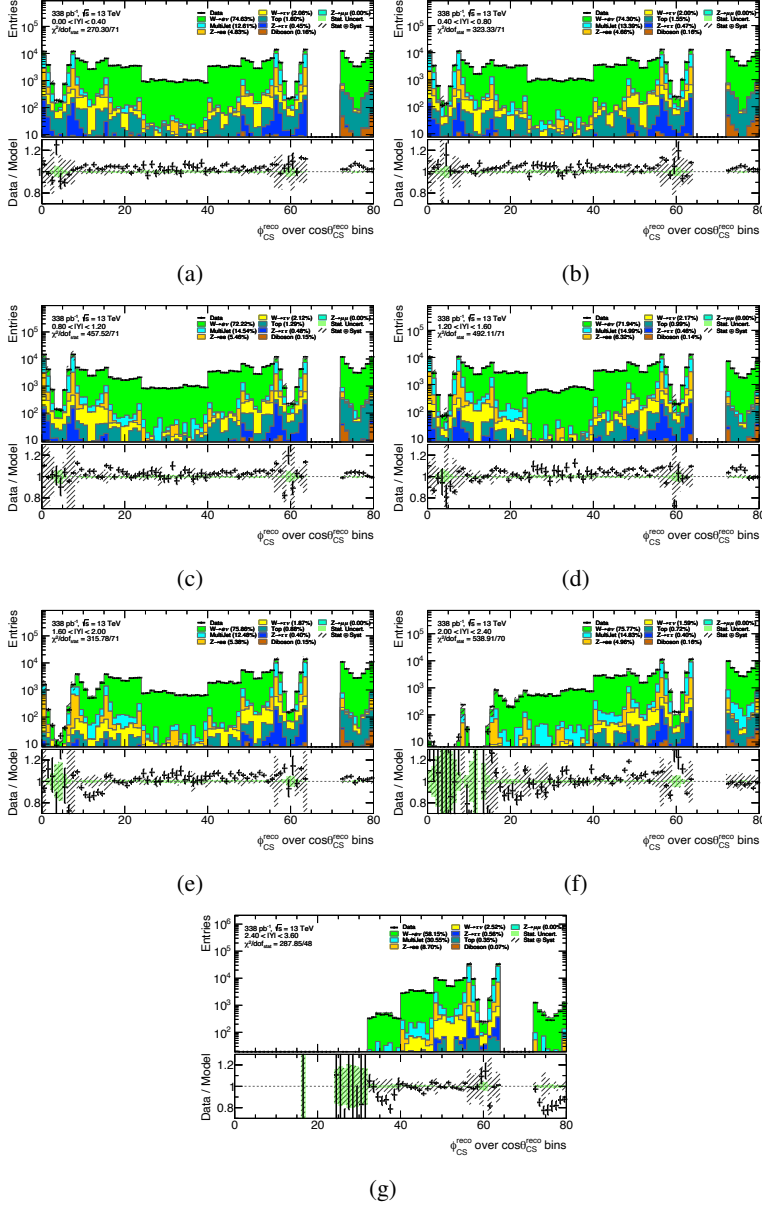


Figure 6.36: Flattened 2D control plots for the $W^+ \rightarrow e^+ \nu$ channel showing ϕ_{CS}^{reco} bins across $\cos \theta_{CS}^{reco}$ for fine $|Y|$ bins. The ratio plots illustrate only the systematic uncertainty associated with the MJ background, a 0.92% uncertainty due to luminosity, and assumed cross-section uncertainties for MC samples: 5% for single boson samples, 10% for diboson samples, and variable uncertainties for top backgrounds.

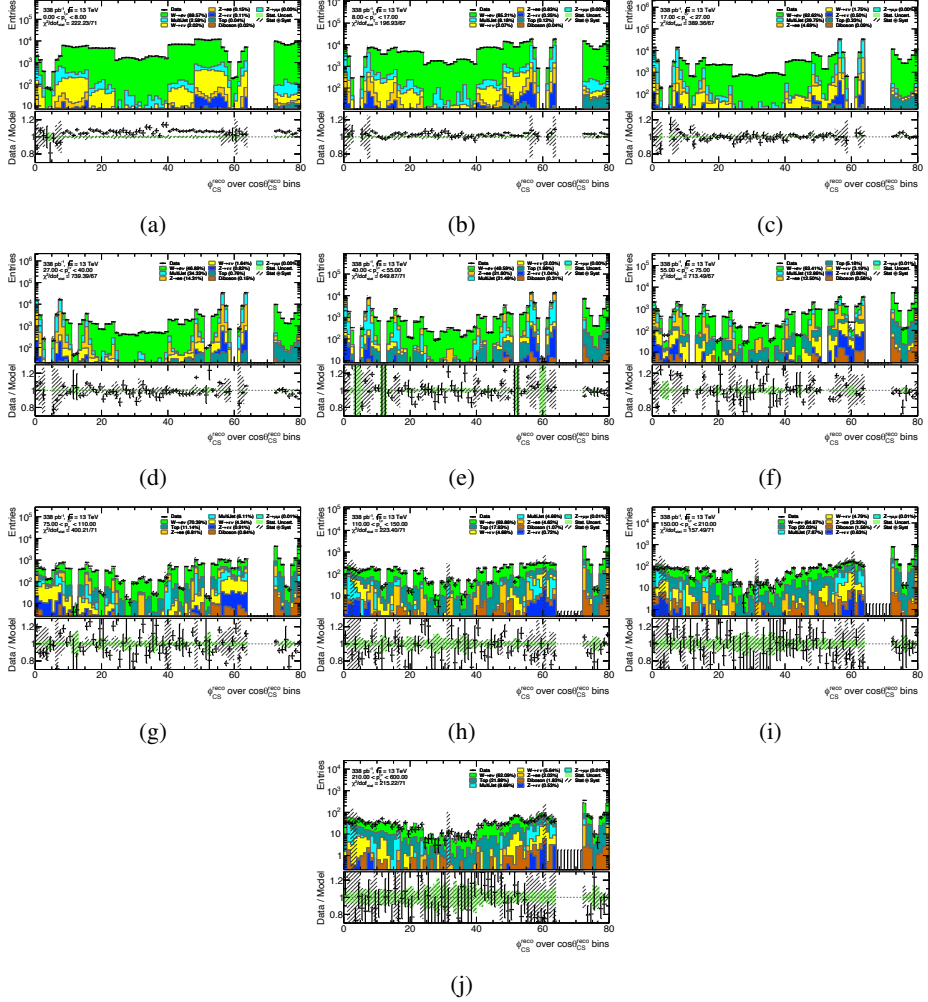


Figure 6.37: Flattened 2D control plots for the $W^+ \rightarrow e^+ \nu$ channel showing ϕ_{CS}^{reco} bins across $\cos \theta_{CS}^{reco}$ for fine $p_T^{\ell, \nu}$ bins. The ratio plots illustrate only the systematic uncertainty associated with the **MJ** background, a 0.92% uncertainty due to luminosity, and assumed cross-section uncertainties for **MC** samples: 5% for single boson samples, 10% for diboson samples, and variable uncertainties for top backgrounds.

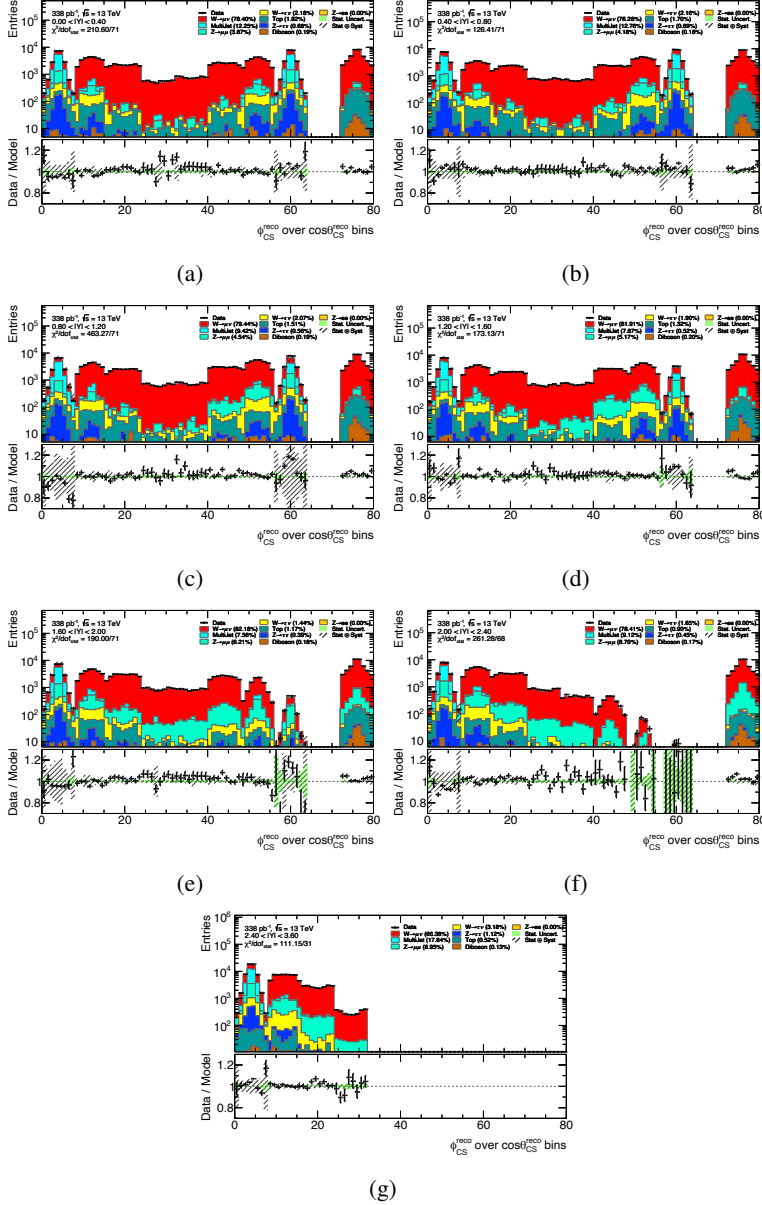


Figure 6.38: Flattened 2D control plots for the $W^- \rightarrow \mu^- \bar{\nu}$ channel showing ϕ_{CS}^{reco} bins across $\cos \theta_{CS}^{reco}$ for fine $|Y|$ bins. The ratio plots illustrate only the systematic uncertainty associated with the **MJ** background, a 0.92% uncertainty due to luminosity, and assumed cross-section uncertainties for **MC** samples: 5% for single boson samples, 10% for diboson samples, and variable uncertainties for top backgrounds.

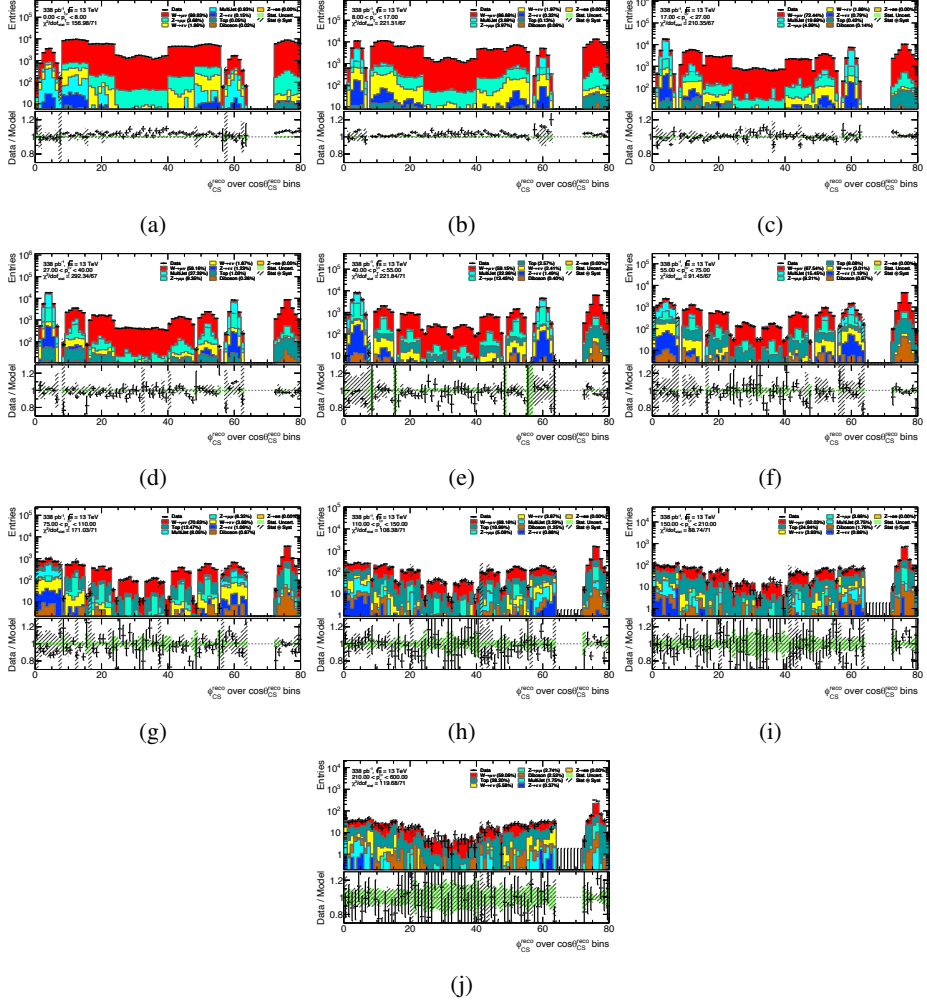


Figure 6.39: Flattened 2D control plots for the $W^- \rightarrow \mu^- \bar{\nu}$ channel showing ϕ_{CS}^{reco} bins across $\cos \theta_{CS}^{reco}$ for fine $p_T^{\ell, \nu}$ bins. The ratio plots illustrate only the systematic uncertainty associated with the **MJ** background, a 0.92% uncertainty due to luminosity, and assumed cross-section uncertainties for **MC** samples: 5% for single boson samples, 10% for diboson samples, and variable uncertainties for top backgrounds.

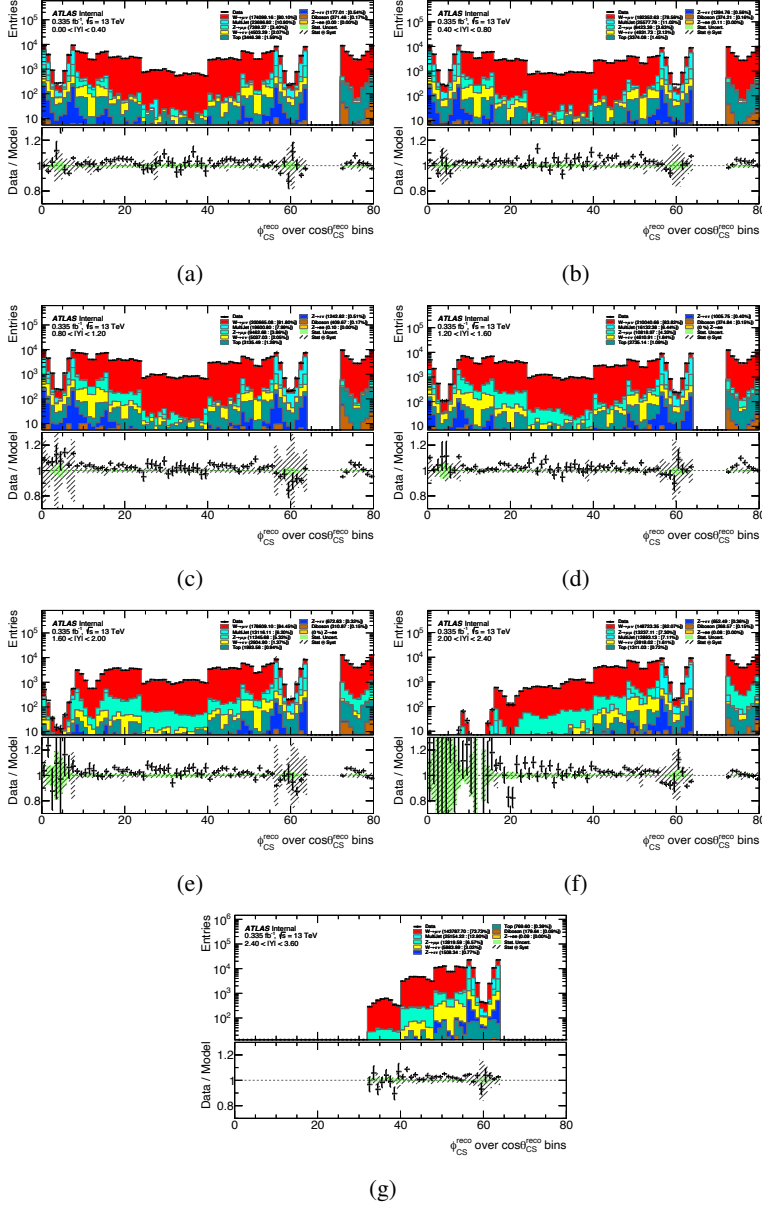
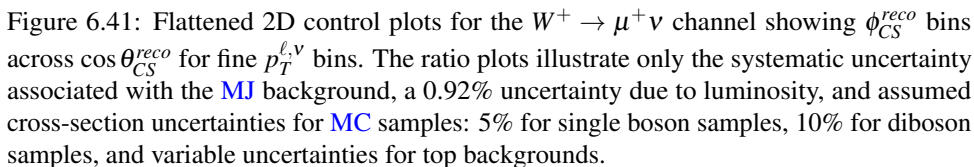


Figure 6.40: Flattened 2D control plots for the $W^+ \rightarrow \mu^+ \nu$ channel showing ϕ_{CS}^{reco} bins across $\cos \theta_{CS}^{reco}$ for fine $|Y|$ bins. The ratio plots illustrate only the systematic uncertainty associated with the **MJ** background, a 0.92% uncertainty due to luminosity, and assumed cross-section uncertainties for **MC** samples: 5% for single boson samples, 10% for diboson samples, and variable uncertainties for top backgrounds.



6.8 Summary

This chapter has established the groundwork for analyzing the Drell-Yan angular coefficients in W decays (W - A_i), based on the findings from the ongoing p_T^W -analysis [169] and utilizing low-pileup data.

The goal of this analysis is to measure the widest possible range of A_i coefficients, despite the limitations of finite statistics. Sensitivity analyses indicated that relaxing kinematic cuts on E_T^{miss} and m_T could enhance sensitivity, particularly for the A_0 and A_4 coefficients, and may allow for the exploration of the Lam-Tung relation at high $p_T^{\ell\nu}$, a correlation not previously measured in W decays (Section 6.3.1). However, the relaxation of kinematic constraints introduced an increase in **MJ** background yield within the signal region. To counterbalance this effect, the analysis group established supplementary selection criteria, particularly implementing a **TightLH** identification criterion for electron channels and an additional calorimeter isolation criterion of $E_T^{\text{cone20}} < 0.05$ across all channels. Specific scale factors were developed to synchronize the data with **MC** samples, adjusting for these new criteria (Section 6.3.2).

Analysis of the electroweak and top background contributions (Section 6.4) identified the **MJ** and Z boson backgrounds as the primary sources of background within the inclusive signal region for all W decay channels ($W^- \rightarrow e^- \bar{\nu}$, $W^+ \rightarrow e^+ \nu$, $W^- \rightarrow \mu^- \bar{\nu}$, and $W^+ \rightarrow \mu^+ \nu$). The significant contribution from the **MJ** background, along with a notable presence of the Z background, underscores the necessity for strict management of these background sources. Although Z background estimation can be managed through **MC** simulations, the dominant **MJ** background demands a data-derived estimation approach.

The author undertook comprehensive **MJ** background studies and formulated a development procedure for **MJ** estimation. Following the general **MJ** estimation approach outlined in Ref. [172], the analysis encountered limitations due to the relaxed kinematic thresholds, confining the **MJ** estimation to two regions instead of four (Section 6.5.1). A correction for hadronic recoil is derived and applied to isolation variables to account for the removal of underlying event and pileup energy during recoil reconstruction (Section 6.5.4). The choice of isolation variables posed unique modeling challenges (Section 6.5.5): E_T^{cone20}/p_T is selected for electron ($e^\pm$) channels, and $p_T^{\text{varcone20}}/p_T$ for muon ($\mu^\pm$) channels. This distinction arises from difficulties in accurately modeling the **MJ** shape across η distributions with track-based isolation variables for electrons. Moreover, it is determined that using E_T^{cone20}/p_T as a universal isolation variable is impractical due to its not proper modeling for muon channels, highlighting the need for channel-specific isolation variables.

The **MJ** background estimation methodology is validated by author using $b\bar{b}$ and $c\bar{c}$ **MC** samples (Section 6.5.6). The analysis of systematic uncertainties associated with the inclusive **MJ** estimation underscored the major influence of variability in linear yield extrapolations as a function of the isolation variable (Section 6.5.7).

The author developed a novel method for **MJ** background acceptance correction, enabling the transfer of **MJ** shapes from coarser to finer analysis bins (Section 6.6.1). This method is particularly relevant for measuring Drell-Yan angular coefficients, which depend on $2D \cos \theta_{\text{CS}}$ vs. ϕ_{CS} distributions across $p_T^{\ell\nu}$ or $y^{\ell\nu}$ bins (as detailed in Chapter 7). Using **MC** samples with kinematics close to **MJ**, this approach enabled the transfer of **MJ** shapes between analysis bins, with systematic uncertainties quantified (Section 6.6.3).

Control plots for the inclusive signal region and finer analysis bins across all four channels, prepared by the author, demonstrated the reliability of the MJ background estimation technique, with predictions aligning well across all bins (Section 6.7). Building on the positive findings at the reconstruction level, the next step involves executing the actual Drell-Yan angular coefficients measurements through the W - A_i fit. Further details on the Drell-Yang angular coefficients measurement methodology will be provided in the forthcoming Chapter 7.

7

DRELL-YAN ANGULAR COEFFICIENTS MEASUREMENT METHODOLOGY

This chapter outlines the core methodology and key steps involved in measuring the Drell-Yan angular coefficients. Utilizing a log-likelihood approach, this method provides a systematic framework for determining and analyzing the angular coefficients. Such an approach has been successfully applied in prior analyses, notably in the study of $Z A_i$ coefficients as documented in Ref. [61], [174], demonstrating its effectiveness and relevance in comparable studies.

The methodology described here primarily focuses on the measurement of A_i angular coefficients as a function of p_T^W , the transverse momentum of the W boson. Nonetheless, the identical approach is adopted for extracting the coefficients in y^W , demonstrating the method's adaptability and consistent applicability across different parameters.

7.1 Moments method

The Moments method, described in this section, represents a robust technique for extracting coefficients from generated MC events, as initially proposed in [50] and later employed in the analysis [61], [174]. This technique enables the clear expression of A_i coefficients as functions of both p_T^W and y^W , whilst ensuring their individual isolation.

At the core of this method is a principle similar to computing the first moment of a probability distribution function, as illustrated by the calculation of the mean value. The mathematical expression of this principle is given by:

$$\mu = \langle x \rangle = \int_{-\infty}^{+\infty} x f(x) dx. \quad (7.1)$$

To extract the coefficients, the moments of the distributions are calculated with respect to a set of trigonometric polynomials $P_i(\theta, \phi)$ (refer to Section 1.2). The calculation process is defined as follows:

$$\langle P_i(\theta, \phi) \rangle = \frac{\int d\sigma(p_T, m, y, \theta, \phi) P_i(\theta, \phi) d\cos\theta d\phi}{\int d\sigma(p_T, m, y, \theta, \phi) d\cos\theta d\phi}. \quad (7.2)$$

This method utilizes the orthogonality of the spherical harmonics associated with the trigonometric polynomials $P_i(\theta, \phi)$, as detailed in Table 1.2, to isolate each coefficient individually. The resulting relationships for each coefficient are as follows:

$$\begin{aligned} \left\langle \frac{1}{2} (1 - 3 \cos^2 \theta) \right\rangle &= \frac{3}{20} \left(A_0 - \frac{2}{3} \right); & \langle \sin 2\theta \cos \phi \rangle &= \frac{1}{5} A_1; \\ \langle \sin^2 \theta \cos 2\phi \rangle &= \frac{1}{10} A_2; & \langle \sin \theta \cos \phi \rangle &= \frac{1}{4} A_3; \\ \langle \cos \theta \rangle &= \frac{1}{4} A_4; & \langle \sin^2 \theta \sin 2\phi \rangle &= \frac{1}{5} A_5; \\ \langle \sin 2\theta \sin \phi \rangle &= \frac{1}{5} A_6; & \langle \sin \theta \sin \phi \rangle &= \frac{1}{4} A_7. \end{aligned} \quad (7.3)$$

It's crucial to underscore that for the moment's definition, as shown in Equation 7.2, a comprehensive integration over the entire lepton phase space is mandatory to ensure the preservation of orthogonality of the polynomials. Therefore, it can only be applied to MC samples.

7.2 Likelihood method

The construction of a likelihood includes the integration of both nominal templates and their varied counterparts, accounting for systematic uncertainties. A set of nuisance parameters (NPs), denoted as $\theta = \{\beta, \gamma\}$, facilitates interpolation between these templates. These NPs are constrained by auxiliary probability density functions.

The first category, represented as β , comprises NPs that encapsulate both experimental and theoretical uncertainties. Each β^m in the set $\beta = \{\beta^1, \dots, \beta^M\}$ is constrained by unit Gaussian probability density functions $G(0|\beta^m, 1)$. These parameters serve as intermediaries between the nominal and varied templates, enabling interpolation. By design, they possess a nominal value of zero, with $\beta^m = \pm 1$ corresponding to $\pm 1\sigma$ variations linked to the specific systematic uncertainty under consideration.

The second category, denoted as γ , includes the nuisance parameters NPs designated to address systematic uncertainties originating from the limited size of the MC samples. Each $\cos\theta_{CS}, \phi_{CS}$ reconstructed bin n corresponds to a specific γ^n within the set $\gamma = \gamma^1, \dots, \gamma^{N_{\text{bins}}}$, where $N_{\text{bins}} = 8 \times 8$ signifies the number of $\cos\theta_{CS}, \phi_{CS}$ bins¹ in each reconstructed kinematic bin (p_T^W, y^W). The nominal value of γ^n defaults to one and serves to normalise the

¹It should be noted that the actual number of $\cos\theta_{CS}, \phi_{CS}$ bins utilized in the fit is 9×8 . This adjustment is due to an additional $\cos\theta_{CS}$ bin created to classify events as either forward ($\cos\theta_{CS} > 0$) or backward ($\cos\theta_{CS} < 0$), ensuring the preservation of ϕ_{CS} shape information for these events. Further elaboration on this adjustment is provided in Section 7.3

expected events within bin n of the templates. These **NPs** are constrained by Poisson probability density functions, expressed as $P(N_{\text{eff}}^n | \gamma^n N_{\text{eff}}^n)$, where N_{eff}^n denotes the effective number of **MC** events in bin n . The descriptor “effective” is employed due to the non-uniform event weights utilised to aptly scale the **MC** samples, which accounts for factors such as detector inefficiencies.

The expected number of events in each bin n can be expressed as:

$$N_{\text{exp}}^n(A, \sigma, \theta) = \left\{ \sum_{j=0}^{N_{\text{bins}}^{\text{ana}}} \sigma_j \times L_{\text{int}} \left[T_{8,j}^n(\beta) + \sum_{i=0}^7 A_{ij} \times T_{ij}^n(\beta) \right] \right\} \times \gamma^n + \sum_B^{\text{bkgs}} T_B^n(\beta) \quad (7.4)$$

In the expression for the expected number of events $N_{\text{exp}}^n(A, \sigma, \theta)$, various parameters and sets of parameters are introduced. The coefficient parameter A_{ij} refers to A_i for observation bin j , and A is the set encompassing all A_{ij} . The signal cross-section parameter for bin j is denoted as σ_j , while σ is the set comprising all σ_j . The set of all **NPs** is represented by θ . The integrated luminosity constant is denoted as L_{int} , and β is the set of all Gaussian-constrained **NPs**. For each bin n , a Poisson-constrained **NP** is represented by γ^n . The template P_i corresponding to bin j is denoted as T_{ij} , and templates representing background contributions are denoted as T_B .

The summation indexed by j accounts for contributions from all truth kinematic bins at the generator level within each reconstructed kinematic bin. This adjustment caters to the migration of events between bins, as elaborated in Chapter 8.1. Bins with significant separation shows minimal contribution, hence, to optimise **CPU** and memory demands, they are pruned if the expected number of events falls below 10^{-4} .

The likelihood is determined by computing the product of Poisson probabilities for all N_{bins} bins, along with the auxiliary constraints for each nuisance parameter β^m :

$$\mathcal{L}(A, \sigma, \theta | N_{\text{obs}}) = \prod_n^{N_{\text{bins}}} \{ P(N_{\text{obs}} | N_{\text{exp}}^n(A, \sigma, \theta)) P(N_{\text{eff}}^n | \gamma^n N_{\text{eff}}^n) \} \times \prod_m^M G(0 | \beta^m, 1) \quad (7.5)$$

Various binning options were investigated, with the final choice being made to maximise the analysis sensitivity. The exact bounderiess for the p_{T}^W bins (in GeV) and y^W bins are specified as follows:

$$p_{T,j}^{W,\text{boundary}} = \{0.0, 8.0, 17.0, 27.0, 40.0, 55.0, 75.0, 110.0, 150.0, 210.0, 600.0\}, \quad (7.6)$$

$$|y_{T,j}^{W,\text{boundary}}| = \{0, 0.4, 0.8, 1.2, 1.6, 2.0, 2.4, 3.6\}. \quad (7.7)$$

7.3 Template folding

A set of observables in the truth space t is defined, characterised by an underlying function $f(t)$. However, various detector effects such as limited acceptance, reconstruction efficiency, and resolution introduce smearing to the observables. As a result, the truth values t are transformed into reconstructed values r with a corresponding distribution $g(r)$. The probability of observing a reconstructed value r given the truth values t is denoted as $p(r|t)$.

This probability can be convolved with the truth distribution to obtain the reconstructed distribution:

$$g(r) = \int f(t) p(r|t) dt \quad (7.8)$$

This process can also be described as folding the truth distribution $f(t)$ through a convolution process to produce the reconstructed distribution $g(r)$.

Similarly, the polynomials used in the decomposition of the differential cross-section can undergo a folding process to describe the reconstructed distributions. In this scenario, the truth variables $t = (\cos \theta_{\text{CS}}^{\text{Truth}}, \phi_{\text{CS}}^{\text{Truth}}, p_{\text{T}}^{W, \text{Truth}})$ and the reconstructed variables $r = (\cos \theta_{\text{CS}}^{\text{Reco}}, \phi_{\text{CS}}^{\text{Reco}}, p_{\text{T}}^{W, \text{Reco}})$ are considered. The folded polynomial $\tilde{P}_{ij}(r|p_{\text{T}}^{W, \text{Truth}} \in (\Delta p_{\text{T}}^{W, \text{Truth}})_j)$ is specifically confined within the finite bin width $(\Delta p_{\text{T}}^{W, \text{Truth}})_j$ and can be mathematically represented as:

$$\tilde{P}_{ij} \left(r | p_{\text{T}}^{W, \text{Truth}} \in (\Delta p_{\text{T}}^{W, \text{Truth}})_j \right) = \int_{(\Delta p_{\text{T}}^{W, \text{Truth}})_j} \int_{\cos \theta_{\text{CS}}^{\text{Truth}}} \int_{\phi_{\text{CS}}^{\text{Truth}}} P_i \left(\cos \theta_{\text{CS}}^{\text{Truth}}, \phi_{\text{CS}}^{\text{Truth}} \right) p(r|t) dt. \quad (7.9)$$

The folded polynomials, denoted as $\tilde{P}_{ij}$, develop a dependency on $p_{\text{T}}^{W, \text{Reco}}$ as a result of the observed migrations in this parameter. This dependency necessitates a distinct consideration from $p_{\text{T}}^{W, \text{Truth}}$. The functions $\tilde{P}_{ij}$ are defined by their $p_{\text{T}}^{W, \text{Reco}}$ dependence, but are organised into bins of $p_{\text{T}}^{W, \text{Truth}}$ using the index j . It is noteworthy to mention that the $\tilde{P}_{ij}$ polynomials serve as continuous representations of the templates T_{ij} , as specified in Equation 7.4.

However, within this particular analysis, the $\tilde{P}_{ij}$ polynomials are not employed directly; they primarily serve as illustrative tools for the underlying principles driving the construction of the actual folded templates that are utilised.

In the absence of analytical expressions for $p(r|t)$, Monte Carlo simulations are leveraged to approximate them. This approximation is realised by calculating the reference coefficients, denoted as A_{ij}^{ref} , utilising the moments method described in Section 7.1. These reference coefficients provide a detailed representation of the 2D angular probability density function (PDF), $f_j(\cos \theta_{\text{CS}}^{\text{Truth}}, \phi_{\text{CS}}^{\text{Truth}})$, across the entire phase space for each $p_{\text{T}}^{W, \text{Truth}}$ bin j :

$$f_j \left(\cos \theta_{\text{CS}}^{\text{Truth}}, \phi_{\text{CS}}^{\text{Truth}} \right) = \sigma_j \left\{ P_8 \left(\cos \theta_{\text{CS}}^{\text{Truth}}, \phi_{\text{CS}}^{\text{Truth}} \right) + \sum_{i=0}^7 A_{ij}^{\text{ref}} P_i \left(\cos \theta_{\text{CS}}^{\text{Truth}}, \phi_{\text{CS}}^{\text{Truth}} \right) \right\}, \quad (7.10)$$

where σ_j represents the differential cross-section within the $p_{\text{T}}^{W, \text{Truth}}$ bin j . For a MC event characterised by a weight w_{event} and corresponding truth and reconstructed variables t and r respectively, an estimation of $p(r|t)$ can be derived using the expression below:

$$p^{\text{MC}}(r|t) = \frac{w_{\text{event}}(r, t)}{f_j \left(\cos \theta_{\text{CS}}^{\text{Truth}}, \phi_{\text{CS}}^{\text{Truth}} \right)}. \quad (7.11)$$

Herein, w_{event} signifies the aggregate product of generator weights and scale factor weights employed in the analysis. Division by f_j addresses the generator dependence on the coefficients used in the template construction. This is contingent upon the MC samples following

the appropriate decomposition and approximating unity. The final templates T_{ij} are then expressed as the summation over all events within each bin j :

$$T_{ij} = \sum_{event \in \Delta_j} \frac{P_i(\cos \theta_{CS}^{\text{Reco}}, \phi_{CS}^{\text{Reco}}) w_{\text{event}}(r, t)}{\sigma_j \left\{ P_8(\cos \theta_{CS}^{\text{Truth}}, \phi_{CS}^{\text{Truth}}) + \sum_{i=0}^7 A_{ij}^{\text{ref}} P_i(\cos \theta_{CS}^{\text{Truth}}, \phi_{CS}^{\text{Truth}}) \right\}}, \quad (7.12)$$

where Δ_j represents the bins of observables associated with the event, which can be expressed as $(\Delta p_T^{W, \text{Truth}})_j$, $(\Delta p_T^{W, \text{Reco}})_j$, $(\Delta \cos \theta_{CS}^{\text{Reco}})_j$, and $(\Delta \phi_{CS}^{\text{Reco}})_j$. Illustrative examples of the templates for $p_T^{W, \text{Truth}}$ bins can be observed in Figures 7.1 and 7.2.

The templates are divided into 10 bins for $\cos \theta_{CS}$, covering the range from -1 to 1.5 , and into 8 bins for ϕ_{CS} , spanning the range from 0 to 2π :

$$\cos \theta_{CS} = \{-1.0, -0.75, -0.5, -0.25, 0., 0.25, 0.5, 0.75, 1.0, 1.25, 1.5\}, \quad (7.13)$$

$$\phi_{CS} = \{0, \pi/4, \pi/2, 3\pi/4, \pi, 5\pi/4, 3\pi/2, 7\pi/4, 2\pi\}. \quad (7.14)$$

To address events where no real solution for p_z^v exists, the range for $\cos \theta_{CS}$ is extended beyond the initial 8 bins. This expansion includes an additional unphysical empty bin for $\cos \theta_{CS}$ with boundaries at 1.0 and 1.5 , alongside a physical bin with boundaries at 1.25 and 1.5 . As detailed in Section 5.6, this extension aims to preserve the inherent shape of $\cos \theta_{CS}$ devoid of distortion. The first bin is not included in the final distribution, as it serves solely to for illustrative purposes and is excluded during the distributions pruning process. The following $\cos \theta_{CS}$ bin is designed to include events identified as either forward ($\cos \theta_{CS} > 0$) or backward ($\cos \theta_{CS} < 0$), thereby preserving the shape information of ϕ_{CS} for these events. In Figures 7.1 and 7.2, these extensions are presented as separate bins within the range of 1.0 to 1.25 and 1.25 to 1.5 . It is important to acknowledge that the templates are weighted by the polynomials, as outlined in Equation 7.12, which may occasion negative values in specific bins. The notable differences in scale for each A_i coefficient can be attributed to the unique sensitivity of each coefficient to specific physical effects within the W boson decay process, leading to observed scale variations (see Section 1.2).

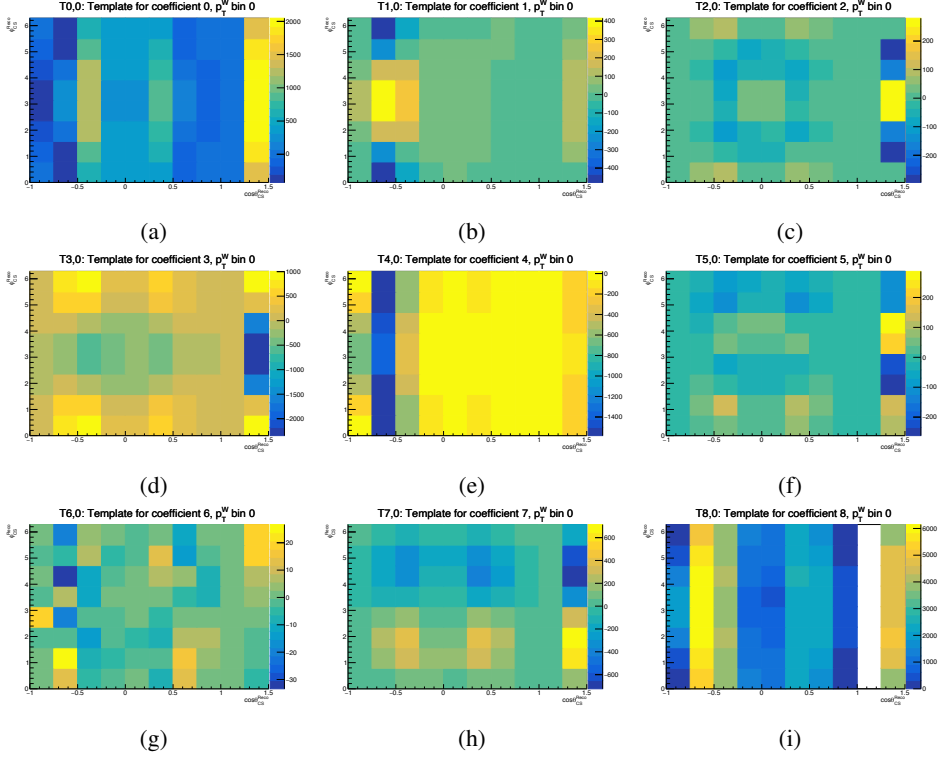


Figure 7.1: Folded polynomial templates projected onto the $(\cos \theta_{\text{CS}}^{\text{Reco}}, \phi_{\text{CS}}^{\text{Reco}})$ plane for $p_T^{W, \text{Truth}}$ bin 0 ($p_T^W < 8$ GeV) for $W^- \rightarrow e^- \bar{\nu}$. The templates are weighted by the polynomials resulting in negative values in some bins.

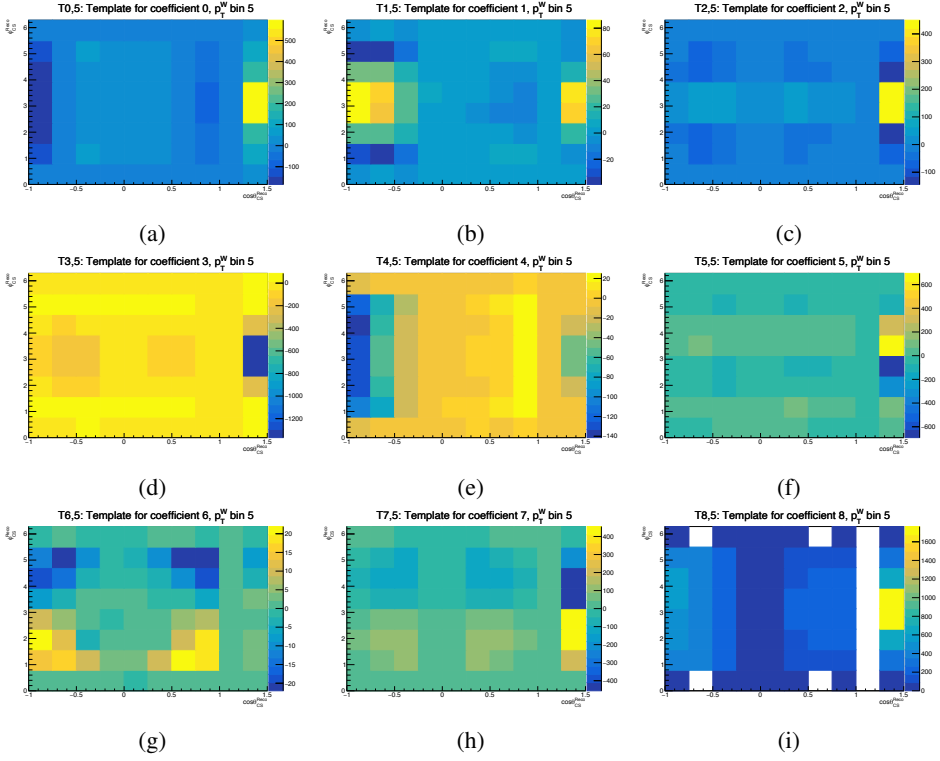


Figure 7.2: Folded polynomial templates projected onto the $(\cos \theta_{\text{CS}}^{\text{Reco}}, \phi_{\text{CS}}^{\text{Reco}})$ plane for $p_{\text{T}}^{W, \text{Truth}}$ bin 5 ($55 < p_{\text{T}}^W < 75$ GeV) for $W^- \rightarrow e^- \bar{\nu}$. The templates are weighted by the polynomials resulting in negative values in some bins.

8

UNCERTAINTIES IN DRELL-YAN ANGULAR COEFFICIENTS MEASUREMENT

This chapter extends the discussion on uncertainties that were partially introduced in Chapter 6. The earlier focus was primarily on the impact of these uncertainties at the reconstruction level, with a special emphasis on achieving Data to Model agreement, especially in the context of the development and study of MJ background estimation techniques. The analysis at that stage evaluated how the selected uncertainties influenced the control plots at the reconstruction level, aiming to ensure robustness in the MJ background estimation process.

However, the scope of this chapter is broader, providing a detailed overview of all the uncertainties that play a role in the measurement of the W - A_i coefficients. It also goes a step further by presenting a systematic breakdown of uncertainties obtained through the analysis of pseudodata, complemented by a short discussion on the features of the W - A_i fit.

8.1 Overview of uncertainties

This section addresses the various sources of uncertainty that contribute to W - A_i analysis. It covers statistical uncertainties (Section 8.1.1), theoretical uncertainties (Section 8.1.3), and experimental uncertainties (Section 8.1.2), including the systematic contributions arising from the MJ background estimation.

The methodology adopted for this analysis, as detailed in Chapter 7, mirrors the approach used in the Z angular coefficient measurement at $\sqrt{s} = 8$ TeV [61], [174]. Like the Z - A_i measurement, this analysis will also show that the predominant source of uncertainty originates from statistical fluctuations in the data, as discussed in Section 8.2. Consequently, this implies that other sources of uncertainties could potentially be estimated with a more conservative level of precision.

For an exhaustive list of the nuisance parameters employed in this analysis, refer to Appendix B.1.

8.1.1 Statistical uncertainties

Uncertainties arising from finite data statistics are categorised into several groups, as illustrated in Table 8.1 using the example of A_0 in the $p_T^{W,\text{Truth}}$ bin 0. These uncertainties linked to the parameter of interest are denoted as data-stat uncertainties, where the most substantial impact stems from the available data statistics, although the resolution in the angular binning also contributes. Each column corresponds to a specific coefficient, while the rows correspond to the $p_T^{W,\text{Truth}}$ bin. To clarify, the first column represents parameters within the same $p_T^{W,\text{Truth}}$ as the parameter of interest, while rows 2 – 8 relate to other coefficients and are termed *shape* parameters, characterised by their non-migrational nature. The first row corresponds to parameters associated with the same coefficient but in different $p_T^{W,\text{Truth}}$ bins, defined as *self-migrational* parameters. Furthermore, the interaction between different $p_T^{W,\text{Truth}}$ values and coefficient numbers is referred to as *cross-migration*. Notably, the separation extends to normalisation factors, categorised as *norm* and *norm-migration*. Furthermore, a non-migrational uncertainty arises due to uncorrelated statistical fluctuations within the likelihood fit.

Detailed insights into the individual migration uncertainty categories for each coefficient can be found in the reference [3]. It is important to emphasise that both self and norm migrations exert an influence on each A_i coefficient, whereas the differential cross-section, A_9 , is solely impacted by norm migration. This distinction arises from the fact that the coefficients represent ratios, and their measurements are inherently tied to both their individual values and the normalisation, whereas A_9 solely quantifies the normalisation aspect.

MC statistical uncertainties are considered to be uncorrelated across the bins within the 3D distribution. This is based on the understanding that while the same set of MC events contributes to the construction of each template, these events receive varying weights from the different polynomials, leading to partial correlation. A similar approach was discussed in the Z angular coefficient measurement at $\sqrt{s} = 8$ TeV [61], [174], where it was shown that assuming complete correlation among the templates yields nearly identical outcomes compared to a more detailed treatment. This assumption is also adopted in the present analysis.

Given that the statistical uncertainties in the data largely dominate this measurement, certain effects related to migrations between $p_T^{W,\text{Truth}}$ bins can lead to anti-correlations between these bins. This can amplify the impact of statistical fluctuations and the resultant anti-correlations from migrations between $p_T^{W,\text{Truth}}$ bins, which obscure the identification of underlying A_i spectra structures. To address the challenges, the same regularization scheme was used as detailed in Ref. [174]. By regularization the model's interpretability is refined by smoothing the spectra, achieved through imposing Gaussian penalty terms on the significance of higher-order derivatives with respect to $p_T^{W,\text{Truth}}$. This method integrates additional, prior knowledge about the parameter distributions into the analysis, drawing parallels to the principles of regularised Bayesian unfolding described in Ref. [175]. The application of this regularization strategy balances the reduction of statistical noise against the introduction of a controlled level of bias, considered as an acceptable compromise for the analysis. This bias, a direct consequence of the regularization's model-dependent assumptions, is important for enhancing the analysis's robustness, enabling a significant reduction in point-to-point variability and the smoothing of A_i coefficient spectra.

		$\leftarrow p_T^W \text{ bin } \rightarrow$				
		0	1	...	...	9
Coefficient $\uparrow$	$A_{0,0p_T}$	$A_{0,1p_T}$	...	Self-migration	...	$A_{0,9p_T}$
	$A_{1,0p_T}$	$A_{1,1p_T}$				$A_{1,9p_T}$
	...					
	Shape			Cross-migration		
	...					
	$A_{7,0p_T}$	$A_{7,1p_T}$				$A_{7,9p_T}$
Coefficient $\downarrow$	$\mu_{0,\text{norm}}$	μ_1	...	Norm-migration	...	μ_9

Table 8.1: Classification of parameters contributing to the data-statistical uncertainty for the measured coefficients, as an example for A_0 in $p_T^{W,\text{Truth}}$ bin 0.

8.1.2 Experimental uncertainties

The primary experimental uncertainties affecting this measurement are expected to arise from hadronic recoil, resolution, and calibration of the signal. Uncertainties on the **MJ** and **EW**+top background estimate also fall into experimental uncertainties category. While systematic uncertainties related to leptons are also considered, they are expected to have a relatively minor influence. Importantly, these experimental uncertainties have an effect solely on the numerator of the templates, as outlined in Section 7.3.

The hadronic recoil (discussed in Section 5.5) is anticipated to be the predominant experimental systematic uncertainty in this measurement. It involves 62 nuisance parameters classified into six categories: statistical uncertainty on the resolution correction, statistical uncertainty on the response correction, systematic uncertainty on the response correction, systematic uncertainty on the ΣE_T correction, systematic uncertainty on the resolution correction due to the extrapolation from Z to W , and systematic uncertainty on the response correction due to the extrapolation from Z to W . Detailed information about these corrections can be found in the support note [152]. To observe the effects of the variations in the nuisance parameters (**NPs**) related to the hadronic recoil on the angular distributions for the $W^- \rightarrow e^- \bar{\nu}$ channel, refer to Reference [3].

Lepton-related systematic uncertainties connected to lepton calibration and efficiency corrections (as discussed in Section 6.3) have a secondary impact on this analysis. Specifically, for electron channels, the efficiency scale factors are distinguished for identification, isolation, reconstruction, and trigger. Similarly, for muon channels, these factors are differentiated for isolation, reconstruction, sagitta bias, trigger, and track-to-vertex association. In general on the reconstruction level, the uncertainty associated with scale factors at a precision typically better than 1%, while the calibration has even smaller impact as demonstrated in [144] and [149].

The uncertainties associated with the **EW**+top background estimates are treated as flat uncertainties on their corresponding cross-sections. Specifically, a 5% uncertainty is assumed for single boson samples, 10% for diboson samples, and variable percentages ranging between 7% and 10% for top backgrounds. More comprehensive details for each sample can be found in Table 6.1 in Section 6.2. These variations are divided into three categories, leading to a total of three nuisance parameters, classified by background type:

boson, diboson, and top. To mitigate the uncertainty in the shape of the $t\bar{t}$ background, an alternative collection of $t\bar{t}$ background MC samples employing HERWIG 7 for simulation was utilized, in contrast to the original set which used POWHEG.

The uncertainties linked to the multijet background estimation are covered in Section 6.6.3. These uncertainties are divided into three categories: yield, shape, and acceptance correction uncertainties. The yield and shape uncertainties contribute to a total of $(2 \times 10) = 20$ nuisance parameters, which are treated as fully correlated across all $p_T^{\ell\nu}$ and $y^{\ell\nu}$ bins. Additionally, there are 10 acceptance correction uncertainties, which are correlated within coarse $p_T^{\ell\nu}$ and $y^{\ell\nu}$ bins (see Eq. 6.10).

8.1.3 Theoretical uncertainties

The only theoretical uncertainties considered relate to the Parton Distribution Functions (PDFs), which affect both the numerator and denominator of the templates. These PDF uncertainties are parameterised by 26 NPs and are of lesser significance for $A_0 - A_7$. For the differential cross-section, they contribute at approximately $\sim 3\%$.

Other theoretical uncertainties, such as those stemming from parton shower modeling, generator modelling, and QED/electroweak corrections, are not included in this analysis. These were considered negligible based on the Z angular coefficient measurement at $\sqrt{s} = 8$ TeV [61], [174], which demonstrated greater precision than the current measurement.

8.2 Systematic uncertainties with pseudodata

A pseudodata test is a simulation-based method used to validate data analysis strategies, estimate uncertainties, and test the statistical properties of estimators. It involves generating data samples through model simulation samples that closely mimic the statistical properties of real experimental data, including the effects of background noise, signal processes, and systematic uncertainties. These simulated samples, called pseudodata, allows to identify potential biases, understand the limits of analysis techniques, and make adjustments before applying them to actual experimental data.

Uncertainties breakdown

The pseudodata fit was performed for this analysis. Figures 8.1-8.4 and 8.5-8.8 present a comprehensive summary of the breakdown of the post-fit systematic uncertainties for all contributions across the four analysis channels ($W^- \rightarrow e^-\bar{\nu}$, $W^+ \rightarrow e^+\nu$, $W^- \rightarrow \mu^-\bar{\nu}$, $W^+ \rightarrow \mu^+\nu$), in both $p_T^{\ell\nu}$ and $y^{\ell\nu}$ bin measurements.

Variation in uncertainty contributions exists among the A_i coefficients, with notable similarities. The analysis is primarily limited by statistics due to the low event count in low- μ data. The subsequent major systematic source is MC statistical uncertainty, stemming from MC sample sizes, being roughly one-third of the data-statistical uncertainty. Following is the MJ background uncertainty, which, despite an initially conservative estimate by the MJ background estimation algorithm, is constrained by the fit, reducing its impact to be on

par with other systematics. This fit sensitivity to **MJ** feature was expected since first Asimov data¹ tests documented in Appendix B.2.

The inspection on uncertainties breakdown plots demonstrates a consistent pattern across all four channels of measurement for both transverse momentum ($p_T^{\ell\nu}$) and rapidity ($y^{\ell\nu}$) analyses. In the case of $p_T^{\ell\nu}$, the total uncertainties for the A_i coefficients, as shown in Figures 8.1-8.4 (a-h), are largely governed by the statistical uncertainty inherent in the data, which shows a growth at higher $p_T^{\ell\nu}$ values. This trend is similarly observed in the differential cross-section, presented in Figures 8.1-8.4 (i), although the representation of absolute uncertainty might not convey this pattern.

When examining the uncertainties over $y^{\ell\nu}$ bins, it's noted that they are fairly uniform across the range, with the exception of the last $y^{\ell\nu}$ bin ([2.4, 3.6]). The analysis selection criteria, which require at least one lepton with $p_T^\ell > 25$ GeV, play a significant role here. Due to collision geometry and decay kinematics, leptons from W boson decays at higher rapidities tend to have lower p_T^ℓ compared to those at lower rapidities. This makes them more likely to fall below the p_T^ℓ threshold, thereby event being excluded from the analysis. The selection criteria for this analysis do not impose any requirements on E_T^{miss} , thus minimizing the impact of E_T^{miss} reconstruction challenges at higher rapidities on the analysis outcomes.

Pull distributions

Despite access to expected systematic uncertainties obtained in test fit using pseudodata, the pull plot serves as a crucial statistical instrument for assessing the fidelity and precision of measurements or fit parameters. The methodology involves aggregating the “pull” values, where each is calculated as the deviation of a measured value from its true (or expected) value, normalized by the associated uncertainty of the measurement $(\theta - \theta_0)/\Delta\theta$, where θ represents the measured value, θ_0 represents the true (or expected) value, and $\Delta\theta$ is the $\pm 1\sigma$ uncertainty associated with the measurement. The utilization of pull plots is instrumental in verifying the accuracy of uncertainty estimations and confirming the absence of bias in the measurements. An ideal pull distribution closely aligns with a standard normal distribution, characterized by a mean of 0 and a standard deviation of 1. This alignment signifies that the measurements are both accurate and that the uncertainties have been correctly assessed.

Figures 8.9 and 8.10 display the pull distributions for the $W^- \rightarrow e^-\bar{\nu}$, $W^+ \rightarrow e^+\nu$, $W^- \rightarrow \mu^-\bar{\nu}$, and $W^+ \rightarrow \mu^+\nu$ channels in the measurements of $p_T^{\ell\nu}$ and $y^{\ell\nu}$, respectively.

The **MJ** background nuisance parameters are significantly constrained, a phenomenon attributable to two main factors. Initially, as it's already mentioned, the **MJ** background estimates are set conservatively, allowing for a wide margin of uncertainty. However, the selection of the fit region configuration enhances the fit's sensitivity to **MJ** background characteristics, resulting in substantial constraints on the associated **NPs**.

¹An Asimov dataset is a synthetic dataset created to precisely align with model predictions, seamlessly integrating systematic uncertainties.

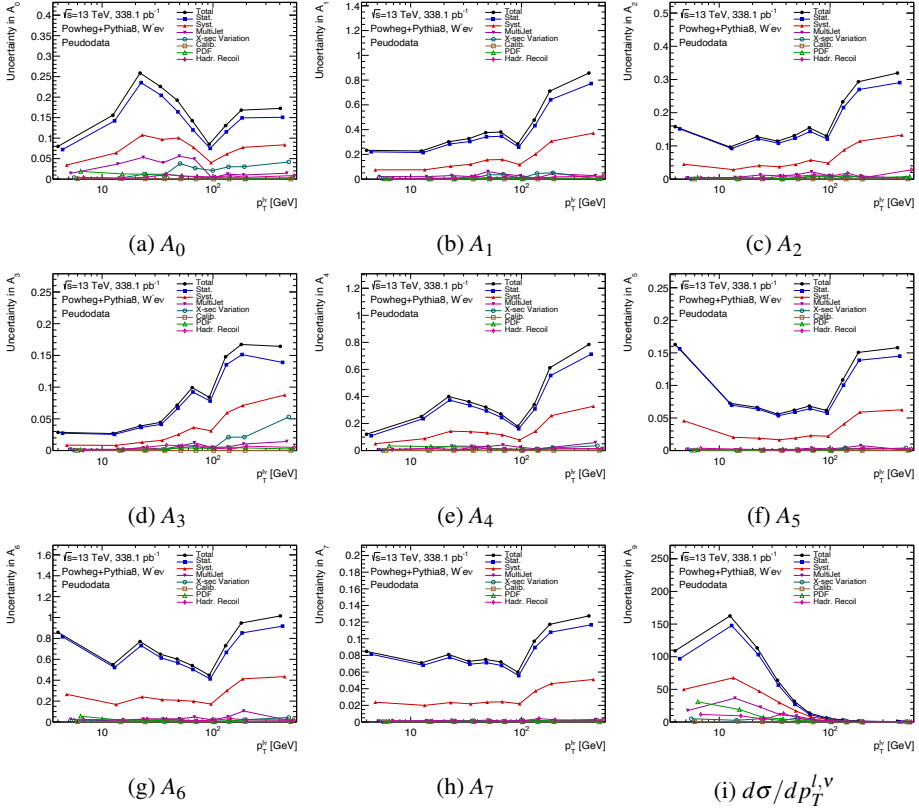


Figure 8.1: The post-fit uncertainty comparison for all contributions in the $W^- \rightarrow e^- \bar{\nu}$ channel for measurement in $p_T^{\ell\nu}$ on pseudodata. Blue is the total statistical uncertainty, red is the total systematic uncertainty, and black is the combination of the statistical and systematic uncertainties. The components of the systematic uncertainty are presented in grouped form. Detailed listings of each systematic category can be found in Tables B.1 and B.2.

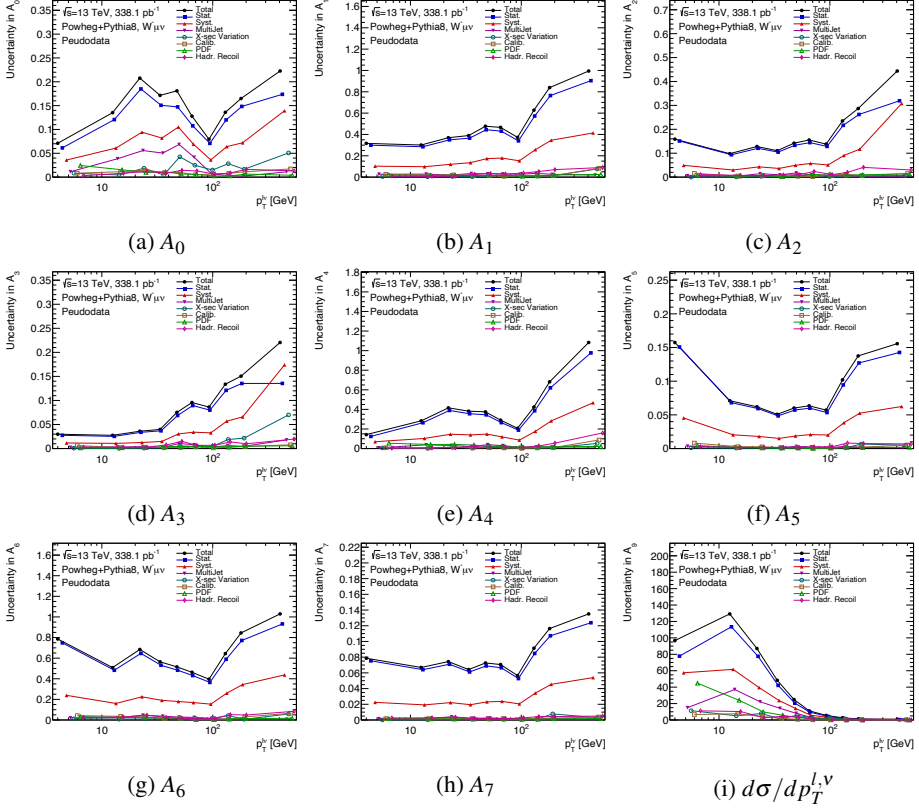


Figure 8.2: The post-fit uncertainty comparison for all contributions in the $W^- \rightarrow \mu^- \bar{\nu}$ channel for measurement in $p_T^{\ell\nu}$ on pseudodata. Blue is the total statistical uncertainty, red is the total systematic uncertainty, and black is the combination of the statistical and systematic uncertainties. The components of the systematic uncertainty are presented in grouped form. Detailed listings of each systematic category can be found in Tables B.1, B.3, and B.4.

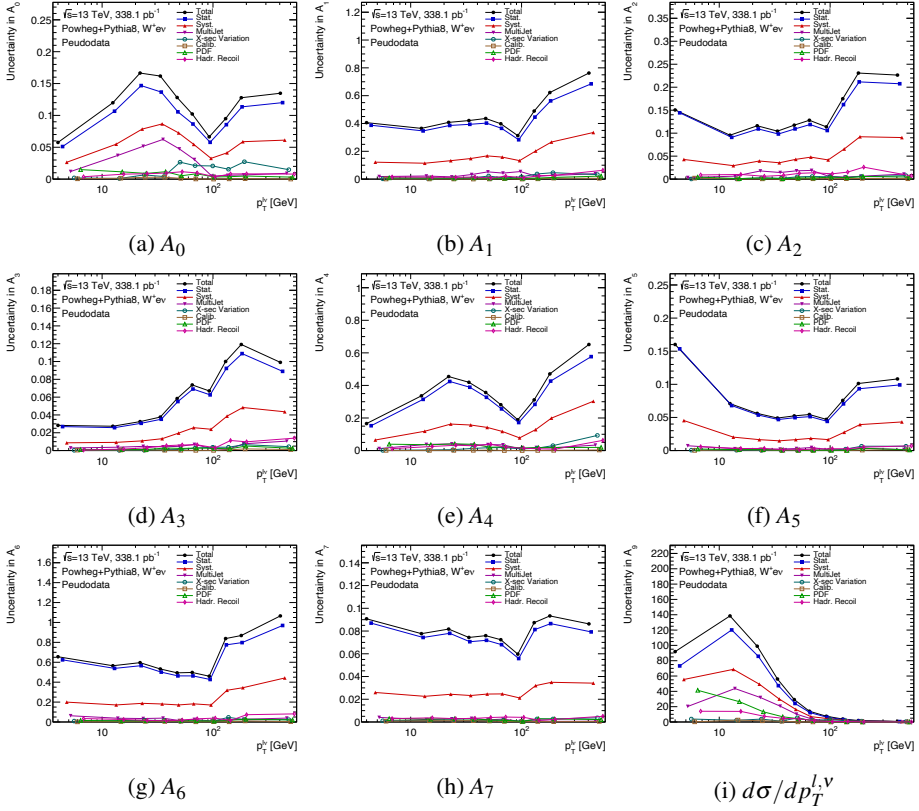


Figure 8.3: The post-fit uncertainty comparison for all contributions in the $W^+ \rightarrow e^+ \nu$ channel for measurement in $p_T^{\ell\nu}$ on pseudodata. Blue is the total statistical uncertainty, red is the total systematic uncertainty, and black is the combination of the statistical and systematic uncertainties. The components of the systematic uncertainty are presented in grouped form. Detailed listings of each systematic category can be found in Tables B.1 and B.2.

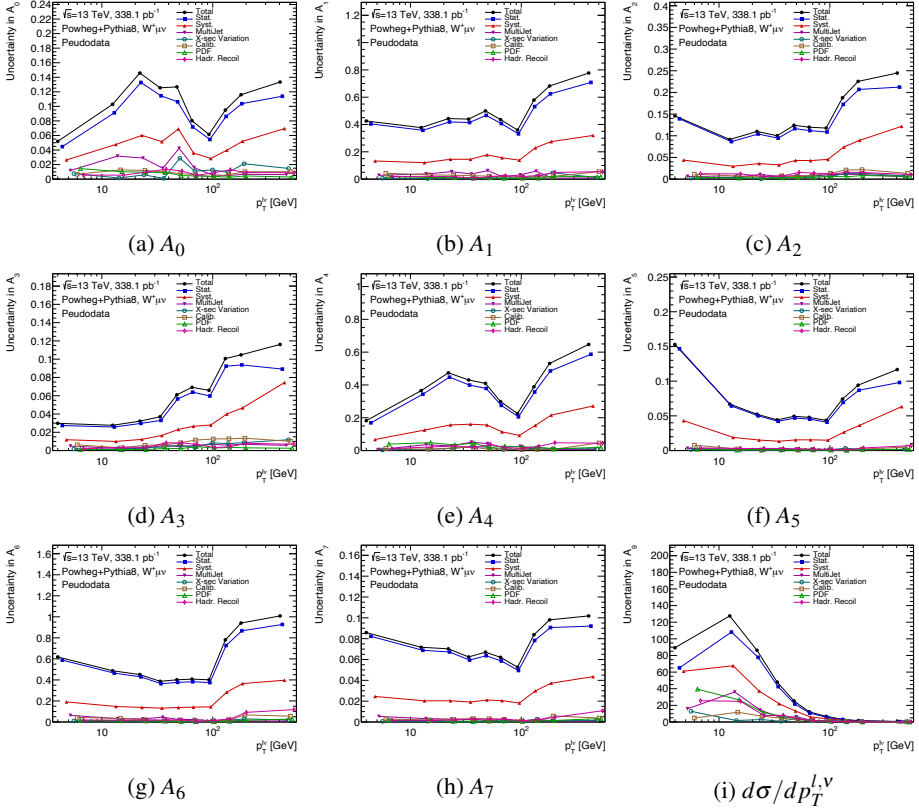


Figure 8.4: The post-fit uncertainty comparison for all contributions in the $W^+ \rightarrow \mu^+ \nu$ channel for measurement in p_T^l on pseudodata. Blue is the total statistical uncertainty, red is the total systematic uncertainty, and black is the combination of the statistical and systematic uncertainties. The components of the systematic uncertainty are presented in grouped form. Detailed listings of each systematic category can be found in Tables B.1, B.3, and B.4.

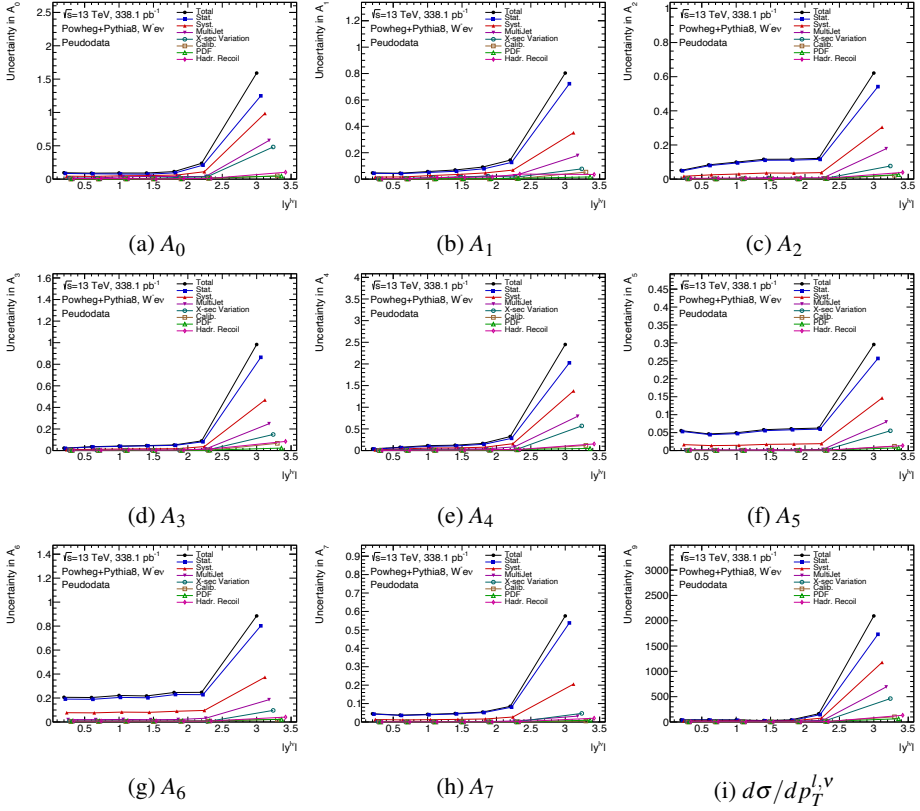


Figure 8.5: The post-fit uncertainty comparison for all contributions in the $W^- \rightarrow e^- \bar{\nu}$ channel for measurement in $y^{\ell\nu}$ on pseudodata. Blue is the total statistical uncertainty, red is the total systematic uncertainty, and black is the combination of the statistical and systematic uncertainties. The components of the systematic uncertainty are presented in grouped form. Detailed listings of each systematic category can be found in Tables B.1 and B.2.

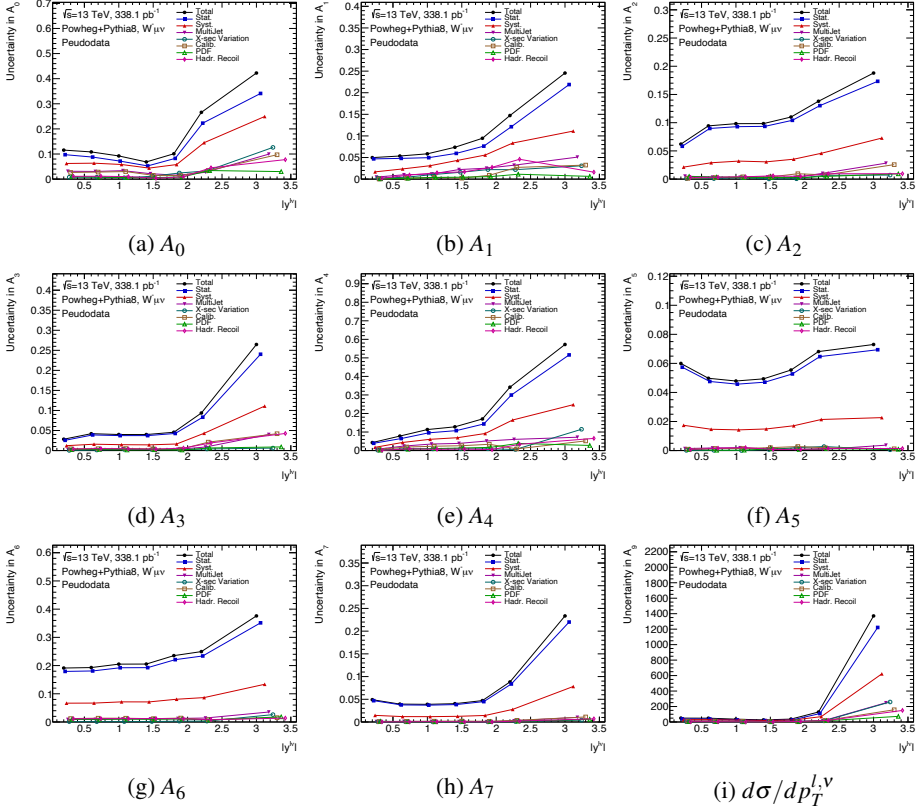


Figure 8.6: The post-fit uncertainty comparison for all contributions in the $W^- \rightarrow \mu^- \bar{\nu}$ channel for measurement in $y^{\ell\nu}$ on pseudodata. Blue is the total statistical uncertainty, red is the total systematic uncertainty, and black is the combination of the statistical and systematic uncertainties. The components of the systematic uncertainty are presented in grouped form. Detailed listings of each systematic category can be found in Tables B.1, B.3, and B.4.

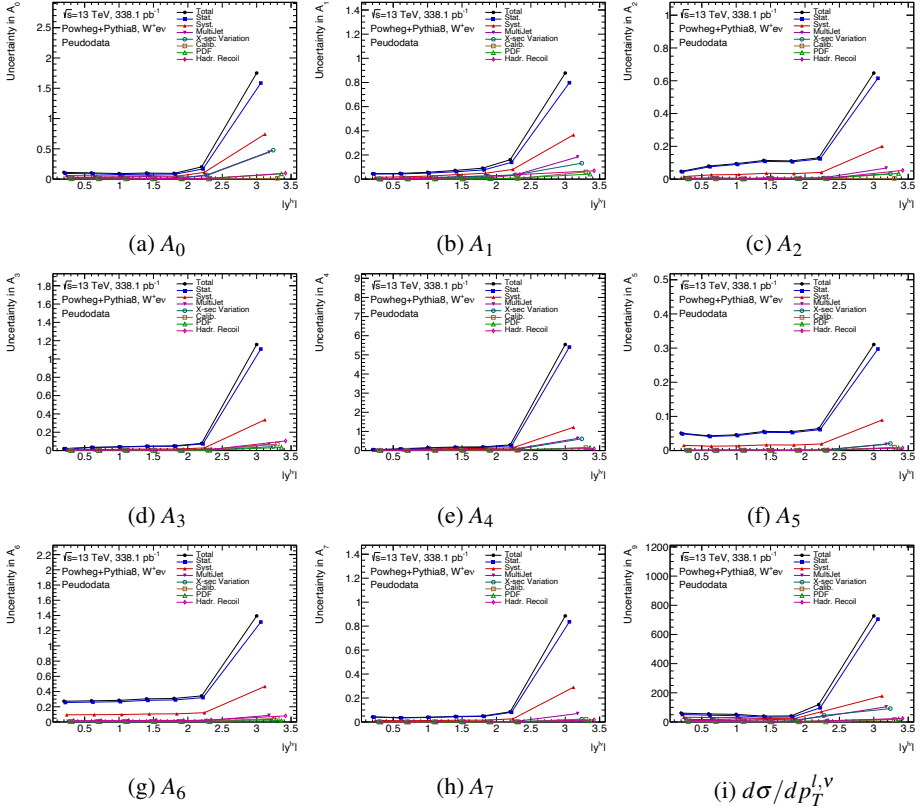


Figure 8.7: The post-fit uncertainty comparison for all contributions in the $W^+ \rightarrow e^+ \nu$ channel for measurement in $y^{\ell\nu}$ on pseudodata. Blue is the total statistical uncertainty, red is the total systematic uncertainty, and black is the combination of the statistical and systematic uncertainties. The components of the systematic uncertainty are presented in grouped form. Detailed listings of each systematic category can be found in Tables B.1 and B.2.

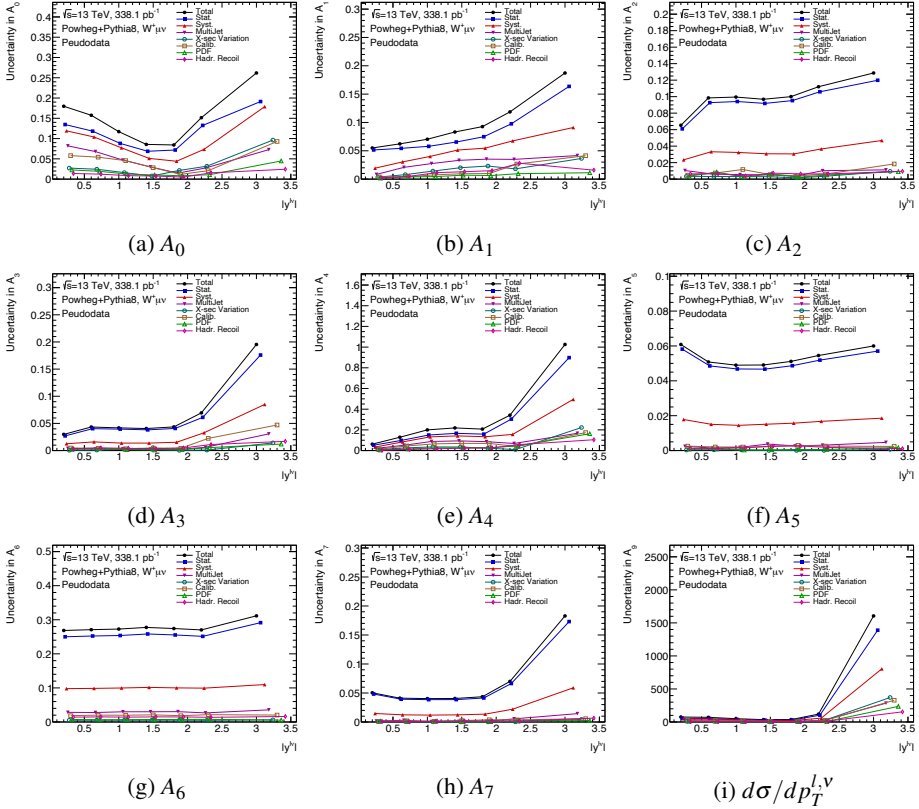
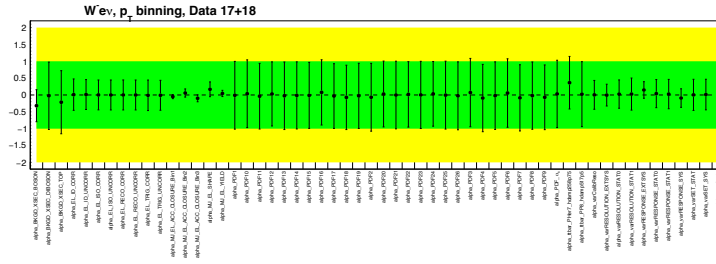
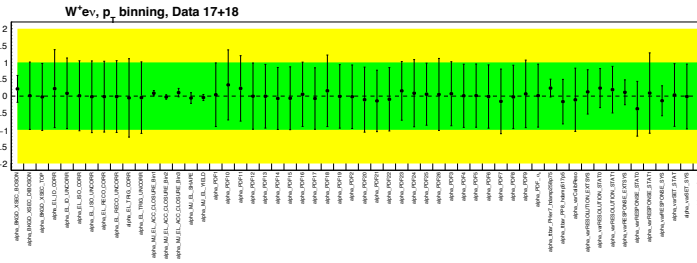


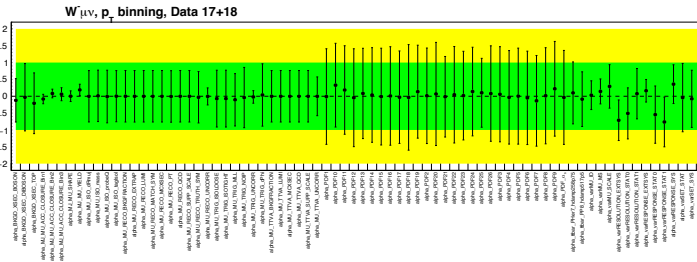
Figure 8.8: The post-fit uncertainty comparison for all contributions in the $W^+ \rightarrow \mu^+ \nu$ channel for measurement in $y^{\ell\nu}$ on pseudodata. Blue is the total statistical uncertainty, red is the total systematic uncertainty, and black is the combination of the statistical and systematic uncertainties. The components of the systematic uncertainty are presented in grouped form. Detailed listings of each systematic category can be found in Tables B.1 and B.2.



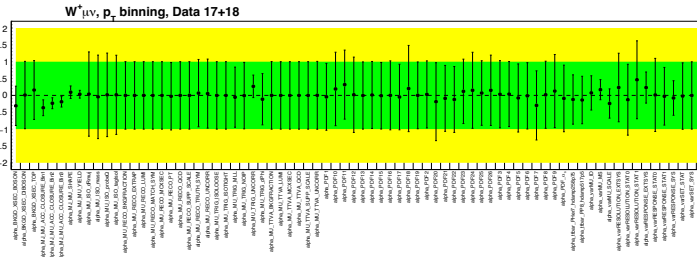
(a)



(b)

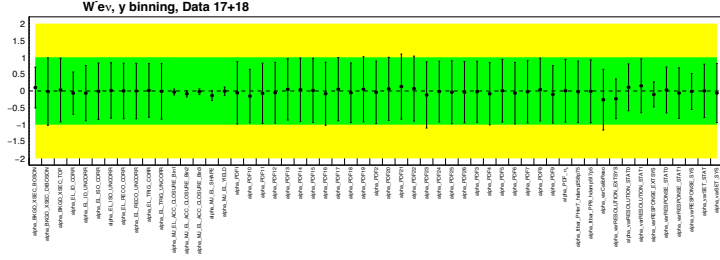


(c)

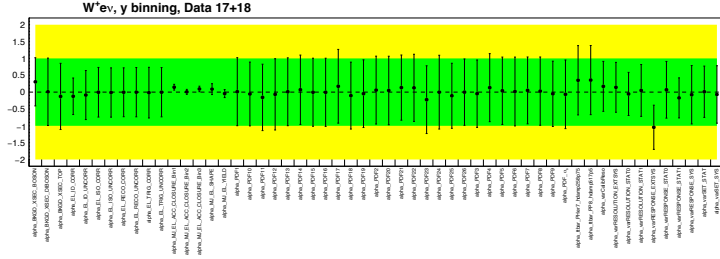


(d)

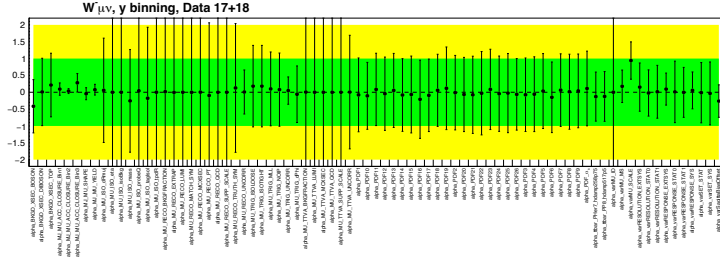
Figure 8.9: Pull distributions for the $W^- \rightarrow e^- \bar{\nu}$, $W^+ \rightarrow e^+ \nu$, $W^- \rightarrow \mu^- \bar{\nu}$, $W^+ \rightarrow \mu^+ \nu$ channels in $p_T^{\ell\nu}$ measurements on pseudodata. Detailed listings of each systematic category can be found in Tables B.1, B.3, and B.4.



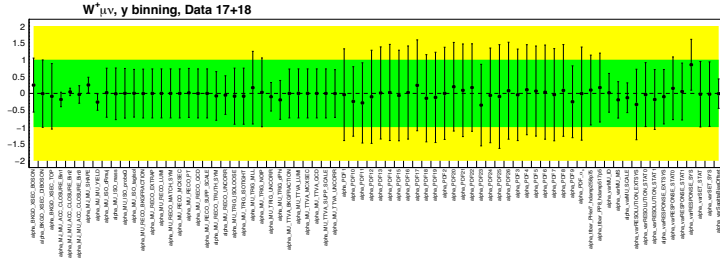
(a)



(b)



(c)



(d)

Figure 8.10: Pull distributions for the $W^- \rightarrow e^- \bar{\nu}$, $W^+ \rightarrow e^+ \nu$, $W^- \rightarrow \mu^- \bar{\nu}$, $W^+ \rightarrow \mu^+ \nu$ channels in $y^{\ell\nu}$ measurements on pseudodata. Detailed listings of each systematic category can be found in Tables B.1, B.3, and B.4.

8.3 Summary

This chapter provides an overview of the uncertainties associated with the measurement of Drell-Yan angular coefficients in W boson decays. This analysis is primarily based on the Z boson A_i measurement at $\sqrt{s} = 8$ TeV [61], [174]. It is demonstrated that the analysis is statistically limited. To evaluate the robustness of the analysis methodology, pseudodata tests were performed across all channels for both $p_T^{\ell\nu}$ and $y^{\ell\nu}$. The effectiveness of the fitting machinery on pseudodata is confirmed, with comprehensive results from the Asimov data fit documented in Appendix B.2. Systematic breakdown plots and pull distributions are as expected, indicating that the analysis includes a mechanism to constrain the MJ background. Details of the $p_T^{\ell\nu}$ and $y^{\ell\nu}$ differential analysis for pseudodata will be presented in the upcoming chapter (see Section 9.1). A significant outcome of this section is the validation of the fitting procedure, confirming its applicability to experimental data, which will be further discussed in the subsequent chapter.

9

EVALUATION OF FIT QUALITY

Following the fit test execution on Asimov data (see Appendix B.2), the fitting procedure was applied to pseudodata. A detailed breakdown of the systematics for pseudodata is provided in Section 8.2, while Section 9.1 introduces the combined measurement of coefficients derived from it. Subsequently, the next phase involved extending the fit to real data. However, this step demonstrated that accurate fitting of the real data would be challenging, as will be detailed in Section 9.2. The remaining portion of the chapter is dedicated to describing the efforts made to explore and attempt to resolve these issues.

9.1 Closure test with pseudodata

Closure tests using pseudodata (see Section 8.2) were conducted to validate the performance and reliability of the fitting procedures employed in this analysis. The combination results for the $p_T^{\ell\nu}$ differential analysis are shown in red in Figures 9.1 and 9.2 for the $e^- \bar{\nu} + \mu^- \bar{\nu}$ and $e^+ \nu + \mu^+ \nu$ channels, respectively, along with the results for the individual channels. Similarly, the outcomes for the $y^{\ell\nu}$ differential analysis can be observed in Figures 9.3 and 9.4.

The results are in close agreement with those obtained from the Asimov data fit, with the analysis focusing primarily on the larger coefficients (A_0 , A_2 , A_3 , and A_4) due to greater measurement sensitivity towards them. Although other coefficients are measured as well, the current analysis lacks the sensitivity required for precise determination of A_5 , A_6 , or A_7 .

Compared to the Asimov fit results (detailed in Appendix B.2), it is clear that the fit is susceptible to numerous variations in pseudodata, primarily due to the statistical noise inherent in it being pseudodata. Being a precision analysis, the fit is particularly sensitive to background mismodeling.

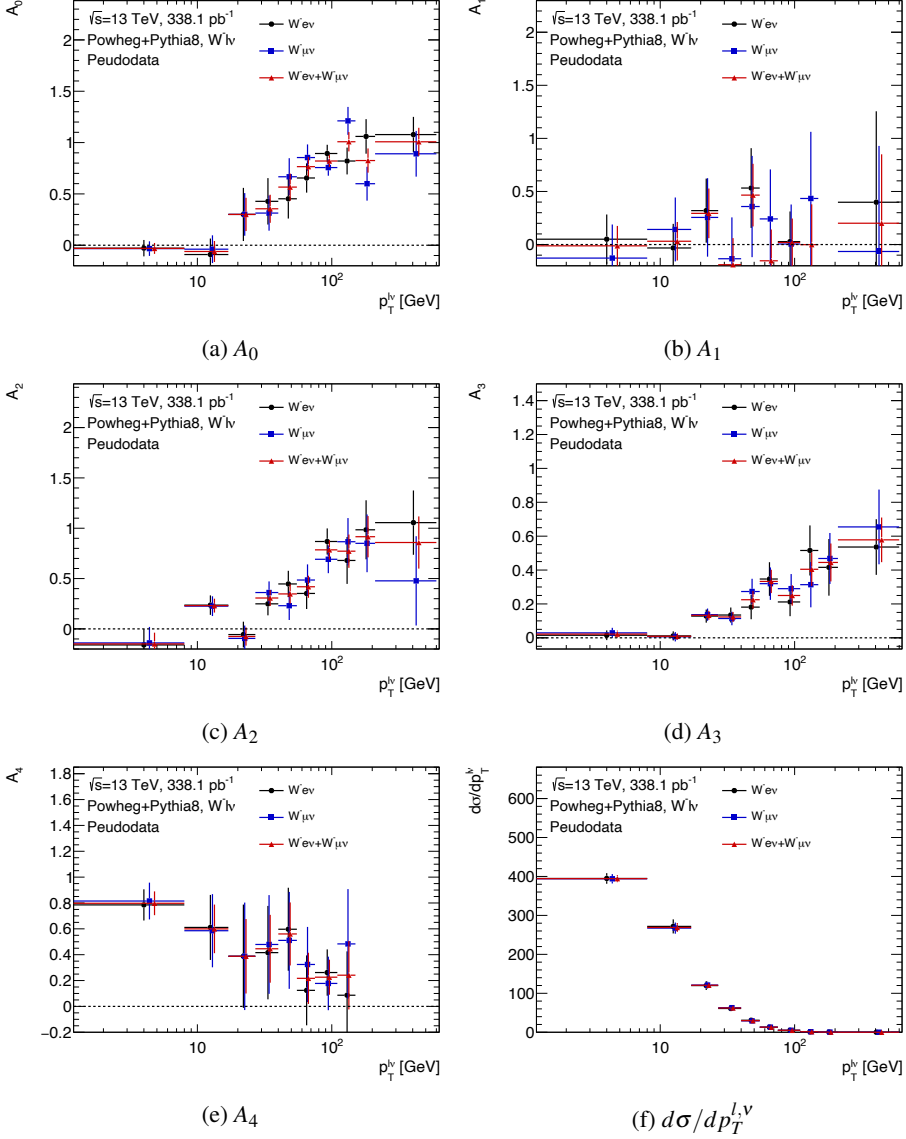


Figure 9.1: Combined measurement of coefficients for W^- as a function of $p_T^{l,v}$ with pseudodata. The measured coefficients from the individual channels are overlayed in black and blue. The error bars represent the total uncertainty on the combined measurements.

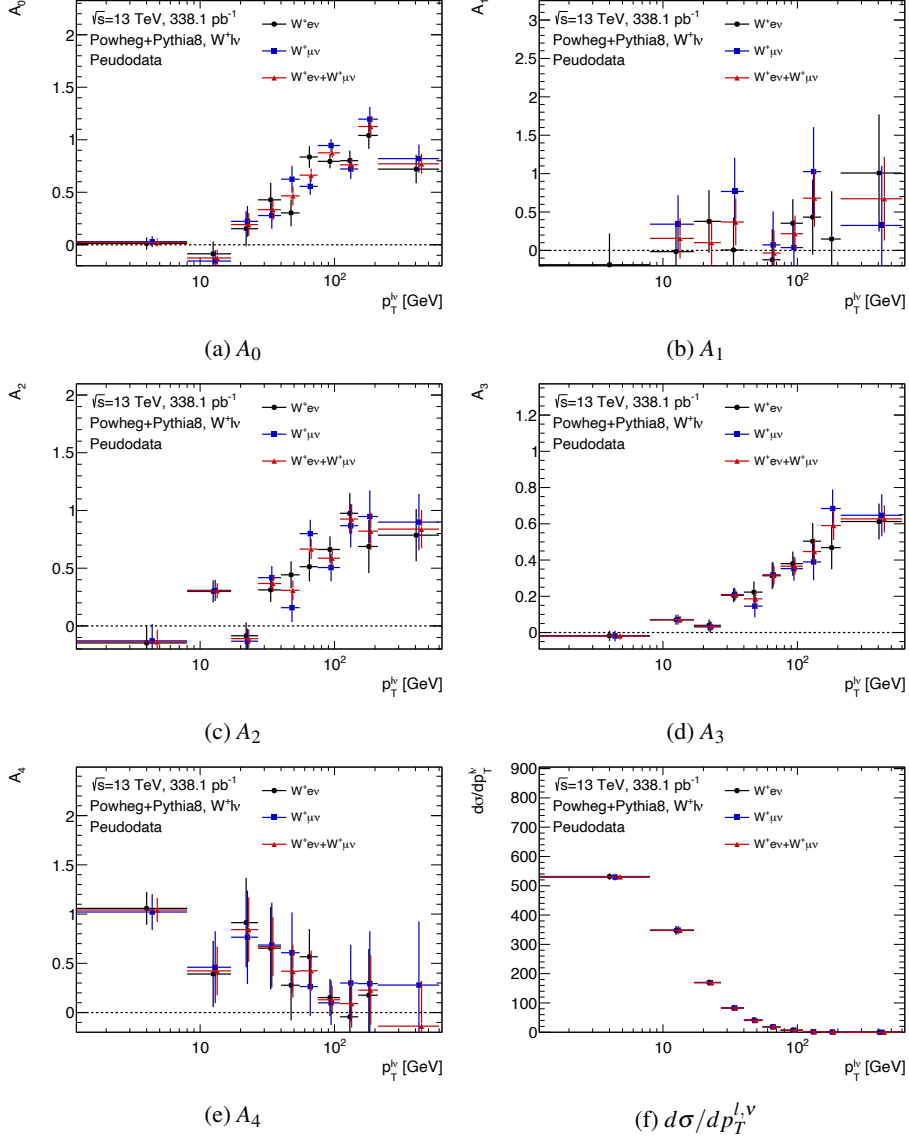


Figure 9.2: Combined measurement of coefficients for W^+ as a function of p_T^{lv} with pseudodata. The measured coefficients from the individual channels are overlayed in black and blue. The error bars represent the total uncertainty on the combined measurements.

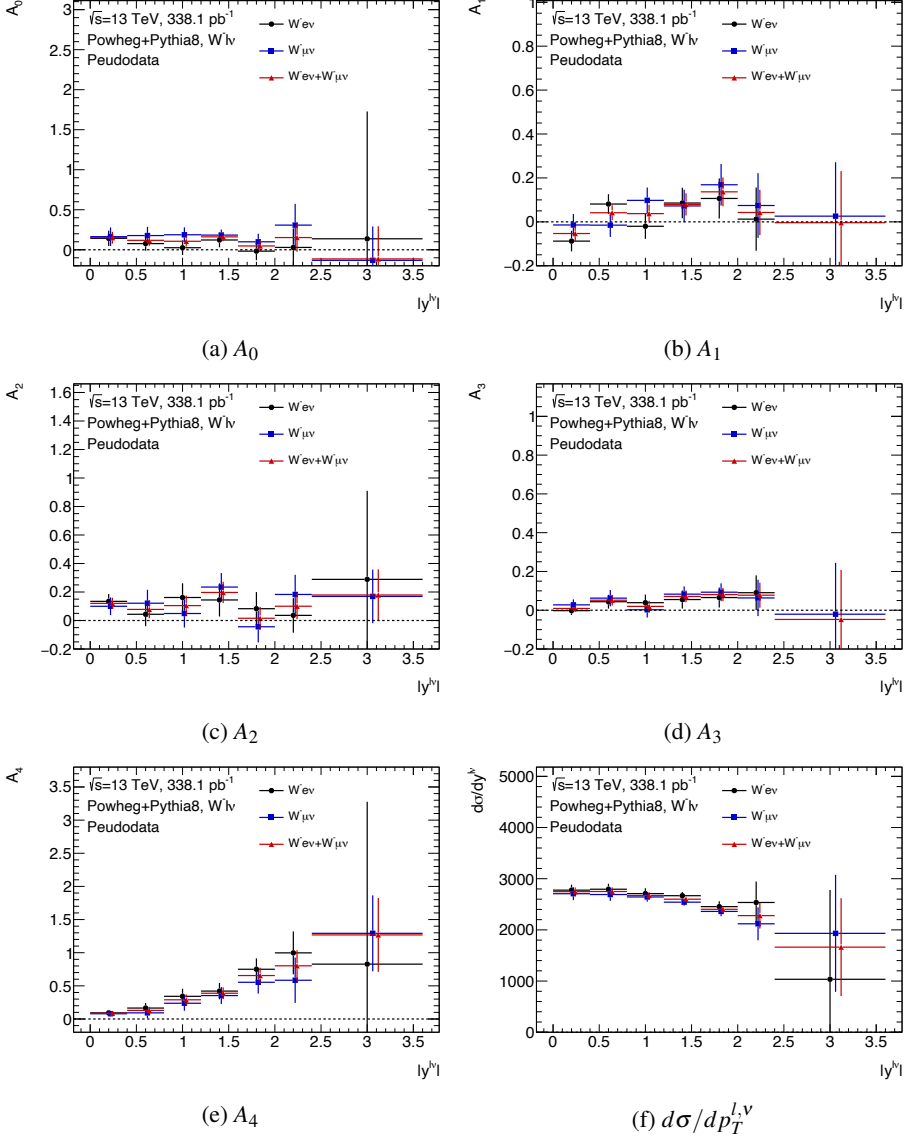


Figure 9.3: Combined measurement of coefficients for W^- as a function of $y^{\ell\nu}$ with pseudodata. The measured coefficients from the individual channels are overlayed in black and blue. The error bars represent the total uncertainty on the combined measurements.

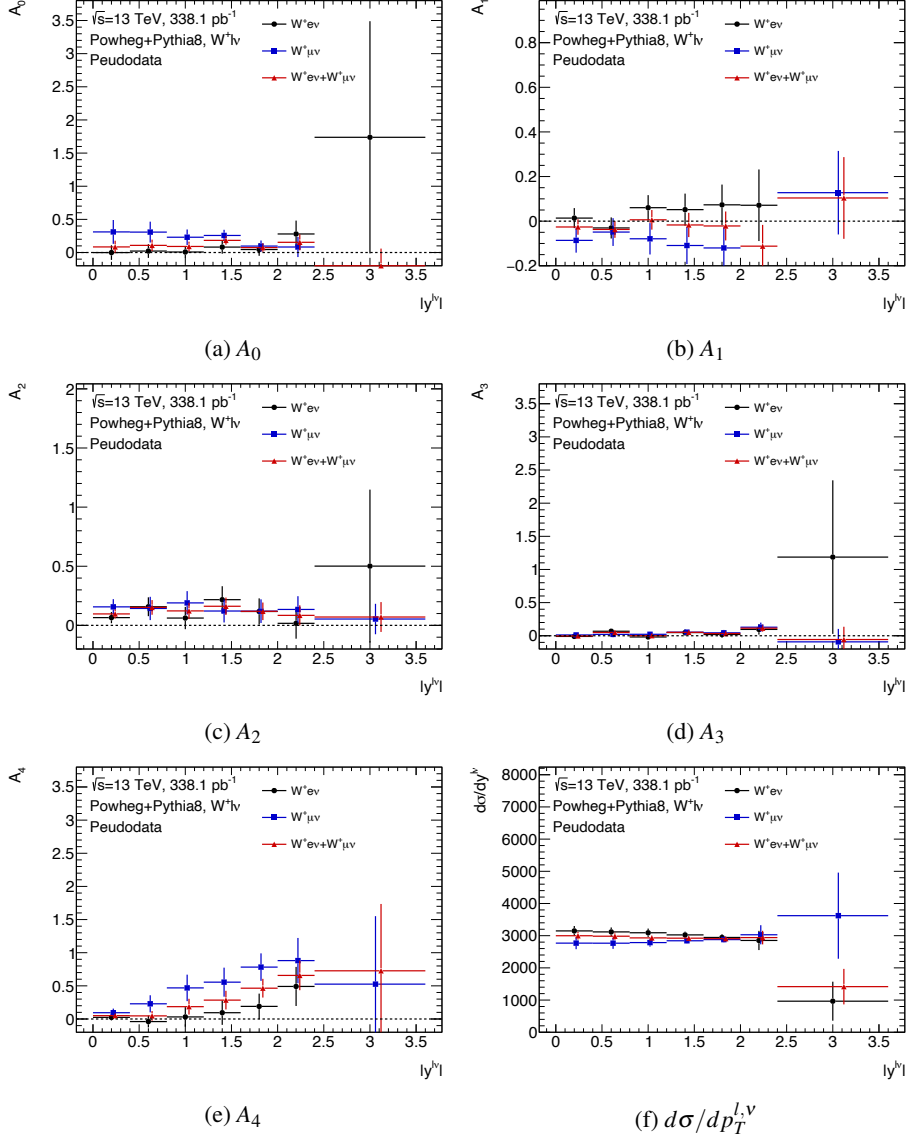


Figure 9.4: Combined measurement of coefficients for W^+ as a function of $y^{\ell\nu}$ with pseudodata. The measured coefficients from the individual channels are overlayed in black and blue. The error bars represent the total uncertainty on the combined measurements.

9.2 Real data fit

When applying the fitting procedure to real data, challenges emerged, appearing as either a lack of convergence or substantial pulls on the background nuisance parameters. In an effort to address the convergence issues, various fitting configurations and minimization strategies were explored (Newton method¹, BFGS² and gradient descent). This was based on the assumption that the fitting process was thought to be caught in a local minimum, thereby resulting in significant pulls. A summary of the performance of different methodologies is provided in Table 9.1. Combinations of channels, analysis binnings, and minimization techniques that are not listed in the Table 9.1 were not explored, as the issue was determined to be global in nature.

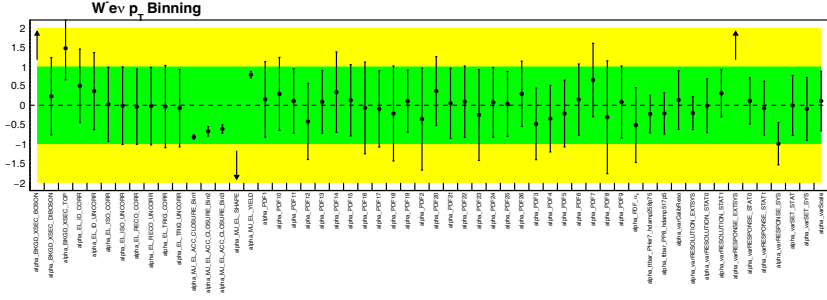
Channel	Binning	Newton method	NM + BFGS	NM + BFGS, no Boson XS NP	Grad. descent
$W^- \rightarrow e^- \bar{\nu}$	$p_T^{\ell\nu}$	Didn't converge	Didn't converge	Didn't converge	Large pulls
$W^+ \rightarrow e^+ \nu$	$y^{\ell\nu}$	Large pulls	Large pulls	Converge w/ errors	Large pulls
$W^- \rightarrow \mu^- \bar{\nu}$	$y^{\ell\nu}$	Large pulls	Large pulls	Large pulls	Large pulls
$W^+ \rightarrow \mu^+ \nu$	$p_T^{\ell\nu}$	Didn't converge	Large pulls	Didn't converge	Didn't converge

Table 9.1: Different fit settings and minimization techniques attempted to have the fit work. The Newton method (NM) and the BFGS algorithm is a simplified version of the Newton's method. Newton's method without BFGS was chosen to continue tests with.

Upon reviewing the pull plots for converged fits it was observed that the variables associated with the Z (boson cross-section NP), top (top cross-section NP) backgrounds, and MJ nuisance parameters (acceptance correction, shape and yield MJ NPs) show notable discrepancies. Figure 9.5 provides an example of the pull distribution for the $W^- \rightarrow e^- \bar{\nu}$ channel in the $p_T^{\ell\nu}$ measurement in real data fit. Although the MJ background nuisance parameters are constrained in a manner consistent with observations from pseudodata tests, as documented in Section 8.2, and align with expectations, nonetheless, the extent of the observed pulls is notably large. Significant pulls in the NPs associated with top and boson cross-sections indicate possible discrepancies in background predictions. This issue was consistent across all channels and both $p_T^{\ell\nu}$ and $y^{\ell\nu}$ binnings. Figure 9.7 shows a marked anti-correlation between the cross-section NPs for the boson and top backgrounds and the MJ yield parameter, as demonstrated by the $W^- \rightarrow e^- \bar{\nu}$ channel in the $p_T^{\ell\nu}$ measurement. This anti-correlation reflects a compensatory behavior within the fit, where a decrease in the MJ contribution is offset by increased contributions from boson and top backgrounds. This pattern implies that the existing selection criteria, which inadvertently favor a higher inclusion of MJ background, may not be optimal for analyses conducted on limited datasets.

¹The Newton method, also known as Newton-Raphson method, is an iterative optimization strategy used to find the roots of a derivative which correspond to the minima or maxima of the function. At each iteration, the Newton method updates the current guess based on the value of the function and its derivatives at that point. Specifically, the update step moves the guess to where the tangent of the function at the current guess intersects the x-axis. Mathematically, this involves calculating the next guess as follows: $x_{\text{next}} = x_{\text{current}} - \frac{f'(x_{\text{current}})}{f''(x_{\text{current}})}$, where f' is the first derivative and f'' is the second derivative of the function f at x_{current} . It is detailed in Ref. [3].

²The Broyden-Fletcher-Goldfarb-Shanno (BFGS) algorithm is an optimization technique used to find the minimum of a function. Unlike the Newton method, which requires the second derivatives, BFGS is a quasi-Newton method that is especially effective in finding the minimum based on gradient evaluations. This makes BFGS particularly suitable for large-scale optimization problems.



(a)

Figure 9.5: Pull distribution for the $W^- \rightarrow e^- \bar{\nu}$ channel in measurement of $p_T^{\ell\nu}$ on experimental data.

The source of the issue becomes more apparent when examining the flattened 2D distributions of ϕ_{CS} across $p_T^{\ell\nu}$ bins, as illustrated in Figures 9.6. The MJ and Z boson backgrounds has very similar shape distributions over ϕ_{CS} . The fit attempts to resolve any signal or background mismodeling by adjusting them simultaneously. Managing the backgrounds in the $W^- \rightarrow e^- \bar{\nu}$ channel's signal region poses a significant challenge, with the MJ background contributing approximately 19% of the yield and the Z boson background, which closely mirrors the MJ shape, contributing about 7%. In the $W^- \rightarrow \mu^- \bar{\nu}$ channel, the situation is somewhat improved, with the MJ background accounting for roughly 10.8% of the yield and the Z boson background for about 6.3%, yet it remains a substantial challenge.

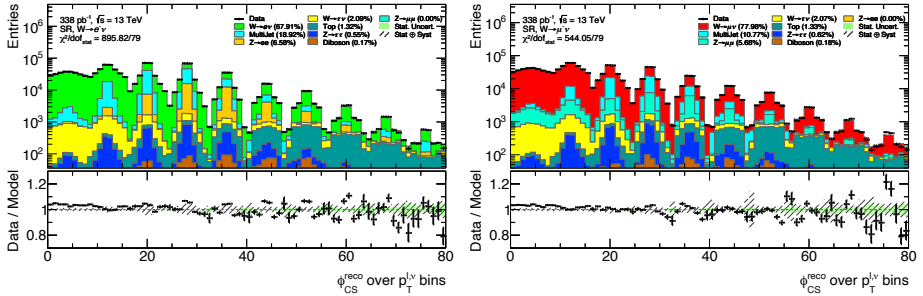
(a) $W^- \rightarrow e^- \bar{\nu}$ (b) $W^- \rightarrow \mu^- \bar{\nu}$

Figure 9.6: Flattened ϕ_{CS} over $p_T^{\ell\nu}$ bins pre-fit distributions for $W^- \rightarrow e^- \bar{\nu}$ (left) and $W^- \rightarrow \mu^- \bar{\nu}$ (right) channels. Only overall multijet systematics uncertainty is shown.



Figure 9.7: Correlation among NPs in the fit for the $W^- \rightarrow e^- \bar{\nu}$ channel during the $p_T^{\ell\nu}$ measurement on experimental data.

9.2.1 Fit configurations

Multiple efforts were undertaken to enhance background management in the fit. A particular focus was on improving the potential performance of the Z boson veto scale factor (see more details in the Section 9.4). The significant presence of the Z boson background highlighted a critical aspect of event selection, particularly the exclusion of events with two well-identified leptons (e.g., two **Tight** and isolated electrons), which directly relates to the efficiency of identifying such events. While the **SFs** employed in the analysis adjust for the efficiencies of identified leptons, they overlook the presence of unidentified leptons. This oversight becomes significant in the context of vetoing events with two good electrons, as the Z boson in this analysis predominantly decays into two leptons. Many events passing the veto do so because the second lepton in the event fails to meet the identification criteria, leading to a discrepancy in the observed number of Z background events between data and **MC**. This discrepancy stems from differences in inefficiency between data and **MC**, which has resulted in an altered count of Z background events. The introduction of additional normalization nuisance parameters to the fit for the Z background, differentiated between the barrel and endcap regions, partially addressed the issue of large pulls. These modifications facilitated a more successful convergence of the fit, although they did not completely eliminate the significant pulls observed in other background components.

From the perspective of **MJ** background systematic uncertainties, various correlation schemes for **MJ** yield and shape systematics were explored. These included option, where all **MJ** NPs are maintained correlated within coarse $p_T^{\ell\nu}$ and $y^{\ell\nu}$ bins; option, which correlates **MJ** shape NPs within coarse $p_T^{\ell\nu}$ and $y^{\ell\nu}$ bins while treating all **MJ** yield NPs as fully correlated; and option, where both **MJ** yield and shape NPs are treated as fully correlated. Also, an effort was undertaken to reintroduce a previously omitted systematic uncertainty related to the **MJ** background, attributable to the constrained **MC** statistics in the **QCD MC** samples ($b\bar{b} + c\bar{c}$ and $JF17$). The pull plot from this evaluation for the $W^+ \rightarrow e^+ \nu$ channel fit over $p_T^{\ell\nu}$ bins is shown in Figure 9.8. However, none of these correlation schemes led to an enhancement in the stability of the fit or resolved issues observed in the pull plots. Further details on these evaluations are provided in [3].

Another strategy tested was to combine the **MJ** and **EW** and top backgrounds into a single template for the fit, while still applying their systematic variations separately. This approach aimed to prevent the systematic uncertainties of each background from cancelling each other during the fitting process. The outcomes of this approach are shown in Figure 9.9 for the $W^- \rightarrow e^- \bar{\nu}$ channel within the $p_T^{\ell\nu}$ measurements. Although this strategy resulted in less deviation for the boson backgrounds' cross-section, it led to the top background normalization nuisance parameter being pulled in the opposite direction. Compared to the baseline fit configuration, this approach results in larger pulls for **MJ** systematic uncertainties, with the exception of the **MJ** shape systematic uncertainty.

Given that these tests were conducted at the fit level, they revealed the presence of Data to Model mismodeling, underscoring the need for targeted investigations. The upcoming Section 9.3 will delve into studies at the reconstruction level, employing a simplified fit model for analysis. Subsequently, Section 9.4 will address enhancements in background modeling.

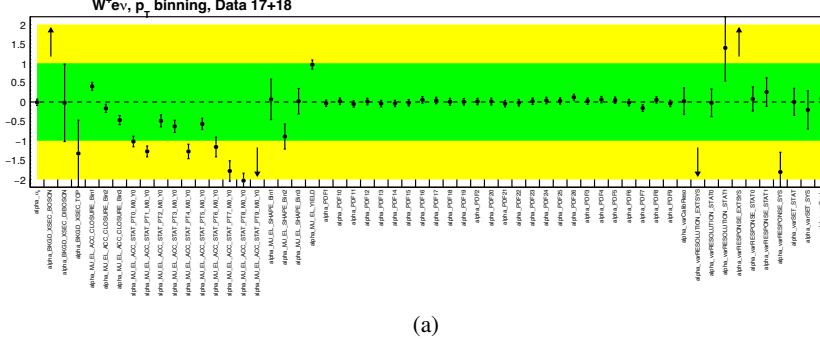


Figure 9.8: Pull distributions for the $W^+ \rightarrow e^+ \nu$ channel in $p_T^{\ell\nu}$ measurements on experimental data, derived using a correlation scheme for **MJ** NPs in which acceptance correction and shape **MJ** NPs are correlated within coarse $p_T^{\ell\nu}$ bins, and **MJ** yield NPs are fully correlated across $p_T^{\ell\nu}$ bins. An additional systematic uncertainty, stemming from limited **MC** statistics in the **QCD MC** samples and affecting the **MJ** background, is incorporated into the fit as uncorrelated across $p_T^{\ell\nu}$ bins.

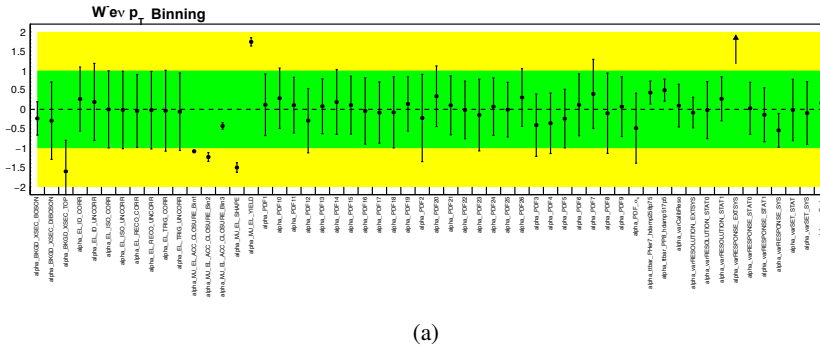
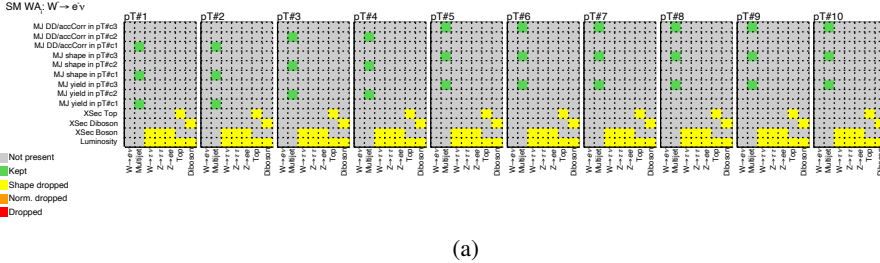


Figure 9.9: Pull distributions for the $W^- \rightarrow e^- \bar{\nu}$ channel in $p_T^{\ell\nu}$ measurements on experimental data, obtained by combining the **MJ** and boson backgrounds to prevent the self-cancellation of their systematic uncertainties.

9.3 Studies with simplified fit model

Given the complexity of the fit employed in this analysis, a streamlined version of the fit was developed using the TRExFitter package [176]. This simplified model conducted the fit solely at the reconstruction level, with the signal cross-section measurement designated as the parameter of interest (POI). This methodology involved conducting a Data-to-Model fit for the distributions detailed in Section 6.7.2, complemented by a bin filtering process to refine the analysis. Bins in distributions were excluded if the anticipated number of events derived from real data was less than 10^{-4} . Rather than incorporating the full suite of experimental and theoretical systematic uncertainties outlined in Section 8.1 and detailed in Appendix B.1, a reduced set of uncertainties was employed. For experimental uncertainties, a selective approach was adopted, including a conservative 1.5% uncertainty on data luminosity, a 5% cross-section normalization uncertainty for single boson samples, 10% for diboson samples, and 10% for top backgrounds. The MJ background-related systematic uncertainties were treated with finer granularity compared to the main fit: all MJ shape, yield, and acceptance correction uncertainties were correlated across each coarse $p_T^{\ell\nu}$ bin, as shown in Figure 9.10. This simplified fit focused on the $W^- \rightarrow e^- \bar{\nu}$ and $W^- \rightarrow \mu^- \bar{\nu}$ channels with $p_T^{\ell\nu}$ binning, primarily aiming to identify potential issues at the reconstruction level and to facilitate the investigation of baseline fit instabilities.



(a)

Figure 9.10: Pruning plots for the simplified fit model for the $W^- \rightarrow e^- \bar{\nu}$ channel during the $p_T^{\ell\nu}$ measurement.

Figure 9.11 presents the results for the POI from the fit, clearly indicating similar behavior in signal cross-section normalization across both channels. Specifically, the first $p_T^{\ell\nu}$ bin ($p_T^{\ell\nu} < 8$ GeV) has an additional 4% normalization. The central portion of the $p_T^{\ell\nu}$ binning does not demonstrate significant deviations in signal cross-section normalization. However, the higher $p_T^{\ell\nu}$ range shows signal renormalizations, more prominently in the $W^- \rightarrow e^- \bar{\nu}$ channel, but also noticeable in the $W^- \rightarrow \mu^- \bar{\nu}$ channel.

It is crucial to highlight that this simplified fit model does not permit alterations to the signal shape for $\cos \theta_{CS}$ vs. ϕ_{CS} distributions, unlike the baseline fit, where the fusion of A_i coefficients impacts both the signal shape and the $p_T^{\ell\nu}$ distribution. Given that the baseline fit is structured around $p_T^{\ell\nu}$ bins, these substantial signal cross-section renormalizations at the start of analysis were not anticipated to cause fit stability issues.

The pull plots for the simplified fit are shown in Figure 9.12. While it is not appropriate to directly compare the pull plot from the simplified fit for the $W^- \rightarrow e^- \bar{\nu}$ channel with that

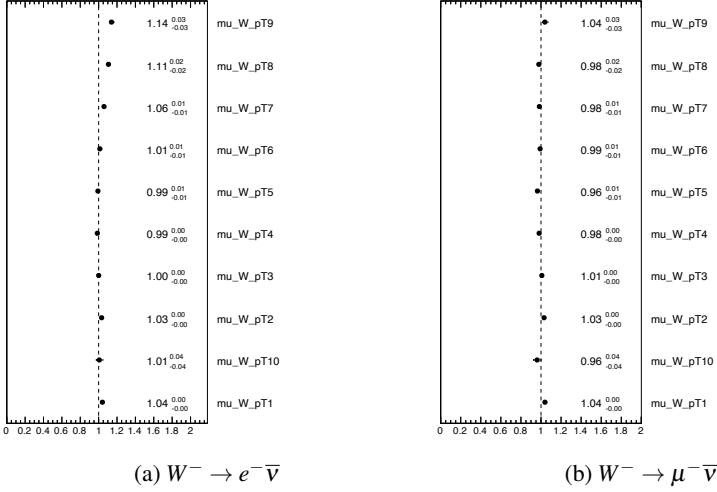


Figure 9.11: Parameters of interest (POI) outcomes from the simplified fit model for the $W^- \rightarrow e^- \bar{\nu}$ (left) and $W^- \rightarrow \mu^- \bar{\nu}$ (right) channels during the $p_T^{\ell\nu}$ measurement.

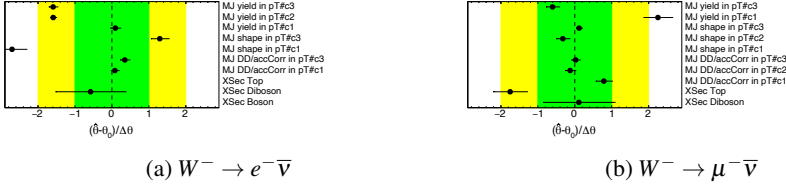


Figure 9.12: Pull distributions from the simplified fit model for the $W^- \rightarrow e^- \bar{\nu}$ (left) and $W^- \rightarrow \mu^- \bar{\nu}$ (right) channels during the $p_T^{\ell\nu}$ measurement. The #c stands for coarse $p_T^{\ell\nu}$ bin number (see Eq. 6.10).

shown in Figure 9.5 due to differences in fit configurations, it similarly indicates that the MJ background experiences significant pulls even at the reconstruction level. The boson cross-section did not meet the set order threshold (established at 0.5) in $W^- \rightarrow \mu^- \bar{\nu}$ channel and is not shown on the pull plot; however, for the $W^- \rightarrow e^- \bar{\nu}$ channel it was observed to be pulled beyond 3σ . The top background is pulled down beyond -3σ for the $W^- \rightarrow e^- \bar{\nu}$ channel and reaches approximately -1.8σ for the $W^- \rightarrow \mu^- \bar{\nu}$ channel, suggesting potential background mismodeling.

To gain insights into the regions responsible for the pulls mentioned earlier, the NP correlation matrix proves to be a valuable tool. Figure 9.13 presents the correlation matrices for the $W^- \rightarrow e^- \bar{\nu}$ and $W^- \rightarrow \mu^- \bar{\nu}$ channels. Notably, the pronounced correlation observed in the top background cross-section normalization across the higher $p_T^{\ell\nu}$ bins (up to 59%) for the $W^- \rightarrow \mu^- \bar{\nu}$ channel exclusively. While the yields of the top background are relatively consistent between the $W^- \rightarrow e^- \bar{\nu}$ and $W^- \rightarrow \mu^- \bar{\nu}$ channels, the fit for the $W^- \rightarrow e^- \bar{\nu}$

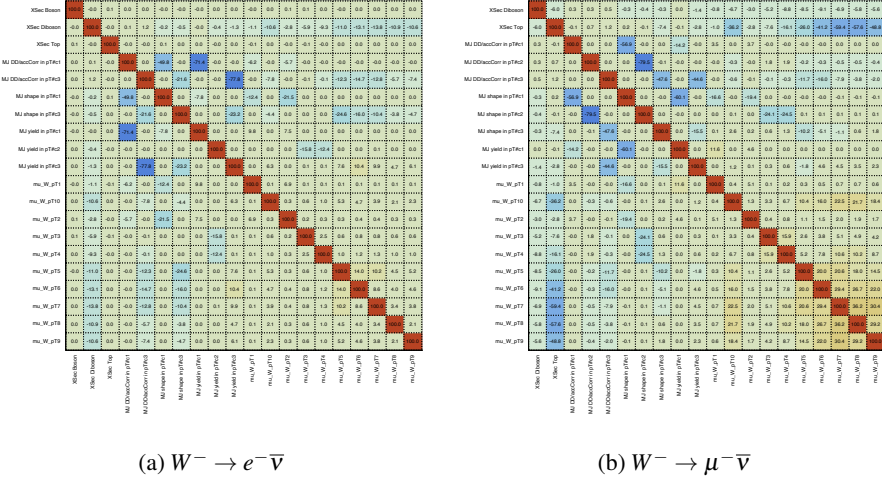


Figure 9.13: Correlation matrices from the simplified fit model for the $W^- \rightarrow e^- \bar{\nu}$ (left) and $W^- \rightarrow \mu^- \bar{\nu}$ (right) channels during the $p_T^{\ell\nu}$ measurement.

channel shows a preference for adjusting the $Z \rightarrow ee$ background over the top background for this $p_T^{\ell\nu}$ bins. Similar to the baseline fit correlation matrix (Figure 9.7), there is also a self-correlation observed among the MJ background NPs within each coarse measurement bin. As anticipated with this simplified model, the MJ background NPs show correlations with the POIs established for the respective coarse $p_T^{\ell\nu}$ bins.

Figures 9.14 display the pre-fit and post-fit pie charts for backgrounds in the $W^- \rightarrow e^- \bar{\nu}$ channel. In the first $p_T^{\ell\nu}$ bin ($p_T^{\ell\nu} < 8$ GeV), the fit notably adjusts the yield contributions of the MJ and $W \rightarrow \tau\nu$ backgrounds by altering their shapes to accommodate the newly renormalized signal cross-section by 4% in this bin. The subsequent bin ($8 < p_T^{\ell\nu} < 17$ GeV) is also influenced, as MJ uncertainties are correlated within this coarse bin. As one progresses through the $p_T^{\ell\nu}$ bins, the fit increases the Z background contribution while reducing the MJ background. Given that from $p_T^{\ell\nu} > 17$ GeV onwards, the MJ and Z shapes appear similar, the fit's preference to adjust the Z background becomes evident. Furthermore, in the highest $p_T^{\ell\nu}$ bins starting from $p_T^{\ell\nu} > 75$ GeV ($p_T^{\ell\nu}$ bin number 7), where the overall top background begins to dominate over the Z background, the fit increasingly relies on the top background for shape adjustments.

For the $W^- \rightarrow \mu^- \bar{\nu}$ channel, the pre-fit and post-fit pie charts, as illustrated in Figures 9.15, demonstrate that the MJ background yield undergoes minimal post-fit changes. This observation can be attributed to the $W^- \rightarrow \mu^- \bar{\nu}$ channel's lower proportion of MJ background compared to the $W^- \rightarrow e^- \bar{\nu}$ channel, indicating a more effective control over it in the analysis. Furthermore, the yields for both the top and electroweak backgrounds also remain largely unchanged, suggesting that the overall Data to Model agreement for the $W^- \rightarrow \mu^- \bar{\nu}$ channel is expected to have satisfactory normalization from the simplified fit perspective.

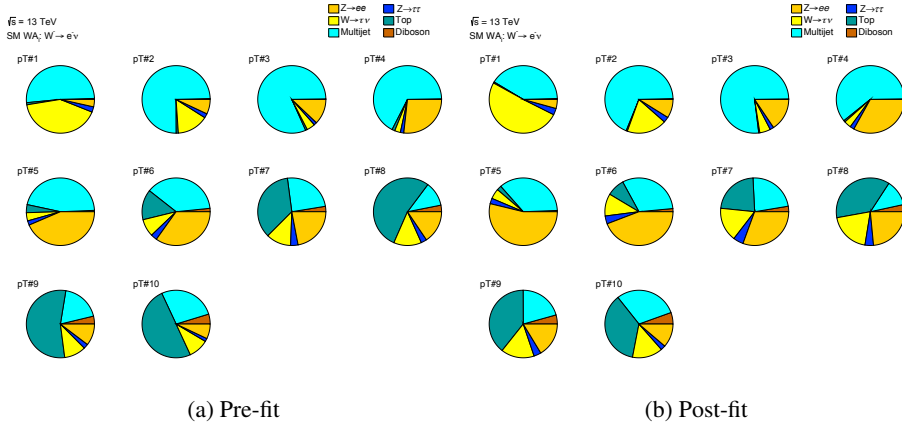


Figure 9.14: Pre-fit (a) and post-fit (b) pie charts for the $W^- \rightarrow e^- \bar{\nu}$ channel using the simplified fit model, in the $p_T^{\ell\nu}$ measurement.

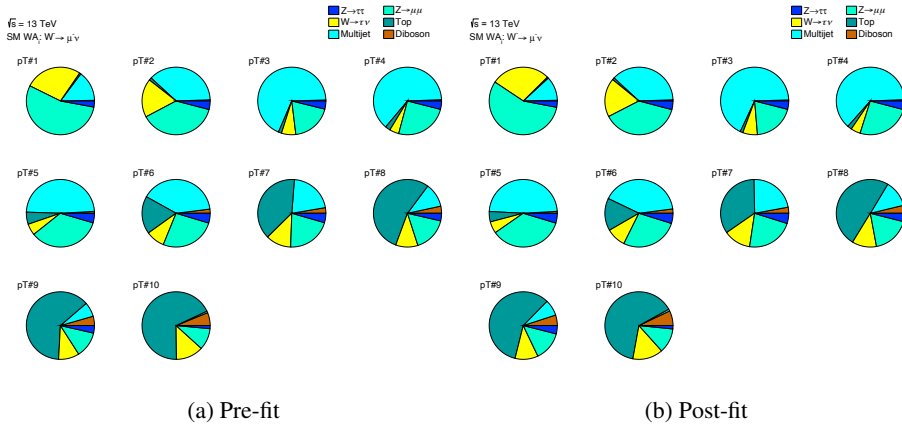


Figure 9.15: Pre-fit (a) and post-fit (b) pie charts for the $W^- \rightarrow \mu^- \bar{\nu}$ channel using the simplified fit model, in the $p_T^{\ell\nu}$ measurement.

9.4 Validating the signal and background components

Considerable effort was dedicated to validating the data flow to ensure the absence of missing components that could highlight issues in the fitting process. As an initial test, it was necessary to verify the coherency of signal samples between electron and muon channels. To achieve this, double ratio plots for $W^- \rightarrow e^- \bar{\nu}/W^- \rightarrow \mu^- \bar{\nu}$ and $W^+ \rightarrow e^+ \nu/W^+ \rightarrow \mu^+ \nu$ across all $p_T^{\ell\nu}$ and $y^{\ell\nu}$ bins were obtained. These plots did not show any issues, indicating coherency between the channels. Further information on this test is available in [3].

The overall $p_T^{\ell\nu}$ distribution for W process predominantly relies on $p_T^{W,\text{Truth}}$ distribution. Initially, it was normalized to NNLO calculations conducted using the DYTURBO program, an optimized version of DYNLO [166], [167], with the MMHT2014nnlo PDF set [168]. The numerical values for this normalization were derived from the corresponding ATLAS publications with the 2015 data at 13 TeV [171]. However, this approach resulted in order of 10% Data to Model discrepancies for the $p_T^{\ell\nu}$ above 100 GeV in both electron and muon channels. To address these, the W normalization was updated to incorporate NNLO+NNLL corrections calculations as provided by [169] covering range up to 600 GeV.

Given that the Z boson represents the second largest source of background across all channels with a substantial contribution, its treatment was also reevaluated. The normalization of $p_T^{Z,\text{Truth}}$ to NNLO was observed to be flat for values above 100 GeV, suggesting a potential reason for the lack of Z boson background in the final $p_T^{\ell\nu}$ bins. Nevertheless, after applying the necessary adjustments, the impact on the $p_T^{\ell\nu}$ Data/Model agreement was found to be minor.

The veto SFs for Z boson background were thoroughly reviewed. While the SFs utilized in the analysis do adjust for the efficiencies of identified leptons, they do not account for unidentified leptons. This oversight implies that, in events featuring a single lepton, only the selection criteria targeting exactly one lepton are accurately modeled after the correction is applied. Consequently, Z boson backgrounds, which predominantly decay into two leptons, exhibit modeling inefficiencies. To address this discrepancy, a secondary set of SFs is introduced to correct for those leptons that failed the lepton selection process, defined by the equation:

$$\text{SF}_{\text{ineff}} = \frac{1 - \epsilon_{\text{data}}}{1 - \epsilon_{\text{MC}}} \quad (9.1)$$

This adjustment is intended for the second leptons that did not meet the selection criteria and, when used in conjunction with the standard SFs, aims to correct the distribution. During the analysis review, it was discovered that while the overall methodology for calculating veto SFs was in place, there was a missing element in the reconstruction SF calculation, specifically the absence of ϵ_{MC} in the latest version of the SF_{reco}. This discrepancy has a minor impact on $p_T^{\ell\nu}$ distributions, and further investigation with p_T^W -analysis selection showed that differences relative to the previous version of the reconstruction SF file, which included ϵ_{MC} , are negligible, staying within the one permille range. This effect is significantly more pronounced for selections like used for this analysis, where no kinematic requirements are applied that might otherwise reduce these backgrounds. In such scenarios, Z events typically shows low E_T^{miss} since neutrinos are not expected in the final state, further underscoring the importance of accurately modeling the inefficiency SF to mitigate discrepancies in Z background events between data and MC.

Given the significant proportion of **MJ** background in both the electron and muon channels, it was crucial to examine the effects of electroweak background normalization mismodeling on the **MJ** shape. As detailed in Section 6.5.1, the first anti-isolated slice is notably influenced by electroweak backgrounds, accounting for approximately 38% of the $W^- \rightarrow e^- \bar{\nu}$ and 7% of the $W^- \rightarrow \mu^- \bar{\nu}$ channels. Consequently, since the correction of the **MJ** background shapes heavily depends on the **MJ** template derived from the first anti-isolated slice (Eq. 6.5), the normalization of electroweak background could significantly affect the results. Figure 9.16 illustrates the impact of a 5% variation in electroweak background in CR1 on the **MJ** template in the first anti-isolated slices for the $W^- \rightarrow e^- \bar{\nu}$ and $W^- \rightarrow \mu^- \bar{\nu}$ channels. The impact is more pronounced in the low $p_T^{\ell\nu}$ region for the $W^- \rightarrow e^- \bar{\nu}$ channel, whereas for the $W^- \rightarrow \mu^- \bar{\nu}$ channel, the effect persists in bins with lower **MJ** population. The baseline A_i fitting process involves adjustments to the $p_T^{\ell\nu}$ distribution for the signal, which, in an ideal scenario, should be propagated to the CR1 region and be accurately reflected in the recalculated **MJ** template shape. However, integrating this into the baseline fit poses substantial challenges. The primary systematic uncertainty related to the **MJ** shape arises from the shape correction applied to the signal region, as detailed in Table 6.6. The impact of this correction on the ϕ_{CS} over $p_T^{\ell\nu}$ bins template shape is effectively illustrated by the black ratio histogram, which compares the first anti-isolated slice with the adjusted **MJ** shape for the $W^- \rightarrow e^- \bar{\nu}$ and $W^- \rightarrow \mu^- \bar{\nu}$ channels, as shown in Figure 9.17. With regard to the $W^- \rightarrow \mu^- \bar{\nu}$ channel, the observed differences can be attributed to a 5% variation in the top and **EW** backgrounds in CR1. However, this is not the case for the $W^- \rightarrow e^- \bar{\nu}$ channel, leading to an additional pull on the **MJ** shape **NP**.

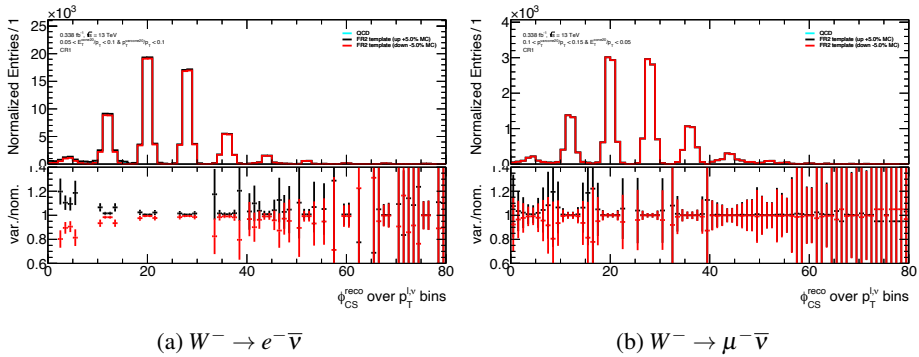


Figure 9.16: Flattened **MJ** template shapes of ϕ_{CS} over $p_T^{\ell\nu}$ bins for the $W^- \rightarrow e^- \bar{\nu}$ (left) and $W^- \rightarrow \mu^- \bar{\nu}$ (right) channels derived from the first anti-isolated slice in the control region 1 (CR1). The impact of a 5% upward and downward variation in the normalization of top and electroweak **MC** samples in the CR1 is illustrated by black and red lines, respectively.

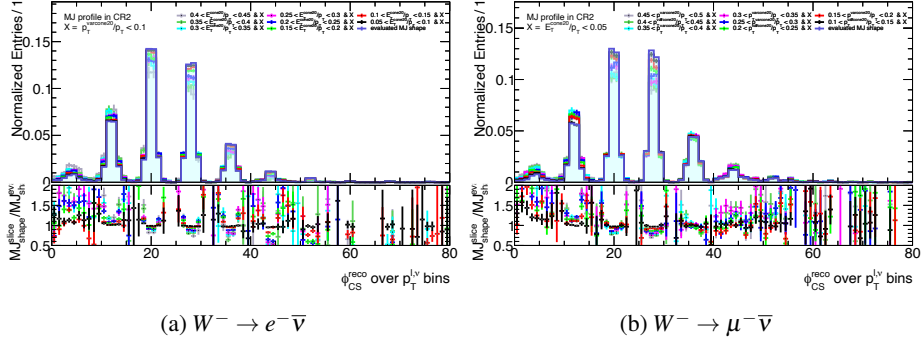


Figure 9.17: Normalised flattened **MJ** shapes in anti-isolated slices of ϕ_{CS} over $p_T^{\ell\nu}$ bins in CR1 for the $W^- \rightarrow e^- \bar{\nu}$ (left) and $W^- \rightarrow \mu^- \bar{\nu}$ (right) channels, along with the shape corrected for the inclusive signal region. On the bottom the ratio to the evaluated **MJ** template is shown.

9.5 Summary

The fitting framework, originally developed for $Z A_i$ measurements with low background contamination, operates successfully with Asimov and pseudodata in the $W A_i$ analysis. The results of the fits are in close agreement, demonstrating that this analysis is primarily sensitive to the larger coefficients (A_0 , A_2 , A_3 , and A_4). Although other coefficients are also measured, the current analysis lacks the sensitivity required for precise determination of A_5 , A_6 , or A_7 (see Section 9.1). However, when applied to real data, significant challenges arise: the fit either fails to converge or leads to excessively large pulls on the background nuisance parameters, illustrated in Figure 9.5 for the $W^- \rightarrow e^- \bar{\nu}$ channel $p_T^{\ell\nu}$ measurement. The author dedicated major efforts to identify the source of issues encountered in the fitting process, employing a simplified fit model (Section 9.3) and conducting thorough validation of both signal and background components (Section 9.4). The substantial contamination of the signal region by Z boson (approximately 7% for $e^\pm$ and 6% for $\mu^\pm$) and **MJ** (approximately 19% for $e^\pm$ and 10% for $\mu^\pm$) backgrounds (see Sections 6.4 and 6.5.7) poses considerable challenges in managing these backgrounds. The situation is further complicated by the fact that the **MJ** and Z boson backgrounds have very similar shapes (see Figure 9.6), leading to heavy correlation and often opposing pulls between the **MJ** and **EW** backgrounds. The A_i fit, with its numerous degrees of freedom to constrain signal and backgrounds across $\cos \theta_{CS}$ vs. ϕ_{CS} distributions for each $p_T^{\ell\nu}$ or $y^{\ell\nu}$ bin, turns out to be too convoluted. This indicates that the ambitious strategy of employing a relaxed kinematic selection for the signal region, which in turn introduces a lot of **MJ** and Z backgrounds, requires further studies and optimisation based on a larger data statistics.

10

CONCLUSIONS AND OUTLOOK

Conclusions

The current understanding of Drell-Yan angular coefficients (A_i) for $W \rightarrow \ell \nu$ in hadronic collisions remains incomplete. The analysis of a few coefficients like A_2 and A_3 , as highlighted in [64], is insufficient for fully grasping the QCD dynamics critical to W production. This thesis presents contributions to the ATLAS experiment, with a particular focus on advances in measuring the W angular coefficients using low-pileup data at $\sqrt{s} = 13$ TeV, with an integrated luminosity of 338.1 pb^{-1} .

The thesis begins by showcasing the author's role in optimizing the ATLAS Transition Radiation Tracker (TRT) in Chapter 4. This includes enhancements in TRT electronics and data acquisition systems, specifically addressing high rate and pileup conditions. The author's efforts in identifying and mitigating "resynchronization storms" have been important in enabling the TRT to handle high-pileup conditions, reaching up to $\langle \mu \rangle = 66$, with a trigger rate of 100 kHz during Run 3.

The core of this thesis is the measurement of Drell-Yan angular coefficients in $W \rightarrow \ell \nu$ decays. Despite the extensive data collected by ATLAS during Run 2 and early Run 3, the focus on low-pileup data was chosen to enhance the resolution of hadronic recoil energy, important for measuring the W transverse momentum and reconstructing its Collins-Soper rest frame, as discussed in Chapter 5. The reduced multijet (MJ) background in low-pileup data further supports this choice. The methodology developed to reconstruct W momentum, particularly the minimal rotation of E_T^{miss} , ensures accurate determination of ϕ_{CS} and $\cos \theta_{\text{CS}}$.

With limited low-pileup data, new strategies were necessary to improve A_i analysis sensitivity. By avoiding traditional kinematic cuts like missing transverse energy (E_T^{miss}) and transverse mass (m_T), the analysis gained sensitivity in the high $p_T^{\ell \nu}$ region, important for testing the Lam-Tung relation ($A_0 - A_2 = 0$). This strategy, while increasing MJ background, required the deployment of advanced techniques to mitigate it, including strict electron identification and isolation techniques, as detailed in Chapter 6.

In the same Chapter, the author presents a robust methodology for estimating MJ background in complex analysis binning using the anti-isolated slices scan method. This method proved effective in estimating both the yield and shape of the MJ background, with

the $p_T^{\text{varcone20}}/p_T$ variable demonstrating suitability in $\mu^\pm$ channels and E_T^{cone20}/p_T in $e^\pm$ channels. The methodology's reliability was confirmed through closure tests with $b\bar{b}$ and $c\bar{c}$ samples.

The extensive development of a new methodology for **MJ** background estimation is a cornerstone of this thesis, enabling detailed partitioning of the **MJ** background across a two-dimensional $\cos\theta_{CS}$ vs. ϕ_{CS} template analysis into 9×8 fine analysis bins over the $p_T^{\ell\nu}$ and $y^{\ell\nu}$ dimensions. The development of a new **MJ** acceptance correction methodology represents an advancement in analyzing three-dimensional phase space, utilizing **QCD MC** samples for this purpose. This method has demonstrated the potential for the use of kinematics information from **MC** $b\bar{b}$ and $c\bar{c}$ (for $\mu^\pm$) and *JF17* (for $e^\pm$) samples to adjust **MJ** templates from broader analysis bins, derived through a data-driven method, to fine analysis bins across $p_T^{\ell\nu}$ and $y^{\ell\nu}$ dimensions. This methodology has been successfully applied across all four analysis channels ($W^- \rightarrow e^-\bar{\nu}$, $W^+ \rightarrow e^+\nu$, $W^- \rightarrow \mu^-\bar{\nu}$, and $W^+ \rightarrow \mu^+\nu$), supporting the reliability of **MJ** background estimations and setting a precedent for future analyses.

Leveraging these investigations, the angular coefficients and production cross-sections of the W boson are attempted to be measured. The fitting framework, initially designed for the analysis of Z boson A_i measurements, was adopted for this study. Tests with Asimov and pseudodata utilizing 338.1 pb^{-1} of data, revealed the framework's capability to measure the larger coefficients (A_0, A_2, A_3, A_4) along with the differential cross-section $d\sigma/dp_T^{l,\nu}$. Despite these advancements, the analysis confronted inherent challenges associated with the statistical limitations of low-pileup data. These constraints have particularly impacted the feasibility of measuring the smaller A_i coefficients (A_5, A_6 , and A_7), which play a role at higher orders of **QCD** corrections ($\mathcal{O}(\alpha_s^2)$). However, applying A_i fit to real data within selected signal region, significant challenges arise: the fit either fails to converge or leads to excessively large pulls on the background nuisance parameters.

To address this, the impact of **MJ** and Z boson backgrounds on the A_i fit within chosen signal region has been analyzed. Specifically, the Z boson background contributes approximately 7% and 6% to the $e^\pm$ and $\mu^\pm$ channels, respectively, while the **MJ** background proves to be more dominant, accounting for about 19% and 10% in the same channels. The interplay and heavy correlation between these backgrounds introduce marked challenges in achieving stability in the fit of real data, often leading to non-convergence. The significant presence of Z boson and **MJ** backgrounds in the signal region poses substantial challenges in effectively controlling these backgrounds. Additionally, the A_i fit, characterized by its multiple degrees of freedom for accommodating backgrounds and signal within $\cos\theta_{CS}$ vs. ϕ_{CS} distributions for each $p_T^{\ell\nu}$ or $y^{\ell\nu}$ bin, shows high sensitivity to background mismodeling. This sensitivity complicates achieving a stable and accurate fit, further emphasizing the complexities inherent in high-precision particle physics analyses.

Outlook

The results of the analysis have demonstrated that the adopted approach faces significant limitations in estimating the Drell-Yan angular coefficients. Despite these challenges, valuable insights were gained toward achieving the ultimate goal of comprehensive measurements of all A_i coefficients in W boson decays. To fully measure all A_i coefficients in W boson decays, acquiring additional low-pileup data through the [ATLAS](#) experiment is critical¹. Within the scope of this analysis, enhanced $p_T^{\ell\nu}$ modeling in the lower $p_T^{\ell\nu}$ regions and improved overall p_T^Z modeling could be advantageous. It is also recommended to further explore the inconsistencies in $p_T^{\text{varcone20}}/p_T$ isolation across the $|\eta|$ distributions for $W^- \rightarrow e^- \bar{\nu}$ and $W^+ \rightarrow e^+ \nu$ channels. Addressing these inconsistencies is important for refining the [MJ](#) background estimation using the anti-isolated slice scan method focused on a single isolation variable. Moreover, addressing the [MC](#) yield mismodeling observed with E_T^{cone20}/p_T for $\mu^\pm$ channels might aid in achieving a more consistent approach. While managing the systematic uncertainty related to the [MJ](#) overall normalization is relatively straightforward, the systematic uncertainty associated with the [MJ](#) shape requires reevaluation, as the extrapolation from anti-isolation scans on which the [MJ](#) estimation relies is likely not linear. The impact of [MC](#) mismodeling within the anti-isolation slices, especially for the first anti-isolated slice where [EW](#) contamination is significant, should be thoroughly investigated and integrated into the analysis.

In light of the observed issues, a modification to the signal region selection is considered as a potential solution. This adjustment aims to decrease the contributions of the [MJ](#) and Z backgrounds, thereby enhancing control over background interference. Given that [MJ](#) is the dominant background, implementing cuts on E_T^{miss} and m_T appears as an effective strategy for the reduction of its impact. Moreover, the contribution from the Z boson background would be reduced, and its shape, differing from that of the [MJ](#), may potentially limit the correlation between these two sources of background in the fit. As explored in Section 6.3.1, although additional cuts should not significantly alter the sensitivity to A_2 , the uncertainty associated with A_1 increases substantially (see Figure 6.2). This change could potentially restrict the new analysis's sensitivity to the Lam-Tung relation, particularly in the high $p_T^{\ell\nu}$ bins.

The author conducted preliminary studies on the selection of a new signal region, exploring two options grounded in the well-defined signal region of the p_T^W -analysis [169]. The first option focuses on setting the p_T threshold for both the lepton and neutrino above 20 GeV, coupled with an m_T cut above 40 GeV. The second option replicates the signal region specifications of the p_T^W -analysis (25 GeV and 50 GeV, respectively). In contrast to the selection criteria utilized in the analysis described in this thesis, both options employ [MediumLH](#) identification for $e^\pm$ and $\mu^\pm$ and implement $p_T^{\text{varcone20}}/p_T < 0.1$ for isolation, foregoing an orthogonal calorimeter-based isolation selection. A summary of the signal region's contamination by [MJ](#) and Z boson backgrounds for these proposed new signal region definitions is provided in Table 10.1.

For the selection criteria set at $p_T^l > 20$ GeV, $E_T^{\text{miss}} > 20$ GeV, and $m_T > 40$ GeV, the contamination of the signal region by the [MJ](#) background decreases significantly —

¹Usage of high-pileup data is not suitable due to the significant resolution uncertainties associated with hadronic recoil.

Signal region selection	Background	$W^- \rightarrow e^- \bar{\nu}$	$W^+ \rightarrow e^+ \nu$	$W^- \rightarrow \mu^- \bar{\nu}$	$W^+ \rightarrow \mu^+ \nu$
$p_T^l > 25 \text{ GeV}, E_T^{\text{miss}} > 0, m_T > 0,$ $p_T^{\text{varcone20}}/p_T < 0.1$ and $E_{\text{cone20}}/p_T < 0.05$ (this analysis)	MJ: Z boson:	18.9% 7.1%	15.6% 6.1%	10.8% 6.3%	8.9% 5.3%
$p_T^l > 20, E_T^{\text{miss}} > 20, m_T > 40 \text{ GeV}$ MediumLH, only $p_T^{\text{varcone20}}/p_T < 0.1$	MJ: Z boson:	11.5% 1.2%	9.2% 1.0%	3.8% 4.2%	3.0% 3.5%
$p_T^l > 25, E_T^{\text{miss}} > 25, m_T > 50 \text{ GeV},$ MediumLH, only $p_T^{\text{varcone20}}/p_T < 0.1$	MJ: Z boson:	3.0% 0.7%	2.5% 0.6%	0.8% 3.6%	0.7% 3.1%

Table 10.1: Comparison of the signal region contamination by **MJ** and Z boson backgrounds for potential new signal region definitions. Complete description of the selection used for current analysis is presented in Table 6.2.

approximately by one third for the $e^\pm$ channels and by a factor of two for the $\mu^\pm$ channels. These adjustments in the **MJ** yield are also accompanied by a notable reduction in the Z boson background within the $e^\pm$ channels. However, the impact on the Z boson background within the $\mu^\pm$ channels is less pronounced.

Adopting the signal region selection criteria from the p_T^W -analysis results in the **MJ** background stabilizing at approximately 3% for the $e^\pm$ channels and 0.8% for the $\mu^\pm$ channels. In contrast, the $\mu^\pm$ channels experience around 3.6% Z boson background, whereas the $e^\pm$ channels have only 0.7%. It is anticipated that selecting a cleaner signal region with diminished backgrounds will enhance the effectiveness of achieving convergence in the $W A_i$ fit. The preliminary control plots for flattened ϕ_{CS} distributions across $p_T^{\ell\nu}$ bins (see Figures 10.1 for $W^- \rightarrow e^- \bar{\nu}$ and $W^- \rightarrow \mu^- \bar{\nu}$ channels) shows that the **MJ** template shape indeed differ from that of the Z shape for the $W^- \rightarrow e^- \bar{\nu}$ and $W^+ \rightarrow e^+ \nu$ channels.

Enhancements in the signal region selection, incorporating more stringent kinematic cuts in line with the ongoing p_T^W -analysis [169], hold promise for future $W A_i$ analyses in the **ATLAS** experiment.

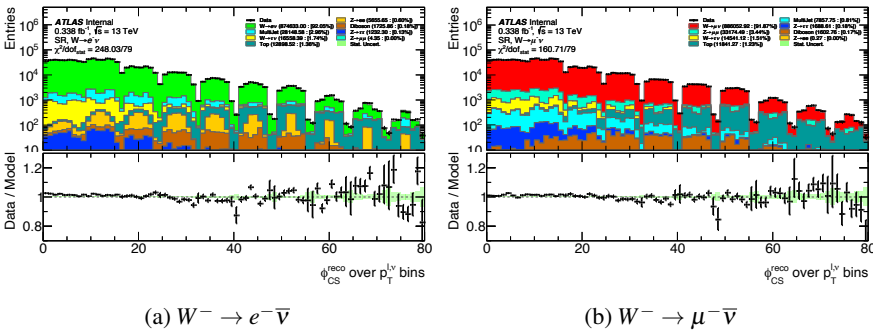


Figure 10.1: Preliminary results for flattened ϕ_{CS} distributions across $p_T^{\ell\nu}$ bins for $W^- \rightarrow e^- \bar{\nu}$ (left) and $W^- \rightarrow \mu^- \bar{\nu}$ (right) channels using proposed more strict signal region criterias: $p_T^l > 25 \text{ GeV}$, $E_T^{\text{miss}} > 25 \text{ GeV}$, $m_T > 50 \text{ GeV}$, MediumLH identification for both $e^\pm$ and $\mu^\pm$, and $p_T^{\text{varcone20}}/p_T < 0.1$ isolation. Only statistical uncertainties are shown. For more information on this signal region and analysis this plots are based on, please refer to [169].



LEPTON FLAVOUR UNIVERSALITY TEST IN W DECAYS IN RUN 2

The thesis initially set out to explore the principle of Lepton Flavor Universality (LFU) in the Standard Model (SM) of particle physics. LFU postulates that in a massless scenario, vector gauge bosons, like the W -boson, should demonstrate an equal coupling across all three generations of leptons (electron, muon, and tau), despite their different masses and distinct couplings to the Higgs boson. Exploration of LFU is critical in particle physics, as LFU is not a necessary condition of the SM. Any deviations observed in the couplings across lepton generations would indicate new physics beyond the SM. On the other hand, if LFU is confirmed, it raises questions about the underlying reasons for such uniformity. The research aimed to directly measure LFU using $W^\pm$ bosons from leptonic W -boson decays. Originally analysis aimed to use full Run 2 data (139 fb^{-1}), however due to resource constraints, firstly employed 3.22 fb^{-1} of proton-proton collision data collected with high-pileup in 2015 and later focused on 340 pb^{-1} data collected with low-pileup in 2017-2018 only. The goal was to achieve a total uncertainty level of 1.5%. However, various challenges emerged during the analysis, and the release of parallel results from the ATLAS Top group addressing key LFU test aspects [177] led to the discontinuation of this particular analysis in March 2021. These required a shift in the research focus, which is now centered on Drell-Yan angular coefficient analysis, leveraging the expertise and methodologies developed during the initial LFU study. This appendix provides a concise summary of the analysis efforts. For an in-depth exploration and additional details, please refer to [178].

A.1 Introduction

The accuracy of LFU can be probed through examining leptonic and semileptonic processes that diverge solely in lepton flavour. This can be achieved by comparing their decay widths. In recent years, interesting hints of lepton non-universality have been seen in semi-leptonic

decays of B hadrons [179] where an excess of τ final states over e, μ final states is seen at the level of 4 standard deviations. Similarly, LEP measurements on W decays suggest a potential non-universality [180], evidenced by a disproportionate occurrence of τ final states:

$$\frac{2\mathcal{B}(W \rightarrow \tau\nu)}{\mathcal{B}(W \rightarrow \mu\nu) + \mathcal{B}(W \rightarrow e\nu)} = 1.077 \pm 0.026 \quad (\text{A.1})$$

resulting in a poor agreement at the level of 2.8 standard deviations, with all correlations included.

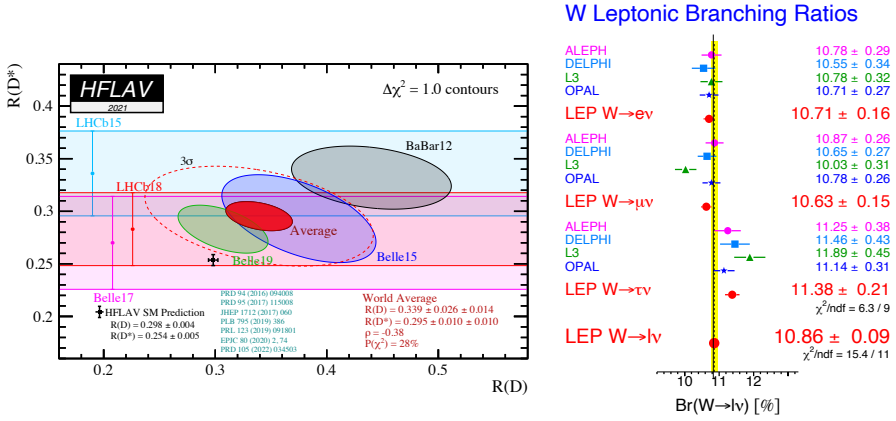


Figure A.1: Left: HFLAV average of all measurements of $R(D)$ and $R(D^*)$ [179]. The red ellipse shows the combined average and the data point is the SM prediction, showing a discrepancy of 3.3σ . Right: W leptonic branching ratios from [180]. Latest results obtained by ATLAS [177] are not shown and would be discussed in Section A.3.

The ATLAS experiment has been known for producing over $\sim 10^9$ decays of W -bosons to leptons in Run 2, which presented a opportunity for a high-precision examination of lepton universality in prompt W decays. This could be achieved by measuring the ratio:

$$\mathcal{R}_{\tau/\ell} = \frac{\mathcal{B}(W^\pm \rightarrow \tau^\pm \nu_\tau \rightarrow \ell^\pm \nu_\ell \nu_\tau \nu_\tau)}{\mathcal{B}(W^\pm \rightarrow \ell^\pm \nu_\ell)}, \quad (\text{A.2})$$

where $\ell = e, \mu$. In this framework, many systematic uncertainties related to lepton identification are expected to be reduced.

A substantial portion of leptons are anticipated to come from prompt W decays, given the branching fraction of τ to leptons is 17.39%. However, it's been noted that a considerable number of leptons from $W \rightarrow \tau \rightarrow \ell$ decay may not pass through the L1 trigger due to their lower momentum.

The preliminary step in the analysis strategy was designed to identify phase space regions enriched in τ decays. This identification could be carried out utilising a multivariate classifier, built upon both kinematic information and the lepton impact parameter d_0 . As these two variables are largely uncorrelated, it was projected that the efficiency could be constrained

from data, aiming to bolster the precision of the investigation into lepton (non-)universality. However, for low-pileup data only the tests with d_0 vs. m_T^W variables were performed.

Similar to the methodology outlined in the Top group analysis paper [177], this analysis is structured to measure the ratio of the parameter of interest $\mathcal{R}_{\tau/\ell}$ in both data and Monte Carlo simulations. In contrast, instead of engaging with tag and prompt leptons, the focus here is directed towards single lepton triggers. This deviation introduces one of the principal analysis challenges: maintaining control over systematics related to single leptons trigger mechanisms.

Control regions are defined to constrain the modelling of predominant backgrounds: $Z \rightarrow \ell\ell$ boson production and QCD fake leptons. An additional $Z \rightarrow \tau\tau$ leptonic control region is employed for d_0 correction studies with in attempt to overcome the Insertable B-Layer (IBL) detector alignment issue.

Drawing parallels with the approach adopted in [177], the following categories of leptons are defined based on their truth origin:

- **prompt (W)** leptons: These leptons originate from $W \rightarrow \ell\nu$ decays.
- **tau** leptons: These are generated through the leptonic decay chain $W \rightarrow \tau\nu \rightarrow \ell\nu\bar{\nu}$.
- **prompt (non- W)** leptons: Originating from Z or other electroweak processes, these leptons do not emanate from W decays, and are associated with, for example, di-boson, single top or $t\bar{t}$ processes.
- **“fake”** leptons: This category includes reconstructed leptons from all other sources, including misidentified leptons.

A two-dimensional fit was preformed to facilitate optimal separation among prompt-, tau-, and fake leptons. The aggregate rate of the W events is allowed to float, along with the parameter of interest – the ratio of $W \rightarrow \tau\nu$ to $W \rightarrow \ell\nu$ events.

A.2 A brief analysis overview

Aiming to achieve a total uncertainty of 1.5%, the initial strategy focused on minimizing the statistical uncertainty by utilizing high-pileup data collected during the entirety of Run 2. However, it quickly became apparent that selecting a signal region would incorporate an extensive amount of data into the analysis, presenting a challenging task for a small team. As a result, the analysis was redirected towards the 2015 data set, with the intention of scaling up once the analysis workflow and procedures were well established.

Investigating high- μ data

Event and object selection criteria are detailed in left column of the Table A.1. To reduce the contribution of multijet (MJ) background and maintain high single lepton trigger efficiency, a threshold of $p_T > 25$ GeV was set for the leading lepton. In contrast to other Run 2 analyses, the transverse mass cut-off, m_T^W , was relaxed to 40 GeV to allow for a greater inclusion of tau leptons. No cuts were made on the z_0 or d_0 variables, as these parameters were the

Objects and event selection		
	High- μ data	Low- μ data
GRL	Pass GRL selection	
Vertex	> 3 associated tracks	> 1 associated tracks
Jets	No b -tagged jets	–
Lepton Selection - Electrons		
Trigger	HLT_e24_lhmedium_L1EM20VH	HLT_e15_lhloose_nod0_L1EM12
p_T^e	> 27 GeV	> 20 GeV
η^e	$ \eta < 1.37$ or $1.52 < \eta < 2.47$	
ID	Tight LH	
Isolation	Tight (working point)	$p_T^{varcone20}/p_T < 0.1$
Lepton Selection - Muons		
Trigger	HLT_mu20_iloose_L1MU15	HLT_mu14
p_T^μ	> 27 GeV	> 20 GeV
η^μ	$ \eta < 2.47$	
ID	Medium	
Isolation	Tight (working point)	$p_T^{varcone20}/p_T < 0.1$
Signal region		
N leptons	Exactly 1	
E_T^{miss}	> 25 GeV	> 20 GeV
m_T	> 40 GeV	
Control region: $Z \rightarrow \ell\ell$, where $\ell = e, \mu$		
N leptons	Exactly 2, same flavor and oppositely charged	
Mass window	$66 \text{ GeV} < m_{\ell\ell} < 116 \text{ GeV}$	
Control region: $Z \rightarrow \tau\tau$		
N leptons	Exactly 2, opposite flavor and oppositely charged	
Mass window	$m_{\ell\ell} < 85 \text{ GeV}$	

Table A.1: Event and object requirements for passing the preliminary selection and inclusion into the control regions for high-pileup data. The requirements for both the electron and muon channels are presented for high and low-pileup data analysis.

Channel	Signal regions		Control regions	
	$W^\pm \rightarrow e^\pm \nu$	$W^\pm \rightarrow \mu^\pm \nu$	$Z \rightarrow ee$	$Z \rightarrow \mu\mu$
$W \rightarrow \tau\nu$	1.5%	1.72%	-	-
$Z \rightarrow \tau\tau$	0.11%	0.12%	0.04%	0.04%
Diboson	0.11%	0.1%	0.11%	0.11%
single top and $t\bar{t}$	0.06%	0.05%	0.02%	0.02%
$W \rightarrow e\nu$	86.71%	-	0.03%	-
$W \rightarrow \mu\nu$	-	92.67%	-	0.01%
$Z \rightarrow ee$	1.25%	-	99.78%	-
$Z \rightarrow \mu\mu$	-	4.01%	-	99.82%
Multijet	10.27%	1.31%	N/A	N/A
Total number of events				
EW + top	14 448 983	16 223 126	4 603	5 151
Data	15 844 096	16 667 946	1 456 927	1 676 489

Table A.2: Event yields for analysis regions in high-pileup data. Electroweak background contributions estimated from simulation. Multijet is estimated by data-driven method. Expectations are expressed as a percentage of the total experimental data events passing selection in each region. Numbers of observed candidate events for the electroweak (EW) plus top processes and Data are shown on the bottom part.

subject of a specific study. The event yields for Data, as well as signal and background event estimations, are presented in Table A.2.

The yield for the signal process $W \rightarrow \tau\nu \rightarrow l\nu\nu$ accounts for 1.5% and 1.7% in the electron and muon channels, respectively. It is evident that the signal region for muons is comparatively cleaner and has a smaller fraction of MJ events (1.3% in the muon channel versus 10.3% for electrons).

For estimating the contribution of MJ events to the background in high-pileup data, a data-driven QCD background estimation method was explored. This approach required the establishment of specialized MJ control regions, defined by softer kinematic event selection criteria ($E_T^{\text{miss}} > 0$ GeV, and $m_T(\ell, E_T^{\text{miss}}) > 0$ GeV), and the application of reversed lepton selection criteria in terms of isolation and identification. This method replicated the algorithm used in early Run 2 for measuring the $W^\pm \rightarrow \ell^\pm \nu$ production cross sections [171], which corresponded to a total integrated luminosity of 81pb^{-1} . Significant deviations for MJ background predictions obtained using $p_T^{\text{varcone20}}/p_T$ and E_T^{cone20}/p_T isolation variables are shown. Based on the results of this study, a simpler MJ template fitting method was employed for the analysis of high-pileup data.

In the control $Z \rightarrow \ell\ell$ regions, as well as in the signal regions number of Data to model discrepancies was observed. The slope in the p_T^ℓ distribution at the hard part of the p_T spectrum in the signal regions is attributed to bad p_T^W modelling. Also beside the discrepancies in the E_T^{miss} distributions, as well as for $\Delta\phi(\ell, E_T^{\text{miss}})$, which likely driven by the absence of corrections for the MJ anti-isolated control region, significant problems for the d_0 impact parameter has been observed. The d_0 impact parameter for the leading lepton

serves as a key discriminative variable to distinguish prompt W -boson decays in this analysis.

The discrepancy in the d_0 data relative to the model is primarily attributed to alignment issues with the Insertable B -Layer (IBL) detector. Uncorrected distributions for this discrepancy are illustrated in Figure A.2: panels (a,c) shows the Z control region, and panel (b,d) presents the inclusive signal regions in the muon and electron channels. To address this, methods for deriving and applying corrections to both prompt and τ leptons were explored. For high-pileup data, corrections for prompt leptons were determined as a function of p_T^ℓ and η^ℓ . However, the correction studies for τ leptons were not conducted.

A multivariate classifier was used as a second variable to help distinguish tau leptons from prompt W decays in high-pileup data. The classifier was constructed using BDT algorithms with gradient minimisation and implemented based on the TMVA package [181], provided as part of the ROOT framework [182]. The achieved BDT score is approximately 0.73 for both electron and muon channels. An additional step was taken to confirm that the scoring performs as anticipated for actual data, even in the presence of Data to Model discrepancies. To achieve this, the $Z \rightarrow \mu\mu$ control region was modified by constraining the pseudo W -boson decay, achieved by converting one of the randomly selected leptons from Z decay to a missing neutrino. Results showed good Data to Model agreement.

Figure A.3 presents a comparative analysis of the normalized shapes for the d_0 variable and BDT score across electron and muon channels. To enhance the sensitivity of the fit, a two-dimensional approach was adopted, dividing the d_0 variable into five bins based on the BDT score. Additionally, for the Asimov fit, $Z \rightarrow \mu\mu$ and MJ template control regions were incorporated, although this may be suboptimal.

The resultant values of the branching ratios for W boson decays in the electron and muon channels, derived using Asimov data, are shown in Eq. A.3 for electrons and Eq. A.4 for muons. The analysis employed the d_0 distribution considering a range from -0.1 to 0.1 mm. Importantly, it should be noted that number of systematic uncertainties were not included in these results. These omitted uncertainties include those associated with the veto on b -jets and the systematic errors in accurately estimating the MJ background.

$$\mathcal{R}_{\tau/e}^{\text{Asimov}} = 1. \oplus_{-0.014357}^{+0.014255}(\text{total}) = 1. \oplus_{-0.010188}^{+0.010192}(\text{stat.}) \oplus_{-0.010116}^{+0.009966}(\text{syst.}) \quad (\text{A.3})$$

$$\mathcal{R}_{\tau/\mu}^{\text{Asimov}} = 1. \oplus_{-0.008812}^{+0.008724}(\text{total}) = 1. \oplus_{-0.005529}^{+0.005535}(\text{stat.}) \oplus_{-0.006861}^{+0.006744}(\text{syst.}) \quad (\text{A.4})$$

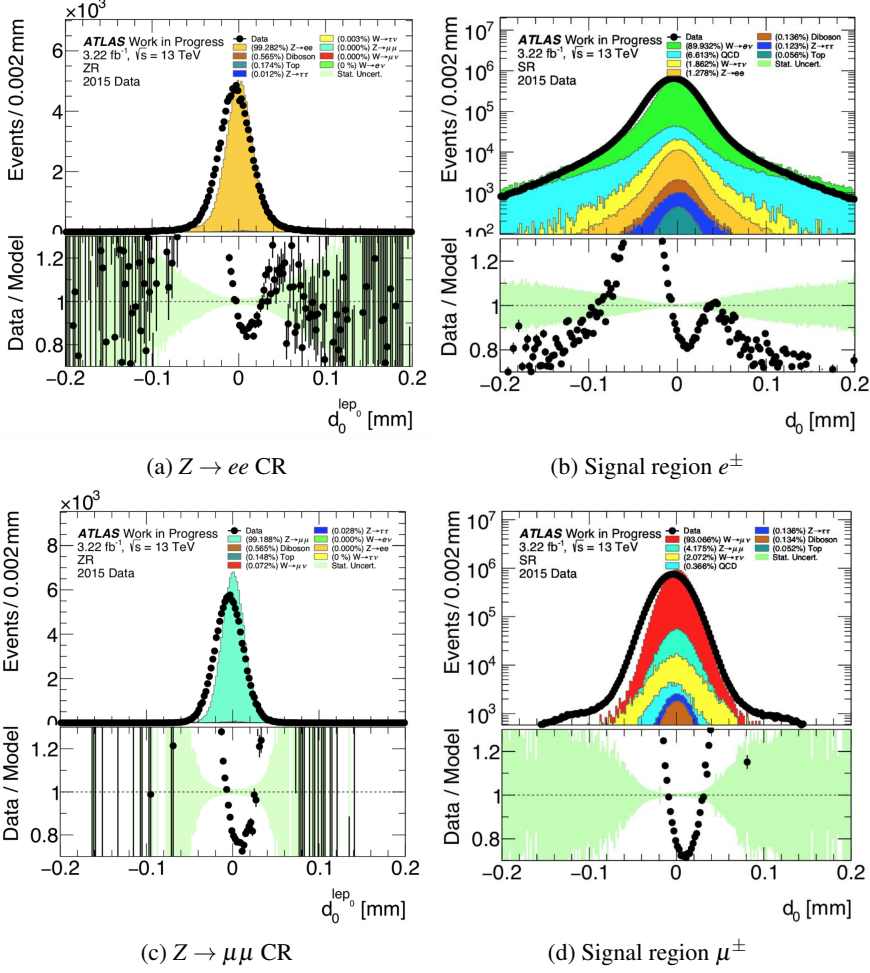


Figure A.2: Control plots for d_0 variable for the $Z \rightarrow \mu\mu$ (a) and $Z \rightarrow ee$ (c) regions. Distributions of the d_0 variable in the inclusive signal region for the $W^\pm \rightarrow \mu^\pm \nu$ channel (b) and for the $W^\pm \rightarrow e^\pm \nu$ channel (d) in the logarithmic scale. The high-pileup data was used.

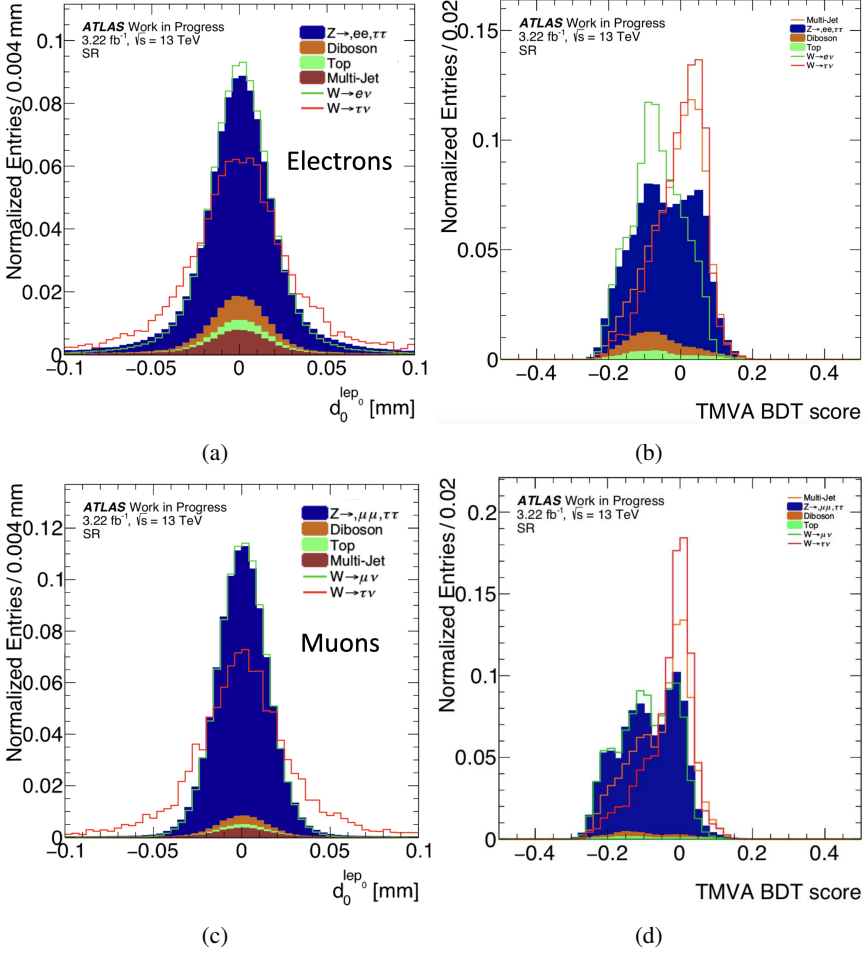


Figure A.3: Normalized distributions of the d_0 variable and BDT (Boosted Decision Tree) score for the signal region in the muon (a,b) and the electron (c,d) channel. The estimation of the MJ background is performed using a data-driven approach. The high-pileup data was used.

Investigating low- μ data

Given the challenges encountered, particularly those related to the crucial aspect of Data/Monte Carlo agreement, and considering the extensive volume of data managed by the author during the analysis (approximately $\mathcal{O}(10\text{TB})$), a decision was taken to investigate the potential of low- μ data. This specific dataset, collected under specialized conditions in 2017 and 2018, offered the advantage of reduced data volume and, consequently, a lighter workload. The close collaboration with the leading research groups engaged in Standard Model W/Z research proved to be of great value. This partnership enabled the integration and repurposing of calibrations and corrections initially developed for other analyses, such as p_T^W -analysis and m^W -analysis.

The event and object selection criteria for the low-pileup data analysis are comprehensively outlined in the right column of Table A.1. Operating in an environment with reduced MJ contamination enabled the lowering of the p_T^ℓ threshold to 20 GeV. Similarly, the E_T^{miss} cut-off was also relaxed to 20 GeV. In alignment with the methods employed in the p_T^W -analysis and m^W -analysis, an isolation criterion of $p_T^{\text{arcone20}}/p_T < 0.1$ was implemented, rather than relying on predefined isolation working points.

Although both the electron and muon channels were subject to investigation, this section will focus exclusively on the muon channel due to its superior measurement precision, attributed to its higher purity. The event yields for Data, and the associated signal and background event estimations, are presented in Table A.3.

In the low-pileup data, the yield for the signal process $W \rightarrow \tau\nu \rightarrow \mu\nu\nu$ constitutes 2.58%, a notable increase compared to the 1.7% observed in the muon channels for high-pileup data. The contribution from MJ events rose to 5.44%.

To estimate the MJ background, a Python-based framework was developed, replicating the MJ estimation algorithm detailed in Reference [172] for the p_T^W -analysis based on anti-isolation scan methodic. This framework's functionality was thoroughly validated through comparisons with the MJ estimations from the p_T^W -analysis. It provided reliable predictions of the MJ shape and yields, accompanied by systematic uncertainties, paralleling the approach described in Section 6.5.

Despite improved overall Data/Model agreement in the low-pileup data, the issue of d_0 mismodelling persisted. To address this for prompt leptons, d_0 bias and resolution corrections were derived using a method similar to that employed in the high-pileup data analysis. Corrections were determined using 8 bins in p_T^μ and 3 bins in η^ℓ , based on data from the $Z \rightarrow \mu\mu$ control region. For tau leptons, due to the reduced statistical availability, a smaller number of bins was utilized in the $Z \rightarrow \tau\tau$ control region: 4 bins in p_T^μ and 2 bins in η^ℓ . Figure A.4 illustrates the impact of the d_0 corrections on the signal region. It was found that the given control regions allow for deriving corrections predominantly for the core part of the d_0 distribution, which has a Gaussian-like behavior.

An Asimov fit was performed to evaluate the potential of the analysis. In the fitting process for low-pileup data, only the Z control region was utilized as an additional region to establish normalization for EW processes. Differing from the approach of using the d_0 variable as a function of BDT score, the transverse mass variable, m_T^W , was used instead, divided into 5 bins.

Moreover, the analysis employed the absolute value of the d_0 distribution, $|d_0|$, considering a range from 0 to 0.5 mm. Most systematic uncertainties were incorporated into the

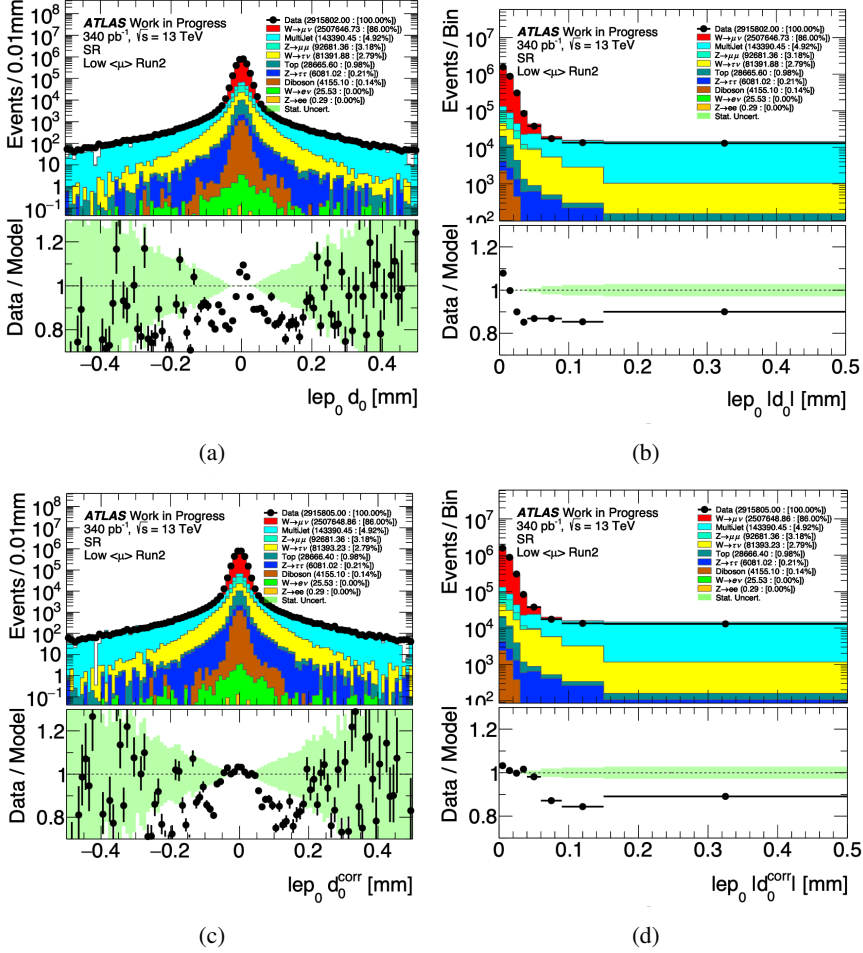


Figure A.4: Impact of the d_0 corrections to the signal region is shown. Before (a,b) and after corrections (c,d).

Channel	Signal region	Control regions	
	$W^\pm \rightarrow \mu^\pm \nu$	$Z \rightarrow \mu\mu$	$Z \rightarrow \tau\tau$
$W \rightarrow \tau\nu$	2.58%	-	0.07%
$Z \rightarrow \tau\tau$	0.16%	0.06%	80.31%
Diboson	0.11%	0.21%	6.63%
single top and $t\bar{t}$	0.9%	0.3%	8.52%
$W \rightarrow e\nu$	-	-	0.74%
$W \rightarrow \mu\nu$	87.31%	0.01%	1.5%
$Z \rightarrow ee$	-	-	0.03%
$Z \rightarrow \mu\mu$	3.24%	99.41%	2.2%
Multijet	5.44%	N/A	N/A
Total number of events			
EW + top	2 657 156	221 888	2 035
Data	2 951 031	228 385	2 082

Table A.3: Event yields for analysis regions in low-pileup data. Electroweak background contributions estimated from simulation. Multijet is estimated by data-driven method. Expectations are expressed as a percentage of the total experimental data events passing selection in each region. Event yields of candidate events for electroweak (EW) plus top processes and Data are shown on the bottom part.

fit, with the exception of three tree-based muon systematic uncertainties: MUONS_SCALE, MUONS_ID, and MUONS_MS. For the Z control region, no systematic uncertainties were applied, except for a fixed systematic uncertainty of 1.5% on luminosity.

The outcome of the Asimov fit is as follows:

$$\mathcal{R}_{W/\mu}^{\text{Asimov}} = 1. \oplus_{-0.0370}^{+0.0373}(\text{total}) = 1. \oplus_{-0.0115}^{+0.0115}(\text{stat.}) \oplus_{-0.0352}^{+0.0355}(\text{syst.}) \quad (\text{A.5})$$

The specific contributions from groups of systematic sources are tabulated in Table A.4.

Systematic group	Impact
γ 's (MC stat.)	3.12%
Multijet estimation	2.18%
Trigger syst.	1.08%
Isolation stat.	0.93%
Norm factors (μ_W, μ_Z)	0.69%
Isolation syst.	0.62%
Trigger stat.	0.46%
Reco stat.	0.15%
Reco syst.	0.12%
Luminosity	0.11%

Table A.4: Systematics uncertainties breakdown for Asimov data for low-pileup data analysis.

A.3 Conclusions and outlook

In the context of high-pileup data, the statistical uncertainty in the measurement of $\mathcal{R}_{\tau/e}^{\text{Asimov}}$ is about 1%. For the muon channel, the statistical uncertainty of $\mathcal{R}_{\tau/\mu}^{\text{Asimov}}$ has been determined to be around 0.55%. Notably, these results were achieved using only the 2015 data, amounting to 3.22 fb^{-1} . It is thus expected that utilizing the full dataset collected by the ATLAS experiment during Run 2 (147 fb^{-1}) would further reduce the statistical uncertainty. However, findings from the low-pileup data studies indicate that the systematic uncertainty is the dominant contributor to the total uncertainty, making this analysis predominantly systematically limited. Integrating the electron and muon channels into a unified fit may provide additional opportunities to minimize uncertainties. However, the environmental activity in the high- μ data presents a significant challenge in controlling the MJ background.

In the analysis of low-pileup data, the Asimov statistical uncertainty for $\mathcal{R}_{W\tau/\mu}^{\text{Asimov}}$ was determined to be 1.15%, accompanied by a systematic uncertainty of 3.5%. It is important to approach the interpretation of this systematic uncertainty with caution, especially considering that 3.2% of it is due to the MC statistics, denoted by γ 's. This aspect could potentially be reduced by rebinning the d_0 variable. Furthermore, it is important to acknowledge that several tree-based muon systematic uncertainties were not included in the analysis, which will require additional exploration in future studies. On the other hand, the MJ background estimate in this analysis was performed with remarkable precision, including both yield- and shape-based systematic uncertainties. These contributed significantly to the overall systematic uncertainty in the fit, with the MJ background alone accounting for a primary contribution of 2.18%.

Parallel to this study, the ATLAS Top group published their findings in 2021 [177], reporting a measured ratio of $\mathcal{R}_{\tau/\mu} = 0.992 \pm 0.013$ [± 0.007 (stat) ± 0.011 (syst)]. Their analysis focused on selecting collision events from the full Run 2 data to create a high-purity sample of $t\bar{t}$ events, where each top quark decays into a W and a b quark, subsequently leading to the leptonic decay of the two W -boson. This approach employed a tag-and-probe method with the dual leptonic W -boson decays allowing perform analysis using

probe leptons with $p_T > 5$ GeV. In each event, tag leptons (electrons or muons) were used for event selection, followed by an unbiased evaluation to determine whether the probe muon originated directly from a W decay ($W \rightarrow \mu \nu_\mu$) or through an intermediate τ lepton ($W \rightarrow \tau \nu_\tau \rightarrow \mu \nu_\mu \nu_\tau \nu_\tau$). The events were then categorized into signal regions for extracting $\mathcal{R}_{\tau/\mu}$ and additional control regions for constraining the normalization of major backgrounds. In this context, analysis of the muon's transverse impact parameter, d_0^μ , was also integral. In addition, corrections within the $t\bar{t}$ event topology were implemented to account for possible discrepancies in detector resolution between the data and the simulation, in particular for muons resulting from τ decays and hadronic decays. The ATLAS top group measurement significantly advanced the testing of LFU with remarkable precision of 1.3%. It has addressed the previously observed 2.6σ discrepancy in W boson decays, specifically in the ratio $\mathcal{R}_{\tau/\mu}$, initially reported by the LEP collaboration.

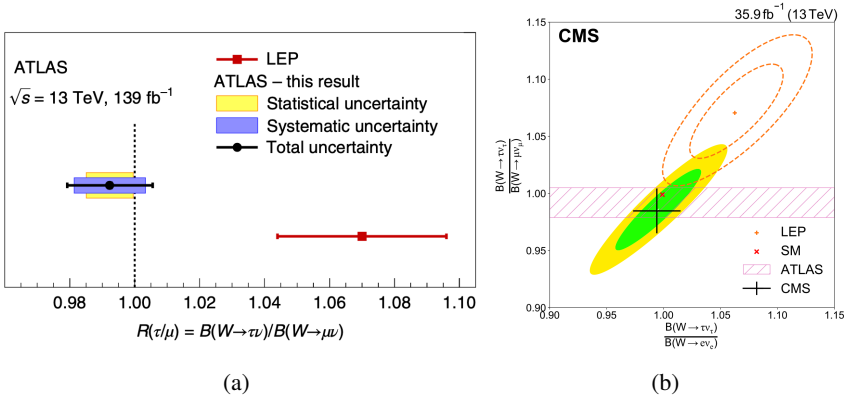


Figure A.5: (a) Summary of ATLAS [177] and LEP [180] results for $\mathcal{R}(\tau/\mu)$. For the ATLAS result the statistical (yellow box) and systematic (blue box) errors are shown separately, along with the total error of the measurement (black bars). The total uncertainty on the LEP result is indicated by the red bars. The vertical dashed line indicates the prediction lepton-flavour universality of the SM, with equal W -boson branching ratios to different lepton flavours. (b) Two-dimensional distribution of the ratio $\mathcal{R}(\tau/e)$ versus $\mathcal{R}(\tau/\mu)$, compared with the corresponding LEP [32], [180], ATLAS [177] and CMS [183] results and with SM expectation. The green and yellow bands for CMS results (dashed lines for the LEP results) correspond to the 68% and 95% CL, respectively, for the resulting two-dimensional Gaussian distribution. The corresponding 68% CL one-dimensional projections (black error bars) are also overlaid for a better visual comparison with the ATLAS $\mathcal{R}(\tau/\mu)$ result.

At the time of the ATLAS Top group's publication, the CMS collaboration had made substantial progress in measuring the branching fractions of the W boson into electron, muon, and tau lepton final states [183]. These measurements utilized proton-proton collision data collected at $\sqrt{s} = 13$ TeV, corresponding to an integrated luminosity of 35.9 fb $^{-1}$. Events with one or two W bosons were selected and categorized based on the multiplicity and flavor of the reconstructed leptons, the number of jets, and the number of jets identified as originating from b quark hadronization. Although primarily designed to capture events

	CMS	LEP	ATLAS	LHCb	CDF	D0
$\mathcal{R}_{\mu/e}$	1.009 ± 0.009	0.993 ± 0.019	1.003 ± 0.010	0.980 ± 0.012	0.991 ± 0.012	0.886 ± 0.121
$\mathcal{R}_{\tau/e}$	0.994 ± 0.021	1.063 ± 0.027	–	–	–	–
$\mathcal{R}_{\tau/\mu}$	0.985 ± 0.020	1.070 ± 0.026	0.992 ± 0.013	–	–	–
$\mathcal{R}_{\tau/\ell}$	1.002 ± 0.019	1.066 ± 0.025	–	–	–	–

Table A.5: Ratios of different leptonic branching fractions measured by LEP [32], [180], LHC [177], [183]–[185], and Tevatron [186], [187].

from $t\bar{t}$ production (similar to the ATLAS analysis), the criteria also included contributions from tW , WW , and $W + \text{jets}$ production, which were thus considered as signal processes in this analysis. The minimum p_T thresholds were set at 10 GeV for electrons and 5 GeV for muons. For each category, events were further binned based on a single kinematic observable specific to that category. Primarily, the analysis utilized the subleading lepton p_T and the hadronic tau p_T for this purpose. A binned maximum likelihood estimate of the W boson branching fractions was conducted simultaneously across each event category. The results, as summarized in Table A.5, include the obtained ratios compared to those measured at LEP, LHC, and Tevatron. The ATLAS $\mathcal{R}_{\tau/\mu}$ extraction showed a smaller uncertainty compared to CMS, benefiting partly from analyzing a four times larger pp data sample.

Table A.5 notably lacks the measurement of $\mathcal{R}_{\tau/e}$ by ATLAS. Performing an analysis with precision exceeding the 2.1% benchmark established by CMS for direct W decays is a significant challenge. Since all CMS results and the most precise ATLAS result are consistent with the LFU hypothesis, the specific research efforts related to LFU analysis in this chapter have been discontinued.

Outlook

Performing an analysis within the direct W -boson decay topology presents significantly greater challenges compared to the $t\bar{t}$ topology. Nevertheless, several strategies can be implemented to improve the precision of the analysis using low-pileup data within the muon channel:

- Optimizing the fit regions and binning strategy across the d_0 variable can significantly improve the statistical robustness of the Monte Carlo samples. Adjusting the binning, particularly in the tails of the d_0 distribution where there is high m_T , can lead to a more precise fit. This adjustment may also influence the systematic contribution from MJ background, as MJ predominantly contributes to the tails of the d_0 distribution.
- Employing a fitting approach over an event classifier variable, as an alternative to the m_T^W distribution, might enhance the fit’s sensitivity and precision. Preliminary statistical studies comparing sensitivity projections from high to low-pileup data indicate that this approach could potentially halve the total statistical uncertainty.
- Mitigating the impact of MJ background systematic uncertainty can be achieved by reducing its contamination in the signal region. Implementing a cut on the muon’s momentum balance significance variable may decrease the MJ background’s systematic

influence in the signal region. Further, applying stricter cuts on E_T^{miss} or m_T^W within additional sensitivity studies could also be beneficial.

Correction of the transverse impact parameter (d_0) was a significant challenge. The data showed better resolution than MC simulations, accompanied by a significant d_0 bias in the Data. Although the developed corrections effectively targeted the central part of the d_0 distribution, they did not fully address the non-Gaussian tails, where an excess of events with secondary vertices was evident. This observation highlights the need to reconsider the range of the d_0 distribution in the fit. For the tau lepton corrections, the limited statistical power in the $Z \rightarrow \tau\tau$ region proved to be a constraint in the correction process. The idea of extrapolating corrections from processes such as $t\bar{t}$ is controversial, since the involvement of the top quark early in the decay chain could significantly influence the d_0 distribution, potentially making it unrepresentative of the tau lepton decays under investigation. In addition, systematic uncertainties associated with the d_0 correction require careful consideration due to their potential impact on the overall accuracy and integrity of the analysis.

B

ADDITIONAL MATERIAL ON THE $W A_i$ FIT

B.1 List of the nuisance parameters

Chapter 8.1 offers a comprehensive overview of the systematic nuisance parameters (NPs) employed in the $W A_i$ fit. This appendix details all NPs utilized in the fit, presented in summarizing tables for each of reference.

Table B.1 catalogues the systematic NPs that demonstrate uniform influence across all analysis channels. Each NP is considered for both upward and downward adjustments, except for the SET_Sys parameter, which is uniquely subjected to a one-sided upward variation.

Table B.2 outlines the electron channel-specific systematic NPs. Each NP is evaluated for variations in both the positive and negative directions.

Lastly, Tables B.3 and B.4 elaborate on the muon channel-specific systematic NPs. These include both up and down variations for each NP, incorporating both tree-based systematic evaluations alongside weight-based trigger and TTVA systematics.

Short name	#NPs	Description
PDF	26	Systematic uncertainty attributed to the parton distribution function employed for weighting each Monte Carlo event.
PDF_Scale	1	Systematic uncertainty associated with the variation of the generator's α_s parameter.
XSec.Boson	1	A flat 5% variation is uniformly applied to the cross-sections of all single boson samples.
XSec.Diboson	1	A flat 10% variation is uniformly applied to the cross-sections of all diboson samples.
XSec.Top	1	A flat variation between 7% and 10% is applied to the cross-sections of all top-associated samples.
Response.Sys	1	Systematic uncertainty associated with the hadronic recoil response correction.
Response.ExtSys	1	Systematic uncertainty associated with the hadronic recoil response correction due to the extrapolation from Z to W .
Response.Stat0	15	Statistical uncertainty associated with the first eigenvector of the hadronic recoil response correction.
Response.Stat1	15	Statistical uncertainty associated with the second eigenvector of the hadronic recoil response correction.
Resolution.ExtSys	1	Systematic uncertainty related to the hadronic recoil resolution correction, arising from the extrapolation from Z to W boson events.
Resolution.Stat0	18	Statistical uncertainty associated with the first eigenvector of the hadronic recoil resolution correction.
Resolution.Stat1	18	Statistical uncertainty associated with the second eigenvector of the hadronic recoil resolution correction.
SET.Stat	48	Statistical uncertainty associated with the ΣE_T reweighting for high values of u_T .
SET.Sys	1	Systematic uncertainty associated with the ΣE_T .
MJ_Yield	3	Uncertainty on the multijet yield estimated for each coarse bin.
MJ_Shape	3	Uncertainty on the multijet template shape estimated for each coarse bin.
MJ_Acc.Stat	10 / 7	Statistical uncertainty on the MJ acceptance correction functions, with the number of nuisance parameters dependent on the number of $p_T^{\ell V}$ or $y^{\ell V}$ bins used.
MJ_Acc.Closure	3	Systematic uncertainty due to the difference between the templates used to create the MJ acceptance correction functions within each coarse bin.

Table B.1: Description of the systematic nuisance parameters that display uniform behaviour across all channels in the analysis. Each parameter is subjected to variations both in the upward and downward directions, with the exception of the SET_Sys parameter, which undergoes a one-sided upward variation.

Short name	#NPs	Description
El_Reso	24	Systematic uncertainty that arises from the resolution of electron momentum measurement.
El_Scale	24	Systematic uncertainty associated with the electron energy scale correction.
El_Trig_Corr	14	Full correlation model systematic variation for trigger-related uncertainty in the electron channel.
El_Trig_Uncorr	1	Statistical uncertainty for the trigger systematic variation in the electron channel.
El_Reco_Corr	30	Full correlation model systematic variation for reconstruction-related uncertainty in the electron channel.
El_Reco_Uncorr	1	Statistical uncertainty for the reconstruction systematic variation in the electron channel.
El_Iso_Corr	14	Full correlation model systematic variation for isolation-related uncertainty in the electron channel.
El_Iso_Uncorr	1	Statistical uncertainty for the isolation systematic variation in the electron channel.
El_IsoWAI_Corr	1	Correlated systematic uncertainty related to electron isolation scale factor. It arises from the difference between tag-and-probe choices for efficiency calculation in the specific analysis phase space.
El_IsoWAI_Uncorr	1	Uncorrelated systematic uncertainty originating from the statistical variations in the efficiency within each $p_T \times \eta$ bin for the additional isolation scale factors tailored to this analysis.
El_ID_Corr	14	Full correlation model systematic variation for identification-related uncertainty in the electron channel.
El_ID_Uncorr	1	Statistical uncertainty for the identification systematic variation in the electron channel.
El_IDWAI_Corr	1	Correlated systematic uncertainty related to electron identification scale factor. It arises from the difference between tag-and-probe choices for efficiency calculation in the specific analysis phase space.
El_IDWAI_Uncorr	1	Uncorrelated systematic uncertainty originating from the statistical variations in the efficiency within each $p_T \times \eta$ bin for the additional identification scale factors tailored to this analysis.

Table B.2: Description of the electron channel-specific systematic nuisance parameters utilised in the analysis. Each parameter (NP) features both up and down variations.

Short name	#NPs	Description
Mu_ID	1	Systematic uncertainty on muon calibration using only information from Inner Detector (ID) information.
Mu_MS	1	Systematic uncertainty on muon calibration using only Muon Spectrometer (MS) information.
Mu_Scale	1	Systematic uncertainty on the energy scale correction for muons.
Sagitta_Bias_Stat	48	Statistical uncertainty on the charge dependency of muon momentum corrections.
Sagitta_Bias_Offset	1	Systematic uncertainty involving the adjustment of the bias offset associated with muon momentum corrections.
Mu_Trig_dPhi	1	Trigger systematic uncertainty related to requirements on $\Delta\phi_{\mu\mu}$ to evaluate detector symmetry.
Mu_Trig_IsoLooseAvg	1	Trigger systematic uncertainty as a result of variations in the loose isolation requirements.
Mu_Trig_IsoTightAvg	1	Trigger systematic uncertainty as a result of variations in the tight isolation requirements.
Mu_Trig_MllTight	1	Trigger systematic uncertainty resulting from variations in the invariant mass window required for the tag and probe pair.
Mu_Trig_NoIP	1	Trigger systematic uncertainty resulting from not requiring a matching interaction point.
Mu_Trig_Uncorr	19	Uncorrelated systematic uncertainty in muon trigger efficiency, driven by the statistical variations within each $p_T \times \eta$ bin.
Mu_TTVA_BkgFraction	1	Systematic uncertainty associated with the subtraction of background fractions.
Mu_TTVA_LumiUncert	1	Systematic uncertainty related to the luminosity used for scaling MC simulations.
Mu_TTVA_MCXSec	1	Systematic uncertainty related to the cross-section used for scaling MC simulations.
Mu_TTVA_QCDTemplate	1	Systematic uncertainty derived from the QCD background fit templates that mimics probe muons.
Mu_TTVA_SuppressionScale	1	Systematic uncertainty associated with variations in the energy required to produce a dimuon pair.
Mu_TTVA_Uncorr	19	Uncorrelated systematic uncertainty for muon track-to-vertex association, reflecting the efficiency variations in each $p_T \times \eta$ bin.

Table B.3: Description of the muon channel-specific systematic nuisance parameters utilised in the analysis. Each parameter (NP) features both up and down variations. The tree-based systematics are shown along with weight-based trigger and TTVA systematics.

Short name	#NPs	Description
Mu_Reco_BkgFraction	1	Systematic uncertainty associated with the subtraction of background fractions.
Mu_Reco_HighToLowExtrap	1	Systematic uncertainty associated with the extrapolation of scale factors from high-pileup events to low-pileup events for muon reconstruction.
Mu_Reco_LumiUncert	1	Systematic uncertainty related to the luminosity used for scaling MC simulations.
Mu_Reco_MatchingSym	1	Systematic uncertainty related to whether the reconstructed muon lies within the cone used for its reconstruction.
Mu_Reco_MCXSec	1	Systematic uncertainty related to the cross-section used for scaling MC simulations.
Mu_Reco_PtDependency	1	Systematic uncertainty associated with the variation in efficiency at high transverse momentum ($p_T > 200$ GeV), where statistical limitations come into play.
Mu_Reco_QCDTemplate	1	Systematic uncertainty related to the QCD background fit templates that mimics probe muons.
Mu_Reco_SuppressionScale	1	Systematic uncertainty arising from variations in the parameter used to estimate the energy required to produce a di-muon pair.
Mu_Reco_TruthSym	1	Systematic uncertainty related to tag-and-probe efficiencies when comparing truth-level MC to reconstructed-level MC.
Mu_Reco_Uncorr	19	Uncorrelated systematic uncertainty for muon reconstruction, reflecting the efficiency variations in each $p_T \times \eta$ bin.
Mu_Iso_dRmuJ	1	Systematic uncertainty related to variations in the requirements for the angular separation between the probe muon and the closest jet.
Mu_Iso_eta	1	Systematic uncertainty related to variations in the η requirements for the tag muon.
Mu_Iso_isoBkg	1	Systematic uncertainty related to the effect of variations in the isolation requirements on background subtraction.
Mu_Iso_mass	1	Systematic uncertainty related to variations in the invariant mass window required for the tag and probe pair.
Mu_Iso_probeQ	1	Systematic uncertainty related to variations in the identification requirements for the probe muon.
Mu_Iso_tagIso	1	Systematic uncertainty related to variations in the isolation requirements for the tag muon.
Mu_Iso_tpdR	1	Systematic uncertainty related to variations in the angular separation between the tag and probe muons.
Mu_Iso_Uncorr	95	Uncorrelated systematic uncertainty for muon isolation, reflecting the efficiency variations in each $p_T \times \eta$ bin.
Mu_AddIso_Corr	1	Systematic uncertainty resulting from differences in the choice of tag and probe for efficiency calculations, specifically for the additional isolation scale factor developed for this analysis.
Mu_AddIso_Uncorr	1	Statistical uncertainty arising from variations in efficiency within each $p_T \times \eta$ bin for the additional isolation scale factor created specifically for this analysis.

Table B.4: Description of the muon channel-specific systematic nuisance parameters utilised in the analysis. Each parameter (NP) features both up and down variations. The weight-based reconstruction and isolation systematics are shown.

B.2 Closure test with Asimov data

An Asimov dataset is a synthetic dataset crafted to precisely align with model predictions, seamlessly integrating systematic uncertainties. It serves as a benchmark for evaluating analysis methodologies and, crucially, as a diagnostic tool to verify the absence of issues within the fit configuration, thus enabling an accurate evaluation of sensitivity and statistical robustness without the dependency on extensive simulations. Closure tests employing Asimov data were performed to confirm the fitting procedures' reliability utilized in this analysis.

The compatibility across different channels suggests the possibility of their combination, leading to an approximate $\sim \sqrt{2}$ improvement in statistical sensitivity relative to analyzing each channel separately. The process of combining individual likelihoods is achieved through the straightforward multiplication of their functions, ensuring that correlated systematic uncertainties are collectively addressed with a unified constraint term. Each likelihood function is composed of two primary elements: one representing the observed data, $\mathcal{L}_{\text{data}}$, and auxiliary terms imposing constraints on the nuisance parameters, $\mathcal{A}_i(\theta_i)$. The resulting combined likelihood is mathematically represented as:

$$\mathcal{L}_{\text{cb}} = \left\{ \prod_i^{\text{channels}} \mathcal{L}_i(A, \theta | N_i) \right\} \left\{ \prod_i^M \mathcal{A}_i(\theta_i) \right\} \quad (\text{B.1})$$

The combination results for the $p_T^{\ell\nu}$ differential analysis are illustrated in red in Figures B.1 and B.2 for the $e^- \nu + \mu^- \nu$ and $e^+ \nu + \mu^+ \nu$ channels, respectively, alongside results for the individual channels. Similarly, the $y^{\ell\nu}$ differential analysis outcomes are presented in Figures B.3 and B.4, offering a clear view of the agreement between combined and individual measurements.

Asimov data testing reveals potential analysis access to large A_i coefficients such as A_1 , A_2 , A_3 , and A_4 . However, the given low-pileup dataset does not afford sensitivity to the A_5 , A_6 , and A_7 coefficients, which become notable at $\mathcal{O}(\alpha_s^2)$.

Figures B.5 and B.6 display the pull distributions for the $W^- \rightarrow e^- \bar{\nu}$, $W^+ \rightarrow e^+ \nu$, $W^- \rightarrow \mu^- \bar{\nu}$, $W^+ \rightarrow \mu^+ \nu$ channels in $p_T^{\ell\nu}$ and $y^{\ell\nu}$ measurements, respectively. In line with the test's design, all nuisance parameters (NPs) demonstrate no pulls on the Asimov data. A significant finding is that the MJ background's systematic uncertainties, previously thought to be overly conservative, are constrained, indicating the fit's sensitivity to the MJ background.

Figures B.7-B.10 summarize the expected post-fit statistical and systematic uncertainties for the A_i coefficients as a function of $p_T^{\ell\nu}$. Likewise, Figures B.11-B.14 detail these uncertainties in relation to y^W , covering all event categories ($W^- \rightarrow e^- \bar{\nu}$, $W^+ \rightarrow e^+ \nu$, $W^- \rightarrow \mu^- \bar{\nu}$, and $W^+ \rightarrow \mu^+ \nu$).

In both $p_T^{\ell\nu}$ and $y^{\ell\nu}$ differential measurements, statistical uncertainty emerges as the predominant source of uncertainty for the A_i coefficients across all bins. The subsequent notable source of uncertainty originates from hadronic recoil and signal MC statistics, with the signal MC statistical uncertainty being roughly one-third of the data-statistical uncertainty, attributed to the significantly larger event count in the signal MC compared to the datasets utilized.

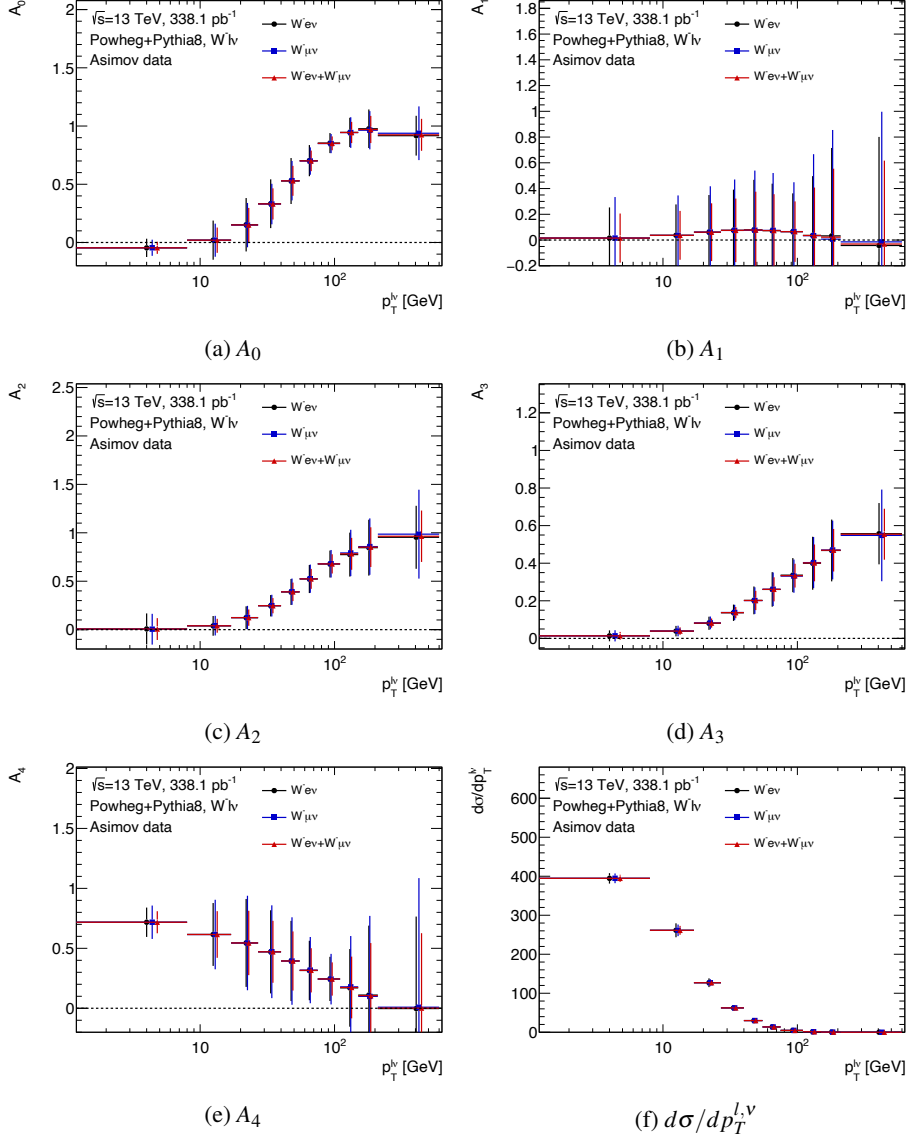


Figure B.1: Combined measurement of coefficients for W^- as a function of $p_T^{l,\nu}$ with Asimov data. The measured coefficients from the individual channels are overlaid in black and blue. The error bars represent the total uncertainty on the combined measurements.

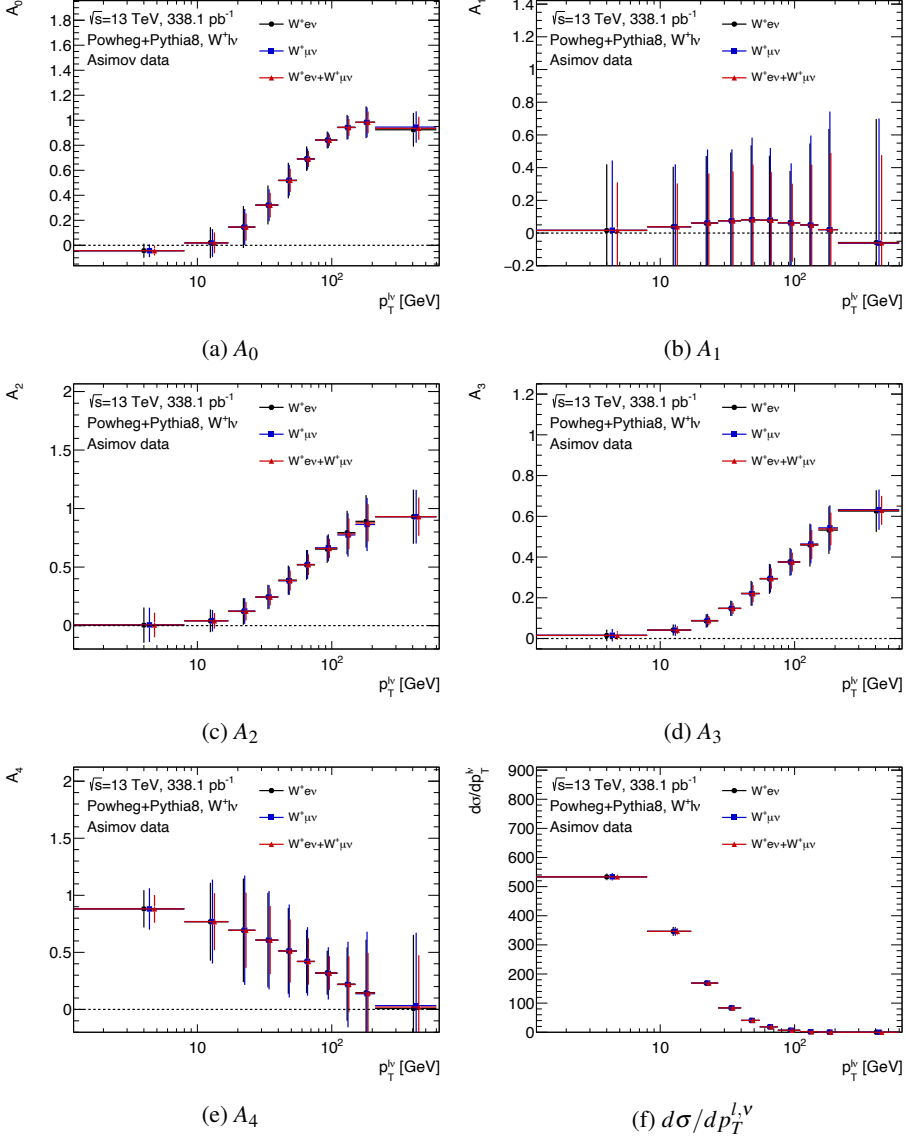


Figure B.2: Combined measurement of coefficients for W^+ as a function of $p_T^{l,v}$ with Asimov data. The measured coefficients from the individual channels are overlaid in black and blue. The error bars represent the total uncertainty on the combined measurements.

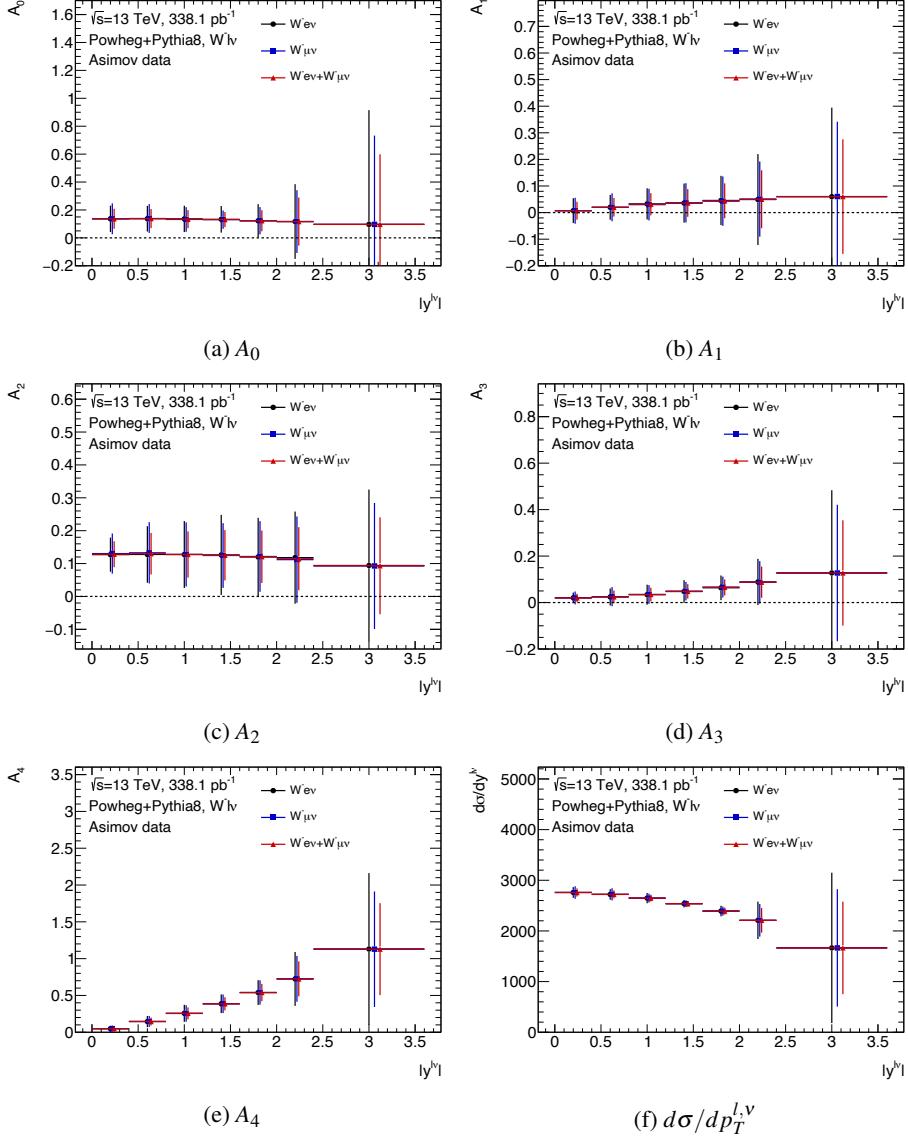


Figure B.3: Combined measurement of coefficients for W^- as a function of $y^{\ell\nu}$ with Asimov data. The measured coefficients from the individual channels are overlaid in black and blue. The error bars represent the total uncertainty on the combined measurements.

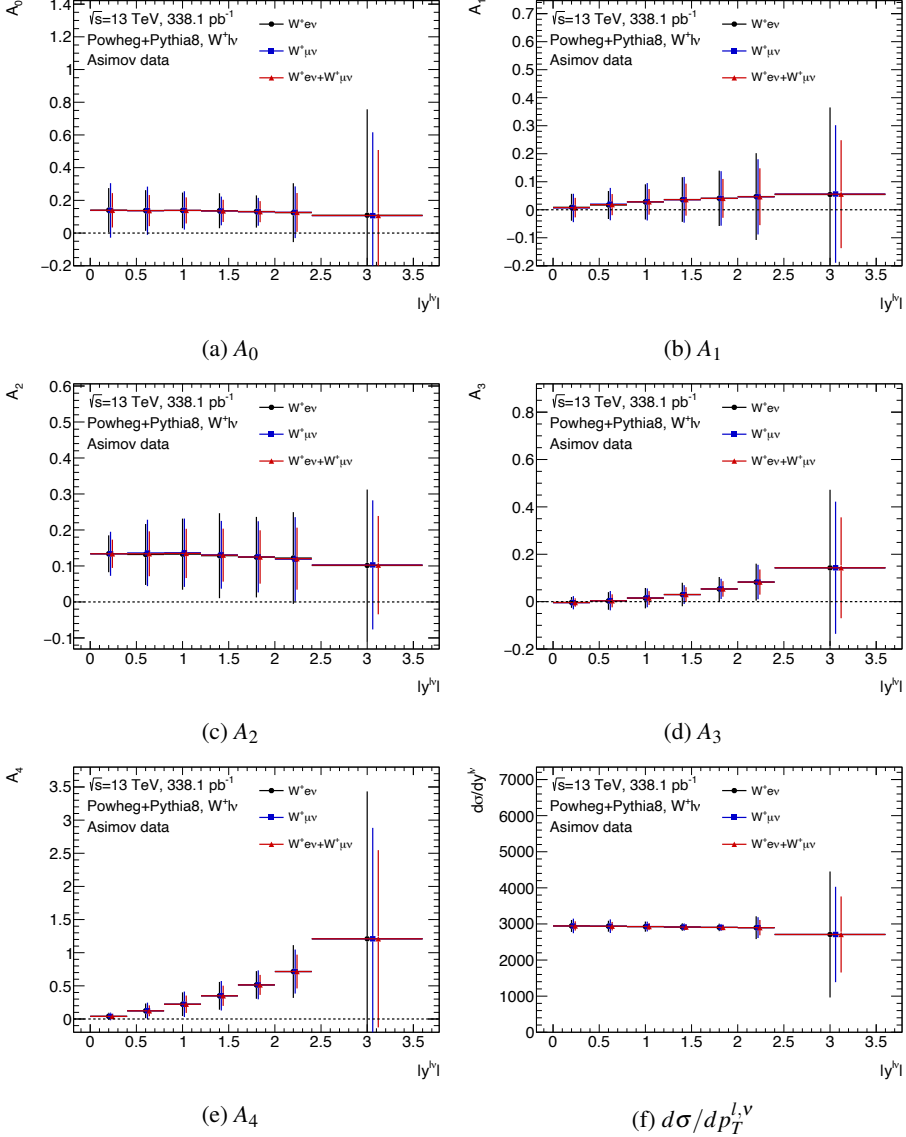


Figure B.4: Combined measurement of coefficients for W^+ as a function of $y^{\ell\nu}$ with Asimov data. The measured coefficients from the individual channels are overlaid in black and blue. The error bars represent the total uncertainty on the combined measurements.

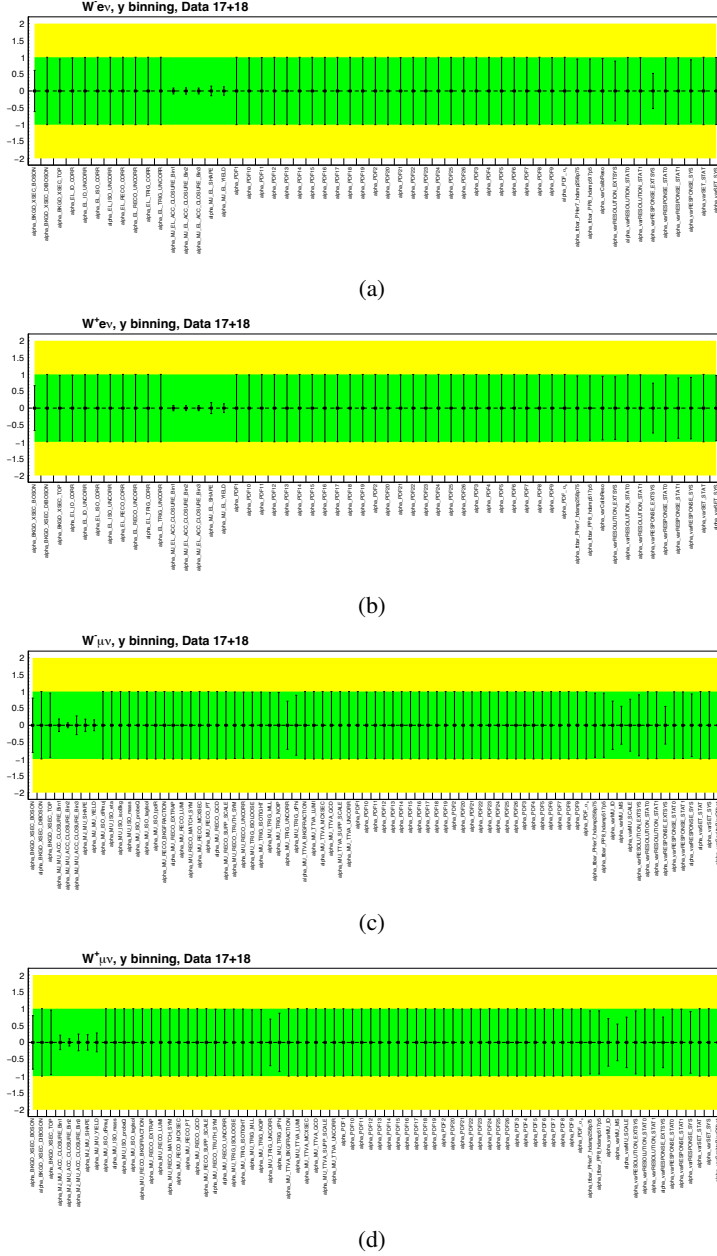


Figure B.6: Pull distributions for the $W^- \rightarrow e^- \bar{\nu}$, $W^+ \rightarrow e^+ \nu$, $W^- \rightarrow \mu^- \bar{\nu}$, $W^+ \rightarrow \mu^+ \nu$ channels in $y^{\ell\nu}$ measurements on Asimov data. Detailed explanations of each systematic category can be found in Tables B.1, B.3, and B.4.

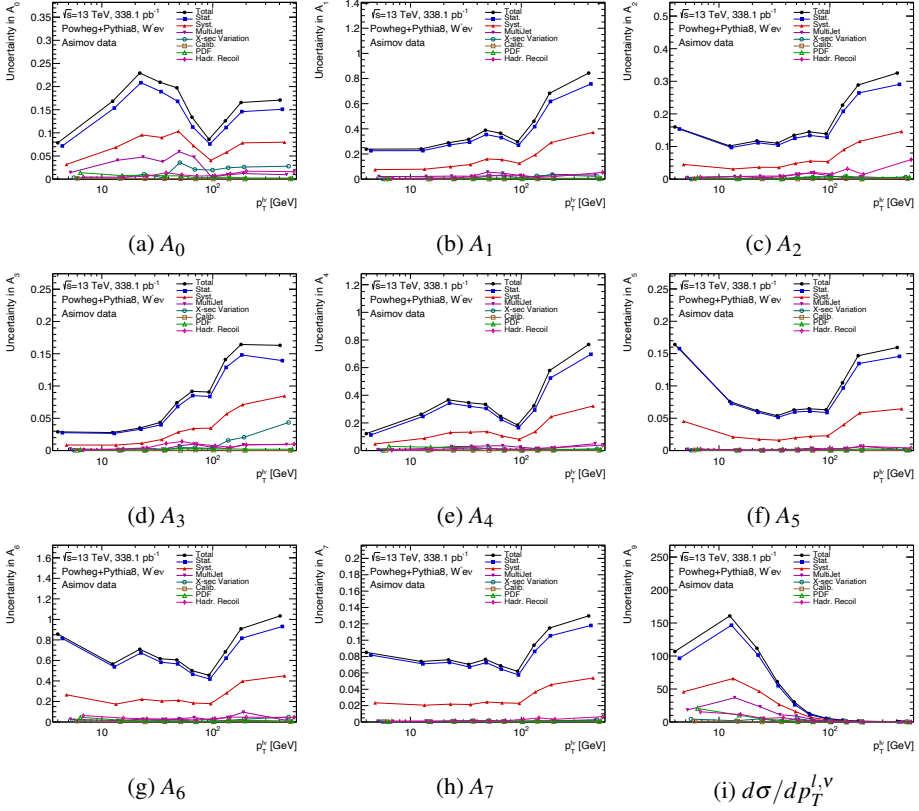


Figure B.7: The uncertainty comparison for all contributions in the $W^- \rightarrow e^- \bar{\nu}$ channel for measurement in $p_T^{\ell V}$ on Asimov data. Blue is the total statistical uncertainty, red is the total systematic uncertainty, and black is the combination of the statistical and systematic uncertainties. The components of the systematic uncertainty are presented in grouped form. Detailed explanations of each systematic category can be found in Tables B.1 and B.2.

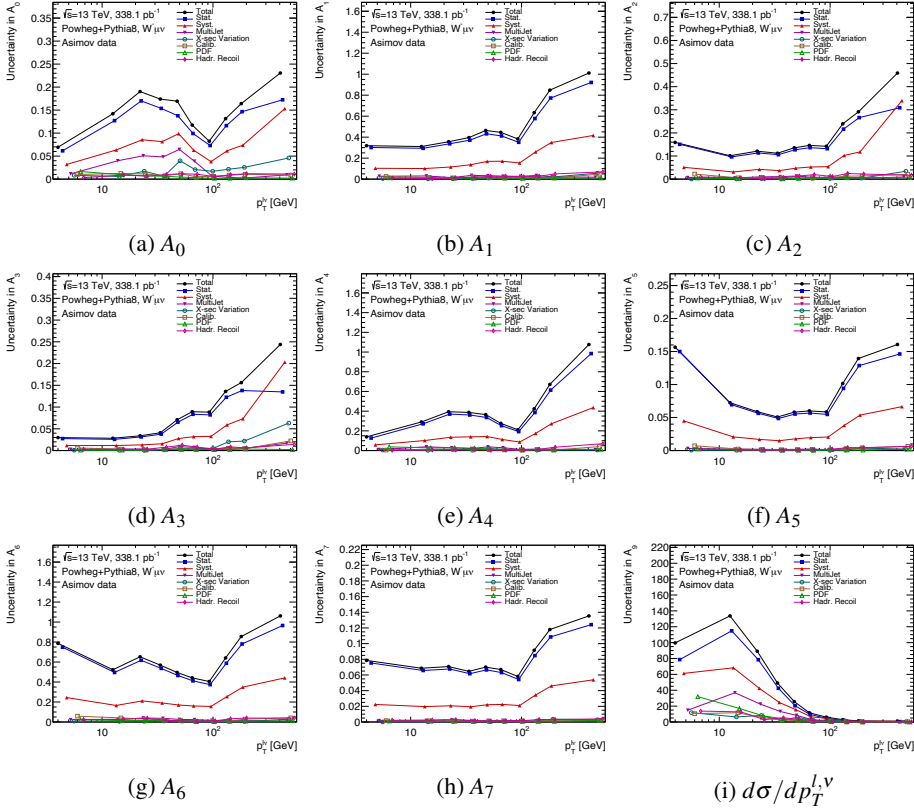


Figure B.8: The uncertainty comparison for all contributions in the $W^- \rightarrow \mu^- \bar{\nu}$ channel for measurement in $p_T^{l\nu}$ on Asimov data. Blue is the total statistical uncertainty, red is the total systematic uncertainty, and black is the combination of the statistical and systematic uncertainties. The components of the systematic uncertainty are presented in grouped form. Detailed explanations of each systematic category can be found in Tables B.1, B.3, and B.4.

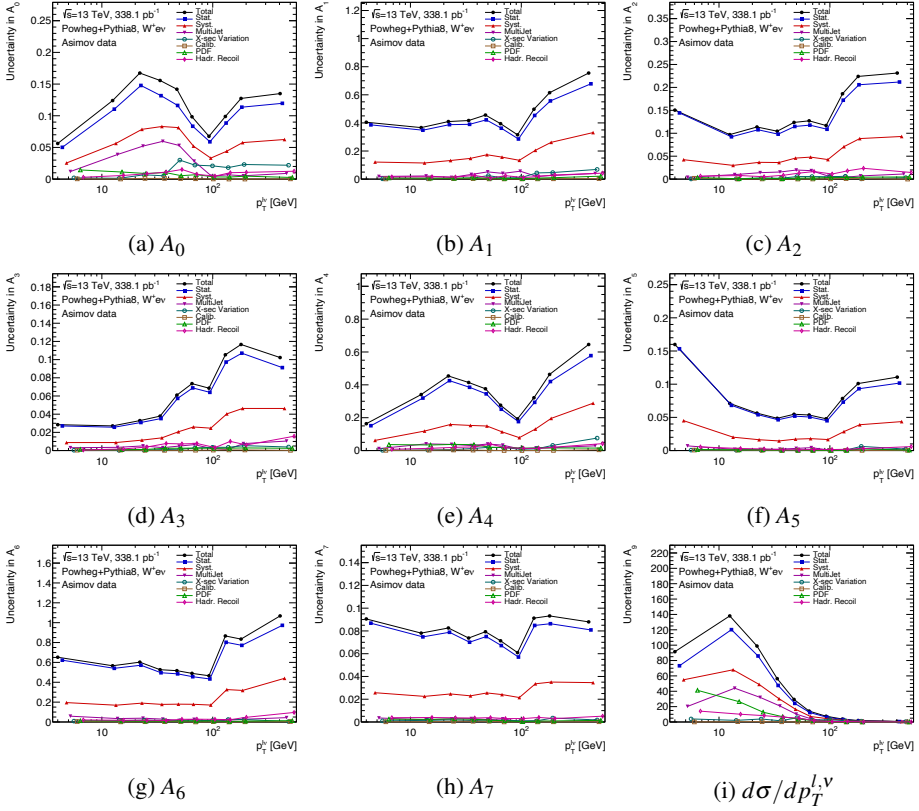


Figure B.9: The uncertainty comparison for all contributions in the $W^+ \rightarrow e^+ \nu$ channel for measurement in $p_T^{l\nu}$ on Asimov data. Blue is the total statistical uncertainty, red is the total systematic uncertainty, and black is the combination of the statistical and systematic uncertainties. The components of the systematic uncertainty are presented in grouped form. Detailed explanations of each systematic category can be found in Tables B.1 and B.2.

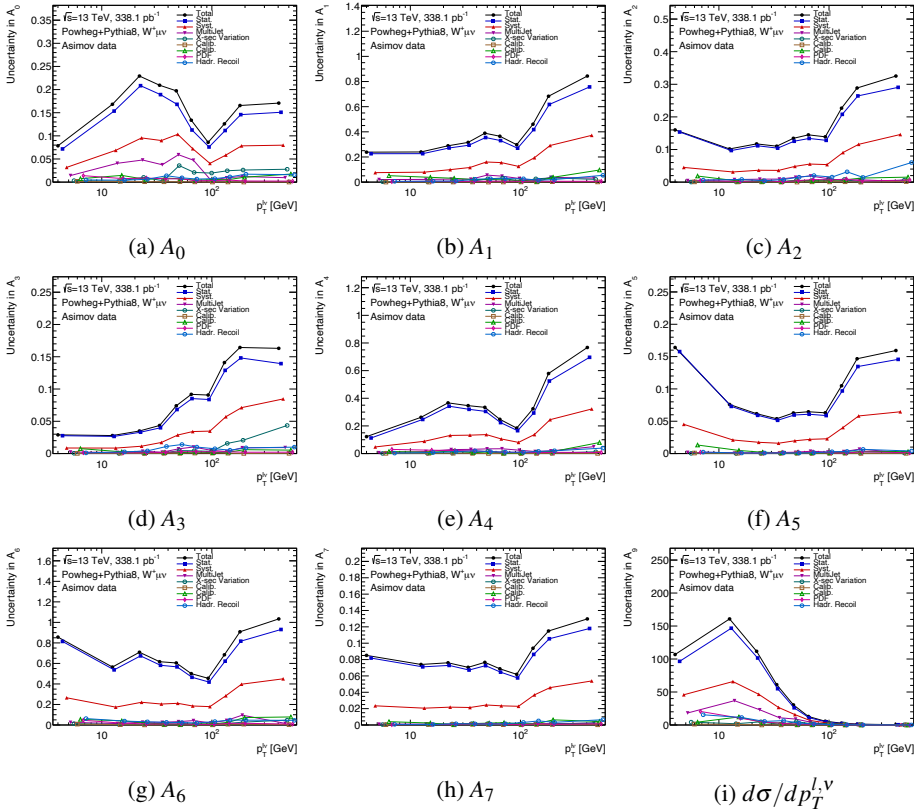


Figure B.10: The uncertainty comparison for all contributions in the $W^+ \rightarrow \mu^+ \nu$ channel for measurement in $p_T^{\ell\nu}$ on Asimov data. Blue is the total statistical uncertainty, red is the total systematic uncertainty, and black is the combination of the statistical and systematic uncertainties. The components of the systematic uncertainty are presented in grouped form. Detailed explanations of each systematic category can be found in Tables B.1, B.3, and B.4.

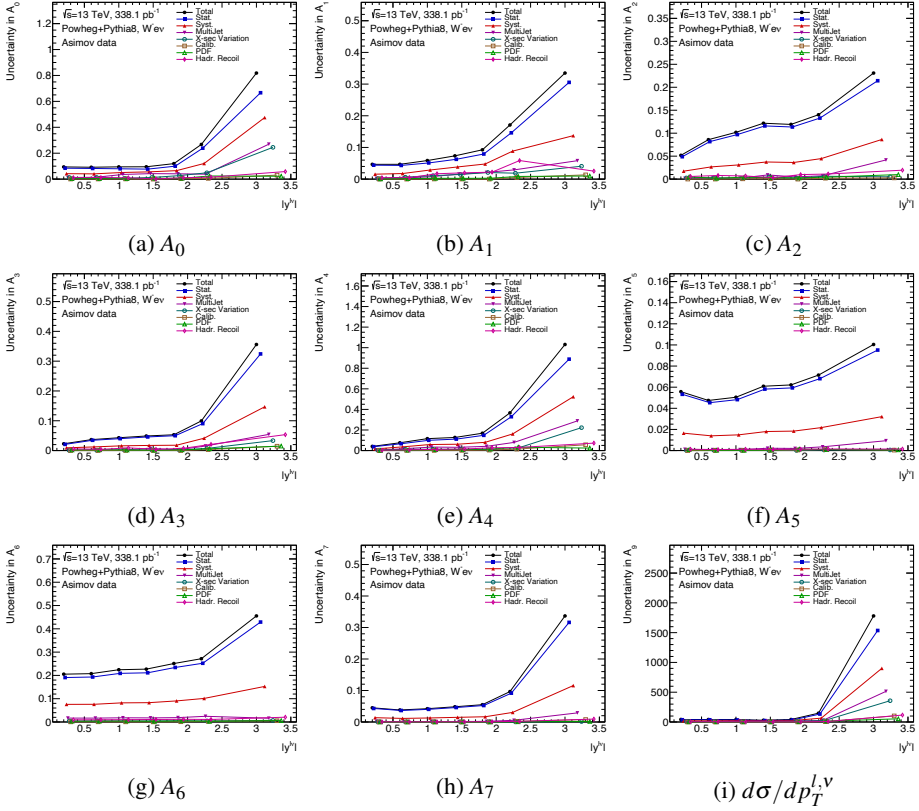


Figure B.11: The uncertainty comparison for all contributions in the $W^- \rightarrow e^- \bar{\nu}$ channel for measurement in $y^{l,v}$ on Asimov data. Blue is the total statistical uncertainty, red is the total systematic uncertainty, and black is the combination of the statistical and systematic uncertainties. The components of the systematic uncertainty are presented in grouped form. Detailed explanations of each systematic category can be found in Tables B.1 and B.2.

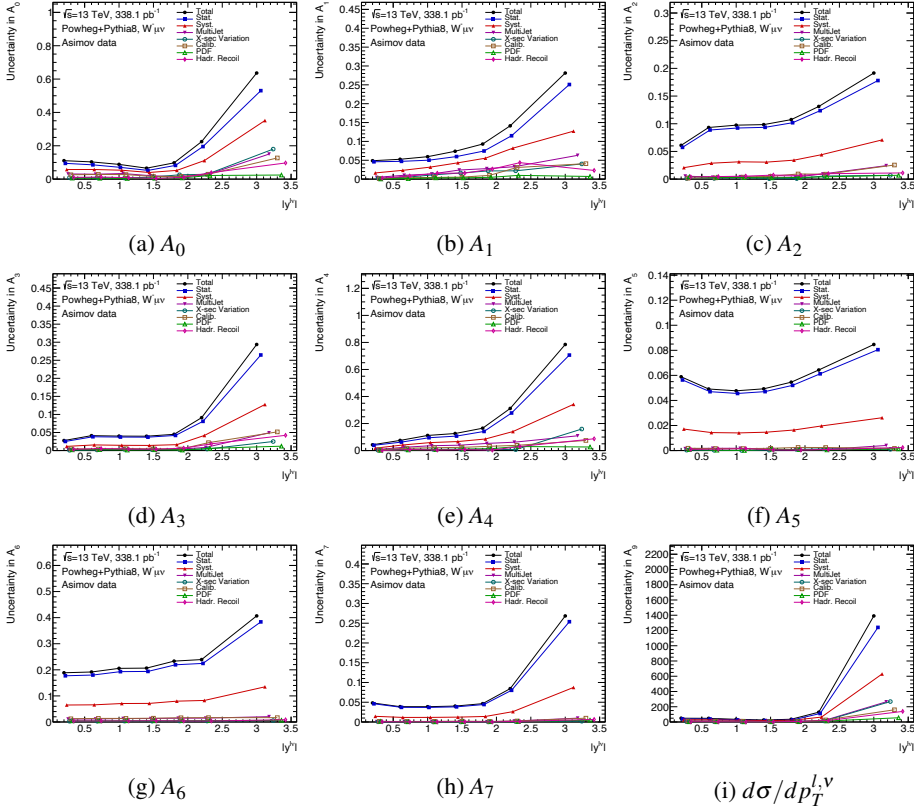


Figure B.12: The uncertainty comparison for all contributions in the $W^- \rightarrow \mu^- \bar{\nu}$ channel for measurement in $y^{\ell\nu}$ on Asimov data. Blue is the total statistical uncertainty, red is the total systematic uncertainty, and black is the combination of the statistical and systematic uncertainties. The components of the systematic uncertainty are presented in grouped form. Detailed explanations of each systematic category can be found in Tables B.1, B.3, and B.4.

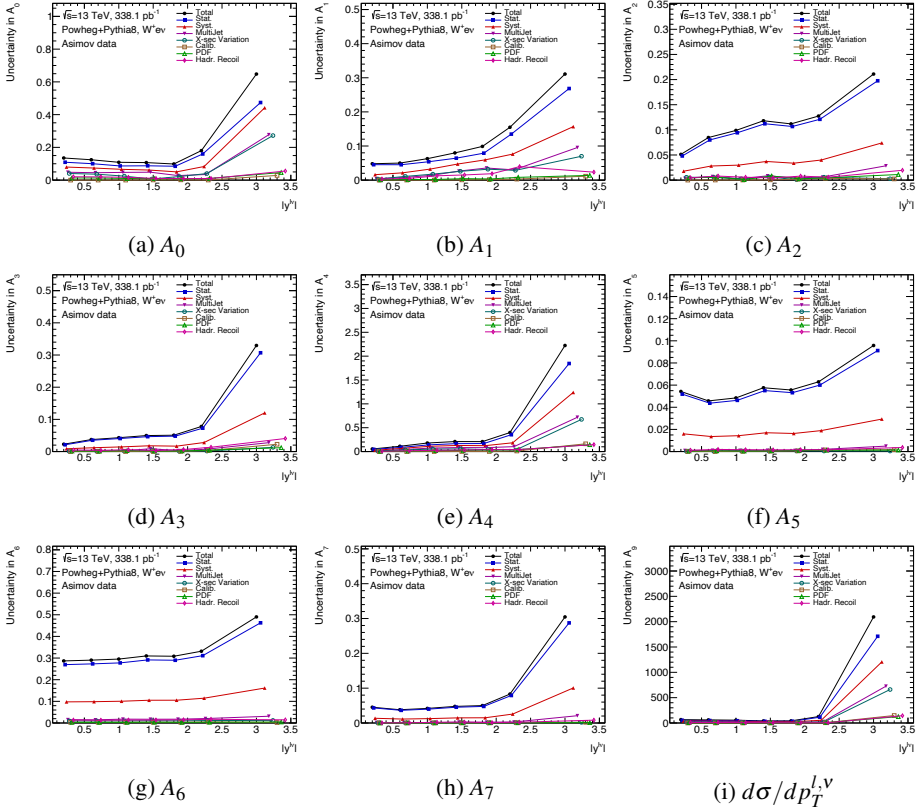


Figure B.13: The uncertainty comparison for all contributions in the $W^+ \rightarrow e^+ \nu$ channel for measurement in $y^{\ell \nu}$ on Asimov data. Blue is the total statistical uncertainty, red is the total systematic uncertainty, and black is the combination of the statistical and systematic uncertainties. The components of the systematic uncertainty are presented in grouped form. Detailed explanations of each systematic category can be found in Tables B.1 and B.2.

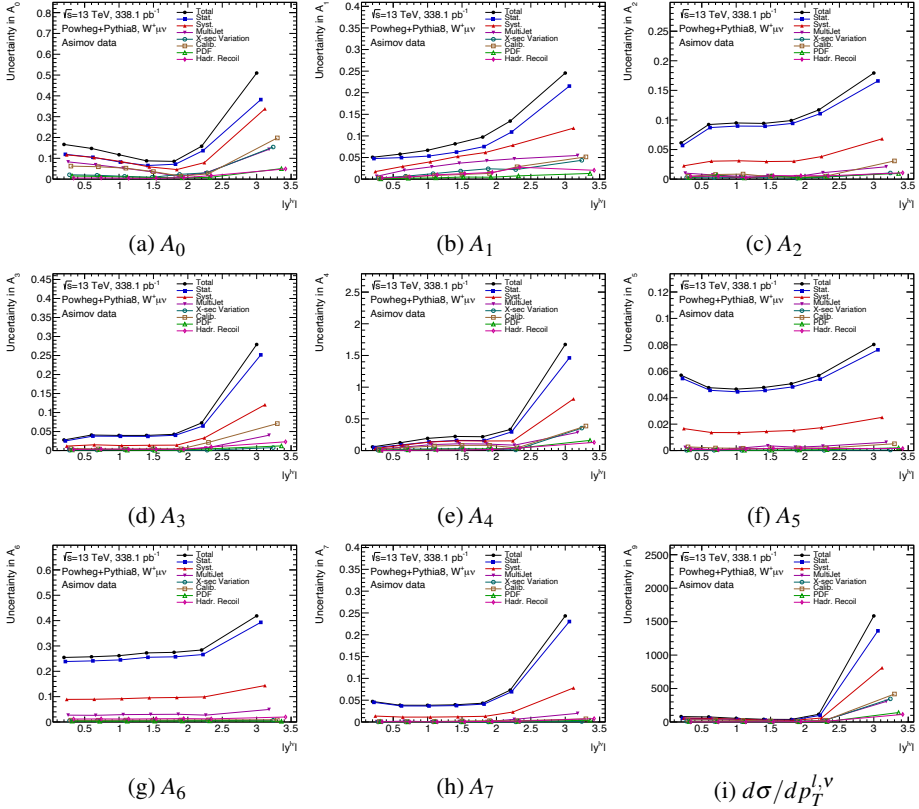


Figure B.14: The uncertainty comparison for all contributions in the $W^+ \rightarrow \mu^+ \nu$ channel for measurement in $y^{\ell\nu}$ on Asimov data. Blue is the total statistical uncertainty, red is the total systematic uncertainty, and black is the combination of the statistical and systematic uncertainties. The components of the systematic uncertainty are presented in grouped form. Detailed explanations of each systematic category can be found in Tables B.1 and B.2.

B.3 Unstable fit results on real data

The information provided in this section is for general information purposes only.

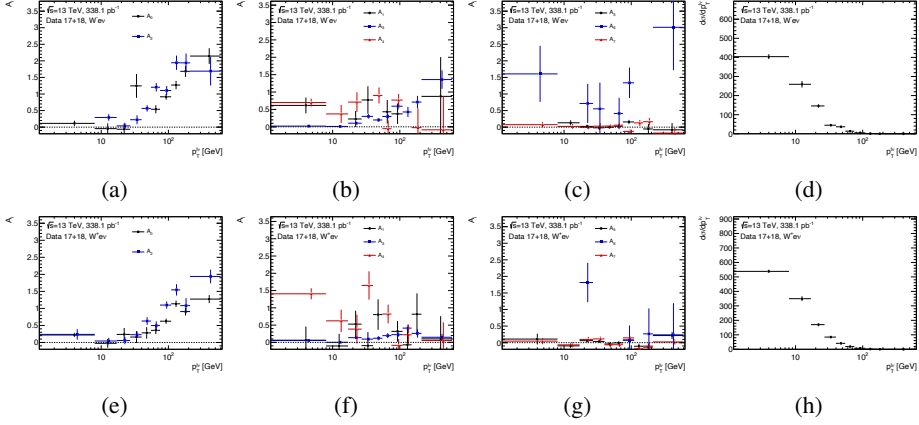


Figure B.15: Unstable real data $W A_i$ fit results for $W^- \rightarrow e^- \bar{\nu}$ (top) and $W^+ \rightarrow e^+ \nu$ (bottom) channels.

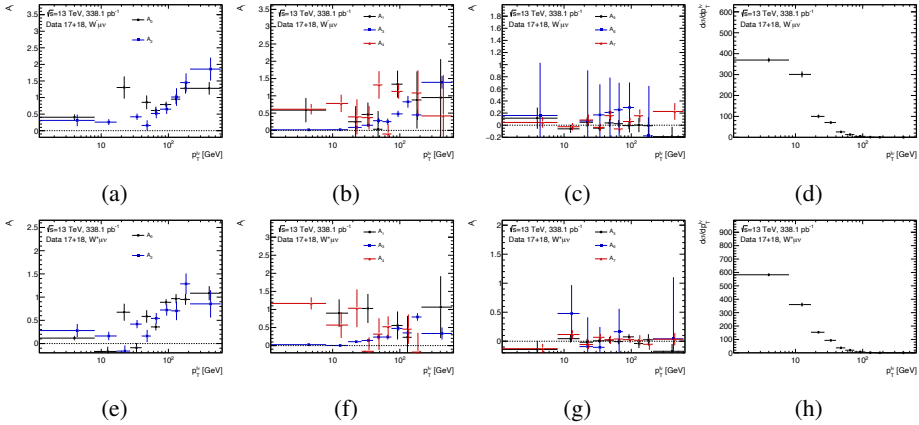


Figure B.16: Unstable real data $W A_i$ fit results for $W^- \rightarrow \mu^- \bar{\nu}$ (top) and $W^+ \rightarrow \mu^+ \nu$ (bottom) channels.

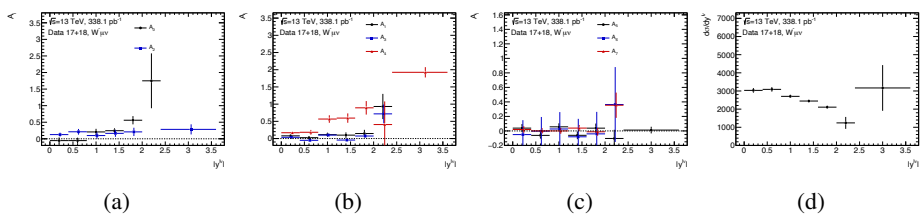
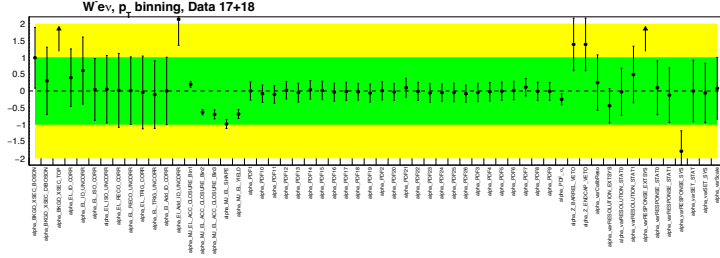
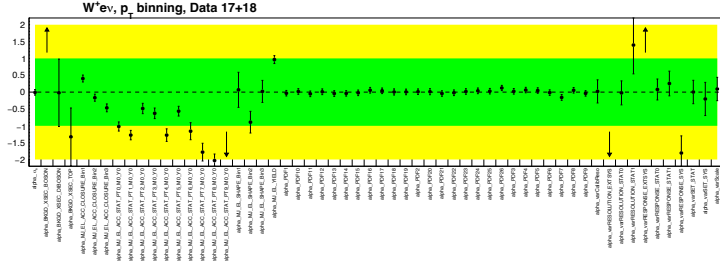


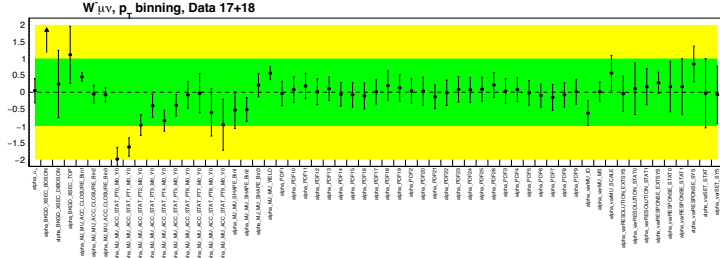
Figure B.17: Unstable real data $W A_i$ fit results for $W^- \rightarrow \mu^- \bar{\nu}$ channel.



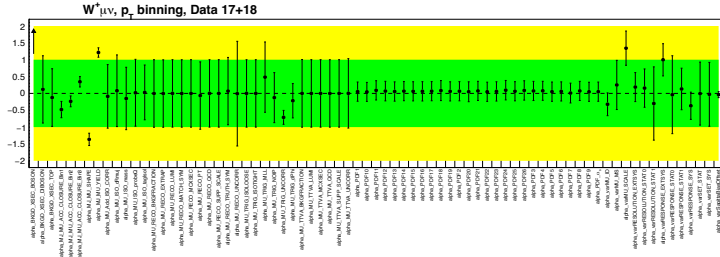
(a)



(b)

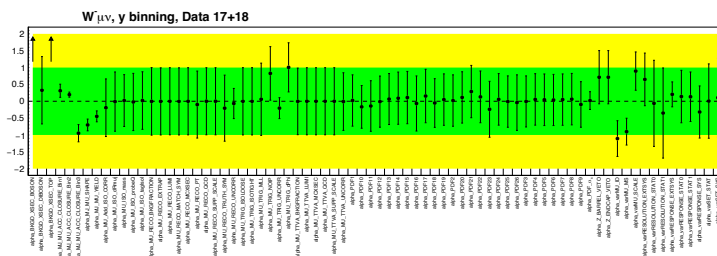


(c)



(d)

Figure B.18: Pull distributions for the $W^- \rightarrow e^- \bar{\nu}_e$, $W^+ \rightarrow e^+ \nu_e$, $W^- \rightarrow \mu^- \bar{\nu}_\mu$, $W^+ \rightarrow \mu^+ \nu_\mu$ channels in $p_T^{\ell\nu}$ measurements on experimental data. Detailed explanations of each systematic category can be found in Tables B.1, B.3, and B.4.



(a)

Figure B.19: Pull distributions for the $W^- \rightarrow \mu^- \bar{\nu}$ channel in $y^{\ell\nu}$ measurements on experimental data. Detailed explanations of each systematic category can be found in Tables B.1, B.3, and B.4.

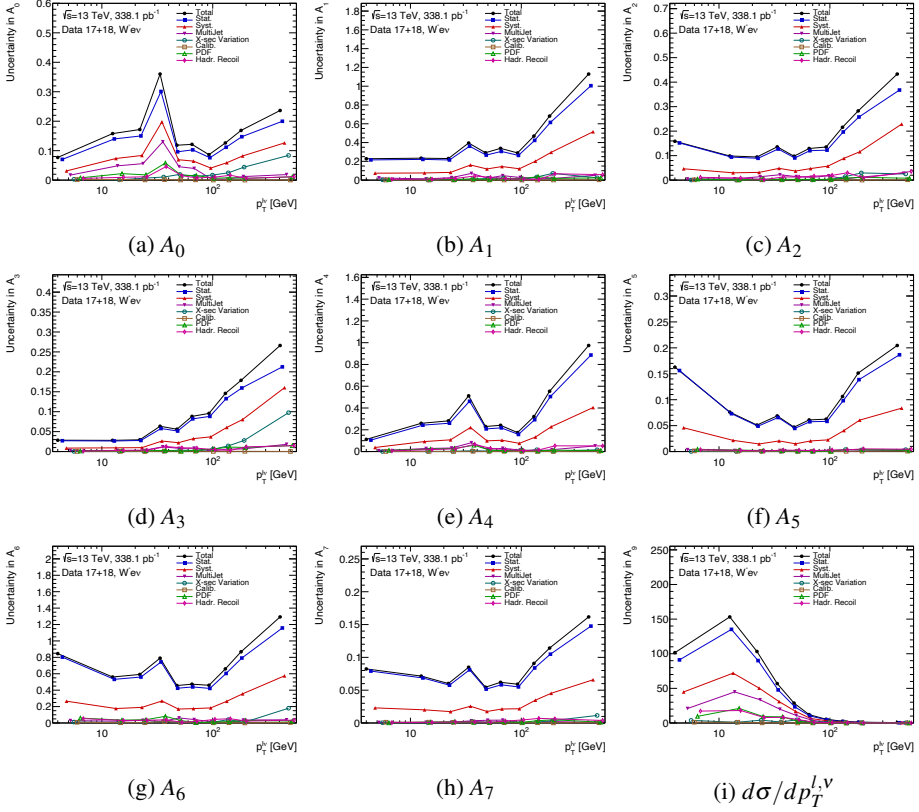


Figure B.20: The uncertainty comparison for all contributions in the $W^- \rightarrow e^- \bar{\nu}$ channel for measurement in $p_T^{\ell\nu}$ on experimental data. Blue is the total statistical uncertainty, red is the total systematic uncertainty, and black is the combination of the statistical and systematic uncertainties. The components of the systematic uncertainty are presented in grouped form. Detailed explanations of each systematic category can be found in Tables B.1 and B.2.

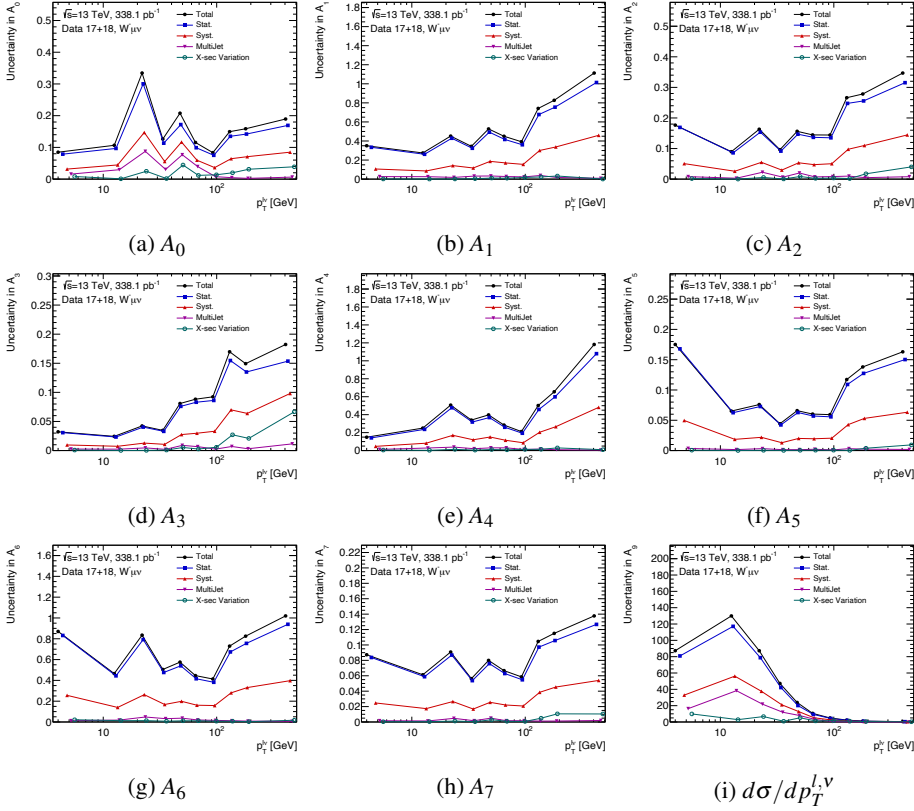


Figure B.21: The uncertainty comparison for all contributions in the $W^- \rightarrow \mu^- \bar{\nu}$ channel for measurement in p_T^{ℓ} on experimental data. Blue is the total statistical uncertainty, red is the total systematic uncertainty, and black is the combination of the statistical and systematic uncertainties. The components of the systematic uncertainty are presented in grouped form. Detailed explanations of each systematic category can be found in Tables B.1, B.3, and B.4.

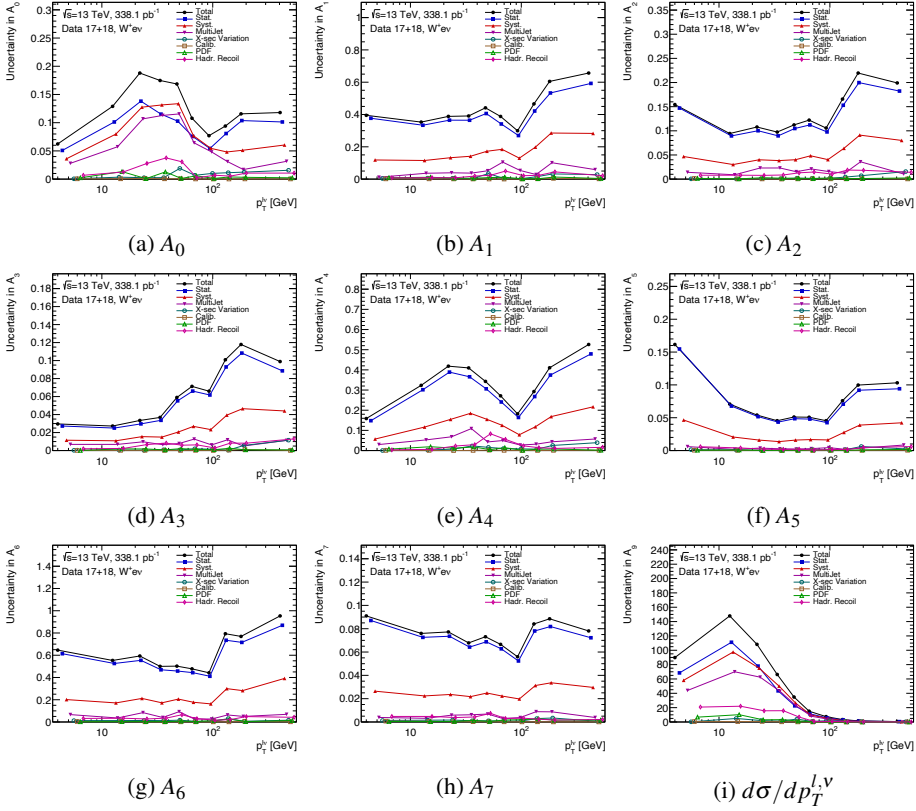


Figure B.22: The uncertainty comparison for all contributions in the $W^+ \rightarrow e^+ \nu$ channel for measurement in $p_T^{l\nu}$ on experimental data. Blue is the total statistical uncertainty, red is the total systematic uncertainty, and black is the combination of the statistical and systematic uncertainties. The components of the systematic uncertainty are presented in grouped form. Detailed explanations of each systematic category can be found in Tables B.1 and B.2.

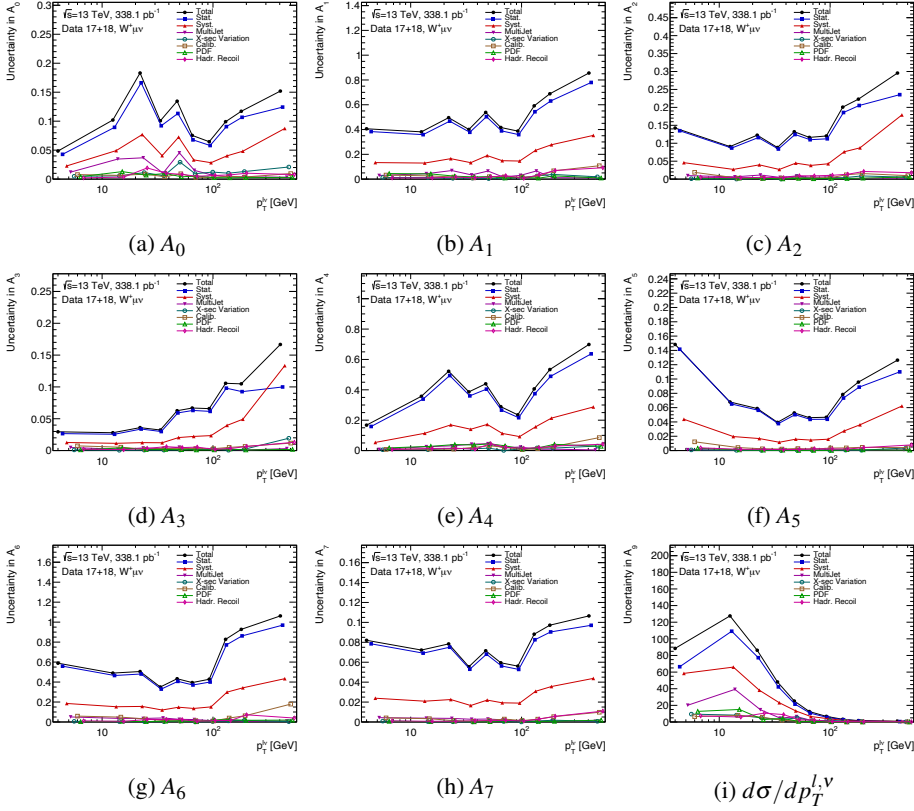


Figure B.23: The uncertainty comparison for all contributions in the $W^+ \rightarrow \mu^+ \nu$ channel for measurement in $p_T^{\ell\nu}$ on experimental data. Blue is the total statistical uncertainty, red is the total systematic uncertainty, and black is the combination of the statistical and systematic uncertainties. The components of the systematic uncertainty are presented in grouped form. Detailed explanations of each systematic category can be found in Tables B.1, B.3, and B.4.

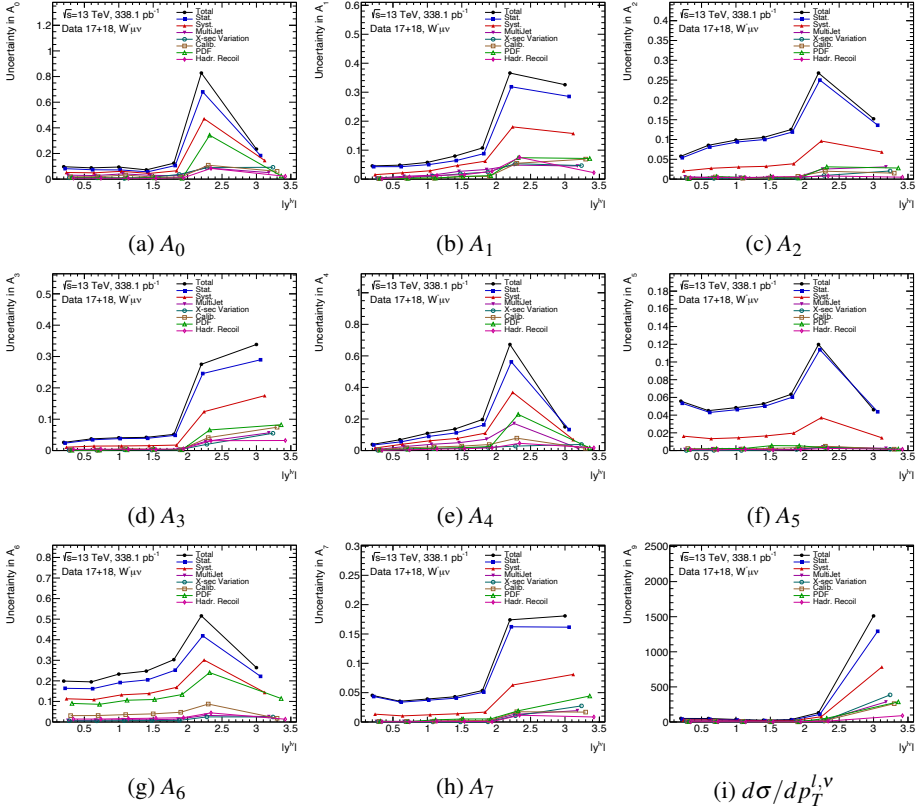


Figure B.24: The uncertainty comparison for all contributions in the $W^- \rightarrow \mu^- \bar{\nu}$ channel for measurement in $y^{\ell\nu}$ on experimental data. Blue is the total statistical uncertainty, red is the total systematic uncertainty, and black is the combination of the statistical and systematic uncertainties. The components of the systematic uncertainty are presented in grouped form. Detailed explanations of each systematic category can be found in Tables B.1, B.3, and B.4.

ACRONYMS

- ALFA** Absolute Luminosity For [ATLAS](#). [54](#)
- ALICE** A Large Ion Collider Experiment. [39](#), [275](#)
- ASDBLR** Amplification, Shaping, Discrimination, and Base-Line Restoration [ASIC](#). [60](#), [61](#)
- ASIC** Application-Specific Integrated Circuit. [60](#), [63](#), [247](#), [249](#), [250](#)
- ATLAS** A Toroidal [LHC](#) ApparatuS experiment at [CERN](#). [7–9](#), [31](#), [33](#), [36–39](#), [42–49](#), [51](#), [52](#), [54–58](#), [60](#), [63](#), [65–71](#), [92](#), [93](#), [95](#), [96](#), [98](#), [193](#), [197](#), [199–202](#), [212–214](#), [247](#), [248](#), [269](#), [271](#), [273](#), [275](#)
- AVF** Adaptive Vertex Fitting algorithm. [73](#)
- BC** Bunch Clock. [62](#), [64](#), [65](#)
- BCID** Bunch Crossing Identifier. [65](#)
- BCR** Bunch Counter Reset signal. [62](#)
- BDT** Boosted Decision Trees. [206](#), [208](#), [209](#)
- BFGS** Broyden-Fletcher-Goldfarb-Shanno minimization algorithm. [184](#)
- BSM** Beyond the Standard Model. [36](#)
- BX** Bunch Crossing. [60](#)
- Cat5** Category 5 cable. [62](#), [68](#)
- CDF** Collider Detector at Fermilab. [31](#), [34](#), [37](#), [38](#), [214](#)
- CERN** European Organization for Nuclear Research. [9](#), [22](#), [39](#), [40](#), [43](#), [62](#), [65](#), [68](#), [247–249](#), [269](#), [275](#)
- CKM** Cabibbo-Kobayashi-Maskawa. [13](#)
- CMS** Compact Muon Solenoid experiment at [CERN](#). [31](#), [39](#), [213](#), [214](#)
- cPFOs** Charged Particle Flow Objects. [82](#)
- CPU** Central Processing Unit. [157](#)
- CS** Collins-Soper. [29](#), [30](#), [34](#), [85](#), [87](#), [99](#)
- CSCs** Cathode Strip Chambers. [54](#), [78](#)
- CTP** Central Trigger Processor. [62](#)
- D0** DZero experiment at Fermilab. [214](#)
- DAQ** Data AcQuisition system. [9](#), [63](#)
- DC** Direct Current. [70](#)
- DSID** DataSet Identifier. [95](#)
- DTMROC** Drift Time Measuring Read-Out Chip. [61](#), [62](#), [64](#), [65](#), [67](#)
- EC** End-Cap. [58](#)
- ECR** Event Counter Reset signal. [62](#)
- EM** Electromagnetic. [37](#), [73](#), [75](#)
- EMC** Electromagnetic Calorimeter. [44](#), [49–51](#), [73](#), [74](#)

- ESR** Equivalent Series Resistance. 69, 70
- EW** Electroweak. 37, 96, 103, 104, 110, 165, 187, 194, 195, 199, 205, 209, 211
- FCal** Forward Calorimeter. 44, 51
- FE** Front End. 61, 62, 69
- FPGA** Field-Programmable Gate Array. 62, 63, 66
- FSR** Final State Radiation. 22
- GOL** Gigabit Optical Link. 62, 67, 69
- HC** Hadronic Calorimeter. 44, 49–51
- HEC** Hadronic Endcap Calorimeter. 50, 51
- HEC1** Hadronic Endcap Calorimeter front wheel. 51
- HEC2** Hadronic Endcap Calorimeter rear wheel. 51
- HFLAV** Heavy Flavor Averaging Group. 202
- HL** High Level. 61
- HLT** High-Level Trigger. 55, 56, 69
- HOLA** High-speed Optical Link for **ATLAS**. 63, 66, 67, 70
- HR** Hadronic Recoil. 83–85
- HT** High Threshold. 58, 59, 61
- IBL** Insertable *B*-Layer detector. 48, 72, 203, 206
- ID** Inner Detector. 43, 44, 47, 65, 71, 73, 78, 79, 82, 102, 220
- IP** Interaction Point. 45, 51, 54, 78
- ISR** Initial State Radiation. 22, 83
- L1** Level-1 hardware trigger. 55, 56, 61, 62, 64, 66, 67, 70, 248
- L1A** Level-1 Accept signal. 62
- L1ID** **L1** Identifier. 65
- LAr** Liquid Argon calorimeter. 50, 51
- LEP** Large Electron-Positron Collider at **CERN**. 33, 40, 202, 213, 214
- LFU** Lepton Flavor Universality. 201, 213, 214
- LH** Likelihood. 74
- LHC** Large Hadron Collider. 6, 7, 23, 35, 36, 39–43, 45, 47, 54, 60–63, 66–69, 214, 247, 248, 250
- LHCb** Large Hadron Collider beauty experiment. 22, 39, 214
- Linac2** Linear Accelerator 2 at **CERN**. 40
- LL** Low Level. 61
- LO** Leading Order. 24, 25, 28, 31, 37
- LS2** **CERN LHC** Long Shutdown 2. 68
- LT** Low Threshold. 58, 61
- LUCID** LUMinosity Cherenkov Integrating Detector. 54
- LVDS** Low-Voltage Differential Signaling. 62
- MC** Monte Carlo. 8, 75, 80, 85, 93–97, 100, 103, 104, 106, 107, 117, 119, 123–129, 132, 134, 137–152, 155–158, 164, 166, 187, 188, 193, 194, 198, 199, 212, 215, 220–222, 269
- MDTs** Monitored Drift Tubes. 52, 54, 78

MJ Multi-Jet. 7–9, 98–100, 103–108, 110–113, 115–117, 119, 120, 122–129, 132–135, 137–153, 163, 165–167, 178, 184, 185, 187–191, 194, 195, 197–200, 203, 205, 206, 208, 209, 212, 214, 218, 222

MS Muon Spectrometer. 44, 52, 78, 79, 220

MVA MultiVariate Analysis. 79

NEWT New Tracking algorithm. 71, 72

NLO Next-to-Leading Order. 24, 28, 31, 33, 37

NNLL Next-to-Next-to-Leading Logarithms. 24, 96, 193

NNLO Next-to-Next-to-Leading Order. 24, 33, 37, 96, 193

NP Nuisance Parameter in the fit. 156, 157, 165–167, 184, 186–188, 190, 191, 194, 217, 222

nPFOs Neutral Particle Flow Objects. 82

NSE Network Search Engine [ASIC](#). 63, 64

P1 Point-1 at LHC. 43, 54

PDF Parton Distribution Functions. 6, 23, 24, 35, 37, 96, 158, 166, 193

PDG Particle Data Group. 23

PF Particle Flow. 82

PFO Particle Flow Object. 82–84

PIX Silicon pixel tracker. 44, 47, 48

PMT Photomultiplier Tubes. 51, 54

POI Parameter Of Interest. 189–191

PP Patch Panel. 62, 63, 67–69

pQCD Perturbative Quantum Chromodynamics. 37

PS Proton Synchrotron. 40

PSB Proton Synchrotron Booster. 40

PV Primary Vertex. 72–75, 83

QCD Quantum Chromodynamics. 5, 6, 11, 12, 14, 22–25, 27, 29, 31, 33–35, 37, 187, 188, 197, 198, 203, 205, 220, 221, 271, 273

QED Quantum Electrodynamics. 11, 15, 16, 37, 96, 166

QPLL Quartz Phase-Locked Loop chip. 67–69

RF Radio-Frequency. 40

RocketIO A high-speed serial transceiver technology by Xilinx. 62, 67–69

ROD Read Out Driver. 61–70

ROI Region of Interest. 55, 56

ROS Read Out System. 62, 66

RPCs Resistive Plate Chambers. 52, 78

S-Link A Simple Link interface specification defined in 1995 at [CERN](#). 62, 63, 65, 66, 70

SCT SemiConductor Tracker. 44, 47, 48, 72

SEU Single Event Upset. 65

SF Scale Factor. 75, 80, 97, 100–102, 187, 193

SLAC Stanford Linear Accelerator Center. 250

- SLD** The [SLAC](#) Large Detector. [33](#)
- SM** Standard Model. [5](#), [6](#), [11–14](#), [16](#), [21](#), [22](#), [31](#), [35](#), [37](#), [39](#), [44](#), [201](#), [202](#), [213](#), [271](#), [273](#)
- SPS** Super Proton Synchrotron. [40](#)
- TDAQ** Trigger and Data Acquisition. [9](#), [44](#), [56](#), [57](#), [60](#), [63](#), [65](#), [70](#), [275](#)
- TGCs** Thin Gap Chambers. [52](#), [78](#)
- TMVA** Toolkit for MultiVariate data Analysis. [206](#)
- ToT** Time-Over-Threshold. [61](#)
- TR** Transition Radiation. [58–61](#)
- TRD** Transition Radiation Detector. [9](#)
- TRT** Transition Radiation Tracker. [7](#), [9](#), [44](#), [47](#), [48](#), [57–70](#), [72](#), [74](#), [197](#), [275](#)
- TTC** Timing, Trigger, and Control. [61](#), [62](#), [65–67](#), [69](#), [250](#)
- TTCrx** A [TTC](#) Receiver [ASIC](#) for [LHC](#) detectors. [62](#)
- TTVA** Track To Vertex Association. [80](#), [81](#), [217](#)
- USA15** Underground Service Area 15. [66](#), [68](#)
- V2** Virtex II Pro XC2VP7 chip. [63](#), [66](#)
- V4** Virtex 4 XC4VLX40 chip. [63](#), [65](#)
- VCSEL** Vertical-Cavity Surface-Emitting Laser. [62](#)
- VEV** Vacuum Expectation Value. [14](#), [19](#), [21](#)
- VME** Versa Module Eurocard. [61](#), [68](#), [69](#)
- ZDC** Zero-Degree Calorimeter. [54](#)

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RESEARCH DATA MANAGEMENT

This thesis has been conducted in accordance with the Institute for Mathematics, Astrophysics, and Particle Physics research data management policy, as outlined in the document available at www.ru.nl (accessed on 29 February 2024).

- All xAOD datasets, Monte Carlo simulations, and software tools are accessible within the [ATLAS](#) Collaboration at [CERN](#) via the Distributed Data Management system (Rucio [[188](#)]) on the grid.
- The `MiniTreeMaker13TeV` software, which preprocesses xAOD data into the “mini-Tree” format, is available on the [CERN](#) GitLab page at <https://gitlab.cern.ch/atlas-wmass/MiniTreeMaker13TeV>, with the specific tag `2affe30`.
- Data and [MC](#) samples, stored in the miniTree format, are located on the [ATLAS](#) EOS storage system:
`/eos/atlas/atlascerngroupdisk/phys-sm/LowMu2017WZ/minitree`.
- For applying additional corrections and performing event preselection on the miniTree format, resulting in the “microTree” format, the `HistMaker` software was utilized, available at <https://gitlab.cern.ch/waiteam/microtrees/HistMaker>, with the tag `v20230406_nom`.
- Control plots and all multijet studies were conducted using the `xTauReader` software, accessible at <https://gitlab.cern.ch/waiteam/xTR/xTauReader>, with the tag `wai20240119`.
- For the extraction of Drell-Yan angular coefficients, the `AiDY` fit software was utilized, accessible at <https://gitlab.cern.ch/waiteam/aidy>, with the tag `1bb83a1f`.

SUMMARY

In particle physics, the Standard Model (SM) is the foundational theory that describes the fundamental particles and forces of the universe. Despite its success in predicting experimental outcomes, the SM falls short of explaining several cosmic mysteries. To uncover what lies beyond the Standard Model, physicists employ both direct and indirect search strategies. Drell-Yan angular coefficient measurements in particle physics serve as an indirect search method, shedding light on the electroweak sector and Quantum Chromodynamics (QCD). These measurements are crucial for refining physics models used in collider experiments like ATLAS. The method involves studying the angular distribution of leptons, such as electrons and muons, produced in the Drell-Yan process, where a quark and an antiquark annihilate to form a vector boson (W or Z boson) that decays into a lepton-antilepton pair. The analysis breaks the differential cross-section into angular coefficients (A_i) and an unpolarized cross-section across angular polynomials. These coefficients, varying from 0 to 8 for Z and W boson production, encapsulate the QCD dynamics of production and the kinematics of boson decay, offering a comprehensive understanding of these fundamental processes.

While the angular coefficients (A_i) has been measured for the Z boson [61], achieving this for the W boson presents significant challenges. The W analysis is complicated by substantial backgrounds from electroweak processes and fake leptons, which require data-driven estimation methods. Additionally, the presence of a neutrino in W decays complicates the reconstruction of the W's rest frame, making the measurement of the complete set of W- A_i angular coefficients particularly challenging. For a long time, this task was considered nearly impossible due to these difficulties.

This thesis presents methodologies for addressing the challenges in measuring the full set of W- A_i angular coefficients, leveraging 338.1 pb^{-1} of low-pileup data at $\sqrt{s} = 13 \text{ TeV}$ from the ATLAS experiment. Despite statistical limitations, the analysis' kinematic selection was optimized to probe the Lam-Tung relation ($A_0 - A_2 = 0$) within regions of high transverse lepton momentum ($p_T^{\ell v}$). This strategy increased the fakes background, necessitating the development of a sophisticated approach for its estimation through complex analysis's 3D binning.

The measurement techniques initially developed for Z- A_i analysis were adapted to study W decays. Yet, controlling significant backgrounds from Z boson decay processes and fake leptons proved challenging in the selected signal region, affecting the stability of the data fit and sometimes preventing convergence. The A_i fitting process, sensitive to the accurate modeling of these backgrounds within the W boson rest frame, highlighted the complexities of balancing signal and background dynamics across different kinematic bins. Despite these obstacles, the research outlined in this thesis successfully navigates through analytical challenges, opening the way for future studies. It sets a foundational direction for the exploration of W- A_i coefficients, contributing to a deeper understanding of particle physics phenomena beyond the current scope.

SAMENVATTING

In de deeltjesfysica is het Standaardmodel (SM) de fundamentele theorie die de fundamentele deeltjes en krachten van het universum beschrijft. Ondanks het succes in het voorspellen van experimentele uitkomsten, schiet het SM tekort in het verklaren van verschillende kosmische mysteries. Om te ontdekken wat er voorbij het Standaardmodel ligt, gebruiken fysici zowel directe als indirecte zoekstrategieën. Drell-Yan hoekcoëfficiëntmetingen in de deeltjesfysica dienen als een indirecte zoekmethode, die licht werpt op de elektrozwakke sector en Quantum Chromodynamica (QCD). Deze metingen zijn cruciaal voor het verfijnen van natuurkundige modellen die gebruikt worden in colliderexperimenten zoals ATLAS. De methode omvat het bestuderen van de hoekverdeling van leptonen, zoals elektronen en muonen, geproduceerd in het Drell-Yan proces, waar een quark en een antiquark annihileren om een vectorboson (W of Z boson) te vormen dat vervalt in een lepton-antilepton paar. De analyse breekt de differentiële doorsnede af in hoekcoëfficiënten (A_i) en een ongepolariseerde doorsnede over hoekpolynomen. Deze coëfficiënten, variërend van 0 tot 8 voor Z en W bosonproductie, omvatten de QCD-dynamiek van productie en de kinematica van bosonverval, en bieden een uitgebreid begrip van deze fundamentele processen.

Hoewel de hoekcoëfficiënten (A_i) zijn gemeten voor het Z boson [61], vormt het bereiken hiervan voor het W boson aanzienlijke uitdagingen. De W analyse wordt gecompliceerd door aanzienlijke achtergronden van elektrozwakke processen en nep leptons, die datagedreven schattingsmethoden vereisen. Bovendien maakt de aanwezigheid van een neutrino in W verval de reconstructie van het rustkader van het W bijzonder uitdagend, waardoor de meting van de volledige set W - A_i hoekcoëfficiënten extra moeilijk wordt. Lange tijd werd deze taak als bijna onmogelijk beschouwd vanwege deze moeilijkheden.

Deze scriptie presenteert methodologieën om de uitdagingen aan te gaan in het meten van de volledige set W - A_i hoekcoëfficiënten, met gebruikmaking van 338.1 pb^{-1} aan low-pileup data bij $\sqrt{s} = 13 \text{ TeV}$ van het ATLAS experiment. Ondanks statistische beperkingen werd de kinematische selectie van de analyse geoptimaliseerd om de Lam-Tung relatie ($A_0 - A_2 = 0$) te onderzoeken binnen gebieden van hoge transversale leptonimpuls ($p_T^{\ell\nu}$). Deze strategie verhoogde de nepachtergrond, wat de ontwikkeling van een geavanceerde benadering voor zijn schatting door middel van complexe analyse's 3D binning noodzakelijk maakte.

De meettechnieken die oorspronkelijk werden ontwikkeld voor de Z - A_i analyse werden aangepast om W verval te bestuderen. Het beheersen van significante achtergronden van Z boson vervalprocessen en nep leptons bleek echter uitdagend in de geselecteerde signaalregio, wat de stabiliteit van de datafit beïnvloedde en soms convergentie verhinderde. Het A_i aanpassingsproces, gevoelig voor de nauwkeurige modellering van deze achtergronden binnen het rustkader van het W boson, benadrukte de complexiteit van het balanceren van signaal- en achtergrond dynamiek over verschillende kinematische bins. Ondanks deze obstakels navigeert het onderzoek dat in deze scriptie wordt uiteengezet succesvol door analytische uitdagingen, en baant het de weg voor toekomstige studies. Het zet een fundamentele

richting voor de verkenning van W - A_i coëfficiënten, en draagt bij aan een dieper begrip van fenomenen in de deeltjesfysica voorbij de huidige reikwijdte.

CURRICULUM VITAE

Daniil Ponomarenko was born on March 27, 1992, in Vladivostok, Russia. He pursued his education at NRNU MEPhI, where he earned his bachelor's degree by studying the modeling of the Photon Spectrometer (PHOS) calorimeter based on PWO_4 with Geant4 for the [ALICE](#) experiment. After completing his degree in July 2013, he continued his studies in the Master's program in particle physics at the same university, focusing on quark-gluon plasma research through π^0 -charged hadron correlation analysis in p-Pb and Pb-Pb collisions at the [ALICE](#) experiment. He attended the Summer School Programme at [CERN](#) in 2014, working under the supervision of Dr. Alexander Vinogradov on a topic aligned with his Master's research. In parallel, from 2013 to 2015, Daniil held the position of Senior Engineer at SAFEDATA LLC, where he was responsible for ensuring the 24-hour availability of the datacenter. In June 2015, he took part in the International School of Subnuclear Physics in Erice, Italy. That same summer, he completed his Master's degree in the department of elementary particles at NRNU MEPhI, under the guidance of Prof. Vladislav Manko and Dr. Dmitry Blau.

From 2015 to 2017, Daniil was a doctoral student at NRNU MEPhI, mentored by Prof. Anatoli Romaniouk. Following his [ATLAS](#) qualification task, which involved developing a new method for calculating energy losses on track for the [TRT](#) detector, he contributed to the search for exotic particles, specifically heavy long-lived multi-charged particles.

In 2017, Daniil joined a joint PhD program between Radboud University and NRNU MEPhI, co-supervised by Prof. Nicolo de Groot and Prof. Anatoli Romaniouk. His initial research focused on testing lepton flavour universality in leptonic W decays using the complete Run 2 dataset from the [ATLAS](#) experiment. However, by 2021, his role shifted to measuring Drell-Yan angular coefficients in leptonic W decays events using low-pileup data, culminating in this thesis. Although part of his research was conducted during brief stays in Nijmegen, Netherlands, the majority of his work took place at [CERN](#), Switzerland.

Since 2015, Daniil has been actively involved in the operational aspects of [ATLAS](#) and [TRT](#). In February 2017, he participated in the International School of Trigger and Data Acquisition in Amsterdam, Netherlands. As a principal software developer, he has spearheaded the development, commissioning, and upkeep of both the online and offline [TRT TDAQ](#) software. Collaborating closely with the [TRT](#) hardware team, he tackled operational challenges that emerged, particularly during intense data-taking periods. For his efforts to improve [TRT](#) operations at high occupancy and trigger rates, Daniil received the [ATLAS](#) Outstanding Achievement Award in 2020. In addition, since 2016 he played a key role in the Transition Radiation Detector prototype studies at [CERN](#)'s North experimental area, particularly in the preparation and deployment of the [TDAQ](#) infrastructure. In 2022, Daniil was named the [TRT](#) Run Coordinator, marking a significant milestone in his professional journey.

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As I conclude this chapter of my life, I look forward to the future with a deep sense of gratitude for the incredible people who have been part of this journey. The support, guidance, and love I've received from all of you have not only shaped this work but have also equipped me with the tools and confidence to take on the next steps in my career. I am excited to carry forward the lessons I've learned from each of you, the friendships we've built, and the knowledge we've shared as I embrace new challenges and opportunities. Your influence will continue to inspire and guide me in the years to come.