

Observations of the Radiation Amplitude Zero effect and of the Diboson Longitudinal-Longitudinal Interactions in High p_T Region using $W^\pm Z$ Production with the ATLAS Detector

by

Prachi Arvind Atmasiddha

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Doctoral Committee:

Professor Junjie Zhu, Chair
Professor Christine Aidala
Assistant Professor Yang Chen
Professor James Wells
Professor Bing Zhou



Prachi Arvind Atmasiddha
patmasid@umich.edu
ORCID iD: 0000-0002-7639-9703

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To my late grandmother, Suhasini Gajanan Saraf, who loved me unconditionally till the end, took care of me as a child, encouraged me in all my academic endeavors, and helped me become a better person.

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PREFACE

This thesis covers a part of the research that I conducted during my Ph.D. at the University of Michigan under the supervision of Junjie Zhu. The contents of the thesis are based on one ATLAS analysis which is ongoing and one internal note regarding the Phase I upgrade of the muon spectrometer. Due to the collaborative nature of both works, not all of the work listed in these papers was conducted by me.

The first part of the thesis describes the work related to the Radiation Amplitude Zero measurement and the di-boson polarization fraction measurement in the high p_T^Z region. My contribution is to the Monte-Carlo sample generation, truth level studies, implementation of theoretical systematics, reconstruction level studies, and generating inputs for the unfolding of the Radiation Amplitude Zero measurement. The second part describes the small-strip Thin Gap Chambers Integration work conducted at CERN on the ground. The University of Michigan ATLAS group was a part of the electronics integration of the sTGCs with my contribution specifically to the readout chain tests and noise studies. Some of my contributions described in this thesis are parts of the publication describing the ATLAS Detector Configuration for Run-3 and also the inclusive phase space paper measuring the joint polarization measurement (my contribution to the paper is the Monte Carlo polarized events generation, and some truth level studies).

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LIST OF ABBREVIATIONS

ADC Analog-to-Digital Converter	CSCs Cathode Strip Chambers
ALEPH Apparatus for LEP Physics	DAC Digital-to-Analog Converter
ALICE A Large Ion Collider Experiment	ddct data-driven closure test
ASIC Application Specific Integrated Circuit	EI End-Cap Inner
aTGC anomalous Triple Gauge Coupling	EM End-Cap Middle
ATLAS A Toroidal LHC Apparatus	EM Electromagnetic
BCID Bunch Crossing ID	EO End-Cap Outer
BDT Boosted Decision Tree	FCal Forward Calorimeter
BI Barrel Inner	FELIX Front-End LInk eXchange
BM Barrel Middle	FFT Fast Fourier Transform
BO Barrel Outer	fJVT forward Jet Vertex Tagger
BSM Beyond Standard Model	FSR Final State Radiation
CERN European Organization for Nuclear Research	HEC Hadronic End-cap Calorimeter
CMS Compact Muon Solenoid	HLT High Level Trigger

IBL Insertable B-Layer

ID Inner Detector

ISR Initial State Radiation

JER Jet Energy Resolution

JES Jet Energy Scale

JVT Jet Vertex Tagger

L1 Level-1

LEP Large Electron-Positron Collider

LHCb Large Hadron Collider Beauty

LHC Large Hadron Collider

LO Leading-Order

LUCID Luminosity Cherenkov Integrating De-
tector

MC Monte Carlo

MDTs Monitored Drift Tubes

MM Micromesh Gaseous Structures

MPI Multi-Parton Interactions

MS Muon Spectrometer

NLO Next-to-Leading Order

NSW New Small Wheel

PCB Printed Circuit Board

PDF Parton Distribution Function

pFEB pad Front End Board

PSB Proton Synchrotron Booster

PS Proton Synchrotron

PV Primary Vertex

QCD Quantum Chromodynamics

QED Quantum Electrodynamics

RAZ Radiation Amplitude Zero

ROC Readout Controller

RPCs Resistive Plate Chambers

SCT Semi-Conductor Tracker

SFOS Same-Flavor Opposite-Sign

sFEB strip Front End Board

SM Standard Model

SPS Super Proton Synchrotron

sTGC small-strip Thin Gap Chambers

TGCs Thin Gap Chambers

TDAQ Trigger and Data Acquisition

TRT Transition Radiation Tracker

TDS Trigger Data Serializer

TTVA track-to-vertex association

ABSTRACT

This thesis focuses on the studies of di-boson polarization states in $W^\pm Z$ production, presenting two novel measurements using pp collisions at a center-of-mass energy of $\sqrt{s} = 13$ TeV. The WZ decaying to leptonic final states is considered. The data was collected at the Large Hadron Collider (LHC) with the ATLAS experiment, utilizing an integrated luminosity of 140.1 fb^{-1} .

The first measurement pertains to the Radiation Amplitude Zero effect. By studying the depth of distributions involving the rapidity differences between the W lepton and the Z boson (ΔY_{3Z}) and between the W boson and the Z boson (ΔY_{WZ}), an agreement is observed between the measured depth in the background-subtracted data consisting only of the transverse-transverse WZ contribution and the Monte Carlo (MC) prediction.

The second measurement involves the determination of the longitudinal-longitudinal WZ polarization fraction. This measurement is performed in regions with predominantly s -channel WZ events, characterized by high p_T^Z values in two fiducial phase spaces: $p_T^Z > 100$ GeV or $p_T^Z > 200$ GeV. To extract the polarization fraction, a multivariate analysis based on a Boosted Decision Trees discriminant is employed. A maximum log-likelihood fit is then executed, yielding a longitudinal-longitudinal polarization fraction (f_{00}) of $0.25^{+0.06}_{-0.06}$ for the $p_T^Z > 200$ GeV region, with an observed (expected) significance of 3.4σ (4.6σ). In the $p_T^Z > 100$ GeV region, the longitudinal-longitudinal polarization fraction is found to be $0.17^{+0.021}_{-0.022}$, with an observed (expected) significance of 7.9σ (8.8σ). Notably, this marks the first measurement of the longitudinal-longitudinal WZ production in the high- p_T^Z phase space.

In addition to the analysis, this thesis covers the contribution of the University of Michigan ATLAS group to the ATLAS New Small Wheel Muon Spectrometer upgrade, particularly the integration and commissioning of the small-strip Thin Gap Chambers electronics. Detailed procedure regarding the integration work, especially the readout chain electronics validations, and detector noise studies is described in the thesis.

CHAPTER 1

Introduction

Understanding the nature of matter and its interactions has been one of the biggest questions of particle physics. The Standard Model explains our current understanding of the subatomic particles and the fundamental forces which drive the interactions between them. The fields and particles are equivalent concepts in the framework of quantum field theory, which describes the Standard Model. In the 1960s, Glashow, Salam, and Weinberg unified the weak and electromagnetic interactions of particle fields into one theory called the electroweak theory [1–3]. This theory together with the theory of strong interactions (Quantum Chromodynamics), forms the Standard Model (SM) of particle physics.

Precision measurements at the Large Hadron Collider (LHC) experiments can improve our knowledge of the Electroweak Symmetry Breaking (EWSB) mechanism. At high energies, the electroweak gauge bosons can be considered massless [4]. This has implications for the physics Beyond Standard Model (BSM). The longitudinal polarization of the W and Z bosons arises from the spontaneous breaking of the electroweak symmetry by the Higgs field via the Higgs mechanism. Hence, performing measurements on the polarized gauge bosons, especially those at high energies can improve our understanding of electroweak physics. The s -channel production of WZ can be studied effectively for peeking into these interesting properties including future prospects to study anomalous Triple Gauge Coupling (aTGC). The analysis performed in WZ decaying to the leptonic final state involves studying different di-boson polarization states in the region where the contribution from both longitudinally-polarized bosons is enhanced. The Radiation Amplitude Zero (RAZ) effect is a property of the SM theory which is explored and utilized to enhance the longitudinal-longitudinal WZ polarization state.

The introduction and theoretical motivations behind this analysis are summarized in this chapter 1, an overview of the ATLAS detector and the object reconstruction essential for the analysis is included in chapter 2. Chapter 3 summarizes the WZ polarization analysis methodology, the results of the Radiation Amplitude Zero measurements are shown in chapter 4, and the results of the

polarization fraction measurements are shown in chapter 5. Chapter 6 includes the summary of the WZ analysis. An introduction of the ATLAS New Small Wheel Muon Spectrometer upgrade is included in chapter 7 and the work conducted by the University of Michigan ATLAS group on the small-strip thin gap chambers electronics integration and commissioning is described in chapter 8.

1.1 The Standard Model of Particle Physics

The SM provides the current best understanding of elementary particles and their interactions and is considered to be one of the triumphs of modern physics. Figure 1.1 shows all the particles with more characteristic information like electric charge, spin, mass, etc. All SM particles are either fermions or bosons. The Fermions are spin-1/2 particles following the rules of the Fermi-Dirac statistics. They make up most of the physical matter we encounter within the universe. The fermions can be categorized into quarks and leptons. The quarks have a color charge, red (R), green (G) or blue (B) and come in six flavours: up (u), charm (c) and top (t) have an electric charge of $+\frac{2}{3}e$ each and down (d), strange (s) and bottom (b) have an electric charge of $-\frac{1}{3}e$ each. The leptons have three families (or generations): electron (e) with the corresponding electron neutrino ν_e , muon with the corresponding muon neutrino (ν_μ), and tau with the corresponding tau neutrino ν_τ . Electrons, muons, and taus have an electric charge of $-e$ and neutrinos are neutral particles. The quarks and leptons also have corresponding anti-particles with opposite charges and the same mass. The gauge bosons are the spin-1 particles and are the force carriers. The photons (γ) are the mediators of the electromagnetic interaction and the gluons (g) are the mediators of the strong interactions. These are electrically neutral and massless particles. On the other hand, $W^\pm$ and Z are the massive mediators of the weak interactions. The Higgs boson is a spin-0 scalar boson that gives masses to all other particles (except neutrinos). The graviton is hypothesized to be the mediator for the gravitational force [5] but has not yet been observed experimentally. The gravitational interactions are not relevant to the work in this thesis, as they are negligible at the atomic scale.

The interactions in the SM are described by the non-abelian Yang-Mills gauge theory [7] with the $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ gauge group. Here $SU(3)_C$ corresponds to the strong interactions [8] and $SU(2)_L \otimes U(1)_Y$ corresponds to the electroweak interactions [3]. Here C is for a color charge, L is for left-handed fields, and Y refers to the weak hypercharge.

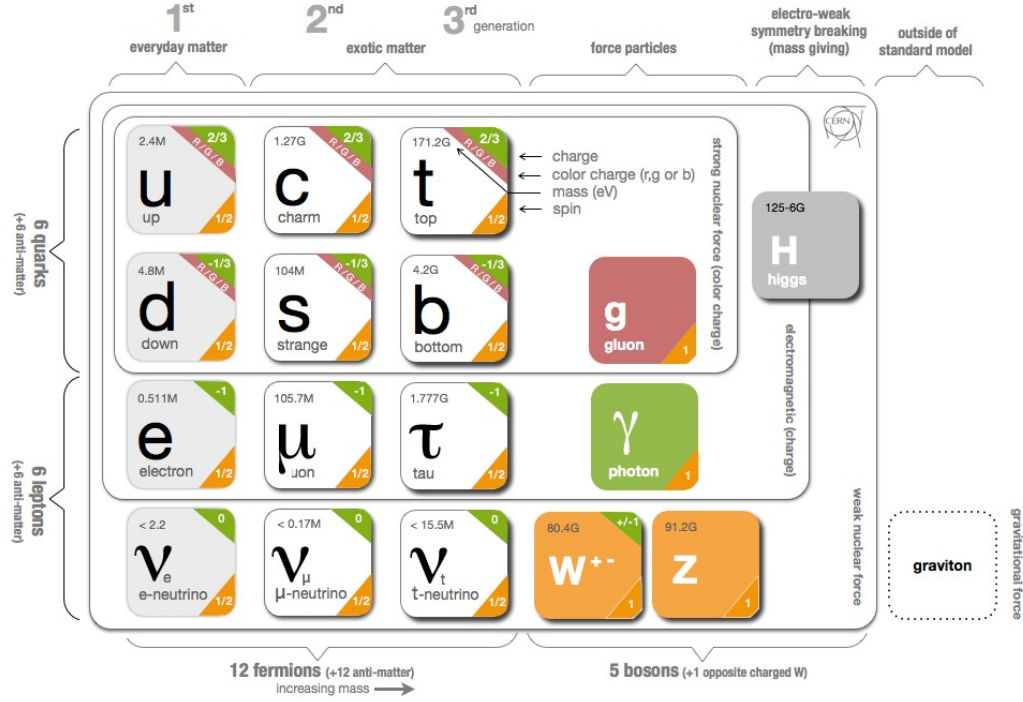


Figure 1.1: Elementary particles. The lepton and quark families are shown as well as the force carriers and the Higgs boson. The Graviton has not been observed experimentally. Picture taken from [6].

1.1.1 Quantum Chromodynamics (QCD)

The strong interaction Lagrangian is written as [8]:

$$\mathcal{L} = \sum_f \bar{q}_f (i\gamma^\mu \partial_\mu - m_f) q_f. \quad (1.1)$$

Here, q_f^α is a quark field of colour α and flavour f . The vector q_f represents

$$q_f = \begin{pmatrix} q_f^1 \\ q_f^2 \\ q_f^3 \end{pmatrix}. \quad (1.2)$$

The Lagrangian given in equation 1.1 is invariant under the $SU(3)_C$ transformation:

$$q_f^\alpha \longrightarrow (q_f^\alpha)' = U_\beta^\alpha q_f^\beta, \quad UU^\dagger = U^\dagger U = 1, \quad \det U = 1, \quad (1.3)$$

where

$$U = \exp \left\{ i \frac{\lambda^a}{2} \theta_a \right\}, \quad (1.4)$$

and $\frac{1}{2}\lambda^a$ ($a = 1, 2, \dots, 8$) denote the generators of the fundamental representation of the $SU(3)_C$ group and θ_a are arbitrary parameters. The λ^a satisfy the following relation:

$$\left[\frac{\lambda^a}{2}, \frac{\lambda^b}{2} \right] = i f^{abc} \frac{\lambda^c}{2}, \quad (1.5)$$

with f^{abc} the $SU(3)_C$ structure constants, which are real and totally antisymmetric.

The final $SU(3)_C$ -invariant Lagrangian of the Quantum Chromodynamics becomes:

$$\mathcal{L}_{\text{QCD}} \equiv -\frac{1}{4} G_a^{\mu\nu} G_{\mu\nu}^a + \sum_f \bar{q}_f (i \gamma^\mu D_\mu - m_f) q_f, \quad (1.6)$$

with

$$G_a^{\mu\nu}(x) = \partial^\mu G_a^\nu - \partial^\nu G_a^\mu - g_s f^{abc} G_b^\mu G_c^\nu. \quad (1.7)$$

The covariant derivative is defined as:

$$D_\mu = \partial_\mu + i g_s \frac{\lambda^a}{2} G_a^\mu. \quad (1.8)$$

Here, λ^a ($a = 0, 1 \dots 8$) are the Gell-Mann matrices, G_a^μ are the gluon fields and g_s is the strong (QCD) coupling constant.

1.1.2 Electroweak Theory

The electroweak theory is based on the $SU(2) \otimes U(1)$ symmetry group [8]. For the sake of this discussion, let's consider a single family of fermions:

$$\psi_1(x) = \begin{pmatrix} u \\ d \end{pmatrix}_L \equiv q_L, \quad \psi_2(x) = u_R, \quad \psi_3(x) = d_R, \quad (1.9)$$

$$\psi_1(x) = \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L, \quad \psi_2(x) = \nu_R, \quad \psi_3(x) = e_R. \quad (1.10)$$

The fermionic spinors, ψ_i s, are left-handed weak-isospin doublets and right-handed weak-isospin singlets. They are defined as follows:

$$\psi_L = \frac{1 - \gamma^5}{2} \psi \quad \text{and} \quad \psi_R = \frac{1 + \gamma^5}{2} \psi. \quad (1.11)$$

The Lagrangian becomes:

$$\mathcal{L}_0 = i\bar{u}(x)\gamma^\mu\partial_\mu u(x) + i\bar{d}(x)\gamma^\mu\partial_\mu d(x) = \sum_{j=1}^3 i\bar{\psi}_j(x)\gamma^\mu\partial_\mu\psi_j(x), \quad (1.12)$$

with

$$\psi_1(x) \xrightarrow{G} \psi'_1(x) \equiv \exp\{iy_1\beta\} U_L \psi_1(x), \quad (1.13)$$

$$\psi_2(x) \xrightarrow{G} \psi'_2(x) \equiv \exp\{iy_2\beta\} \psi_2(x), \quad (1.14)$$

$$\psi_3(x) \xrightarrow{G} \psi'_3(x) \equiv \exp\{iy_3\beta\} \psi_3(x). \quad (1.15)$$

Here, the $SU(2)_L$ transformation acts on the doublet field:

$$U_L \equiv \exp\left\{i\frac{\sigma_i}{2}\alpha^i\right\} \quad (i = 1, 2, 3). \quad (1.16)$$

The parameters y_i are called hypercharges since the $U(1)_Y$ phase transformation is analogous to the QED one.

Requiring the Lagrangian to be invariant under the local gauge transformations, with $\alpha^i = \alpha^i(x)$ and $\beta = \beta(x)$:

$$D_\mu\psi_1(x) \equiv \left[\partial_\mu + ig\widetilde{W}_\mu(x) + ig'y_1B_\mu(x)\right]\psi_1(x), \quad (1.17)$$

$$D_\mu\psi_2(x) \equiv \left[\partial_\mu + ig'y_2B_\mu(x)\right]\psi_2(x), \quad (1.18)$$

$$D_\mu\psi_3(x) \equiv \left[\partial_\mu + ig'y_3B_\mu(x)\right]\psi_3(x), \quad (1.19)$$

with

$$\widetilde{W}_\mu(x) \equiv \frac{\sigma_i}{2} W_\mu^i(x). \quad (1.20)$$

The Lagrangian term $\mathcal{L}_{\text{fermion}}$ becomes:

$$\mathcal{L}_{\text{fermion(Electroweak)}} = \sum_{j=1}^3 i \bar{\psi}_j(x) \gamma^\mu D_\mu \psi_j(x). \quad (1.21)$$

For the gauge-invariant kinetic term, the following fields are introduced:

$$B_{\mu\nu} \equiv \partial_\mu B_\nu - \partial_\nu B_\mu, \quad (1.22)$$

$$\widetilde{W}_{\mu\nu} \equiv -\frac{i}{g} \left[(\partial_\mu + ig \widetilde{W}_\mu), (\partial_\nu + ig \widetilde{W}_\nu) \right] = \partial_\mu \widetilde{W}_\nu - \partial_\nu \widetilde{W}_\mu + ig [W_\mu, W_\nu], \quad (1.23)$$

with

$$\widetilde{W}_{\mu\nu} \equiv \frac{\sigma_i}{2} W_{\mu\nu}^i, \quad W_{\mu\nu}^i = \partial_\mu W_\nu^i - \partial_\nu W_\mu^i - g \epsilon^{ijk} W_\mu^j W_\nu^k. \quad (1.24)$$

The $\mathcal{L}_{\text{gauge}}$ Lagrangian also has the contribution from electroweak theory:

$$\mathcal{L}_{\text{gauge (Electroweak)}} = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{2} \text{Tr} [\widetilde{W}_{\mu\nu} \widetilde{W}^{\mu\nu}] = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W_{\mu\nu}^i W_i^{\mu\nu}. \quad (1.25)$$

where Y and τ_i are the $U(1)$ and $SU(2)$ gauge symmetry group generators, respectively. $Y = Q - T_3$ is the weak hypercharge with Q being the electric charge and T_3 being the weak isospin with a value of $\pm 1/2$ for the left-handed doublets and zero for the right-handed singlets. B_μ and W_μ^i are the gauge bosons, and g', g are the coupling constants.

Until now all the particles in the equations above are massless. The mass terms can also be added to the Lagrangian. Although, the mass terms violate the gauge invariance under the local transformations. This issue is solved by introducing the Higgs mechanism.

1.1.3 The Higgs Mechanism

Here is the description of the electroweak symmetry breaking in a complex scalar field (then later move on to the SM minimal Higgs model containing a weak-isospin doublet of complex scalar fields). The reason for this first description is to explain the source of the longitudinal polarization in the gauge bosons.

Let's consider a complex scalar field:

$$\phi = \frac{1}{\sqrt{2}}(\phi_1 + i\phi_2), \quad (1.26)$$

with a Lagrangian:

$$\mathcal{L} = (\partial_\mu \phi)^* (\partial^\mu \phi) - V(\phi) \quad \text{with} \quad V(\phi) = \mu^2 (\phi^* \phi) + \lambda (\phi^* \phi)^2. \quad (1.27)$$

Thus we have

$$\mathcal{L} = \frac{1}{2}(\partial_\mu \phi_1)(\partial^\mu \phi_1) + \frac{1}{2}(\partial_\mu \phi_2)(\partial^\mu \phi_2) - \frac{1}{2}\mu^2(\phi_1^2 + \phi_2^2) - \frac{1}{4}\lambda(\phi_1^2 + \phi_2^2)^2. \quad (1.28)$$

This Lagrangian is invariant under the global $U(1)$ gauge symmetry (i.e. it is invariant under the transformation $\phi \rightarrow \phi' = e^{i\alpha}\phi$, because $\phi'^* \phi' = \phi^* \phi$).

The sign of μ^2 decides the shape of the potential: $\mu^2 > 0$ means the zero of the potential occurs when both the real fields (in the complex field) are zero, and $\mu^2 < 0$ indicates that there is an infinite number of minima shown as a circle described in equation 1.29 (See figure 1.2):

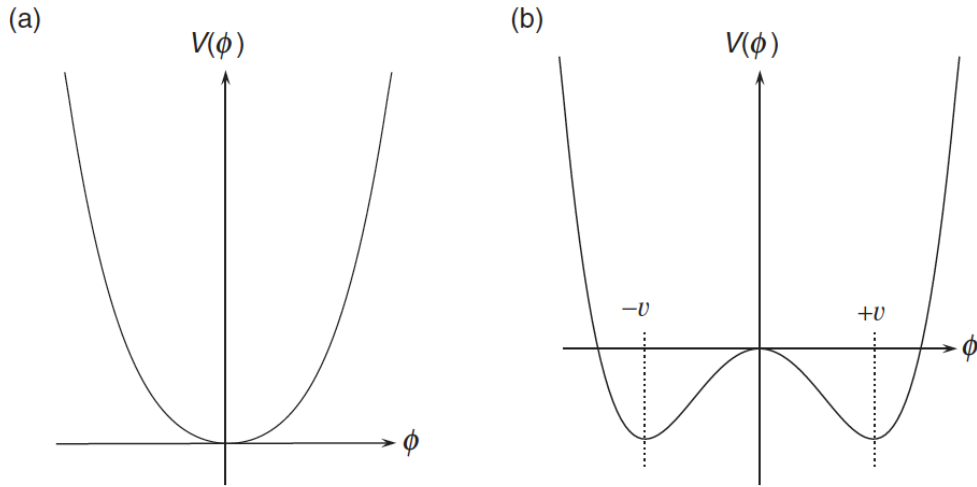


Figure 1.2: The $V(\phi) = \mu^2 (\phi^* \phi) + \lambda (\phi^* \phi)^2$ potential for a complex scalar field for $\mu^2 > 0$ (a) and $\mu^2 < 0$ (b).

$$\phi_1^2 + \phi_2^2 = \frac{-\mu^2}{\lambda} = v^2. \quad (1.29)$$

The physical vacuum state will be one of the points on this circle and once the vacuum point is selected, the $U(1)$ symmetry of the Lagrangian breaks. Without loss of generality, the vacuum point

can be one on the real axis line making the vacuum state to be $(\phi_1, \phi_2) = (v, 0)$, and the complex scalar field ϕ can be expanded about this vacuum state as:

$$\phi = \frac{1}{\sqrt{2}}(\eta(x) + v + i\xi(x)), \quad (1.30)$$

where $\phi_1(x) = \eta(x) + v$ and $\phi_2(x) = \xi(x)$.

Next, the example of local $U(1)$ gauge symmetry is used to introduce the main ideas of the Higgs mechanism here. The Lagrangian of a complex scalar field is not invariant under the local gauge transformation $\phi(x) \rightarrow \phi'(x) = e^{ig\chi(x)}\phi(x)$. However, it is invariant if the derivative in the Lagrangian is changed to a covariant derivative:

$$\partial_\mu \rightarrow D_\mu = \partial_\mu + igB_\mu. \quad (1.31)$$

The resulting Lagrangian becomes gauge invariant:

$$\mathcal{L} = (D_\mu \phi)^* (D^\mu \phi) - V(\phi^2), \quad (1.32)$$

as long as the gauge field transforms as: $B_\mu \rightarrow B'_\mu = B_\mu - \partial_\mu \chi(x)$.

The full expression of the Lagrangian becomes:

$$\mathcal{L} = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + (\partial_\mu \phi)^* (\partial^\mu \phi) - \mu^2 \phi^2 - \lambda \phi^4 \quad (1.33)$$

$$- igB_\mu \phi^* (\partial^\mu \phi) + ig(\partial_\mu \phi^*) B^\mu \phi + g^2 B_\mu B^\mu \phi^* \phi. \quad (1.34)$$

In the case of $\mu^2 < 0$, the physical vacuum state breaks the symmetry of the Lagrangian. The vacuum state is chosen to be $\phi_1 + i\phi_2 = v$. The complex scalar field is expanded as given in equation 1.30:

$$\mathcal{L} = \underbrace{\frac{1}{2}(\partial_\mu \eta)(\partial^\mu \eta) - \lambda v^2 \eta^2}_{\text{massive } \eta} + \underbrace{\frac{1}{2}(\partial_\mu \xi)(\partial^\mu \xi)}_{\text{massless } \xi} - \underbrace{\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}g^2 v^2 B_\mu B^\mu}_{\text{massive gauge field}} - V_{\text{int}} + gvB_\mu(\partial^\mu \xi), \quad (1.35)$$

where $V_{\text{int}}(\eta, \xi, B)$ contains the three- and four-point interaction terms of the fields η , ξ , B . This Lagrangian includes a massive scalar field η and a massless Goldstone boson ξ . The B field has acquired a mass term.

Rewriting the Lagrangian as:

$$\frac{1}{2}(\partial_\mu \xi)(\partial^\mu \xi) + gvB_\mu(\partial^\mu \xi) + \frac{1}{2}g^2 v^2 B_\mu B^\mu = \frac{1}{2}g^2 v^2 \left[B_\mu + \frac{1}{gv}(\partial_\mu \xi) \right]^2. \quad (1.36)$$

With a transformation $B_\mu(x) \rightarrow B'_\mu(x) = B_\mu(x) + \frac{1}{g\nu}\partial_\mu\xi(x)$ and also with $\phi(x) \rightarrow \phi'(x) = e^{-ig\frac{\xi(x)}{g\nu}}\phi(x) = e^{-i\xi(x)/\nu}\phi(x)$, we get a Lagrangian free of $\xi(x)$ term:

$$\mathcal{L} = \underbrace{\frac{1}{2}(\partial^\mu\eta)(\partial_\mu\eta) - \lambda\nu^2\eta^2}_{\text{massive } \eta} + \underbrace{-\frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}g^2\nu^2 B''_\mu B'_\mu}_{\text{massive gauge field}} - V_{int}. \quad (1.37)$$

ξ can be eliminated from $\phi(x)$ by rewriting equation 1.30 as $\phi(x) \approx \frac{1}{\sqrt{2}}[\nu + \eta(x)]e^{i\xi(x)/\nu}$ which changes equation 1.30 to $\phi(x) \rightarrow \phi'(x) = \frac{1}{\sqrt{2}}e^{-i\xi(x)/\nu}[\nu + \eta(x)]e^{i\xi(x)/\nu} = \frac{1}{\sqrt{2}}(\nu + \eta(x))$. The degree of freedom related to the Goldstone field $\xi(x)$ is removed completely and manifests itself as the longitudinal polarization state of the massive boson B . This example consists of one gauge field B and one corresponding Goldstone field $\xi(x)$.

Now let's move to the SM Higgs mechanism [9, 10]. The Higgs mechanism is embedded in the $U(1)_Y \otimes SU(2)_L$ local gauge symmetry of the electroweak sector of the SM. There have to be three Goldstone fields associated with three bosons W^+ , W^- , and Z . The model consists of two complex scalar fields placed in a weak-isospin doublet:

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}. \quad (1.38)$$

The Lagrangian with this scalar field is:

$$\mathcal{L} = (\partial_\mu\phi)^\dagger (\partial^\mu\phi) - V(\phi), \quad (1.39)$$

with the Higgs potential being,

$$V(\phi) = \mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2. \quad (1.40)$$

The degenerate minima are present for

$$\phi^\dagger\phi = \frac{1}{2}(\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2) = \frac{\nu^2}{2} = -\frac{\mu^2}{2\lambda}. \quad (1.41)$$

Because of the need for a massless photon, the minimum must correspond to a non-zero vacuum expectation value (VEV) only of the neutral field ϕ^0 . The field expanded about this minimum is:

$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1(x) + i\phi_2(x) \\ \nu + \eta(x) + i\phi_4(x) \end{pmatrix}. \quad (1.42)$$

After the spontaneous electroweak symmetry breaking, there will be a massive scalar field and

three massless Goldstone bosons, which gives the longitudinal degrees of freedom of the $W^\pm$ and Z bosons. The previous example explains this mechanism for one massive boson. The Higgs doublet is written in the unitary gauge:

$$\phi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}. \quad (1.43)$$

The $\mathcal{L}_{Higgs}$ can be written as:

$$\mathcal{L}_{Higgs} = T(\phi) - V(\phi) = (D_\mu \phi)^\dagger (D^\mu \phi) - \mu^2 \phi^\dagger \phi - \lambda (\phi^\dagger \phi)^2. \quad (1.44)$$

The term $V(\phi)$ is:

$$V(\phi) = -\frac{\mu^4}{4\lambda} - \mu^2 H^2 + \lambda v H^3 + \frac{\lambda}{4} H^4. \quad (1.45)$$

Here the mass of the Higgs boson can be derived as $M_H = \sqrt{-2\mu^2} = \sqrt{2\lambda}v$.

The kinetic term can be written as:

$$\begin{aligned} T(\phi) &\equiv (D_\mu \phi)^\dagger D^\mu \phi \\ &= \frac{1}{2} (\partial_\mu H) (\partial^\mu H) + \frac{(v+H)^2}{4} \left[W_\mu^1 W^{1\mu} + W_\mu^2 W^{2\mu} + \frac{1}{2} (g W_\mu^3 - g' B_\mu) (g W^{3\mu} - g' B^\mu) \right]. \end{aligned} \quad (1.46)$$

Equation 1.46 implies that the four gauge bosons, $W_\mu^1, W_\mu^2, W_\mu^3$, and B_μ , are not mass eigenstates. The following equations show the mixing between different $SU(2)$ and $U(1)$ fields (W_μ^i and B_μ):

$$A_\mu = W_\mu^3 \sin \theta_W + B_\mu \cos \theta_W \quad (\text{Photon}), \quad (1.47)$$

$$Z_\mu = W_\mu^3 \cos \theta_W - B_\mu \sin \theta_W \quad (Z \text{ boson}), \quad (1.48)$$

$$W_\mu^\pm = \frac{1}{\sqrt{2}} (W_\mu^1 \pm W_\mu^2) \quad (W^\pm \text{ boson}). \quad (1.49)$$

Here, θ_W is the weak mixing angle (or the Weinberg angle):

$$\sin \theta_W = \frac{g}{\sqrt{g^2 + g'^2}}, \quad \cos \theta_W = \frac{g'}{\sqrt{g^2 + g'^2}}. \quad (1.50)$$

Now we can write the term $T(\phi)$ as:

$$T(\phi) = (D_\mu \phi)^\dagger (D^\mu \phi)$$

$$\begin{aligned}
&= \frac{1}{2} (\partial_\mu H)^2 + m_W^2 W^{+\mu} W_\mu^- + \frac{2m_W^2}{v} W^{+\mu} W_\mu^- H + \frac{m_W^2}{v^2} W^{+\mu} W_\mu^- H^2 \\
&\quad \frac{1}{2} m_Z^2 Z^\mu Z_\mu + \frac{m_Z^2}{v} Z^\mu Z_\mu H + \frac{m_Z^2}{2v^2} Z^\mu Z_\mu H^2,
\end{aligned} \tag{1.51}$$

where $m_W = \frac{1}{2} v g_2$, $m_Z = \frac{1}{2} v \sqrt{g_1^2 + g_2^2}$ and $m_W/m_Z = \cos \theta_W$. Also, here

$$D_\mu \phi = \left(\partial_\mu + \frac{ig}{2} \vec{\tau} \cdot \vec{W}_\mu + \frac{ig'}{2} B_\mu \right) \phi \tag{1.52}$$

1.1.4 The Standard Model Lagrangian

The complete standard model lagrangian can be written as [11]:

$$\mathcal{L}_{\text{SM}} = \mathcal{L}_{\text{fermion}} + \mathcal{L}_{\text{gauge}} + \mathcal{L}_{\text{Higgs}} + \mathcal{L}_{\text{Yukawa}}. \tag{1.53}$$

The $\mathcal{L}_{\text{gauge}}$ term is:

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4} G_{\mu\nu}^i G^{\mu\nu i} - \frac{1}{4} W_{\mu\nu}^i W^{\mu\nu i} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu}. \tag{1.54}$$

where the field strength tensors for $SU(3)$, $SU(2)$, and $U(1)$ are, respectively

$$\begin{aligned}
G_{\mu\nu}^i &= \partial_\mu G_\nu^i - \partial_\nu G_\mu^i - g_s f_{ijk} G_\mu^j G_\nu^k, \quad i, j, k = 1 \cdots 8, \\
W_{\mu\nu}^i &= \partial_\mu W_\nu^i - \partial_\nu W_\mu^i - g \epsilon_{ijk} W_\mu^j W_\nu^k, \quad i, j, k = 1 \cdots 3, \\
B_{\mu\nu} &= \partial_\mu B_\nu - \partial_\nu B_\mu.
\end{aligned} \tag{1.55}$$

The $SU(2)_L$ and $U(1)_Y$ representations are chiral, so no fermion mass terms are allowed. $\mathcal{L}_{\text{fermion}}$ therefore consists entirely of gauge-covariant kinetic energy terms,

$$\begin{aligned}
\mathcal{L}_{\text{fermion}} &= \bar{q}_L i \not{D} q_L + \bar{\ell}_L i \not{D} \ell_L \\
&\quad + \bar{u}_R i \not{D} u_R + \bar{d}_R i \not{D} d_R + \bar{e}_R i \not{D} e_R + \bar{\nu}_R i \not{D} \nu_R.
\end{aligned}$$

This is the Lagrangian which includes a single generation of leptons and quarks.

$$\begin{aligned}
L - \text{doublets} : \quad q_L &= \begin{pmatrix} u \\ d \end{pmatrix}_L, \quad \ell_L = \begin{pmatrix} \nu \\ e \end{pmatrix}_L \\
R - \text{singlets} : \quad &u_R, d_R, e_R, \nu_R
\end{aligned}$$

The terms in the equation 1.1.4 are as follows:

$$\begin{aligned} \bar{q}_L i \not{D} q_L &= i \sum_{\alpha, \beta=1}^3 \left(\bar{u}_L^{0\alpha} \bar{d}_L^{0\alpha} \right) \gamma^\mu \\ &\times \left[\left(\partial_\mu I + \frac{ig}{2} \vec{\tau} \cdot \vec{W}_\mu + \frac{ig'}{6} I B_\mu \right) \delta_{\alpha\beta} + \frac{ig_s}{2} \vec{\lambda}_{\alpha\beta} \cdot \vec{G}_\mu I \right] \begin{pmatrix} u_{L\beta} \\ d_{L\beta} \end{pmatrix}, \end{aligned} \quad (1.56)$$

where α and β are color charges. These color indices are suppressed in the later equations.

$$\begin{aligned} D_\mu q_L &= \left(\partial_\mu + \frac{ig}{2} \vec{\tau} \cdot \vec{W}_\mu + \frac{ig'}{6} B_\mu \right) q_L, & D_\mu u_R &= \left(\partial_\mu + \frac{2ig'}{3} B_\mu \right) u_R, \\ D_\mu \ell_L &= \left(\partial_\mu + \frac{ig}{2} \vec{\tau} \cdot \vec{W}_\mu - \frac{ig'}{2} B_\mu \right) \ell_L, & D_\mu d_R &= \left(\partial_\mu - \frac{ig'}{3} B_\mu \right) d_R, \\ D_\mu e_R &= \left(\partial_\mu - ig' B_\mu \right) e_R, & D_\mu \nu_R &= \partial_\mu \nu_R, \end{aligned} \quad (1.57)$$

where it is understood that there are also gluon couplings for the q_L, u_R , and d_R . These are after calculating hypercharge Y eigenvalues.

$\mathcal{L}_{\text{Higgs}}$ is:

$$\mathcal{L}_{\text{Higgs}} = T(\phi) + V(\phi). \quad (1.58)$$

The terms are shown in equations 1.51 and 1.1.3.

The fermions acquire masses by Spontaneous Symmetry Breaking, $\mathcal{L}_{\text{Yukawa}}$ term (with fermion mass terms) becomes:

$$\mathcal{L}_{\text{Yukawa}} = -\bar{u}_L^0 \left(\frac{\nu + H}{\sqrt{2}} \right) u_{nR}^0 + (d, e, \nu) \text{ terms} + \text{h.c.} \quad (1.59)$$

The $\mathcal{L}_{\text{Yukawa}}$ term related to the first generation of leptons (the interactions of the Higgs field with the leptons) becomes:

$$L_{\text{Yukawa}}^e = -g_e \left(\bar{\ell}_L \phi e_R + \phi^\dagger \bar{e}_R \ell_L \right). \quad (1.60)$$

This Lagrangian is invariant under the $SU(2) \otimes U(1)$ transformation. After inputting equation 1.43 in the above equation, we get the electron mass as $m_e = \frac{g_e \nu}{\sqrt{2}}$ since

$$L_{\text{Yukawa}}^e = -\frac{g_e \nu}{\sqrt{2}} (\bar{\ell}_L e_R + \bar{e}_R \ell_L) + \frac{g_e}{\sqrt{2}} (\bar{e}_L e_R + \bar{e}_R \ell_L) H. \quad (1.61)$$

The $\mathcal{L}_{\text{Yukawa}}$ term related to the first generation of quarks (the interactions of the Higgs field with the quarks) becomes:

$$L_{\text{Yukawa}}^Q = -g_d \bar{q}_L \phi d_R + g_u \bar{q}_L \phi u_R + \text{h.c.} \quad (1.62)$$

which after inputting equation 1.43 becomes:

$$L_{\text{Yukawa}}^Q = -m_d \bar{d}d + m_u \bar{u}u + \frac{m_d}{v} \bar{d}dH + \frac{m_u}{v} \bar{u}uH. \quad (1.63)$$

The same equations hold true for the other generations of leptons and quarks.

1.2 Polarization in Massive Spin-1 Bosons

The Proca Lagrangian, which is used to obtain field equations for massive spin-1 particles, is given as follows:

$$\mathcal{L}_m = -\frac{1}{4}F^{\mu\nu}F_{\mu\nu} + \frac{1}{2}m^2 B^\mu B_\mu. \quad (1.64)$$

From the Euler-Lagrange equation, the corresponding free-field equation becomes

$$(\square + m^2)B^\mu - \partial^\mu(\partial_\nu B^\nu) = 0. \quad (1.65)$$

By taking the derivative of this equation:

$$(\square + m^2)\partial_\mu B^\mu - \partial_\mu \partial^\mu(\partial_\nu B^\nu) = 0, \quad (1.66)$$

$$(\square + m^2)\partial_\mu B^\mu - \square(\partial_\nu B^\nu) = 0, \quad (1.67)$$

$$m^2 \partial_\mu B^\mu = 0, \quad (1.68)$$

giving:

$$\partial_\mu B^\mu = 0. \quad (1.69)$$

Equations 1.2 and 1.2 give the plane wave solutions ($B^\mu = \epsilon^\mu e^{-iq \cdot x}$). Here, q is the four-momentum of the massive particle. This then results in:

$$q_\mu \epsilon^\mu = 0. \quad (1.70)$$

This constraint means only three degrees of freedom are independent. Assuming a boson is traveling in the z -direction, two of these can be the circular polarization states:

$$\epsilon_-^\mu = \frac{1}{\sqrt{2}}(0, 1, -i, 0) \quad \text{and} \quad \epsilon_+^\mu = -\frac{1}{\sqrt{2}}(0, 1, i, 0). \quad (1.71)$$

The third polarization should be orthogonal to these polarization states:

$$\epsilon_L^\mu = \frac{1}{m}(p_z, 0, 0, E). \quad (1.72)$$

The polarizations in massive bosons manifest themselves via different kinematic variables' unique properties. These are explored in this analysis for training an MVA discriminant for separating different polarization states.

1.3 Motivation for Longitudinal-longitudinal $W^\pm Z$ Interaction Studies

As mentioned in the Higgs mechanism section, the longitudinal polarization of the W (or Z) boson is born from the electroweak symmetry breaking by the Higgs field. This is a critical prediction of the SM theory and should be tested experimentally. The longitudinal-longitudinal diboson interactions also are key to searching for new physics or new couplings. Much research has been carried out to study the longitudinal-longitudinal vector boson scattering (VBS) processes, however, the cross-sections of these VBS processes are very low. The ATLAS and CMS Collaborations recently published first measurements of same-sign $W^\pm W^\pm$ VBS, WZ VBS, ZZ VBS, and opposite-sign $W^+ W^-$ VBS production [12–21]. CMS also performed a measurement of the longitudinal-longitudinal fraction using same-sign $W^\pm W^\pm$ VBS events. However, the observed significance of the longitudinally polarized diboson fraction was at the level of 2σ [22].

In this analysis, we present diboson polarization measurements done using $WZ \rightarrow \ell \nu \ell' \ell'$ ($\ell, \ell' = e, \mu$) events with 140.1 fb^{-1} of pp collision data taken at $\sqrt{s} = 13 \text{ TeV}$ by the ATLAS detector. For future reference in this thesis, 0 (or sometimes L) will be used for longitudinal and T for transverse polarizations. For example, 0T or $W_0 Z_T$ corresponds to W being longitudinal and Z being transverse. The reasons to choose this channel are as follows:

1. Large production rate of the $W^\pm Z$ process and low instrumental background;
2. All event kinematics are available with the fully-leptonic final state (except the z component of the neutrino momentum, p_z^ν , which has to be reconstructed using the transverse missing energy);
3. The RAZ effect which reduces the contribution from the $W_T Z_T$ and mixed polarization states ($W_0 Z_T$ and $W_T Z_0$) is expected in the WZ process.

The Feynman diagrams associated with $W^\pm Z$ production include s -, t -, and u -channels as shown in figure 1.3 at the leading-order (LO) QCD. The fraction of a single vector boson in the diboson

production to have a longitudinal polarization is $\sim 26\%$ [23] which makes the diboson longitudinal-longitudinal fraction to be $\sim 7\%$. Trying to probe mostly the s -channel contribution is a very tiny signal. For both t - and u -channels, the W and Z bosons are radiated from the initial quark and

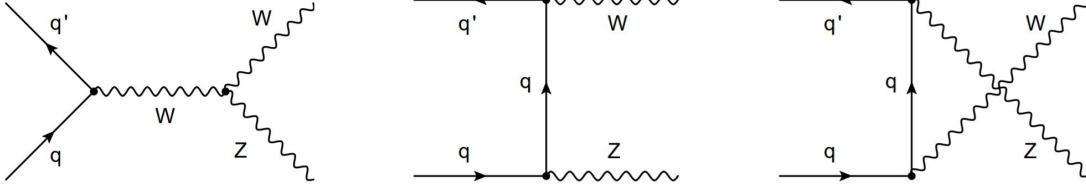


Figure 1.3: Leading-order Feynman diagrams for WZ production. The three diagrams represent contributions from the s -channel (left), t -channel (middle), and u -channel (right).

antiquark and thus tend to have low boson transverse momenta. The reason that WZ production is dominated by the TT polarization is due to the presence of a t -channel pole for the transverse polarizations that significantly enhances the forward-scattering amplitude (like Rutherford scattering). Such contribution is absent for longitudinally-polarized bosons. This forward enhancement is tamed at high vector boson transverse momenta [24]. By requiring events with high Z boson transverse momentum, contributions from the t - and u - channels are greatly reduced.

1.3.1 Helicity Amplitudes for WZ Production

For WZ production at the LHC, we have $f_1(p_1)\bar{f}_2(p_2) \rightarrow W(p_W)Z(p_Z)$ where f_i represents a quark and p_i denotes the particle four-momentum. The helicity amplitude, $\mathcal{M}(\lambda_W, \lambda_Z)$, where $\lambda_W(\lambda_Z)$ denotes the $W(Z)$ boson polarization ($\lambda_{W,Z} = \pm 1, 0$ for transverse and longitudinal polarizations, respectively), can be written as [25]:

$$\mathcal{M}(\pm, \mp) = F \sin \theta (\lambda_W - \cos \theta) X, \quad (1.73)$$

$$\mathcal{M}(\pm, \pm) = F \sin \theta \left[\left(\lambda_W (r_Z - r_W) - \beta + \cos \theta + \beta \frac{\alpha - \beta \cos \theta}{1 - r_W} \right) X + 2\beta Y \right], \quad (1.74)$$

$$\mathcal{M}(0, 0) = F \frac{\sin \theta}{\sqrt{2r_W 2r_Z}} \left[\left(-\beta \rho + \beta_W \beta_Z \cos \theta + \beta \rho \frac{\alpha - \beta \cos \theta}{1 - r_W} \right) X + 2\beta \rho Y \right], \quad (1.75)$$

$$\mathcal{M}(\pm, 0) = F \frac{1 - \lambda_W \cos \theta}{\sqrt{2r_Z}} \left[\left(2\lambda_W r_Z - \beta + \beta_Z \cos \theta + \beta \frac{\alpha - \beta \cos \theta}{1 - r_W} \right) X + 2\beta Y \right], \quad (1.76)$$

$$\mathcal{M}(0, \pm) = F \frac{1 + \lambda_Z \cos \theta}{\sqrt{2r_W}} \left[\left(-2\lambda_Z r_W - \beta + \beta_W \cos \theta + \beta \frac{\alpha - \beta \cos \theta}{1 - r_W} \right) X + 2\beta Y \right]. \quad (1.77)$$

The factor F contains coupling factors, $F = Ce^2/\sqrt{2}\sin\theta_W$, where θ_W is the weak mixing angle, and the color factor $C = \delta_{i_1 i_2} V_{f_1 f_2}$. Here i_1 (i_2) is the color index of the incoming quark (antiquark) and $V_{f_1 f_2}$ is the quark mixing matrix element. The angle θ is the center of mass scattering angle of the W boson with respect to the fermion (f_1) direction. We have $\alpha = 1 - r_W - r_Z$, $\beta = (\alpha^2 - 4r_W r_Z)^{1/2}$, $\beta_W = 1 + r_W - r_Z$, $\beta_Z = 1 - r_W + r_Z$, $\rho = 1 + r_W + r_Z$, and $r_V = m_V^2/s$ with $V = W, Z$.

The kinematic variables are defined by:

$$s = (p_1 + p_2)^2, \quad t = (p_1 - p_W)^2 = -\frac{s}{2}(\alpha - \beta \cos\theta), \quad u = (p_1 - p_Z)^2 = -\frac{s}{2}(\alpha + \beta \cos\theta). \quad (1.78)$$

X and Y are combinations of coupling factors:

$$X = \frac{s}{2} \left(\frac{g_-^{f_1}}{u} + \frac{g_-^{f_2}}{t} \right), \quad Y = g_-^{f_1} \frac{m_Z^2 s}{2u(s - m_W^2)}, \quad (1.79)$$

where m_W (m_Z) is the W (Z) boson mass and $g_-^f = (T_3^f - Q_f \sin^2 \theta_W) / (\sin \theta_W \cos \theta_W)$ is the coupling of the Z boson to left-handed fermions. Here $T_3^f = \pm \frac{1}{2}$ represents the third component of the weak isospin and Q_f is the electric charge of the fermion f .

1.3.2 Radiation Amplitude Zero Effect

From the five equations shown above, it is important to notice that $\mathcal{M}(\pm, \mp)$ receives contributions only from $J \geq 2$ partial waves, i.e., only from the u - and t - channel fermion-exchange diagrams. The $\mathcal{M}(\pm, \mp)$ amplitudes do not depend on Y and vanish for a particular angle θ_0 with

$$\frac{g_-^{f_1}}{u} + \frac{g_-^{f_2}}{t} = 0 \quad \text{or} \quad \cos\theta_0 = \frac{\alpha}{\beta} \left(\frac{g_-^{f_1} + g_-^{f_2}}{g_-^{f_1} - g_-^{f_2}} \right).$$

The existence of the zero in $\mathcal{M}(\pm, \mp)$ at $\cos\theta_0$ is a direct consequence of the contributing Feynman diagrams and the left-handed coupling of the W boson to fermions [25]. Unlike the $W^\pm \gamma$ case with its massless photon kinematics, the zero has an energy dependence through α and β which is, however, rather weak for energies sufficiently above the WZ mass threshold. More explicitly, for $s \gg M_V^2$, the zero is located at $\cos\theta_0 \simeq \frac{1}{3} \tan^2 \theta_W \simeq 0.1$ for $d\bar{u} \rightarrow W^- Z$. For the charge conjugate process, the sign of $\cos\theta_0$ changes.

Maximal helicity violating (MHV) amplitudes, $\mathcal{M}(\pm, \pm)$, are suppressed in the SM massless limit [26, 27]. The suppression of SM amplitudes with only one longitudinal boson ($\mathcal{M}(\pm, 0)$ and $\mathcal{M}(0, \pm)$) can be understood as a consequence of the symmetry under which all the SM doublets

(Higgs and fermions) change sign, namely $H \rightarrow -H$, $Q_L \rightarrow -Q_L$ and $L_L \rightarrow -L_L$ [24]. Since the symmetry is only broken by the Higgs Vacuum Expectation Value v , it produces a selection rule that controls whether even or odd powers of v (actually, of m_W) are present in the amplitudes [28]. Transversely-polarized vector bosons are even under the symmetry, while longitudinal polarizations are odd because they are related to the Goldstone components of the Higgs doublet through the Equivalence Theorem [29, 30]. The amplitudes for producing one transverse and one longitudinal state are odd, hence they scale like m_W/E in the SM.

At high energies, $s \gg m_V^2$, strong cancellations occur between the various terms in the square brackets in the above equations and only the $\mathcal{M}(\pm, \mp)$ and $\mathcal{M}(0, 0)$ amplitudes remain nonzero:

$$\mathcal{M}(\pm, \mp) \longrightarrow \frac{F}{\sin \theta} (\lambda_W - \cos \theta) \left[(g_-^{f_1} - g_-^{f_2}) \cos \theta - (g_-^{f_1} + g_-^{f_2}) \right], \quad (1.80)$$

$$\mathcal{M}(0, 0) \longrightarrow \frac{F}{2} \sin \theta \frac{m_Z}{m_W} (g_-^{f_2} - g_-^{f_1}). \quad (1.81)$$

The combined effect of the zero in $\mathcal{M}(\pm, \mp)$ and the gauge cancellations at high energies in the remaining helicity amplitudes results in an approximate zero for the $f_1 \bar{f}_2 \rightarrow WZ$ differential cross section at $\cos \theta \simeq \cos \theta_0$. Because of the $1/\sin \theta$ behavior of $\mathcal{M}(\pm, \mp)$, the $\mathcal{M}(\pm, \mp)$ amplitudes dominate outside of the region of zero.

The RAZ effect reduces the TT contribution in the central region, i.e., for $\cos \theta$ approaching 0 at the tree level. At LO and in the high-energy limit, the squared amplitudes for TT and 00 for WZ production are:

$$|\mathcal{M}_{WZ}^{TT}|^2 = \frac{g^4}{32} \left(\frac{s}{t} - \frac{s}{u} \right)^2 \sin^2 \theta_V (1 + \cos^2 \theta), \quad (1.82)$$

$$|\mathcal{M}_{WZ}^{00}|^2 = \frac{g^4}{16} \sin^2 \theta. \quad (1.83)$$

While the corresponding squared amplitudes for $W^\pm W^\mp$ production are:

$$|\mathcal{M}_{WW}^{TT}|^2 = \frac{g^4}{32} \left(\frac{s}{t} + \frac{s}{u} \right)^2 \sin^2 \theta (1 + \cos^2 \theta), \quad (1.84)$$

$$|\mathcal{M}_{WW}^{00}|^2 = \frac{g^4}{32} \sin^2 \theta. \quad (1.85)$$

Where t and u being equal, we have $\cos \theta = 0$ and $\theta = \pi/2$. In this case, the squared amplitude of the TT component of WZ ($|\mathcal{M}_{WZ}^{TT}|^2$) goes to zero. But as seen from equation 1.84, WW production does not show this behavior. On the other hand, it is clear from equation 1.83 that for $\theta \simeq \pi/2$, the longitudinal-longitudinal contribution is maximal. Because WW does not show RAZ, the 00

fraction goes to about 10% for $p_T^V > 1$ TeV. However, WZ has around 30–40% for the 00 fraction. This can be seen from figure 1.4.

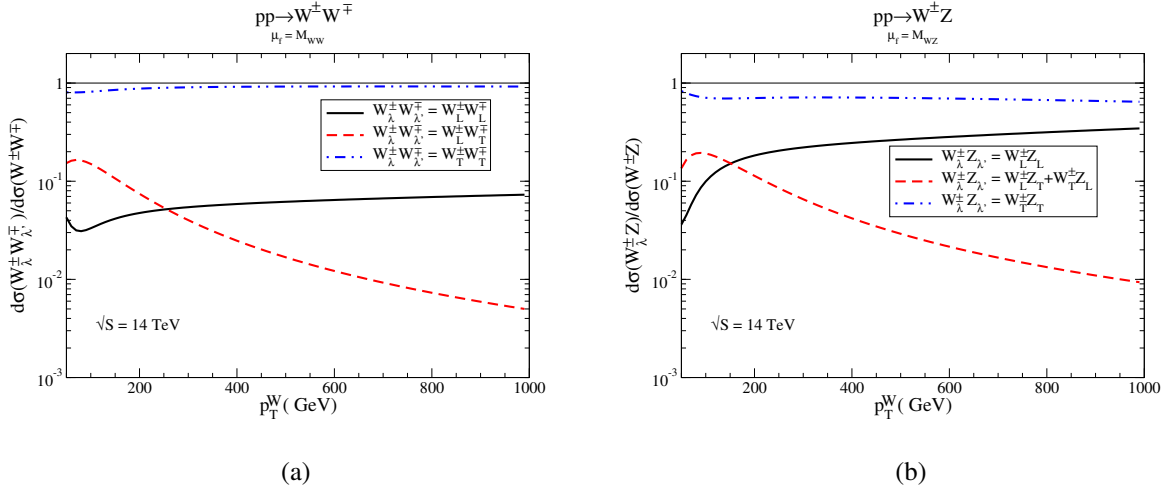


Figure 1.4: Ratio of transverse momentum distributions of polarized gauge boson to the total distribution summed over polarizations. These are shown using the W transverse momentum, p_T^W , for $W^\pm W^\mp$ ((a)) and $W^\pm Z$ ((b)). Plots were taken from Ref. [4].

The RAZ effect is only seen at LO and not in the case where WZ is produced together with jets. An analog explanation in terms of a dipole field is as follows. The interacting initial quarks are like a dipole and the W and Z bosons are like the electric field which has a spatial pattern (which produces the RAZ effect). However, the presence of a gluon field in the gauge field destroys this spatial pattern and hence the RAZ effect is not seen in events with jets.

Figure 1.5 shows the $\cos \theta_W$ distribution (here and in all the plots later θ_W is defined as the scattering angle of the W boson defined in the WZ rest frame with respect to the z -axis) in case of $WZ + 0$ jet (figure 1.5a) and $WZ + 1$ jet (figure 1.5b) events. In the case of $WZ + 0$ jet, there is a significant dip in the $\cos \theta_W$ distribution for the TT component and the 00 component is the most dominant one in the central region. But that is not the case for the $WZ + 1$ jet scenario.

To increase the 00 contribution, a cut on the transverse momentum of the WZ system (p_T^{WZ}) is applied such that events with $p_T^{WZ} < 70$ GeV are selected. This helps remove events with jets as the initial state radiation (ISR) jet production boosts the entire WZ system. This can be seen from figure 1.6 [24], where θ^* denotes the polar scattering angle in the collision rest-frame, oriented in the direction that goes from the incoming antiquark to the outgoing W boson.

The RAZ effect can be seen in $W\gamma$ and WZ production. RAZ has been observed using $W\gamma$ events at DØ and CMS experiments [31–33], as shown in figure 1.7. In the case of the DØ measurement,

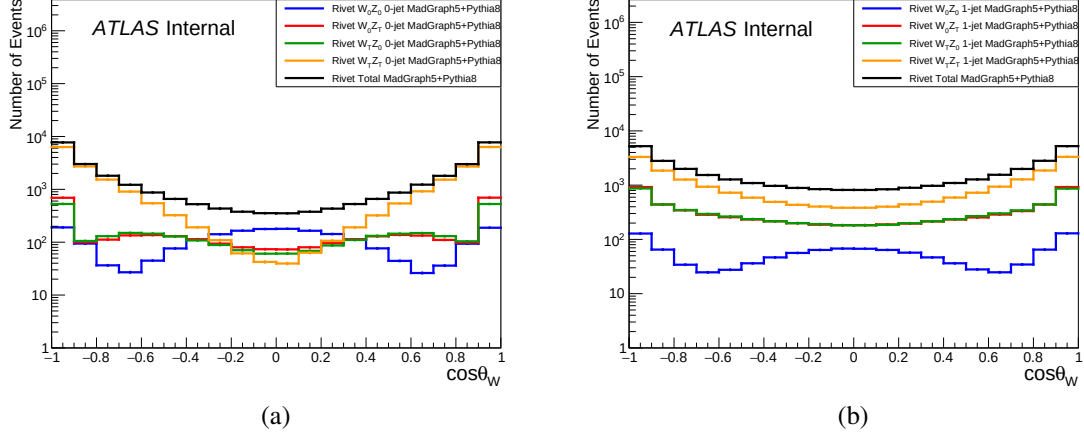


Figure 1.5: $\cos\theta_W$ distribution for all four diboson polarizations and their sum with 0 jet events (a) and 1 jet events (b). No selection cuts are applied.

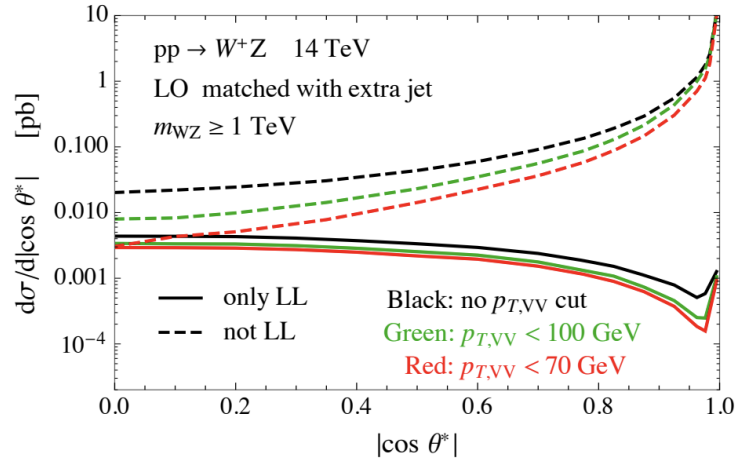


Figure 1.6: Tree-level differential cross-section matched with an extra jet with invariant mass $M_{WZ} \geq 1$ TeV.

the depth of the dip in the distribution of the charge-signed pseudo-rapidity difference between the W lepton and γ ($Q_\ell \times \Delta\eta(\ell, \gamma)$) was measured. In the case of the CMS measurement, it was just the pseudo-rapidity difference ($\Delta\eta(\ell, \gamma)$). As $W\gamma$ only has $0T$ and TT polarization components (γ being massless), it is easier to measure the dip using inclusive $W\gamma$ events.

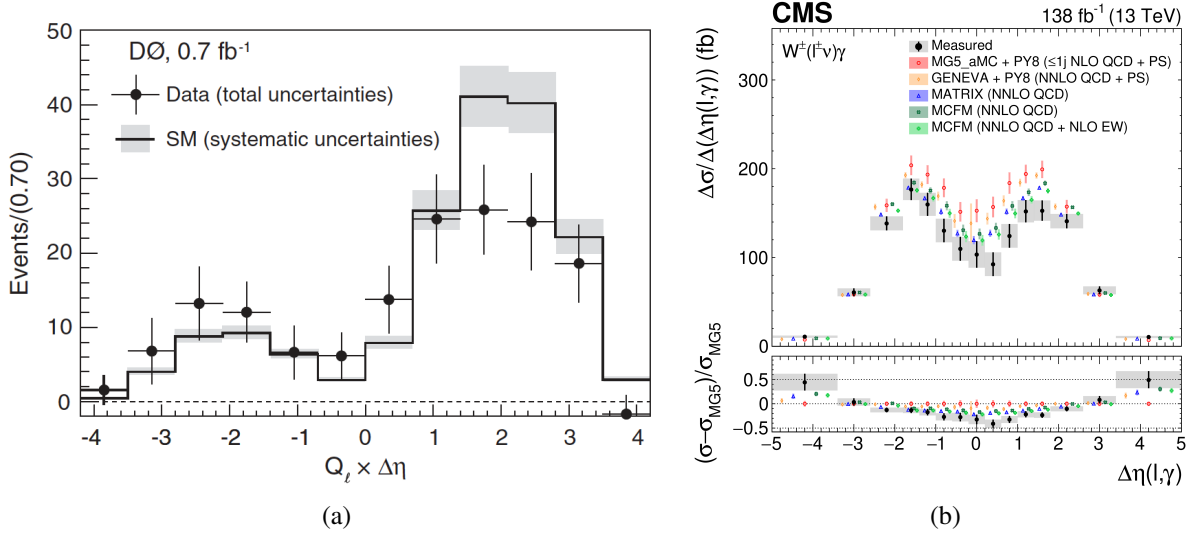


Figure 1.7: In the case of $D\bar{O}$ measurement, the depth of the dip in the distribution of the charge-signed pseudorapidity difference between the W lepton and γ is measured (a). In the case of CMS measurement, it was just the pseudorapidity difference (b).

In the case of WZ production, it is more challenging to observe the RAZ effect using inclusive events since 00 and $T0$ make the dip less significant. Also, the W boson reconstruction using the neutrino p_z calculation washes away the dip. To measure the RAZ effect in WZ events, we can look at the rapidity differences between W and Z bosons (ΔY_{WZ}) and also between the W lepton and the Z boson (ΔY_{3Z}). Figure 1.8 shows the ΔY_{3Z} and ΔY_{WZ} distributions for WZ events with different polarization states. It is important to note that in this plot each individual polarization state is not stacked together.

1.3.3 Sensitivity to New Physics

At high energies, different helicity configurations of diboson have different dependencies on the energy for SM and BSM contributions (see table 1.1). In effective field theory calculations, 00 is the only helicity configuration with quadratic energy growth. Measurement of the fraction of 00 can be used to constrain new physics. Figure 1.9 shows fractions f_{00} , $f_{0T/T0}$ and f_{TT} for WZ production with a center-of-mass energy of 14 TeV as a function of p_T^V for SM and BSM model with cut off $\Lambda = 1$ TeV. The fraction f_{00} significantly increases at high p_T^V for new physics models.

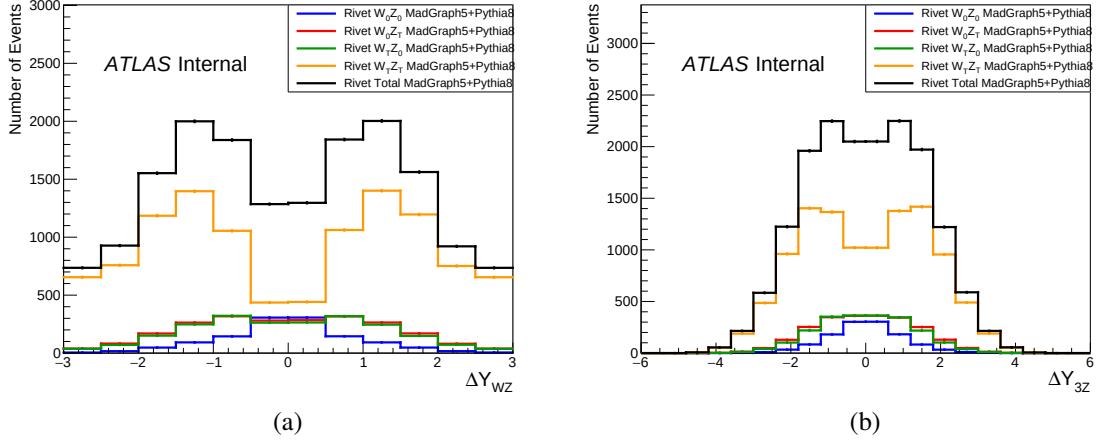


Figure 1.8: Rapidity difference between the W boson and the Z boson (ΔY_{WZ} , (a)) and rapidity difference between the lepton from the W decays and the Z boson (ΔY_{3Z} , (b)) for events with $p_T^{WZ} < 70$ GeV. It is important to point out that contributions for these four individual polarization states are not stacked together. A dip with ΔY_{WZ} (or ΔY_{3Z}) around 0 is observed for the TT component for both distributions. The presence of a dip with a rapidity difference close to 0 indicates the RAZ effect for the TT component.

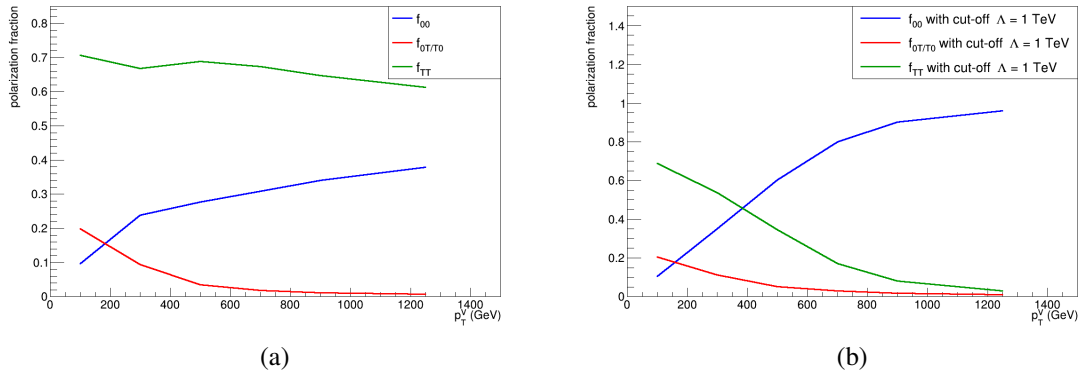


Figure 1.9: Diboson polarisation fractions f_{00} , $f_{0T/T0}$, and f_{TT} for the WZ process at the 14 TeV LHC as a function of the vector boson p_T^V in the SM (a) and for a new physics model with a cut-off value of $\Lambda = 1$ TeV (b). Numbers used in both plots are taken from Ref. [34].

	SM	BSM
$q\bar{q} \rightarrow V_0 V_0$	~ 1	$\sim E^2/M^2$
$q\bar{q} \rightarrow V_{\pm} V_0$	$\sim m_W/E$	$\sim m_W E/M^2$
$q\bar{q} \rightarrow V_{\pm} V_{\pm}$	$\sim m_W^2/E^2$	$\sim E^2/M^2$
$q\bar{q} \rightarrow V_{\pm} V_{\mp}$	~ 1	~ 1

Table 1.1: High-energy scaling of diboson amplitudes for transverse ($\pm$) and longitudinal (0) polarizations in the SM and in BSM. The variable M is the scale for BSM, and m_W is the mass of the W boson. This table is taken from Ref. [24].

1.3.4 WZ and Vh at High Energies

WZ production at high energies could give us a hint of the physics before the electroweak symmetry is broken [4]. The Goldstone-boson equivalence theorem states that at high energies an amplitude involving external longitudinal vector bosons is equivalent to the same amplitude with the external longitudinal vector bosons replaced by the corresponding Goldstone bosons [29, 30]. One important prediction of the Goldstone-boson equivalence theorem is that

$$\sigma(W_0 Z_0)/\sigma(W_0 h) \approx 1, \quad (1.86)$$

$$\sigma(W_0 Z_0)/\sigma(Z_0 h) \approx 2. \quad (1.87)$$

$\sigma(W_0 Z_0)/\sigma(W_0 h)$ is a factor of two lower compared to $\sigma(W_0 Z_0)/\sigma(Z_0 h)$ since the W boson is either positively charged (W^+) or negatively-charged (W^-), while the Z boson is charge-neutral. Table 1.2 shows the cross sections of $W_0 Z_0$, $W_0 h$, and $Z_0 h$ as a function of the boson p_T . Table 1.3 shows the two cross-section ratios: $\sigma(W_0 Z_0)/\sigma(W_0 h)$ and $\sigma(W_0 Z_0)/\sigma(Z_0 h)$. Figure 1.10 shows the two ratios as a function of the boson p_T . A measurement of the two ratios as a function of the boson p_T using a large data sample will be interesting.

p_T^V [GeV]	[0, 200]	[200, 400]	[400, 600]	[600, 800]	[800, 1000]	[1000, 1500]
$\sigma(W_0 Z_0)$ (fb)	784	58.5	4.84	0.799	0.188	0.0749
$\sigma(W_0 h)$ (fb)	387	46.5	4.30	0.726	0.169	0.0671
$\sigma(Z_0 h)$ (fb)	198	24.5	2.24	0.367	0.0835	0.0327

Table 1.2: Helicity cross sections for the WZ process at the 14 TeV LHC in different vector boson p_T^V bins. LO calculations are used. Numbers are taken from Ref. [34].

p_T^V [GeV]	[0, 200]	[200, 400]	[400, 600]	[600, 800]	[800, 1000]	[1000, 1500]
$\sigma(W_0Z_0)/\sigma(W_0h)$	2.03	1.26	1.13	1.10	1.11	1.11
$\sigma(W_0Z_0)/\sigma(Z_0h)$	3.96	2.39	2.16	2.18	2.25	2.29

Table 1.3: Cross section ratios of $\sigma(W_0Z_0)/\sigma(W_0h)$ and $\sigma(W_0Z_0)/\sigma(Z_0h)$ at the 14 TeV LHC in different vector boson p_T^V bins. LO calculations are used.

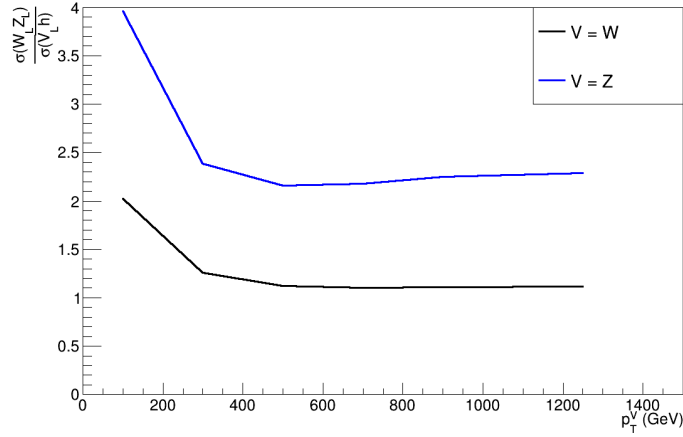


Figure 1.10: Cross-section ratios $\sigma(W_0Z_0)/\sigma(W_0h)$ and $\sigma(W_0Z_0)/\sigma(Z_0h)$ for the WZ process at the 14 TeV LHC as a function of the vector boson p_T^V . Numbers are taken from Ref. [34].

CHAPTER 2

The Large Hadron Collider and the ATLAS Detector

2.1 The Large Hadron Collider

The LHC is the largest particle accelerator in the world [35, 36]. It has a circumference of 27 kilometers and is located around 100 meters underground on the France-Swiss border near Geneva. It is the latest addition to the CERN accelerator complex. It is operated by the European Organization for Nuclear Research European Organization for Nuclear Research (CERN) (in French it is called “Conseil Européen pour la Recherche Nucléaire”). Two beams of hadrons (protons or lead ions) are accelerated to a maximum speed of about 99.9999991% of the speed of light [37]. Both bunches are accelerated in opposite directions and collide at four interaction points, each corresponding to a detector. These four detector collaborations are A Toroidal LHC Apparatus (ATLAS), Compact Muon Solenoid (CMS), A Large Ion Collider Experiment (ALICE), and Large Hadron Collider Beauty (LHCb). ATLAS and CMS are two general-purpose detectors built to perform precision measurements and search for new physics beyond the SM. ALICE is designed to study heavy ion collisions and the quark-gluon plasma created just after the collisions. LHCb mainly studies *b*-physics.

The beams travel in separate beam pipes in ultrahigh vacuum (around 10^{-6} mbar). The superconducting magnets are used to guide two beams inside a circular accelerator ring. The magnets used include 1,232 dipole magnets (which bend the beam), 392 quadrupole magnets (which focus the beam), and magnets used for squeezing particles together just before the collision. Radiofrequency cavities increase the energy of the particles by around 14 times the injected energy at the LHC.

The CERN accelerator complex (shown in figure 2.1) is a large complex consisting of a series of accelerators used to increase the energy of the proton beams successively [38]. The Linear accelerator 4 (Linac4) is the source of proton beams. It accelerates negative hydrogen ions to 160 MeV which then enter into the Proton Synchrotron Booster (PSB). During this injection, electrons are stripped off of the hydrogen ions leaving only protons behind, and are accelerated up to 2 GeV

in this booster. Then the beam is injected into the Proton Synchrotron (PS) pushing it to 26 GeV and then into the Super Proton Synchrotron (SPS) accelerating it up to 450 GeV. Finally, it enters the two LHC beam pipes. One beam circulates in the clockwise direction and the other in the anti-clockwise direction. Within 20 to 25 minutes, the beam reaches the desired energy of 6.5 TeV. The lead ions are also accelerated starting from the Linear accelerator 3 (Linac3) and then are collected and accelerated in the Low Energy Ion Ring (LEIR). After which they follow the same route as the protons. The protons or the ions are made to collide at four interaction points.

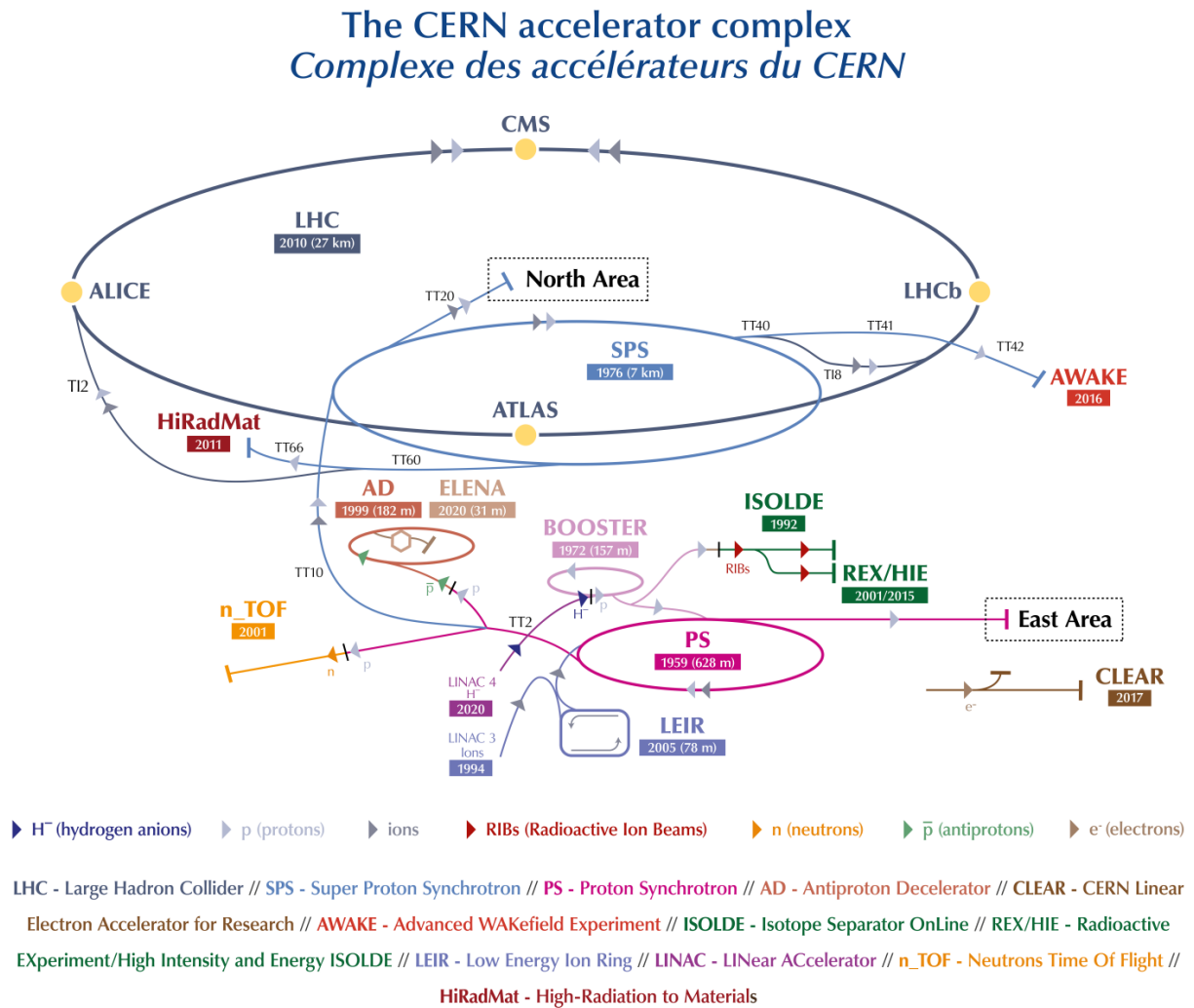


Figure 2.1: The CERN accelerator complex [39].

2.2 The ATLAS Detector

The ATLAS detector is one of the two general-purpose detectors. It is a cylindrical-shaped detector with a diameter of 25 m and a length of 46 m. It weighs approximately 7000 tonnes. The sub-detectors are arranged around the interaction beamline in a cylindrical fashion as layers (see figure 2.2). Every layer is specialized to detect and record the energy and momentum of different kinds of particles.

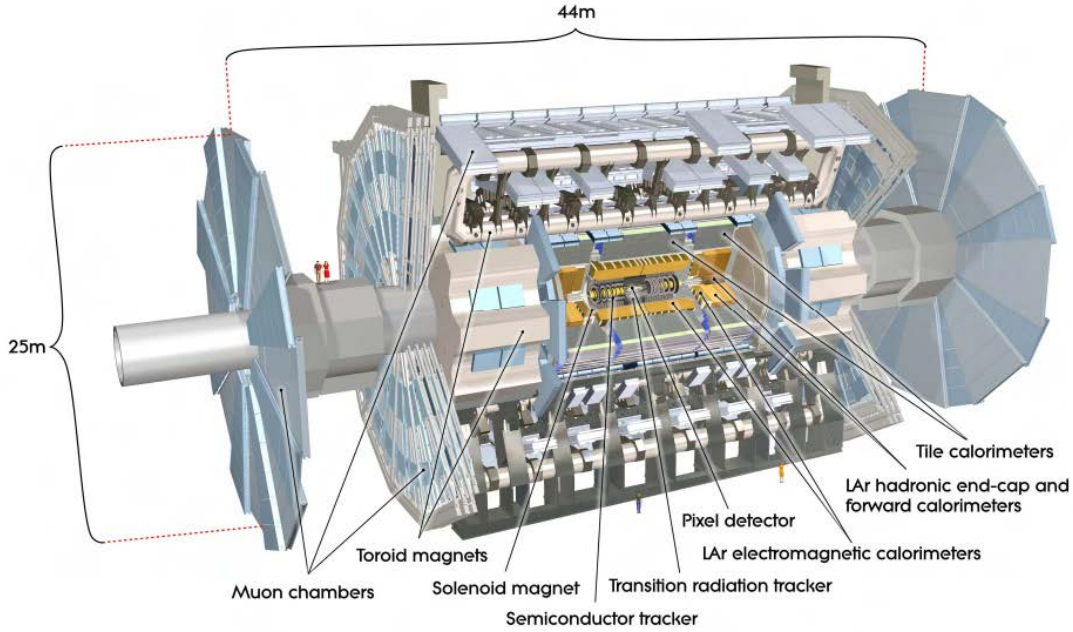


Figure 2.2: A view of the ATLAS detector.

Figure 2.3 shows the right-handed coordinate system used. The origin of the coordinate system is the interaction point. The positive x -axis points towards the center of the LHC ring. The y -axis points vertically upwards, and the z -axis is in one of the beam directions. The radial coordinate, r , is defined in the $x-y$ plane, and the azimuthal angle ϕ is also measured in the $x-y$ plane with respect to the positive x -axis. The pseudorapidity η for particles coming from the collision point is defined as $\eta = -\log[\tan(\frac{\theta}{2})]$, where θ is the polar angle of the particle with respect to the positive z -axis. The rapidity definition is $y = \frac{1}{2} \ln(\frac{E+p_z}{E-p_z})$. These two definitions are independent of the longitudinal boost of the reference frame for massless particles, which is important for hadron collider physics. Since the collisions are happening in the z direction, the transverse plane is important due to the total momentum in both the initial and final state is zero in this plane. The transverse momentum is defined as the transverse component of the particle momentum in the $x-y$ plane and the transverse energy is defined as $E \sin \theta$, where E is the energy of the particle. Another important definition is

$\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, the distance between two particles in the $\eta - \phi$ plane.

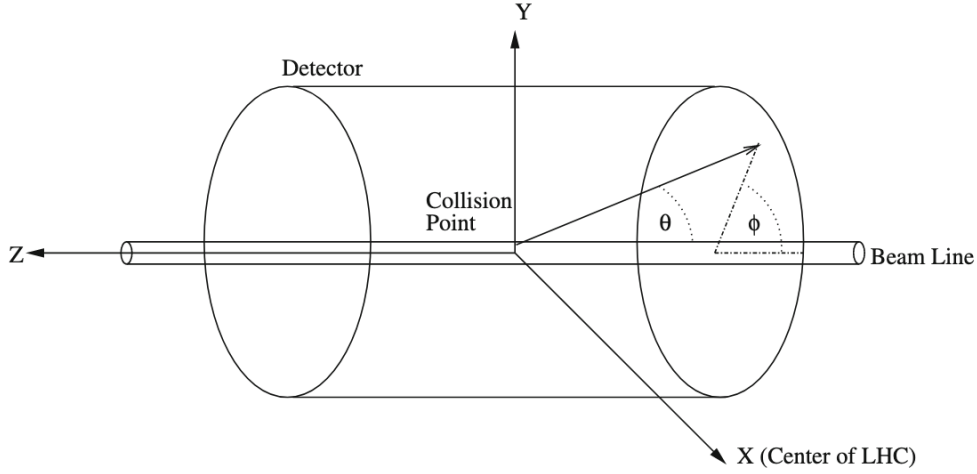


Figure 2.3: The ATLAS co-ordinate system [40].

There are three main sub-detectors for particle detection: the Inner Detector (ID), the Calorimeter system, and the Muon Spectrometer (MS). The ID is mainly for charged particle tracking and for collision vertex reconstruction. The entire ID is immersed in a magnetic field of 2 T. The magnetic field is approximately in the z direction. Charged particles are bent in the ϕ direction and the track curvature is measured to determine the momentum. The sampling calorimeters are used to sample the energy of charged and neutral particles. The electromagnetic calorimeter is mainly used to determine the energies of electrons and photons. Hadronic particles with color form jets and the jet showers deposit their energies in the hadronic calorimeter. The electromagnetic showers are narrower than the jet showers in hadronic calorimeters. Muons penetrate through all the sub-detectors including the calorimeters and leave tracks in the muon spectrometer. The magnetic field's bending power in the MS ranges from 1 to 7.5 T · m depending on the pseudorapidity region [41]. The muon tracks are reconstructed using different muon stations in the MS and are matched to the ID. Weakly-interacting particles like neutrinos escape from the detector and do not leave any signature. They can only be reconstructed using E_T^{miss} , the missing transverse energy. Figure 2.4 describes the detection principles of the ATLAS detector to different types of particles.

2.2.1 ATLAS Magnet System

The ATLAS magnet system is crucial for charged particles' charge and momentum measurements [41, 43]. It is made up of four systems: a barrel toroid magnet, two End-Cap toroid magnets, and a central solenoid magnet (see figure 2.5).

The central solenoid is mainly used for bending charged particles inside the ID. It provides an

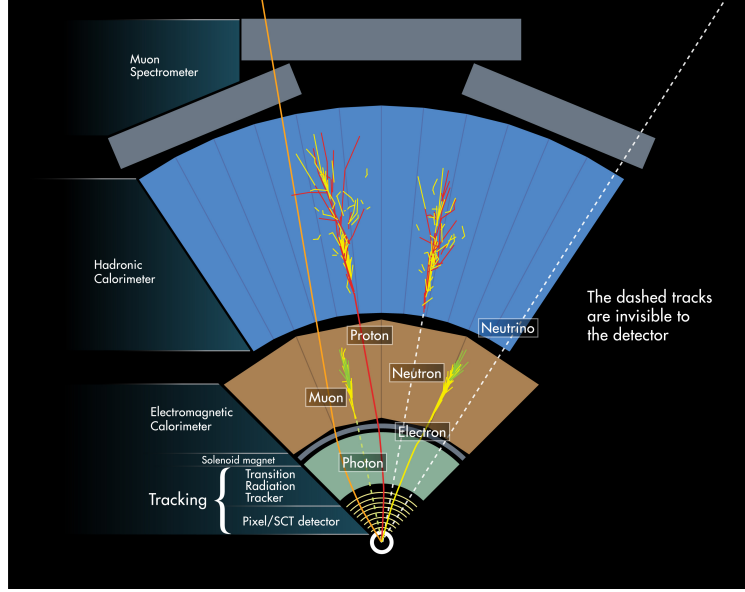


Figure 2.4: Detection principles of the ATLAS detector for different types of particles [42].

axial magnetic field of 2 T and weighs 5 tonnes. Its thickness in front of the EM calorimeter has been minimized and optimized to reduce the impact on the energy measurement. It has 9 km of superconducting wire, operates with a nominal current of 7.73 kA, and stores an energy of ~ 38 MJ.

The barrel toroid and the End-Cap toroid are used to bend the muons in the muon spectrometer. The barrel toroid is made up of eight separate coils and has a stored energy of 1.08 GJ. Each of the End-Cap toroid magnets provides a magnetic field of around 4 T and weighs around 240 tonnes. Each stores an energy of 0.25 GJ. Both magnets work with an operating nominal current of 20.5 kA and have to be cooled down to a temperature of 4.7 K.

2.2.2 The Inner Detector

The inner detector consists of a Pixel detector, a Semi-Conductor Tracker (SCT), and a Transition Radiation Tracker (TRT) [45–47] (see figure 2.6). The inner detector needs to provide high precision and fine granularity for reconstructing tracks and impact parameters very close to the interaction points to deal with high-density particle hits. In the SCT, pixel and silicon strips are used. At least four strip layers and three-pixel layers are crossed by each track. The TRT provides a large number of tracking points (36 points per track). The combination of all these different technologies gives a very robust pattern recognition and high precision in the $\phi - z$ phase space.

The Pixel Detector and the Insertable B-Layer: The pixel detector [47, 50] covers the radial distance from ~ 33 mm to 150 mm. It is made up of a total of 2,024 silicon pixel modules with three

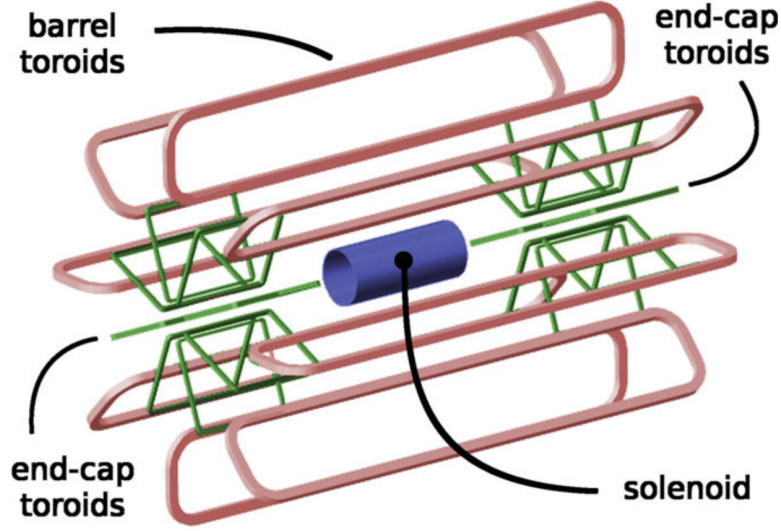


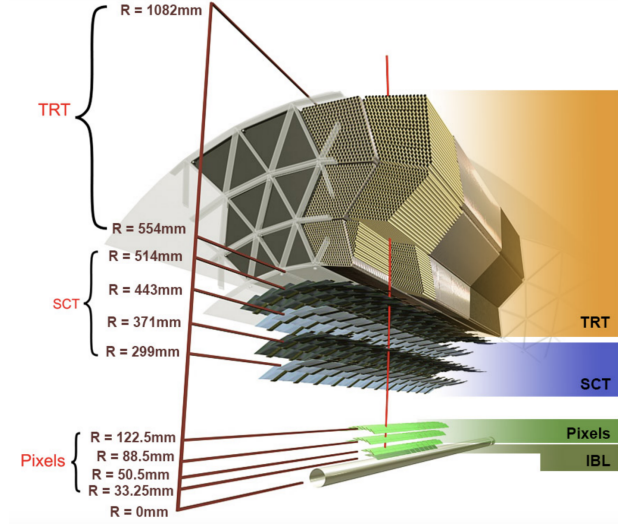
Figure 2.5: The geometry of the ATLAS magnet system [44].

layers in the barrel and one Insertable B-Layer (IBL) with 1,736 modules and two End-Caps of three disks each (with 288 modules). The IBL was installed later in 2014 which brought the closest radial distance to ~ 33 mm. The inner barrel layers are important for reconstructing the primary vertices and improving b -tagging [51]. Each pixel is of the size $50\ \mu\text{m} \times 400\ \mu\text{m}$ for the external three layers and $50\ \mu\text{m} \times 250\ \mu\text{m}$ for the IBL. The readout from one module is collected using 16 radiation-hard chips, with a combined total of ~ 92 million readout channels. Table 2.1 lists the main characteristics of the IBL and Pixel detectors.

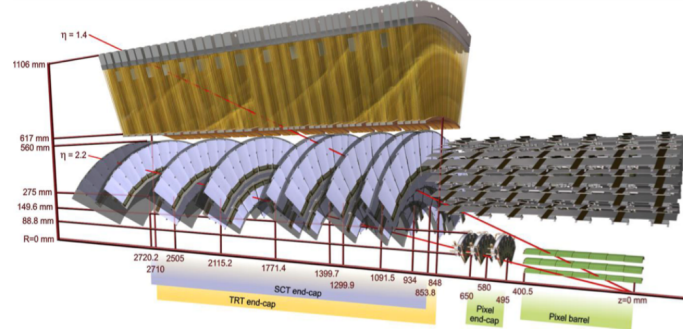
	IBL	Pixel
Element Size	$50\ \mu\text{m} \times 250\ \mu\text{m}$	$50\ \mu\text{m} \times 400\ \mu\text{m}$
Intrinsic Resolution in $r - \phi$ (μm)	10	10
Intrinsic Resolution in z (μm)	60	115
Barrel Layer Radii (mm)	33.25	50.5, 88.5, 122.5
Disk Layer z (mm)		495, 580, 650

Table 2.1: Main Characteristics of the IBL and Pixel detectors [48].

The Semi-Conductor Tracker: The SCT [52] consists of four concentric cylindrical barrel layers and two End-Caps with nine disks each and surrounds the Pixel detector. It provides typically four space points for particles originating in the interaction point region. Most modules are made of 4 sensors two on each side daisy-chained together to give 768 strips with $80\ \mu\text{m}$ pitch. The two other sensors are glued back-to-back to the first one with a stereo angle of $40\ \text{mrad}$. There is a total of 4,088 two-sided modules. The strips in the barrel are approximately parallel to the solenoid



(a)



(b)

Figure 2.6: The ID 3D view in the barrel region (a) [48] and the ID 3D view in the End-Cap region (b) [49].

field and the beam axis. The direction of the strips in the End-Cap module is radial. The strips are read out by a total of ~ 6.3 million channels. Its layout is optimized such that each particle crosses at least four layers of silicon, which improves the track measurement precision. The main characteristics of SCT are shown in table 2.2.

	IBL
Element Size	$80 \mu\text{m}$
Intrinsic Resolution in $r - \phi$ (μm)	17
Barrel Layer Radii (mm)	299, 371, 443, 514
Disk Layer z (mm)	839 – 2,735

Table 2.2: Main Characteristics of the SCT detector [48].

Transition Radiation Tracker: The TRT is the outermost detector of the inner detector surrounding the SCT. It is made of 298,304 drift tubes (straws) with 4 mm diameter and readout by around 350,848 readout channels [47]. The barrel straws are arranged in three cylindrical layers and 32 phi sectors. Those in the End-Cap region are oriented radially. Charged particles with $p_T > 0.5$ GeV and $|\eta| < 2.0$ traverse around 30 straws. The TRT provides electron identification via transition radiation from polypropylene fibers (barrel) or foils (endcaps) interleaved between the straws. The much higher energy of the transition radiation photons (~ 6 keV compared with the few hundred eV deposited by an ionizing particle in the Xe, CO₂, O₂ gas) is detected by a second, high-threshold, discriminator in the radiation-hard front-end electronics [47]. Table 2.3 lists the characteristics of TRT.

	IBL
Element Size	4 mm
Intrinsic Resolution in $r - \phi$ (μm)	130
Barrel Layer Radii (mm)	554 – 1,082
Disk Layer z (mm)	848 – 2,710

Table 2.3: Main Characteristics of the TRT detector [48].

The readout systems of Pixel and SCT use optical transmission for the outgoing data and incoming timing trigger and control data. There are two optical links operating. Because of the high radiation environment close to the interaction point, the detectors get heated up. The Pixel and SCT detectors are cooled using a bi-phase evaporative system.

2.2.3 The Calorimetry

The different ATLAS calorimeters (see figure 2.7) are designed using different techniques catering to various requirements of the physics processes of interest and of the radiation environment up to $|\eta| < 4.9$. The EM calorimeter in the η range of the ID has fine granularity for precise measurements of electrons and photons, however, a coarse structure is used for the rest of the calorimeters used for the jet and E_T^{miss} reconstruction. The total thickness of the EM calorimeter (> 22 radiation lengths in barrel and > 24 radiation lengths, X₀s, in the end-cap) and the thickness of the active calorimeters are determined to make sure the showers are contained in calorimeters and do not leak into the muon spectrometer often.

The LAr Electromagnetic (EM) Calorimeter: The EM calorimeter is a lead-LAr detector with accordion-shaped kapton electrodes and lead absorber plates over its full coverage [53, 54]. The Liquid Argon sampling calorimeter technique with “accordion-shaped” electrodes is used for it. The

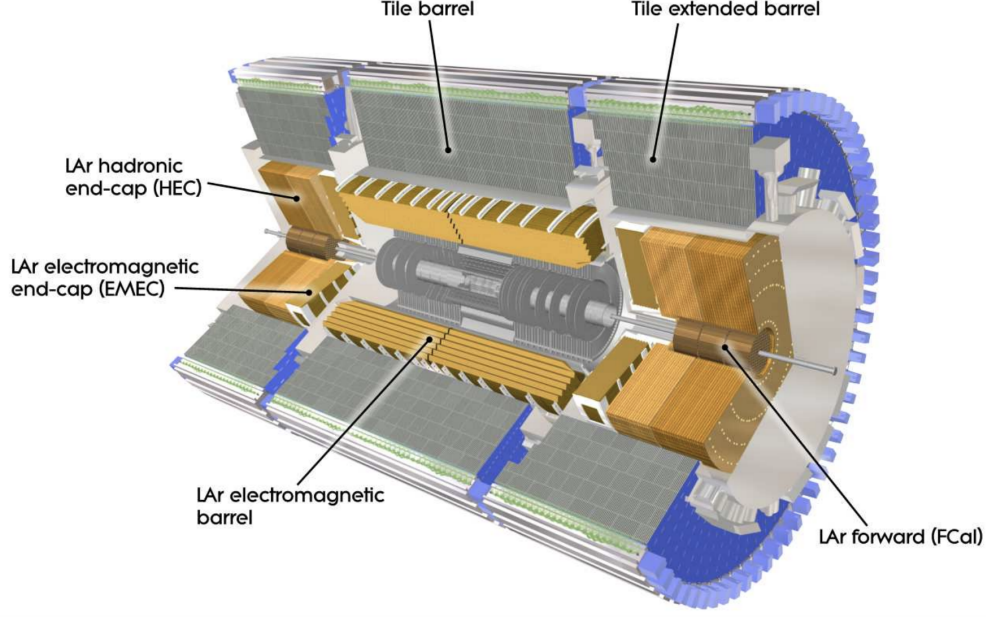


Figure 2.7: A cut-away view of the ATLAS calorimetry [41].

EM calorimeter encompasses $|\eta| < 1.475$ in the barrel part (EMB) and $1.375 < |\eta| < 3.25$ and two end-cap components (EMEC). The barrel and endcap calorimeters are immersed in three LAr-filled cryostats and are segmented into three layers for $|\eta| < 2.5$.

- The first layer covers $|\eta| < 1.4$ and $1.5 < |\eta| < 2.4$ (thickness of about $4.4 X_0$). It has fine segmentation in $\Delta\eta \times \Delta\phi$, 0.003×0.1 in the EMB. This provides event-by-event differences between single-photon showers and overlapping showers from the neutral hadrons.
- The second layer (L2) collects most of the energy from photon and electron showers. The thickness is about $17X_0$ and the granularity is of 0.025×0.025 in $\Delta\eta \times \Delta\phi$.
- The third layer has granularity of 0.05×0.025 in $\Delta\eta \times \Delta\phi$ and a depth of $2X_0$. This layer is used to correct the leakage of the showers after EM.
- A thin Presampler Layer (PS) is located in the interval $|\eta| < 1.8$ and is used to correct for the energy loss upstream of the calorimeter. PS has a granularity of 0.025×0.1 in $\Delta\eta \times \Delta\phi$.
- There is a lot of material between EMB and EMEC ($1.37 < |\eta| < 1.52$).

The Hadronic calorimeters: Partons generated from the collisions quickly fragment and form charged or neutral hadrons. These hadrons interact with the scintillating material of the calorimeters to form jets and collimated energy deposits. Charged hadrons leave tracks in the inner detector. All hadrons have an EM component which deposits energy in the electromagnetic calorimeter and a

hadronic component which is formed from the energy deposits in the hadronic calorimeter.

There are three hadronic calorimeters in the ATLAS experiment:

- **Tile Calorimeter:**

The Tile Calorimeter [41, 55] is situated directly outside the EM calorimeter. It is a sampling calorimeter with steel as an absorber and scintillating tiles as the active material. Its barrel covers the region $|\eta| < 1.0$ and the extended barrels cover the range $0.8 < |\eta| < 1.7$. It goes from 2.28 m to 4.25 m radially. It has three layers with ~ 1.5 , 4.1, and 1.8 interaction lengths (λ) deep in the barrel and 1.5, 2.6, and 3.3 λ in the extended barrel. The two sides of the scintillating tiles are read out by wavelength-shifting fibers into two separate photomultiplier tubes.

- **LAr hadronic End-Cap calorimeter:**

The Hadronic End-cap Calorimeter (HEC) [41, 53] has two independent wheels per End-Cap and is situated behind the End-Cap LAr EM calorimeters. For this calorimeter copper is used as the absorber and LAr gaps as scintillators. There is an overlapping region between the HEC and the forward calorimeter (extends up to $|\eta| = 3.2$) and between HEC and the tile calorimeter (extends up to $|\eta| = 1.5$). to reduce the drop in the material density. Every wheel is made up of identical wedge-shaped modules. There are a total of four layers for each End-Cap side. The outer radius of the copper plates is 2.03 m and the inner radius is 0.475 m (except in the overlapping region between FCal and HEC it is 0.372 m).

- **LAr Forward Calorimeter:**

The Forward Calorimeter (FCal) [41, 53] is integrated into the end-cap cryostats for the uniform calorimetric coverage and low radiation background levels in the muon spectrometer. The depth of FCal is approximately 10 λ s and consists of three modules: one made of copper (for electromagnetic measurements) and the other two made of tungsten (primarily for hadronic interactions). It is a metal matrix structure with electrodes consisting of concentric rods and tubes parallel to the beam axis. The LAr in the gap between the rod and the tube is the sensitive medium.

2.2.4 The Muon Spectrometer

The MS [41, 56, 57] are situated in the outermost parts of the detector as the muons are known to penetrate through most of the material in front. Different technology chambers are a part of MS for trigger and high-precision tracking purposes. The muon tracks are deflected by the large superconducting air-core toroid magnets. For $|\eta| < 1.4$, the muons bend due to the barrel toroid. In

the End-Cap region of $1.6 < |\eta| < 2.7$, the End-Cap magnets bend the muons, and for the overlap region of $1.4 < |\eta| < 1.6$, the barrel and End-Cap magnetic fields help bend the muons. The field is mostly perpendicular to the muon trajectories and the magnet system is optimized to minimize the degradation of resolution due to multiple scattering. The deflection of muons is measured in the $r - z$ plane.

Four different technologies are used:

Monitored Drift Tubes (MDT): The Monitored Drift Tubes (MDTs) are pressurized drift tubes made up of aluminum with a diameter of 2.970 mm. The operating gas mixture is made up of 93% Ar and 7% CO₂ pressurized at 3 bar. The ionization procedure inside the tube generates electrons which are collected by the central tungsten-rhenium wire with a diameter of 50 μm (the potential is maintained at 3,080V). One MDT chamber has two groups of tube layers (or multilayers) separated by a mechanical structure. The innermost layer consists of four tubes for enhancing the pattern recognition ability and the middle and out layers consist of three layers per multilayer (figure 2.8). MDT provides a robust structure with good operational reliability. Because the field inside is a radial field, the accuracy of the measurement only weakly depends on the angle of incidence. The expected resolution of 80 μm is observed [41].

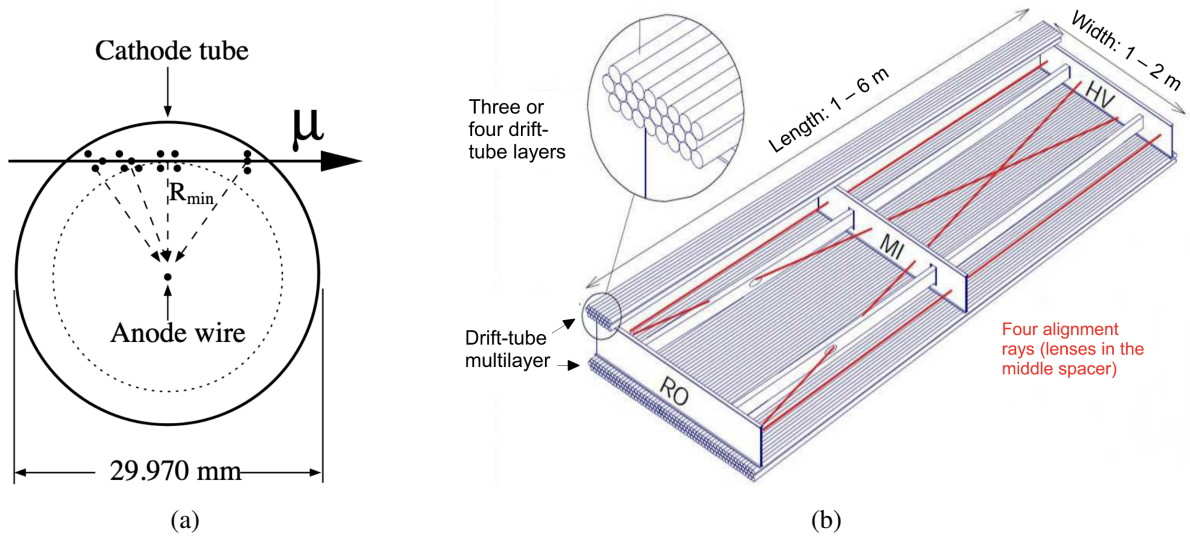


Figure 2.8: The MDT tube cross-section view with ionization clusters distributed along the track (a) [58] and the mechanical structure of an MDT chamber (b) [41]. Two groups of multilayers each with three layers are separated by a mechanical structure.

Cathode Strip Chambers: The Cathode Strip Chambers (CSCs) detector is located in the innermost station in the region $2 < |\eta| < 2.7$. MDT's safe operation threshold is about 150 Hz/cm² while CSC is considered safe up to 1,000 Hz/cm². Each CSC wheel consists of eight small and

eight large chambers. Each chamber has four CSC planes giving four independent measurements in η and ϕ .

The CSC is a multiwire proportional chamber with radially oriented wires with an operating voltage of 1,900 V. The gas mixture used is Ar/CO₂ (80%/20%). There are two cathode planes one perpendicular and another parallel to the wires. With readout pitches of 5.31 mm and 5.56 mm for large and small chambers respectively, in the bending direction, the CSC provides a resolution of around 60 μ m per CSC plane. In the non-bending direction, it is around 5 mm [41]. It has good timing resolution (about 7 ns) with good two-track resolution and low neutron sensitivity. See figure 2.9 for the structure of CSC.

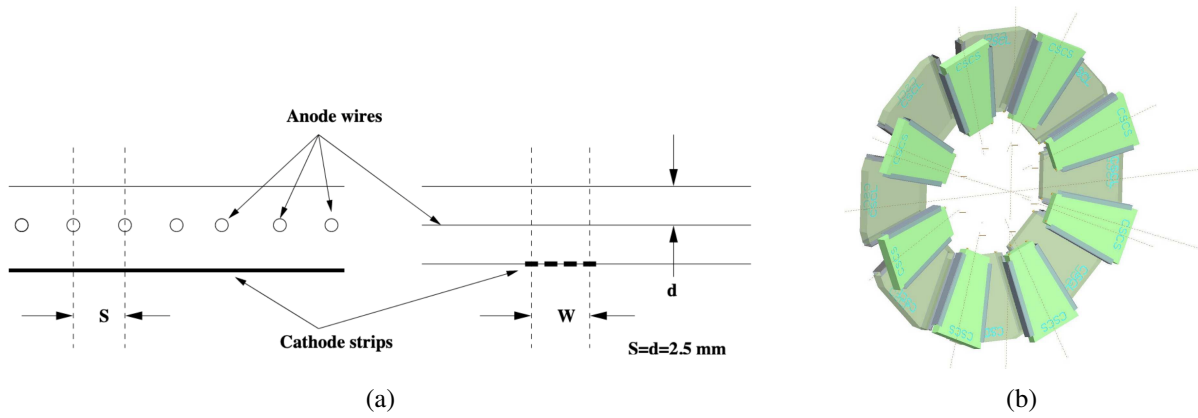


Figure 2.9: The cross-section of the CSC chamber in the wire length direction (a) [41] and the CSC End-Cap wheel structure with small and large chambers (b) [41].

Resistive Plate Chambers: The Resistive Plate Chambers (RPCs) are used as trigger chambers in the barrel region and have three concentric cylindrical layers (trigger stations) around the beam axis. Because of the large lever arm between the outer and inner layers, a high momentum trigger can be achieved in the range of 9-35 GeV (high p_T trigger) and two inner layers provide a low- p_T trigger in the range of 6-9 GeV. The redundancy in the track measurement allows the use of a coincidence scheme that rejects fake tracks from noise and improves trigger efficiency.

RPCs are gaseous parallel electrode-plate (no wire) detectors. An electric field of around 4.9 kV/mm is attained. The gas mixture used is C₂H₂F₄/Iso-C₄H₁₀/SF₆ (94.7/5/0.3) and has a gas gap of 2 mm. See figure 2.10 for the RPC detector and chamber structure.

Thin Gap Chambers: The Thin Gap Chambers (TGCs) provide a trigger in the End-Cap region. The determination of the azimuthal coordinate complements the MDT's measurement in the radial direction. The middle layer of MDts in the End-Cap (EM-wheel) has seven layers of TGCs and the inner layer has two layers. The inner layer (I layer), which is the innermost muon station, is

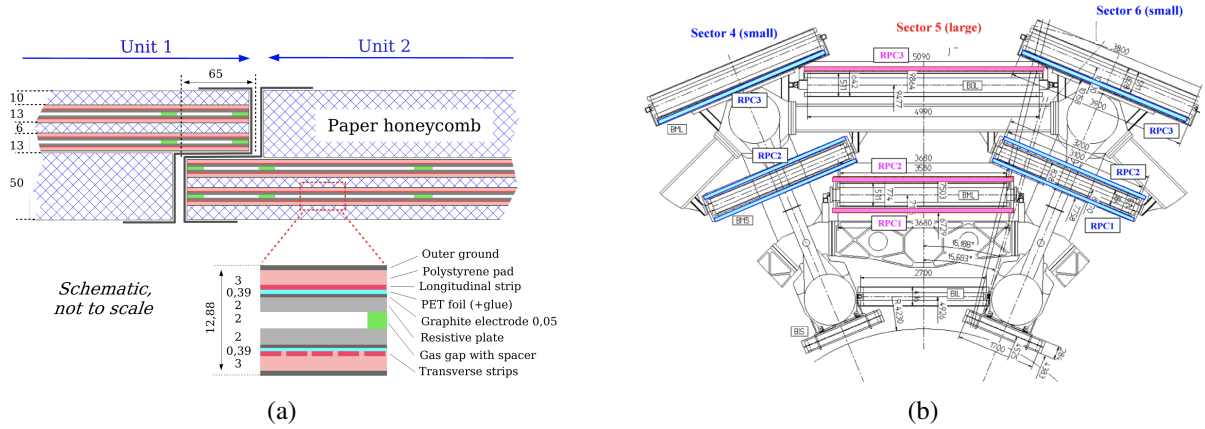


Figure 2.10: The cross-section of an RPC with two units joined to form a chamber (a) [41] and the RPC stations with respect to the MDT station positions (b) [41].

segmented radially into two non-overlapping regions: End-Cap (EI) and forward (FI), also known as the small wheel (all the TGCs, MDTs, and CSCs in the small wheel are replaced in 2023 by the New Small Wheel. See section 7). They are formed with two doublets i.e. four layers. The middle layers (big wheels) have one triplet and two doublets i.e. seven layers.

The TGCs are also multiwire proportional chambers with a wire-to-cathode distance (1.4 mm) smaller than the wire-to-wire distance (1.8 mm). A highly quenching gas mixture of $\text{CO}_2/\text{n-pentane}$ (55%/45%) is used. The high electric field and the small wire-to-wire distance lead to very good time resolution. The signals arrive with 99% probability inside a time window of 25 ns considering the variations in the propagation time on wires and strips. See figure 2.11 for the structure of TGCs.

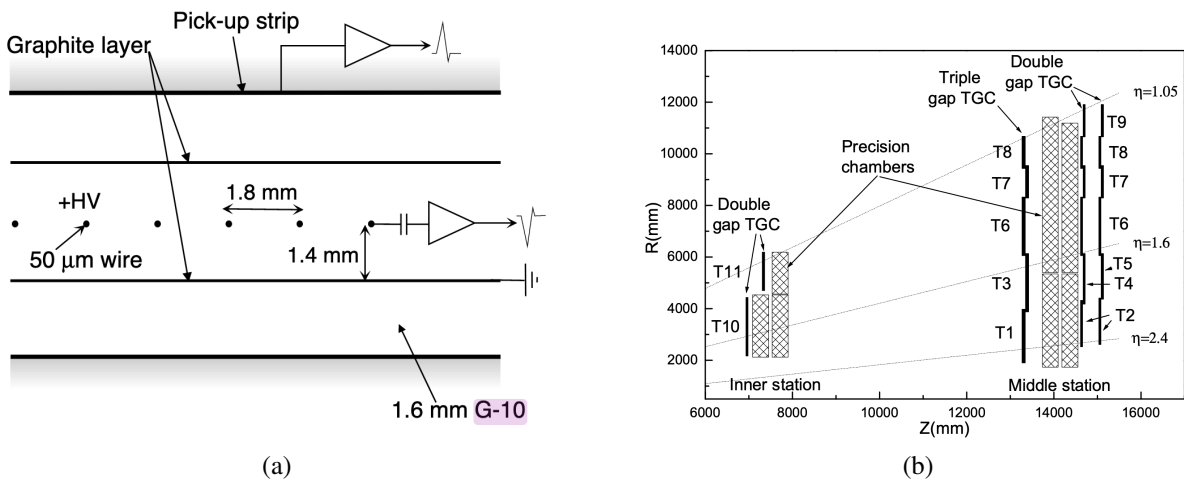


Figure 2.11: The cross-section view of the TGC detector (a) [41] and different TGC layers in the End-Cap (I layer and Big Wheels) (b) [41].

There are three stations in the barrel (Barrel Inner (BI), Barrel Middle (BM) and Barrel Outer (BO)) and the End-Cap (End-Cap Inner (EI), Electromagnetic (EM) or Big Wheel and End-Cap Outer (EO) or Outer Wheel). The MDT and CSC chambers are used for precision tracking and muon chambers cover the $|\eta| < 2.7$ region. The innermost MDT station is replaced with Cathode-Strip Chambers ($2.0 < |\eta| < 2.7$) because of the high background rate in that region. Every MDT chamber provides 6-8 η measurements along the muon track and the CSCs give four simultaneous measurements of η and ϕ . The RPCs and TGCs are used for triggering and cover $|\eta| < 2.4$. The three stations of RPCs cover $|\eta| < 1.05$ in the barrel and one triplet station and two doublets cover $1.0 < |\eta| < 2.4$ in the End-Cap. The RPCs and TGCs improve the determination of the track coordinate in the non-bending direction (the second coordinate). The single-hit resolution for MDTs and CSCs is $80\ \mu\text{m}$ and $60\ \mu\text{m}$, respectively (in the bending plane) and the spatial resolution of RPCs and TGCs is 5-10 mm in both the bending and non-bending direction.

2.2.5 Trigger and Data Acquisition System

A Trigger and Data Acquisition (TDAQ) system is essential for large-scale experiments like ATLAS for effective event storage. A bunch-crossing happens every 25 ns and every bunch-crossing corresponds to around 10 to 60 [59] mean interactions (see figure 2.12). Not all data collected can be stored: for Run-2, the storage required per event is around 1.7 MB [60]. This corresponds to the insane amount of data that cannot be realistically stored. For this purpose, trigger systems and algorithms are developed to store only the most meaningful data having physical importance. After the High-Level-Trigger, the event acceptance rate becomes around 1 kHz and reduces the data rate to $\sim 1.2\ \text{GB/s}$ [59].

The TDAQ system [61] is responsible for online event processing, selection, and storage. It is a two-level trigger system [62]. Figure 2.13 shows the diagrammatic representation of the TDAQ system of ATLAS.

The two stages of ATLAS trigger:

Level-1 (L1) Trigger: It is a hardware-based trigger system based on information from the calorimeter and muon detectors [63].

- The L1 calorimeter (L1Calo) trigger takes signals from the calorimeter detectors as input. The analog detector signals are digitized and calibrated by the pre-processor, and sent in parallel to the Cluster Processor (CP) and Jet/Energy-sum Processor (JEP). The CP system performs the identification of electron, photon, and τ -lepton candidates above a programmable threshold, and the JEP system identifies jet candidates and produces global sums of total and missing transverse energy. The small systematic shifts in energy, which have a large impact on the

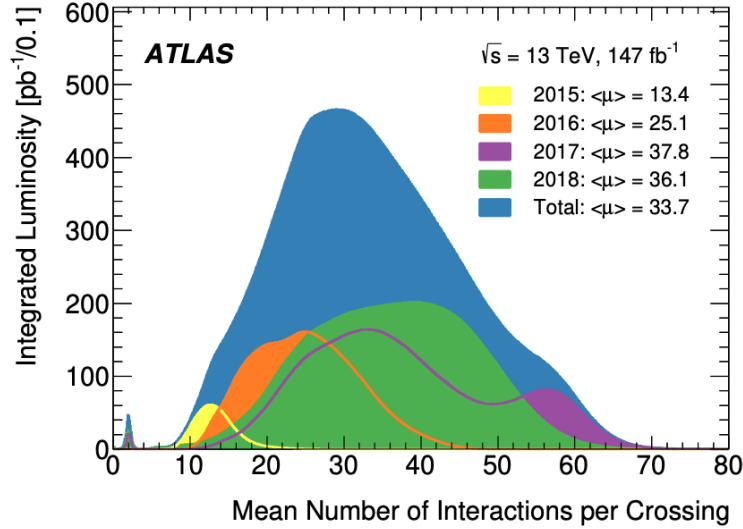


Figure 2.12: Mean number of interactions per crossing for the dataset used [59].

quantities like the missing transverse energy are mitigated in the L1Calo trigger by a dedicated pedestal correction algorithm implemented in the firmware.

- The L1 Muon (L1Muon) trigger uses hits from RPCs and TGCs (described in section 2.2.4). To reduce the rate in the endcap regions of particles not originating from the interaction point, the L1Muon trigger applies coincidence requirements between the outer and inner TGC stations, as well as between the TGCs and the tile calorimeter (for Run 2).

The trigger decision formation happens in the Central Trigger Processor (CTP), after receiving inputs from L1Calo and L1Muon triggers. It also receives signals from several other detector subsystems such as the Minimum Bias Trigger Scintillators (MBTS), the Luminosity Cherenkov Integrating Detector (LUCID), and the zero-degree calorimeter (ZDC). CTP also applies dead time between two L1 triggers so that there is no overlap of readout windows (simple dead time) and also to restrict the number of L1 accepts in a given number of bunch crossings (complex dead time).

The L1 trigger may use event-level quantities (e.g. the total energy in the calorimeter), the multiplicity of objects above thresholds (e.g. the transverse momentum of a muon, etc.), or consider topological requirements (such as invariant masses or angular distances) for event selection. The L1 trigger accepts events at a rate up to the maximum detector read-out rate of 100 kHz, down from the bunch crossing rate of about 40 MHz, within a latency of $2.5 \mu\text{s}$.

For each L1-accepted event, the Front-End (FE) detector electronics read out the event data for all the detectors. The data are sent first to ReadOut Drivers (RODs), where initial processing and formatting are performed and then sent to the ReadOut System (ROS) to buffer the data. The data

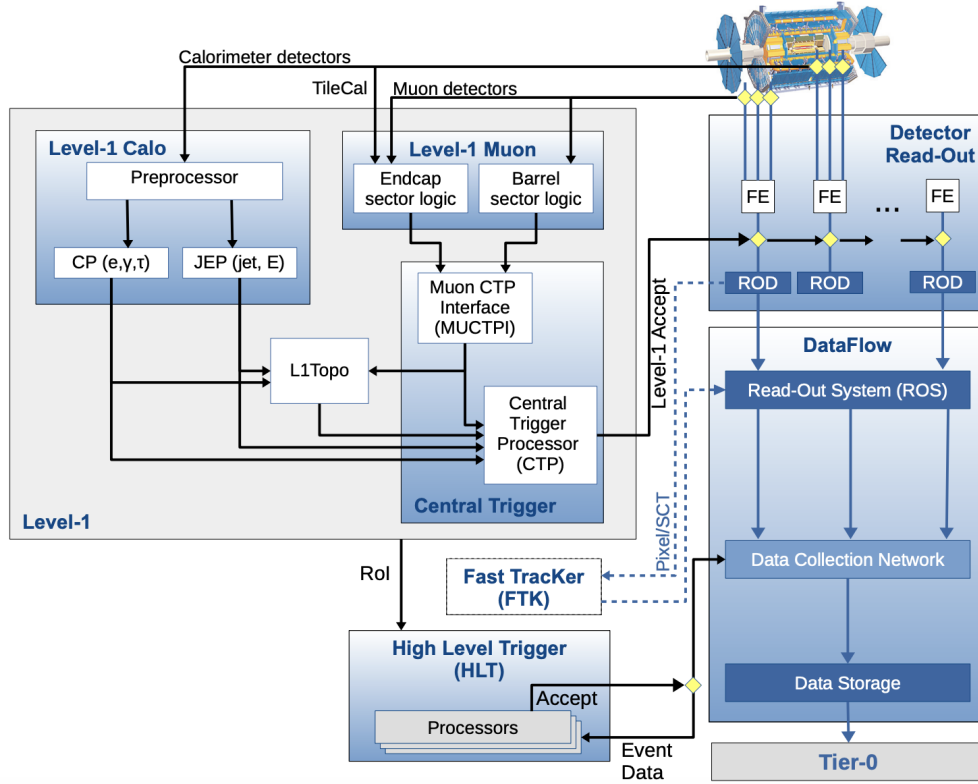


Figure 2.13: The ATLAS TDAQ system in Run 2 showing the components relevant for triggering as well as the detector read-out and data flow [61].

from the different sub-detectors are sent from the ROS to the High-Level-Trigger when requested by the HLT. The L1 triggers also identify Regions-of-Interest (RoIs) in η and ϕ within the detector to be investigated by the HLT.

High Level Trigger (HLT): This is the software-based second stage of the trigger [64]. It includes fast trigger algorithms followed by more precise and more CPU-intensive algorithms similar to the offline analysis algorithms. The algorithms execute one or more feature extraction algorithms requesting event-data fragments in an RoI or requesting information from the full detector (e.g. for the reconstruction of the missing transverse momentum). The physics output rate of the HLT during an ATLAS data-taking run is on average 1.2 kHz with an average physics throughput to permanent storage of 1.2 GB/s. Once an event is accepted by the HLT, the Sub-Farm Output (SFO) sends the data to permanent storage for offline reconstruction and exports the data to the Tier-0 facility at CERN's computing centre [65].

2.3 Object Reconstruction

One of the most important aspects of the data analysis at the ATLAS experiment is object reconstruction. Signatures (momentum and energy) in different parts of the detector are combined to reconstruct a physics object (electron, muon, jet, missing E_T , etc). The object reconstruction, identification and isolation efficiencies, the detector acceptance of these objects, etc decide how you should define the particles at the truth level. The most important objects used for this analysis are the leptons and the missing E_T . This section tries to explain in depth the reconstruction of the most important objects for this analysis. It also gives an overview of the trigger used to store the detector information for online object reconstruction. The actual recommendations used for the analysis might be different from the ones described in this section. The description here is detailed but shows a broader overview of how objects are reconstructed.

2.3.1 Electrons and Photons

2.3.1.1 Reconstruction

As electrons and photons both deposit energy in the electromagnetic calorimeter, it is important to do their reconstructions in such a way that it removes the ambiguity of the object being reconstructed as an electron or a photon. Figure 2.14 shows different layers of the detector and how an electron is reconstructed by combining the information from all these layers.

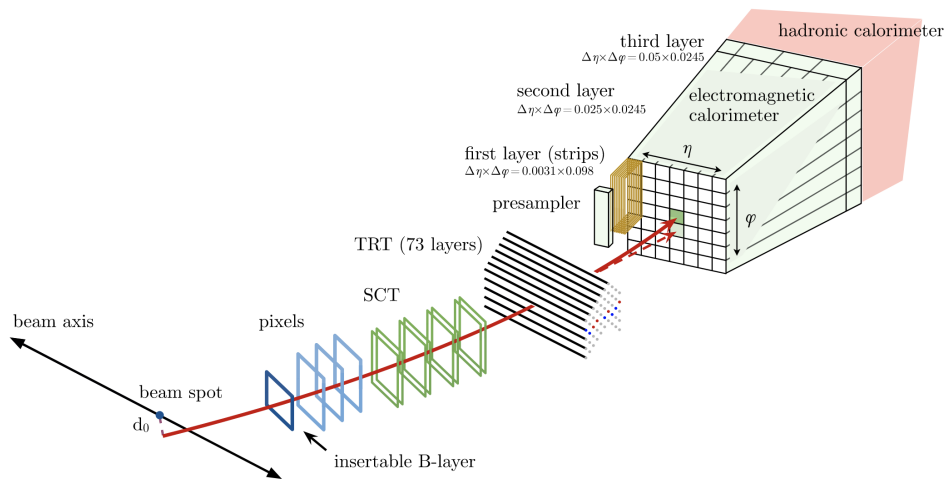


Figure 2.14: Schematic illustration of the electron path through different layers of the detector. The red trajectory shows a hypothetical electron traveling through the pixel, silicon strip, and TRT detectors of the inner detector and then entering into the electromagnetic calorimeter.

The electron loses its energy via bremsstrahlung and the radiated photon can be further converted

into an electron-positron pair. This results in a shower that deposits energy in a very collimated fashion in the detector and these energy deposits of the shower constitute one cluster corresponding to an electron or a photon. The second layer of the EM calorimeter contributes to most of the electron's energy deposition. The $\eta \times \phi$ space is divided into a grid of 200×256 elements (towers) of size $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$.

Initially, the sliding-window algorithm was used [66–68] to reconstruct fixed-size clusters of the calorimeter cells. However, now, improved dynamic and variable size clusters, called superclusters are used. The dynamic clusters change in size as needed to recover energy from bremsstrahlung photons or from electrons coming from photon conversions. An electron is defined as an object consisting of a cluster built from energy deposits in the calorimeter (supercluster) and a matched track (or tracks). A converted photon is a cluster matched to neither an electron track nor a conversion vertex.

A topo-cluster reconstruction algorithm [68, 69] is used for reconstructing clusters with energy deposits in topologically connected EM and hadronic calorimeter cells. The cluster seed and neighbors are determined based on the significance value $|s_{cell}^{EM}|$ defined as:

$$s_{cell}^{EM} \equiv \frac{E_{cell}^{EM}}{\sigma_{noise, cell}^{EM}}, \quad (2.1)$$

where E_{cell}^{EM} is the cell energy at the EM scale¹ and $\sigma_{noise, cell}^{EM}$ is the expected cell noise (electronic noise + pile-up noise corresponding to the average instantaneous luminosity expected for Run 2). Electron and photon reconstruction starts from the topo-clusters but uses energy from the EM calorimeter (+ energy in the Presampler and the scintillator in $1.37 < |\eta| < 1.63$).

Track reconstruction of electrons and photons is performed [54]. The topo-clusters are then matched to the inner detector tracks, which are refitted to account for bremsstrahlung. The algorithm also builds conversion vertices and matches them to the selected topo-clusters. Independently, electron and photon supercluster reconstructions proceed using the matched clusters. The EM topo-clusters that pass the criteria for being seeds are the basis for supercluster building. Initial position corrections and energy calibrations are applied to the resulting superclusters. The supercluster-building algorithm matches tracks to the electron superclusters and conversion vertices to the photon superclusters in a similar way the topo-clusters are matched to the tracks. The electron and photon objects to be used for analyses are then built. A given seed cluster can produce both electrons and photons simultaneously. If an easily identified electron (a cluster with a good track attached and no

¹The EM scale is the basic signal scale accounting correctly for the energy deposited in the calorimeter by electromagnetic showers.

good photon conversion vertex) or an easily identified photon (a cluster with no good track attached) is reconstructed, then that is created as an electron or photon for the analysis respectively, otherwise, both electron and photon objects are created and marked as ambiguous. Figure 2.16a shows the electron reconstruction efficiencies.

The reconstructed energies of electrons or photons are calibrated, and discriminating variables used to separate electrons or photons from the background are added (see section 2.3.1.3). Figure 2.15 shows the flow diagram for the electron and photon reconstruction.

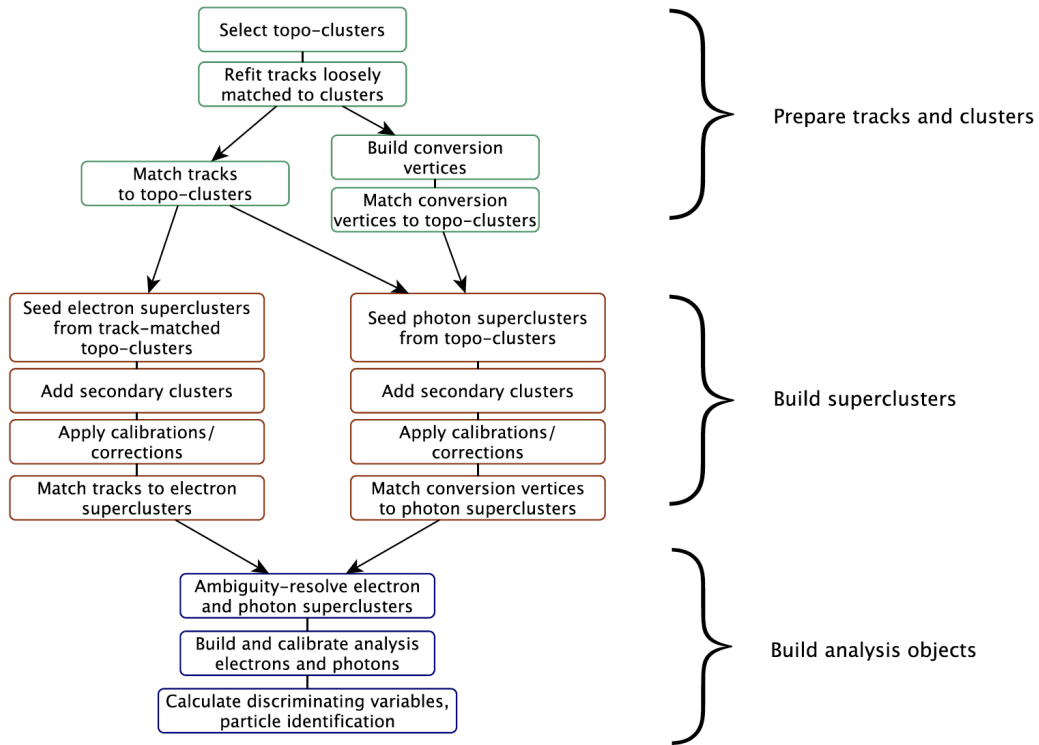


Figure 2.15: The flow diagram for the electron and photon reconstruction.

2.3.1.2 Energy Calibration

Significant loss of energy in front of the Presampler and the EM calorimeter is observed, which is around a few percent to 20% of the electron energy is lost in front of the EM calorimeter (for 100 GeV electron) and around 5% of energy is lost outside of the cluster [70] (see figure 2.16b). It is important to correct this effect to get an idea of the true electron energy.

The procedure described in [71] is followed closely for the energy calibration but updated for the new reconstruction algorithm. Estimation of energy of electrons and photons from the deposits of energy in the calorimeter is performed using the multivariate regression algorithm trained on the

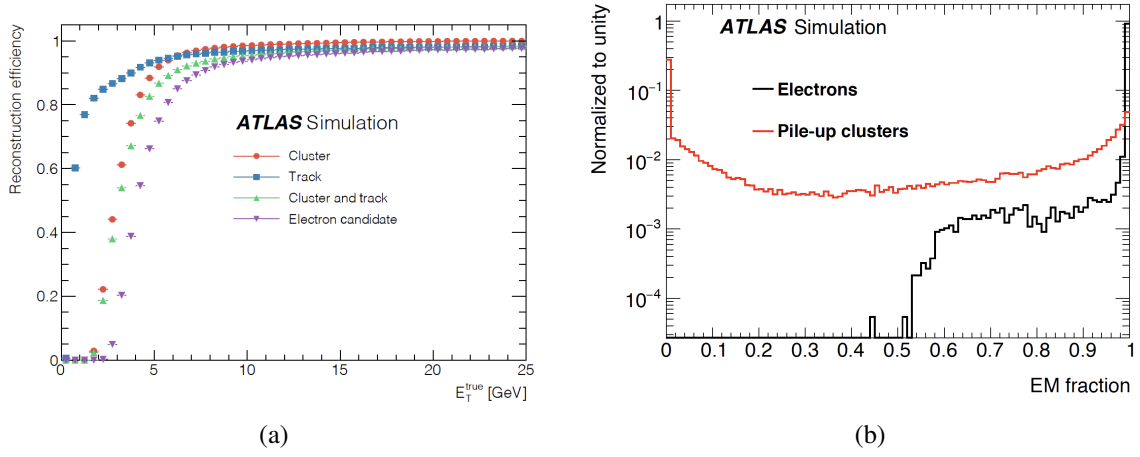


Figure 2.16: The cluster, track, cluster + track and electron efficiencies as a function of generated electron E_T (a) and the simulated distribution of f_{EM} = ratio of the EM energy to the total cluster energy (only for clusters with an EM energy of 400 MeV are considered) (b).

simulated events. The relative energy scales of different layers of the EM calorimeter are adjusted. The ratio of the measured calorimeter energy to the track momentum for Z decays to electron and positron is studied to consider the local non-conformities like the geometrical boundaries between different detector modules, etc. An overall energy scale correction is applied to data using the simulated sample (equation 2.2) and a resolution correction due to the mis-modeling is applied to the MC sample using the data (equation 2.3). $Z \rightarrow ee$ decays are used for this. The energy scale derived from here is validated using radiative decays of Z boson ($Z \rightarrow \ell\ell\gamma$).

$$E^{\text{data,corr}} = E^{\text{data}} / (1 + \alpha_i), \quad (2.2)$$

$$\frac{\sigma_E}{E}^{\text{MC,corr}} = \frac{\sigma_E}{E}^{\text{MC}} \oplus c_i, \quad (2.3)$$

where i corresponds to different η regions, α_i is the difference in energy scale between data and simulation, and c_i is the η dependent additional constant term corresponding to the energy resolution mis-modelling in the simulation. Different systematic uncertainties on the energies are evaluated [72].

2.3.1.3 Identification

The electron identification is performed using a likelihood-based discriminant constructed from various discriminating variables in equation 2.4 [67]:

$$d_L = \frac{L_S}{L_S + L_B}, \quad (2.4)$$

where L_S and L_B are defined as follows:

$$L_{S(B)}(\mathbf{x}) = \prod_{i=1}^n P_{S(B),i}(x_i). \quad (2.5)$$

The probability density functions (pdfs), P , are created by smoothing histograms of n discriminating variables with an adaptive kernel density estimator (KDE [73]) as implemented in TMVA [74]. The pdfs separately for signal and background are used in nine $|\eta|$ bins and seven E_T bins.

The variables used for the formation of the discriminant can largely be divided into properties of the primary electron track, the lateral and longitudinal development of the electromagnetic shower in the EM calorimeter, and the spatial compatibility of the primary electron track with the reconstructed cluster.

The operating points used for electron identification are *Very Loose*, *Loose*, *Medium*, and *Tight* corresponding to increasing thresholds for LH discriminant. Requirements on tracking for different working points [67] ($Tight \subset Medium \subset Loose$):

- ***Loose***: at least two hits in the pixel detector and seven hits total in the pixel and silicon-strip detectors combined.
- ***Medium and Tight***: For *Medium*, the requirement consists of the *Loose* criteria + one of these pixel hits must be in the innermost pixel layer (or in the next-to-innermost layer if the innermost layer is non-operational).

For *tight*, along with *Medium* requirements, the extra requirements are for w_{stot} (a measure of shower width) and $E/p < 10$ (ratio of the cluster energy to the track momentum).

- ***Very Loose***: Defined for online selection. Only one hit in the pixel layer.

Figure 2.17 shows the electron identification efficiency as a function of E_T and η .

For photon identification, three different working points are used. The primary identification is labeled as *Tight* and less restrictive selections, *Medium* and *Loose*, are used for trigger algorithms. The *Tight* identification is optimized using TMVA, and performed separately for converted and

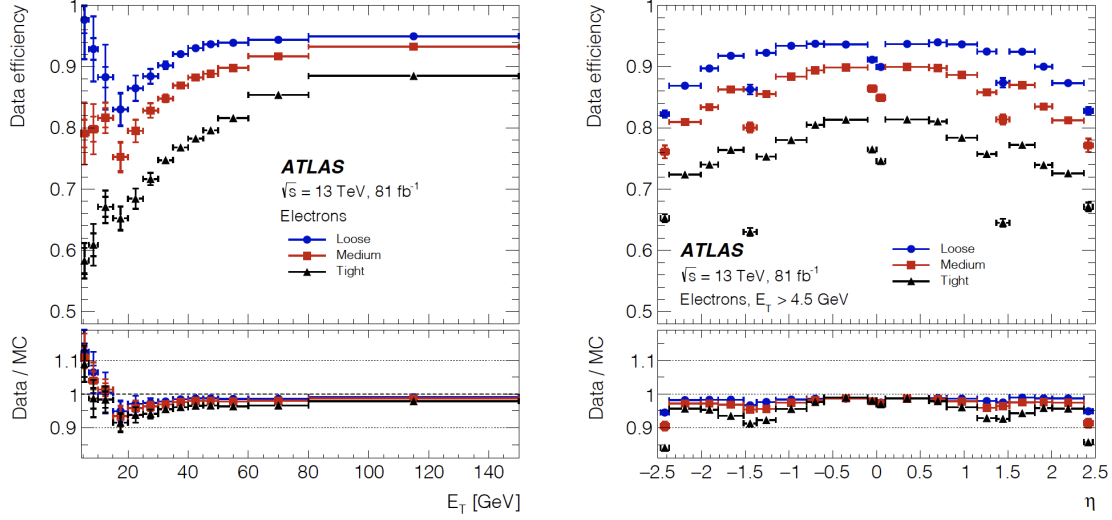


Figure 2.17: The electron identification efficiency in $Z \rightarrow ee$ events in data as a function of E_T (left) and η (right) for *Loose*, *medium*, and *Tight* operating points. The efficiencies are obtained by applying data-to-simulation efficiency ratios measured in $J/\psi \rightarrow ee$ and $Z \rightarrow ee$ events to $Z \rightarrow ee$ simulation. The inner uncertainties are statistical and the total uncertainties are the statistical and systematic uncertainties in the data-to-simulation efficiency ratio added in quadrature. For both plots, the bottom panel shows the data-to-simulation ratios [75].

unconverted photons with different methods and all three methods show reasonable agreement.

2.3.1.4 Isolation

The prompt production of electrons, muons, and photons is defined as the process of leptons or photons originating from the hard-scattering vertex and from the decay of heavy resonances such as the Higgs, W , and Z bosons. The background that can contribute to this consists of semileptonic decays of heavy quarks, hadrons misidentified as leptons and photons, and photons converting into electron-positron pairs in the detector material upstream of the EM calorimeter. For prompt leptons, the activity is light around the main candidate both in the calorimeter and the inner detector. The challenge comes from the cases where the environment around the prompt objects is supposed to be busy, such as that in the case of $t\bar{t}$ production.

The isolation variable or criteria can be defined by identifying the candidate, its direction, and its contribution to the activity within the cone and then by subtracting this activity from the other activity happening in a cone defined in the $\eta \times \phi$ space around it (a cone is defined with $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$).

Two types of isolation criteria are defined:

Calorimeter-based isolation: The raw calorimeter isolation [67] $E_{T,\text{raw}}^{\text{isolXX}}$ is built by summing the transverse energy of positive energy topological clusters whose barycentre falls within a cone of $\Delta R = \text{XX}/100$ centered around the electron or photon cluster barycentre. From this, the EM particle energy ($E_{T,\text{core}}$) is subtracted by removing the energy content from the $\Delta\eta \times \Delta\phi = 0.125 \times 0.175$ cells. Additional leakage ($E_{T,\text{leakage}}(E_T, \eta, \Delta R)$) is determined using a simulation sample of single electrons and subtracted along with pile-up and underlying event correction ($E_{T,\text{pile-up}}(\eta, \Delta R)$).

The fully corrected calorimeter isolation is given as follows:

$$E_T^{\text{coneXX}} = E_{T,\text{raw}}^{\text{isolXX}} - E_{T,\text{core}} - E_{T,\text{leakage}}(E_T, \eta, \Delta R) - E_{T,\text{pile-up}}(\eta, \Delta R) \quad (2.6)$$

Track-based isolation: The track isolation variable ($p_T^{\text{varconeXX}}$) is computed by summing the transverse momentum of selected tracks within a cone centered around the electron track or the photon cluster direction. The electron or converted photon tracks are excluded. A variable cone size is used for this (see equation 2.7) (smaller cone size for larger transverse momenta):

$$\Delta R = \min\left(\frac{10}{p_T[\text{GeV}]}, \Delta R_{\text{max}}\right) \quad (2.7)$$

where ΔR_{max} is typically 0.2.

Definitions of electron isolation working points are described in table 2.4.

Working Point	Calorimeter Isolation	Track Isolation
<i>Gradient</i>	$\epsilon = 0.1143 \times p_T + 92.14\%$ (with E_T^{cone20})	$\epsilon = 0.1143 \times p_T + 92.14\%$ (with $p_T^{\text{varcone20}}$)
<i>HighPtCaloOnly</i>	$E_T^{\text{cone20}} < \max(0.015 \times p_T, 3.5 \text{ GeV})$	—
<i>Loose</i>	$E_T^{\text{cone20}}/p_T < 0.20$	$p_T^{\text{varcone20}}/p_T < 0.15$
<i>Tight</i>	$E_T^{\text{cone20}}/p_T < 0.06$	$p_T^{\text{varcone20}}/p_T < 0.06$

Table 2.4: Electron Isolation working points.

2.3.1.5 Charge Mis-identification

The electron charge reconstruction is dependent solely on the measurement of the electron track curvature in the inner detector. The interaction of the electron with the detector material can give rise to secondary particles which pose two main challenges to charge reconstruction: 1) The incorrect track curvature determination, and 2) choosing the incorrect track for curvature determination. The first effect is more dominant for high p_T electrons. The probability to determine the charge incorrectly increases linearly with energy because of this effect. The second effect becomes relevant

when the electron has collinear radiation emission and the radiated photon gets converted to a pair of electrons and positron. A Boosted Decision Tree (BDT) discriminant [67] is used to reject the electrons with misidentified charges. Around 90% of electrons with misidentified charge are rejected. After re-optimizing the BDT variable defined in [67], the fraction of wrongly charged electrons passing selection criteria is reduced by a factor of 3 – 5 as a function of E_T and by up to a factor of 10 at high $|\eta|$. Figure 2.18 shows the electron charge misidentification efficiency with the updated BDT variable.

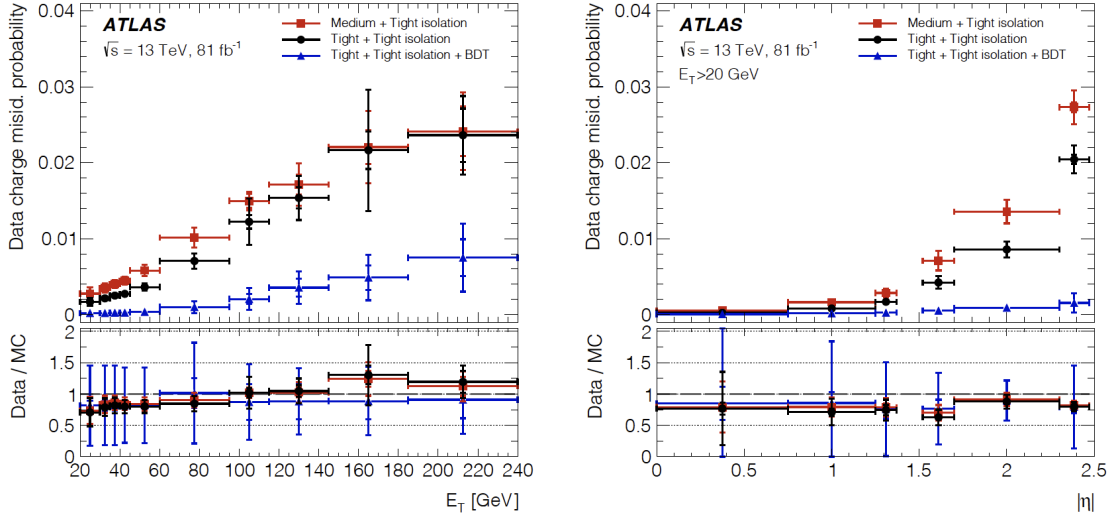


Figure 2.18: Charge misidentification probabilities in data as a function of E_T (left) and $|\eta|$ (right). The energies are corrected for the loss of energy caused due to the interactions with the material. The inner uncertainties are statistical and the outer are statistical + systematic in the lower parts of both distributions [75].

2.3.2 Muons

2.3.2.1 Reconstruction

The muon candidates are reconstructed using the ID and MS tracks along with the calorimeter information. The ATLAS New Tracking (NEWT) reconstruction algorithm is used for track reconstruction in ID [76]. The reconstruction in the ID is performed using the Pixel, SCT, and TRT detectors. Seeding is an important aspect of the *inside-out* track finding algorithm. The pixel clusters provide 2D positions giving direct space points, however, SCT does not provide direct space points as they provide points only in one direction. Two back-to-back modules of SCT (at a stereo angle of 40 mrad) have to be used to create a space point. The space points for seeds are used as follows: all space points in the pixel detector, all space points in the SCT, two space points in the

pixel detector and one in the SCT, or one in the pixel detector and two in the SCT (this last one has high fake rate so not used by the inside-out reconstruction sequence)

A window search is used in the seed propagation direction and hits within the road window are collected and track candidates are formed using a combinatorial Kalman filter [77]. Each seed can only become a part of a single-track candidate. The seed is discarded if all the clusters in the seed are used by another track candidate already or if the road search fails to find sufficient hits which pass the track hit criteria. Approximately 35% of seeds in data become track candidates [78]. An ambiguity-solving algorithm is used to select the final track candidates where more than one tracks have a few space points common in them. This is done by assigning a relative track score to each track in the ambiguous set of tracks.

An outside-in track reconstruction is also performed using the TRT hits and then extending the track going inside layer-by-layer. This however causes the tracks to have higher fake rates.

Standalone tracks are reconstructed using the hits in the MS. Initially muon segments are constructed in different MS stations separately using Hough Transform [79]. These are then combined together into preliminary tracks using a loose constraint on the tracks to point to the IP and a parabolic trajectory (which is a first-order approximation of the muon bending in the magnetic field). Energy loss in calorimeters is also taken into account.

A global track reconstruction is also developed to combine information from various detectors, ID MS as well as the calorimeters. There are five main types of reconstructed muons:

Combined (CB) Muons: These are reconstructed by matching ID and MS tracks also considering calorimeter energy loss. It is mostly done using an outside-in approach. Based on the preliminary trajectory the hits are updated and fitted again. For higher η ($|\eta| > 2.5$), the MS tracks can be combined with the short track segments formed from the hits in the pixel and the SCT detectors. This is considered a subset of CB Muons called silicon-associated forward (SiF) muons.

Inside-out Combined (IO) Muons: To recover some more efficiency of muon reconstruction, an inside-out approach is also used for combining ID tracks with at least three loosely-aligned MS hits along with the energy loss in the calorimeters. This algorithm recovers some efficiency for example in regions of limited MS coverage and for low- p_T muons that may not reach the middle MS station.

Muon Spectrometer Extrapolated (ME) Muons: These are the muons whose MS tracks cannot be matched to any ID track. So, the MS tracks are extrapolated to the beam line taking into account the estimated energy loss in the calorimeters. These are mainly used to extend the reconstruction of muons outside the ID acceptance exploiting full MS coverage up to $|\eta| \sim 2.7$.

Segment-tagged (ST) Muons: When the muons cross only one layer of MS chambers because of

low p_T or because they fall into a low acceptance region. These muons should have at least one segment reconstructed in MS matching tight angular requirements with the ID track. The muon parameters are taken from the ID track fit.

Calorimeter-tagged (CT) Muons: CT muons are those whose ID tracks are extrapolated to have calorimeter energy deposits corresponding to a minimum-ionizing particle. The muon parameters are again taken from the ID track. The other muon reconstruction algorithms make use of around $p_T > 2$ GeV ID tracks, CT uses a threshold of 5 GeV because of large background contamination.

2.3.2.2 Identification

The selection working points (WPs) are defined to cater to the needs of different analyses. The different requirements of analyses include the efficiency of prompt-muon identification, resolution of the momentum measurement, and rejection of background due to non-prompt muons (among non-prompt muons, a distinction is made between muons originating from in-flight decay of light hadrons and those from heavy flavor hadrons).

The two main metrics for optimizing the rationale for each WP are as follows:

- Prompt muon efficiency: it is the probability that a prompt muon traversing the detector is reconstructed as a muon and satisfies the WP.
- Purity in simulation: one minus the hadron misidentification rate, where, hadron misidentification rate is the fraction of light hadrons reconstructed as muons and satisfying the WP.

Three standard selection WPs are designed: *Loose*, *Medium*, and *Tight* with $Tight \subset Medium \subset Loose$. Two additional WPs are also defined for extreme phase space regions: High p_T , and Low p_T (cut-based and multivariate) [57].

A few clarifications before defining the working point criteria:

- Precision stations: The MS stations in which the muon has at least three hits in the MDT and CSC detectors
- Precision hole station: a station where the muon has less than three hits and is missing at least three hits that are expected given its trajectory and the detector layout and operational status.
- q/p compatibility: Defined for CB and IO muons with MS track:

$$q/p \text{ compatibility} = \frac{|q/p_{ID} - q/p_{MS}|}{\sqrt{\sigma^2(q/p_{ID}) + \sigma^2(q/p_{MS})}}, \quad (2.8)$$

where q/p_{ID} and q/p_{MS} are the measurements in the ID and MS of the ratio of the charge q to momentum p of the muon, expressed at the IP, while $\sigma^2(q/p_{\text{ID}})$ and $\sigma^2(q/p_{\text{MS}})$ are the corresponding uncertainties.

- ρ' is defined for CB and IO muons with an MS track:

$$\rho' = \frac{|p_{T,\text{ID}} - p_{T,\text{MS}}|}{p_{T,\text{CB}}}, \quad (2.9)$$

where $p_{T,\text{ID}}$ and $p_{T,\text{MS}}$ are respectively the muon p_T measured in the ID and in the MS, while $p_{T,\text{CB}}$ is the value resulting from the combined track fit.

The selection working points are defined as follows:

Medium: This WP accepts only CB and IO for $|\eta| < 2.5$. These are required to have at least two precision stations, except in the region $|\eta| < 0.1$, where only one precision station is sufficient, provided that at most one precision hole station is present. For a loose agreement between ID and MS, q/p compatibility < 7 . This WP extends to ME and SiF muons in the range $2.5 < |\eta| < 2.7$ requiring at least 3 precision stations. In $t\bar{t}$, among *Medium* WP prompt leptons, 98% are CB muons.

Loose: All *Medium* WP muons pass *Loose* selection. On top of it, it includes CT and ST for $|\eta| < 0.1$ (this is a gap in MS coverage leading to low efficient CB muons). IO muons with $p_T < 7$ GeV and only one precision station are accepted in the range $|\eta| < 1.3$ but they also should independently be reconstructed as ST muons. In $t\bar{t}$ considering prompt muons with *Loose* selection criteria, about 97% are CB+IO, $\sim 1.5\%$ are CT+ST in $|\eta| < 0.1$ (majority CT). The efficiency increases by 20% from *Medium* to *Loose* for $3 < p_T < 5$ GeV and by 1-2% for higher p_T .

Tight: The muons with *Medium* selection WP which are also CB and IO pass *Tight* selection if they have at least two precision stations. The normalized χ^2 of the combined track has to be less than 8. There are requirements placed on the q/p compatibility and ρ' depending on the p_T and $|\eta|$ of the muon. The Tight WP achieves a background reduction of more than 50% compared to *Medium* in the region $6 < p_T < 20$ GeV, with a corresponding efficiency loss for prompt muons of approximately 6%.

High p_T : The reconstruction of high p_T muons poses challenge due to the almost straight trajectory. A good design resolution has to be achieved for these tracks in the MS which is possible for the presence of at least three precision stations. Combined track fit (with ID) can recover the resolution to some extent. Only CB and IO muons passing *Medium* requirements are accepted for High p_T WP (with a few exceptions.) Muons are rejected in the regions where the relative alignment between traversed chambers is not known precisely. The muon rejection is seen in the barrel-endcap overlapping region and also in the regions where the support structures are present.

Low p_T : Because of the very low p_T of the muons for this working point, the muon may not reach the middle station or any station of the MS. So even though both CB and IO muons are used in this selection WP, a significant fraction of muons are reconstructed only as IO. These muons should also be reconstructed as ST muons. At least one precision station is required (except for $|\eta| < 1.3$, where muon with $p_T > 3$ GeV can reach the second station, so at least two precision stations are required). Low p_T WP is identical to *Medium* above 18 GeV. Selection has to be imposed to reject light-hadron decays (e.g. a kink in the trajectory in ID). In the cut-based approach for Low p_T muons, requirements are imposed separately on different discriminating variables, and in the multivariate WP, a boosted decision tree approach is considered [57].

The muons should satisfy some requirements to make sure it comes from the hard-scattering proton-proton interactions. These are mainly the requirements for the impact parameters.

- d_0 *significance* or $|d_0|/\sigma(d_0)$ should be less than 3. Here, $|d_0|$ is the distance from the beamline to the point of closest approach of the muon track in the transverse plane, and $\sigma(d_0)$ accounts for the beam width.
- $|z_0 \sin\theta| < 0.5$ mm. Here, z_0 is the coordinate along the beam axis of the point of closest approach of the muon track to the beamline, measured relative to the reconstructed primary vertex², and θ is the polar angle of the muon track.

There are two types of variables defined: Track-based and calorimeter based. Both have complimentary functions but also have some redundancies. Track-based has better resolution and lower pile-up and the calorimeter-based includes neutral particles and particles below the ID track p_T threshold. But charged particles are measured by both methods so using a combination of the two can have some overlaps. So, another particle-flow-based isolation is also developed. Here are the definitions used in defining the isolation requirements given in table 2.5.

- **Track-based Isolation:** the scalar sum of the transverse momenta of the ID tracks associated with the primary vertex in an $\eta - \phi$ cone of a given size ΔR around the muon, excluding the muon track itself.

p_T^{cone20} means the cone is defined with $\Delta R = 0.2$. or $p_T^{\text{varcone30}}$ means the cone is defined with $\Delta R = \min(10 \text{ GeV} / p_T^\mu, 0.3)$. The minimum required p_T of the tracks depends on the isolation WP.

- **Calorimeter-based Isolation:** the sum of the transverse energy of topological cell clusters in a cone of size $\Delta R = 0.2$ around the position of the muon, extrapolated to the calorimeters,

²Collision vertices are reconstructed from ID tracks that satisfy $p_T > 0.5$ GeV, and the primary vertex is chosen as the vertex with the largest Σp_T^2 for the tracks associated with this vertex position.

after subtracting the contribution from the energy deposit of the muon itself and correcting for pile-up effects: $E_T^{\text{topoetcone20}}$.

- Particle-flow-based Isolation: the sum of track-based isolation, chosen in the configuration with $p_T^{\text{varcone30}}$ for $p_T^\mu < 50$ GeV and p_T^{cone20} for $p_T^\mu > 50$ GeV.
- E_T^{neflow20} is the transverse energy of neutral particle-flow objects in a cone of size $\Delta R = 0.2$ around the muon.

Isolation WP	Definition	Track p_T
<i>PflowLoose*</i>	$(p_T^{\text{varcone30}} + 0.4 E_T^{\text{neflow20}}) < 0.16 \cdot p_T^\mu$	$p_T > 500$ MeV
<i>PflowTight*</i>	$(p_T^{\text{varcone30}} + 0.4 E_T^{\text{neflow20}}) < 0.045 \cdot p_T^\mu$	
<i>Loose*</i>	$p_T^{\text{varcone30}} < 0.15 \cdot p_T^\mu, E_T^{\text{topoetcone20}} < 0.3 \cdot p_T^\mu$	$p_T > 1$ GeV
<i>Tight*</i>	$p_T^{\text{varcone30}} < 0.04 \cdot p_T^\mu, E_T^{\text{topoetcone20}} < 0.15 \cdot p_T^\mu$	
<i>HighPtTrackOnly</i>	$p_T^{\text{cone20}} < 1.25$ GeV	$p_T > 1$ GeV
<i>TightTrackOnly*</i>	$p_T^{\text{varcone30}} < 0.06 \cdot p_T^\mu$	
<i>PLBDTLoose (PLBDTTight)</i>	$p_T^{\text{varcone30}} < \max(1.8 \text{ GeV}, 0.15 \cdot p_T^\mu)$ BDT cut to mimic <i>TightTrackOnly</i> (<i>Tight</i>) efficiency	$p_T > 1$ GeV

Table 2.5: The isolation working points for muons. WPs marked with * exist in two variants: one with the cone ΔR parameter decreasing with p_T^μ as $\min(10\text{GeV}/p_T^\mu, 0.3)$, the other remaining constant at $\Delta R = 0.2$ for $p_T^\mu > 50$ GeV [57].

See figure 2.19 for the muon reconstruction and identification efficiency measured in data with *Medium*, *PflowLoose* isolation and vertex association criteria.

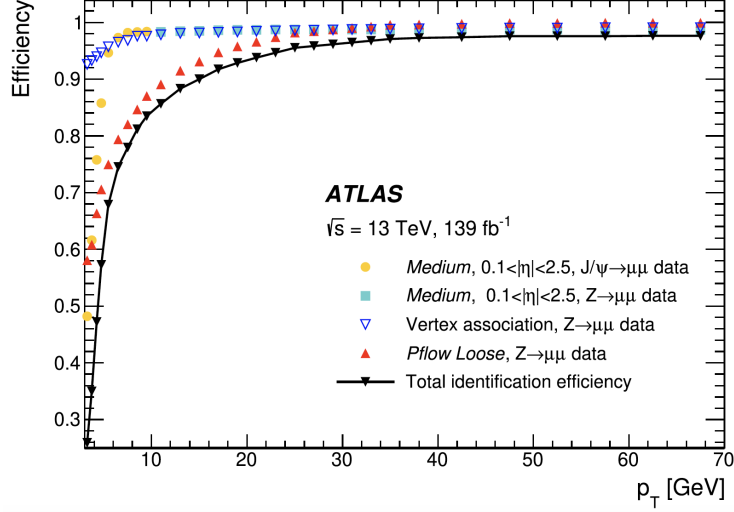


Figure 2.19: Muon reconstruction and identification efficiency measured in data with $Z \rightarrow \mu\mu$ and $j/\psi \rightarrow \mu\mu$ [57].

2.3.3 Jets

The partons with color charge produced from the scattering processes cannot exist individually. This is due to the feature of Quantum Chromodynamics (QCD) called asymptotic freedom. Therefore, when quarks or gluons are produced from initial interactions of the particles, they quickly fragment and form hadrons. This results in a shower of charged and neutral hadrons and manifests itself as a collimated energy deposition in the calorimeters and multiple tracks in the inner detector. This analysis does not directly look at jets but uses a selection on p_T^{WZ} ($p_T^{WZ} < 70, 40, 20, 10$ GeV) to enhance the RAZ effect by reducing the jet activity in the sample. Correct reconstruction and calibration of jets is indirectly also essential for the E_T^{miss} calculation as E_T^{miss} is very important to reconstruct neutrino p_z .

Initially for Run 1 analysis vast majority of analyses used the jets reconstructed from the topological clusters of calorimeters (topo-clusters) [80]. The Jet Energy Scale (JES) correction factor [81–84] also considered the tracks corresponding to the reconstructed jets. The jet resolution has been improved using the tracks [81].

The topological clusters are reconstructed by the energy deposits in the longitudinal and lateral calorimeter cells [80]. These are seeded by cells whose $|E|$ exceeds the expected noise by 4 times its standard deviation. A large fraction of low-energy particles cannot be seeded because of this. For example, in the central barrel, 25% of 1 GeV particles do not seed. Using both tracker and calorimeter information improves the performance of the jet reconstruction.

2.3.3.1 Particle-flow Algorithm

The particle flow algorithm is an approach where the jet reconstruction is performed using both tracker and calorimeter information. The calorimeter deposits of the charged hadrons are removed from consideration and instead use the corresponding tracks in the inner tracker. Basically, the double counting of the signal from the tracker and calorimeter is avoided using this algorithm for charged hadrons.

Here is a basic and initial description of the particle-flow algorithm. However, over time some more changes have been made to the algorithm. The latest changes can be found in section 4 of Ref. [85].

The advantages of the “particle flow” algorithm [86]:

- The momentum resolution for the low-energy charged particles in the tracker is much better compared to the energy resolution of the calorimeter. For some other softer particles, the energy deposits do not pass the noise threshold in the calorimeters.
- The angular resolution of a charged particle is much better than that of the calorimeter
- The Low- p_T charged particles inside a hadronic jet can get swept out of the jet cone by the magnetic field and they are not a part of the calorimeter clusters. But using the tracker information, they can be included in the clusters by looking at the track’s azimuthal coordinate (the magnetic field is assumed to be in the direction of the z -axis. and hence the displacement of the charged particle is assumed to be happening in the azimuthal plane).

The particle flow algorithms were pioneered in the Apparatus for LEP Physics (ALEPH) experiment at Large Electron-Positron Collider (LEP) [87] and successfully used by many experiments till now and ATLAS has been using it since 2017.

Figure 2.20 shows the flow chart of the particle flow algorithm.

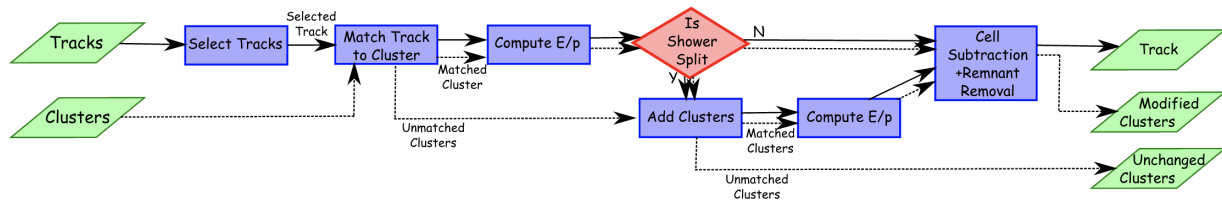


Figure 2.20: The flow chart for the particle flow algorithm [86].

Here is a more detailed description of the different steps of this algorithm. Some parameters are defined which help understand the distribution of the energy deposited by a particle or many particles in different topological clusters.

- The fraction of the particle's energy deposited in cluster i with respect to the total energy deposited by the particle in all its topo-clusters.

$$\varepsilon_i^{\text{clus}} = \frac{E_{\text{true},\pi}^{\text{clus } i}}{E_{\text{true},\pi}^{\text{all topo-clusters}}}, \quad (2.10)$$

where $E_{\text{true},\pi}^{\text{clus } i}$ is the true energy deposited by the particle in the topo-cluster i . The leading topo-cluster is the one with the highest value of $\varepsilon_i^{\text{clus}}$. n_{clus}^{90} is the minimum number of topo-clusters required to capture at least 90% of the particle's true deposited energy ($\sum_{i=0}^n \varepsilon_i^{\text{clus}} > 90\%$).

- The purity of a topo-cluster: The fraction of energy inside the cluster i which originates from the given particle. The leading topocluster purity is given by ρ_i^{clus} :

$$\rho_i^{\text{clus}} = \frac{E_{\text{true},\pi}^{\text{clus } i}}{E_{\text{true,all particles}}^{\text{clus } i}}. \quad (2.11)$$

The important quantity to look at is the fraction of particles for which at least 90% of the particle energy is inside a single topo-cluster i.e. $n_{\text{clus}}^{90} = 1$.

For the track selection, a tight selection is used. At least 9 hits in the silicon detectors (with no missing pixel hit if one is expected) [88]. Tracks should have $|\eta| < 2.5$ and $p_T > 0.5$ GeV. This helps in selecting tracks, which deposit energy below the seeding threshold in the calorimeter. Tracks with $p_T > 40$ GeV are not selected. Tracks from muons and electrons are not considered (hence not used for calorimeter subtraction).

Two metrics are used for matching tracks to topo-clusters:

- $E^{\text{clus}}/p^{\text{trk}} > 0.1$,
- $\Delta R' = \sqrt{(\frac{\Delta\phi}{\sigma_\phi})^2 + (\frac{\Delta\eta}{\sigma_\eta})^2} < 1.64$. This is the distance between the track and topo-cluster barycentres in the angular space.

Expected deposited energy in the calorimeter is determined using: $\langle E_{\text{dep}} \rangle = p^{\text{trk}} \langle E_{\text{ref}}^{\text{clus}} / p_{\text{ref}}^{\text{trk}} \rangle$. A selection on a discriminant, $S(E^{\text{clus}}) = \frac{E^{\text{clus}} - \langle E_{\text{dep}} \rangle}{\sigma(E_{\text{dep}})}$, is used to distinguish between single or multiple topo-cluster cases. Cell-by-cell subtraction of the energy is performed using three EM layers and one hadronic calorimeter layer (Tile and HEC are considered together to be one layer) [86].

2.3.3.2 Jet reconstruction and calibration

An anti- k_t algorithm is used for the actual jet reconstruction with a radius of 0.4 [89, 90]. The tracks are selected by requiring $|z_0 \sin \theta| < 2$ mm, where z_0 is the distance of the closest approach of

the track to the hard-scatter primary vertex along the z -axis. The jets are reconstructed either by combining the tracks and the calorimeter topological clusters (particle-flow or PFlow) or by only using the topological clusters (EM). The topological clusters used are the positive-energy clusters.

The jet energy scale calibration is used to restore the jet energy to that at the particle level. The full calibration chain is shown in figure 2.21.

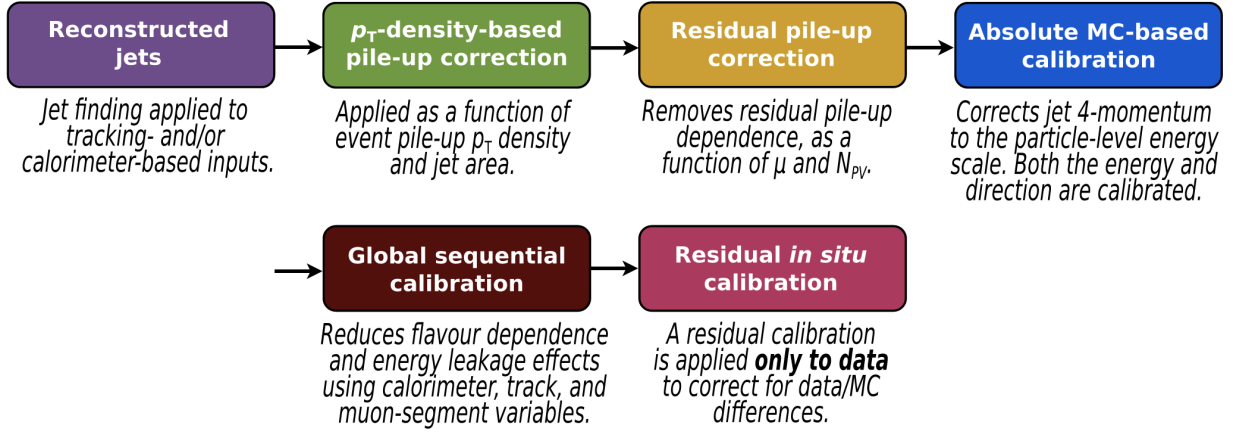


Figure 2.21: The stages of Jet Energy Scale calibration. Each of these is applied to the four-momentum of the jet [85].

For the pile-up corrections, a jet p_T -density-based subtraction of the per-event pile-up contribution to the jet p_T is done. The pile-up contribution is estimated from the median p_T density, ρ , of jets in $y - \phi$ plane, $\langle p_T/A \rangle$ (A is the measure of the susceptibility of the jet to pile-up). The pile-up correction (the residual correction) also depends on μ , the mean number of interactions per bunch crossing, and N_{PV} , the number of reconstructed primary vertices in the event. The final jet p_T after all the pile-up corrections is:

$$p_T^{\text{corr}} = p_T^{\text{reco}} - \rho \times A - \alpha \times (N_{PV} - 1) - \beta \times \mu. \quad (2.12)$$

The fitted values of α and β are used.

The absolute jet energy scale and η calibrations are done to correct the reconstructed jet four-momentum to the particle-level energy scale accounting for non-compensating calorimeter response, energy losses in passive material, out-of-cone effects and biases in the jet η reconstruction [85]. These biases come from mainly the transition between different calorimeter technologies and sudden changes in the calorimeter granularity. A jet energy response, R is defined as $E^{\text{reco}}/E^{\text{true}}$, is measured in E^{true} and η_{det} bins. The average response is parameterized as a function of E^{reco} using a numerical inversion procedure [91] jet calibration factor is the inverse of the average energy

response. A second correction is performed using the difference between the reconstructed and truth η (η^{reco} and η^{true} resp.). This is again determined as a function of E^{true} and η_{det} . And as before a numerical inversion procedure is implemented to derive corrections in E^{reco} from E^{true} . EMtopo and PFlow jets after these calibrations are called to be at EM+JES scale and PFlow+JES scale, respectively.

The jets originating from different sources (e.g. gluons and quarks) have different particle compositions and shower shapes. The quark-initiated jet often consists of hadrons with a higher proportion of the jet p_T that penetrate further inside the calorimeter and a gluon-initiated jet will typically contain more particles of softer p_T having lower calorimeter response and wider transverse profile. The global sequential calibration (GSC) applied a series of multiplicative corrections to reduce the effects of these differences.

An independent jet four-momentum correction is derived as a function of p_T^{true} and $|\eta_{\text{det}}|$ for each observable by inverting the reconstructed jet response.

The differences caused by imperfect simulation of both detector material and the physics processes can be corrected by applying in situ jet calibrations. The jet response is calculated by balancing the p_T of a jet against that of a well-calibrated reference object or system.

Figure 2.22 shows the ratio of the PFlow+JES jet response in data to that in nominal MC event generators and a comparison of the combined correction and its uncertainty for PFlow+JES and EM+JES jets.

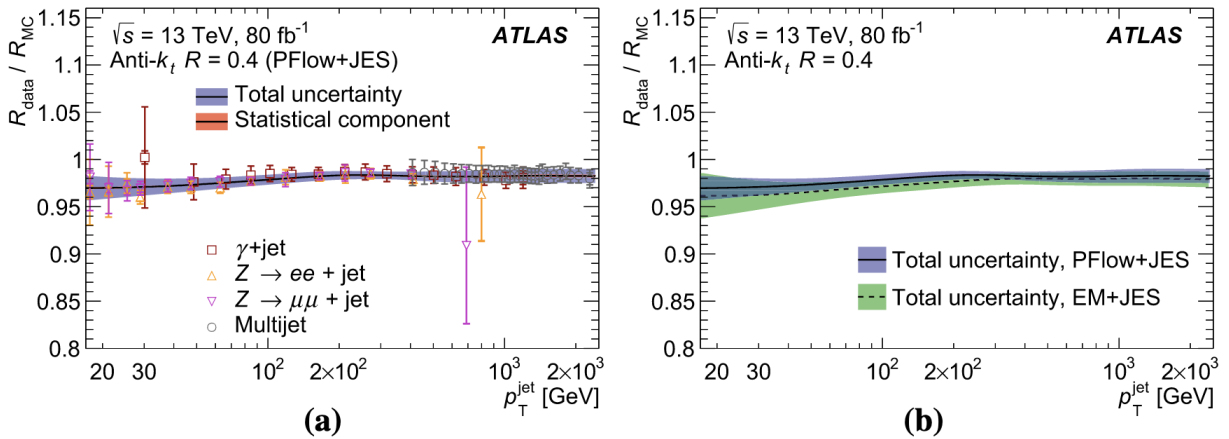


Figure 2.22: The ratio of the PFlow+JES jet response in data to that in the nominal MC event generators as a function of jet p_T for Z+jet, γ +jet, and multijet in situ calibrations (a). A comparison of the combined correction and its uncertainty for PFlow+JES and EM+JES jets (b) [85].

The Jet Energy Resolution (JER) is important for many detailed measurements and studies of SM

particles decaying to jets and also for the searches for physics beyond SM involving jets. It has a key role in determining missing transverse energy. The functional form of JER is as follows [92]:

$$\frac{\sigma(p_T)}{p_T} = \frac{N}{p_T} \oplus \frac{S}{\sqrt{p_T}} \oplus C, \quad (2.13)$$

where N is the noise term due to the contribution of electronic noise to the signal measured by the detector front-end electronics and also due to pile-up. This contribution scales like $1/p_T$. S is the stochastic term that includes the statistical fluctuations in the amount of energy deposited and it is scaled like $1/\sqrt{p_T}$. This one is important for the jet p_T up to several hundred GeV. The constant term is for the fluctuations that are a constant fraction of the jet p_T for example the energy deposits in the passive material in the detector (e.g. cryostats and solenoid coil), the starting point of hadron showers and non-uniformities of response across the calorimeter and this is dominated in the high- p_T region above ~ 400 GeV. Figure 2.23 shows the jet energy resolution for fully calibrated PFlow+JES and EM+JS jets as a function of jet p_T and $|\eta^{jet}|$.

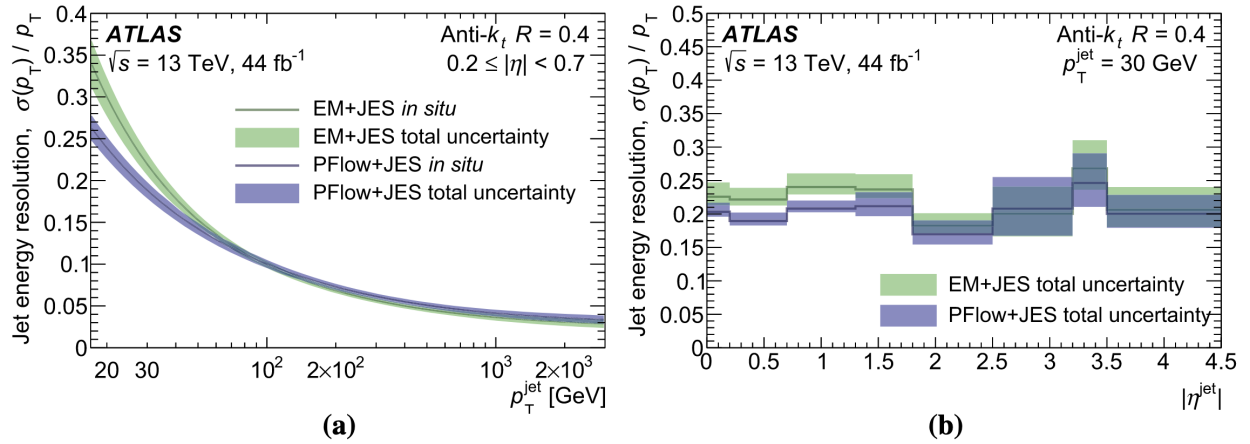


Figure 2.23: The relative jet energy resolution for fully calibrated PFlow+JES jets (blue) and EM+JES jets (green) as a function of jet p_T (a) and η (b). The fit to the resolution (as a function of p_T^{jet}) for the PFlow+JES jets is improved compared to that of EM+JES jets [85].

2.3.3.3 Jet Vertex Tagger (JVT) and forward Jet Vertex Tagger (fJVT)

The pile-up interactions interfere with reconstructing hard-scatter events. The jets are reconstructed as groups of topologically related energy deposits in the calorimeters and therefore the soft energy depositions from pile-up have complex effects on the jet energy measurement and jet structure observables. The pile-up can also generate additional jets in the event. Some pile-up subtraction methods are used to reduce the effects of pile-up in jet reconstruction. However, some pile-up jets remain even after pile-up subtraction mainly due to localized fluctuations in pile-up activity.

Matching of every jet with the tracks not originating from the hard-scatter interaction is useful to remove their contribution.

Jet vertex fraction is a variable defined for each jet with respect to each Primary Vertex (PV). For a given jet_{*i*}, its JVF wrt the primary vertex PV_{*j*} is given by:

$$\text{JVF}(\text{jet}_i, \text{PV}_j) = \frac{\sum_m p_T(\text{track}_m^{\text{jet}_i}, \text{PV}_j)}{\sum_n \sum_l p_T(\text{track}_l^{\text{jet}_i}, \text{PV}_n)}. \quad (2.14)$$

Here, *m* runs over all tracks originating from PV_{*j*}³ matched to jet_{*i*}, *n* over all primary vertices in the event and *l* over all tracks originating from PV_{*n*} matched to jet_{*i*}. Only tracks with *p_T* > 500 MeV are considered.

The JVF value is between 0 and 1 (-1 for jets with no associated tracks). Towards 0 means more like a pile-up and 1 means more like a hard-scatter track. JVF can be looked at as the fraction of track *p_T* contributed to jet *i* due to the second vertex PV_{*j*}.

The quantity corrJVF is a variable similar to JVF but corrected for the *N_{PV}* (number of primary vertices in the event) dependence:

$$\text{corrJVF} = \frac{\sum_m p_T^{\text{track}}(\text{PV}_0)}{\sum_l p_T^{\text{track}}(\text{PV}_0) + \frac{\sum_{n \geq 1} \sum_l p_T^{\text{track}}(\text{PV}_n)}{(k \cdot n_{\text{track}}^{\text{PU}})}}. \quad (2.15)$$

Here, $\sum_m p_T^{\text{track}}(\text{PV}_0)$ is the scalar sum of the *p_T* of the tracks that are associated with the jet and originate from the hard-scatter vertex. $\sum_{n \geq 1} \sum_l p_T^{\text{track}}(\text{PV}_n) = p_T^{\text{PU}}$ is the scalar sum of the *p_T* of the associated tracks that originate from any of the pile-up interactions. The track-to-vertex association is modified to improve b-quark jet efficiency. First, if a track is assigned to more than one vertex, the one with higher $\sum (p_T^{\text{track}})^2$ is preferred. and second, if no association with any primary vertex is seen and if $|\Delta z| < 3$ mm wrt the hard-scatter vertex, it is assigned to the hard-scatter primary vertex. This incorporates the in-flight decays of the hadrons (like *b*-hadron decays). $\langle p_T^{\text{PU}} \rangle$ increases linearly with the total number of pile-up tracks per event ($n_{\text{track}}^{\text{PU}}$). To correct for this, p_T^{PU} is divided by $(k \cdot n_{\text{track}}^{\text{PU}})$ with *k* = 0.01 as a definition for JVF. $n_{\text{track}}^{\text{PU}}$ is computed from all tracks associated with vertices other than the hard-scatter vertex. The interpretation of corrJVF is similar to that of JVF calculation.

R_{pT} is defined as the scalar sum of the *p_T* of the tracks that are associated with the jet and originate

³Tracks are associated to vertices based on the requirement $|\Delta z \times \sin \theta| < 1$ mm. If more than one vertex satisfies this requirement, the vertex with the largest $\sum p_T^2$ of tracks is used.

from the hard-scatter vertex divided by fully calibrated jet p_T that includes pile-up subtraction:

$$R_{pT} = \frac{\sum_k p_{T,k}^{\text{track}}(PV_0)}{p_T^{\text{jet}}}. \quad (2.16)$$

For pile-up jets, R_{pT} peaks at 0 and steeply falls. For hard-scatter jets, it has a larger spread.

The *jet vertex tagger* (JVT) (which is used in our analysis), is a new discriminant constructed using R_{pT} and corrJVF as a two-dimensional likelihood derived from simulated dijet events and based on k-nearest neighbor (kNN) algorithm [93]. A two-dimensional plane of corrJVF- R_{pT} is considered for this. The relative probability for a jet at one point in this plane to be of signal type is computed as a ratio of the number of hard-scatter jets to the number of hard-scatter plus pile-up jets found in a local neighborhood around that point using a training sample of signal and pile-up with jet having $20 < p_T < 50$ GeV and $|\eta| < 2.4$. The dynamic definition of the local neighborhood is the 100 nearest neighbors around the test point using a Euclidean metric in the R_{pT} -corrJVF space (scaled so that the variables have the same range). Figure 2.24 shows the jet efficiencies for minimum JVT cut of 0.2, 0.4, and 0.7 (looser to tighter). It is measured in bins of $p_T^{\text{ref}} = p_T^Z$. The difference between data and MC is within the statistical uncertainties.

The simulation studies are performed for constructing the fJVT tagger. Three different kinds of reconstructed jets are looked at here: *hard-scatter jets*, *QCD pile-up jets*, and *stochastic pile-up jets*. *QCD pile-up jets* are the ones where the particles stem mostly from a single QCD process occurring in a single pile-up interaction and *stochastic pile-up jets* combine particles from different interactions [94].

The primary parameters for the *forward jet vertex tagging* (fJVT) algorithm [94] are:

- The maximum JVT value, JVT_{max} : this is to reject central hard-scatter jets. JVT_{max} is set to 0.14 corresponding to an efficiency of selecting pileup jets of 93% in dijet events.
- minimum R_{pT} requirement: This is to ensure the selected pile-up jets are QCD pile-up jets. The minimum R_{pT} requirement defines the operating point in terms of efficiency for selecting QCD pile-up jet and contamination from stochastic pile-up jets. A minimum R_{pT} of 0.2 is required, corresponding to an efficiency of 70% for QCD pile-up jets and 20% for stochastic pile-up jets in dijet events.

The selected jets are assigned to the vertex PV_i corresponding to the highest R_{pT}^i value. For each pile-up vertex, i ($i \neq 0$), the missing transverse momentum $\langle \mathbf{p}_{T,i}^{\text{miss}} \rangle$ is computed as the weighted

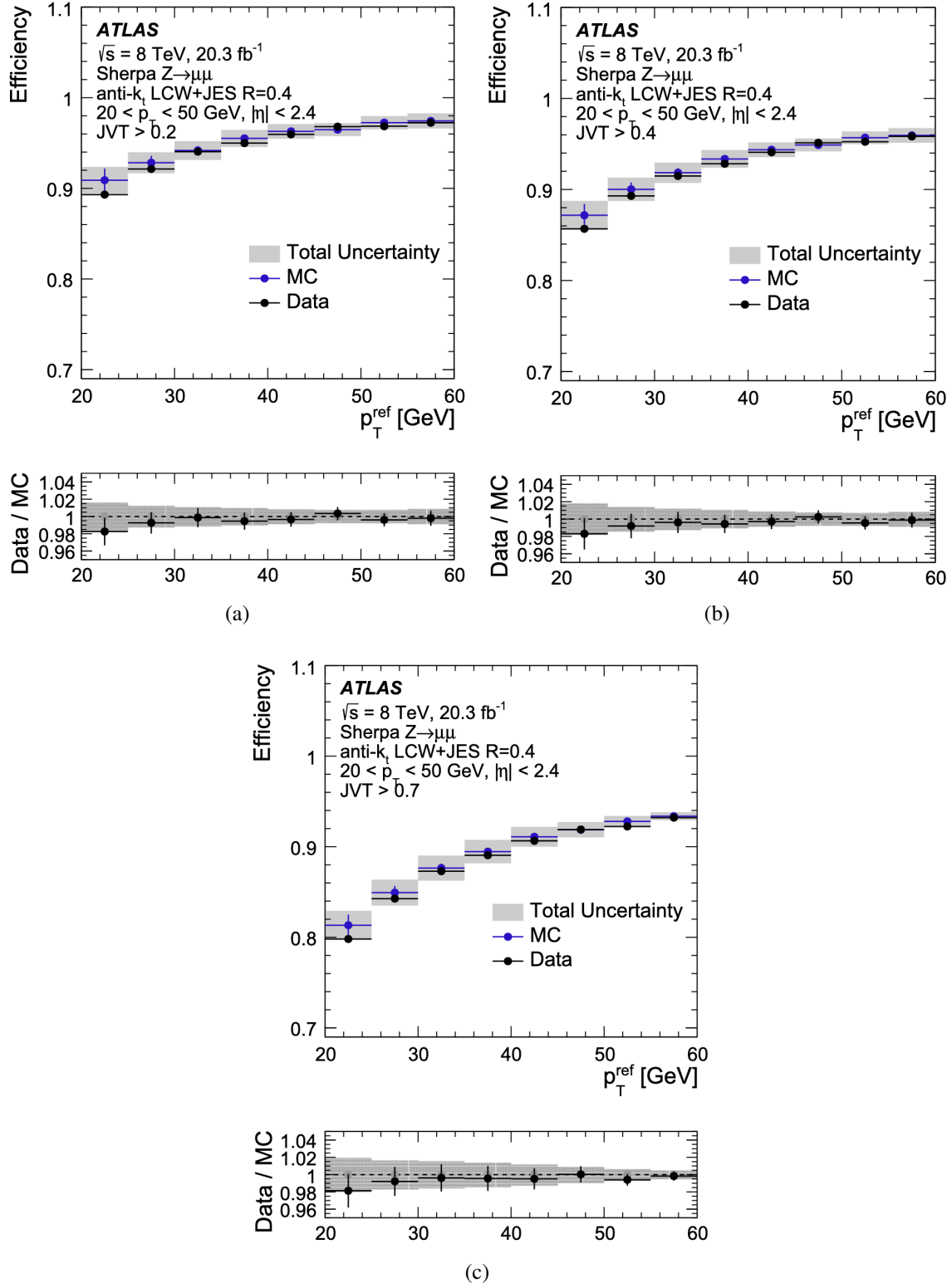


Figure 2.24: Efficiencies measured in $Z \rightarrow \mu\mu + \text{jets}$ events as a function of p_T^{ref} in data and MC simulation for JVT > 0.2 (a) JVT > 0.4 (b) JVT > 0.7 (c) where $p_T^{\text{ref}} = p_T^Z$.

vector sum of the jet ($\mathbf{p}_T^{\text{jet}}$) and the track ($\mathbf{p}_T^{\text{track}}$) transverse momenta:

$$\langle \mathbf{p}_{T,i}^{\text{miss}} \rangle = -\frac{1}{2} \left(\sum_{\text{tracks} \in \text{PV}_i} k \mathbf{p}_T^{\text{track}} + \sum_{\text{jets} \in \text{PV}_i} \mathbf{p}_T^{\text{jet}} \right). \quad (2.17)$$

The factor k accounts for intrinsic differences between the jet and track terms and is set to be 2.5 to optimize the overall rejection of forward pile-up jets. The fJVT discriminant for a given forward jet, with respect to the vertex i , is defined as the normalized projection of the missing transverse momentum on $\mathbf{p}_T^{\text{fj}}$:

$$\text{fJVT}_i = \frac{\langle \mathbf{p}_{T,i}^{\text{miss}} \rangle \cdot \mathbf{p}_T^{\text{fj}}}{|\mathbf{p}_T^{\text{fj}}|^2}, \quad (2.18)$$

where $\mathbf{p}_T^{\text{fj}}$ is the forward jet's transverse momentum. This is defined as such because the amount of missing transverse momentum in the direction of the forward jet needed for the jet to be tagged should be proportional to the jet's transverse momentum. The forward jet is therefore tagged as pile-up if its fJVT value, defined as $\text{fJVT} = \max(\text{fJVT}_i)$, is above a threshold. The fJVT discriminant tends to have larger values for *QCD pile-up jets*. The hard-scatter jet efficiency and pile-up jet efficiency in the simulated Z +jets as a function of p_T of the forward jet are shown in figure 2.25.

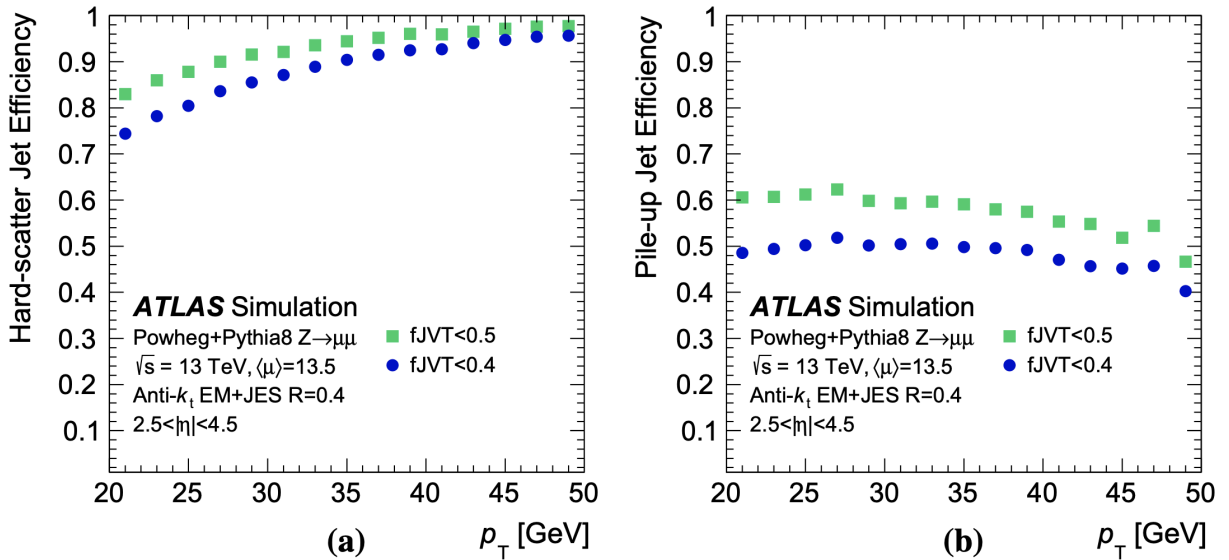


Figure 2.25: The hard-scatter jet (a) and the pile-up jet (b) reconstruction efficiencies as a function of the forward jet p_T [94].

2.3.3.4 B-tagging

The b -jets used in the analysis are tagged using the DL1 deep-learning Neural Network tagger [95]. The DL1 tagger is the high-level b -tagging algorithm based on deep feed-forward neural network (NN) trained using Keras [96] with Theano [97] backend and the Adam [98] optimizer. It has a multidimensional output corresponding to the probabilities for a jet to be b -jet, a c -jet, or a light-flavor jet. The topology of the output consists of a mixture of fully connected hidden and Maxout layers [99]. Variables related to the properties of the secondary and tertiary vertices (distance to the primary vertex, invariant mass and the number of tracks, energy, energy fraction, and rapidity of the tracks associated with the secondary and tertiary vertices). It has a smaller memory footprint compared to BDT. More details about this variable can be found in [100]. The final discriminant used is:

$$D_{\text{DL1}} = \ln\left(\frac{p_b}{f_c \cdot p_c + (1 - f_c) \cdot p_{\text{light}}}\right), \quad (2.19)$$

where p_b is the b -jet probability, p_c is the c -jet probability and light-flavour jet probability, f_c is the effective c -jet fraction in the background training sample. Figure 2.26 shows the b -tagging efficiency simulation-to-data scale factors as a function of jet p_T with 70% single-cut operating point using the DL1 tagger.

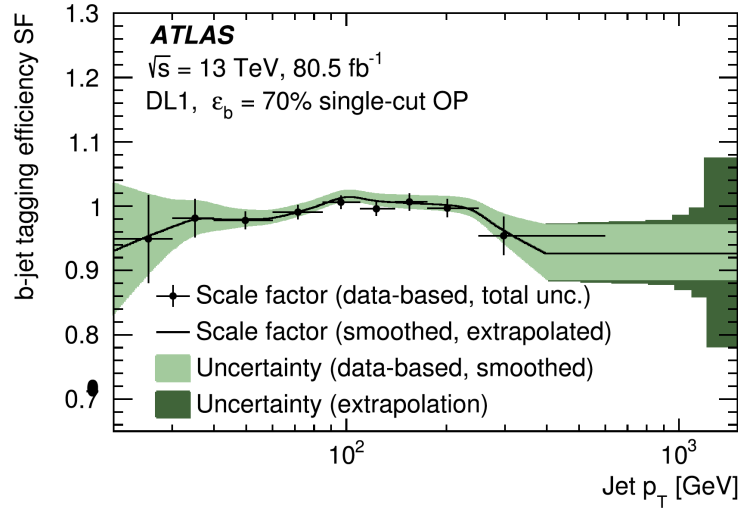


Figure 2.26: The b -tagging efficiency simulation-to-data scale factors as a function of jet p_T after smoothing [101] and extrapolation of the simulation-to-data scale factors for $p_T \geq 400$ GeV measured in high p_T bins [100].

2.3.4 Missing Transverse Energy

The missing transverse momentum of an event depends on two main terms: *hard* and *soft* [102]. The hard term includes the calibrated objects coming from the hard-scattering process. The hard term is the vectorial sum of the transverse momenta of the reconstructed and calibrated objects coming from the hard-scattering process i.e. the vectorial sum of the $E_T^{\text{miss},p}$, with $p \in \{e, \gamma, \tau_{\text{had}}, \mu, \text{jet}\}$. The soft term is exclusively reconstructed from tracks from the hard-scatter vertex, hence only using the p_T -flow from soft charged particles. This is indicative of (hadronic) recoil, consisting of the event components that would not be represented by reconstructed and calibrated particles or jets [102]. As the hard objects are all calibrated, the pile-up correction is already included in their transverse momenta. The tracks used for reconstructing the soft term come from the primary vertex and hence they are relatively robust against pile-up. Both E_T^{miss} (2.3.4) and ΣE_T (2.3.4) are used for correct evaluation and impact of different objects on the missing transverse energy calculation:

$$\mathbf{E}_T^{\text{miss}} = - \sum_{\text{selected electrons}} \mathbf{p}_T^e - \sum_{\text{accepted photons}} \mathbf{p}_T^\gamma - \sum_{\text{accepted } \tau\text{-leptons}} \mathbf{p}_T^{\tau_{\text{had}}} - \sum_{\text{selected muons}} \mathbf{p}_T^\mu - \sum_{\text{accepted jets}} \mathbf{p}_T^{\text{jet}} - \sum_{\text{unused tracks}} \mathbf{p}_T^{\text{track}}, \quad (2.20)$$

and

$$\Sigma E_T = \sum_{\text{selected electrons}} p_T^e + \sum_{\text{accepted photons}} p_T^\gamma + \sum_{\text{accepted } \tau\text{-leptons}} p_T^{\tau_{\text{had}}} + \sum_{\text{selected muons}} p_T^\mu + \sum_{\text{accepted jets}} p_T^{\text{jet}} + \sum_{\text{unused tracks}} p_T^{\text{track}}. \quad (2.21)$$

The E_T^{miss} and ΣE_T have to be reconstructed from mutually exclusive detector signals. The “signal ambiguity resolution” has to be implemented for this using a defined sequence for selected contributions with a rejection tactic based on common signal usage between different objects. The most common order used for E_T^{miss} reconstruction sequence for the hard-object contribution is as follows: electrons (e), followed by photons (γ), then hadronically decaying τ -leptons (τ_{had}) and finally jets. Muons (μ) are reconstructed using ID and MS tracks with energy loss in the calorimeter, leading to little signal overlap with other objects. Dedicated methods are used to mitigate the overlap between muons and jets and also between hard scatter tracks and jets. The jet vertex tagger algorithm (JVT) is used to tag a jet matching with tracks from pile-up(0) or from hard-scatter(1) [103] (see section 2.3.3.3). High-quality ID tracks from the hard-scatter vertex that are associated with jets rejected by overlap removal or that are associated with jets likely from pile-up (tagged by JVT) contribute to the $E_T^{\text{miss, soft}}$ term. See figure 2.27 for the reconstructed E_T^{miss} .

E_T^{miss} resolution is determined by the width of the combined distribution of the differences between the measured $E_{x(y)}^{\text{miss}}$ and the components of the true missing transverse momentum vector

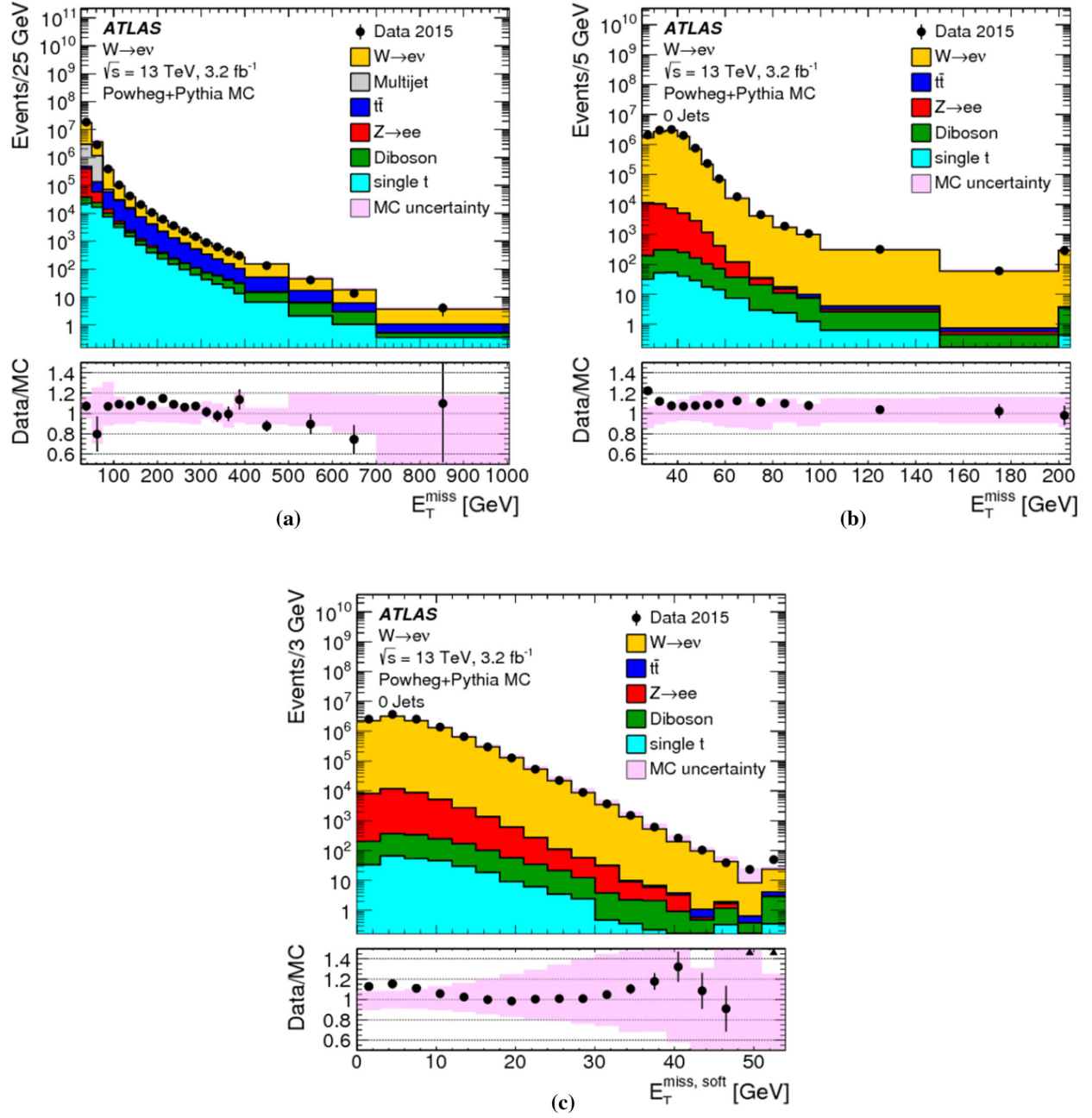


Figure 2.27: Distributions of the total E_T^{miss} in the inclusive case (a) the $N_{\text{jet}} = 0$ (b), and the soft term $E_T^{\text{miss, soft}}$ reconstructed in $N_{\text{jet}} = 0$ events (c) with $W \rightarrow e\nu$ in data. Expected MC simulation is superimposed as well including all relevant background final states. The shaded area indicates the total uncertainty for MC simulations, including the overall statistical uncertainty combined with systematic uncertainties. The last bins contain overflows [102].

$E_T^{\text{miss, true}}$ [102]. It is measured in terms of RMS 2.3.4:

$$\text{RMS}_{x,(y)}^{\text{miss}} = \text{RMS}(E_{x(y)}^{\text{miss}} - E_{x(y)}^{\text{miss, true}}). \quad (2.22)$$

Apart from some biases in this method, it is an appropriate general measure of how well E_T^{miss} represents $E_T^{\text{miss, true}}$. Dedicated inclusive $W \rightarrow e\nu$ and $W \rightarrow \mu\nu$ samples are used (along with $t\bar{t}$ MC samples). Figure 2.28 shows the E_T^{miss} resolution measured as a function of the true missing transverse momentum for events with neutrinos in the final state.

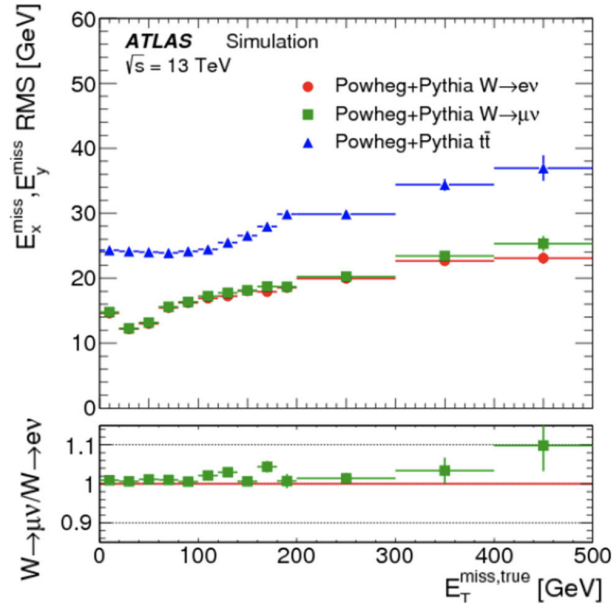


Figure 2.28: E_T^{miss} resolution measured by $\text{RMS}_{x,(y)}^{\text{miss}}$ as a function of $E_T^{\text{miss, true}}$ for $W \rightarrow e\nu$, $W \rightarrow \mu\nu$ and $t\bar{t}$ samples from MC simulations [102].

CHAPTER 3

WZ Polarization Studies

3.1 Data and Monte Carlo Samples

3.1.1 Data Samples

The data used was collected in Run 2 at the ATLAS experiment from the collisions of proton-proton (pp) performed at the LHC. It was collected between 2015 to 2018 with a center-of-mass energy of $\sqrt{s} = 13$ TeV. The data used was taken with 25 ns bunch crossing. The data passing the quality criteria based on the data-quality flags is used (this is done using Good Run List or GRL) [104]. See appendix B for the Good Run List used.

The GRL ensures the detector was operating correctly when the data was recorded. The dataset corresponds to an integrated luminosity of 140.1 fb^{-1} [105]. The newest luminosity calibration is performed which gives the corrected luminosity with an uncertainty of 0.83% [106]. It is obtained using the LUCID-2 detector [107] for the primary luminosity measurement.

3.1.2 Monte Carlo Simulated Samples

The backgrounds and the signal polarized and unpolarized samples are generated using Monte Carlo (MC) Simulation. MC samples used for signal and background estimations are shown in Appendix A.

3.1.2.1 Signal simulations for polarised WZ production

The WZ polarised samples are generated using MADGRAPH 5 [108] version 2.7.3. The Leading-Order (LO) WZ 0+1 jet samples are produced and merged and showered together using PYTHIA version 8.244 [109]. These are the samples generated with specific polarizations. These samples have $W^\pm$ and Z bosons decay to two lepton flavors (e, μ). Separate samples with at least one boson decaying to the τ lepton have been generated. Lepton filters are applied to select events where τ

decays to e or μ . Different MC samples are generated for $p_T^Z \geq 150$ GeV and $p_T^Z < 150$ GeV in order to increase statistics for events with high p_T^Z . The NNPDF3.0nlo [110] PDF sets are used for modeling the Parton Distribution Function (PDF). Many variations of these PDF sets are used to estimate the uncertainties related to the MC event generation (NNPDF30_nlo_as_0118 with 100 replicas for the PDF uncertainty calculations and 8 more variations for QCD scale uncertainty calculations. The NNPDF30_nlo_as_0119 and NNPDF30_nlo_as_0117 PDF sets are used for the calculation of the α_s uncertainty). Appendix A lists more details of the generated polarised samples. Events passed through Pythia showering (after merging and hadronization) are used for truth-level studies. After that, the events are also passed through the detailed GEANT simulation of the ATLAS detector. A detailed description of what a PDF set is can be found in section 3.6.1.

3.1.2.2 Signal simulations for unpolarised WZ production

Inclusive WZ events with W and Z bosons unpolarized were generated at Next-to-Leading Order (NLO) in QCD with POWHEG+PYTHIA8 and MADGRAPH+PYTHIA. These samples are used to cross-check the modeling of the polarized WZ samples.

Inclusive unpolarized WZ events were generated with POWHEG+PYTHIA8 with NLO QCD matrix elements matched to parton showers (PS). The CT10NLO PDF set is used for the hard-scattering process, while the CTEQ6L1 PDF set is used for the PS.

An alternative MC sample is generated at NLO in QCD with MADGRAPH and PYTHIA 8, and merged by the FxFx scheme [111] with processes including one or two extra jets (also at NLO): $pp \rightarrow WZ + j \rightarrow \ell\nu\ell\ell + j$ and $pp \rightarrow WZ + 2j \rightarrow \ell\nu\ell\ell + 2j$. The jets had a minimum p_T of 10 GeV and the merging scale, k_T , (q_{Cut}) was set at 25 GeV. The PDF set used is NNPDF3.0. The default dynamic renormalization and factorization scale set by MADGRAPH (option “-1”) was used.

For the generation of pseudodata, the SHERPA 2.2.2 MC event generator can model WZ events with up to one parton at NLO and 2 to 3 partons at LO. Generator level cuts require $m_{\ell\ell} > 4$ GeV, $p_T(\ell_1) > 5$ GeV, $p_T(\ell_2) > 5$ GeV. The SHERPA generator [112–119] provides full modeling of high-energy pp collisions, including hard-scattering, parton shower, hadronization and underlying event. In the generation of this sample, diagrams with a larger number of partons in the final state, are weighted down. This results in a larger number of MC events for higher parton numbers and therefore smaller statistical uncertainties in phase spaces dominated by diagrams with more than 1 parton. This sample is generated using the NNPDF3.0 PDF. The default dynamic renormalization and factorization scale set internally by SHERPA is used.

3.1.2.3 Simulations for prompt background processes

The background processes come from physics processes with one misidentified lepton or from three or more prompt leptons. The former is estimated using data-driven techniques (see section 3.5.2). Main irreducible backgrounds for this analysis:

1. ZZ : Both $q\bar{q}$ -initiated and gg -initiated events are generated using SHERPA 2.2.2. The central PDF set used is NNPDF3.0NNLO. This is generated using the matrix element calculation accurate to NLO QCD for 0 and 1 jet and LO for 2 and 3 jets.
2. $t\bar{t}Z$ and $t\bar{t}W$: generated at NLO in QCD using the MADGRAPH5_AMC@NLO MC generator with the NNPDF3.0NNLO PDF set and hadronization using pythia.
3. VVV : Triboson events were simulated by the SHERPA 2.2.2 event generator at NLO accuracy with 0 additional partons and at LO accuracy with one and two additional partons.
4. $t\bar{t}$: generated at NLO with the POWHEG + PYTHIA 8, using NNPDF3.0 in the event generation and NNPDF2.3 in the simulation of the shower. The h_{damp} parameter that controls the emission of the first gluon is set to 1.5 times the top-quark mass. The A14 tune together with NNPDF2.3LO PDF set is applied for PYTHIA 8 showering.
5. $Z\gamma$ and $W\gamma$: generated with SHERPA version 2.2.2 at next-to-leading order NLO accuracy using the NNPDF3.0NNLO PDF set.
6. $Z + j$: generated with the POWHEG+PYTHIA MC generator at NLO using the CT10 PDF set. For the modeling of the parton shower, PYTHIA 8 is used with the AZNLO tune [120]. In order to simulate the final QED radiation, the samples are interfaced to Photos++ [121].
7. Electroweak WZ production, $WZjj$ -EW, arising at the order α_{EW}^6 electroweak processes is also considered as a background and not part of the measured signal. This is generated at LO accuracy using MADGRAPH + PYTHIA 8. The PDF set used is NNPDF3.0NNLO. In the simulation of the parton shower, the NNPDF2.3 PDF set is used.

3.2 Generator Level Studies

3.2.1 Phase Spaces

As the goal of the analysis is to measure the polarization fractions (especially the diboson longitudinal-longitudinal polarization) in a region where WZ is produced predominantly in the s -channel, two high p_T signal regions are decided upon as shown in table 3.1. The selections combining the first five rows in the table are used in the joint polarization studies in the inclusive

phase space [122]. The last two rows show the added selections, particularly for this analysis. The lower p_T^{WZ} criterion is important to reduce jet activities in the events as it is needed to enhance the 00 contributions taking advantage of the RAZ (see section 1.3.2). The cut of $p_T^{WZ} < 70$ GeV was decided based on the studies done by the theorists ([24] and [34]) (also see figure 1.6). The idea was to measure polarization fractions as a function of the p_T^Z cut. However, due to statistical limitations, it was decided to use two different cuts $p_T^Z > 100$ (200) GeV.

	Variable	Fiducial region selection
Inclusive Analysis Phase Space	Lepton $ \eta $	< 2.5
	p_T of ℓ_Z , p_T of ℓ_W [GeV]	$> 15, > 20$
	$m_{\ell\ell}$ range [GeV]	$ m_{\ell\ell} - m_Z < 10$
	m_T^W [GeV]	> 30
	$\Delta R(\ell_Z^-, \ell_Z^+)$, $\Delta R(\ell_Z, \ell_W)$	$> 0.2, > 0.3$
High p_T Analysis Phase Space	p_T^{WZ} [GeV]	< 70
	p_T^Z [GeV]	> 100 (200)

Table 3.1: Definition of the two 00-enhanced fiducial phase spaces used.

For studying the RAZ effect, no p_T^Z cut was applied. However, several p_T^{WZ} cuts are chosen to measure this effect as a function of decreased jet activity. The phase space definition can be found in table 3.2.

Variable	Fiducial region selection
Lepton $ \eta $	< 2.5
p_T of ℓ_Z , p_T of ℓ_W [GeV]	$> 15, > 20$
$m_{\ell\ell}$ range [GeV]	$ m_{\ell\ell} - m_Z < 10$
m_T^W [GeV]	> 30
$\Delta R(\ell_Z^-, \ell_Z^+)$, $\Delta R(\ell_Z, \ell_W)$	$> 0.2, > 0.3$
p_T^{WZ} [GeV]	four regions with $< 10, < 20, < 40, < 70$

Table 3.2: Definition of the four Radiation Amplitude Zero fiducial phase spaces used.

The phase space definition (fiducial phase space) depends on the particle-level object definitions and recommendations agreed upon in the ATLAS analysis [123]. This is to remove detector effects on the measurements and establish a fair way of comparison between the experimental measurements and the theoretical predictions. This leads to particle-level object definitions which are very close to the experimentally reconstructed objects and kinematic and geometrical acceptances.

The phase space definitions are listed below:

1. The leptons selected should be prompt leptons i.e. leptons that are not produced in the decay of a hadron or a τ lepton or their descendants. There are three types of prompt leptons defined:

Born, Bare, and Dressed. The prompt photons or lepton-associated photons are defined as the photons produced in hard-scattering processes, photons produced as initial state radiations from quarks involved in hard-scattering processes, and photons from resonance decays like $H \rightarrow \gamma\gamma$ [123].

The born leptons are those prior to Quantum Electrodynamics (QED) Final State Radiation (FSR). The bare leptons are those after QED FSR. The leptons that are used in this analysis are dressed leptons. A cone of $\Delta R < 0.1$ is used for clustering all photons around the direction of the bare lepton, forming a lepton after partial QED radiation recovery. The protocol is to use all leptons not from hadron decays. This definition is shown to have reduced the contribution of Initial State Radiation (ISR) photon energy to dressed lepton energy significantly. Dressed leptons are designed to be the closest to the measurement in the electron channel. Since the majority of QED FSR photons are collinear and close to the electromagnetic cluster, the ATLAS reconstruction algorithm will combine the energies of the bare electron and the photons as the energy of the reconstructed electron cluster [124].

2. The final state prompt leptons are associated to the parent W or Z boson using an algorithmic approach (called the “resonant shape” algorithm) based on an estimator conserving charge and lepton flavor. This tries to reduce the bias that comes from associating prompt leptons to parents by only using reconstructed Z mass and not W mass (as there are larger uncertainties associated with it) [125].

In this algorithm, all possible combinations of $(\nu - \ell)$ that satisfy lepton number conservation and all possible combinations of pairs of Same-Flavor Opposite-Sign (SFOS) leptons are formed and the invariant mass of each combination is calculated. At most there are two possible combinations. A probability is calculated for every combination using the following formula:

$$P_k = \left(\frac{1}{M_{(\ell\ell)k}^2 - M_Z^2 + i\Gamma_Z M_Z} \right)^2 \times \left(\frac{1}{M_{(\ell\nu)k}^2 - M_W^2 + i\Gamma_W M_W} \right)^2, \quad (3.1)$$

where $k = 1, 2$. The final choice is based on the highest value of P_k .

3. The leptons should satisfy the pseudorapidity requirement of $|\eta| < 2.5$ because the inner tracking detector covers this pseudorapidity range.
4. The transverse mass of the W boson is defined as follows:

$$m_T^W = \sqrt{2p_T^\ell p_T^\nu (1 - \cos \Delta\phi)}, \quad (3.2)$$

This definition is detector friendly as it is invariant under the Lorentz boost along the z -

direction. The $\Delta\phi$ is the angle between the lepton and neutrino from the decay of the W boson measured in the transverse plane.

5. The lepton p_T cut depends on the reconstruction and isolation efficiencies of electrons and muons.
6. $\Delta R(\ell_Z^-, \ell_Z^+) > 0.2$ and $\Delta R(\ell_Z, \ell_W) > 0.3$: these selections are applied to make sure the leptons do not overlap creating ambiguity for the nature or source of those leptons.

3.2.2 Polarized Event Generation

The best possible event generator to emulate real physics is the NLO generator. There are several generators available that can produce WZ events with NLO QCD precision (not NLO QCD+EW precision) e.g. `MADGRAPH` `SHERPA` `POWHEG`, etc. However, it wasn't possible until 2020 to generate specifically polarized events. Now `MADGRAPH` version 2.7.0 onwards, the diboson events can be produced associated with specific polarizations [126]. But NLO QCD or EW (Electroweak) corrections cannot be included in this `MADGRAPH` framework. A few theorists published NLO QCD (see [127]) and NLO QCD+EW (see [128–130]) calculations and provided us the corrections for our specific phase space requirements.

Longitudinal (0) and transverse (T) polarization states of W and Z bosons can be simulated, but not for left (L) and right (R) transverse polarization states for the intermediate particles. To emulate the NLO effect using the polarized sample generator we have, $WZ + 0$ and 1 jets are produced together at Leading Order and later merged using `PYTHIA`. The event generation calculations consist of matrix element calculations of the jet emissions and the parton shower calculations for softer emissions up to a few GeV scale where the perturbation theory breaks down. A merging scheme is used to avoid the double counting of the radiation emissions while combining the cases with multiple real emissions included at the tree level. The merging algorithm vetos parton shower emissions that overlap with the matrix element calculation. The two samples in our case are merged together using CKKW-scheme [115, 131]. If an event (with additional emissions on top of the born process in the matrix-element calculation) includes an emission below a merging scale, the event is vetoed. And on the other hand, if the event has a non-maximal number of considered emissions, the parton shower emissions above the merging scale are vetoed. This veto removes the double-counting. The merging scale used in this analysis is 25 GeV. In the original CKKW-scheme, the Sudakov form factors to correct for the non-emission probabilities are derived analytically. An extension of this scheme, the CKKW-L scheme generates the Sudakov form factors dynamically

from the shower by vetoing events rather than emissions, which is more flexible [132]:

$$pp > W^\pm\{X\}Z\{Y\} > W^+ > \ell^+ \nu_\ell, W^- > \ell^- \bar{\nu}_\ell, Z > \ell^+ \ell^-, \quad (3.3)$$

$$pp > W^\pm\{X\}Z\{Y\}j > W^+ > \ell^+ \nu_\ell, W^- > \ell^- \bar{\nu}_\ell, Z > \ell^+ \ell^-. \quad (3.4)$$

Here, X and Y can be 0 (longitudinal) or T (transverse). The polarization fractions are not Lorentz invariant, hence the polarization fractions have to be measured in a particular frame. The natural frames for this are the laboratory frame and the di-boson center-of-mass frame. It is called the Modified Helicity frame. The definition of this frame can be seen in figure 3.1.

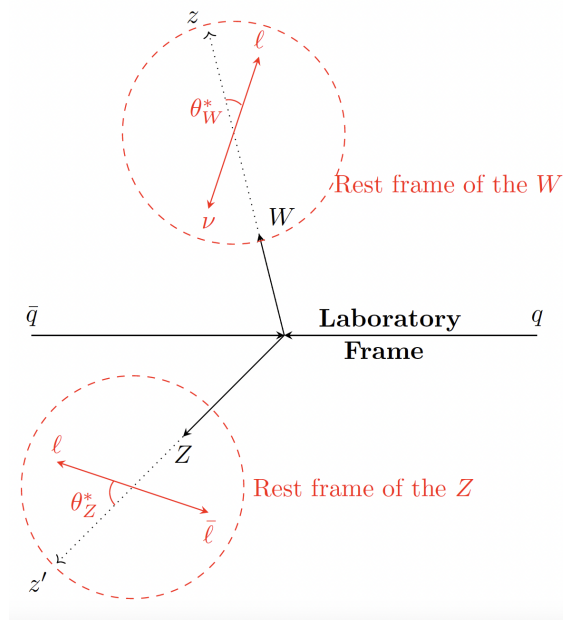
A RIVET analysis [133] is used to perform a truth level analysis with “dressedLeptons” after PYTHIA parton shower.

3.2.3 Variable Definitions

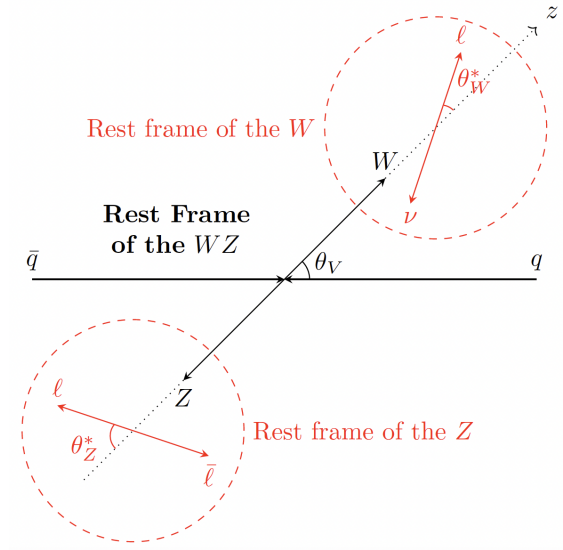
A lot of kinematic variables are looked at for studying the different polarization states. All these variables can be reconstructed including the neutrino p_z which is calculated using the W mass constraint. These variables include lepton p_T , η and ϕ , E_T^{miss} , the transverse momentum of the W boson (p_T^W), the transverse momentum of the Z boson (p_T^Z), the W boson transverse mass (m_T^W), the Z boson invariant mass (M_Z), the transverse mass of the WZ system (m_T^{WZ}), the transverse momentum of the WZ system (p_T^{WZ}), the invariant mass of the WZ system (m^{WZ}), and the R_{21} variable which is defined as $R_{21} = p_T^{V_2}/p_T^{V_1}$ where $p_T^{V_2} \leq p_T^{V_1}$.

There are some important angular variables that are sensitive to the polarization of the vector bosons. One of those is the $\cos\theta_W$ calculated in the WZ rest frame, where θ_W refers to the angle between the W boson in the WZ rest frame with respect to the positive lab z -axis. Other important variables which carry the polarization information are the lepton angular variables $\cos\theta_\ell^*$ is defined as the cosine of the decay angle θ^* of the charged lepton produced in the decay of the W or Z boson. For the Z decay, the negatively-charged lepton angle is used. These angular variables have to be defined in a particular frame (specifically the frame in which the polarization is defined i.e. the WZ rest frame). See figure 3.1 to see the definitions of variables in two different frames: The helicity frame (see figure 3.1a) or the laboratory frame and the Modified Helicity frame (see figure 3.1b).

The lepton decay angles in this analysis are calculated in the *Modified Helicity Frame*. For the diboson polarization measurement, it is interesting to have the same z -axis for both bosons. This allows us to talk meaningfully of correlations between the polarization of bosons, both being longitudinal along the same axis. Figure 3.2 shows the $\cos\theta_\ell^*(W)$ and $\cos\theta_\ell^*(Z)$ distributions respectively for events with the other boson unpolarized in the 00-enhanced fiducial phase-space.



(a)



(b)

Figure 3.1: Definition of $\cos\theta_\ell^*$: in the helicity frame (a) and in the modified helicity frame (b).

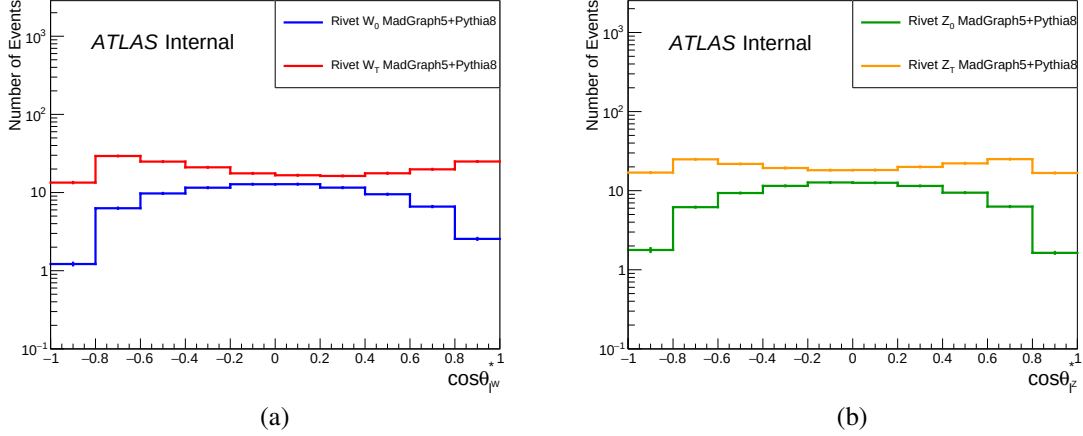


Figure 3.2: Distributions (in 00-enhanced phase space of $p_T^Z > 200$ GeV) of $\cos\theta_\ell^*(W)$ for two polarizations of the W boson (0 and T) with the Z boson unpolarized (a), $\cos\theta_\ell^*(Z)$ for two polarizations of the Z boson (0 and T) with the W boson unpolarized (b).

The computation of this angle is, however, not straightforward in data because of the big uncertainty on the measurement of the momentum of neutrino in the z direction. This affects strongly the reconstruction of the $\cos\theta_\ell^*$ variable for the W boson, but also the $\cos\theta_\ell^*$ of the Z boson, because of the boost in the WZ rest frame of the *Modified Helicity Frame*.

Other angular variables include the angle between the direction of the boson in the WZ rest frame with respect to the direction of the WZ system ($\cos\theta_V$), the rapidity difference between the W boson and the Z boson (ΔY_{WZ}), the rapidity difference between the lepton from the W decays and the Z boson ΔY_{3Z} , ϕ difference between the lepton from the W decays and the negatively-charged lepton from the Z decays ($\Delta\Phi(\ell_W, \ell_Z)$).

3.2.4 Truth Level Studies

Figures 3.3 and 3.4 show the distributions of $\cos\theta_W$, the scattering angle of the $W^\pm$ boson in the lab frame (figure 3.3) and the WZ rest frame (figure 3.4) respectively with respect to the positive lab z -axis after different selection criteria mentioned in table 3.1. In the 00-enhanced region, the W_0Z_0 contribution is higher for the $\cos\theta_W$ calculated in the WZ rest frame. For the rest of this note, if unspecified, θ_W refers to the angle between the W boson in the WZ rest frame with respect to the positive lab z -axis.

Figure 3.5 shows the $\cos\theta_W$ distributions for 0-jet and 1-jet events respectively. It can also be seen that the 0-jet events show a high fraction of W_0Z_0 events in the central region of $\cos\theta_W$ in all the selection criteria, whereas, the 1-jet events show lower fractions of W_0Z_0 , which improve as we

apply different selections and go into the 00-enhanced phase-space.

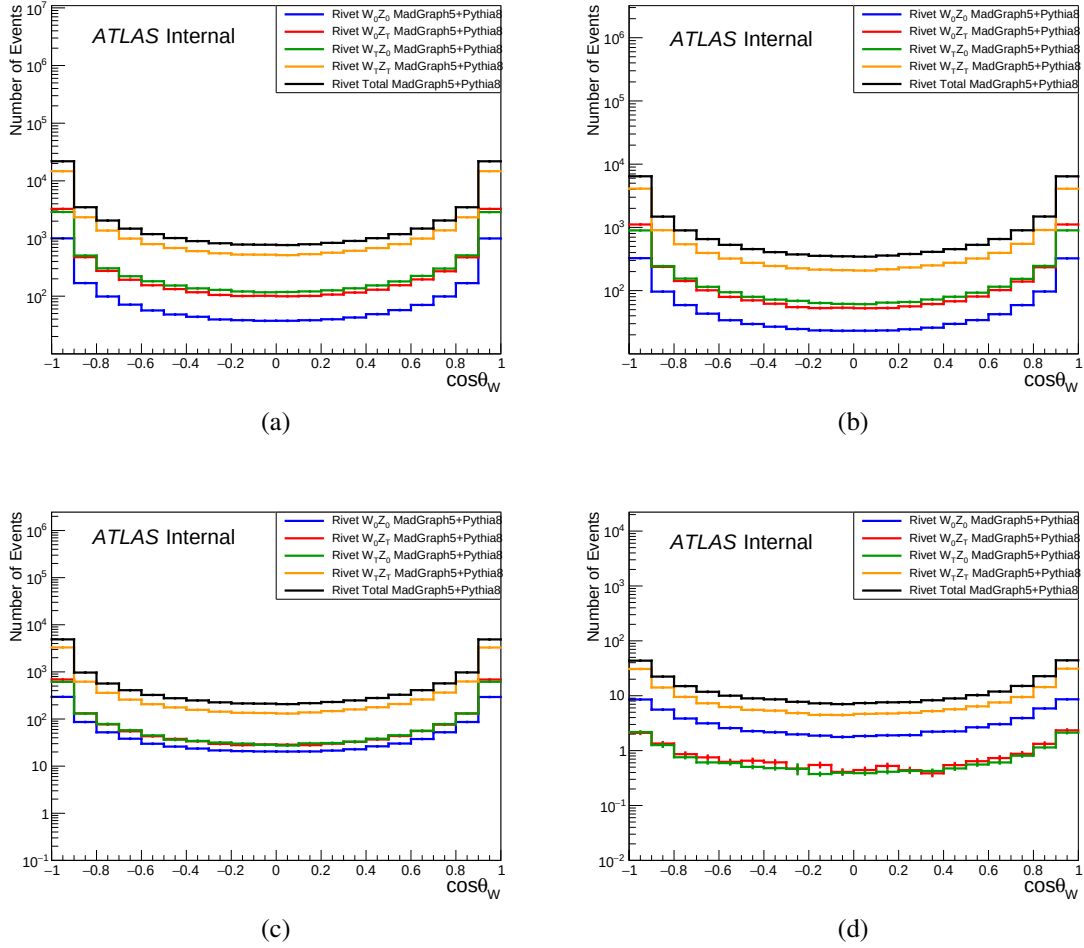


Figure 3.3: $\cos\theta_W$ distribution in the lab frame for all 4 diboson polarizations and their sum: after selecting events with possible truth level W and Z candidates but no selection cuts applied (a), after the selection cuts for inclusive phase-space defined in table 3.1 (b), after the $p_T^{WZ} < 70$ GeV cut (c), and after the $p_T^Z > 200$ GeV cut (d).

The single boson polarisation fractions are calculated as follows:

$$f_0^W = \frac{\sigma_{00} + \sigma_{0T}}{\sigma_{00} + \sigma_{0T} + \sigma_{T0} + \sigma_{TT}}, \quad (3.5)$$

$$f_T^W = \frac{\sigma_{T0} + \sigma_{TT}}{\sigma_{00} + \sigma_{0T} + \sigma_{T0} + \sigma_{TT}}, \quad (3.6)$$

$$f_0^Z = \frac{\sigma_{00} + \sigma_{T0}}{\sigma_{00} + \sigma_{0T} + \sigma_{T0} + \sigma_{TT}}, \quad (3.7)$$

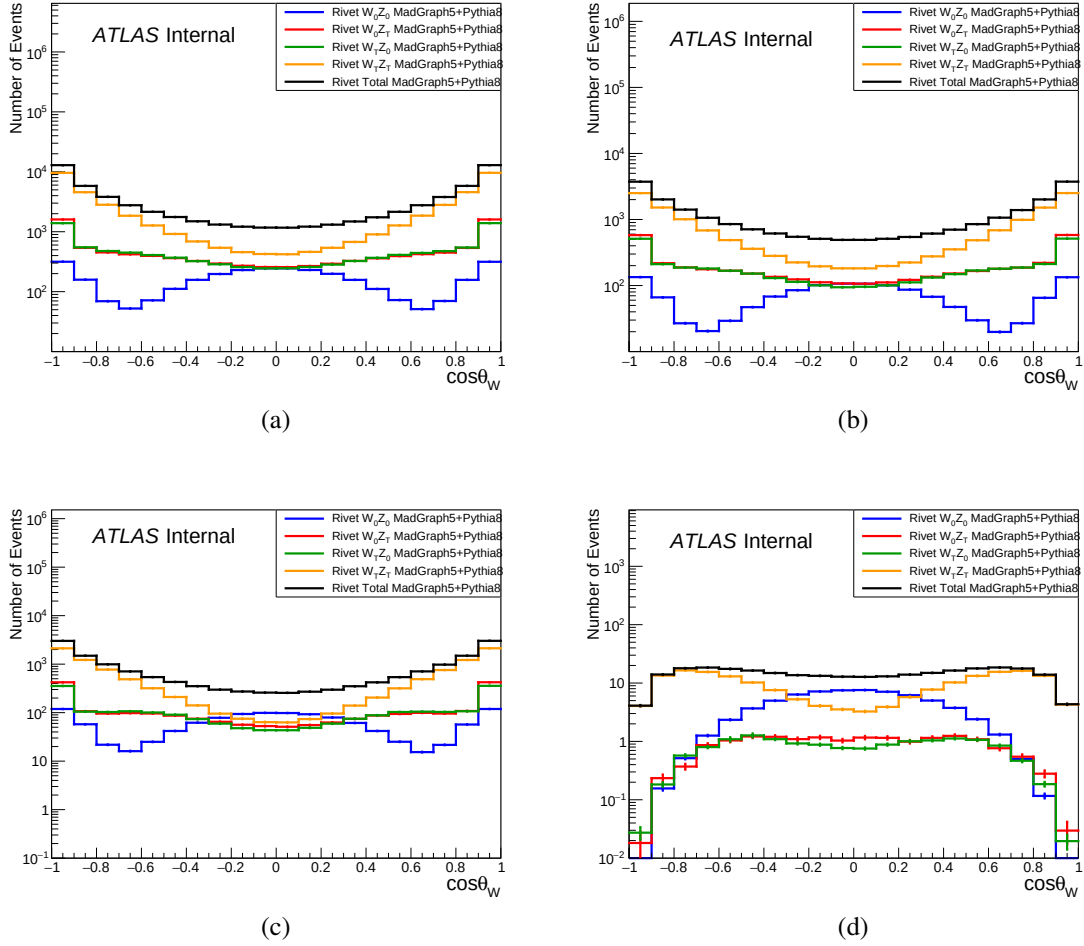
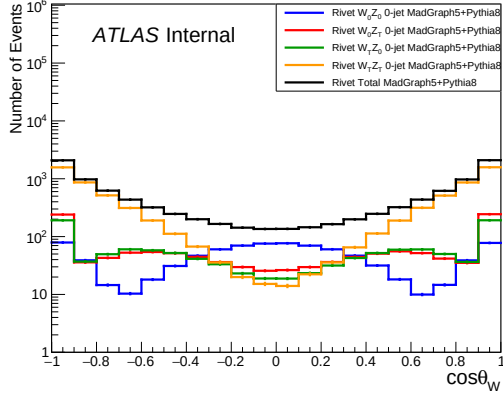
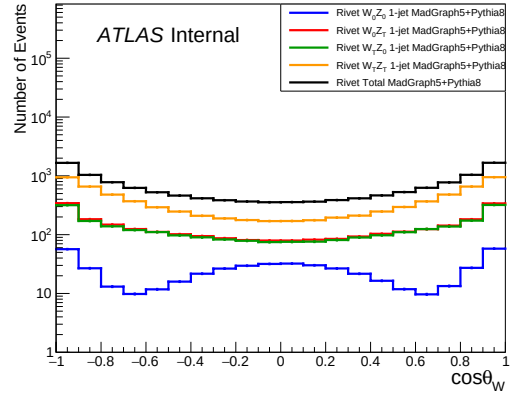


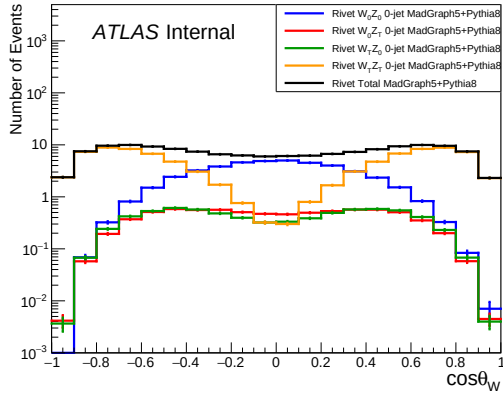
Figure 3.4: $\cos \theta_W$ distribution in the WZ rest frame for all 4 diboson polarizations and their sum: after selecting events with possible truth level W and Z candidates but no selection cuts applied (a), after the selection cuts for inclusive phase-space defined in table 3.1 (b), after the $p_T^{WZ} < 70$ GeV cut (c), and after the $p_T^Z > 200$ GeV cut (d). Events with 0 jets and 1 jet are merged using PYTHIA.



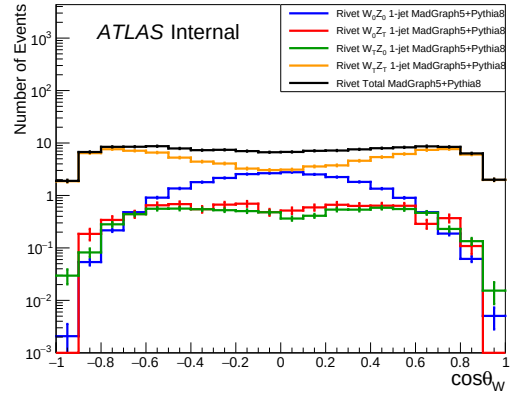
(a)



(b)



(c)



(d)

Figure 3.5: $\cos\theta_W$ distribution in the WZ rest frame for all 4 diboson polarizations and their sum. After the selection cuts for the inclusive phase-space defined in table 3.1 $WZ + 0$ jets (a) and $WZ + 1$ jets (b), and in the the $p_T^Z > 200$ GeV signal region with $WZ + 0$ jets (c) and $WZ + 1$ jets (d).

$$f_T^Z = \frac{\sigma_{0T} + \sigma_{TT}}{\sigma_{00} + \sigma_{0T} + \sigma_{T0} + \sigma_{TT}}, \quad (3.8)$$

where σ_{00} (σ_{TT}) is the cross section for events with both bosons longitudinally-polarized (transversely-polarized), σ_{0T} is the cross section for events where the W boson is longitudinally-polarized and the Z boson is transversely-polarized, while σ_{T0} is the cross section for events where the W boson is transversely-polarized and the Z boson is longitudinally-polarized. $f_{L/R}^W$ and $f_{L/R}^Z$ cannot be calculated using the WZ polarised samples because it is not possible to use MadGraph to generate polarised samples yet with W and Z bosons with left and right polarisations.

The diboson polarisation fractions are calculated as follows:

$$f_{00} = \frac{\sigma_{00}}{\sigma_{00} + \sigma_{0T} + \sigma_{T0} + \sigma_{TT}}, \quad (3.9)$$

$$f_{0T} = \frac{\sigma_{0T}}{\sigma_{00} + \sigma_{0T} + \sigma_{T0} + \sigma_{TT}}, \quad (3.10)$$

$$f_{T0} = \frac{\sigma_{T0}}{\sigma_{00} + \sigma_{0T} + \sigma_{T0} + \sigma_{TT}}, \quad (3.11)$$

$$f_{TT} = \frac{\sigma_{TT}}{\sigma_{00} + \sigma_{0T} + \sigma_{T0} + \sigma_{TT}}. \quad (3.12)$$

Table 3.3 shows the expected number of events at 140.1 fb^{-1} of data and polarization fractions with no cut applied, in the inclusive phase-space, after $p_T^{WZ} < 70 \text{ GeV}$ and in the two 00-enhanced fiducial phase spaces as defined in Table 3.1. The 00 fraction is 5.7% in the inclusive phase space, and it increases to 16.1% with the cuts $p_T^{WZ} < 70 \text{ GeV}$ and $p_T^Z > 100 \text{ GeV}$. The fraction further increases to 23.7% if the p_T^Z cut is increased to 200 GeV.

To observe the RAZ effect, the rapidity difference distributions defined as ΔY_{WZ} and ΔY_{3Z} (which is the rapidity difference between the W lepton and the Z boson) have to look for TT events. The measure of the RAZ effect is defined by the dip in these distributions in terms of the “depth” variable:

$$\mathcal{D} = 1 - \frac{N(|\Delta Y| < 0.5)}{N(0.5 < |\Delta Y| < 1.5)/2}, \quad (3.13)$$

where $N(|\Delta Y| < 0.5)$ and $N(0.5 < |\Delta Y| < 1.5)$ indicate a number of TT events with ΔY_{3Z} (or ΔY_{WZ}) less than 0.5 and between 0.5 and 1.5, respectively. The factor of two in the denominator is to make sure the same rapidity difference range is used for both the denominator and numerator. If $N(|\Delta Y| < 0.5) = N(0.5 < |\Delta Y| < 1.5)/2$, then $\mathcal{D} = 0$. A larger depth value indicates a deeper dip observed (if $\mathcal{D} > 0$ then there is a dip).

The depth variable is calculated for four different signal regions defined in table 3.2. As the p_T^{WZ} cut

Selection cut	Polarization	Cross-section (pb)	No. of expected events			Fraction
			Total	0-jet	1-jet	
Without any cuts	W_0Z_0	0.0229	3214	2127	1103	4.7%
	W_0Z_T	0.0701	9825	3333	6511	14.3%
	W_TZ_0	0.0678	9496	3029	6482	13.8%
	W_TZ_T	0.330	46259	25472	20834	67.2%
Inclusive phase-space	W_0Z_0	0.00978	1370	888.9	490.5	5.7%
	W_0Z_T	0.0280	3924	1229	2698	16.4%
	W_TZ_0	0.0264	3699	1130	2566	15.5%
	W_TZ_T	0.106	14873	7415	7487	62.3%
$p_T^{WZ} < 70$ GeV	W_0Z_0	0.00875	1225.62	887.2	346.8	7.3%
	W_0Z_T	0.0165	2306	1228	1082	13.8%
	W_TZ_0	0.0155	2175	1129	1041	13.0%
	W_TZ_T	0.0785	10992	7403	3598	65.8%
$p_T^Z > 200$ GeV	W_0Z_0	0.000485	67.95	43.4	24.51	23.7%
	W_0Z_T	0.000119	16.64	7.56	9.14	5.8%
	W_TZ_0	0.000107	15.0	7.28	7.83	5.2%
	W_TZ_T	0.00133	186.6	88.40	99.26	65.2%
$p_T^Z > 100$ GeV	W_0Z_0	0.00258	361.4	252.1	109.2	16.1%
	W_0Z_T	0.00176	246.0	118.4	126.8	11.0%
	W_TZ_0	0.00160	224.3	115.9	109.7	10.0%
	W_TZ_T	0.0100	1407	703.0	700.8	62.9%

Table 3.3: Expected number of events corresponding to an integrated luminosity of 140.1 fb^{-1} with $WZ \rightarrow \ell \nu \ell \ell$ ($\ell = e, \mu$) in the final state (τ decays are not included) using a Rivet routine at the truth level. The cross-section numbers shown here are for merged LO 0 + 1 jet events. The NLO/LO scale factor is not applied. Effects due to detector resolutions and object identification efficiencies are not included.

is tightened, more and more jet activity is removed, which gives a higher value of the depth variable. At the truth level, the dips in the ΔY_{WZ} distributions are deeper than those in the ΔY_{3Z} distribution. The depth versus p_T^{WZ} cut is shown in figure 3.6. The depth value for (only TT) ΔY_{WZ} distribution is $\sim 0.6 - 0.8$ and for (only TT) ΔY_{3Z} distribution is $\sim 0.27 - 0.36$. This is mainly because the W boson carries more information about the polarization than just the lepton from the decay.

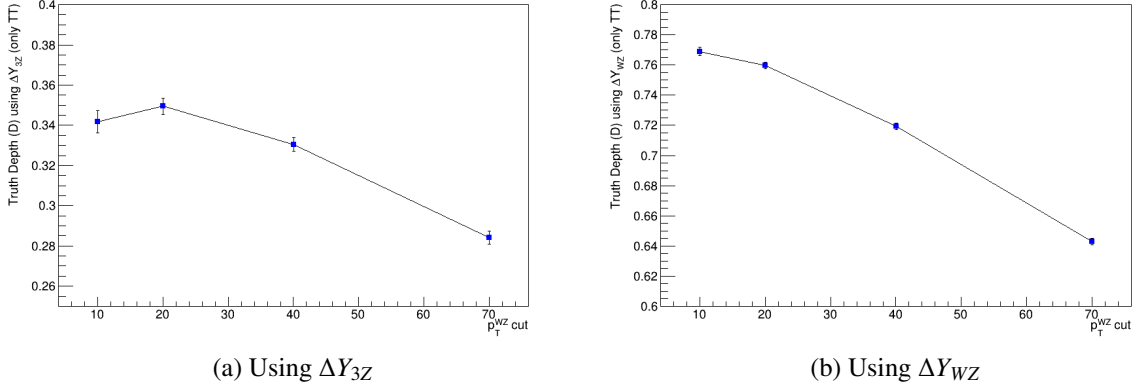


Figure 3.6: Truth Depth versus p_T^{WZ} cut using ΔY_{3Z} (a) and ΔY_{WZ} (b) distributions.

Table 3.4 shows the expected number of events at 140.1 fb^{-1} of data and polarization fractions after $p_T^{WZ} < 10, 20, 40$ and 70 GeV as defined in table 3.2.

Selection cut	Cross-section (pb)	No. of exp events	Depth (ΔY_{3Z})	Depth (ΔY_{WZ})
$p_T^{WZ} < 10 \text{ GeV}$	0.0233	3270	0.342	0.769
$p_T^{WZ} < 20 \text{ GeV}$	0.0424	5943	0.349	0.760
$p_T^{WZ} < 40 \text{ GeV}$	0.0635	8897	0.330	0.719
$p_T^{WZ} < 70 \text{ GeV}$	0.0785	10992	0.284	0.643

Table 3.4: In the RAZ regions, Expected number of events and the depth calculations corresponding to an integrated luminosity of 140.1 fb^{-1} with $WZ \rightarrow \ell \nu \ell \ell$ ($\ell = e, \mu$) in the final state (τ decays are not included) using a Rivet routine at the truth level. The cross-section numbers shown here are for merged LO 0 + 1 jet events. The NLO/LO scale factor is not applied. Effects due to detector resolutions and object identification efficiencies are not included.

3.2.4.1 Comparison with the NLO inclusive sample at the truth level

The sum of the four diboson polarised samples was compared to the NLO samples of POWHEG+PYTHIA8 [134, 135], MADGRAPH aMC@NLO [108, 136–138], and SHERPA [139, 140] samples. Figure 3.7 shows only shape comparisons between different NLO

generators for variables p_T^{WZ} , R_{21} (defined as the ratio of the subleading boson p_T and the leading boson p_T), lepton p_T and p_T^Z after the $p_T^Z > 200$ GeV selection. Figure 3.8 shows more comparisons for other kinematic variables (lepton η , ΔY_{WZ} , $\cos\theta_W$, and $\cos\theta_\ell(W)$) between NLO and LO in the 00-enhanced phase-space. It is shown that the sum of the polarized samples can describe the NLO effect well.

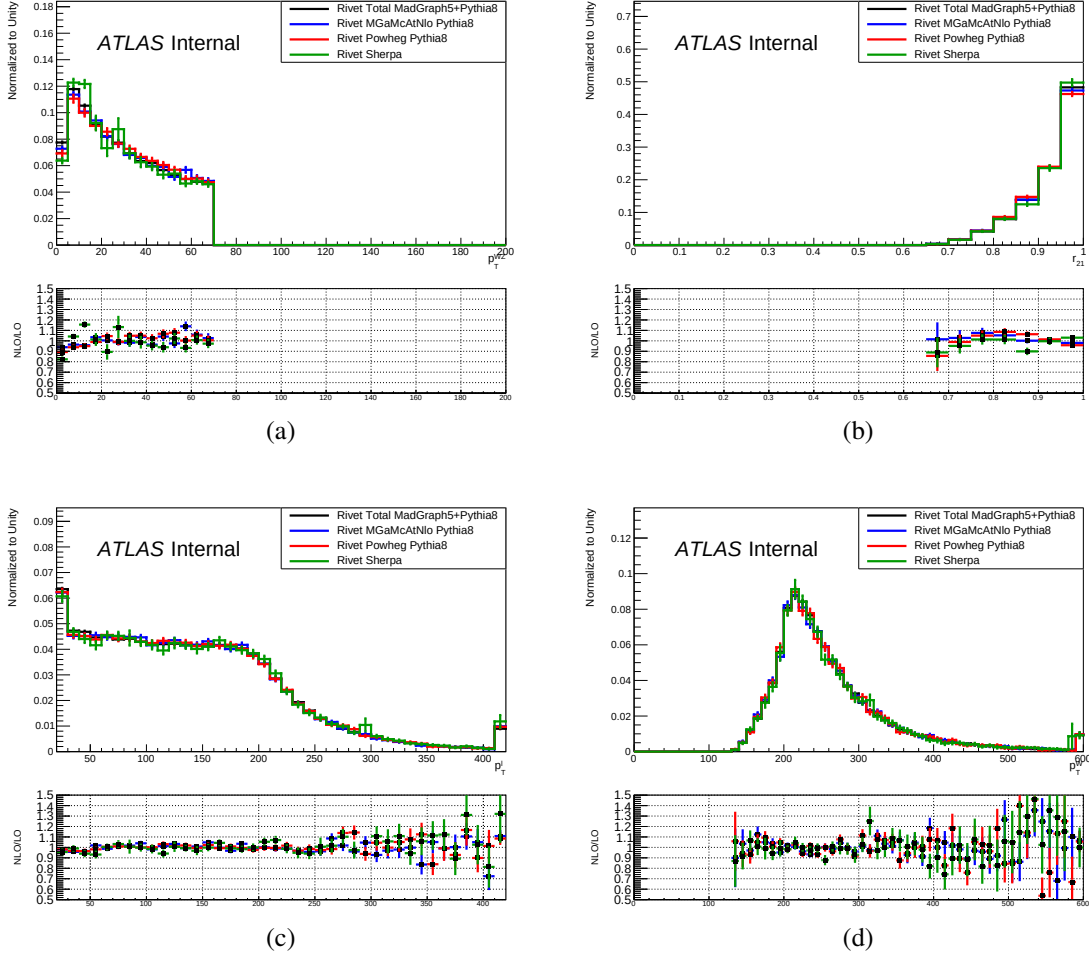


Figure 3.7: Comparison between NLO (POWHEG+PYTHIA8, MADGRAPH aMC@NLO and SHERPA) and the sum of LO polarized samples for p_T^{WZ} (a) and R_{21} (b) in the W_0Z_0 enhanced phase space, p_T for all the three leptons (c), and p_T^W (d).

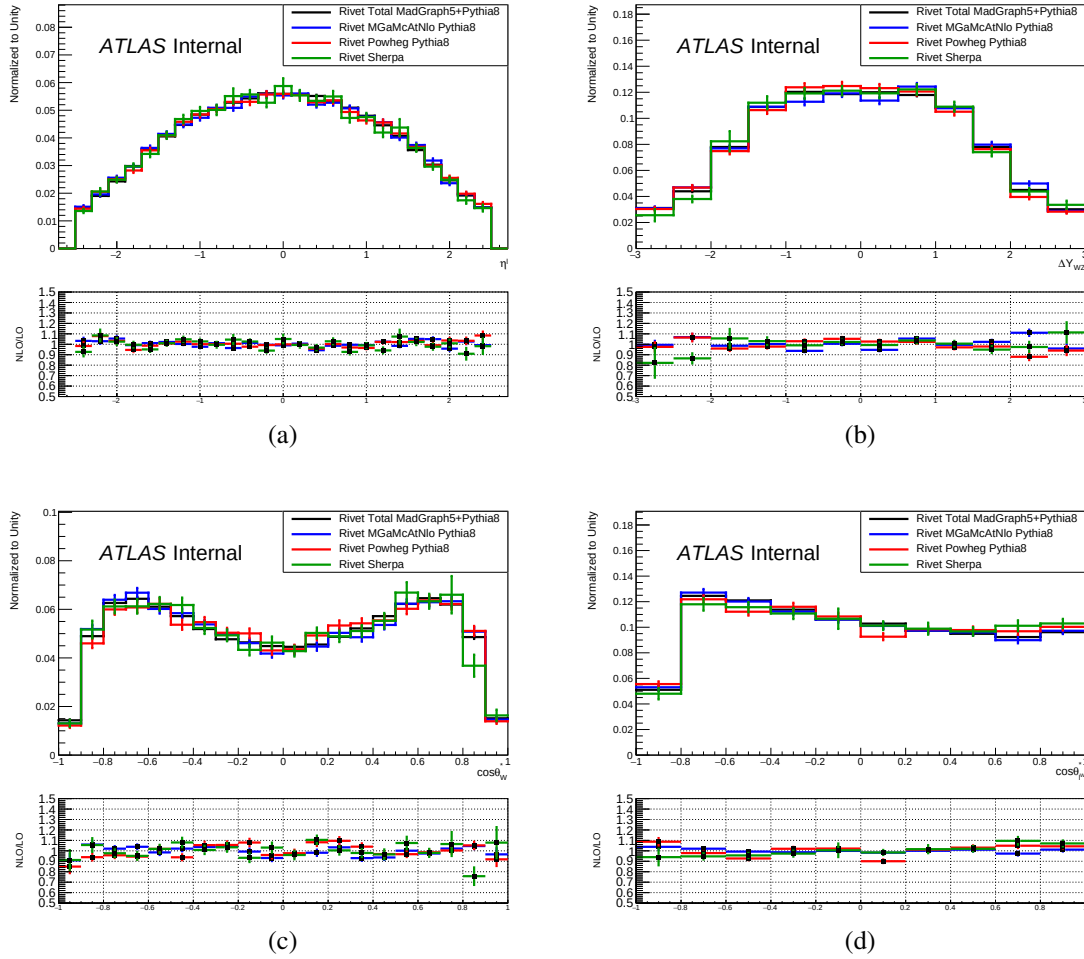


Figure 3.8: Comparison between NLO (POWHEG+PYTHIA8, MADGRAPH aMC@NLO and SHERPA) and the sum of LO polarized samples for different kinematic variables: The distribution of the η for all the three leptons (a), ΔY_{WZ} (b), $\cos \theta_W$ (c), and $\cos \theta_{\ell^*}(W)$ (d).

3.2.4.2 Comparison with the NLO calculations with different polarizations

In 2021, theorists provided the NLO QCD corrections to the different LO di-boson polarization states separately [127]. The calculations rely on the double-pole approximation for the gauge-invariant treatment of resonant diagrams and on the separation of polarizations in weak-boson propagators at the amplitude level. However, only the cross-section and some kinematic distributions in certain fiducial regions can be calculated, and no events can be generated for `GEANT4` simulation studies.

The above-mentioned theorists performed the calculations for generating different kinematic distributions in the 00-enhanced phase space we are using (specifically the $p_T^{WZ} < 70$ GeV RAZ region and $p_T^Z > 200$ GeV signal region). The important difference to note is that these NLO QCD calculations are done at Parton level and the `MADGRAPH` samples we are using for the truth comparisons with the former ones have undergone `PYTHIA` Parton showering. The distributions provided to us by the theorists are produced using fully leptonic final states. Particularly the decay channels used are $W^+ \rightarrow e^+ \nu_e$ (or $W^- \rightarrow e^- \bar{\nu}_e$) and $Z \rightarrow \mu^+ \mu^-$. The distributions generated using the polarized `MADGRAPH` samples have W and Z decaying to both e and μ leptonic channels. Hence, only the shape of the distributions is compared.

Figures 3.9 and 3.10 show shape comparisons of ΔY_{WZ} and $\cos \theta_W$ distributions between the NLO QCD calculations and LO-merged polarized MC samples for four different polarization states (00, 0T, T0, TT). Since 0T and T0 have small contributions in our fiducial region, comparison plots for more kinematic variables for 00 and TT polarization states are shown in figures 3.11, 3.12, 3.13, 3.14 and 3.15. Since the LO-merged polarized MC samples have parton shower effects included, we also included the ratio of ratios (the bottommost panel of the distribution)

$$\frac{(NLO/LO_{merged})_{XX}}{(NLO/LO_{merged})_{TT}}, \quad (3.14)$$

where $XX = 00, 0T, T0, \text{ or } TT$. The middle panel is the ratio of NLO/LO_{merged} . A discrepancy is observed for the p_T^{WZ} variable, which is expected because of the parton shower effects included in the `MADGRAPH` samples. However, good agreement is observed for other kinematic variables such as p_T^Z , m_T^{WZ} , the W lepton $p_T^\ell(W)$, and the Z lepton $p_T^\ell(Z)$ for both 00 and TT polarizations.

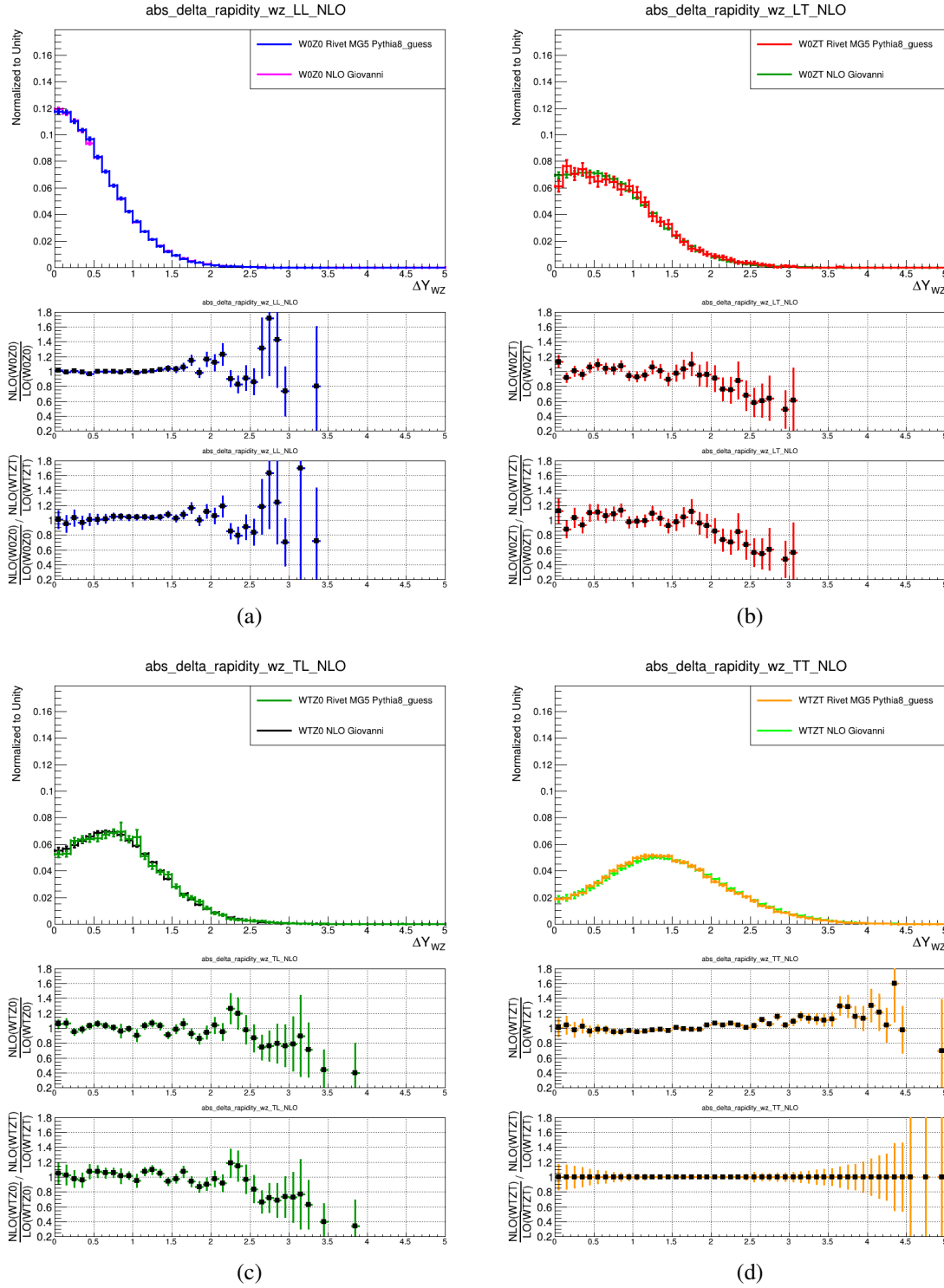


Figure 3.9: Shape Comparison between NLO QCD calculations by theorists and MC sample for 00 (a), 0T (b), T0 (c), and TT (d) separately in the 00-enhanced phase space with $p_T^Z > 200$ GeV for ΔY_{WZ} .

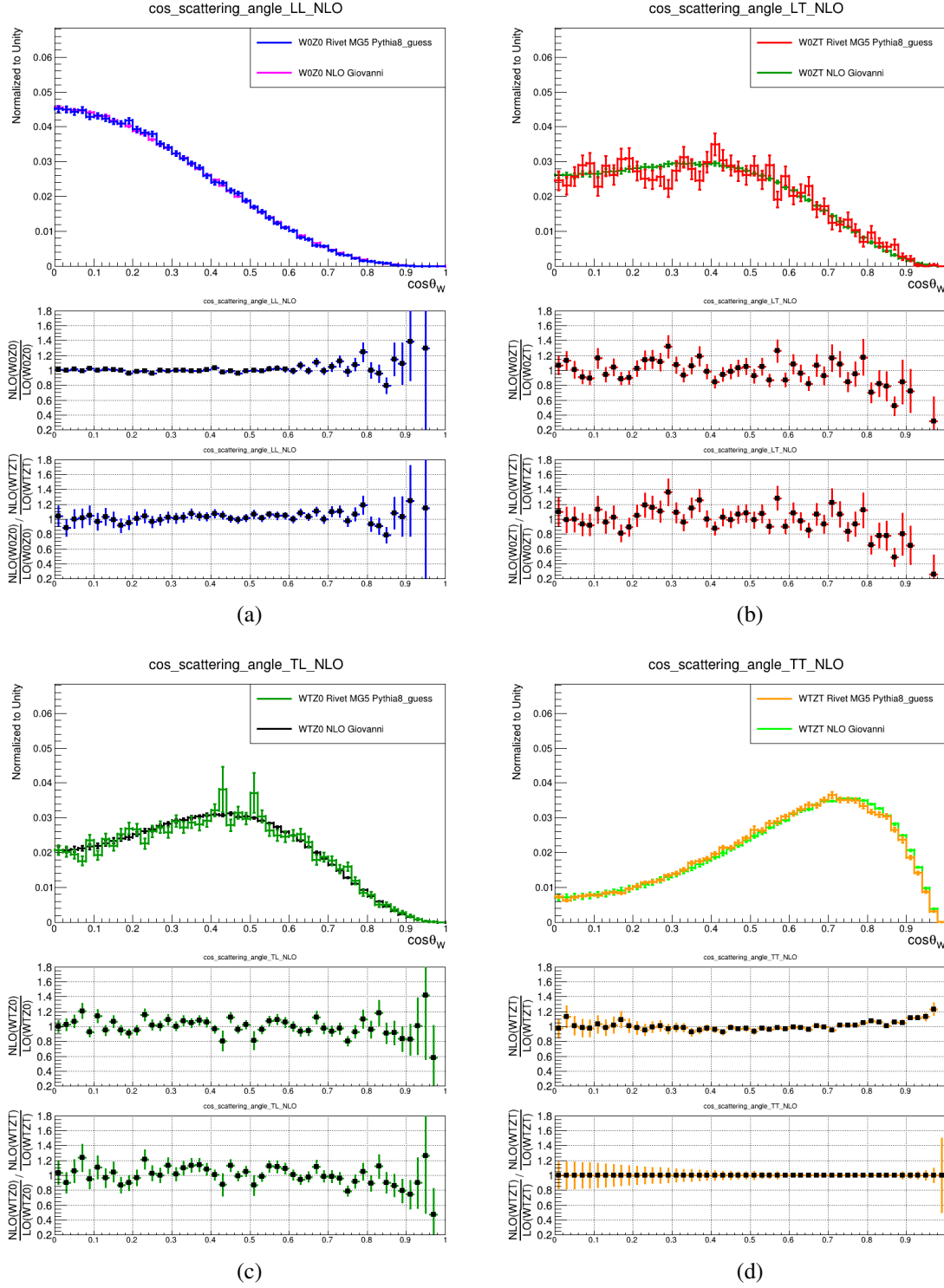


Figure 3.10: Shape comparison between NLO calculations by theorists and MC sample for 00 (a), 0T (b), T0 (c), and TT (d) separately in the 00-enhanced phase space with $p_T^Z > 200$ GeV for $\cos\theta_W$.

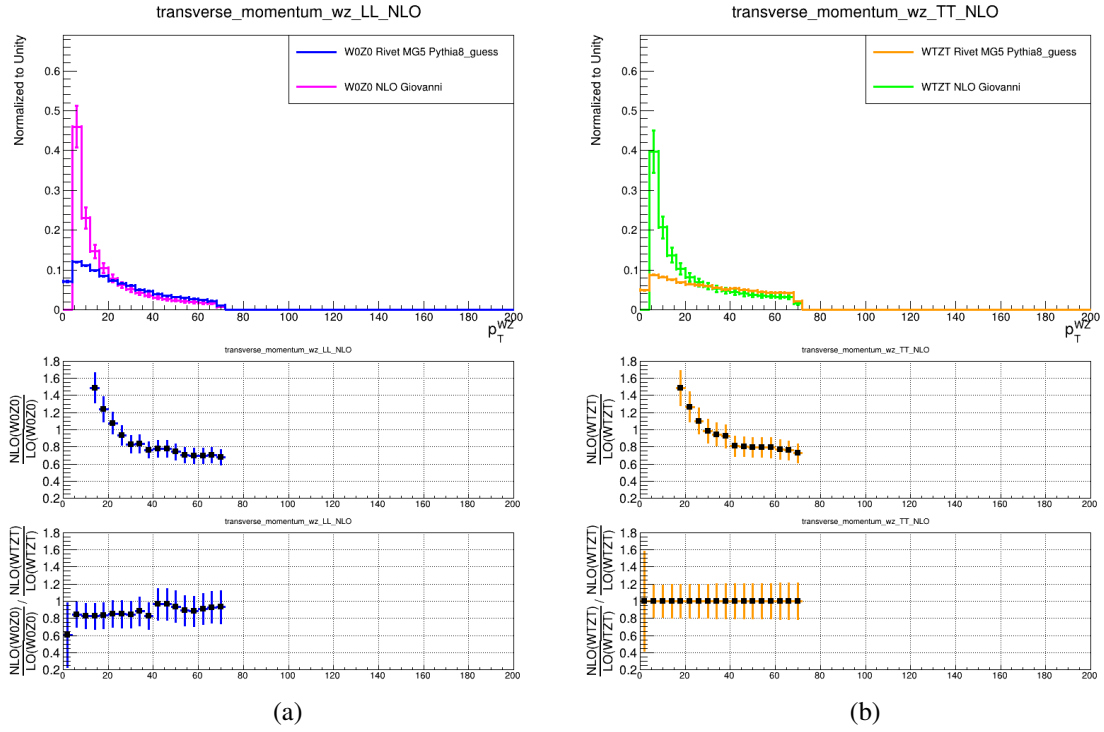


Figure 3.11: Shape comparison between NLO calculations by theorists and MC sample for 00 (a) and TT (b) separately in the 00-enhanced phase space with $p_T^Z > 200$ GeV for p_T^{WZ} .

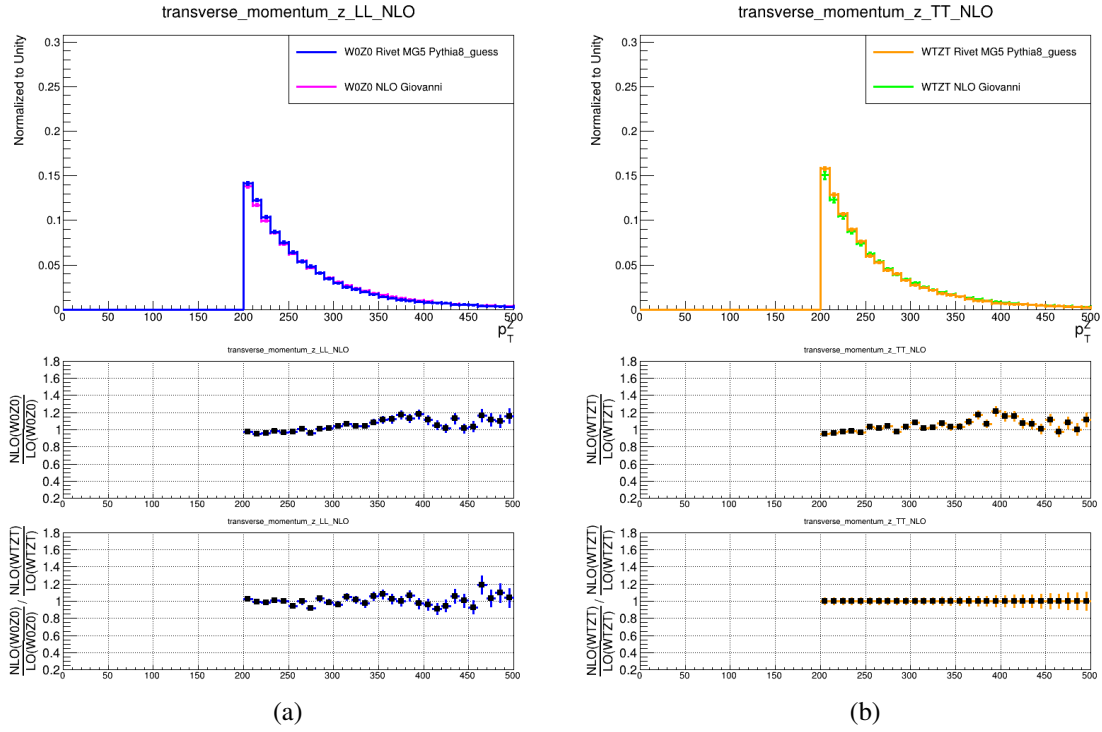


Figure 3.12: Shape comparison between NLO calculations by theorists and MC sample for 00 (a) and TT (b) separately in the 00-enhanced phase space with $p_T^Z > 200$ GeV for p_T^Z .

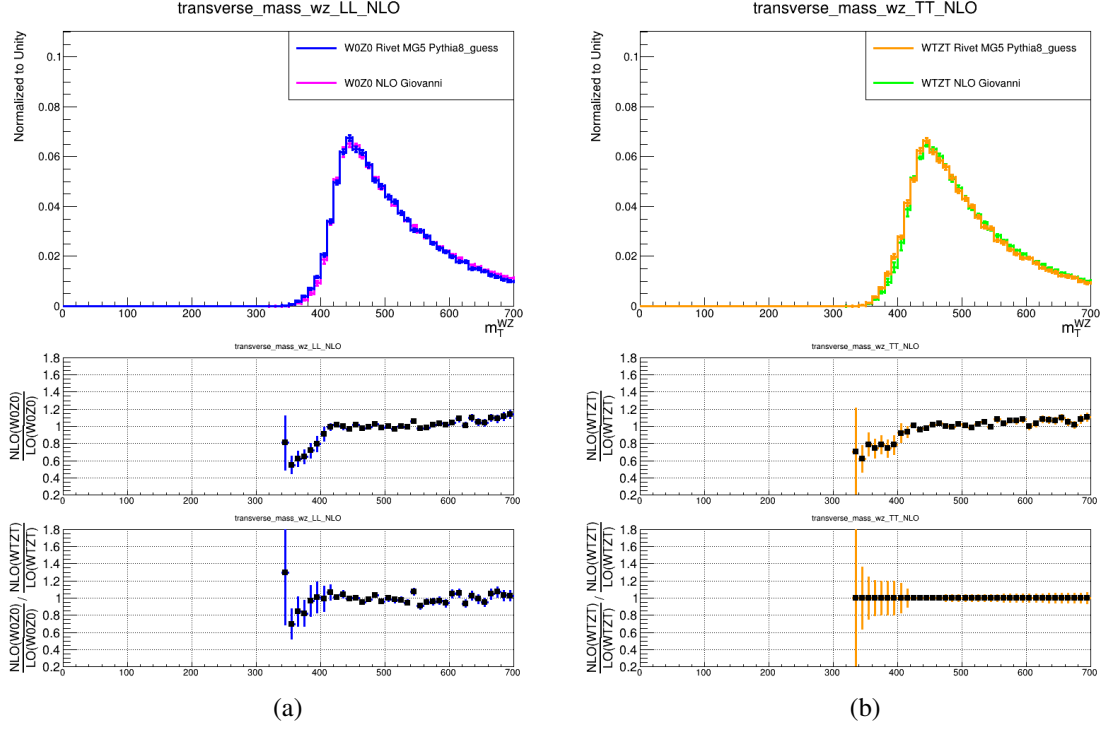


Figure 3.13: Shape comparison between NLO calculations by theorists and MC sample for 00 (a) and TT (b) separately in the 00-enhanced phase space with $p_T^Z > 200$ GeV for m_T^{WZ} .

Table 3.5 shows predictions of diboson polarization fractions from the NLO QCD calculations and from the LO-merged MADGRAPH samples for the signal region with $p_T^Z > 200$ GeV. Good agreement between these two predictions has been observed.

	f_{00}	f_{0T}	f_{T0}	f_{TT}
Predictions using NLO calculations	23.6%	5.0%	4.6%	66.8%
Predictions using LO-merged 0+1 jets MADGRAPH samples	23.8%	5.8%	5.2%	65.2%

Table 3.5: Predictions of diboson polarization fractions from the NLO QCD calculations and from the LO-merged MADGRAPH samples for the signal region with $p_T^Z > 200$ GeV. It should be pointed out that the fractions from the NLO calculations are performed at the particle level, while the fractions for the LO-merged MADGRAPH samples are performed after parton showering.

3.2.4.3 Comparison with the NLOEW calculations with different polarizations

In 2022, some other theorists provided us the NLO QCD+EW calculations for WZ events in separate di-boson polarization states [128–130] for the 00-enhanced regions ($p_T^{WZ} < 70$ GeV RAZ region, $p_T^Z > 100$ GeV and $p_T^Z > 200$ GeV signal regions). Similar to the NLO QCD calculations, these NLO EW calculations also rely on the double-pole approximation and are then separated into

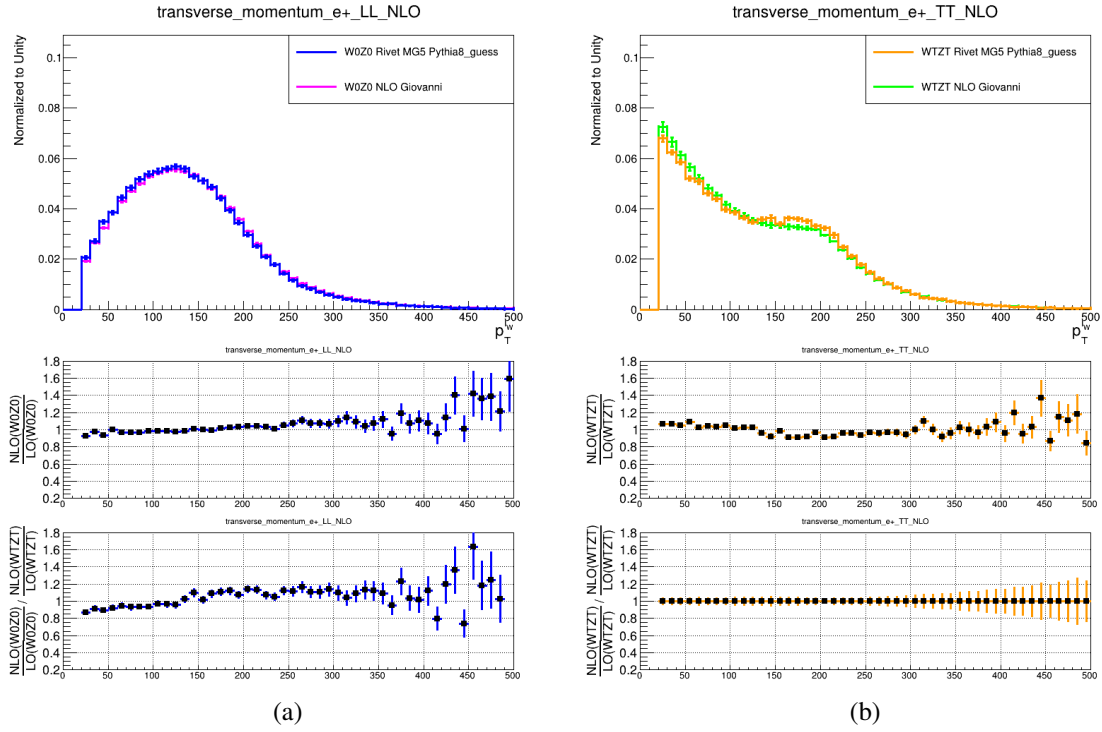


Figure 3.14: Shape comparison between NLO calculations by theorists and MC sample for 00 (a) and TT (b) separately in the 00-enhanced phase space with $p_T^Z > 200$ GeV for $p_T^\ell(W)$.

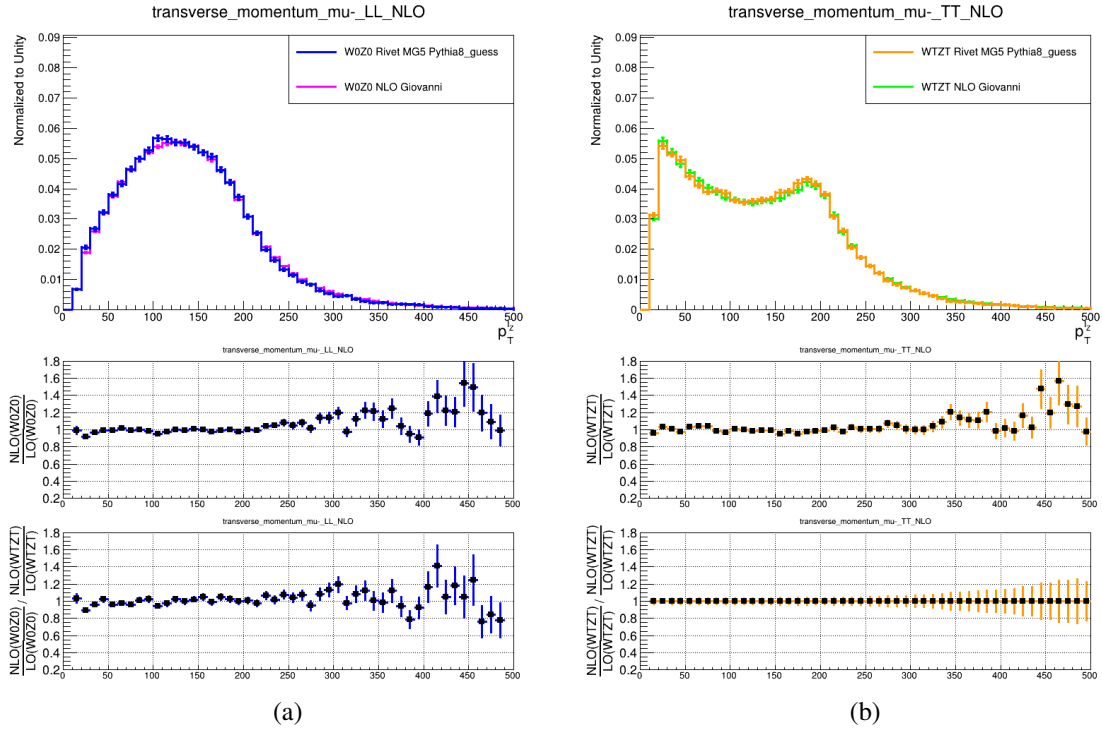


Figure 3.15: Shape comparison between NLO calculations by theorists and MC sample for 00 (a) and TT (b) separately in the 00-enhanced phase space with $p_T^Z > 200$ GeV for $p_T^l(Z)$.

different polarization states at the amplitude level. The interference terms for the left and right polarized bosons are also included in the calculations separately for different polarization states. The calculations shown in the following figures are performed for $W^+ \rightarrow e^+ \nu_e$ and $Z \rightarrow \mu^+ \mu^-$.

It should be again pointed out that the NLO calculations for different polarization states are performed at the parton level, while the LO-merged `MADGRAPH` samples we generated are after parton showering.

Figures 3.16 and 3.17 show shape comparisons of ΔY_{3Z} and distributions between the theoretical calculations for NLO QCD+EW and NLO QCD to show the size of the NLO EW effect (this is shown in the RAZ region $p_T^{WZ} < 70$ GeV). It can be seen that the NLO EW corrections are small and flat for all four polarization states for both variables. A small effect is expected since events used for RAZ studies tend to have low p_T leptons.

The NLO(QCD+EW)/NLO(QCD) corrections in the signal region of $p_T^Z > 100$ GeV are much bigger as can be seen from figure 3.18. See appendix C for more comparisons.

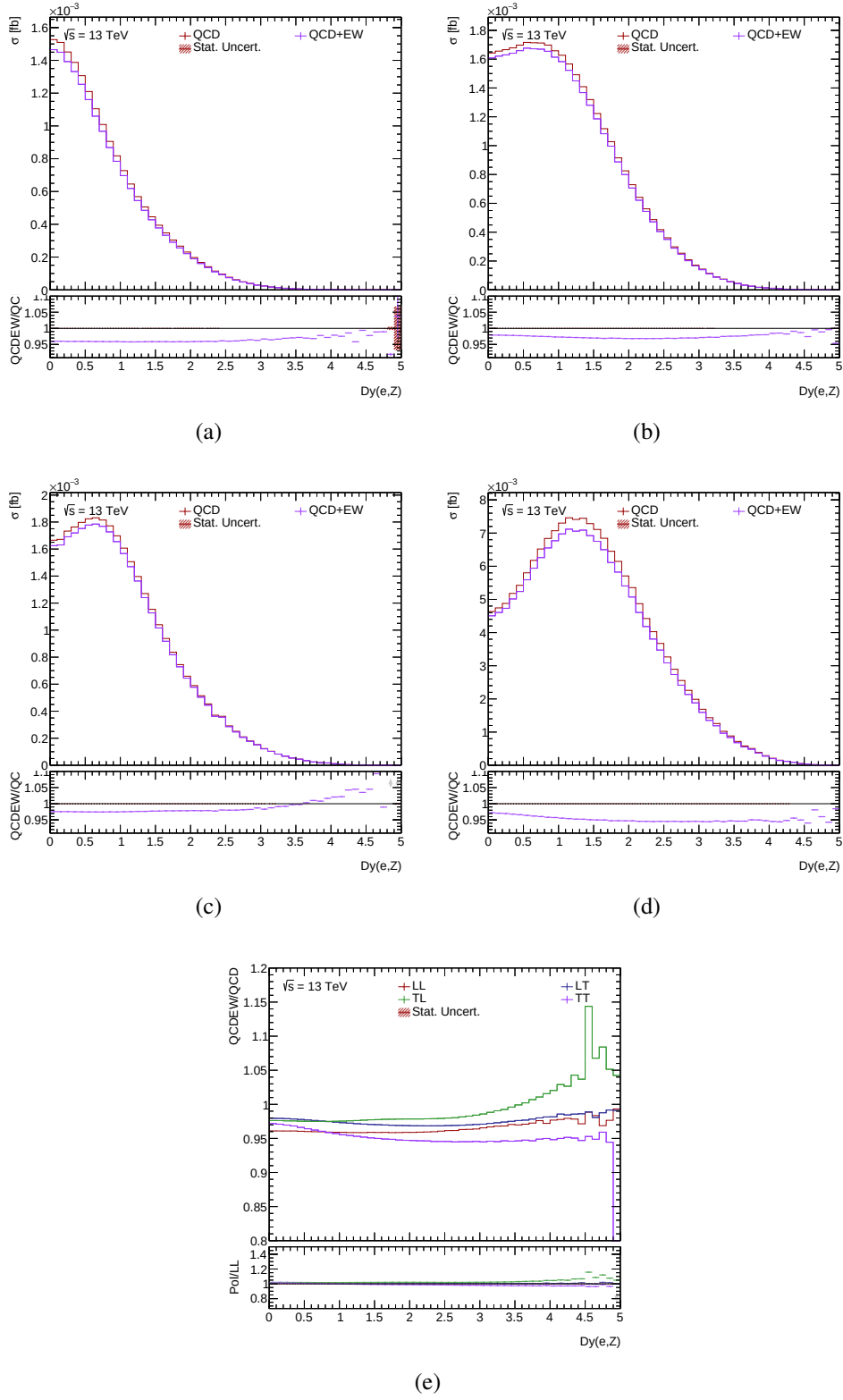


Figure 3.16: Comparison between NLO QCD + EW and NLO QCD of ΔY_{3Z} for the four polarizations in the RAZ region $p_T^{WZ} < 70$ GeV. Shown are the comparisons for 00 (a), 0T (b), T0 (c), and TT (d), and NLO(QCD+EW)/NLO(QCD) for all four polarizations overlayed (e).

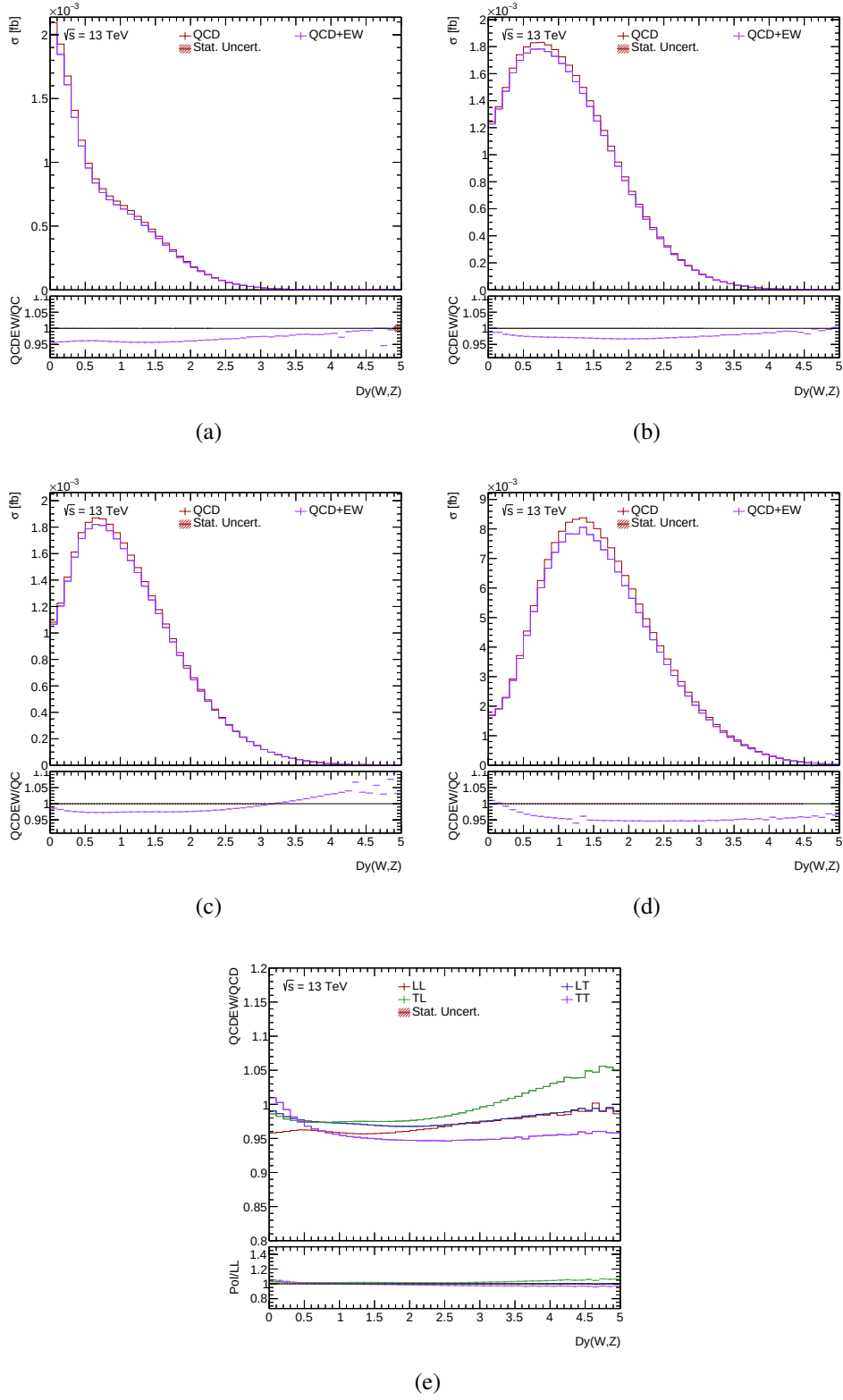


Figure 3.17: Comparison between NLO QCD + EW and NLO QCD of ΔY_{WZ} for the four polarizations in the RAZ region $p_T^{WZ} < 70$ GeV. Shown are the comparisons for 00 (a), 0T (b), T0 (c), and TT (d), and NLO(QCD+EW)/NLO(QCD) for all four polarizations overlaid (e).

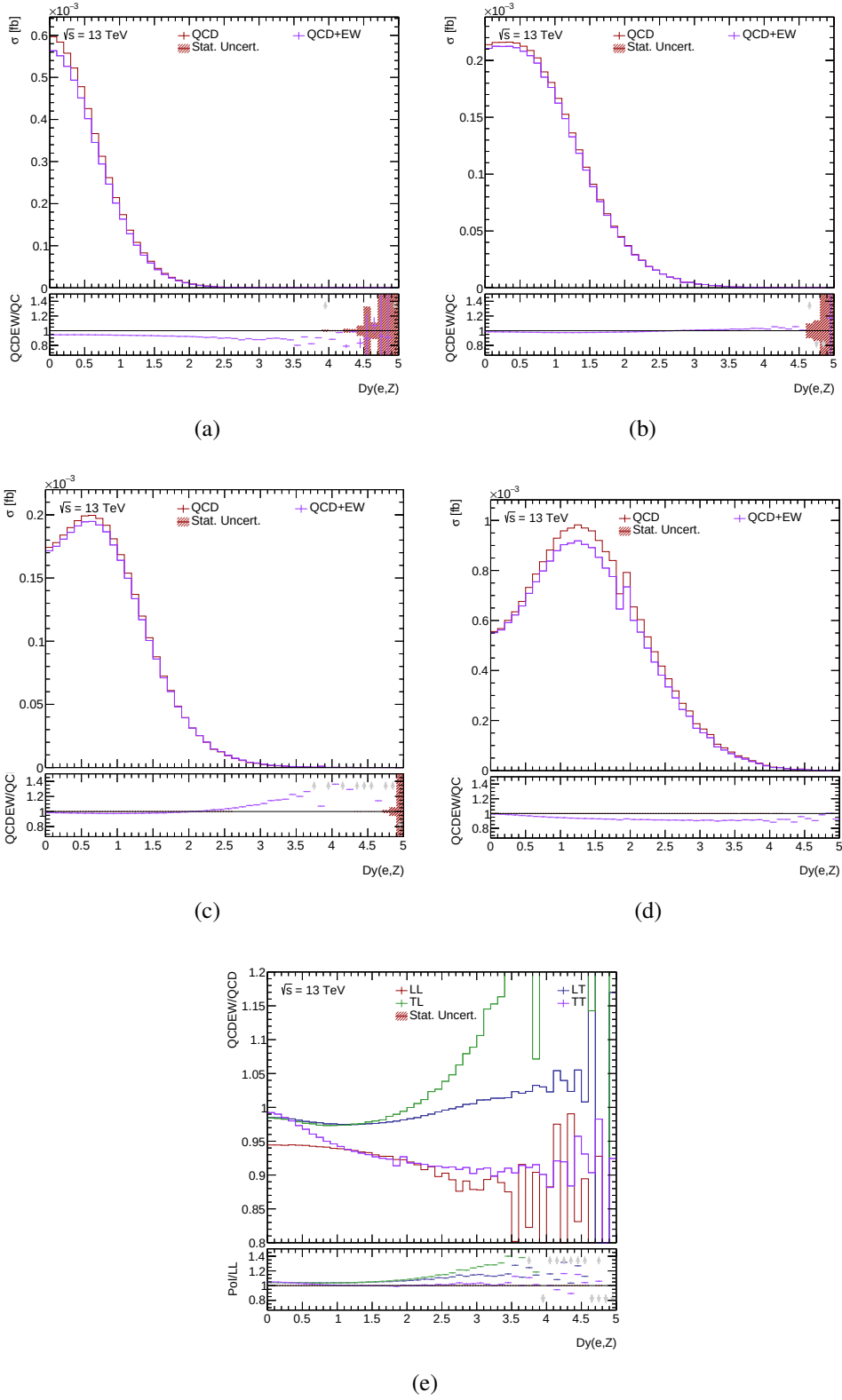


Figure 3.18: Comparison between NLO QCD + EW and NLO QCD of ΔY_{WZ} for the four polarizations in the 00-enhanced signal region with $p_T^Z > 100$ GeV. Shown are the comparisons for 00 (a), 0T (b), T0 (c), and TT (d), and NLO(QCD+EW)/NLO(QCD) for all four polarizations overlaid (e).

3.3 Event Selection

The measurement is performed using Analysis Release 21.2.188 [141]. The objects used in the measurement are calibrated and the latest scale factors and corrections are applied to correct the MC selection efficiencies to the ones in the data, following the recommendations of the combined performance groups [142]. The analysis uses derivations of data and MC samples, where events with three leptons (e or μ) and tight slimming are preselected [143]. These datasets are processed in the derivation framework which produces about 80 different derived formats that contain a subset of events and reduced reconstruction information tailored for specific physics analysis and performance groups. further processing or final physics results.

3.3.1 Lepton Object Selection

Three levels of object selections are used: baseline, Z selection, and W selection, with increasing strictness and these are applied sequentially i.e. all the W -selection leptons are also Z -selection leptons, all Z leptons are also baseline leptons. The leptons used in our signal have to pass Z and W criteria to suppress contributions from fake-lepton backgrounds.

3.3.1.1 Muon object selection

Muons are reconstructed by combining measurements from the Inner Detector (ID) and Muon Spectrometer (MS). The muon momentum calibration is applied before any object selection. The three levels of muon object selection — baseline, Z , and W muons — are summarized in table 3.6.

Baseline muons have the lowest p_T threshold, $p_T > 5$ GeV. The threshold for Z -selection muons is increased to $p_T > 15$ GeV and the tightest requirement is applied on W -selection muons: $p_T > 20$ GeV. The muons associated to the Z and W boson decays are required to have $|\eta| < 2.5$, matching the fiducial phase-space definition presented in table 3.1. However, the baseline muons are required to have $|\eta| < 2.7$ to increase the rejection of the ZZ background contamination by applying a veto on the events with more than three leptons, see section 3.3.5. All muons within $|\eta| < 2.5$ are required to pass the lepton-vertex association selection [144]. The significance of the track's transverse impact parameter relative to the beamline must satisfy $|d_0/\sigma_{d_0}| < 3$, and the longitudinal impact parameter, z_0 (the difference between the value of z of the point on the track at which d_0 is defined and the longitudinal position of the primary vertex), is required to satisfy $|z_0 \cdot \sin(\theta)| < 0.5$ mm.

Baseline muons are required to pass the `Loose` quality selection determined by the centrally provided tool by ATLAS for muon selection [145]. `Loose` muons include calorimeter-tagged muons, which is used for Z -selection muons and the `Tight` working point used for the W -selection

muons. Baseline and Z-selection muons are required to pass the `PflowLoose_FixedRad` (i.e. track isolation cone radius is fixed at high p_T) isolation requirement, while W -selection muons must pass the `PflowTight_FixedRad` requirement.

An overlap removal procedure is applied to the selections of the Z and W bosons (also described in section 3.3.4). This is to separate prompt muons from those originating from the decay of hadrons in a jet.

Muon object selection			
Selection	Baseline selection	Z selection	W selection
$p_T > 5$ GeV	✓	✓	✓
$ \eta < 2.7$	✓	✓	✓
Loose quality	✓	✓	✓
$ d_0/\sigma(d_0) < 3$ (for $ \eta < 2.5$ only)	✓	✓	✓
$ \Delta z_0 \sin \theta < 0.5$ mm (for $ \eta < 2.5$ only)	✓	✓	✓
<code>PflowLoose_FixedRad</code> isolation	✓	✓	✓
Overlap Removal		✓	✓
$p_T > 15$ GeV		✓	✓
$ \eta < 2.5$		✓	✓
Medium quality		✓	✓
$p_T > 20$ GeV			✓
Tight quality			✓
<code>PflowTight_FixedRad</code> isolation			✓

Table 3.6: Three levels of muon object selection used in the analysis.

3.3.1.2 Electron object selection

Electrons are reconstructed from clusters of energy deposits in the electromagnetic calorimeter, matched to an ID track. The momentum of raw reconstructed electrons is calibrated using the tool used to compute the energy of electrons and photons, including all necessary corrections and relative systematics package [146]. All electrons are required to pass object quality requirements, which ensures the rejection of electrons with clusters affected by the presence of dead electronics and high-voltage regions of the detector. The three levels of selection applied to candidate electrons are summarized in table 3.7, where precision electron CP recommendations are used [147]. Different electron selection criteria were used, especially the identification and isolation working points.

Baseline electrons are required to have $p_T > 5$ GeV; Z -selection electrons have $p_T > 15$ GeV, and W -selection electrons have $p_T > 20$ GeV. The electron p_T is calculated from the four-vector of an

electron based on its calorimetric energy and its direction as measured in the tracker. An electron is required to be reconstructed within $|\eta^{\text{cluster}}| < 2.47$, and within the tracking volume $|\eta| < 2.5$. The calorimeter crack region - $1.37 < |\eta^{\text{cluster}}| < 1.52$ - is excluded only at the level of Z-selection and W-selection for the electrons, to allow for more efficient ZZ background rejection using baseline electrons. A likelihood (LH) identification criterion is used for electron candidates [54, 148]. Baseline electrons are required to pass `LooseLH+BLayer` (B-Layer or BL is the innermost layer of the pixel detector in the inner detector of the ATLAS experiment. A cut is placed on the hits recorded in that layer, which is useful in suppressing conversion background) identification, which has an efficiency in the range 84 – 96% for electrons with $10 < p_T < 80$ GeV. `MediumLH` and `TightLH` identification are applied for Z and W selection accordingly. The efficiency ranges between 72-93% for the `MediumLH` ID, and between 68-88% for the `TightLH`, for electrons with $10 < p_T < 80$ GeV. All electrons are required to pass the lepton-vertex association selection [144]. Therefore, the transverse impact parameter significance of the electron tracks is required to satisfy $|d_0/\sigma(d_0)| < 5$, and the longitudinal impact parameter is required to satisfy $|\Delta z_0 \sin \theta| < 0.5$ mm. The significance of the track's transverse impact parameter relative to the beamline must satisfy $|d_0/\sigma_{d_0}| < 5$ and the longitudinal impact parameter, z_0 (the difference between the value of z of the point on the track at which d_0 is defined and the longitudinal position of the primary vertex), is required to satisfy $|z_0 \cdot \sin(\theta)| < 0.5$ mm.

A `Loose_VarRad` (variable radius or shrinking cone isolation requirement) is applied on baseline electrons. Electrons have to fulfill the `HighPtCaloOnly` isolation requirement to pass Z-selection and the `Tight_VarRad` isolation requirement to pass W-selection.

Additionally, a tool is used to remove ambiguities between electrons and photons in the W-selection. This distinguishes between cases where a candidate passes either only the electron reconstruction or both the electron and photon reconstruction algorithms. In the W-selection, electrons are required to not pass the photon reconstruction in order to suppress $Z\gamma$ background. Its inefficiency on true electrons from the W-boson decay is ~ 5 %. A further rejection of converted photons misidentified as electrons is ensured by using a dedicated `DFCommonAddAmbiguity` tagger [149]. All electrons with `DFCommonAddAmbiguity` > 0 are rejected for the W-selection. The inefficiency of this requirement on true electrons from the W-boson decay is ~ 0.5 %. But it further rejects $Z\gamma$ background events by 35 % in the inclusive WZ event selection described in section 3.3.5.

A correction to the MC due to the misidentification of the charge of the electrons is applied. An official tool [150] is used to obtain the scale factor to correct the MC and the associated systematic uncertainties. The scale factors are applied to electrons passing the Z-selection and W-selection of the electrons.

Electron object selection			
Selection	Baseline selection	Z selection	W selection
$p_T > 5 \text{ GeV}$	✓	✓	✓
Electron object quality	✓	✓	✓
$ \eta^{\text{cluster}} < 2.47, \eta < 2.5$	✓	✓	✓
LooseLH+BLayer identification	✓	✓	✓
$ d_0/\sigma(d_0) < 5$	✓	✓	✓
$ \Delta z_0 \sin \theta < 0.5 \text{ mm}$	✓	✓	✓
Loose_VarRad isolation	✓	✓	✓
Overlap removal		✓	✓
$p_T > 15 \text{ GeV}$		✓	✓
Exclude $1.37 < \eta^{\text{cluster}} < 1.52$		✓	✓
MediumLH identification		✓	✓
HighPtCaloOnly isolation		✓	✓
$p_T > 20 \text{ GeV}$			✓
TightLH identification			✓
Tight_VarRad isolation			✓
DFCommonAddAmbiguity ≤ 0			✓

Table 3.7: Three levels of electron object selection used in the analysis.

3.3.2 Jet Object Selection

Jets are reconstructed from particle flow objects using the anti- k_t algorithm with a radius parameter of $\Delta R = 0.4$. Only jets with $p_T > 30 \text{ GeV}$ and $|\eta| < 4.5$ are considered. The consolidated jet recommendations from ATLAS [151] are used.

Pile-up jets are removed using the pile-up jet vertex taggers `JVT` for central jets and `fJVT` for forward jets, following recommendations in Ref. [152]. For jets with $p_T < 60 \text{ GeV}$ and $|\eta| < 2.4$, the output of the jet vertex tagger `JVT` (section 2.3.3.3 defines `JVT`) is required to be larger than 0.5, in order to suppress jets originating from pile-up, following the `Tight` working point recommendation detailed in Ref. [152].

For jets with $p_T < 120 \text{ GeV}$ and $2.5 < |\eta| < 4.5$, the `fJVT` (section 2.3.3.3 defines `fJVT`) tagger is applied, using its `Loose` working point, as defined in Ref. [152]. The MC efficiencies of both taggers are corrected using data/MC calibrations from May 2020, as defined in Ref. [152].

In the analysis, b -tagged jets are used. Jets in the central region with $p_T > 25 \text{ GeV}$ containing b -hadrons are tagged using the `DL1r` tagger with the recommended configuration in Ref. [153]. The 70% b -tagging efficiency working point is used. The flavor tagging efficiencies are corrected

based on data-driven calibration analyses [154].

3.3.3 Missing Transverse Energy

The missing transverse momentum (E_T^{miss}) in the events is defined as the transverse momentum imbalance in the detector. E_T^{miss} is calculated as the negative vector sum of the momentum of user-selected calibrated objects (electrons, muons, jets), and of the soft-event contribution, which is reconstructed from tracks or calorimeter cell clusters not associated with the hard objects. In the presented analysis, E_T^{miss} is reconstructed with a dedicated tool using calibrated electrons and muons passing the baseline selection and calibrated jets before any selection (full jet container). Pile-up degrades the resolution of the calorimeter-based measurement of the soft term. Following the Jet/ETmiss group recommendations [155], the `PFLow` E_T^{miss} reconstruction with the track-based measurement of the soft term is used in the analysis.

3.3.4 Object Overlap Removal

Lepton and jet candidates can be reconstructed from the same detector information, requiring an overlap ambiguity to be resolved. The overlap removal procedure are done among baseline level leptons and jets, but with isolation requirements released for leptons. The overlap removal procedure follows the recommendations described in the Harmonization Document [156], and is implemented similar to the tool here [157].

Additional overlap removal is then applied to keep the electron with highest p_T for electrons sharing the same ID-track and the electron with highest cluster E_T for electrons with clusters close to each other. For CaloTagged muons which share the same InnerDetector track as the electron, the muon is removed.

3.3.5 Inclusive WZ Event Selection

The selection of WZ candidate events is summarized in Table 3.8. In order to decrease the background contribution from ZZ processes with four leptons in the final state, a “ZZ veto” is applied. This implies a rejection of events with more than three leptons passing the baseline muon or electron selections. The selection of leptons used for the veto, and hence the baseline selection, is optimized to find prompt electron and muon candidates with as wide kinematic acceptance as possible. Thus, baseline muons before any overlap removal, and baseline electrons that survive overlap removal with muons are used for counting the number of leptons for the ZZ veto. WZ candidate events are required to have exactly three leptons passing the Z lepton identification selection. A Z boson candidate is built by requiring two selected leptons of the same flavor that

are oppositely charged (SFOC). If more than one pair of leptons builds a Z candidate, the pair with $m_{\ell\ell}$ closest to the Z boson mass is taken. The W boson candidate is selected by requiring the third remaining lepton to pass the W lepton selection. The transverse momentum threshold of the leading lepton is increased to 25 GeV for the 2015 sample and to 27 GeV for 2016–2018 to increase the chances that the lepton firing the trigger is above the trigger efficiency turn-on curve. The SFOC lepton pair is required to have an invariant mass within 10 GeV of the Z boson mass. Finally, the transverse mass of the W candidate is required to be above 30 GeV. The transverse mass is defined as:

$$m_T^W = \sqrt{2p_T^\ell E_T^{\text{miss}} (1 - \cos \Delta\phi)}. \quad (3.15)$$

Here, $\Delta\phi$ is the angular difference between the W lepton and the neutrino measured in the transverse plane.

Inclusive event selection	
Event cleaning	Reject LAr, Tile, and SCT corrupted events and incomplete events
Primary vertex	Hard scattering vertex with at least two tracks
Trigger 2015	HLT_e24_lhmedium_L1EM20VH HLT_e60_lhmedium HLT_e120_lhloose HLT_mu20_iloose_L1MU15 HLT_mu50
Trigger 2016–2018	HLT_e26_lhtight_nod0_ivarloose HLT_e60_lhmedium_nod0 HLT_e140_lhloose_nod0 HLT_mu26_ivarmedium HLT_mu50
ZZ veto	Less than 4 baseline leptons
N leptons	Exactly three leptons passing the Z lepton selection
Leading lepton p_T	$p_T^{\text{lead}} > 25$ GeV (in 2015) or $p_T^{\text{lead}} > 27$ GeV (in 2016-2018)
Z leptons	Two same flavor oppositely charged leptons passing Z -lepton selection
Z invariant mass	$ M_{\ell\ell} - M_Z < 10$ GeV
W lepton	Remaining lepton passes W -lepton selection
W transverse mass	$m_T^W > 30$ GeV

Table 3.8: Overview of the inclusive WZ event selection.

To compute the W -boson center-of-mass needed in polarization measurements, the neutrino longitudinal momentum needs to be reconstructed. The transverse component is identified as the missing transverse energy E_T of the event. The W -boson mass is used as a constraint to find the neutrino p_z . If there are two physical solutions, the smallest solution in absolute is chosen; and if there is no physical solution, the real part of the complex solution is chosen.

3.3.6 Signal Region Definitions

For this analysis, three signal regions are defined by applying extra requirements to the inclusive WZ selection described in the previous section (see table 3.8). The signal regions are defined by using different selections on the p_T^{WZ} aiming to reduce the jet activity, and on the p_T^Z in order to increase the contributions from the s -channel and target high-energy W and Z bosons. An overview table of the event level selections applied on top of the WZ inclusive selections for the signal regions

can be seen in table 3.9.

Selection	Signal regions		
	Radiation Amplitude Zero	00-enriched $p_T^Z > 100$ GeV	00-enriched $p_T^Z > 200$ GeV
Pass inclusive WZ event selection	✓	✓	✓
Transverse momentum of the Z boson (p_T^Z)	-	> 100 GeV	> 200 GeV
Transverse momentum of the WZ system (p_T^{WZ})	scan using $< 10, 20, 40, 70$ GeV	< 70 GeV	< 70 GeV

Table 3.9: Overview of the selection criteria used to build the signal regions.

3.4 Trigger

The ATLAS experiment has developed algorithms for triggering different physics objects to save the most important data [62, 158, 159] because of the limited computing and storage resources. This analysis is based on the selection of three leptons making up W and Z bosons. Hence, the triggers used for this analysis correspond to the lowest un-prescaled single lepton triggers, as shown in table 3.10. These are all high-level triggers with requirements on the different reconstructed aspects of electrons and muons.

Data year	Electron triggers	Muon triggers
2015	HLT_e24_lhmedium_L1EM20VH HLT_e60_lhmedium HLT_e120_lhloose	HLT_mu20_loose_L1MU15 HLT_mu50
2016 - 2018	HLT_e26_lhtight_nod0_ivarloose HLT_e60_lhmedium_nod0 HLT_e140_lhloose_nod0	HLT_mu26_ivarmedium HLT_mu50

Table 3.10: The triggers used for this analysis. Only electron and muon triggers are used.

The electron trigger uses the threshold on electron E_T (e.g. `_e24_` means a threshold of 24 GeV is used for these electrons). It uses an electron identification based on a multivariate technique using an LH (Likelihood) discriminant with four working points: ‘lhvloose’, ‘lhloose’, ‘lhmedium’, and ‘lhtight’. This identification is designed to be as close to the offline version as possible. A few differences with the offline version are:

- the discriminating variables used online have different resolutions
- the momentum loss due to bremsstrahlung, $\Delta p/p$, is not accounted for in the online LH.
- The suffix ‘nod0’ means the trigger does not include the transverse impact parameter relative to the beam-line, d_0 , and its significance, $|d_0/\sigma(d_0)|$, in the online LH. This reduces

inefficiency due to the absence of the bremsstrahlung-aware re-fit in the HLT and preserves efficiency for electrons from exotic processes which do not originate from the primary vertex.

- An optional requirement of isolation denoted ‘ivarloose’ is also present. This tracking-only isolation should satisfy $p_T^{\text{iso}}(R^{\text{var}} < 0.2)/p_T < 0.10$ and is calculated similarly to the offline isolation working points
- Sometimes, the trigger is seeded by L1EM20VH, requiring $E_T > 20$ GeV and applies an E_T -dependent veto against energy deposited in the hadronic calorimeter behind the electromagnetic cluster of the electron candidate (hadronic veto, denoted by H in the trigger name). The E_T threshold is varied slightly as a function of η to compensate for passive material in front of the calorimeter (denoted by V in the trigger name).

The muon triggers use muon p_T threshold and isolation working points ‘iloose’ and ‘ivarmedium’. Some triggers are seeded by ‘L1MU15’, which requires a transverse momentum above 15 GeV. At a transverse momentum above 50 GeV, this trigger is complemented by a trigger not requiring isolation (mu50). This is to recover a small efficiency loss in the high transverse momentum region.

3.5 Background Estimation

3.5.1 Overview

Several background processes may mimic the experimental signature of WZ production and contribute to the selected event sample. Backgrounds with at least one fake lepton (reducible background) are estimated using a data-driven method, and backgrounds with at least three prompt leptons (irreducible background) are estimated using MC simulation.

After the $p_T^Z > 100$ (200) GeV cut is applied, fake backgrounds and other backgrounds are all found to be small or negligible, and we are left with high-purity WZ events. These backgrounds are only important in the inclusive CR where the background contribution is in general $< 10\%$.

3.5.2 Background due to Fake Leptons

A statistics-based approach is used in the matrix method to estimate the reducible background [23, 160, 161]. It uses the differences in object characteristics between real and fake leptons. The real and fake lepton categories are defined according to their origins:

- Real leptons (R): are prompt leptons originating from the W or Z boson decays.

- Fake leptons (F): leptons in jets, hadrons misidentified as leptons or photon conversions.

The three leptons are sorted following the same rule as in Section 3.3. The final selection can contain contributions of real leptons and fake leptons (reducible background) from the following event categories.

- N_{RRR} : the number of events with three real leptons originating from prompt leptons. Here, the WZ signal events and backgrounds with 3 prompt leptons coming from ZZ and $t+Vj$ are contributing (irreducible background).
- N_{RRF} : the number of events with one fake lepton associated with the W decay plus two prompt real leptons associated with the Z boson. This category mostly consists of Z +jets, $Z+\gamma$ and $t\bar{t}$.
- N_{FRR} and N_{RFR} : the number of events where one fake lepton is entering the Z selection. Here the Z +jets, $Z+\gamma$ are contributing when one of the two Z leptons is wrongly paired with a fake lepton to form the Z . The $t\bar{t}$ background can also contribute to this category. In $\mu^\pm\mu^\mp e^\mp$ and $e^\pm e^\mp\mu^\mp$ channel, since the Real leptons, in this case, is with a different flavor, the Z +jets, and $Z+\gamma$ contribution is negligible and $t\bar{t}$ become the dominant process.
- N_{FFR} , N_{FRF} , N_{RFF} , N_{FFF} : the number of events in which two or three of the selected leptons are fakes. In this case, the W +jets, Z +jets, $t\bar{t}$ events and QCD are contributing. Nevertheless, the number of events with three fakes is very small and can be neglected. This is reflected by the fact that the number of events with two fakes is a magnitude smaller than the number of events with one fake.

Leptons can also be classified as “loose” or “tight” leptons according to the isolation and/or reconstruction quality. The “tight” leptons are just the leptons passing W or Z lepton cuts as described in Section 3.3. The “loose” leptons are defined from the leptons passing baseline level isolation and/or reconstruction quality cuts as described in Section 3.3. In addition, “loose” leptons must also pass the same p_T and η cuts as the “tight” leptons. Finally, “loose” leptons must pass the overlap removal requirements. To implement the matrix method, a “loose*” criteria is defined as leptons passing “loose” but failing “tight”. The “loose*” leptons are marked as L and “tight” leptons are marked as T for convenience in the following text. Using this, “ e ” is defined as the probability that a real “loose” lepton passes “tight” criteria, and f is the probability that a “loose” fake lepton passes “tight” criteria. Since leptons from the Z and from the W have different selections, two different fake efficiencies need to be calculated for muons and for electrons respectively. The method assumes that the number of events with varying numbers of loose and tight leptons can be expressed as a linear combination of numbers of events with real and fake leptons.

3.5.2.1 Derivation of the Formula for the reducible background

In a three-lepton final state, the matrix would be an 8×8 matrix to account for all possible combinations of real and fake leptons. However, it has been found in the MC that for cases where three leptons are fakes the number N_{FFF} is very small and can therefore be set to 0. Doing so the matrix becomes an over-constrained 8×7 system. In order to have a more readily tractable problem the information provided by the corresponding N_{LLL} terms was not considered. Consequently, the matrix equation is simplified and the matrix dimension is reduced to 7×7 . Here e ($\bar{e}$) denotes the probability that a real lepton (denoted by R) is identified as a “tight” (“loose”*) lepton, and f ($\bar{f}$) the probability that a loose fake lepton (denoted by F) is misidentified as a “tight” (“loose”*) lepton. One can write down a set of equations relating the number of events with at most two fake leptons to the number of events with at most two “loose”* leptons:

$$\begin{pmatrix} N_{TTT} \\ N_{TTL} \\ N_{TLT} \\ N_{LTT} \\ N_{TLL} \\ N_{LTL} \\ N_{LLT} \end{pmatrix} = \begin{pmatrix} e_1 e_2 e_3 & e_1 e_2 \bar{f}_3 & e_1 f_2 e_3 & f_1 e_2 e_3 & e_1 f_2 \bar{f}_3 & f_1 e_2 \bar{f}_3 & f_1 f_2 e_3 \\ e_1 e_2 \bar{e}_3 & e_1 e_2 \bar{f}_3 & e_1 f_2 \bar{e}_3 & f_1 e_2 \bar{e}_3 & e_1 f_2 \bar{f}_3 & f_1 e_2 \bar{f}_3 & f_1 f_2 \bar{e}_3 \\ e_1 \bar{e}_2 e_3 & e_1 \bar{e}_2 \bar{f}_3 & e_1 \bar{f}_2 e_3 & f_1 \bar{e}_2 e_3 & e_1 \bar{f}_2 \bar{f}_3 & f_1 \bar{e}_2 \bar{f}_3 & f_1 \bar{f}_2 e_3 \\ \bar{e}_1 e_2 e_3 & \bar{e}_1 e_2 \bar{f}_3 & \bar{e}_1 f_2 e_3 & \bar{f}_1 e_2 e_3 & \bar{e}_1 f_2 \bar{f}_3 & \bar{f}_1 e_2 \bar{f}_3 & \bar{f}_1 f_2 e_3 \\ e_1 \bar{e}_2 \bar{e}_3 & e_1 \bar{e}_2 \bar{f}_3 & e_1 \bar{f}_2 \bar{e}_3 & \bar{f}_1 \bar{e}_2 \bar{e}_3 & e_1 \bar{f}_2 \bar{f}_3 & \bar{f}_1 \bar{e}_2 \bar{f}_3 & \bar{f}_1 \bar{f}_2 \bar{e}_3 \\ \bar{e}_1 e_2 \bar{e}_3 & \bar{e}_1 e_2 \bar{f}_3 & \bar{e}_1 \bar{f}_2 \bar{e}_3 & \bar{f}_1 e_2 \bar{e}_3 & \bar{e}_1 \bar{f}_2 \bar{f}_3 & \bar{f}_1 e_2 \bar{f}_3 & \bar{f}_1 \bar{f}_2 \bar{e}_3 \\ \bar{e}_1 \bar{e}_2 e_3 & \bar{e}_1 \bar{e}_2 \bar{f}_3 & \bar{e}_1 \bar{f}_2 e_3 & \bar{f}_1 \bar{e}_2 e_3 & \bar{e}_1 \bar{f}_2 \bar{f}_3 & \bar{f}_1 \bar{e}_2 \bar{f}_3 & \bar{f}_1 \bar{f}_2 e_3 \end{pmatrix} \begin{pmatrix} N_{RRR} \\ N_{RRF} \\ N_{RFR} \\ N_{FRR} \\ N_{RFF} \\ N_{FRF} \\ N_{FFR} \end{pmatrix}. \quad (3.16)$$

The estimate for the reducible background can be written in the following form :

$$\begin{aligned} N_{TTT} - e_1 e_2 e_3 N_{RRR} &= [N_{TTL} - e_1 e_2 \bar{e}_3 N_{RRR}] \frac{f_3}{\bar{f}_3} + [N_{TLT} - e_1 \bar{e}_2 e_3 N_{RRR}] \frac{f_2}{\bar{f}_2} + [N_{LTT} - \bar{e}_1 e_2 e_3 N_{RRR}] \frac{f_1}{\bar{f}_1} \\ &\quad - [N_{TLL} - e_1 \bar{e}_2 \bar{e}_3 N_{RRR}] \frac{f_2}{\bar{f}_2} \frac{f_3}{\bar{f}_3} - [N_{LTL} - \bar{e}_1 e_2 \bar{e}_3 N_{RRR}] \frac{f_1}{\bar{f}_1} \frac{f_3}{\bar{f}_3} - [N_{LLT} - \bar{e}_1 \bar{e}_2 e_3 N_{RRR}] \frac{f_1}{\bar{f}_1} \frac{f_2}{\bar{f}_2} \end{aligned} \quad (3.17)$$

The terms N_{TTL} , N_{TLT} , N_{LTT} , N_{TLL} , N_{LTL} and N_{LLT} are taken from data in the signal region (either by applying all the WZ selection requirements or reverting the tight lepton requirements), while the MC simulation is used to estimate the contribution from the irreducible background (N_{ijk}^{irr}) in those regions.

$$\begin{aligned} N_{fake} = N_{TTT} - e_1 e_2 e_3 N_{RRR} &= [N_{TTL} - N_{TTL}^{irr}] \frac{f_3}{\bar{f}_3} + [N_{TLT} - N_{TLT}^{irr}] \frac{f_2}{\bar{f}_2} + [N_{LTT} - N_{LTT}^{irr}] \frac{f_1}{\bar{f}_1} \\ &\quad - [N_{TLL} - N_{TLL}^{irr}] \frac{f_2}{\bar{f}_2} \frac{f_3}{\bar{f}_3} - [N_{LTL} - N_{LTL}^{irr}] \frac{f_1}{\bar{f}_1} \frac{f_3}{\bar{f}_3} - [N_{LLT} - N_{LLT}^{irr}] \frac{f_1}{\bar{f}_1} \frac{f_2}{\bar{f}_2} \end{aligned} \quad (3.18)$$

The *fake factor* (F_i) is defined as $F_i = \frac{f_i}{\bar{f}_i}$. Using this definition the estimate for reducible background (N_{fake}) can be written as

$$N_{fake} = [N_{TTL} - N_{TTL}^{irr}]F_3 + [N_{TLT} - N_{TLT}^{irr}]F_2 + [N_{LTT} - N_{LTT}^{irr}]F_1 - [N_{TLL} - N_{TLL}^{irr}]F_2F_3 \quad (3.19)$$

$$- [N_{LTL} - N_{LTL}^{irr}]F_1F_2 - [N_{LLT} - N_{LLT}^{irr}]F_1F_2,$$

and using $N_{ijk}^{red} = N_{ijk} - N_{ijk}^{irr}$, Eqn. 3.19 for N_{fake} can be written as

$$N_{fake} = N_{TTL}^{red}F_3 + N_{TLT}^{red}F_2 + N_{LTT}^{red}F_1 - N_{TLL}^{red}F_2F_3 - N_{LTL}^{red}F_1F_3 - N_{LLT}^{red}F_1F_2. \quad (3.20)$$

The fake efficiencies are measured in data and in bins of p_T . Since the same selection applies for both Z leptons $F_2^i = F_3^i$, where i corresponds to the p_T binning used on fake factors. The fakes factors were also calculated in bins of η but due to the limited statistics only the p_T binning was used.

To take into account the p_T binning, Eqn. 3.20 can be written using sums over the i, j p_T bins, as shown in equation 3.21:

$$N_{fake} = \sum_i N_{TTL}^{red,i} F_3^i + \sum_i N_{TLT}^{red,i} F_2^i + \sum_i N_{LTT}^{red,i} F_1^i - \sum_i \sum_j N_{TLL}^{red,i,j} F_2^i F_3^j - \quad (3.21)$$

$$- \sum_i \sum_j N_{LTL}^{red,i,j} F_1^i F_3^j - \sum_i \sum_j N_{LLT}^{red,i,j} F_1^i F_2^j$$

3.5.2.2 Fake-enriched control regions for the determination of lepton fake factors

The electrons and muons from the Z and the W boson candidates have different isolation and identification criteria. Therefore, two different fake efficiencies are calculated for each flavor.

The fake factors measured are actually an average of fake factors from different sources, like heavy and light flavor jets and converted photons. Therefore, the control region (CR) used to measure the fake factors should have a similar composition as in the signal regions. The sources of different fake leptons:

- For fake W leptons: $Z + \text{jets}$, $Z\gamma$
- For fake Z leptons: $t\bar{t}$.

For muons, almost all the fake muons are coming from the heavy flavor jets. The reducible backgrounds are dominated by $Z + \text{jets}$ in TTL events where the fakes are mostly fake W leptons.

While for TLL events where the fakes are mostly fake Z leptons, the reducible backgrounds are dominated by $t\bar{t}$ process.

The control region for the W lepton fake factors is called $Z + \text{“fake”}$ control region. A $t\bar{t}$ control region is defined for Z lepton fake factors as they should be derived from a heavy-flavor jet dominant control region.

The definitions of these CRs are as follows:

- Control region $Z + \text{“fake” } e (\mu)$ ($ZjeCR$ or $Zj\mu CR$): Events with two opposite-sign muons (electrons) passing the Z “tight” muon (electron) selection and an additional electron (muon) is used. A missing transverse energy E_T^{miss} cut is applied ($E_T^{miss} < 30$ GeV). The “loose” requirement is applied on the additional lepton, but the d_0 significance cut is removed to include more fake leptons. The mass $m_{\mu\mu}$ (m_{ee}) is required to be between 85 and 96 GeV. This tighter and asymmetric cut in the lower part of the Z mass spectrum is applied to further reduce the contribution of photon conversions from FSR.
- Control region $t\bar{t}$ ($teCR$ and $t\mu CR$): Events with an opposite-sign $e\mu$ pair passing the W lepton selection and an additional electron or muon are used. The additional lepton is required to have the same sign as the one with the same flavor in the $e\mu$ pair, which means having two same-sign electrons or muons. In this case, events with Z are significantly suppressed. An additional cut of $E_T^{miss} > 25$ GeV and the presence of exactly one b-tagged jet is also required. The “loose” requirement is applied on the additional lepton, but the d_0 significance cut is removed to include more fake leptons. To make sure the fake e/μ is correctly selected, the fake e/μ candidate is required to have lower p_T and larger absolute value of the d_0 significance than the lepton sharing the same flavor and sign in the selection. Furthermore, the absolute value of the d_0 significance of the second real lepton is required to be smaller than 1.0. The invariant mass of the $e\mu$ pair is required to be $|m_{e\mu} - 91.1876| < 10$ GeV.

To calculate fake factors, the contribution from an irreducible background in each CR is subtracted. The fake factor is finally determined for four p_T bins as shown in figure 3.19. The binning used is [15, 20, 30, 50, 200].

3.5.2.3 Matrix Method Background closure test

An MC closure test is performed using events in the inclusive signal region. The pseudo data is the sum of the MC $Z + \text{jets}$, $t\bar{t}$ and $Z + \gamma$ contributions and is used to calculate fake factors and to estimate N_{TTL} , N_{TLT} , N_{LTT} , N_{TLL} , N_{LTL} , and N_{LLT} . Table 3.11 shows the closure result. Both statistical and systematic uncertainties are shown. Systematic uncertainties also include the statistical uncertainty on the fake factors estimations.

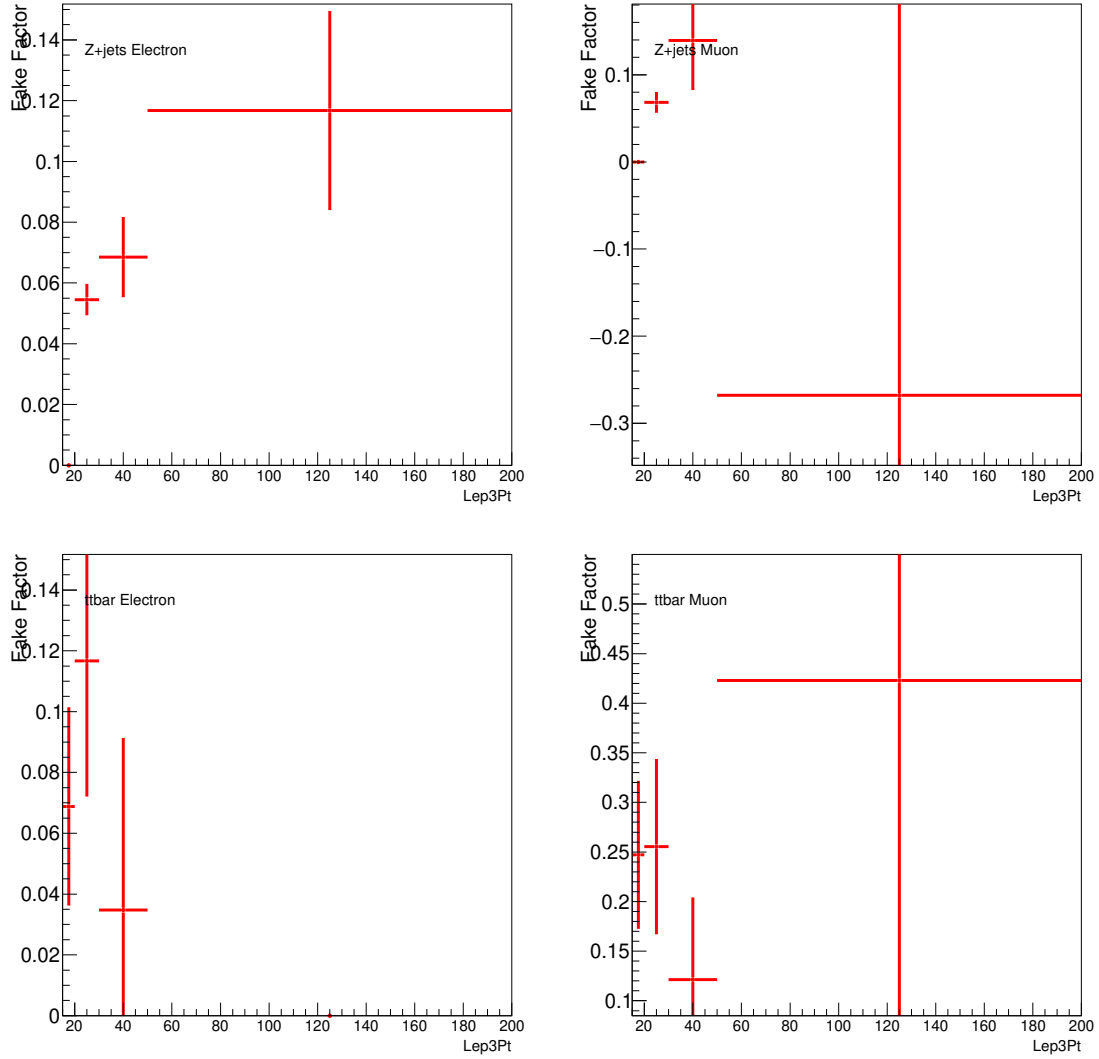


Figure 3.19: Fake factor as a function of the transverse momentum of the lepton measured from data. The top two plots show fake factors measured in the Z+jets CRs, while the bottom two plots show fake factors measured in the $t\bar{t}$ CRs. The left plots are for electrons and the right plots are for muons.

Channels	$\mu\mu\mu$	$e\mu\mu$	μee	eee
Sum of Z+jets, $t\bar{t}$, and $Z + \gamma$	207.13 $\pm$ 8.72	314.06 $\pm$ 13.11	103.11 $\pm$ 6.56	230.59 $\pm$ 10.47
Matrix result	269.96 $\pm$ 38.63	374.48 $\pm$ 29.05	108.20 $\pm$ 16.67	223.10 $\pm$ 18.12
Ratio	0.77 $\pm$ 0.11	0.84 $\pm$ 0.07	0.95 $\pm$ 0.16	1.03 $\pm$ 0.10

Table 3.11: Closure test of the matrix method using the pseudo data.

3.5.2.4 Systematic uncertainties

The statistical uncertainty on the final matrix method yield comes from the statistical uncertainty on the N_{TTL} , N_{TLT} , N_{LTT} , N_{TLL} , N_{LTL} and N_{LLL} . These yields are multiplied by corresponding fake factors (or a combination of fake factors). Thus their statistical uncertainties are scaled by those fake factors (or a combination of fake factors) and are then propagated to the final uncertainty.

The systematic uncertainty in the background measurement contains uncertainties affecting the fake factors, including the statistical uncertainties of control regions and the cuts used to build the control regions. The statistical uncertainties of fake control regions (due to a limited number of events used to determine fake factors) are taken as systematic uncertainties. A systematic uncertainty because of the E_T^{miss} cut applied is also considered. The fake control regions are strictly orthogonal to the (Loose) signal regions. The $\pm 1\sigma$ variations of statistic uncertainty of fake CRs are propagated to the variation of fake factors, which are finally propagated to the fake estimation yields.

3.6 Systematic Uncertainties

3.6.1 Theoretical Systematic Uncertainties

The PDF and Scale uncertainties on the polarization fractions in the 00-enhanced fiducial phase-space are calculated using a Rivet routine on the WZ polarised samples. Along with the recommendations by the ATLAS PMG group [162], a tool developed by the PMG group specifically for calculating theory systematic uncertainties was used [163].

Even though theoretical uncertainties could be sizable for some cross-section calculations, the effects on polarization fraction measurements are expected to be smaller since we rely on the shapes from MC simulations in the template fit method to determine the fractions. For the RAZ measurement, the cross-section uncertainties on the 00, 0T, and T0 states are important since their contributions need to be subtracted from data to obtain the TT-only ΔY_{WZ} or ΔY_{3Z} distribution.

In the high p_T regions of $p_T^Z > 100$ GeV and $p_T^Z > 200$ GeV, a shape uncertainty is applied to the BDT distributions by reweighting the distributions of a couple of variables event-by-event using

the theorists' calculations described in section 3.2.4.3. More details about how this uncertainty is applied can be found in section 3.6.1.4.

The PDF, α_s , renormalization and factorization scale, and parton shower uncertainties on the polarisation fractions are given in tables 3.12 and 3.13, for $WZ \rightarrow \ell \nu \ell \ell$ with $\ell = e, \mu$ in the final state (τ decays to e or μ are not considered here). The nominal cross-section values, when checked for $e\mu\tau$ final states with τ decays considered (inclusive phase space), are very similar to those for the $e\mu$ final state (within 0.02%). These uncertainties on cross sections of different polarization states for the RAZ measurement are shown in table 3.14 and the same on the depth ($\mathcal{D}$) variable are shown in tables 3.15 and 3.16.

3.6.1.1 PDF and α_s Uncertainties

The PDFs are essential for event simulation and are actually obtained from the fits to the actual measurements. The variations of the fit parameters are used and their impact on the fits is used to get pdf variations. All these variations make one pdf set. Many such sets exist, employing different fitting approaches.

The PDF set provided by the NNPDF 3.0 PDF (central pdf - 260000) has been used. The PDF4LHC recommendations [164, 165] have been followed to obtain the 68% confidence level for the PDF uncertainty. The cross-section corresponding to the central pdf is supposed to be the mean of the other 100 replicas provided in the NNPDF 3.0 PDF set. For the polarisation fractions, because of the combination of different MC samples, the fraction corresponding to the central PDF is not the mean of the fractions for the other 100 replicas. However, the difference between the mean fraction obtained from the 100 replicas and the fraction obtained from the central PDF is very negligible (0.002% or less). The PDF uncertainty is the standard deviation of these 100 replicas for each polarised MC sample. Following the recommendation in [164], the PDF and α_s uncertainties are calculated and combined, where variations of $\alpha_s = 0.117$ and $\alpha_s = 0.119$ are used along with the nominal value of $\alpha_s = 0.118$. Equations 3.22, 3.23 and 3.24 show the formulae for the uncertainty calculations.

The polarization fractions for 00-enhanced fiducial phase space for all the replicas including the central one are: $f_{\text{fid}}^{(k)}$, where $k \in 0, 1, 2, \dots, N_{\text{mem}}$ and $N_{\text{mem}} = 100$. The PDF set with $k = 0$ corresponds to the central PDF.

The PDF uncertainty is calculated as follows considering 100 replicas of the NNPDF 3.0 PDF:

$$\Delta^{\text{PDF}} f_{\text{fid}} = \sqrt{\frac{1}{(N_{\text{mem}} - 1)} \sum_{k=1}^{N_{\text{mem}}} \left(f_{\text{fid}}^{(k)} - \langle f_{\text{fid}} \rangle \right)^2}, \quad (3.22)$$

The mean value of a polarization fraction, $\langle f_{\text{fid}} \rangle$, is computed as:

$$\langle f_{\text{fid}} \rangle = \frac{1}{N_{\text{mem}}} \sum_{k=1}^{N_{\text{mem}}} f_{\text{fid}}^{(k)}. \quad (3.23)$$

The dependencies of the parton distribution function on the strong coupling are evaluated by including variations of the PDF sets using values for α_s evaluated at the Z boson mass. The nominal PDF set uses a value of 0.118. The uncertainty due to the variation of the α_s used is calculated as follows:

$$\Delta^{\alpha_s} f_{\text{fid}} = r \cdot \frac{f_{\text{fid}}(\alpha_s = 0.119) - f_{\text{fid}}(\alpha_s = 0.117)}{2}, \quad (3.24)$$

where in this case $r = 1$. The variations are based on the current PDG uncertainty on α_s given as $\alpha_s(m_Z^2) = 0.1180 \pm 0.0010$.

To combine these two uncertainties equation 3.25 is used:

$$\Delta^{\text{PDF}+\alpha_s} f_{\text{fid}} = \sqrt{(\Delta^{\text{PDF}} f_{\text{fid}})^2 + (\Delta^{\alpha_s} f_{\text{fid}})^2}. \quad (3.25)$$

The cross-sections for the other PDF sets such as PDF4LHC15_nlo_30_pdfas, CT14nlo, MMHT2014nlo68clas118 were also looked at (in the inclusive phase space) and they were found to be within 68% confidence interval set by the NNPDF 3.0 PDF set replicas.

3.6.1.2 QCD Scale Uncertainties

The matrix elements depend on the particle kinematics of the considered phase space point as well as on the factorization and renormalization scales μ_F and μ_R . These scales are unphysical, and a full calculation to all orders of perturbation theory would not depend on these scales.

For the QCD scale uncertainties, the values of the renormalization and factorization (μ_R and μ_F respectively) scales are varied by a factor of 0.5 and 2 from the nominal values. From seven such variations (except the extreme cases of $\{0.5, 2\}$ and $\{2, 0.5\}$), the maximum and minimum values of the cross-sections are considered and the differences between these with respect to the nominal value are obtained as the up and down scale uncertainties.

3.6.1.3 Parton Shower Uncertainty Using Eigentune Variations

Due to some issues with the HERWIG generator for polarization bosons, no MC samples are generated for WZ production with HERWIG used for parton showering. Instead, the recommendations suggested by the PMG group [162] are used. Variations on Initial State Radiation (ISR)/FSR/Multi-

Parton Interactions (MPI) and color reconnection parameters (Eigentune variations) are used to estimate the Parton shower uncertainty. In total ten up and down variations were used to generate samples as explained in the reference. The deviations of all these variations from the nominal value are squared and then summed in quadrature. The uncertainties are shown in table 3.14.

Cross-section (fb)	Nominal	PDF + α_s Unc (%)	Scale Unc (%)	Shower Unc (%)
σ_{00}	0.485	± 1.68	+4.86 -4.39	± 3.56
σ_{0T}	0.119	± 1.40	+7.33 -6.38	± 6.97
σ_{T0}	0.107	± 1.43	+7.06 -6.14	± 2.92
σ_{TT}	1.33	± 1.56	+8.58 -7.33	± 1.67
Fraction	Nominal	PDF + α_s Unc (%)	Scale Unc (%)	Shower Unc (%)
f_{00}	0.237	± 0.254	+2.272 -2.497	± 2.77
f_{0T}	0.0581	± 0.372	+0.669 -0.798	± 6.30
f_{T0}	0.0524	± 0.285	+0.634 -0.736	± 2.74
f_{TT}	0.652	± 0.115	+0.963 -0.873	± 0.759

Table 3.12: For the signal region with $p_T^Z > 200$ GeV: central value and theoretical uncertainties on the cross sections and polarisation fractions for $WZ \rightarrow \ell \nu \ell \ell$ production with $\ell = e, \mu$.

Cross-section (fb)	Nominal	PDF + α_s Unc (%)	Scale Unc (%)	Shower Unc (%)
σ_{00}	2.58	± 1.61	+3.14 −2.59	± 2.65
σ_{0T}	1.76	± 1.45	+5.54 −4.55	± 2.77
σ_{T0}	1.60	± 1.48	+5.12 −4.21	± 2.84
σ_{TT}	10.04	± 1.48	+5.21 −4.32	± 1.47
Fraction	Nominal	PDF + α_s Unc (%)	Scale Unc (%)	Shower Unc (%)
f_{00}	0.161	± 0.225	+2.698 −2.974	± 2.99
f_{0T}	0.110	± 0.286	+0.647 −0.800	± 2.35
f_{T0}	0.100	± 0.192	+0.688 −0.810	± 2.48
f_{TT}	0.629	± 0.095	+0.890 −0.798	± 0.867

Table 3.13: For the signal region with $p_T^Z > 100$ GeV: central value and theoretical uncertainties on the cross sections and polarisation fractions for $WZ \rightarrow \ell \nu \ell \ell$ production with $\ell = e, \mu$.

Region	Pol State	Cross-section (pb)	PDF + α_s (%)	Scale (%)	Shower (%)
$p_T^{WZ} < 10 \text{ GeV}$	σ_{00}	0.00282	± 1.74	+5.20 -6.31	± 20.6
	σ_{0T}	0.00399	± 1.76	+5.78 -6.97	± 19.6
	σ_{T0}	0.00370	± 1.76	+5.75 -6.93	± 19.7
	σ_{TT}	0.0233	± 1.76	+4.75 -5.87	± 20.8
$p_T^{WZ} < 20 \text{ GeV}$	σ_{00}	0.00505	± 1.70	+5.18 -6.29	± 10.9
	σ_{0T}	0.00721	± 1.72	+5.73 -6.92	± 9.07
	σ_{T0}	0.00670	± 1.71	+5.68 -6.86	± 9.21
	σ_{TT}	0.0424	± 1.72	+4.69 -5.82	± 10.8
$p_T^{WZ} < 40 \text{ GeV}$	σ_{00}	0.00740	± 1.67	+4.69 -5.78	± 4.21
	σ_{0T}	0.0116	± 1.66	+4.87 -6.06	± 1.96
	σ_{T0}	0.0109	± 1.65	+4.81 -5.98	± 2.02
	σ_{TT}	0.0635	± 1.67	+4.16 -5.27	± 3.82
$p_T^{WZ} < 70 \text{ GeV}$	σ_{00}	0.00875	± 1.65	+4.21 -5.28	± 1.62
	σ_{0T}	0.0165	± 1.59	+5.29 -4.99	± 2.22
	σ_{T0}	0.0155	± 1.58	+5.33 -4.86	± 2.22
	σ_{TT}	0.0785	± 1.62	+3.62 -4.62	± 0.897

Table 3.14: Central value and theoretical uncertainties on the cross-sections for different regions of p_T^{WZ} for the RAZ measurement with $WZ \rightarrow \ell \nu \ell \ell$ production where $\ell = e, \mu$.

Region	Depth ($\mathcal{D}$)	PDF + α_s (%)	Scale (%)	Shower (%)
$p_T^{WZ} < 10$ GeV	0.342	± 0.311	$+1.91$ -1.63	± 5.05
$p_T^{WZ} < 20$ GeV	0.349	± 0.315	$+1.77$ -1.51	± 3.35
$p_T^{WZ} < 40$ GeV	0.330	± 0.356	$+1.53$ -1.29	± 4.02
$p_T^{WZ} < 70$ GeV	0.284	± 0.493	$+1.72$ -1.96	± 5.83

Table 3.15: Central value and theoretical uncertainties on the depth calculations using ΔY_{3Z} for different regions of p_T^{WZ} for the RAZ measurement with $WZ \rightarrow \ell \nu \ell \ell$ production where $\ell = e, \mu$.

Region	Depth ($\mathcal{D}$)	PDF + α_s (%)	Scale (%)	Shower (%)
$p_T^{WZ} < 10$ GeV	0.769	± 0.0402	$+0.262$ -0.226	± 0.958
$p_T^{WZ} < 20$ GeV	0.760	± 0.0520	$+0.216$ -0.186	± 1.64
$p_T^{WZ} < 40$ GeV	0.719	± 0.105	$+0.553$ -0.679	± 1.53
$p_T^{WZ} < 70$ GeV	0.643	± 0.205	$+1.60$ -1.87	± 2.48

Table 3.16: Central value and theoretical uncertainties on the depth calculations using ΔY_{WZ} for different regions of p_T^{WZ} for the RAZ measurement with $WZ \rightarrow \ell \nu \ell \ell$ production where $\ell = e, \mu$.

3.6.1.4 Theoretical Systematic Uncertainty due to the NLO QCD+EW Corrections

The NLO EW corrections explained in section 3.2.4.3 are propagated to the reconstruction level calculations in the two high p_T signal regions. Two kinematic variables at the truth level are used to calculate the NLO QCD+EW reweighting factors: the average of the transverse momenta of all three leptons ($\text{Avg}(p_T(\ell)s)$) and ΔY_{3Z} . The ΔY_{3Z} is used because it has the largest impact on the BDT and $\text{Avg}(p_T(\ell)s)$ is used to factor in the impact of the lepton p_{Ts} . The ΔY_{3Z} is used because it has the largest impact on the BDT and $\text{Avg}(p_T(\ell)s)$ is used to factor in the impact of the lepton p_{Ts} . Figures 3.20, 3.21, 3.22, 3.23, 3.24, and 3.25 show the comparisons between NLO QCD+EW with constant k -factors from table 3.17 (along with (NLO QCD/LO 0+1 jet) k -factor) and (NLO QCD+EW/NLO QCD) corrections using event-by-event reweighting of the same variable for different polarization states separately (the jet-multiplicity k -factors are common to both). All these k -factors are detailed in section 3.7.

- For the reweighted distributions, an event-by-event (NLO QCD)/(LO) reweighting factor is applied using the reconstructed value of the reweighting variable (the sum of different polarization states is reweighted to SHERPA NLO QCD distribution bin-by-bin. The reco-level variable value for the event is used to apply the event-by-event reweighting using this bin-by-bin reweighted distribution).
- The NLO(QCD+EW)/NLO(QCD) correction is also applied event-by-event using the truth value of the reweighting variable for that event. This factor is again taken from the theorists' bin-by-bin calculations described in section 3.2.4.3.

The effect of the NLO QCD+EW reweighting is then propagated in all distributions and to the BDT (using the event-by-event weights). The shape effects on the BDT are used as a theoretical uncertainty on the fit. The uncertainty is considered correlated for all polarizations. Only the shape effect of this uncertainty is considered for the polarization fraction extraction since the total normalization/fraction is directly measured from the data. Figures 3.24 and 3.25 show the BDT output for different polarization states.

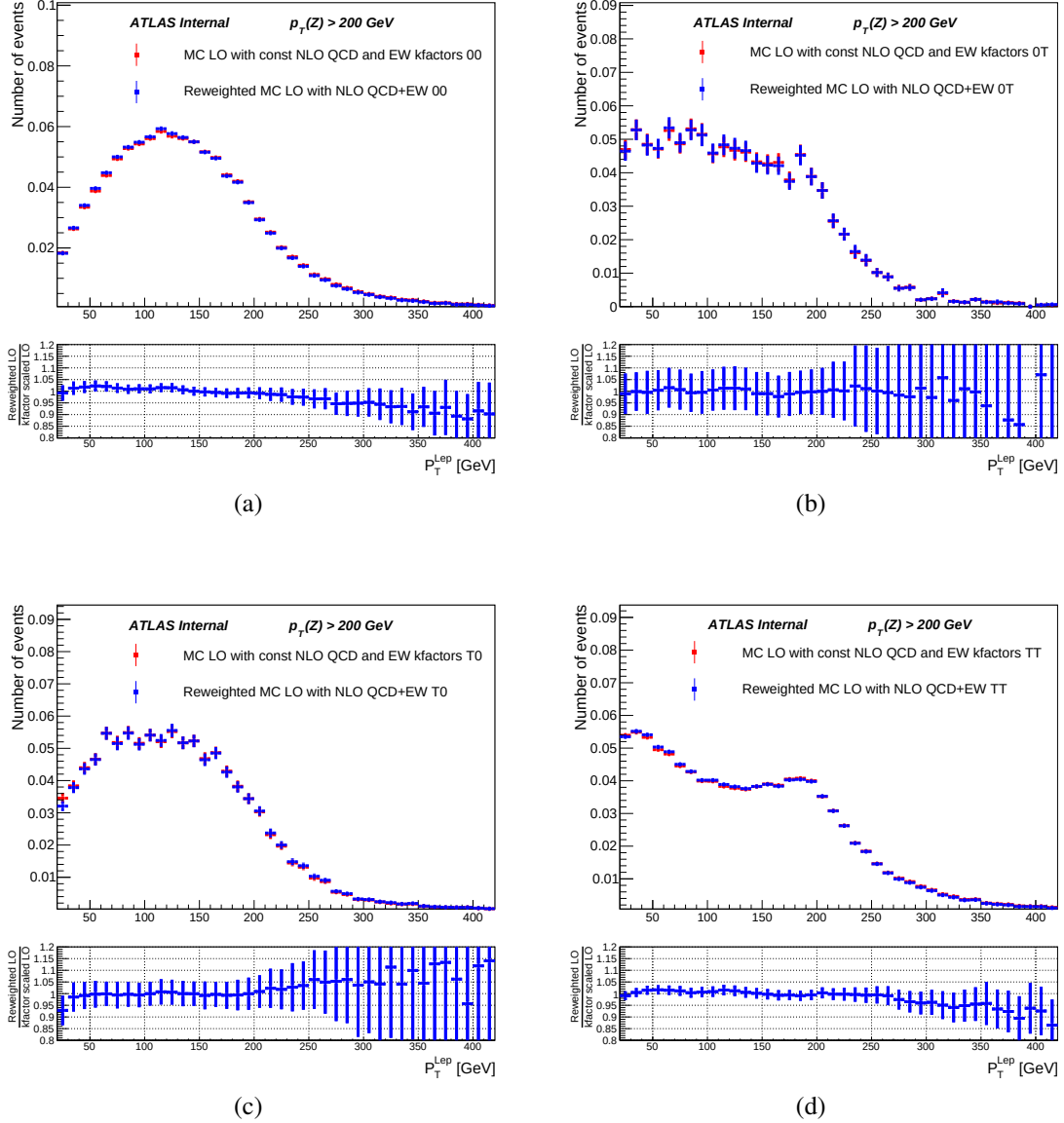


Figure 3.20: Comparisons between 2 different types of NLO corrections on $p_T(\text{Leptons})$ distribution in the signal region $p_T^Z > 200$ GeV for 00 (a), 0T (b), T0 (c), TT (d). *red* is nominal with which a constant NLO (QCD) KFactor + constant NLO (QCD+EW) k -factor is applied. *Blue* is the reweighted with event-by-event NLO(QCD+EW)/NLO (QCD) factor applied. The reweighting is done using $\text{Avg}(p_T(\ell))$ s distributions as explained above.

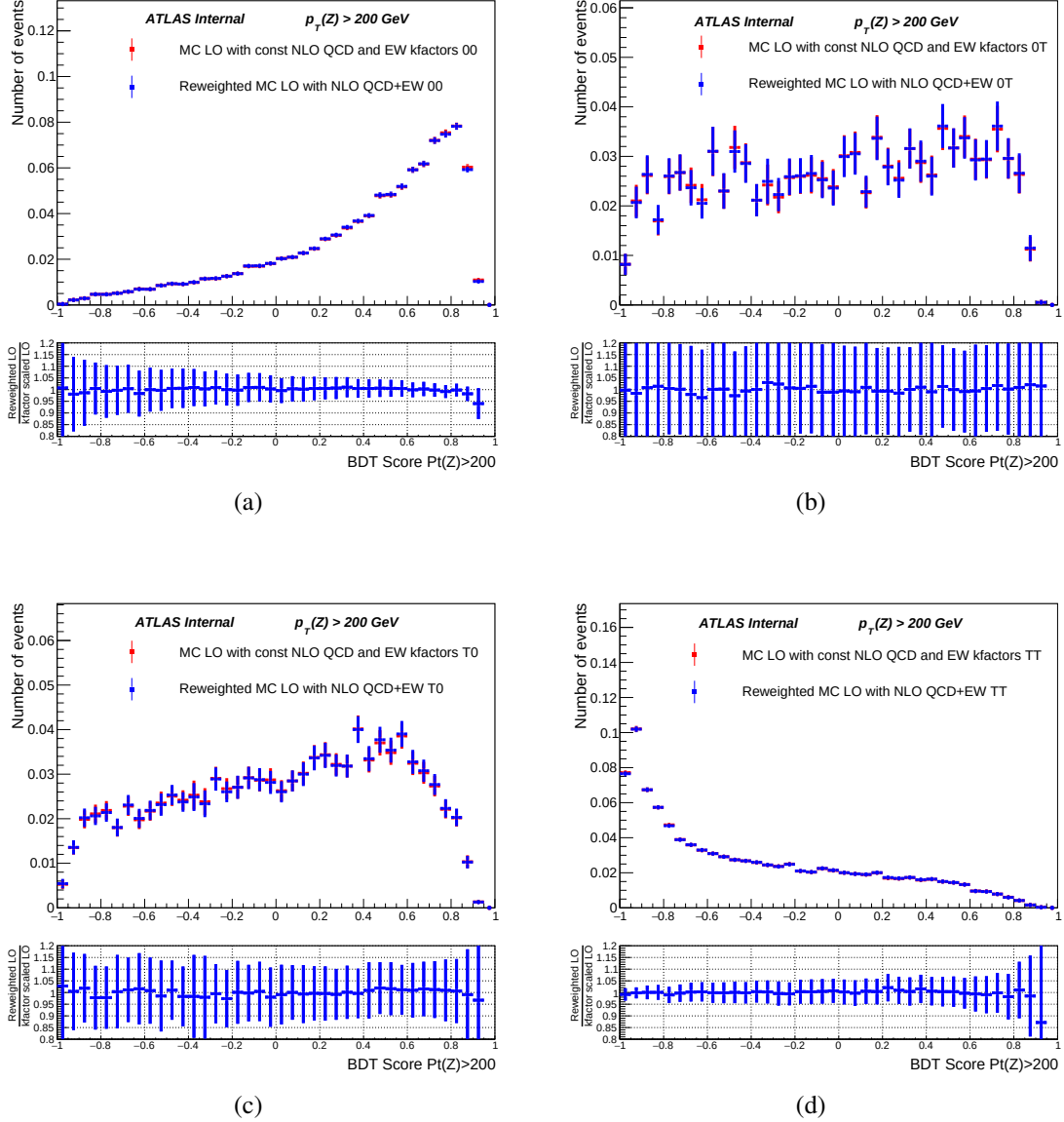


Figure 3.21: Comparisons between 2 different types of NLO corrections on BDT score distribution in the signal region $p_T^Z > 200$ GeV for 00 (a), 0T (b), T0 (c), TT (d). *red* is nominal with which a constant NLO (QCD) KFactor + constant NLO (QCD+EW) k -factor is applied. *Blue* is the reweighted with event-by-event NLO(QCD+EW)/NLO (QCD) factor applied. The reweighting is done using $\text{Avg}(p_T(\ell))$ s distributions as explained above.

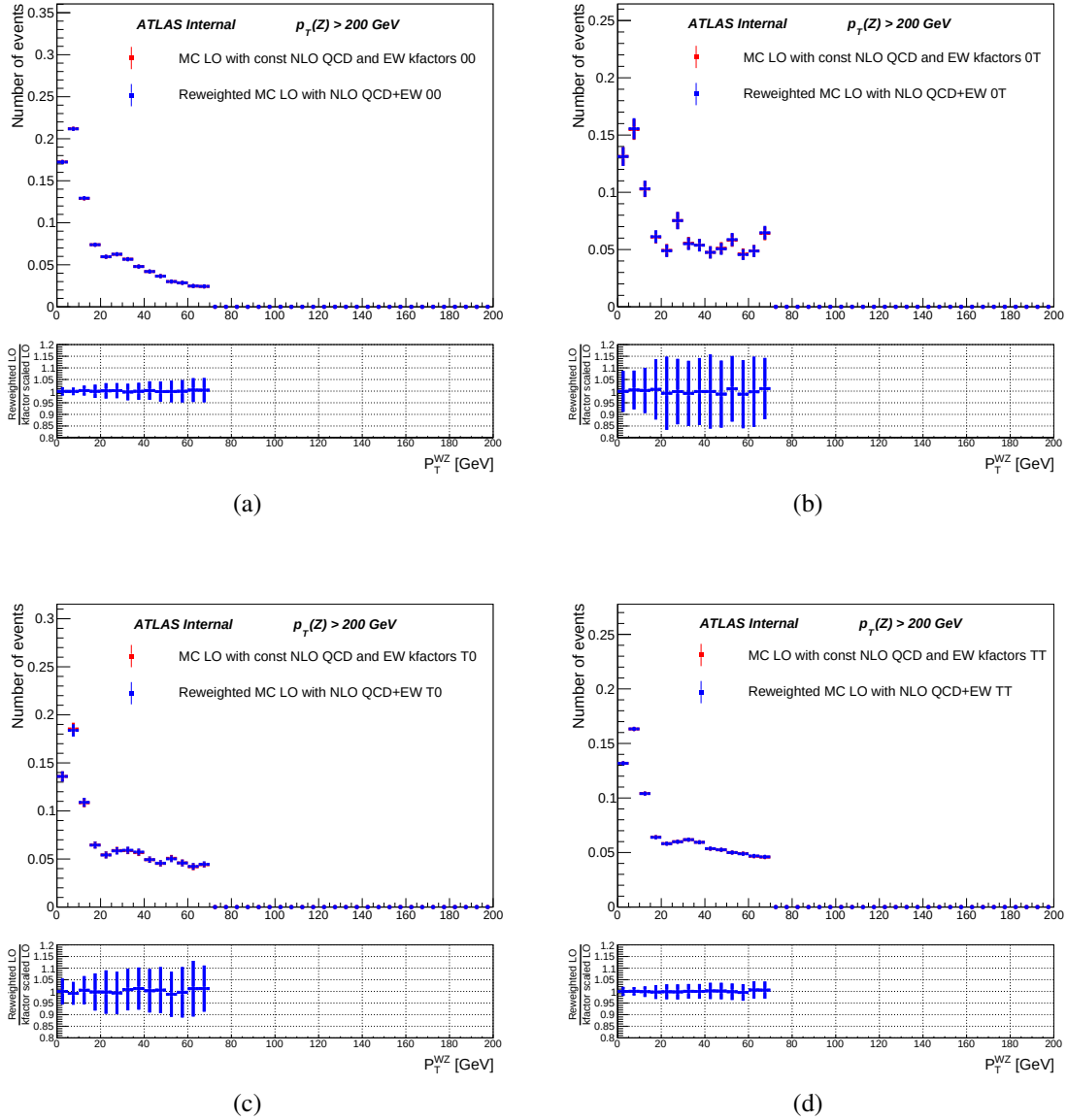


Figure 3.22: Comparisons between 2 different types of NLO corrections on $p_T^{Z WZ}$ distribution in the signal region $p_T^Z > 200$ GeV for 00 (a), 0T (b), T0 (c), TT (d). *red* is nominal with which a constant NLO (QCD) KFactor + constant NLO (QCD+EW) k -factor is applied. *Blue* is the reweighted with event-by-event NLO(QCD+EW)/NLO (QCD) factor applied. The reweighting is done using $\text{Avg}(p_T(\ell))$ s distributions as explained above.

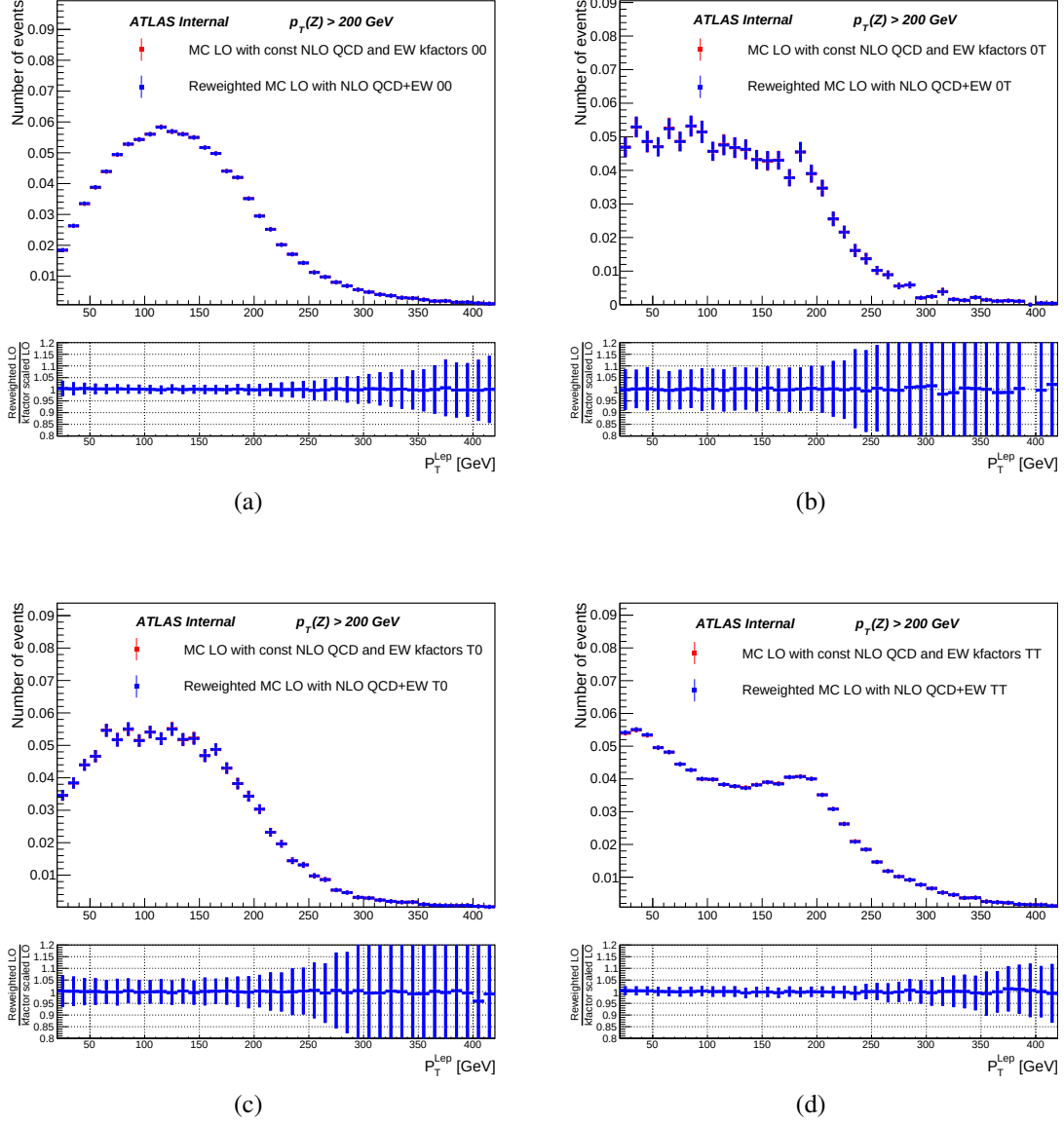


Figure 3.23: Comparisons between 2 different types of NLO corrections on $p_T(\text{Leptons})$ distribution in the signal region $p_T^Z > 200$ GeV for 00 (a), 0T (b), T0 (c), and TT (d). *red* is nominal with which a constant NLO (QCD) KFactor + constant NLO (QCD+EW) k -factor is applied. *Blue* is the reweighted with event-by-event NLO(QCD+EW)/NLO (QCD) factor applied. The reweighting is done using ΔY_{3Z} distributions as explained above.

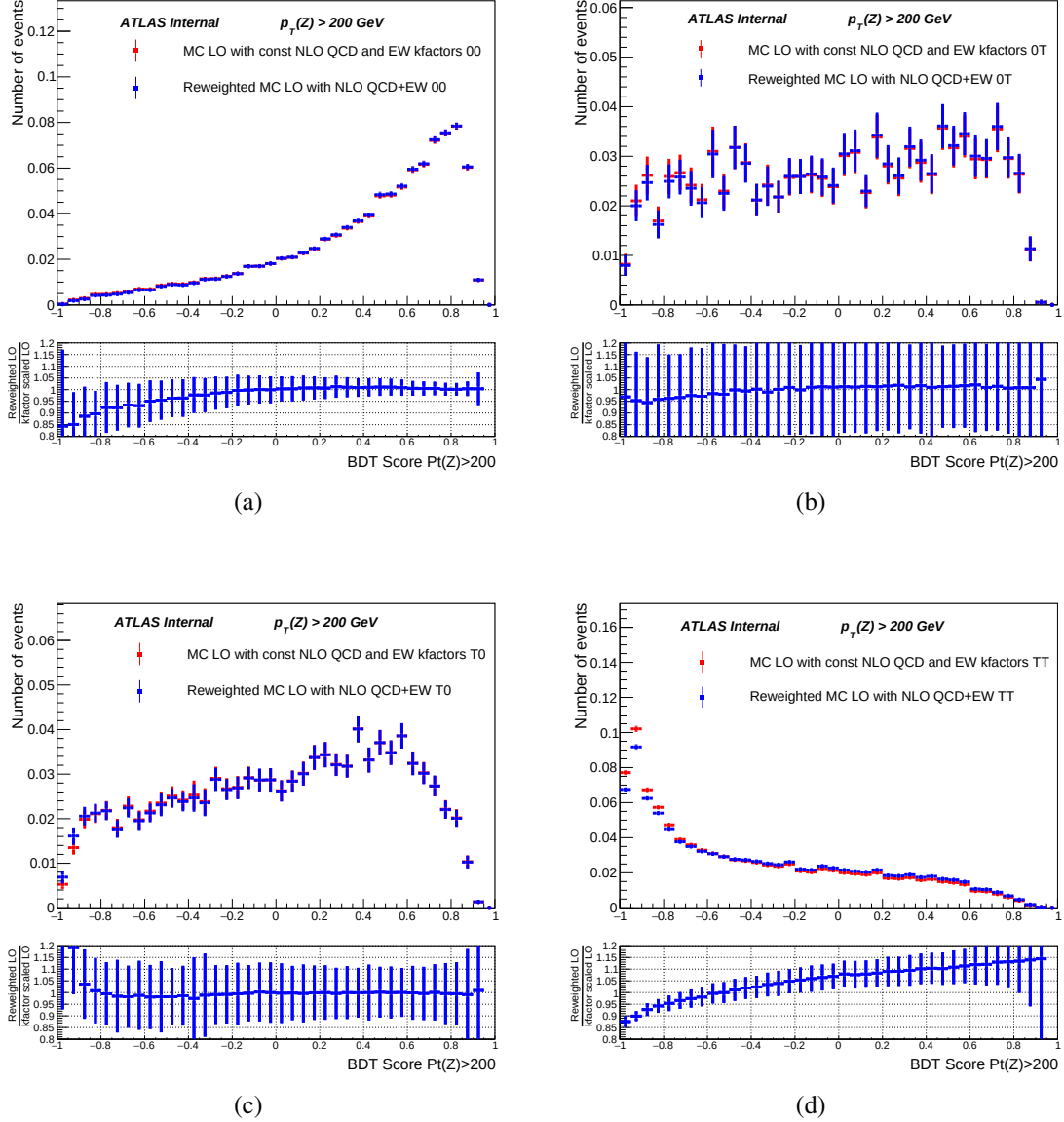


Figure 3.24: Comparisons between 2 different types of NLO corrections on BDT score distribution in the signal region $p_T^Z > 200$ GeV for 00 (a), 0T (b), T0 (c), and TT (d). *red* is nominal with which a constant NLO (QCD) KFactor + constant NLO (QCD+EW) k -factor is applied. *Blue* is the reweighted with event-by-event NLO(QCD+EW)/NLO (QCD) factor applied. The reweighting is done using ΔY_{3Z} distributions as explained above.

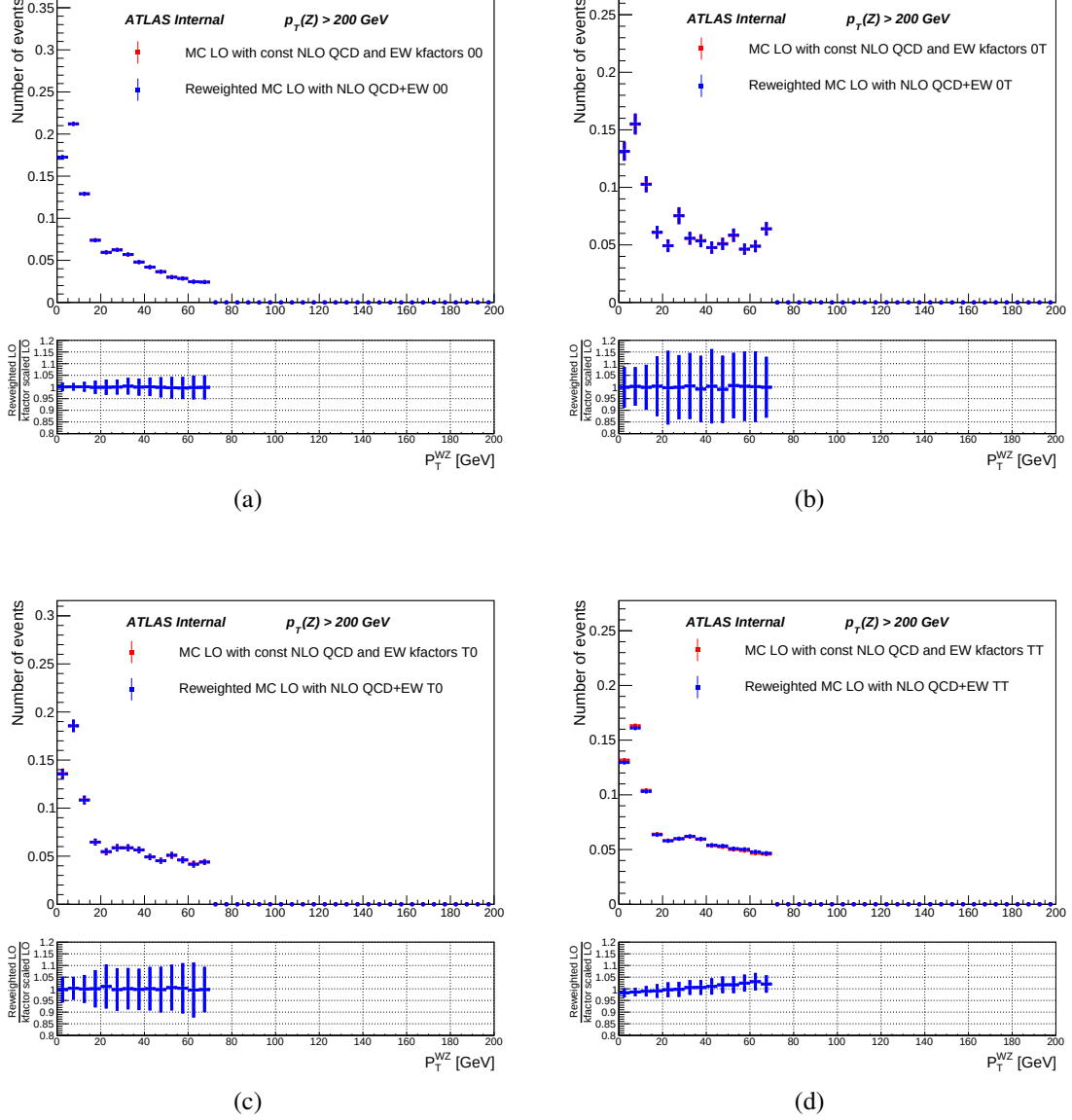


Figure 3.25: Comparisons between 2 different types of NLO corrections on $p_T(WZ)$ distribution in the signal region $p_T^Z > 200$ GeV for 00 (a), 0T (b), T0 (c), and TT (d). *red* is nominal with which a constant NLO (QCD) KFactor + constant NLO (QCD+EW) k -factor is applied. *Blue* is the reweighted with event-by-event NLO(QCD+EW)/NLO (QCD) factor applied. The reweighting is done using ΔY_{3Z} distributions as explained above.

3.6.2 Experimental Systematic Uncertainties

This section describes the instrumental systematic uncertainties that are included in the final measurement. Some of these are explained in references [132, 166–168].

3.6.2.1 Luminosity

The uncertainty in the combined 2015–2018 integrated luminosity is 0.83 % [106]. It is derived, following a methodology similar to that detailed in Ref. [169], from the calibration of the luminosity scale using x – y beam-separation scans. This uncertainty is applied to 00, 0T, and T0 production for the RAZ measurement as well as all the processes in the polarization fraction measurement that have their normalization estimated from MC.

3.6.2.2 Muons

Systematic uncertainties attributed to the muons originate from reconstruction efficiency and transverse momentum resolution and scale. The uncertainty due to the reconstruction efficiency comes from the statistical and systematic uncertainties of determining the scale factors. To evaluate this uncertainty, scale factors are varied up and down following their corresponding source of systematics. The collection of uncertainties is taken directly from the standard tool provided by the Muon Combined Performance (MCP) group, where the uncertainties from identification, isolation, and track-to-vertex-association are considered. The varied scale factors result in the varied shapes of spectra hence leading to an altered signal yield. The correction of the p_T of the muon is affected by both scale and resolution uncertainties. To evaluate the resolution uncertainty, the correction of p_T of the muon is varied also through the tool provided by the MCP group, where the effect from ID and MS are considered separately. The effect of the scale uncertainty is evaluated similarly through the tool with the keyword `SCALE`. The varied p_T also leads to the varied shapes of spectra then affects the signal yield.

Here are the muon-related systematics used in this analysis (the specific ATLAS names are used in the plots later so those names are given as reference here and also the names for other object reconstruction uncertainties below):

- MUON_EFF_ISO_STAT: statistical uncertainty on the isolation scale SF
- MUON_EFF_ISO_SYS: systematic uncertainty on the isolation scale SF
- MUON_EFF_RECO_STAT: statistical component of the muon ID efficiency uncertainty
- MUON_EFF_RECO_STAT_LOWPT: statistical component of the low-pt muon ID efficiency uncertainty

- MUON_EFF_RECO_SYS: systematic component of the muon ID efficiency uncertainty
- MUON_EFF_RECO_SYS_LOWPT: systematic component of the low-pt muon ID efficiency uncertainty.
- MUON_EFF_TTVA_STAT: statistical component of the uncertainty on the track-to-vertex association (TTVA) SF
- MUON_EFF_TTVA_SYS: systematic component of the uncertainty on the TTVA SF
- MUON_ID: uncertainty arising from the smearing of the muon ID track
- MUON_MS: uncertainty arising from the smearing of the MS track
- MUON_SAGITTA_RESBIAS: variations in the scale of the momentum (charge dependent), based on the residual charge-dependent bias after corrections
- MUON_SAGITTA_RHO: Variations in the scale of the momentum (charge dependent), based on a combination of correction on combined (Z scale) and recombination of the corrections
- MUON_SCALE: variations in the muon momentum scale

3.6.2.3 Electrons

As for the electrons, systematic uncertainties come from reconstruction efficiency and transverse momentum resolution and scale. The reconstruction uncertainties originate from the measurement of scale factors. The Scale Factor (SF) measurements represent auxiliary measurements done in each of the different bins and thus are statistically independent of each other. Systematic uncertainties can be either correlated or uncorrelated between the different bins. In the “TOTAL” model, all systematics are combined and categorized into three terms: reconstruction, identification, and isolation. The electron p_T correction is varied to get the corresponding uncertainties. In the “full” model, every variation corresponds to a different source of systematics in a specific decorrelated (η) region. In this analysis, a very simplified model “1NP_v1” is used to combine and categorize these variations into two terms EG_RESOLUTION_ALL and EG_SCALE_ALL, where all the physical effects are summed in quadrature and considered fully correlated in eta.

Here are the EGamma-related systematics used in this analysis:

- EG_RESOLUTION_ALL: EGamma resolution uncertainty
- EG_SCALE_AF2: EGamma scale uncertainty applied to AF2 (fast simulation) samples
- EG_SCALE_ALL: EGamma scale uncertainty

- EL_EFF_ID_TOTAL_1NPCOR_PLUS_UNCOR: electron identification (ID) efficiency uncertainty
- EL_EFF_Iso_TOTAL_1NPCOR_PLUS_UNCOR: electron isolation efficiency uncertainty
- EL_EFF_Reco_TOTAL_1NPCOR_PLUS_UNCOR: electron reconstruction efficiency uncertainty

3.6.2.4 Jets

Uncertainties on the jet energy scale affect the E_T^{miss} reconstruction. The systematic variation is applied through a dedicated tool. It contains a full treatment of bin-to-bin correlations for systematic uncertainties. This is achieved through the splitting of the nuisance parameters coming from the various in-situ techniques. A “global reduction” model is used to evaluate the total uncertainty. The MC jets are also smeared by the tool to correct for the resolution. A “SimpleJER” model is used to estimate the uncertainty related to the jet resolution correction.

Here are the jet-related systematics used in this analysis:

- JET_EtaIntercalibrationNonClosure_2018data, JET_EtaIntercalibrationNonClosure_highE, JET_EtaIntercalibrationNonClosure_negEta, JET_EtaIntercalibrationNonClosure_posEta, JET_GroupedNP_X(3), JET_EtaIntercalibration_TotalStat, JET_EtaIntercalibrationModelling: Jet Energy Scale (JES) uncertainties. The Eta inter-calibration uncertainties related to the modeling, non-closure and statistical uncertainties.
- JET_JER_EffectiveNP_X(7), JET_JER_DataVsMC_MC16: Jet Energy Resolution (JER) uncertainties (grouped and based on the difference between data and MC)
- JET_JvtEfficiency, JET_fJvtEfficiency: central (JVT) and forward (fJVT) pile-up tagging efficiency uncertainty
- JET_BJES_Response: Jet energy uncertainty for b -jets
- JET_EffectiveNP_X(8): Jet energy scale uncertainty from the in situ analysis grouped together
- JET_Flavor_Composition: Jet flavour composition mismodelling uncertainty
- JET_Flavor_Response: Jet flavour response mismodelling uncertainty

- JET_PunchThrough_MC16: Uncertainty related to punch-through jets (very high-energy jets which escape the detector)
- JET_SingleParticle_HighPt: Uncertainty related to high-momentum jets
- JET_Pileup_OffsetMu, JET_Pileup_OffsetNPV, JET_Pileup_PtTerm, JET_Pileup_RhoTopology: The pileup dependent uncertainty for the offsets in μ (the mean number of interactions per bunch crossing), in N_{PV} (the number of primary vertices), in the p_T -term and the ρ density (in $y-\phi$ plane, p_T/A).

3.6.2.5 Flavour Tagging

- FT_EFF_Eigen_B_X (9), FT_EFF_Eigen_C_X (4), FT_EFF_Eigen_Light_X (4): b -tagging efficiency uncertainties (b -jet, c -jet and light jet scale factor uncertainties).
- FT_EFF_extrapolation: weight-based uncertainty to take into account the extrapolation of the b -tagging weights to high p_T regimes.
- FT_EFF_extrapolation_from_charm: weight based uncertainty to take into account extrapolating the c -jet mistag rate to high p_T regimes

3.6.2.6 Missing transverse momentum

Missing transverse momentum is calculated using the pre-selected leptons and jets. The uncertainties of those objects are then passed into the uncertainties of E_T^{miss} reconstruction. Besides those uncertainties, the uncertainties due to soft terms scale and resolution are also considered using a dedicated tool. The uncertainties on the soft track component are derived from the agreement between data and MC of the p_T balance between the hard and soft E_T^{miss} (MET) components. The uncertainties are categorized as follows:

- MET_SoftTrk_Scale: uncertainty corresponding to offset along the p_T -Hard axis
- MET_SoftTrk_ResoPara: smearing by resolution uncertainty along the p_T -Hard axis
- MET_SoftTrk_ResoPerp: smearing by resolution uncertainty perpendicular to the p_T -Hard axis

The resolution smearing is applied correlated with the positive scale uncertainty because the positive scale shift produces better data-MC agreement.

3.6.2.7 Pileup

The systematic uncertainty (PRW_DATASF) of pile-up reweighting comes from the DataScaleFactor (reweighting of the distribution of primary vertices from simulations to match data), which scales the μ to improve the data/MC agreement. The nominal value of DataScaleFactor is set to 1.0/1.09. It is then varied to 1.0 and 1/1.18 to represent the systematic uncertainty.

3.6.2.8 Systematic uncertainties on background contributions

The uncertainties on the number of reducible background events arising from misidentified leptons and determined using the data-driven matrix method are detailed in section 3.5.2. Systematic uncertainties sources listed in section 3.5.2.4 are considered, resulting in a total uncertainty of the order of 20 to 25%.

- FakeBkg_Stat: Statistical uncertainty on the fake estimation
- FakeBkg_MetCut: Uncertainty due to the change in E_T^{miss} cut.

The uncertainty due to irreducible background sources is evaluated by propagating PDF and QCD scale uncertainties into the MC cross-sections. In the statistical analysis, these are implemented as global normalization uncertainties: an uncertainty of 13% is attributed to $t\bar{t} + V$ simulations [170], a 15% uncertainty is attributed to ZZ contributions, and a 20% is attributed to the $WZjj$ -EW and to triboson processes which contributions are negligible [171, 172].

3.7 Polarization Sample Reweighting to the NLO Precision

The current MADGRAPH generator cannot produce polarized samples with NLO accuracy. While dealing with the inclusive region, a constant LO $\rightarrow$ NLO QCD k -factor of 1.525 is applied. It is derived by dividing the $WZQCD$ Sherpa sample by the sum of polarized samples using inclusive region selection yield. The jet-multiplicity distribution is checked after that. There was a difference in data and the stacked background. The jet-multiplicity reweighting factors are derived separately for events with 0, 1, 2, and ≥ 3 jets (1.03, 0.84, 0.93, and 0.42 respectively) and applied to the W_0Z_0 , W_0Z_T , W_TZ_0 , W_TZ_T estimations. This reweighting corrects for some higher-order effects. All these above scale factors are also applied to the RAZ signal regions. The NLO QCD+EW corrections are not significant in both inclusive and RAZ regions so they are not applied. However, they are more relevant for the high p_T signal regions of $p_T^Z > 100$ GeV and $p_T^Z > 200$ GeV. All k -factors applied to these signal regions are described below:

1. To the nominal distribution, a constant NLO QCD k -factor of 1.420 for the $p_T^Z > 100$ GeV

region and 1.348 for the $p_T^Z > 200$ GeV region is applied. These are derived by dividing the $WZQCD$ Sherpa sample by the sum of polarized samples using inclusive region selection yield.

2. On top of these, jet-multiplicity reweighting factors described above are applied.
3. Next, constant (NLO QCD+EW)/(NLO QCD) k -factors are also applied, which are taken from the theorists' calculations. The factors are shown in table 3.17¹.

Polarization	$p_T^Z > 200$ GeV	$p_T^Z > 100$ GeV
00	0.89	0.94
0T	0.93	0.98
T0	1.0	0.98
TT	0.90	0.94
Unpolarized (Sherpa pseudodata)	0.90	0.95

Table 3.17: (NLO QCD+EW)/(NLO QCD) k -factors used.

3.8 Data/MC Comparisons in the Inclusive Phase Space

Before unblinding the signal regions for both measurements, we check the comparisons between the data and MC (signal+background) in the inclusive phase space. This phase space is far from both the signal regions (RAZ and polarization fraction measurement). This gives us an idea about any mis-modeled backgrounds. Here data is compared with the background and signal by stacking the following estimations: ZZ , VVV , $WZEW$, $t\bar{t}V$, Fake, W_0Z_0 , W_0Z_T , W_TZ_0 , W_TZ_T . Figure 3.26a shows a good agreement between data and MC for the number of jets and figure 3.26b shows good agreement between different leptonic channels: 1 means $\mu\mu\mu$, 2 means $\mu\mu e$, 3 means μee , and 4 means eee . Figures 3.26, 3.27 and 3.28 for the Data/MC comparisons in the inclusive phase space.

¹These are not the final k -factors. Improved k -factors are being applied in the ongoing analysis. The difference with respect to improved ones is very small (maximum up to 3%)

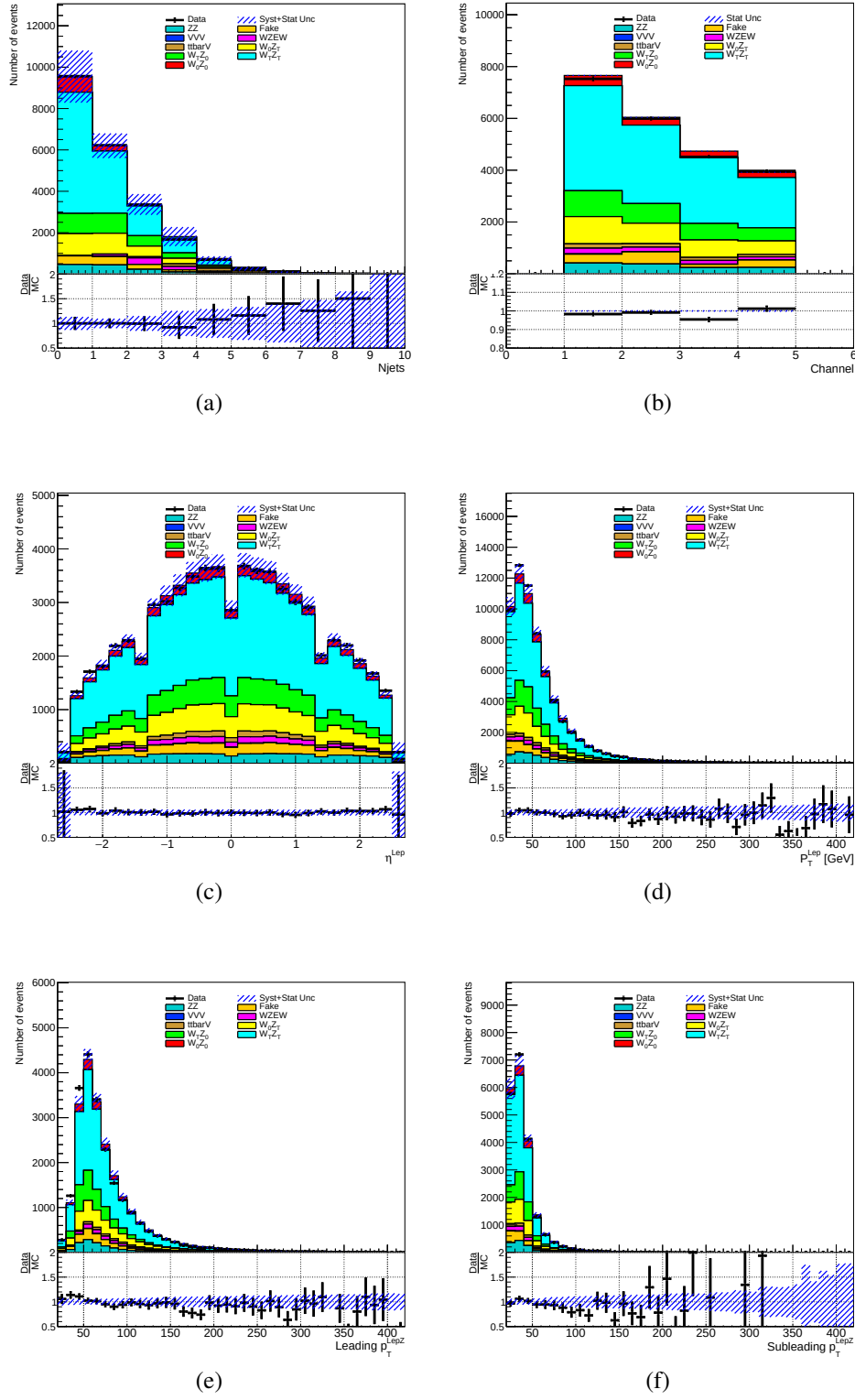


Figure 3.26: Comparison between data and prediction for the number of jets (a), the number of events in each channel (b) and using only stat uncertainty), lepton η (c), lepton p_T (d), the leading Z lepton p_T (e), and the subleading Z lepton p_T (f) in the WZ inclusive phase space. This uses an integrated luminosity of 140.1 fb^{-1} .

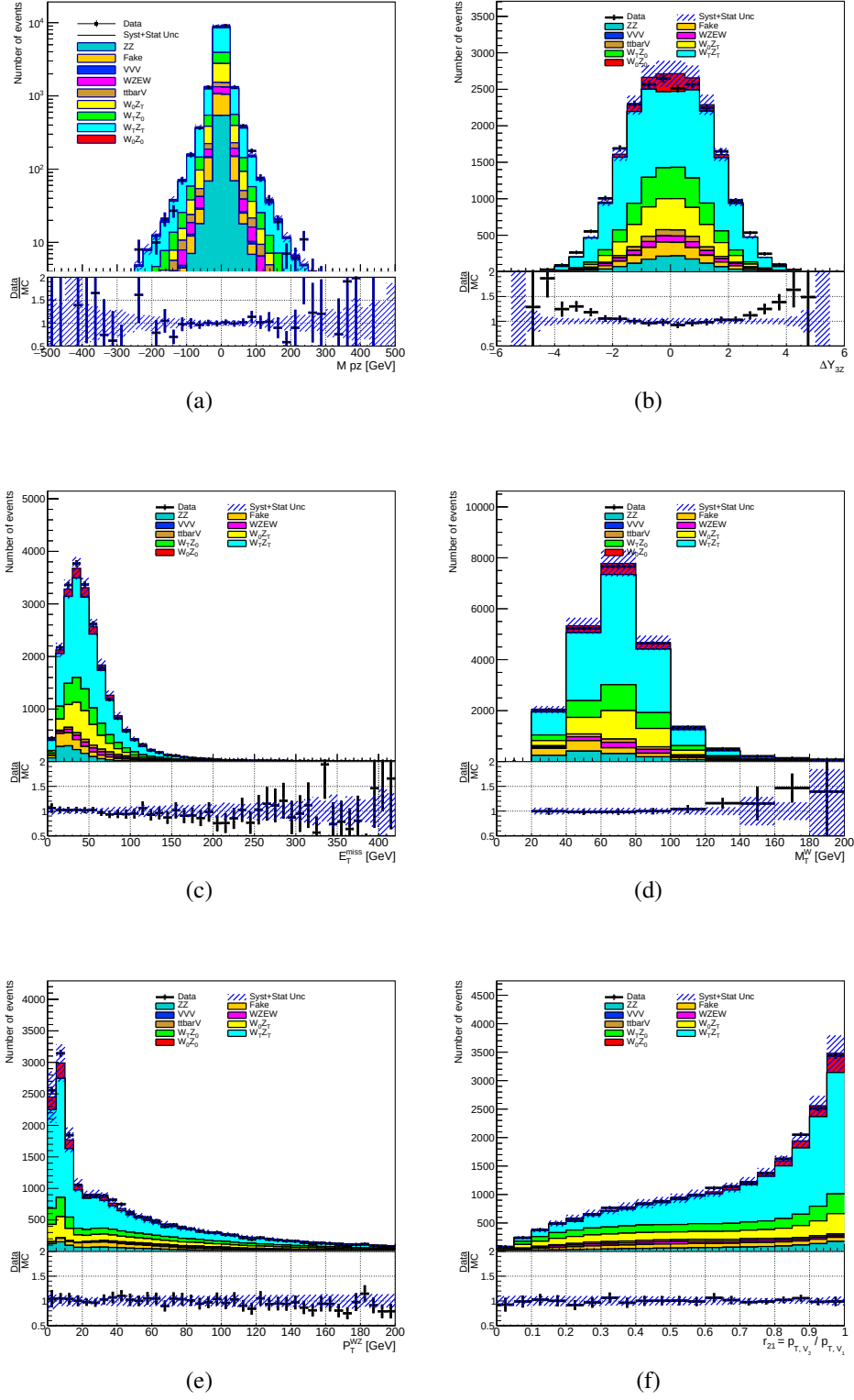
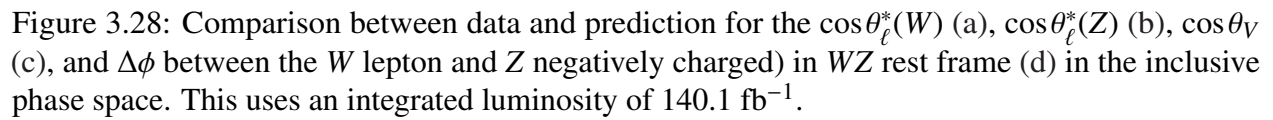


Figure 3.27: Comparison between data and prediction for the reconstructed neutrino p_z using E_T^{miss} (a), rapidity difference between $\ell(W)$ and Z boson (b), E_T^{miss} (c), M_T^W (d), p_T^{WZ} (e), and R_{21} (f) in the WZ inclusive region. This uses an integrated luminosity of 140.1 fb^{-1} .



CHAPTER 4

Observation of the Radiation Amplitude Zero Effect

It is seen from section 3.2.4 that we expect to observe a dip in the ΔY_{WZ} and ΔY_{3Z} distributions of TT-only events with low jet-activity. The jet activity is lowered by having $p_T^{WZ} < 10, 20, 40, 70$ GeV cuts. We also observed that the dip in the ΔY_{WZ} truth distribution is deeper compared to that in the ΔY_{3Z} distribution. This could be due to the fact that the W boson carries more polarization information than just the lepton decayed from it.

4.1 Observation of the RAZ Effect

4.1.1 Data-MC Comparisons

Figures 4.1 and 4.2 show ΔY_{3Z} and ΔY_{WZ} distributions for events with different p_T^{WZ} cuts applied. Other kinematic distributions are also checked, for example, $\cos \theta_W$, $\Delta \phi(\ell_W, \ell_Z)$, ΔY_{3N} distributions are shown in figures 4.3, 4.4 and 4.5 respectively. Here ΔY_{3N} refers to the rapidity difference between the lepton from the W boson and the negatively-charged lepton from the Z boson. More comparison plots can be found in Appendix D.

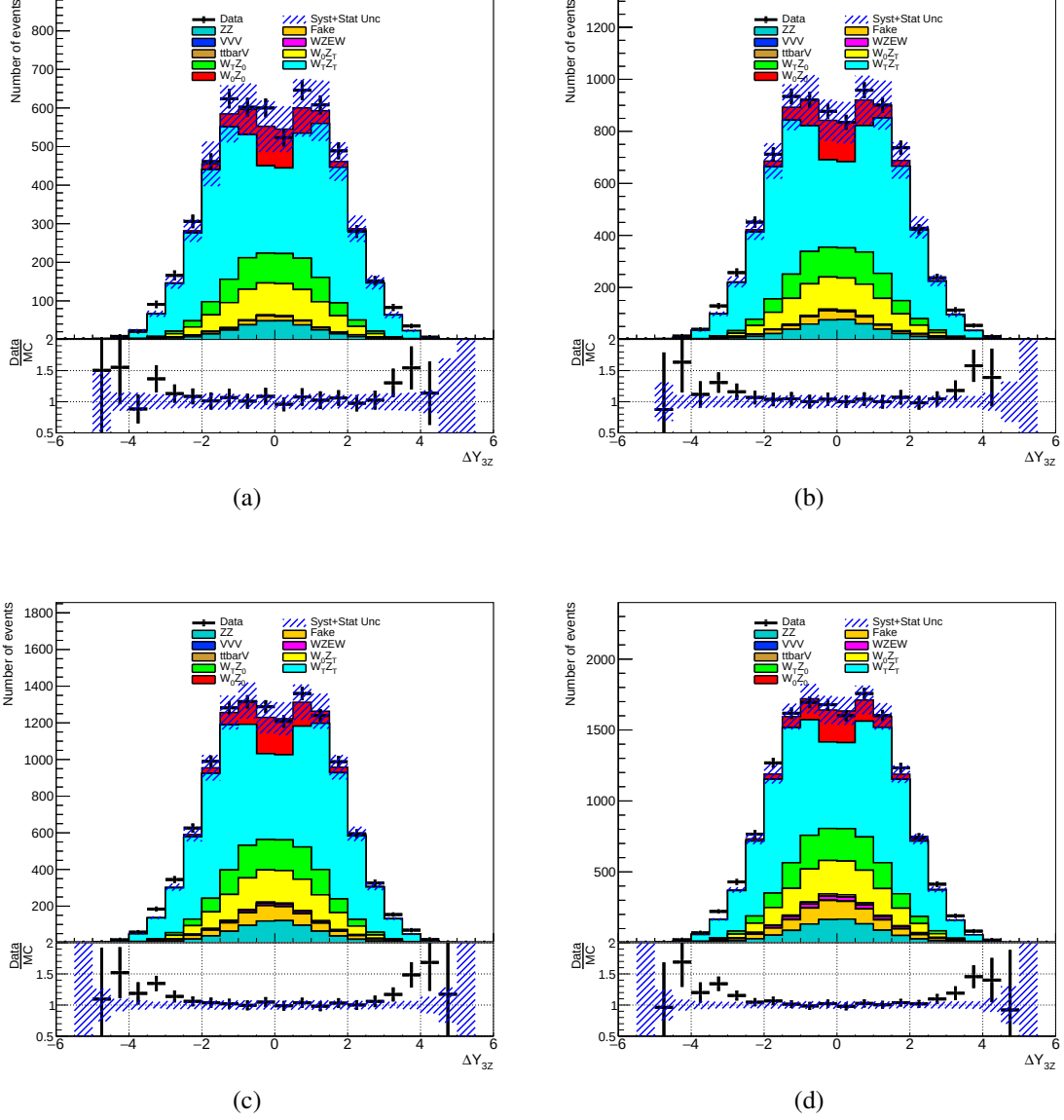


Figure 4.1: Comparison between data and prediction for the ΔY_{3Z} distribution in the $p_T^{WZ} < 10$ GeV region (a), $p_T^{WZ} < 20$ GeV region (b), $p_T^{WZ} < 40$ GeV region (c), and $p_T^{WZ} < 70$ GeV region (d). This uses an integrated luminosity of 140.1 fb^{-1} at $\sqrt{s} = 13$ TeV.

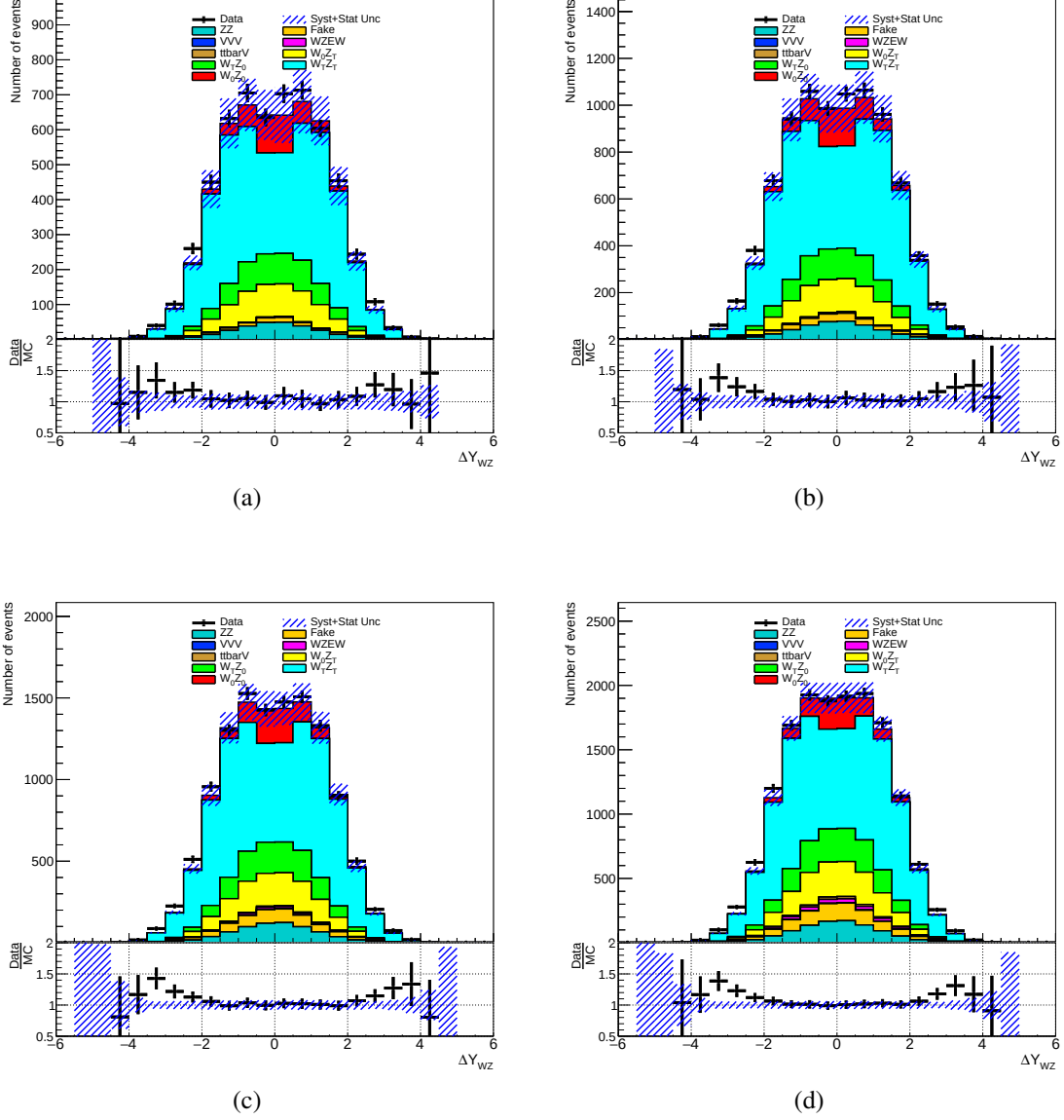


Figure 4.2: Comparison between data and prediction for the ΔY_{WZ} distribution in the $p_T^{WZ} < 10$ GeV region (a), $p_T^{WZ} < 20$ GeV region (b), $p_T^{WZ} < 40$ GeV region (c), and $p_T^{WZ} < 70$ GeV region (d). This uses an integrated luminosity of 140.1 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$.

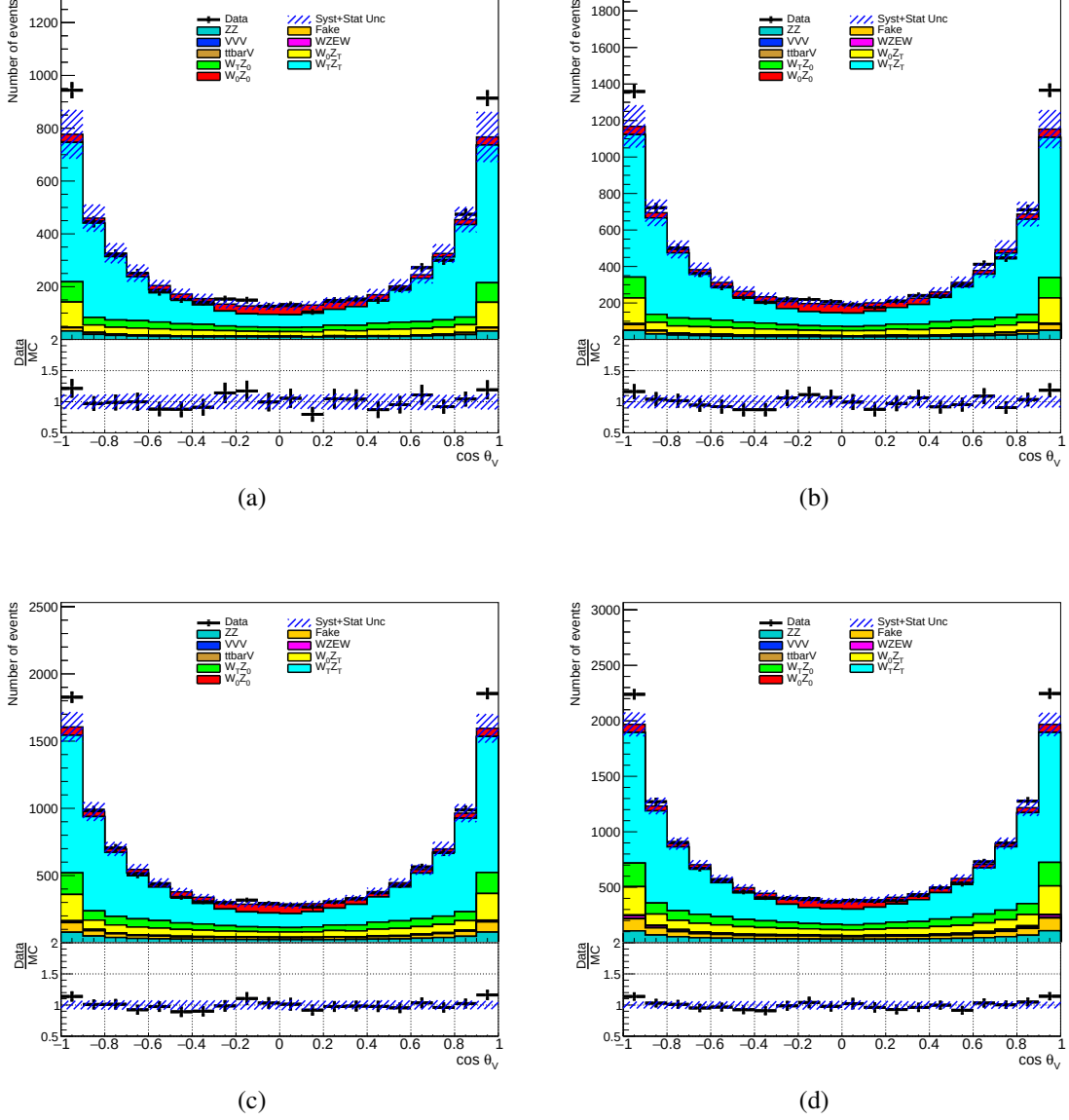


Figure 4.3: Comparison between data and prediction for the $\cos \theta_W$ distribution in the $p_T^{WZ} < 10$ GeV region (a), $p_T^{WZ} < 20$ GeV region (b), $p_T^{WZ} < 40$ GeV region (c), and $p_T^{WZ} < 70$ GeV region (d). This uses an integrated luminosity of 140.1 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$.

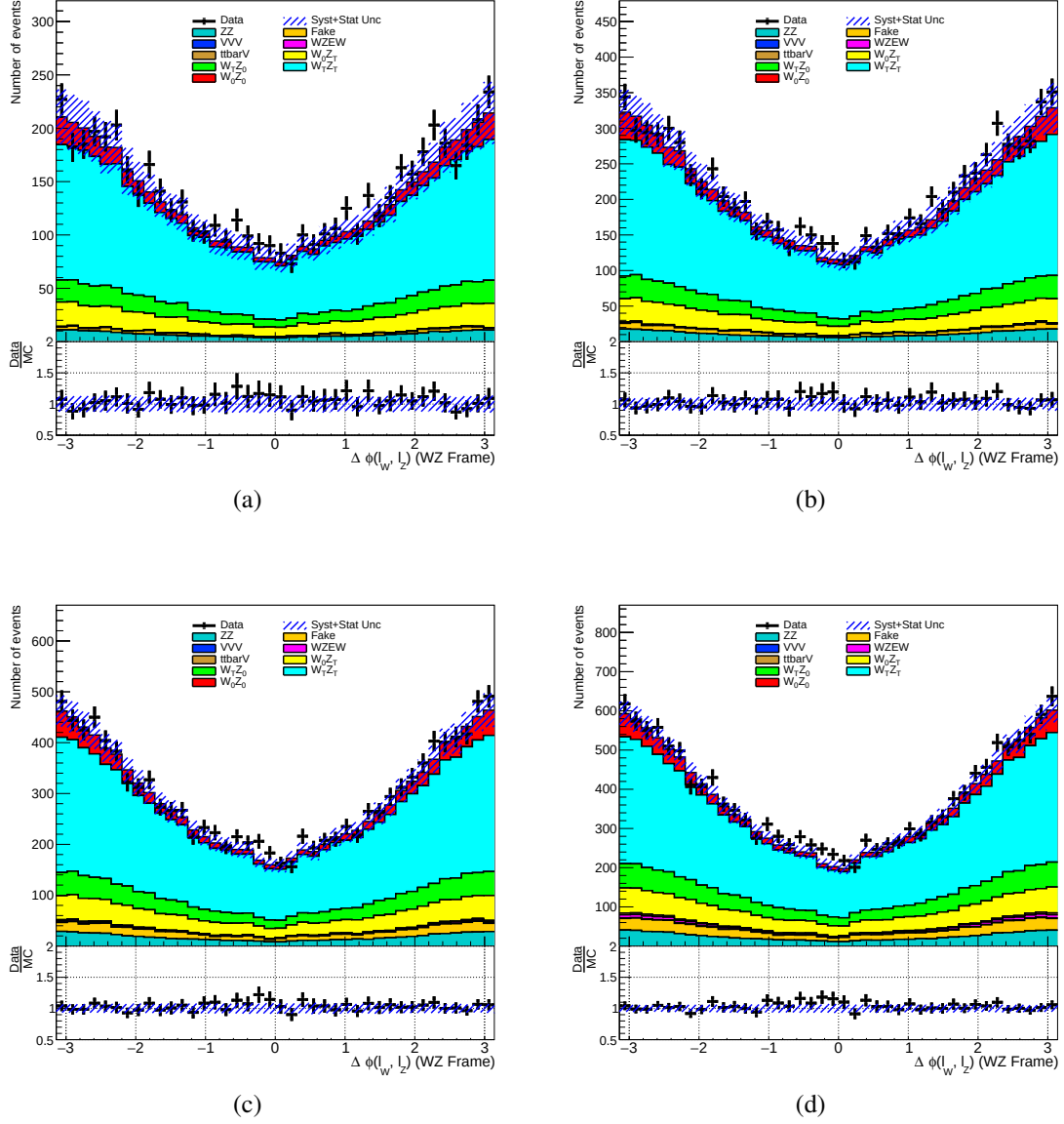


Figure 4.4: Comparison between data and prediction for the $\Delta\phi(\ell_W, \ell_Z)$ in WZ rest frame distribution in the $p_T^{WZ} < 10$ GeV region (a), $p_T^{WZ} < 20$ GeV region (b), $p_T^{WZ} < 40$ GeV region (c), and $p_T^{WZ} < 70$ GeV region (d). This uses an integrated luminosity of 140.1 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$.

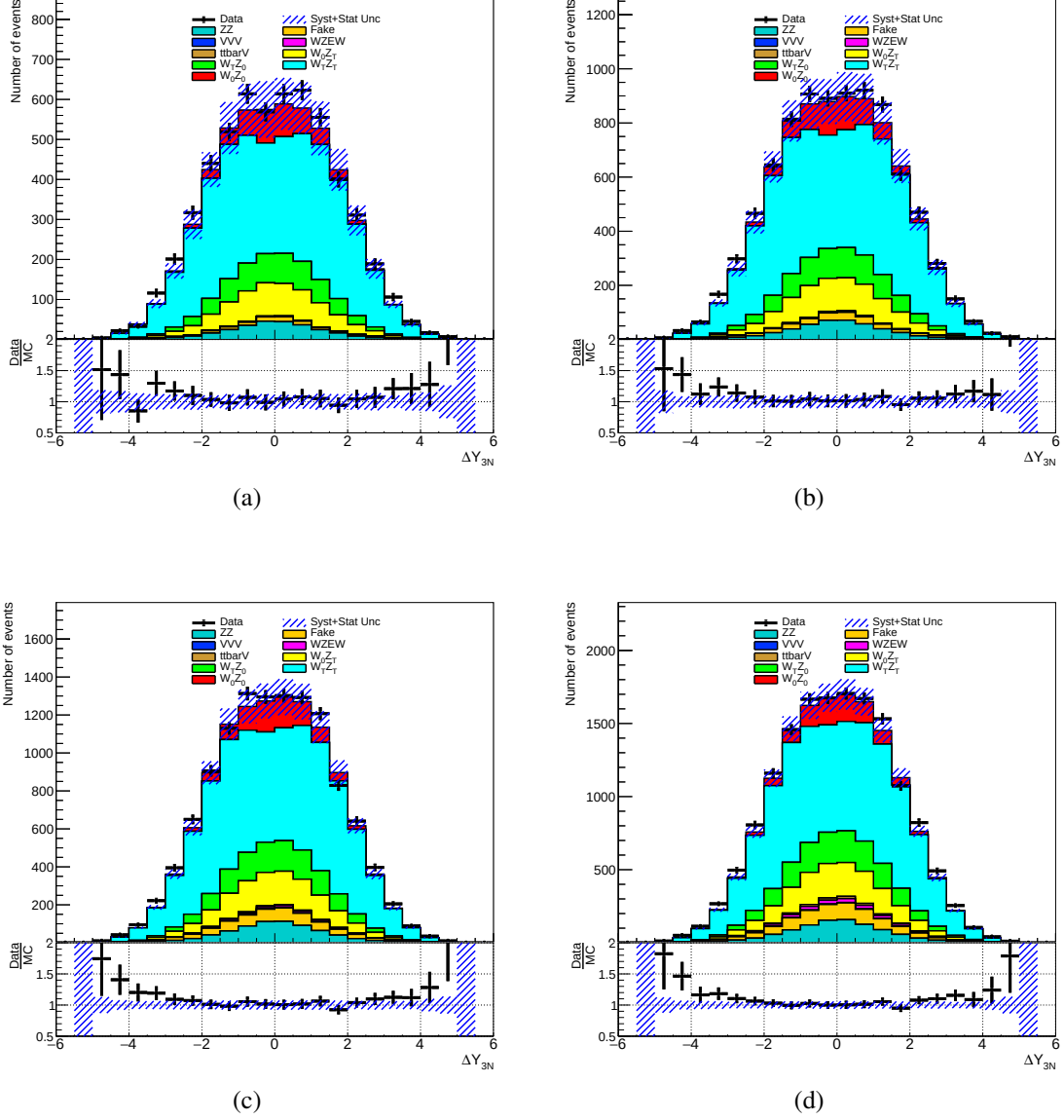


Figure 4.5: Comparison between data and prediction for the ΔY_{3N} distribution in the $p_T^{WZ} < 10$ GeV region (a), $p_T^{WZ} < 20$ GeV region (b), $p_T^{WZ} < 40$ GeV region (c), and $p_T^{WZ} < 70$ GeV region (d). This uses an integrated luminosity of 140.1 fb^{-1} at $\sqrt{s} = 13$ TeV.

Table 4.1 shows background and signal yields in the RAZ regions.

Process	$p_T^{WZ} < 10 \text{ GeV}$	$p_T^{WZ} < 20 \text{ GeV}$	$p_T^{WZ} < 40 \text{ GeV}$	$p_T^{WZ} < 70 \text{ GeV}$
Total Prompt Bkg	292 ± 51	481 ± 80	837.7 ± 106	1315 ± 137
ZZ	276 ± 49	437 ± 73	699 ± 100	975 ± 150
VVV	7.0 ± 1.3	11 ± 1.9	18 ± 2.6	25 ± 3.07
$WZEW$	7.3 ± 1.8	24 ± 4.0	84 ± 9.1	210 ± 20
$t\bar{t}V$	2.5 ± 1.3	9.7 ± 2.6	38 ± 6.6	105 ± 16
Fake	79 ± 44	210 ± 87	518 ± 180	838 ± 304
$WZQCD$ Sherpa	4761 ± 442	7131 ± 582	10118 ± 576	12732 ± 586
W_0Z_0	447 ± 52	665 ± 69	881 ± 70	1017 ± 67
W_0Z_T	609 ± 78	914 ± 105	1309 ± 121	1761 ± 138
W_TZ_0	561 ± 70	847 ± 97	1221 ± 113	1656 ± 127
W_TZ_T	3453 ± 414	5147 ± 541	6935 ± 552	8370 ± 559
Sum	5070 ± 639	7573 ± 812	10347 ± 826	12803 ± 859

Table 4.1: Expected signal and background yields in the RAZ signal regions ($p_T^{WZ} < 10 \text{ GeV}$, $p_T^{WZ} < 20 \text{ GeV}$, $p_T^{WZ} < 40 \text{ GeV}$, and $p_T^{WZ} < 70 \text{ GeV}$). No QCD+EW k -Factors are applied.

4.1.2 Depth ($\mathcal{D}$) Calculation

Figures 4.6 and 4.7 show the ΔY_{3Z} and ΔY_{WZ} comparison between data (with all other contributions subtracted) and prediction only for the TT component for events with $p_T^{WZ} < 10, 20, 40, 70 \text{ GeV}$. There are clearly dips with ΔY_{3Z} (or ΔY_{WZ}) around 0 observed for all plots. The depth in the distributions is defined as given in equation 3.2.4. $\mathcal{D} > 0$ indicates a dip in the distributions. A larger depth value indicates a deeper dip observed.

Figure 4.8 shows the depth variable calculated for both ΔY_{3Z} and ΔY_{WZ} distributions (using the background-subtracted distributions). As expected, the depth decreases as p_T^{WZ} increases in the MC simulation. Due to the E_T^{miss} measurement and the neutrino p_z calculation using the W -mass constraint, the ΔY_{WZ} dip is actually more shallow than the ΔY_{3Z} dip, contrary to what we see in the truth studies (See figure 3.6). The dips are found in agreement with the SM predictions.

4.1.3 Uncertainties on the $\mathcal{D}$ measurement

Recommendations mentioned in section 3.6.1 are followed to estimate the theoretical systematic uncertainties (PDF, Scale, and Parton shower) on the RAZ measurements. The scale uncertainties are calculated after subtracting the backgrounds. The backgrounds include 00, 0T, and T0 contributions,

which really contribute to the theoretical uncertainties. See table 4.2 for these uncertainties applied to the reconstruction level selection.

Region	Number of events	PDF + α_s Uncertainty (%)	Scale Uncertainty (%)
$p_T^{WZ} < 10$ GeV	3714	± 0.763	+2.95 -2.44
$p_T^{WZ} < 20$ GeV	5486	± 0.758	+2.97 -2.46
$p_T^{WZ} < 40$ GeV	7298	± 0.773	+2.79 -2.25
$p_T^{WZ} < 70$ GeV	8825	± 0.802	+2.52 -2.41
Region	Depth with ΔY_{3Z}	PDF + α_s Uncertainty (%)	Scale Uncertainty (%)
$p_T^{WZ} < 10$ GeV	0.386	± 1.64	+5.62 -6.32
$p_T^{WZ} < 20$ GeV	0.371	± 1.65	+5.73 -6.44
$p_T^{WZ} < 40$ GeV	0.338	± 1.74	+5.60 -6.43
$p_T^{WZ} < 70$ GeV	0.320	± 1.79	+5.10 -6.06
Region	Depth with ΔY_{WZ}	PDF + α_s Uncertainty (%)	Scale Uncertainty (%)
$p_T^{WZ} < 10$ GeV	0.256	± 2.24	+7.84 -8.79
$p_T^{WZ} < 20$ GeV	0.256	± 2.19	+7.82 -8.79
$p_T^{WZ} < 40$ GeV	0.258	± 2.18	+7.23 -8.315
$p_T^{WZ} < 70$ GeV	0.245	± 2.26	+6.57 -7.83

Table 4.2: The uncertainties on the total number of events and on the depth variable calculation with data-background in the different regions for RAZ measurement (Inclusive + $p_T^{WZ} < 10, 20, 40, 70$ GeV).

Figures 4.9, 4.10, 4.11, and 4.12 show the contributions of the different systematic uncertainties to the $\mathcal{D}$ variable for $p_T^{WZ} < 10, 20, 40$ and 70 GeV respectively. For two-sided uncertainties, the largest one is considered (e.g. for scale uncertainties). The sources of dominating systematics for

different regions are:

- $p_T^{WZ} < 10$ GeV: Parton Shower, Renormalization, and Factorization Scale, and Pile-up reweighting;
- $p_T^{WZ} < 20$ GeV: Renormalization and Factorization Scale, JET_GroupedNP_1, and JET_GroupedNP_2;
- $p_T^{WZ} < 40$ GeV: FakeBkg_Stat, Renormalization and Factorization Scale, and FakeBkg_MetCut;
- $p_T^{WZ} < 70$ GeV: FakeBkg_Stat, Renormalization and Factorization Scale, and FakeBkg_MetCut.

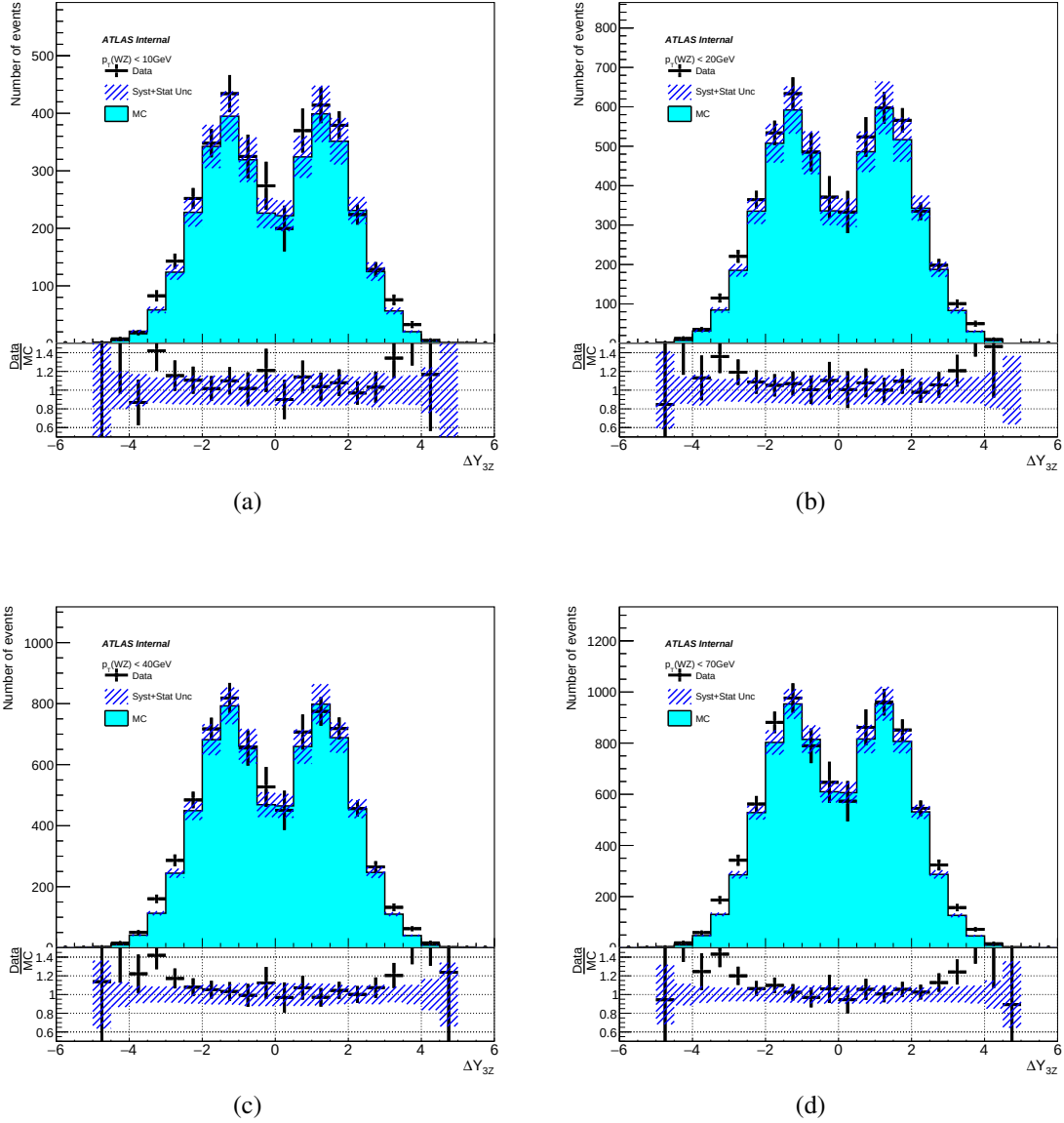


Figure 4.6: Comparison between data and prediction for the ΔY_{3Z} distribution in the $p_T^{WZ} < 10 \text{ GeV}$ region (a), $p_T^{WZ} < 20 \text{ GeV}$ region (b), $p_T^{WZ} < 40 \text{ GeV}$ region (c), and $p_T^{WZ} < 70 \text{ GeV}$ region (d). For data, other contributions are removed except TT. For MC, only the TT component is shown. This uses an integrated luminosity of 140.1 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$.

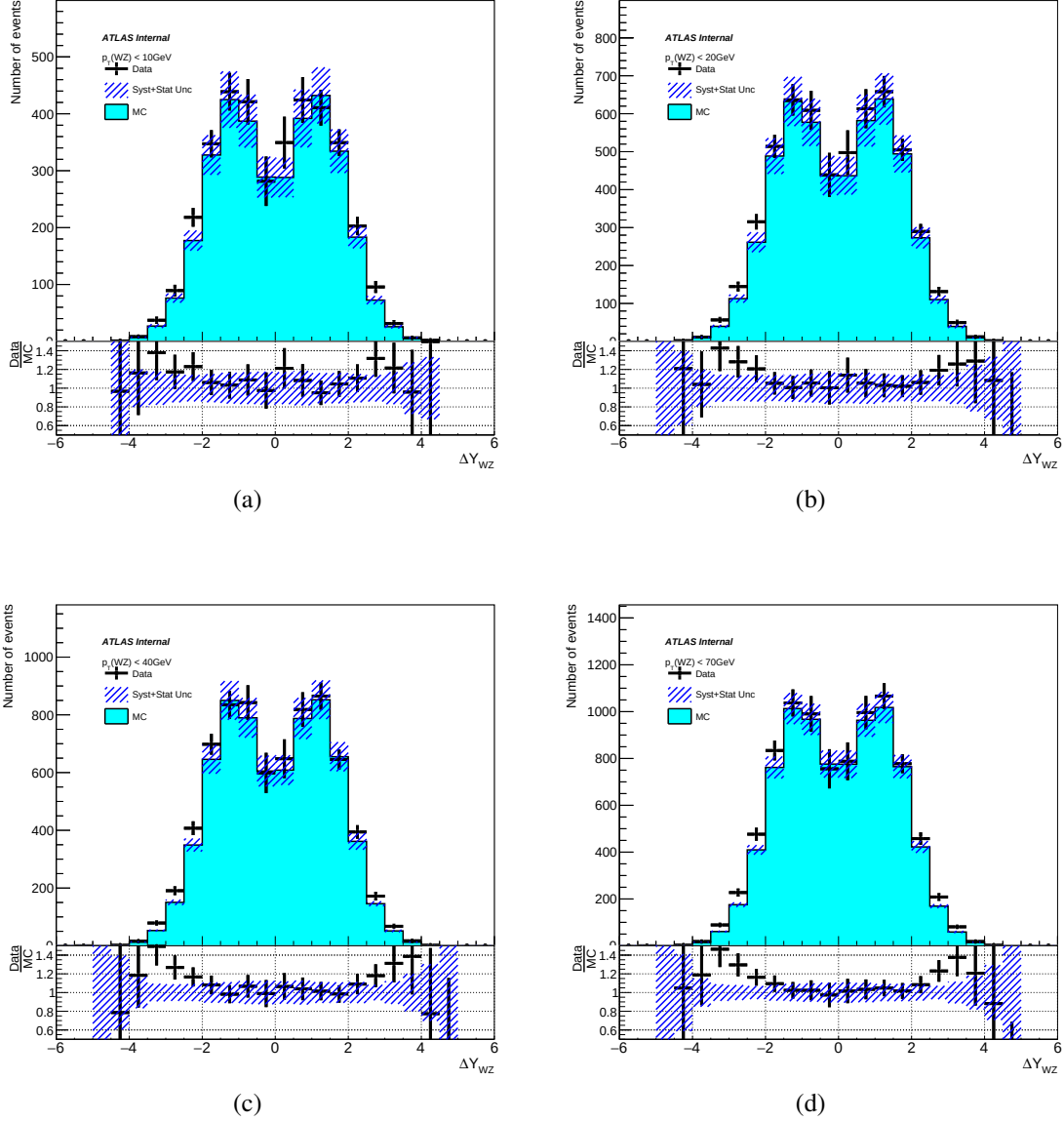


Figure 4.7: Comparison between data and prediction for the ΔY_{WZ} distribution in the $p_T^{WZ} < 10$ GeV region (a), $p_T^{WZ} < 20$ GeV region (b), $p_T^{WZ} < 40$ GeV region (c), and $p_T^{WZ} < 70$ GeV region (d). For data, other contributions are removed except TT. For MC, only the TT component is shown. This uses an integrated luminosity of 140.1 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$.

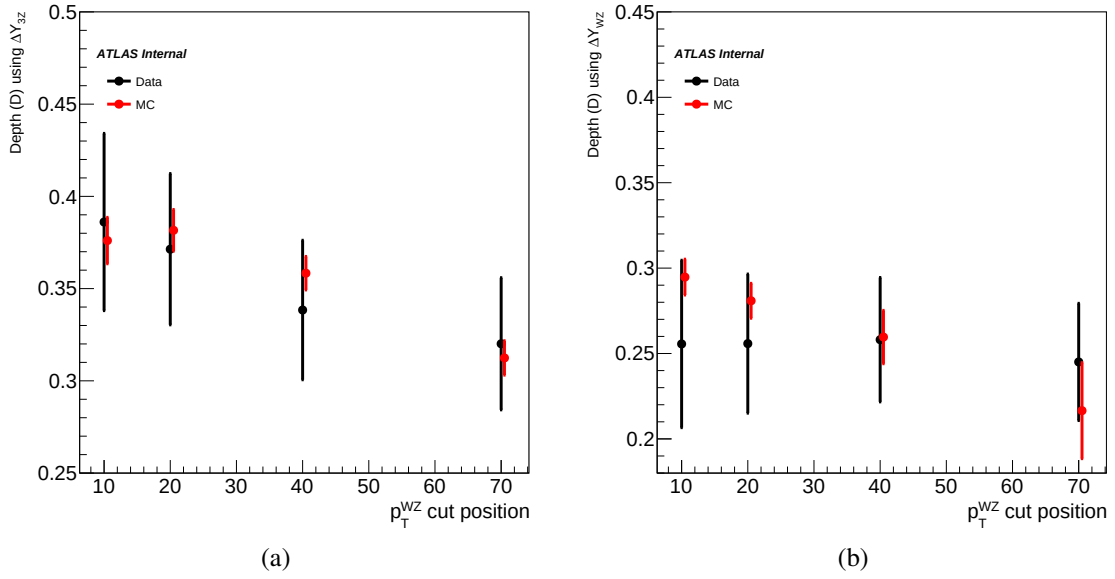


Figure 4.8: Comparison between data and prediction for the depth variable defined for the ΔY_{3Z} (a) and ΔY_{WZ} (b) distributions. This uses an integrated luminosity of 140.1 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$.

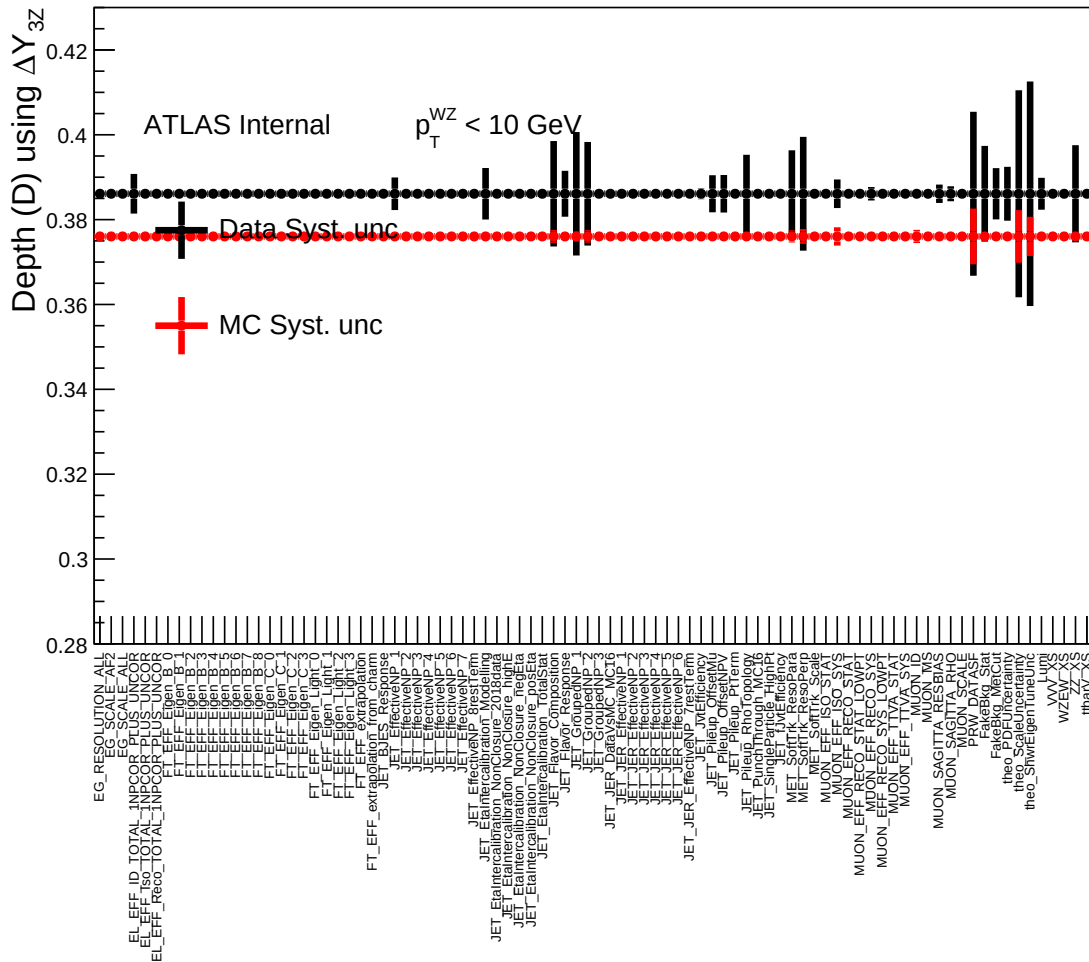
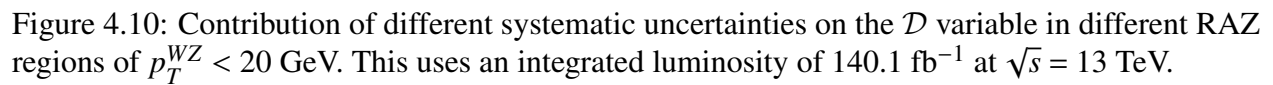
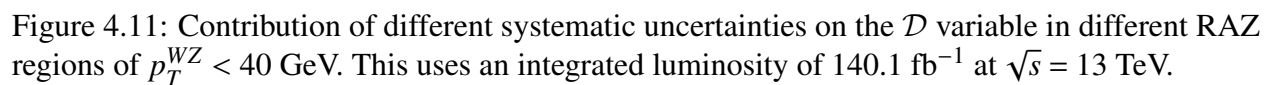


Figure 4.9: Contribution of different systematic uncertainties on the $\mathcal{D}$ variable in different RAZ regions of $p_T^{WZ} < 10$ GeV. This uses an integrated luminosity of 140.1 fb^{-1} at $\sqrt{s} = 13$ TeV.





Variable	Region	Depth	Stat Unc	Syst Unc	Stat+Syst Unc
ΔY_{3Z}	$p_T^{WZ} < 10 \text{ GeV}$	0.39	$\pm 0.05 \text{ (12.4\%)}$	$\pm 0.05 \text{ (12.5\%)}$	$\pm 0.07 \text{ (17.7\%)}$
	$p_T^{WZ} < 20 \text{ GeV}$	0.37	$\pm 0.04 \text{ (11.1\%)}$	$\pm 0.04 \text{ (12.0\%)}$	$\pm 0.06 \text{ (16.3\%)}$
	$p_T^{WZ} < 40 \text{ GeV}$	0.34	$\pm 0.04 \text{ (11.2\%)}$	$\pm 0.04 \text{ (11.8\%)}$	$\pm 0.06 \text{ (16.3\%)}$
	$p_T^{WZ} < 70 \text{ GeV}$	0.32	$\pm 0.04 \text{ (11.2\%)}$	$\pm 0.04 \text{ (13.0\%)}$	$\pm 0.05 \text{ (17.2\%)}$
ΔY_{WZ}	$p_T^{WZ} < 10 \text{ GeV}$	0.26	$\pm 0.05 \text{ (19.1\%)}$	$\pm 0.04 \text{ (16.2\%)}$	$\pm 0.06 \text{ (25.1\%)}$
	$p_T^{WZ} < 20 \text{ GeV}$	0.26	$\pm 0.041 \text{ (15.9\%)}$	$\pm 0.04 \text{ (14.9\%)}$	$\pm 0.06 \text{ (21.8\%)}$
	$p_T^{WZ} < 40 \text{ GeV}$	0.26	$\pm 0.04 \text{ (14.1\%)}$	$\pm 0.03 \text{ (13.3\%)}$	$\pm 0.05 \text{ (19.4\%)}$
	$p_T^{WZ} < 70 \text{ GeV}$	0.25	$\pm 0.03 \text{ (14.0\%)}$	$\pm 0.03 \text{ (14.2\%)}$	$\pm 0.05 \text{ (20.0\%)}$

Table 4.3: Systematic and statistical uncertainties on the depth ($\mathcal{D}$) variable calculation with data–background in the different regions for RAZ measurement.

4.2 Unfolding results in the RAZ regions

The unfolding is the procedure of inferring the truth distribution from the reconstructed one, where the reconstructed distributions include distortions from the detector effects, such as limited acceptance, the reconstruction efficiency, and the finite resolution [173].

The unfolding can be expressed in short with the following expression:

$$v_i = \sum_j R_{ij} \mu_j + \beta_i. \quad (4.1)$$

Here, v_i is the number of reconstructed events in bin i of the distribution, R_{ij} is the element of the response matrix, μ_j is the estimate of true events in bin j , and β_i is the number of expected background events in bin i . The response matrix elements are as follows:

$$R_{ij} = p(r \in (\Delta r)_i | t \in (\Delta t)_j). \quad (4.2)$$

It is the probability of reconstructing truth values from the interval $(\Delta t)_j = [t_j - \Delta t/2, t_j + \Delta t/2]$ as the reconstructed value in the interval $(\Delta r)_i = [r_i - \Delta r/2, r_i + \Delta r/2]$. The response matrix $\mathbf{R} = \mathbf{M}\boldsymbol{\epsilon}$, where $\mathbf{M}$ is the matrix with the conditional probability that a selected event, generated in a bin i , is reconstructed in a bin j . $\boldsymbol{\epsilon}$ is a diagonal matrix whose elements are the probabilities of reconstructing an event generated in a given bin.

The goal is to estimate μ_j from the other information along with the corresponding covariance matrix. As shown in equation 4.1, the matrix $\mathbf{R}$ has to be inverted to get $\boldsymbol{\mu}$. This matrix inversion poses a lot of issues related to the singularity of the matrix, not accounting for the large statistical fluctuations, etc. Many methods have been designed to unfold the data like bin-by-bin correction [174], Singular Value

Decomposition (SVD) using Tikhonov regularization [175], Iterative Bayes-inspired regularized unfolding [176], Iterative Dynamically Stabilized method (IDS) [177], Full Bayesian Unfolding (FBU) [178].

Differential detector-level distributions within the fiducial phase space are corrected for detector resolution and for QED final-state radiation effects using simulated signal events and an Iterative Bayes unfolding method [176]. Here is a broader description of the method:

It can be explained in terms of a set of independent causes (C_i with $i = 1, 2, \dots, n_C$) which can produce several effects E_j ($j = 1, 2, \dots, n_E$). Here, the cause C_i can be an event being in a truth bin i and the effect E_j can be thought of as an observation (or reconstruction) of an event in a bin j . Bayes' theorem can be written as follows:

$$P(C_i | E_j) = \frac{P(E_j | C_i) P(C_i)}{\sum_{l=1}^{n_C} P(E_j | C_l) P(C_l)}, \quad (4.3)$$

where $\sum_{i=1}^{n_C} P_0(C_i) = 1$ and $\sum_{i=1}^{n_C} P(C_i | E_j) = 1$, which states that each effect must come from one or more causes, and $\epsilon_i \equiv \sum_{j=1}^{n_E} P(E_j | C_i)$ is the efficiency of detecting a cause C_i in any of the effects.

After the observations are made, we have the number of events having each of the effects: $n(E) \equiv \{n(E_1), n(E_2), \dots, n(E_{n_E})\}$. Taking into account the inefficiency, we have

$$\hat{n}(C_i) = \frac{1}{\epsilon_i} \sum_{j=1}^{n_E} n(E_j) P(C_i | E_j) \quad \epsilon_i \neq 0, \quad (4.4)$$

$$\hat{n}(C_i) = \sum_{j=1}^{n_E} M_{ij} n(E_j), \quad (4.5)$$

$$\text{where } M_{ij} = \frac{P(E_j | C_i) P_0(C_i)}{\left[\sum_{l=1}^{n_E} P(E_l | C_i) \right] \left[\sum_{l=1}^{n_C} P(E_j | C_l) P_0(C_l) \right]}.$$

The probability of a cause C_i can be calculated as:

$$\hat{P}(C_i) \equiv P(C_i | n(E)) = \frac{\hat{n}(C_i)}{\hat{N}_{\text{true}}}, \quad (4.6)$$

$$\text{where } \hat{N}_{\text{true}} = \sum_{i=1}^{n_C} \hat{n}(C_i).$$

The iterative process goes as follows:

1. The expected number of events $n_0(C_i) = P_0(C_i) N_{\text{obs}}$ are calculated using the total number of observed events, N_{obs} and the initial probability $P_0(C_i)$, which can be determined using

some *a priori* knowledge of the data (giving the best agreement). However, if there is no idea about how the actual probability distribution looks like, one can use the uniform distribution.

2. calculate $\hat{n}(C)$ and $\hat{P}(C)$.
3. Calculate a χ^2 between $\hat{n}(C)$ and $n_0(C)$. If the value is not converging, then the iterative process has to be continued.
4. The new $P_0(C)$ is replaced by $\hat{P}(C)$, and $n_0(C)$ by $\hat{n}(C)$. The step 2 is repeated.

The backgrounds can be treated as additional causes $C_{nc+1} \dots$ etc. The number of iterations can be optimized. The uncertainties on different $n(C_i)$ are generally correlated. Various contributions to the covariance matrix are considered. e.g. Contribution due to $P_0(C_i)$, the starting hypothesis. A systematic uncertainty can be evaluated by studying the stability of the results for various starting hypotheses. Contributions due to $n(E)$ and due to $P(E_j | C_i)$ are considered for the covariance matrix calculation [176].

In this analysis, the Iterative Bayesian method [179] is used for the following reasons:

- The mathematical treatment of the response matrix, as the collection of probabilities of measured data given the true data, avoids the direct calculation of matrix inversion. It also provides a correlation matrix of the results.
- It can take different background sources into account.
- It is very fast, allowing uncertainties to be computed via ToyMC pseudo-experiments in reasonable time $O(\min)$.
- It is already implemented in the RooUnfold [180] framework.
- There is only one regularisation parameter, the number of iterations. The regularisation process is straightforward.
- The dependence of the posterior (output of an iteration during unfolding) on the prior (input distribution) is negligible. Although, it gives the best results if a realistic guess of the true distribution is assumed initially.

The Iterative Bayes technique is implemented in the RooUnfold toolkit [180] which is utilized within the VIPUnfolding tool [181] used for this unfolding analysis. The framework implements the determination of data statistical uncertainty using toys as specified in [182]. The total number of iterations used for the unfolding of ΔY_{3Z} is three and that for the unfolding of ΔY_{WZ} is ten (it has been selected such that it is converging as well as inducing lower statistical fluctuations). See figures E.1, E.2, E.3 and E.4 in Appendix E for the impact of the number of iterations on the

unfolding.

The basic inputs to the unfolding framework are as follows:

- Efficiency Correction = $\frac{\text{No. of events passing reco+truth}}{\text{No. of events passing truth}}$, and is expected to be around 0.5 for the tri-lepton selection. This reverses the effect of events lost in the detector simulation
- Fiducial Correction = $\frac{\text{No. of events passing reco+truth}}{\text{No. of events passing reco}}$ and should be ideally close to 1. This reverses the effect of events passing the reco selection but not passing the selection at the truth level.
- Migration Matrix is a 2D histogram of the true versus reco value of the unfolding variable. This is generated using the events which pass both the reco and the truth selection.
- Purity is the fraction of events in each bin that are in this bin in both the truth and the reco selection
- Stability is the fraction of reconstructed events that haven't migrated out of their truth bin.

Here, the unfolding is performed for the distributions of ΔY_{WZ} and ΔY_{3Z} variables. The signal consists of only the `MADGRAPH` (0+1jet) TT events and the background contains all the reducible and non-reducible backgrounds including 00, 0T, and T0 contributions. A shape comparison is made between the unfolded distribution and the truth distribution. In general, the unfolding procedure can be divided into three steps: initially, the estimated background is subtracted from data, and this includes all non-polarization backgrounds as well as 00, 0T, and T0. Next, fiducial factors are applied to correct for the number of events that fall into the reco-level phase space, i.e., for events that pass reco selection but not the truth fiducial selection. Then the inversion of the response matrix takes place and the efficiency factors are applied to account for the detector's imperfect efficiency and events that fall out of the reco-level phase space.

A technical closure test has been performed using simulated 00 events as Asimov data and reconstructed signal (no background included) and the distributions of ΔY_{WZ} and ΔY_{3Z} variables are unfolded, using a `MADGRAPH` (0+1 jet) 00 migration matrix, is found to agree with the 00 truth-level distribution. This was just a validation check.

4.2.1 Unfolding Uncertainty due to the Prior

A basic unfolding uncertainty probes the sensitivity of the unfolding method, with its regularization procedure, to data/MC shape differences for the unfolded observable is done through a data-driven closure test (ddct), using the truth-reco matched events in MC: First the MC distribution of the unfolded observable is reweighted at truth level, such that the reco-level MC distribution of this observable (reweighted reco MC) matches the (background-subtracted) data (multiplied by the fraction

of matched events at reco-level). Next, the reweighted reco MC (acting as pseudodata) is unfolded with the transfer matrix from MC that is not reweighted. Lastly, the basic unfolding uncertainty is obtained by comparing the result of the unfolding with the reweighted truth distribution [177, 182]. In the following tables, this MC closure uncertainty will be labeled as “unf” uncertainty.

4.2.2 Unfolded Results

The following two subsections show detailed results for the $p_T^{WZ} < 10$ GeV and $p_T^{WZ} < 70$ GeV regions. Results without any p_T^{WZ} and with $p_T^{WZ} < 20$ GeV and $p_T^{WZ} < 40$ GeV are shown in Appendix E .

4.2.2.1 Results for ΔY_{3Z}

- **$p_T^{WZ} < 10$ GeV:** Table 4.4 contains the bin entries of the unfolded distribution alongside their relative uncertainties. Additionally, the different uncertainty contributions are broken down according to their respective sources. For all values of ΔY_{3Z} , the uncertainty is dominated by systematic uncertainties. The largest contributions to these come from the uncertainties related to theory, data statistics, JET, pile-up reweighting, and MET. The data statistical uncertainties are on the order of the jet systematics.

Figures 4.13, and 4.14 contain the information going into the unfolding as well as the results. The deviations from expected (close to 1) for fiducial corrections are quite large and the corrections are around 50%. The efficiency corrections are also lower than 50% where the expected are around 50%. This is mostly due to the migrations in the p_T^{WZ} bins. The other unfolding methods shown in figure 4.13a are simple internal cross-checks by the VIPUnfolding tool which is useful to spot implementation errors by exposing significant differences between the pure VIPUnfolding calculations and those interfacing with RooUnfold. Figure 4.13b is the final unfolded distribution. The purity and stability are both extremely close to the ideal value of 1 which speaks to the very good reconstruction of ΔY_{3Z} which can also be seen in the migration matrix.

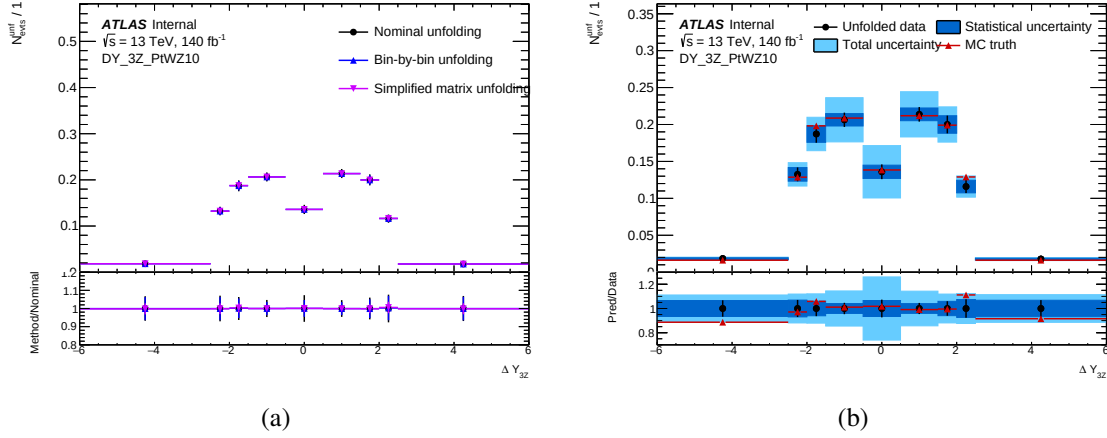
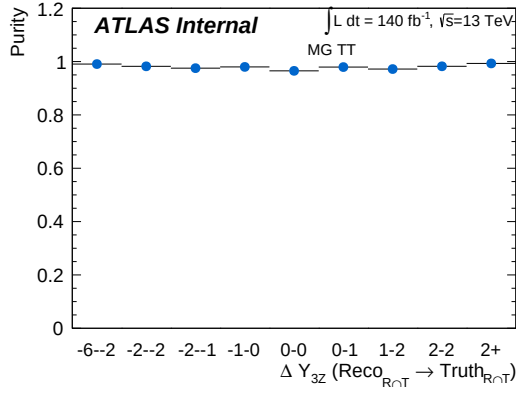


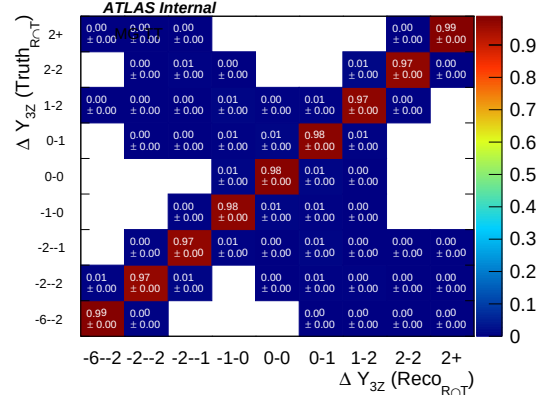
Figure 4.13: Plots for unfolding ΔY_{3Z} distributions in the $p_T^{WZ} < 10$ GeV region: Results from different unfolding methods (a), and the shape comparison of the unfolded data distribution with the truth MC (b).

Bin	-6 - -2.5	-2.5 - -2	-2 - -1.5	-1.5 - -0.5	-0.5 - 0.5	0.5 - 1.5	1.5 - 2	2 - 2.5	2.5 - 6
Results	0.0641	0.0662	0.0936	0.206	0.136	0.214	0.100	0.0580	0.0621
Comb. Unc.	11.1%	11.9%	12.1%	14.5%	26.0%	14.3%	11.9%	12.4%	11.4%
Stat. Unc.	6.58%	6.94%	6.02%	4.06%	6.60%	4.03%	5.92%	7.37%	6.81%
Sys. Unc.	8.85%	9.27%	9.71%	12.0%	18.9%	11.9%	9.51%	9.47%	9.00%
Bkg. Unc.	1.78%	2.91%	3.95%	7.02%	16.6%	6.86%	4.09%	3.09%	1.87%
Stat. Unc. (MC)	1.42%	1.27%	1.05%	0.70%	0.89%	0.67%	1.05%	1.36%	1.38%
fakes	0.23%	0.39%	0.47%	0.07%	1.36%	0.19%	0.45%	0.09%	0.12%
bkg	0.79%	0.73%	0.54%	0.07%	2.00%	0.04%	0.58%	0.67%	0.79%
unf	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
lumi	0.34%	0.27%	0.18%	0.05%	0.69%	0.04%	0.20%	0.24%	0.34%
el	0.63%	0.33%	0.18%	0.12%	0.89%	0.13%	0.24%	0.45%	0.62%
jet	1.57%	1.05%	0.90%	0.37%	3.29%	0.43%	0.87%	1.16%	1.44%
met	1.07%	1.01%	0.89%	0.26%	2.73%	0.11%	0.62%	0.46%	1.86%
muon	0.41%	0.44%	0.32%	0.21%	1.03%	0.38%	0.41%	0.45%	0.47%
prw	1.10%	1.50%	0.73%	0.37%	1.95%	0.62%	0.51%	1.78%	1.33%
theo	8.54%	9.32%	10.2%	13.8%	24.6%	13.7%	10.1%	9.56%	8.58%

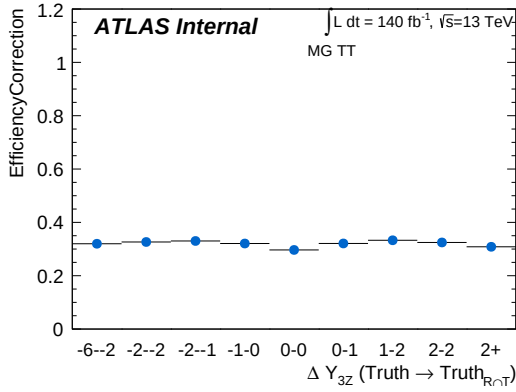
Table 4.4: Unfolding results and uncertainties on ΔY_{3Z} with $p_T^{WZ} < 10$ GeV.



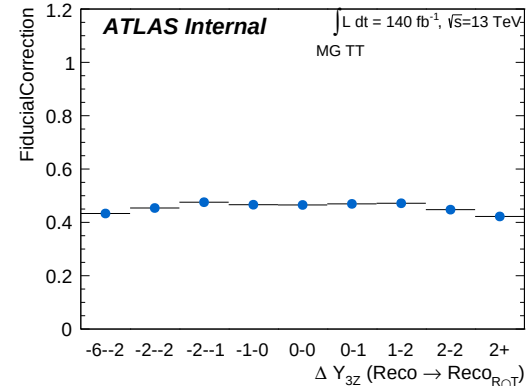
(a)



(b)



(c)



(d)

Figure 4.14: Plots for unfolding ΔY_{3Z} distributions in the $p_T^{WZ} < 10$ GeV region: Purity (a), Response Matrix (b), bin-by-bin efficiency corrections (c), and bin-by-bin fiducial corrections (d).

- $p_T^{WZ} < 70$ GeV

Table 4.5 and figures 4.15, and 4.16 show the analogous results for the region with $p_T^{WZ} < 70$ GeV. But compared to the $p_T^{WZ} < 10$ GeV results, the fiducial and efficiency corrections have a much better agreement with the expected ones. This might be due to fewer migrations between p_T^{WZ} bins because of the looser p_T^{WZ} cut. Additionally, the statistical uncertainties are now smaller compared to the $p_T^{WZ} < 10$ GeV region as the looser cut leads to more data statistics. The dominant uncertainties for this region and ΔY_{3Z} are uncertainties related to theory, fake, data statistics, and background.

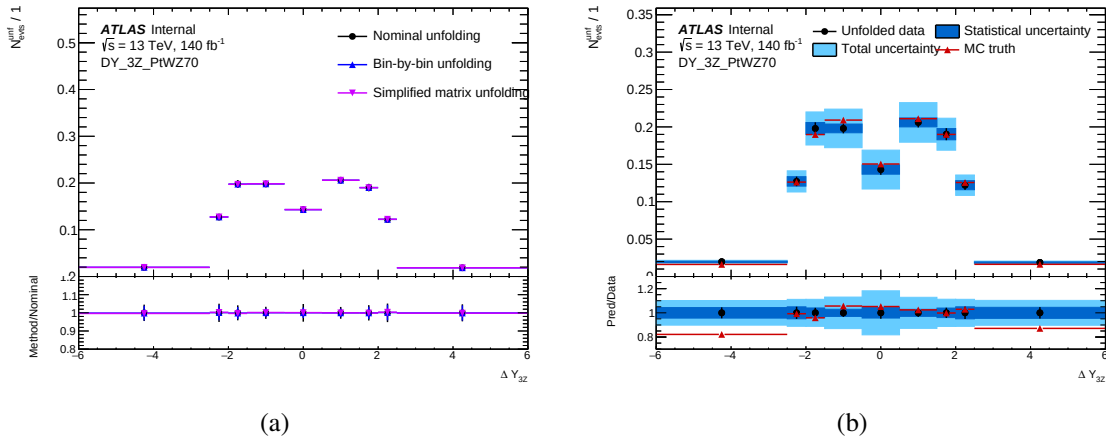


Figure 4.15: Plots for unfolding ΔY_{3Z} distributions in the $p_T^{WZ} < 70$ GeV region: Results from different unfolding methods (a), and the shape comparison of the unfolded data distribution with the truth MC (b).

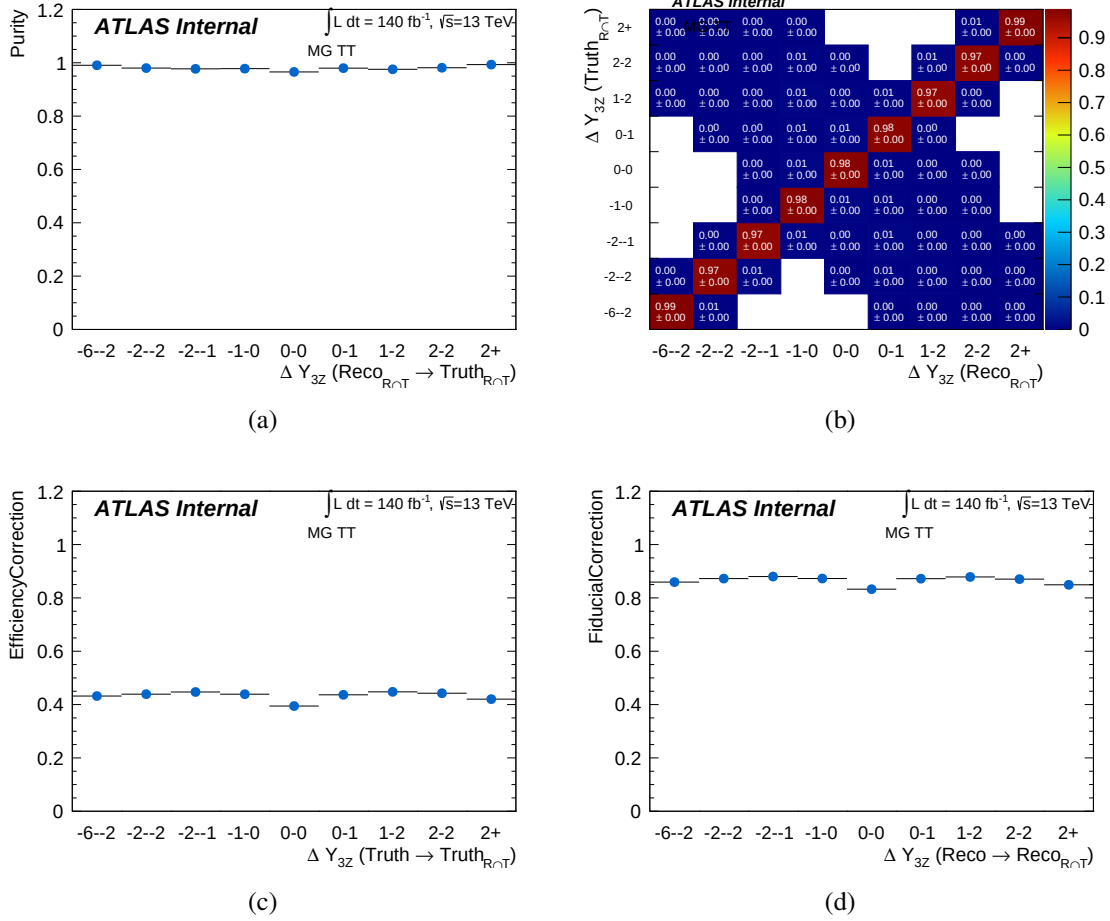


Figure 4.16: Plots for unfolding ΔY_{3Z} distributions in the $p_T^{WZ} < 70$ GeV region: Purity (a), Response Matrix (b), bin-by-bin efficiency corrections (c), and bin-by-bin fiducial corrections (d).

Bin	-6 - -2.5	-2.5 - -2	-2 - -1.5	-1.5 - -0.5	-0.5 - 0.5	0.5 - 1.5	1.5 - 2	2 - 2.5	2.5 - 6
Results	0.0688	0.0636	0.0990	0.198	0.143	0.206	0.0951	0.0610	0.0655
Comb. Unc.	10.1%	11.1%	11.1%	13.0%	18.1%	12.8%	11.2%	11.1%	10.2%
Stat. Unc.	4.35%	4.96%	4.02%	2.95%	4.30%	2.89%	3.95%	4.97%	4.55%
Sys. Unc.	8.93%	9.83%	10.2%	12.6%	16.9%	12.4%	10.3%	9.85%	8.97%
Bkg. Unc.	2.18%	1.65%	1.67%	0.92%	5.01%	0.73%	1.81%	1.75%	2.12%
Stat. Unc. (MC)	0.71%	0.68%	0.55%	0.34%	0.46%	0.34%	0.54%	0.69%	0.72%
fakes	1.77%	1.11%	1.33%	0.47%	4.15%	0.12%	1.52%	1.29%	1.72%
bkg	1.17%	0.96%	0.81%	0.18%	2.55%	0.14%	0.81%	0.96%	1.12%
unf	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
lumi	0.40%	0.29%	0.23%	0.09%	0.71%	0.07%	0.22%	0.29%	0.39%
el	0.44%	0.28%	0.14%	0.07%	0.46%	0.14%	0.08%	0.22%	0.40%
jet	0.61%	0.63%	0.44%	0.12%	1.18%	0.25%	0.49%	0.45%	0.62%
met	0.11%	0.02%	0.24%	0.07%	0.51%	0.04%	0.11%	0.20%	0.18%
muon	0.29%	0.26%	0.36%	0.08%	0.70%	0.11%	0.27%	0.40%	0.29%
prw	0.52%	0.39%	0.17%	0.01%	0.17%	0.48%	0.20%	0.32%	0.07%
theo	8.84%	9.77%	10.2%	12.6%	16.8%	12.4%	10.3%	9.80%	8.90%

Table 4.5: Unfolding results and uncertainties on ΔY_{3Z} with $p_T^{WZ} < 70$ GeV.

4.2.2.2 Results for ΔY_{WZ}

- $p_T^{WZ} < 70 \text{ GeV}$:

The unfolding of ΔY_{WZ} is done with the same procedure as that of ΔY_{3Z} . The results for the unfolding in the $p_T^{WZ} < 70 \text{ GeV}$ region can be seen in table 4.6. In this region, the systematic uncertainties dominate for all bins although background uncertainties have a comparable size. The dominant systematic uncertainties come from the choice of unfolding procedure/prior itself as well as the MC statistics.

Out of the other systematics, the dominant ones in the central region come from the theory uncertainties and the estimation of the fakes. Otherwise, the jet, electron, muon, and pile-up reweighting uncertainties are of comparable size while the met uncertainties play a smaller role.

Figures 4.17 and 4.18 show the inputs and results of the unfolding. It can be seen that both the fiducial and the efficiency corrections are now close to expected with the fiducial correction being close to 1 and the efficiency correction almost reaching 50% in the central region.

Additionally, the purity and stability show a significant reduction from the ideal value of one, instead, going as low as ~ 0.2 . This is due to the reconstruction of W boson using an almost perfect procedure at the truth level, but not so perfect W reconstruction at the reco-level because of the neutrino p_z reconstruction using E_T^{miss} (MET).

All of these effects combined lead to the unusual value larger than one of the central BinByBin correction values in the bottom left of 4.17 which indicates that due to the migrations more events are expected in the central bin at reco level than at truth level. Normally this is the other way around due to the efficiency corrections.

- $p_T^{WZ} < 10 \text{ GeV}$:

Table 4.7 and figures 4.19 and 4.20 show the analogous results for the region with $p_T^{WZ} < 10 \text{ GeV}$. The main differences are again the fiducial and efficiency corrections as well as a change in the overall data statistics.

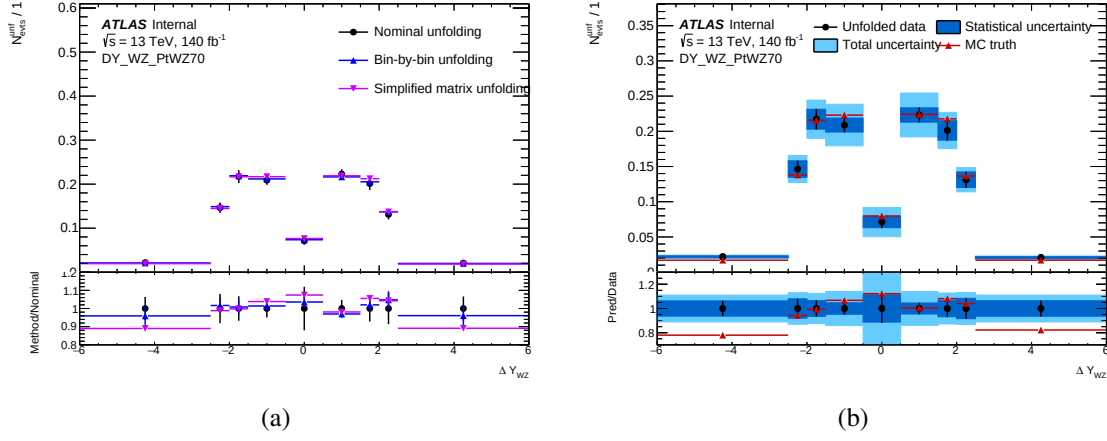
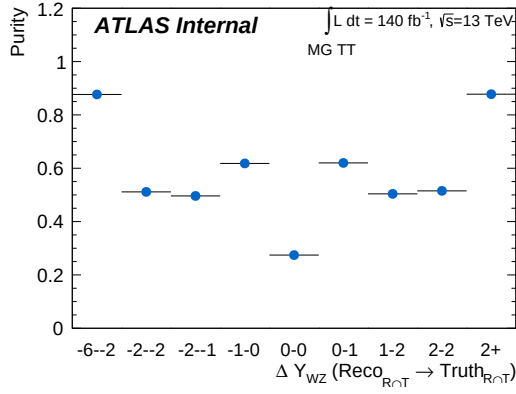


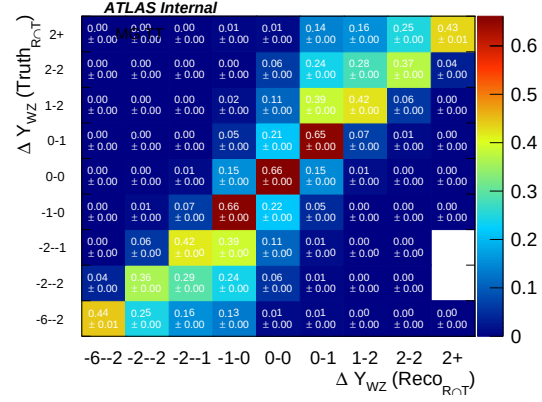
Figure 4.17: Plots for unfolding ΔY_{WZ} distributions in the $p_T^{WZ} < 70$ GeV region: Results from different unfolding methods (a), and the shape comparison of the unfolded data distribution with the truth MC (b).

Bin	-6 - -2.5	-2.5 - -2	-2 - -1.5	-1.5 - -0.5	-0.5 - 0.5	0.5 - 1.5	1.5 - 2	2 - 2.5	2.5 - 6
Results	0.0764	0.0732	0.109	0.209	0.0711	0.223	0.101	0.0656	0.0724
Comb. Unc.	11.1%	13.0%	12.4%	14.1%	29.1%	13.9%	12.8%	13.1%	11.1%
Stat. Unc.	6.32%	7.99%	6.50%	4.75%	11.2%	4.55%	6.84%	8.42%	6.39%
Sys. Unc.	8.74%	10.0%	10.5%	13.2%	25.0%	13.1%	10.6%	9.83%	8.76%
Bkg. Unc.	2.68%	2.12%	1.69%	1.30%	9.71%	1.08%	1.77%	2.02%	2.45%
Stat. Unc. (MC)	1.28%	1.61%	1.21%	0.74%	1.61%	0.70%	1.25%	1.59%	1.25%
fakes	2.33%	1.53%	1.06%	0.83%	8.00%	0.17%	1.11%	1.38%	2.05%
bkg	1.19%	1.15%	0.87%	0.43%	4.88%	0.34%	0.87%	1.06%	1.17%
unf	0.68%	2.54%	1.94%	0.11%	4.25%	1.93%	2.35%	0.91%	0.91%
lumi	0.44%	0.37%	0.25%	0.16%	1.49%	0.13%	0.25%	0.34%	0.44%
el	0.43%	0.52%	0.30%	0.14%	1.38%	0.37%	0.39%	0.43%	0.52%
jet	0.54%	1.28%	0.82%	0.37%	3.00%	0.19%	0.69%	1.19%	0.74%
met	0.10%	1.58%	0.36%	0.32%	1.88%	0.07%	0.32%	0.26%	0.76%
muon	0.83%	1.73%	1.18%	0.41%	1.88%	0.73%	2.06%	0.97%	0.69%
prw	0.65%	0.62%	0.42%	0.13%	0.50%	0.07%	0.05%	1.20%	0.35%
theo	8.52%	9.22%	10.1%	13.2%	24.2%	12.9%	10.1%	9.46%	8.49%

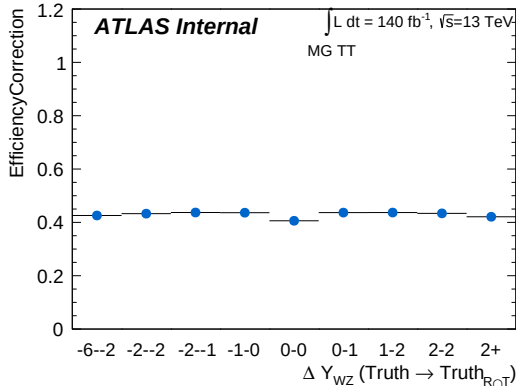
Table 4.6: Unfolding results and uncertainties of ΔY_{WZ} distribution with $p_T^{WZ} < 70$ GeV.



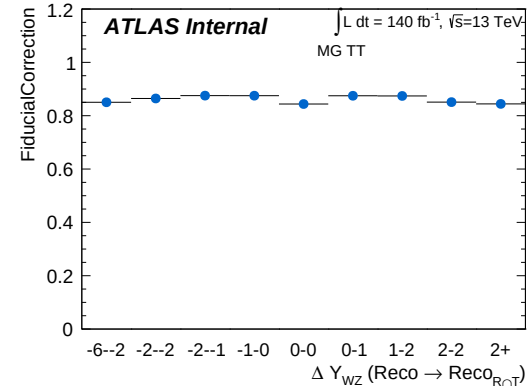
(a)



(b)



(c)



(d)

Figure 4.18: Plots for unfolding ΔY_{WZ} distributions in the $p_T^{WZ} < 70$ GeV region: Purity (a), Response Matrix (b), bin-by-bin efficiency corrections (c), and bin-by-bin fiducial corrections (d).

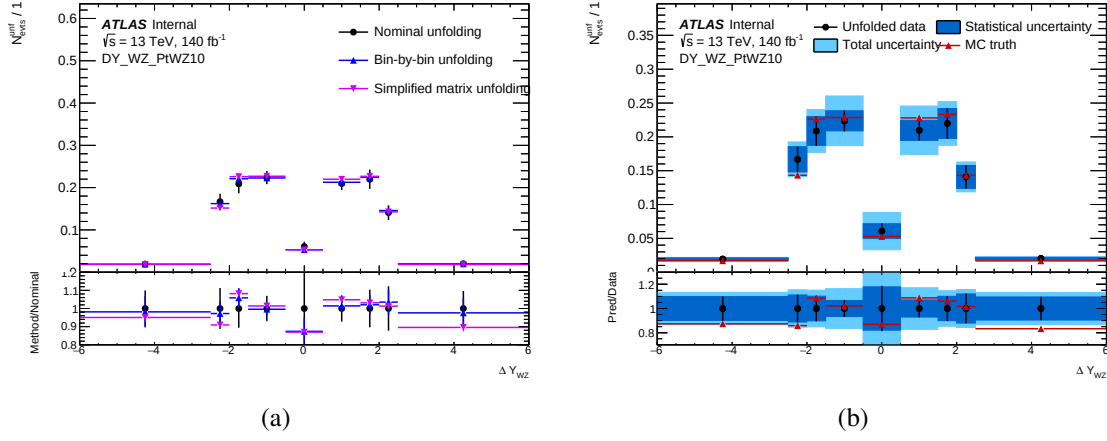
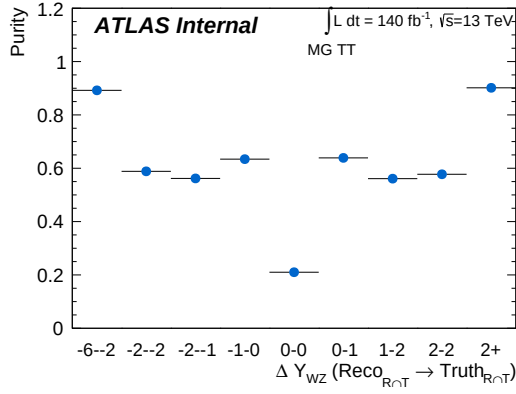


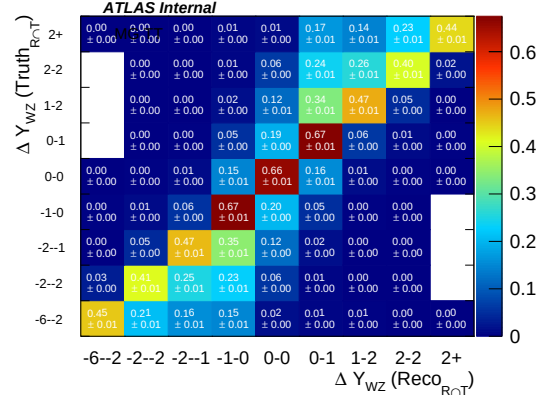
Figure 4.19: Plots for unfolding ΔY_{WZ} distributions in the $p_T^{WZ} < 10$ GeV region: Results from different unfolding methods (a), and the shape comparison of the unfolded data distribution with the truth MC (b).

Bin	-6 - -2.5	-2.5 - -2	-2 - -1.5	-1.5 - -0.5	-0.5 - 0.5	0.5 - 1.5	1.5 - 2	2 - 2.5	2.5 - 6
Results	0.0675	0.0834	0.104	0.224	0.0607	0.210	0.110	0.0704	0.0703
Comb. Unc.	13.4%	15.4%	15.1%	16.4%	45.4%	17.1%	14.6%	15.6%	13.2%
Stat. Unc.	9.85%	11.1%	10.1%	6.63%	17.8%	7.08%	10.0%	12.0%	9.54%
Sys. Unc.	9.03%	10.3%	10.5%	12.7%	32.1%	13.1%	10.0%	9.72%	9.12%
Bkg. Unc.	1.25%	2.43%	3.86%	7.91%	26.6%	8.38%	3.63%	2.50%	1.46%
Stat. Unc. (MC)	2.14%	2.31%	2.04%	1.17%	2.97%	1.19%	1.96%	2.42%	2.04%
fakes	0.20%	0.79%	0.80%	0.27%	2.90%	0.41%	0.09%	0.22%	0.15%
bkg	0.76%	0.83%	0.54%	0.25%	3.83%	0.29%	0.58%	0.75%	0.80%
unf	0.92%	3.88%	3.79%	0.92%	11.6%	2.01%	0.55%	0.68%	0.57%
lumi	0.37%	0.32%	0.20%	0.12%	1.44%	0.14%	0.21%	0.31%	0.38%
el	0.83%	0.55%	0.42%	0.23%	2.29%	0.41%	0.59%	0.80%	0.92%
jet	1.33%	1.88%	1.18%	0.75%	6.55%	0.65%	0.76%	2.54%	1.66%
met	2.00%	1.44%	1.20%	0.89%	7.12%	0.47%	1.40%	0.56%	2.22%
muon	0.96%	1.77%	0.77%	0.73%	2.14%	0.78%	2.82%	2.19%	1.21%
prw	1.64%	1.86%	0.34%	0.47%	4.91%	0.64%	0.64%	0.60%	1.78%
theo	8.14%	8.81%	10.1%	14.8%	37.9%	15.3%	9.87%	8.96%	8.15%

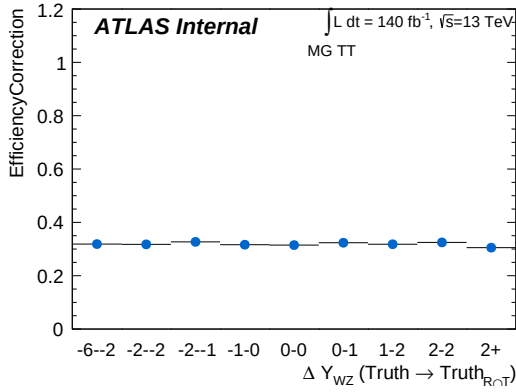
Table 4.7: Unfolding results and uncertainties of ΔY_{WZ} distribution with $p_T^{WZ} < 10$ GeV.



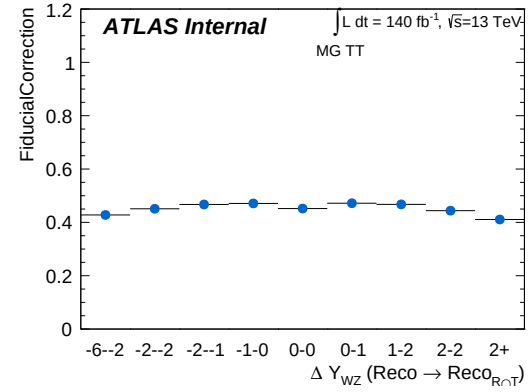
(a)



(b)



(c)



(d)

Figure 4.20: Plots for unfolding ΔY_{WZ} distributions in the $p_T^{WZ} < 10$ GeV region: Purity (a), Response Matrix (b), bin-by-bin efficiency corrections (c), and bin-by-bin fiducial corrections (d).

CHAPTER 5

Measurement of the Longitudinal-longitudinal Polarization Fraction in High- p_T^Z Regions

The main goal of this analysis is to measure the longitudinal-longitudinal fractions in the two high p_T signal regions ($p_T^Z > 100$ GeV and $p_T^Z > 200$ GeV), for which the reconstruction level selections are defined in section 3.3.6. The idea is to measure the W_0Z_0 fractions in the regions close to having the s -channel as the dominant channel, where both the bosons are directly interacting with each other. The high p_T selection enhances the W_0Z_0 contribution. A multivariate analysis using BDT is used for discriminating W_0Z_0 from other polarization states.

5.1 Validations of the Signal Regions

5.1.1 Comparison between the NLO SHERPA and LO-merged MADGRAPH Samples in the Signal Regions

This section shows the comparison between the inclusive NLO SHERPA sample (no separation of polarization states) and the LO-merged MADGRAPH sample (with all polarization states summed together) at the reconstruction level in one of the 00-enhanced signal regions (Inclusive phase space + $p_T^{WZ} < 70$ GeV + $p_T^Z > 100$ GeV). Both the (NLO QCD)/LO and (NLO QCD+EW)/(NLO QCD) k-factors are applied to both SHERPA and MADGRAPH distributions here.

Figures 5.1, 5.2, 5.3, 5.4, and 5.5 show the comparisons for the signal region with $p_T^{WZ} < 70$ GeV and $p_T^Z > 100$ GeV. Similar plots for the region with $p_T^{WZ} < 70$ GeV and $p_T^Z > 200$ GeV are shown in Appendix F. Good agreement is found between the NLO SHERPA sample and the LO-merged MADGRAPH sample at the reconstruction level. All the variables used in the BDT training are included. The BDT score shown in figure 5.3 is discussed in section 5.2.

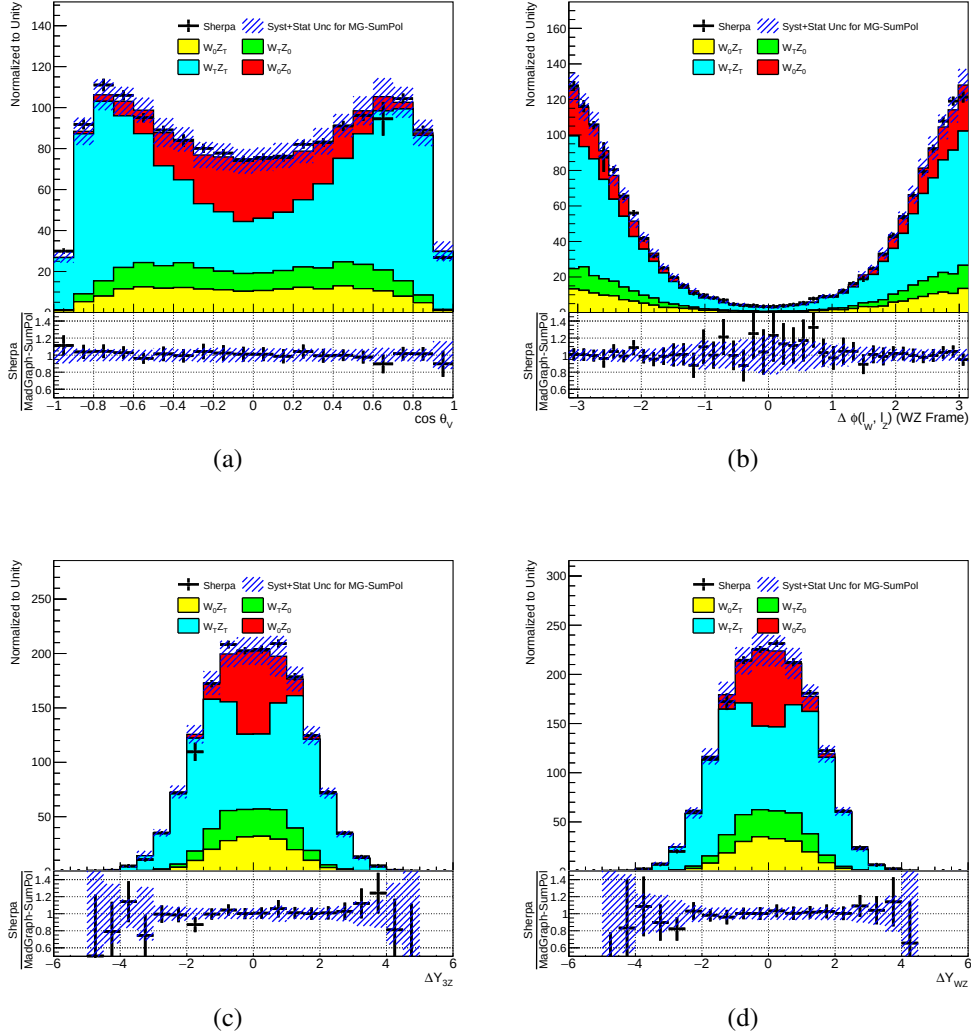


Figure 5.1: Comparison between the inclusive NLO SHERPA sample and the LO-merged MADGRAPH sample in the signal region $p_T^{WZ} < 70$ GeV and $p_T^Z > 100$ GeV for $\cos \theta_V$ (a), $\Delta \phi(\ell_W, \ell_Z)$ in the WZ rest frame (b), the rapidity difference between the W and Z bosons (ΔY_{WZ}) (c), and rapidity difference between the W lepton and the Z boson (ΔY_{3Z}) (d). All variables are calculated at the reconstruction level. This uses an integrated luminosity of 140.1 fb^{-1} at $\sqrt{s} = 13$ TeV.

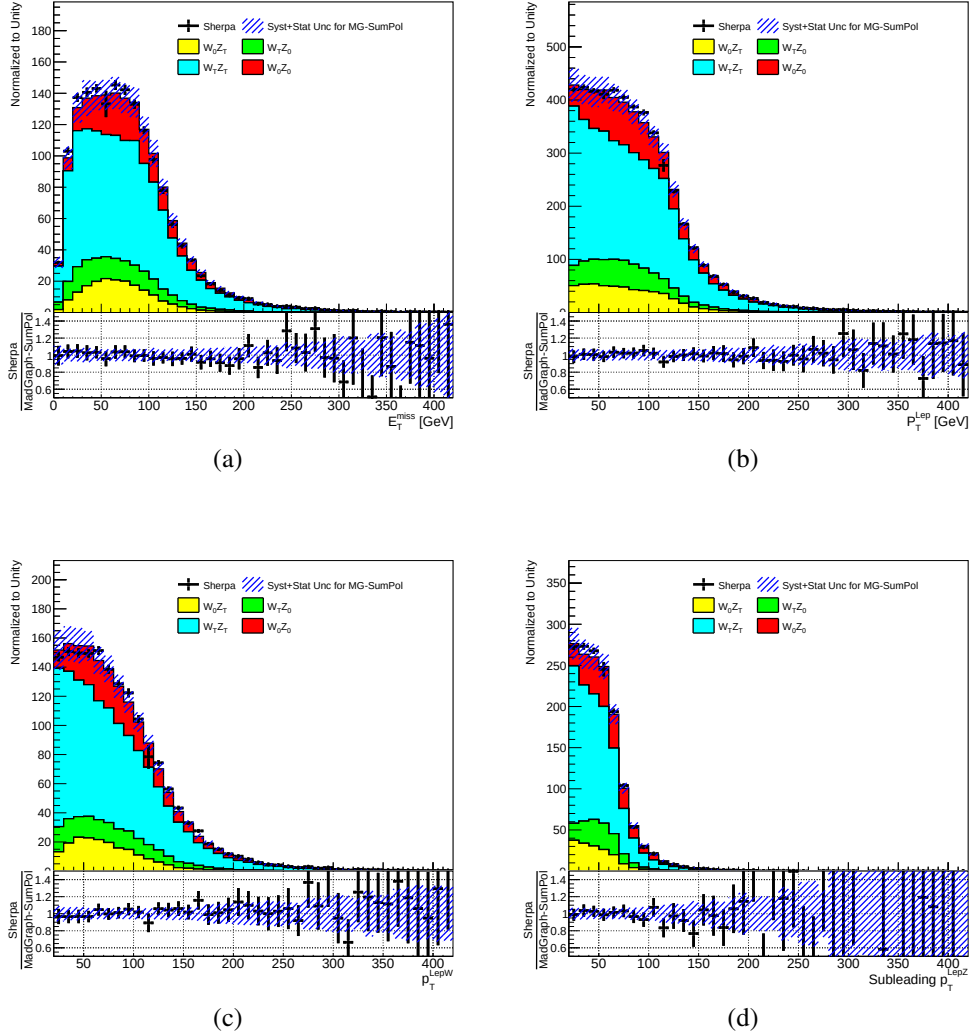


Figure 5.2: Comparison between the inclusive NLO SHERPA sample and the LO-merged Mad-Graph sample in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 100$ GeV) for E_T^{miss} (a), p_T of three charged leptons (b), p_T of the W lepton (c), and p_T of the subleading Z lepton (d). All variables are calculated at the reconstruction level. This uses an integrated luminosity of 140.1 fb^{-1} at $\sqrt{s} = 13$ TeV.

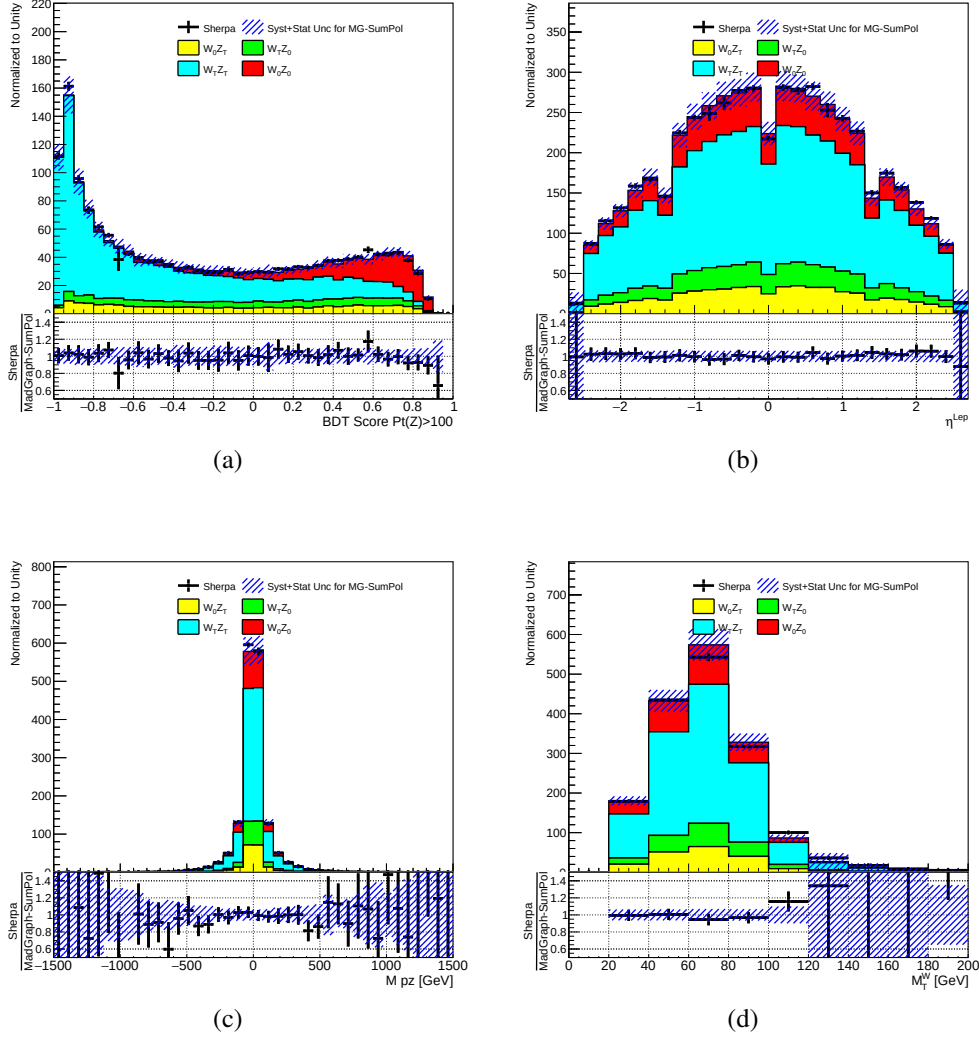


Figure 5.3: Comparison between the inclusive NLO SHERPA sample and the LO-merged Mad-Graph sample in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 100$ GeV) for the BDT score (a), η^{Lep} of three leptons (b), reconstructed neutrino p_z (c), and m_T^W (d). All variables are calculated at the reconstruction level. This uses an integrated luminosity of 140.1 fb^{-1} at $\sqrt{s} = 13$ TeV.

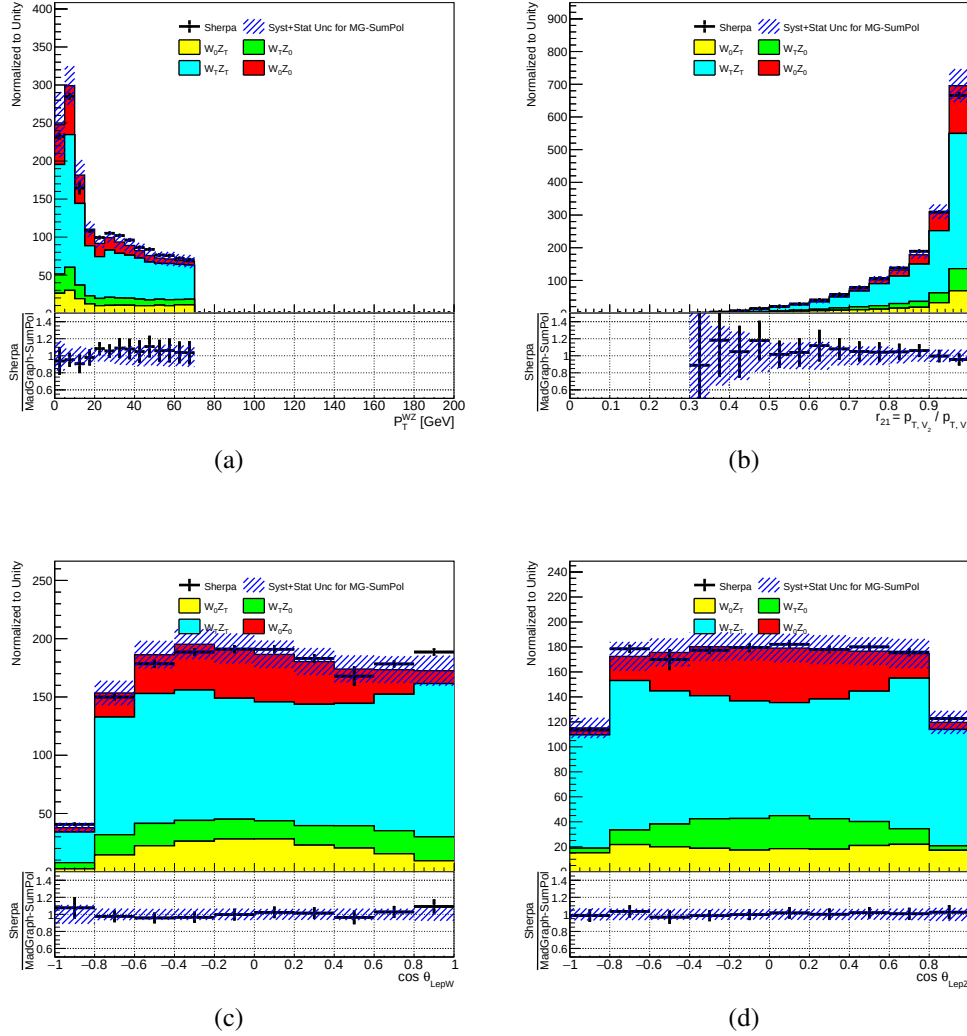


Figure 5.4: Comparison between the inclusive NLO SHERPA sample and the LO-merged MadGraph sample in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 100$ GeV) for p_T^{WZ} (a), $r_{21} = \frac{p_{T,V_2}}{p_{T,V_1}}$ (b), ratio of the lower p_T vector boson to the higher p_T one among the W and Z bosons, $\cos \theta_{\ell}^*(W)$ (c), and $\cos \theta_{\ell}^*(Z)$ (d). All variables are calculated at the reconstruction level. This uses an integrated luminosity of 140.1 fb^{-1} at $\sqrt{s} = 13$ TeV.

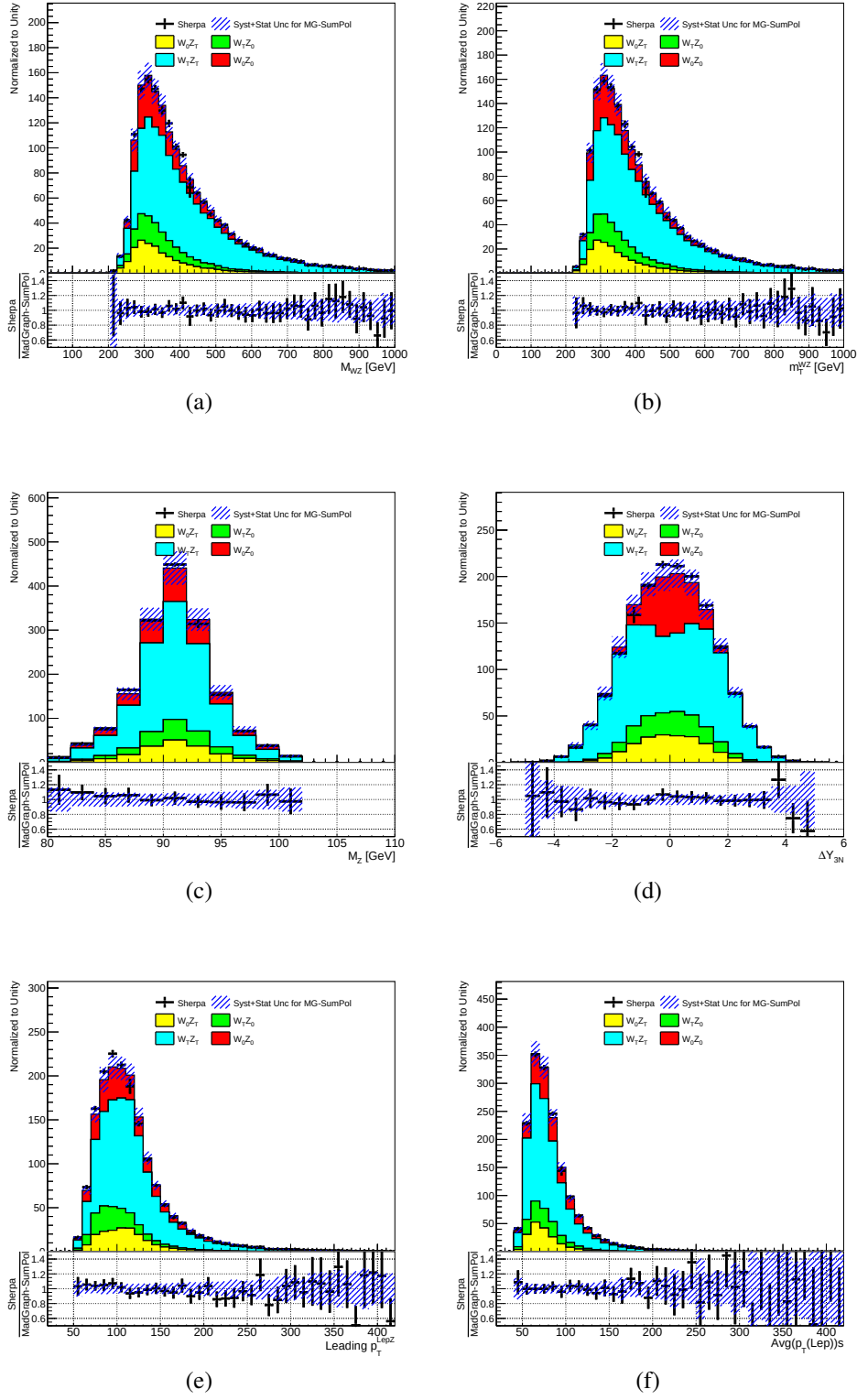


Figure 5.5: Comparison between the inclusive NLO SHERPA sample and the LO-merged Mad-Graph sample in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 100$ GeV) for M_{WZ} (a), $m_T(WZ)$ (b), M_Z (c), ΔY_{3N} (d), the leading p_T Z lepton (e), and $\text{Avg}(p_T(\ell))s$ (f). All variables are calculated at the reconstruction level. This uses an integrated luminosity of 140.1 fb^{-1} at $\sqrt{s} = 13$ TeV.

5.1.2 Data-MC Comparisons

Figures 5.6, 5.7, 5.8, 5.9, and 5.10 the Data-MC comparisons in the $p_T^Z > 100$ GeV signal region. Corresponding comparisons in the $p_T^Z > 200$ GeV regions are included in Appendix G.

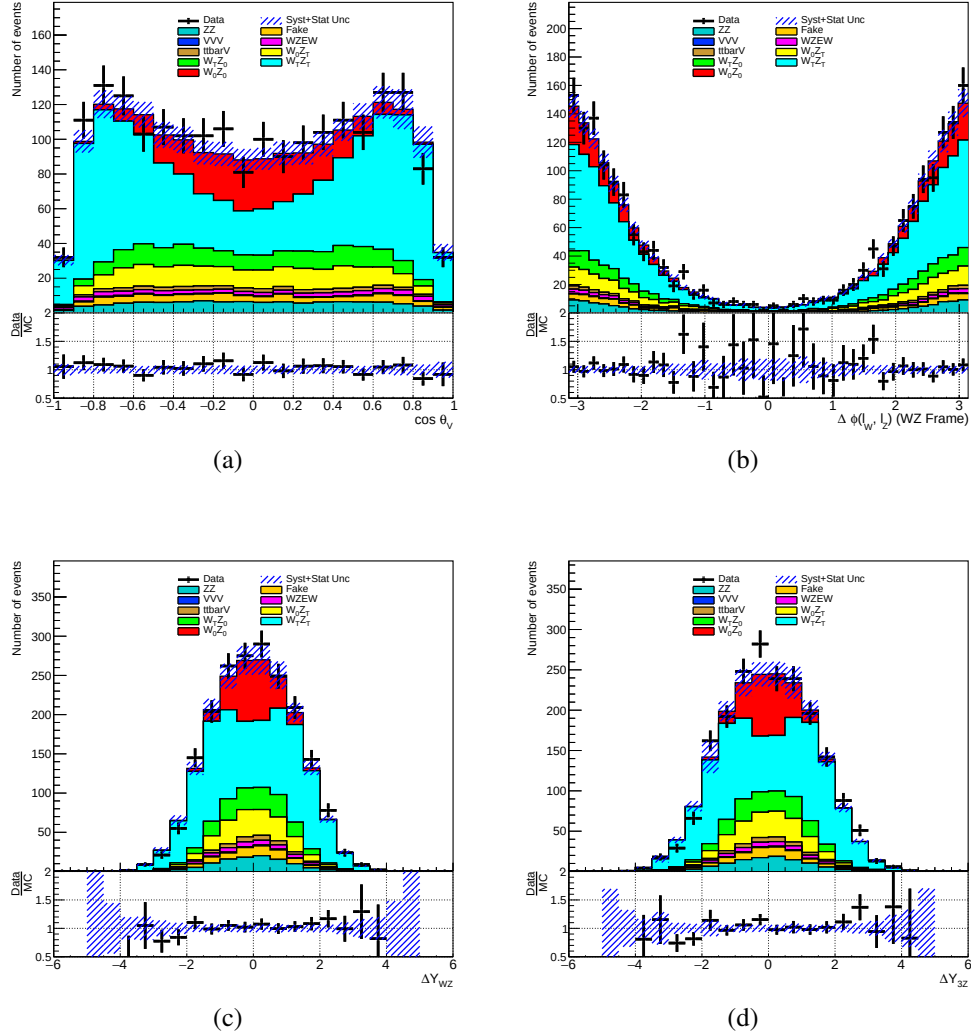


Figure 5.6: Comparison between the data and the SM prediction in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 100$ GeV) for the $\cos \theta_V$ (a), $\Delta \phi(\ell_W, \ell_Z)$ in WZ rest frame (b), rapidity difference between the W and Z bosons (ΔY_{WZ}) (c), and rapidity difference between the W lepton and the Z boson (ΔY_{3Z}) (d). All variables are calculated at the reconstruction level. This uses an integrated luminosity of 140.1 fb^{-1} at $\sqrt{s} = 13$ TeV.

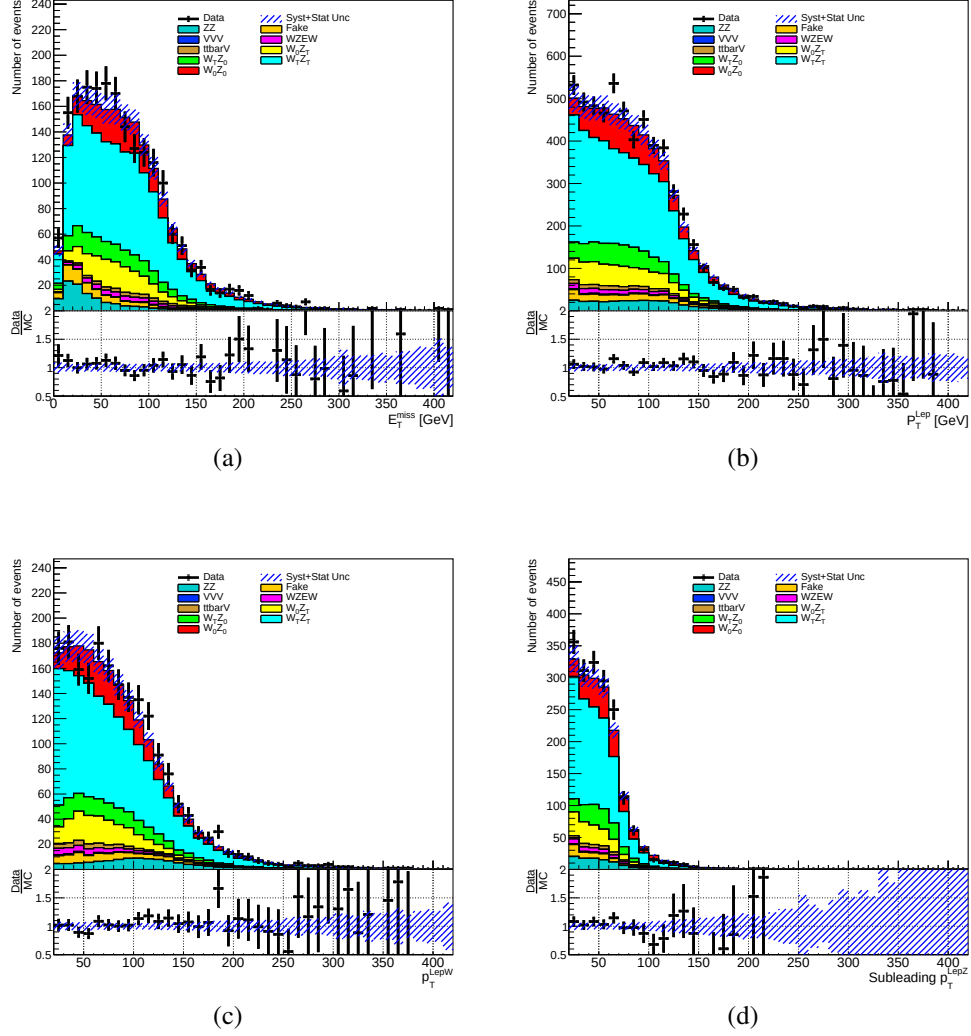


Figure 5.7: Comparison between the data and the SM prediction in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 100$ GeV) for E_T^{miss} (a), p_T of selected 3 leptons (b), p_T of the W lepton (c), and p_T of the subleading Z lepton (d). All variables are calculated at the reconstruction level. This uses an integrated luminosity of 140.1 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$.

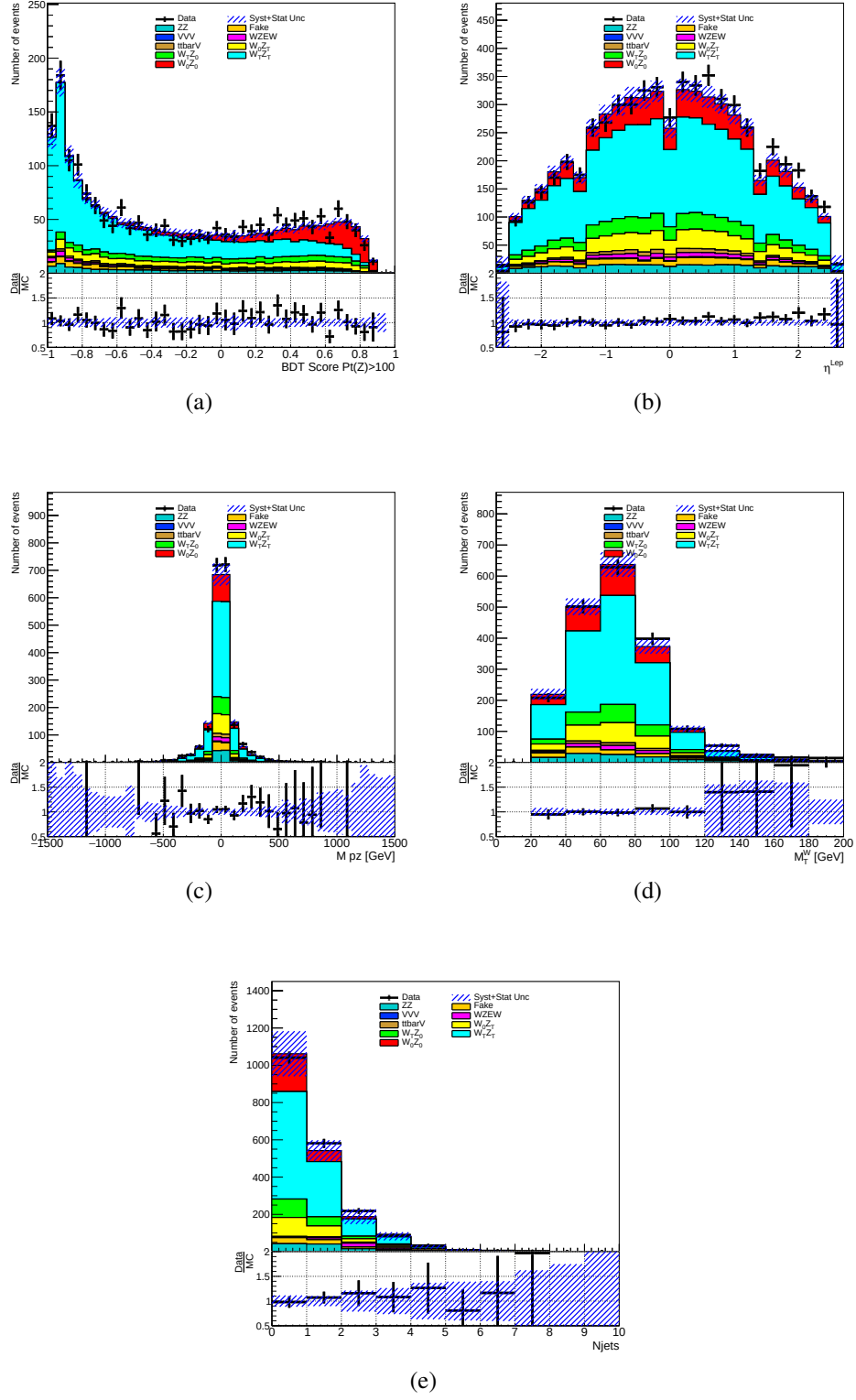


Figure 5.8: Comparison between the data and the SM prediction in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 100$ GeV) for the BDT score (a), η^{Lep} of three leptons (b), reconstructed neutrino p_z (c), m_T^W (d), and the number of jets (e). All variables are calculated at the reconstruction level. This uses an integrated luminosity of 140.1 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$.

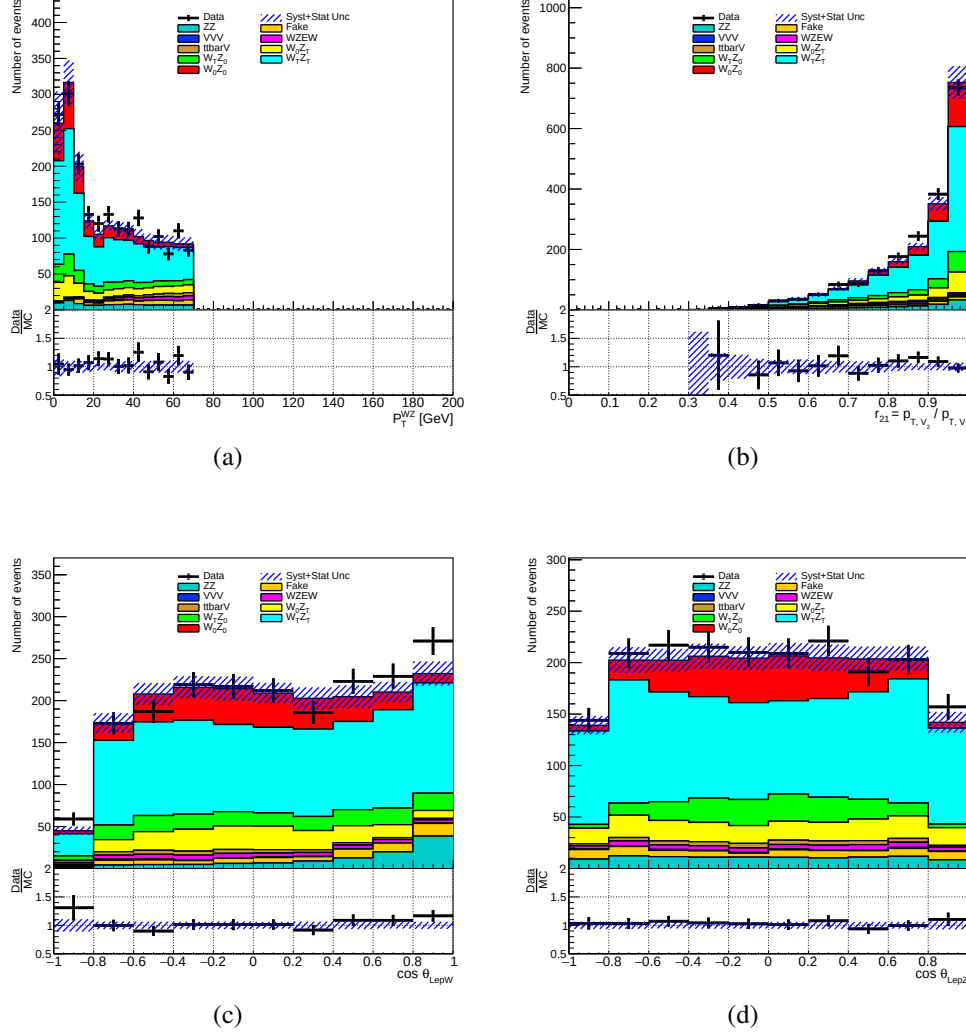


Figure 5.9: Comparison between the data and the SM prediction in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 100$ GeV) for p_T^{WZ} (a), $r_{21} = \frac{p_{T,V_2}}{p_{T,V_1}}$, i.e. ratio of the subleading vector boson p_T to the leading vector boson p_T (b), $\cos \theta_{\ell}^*(W)$ (c), and $\cos \theta_{\ell}^*(Z)$ (d). All variables are calculated at the reconstruction level. This uses an integrated luminosity of 140.1 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$.

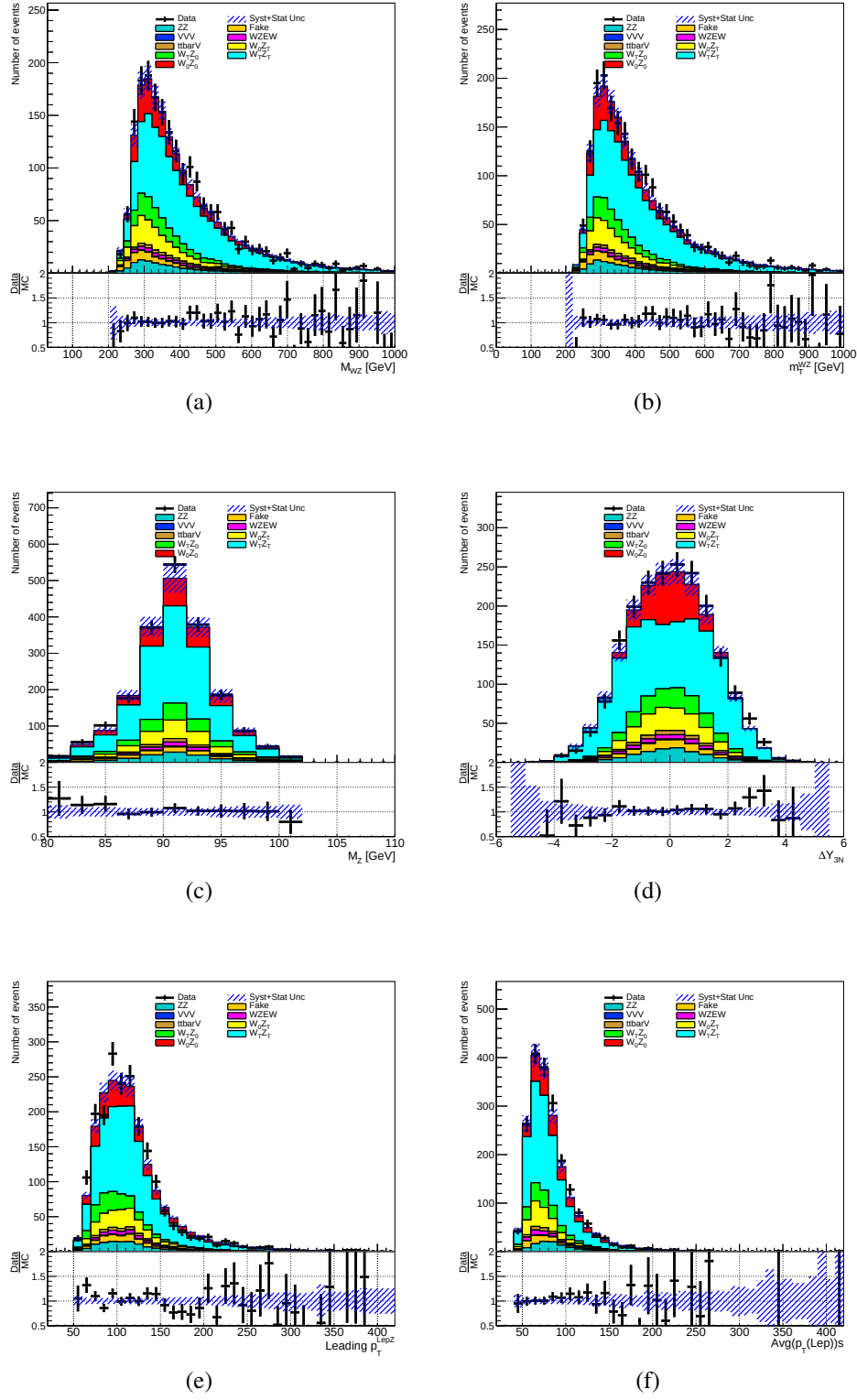


Figure 5.10: Comparison between the data and the SM prediction in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 100$ GeV) for M_{WZ} (a), $m_T(WZ)$ (b), M_Z (c), ΔY_{3N} (d), p_T of the leading Z lepton (e), and $\text{Avg}(p_T(\ell))$ s (f). All variables are calculated at the reconstruction level. This uses an integrated luminosity of 140.1 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$.

Table 5.1 shows the number of events for all the signal and background processes in the signal regions: $p_T^{WZ} < 70$ GeV, $p_T^Z > 200$ GeV, and $p_T^{WZ} < 70$ GeV and $p_T^Z > 100$ GeV.

Process	$p_T^Z > 200$ GeV	$p_T^Z > 100$ GeV
Total Prompt Bkg	24.1 ± 4.62	192.9 ± 19.2
ZZ	10.1 ± 4.12	107.0 ± 19.4
VVV	2.15 ± 0.443	7.90 ± 1.19
WZEW	6.16 ± 1.00	43.0 ± 5.79
$t\bar{t}V$	5.69 ± 1.52	35.0 ± 6.07
Fake	2.83 ± 6.38	71.2 ± 42.5
WZQCD Sherpa	199.7 ± 24.6	1658 ± 110.0
W_0Z_0	49.2 ± 3.67	279.1 ± 15.2
W_0Z_T	12.7 ± 2.42	189.4 ± 21.0
W_TZ_0	11.1 ± 1.57	168.6 ± 18.1
W_TZ_T	127.5 ± 13.9	1014 ± 80.9
Sum	200.4 ± 21.8	1651 ± 127.0

Table 5.1: Expected signal and background yields in the signal regions ($p_T^{WZ} < 70$ GeV, $p_T^Z > 200$ GeV) and ($p_T^{WZ} < 70$ GeV and $p_T^Z > 100$ GeV). Here, the QCD+EW k -Factors are applied, which are mentioned in section 3.7.

5.2 Multivariate Analysis (using BDTs)

A Boosted Decision Trees (BDT) are trained to separate the 00 polarization state from other 0T, T0, TT states. Two separate BDTs are trained in the different signal regions of $p_T^Z > 100$ GeV and $p_T^Z > 200$ GeV for template fitting. A broader overview of the principles of the BDTs used in this analysis can be found in Ref. [132]. A more detailed description can be found in Ref. [74].

Simple decision trees are the bases of the BDTs. The entire set of events is divided into two categories, signal, and background, by going over the variables with the most impact on the decision one by one. At every step, the events are split into smaller “leaf nodes” using a binary decision on the variable. A schematic of a BDT can be seen in figure 5.11. For this, 20 and 50 equidistant cuts on the variable at hand are checked for a binary decision. After applying every cut, a “gini-index” is calculated:

$$\text{gini-index} = p(1 - p), \quad (5.1)$$

where $p = n_S / (n_S + n_B)$ is the signal purity of the set of events split into each binary category. A node is split if its gini-index is larger than the weighted combination of the Gini-indices of the two

sub-nodes created by a cut. The maximum decrease of the gini-index for all tested cut values in all observables is used for the split of the node. The splitting stops when the maximum depth of the tree is reached or the minimum number of events is reached at the end. Once the splitting is stopped, the final nodes are called the “leaf nodes”.

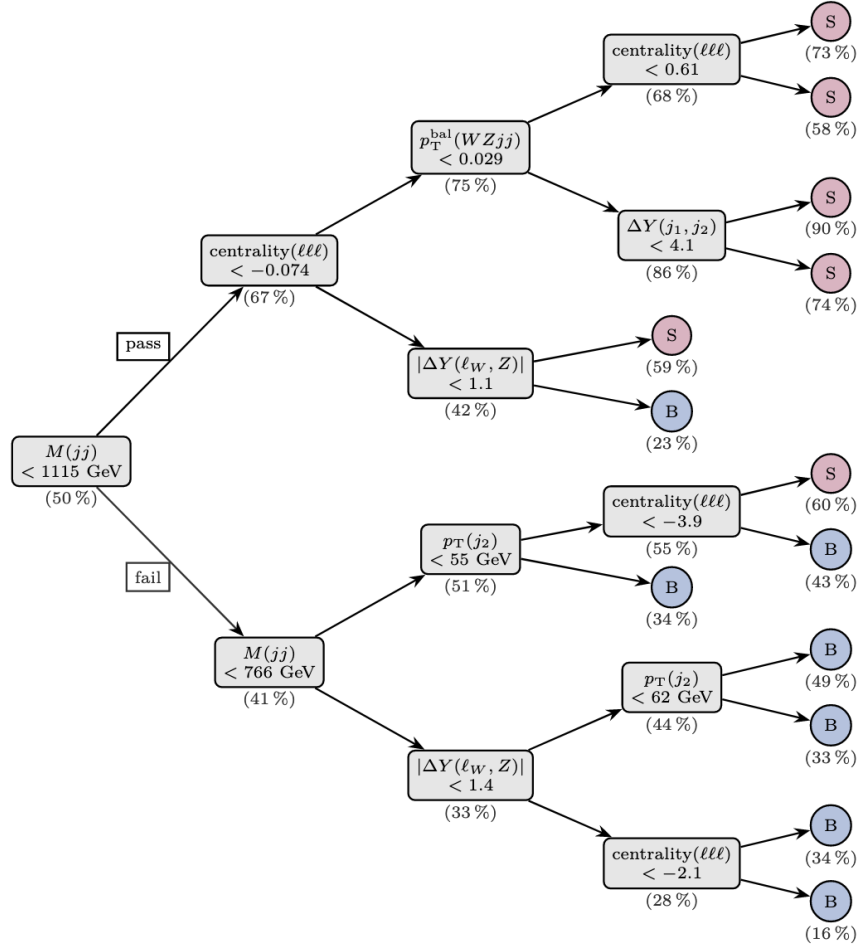


Figure 5.11: Schematic of a single binary decision tree [132]. The starting and intermediate nodes are drawn as rounded rectangles and the final leaf nodes are drawn as red (signal) or blue (background) circles. Each node is divided into two using the selection written in the middle. If the selection is satisfied the passed node is written on the upper side and the failed node is written on the lower side. The signal purity of all the nodes is written below the nodes.

A large systematic uncertainty arises with this simple decision tree method because of the fluctuations in the training events. To solve this issue, multiple decision trees are trained. All these trees are then combined to get the final decision output. A technique called “gradient boosting” is used to train different trees in this analysis. In this approach, the training events are iteratively reweighted

using the previous tree by increasing the weight w_i of a misclassified event i by

$$w_i \rightarrow w_i \cdot \frac{1-f}{f}, \quad (5.2)$$

where f is the misclassification rate of the decision tree from the previous boosting iteration. All the event weights are decreased by a constant factor to compensate for the change in the sum of weights.

The final function (BDTScore) is $F(\mathbf{x}; P)$ which is the weighted sum of the base functions obtained from the many trained decision trees (also called “weak-learners”), $f(x; a_m)$:

$$F(\mathbf{x}; P) = \sum_{m=0}^M \beta_m f(x; a_m); \quad P \in \{\beta_m; a_m\}_0^M. \quad (5.3)$$

The parameters, P , are optimized such that the difference between the model response $F(\mathbf{x}; P)$ and the true value y obtained from the training sample is minimized via minimizing a loss function. For the Gradient Boost, the loss function used is:

$$L(F, y) = \ln(1 + e^{-2F(\mathbf{x})y}). \quad (5.4)$$

The loss function is calculated at every iteration and the weight of each tree is decided to minimize the loss function over all the events and the next tree is added by adjusting the boosted tree.

A new parameter called “Shrinkage” is also added sometimes to significantly improve the accuracy of the prediction e.g. in difficult settings. A small Shrinkage, which controls the weights of the individual trees, reduces the learning rate demanding more trees.

This procedure is combined with “bagging” to reduce the sensitivity to statistical fluctuations in the training sample. Each iteration is performed using a randomized subset of the events in the training set. The size of the subset, `BaggedSampleFraction`, used is 0.6.

To avoid overtraining, the training is performed on a subset of events (training set) and tested on another set (testing set). In this analysis, the training and testing events are approximately half of all the events.

5.2.1 BDT Training Variables

The training is performed using the events that pass the selection defined in Section 3.3.6. The sensitivity of several observables to different diboson polarization states was investigated. Table 5.2 shows the full list of observables considered for the training, it also includes the ranking based on

the following figures of merit [132] (The input distributions are labeled as n_1 and n_2):

- Non overlap (f_{N-O}) :

$$f_{N-O}(n_1, n_2) = 1 - f_O = 1 - \sum_{i=1}^{N_{bins}} \min(n_{1,i}, n_{2,i}).$$

The non-overlap between the signal and background normalized distribution is determined using this figure of merit.

- Separation (f_{Sep}) :

$$f_{Sep}(n_1, n_2) = \sum_{i=1}^{N_{bins}} \frac{(n_{1,i} - n_{2,i})^2}{n_{1,i} + n_{2,i}}.$$

The separation is a performance evaluation metric using normalized distributions (originally proposed in [183]).

- Reduced χ^2 ($f_{red. \chi^2}$) :

$$\chi^2(n_1, n_2) = \sum_{i=1}^{N_{bins}} \frac{(n_{1,i} - n_{2,i})^2}{\Delta n_{1,i}^2 + \Delta n_{2,i}^2},$$

where $n_{1,i}$ and $n_{2,i}$ are the values of the i th bin of the normalized distributions of the two input histograms and $\Delta n_{1,i}$ and $\Delta n_{2,i}$ are the absolute uncertainties in bin i for the corresponding distributions. In this case, this would be signal and background. Larger values of χ^2 indicate disagreement.

- Approximated ROC-integral (f_{ROC}): The Receiver Operating Characteristic (ROC) curve is a plot of background rejection over signal acceptance. The curve is determined by continuously varying a cut selection threshold. Binned distributions are used for this.

5.2.2 Setup and Training

The BDT is trained to discriminate the 00 polarization state against all other polarization states of 0T, T0, and TT states. The other background processes are not included in the training due to extremely low statistics. Two statistically independent samples are used by splitting the signal and background events, one is used for training and the other for testing. For this analysis, the separation is done into odd and even event numbers.

Observable	$f_{\text{N-O}}$	f_{Sep}	$f_{\text{red. } \chi^2}$	f_{ROC}
ΔY_{3Z}	0.44	0.255	1980.93	0.75
ΔY_{WZ}	0.40	0.213	1645.73	0.72
ΔY_{3N}	0.39	0.207	1609.96	0.72
$\cos \theta^\ell(Z)$	0.21	0.066	500.26	0.61
Subleading $p_T^\ell(Z)$	0.20	0.060	450.86	0.59
$m_T(WZ)$	0.18	0.046	339.54	0.59
M_{WZ}	0.18	0.046	338.13	0.59
$\cos \theta^\ell(W)$	0.16	0.037	277.49	0.58
$p_T^\ell(W)$	0.13	0.027	189.76	0.52
$p_T(WZ)$	0.12	0.021	148.98	0.55
E_T^{miss}	0.11	0.021	167.75	0.47
R_{21}	0.11	0.017	120.92	0.49
Leading $p_T^\ell(Z)$	0.10	0.012	84.88	0.52
$\Delta\Phi(\ell_W, \ell_Z)$ (lab frame)	0.09	0.020	157.31	0.48
$\Delta\Phi(\ell_W, \ell_Z)$ (WZ frame)	0.09	0.019	152.17	0.47
$\eta^\ell(W)$	0.07	0.010	75.35	0.52
p_T^W	0.06	0.010	66.77	0.50
p_T^Z	0.05	0.004	25.62	0.46
m_T^W	0.03	0.005	37.24	0.44
Leading $\eta^\ell(Z)$	0.03	0.002	18.69	0.48
M_Z	0.02	0.001	9.54	0.48
Subleading $\eta^\ell(Z)$	0.02	0.001	7.98	0.48
Leading $\phi^\ell(Z)$	0.01	0.000	1.19	0.48
$\phi^\ell(W)$	0.01	0.000	0.93	0.48
Subleading $\phi^\ell(Z)$	0.01	0.000	0.62	0.48

Table 5.2: Overview of the variables considered for the MVA training and their ranking, based on different figures of merit. For the actual BDT training, the $\Delta\Phi$ and η related distributions were discarded due to their low separation power.

Parameter	Value
BoostType	Grad
NTrees	200
MaxDepth	4
MinNodeSize	2.5%
nCuts	20
Shrinkage	0.06
NegWeightTreatment	Pray

Table 5.3: List of parameters set at the beginning of the optimization.

5.2.3 Optimization

The optimizing procedure is important for making the BDT training robust against uncertainties and also to avoid overtraining. The input and meta parameters are optimized in this process. Initially, the variables optimization is performed and then the meta-parameters are optimized.

The meta parameters of the starting BDT are displayed in table 5.3. The variable optimization is done iteratively, it starts with the ΔY_{3Z} that has the best separation power when considering a singular variable, and from there, variables are added or dropped one by one with the goal of maximizing the approximated significance $Z = \frac{S}{\sqrt{B+(0.3 \times B)^2}}$ on the test set. To quantify the overtraining the χ^2 of the training and test samples are compared for signal and background separately. The configuration is deemed overtrained if either of the values exceeds 2.0 or both are larger than 1.5.

If either value exceeds 2.0 or both are larger than 1.5 the configuration is considered overtrained. Overtrained configurations are discarded and the next best configuration is checked instead until one is found that is not overtrained. This overtraining check is not performed for the first two iterations as there is a high probability that all configurations are overtrained when using that few variables.

The resulting variables in order of their addition to the BDT training are: ΔY_{3Z} , $p_T(WZ)$, $p_T^\ell(W)$, the subleading $p_T^\ell(Z)$, $\cos \theta^\ell(W)$, E_T^{miss} , and $\cos \theta^\ell(Z)$.

For the meta-parameter optimization, a simple grid search over a multitude of values is performed. The values included in the search are:

- MaxDepth (maximum depth of the tree allowed): 3, 4, 5
- MinNodeSize (min number of events allowed in a node for the decision to stop the splitting): 1%, 2%, 2.5%, 4%
- nCuts (number of equidistant cuts checked for a variable): 20, 50

Parameter	Value
BoostType	Grad
NTrees	1000
MaxDepth	4
MinNodeSize	1%
nCuts	50
Shrinkage	0.02
NegWeightTreatment	Pray

Table 5.4: List of parameters set for the training for the $p_T^Z > 200$ GeV region.

Variable
ΔY_{3Z}
$p_T(WZ)$
$p_T^\ell(W)$
Subleading $p_T^\ell(Z)$
E_T^{miss}
$\cos \theta^\ell(Z)$
$\cos \theta^\ell(W)$

Table 5.5: List of variables used in final BDT for the $p_T^Z > 200$ GeV region.

- Shrinkage (for lowering the learning rate): 0.01, 0.02, 0.04, 0.06
- NTrees (number of trees to be trained and later combined): 200, 400, 600, 800, 1000, 1300.

These parameters and the chosen value for each in the $p_T^Z > 200$ GeV region are displayed in table 5.4.

The effect of changing the NTrees meta parameter on the significance and χ^2 overtraining values can be seen in figure H.1 in Appendix H.

The final list of variables used in the BDT training can be found in table 5.5 for $p_T^Z > 200$ GeV region. They appear in the order in which they were added during the optimization.

Figure 5.12 shows the comparison of training and testing samples separately for signal and background events. The middle and bottom panels show the ratio between the BDT output on the training and testing samples, for signal and background respectively. The ratios agree within 10% indicating a good stability of the training method.

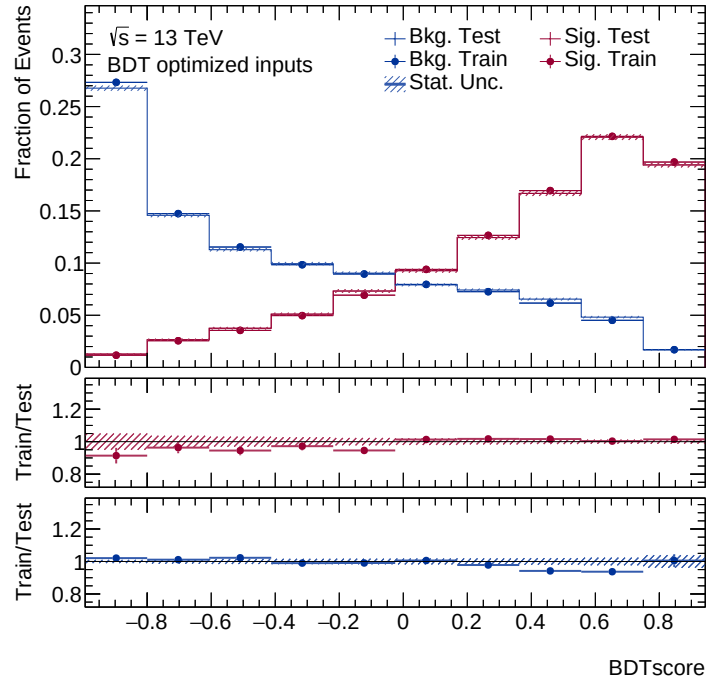


Figure 5.12: Comparison of the BDT score distribution of the signal (red) and the sum of the backgrounds (blue) for the training samples (dots) and the testing samples (bars). The middle and bottom panels show the ratio between training and testing, for signal and background respectively.

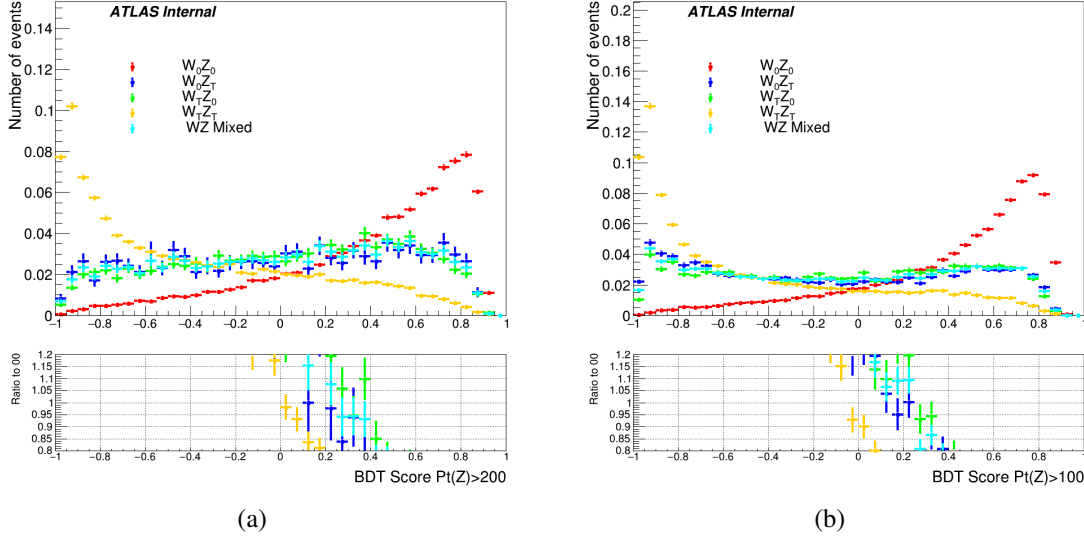


Figure 5.13: BDT score distributions for $p_T^Z > 200$ GeV (a) and $p_T^Z > 100$ GeV (b) obtained for different 00, 0T, T0, and TT polarization states. There is a clear shape difference between the 00 state and the other polarization contributions. The shape of the mixed polarisations (0T and T0) are almost identical to each other.

5.2.4 Output Validation

Figure 5.13 shows the BDT score distributions for the individual polarizations. A clear separation can be seen between the 00 and TT states. The shapes of the mixed 0T and T0 states are practically indistinguishable and effectively identical. However, the degree of distinguishability between the mixed polarizations and the 00 one is higher than that between 0T and T0.

The BDT score distributions obtained by using Sherpa and the LO-merged Madgraph samples are compared in figure 5.14. The distributions agree overall within uncertainties.

The final meta parameter settings and variables after optimization in the $p_T^Z > 100$ GeV region are listed in tables 5.6 and 5.7 respectively.

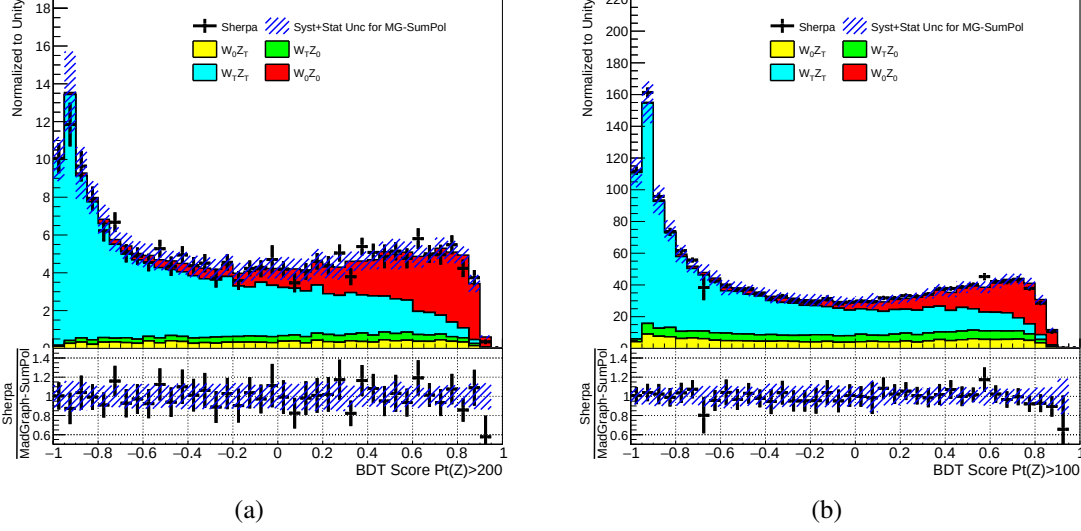


Figure 5.14: Comparison between the inclusive NLO Sherpa sample (no separation of polarization states) and the LO-merged MadGraph sample (all polarization states summed together) for the BDT Score in the regions $p_T^Z > 200$ GeV (a) and $p_T^Z > 100$ GeV (b).

Parameter	Value
BoostType	Grad
NTrees	800
MaxDepth	5
MinNodeSize	1%
nCuts	50
Shrinkage	0.01
NegWeightTreatment	Pray

Table 5.6: List of parameters set for the training for the $p_T^Z > 100$ GeV region.

Variable
ΔY_{3Z}
Subleading $p_T^\ell(Z)$
$p_T(WZ)$
$p_T^\ell(W)$
E_T^{miss}
$m_T(W)$
M_{WZ}
$\cos\theta^\ell(Z)$
$\cos\theta^\ell(W)$
$m_T(WZ)$
Leading $p_T^\ell(Z)$

Table 5.7: List of variables used in final BDT for the $p_T^Z > 100$ GeV region.

5.2.5 Template Fitting

The binned likelihood fit method is used for a template fit based on the BDT Score variable. The package HistFactory [184] in ROOT is used for this purpose. The framework based on RooFit [185] is used for the implementation of fundamental statistical tools.

The likelihood estimation is the probability of the observed data given a particular theoretical expectation or parameter. Here, this parameter is μ_S , which is the scaling of the expected signal events to the observed signal events.

$$\text{Events observed} = \mu_S \cdot S + B, \quad (5.5)$$

where S is the expected number of signal events and B is the expected number of background events. A simple form of likelihood can be defined as:

$$L(\mu_S) = \prod_{i=1}^n f(x_i; \mu_S). \quad (5.6)$$

μ_S is used for the cross-section measurement and hence called the parameter-of-interest. Additionally, other nuisance parameters (NPs) can be considered for modeling the effects of different systematic uncertainties.

The likelihood function is constructed as follows [132]:

$$L(\mu_S, \theta) = \left(\prod_{i=1}^n f(x_i; \mu_S, \theta) \right) \cdot f(\theta^{\text{ext}}; \theta). \quad (5.7)$$

Here, the constraint term $f(\theta^{\text{ext}}; \theta)$ is added with the externally measured value of the NP θ^{ext} and the true value θ .

$$L(\mu_S, \mu_B, \gamma, \theta) = \prod_{\substack{r \in \\ \text{regions bins in } r}} \prod_{j_r \in} \text{Pois}(n_{j_r} | \gamma_{j_r} \cdot \nu_{j_r}) \text{Pois}(m_{j_r} | \gamma_{j_r} \cdot \tau_{j_r}) \cdot \prod_{\theta_p \in \theta} G(0; \theta_p, 1). \quad (5.8)$$

(This requires that the effect of potential differences between external measurements of nuisance parameters θ and their values used for the evaluation of the nominal predictions can be neglected.)

Here,

$$P(n_j | \mu_S s_j + b_j) = \text{Pois}(n_j | \mu_S s_j + b_j) = \frac{\mu_S s_j + b_j^{n_j}}{n_j!} e^{-(\mu_S s_j + b_j)}. \quad (5.9)$$

The predicted expectation values for the signal and background process s_{j_r} and b_{j_r} depend on the nuisance parameters θ .

$$\nu_{j_r} = \mu_S \cdot s_{j_r}(\theta) + b_{j_r}(\theta, \mu_B), \quad (5.10)$$

μ_S : Scale factor for signal strength, μ_B : Set of nuisance parameters without explicit constraint term, γ : Set of nuisance parameters with Poissonian constraint term, θ : Set of nuisance parameters with Gaussian constraint term, τ_{j_r} : Scale factor introduced to allow for nominal value of associated γ_{j_r} to be 1, n_{j_r} : Measurement of event yield in bin j_r , m_{j_r} : Observed prediction from simulations for event yield in bin j_r as measurement of true underlying prediction of simulation.

A profile likelihood ratio is defined as:

$$\lambda(\mu_S) = \frac{L(\mu_S, \hat{\mu}_B, \hat{\gamma}, \hat{\theta})}{L(\hat{\mu}_S, \hat{\mu}_B, \hat{\gamma}, \hat{\theta})}, \quad (5.11)$$

where the likelihood in the denominator is evaluated at its maximum, i.e. the maximum likelihood estimators (indicated by the single hat, e.g. $\hat{\theta}$) of each parameter are used. The parameter of interest, here the signal strength parameter μ_S , in the numerator is a free parameter in the profile likelihood ratio $\lambda(\mu_S)$ and constrains the maximization of the associated likelihood. That means the remaining parameters, i.e. the nuisance parameters, are chosen to maximize the likelihood for a given μ_S . These constrained maximum likelihood estimators of the parameters depend on μ_S and are indicated by a double-hat (e.g. $\hat{\hat{\theta}}$).

This profile likelihood ratio is constrained to values of $0 \leq \lambda(\mu_S) \leq 1$ and quantifies the compatibility to data of a theory hypothesis described by a given μ_S compared to the hypothesis with global maximum likelihood estimators.

The test statistic used here is:

$$q_0 = \begin{cases} -2 \ln \lambda(0) & \hat{\mu}_S \geq 0, \\ 0 & \hat{\mu}_S < 0, \end{cases} \quad (5.12)$$

A hypothesis test is performed using the measurement of p -value. The null hypotheses giving a p -value below a threshold are rejected. It can be written in terms of significance Z as:

$$p_{\mu_S} = \int_{Z_{\mu_S}}^{\infty} G(x; 0, 1) dx. \quad (5.13)$$

This transformation can also be applied using the inverse cumulative distribution function of the normal Gaussian distribution Φ^{-1} as

$$Z_{\mu_S} = \Phi^{-1}(1 - p_{\mu_S}). \quad (5.14)$$

The p -value for a given hypothesis with μ_S is obtained as:

$$p_{\mu_S} = \int_{q_{0, \text{obs}}}^{\infty} f(q_0 | \mu_S) dq_0. \quad (5.15)$$

Toy datasets are used to obtain $f(q_0 | \mu_S)$. A significance for background-only hypothesis, $Z_0 = 5\sigma$ (corresponding to the p -value of 2.87×10^{-7}) is needed for a signal observation. Also, in a special case with a large sample limit, the discovery significance is

$$Z_0 = \sqrt{q_0} = \begin{cases} \sqrt{-2 \ln \lambda(0)} & \hat{\mu}_S \geq 0, \\ 0 & \hat{\mu}_S < 0. \end{cases} \quad (5.16)$$

We are using this asymptotic formula for the significance calculation.

5.2.6 Fitting Strategies

Two different fitting strategies are used for the extraction of the 00-fraction:

- Three parameter fit strategy: Three unconstrained parameters used are f_{00} (longitudinal-longitudinal polarization fraction), f_{Mixed} (mixed polarization fraction combining 0T and T0), and N_{tot} (Total number of signal events 00+0T+T0+TT).

- Two parameter fit strategy: Two unconstrained parameters used are f_{00} (longitudinal-longitudinal polarization fraction) and N_{tot} (Total number of signal events 00+0T+T0+TT)

5.2.6.1 Fit with three unconstrained parameters

The first strategy uses three unconstrained parameters. It focuses on the polarization fractions of doubly-longitudinal events (00), doubly-transversal events (TT), and mixed events (0T and T0) f_{00} , f_{Mixed} and f_{TT} . The mixed polarizations of f_{0T} and f_{T0} are combined as they have a very small contribution and also effectively identical shapes, see Figure 5.13. The fit scaling parameters μ_i with $i \in \{00, \text{Mixed}, \text{TT}\}$ are linked together as follows:

$$\mu_{00} = \frac{f_{00} \times N_{\text{tot}}}{N_{\text{Template},00}^{\text{MC}}}, \quad (5.17)$$

$$\mu_{\text{Mixed}} = \frac{f_{\text{Mixed}} \times N_{\text{tot}}}{N_{\text{Template},\text{Mixed}}^{\text{MC}}}, \quad (5.18)$$

$$\mu_{\text{TT}} = \frac{(1 - f_{00} - f_{\text{Mixed}}) \times N_{\text{tot}}}{N_{\text{Template},\text{TT}}^{\text{MC}}}, \quad (5.19)$$

where $N_{\text{Template},i}^{\text{MC}}, i \in \{00, \text{Mixed}, \text{TT}\}$, is the integral over the Monte Carlo template.

The templates generated by MC at the truth level undergo several distortions:

- Some events of the Total Phase Space do not pass the fiducial cuts leading to a first distortion of the template. This acceptance is assessed for all templates by so-called A-factors.
- Some events in the fiducial phase space are not reconstructed because the detector is not perfectly efficient. Also, some events from outside the fiducial phase space can migrate into the measurement phase space. This overall effect called the efficiency of the detector is assessed by so-called C-factors.
- The template shape can be distorted due to migrations among the bins in the measurement phase space.

Shape effects on the template caused by event migration among the bins in the measurement phase space and from outside the fiducial phase space are taken into account by putting the templates (with generated events in the total phase space) through the detector simulation and by reconstructing them in the same way as the data. All shape distortions should therefore be propagated to the template if the modeling of the detector response is correct. This has been checked by independent

measurements done by the ATLAS combined detector performance groups. Scale and correction factors make sure that the simulation describes the data well.

Fits using the three free parameters configuration are performed using the two 00-enriched signal regions. Figure 5.15 shows the pre- and Post-fit BDT distribution for the fit performed in the 00-enriched $p_T^Z > 200$ GeV and $p_T^Z > 100$ GeV regions respectively.

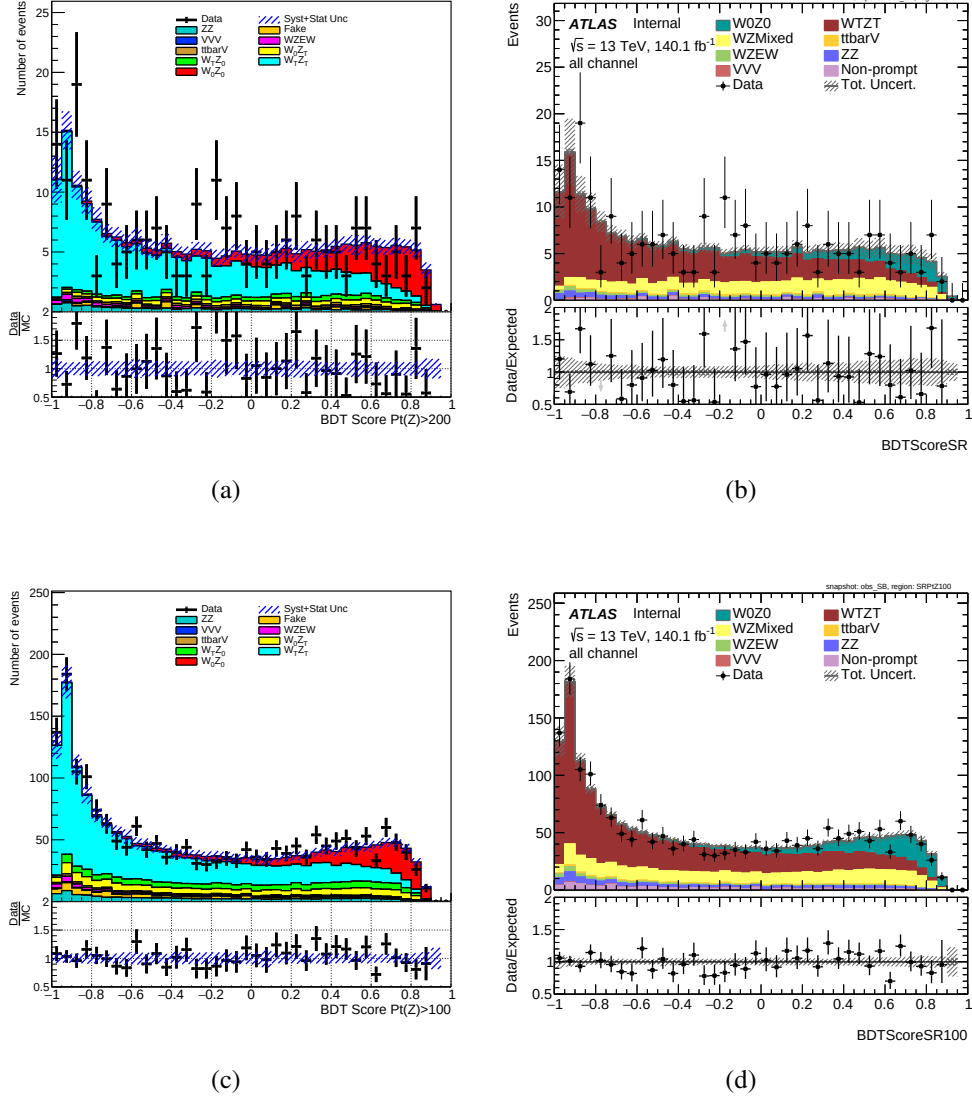


Figure 5.15: Pre-fit and Post-fit distributions for the $S + B$ hypothesis using the three-parameter fit strategy. Pre-fit plots are shown on the left and Post-fit plots are shown on the right. The top plots are for the $p_T^Z > 200$ GeV region, and the bottom plots are for the $p_T^Z > 100$ GeV region.

Table 5.8 and table 5.9 show the pre- and post-fit yields for $p_T^Z > 200$ and $p_T^Z > 100$ regions respectively.

	Pre-Fit	Post-fit
Non-prompt	2.8 ± 1.2	2.8 ± 0.8
VVV	2.1 ± 0.4	2.1 ± 0.4
ZZ	10.1 ± 1.7	10.1 ± 1.6
WZEW	6.2 ± 1.3	6.2 ± 1.3
$t\bar{t}V$	5.7 ± 0.8	5.7 ± 0.8
WZMixed	23.7 ± 0.9	50 ± 40
$W_T Z_T$	128 ± 5	130 ± 40
Obs. Data	236	
$W_0 Z_0$	49.2 ± 1.5	28.6 ± 2.2
Total Expected	227 ± 8	236 ± 16

Table 5.8: The Pre- and Post-fit yields for the signal region $p_T^Z > 200$ GeV with three-parameter fit strategy.

	Pre-Fit	Post-fit
Non-prompt	71 ± 30	69 ± 25
VVV	7.9 ± 1.6	7.8 ± 1.6
ZZ	107 ± 16	106 ± 16
WZEW	43 ± 9	42 ± 9
$t\bar{t}V$	35 ± 5	34 ± 5
WZMixed	358 ± 13	410 ± 160
$W_T Z_T$	1014 ± 33	1040 ± 170
Obs. Data	1980	
$W_0 Z_0$	279 ± 6	264 ± 9
Total Expected	1920 ± 60	1980 ± 50

Table 5.9: The Pre- and Post-fit yields for the signal region $p_T^Z > 100$ GeV with three-parameter fit strategy.

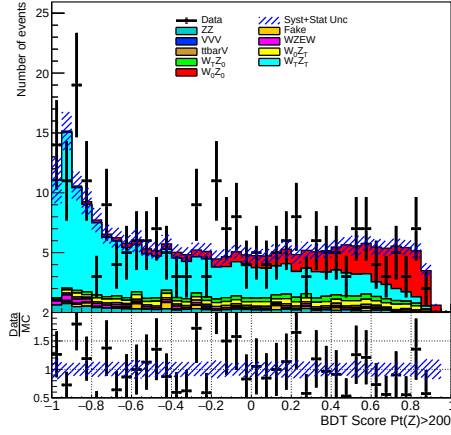
5.2.6.2 Fit with two unconstrained parameters

The second strategy combines the mixed and transversal-transversal contributions into one, “Rest” sample. This merging is motivated by the low contribution of mixed fractions and also the large anti-correlations between the free parameters (see figure 5.17). This merging improves the f_{00} significance. This strategy effectively puts a constraint on the result and assumes the ratio $f_{\text{Mixed}}/f_{\text{TT}}$ is to be as predicted by the SM in our MC simulation. Even if more model dependent this measurement still provides useful information for constraining some BSM models. The implementation of this constraint in the fit reduces the fractions to measure to two, f_{00} and f_{Rest} . The relationships with the scaling parameters can be written as:

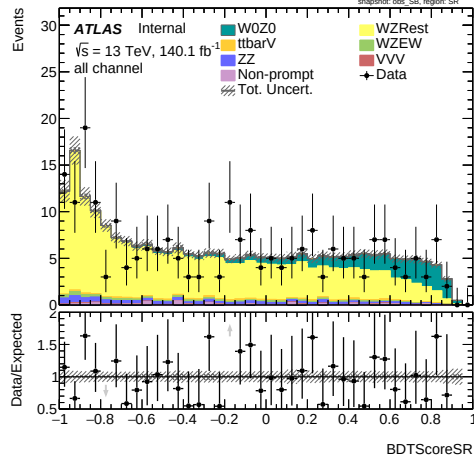
$$\mu_{00} = \frac{f_{00} \times N_{\text{tot}}}{N_{\text{Template},00}^{\text{MC}}}, \quad (5.20)$$

$$\mu_{\text{Rest}} = \frac{(1 - f_{00}) \times N_{\text{tot}}}{N_{\text{Template},\text{Rest}}^{\text{MC}}}. \quad (5.21)$$

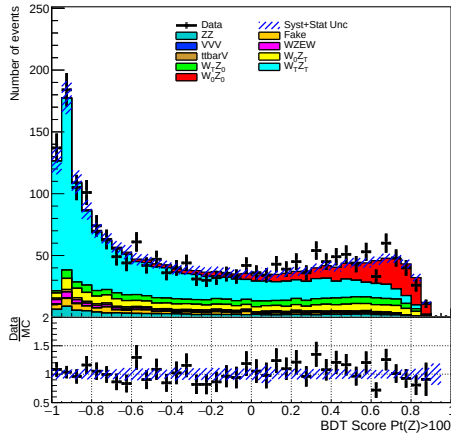
Fits using the two free parameter configurations are performed using the two 00-enriched signal regions. Figure 5.16 shows the pre- and Post-fit BDT distribution for the fit performed in the 00-enriched $p_T^Z > 200$ GeV and $p_T^Z > 100$ GeV regions respectively.



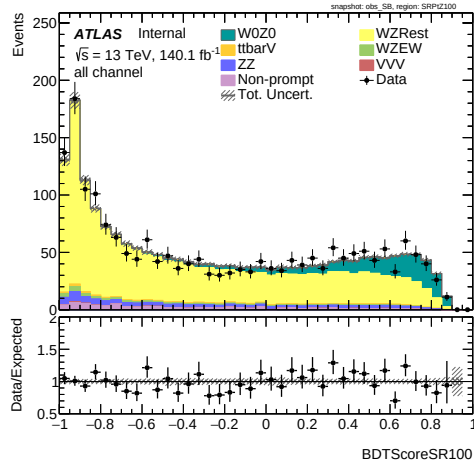
(a)



(b)



(c)



(d)

Figure 5.16: Pre-fit and Post-fit distributions for the $S + B$ hypothesis using the two-parameter fit strategy. Pre-fit plots are shown on the left and Post-fit plots are shown on the right. The top plots are for the $p_T^Z > 200$ GeV region, and the bottom plots are for the $p_T^Z > 100$ GeV region.

Table 5.10 and table 5.11 show the pre- and post-fit yields for $p_T^Z > 200$ and $p_T^Z > 100$ regions respectively.

	Pre-Fit	Post-fit
Non-prompt	2.8 ± 1.2	2.8 ± 0.8
VVV	2.1 ± 0.4	2.1 ± 0.4
ZZ	10.1 ± 1.7	10.1 ± 1.6
WZEW	6.2 ± 1.3	6.2 ± 1.3
$t\bar{t}V$	5.7 ± 0.8	5.7 ± 0.8
WZRest	151 ± 5	173 ± 13
Obs. Data	236	
W_0Z_0	49.2 ± 1.5	35.8 ± 2.8
Total Expected	227 ± 8	236 ± 16

Table 5.10: The Pre- and Post-fit yields for the signal region $p_T^Z > 200$ GeV with two parameter fit strategy.

	Pre-Fit	Post-fit
Non-prompt	71 ± 30	70 ± 25
VVV	7.9 ± 1.6	7.8 ± 1.6
ZZ	107 ± 16	106 ± 16
WZEW	43 ± 9	42 ± 9
$t\bar{t}V$	35 ± 5	35 ± 5
WZRest	1370 ± 50	1440 ± 50
Obs. Data	1980	
W_0Z_0	279 ± 6	273 ± 10
Total Expected	1920 ± 60	1980 ± 50

Table 5.11: The Pre- and Post-fit yields for the signal region $p_T^Z > 100$ GeV with two parameter fit strategy.

5.2.7 Fit Results

5.2.7.1 Three Parameter Fit Strategy

Tables 5.12 and 5.13 summarize the fit results in the two 00-enriched regions using the three-parameter fit strategy. It shows the expected and observed significances for the 00 measurements, the measured fractions, the fitted value for the free parameters, and the overall scaling of the samples. The observed (expected) significances are 1.642σ (2.611σ) and 4.783σ (5.708σ) for the 00-enriched regions with $p_T^Z > 200$ GeV and $p_T^Z > 100$ GeV cuts respectively.

	Exp.	Obs.
significance	2.6σ	1.6σ
f_{00}	$0.25 \pm_{0.10}^{0.10}$	$0.14 \pm_{0.09}^{0.09}$
f_{Mixed}	$0.12 \pm_{0.12}^{0.19}$	$0.23 \pm_{0.22}^{0.18}$
N_{tot}	$200 \pm_{17}^{18}$	$209 \pm_{18}^{18}$
$1 - \text{Sum}$	0.636	0.631
μ	$1.0 \pm_{0.4}^{0.4}$	$0.6 \pm_{0.4}^{0.4}$
$\mu_{WZ(\text{TT})}$	$1.00 \pm_{0.20}^{0.23}$	$1.03 \pm_{0.21}^{0.27}$
$\mu_{WZ(\text{Mixed})}$	$1.0 \pm_{1.0}^{1.7}$	$2.1 \pm_{2.0}^{1.6}$

Table 5.12: Measured fit parameter values with their uncertainties for the $p_T^Z > 200$ GeV region with the three-parameter fit strategy. f_{TT} is determined by calculating $1 - f_{00} - f_{\text{Mixed}}$. The μ values are calculated from the nominal Post-fit values of the fit parameters.

	Exp.	Obs.
significance	5.7σ	4.8σ
f_{00}	$0.169 \pm_{0.032}^{0.034}$	$0.15 \pm_{0.04}^{0.04}$
f_{Mixed}	$0.22 \pm_{0.09}^{0.08}$	$0.24 \pm_{0.10}^{0.09}$
N_{tot}	$1650 \pm_{80}^{70}$	$1730 \pm_{80}^{80}$
$1 - \text{Sum}$	0.614	0.606
μ	$1.00 \pm_{0.20}^{0.21}$	$0.95 \pm_{0.23}^{0.25}$
$\mu_{WZ(\text{TT})}$	$1.00 \pm_{0.10}^{0.13}$	$1.03 \pm_{0.12}^{0.14}$
$\mu_{WZ(\text{Mixed})}$	$1.0 \pm_{0.4}^{0.4}$	$1.2 \pm_{0.5}^{0.4}$

Table 5.13: Measured fit parameter values with their uncertainties for the $p_T^Z > 100$ GeV region with the three-parameter fit strategy. f_{TT} is determined by calculating $1 - f_{00} - f_{\text{Mixed}}$. The μ values are calculated from the nominal Post-fit values of the fit parameters.

Figure 5.17 shows the observed Post-fit correlations between the nuisance parameters N_{tot} , f_{00} and f_{Mixed} . Large anti-correlations are observed between f_{00} and f_{Mixed} . The nuisance parameter pull of

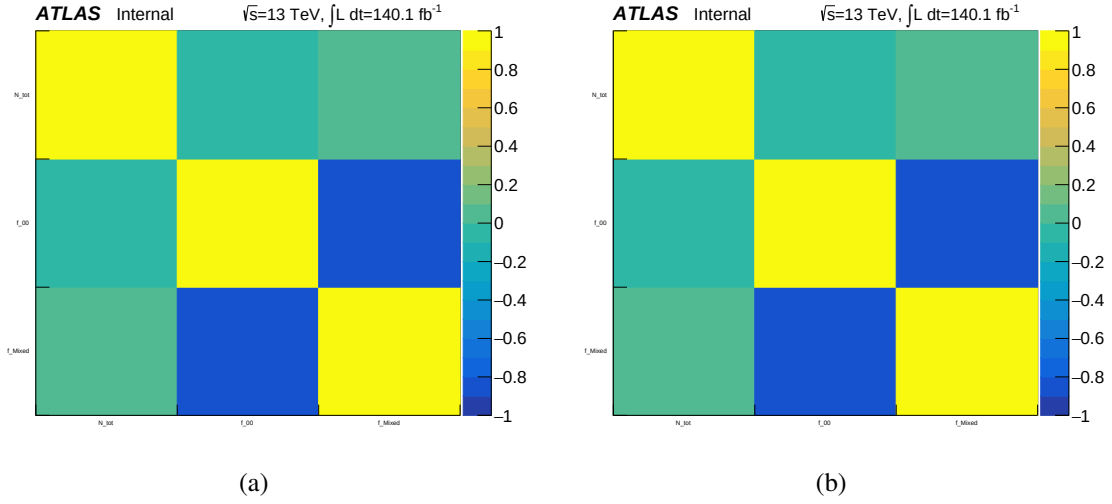


Figure 5.17: Observed post fit nuisance parameter correlations for the stat-only fit of the $S + B$ hypothesis in the 00-enriched $p_T^Z > 200$ GeV region (a) and 00-enriched $p_T^Z > 100$ GeV region (a) with the three-parameter fit strategy.

the expected fits is shown in figure 5.18. No significant pulls or constraints are visible in the fits. As an example of the fit, figure 5.19 shows the likelihood scans for the full-data fit of the $S + B$ hypothesis in the 00-enriched $p_T^Z > 200$ GeV and $p_T^Z > 100$ GeV regions.

5.2.7.2 Two Parameter Fit Strategy

Tables 5.14 and 5.15 summarizes the fit results in the two 00-enriched regions using the two-parameter fit strategy. It shows the expected and observed significances for the 00 measurements, the measured fractions, the fitted value for the free parameters, and the overall scaling of the samples. The observed (expected) significances are 3.4σ (4.6σ) and 7.9σ (8.8σ) for the 00-enriched regions with $p_T^Z > 200$ GeV and $p_T^Z > 100$ GeV cuts respectively.

Figure 5.20 shows the observed Post-fit correlations between the nuisance parameters N_{tot} and f_{00} . No anti-correlations were observed for this.

The nuisance parameter pull of the expected fits is shown in figure 5.21. No significant pulls or constraints are visible in the fits. As an example of the fit, figure 5.22 shows the likelihood scans for the full-data fit of the $S + B$ hypothesis in the 00-enriched $p_T^Z > 200$ GeV and $p_T^Z > 100$ GeV regions.

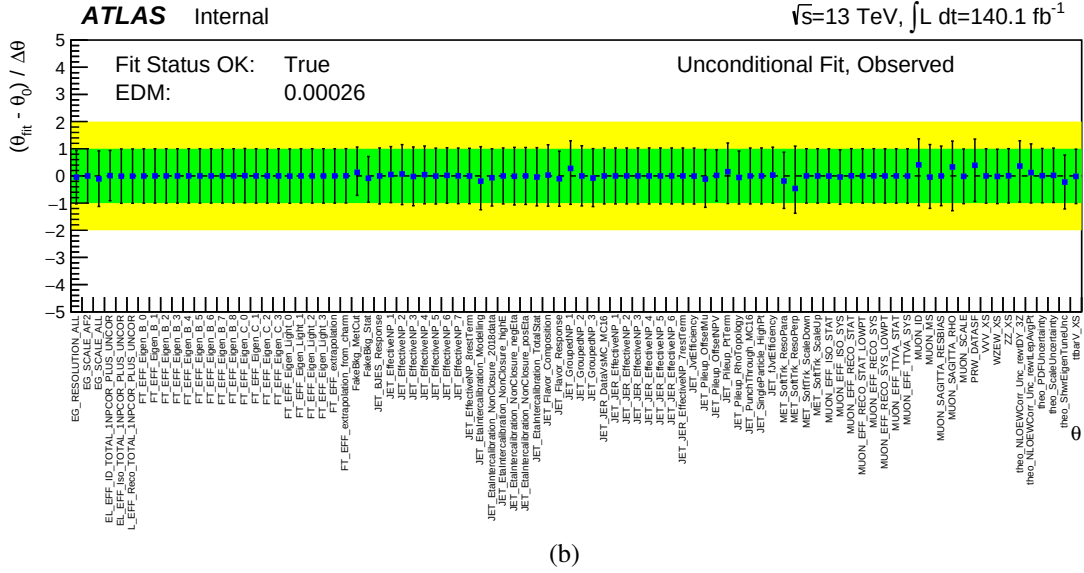
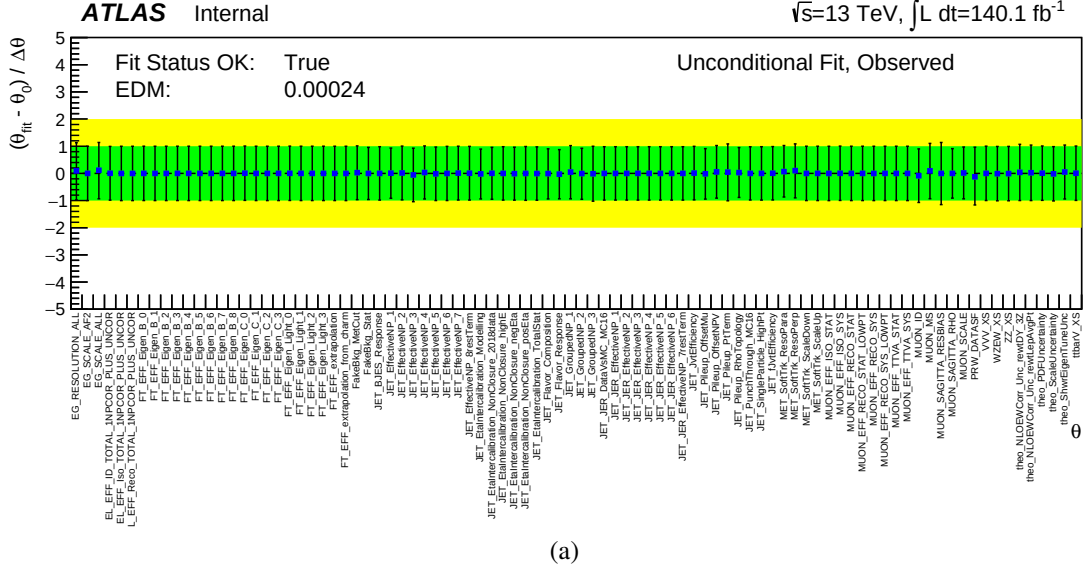


Figure 5.18: Observed post fit nuisance parameter pulls for the fit of the $S + B$ hypothesis in the 00-enriched $p_T^Z > 200$ GeV region (a) and 00-enriched $p_T^Z > 100$ GeV region (b) with the three-parameter fit strategy.

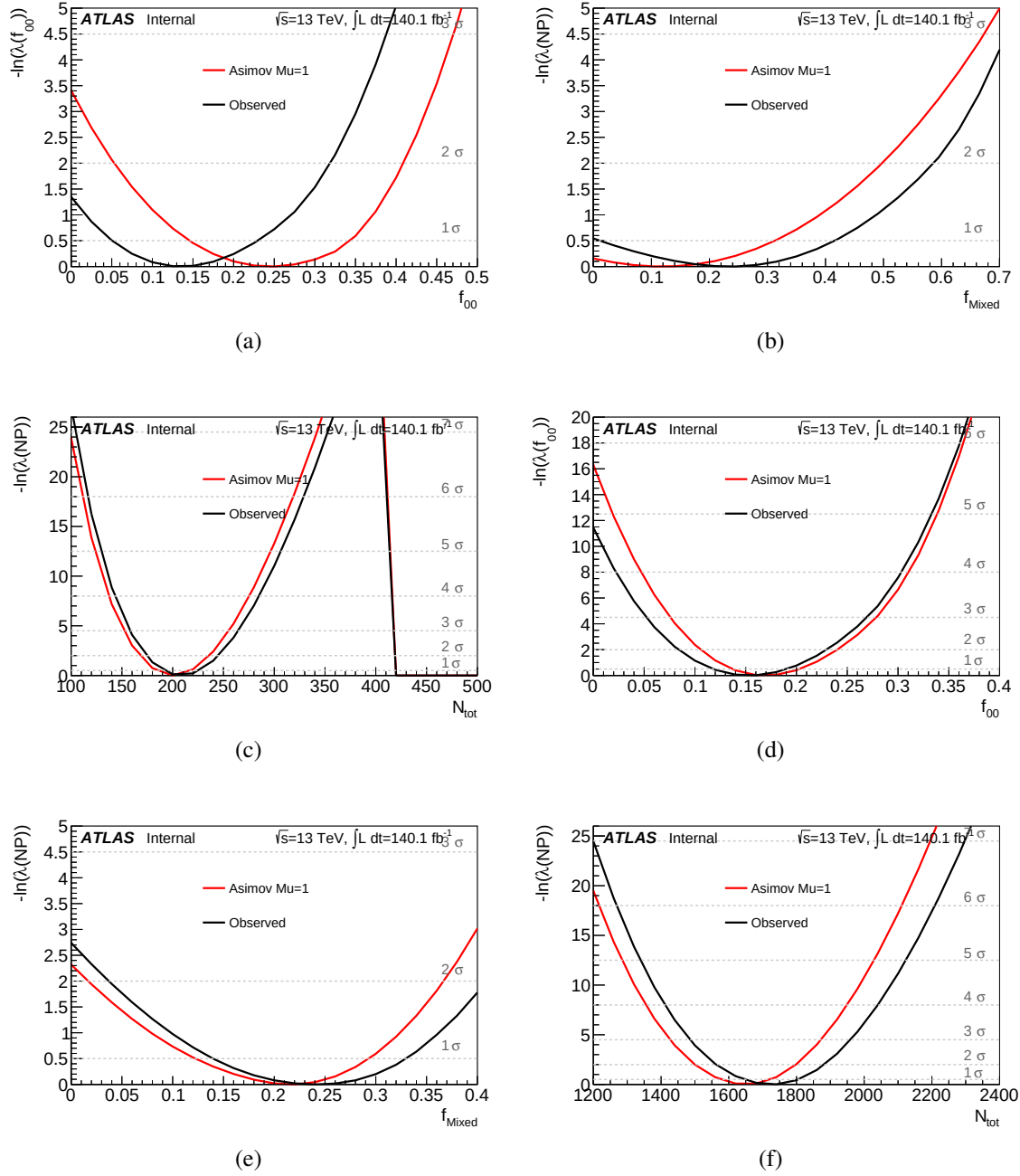


Figure 5.19: Likelihood scans for the full data fit of the $S + B$ hypothesis with the three-parameter strategy. The scans in the $p_T^Z > 200$ GeV region are shown for f_{00} (a), f_{Mixed} (b), N_{tot} (c) and in the $p_T^Z > 100$ GeV region are also shown for f_{00} (d), f_{Mixed} (e), and N_{tot} (f).

	Exp.	Obs.
significance	4.6σ	3.4σ
f_{00}	$0.25 \pm_{0.06}^{0.06}$	$0.17 \pm_{0.06}^{0.06}$
N_{tot}	$200 \pm_{17}^{18}$	$208 \pm_{18}^{18}$
$1 - \text{Sum}$	0.755	0.828
μ	$1.00 \pm_{0.25}^{0.27}$	$0.73 \pm_{0.25}^{0.27}$
$\mu_{WZ(\text{Rest})}$	$1.00 \pm_{0.11}^{0.12}$	$1.14 \pm_{0.13}^{0.13}$

Table 5.14: Measured fit parameter values with their uncertainties for $p_T^Z > 200$ GeV region with two-parameter fit strategy. f_{TT} is determined by calculating $1 - f_{00} - f_{\text{Mixed}}$. The μ values are calculated from the nominal Post-fit values of the fit parameters.

	Exp.	Obs.
significance	8.8σ	7.9σ
f_{00}	$0.17 \pm_{0.022}^{0.021}$	$0.16 \pm_{0.024}^{0.025}$
N_{tot}	$1650 \pm_{80}^{70}$	$1730 \pm_{80}^{80}$
$1 - \text{Sum}$	0.83	0.84
μ	$1.00 \pm_{0.14}^{0.13}$	$0.98 \pm_{0.16}^{0.17}$
$\mu_{WZ(\text{Rest})}$	$1.00 \pm_{0.05}^{0.05}$	$1.06 \pm_{0.05}^{0.05}$

Table 5.15: Measured fit parameter values with their uncertainties for $p_T^Z > 100$ GeV region with two-parameter fit strategy. f_{TT} is determined by calculating $1 - f_{00} - f_{\text{Mixed}}$. The μ values are calculated from the nominal Post-fit values of the fit parameters.

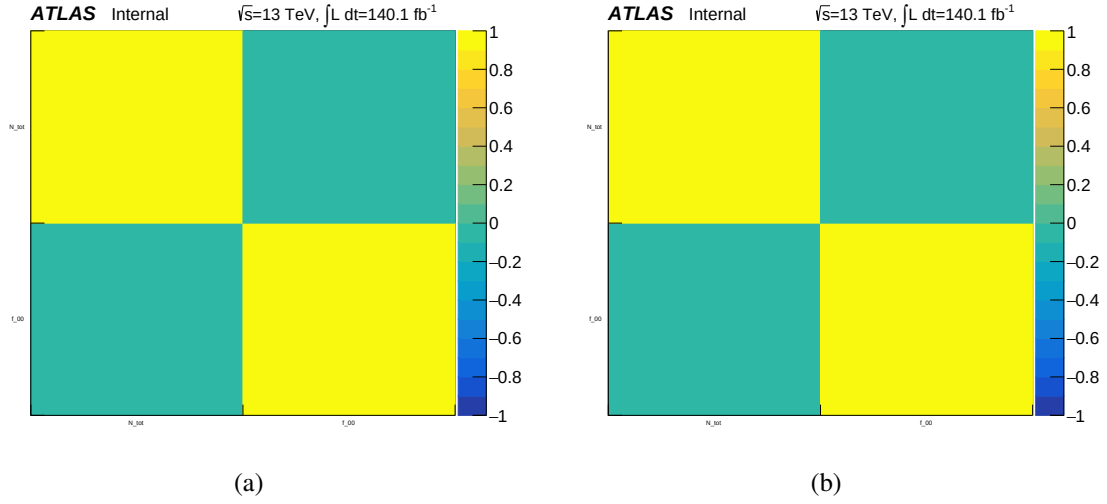


Figure 5.20: Observed post fit nuisance parameter correlations for the stat-only fit of the $S + B$ hypothesis in the 00-enriched $p_T^Z > 200$ GeV region (a) and 00-enriched $p_T^Z > 100$ GeV region (a) with the two-parameter fit strategy.

5.2.8 Post-fit Data-MC Comparisons

Figures 5.23, 5.24, 5.25, 5.26, and 5.27 are the post-fit distributions for different variables in the $p_T^Z > 100$ GeV region and with the two-parameter fit strategy. The procedure of making these comparisons sets the values and uncertainties of all the nuisance parameters to their post-fit values. It then builds the distributions by considering the templates and the post-fit correlations.

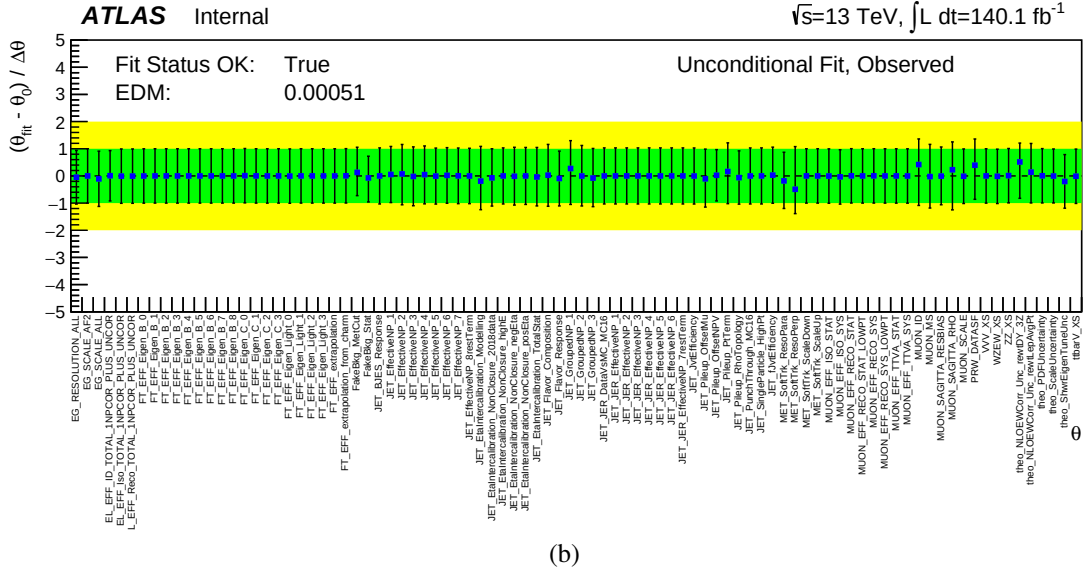
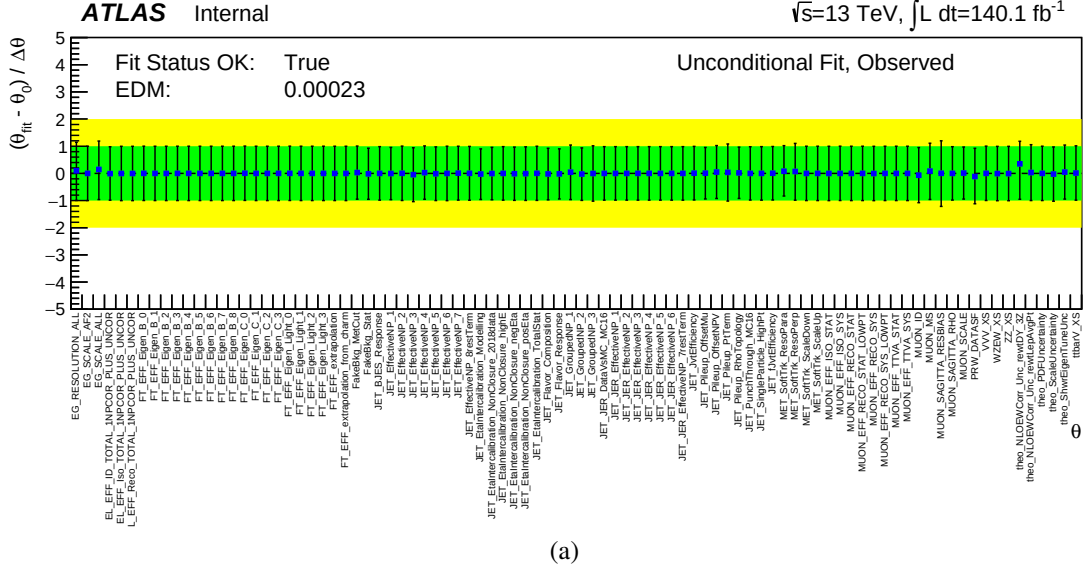


Figure 5.21: Observed post fit nuisance parameter pulls for the fit of the $S + B$ hypothesis in the 00-enriched $p_T^Z > 200$ GeV region (a) and 00-enriched $p_T^Z > 100$ GeV region (b) with the two-parameter fit strategy.

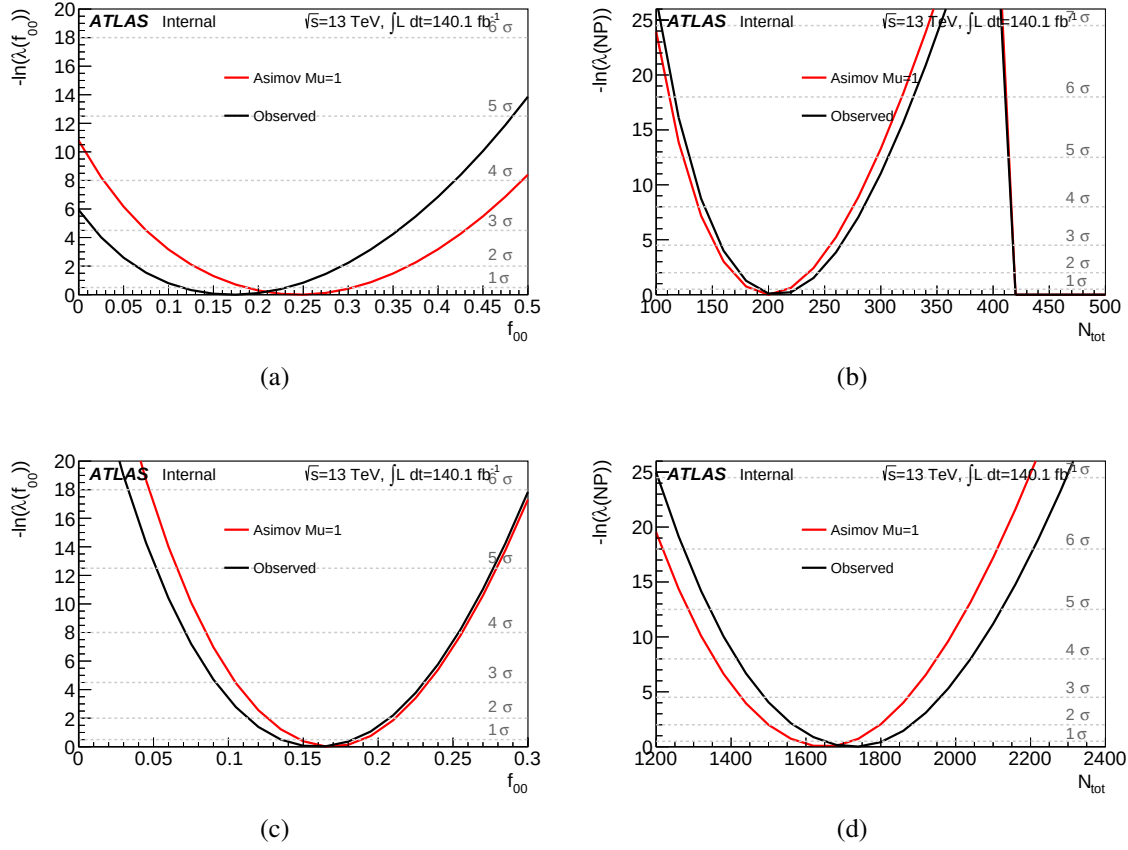


Figure 5.22: Likelihood scans for the full data fit of the $S + B$ hypothesis with the two-parameter strategy. The scans in the $p_T^Z > 200$ GeV region are shown for f_{00} (a), N_{tot} (b) and in the $p_T^Z > 100$ GeV region are also shown for f_{00} (c), and N_{tot} (d).

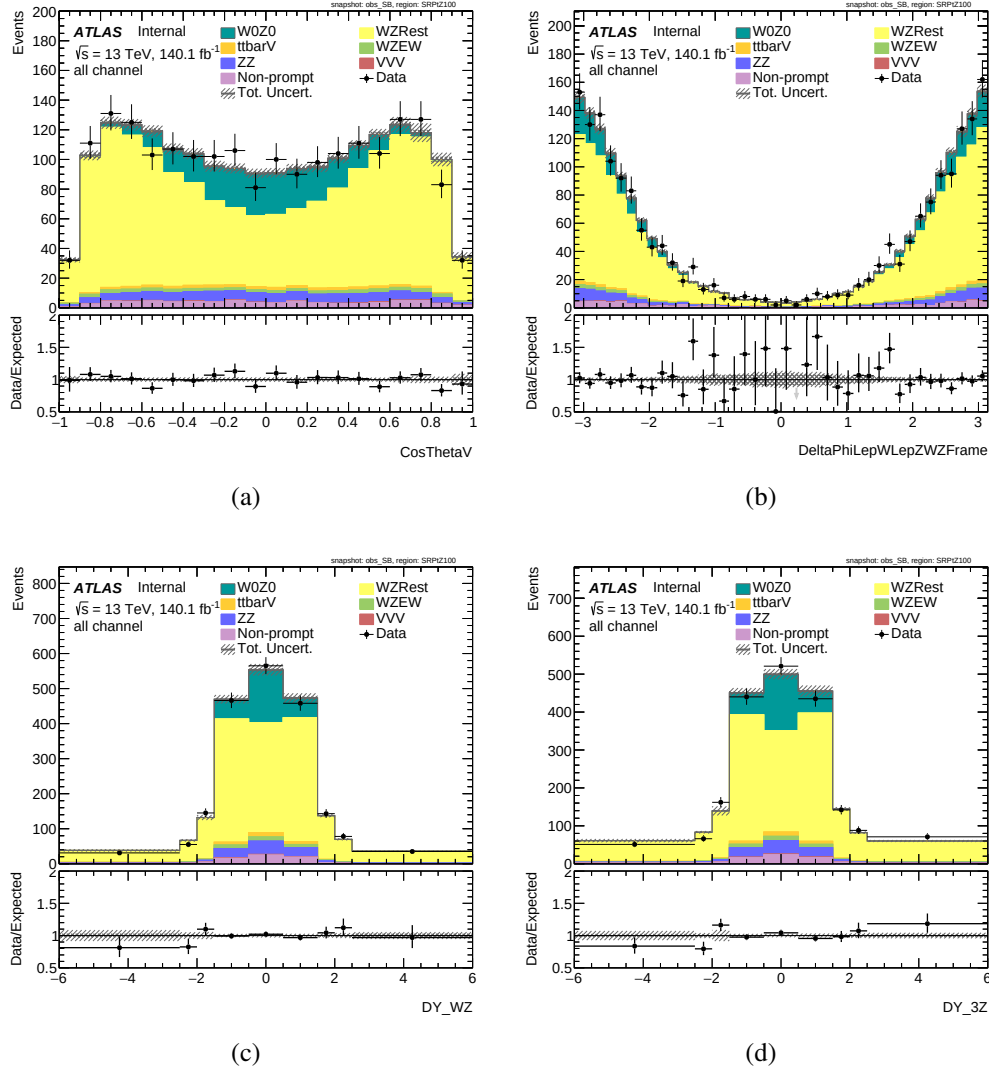


Figure 5.23: Post-fit Data-MC Comparison in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 100$ GeV) using two parameter fit strategy for $\cos\theta_V$ (a), $\Delta\phi(\ell_W, \ell_Z)$ in the WZ rest frame (b), rapidity difference between the W and Z bosons (ΔY_{WZ}) (c), and rapidity difference between the W lepton and the Z boson (ΔY_{3Z}) (d).

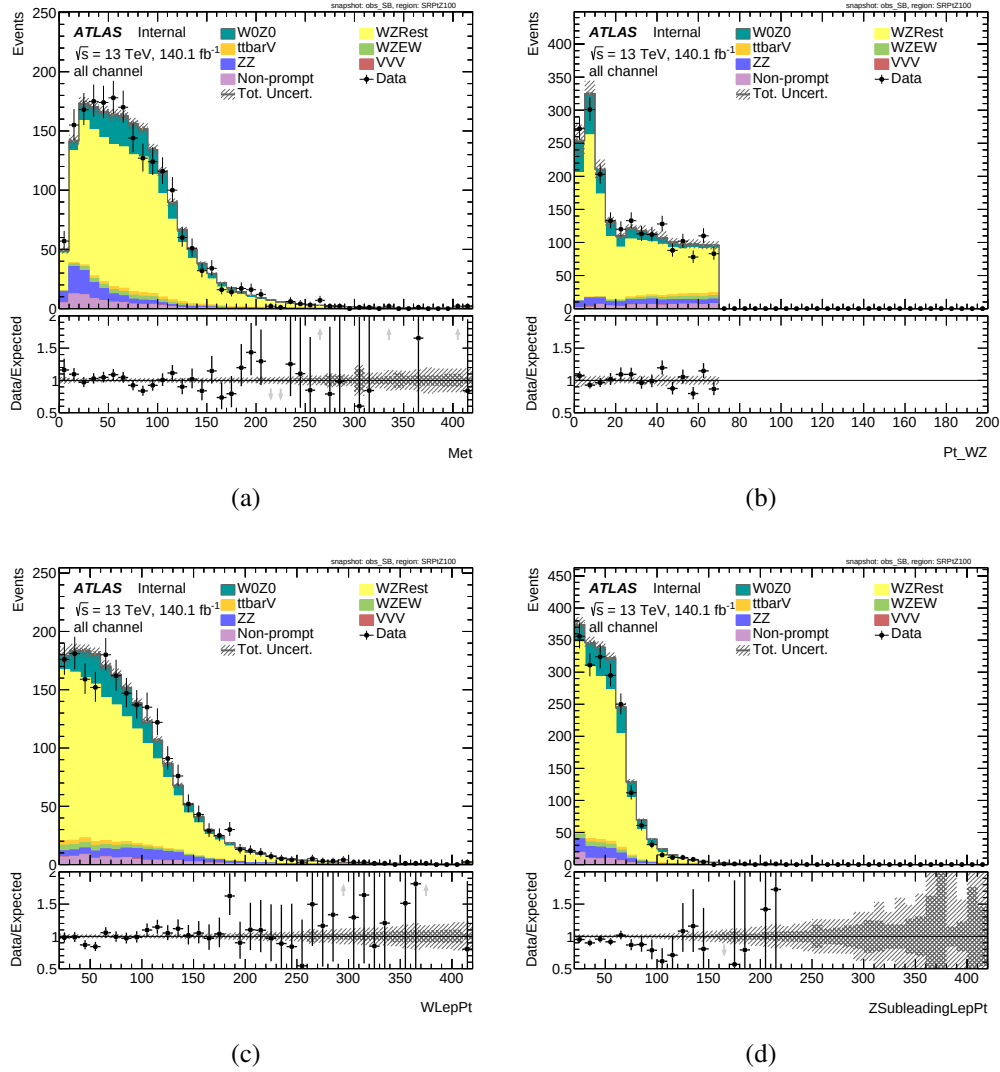
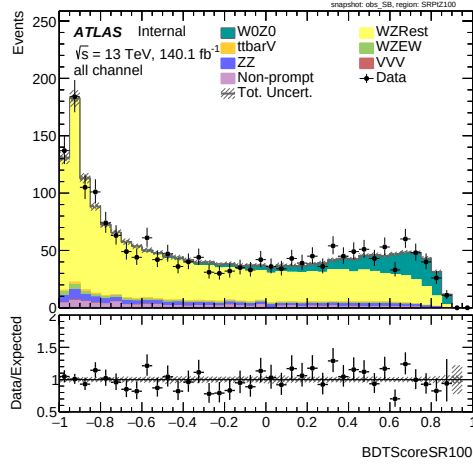
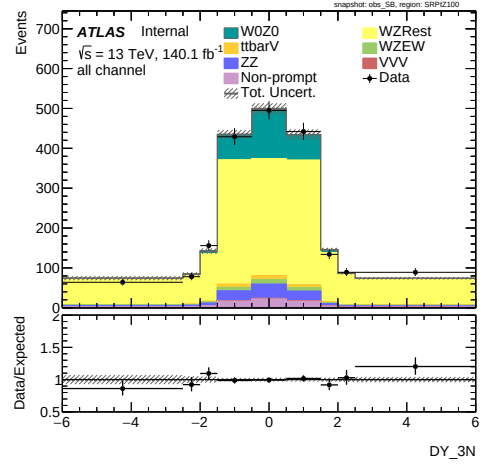


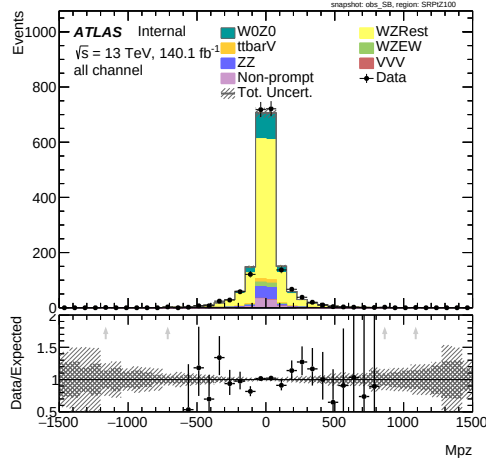
Figure 5.24: Post-fit Data-MC Comparison in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 100$ GeV) using two parameter fit strategy for MET (a), p_T^{WZ} (b), p_T of the W lepton (c), and p_T of the subleading Z lepton (d). All variables are calculated at the reconstruction level.



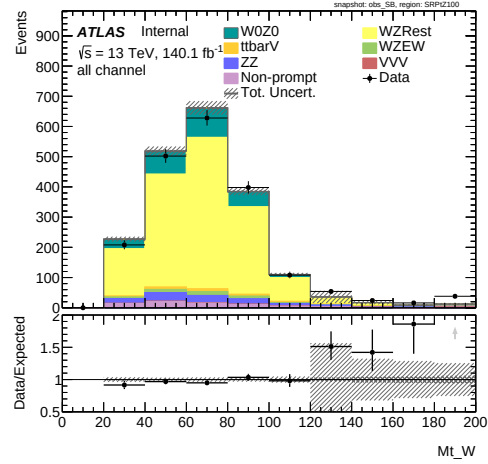
(a)



(b)



(c)



(d)

Figure 5.25: Post-fit Data-MC Comparison in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 100$ GeV) using the two-parameter fit strategy for the BDT score (a), rapidity difference between the lepton from the W boson and the negatively charged lepton from the Z boson (b), reconstructed neutrino p_z (c), and m_T^W (d). All variables are calculated at the reconstruction level.

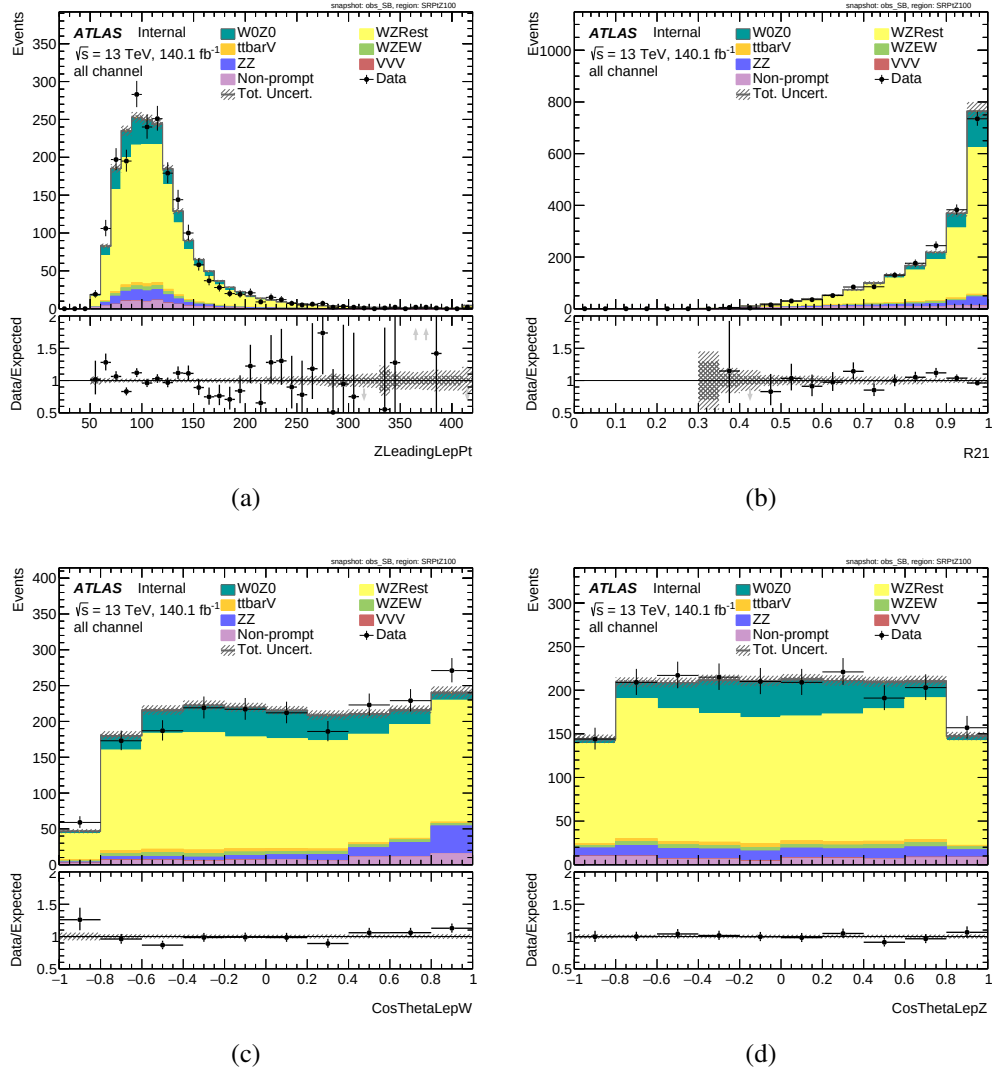


Figure 5.26: Post-fit Data-MC Comparison in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 100$ GeV) using the two-parameter fit strategy for p_T of the leading Z lepton (a), $r_{21} = \frac{p_{T,V_2}}{p_{T,V_1}}$ which is the ratio of the p_T of the subleading vector boson to the p_T of the leading vector boson (b), $\cos\theta_{\ell}^*(W)$ (c), and $\cos\theta_{\ell}^*(Z)$ (d). All variables are calculated at the reconstruction level.

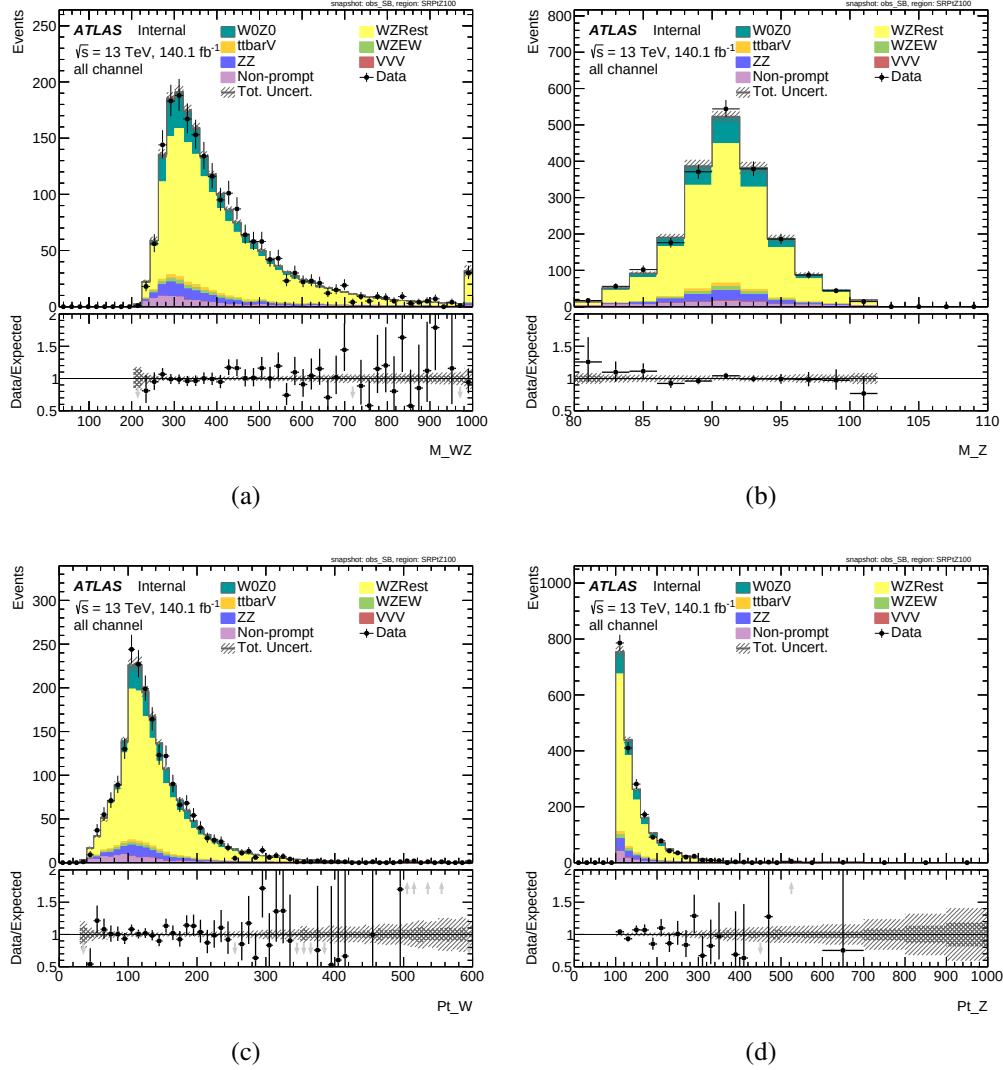


Figure 5.27: Post-fit Data-MC Comparison in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 100$ GeV) using the two-parameter fit strategy for M_{WZ} (a), M_Z (b), p_T^W (c) and p_T^Z (d).

CHAPTER 6

Summary of the WZ Polarization Measurements

The thesis describes two novel measurements conducted by the ATLAS collaboration: the first observation of the RAZ effect in WZ events and the first measurement of longitudinal-longitudinal diboson fractions using WZ events in the phase space where the 00 contribution is enhanced.

The RAZ effect is observed by studying transversal-transversal WZ events with reduced jet activity. This is achieved by selecting events with a lower p_T^{WZ} ($p_T^{WZ} < 10, 20, 40, 70$ GeV). The analysis identifies a dip in the distributions of the rapidity difference variables (ΔY_{3Z} and ΔY_{WZ}) by introducing a depth variable ($\mathcal{D}$). A positive value of $\mathcal{D}$, obtained from background-subtracted data, indicates the presence of a dip. The background includes prompt and non-prompt backgrounds and also 00, 0T, and T0 contributions. The measured $\mathcal{D}$ values for four different p_T^{WZ} regions using ΔY_{3Z} and ΔY_{WZ} are provided (using ΔY_{3Z} : $0.39 \pm 0.07, 0.37 \pm 0.06, 0.34 \pm 0.06, 0.32 \pm 0.05$ respectively; using ΔY_{WZ} : $0.26 \pm 0.06, 0.26 \pm 0.06, 0.26 \pm 0.05, 0.25 \pm 0.05$ respectively). The measured $\mathcal{D}$ values are compared to the reconstructed values using MC samples consisting TT-only events, demonstrating good agreement.

Additionally, the thesis discusses the measurement of longitudinal-longitudinal diboson fractions in two high- p_T regions: $p_T^Z > 100$ GeV and $p_T^Z > 200$ GeV (with $p_T^{WZ} < 70$ GeV selection applied to both regions). Two fitting strategies, namely three-parameter and two-parameter fit strategies, are employed. The two-parameter fit strategy yields the most significant results, indicating a longitudinal-longitudinal fraction (f_{00}) of $0.25^{+0.06}_{-0.06}$ in the $p_T^Z > 200$ GeV region, with an observed (expected) significance of 3.4σ (4.6σ), and f_{00} of $0.17^{+0.021}_{-0.022}$ in the $p_T^Z > 100$ GeV region, with an observed (expected) significance of 7.9σ (8.8σ). The analysis emphasizes the increasing relevance of new physics contributions in W_0Z_0 at high $p_T(V)$, suggesting that this investigation serves as a foundational step toward conducting further measurements related to diboson polarization states within the SM and beyond.

It is worth noting that this analysis is still ongoing within the ATLAS collaboration and is under the internal review process.

CHAPTER 7

ATLAS New Small Wheel Upgrade

The High-Luminosity Large Hadron Collider (HL-LHC) will run with an instantaneous luminosity of up to $5 - 7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$. The current ATLAS Muon Spectrometer detector, trigger, and readout systems could not handle the expected high trigger and event rates, and an upgrade is required. The Small Wheel, the innermost station of the muon End-Cap system, needs to be replaced by the New Small Wheel (NSW). The system is expected to have improved trigger selectivity and excellent tracking capabilities. It is required to have 1 mrad online angular resolution, $150 \mu\text{m}$ spatial resolution, and a trigger latency within $1.2 \mu\text{s}$.

7.1 Motivations

At high luminosity, the background rate is going to increase significantly, especially in the End-Cap region [186]. This causes substantial degradation of tracking performance, both in terms of efficiency and resolution in the inner end-cap station. The background rate can go up to 15 kHz/cm^2 . The NSW upgrade is required to discriminate against the high background rate without having to increase the muon p_T threshold. The low p_T threshold is essential for the physics program planned for the HL-LHC, e.g. for studies of Higgs boson properties and new physics searches.

There are two main important problems to address at high luminosity:

1. High luminosity (and hence high background rates), especially in the End-Cap region, will cause the degradation of the muon tracking performance.
2. The previous (before the Long Shutdown 2) Level-1 ATLAS trigger in the End-Cap region depends on the Big Wheel TGC chambers. Low energy particles, mostly protons, are generated in the material between the Small-Wheel and the middle End-Cap muon station. This causes the Level-1 trigger to have approximately 90% fakes (according to studies performed using data taken in 2012). High luminosity is going to make this problem worse due to the high backgrounds expected. Figure 7.1 shows the trigger rate versus η . It can

be seen that the L1 rate is very high compared to the matched muons with $p_T > 10$ GeV, indicating the presence of fakes.

Figure 7.2 shows the $y-z$ plane of the ATLAS End-Cap region before and after the NSW upgrade. Three layers of TGC chambers provide around 3 mrad of angular resolution. During the Phase-II Upgrade, there is a plan to use the ATLAS MDT detector as a trigger device at Level-1 and it will improve the angular measurement with a resolution of 1 mrad. Therefore, the New Small Wheel should also have a similar angular resolution. The expected single-lepton level-1 muon rate in the high-luminosity high-background environment is around 60 kHz (three times higher than what is allowed, which is 20 kHz). To reduce the muon rate to 20 kHz, the trigger track segment reconstruction has to be improved in NSW.

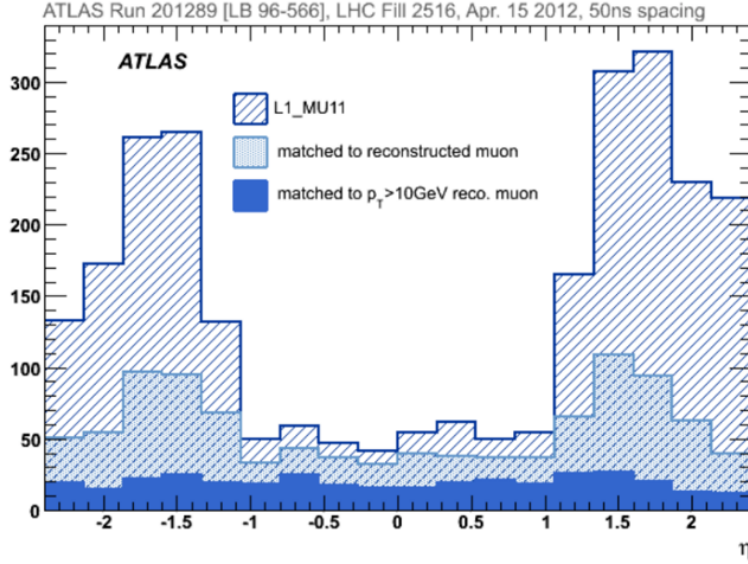


Figure 7.1: Distribution of trigger rate vs pseudo-rapidity.

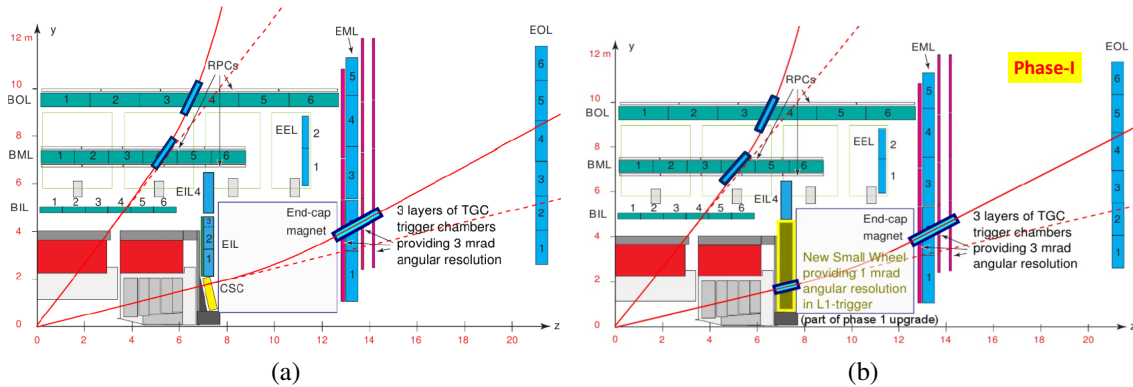


Figure 7.2: The $y-z$ view of the ATLAS End-Cap region before (a) and after (b) the NSW upgrade.

The NSW detector as shown in figure 7.3 will be the innermost station of the ATLAS muon spectrometer in the End-Cap region. It consists of two state-of-the-art detectors: (a) Micromesh Gaseous Structures (MM) or Micromegas, and (b) small-strip Thin Gap Chambers (sTGC). Each wheel is made up of eight large and eight small sectors. Each sector has four wedges (in total 64 wedges for each technology): two MM wedges sandwiched between two sTGC wedges. Each sTGC wedge is made up of three quadruplets, and each quadruplet has four layers of sTGC.

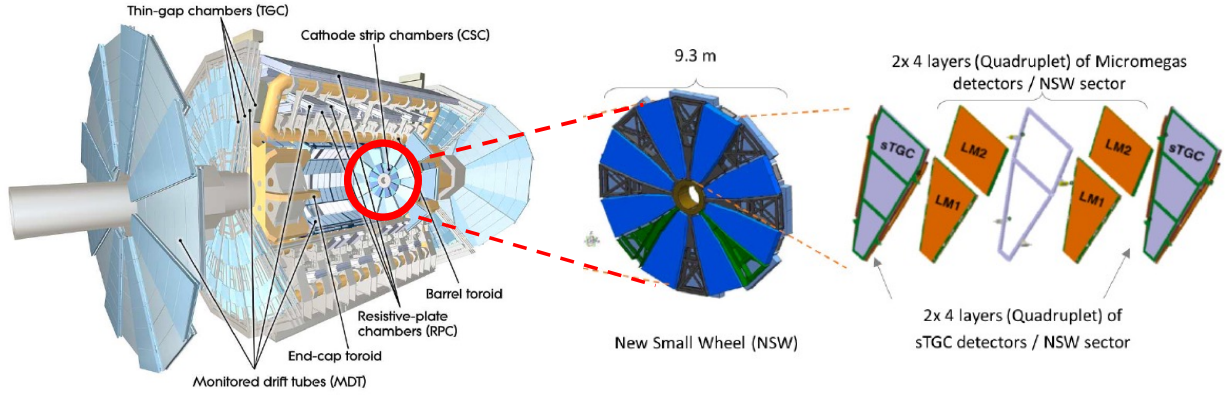


Figure 7.3: The location and layout of the ATLAS NSW detector.

7.2 Detector Technologies

7.2.1 Micromesh Gaseous Structures (Micromegas or MM)

These are used for precision tracking and triggering purposes [186]. MM detectors are made up of a planar (drift) electrode with a few millimeters thick gas gap. This gas gap also contains a thin metallic mesh (micromesh) which is at a distance of around 100-150 μm from the readout electrodes. This region is the amplification region. The structure of the Micromegas detector can be seen in figure 7.4a. The electric field in the amplification region is around 50-100 times stronger (40-50 kV/cm) than the one in the drift region (a few hundred V/cm).

A layer of resistive strips is added on top of the thin insulator directly above the readout electrode. Because of this, the readout electrode is not directly in contact with the charge in the amplification region generating sparks in the detector and instead is capacitively coupled. A positive high voltage is applied to the resistive strip layer and the micromesh is kept at the ground potential. This further stabilizes the system against sparks. Charged particles going through the gaseous medium (which is made up of Ar-93% and CO₂-7%) ionize it and electrons freed from this process are drifted towards the mesh. The signal is amplified in the amplification region where above 95% of the electrons enter through the mesh. The electrons drift with a factor of hundreds faster in the amplification

region than in the conversion region. Positive ions produced in the amplification region drifted back to the mesh much slower than electrons, but still faster compared to other technologies. This makes MM a good detector for high particle fluxes.

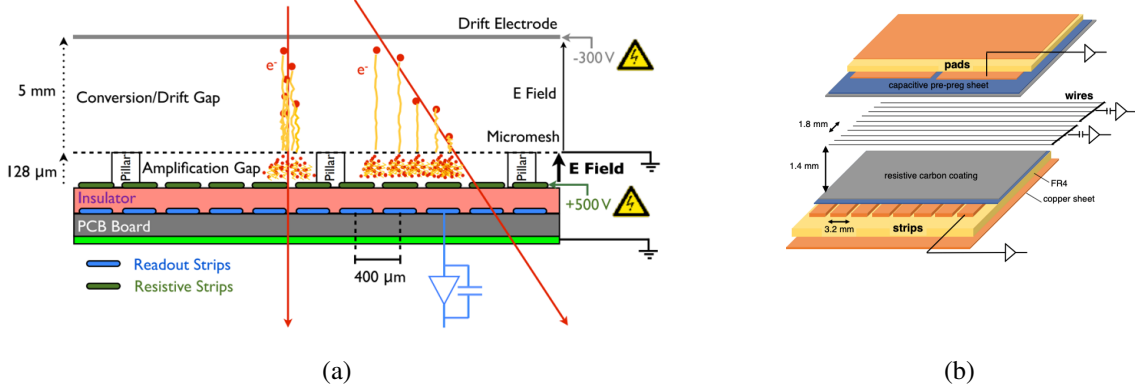


Figure 7.4: A cross-section of the MM detector (a). A diagram of the sTGC detector (b).

7.2.2 small-strip Thin Gap Chambers

sTGC are also used for both precision tracking and triggering. It is a multiwire proportional chamber with 50 μm thick tungsten wires placed 1.8 mm apart. They can be used to obtain the azimuthal coordinates of the hits. There are two cathode planes placed at a distance of 1.4 mm from the wire plane. The resistive coating on the cathode planes has a resistivity of 100 kΩ/□. On one side of the wires, there are strips, and on the other side pads. The pads have a surface area between 20 to 650 cm². These are convenient for determining the region of interest for trigger purposes which are then applied to strips to collect charge information for those strips in that region. The strips are for precise position measurement with a pitch of 3.2 mm. The detailed structure of sTGC can be seen in figure 7.4b. From the innermost quadruplet to the outermost one, they are called QS1 (QL1), QS2 (QL2), and QS3 (QL3) for small (large) wedges. The layouts of the large and small sectors are shown in figure 7.5. The parameters of the sTGC detector are summarized in table 7.1.

sTGC Detector Parameters	
cathode-anode gap	1.4mm
wire pitch	1.8mm
cathode resistivity	100 – 200 kΩ/□
readout strip pitch	3.2 mm
operating gas	N-pentane+55% CO ₂ Mix

Table 7.1: sTGC detector parameters.

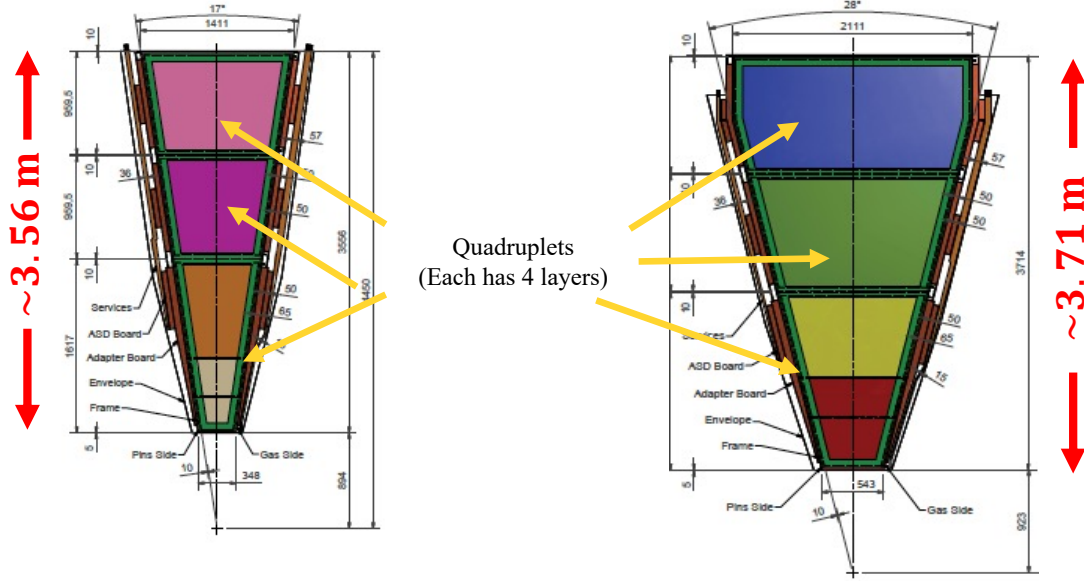


Figure 7.5: sTGC Small (left) and Large Sectors (right) (the images might not be in the real proportion).

7.3 Trigger and Data Acquisition System

The MM detector has in total around 2.4 million detector channels while the sTGC detector has about 360K detector channels. The trigger and data acquisition system for the NSW detector is shown in figure 7.6. The description in this section is mainly of the sTGC detector.

7.3.1 Front-End ASICs

The VMM (Venetios MicroMegas) is a custom-made Application Specific Integrated Circuit (ASIC) [187] specially designed for MicroMegas and sTGC detectors. It was developed at Brookhaven National Laboratory. It is fabricated in the 130 nm Global Foundries 8RF-DM process (former IBM 8RF-DM) [188]. The VMM architecture is shown in figure 7.7.

It operates for both charge polarities. There are total 64 channels per VMM whose input is connected to the output of the analog signal from one detector channel. The analog charge is amplified using a charge amplifier operated at low noise. Different polarities are set for different types of sTGC channels: positive for pads and strips and negative for wires. A shaper is then used to stabilize the baseline. It also has adjustable peaking times in four values (25, 50, 100, and 200 ns). After the shaper, the signal goes through a discriminator (controlled by a 10-bit Digital-to-Analog Converter (DAC) common to all channels) with a trimmer, the peak detector, and the time detector.

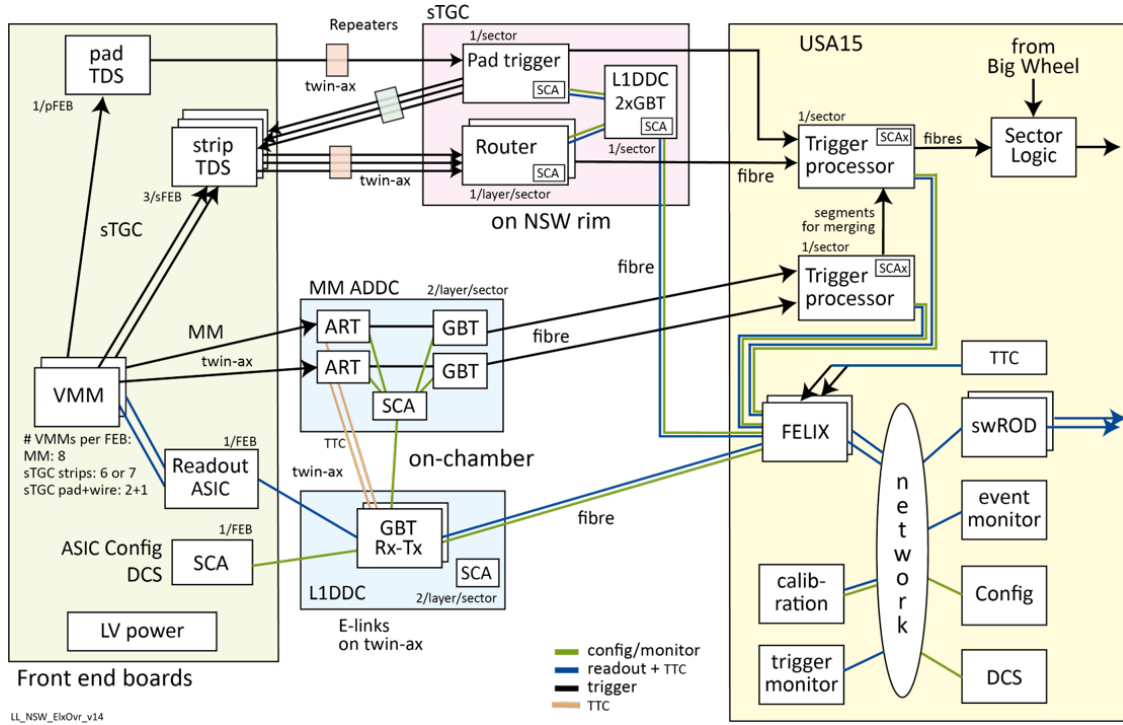


Figure 7.6: Diagram of the distribution of slow-control, global clock, TTC, and the trigger and data readout path for the NSW system.

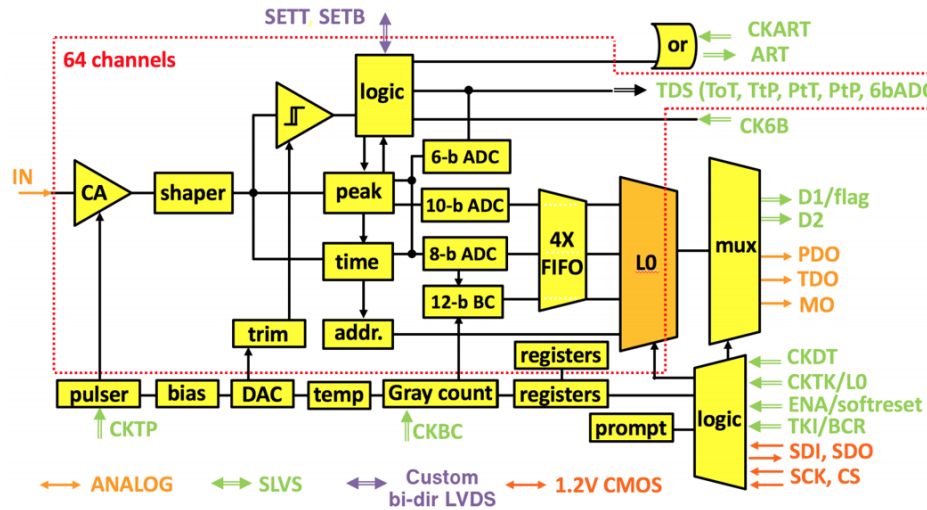


Figure 7.7: Block diagram of the VMM, the main front-end ASIC for both sTGC and MM detectors.

The time and peak detector signals are then passed through three kinds of ADCs: 6-bit, 8-bit, and 10-bit ADC. These Analog-to-Digital Converter (ADC)s are used to digitize the signal. The 8-bit ADC timing information and 10-bit ADC charge measurement are buffered as L0 data.

The VMM provides an output in different forms to the trigger chain: Time-over-Threshold (ToT), Threshold-to-Peak (TtP), Peak-to-Threshold (PtT), and 10 ns pulse occurring at peak (PtP). The common electronics circuits to all 64 channels include a pulse, which can be used to generate a test pulse with configured amplitude, a test-pulse DAC (along with the threshold DAC), a mixed-signal multiplexer, the control logic, and the Address in Real Time (ART) which consists of dedicated digital outputs (flag and address) for the first above threshold event. Depending on the configuration, the 10-bit ADC has a conversion time of 200 – 380 ns. In comparison, the 6-bit ADC has a conversion time of 25 – 68.75 ns. The VMM features two parallel outputs of readout and trigger data. The direct output trigger data is constantly output every 25 ns clock cycle. At the same time, digital logic exists for data buffering, trigger matching, and event building for the readout data. The VMM’s analog circuit can operate in a large dynamic range. The same ASD is used for both MM and sTGC.

The detector capacitance range from 100 pF for a MM strip and up to 3 nF for an sTGC pad. At the same time, the input charge from a muon in the MM is around 70 fC per channel while a low-energy neutron can deposit as much as 50 pC of charge in a sTGC pad. Therefore, the VMM must be able to have a linear response up to 2 pC and at the same time have the ability to recover quickly (500 – 1000 ns) from large charge deposits of up to 50 pC.

A Readout Controller (ROC) ASIC is used for handling, pre-processing, and formatting the data generated by the VMM upstream chips [189]. One ROC can aggregate Level-0 data from up to 8 VMMs. Each VMM data connection consists of two serial links each at 320 Mbps. Figures 7.8 and 7.9 show the data formats for the input and output of the ROC ASIC respectively.

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31		
header	V	P	orbit(2)		BCID(12)																													
hit data	1	P	R	T	CHAN (6)						ADC (10)										TDC (8)								N	rel BCID(3)				

Figure 7.8: The input format of the Readout Controller

	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39
null evnt hdr	SOP (8)								0	1	ROC ID (6)						Level-1 ID (8)								EOP (8)															
hit header	SOP (8)								0	0	orbit (2)		BCID (12)						Level1 ID (16)																					
hit header no TDC	SOP (8)								1	0	orbit (2)		BCID (12)						Level1 ID (16)																					
hit data	P	N	rel BCID (3)			VMMid (3)			Chan (6)						ADC (10)						TDC (8)																			
hit data no TDC	P	N	rel BCID (3)			VMMid (3)			Chan (6)						ADC (10)																									
dummy hit data	P	0	3'b0			VMMid (3)			6'b0						11_1111_1111						8'b0																			
dummy hit data no TDC	P	0	3'b0			VMMid (3)			6'b0						11_1111_1111																									
trailer opt A	E	TO	VMM missing data flags (8)								LO ID (4)				length (no hits) (10)						checksum (8)								EOP (8)											

Figure 7.9: The output format of the Readout Controller

The maximum data speed that the ROC can achieve is 640 Mbps by using one 320 Mbps link for odd bits and another for even bits. The configurable values are 80, 160, 320, and 640 Mbps. The data is stored in a FIFO (First In First Out) to be read by 4 sROCs in a configurable manner. Each

sROC can handle up to 4 VMMs. The xBar module interconnects 8 VMM Capture modules to 4 sub-ROCs (sROCs). The sROCs form Level-1 packets according to the information sent by Time Trigger and Control signal received. The ROC also forwards the Bunch-Crossing clock and Bunch Crossing Reset to the Trigger Data Serializer ASIC and VMM.

The Trigger Data Serializer (TDS) [190] is used to serialize the trigger data from both pads and strips. It performs pad-strip matching using the region of interest determined using different staggered pad layers. The same TDS chip has two operating modes: pad and strip. Each TDS handles 128 channels in the strip mode and 104 channels in the pad mode. The pads from different layers are staggered in different layers. The overlapping region from these layers is called a logical pad. The information from the pad TDS is processed by the Pad Trigger Board. If there is a 3 out of 4 coincidence in a logical pad, the strip band ID (Eta), Phi ID, and Bunch Crossing ID (BCID) are transferred to the Strip TDS. The router then collects the 6-bit ADC charge data of those overlapping strips from the strip TDS and sends it to the trigger processor. The data flow for the sTGC trigger chain is shown in figure 7.10. The digitized outputs of the amplifier-shaper-discriminator ASIC (VMM) are sent to the TDS and it serializes the output at 4.8 Gbps. This ASIC has power consumption lower than 1 W and achieves an overall latency of around 100 ns for each mode.

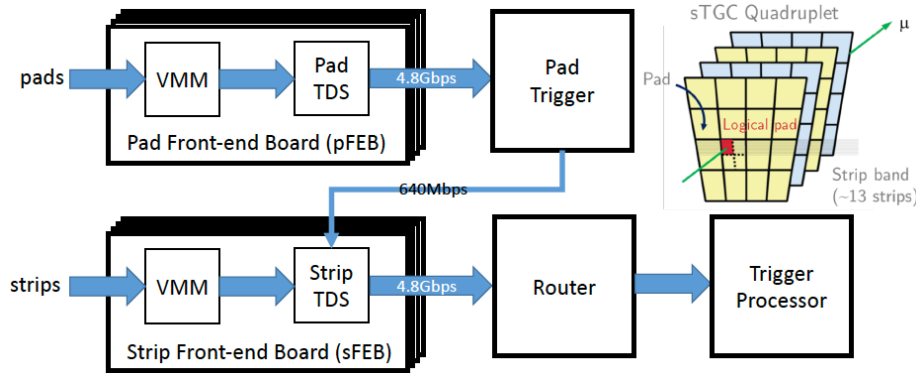


Figure 7.10: The sTGC trigger chain data flow.

The GBT-SCA ASIC (Giga-Bit Transceiver - Slow Control Adapter) is an integrated circuit built in a commercial 130 nm CMOS technology and is part of the GBT chipset whose purpose is to distribute control and monitoring signals to the front-end electronics [191].

The FEAST [192] is the DC-DC converter to provide power to the ASICs on the front-end boards. It takes 10V as input and regulates the low voltage with a maximum of 4 A. Figure 7.11 shows the FEAST layout and the cooling scheme.

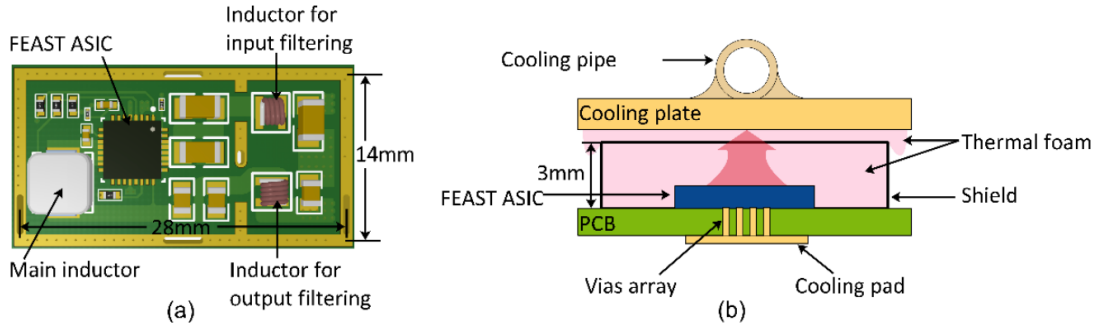


Figure 7.11: Layout of the FEAST module (a) and the cooling scheme (b) [193].

7.3.2 Front-End Boards

The front-end boards are custom-made for different types of electrodes. pad Front End Board (pFEB)s are the front-end boards designed for the digitization and readout of pads and wires and strip Front End Board (sFEB)s are for strips. There are two types of sFEBs: one with 8 VMMs (sFEB8) and one with 6 VMMs (sFEB6). For the quadruplets 2 and 3, the first two VMMs are not used so in a slightly later stage of the integration, the sFEB6s are used on quadruplets 2 and 3. An sFEB and a pFEB are shown in figure 7.12a. These FEBs are connected to the detector channels (strips, pads, or wires) via an adapter board which is a 4-6 layered Printed Circuit Board (PCB). It is soldered on the side of the gas gap using jumper wires. Connections from the front-end board to the adapter board are shown in figure 7.12b.

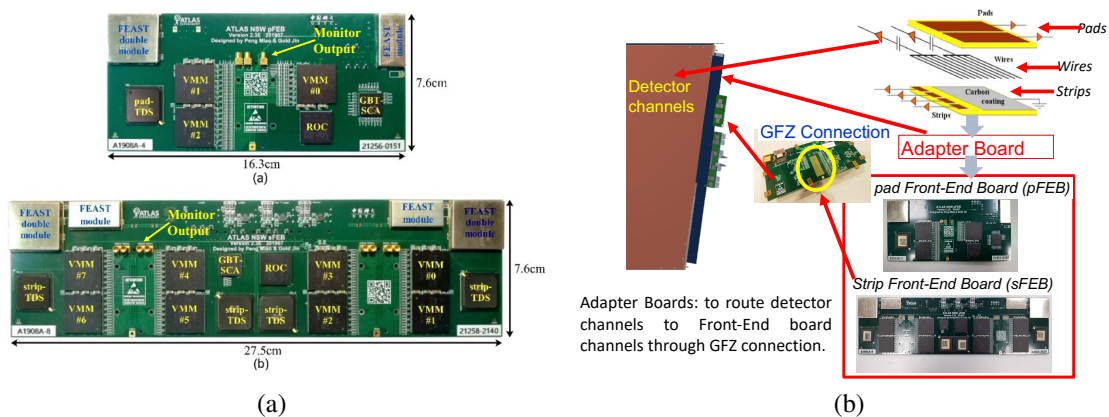


Figure 7.12: pFEB and sFEB boards (a) and connections of these FEBs to detector channels via the adapter board using the GFZ connector (b).

The amplifiers on the VMM channels on the front-end boards have to be protected from electrostatic

discharges because of the high-rate environment. Figure 7.13 shows the customized analog circuitry. The ESD protection circuit is experimentally tested against tens of thousands of emulated discharges with both sTGC and Micromegas detectors. The sTGC strip front-end boards have a “pull up” scheme for providing a mild compensation current to correct the bias current and working node inside the VMM. A pull-up resistor of 400 k Ω / is decided for this purpose. The “ π -network” scheme is implemented for the wires and pads front-end boards. A small capacitance (a few hundred pF) of C_π is connected in series with the bigger capacitance of the pad channel in the detector (up to 3 nF).

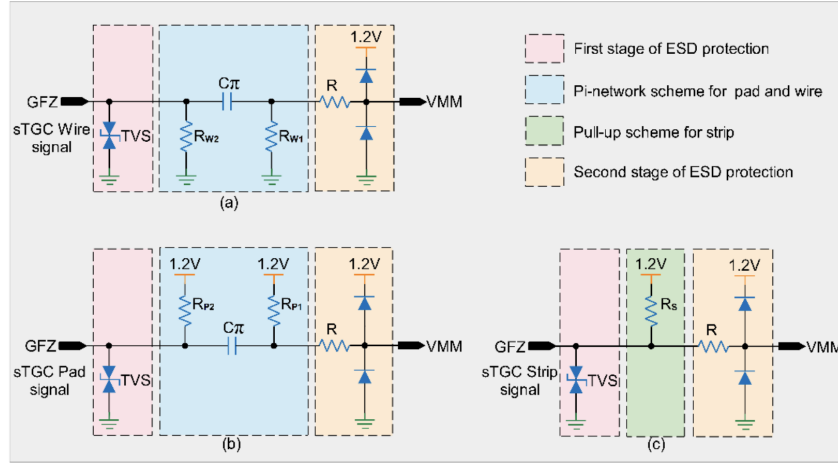


Figure 7.13: The sTGC FEB analog input circuit which incorporates the ESD protection and the special compensative scheme for the VMM to handle high-rate and high-charge signals [193].

7.3.3 Trigger Chain Data Flow

The goal of the trigger chain is to determine the coarse region of interest using pads and collect and send the corresponding strip 6-bit ADC charge information to the Router board and then to the Trigger Processor for further processing (see figure 7.10).

For each sector of sTGC, there are total of 8 layers of detector information collected (4 layers of each wedge as one sector consists of 2 sTGC wedges). The 3-out-of-4 coincidences of the pads from 4 layers each are determined using the logical pad information. A logical pad is defined as the overlapping region of four layers of pads when a muon passes through in a certain direction, where all layers have different pad positions and sizes. It is also called a “pad tower” (see figure 7.10). The VMM provides direct outputs to the TDS ASIC (TDS can be configured in the pad or strip mode). The output for example ToT (Time-Over-Threshold) is a 1-bit flag (whether a hit is detected or not). Each TDS can send the 12-bit BCID information and the output status bits from up to 104 channels to the Pad Trigger board [186, 194] using a 4.8 Gbps data link. The Pad Trigger board

is mounted on the rim of the NSW detector. It is a commercial FPGA-based board that collects high-speed serial data from 24-pad TDS chips. An algorithm is used to determine the region of interest (ROI) for that event. The ROI information i.e. Band ID and Phi ID which is associated with strips corresponding to the ROI is sent as a Pre-L1 trigger to the Strip TDS using a 640 Mbps data link. One Strip TDS receives the 6-bit ADC information from two VMMs (up to 128 channels) and it is stored in a buffer of the TDS chip. When the Pre-L1 trigger is received by the strip TDS, a trigger matching algorithm is performed based on the BCID information and the matched data is sent to the Router using a 4.8 Gbps link. The Router board [186, 194] also mounted on the NSW rim, collects this output and passes the information to the Trigger Processor Board. The latency requirement by the trigger path is $1\ \mu\text{s}$ to be included in the L1 trigger along with the big wheel TGCs.

7.3.4 Readout Chain Data Flow

The Front-End LInk eXchange (FELIX) [195] is used in the Back-End system as the interface between the data acquisition, detector control, timing, trigger, and control (TTC) systems and new or updated trigger and detector front-end electronics. The FELIX system uses commodity server technology in combination with FPGA-based Peripheral Component Interconnect express I/O cards. The FELIX sends TTC link including L0/L1 trigger accept signals (L0A/L1A), BC clock, and front-end configuration data to each FEB.

Figure 7.14 shows the workflow of the readout chain for sTGC. FELIX passes the NSW ASIC configuration data (1728 bits per VMM, 1290 bits per TDS, 1024 bits per ROC) to GBT-SCA and then GBT-SCA executes NSW ASIC configuration operations. FELIX sends the Level-0 and Level-1 triggers to ROC in the same BCID for the single-level trigger which is used in phase I. The 10-bit ADC information processed in VMM is stored in the buffers as L0 data. When VMM receives the L0A Trigger from ROC (Readout Controller), the data is first passed on to ROC after performing L1A matching (using the L0ID) within a window of 8 BCs. This ROC selects the data that matches with the L1A, packages it, and sends it to FELIX. All the links coming from the Front-Ends are electronic and those coming from FELIX are optical, hence L1DDC cards [196] are used for the transmission between Front-Ends and FELIX. Gigabit Transceiver (GBT) [197] is embedded on the L1DDC cards. The GBT handles the transmission from an optical signal to an electrical signal and vice versa. Commercial off-the-shelf (COTS) servers connected to FELIX systems via the same network run the new Software Readout Driver (SW ROD) infrastructure for event fragment building and buffering, with support for detector- or trigger-specific data processing, and serve the data upon request to the ATLAS High-Level Trigger for Event Building and Selection [195].

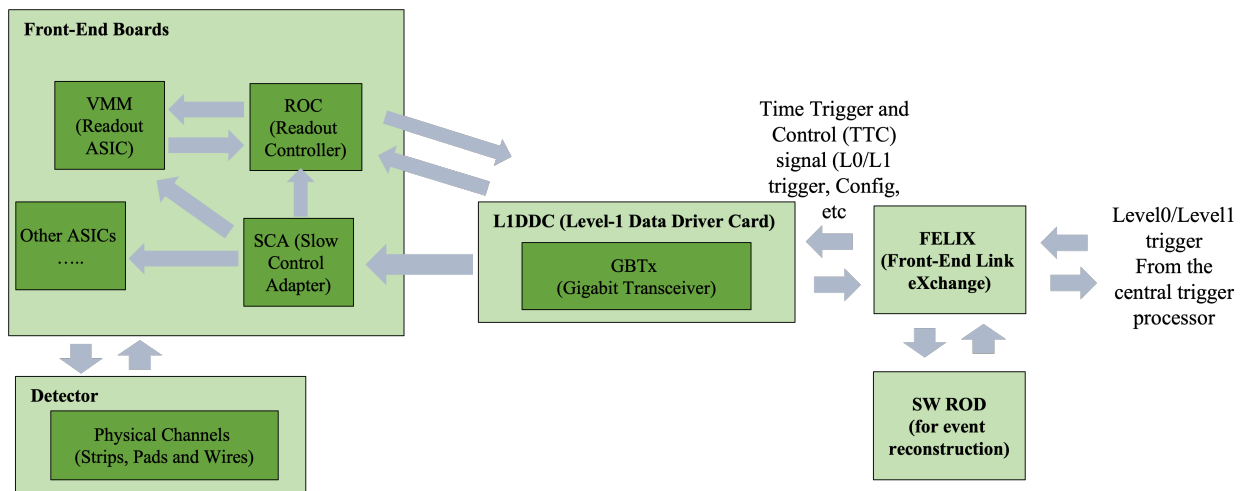


Figure 7.14: The Readout chain flow for sTGC.

CHAPTER 8

Electronics Integration and Commissioning of the sTGC Detector

The small-strip Thin Gap Chambers integration and commissioning were completed at CERN [198]. Different sTGC quadruplets are constructed at different production sites namely Canada, Chile, China, Israel, and Russia. They are then shipped to CERN for assembly. Assembling different quadruplets into wedges, mounting front-end boards and all other electronics components on the wedges, and then validating the data flow for both trigger and readout chains is the general overview of the integration and commissioning workflow (see figure 8.3). The University of Michigan team was coordinating electronics integration and commissioning of the sTGC wedges. Section 8.1 gives a brief overview of everything that is done to prepare and assemble the quadruplets into wedges. The work performed by the University of Michigan team is divided into sections 8.2 8.3 8.4 8.5.

The small wedges are the ones that span an azimuthal angle of around 17° and the large wedges span an azimuthal angle of around 28° . The small wedges are mounted closer to the interaction point (IP) and the Large wedges are mounted closer to the cavern walls (HO). In one small or large sector there are 4 wedges: 2 Micromegas wedges sandwiched between 2 sTGC wedges. So the wedges (MM or sTGC) which are on the outside of a sector (i.e. either closer to IP or HO) are "Confirm" wedges and the rest are "Pivot" wedges (see figure 8.1). The side on the positive z -axis is called Side-A and that on the negative z -axis is called Side-C. The total number of sTGC small and large wedges is 16 each on one side (two in one sector and a total of eight small and large sectors) so there was a total of 64 sTGC wedges.

Figure 8.2 shows the entire workflow of the integration procedure at CERN. This is the flow decided at the late stage in the integration process. The workflow went through several changes according to the modifications in the timelines. The total time required for the entire integration of one wedge was 8 weeks (in the last stages of the integration as a result of the acquired experience). A lot of tasks were performed in parallel on several wedges.

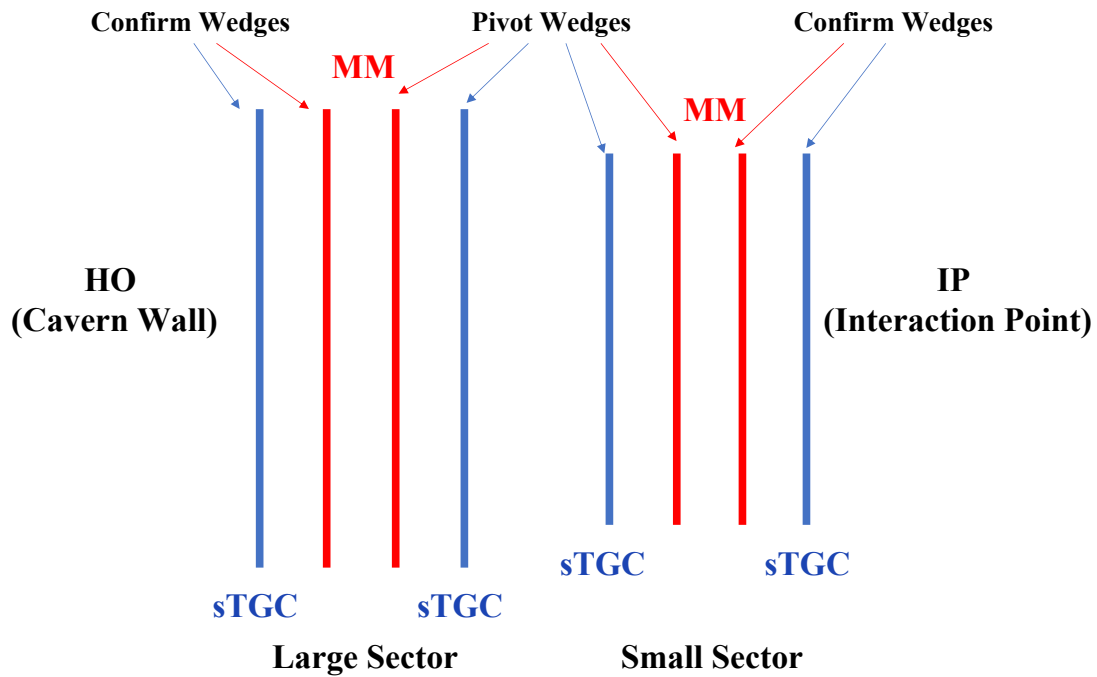


Figure 8.1: The NSW wedges and nomenclature.

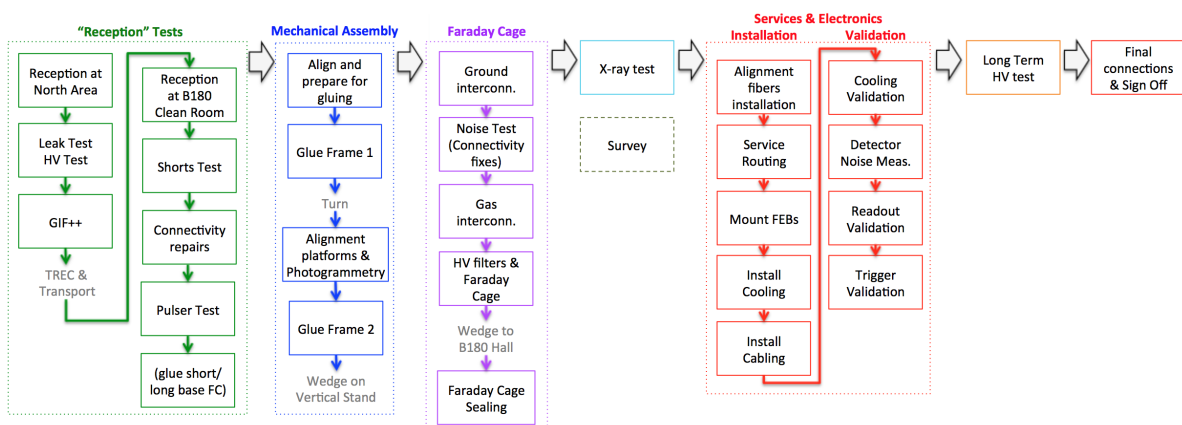
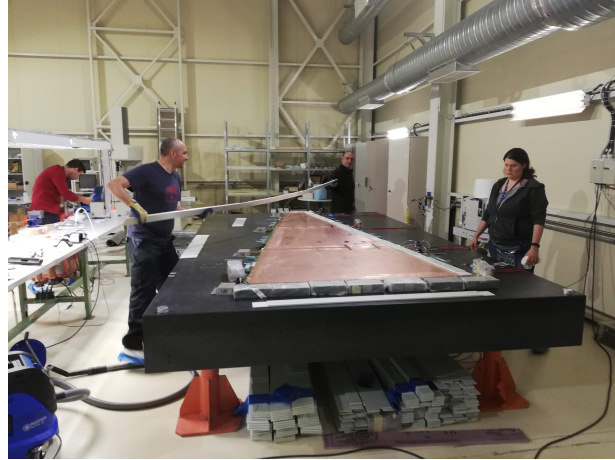


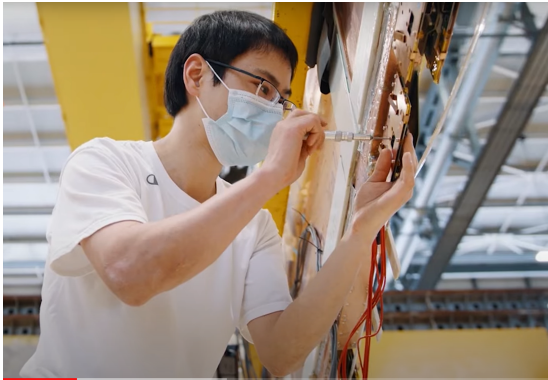
Figure 8.2: sTGC integration workflow, from late in production, when it was fully optimized. Each color reflects the work of a distinct team and is described in one of the following sections.



(a) Quadruplet Reception Testing



(b) Wedge Assembly



(c) Electronics Installation



(d) Wedge Testing

Figure 8.3: The four main stages of the sTGC integration: quadruplet reception and validation (a), mechanical assembly of quadruplets into wedges (b), installation of electronics and services onto the assembled wedges (c), and testing of the complete electronics and detector system (d).

8.1 Overview of the Quadruplet Reception and Assembly

The quadruplets are shipped to CERN from the corresponding construction sites in batches of a maximum of 4 to 5. The drawing of a QS1 quadruplet is shown in figure 8.4.

One quadruplet, as the name suggests, has four layers of the detector technology (in this case, sTGC) with two doublets. Every layer, as shown in figure 7.4b, has two types of cathodes separated by 2.85 mm with the wire layer in the middle. Every doublet has two layers with the strip cathodes in the middle. The strip and pad adapter boards for one layer are on opposite sides of the layer. The strips (pads) are connected to the strip (pad) adapter boards using wire jumpers. A Wire-2 Adapter Board (W2AB) on the larger one out of the parallel sides of the quadruplet is used to read out wire channels. W1AB and W0AB (for inner radius wire channels of Q1 only) are used to distribute high voltage (HV) to the wire groups.

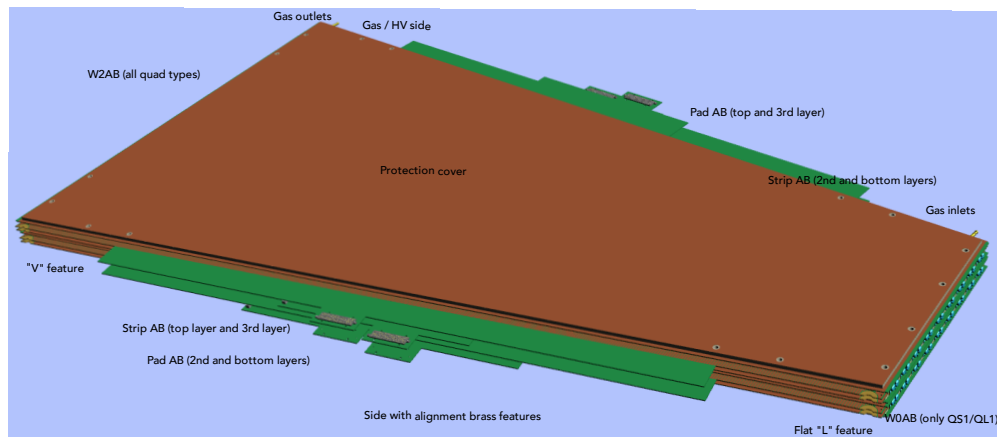


Figure 8.4: Drawing of a QS1P quadruplet illustrating some relevant features for wedge assembly.

They underwent some tests before they were sent to be glued together to make wedges. These tests include the gas tightness test along with the HV test to check the damages during transport, irradiation tests using nominal high voltage to check for the Malter effect, connectivity tests which included the shorts test, and pulser test which determines potential disconnected or problematic channels. Along with checking the gas gaps are gas-tight, some inlets were found to be partially obstructed increasing the gas impedance. A ballooning effect was seen because the protection cover of the quadruplet was not completely attached to the outer cathode so the gas inflates the outermost gas gap. After receiving the quadruplets, they underwent the HV test using only CO₂ as the gas instead of the flammable mixture of 55% CO₂:45% n-pentane. It is also called the “dry” HV test. This test is to check for damaged cables or extensions, sparks, and broken wires.

After the gas tightness and the HV tests, the quads are kept in the GIF++ bunker of CERN, which is equipped with a Cesium-137 gamma-ray source. The nominal gas mixture of 45% n-pentane and 55% CO₂ was used for these tests. Lead plates can be placed between the source and the quads to change the rate of the gamma-ray source. Different quadruplets are irradiated under different attenuations as different quadruplets (Q1, Q2, Q3) are positioned at different radii in the NSW, which are exposed to different background rates (e.g. the innermost quadruplets with lower radii are subjected to higher background rates during the LHC runs). Q1s are irradiated with an attenuation of 2.2, Q2s with 4.6, and Q3s with 10 (here, attenuation is inversely proportional to the background rate).

The short tests are done on the fly to identify problematic strip channels especially if a few strips are shorted together or shorted to the ground. A special short board is used to perform these tests. If the resistance between two strips or between a strip and the ground is less than 300 k Ω , then some measures are taken so that the problematic channels are disconnected from the VMM channels as these can damage the entire VMM ASIC. The pulser tests are also conducted after the short tests are done and the shorted channels are fixed (as many as possible). There is a pulse generator that sends pulses to wires, pads, and strips. Analog outputs from the channels are read by the oscilloscope. Problematic channels have comparatively lower amplitude than good channels.

After the reception tests are performed, the quadruplets are assembled into wedges. Before that, the quadruplets are checked for any non-conformities and travel damages. Different layer grounds were checked to be independent of each other. This was especially necessary for high-frequency currents. Many quadruplets did not have pad channel grounding connections (figure 8.5a). This was found to be essential because the high-frequency currents were taking a longer return path creating high impedance in the detector increasing the noise. This is explained later in section 8.5.2. After a few such checks, the quadruplets are aligned in the *XY* plane on a granite table. Any differences in the *z*-axis (thickness of the quadruplets) are smoothed using the FR4 shims. Then, one side of the assembled wedge is glued together using a fiberglass support frame. This gives the wedge mechanical strength making it one whole entity instead of three quadruplets (see figure 8.5b). After this, the wedge is very carefully rotated and the alignment platforms are glued on the other side of the wedge. The source plates are designed to hold in place the optical fibers whose ends are used as light sources. The alignment system requires the position of these light sources to be determined with respect to the active detector elements, in this case, the sTGC strips. The same precision inserts (V and L features) in the strip cathode boards used to align the quads during quadruplet construction and wedge assembly are used as a reference when gluing the source plates on the wedge surface. To make sure the alignment platforms are positioned precisely at the specific required locations, a survey technique called Photogrammetry is used. This takes a lot of photos of the platforms from



Figure 8.5: The ground connections are not performed for the pad channels on the quadruplets shown in (a). The support frame is glued on the first side of the wedge, as shown in (b).

various angles and positions and later they are all analyzed using dedicated software. This technique can measure the position of the targets in a given coordinate system at a precision of $100\ \mu\text{m}$.

After this, the second side frame is glued to the wedge. A final check is done for the problematic channels by doing an analog noise measurement using an oscilloscope. This check includes detecting shorts, disconnections, high resistance developed on the signal line, etc. The noise is sensitive to the difference in the input capacitance. A movable diagnostic system is developed (consisting of the sTGC wedge, FEBs, and a data-acquisition firmware (miniDAQ [199])). A software is developed which runs over different parameters and VMM channels to store the noise information collected via an oscilloscope. The detected problems are fixed as much as possible before the Faraday cage is installed on the wedge. The Faraday cage provides good shielding to the protruding FEB connections of the adapter boards from outside electromagnetic disturbances. The Faraday cage is constructed out of copper-laminated FR4 pieces. All the Faraday cage pieces are electrically connected to each other and also to the outer copper surface. The second function of the Faraday cage is to enclose the gas inside the detector, especially the flammable n-pentane. Hence, gas tightness is an important aspect to check for the Faraday cage as well. After the Faraday cage is installed, the long-term HV tests are performed using the nominal gas mixture at 2800 V. The tests are done in a gas room facility.

Next, the X-ray alignment is checked for the strips to locate the position of the strips with respect to the source plates (i.e. the alignment platforms). This is possible because the alignment platforms are precisely positioned on the wedge surface using the brass "V" and "L" features of the uppermost sTGC cathode strip boards as a reference. The wedge is irradiated with the X-rays using an X-ray

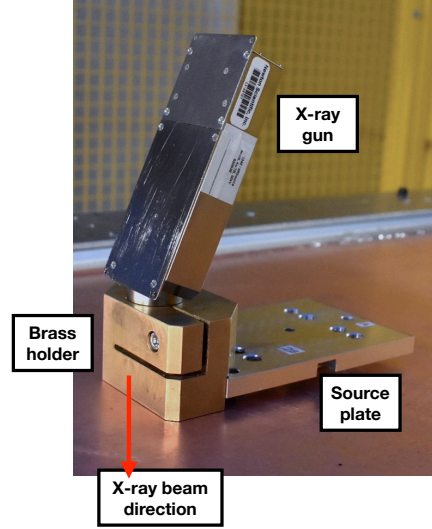


Figure 8.6: The X-ray gun used for the irradiation of the sTGC wedges during the X-ray survey. The gun is inserted into the brass holder and then mounted on a source plate. The red arrow denotes the direction of the X-ray beam, perpendicular to the surface of the quadruplet.

gun inserted in brass holders with a hole (to collimate the beam) mounted on the source plates (see figure 8.6). The perpendicularity of the beam is assumed and also verified by CERN's Metrology department and by in situ calibration. The wedge is flushed with CO_2 with high voltage applied and it is kept horizontal while the wedge can be irradiated up to 60 points per layer. The strips are read out using the sFEBs and the miniDAQ system. The offline data analysis consists of reconstructing the position of the X-ray profile using two methods: clustering algorithm and using raw hits. The clustering method can pose a challenge as many X-rays are striking the strips at the same time [200]. Hence, position reconstruction using raw hits is also used. The largest correction applied to the reconstructed position comes from the angle of the X-ray beam. The difference between the expected and observed positions is seen due to the local misalignments of the strips and other non-conformities. The results obtained along with the Coordinate Measuring Machine (CMM) measurements recorded in the construction database are combined into a global alignment fit, where the relative strip positions are described using a 4-parameter model.

8.2 Front-End Board Reception

The front-end boards for the sTGC after production are then transported to CERN for integration. They were received in 7 batches. The testing procedure was not streamlined for the first batch of boards. But the results from the first batch gave an idea about potential issues with the boards and the testing methods. The procedure is then properly streamlined with the next batches of the

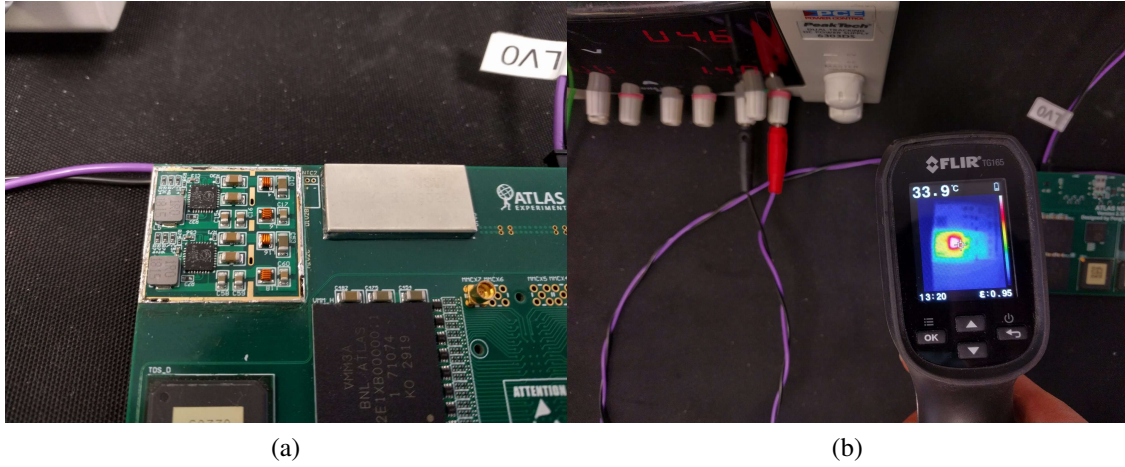


Figure 8.7: The shorted FEAST causing high current.

front-end boards. Once the boards are received, they are separated into sFEBs and pFEBs, and their unique identification is noted down along with the type. The power consumption and currents are verified for the boards. Any issue with the power consumption or current can lead to issues for the FEAST ASIC which is the DC-DC converter supplying power to the board ASICs. Almost all the boards ran with a current in the safe range except one. The lower FEAST was shorted as seen in figure 8.7. The current before the configuration was found to be 2.2 A, which is definitely higher than the 15% increase that was allowed in the current. Also, the shorted FEAST became hot very quickly compared to other good FEASTs, and the hot spot can be seen in figure 8.7.

The front-end boards are tested for problematic channels by performing Readout and Trigger chain tests on the bench before installing cooling plates. The setups for both tests are shown in figure 8.8.

The sFEBs are rejected if at least one VMM is found to have more than 2 problematic channels and the pFEBs are rejected if at least one VMM is found to have more than 1 problematic channel. The failed boards are then repaired by replacing the problematic VMMs with new ones. The newly repaired boards are again checked on-bench before placing them on the detector.

8.2.1 Baseline Scan

For the VMM channels, the baseline is set at 160 mV and the deviation from the nominal value is observed to be less than 40 mV (the value is expected to be between 150 and 200 mV) [193]. This parameter depends on the correct functioning of the amplifier circuits and baseline restoration mechanism. A script developed by the Micromegas Group was used to perform the baseline and threshold scans. The 12-bit ADC and the 2 General Purpose Inputs and Outputs (GPIOs) on the SCA chip of the front-end board are used for the scan. The 12-bit ADC is calibrated such that 4095

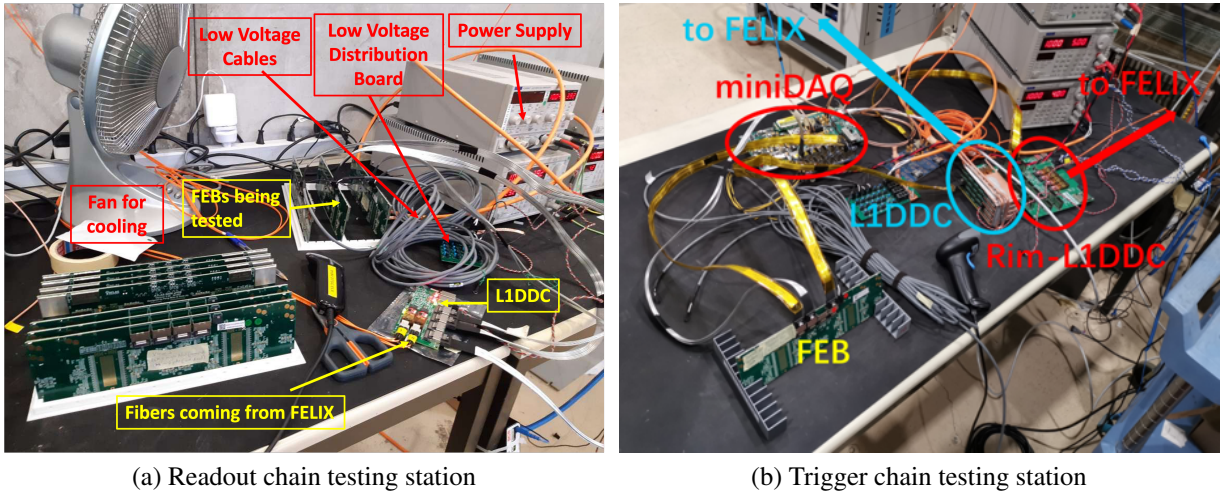


Figure 8.8: Setups of the FEB reception tests: readout chain (a), and trigger chain testing station setup (b).

ADC counts correspond to 1000 mV. Figure 8.9a shows the nominal baseline as a function of the channel number for an sFEB8 and figure 8.9b shows the average baseline values as a function of the channel number for a pFEB. A few problematic channels seem to have very low baseline values.

The entire VMM can have high or low baselines, this was found to be the case with a few VMMs. This is mainly due to some damage to the Monitor Output and the connection of the ADC to the monitor output (See figure 7.12a for the monitor output on the FEBs.). The baseline of a VMM can be recovered by enabling Monitor Output (MO) in the configurations (see figure 8.10).

8.2.2 Readout Chain Validation Using Test-Pulses

A dedicated package is written to analyze the output of the readout test pulse and combine the results of the baseline scans and the test pulse readout into a CSV format.

The readout chain is validated by sending the configuration to generate test pulses. These are generated by the common pulser electronics circuit in the VMM, which generates test pulses with given amplitudes. The tp-DAC (test-pulse Digital to Analog converter) is set for inputting the amplitude. The ROC is set to the L1 trigger-matching mode where L0A and L1A signals are sent in the same BC. Trigger and test pulses are sent via the Timing-Trigger-Control system. The data is recorded for a continuous stream of test pulses for around 20 seconds. All channels should ideally receive a similar number of test pulses and the threshold is set such that it should pass all the test pulses. If a channel receives a significantly lesser number of test pulses, then the channel is considered to be a problematic channel. The charge (pdo) information is also looked at in deciding

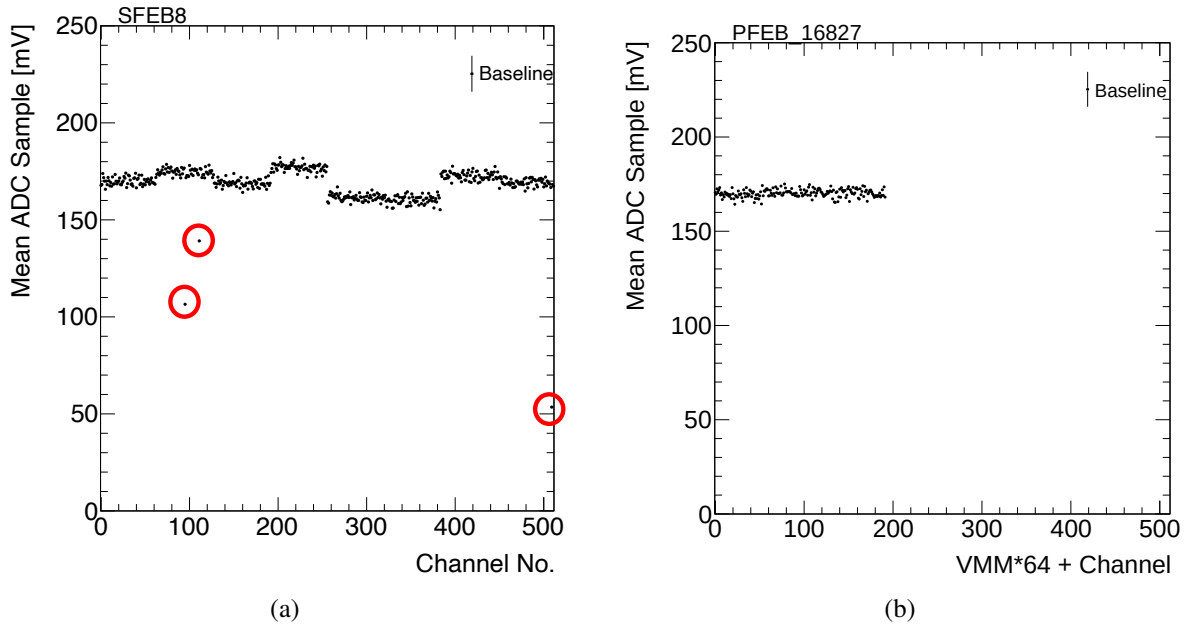


Figure 8.9: The baseline measurements of the FEB channels: shows the baseline for an sFEB8 (a), and shows the baseline for a pFEB (b). The sFEB8 has 8 VMMs and pFEB has 3 VMMs. The x-axis is VMM number times 64 + the channel number.

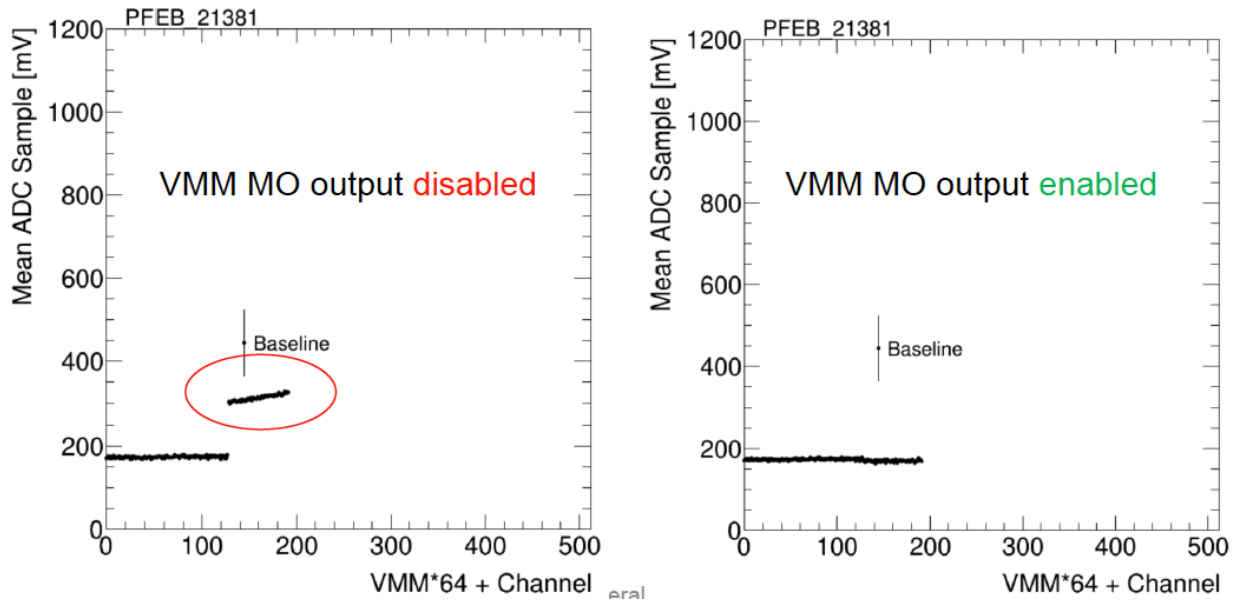


Figure 8.10: The MO issue for the VMM baseline.

whether the FEB is of good quality or not. Figures 8.11 and 8.12 show different problems observed during the FEB reception test-pulse readout tests.

1. **Stuck Pdo:** Some channels had pdo values that were stuck at values divisible by 16 (See figure 8.11a for a normal pdo distribution and figure 8.11b for a distribution with a pdo stuck at value 544). The last 4 bits of the 10-bit ADC fail to be decoded causing the PDO value to migrate to a value divisible by 16.
2. **Low efficiency:** Some channels did not record some or all the test pulses sent and it showed up in the hits versus channel number distribution (see figures 8.11c, 8.11d and 8.11e). A lot of different parameters are checked and tuned to sometimes recover the channels with such issues, for example, CKDT (160 MHz clock), VMM channel tagging offset, VMM L0 offset, ROC Ctrl Delay and Ctrl Phase, VMM TP phase, CKBC phase (40 MHz clock), ADC conversion time, etc. The completely dead channels sometimes have an issue with the amplifier. The signal is not amplified enough and therefore, does not pass the threshold.
3. **High or Low Pdo:** Figure 8.12a shows the normal distribution of pdo versus channels. The normal distribution for one VMM is bell-curve shaped. This is a feature of the VMM chip. A 4-degree polynomial is fitted to the bell-shaped normal distribution. If the actual value of the pdo for that channel is outside 30% of the fit value for that channel, the channel is marked as problematic (see figures 8.12e and 8.12f). If the pdo value is between 20% to 30% compared to the fit value, then the channel is considered to be in a warning status. The mean of all the channels on one VMM is also checked to see if it is high or low (see figures 8.12b and 8.12c for a mean value of VMM pdo channels being low and high, respectively).
4. **Saturated Pdo:** Sometimes all the pdo values get stuck to the maximum possible value of the 10-bit ADC i.e. 1022 (see figure 8.12d).

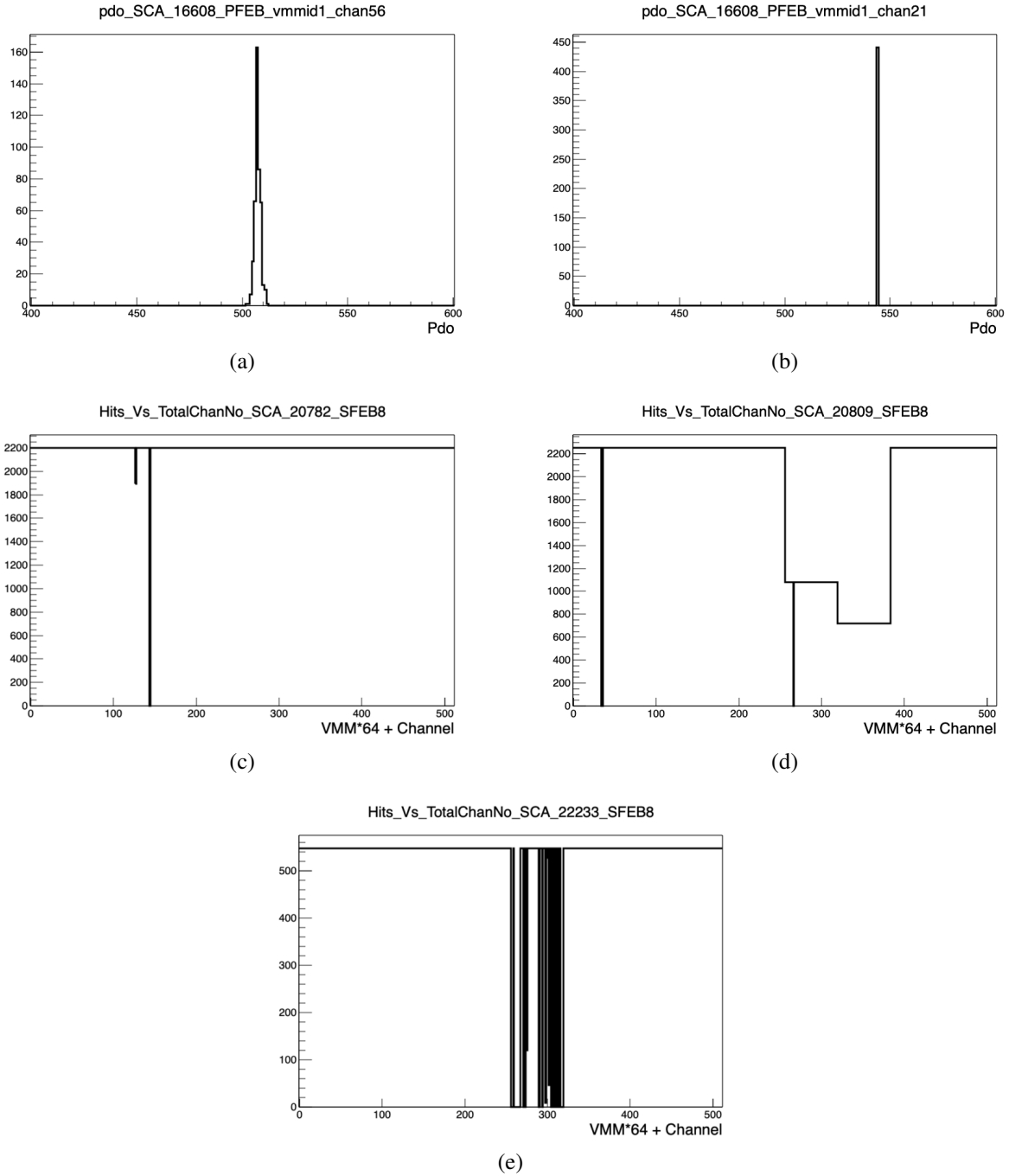


Figure 8.11: The normal pdo distribution of a channel (a). Pdo distribution of channel which has stuck pdo issue (b). Low efficiency and dead channels (c). Low efficiency VMMs (d). Many many dead channels were found and many parameters (CKDT (160 MHz), VMM channel tagging offset, VMM L0 offset, ROC Ctrl Delay and Ctrl Phase, VMM TP phase, CKBC phase, ADC conversion time, etc) were checked to recover as many channels as possible however, they did not work (e).

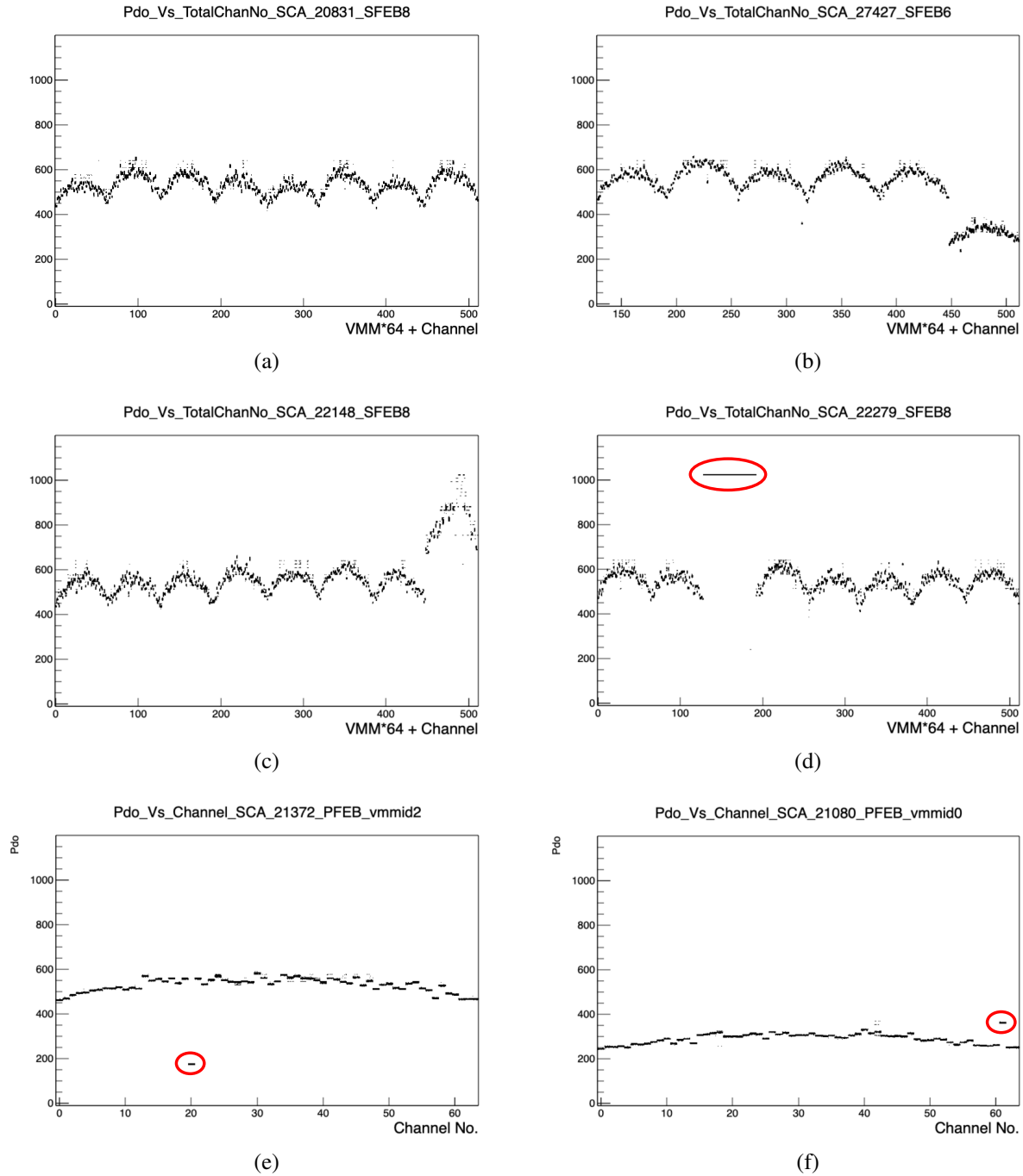


Figure 8.12: The normal Pdo vs channel distribution (a). Low Pdo for the entire VMM (b). High Pdo for the entire VMM (c). Pdo saturated at the highest value available for pdo, which is 1022 (d). Individual channels having low pdo values (e). Individual channels having high pdo values (f).

There are several parameters that have to be tuned sometimes to have good data read out. As there are many data transmissions in a front-end board, to achieve synchronous readout, all the clock phases and delays for these transmissions have to be tuned correctly. These clock phases and delays include the following:

1. The internal ROC 40 MHz and 160 MHz clock phase. These affect the TTC signal reception from ROC;
2. ROC-VMM 160 MHz clock phase;
3. Bunch Crossing Offset;
4. Time Trigger and Control Delay and Phase;
5. GBTx phases.

8.2.3 Trigger Chain Validation

The trigger chain of the FEB is also validated using on-bench tests. The work is described in Ref. [201] in more detail.

For pFEB trigger chain validation, the pFEBs are configured in direct timing output mode. For this test, the VMM sends the Time-over-Threshold (ToT) output whenever a channel receives a test pulse. The pad-TDS receives the ToT pulses of up to 104 channels from two VMMs and generates serialized yes-or-no information every 25 ns at a speed of 4.8 Gbps. The TDS output data is decoded and checked and the output from the channels is validated. The test pulse is sent periodically for a few minutes and the output hit channels are continuously monitored during that time. This test determines the number of dead channels in the trigger chain. These could be dead VMM channels or dead TDS channels. In rare cases, dead trigger channels may be due to a malfunction of the VMM Test Pulser (TP). This can be confirmed by checking the Monitored Output (MO) of the VMM using an oscilloscope.

The sFEB trigger chain tests are also performed. The sFEB TDS receives the ROI information from the Pad trigger board, performs trigger matching for the VMM strip 6-bit, ADC and sends out trigger-matched data. The following tests are performed to validate the sFEB trigger chain:

1. **Errors in TDS outputs:** These are checked using a pseudorandom binary sequence pattern (PRBS). The PRBS pattern is used to check the TDS 4.8 Gbps output. This validates the TDS serializer, cable connectivity, clock distribution, and the 4.8 Gbps checker and decoder.
2. **strip-TDS trigger reception checks:** The strip-TDS receives the trigger ROI information from the Pad trigger board with one clock line, one trigger enable line, one BCID line, and

one band-phi ID at the speed of 640 Mbps (see figure 8.13). This information is sent using the miniDAQ system. The output data from TDS is checked and compared with the BCID and band-phi ID. Poor cable connectivity, improper TDS clock phase, or chip damage results in errors in trigger reception.

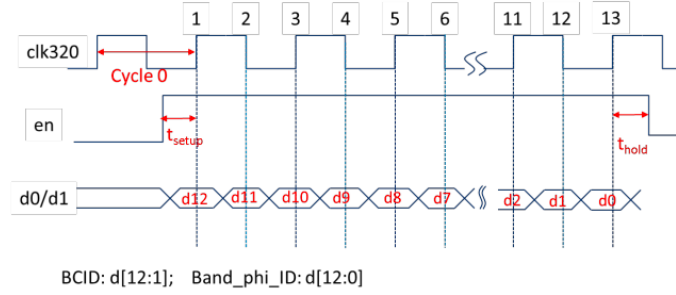


Figure 8.13: The ROI information sent to the strip-TDS by the Pad trigger board.

3. **TDS-VMM clock phase scan:** The TDS receives 6-bit ADC data from the VMM at 320 Mbps. The clock phase for the 160 Mbps clock from the TDS to the VMM needs to be scanned in order to get the proper phase. The VMM-TDS clock has 32 possible phases, however, only half of the phases are scanned, to save time. The selection of the range of phases is done such that the working phases will be sandwiched by two bad phase areas. The software will choose the median value of the good phases. Examples of the phase scan for an sFEB8 (with four TDS and eight VMM chips) are shown in figure 8.14a.
4. **6-bit ADC linearity scan:** The VMM test pulse amplitude is controlled by the TP DAC setting value. The value can range from 0 to 1023. A 6-bit ADC linearity is performed by configuring the VMM test pulse DAC from 200 to 1000 with a step size of 100 and recording the corresponding 6-bit ADC output data. Figure 8.14b shows the 6-bit ADC linearity scan result for an sFEB8.

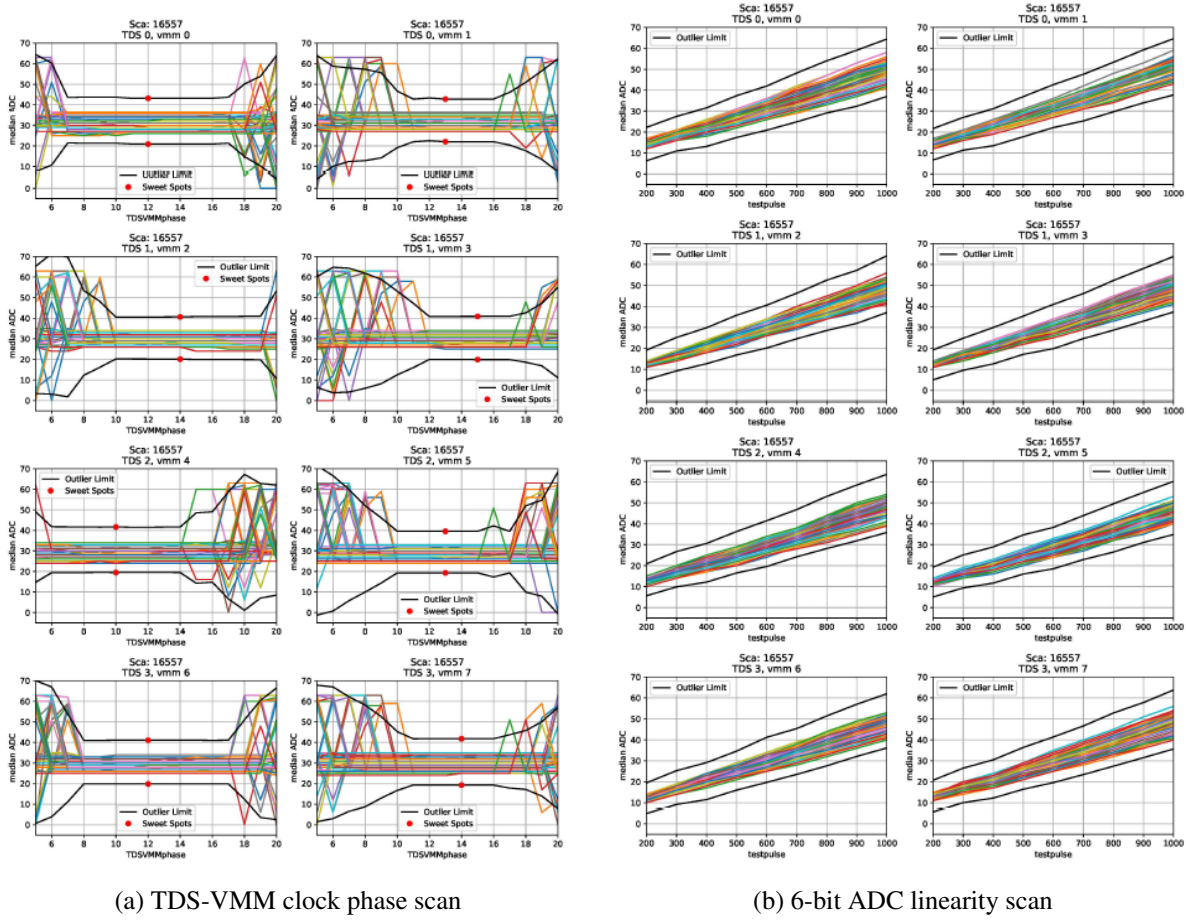


Figure 8.14: TDS-VMM clock phase scan (a), and 6-bit ADC linearity scan (b).

8.3 Electronics Installation

The installation and integration of all the electronics components were conducted at a 1500 m² CERN site (see figure 8.15a). The electronics installation was conducted over several stages:

1. Installing and routing alignment optical fibers on the surface of the wedge.
2. The LVDB (Low Voltage Distribution Board) is glued on the Faraday cage. The LV cables are connected in a fixed pattern to this board. Each cable connects to one FEB. The shields of the LV cables are connected to the wedge ground.
3. The temperature sensors are directly epoxied to the wedge surface.
4. Installation of front-end boards: Initially, the cooling plates are mounted on the boards. Foam pieces of different thicknesses are placed between different ASICs and the cooling plate

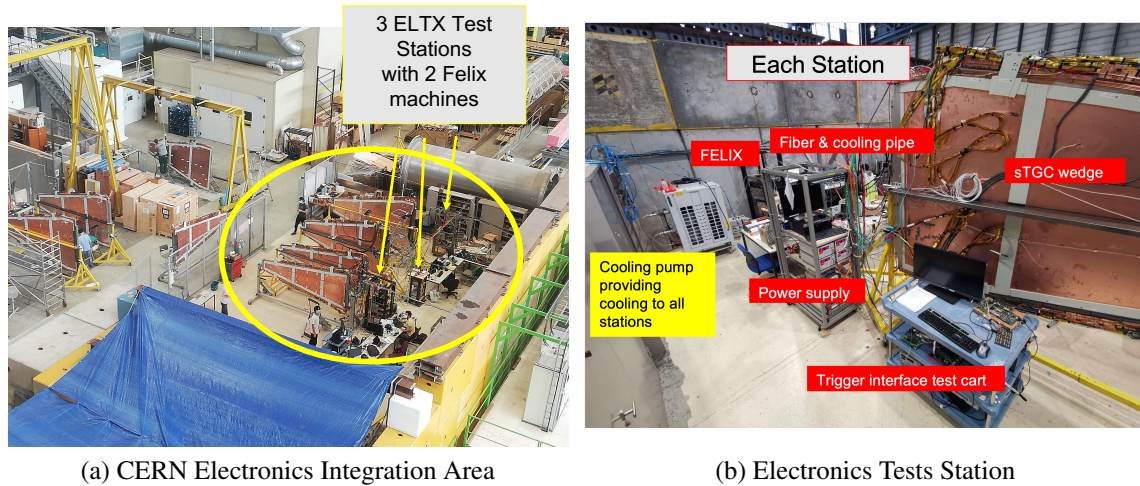


Figure 8.15: The building-180 integration area at CERN (a). Electronics testing station (b).

is made of copper. This is to ensure good thermal conductivity between the cooling pipes (placed on the copper plate) and the ASICs. Custom-made ULTEM clips are clipped to the sides of the board to create a stable distance between the board and the cooling plate so that once the plates are clipped to the board, they do not apply too much pressure on the board ASICs. Two beryllium-copper C-shaped clips are placed on either corner of the FEB to ensure proper thermal contact between the FEB and the FEAST Faraday cages. This is to cool down the high heat produced by the FEASTs. The boards with cooling plates are then attached to the adapter board. Custom-made plastic pieces are used to again create a stable space between the GFZ connector and the adapter board (see figure 8.16).

5. Installing L1DDCs. The L1DDCs are first arranged into arrays of 4 cards along with thermal foam and cooling plates to cool the cards. The L1DDC ground is tied to the wedge ground.
6. Installation of cooling pipes.
7. Installation of signal TwinAx cables, serial repeaters, and B-field sensors.

For the last 2 batches of boards, the current stability was verified (along with temperature monitoring) after the cooling plates are mounted on the boards. The temperature is monitored using the built-in temperature sensors in VMMs.

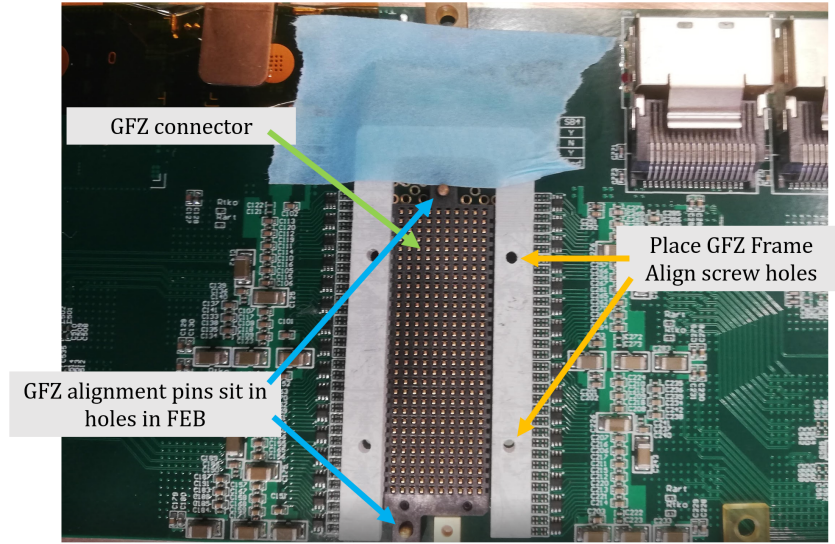


Figure 8.16: GFZ connector placed on the board with the precision frame.

8.4 On-wedge electronics testing

The functioning of the electronics is checked after the complete installation of all electronic components on the wedge. Figure 8.15b shows the test station for the wedge tests. Before any tests, the cooling is checked to be working fine to ensure safe electronics operations. Then, baseline scans are performed along with threshold calibrations. The noise of each channel is checked to note down problematic channels and also ensure that the connectivity between the detector channel and the electronics channel is good. If there are issues, they are tried to be rectified by replacing the front-end boards or the cables. Occasionally, the detector is opened to improve the grounding and connections, but this is done only after careful examination of the issue as these measures can further damage the detector. One of the tested wedges was rejected because many issues were found on the wedge.

8.4.1 Cooling and Current Monitoring

The cooling of the VMMs is an important aspect to keep the chips working in a high-rate environment without issues. The VMMs degrade quickly at high temperatures. The desired temperature for VMMs are between 30 °C to 40 °C, and should be kept below 50 °C. The VMM has a built-in temperature sensor. The sensor output is digitized by the SCA-ADC. The conversion formula from the V_{sensor} (mV) output to Celsius is described in equation 8.1.

$$T(^{\circ}\text{C}) = \frac{725 - V_{\text{sensor}}}{1.85} \quad (8.1)$$

A GUI interface created by one of the team members is used to monitor the temperatures. Figure 8.17 shows all the VMMs of the entire wedge and the maximum temperature reached during the 20 to 30-minute time period. If there are certain VMMs that have high temperatures, the cooling for the front-end board to which the VMM belongs is checked. If the contact between the cooling pipe and the cooling plate is not good, adjustments are made to improve it. Sometimes the issues with the cooling pads and electronics are also evaluated to improve temperature readings. The MO output issue also shows up here when sometimes the VMM temperature values are unrealistic (100 °C) which can be solved by enabling the MO output configuration. Figure 8.18 shows the temperature modulation which is indicative of the chiller’s cooling cycle.

L1DDC temperatures can be obtained via the L1DDC SCA. Fewer issues were found with L1DDC temperatures due to the rigid structure of the L1DDC cooling array. Any poor connection is filled in with DOWSIL™ SE 4485 thermally conductive adhesive. It was found to be easier to apply thermal adhesive in place, rather than by removing an L1DDC array already connected to the rest of the cooling pipe.

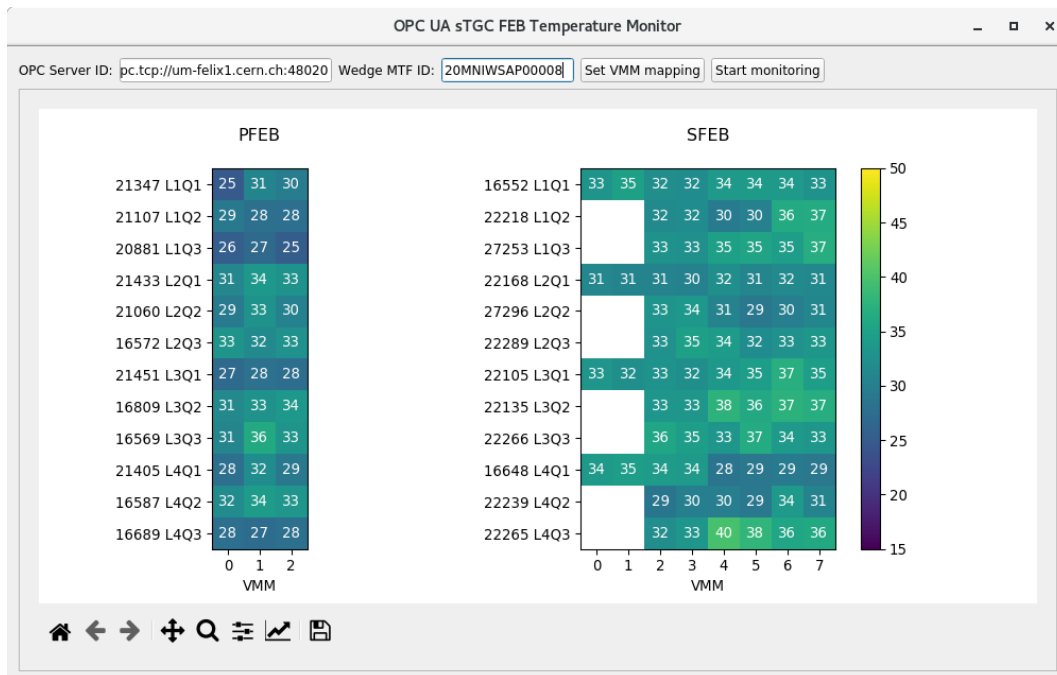


Figure 8.17: An example of the temperature monitoring GUI for an sTGC wedge during integration testing. All VMM’s temperatures are below 50 Celsius.

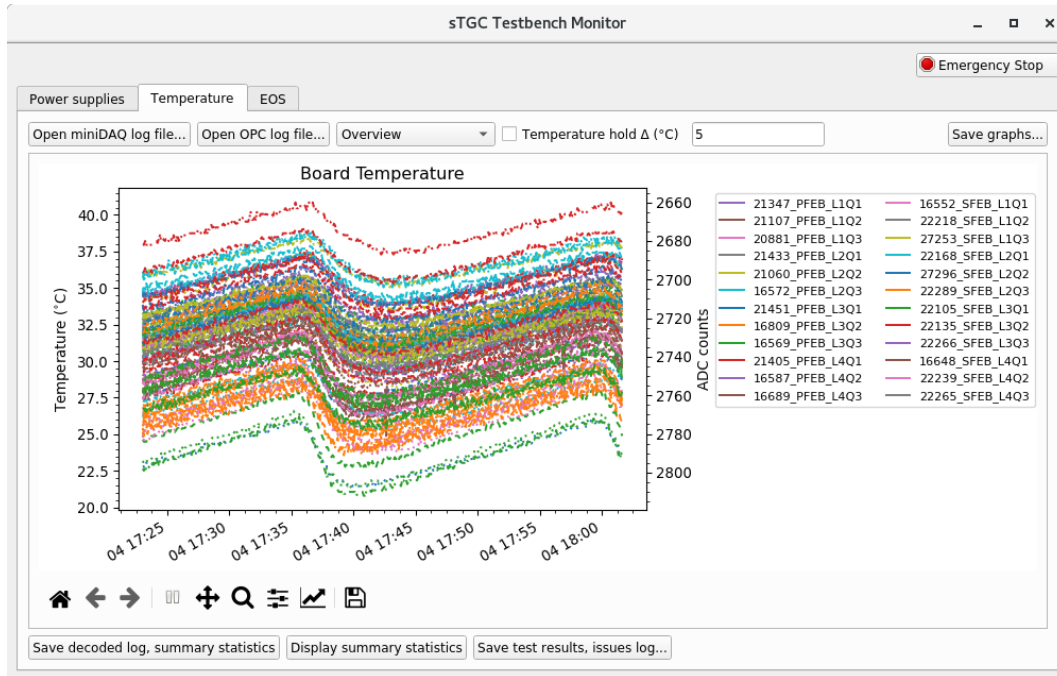


Figure 8.18: An example of the long-term temperature monitoring tracking system during integration testing. As can be seen for both pad and strip FEBs, all VMM temperatures are below 50 °C.

8.4.2 Baseline and Threshold Scans

Details about the baseline scans can be found in section 8.2.1. The SCA-ADC has a lower bandwidth compared to for example an oscilloscope. It cannot sample all the frequencies, especially in case of high noise in a channel. Because the pads have a large area and capacitance, the channel connected to a pad can experience high noise. This has an effect on the baseline measurement by the SCA-ADC. That can be seen in figure 8.19. The baseline for such channels is lower than expected. Figure 8.20 shows the analog baseline measurement of the same board using an oscilloscope, which has higher bandwidth.

Figure 8.21 shows typical baseline levels for all VMM channels after mounting the board on the detector. The baseline levels here are similar to the ones measured in the FEB reception test as shown in figure 8.9, but with higher standard deviations for channels connected to the detector. Muon signals are only digitized if they pass the set threshold. Each electronic channel's threshold must be set such that muon hits efficiently cross thresholds but the noise does not. Measurements with cosmic rays and test beams found that 50 mV above the baseline is an efficient value for pad channels and 20 mV for strip channels. Strip thresholds are lower because the strip channels are operated at 1 mV/fC gain instead of the 3 mV/fC setting for pads.

In order to calibrate the thresholds, a global value of the threshold is first set for all channels in a

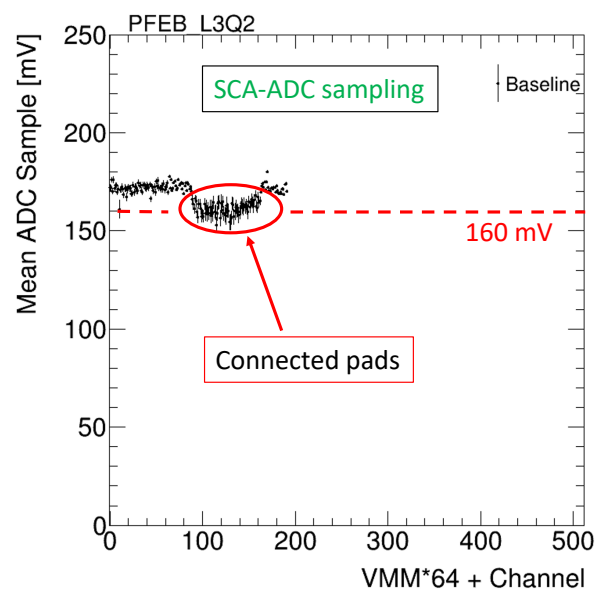


Figure 8.19: The baseline measurements of the pFEB channels for on-wedge tests using SCA-ADC.

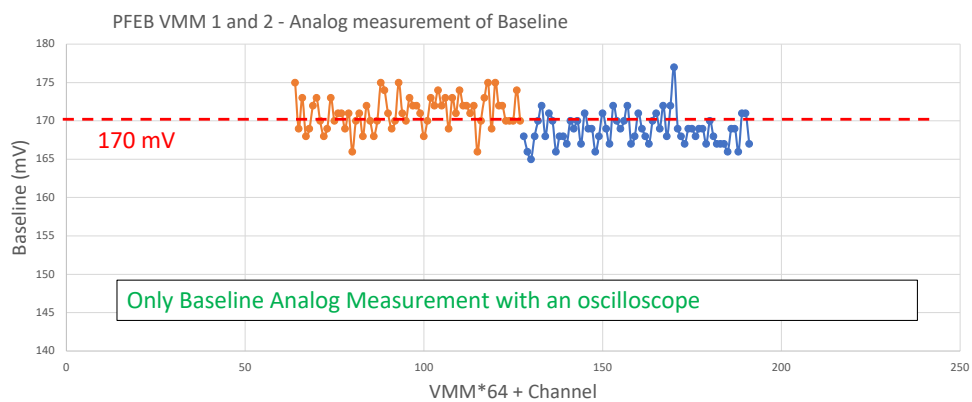


Figure 8.20: The baseline measurements of the pFEB channels using the oscilloscope.

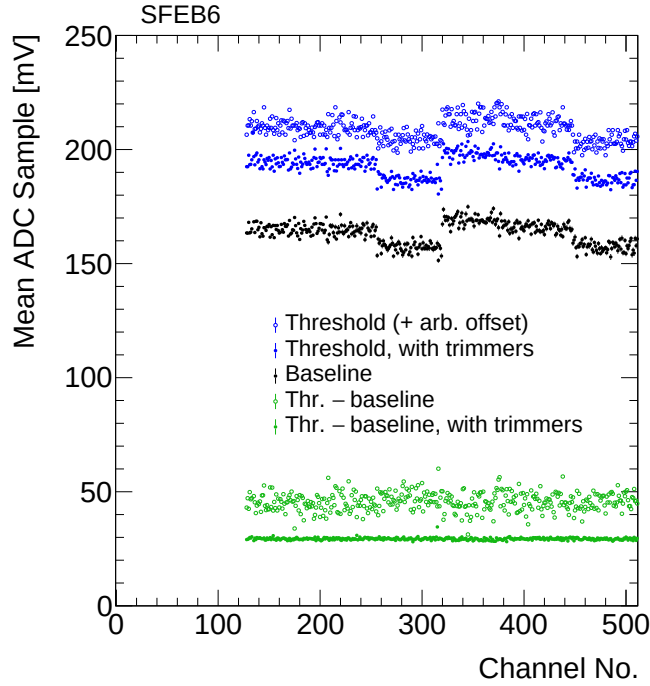


Figure 8.21: Baseline scan and threshold equalization for all the channels on a 6-VMM sFEB after mounting on the detector wedge.

single VMM. This global value is higher than the threshold we desire and a trimmer value is set for each channel to trim down the threshold for each particular channel. A scanning algorithm measures the thresholds using the SCA-ADC and adjusts the global and trimmer values to find the optional setting for each VMM channel. The algorithm equalizes the difference between the threshold and the baseline for every channel, as shown in the row of green solid dots in figure 8.21. The equalized threshold may then be adjusted by changing the single global threshold value up or down to the desired threshold value.

8.4.3 Documentation of the Test Results

The on-wedge electronics testing results for sTGCs are stored in the CERN Oracle database together with the results for MicroMegas wedges. The database space is shared by CERN and all experiments and research groups associated with the LHC. The relational database can be queried using SQL or other languages using as SQL-based toolkit. It can also be manipulated by using the Oracle SQLDeveloper GUI program.

Every piece of hardware used in sTGC is given a unique ID. These pieces range from very fundamental pieces like a data cable to complex assemblies like an entire NSW wheel. The final data is recorded in the database after the sTGC integration and commissioning are done. The

recorded data includes electronics cards to wedge association, current readouts for each FEB from the FELIX system, and current readouts for each FEB from a low-voltage power supply. The latter two reports contain the minimum, maximum, and mean current values recorded over a time interval. The wedge association data includes the MTFID and SCAID (if applicable) of all FEBs, L1DDCs, LVDBs, GBTx fiber cables, and serial repeaters that are installed on a given sTGC wedge. The database also includes a “functional framework” for the entire NSW system where a virtual skeleton of the physical detector is established with the proper associations between electronic components.

The details included about the FEB reception test or the wedge electronics tests are highly categorized. Some of the categories include the testing station (on-bench or on-wedge), the name of the test e.g. current readout, temperature, baseline, noise, test-pulse readout, and trigger chain readout. These test issues are associated with different electronics components and those are also specified in the database e.g. a board issue, issue related to VMM, TDS or ROC chip, FEAST, or to the TDS, VMM channels. The issues include inefficiency in readout for chip or channel, dead channel or chip. Sections 8.2 and 8.4 show details of more issues related to the baseline, readout chain, and noise tests. The quality of the boards is also categorized into the following categories: PERFECT (no issues), GOOD (have VMMs with more than two problematic channels for sFEB and with more than one problematic channel for pFEB), BAD (boards which fail the above categories). A lot of warning categories are also introduced for the boards which are not totally useless but have more than the expected number of issues. Another category is whether the board passed the QA/QC requirements or failed. The failed boards are not mounted on the wedges. Extra comments are also added to the database e.g. regarding some issues which cannot be inputted through the different categories.

A specialized GUI was created to allow a member of the sTGC I&C team to upload data using the predefined templates included in the GitLab repository. Data results must be organized by sTGC wedge or by FEB batch deliveries. A separate GUI was created to allow users to retrieve the sTGC electronics testing results from the database using the python program included in the `elx_db_output` GitLab repository (see figure 8.22). Queries can be made for wedge tests, equipment type, test location, and wedge association constraints. When searching for results associated with a specific FEB, a visual interface is available for faster issue identification. Results can also be exported from the interface in CSV format.

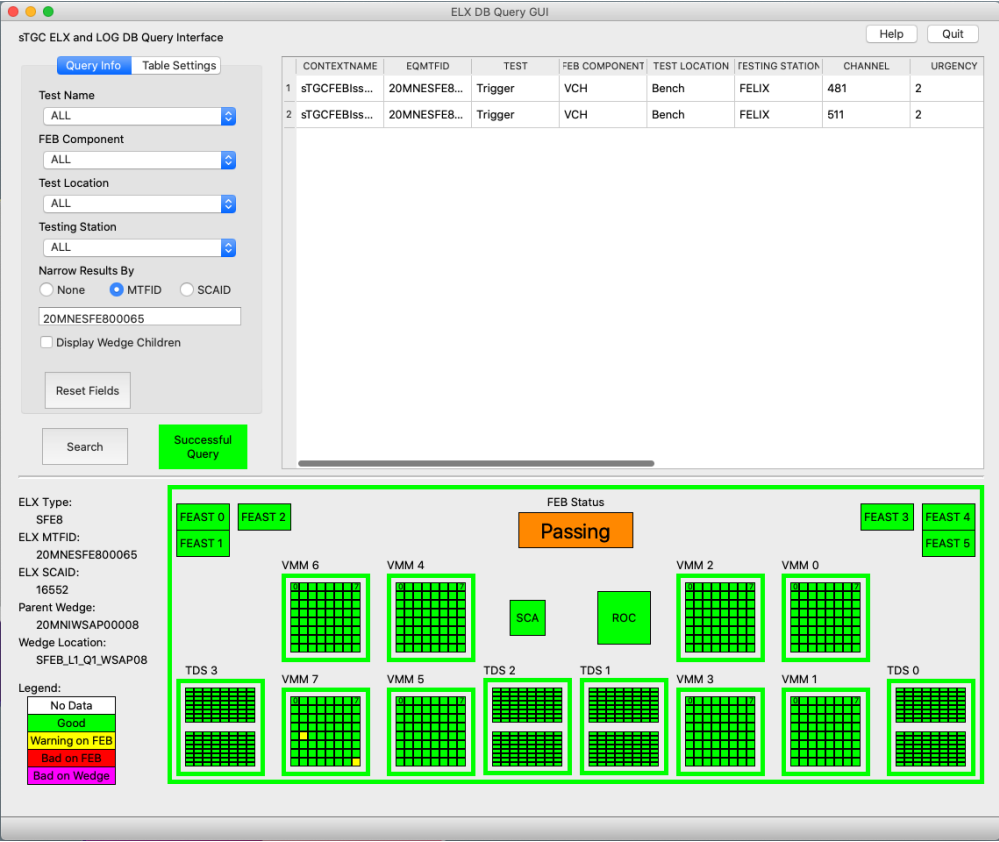


Figure 8.22: The custom GUI for querying wedge-related and FEB-related data collected during the sTGC testing process.

8.5 Noise studies

There was a dedicated effort for understanding noise in the detector system, especially for large pads, as they have higher capacitance. The noise is directly proportional to the input capacitance of the amplifier. The noise level also signifies if the VMM channel connection to the detector channel is good. If there is some resistance between the connection, it shows a lower noise. We have found some high-resistance channels for strips and pads during our tests. The noise distribution shows a clear drop when the VMM channels are not connected properly to their detector counterparts. The high noise issues can be caused sometimes when the channels are accidentally connected to the ground. The characteristic noise behaviors are used to distinguish between different noise issues, for example, shorted channels (to the ground or to other channels), disconnected channels, channels with some grounding scheme issues, resistive channels, etc.

The noise is measured by checking the fluctuations in the baseline for each VMM channel. Many baseline data points are collected to find the standard deviation on the baseline measurement. Figure 8.23a shows the typical noise behavior of pads and figure 8.23b for the typical noise behavior of strips. As mentioned before, the SCA-ADC bandwidth is lower than that of an oscilloscope, because it filters out high-frequency signals. Typically, for strips, a noise of 4 mV measured by the oscilloscope can be translated to a noise of 1.5 to 2 mV using SCA-ADC, and for pads, the noise of 10 mV measured by the oscilloscope is translated to a noise of 5 mV using SCA-ADC.

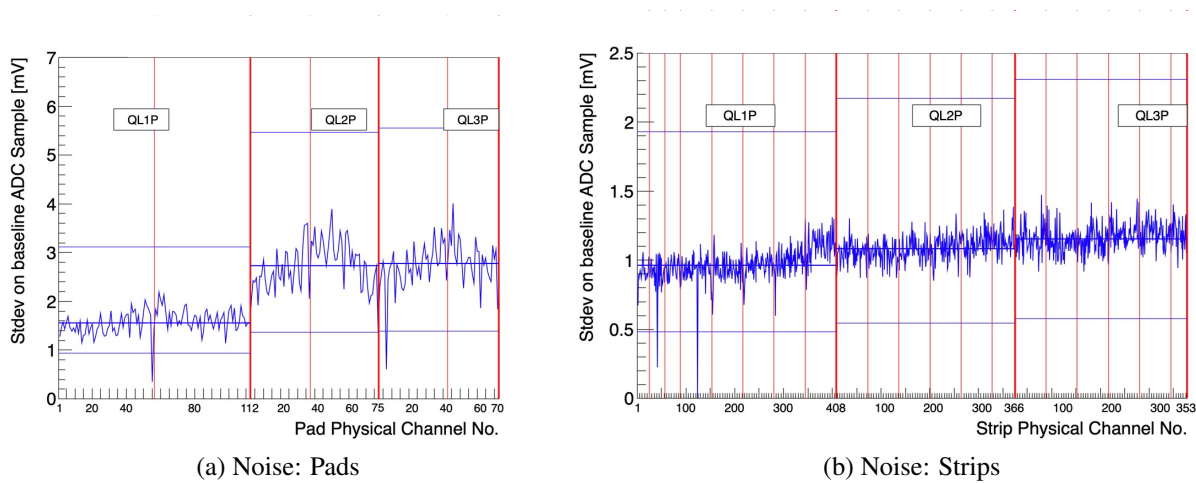


Figure 8.23: The noise (mV) versus channel number for strips and pads.

8.5.1 Irradiated Noise due to FEAST DC-DC Converter on the FEBs

The main source of noise in the VMM channels comes from the high switching frequencies of the FEAST. Figure 8.24 shows the Fast Fourier Transform (FFT) of the waveform of the noise on a typical pad channel. The figure shows different components of the noise on the channel (thermal and FEAST). The FEAST noise is seen as spikes at switching frequencies (2 MHz, 4 MHz, 6 MHz, etc). The advantage of these spikes in the FFT noise is to verify the connectivity between the detector and the electronics channel. If the connection is not established properly, then sometimes the spikes are not visible on the FFT. If this is the case, then the board is removed and the GFZ connector is checked for problems. For example, some glue is found on the GFZ pins which can cause the connection failure. Then, acetone is applied to clean the glue and the board is placed on the adapter board again. Of course, the noise has to be as low as possible. Initially, the FEASTs were placed near the signal traces on the version 2.3a FEB prototype. This caused the noise to be very large. Hence, the decision was made to move the FEASTs further away from the signal traces (in FEB version 2.3e) and placed them close to the corners of the FEB. Figure 8.24 shows the noise in FEBs after moving the FEASTs further away from the signal traces.

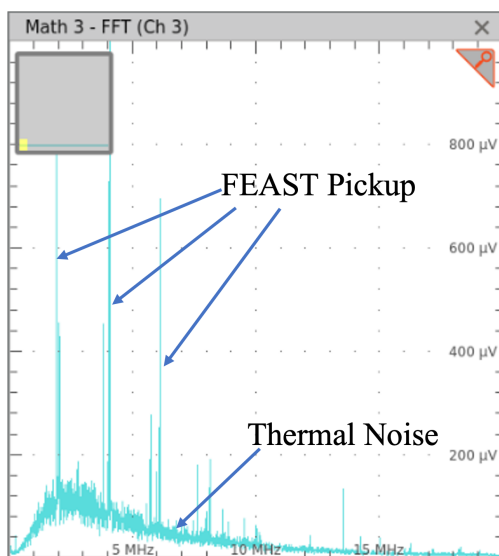


Figure 8.24: The high-frequency noise generated by the switching buck converters.

8.5.2 Grounding Schemes

For a detector's pad channel, a muon injects a much lower charge (200k electrons) to the amplifier than the charge (2 pC) generated by a muon in the detector. This is because of the π -network on the input channel. With some experience, it was found that a threshold of around 50 mV above the baseline is enough to ensure more than 95% hit efficiency for pads.

It is therefore crucial to make sure the electromagnetic noise in the detector channel is well below the 50 mV threshold. The main aspect of noise mitigation and control is the grounding scheme of the different components of the detector. The adapter board is a large dense PCB. It serves as a connection between the detector channel signal traces and the channels of the front-end boards. The FEB analog is connected to the detector ground via the adapter board. The detector ground layer is also connected to the adapter board ground plane using two different schemes. In one scheme, only the ends of the two ground planes are connected (see figure 8.25a). In the other scheme, there is a ground return path present right next to every signal trace (see figure 8.25b).

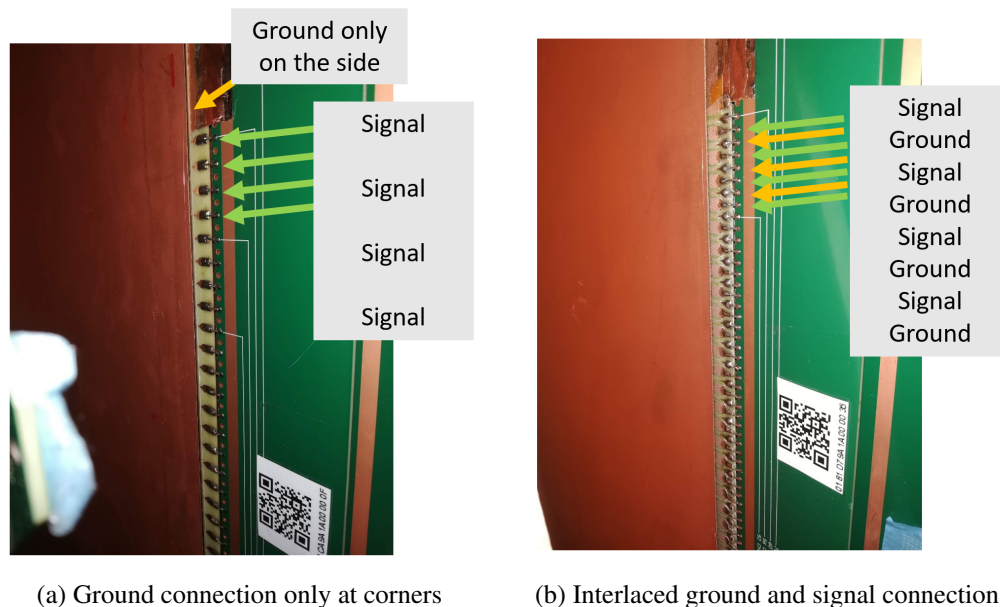


Figure 8.25: Quadruplets with ground connections only at the two ends of the adapter board.(a) Signal jumpers in the middle of the detector layer are very far from any ground connection point. Quadruplets with the interlaced ground and signal connections (b). A jumper between the adapter board ground and the detector layer ground is present near every signal trace jumper.

We saw the noise was significantly lower in the case of some external sources of noise if the second grounding scheme of the detector was used. This is due to the increased impedance in the first scheme. The low-frequency signal prefers the shortest distance between the grounds and the high-frequency signal prefers the least amount of area between the signal and the return paths. In the first scheme, the return path is present only at the ends of the detector plane, the signal traces in the middle have to cover a larger area for returning, which increases the inductance and therefore the impedance in the detector. High impedance causes high noise. The sTGC detector deals with high-frequency signals up to a few MHz and hence care has to be taken with the return paths for these signals. See figure 8.26 for the different return paths and the area they enclose. Having return paths close to the signal traces is very important for reducing the impedance in the detector (and

effectively reducing the noise).

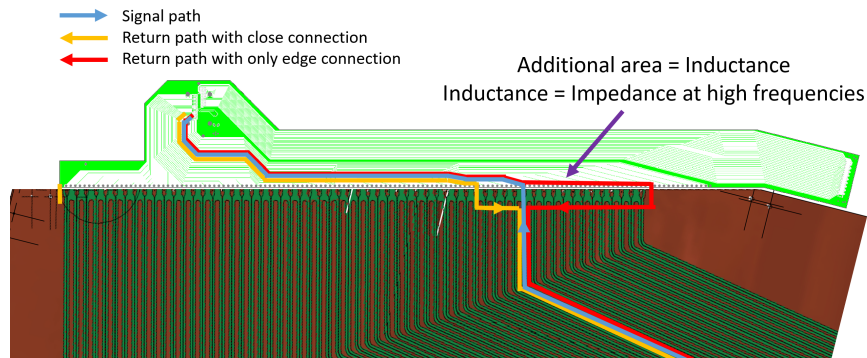


Figure 8.26: The return current must take the long path to the edge of the adapter board if no intermediate ground connections are available. The large loop corresponds to a large impedance for high-frequency currents. The lack of a low-impedance return path means the signal lines easily couple to outside noise sources.

Figure 8.27 shows the noise versus channel distribution for the pads of a large wedge before and after adding a few more return paths in the middle (in the case of the first scheme where the ground planes were connected only at the ends). The yellow marks show the positions of the additional return path connections added from the adapter board ground to the detector ground layer.

As this issue was noticed while integrating Side A wedges, some wedges had already been constructed and hence the issue wasn't rectified in all the wedges of Side A. However, later this correction was applied to all constructed wedges of side C.

The grounding scheme of all the electronics and detector components was checked to make sure all the components were grounded properly. During this inspection, it was found that the serial repeaters (which would be used for the trigger chain data flow) had their shield disconnected from the main wedge ground (see the red dotted line in figure 8.28a). The grounding scheme was fixed, which reduced the noise in the system without terminating the cables.

The GBTx on the L1DDC, the SCA, and the ROC on the FEBs communicate using the CERN Scalable Low Voltage Signaling (SLVS) standard. The communication lines between the two PCBs are DC-coupled. Because of this, any difference in the ground potential can cause the data unintelligible. In the initial scheme the grounds of the L1DDC and the FEBs were supposed to be separate, but that caused the ground potentials to be different. In the final scheme, the two grounds are connected to the same wedge ground.

Both sFEB and pFEB use different amounts of currents because of the different numbers of ASICs used. However, the return paths of the FEBs are all connected to the LVDB grounds so all the FEB

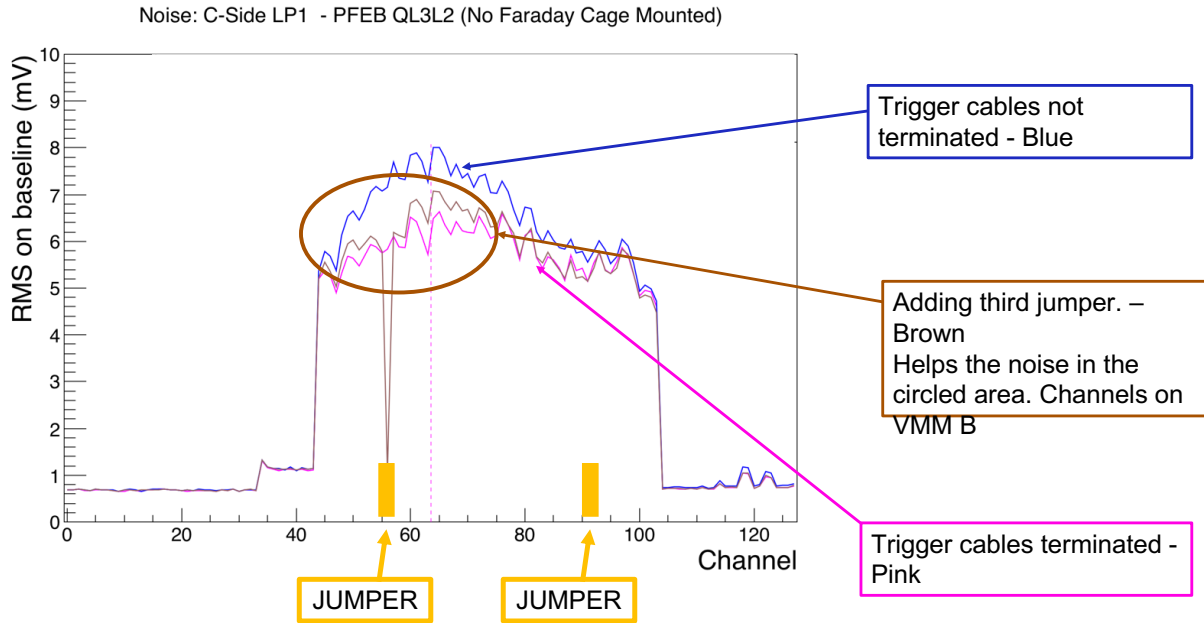


Figure 8.27: Adding two additional copper braid jumpers between the detector layer ground and the adapter board, in the middle of the adapter board, removes the coupling to additional noise sources such as trigger cables whose shield and signal traces are intentionally left floating. One of the signal channels was accidentally broken during the installation of the second jumper (the one on the left, around channel 55) and exhibits extremely low noise, as it was no longer connected to the detector. This was fixed later. The noise measurement here is performed using an oscilloscope.

return lines have equal output currents. Hence, an imbalance in the input and output currents of a FEB was observed. However, when the currents of all the FEBs on a layer were added together, the input and output currents matched. This meant that some of the input currents of one FEB were returning from the output of another (the return currents from the sFEBs was going through the return paths of pFEBs). Table 8.1 includes the details. The sFEBs and pFEBs are basically connected to the opposite sides of the quadruplet so the return current from sFEBs travels all the way across the quadruplet (as shown in figure 8.29). This charge motion on the detector plane can induce noise in the system. Two ways were used to mitigate this issue:

1. Directly connecting the strip and pad ground planes together.
2. Connecting the detector layer grounds to the outer Faraday cage which is the big reservoir for the charges (see figure 8.30).

These measures split the extra current in the detector and the current took shorter return paths to the ground reference potential, reducing the noise in the system.

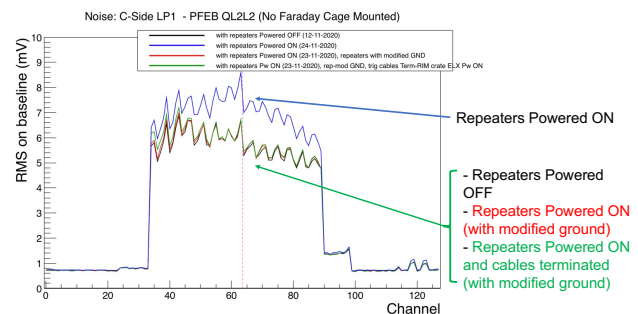
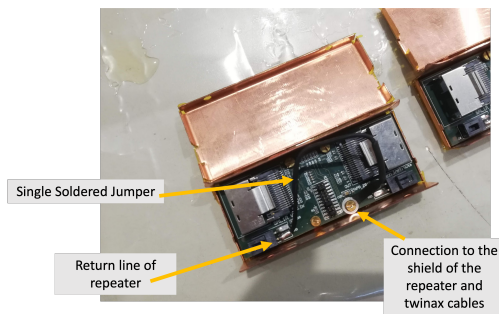
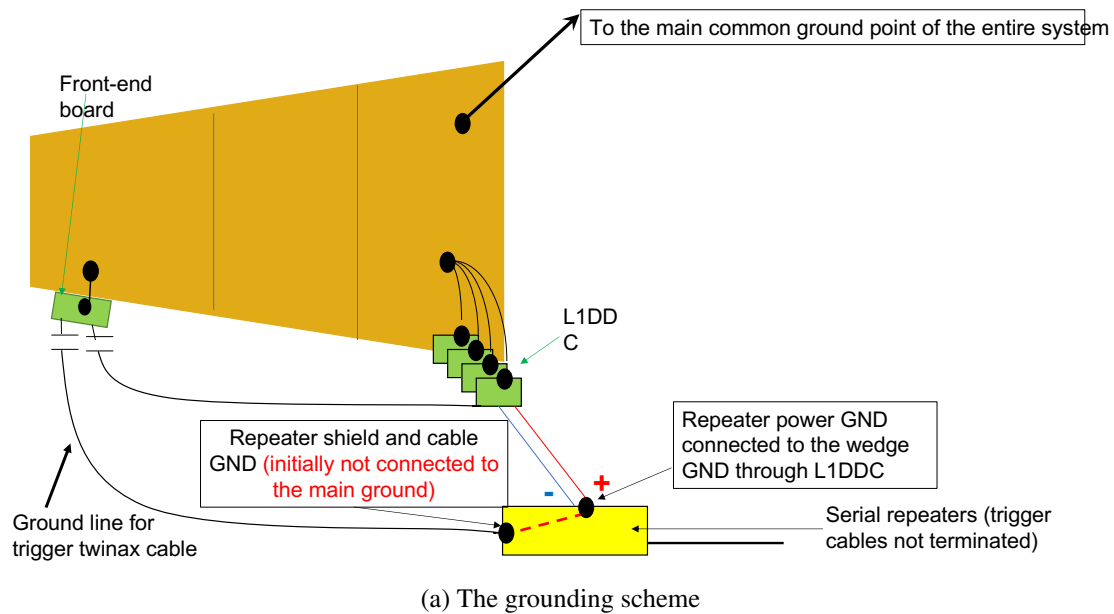


Figure 8.28: The shield of the serial repeaters was not connected to the main wedge ground (a) . After connecting it back (b), the noise level was reduced (c).

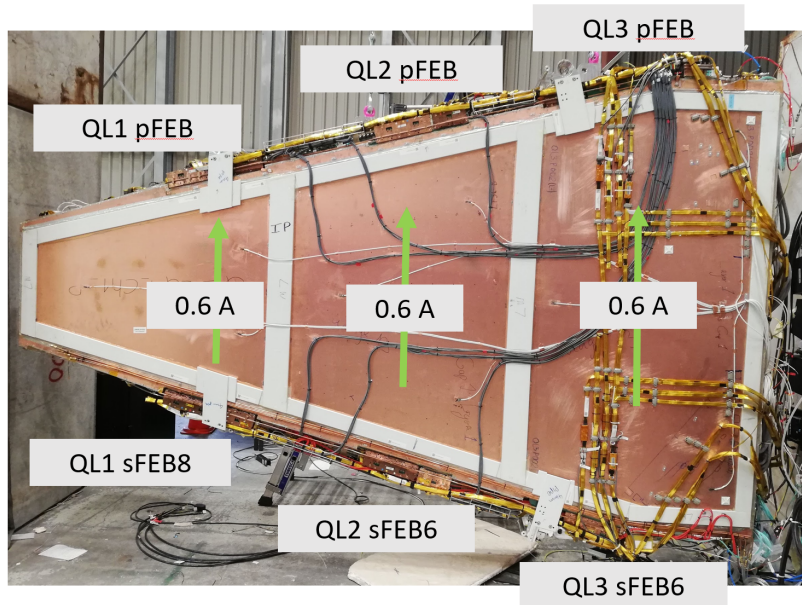


Figure 8.29: 1.8 A of DC current flows through each detector layer's ground plane because of the difference in power consumption of the sFEB and pFEB sides. This current on the ground plane translates to potential differences on the ground across the two sides of the detector. Fluctuations in the power supply levels also cause ripples across the ground level due to this current flow.

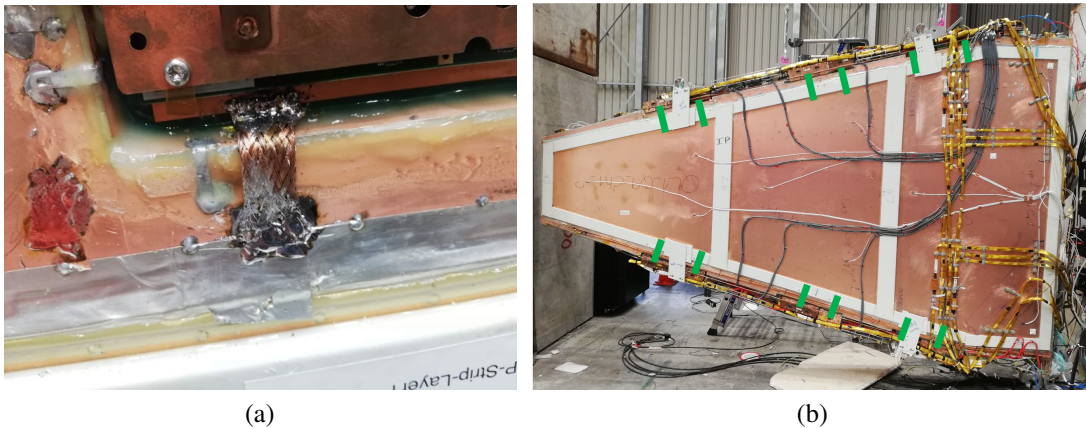


Figure 8.30: Thick soldered copper braid connection (a). These copper braids are soldered below each FEB on all detector layers. Connecting the detector layer's ground on both sides of the wedge makes the outside Faraday cage a parallel path for current to flow from one side of the wedge to the other (b). Disruptive current can therefore go outside of the wedge instead of entering the detector layer ground.

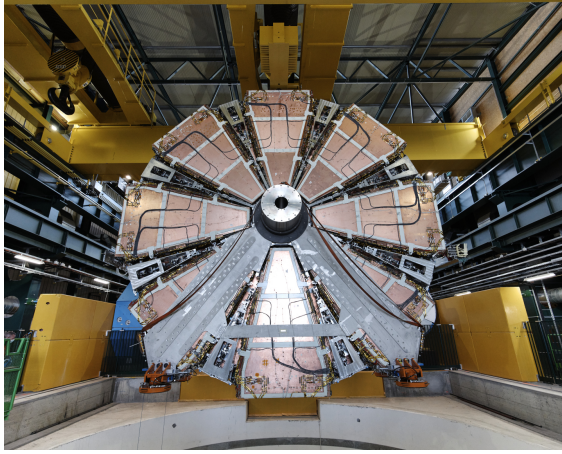
Quad	Layer	Board	Input Current	Return Current
QL3P	L3	sFEB6	1.8 A	1.3 A
QL3P	L3	pFEB	0.8 A	1.4 A
QL2P	L3	sFEB6	1.9 A	1.3 A
QL2P	L3	pFEB	0.8 A	1.4 A
QL1P	L3	sFEB8	2.3 A	1.4 A
QL1P	L3	pFEB	0.8 A	1.4 A

Table 8.1: FEB input and output currents measured on a large pivot wedge.

8.6 Current Status of the NSW Detector in Run-3

The NSW side A was lowered in the ATLAS cavern in July 2021 (see figures 8.31a and 8.31b) and side C was lowered in November 2021 (see figure 8.31c).

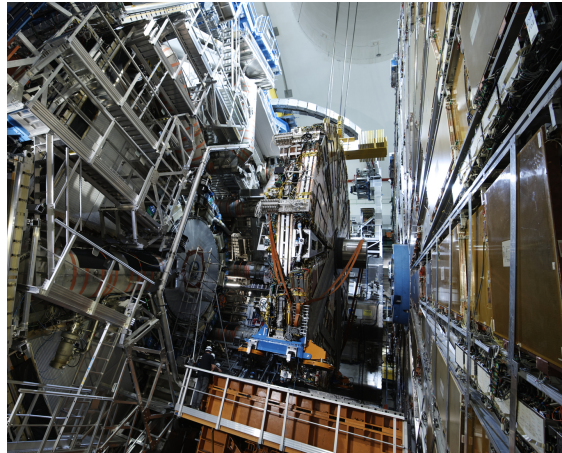
A dedicated effort is ongoing to include the NSW in the ATLAS Run-3 readout and trigger. NSW Front-end electronics are controlled by more than 70 million configuration registers. A very large number of inter-chip and inter-board high-speed data communication requires complex and dedicated calibration procedures. A dedicated team is working to complete key Front-end electronics calibrations enabling the readout of MM/sTGC during the first year of Run-3. All VMM baseline, and threshold calibrations along with the trimming scans, ROC, and GBTx phase calibrations were completed in 2022. Time calibration is very important for synchronizing trigger and readout as there are around 2.5 million channels with large variations in signal arrival time and trigger latency (fiber length, cabling, etc). It is essential to adjust the timing offset (per clock phase step and per Bunch Crossing (BC)) for correct charge hit arrival time assignment (see figure 8.32) and readout with maximum efficiency. Several campaigns were conducted to time-in the sTGC and MM using special commissioning beam (beam splashes, 900 GeV beam) and early Run 3 collisions during the LHC intensity ramp-up. All readout channels are successfully tuned for Level-1 readout.



(a)



(b)



(c)

Figure 8.31: Lowering of NSW Side A in the ATLAS experimental cavern [202] (b) (a) and the NSW side C was placed inside the ATLAS detector after lowering [203] (c).

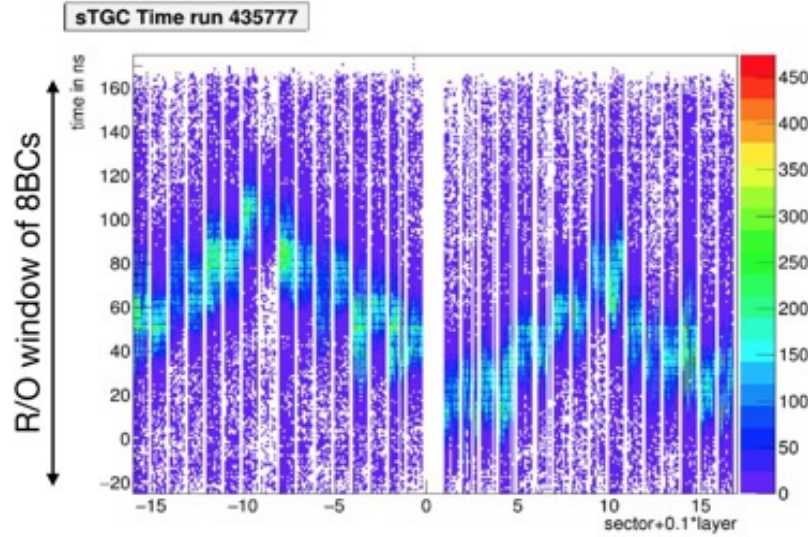


Figure 8.32: The hit arrival time per sector. It can be seen that all sectors' arrival times are within the expected eight Bunch Crossings window.

All 32 sectors of sTGC and MM joined the ATLAS run in October 2022 (see figure 8.33). The ATLAS NSW team made a lot of progress to commission the system with the full workflow (detector slow control, DAQ, online monitoring, and software/performance) operational.

Preliminary performance studies were also performed. These studies were conducted to understand the impact of the clustering algorithm, charge calibration, and detector as-built alignment on the tracking. The efficiency measurements were useful for the validation of the NSW offline reconstruction workflow. Figure 8.34 shows the detection efficiency for requiring four out of eight layer hits for each station for both MM and sTGC. The resolution measured is around ~ 100 to $200 \mu\text{m}$ going from the incident angle (with respect to the direction perpendicular to the detector plane) of 0 to 30 deg respectively.

Tireless efforts from the NSW DAQ taskforce, FELIX, and swROD teams led to significant improvements in the DAQ stability in 2022. The NSW has been included in the readout for all 32 sectors with the desired maximum Level-1 trigger rate (100 kHz) since 2023.

Development tasks are ongoing to integrate the NSW detector into the ATLAS Level-1 trigger system (for muon trigger in the End-Cap region). ATLAS reached a Level-1 trigger rate of 94 kHz in 2022 at $\langle\mu\rangle \sim 55$. Here, $\langle\mu\rangle$ is the average number of additional proton-proton collisions per bunch crossing. The plan is to go beyond $\langle\mu\rangle \sim 60$ which requires the inclusion of all phase-I upgrade systems (LAr and NSW) in the Level-1 trigger to maintain a bandwidth of 100 kHz (5% downtime).

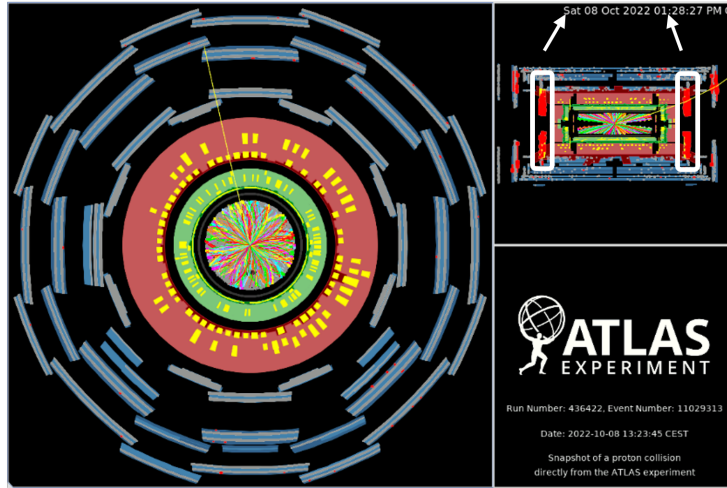


Figure 8.33: Event display with NSW A and C included. The small event display in the right-top corner shows both NSW A and C included.

ATLAS decided to integrate NSW to join the Big Wheel Sector Logic (SL) for level-1 muon trigger in 2023 with a step-wise implementation. A task force was formed in February 2023 to prioritize the commissioning of the sTGC pad-based trigger while the MM trigger and the sTGC strip-based trigger development going in parallel.

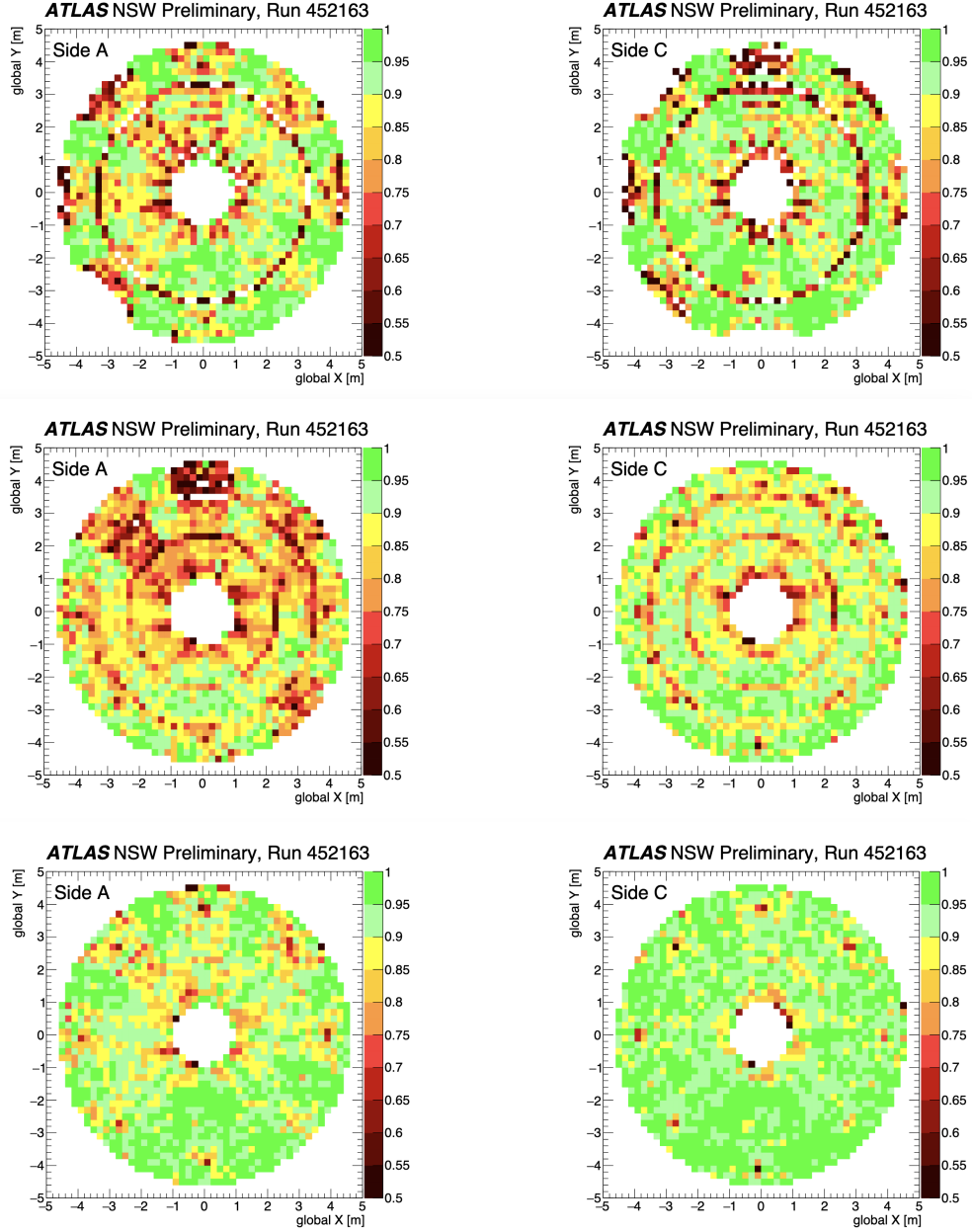


Figure 8.34: Efficiency measurement using sTGC NSW side A (top left), sTGC NSW side C (top right), MM NSW side A (middle left), MM NSW side C (middle right), combined NSW side A (bottom left), and combined NSW side C (bottom right) [204].

APPENDICES

A List of Signal and Background samples

The WZ signal samples used are listed in Table A.1.

DSID	Process	Generators	PDF	Events	Filter eff.	Cross-section [pb]
507019	$W_0Z_0 \rightarrow \ell\nu\ell\ell$ ($p_T^\ell \geq 150$ GeV) ($\ell = e, \mu$) final state	MADGRAPH 1 + PYTHIA 8	NLO NNPDF30	~350K	1.0	0.0024187
507020	$W_0Z_0 \rightarrow \ell\nu\ell\ell$ ($p_T^\ell < 150$ GeV) ($\ell = e, \mu$) final state	MADGRAPH 1 + PYTHIA 8	NLO NNPDF30	~550K	1.0	0.020537
507021	$W_0Z_T \rightarrow \ell\nu\ell\ell$ ($p_T^\ell \geq 150$ GeV) ($\ell = e, \mu$) final state	MADGRAPH 1 + PYTHIA 8	NLO NNPDF30	~280K	1.0	0.0085869
507022	$W_0Z_T \rightarrow \ell\nu\ell\ell$ ($p_T^\ell < 150$ GeV) ($\ell = e, \mu$) final state	MADGRAPH 1 + PYTHIA 8	NLO NNPDF30	~660K	1.0	0.061592
507023	$W_TZ_0 \rightarrow \ell\nu\ell\ell$ ($p_T^\ell \geq 150$ GeV) ($\ell = e, \mu$) final state	MADGRAPH 1 + PYTHIA 8	NLO NNPDF30	~260K	1.0	0.0025554
507024	$W_TZ_0 \rightarrow \ell\nu\ell\ell$ ($p_T^\ell < 150$ GeV) ($\ell = e, \mu$) final state	MADGRAPH 1 + PYTHIA 8	NLO NNPDF30	~660K	1.0	0.065272
507025	$W_TZ_T \rightarrow \ell\nu\ell\ell$ ($p_T^\ell \geq 150$ GeV) ($\ell = e, \mu$) final state	MADGRAPH 1 + PYTHIA 8	NLO NNPDF30	~15M	1.0	0.025954
507026	$W_TZ_T \rightarrow \ell\nu\ell\ell$ ($p_T^\ell < 150$ GeV) ($\ell = e, \mu$) final state	MADGRAPH 1 + PYTHIA 8	NLO NNPDF30	~1.66M	1.0	0.30445
507027	$W_0Z_0 \rightarrow \ell\nu\ell\ell$ ($p_T^\ell \geq 150$ GeV) ($\ell = e, \mu, \tau$) final state with τ decays	MADGRAPH 1 + PYTHIA 8	NLO NNPDF30	~40K	0.19282	0.003025
507028	$W_0Z_0 \rightarrow \ell\nu\ell\ell$ ($p_T^\ell < 150$ GeV) ($\ell = e, \mu, \tau$) final state with τ decays	MADGRAPH 1 + PYTHIA 8	NLO NNPDF30	~60K	0.17178	0.02567
507029	$W_0Z_T \rightarrow \ell\nu\ell\ell$ ($p_T^\ell \geq 150$ GeV) ($\ell = e, \mu, \tau$) final state with τ decays	MADGRAPH 1 + PYTHIA 8	NLO NNPDF30	~70K	0.20178	0.01072
507030	$W_0Z_T \rightarrow \ell\nu\ell\ell$ ($p_T^\ell < 150$ GeV) ($\ell = e, \mu, \tau$) final state with τ decays	MADGRAPH 1 + PYTHIA 8	NLO NNPDF30	~160K	0.17366	0.076918
507031	$W_TZ_0 \rightarrow \ell\nu\ell\ell$ ($p_T^\ell \geq 150$ GeV) ($\ell = e, \mu, \tau$) final state with τ decays	MADGRAPH + PYTHIA 8	NLO NNPDF30	~30K	0.20127	0.003185
507032	$W_TZ_0 \rightarrow \ell\nu\ell\ell$ ($p_T^\ell < 150$ GeV) ($\ell = e, \mu, \tau$) final state with τ decays	MADGRAPH + PYTHIA 8	NLO NNPDF30	~160K	0.17607	0.081536
507033	$W_TZ_T \rightarrow \ell\nu\ell\ell$ ($p_T^\ell \geq 150$ GeV) ($\ell = e, \mu, \tau$) final state with τ decays	MADGRAPH + PYTHIA 8	NLO NNPDF30	~350K	0.19491	0.03242
507034	$W_TZ_T \rightarrow \ell\nu\ell\ell$ ($p_T^\ell < 150$ GeV) ($\ell = e, \mu, \tau$) final state with τ decays	MADGRAPH 1 + PYTHIA 8	NLO NNPDF30	~300K	0.16602	0.38058
364253	$WZ \rightarrow \ell\nu\ell\ell$ ($\ell = e, \mu, \tau$)	SHERPA 2.2.2	NNLO NNPDF30	~74M	1.00	4.57
361601	$WZ \rightarrow \ell\nu\ell\ell$ ($\ell = e, \mu, \tau$)	POWHEG+PYTHIA 8	NLO CT10	~30M	1.00	4.51
361293	$WZ \rightarrow \ell\nu\ell\ell$ ($\ell = e, \mu, \tau$)	MADGRAPH 1 + McAtNlo + PYTHIA 8	NNLO NNPDF30	~3.9M	0.34	1.70

Table A.1: Summary of signal MC samples used.

DSID	Process	Generators	PDF	Events	Filter eff.	Cross-section [pb]
364250	$q\bar{q} \rightarrow ZZ \rightarrow \ell\ell\ell\ell$	SHERPA 2.2.2	NNLO NNPDF30	18758127	1.00	1.252
364283	$ZZ \rightarrow \ell\ell\ell\ell$ EW6	SHERPA 2.2.2	NNLO NNPDF30	284282	1.0	0.011
345705	$gg \rightarrow \ell\ell\ell\ell$ 0M4l130	SHERPA 2.2.2	NNLO NNPDF30	218297	1.00	0.0099
345706	$gg \rightarrow \ell\ell\ell\ell$ 130M4l	SHERPA 2.2.2	NNLO NNPDF30	1559741	1.00	0.010
361106	$Z \rightarrow ee$	Powheg+Pythia8	CT10	10046079	1.00	1901.1
361107	$Z \rightarrow \mu\mu$	Powheg+Pythia8	CT10	13091504	1.00	1901.1
361108	$Z \rightarrow \tau\tau$	Powheg+Pythia8	CT10	174191	1.00	1901.1
366140	$Z\gamma \rightarrow e e \gamma$ ($7 < p_T^\gamma < 15$)	SHERPA 2.2.2	NNLO NNPDF30	97104	1.00	46.293
366141	$Z\gamma \rightarrow e e \gamma$ ($15 < p_T^\gamma < 35$)	SHERPA 2.2.2	NNLO NNPDF30	465414	1.00	29.281
366142	$Z\gamma \rightarrow e e \gamma$ ($35 < p_T^\gamma < 70$)	SHERPA 2.2.2	NNLO NNPDF30	55151	1.00	5.1577
366143	$Z\gamma \rightarrow e e \gamma$ ($70 < p_T^\gamma < 140$)	SHERPA 2.2.2	NNLO NNPDF30	48792	1.00	0.40363
366144	$Z\gamma \rightarrow e e \gamma$ ($p_T^\gamma > 140$)	SHERPA 2.2.2	NNLO NNPDF30	68773	1.00	0.053018
366145	$Z\gamma \rightarrow \mu\mu\gamma$ ($7 < p_T^\gamma < 15$)	SHERPA 2.2.2	NNLO NNPDF30	135223	1.00	46.276
366146	$Z\gamma \rightarrow \mu\mu\gamma$ ($10 < p_T^\gamma < 35$)	SHERPA 2.2.2	NNLO NNPDF30	643346	1.00	29.28
366147	$Z\gamma \rightarrow \mu\mu\gamma$ ($35 < p_T^\gamma < 70$)	SHERPA 2.2.2	NNLO NNPDF30	78275	1.00	5.1566
366148	$Z\gamma \rightarrow \mu\mu\gamma$ ($70 < p_T^\gamma < 140$)	SHERPA 2.2.2	NNLO NNPDF30	68585	1.00	0.40322
366149	$Z\gamma \rightarrow \mu\mu\gamma$ ($p_T^\gamma > 140$)	SHERPA 2.2.2	NNLO NNPDF30	79303	1.00	0.05289
364242	$WWW \rightarrow 3\ell 3\nu$	SHERPA 2.2.2	NNLO NNPDF30	59628	1.00	0.0072
364243	$WWZ \rightarrow 4\ell 2\nu$	SHERPA 2.2.2	NNLO NNPDF30	121997	1.00	0.0018
364244	$WWZ \rightarrow 2\ell 4\nu$	SHERPA 2.2.2	NNLO NNPDF30	5263	1.00	0.0035
364245	$WZZ \rightarrow 5\ell 1\nu$	SHERPA 2.2.2	NNLO NNPDF30	135691	1.00	0.00019
364246	$WZZ \rightarrow 3\ell 3\nu$	SHERPA 2.2.2	NNLO NNPDF30	63202	0.45	0.0017
364247	$ZZZ \rightarrow 6\ell 0\nu$	SHERPA 2.2.2	NNLO NNPDF30	111922	1.00	0.000014
364248	$ZZZ \rightarrow 4\ell 2\nu$	SHERPA 2.2.2	NNLO NNPDF30	73266	0.22	0.00038
364249	$ZZZ \rightarrow 2\ell 4\nu$	SHERPA 2.2.2	NNLO NNPDF30	3190	0.44	0.00038
410470	$t\bar{t}(\geq 1\ell)$	POWHEG+PYTHIA 8		24549057	0.54	729.7
410218	$t\bar{t}ee$	aMcAtNlo+PYTHIA 8		2131415	1.0	0.037
410219	$t\bar{t}\mu\mu$	aMcAtNlo+PYTHIA 8		2492926	1.0	0.037
410155	$t\bar{t}W$	aMcAtNlo+PYTHIA 8		1951871	1.0	0.548
364739	iZ OF	MADGRAPH + PYTHIA 8	NLO NNPDF30	1398000	1.00	0.015
364740	iZ OF	MADGRAPH + PYTHIA 8	NLO NNPDF30	1996000	1.00	0.026
364741	iZ SF	MADGRAPH + PYTHIA 8	NLO NNPDF30	699000	1.00	0.0077
364742	iZ SF	MADGRAPH + PYTHIA 8	NLO NNPDF30	898000	1.00	0.013

DSID	Process	Generators	PDF	Events	Filter eff.	Cross-section [pb]
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Table A.2: Summary of background MC simulation.

B Good Run List Used

The following Good Run Lists were used:

For 2015 data: `/cvmfs/atlas.cern.ch/repo/sw/database/GroupData/GoodRunsLists/data15_13TeV/20170619/data15_13TeV.periodAllYear_DetStatus-v89-pro21-02_Unknown_PHYS_StandardGRL_All_Good_25ns.xml`

For 2016 data: `/cvmfs/atlas.cern.ch/repo/sw/database/GroupData/GoodRunsLists/data16_13TeV/20180129/data16_13TeV.periodAllYear_DetStatus-v89-pro21-01_DQDefects-00-02-04_PHYS_StandardGRL_All_Good_25ns.xml`

For 2017 data: `/cvmfs/atlas.cern.ch/repo/sw/database/GroupData/GoodRunsLists/data17_13TeV/20180619/data17_13TeV.periodAllYear_DetStatus-v99-pro22-01_Unknown_PHYS_StandardGRL_All_Good_25ns-Triggerno17e33prim.xml`

For 2018 data: `/cvmfs/atlas.cern.ch/repo/sw/database/GroupData/GoodRunsLists/data18_13TeV/20190318/data18_13TeV.periodAllYear_DetStatus-v102-pro22-04_Unknown_PHYS_StandardGRL_All_Good_25ns-Triggerno17e33prim.xml`

C (NLO QCD+EW)/(NLO QCD) corrections

Comparable distributions are shown in figures C.1, C.2, C.3, C.4 and C.5 for the 00 enhanced region with the additional $p_T^Z > 100$ region and in figures C.7, C.8, C.9, C.10 and C.11 for the 00 enhanced region with the additional $p_T^Z > 200$ region for most variables present in the BDT. In addition, a comparison of NLO (QCD+EW)/NLO (QCD) between the four polarizations is listed to show the size of the NLO EW effect for different variables. The overall NLO EW effect reduces the cross section for each individual polarization state. However, the T0 and 0T cross sections only change by at most 4%, while the 00 and TT cross sections change by about 13%. However, these changes in cross-sections will have small effects on the polarization fraction measurements since only shapes are used in the final fit.

However, for many kinematic distributions, the EW corrections in this region are sizeable and

non-flat between various polarization states. This can be seen particularly well for the transverse momentum of the electron above 200 GeV. For that variable, the corrections for the T0 state are slightly positive and increasing with higher transverse momentum whereas for the 0T polarization, they are slightly negative and decreasing. Furthermore, the 00 and TT polarizations share the same corrections that are negative and further decrease with higher energies.

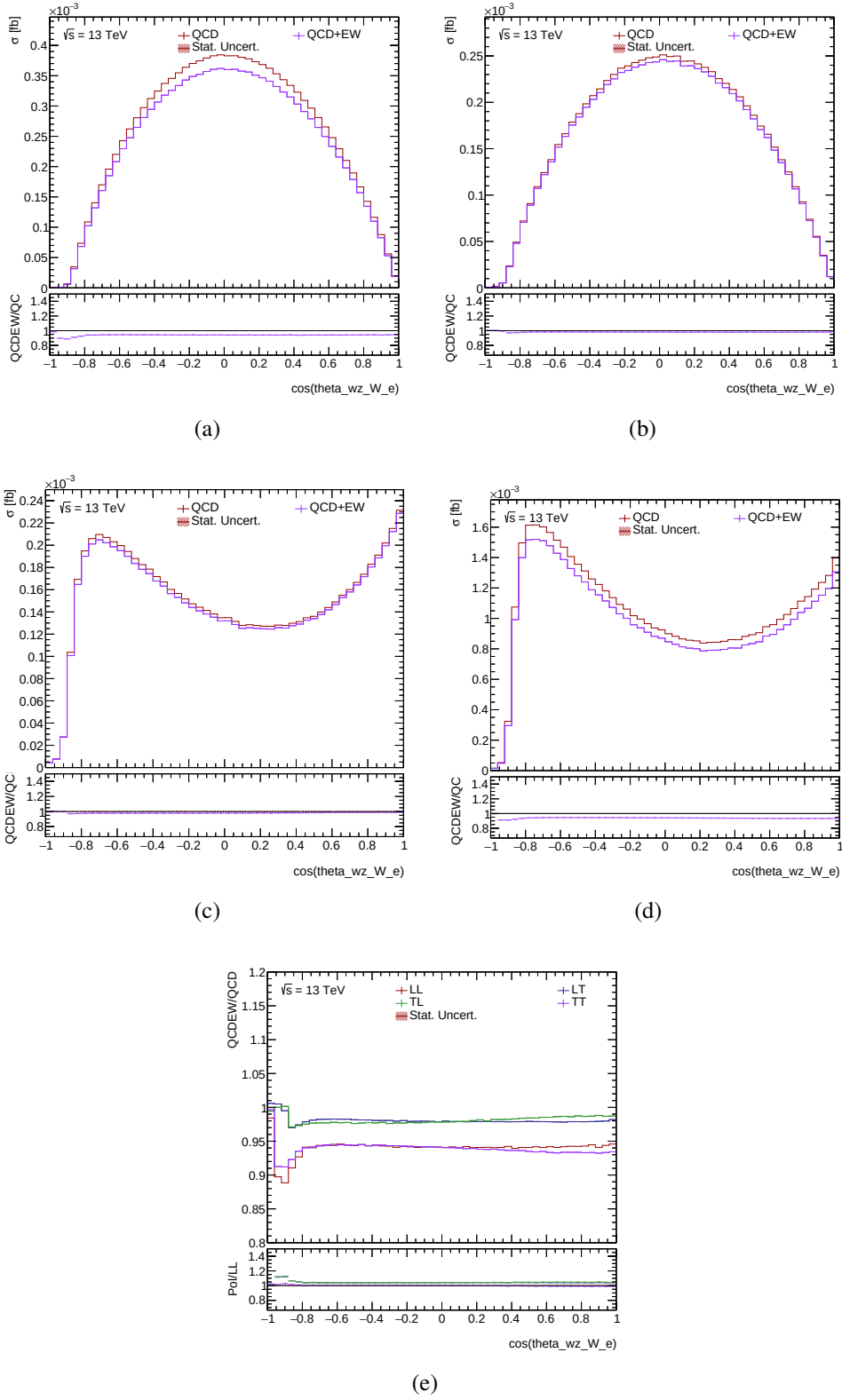


Figure C.1: Comparison between NLO QCD + EW and NLO QCD of $\cos\theta^\ell(W)$ for the four polarizations in the 00-enhanced signal region with $p_T^Z > 100$ GeV. Shown are the comparisons for 00 (a), 0T (b), T0 (c), and TT (d), and NLO(QCD+EW)/NLO(QCD) for all four polarizations overlayed (e).

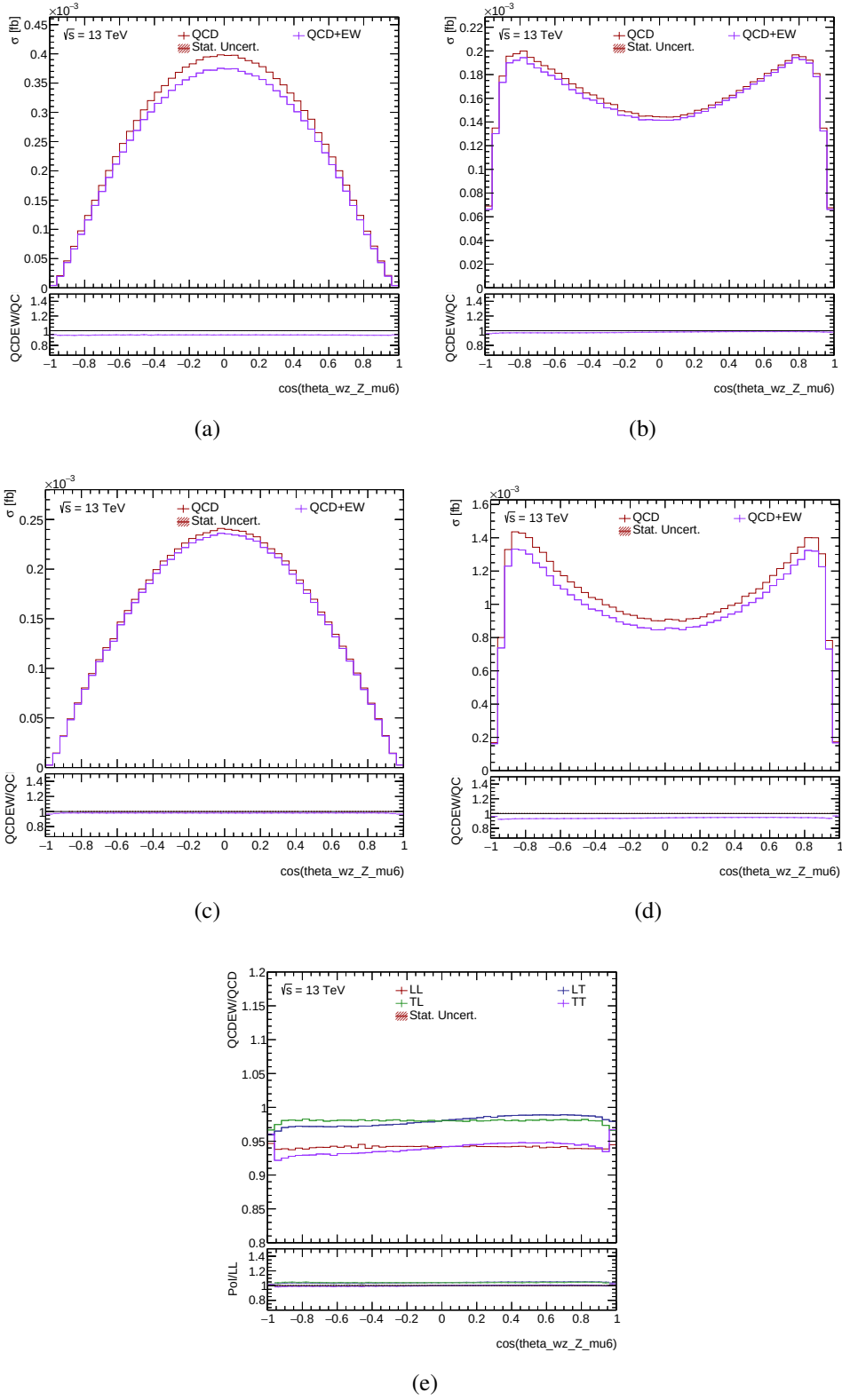


Figure C.2: Comparison between NLO QCD + EW and NLO QCD of $\cos\theta^\ell(Z)$ for the four polarizations in the 00-enhanced signal region with $p_T^Z > 100$ GeV. Shown are the comparisons for 00 (a), 0T (b), T0 (c), and TT (d), and NLO(QCD+EW)/NLO(QCD) for all four polarizations overlaid (e).

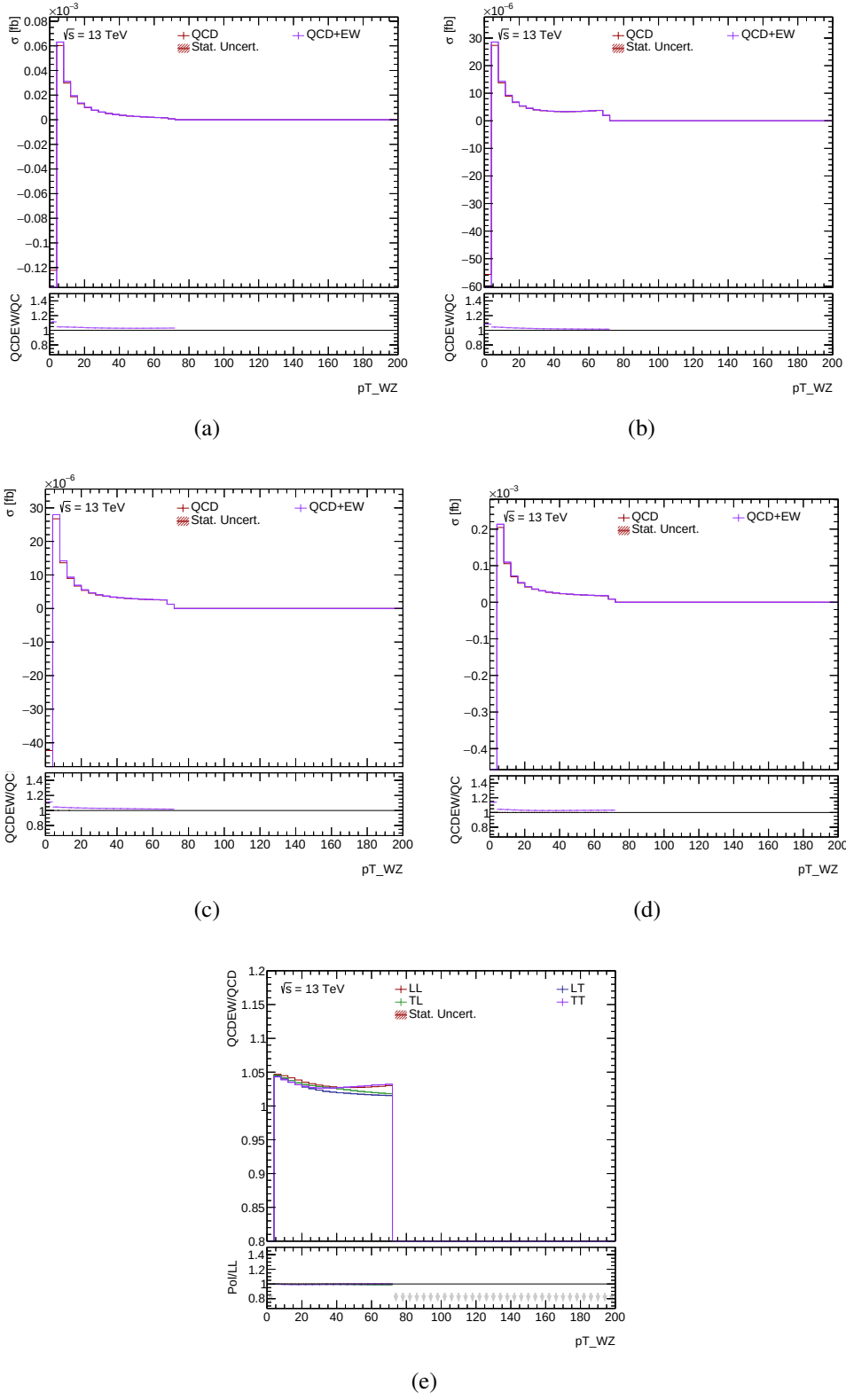


Figure C.3: Comparison between NLO QCD + EW and NLO QCD of p_T^{WZ} for the four polarizations in the 00-enhanced signal region with $p_T^Z > 100$ GeV. Shown are the comparisons for 00 (a), 0T (b), T0 (c), and TT (d), and NLO(QCD+EW)/NLO(QCD) for all four polarizations overlayed (e).

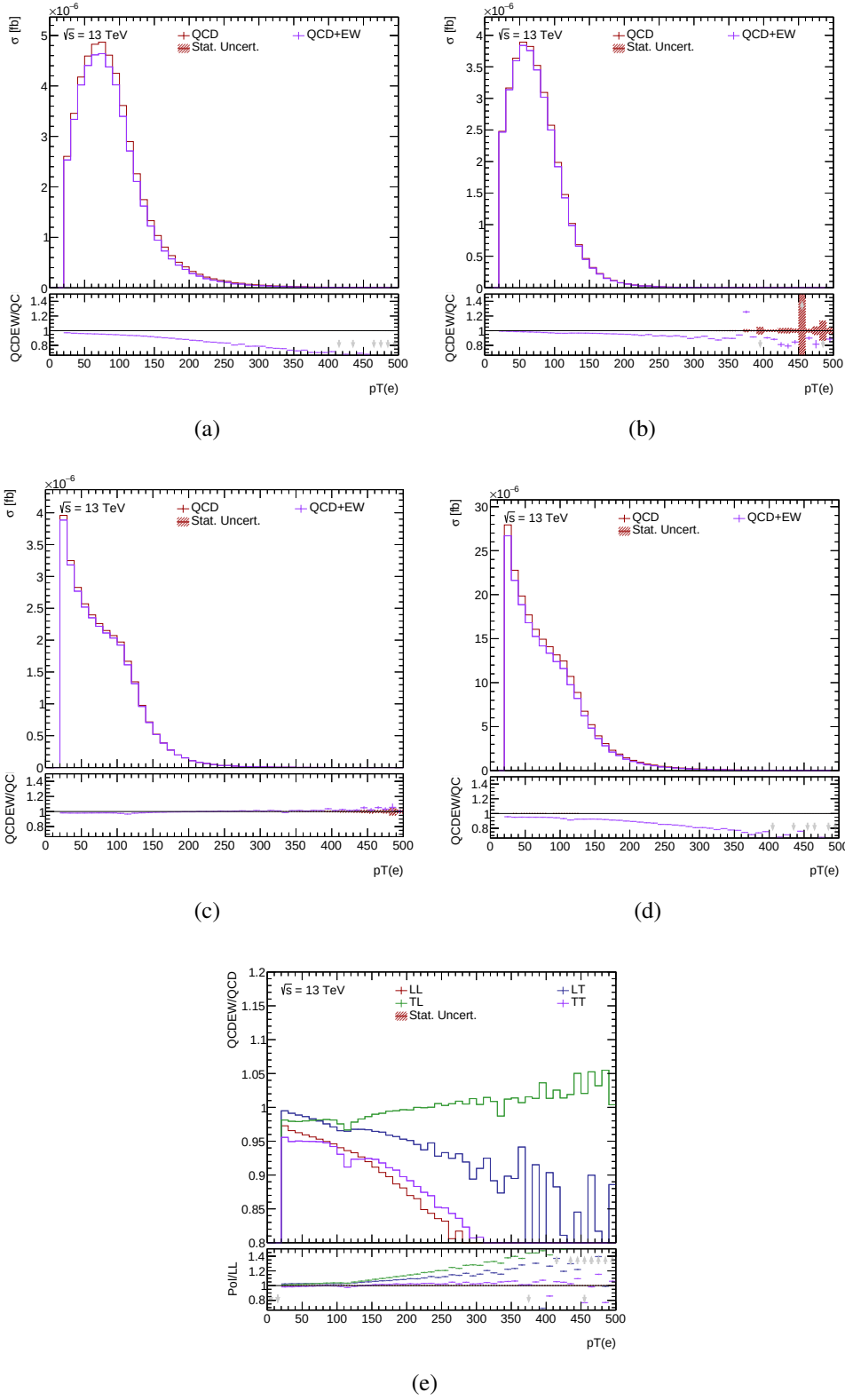


Figure C.4: Comparison between NLO QCD + EW and NLO QCD of $p_T^\ell(W)$ for the four polarizations in the 00-enhanced signal region with $p_T^Z > 100$ GeV. Shown are the comparisons for 00 (a), 0T (b), T0 (c), and TT (d), and NLO(QCD+EW)/NLO(QCD) for all four polarizations overlaid (e).

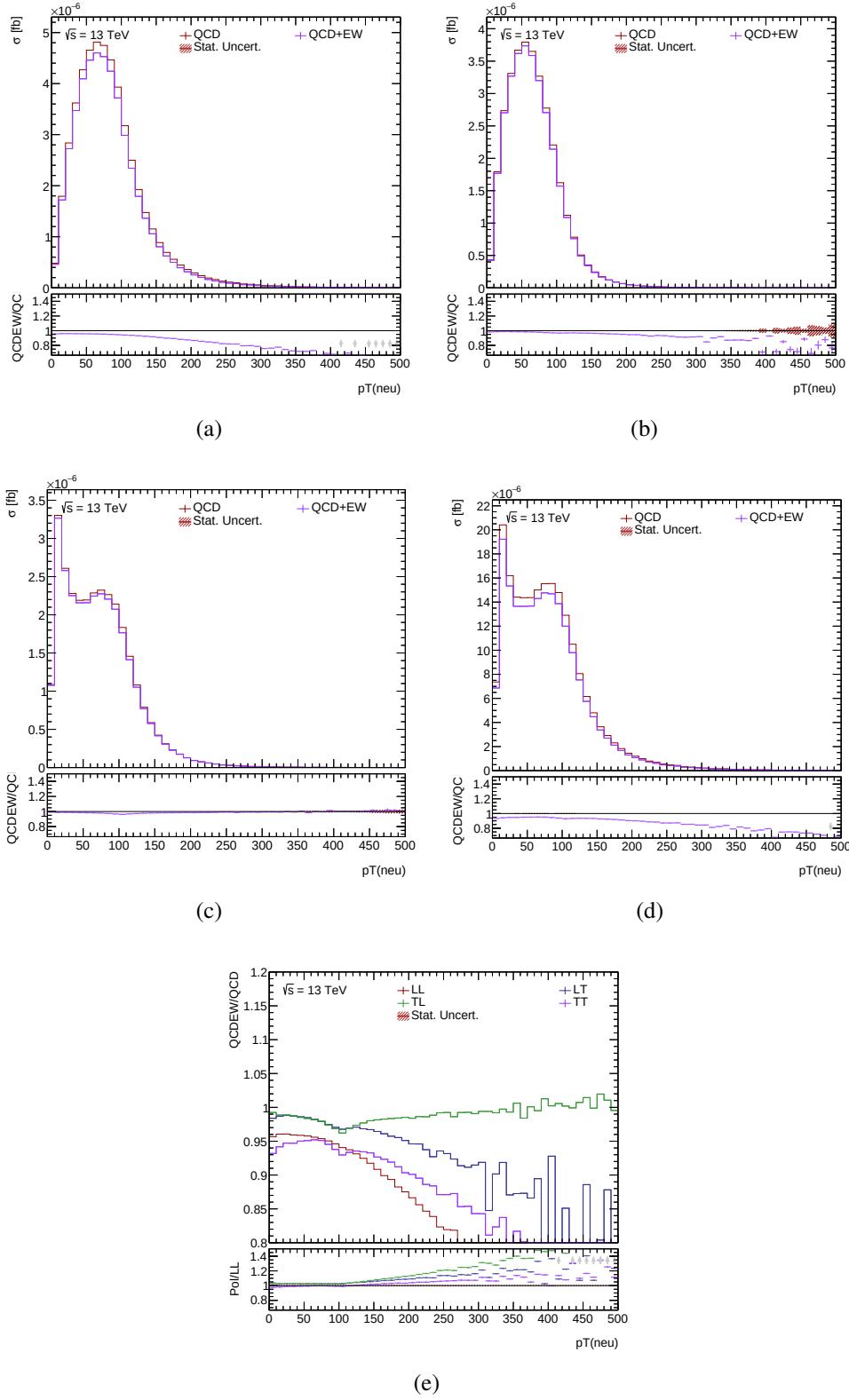


Figure C.5: Comparison between NLO QCD + EW and NLO QCD of $p_T(\nu)$ for the four polarizations in the 00-enhanced signal region with $p_T^Z > 100$ GeV. Shown are the comparisons for 00 (a), 0T (b), T0 (c), and TT (d), and NLO(QCD+EW)/NLO(QCD) for all four polarizations overlaid (e).

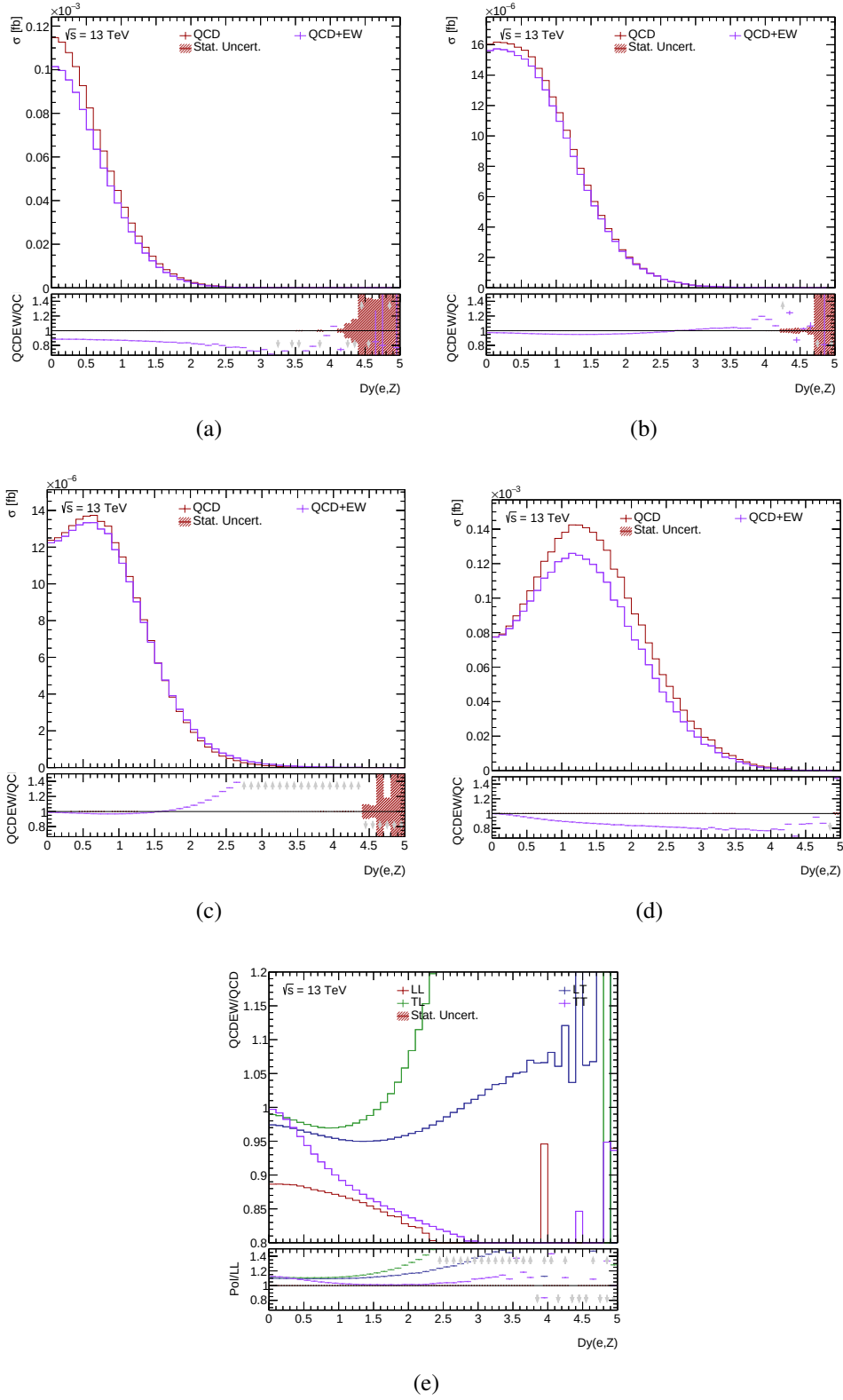
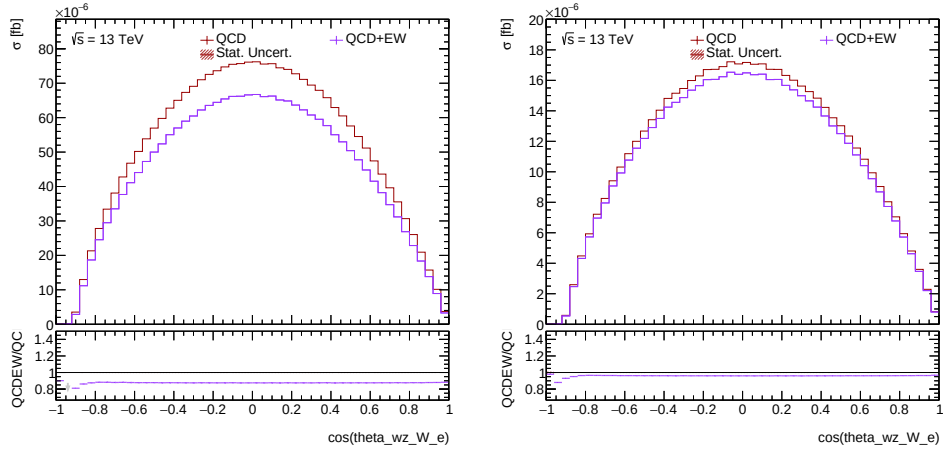
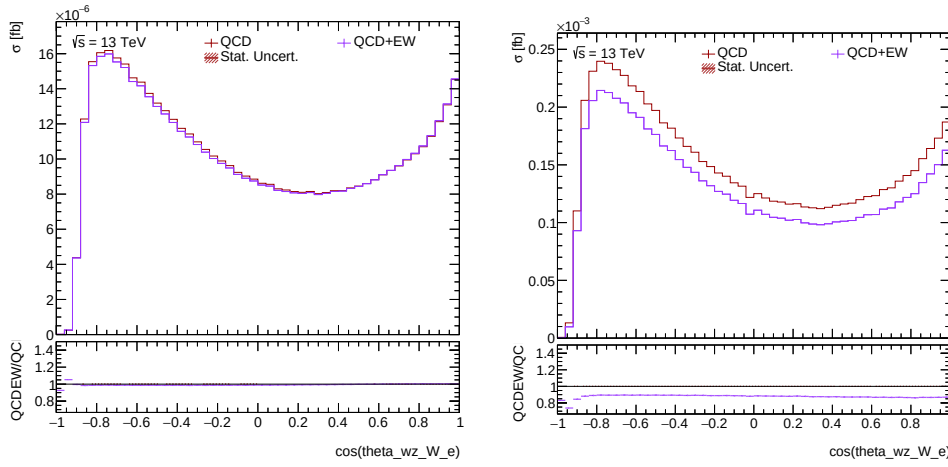


Figure C.6: Comparison between NLO QCD + EW and NLO QCD of ΔY_{3Z} for the four polarizations in the 00-enhanced signal region with $p_T^Z > 200$ GeV. Shown are the comparisons for 00 (a), 0T (b), T0 (c), and TT (d), and NLO(QCD+EW)/NLO(QCD) for all four polarizations overlayed (e).



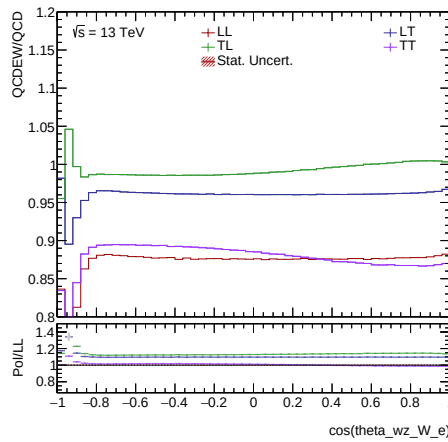
(a)

(b)



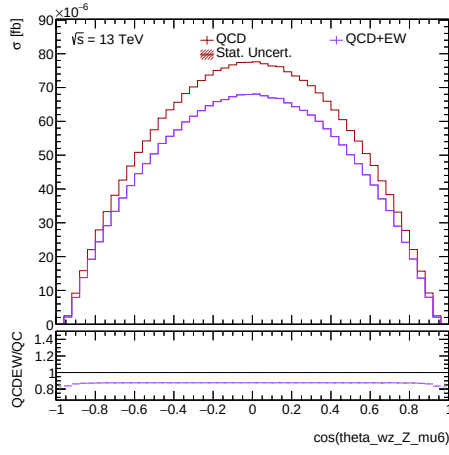
(c)

(d)

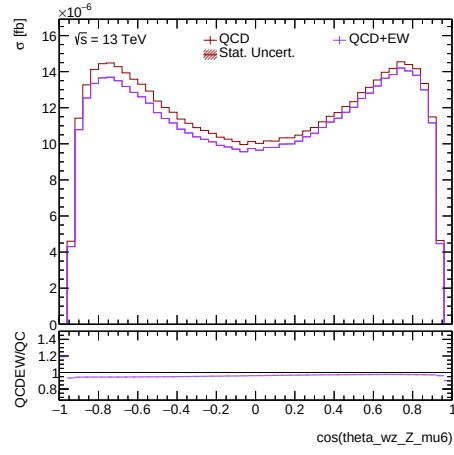


(e)

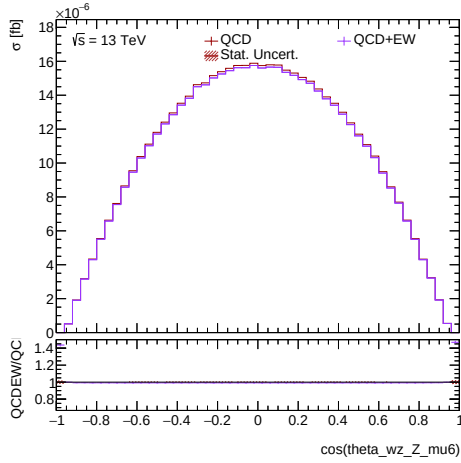
Figure C.7: Comparison between NLO QCD + EW and NLO QCD of $\cos\theta^\ell(W)$ for the four polarizations in the 00-enhanced signal region with $p_T^Z > 200$ GeV. Shown are the comparisons for 00 (a), 0T (b), T0 (c), and TT (d), and NLO(QCD+EW)/NLO(QCD) for all four polarizations overlaid (e).



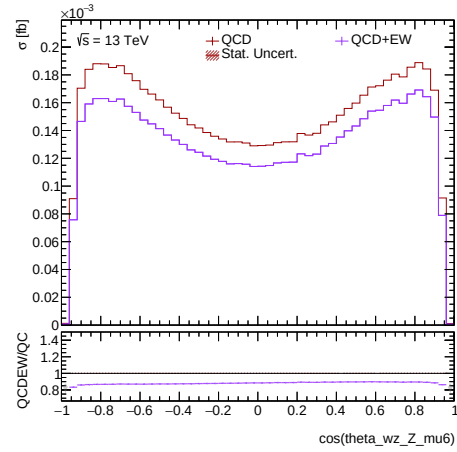
(a)



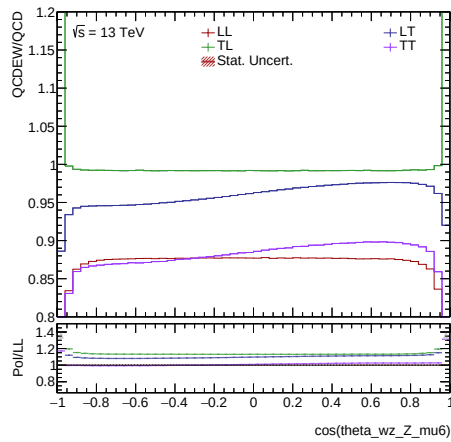
(b)



(c)



(d)



(e)

Figure C.8: Comparison between NLO QCD + EW and NLO QCD of $\cos\theta^\ell(Z)$ for the four polarizations in the 00-enhanced signal region with $p_T^Z > 200$ GeV. Shown are the comparisons for 00 (a), 0T (b), T0 (c), and TT (d), and NLO(QCD+EW)/NLO(QCD) for all four polarizations overlaid (e).

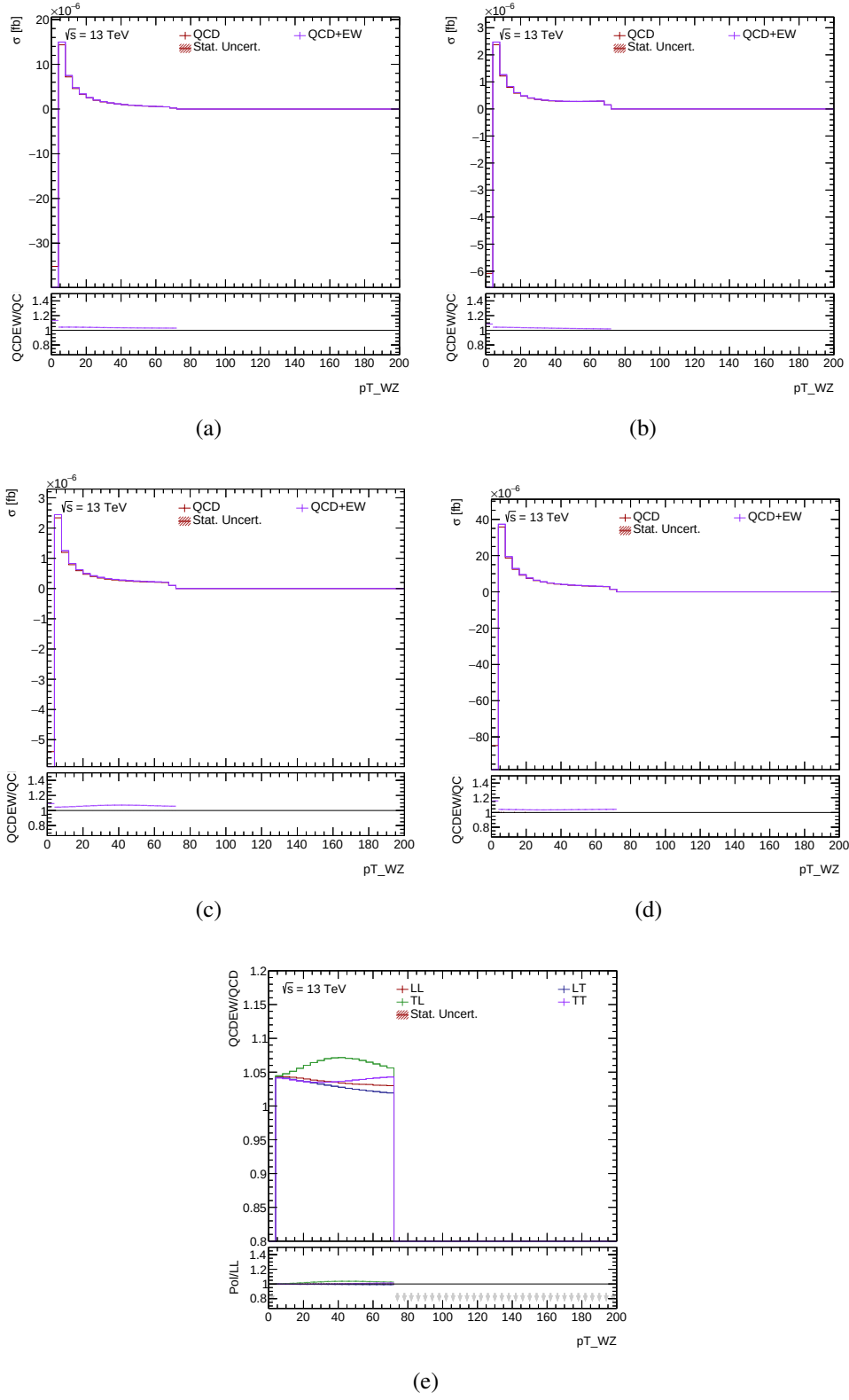


Figure C.9: Comparison between NLO QCD + EW and NLO QCD of p_T^{WZ} for the four polarizations in the 00-enhanced signal region with $p_T^Z > 200$ GeV. Shown are the comparisons for 00 (a), 0T (b), T0 (c), and TT (d), and NLO(QCD+EW)/NLO(QCD) for all four polarizations overlayed (e).

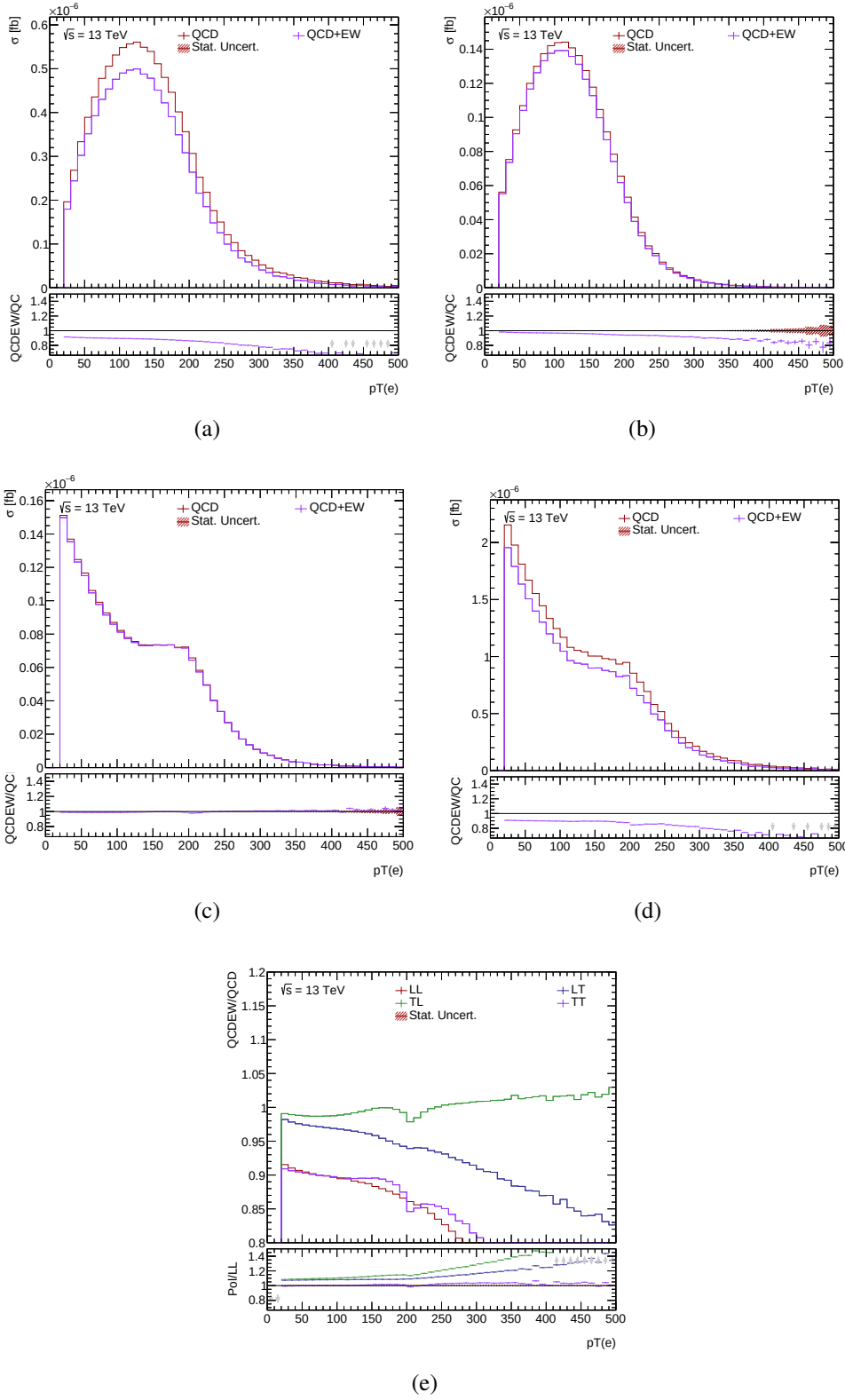


Figure C.10: Comparison between NLO QCD + EW and NLO QCD of $p_T^\ell(W)$ for the four polarizations in the 00-enhanced signal region with $p_T^Z > 200$ GeV. Shown are the comparisons for 00 (a), 0T (b), T0 (c), and TT (d), and NLO(QCD+EW)/NLO(QCD) for all four polarizations overlayed (e).

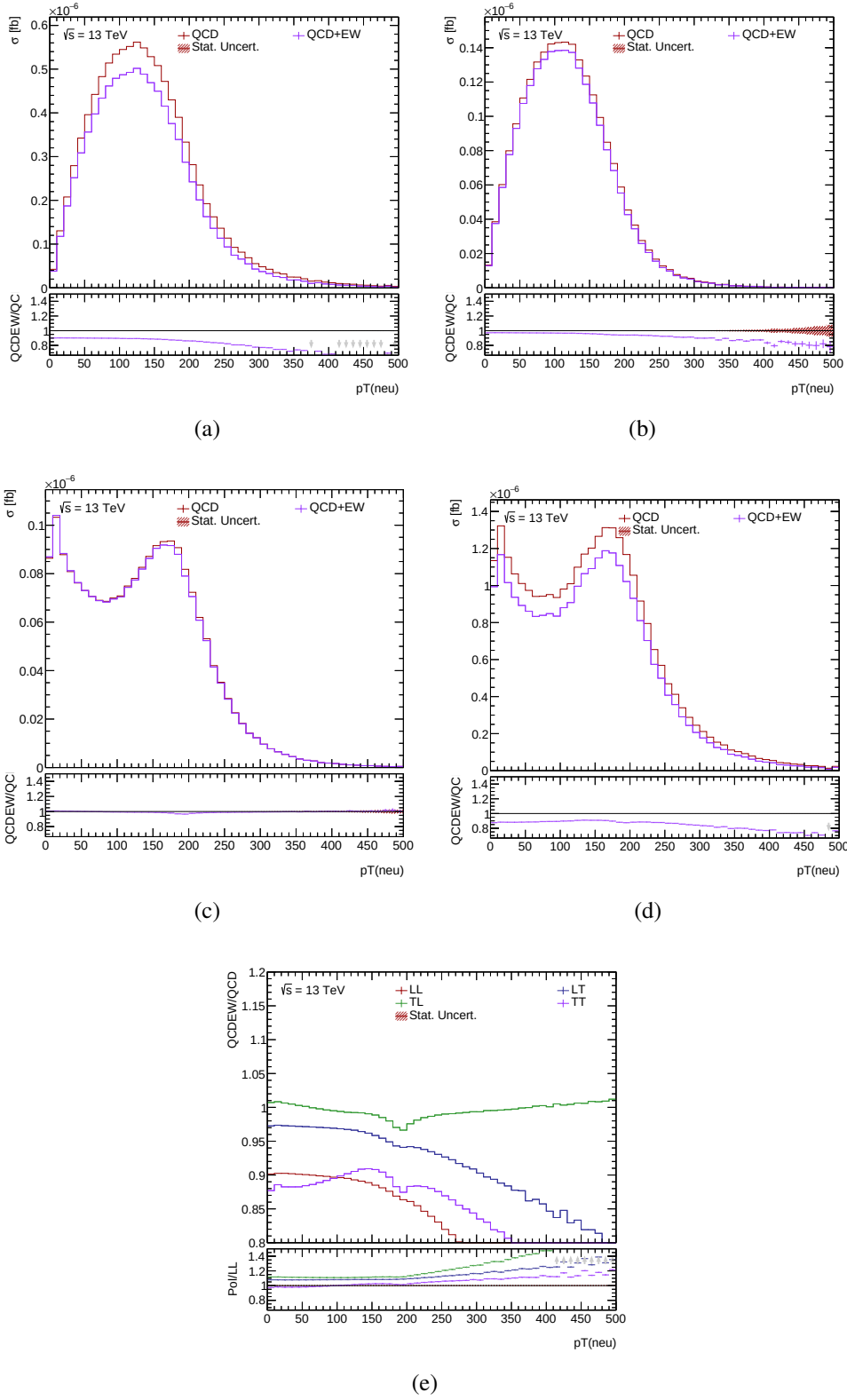


Figure C.11: Comparison between NLO QCD + EW and NLO QCD of $p_T(\nu)$ for the four polarizations in the 00-enhanced signal region with $p_T^Z > 200$ GeV. Shown are the comparisons for 00 (a), 0T (b), T0 (c), and TT (d), and NLO(QCD+EW)/NLO(QCD) for all four polarizations overlayed (e).

D Data-MC Comparisons for RAZ regions

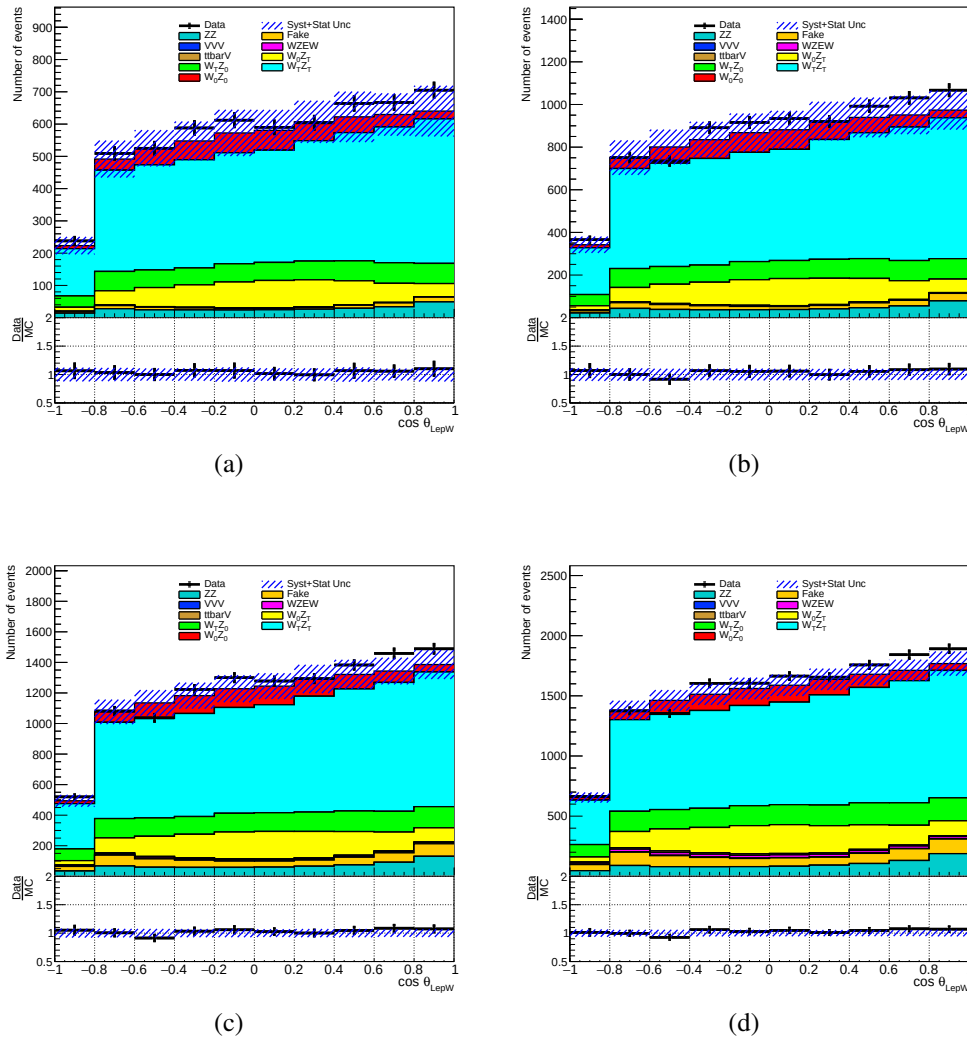


Figure D.1: Comparison between data and prediction for the $\cos\theta_\ell^*(W)$ distribution in the $p_T^{WZ} < 10$ GeV region (a), $p_T^{WZ} < 20$ GeV region (b), $p_T^{WZ} < 40$ GeV region (c), and $p_T^{WZ} < 70$ GeV region (d). This uses an integrated luminosity of 140.1 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$.

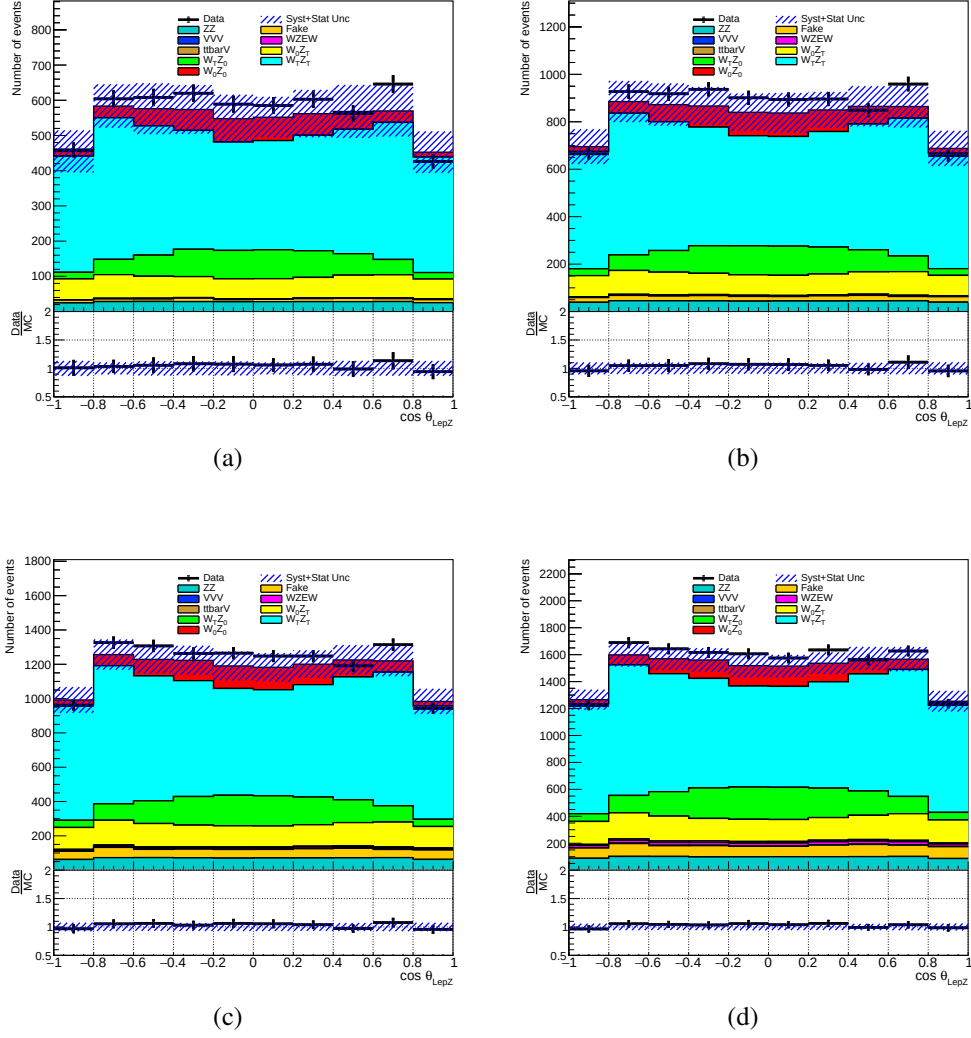


Figure D.2: Comparison between data and prediction for the $\cos \theta_{\ell^*}^*(Z)$ distribution in the $p_T^{WZ} < 10$ GeV region (a), $p_T^{WZ} < 20$ GeV region (b), $p_T^{WZ} < 40$ GeV region (c), and $p_T^{WZ} < 70$ GeV region (d). This uses an integrated luminosity of 140.1 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$.

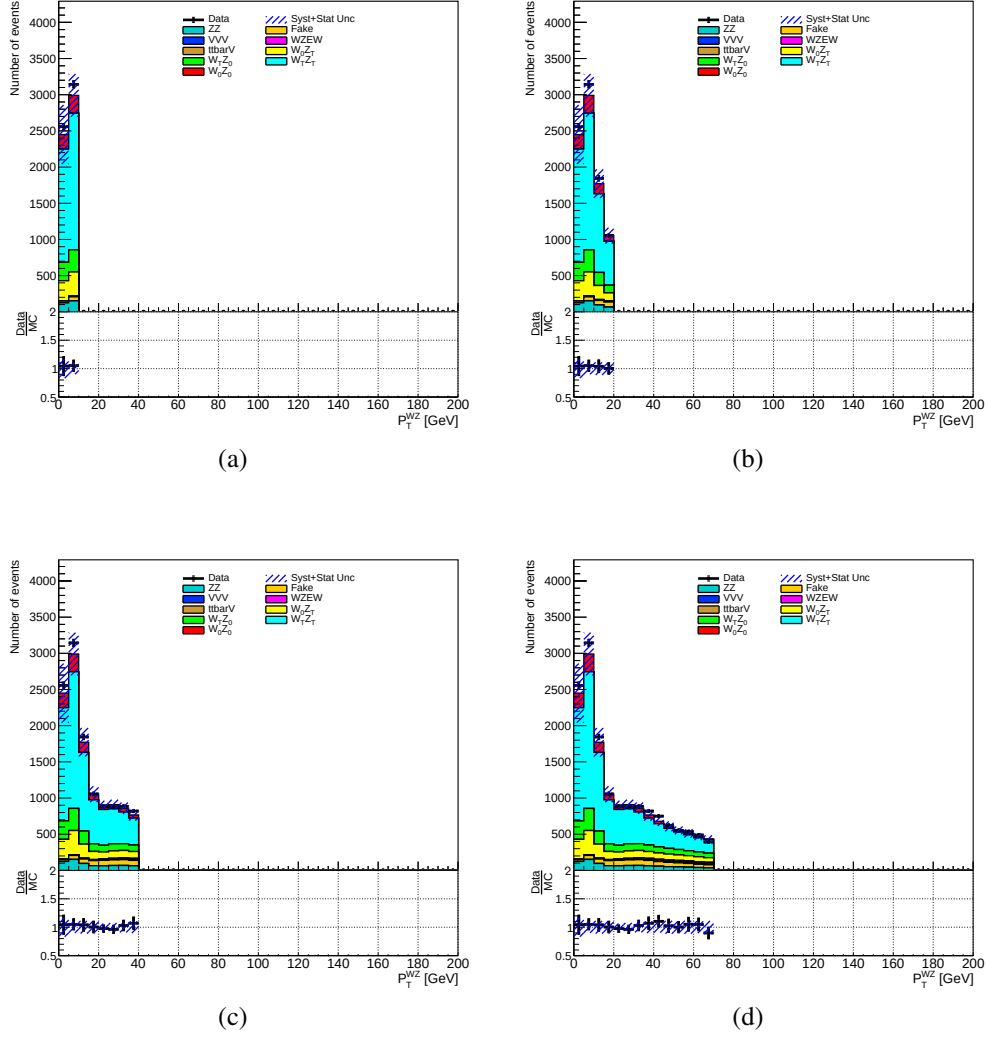


Figure D.3: Comparison between data and prediction for the p_T^{WZ} distribution in the $p_T^{WZ} < 10$ GeV region (a), $p_T^{WZ} < 20$ GeV region (b), $p_T^{WZ} < 40$ GeV region (c), and $p_T^{WZ} < 70$ GeV region (d). This uses an integrated luminosity of 140.1 fb^{-1} at $\sqrt{s} = 13$ TeV.

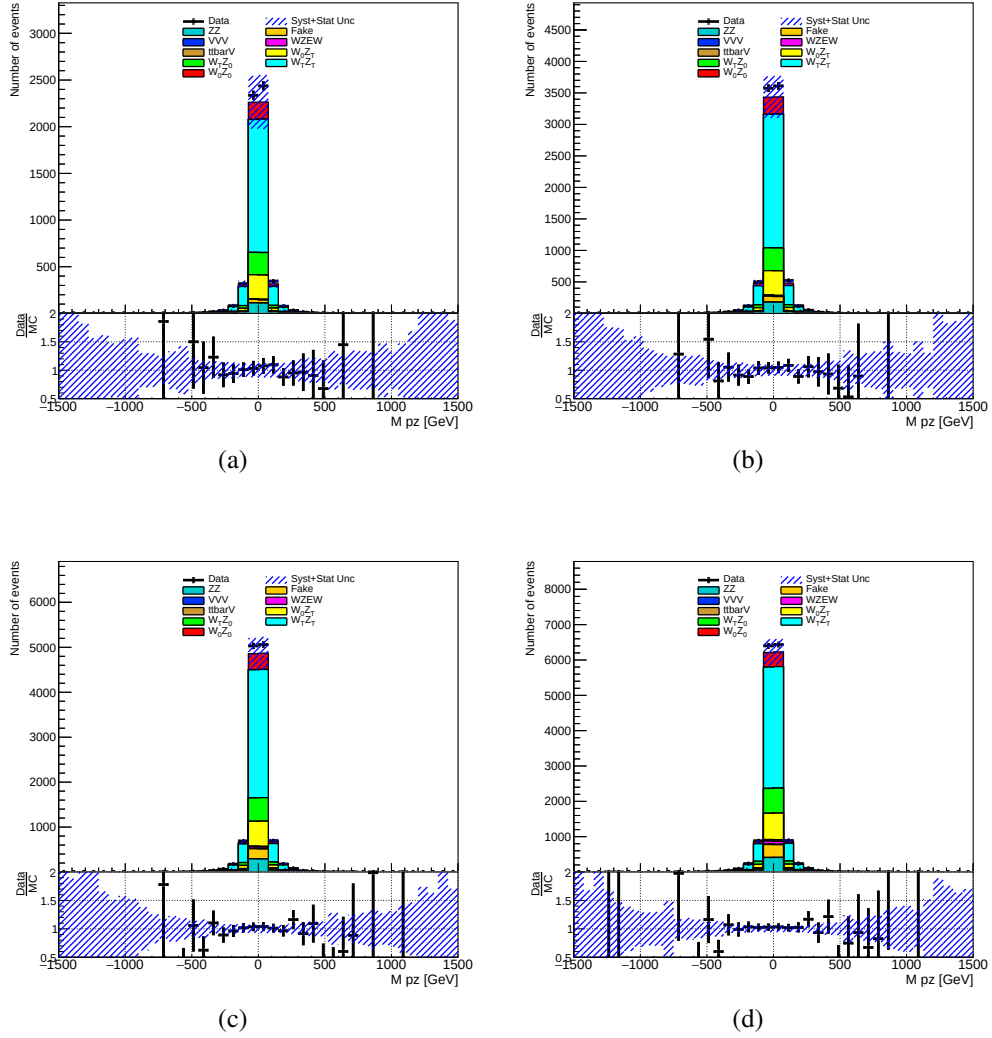


Figure D.4: Comparison between data and prediction for the reconstructed neutrino p_z distribution in the $p_T^{WZ} < 10$ GeV region (a), $p_T^{WZ} < 20$ GeV region (b), $p_T^{WZ} < 40$ GeV region (c), and $p_T^{WZ} < 70$ GeV region (d). This uses an integrated luminosity of 140.1 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$.

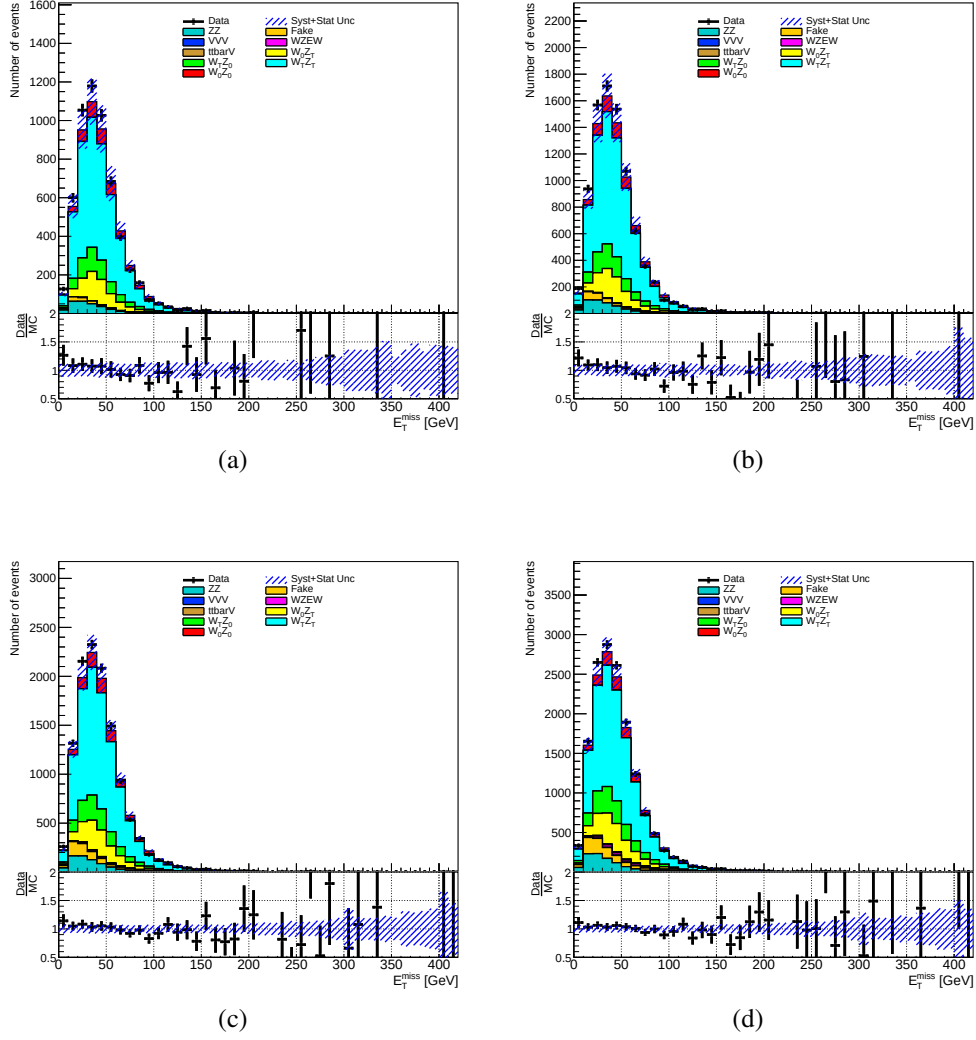


Figure D.5: Comparison between data and prediction for the E_T^{miss} distribution in the $p_T^{WZ} < 10$ GeV region (a), $p_T^{WZ} < 20$ GeV region (b), $p_T^{WZ} < 40$ GeV region (c), and $p_T^{WZ} < 70$ GeV region (d). This uses an integrated luminosity of 140.1 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$.

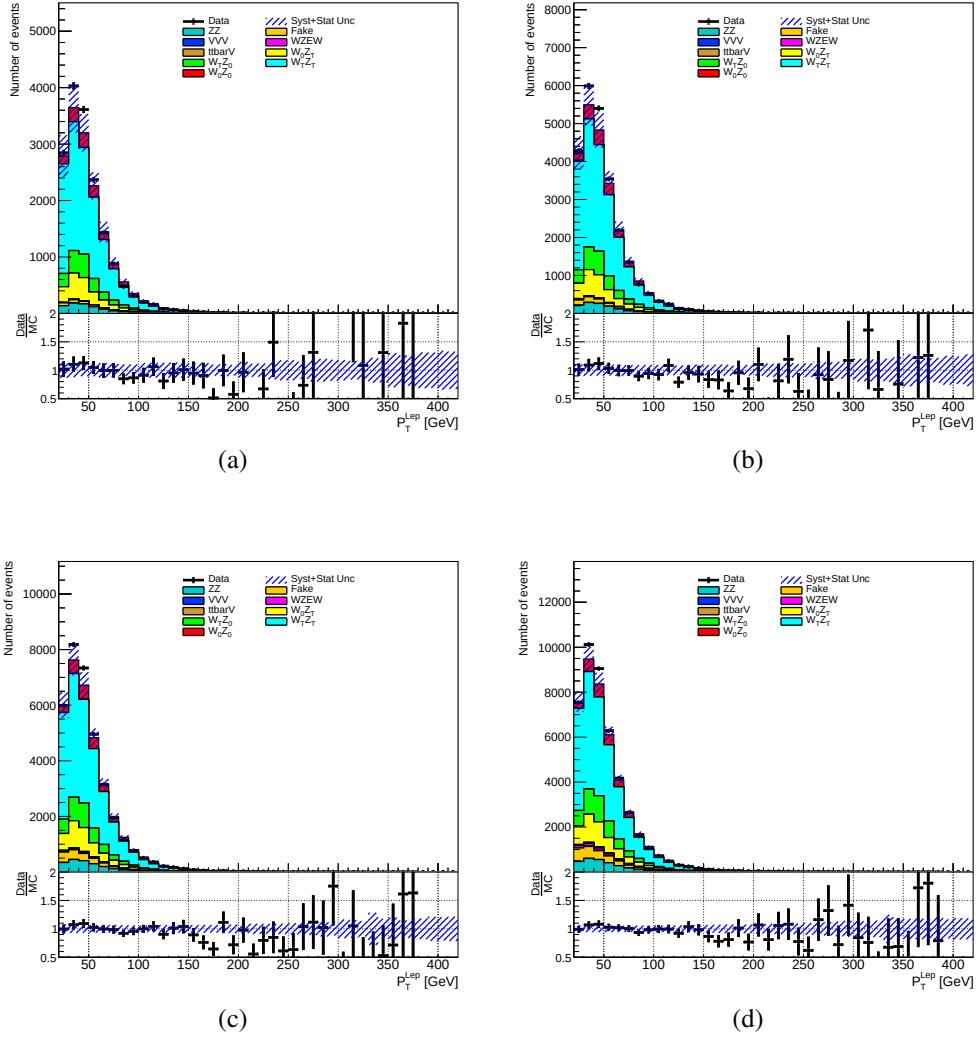


Figure D.6: Comparison between data and prediction for p_T of the three leptons distribution in the $p_T^{WZ} < 10$ GeV region (a), $p_T^{WZ} < 20$ GeV region (b), $p_T^{WZ} < 40$ GeV region (c), and $p_T^{WZ} < 70$ GeV region (d). This uses an integrated luminosity of 140.1 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$.

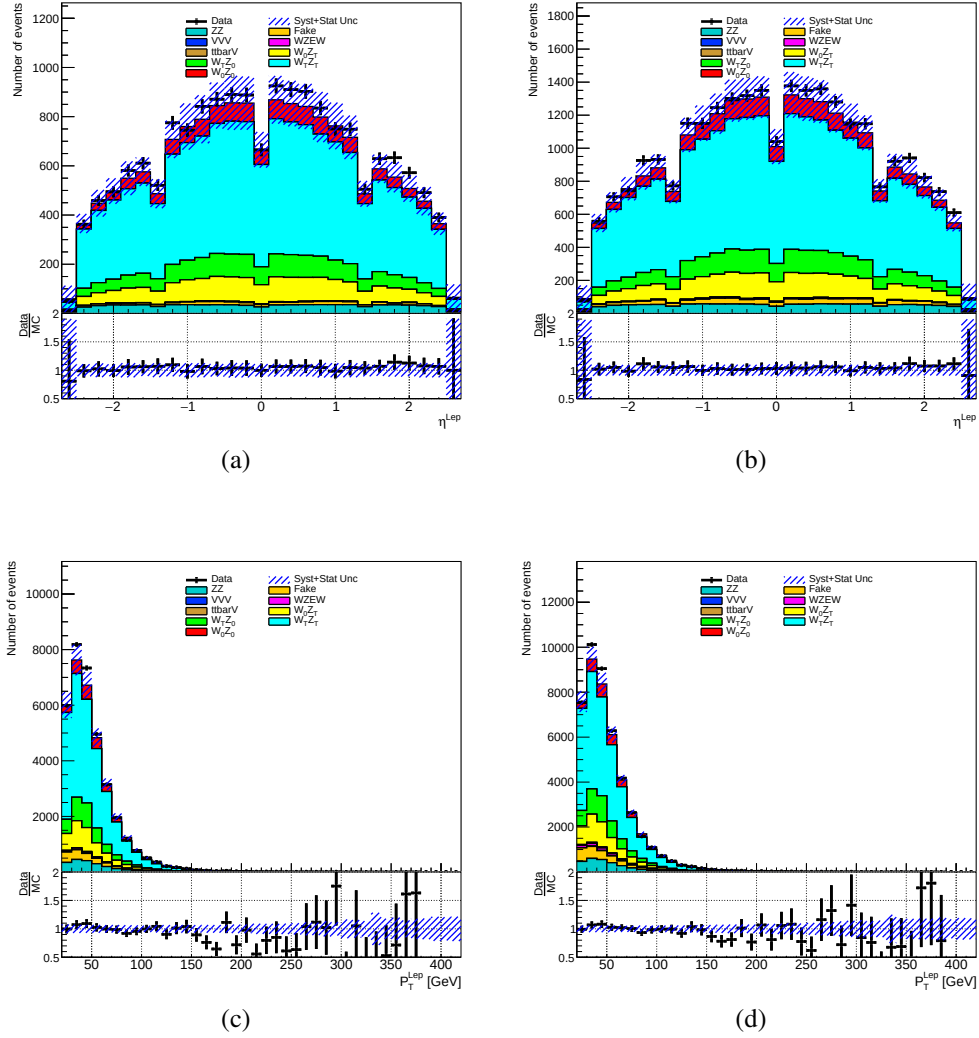


Figure D.7: Comparison between data and prediction for η of the three leptons distribution in the $p_T^{WZ} < 10$ GeV region (a), $p_T^{WZ} < 20$ GeV region (b), $p_T^{WZ} < 40$ GeV region (c), and $p_T^{WZ} < 70$ GeV region (d). This uses an integrated luminosity of 140.1 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$.

E Unfolded results

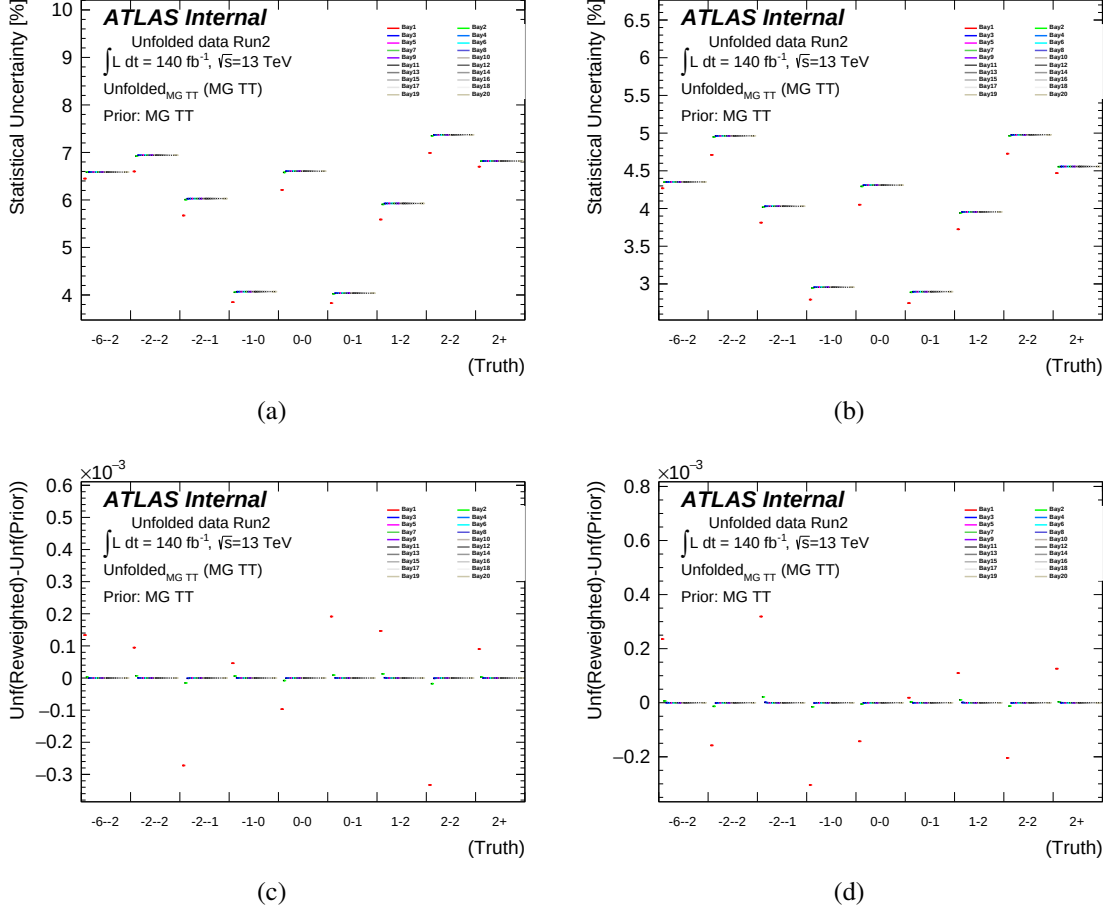
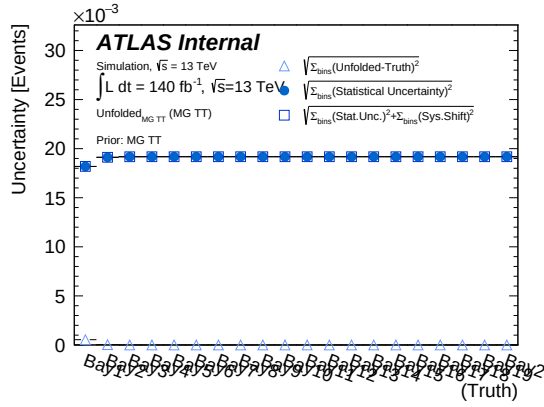
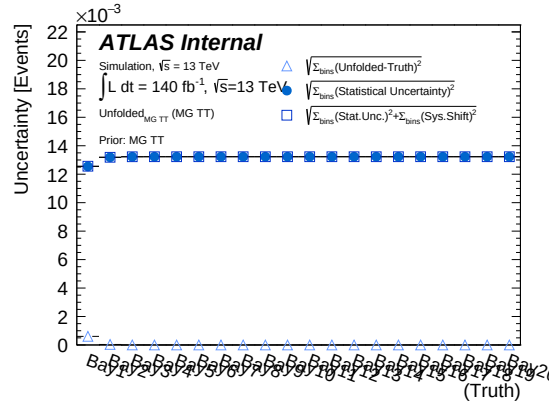


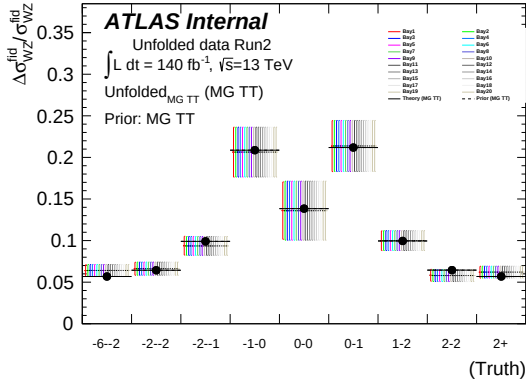
Figure E.1: Effect of the number of iterations in Bayesian unfolding: Statistical uncertainty on unfolded ΔY_{3Z} in the $p_T^{WZ} < 10 \text{ GeV}$ region (a), statistical uncertainty on unfolded ΔY_{3Z} distribution in the $p_T^{WZ} < 70 \text{ GeV}$ region (b), uncertainty from the data-driven closure test (unf) on unfolded ΔY_{3Z} in the $p_T^{WZ} < 10 \text{ GeV}$ region (c), and uncertainty from the data-driven closure test (unf) on unfolded ΔY_{3Z} in the $p_T^{WZ} < 70 \text{ GeV}$ region (d).



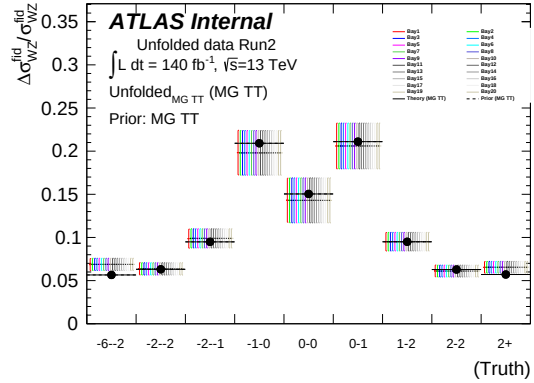
(a)



(b)



(c)



(d)

Figure E.2: Effect of the number of iterations in Bayesian unfolding: Uncertainty on ΔY_{3Z} distribution in the $p_T^{WZ} < 10$ GeV region (a), Uncertainty on ΔY_{3Z} distribution in the $p_T^{WZ} < 70$ GeV region (b), Unfolded ΔY_{3Z} distribution in the $p_T^{WZ} < 10$ GeV region (c), and Unfolded ΔY_{3Z} distribution in the $p_T^{WZ} < 70$ GeV region (d).

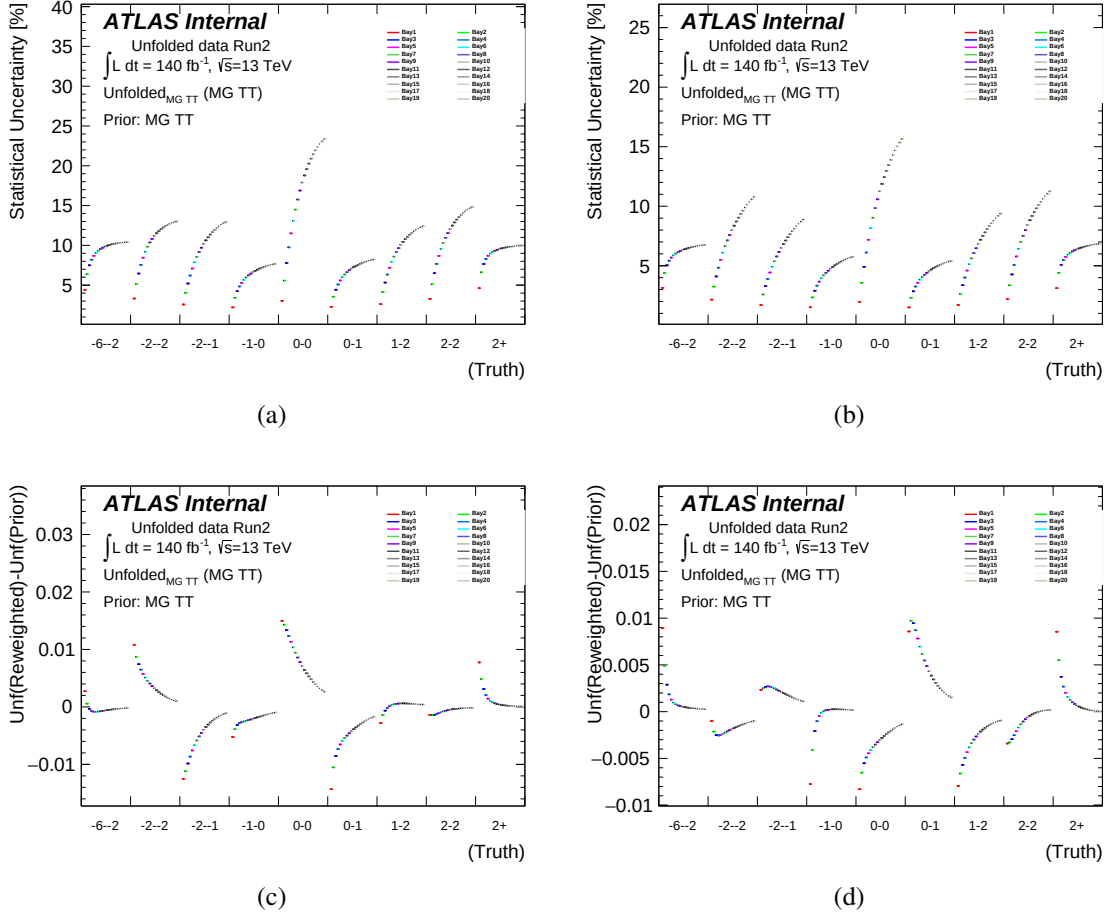


Figure E.3: Effect of the number of iterations in Bayesian unfolding: Statistical uncertainty on unfolded ΔY_{WZ} in the $p_T^{WZ} < 10 \text{ GeV}$ region (a), statistical uncertainty on unfolded ΔY_{WZ} distribution in the $p_T^{WZ} < 70 \text{ GeV}$ region (b), uncertainty from the data-driven closure test (unf) on unfolded ΔY_{WZ} in the $p_T^{WZ} < 10 \text{ GeV}$ region (c), and uncertainty from the data-driven closure test (unf) on unfolded ΔY_{WZ} in the $p_T^{WZ} < 70 \text{ GeV}$ region (d).

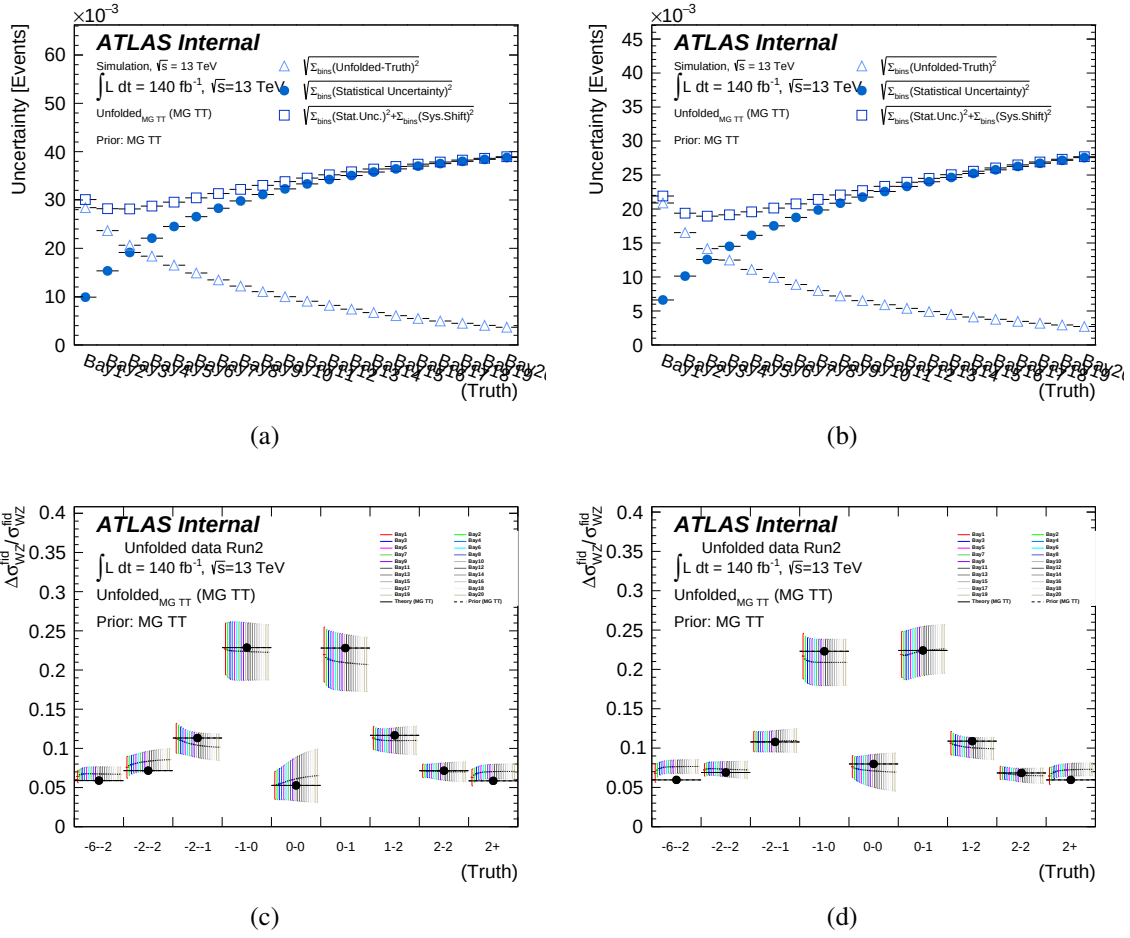
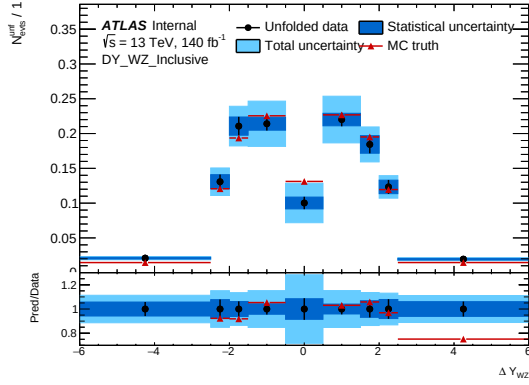
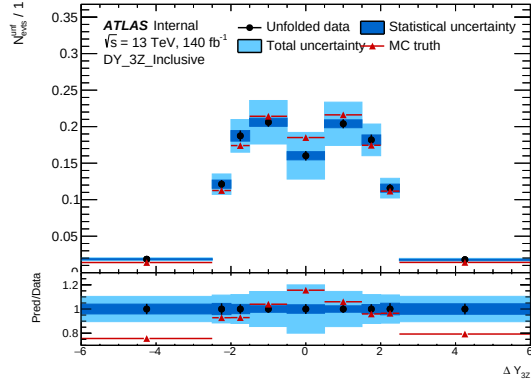


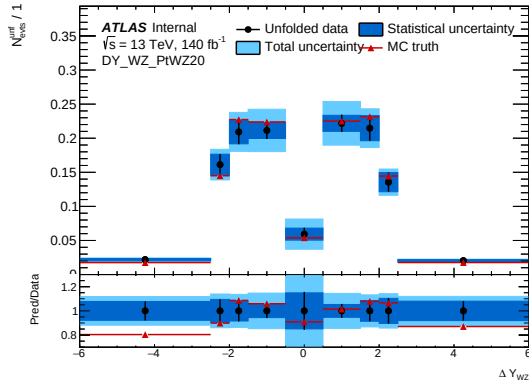
Figure E.4: Effect of the number of iterations in Bayesian unfolding: Uncertainty on ΔY_{WZ} distribution in the $p_T^{WZ} < 10$ GeV region (a), Uncertainty on ΔY_{WZ} distribution in the $p_T^{WZ} < 70$ GeV region (b), Unfolded ΔY_{WZ} distribution in the $p_T^{WZ} < 10$ GeV region (c), and Unfolded ΔY_{WZ} distribution in the $p_T^{WZ} < 70$ GeV region (d).



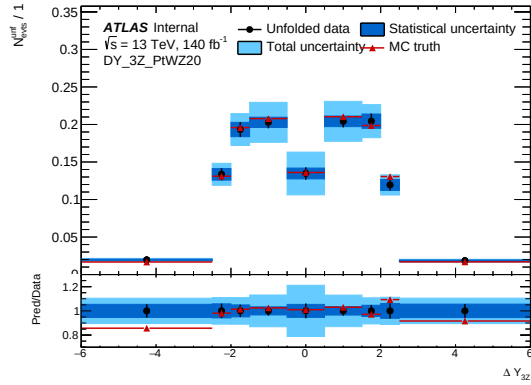
(a)



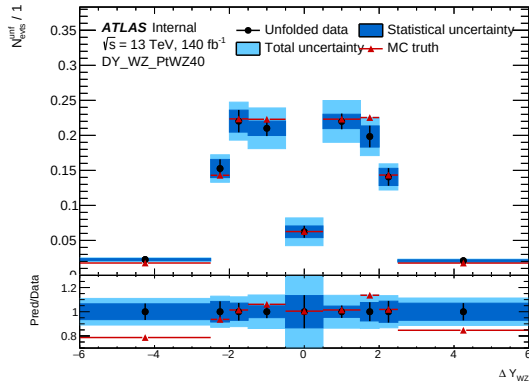
(b)



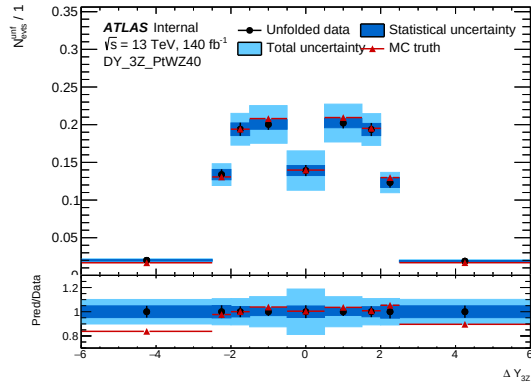
(c)



(d)



(e)



(f)

Figure E.5: Unfolded ΔY_{WZ} distributions in the Inclusive (a), $p_T^{WZ} < 20$ GeV (c), and $p_T^{WZ} < 40$ GeV (e) regions and unfolded ΔY_{3Z} distributions in the Inclusive (b), $p_T^{WZ} < 20$ GeV (d), and $p_T^{WZ} < 40$ GeV (f) regions.

F NLO Sherpa compared to LO-merged MadGraph samples at reco level

Figures F.1, F.2, F.3, F.4 and F.5 are the comparisons between SHERPA and MADGRAPH (sum of polarized and k-factors applied) in the region $p_T^Z > 200$ GeV.

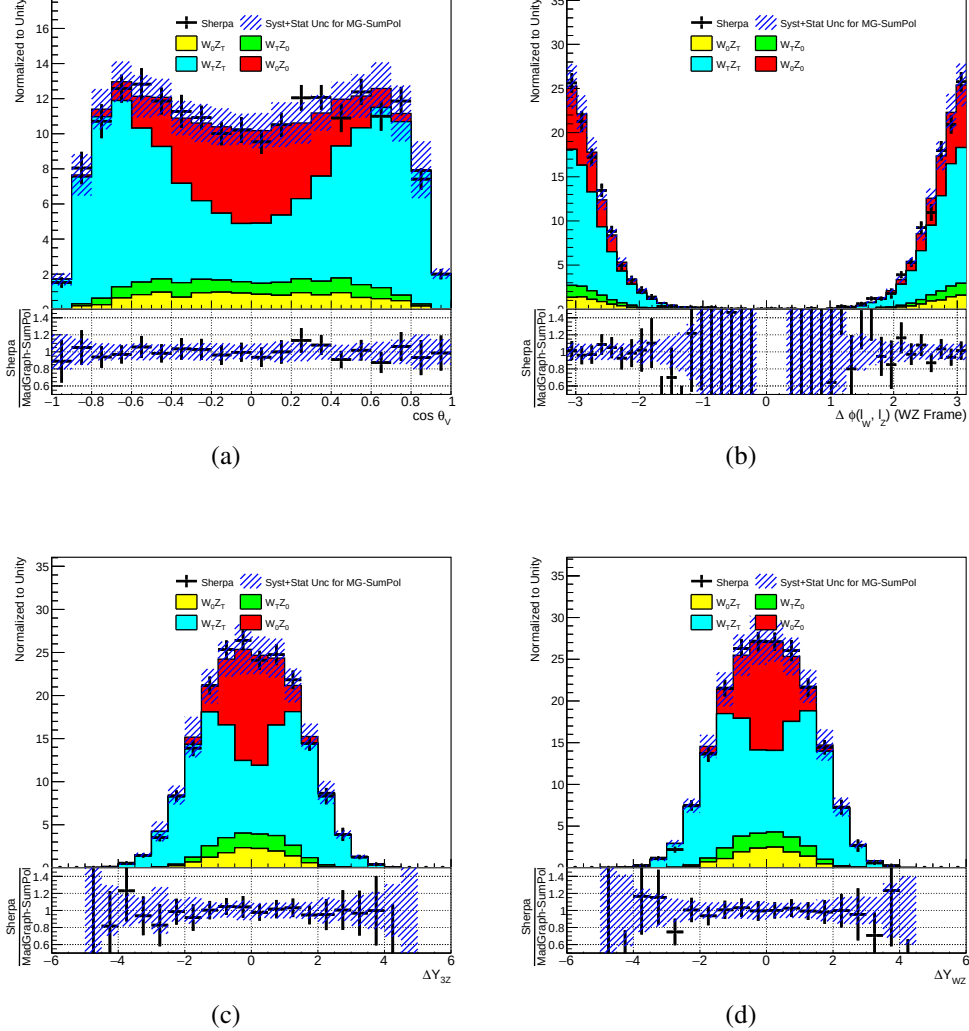


Figure F.1: Comparison between the inclusive NLO SHERPA sample ((no separation of polarization states) and the LO-merged MADGRAPH sample (all polarization states summed together) in the signal region $p_T^{WZ} < 70$ GeV and $p_T^Z > 200$ GeV for $\cos \theta_V$ (a), $\Delta \phi(\ell_W, \ell_Z)$ in WZ rest frame (b), rapidity difference between W and Z (ΔY_{WZ}) (c), and rapidity difference between the W lepton and Z (ΔY_{3Z}) (d). All variables are calculated at the reconstruction level. This uses an integrated luminosity of 140.1 fb^{-1} at $\sqrt{s} = 13$ TeV.

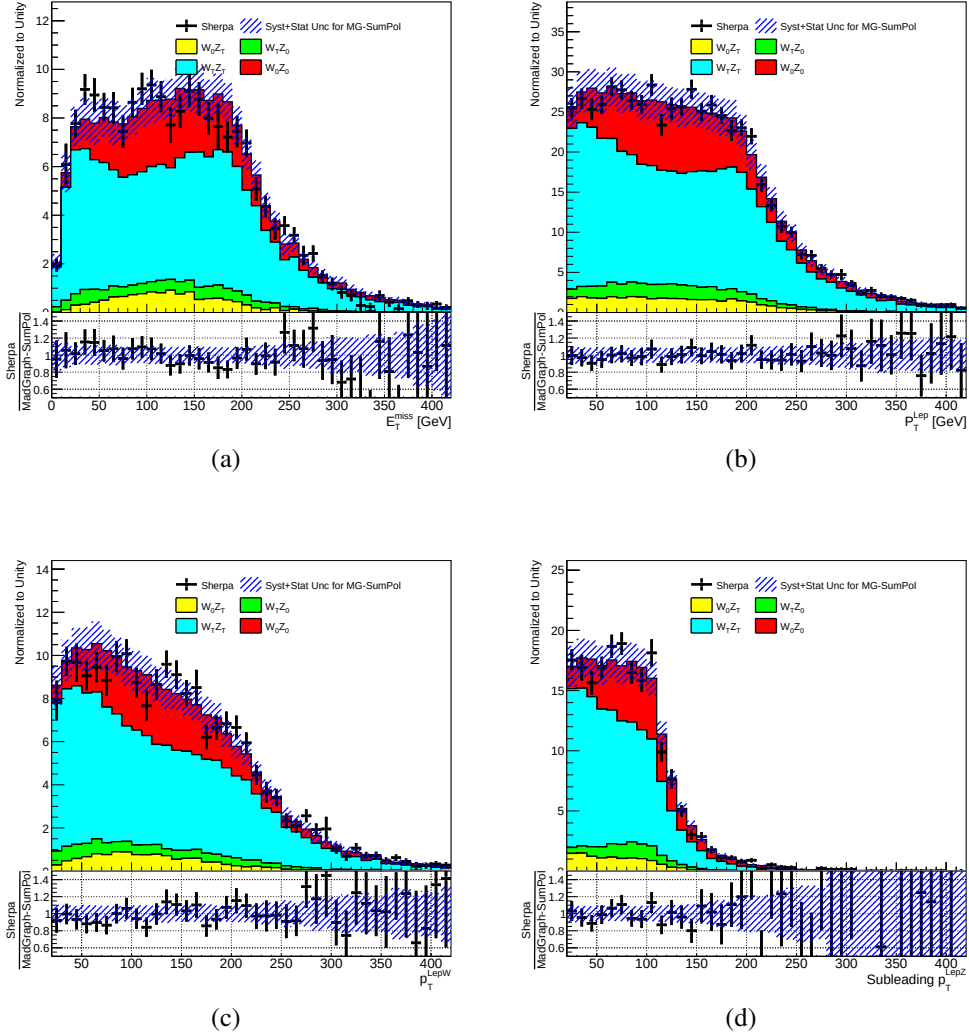


Figure F.2: Comparison between the inclusive NLO SHERPA sample (no separation of polarization states) and the LO-merged MadGraph sample (all polarization states summed together) in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 200$ GeV) for E_T^{miss} (a), p_T of three charged leptons (b), p_T of W lepton (c), and p_T of subleading Z lepton (d). All variables are calculated at the reconstruction level. This uses an integrated luminosity of 140.1 fb^{-1} at $\sqrt{s} = 13$ TeV.

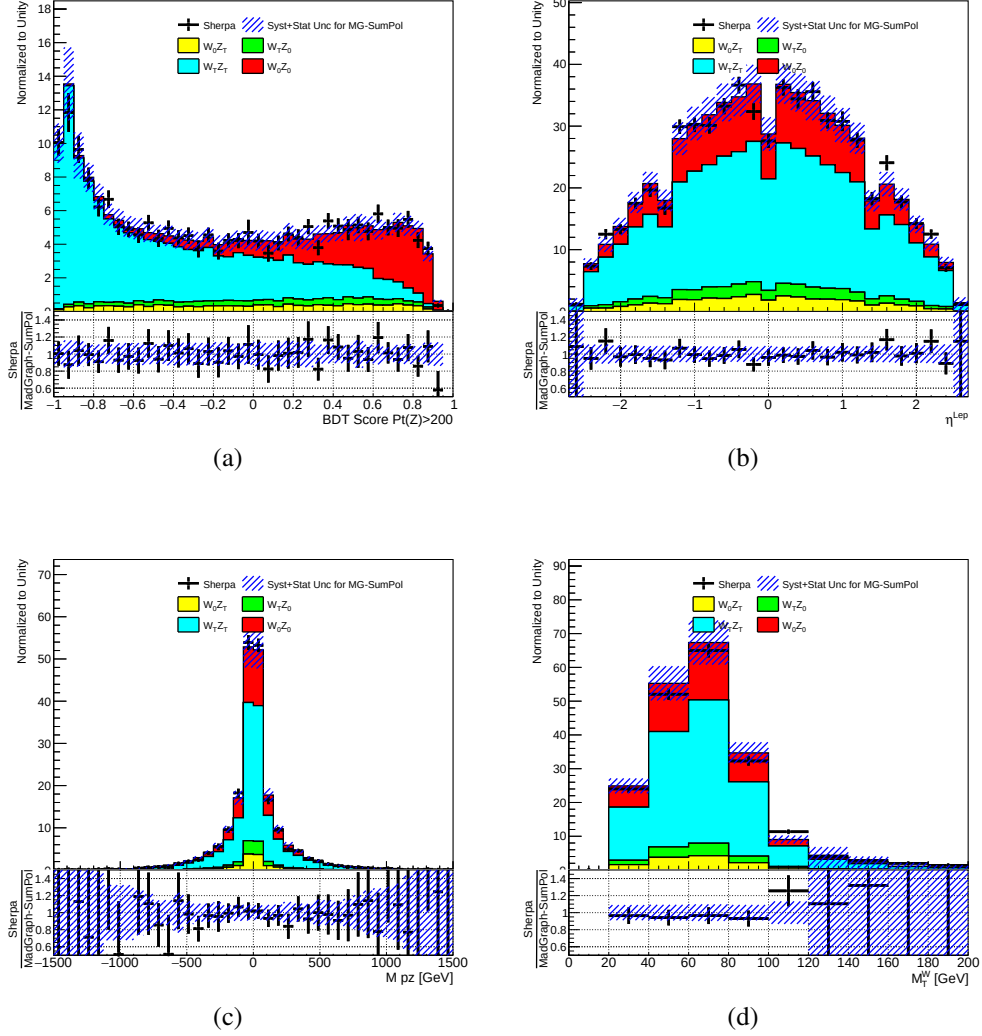


Figure F.3: Comparison between the inclusive NLO SHERPA sample (no separation of polarization states) and the LO-merged MadGraph sample (all polarization states summed together) in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 200$ GeV) for the BDT score (a), η^{Lep} of three leptons (b), reconstructed neutrino p_z (c), and m_T^W (d). All variables are calculated at the reconstruction level. This uses an integrated luminosity of 140.1 fb^{-1} at $\sqrt{s} = 13$ TeV.

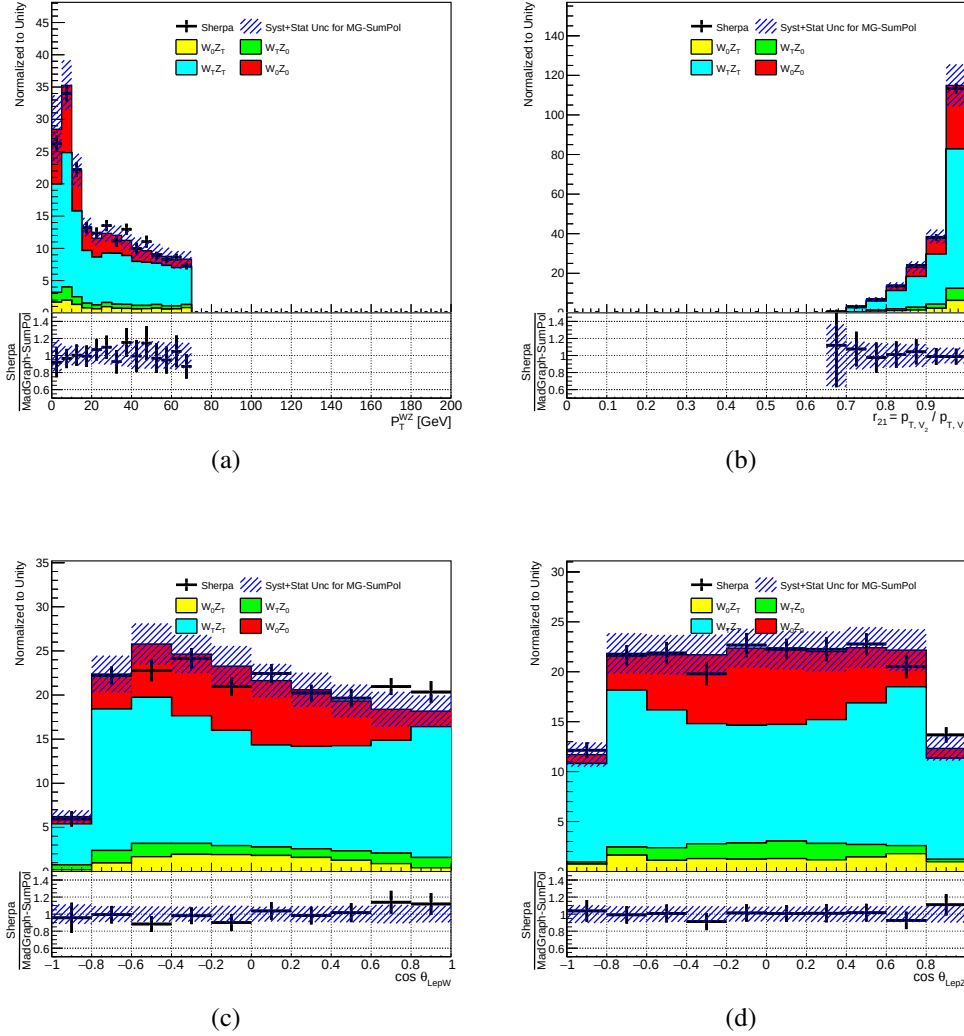


Figure F.4: Comparison between the inclusive NLO SHERPA sample (no separation of polarization states) and the LO-merged MadGraph sample (all polarization states summed together) in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 200$ GeV) for p_T^{WZ} (a), $r_{21} = \frac{p_{T,V_2}}{p_{T,V_1}}$ ratio of the subleading vector boson p_T to the leading vector boson p_T (b), $\cos\theta_\ell^*(W)$ (c), and $\cos\theta_\ell^*(Z)$ (d). All variables are calculated at the reconstruction level. This uses an integrated luminosity of 140.1 fb^{-1} at $\sqrt{s} = 13$ TeV.

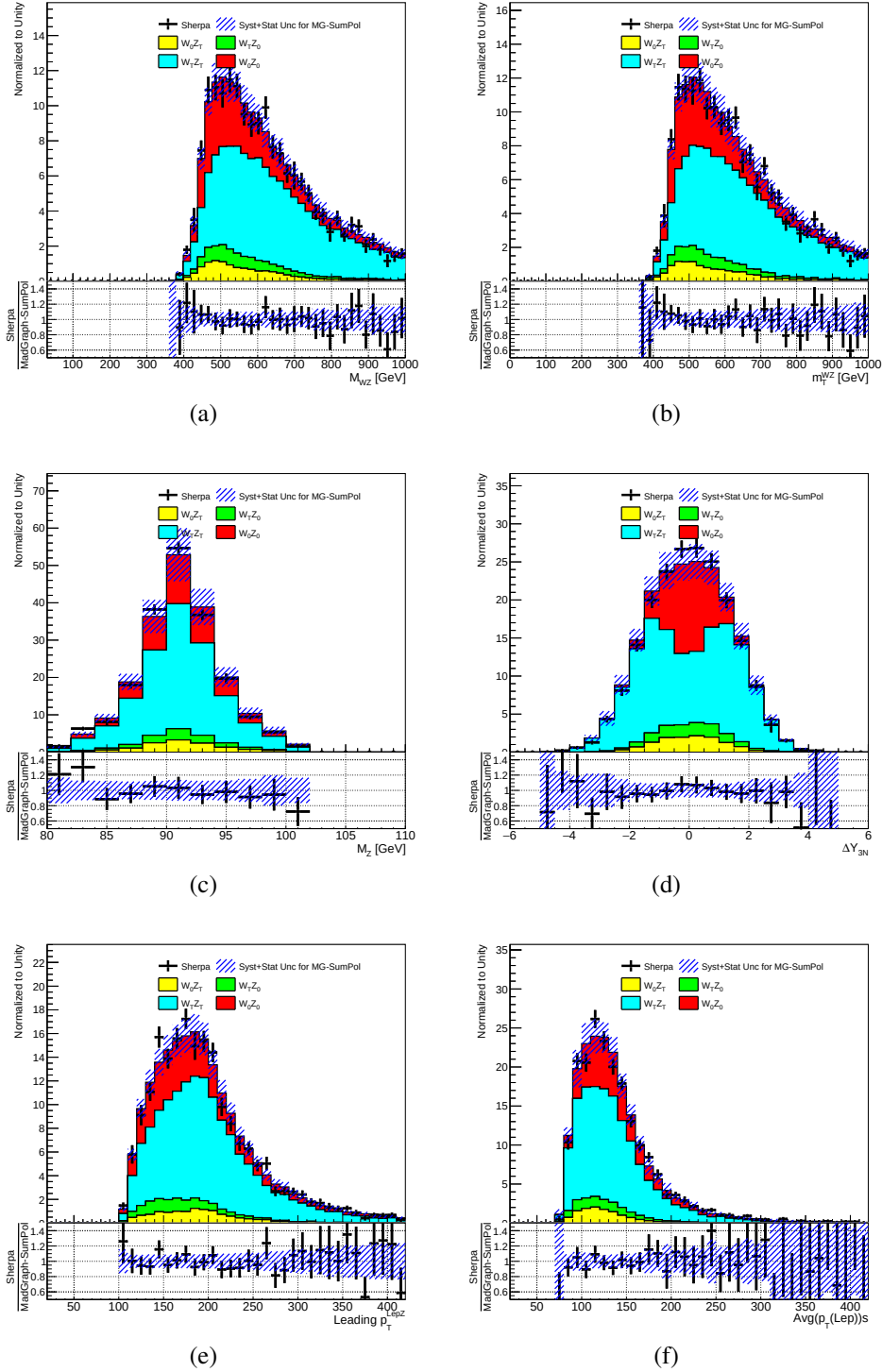


Figure F.5: Comparison between the inclusive NLO SHERPA sample (no separation of polarization states) and the LO-merged MadGraph sample (all polarization states summed together) in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 200$ GeV) for M_{WZ} (a), $m_T(WZ)$ (b), M_Z (c), ΔY_{3N} (d), leading p_T Z lepton (e), and $\text{Avg}(p_T(\ell))s$ (f). All variables are calculated at the reconstruction level. This uses an integrated luminosity of 140.1 fb^{-1} at $\sqrt{s} = 13$ TeV.

G Data-MC Comparisons in high p_T^Z signal regions (Pre-Fit)

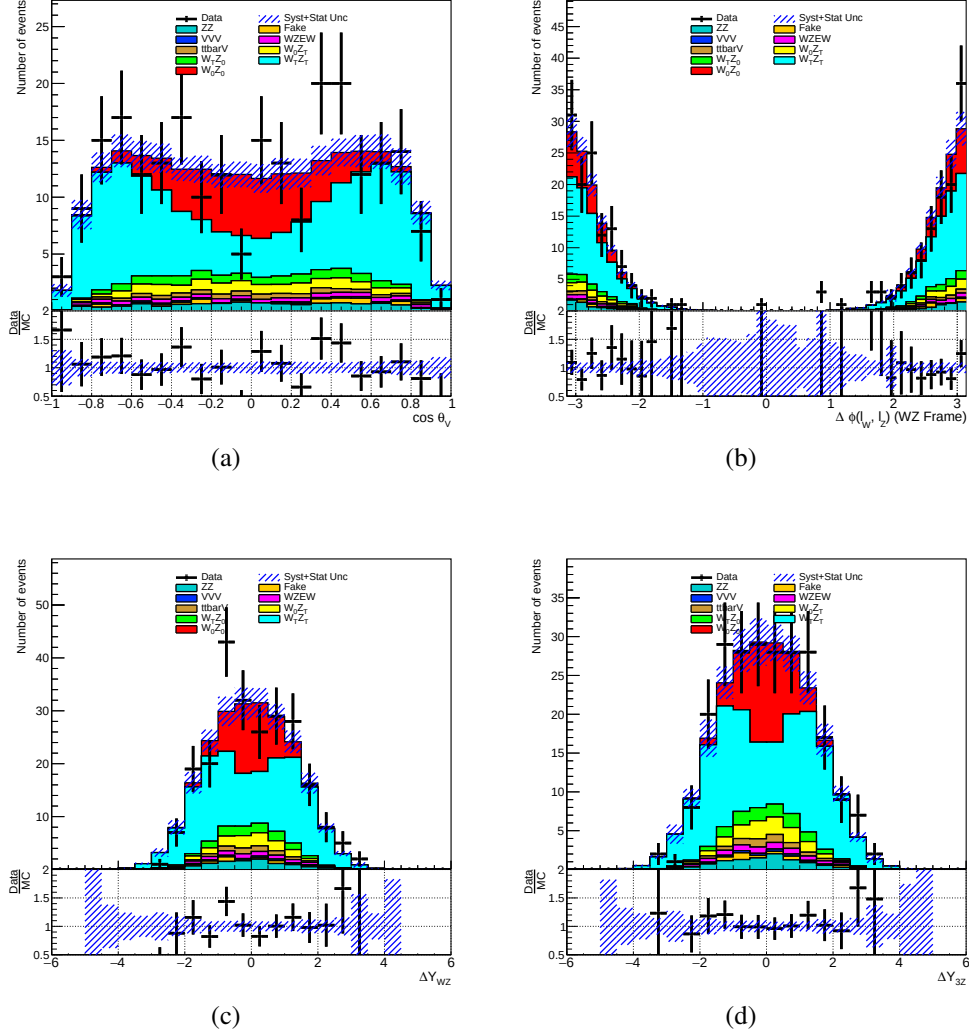


Figure G.1: Comparison between the data and the SM prediction in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 200$ GeV) for the $\cos\theta_V$ (a), $\Delta\phi(\ell_W, \ell_Z)$ in WZ rest frame (b), rapidity difference between W and Z (ΔY_{WZ}) (c), and rapidity difference between W lepton and Z (ΔY_{3Z}) (d). All variables are calculated at the reconstruction level. This uses an integrated luminosity of 140.1 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$.

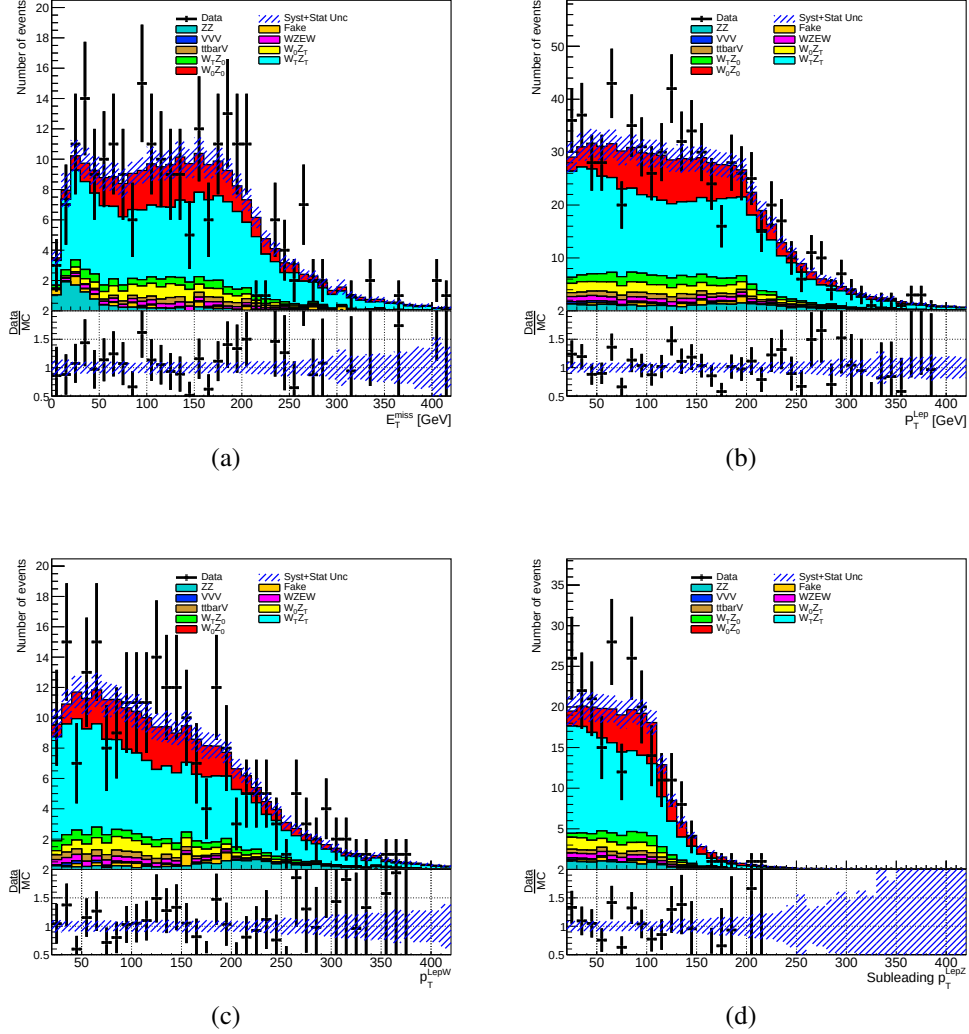


Figure G.2: Comparison between the data and the SM prediction in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 200$ GeV) for E_T^{miss} (a), p_T of selected 3 leptons (b), p_T W lepton (c), and p_T of subleading Z lepton (d). All variables are calculated at the reconstruction level. This uses an integrated luminosity of 140.1 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$.

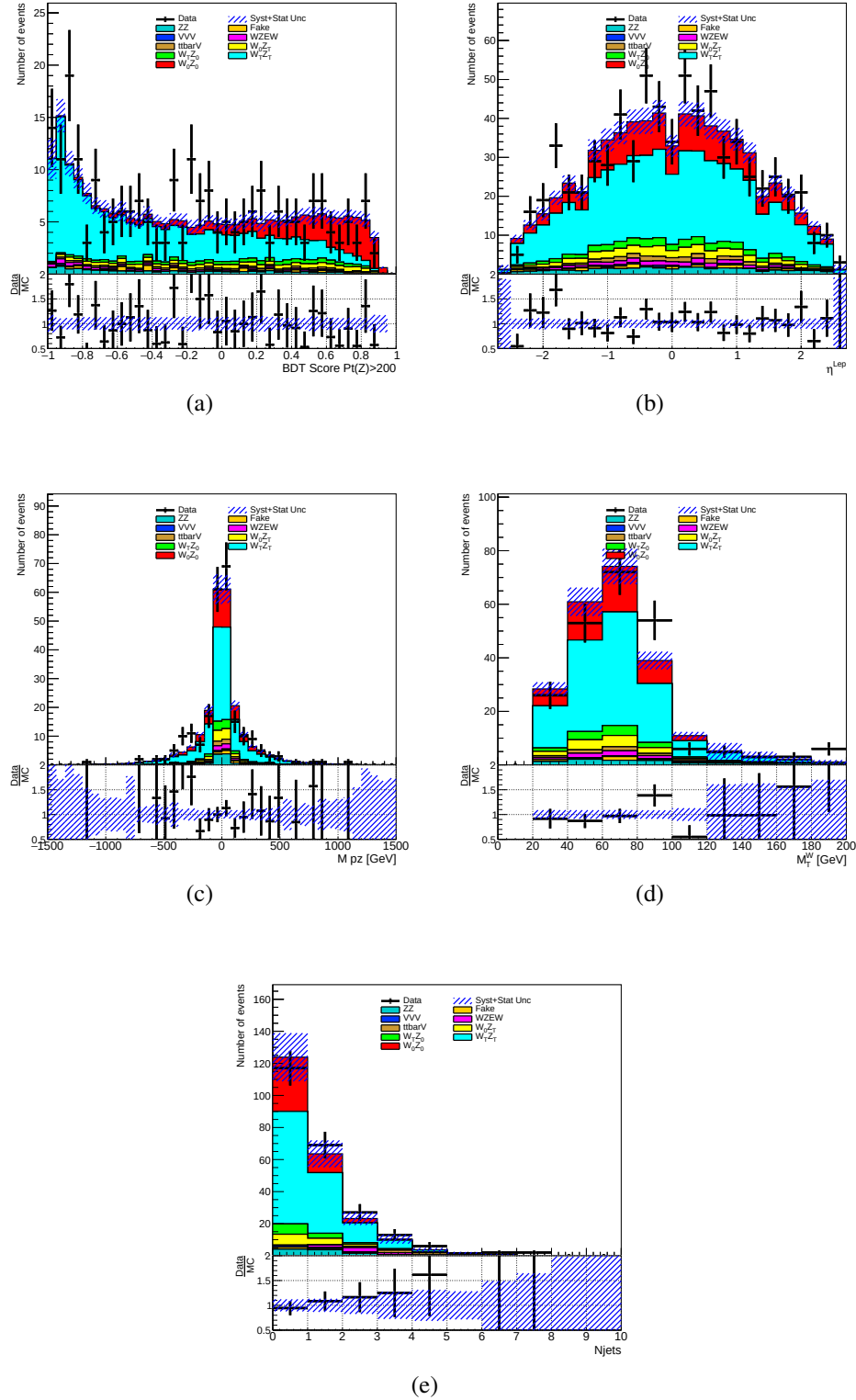


Figure G.3: Comparison between the data and the SM prediction in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 200$ GeV) for the BDT score (a), η^{Lep} of three leptons (b), reconstructed neutrino p_z (c), m_T^W (d), and the number of jets (e). All variables are calculated at the reconstruction level. This uses an integrated luminosity of 140.1 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$.

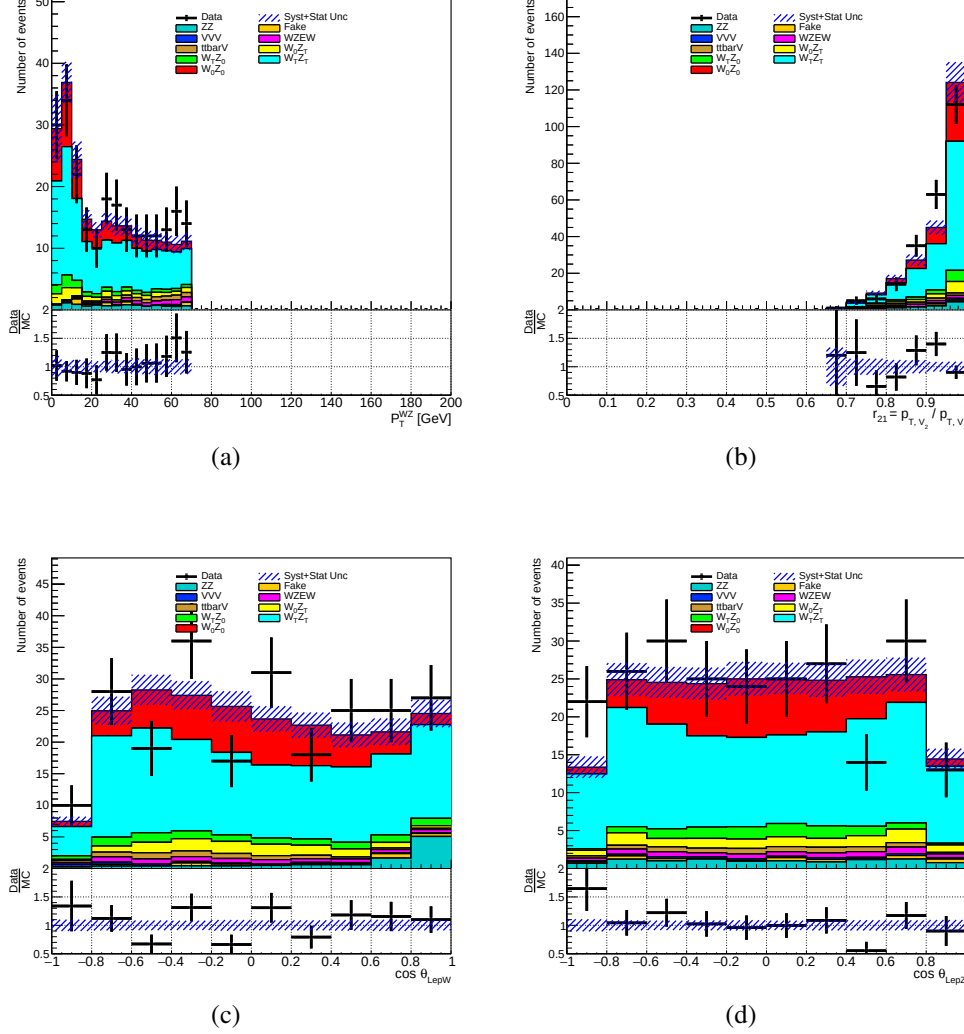


Figure G.4: Comparison between the data and the SM prediction in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 200$ GeV) for p_T^{WZ} (a), $r_{21} = \frac{p_{T,V_2}}{p_{T,V_1}}$, i.e. ratio of the subleading vector boson p_T to the leading vector boson p_T (b), $\cos \theta_{\ell}^*(W)$ (c), and $\cos \theta_{\ell}^*(Z)$ (d). All variables are calculated at the reconstruction level. This uses an integrated luminosity of 140.1 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$.

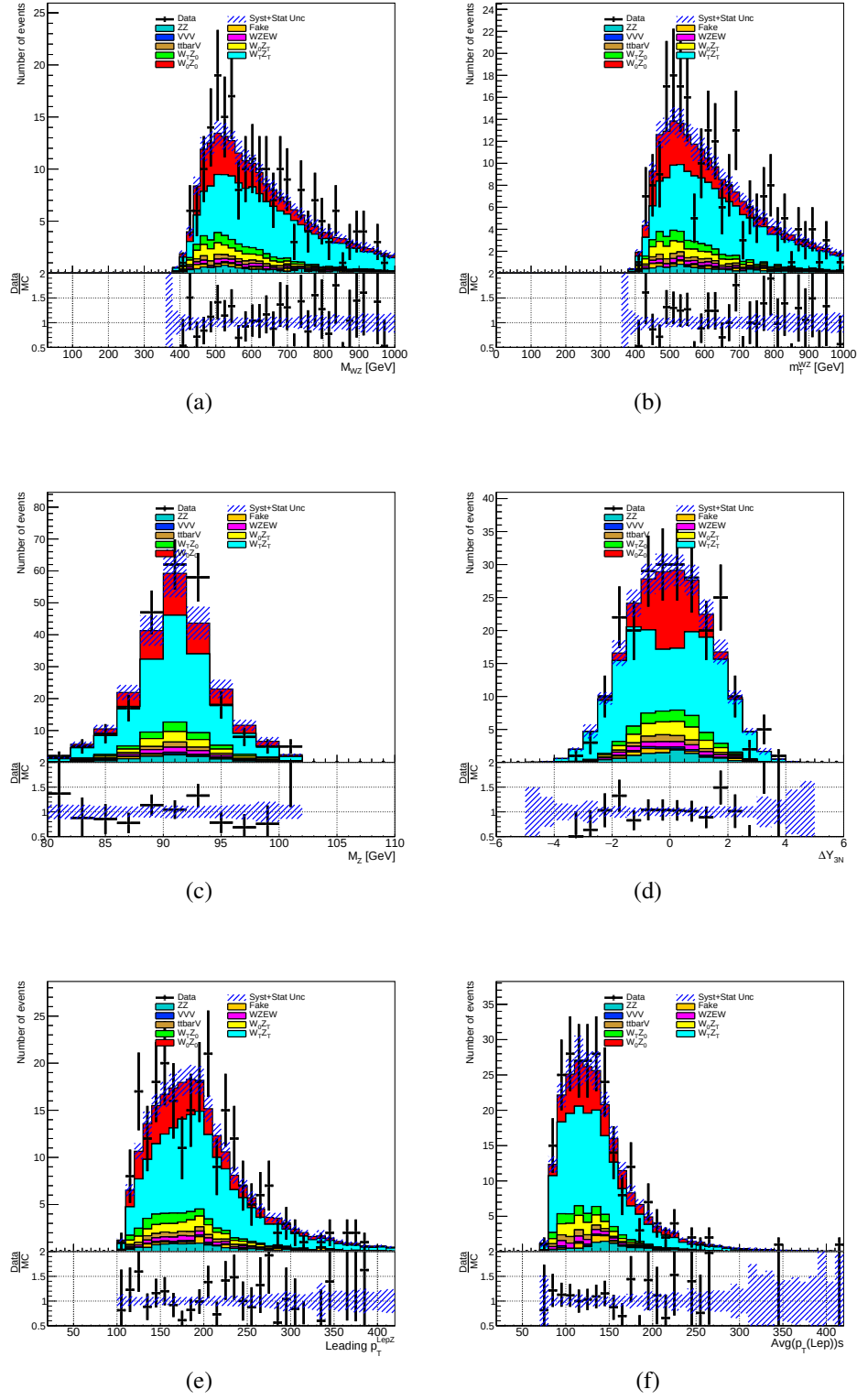


Figure G.5: Comparison between the data and the SM prediction in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 200$ GeV) for M_{WZ} (a), $m_T(WZ)$ (b), M_Z (c), ΔY_{3N} (d), p_T of the leading Z lepton (e), and $\text{Avg}(p_T(\ell))s$ (f). All variables are calculated at the reconstruction level. This uses an integrated luminosity of 140.1 fb^{-1} at $\sqrt{s} = 13 \text{ TeV}$.

H Multivariate Analysis

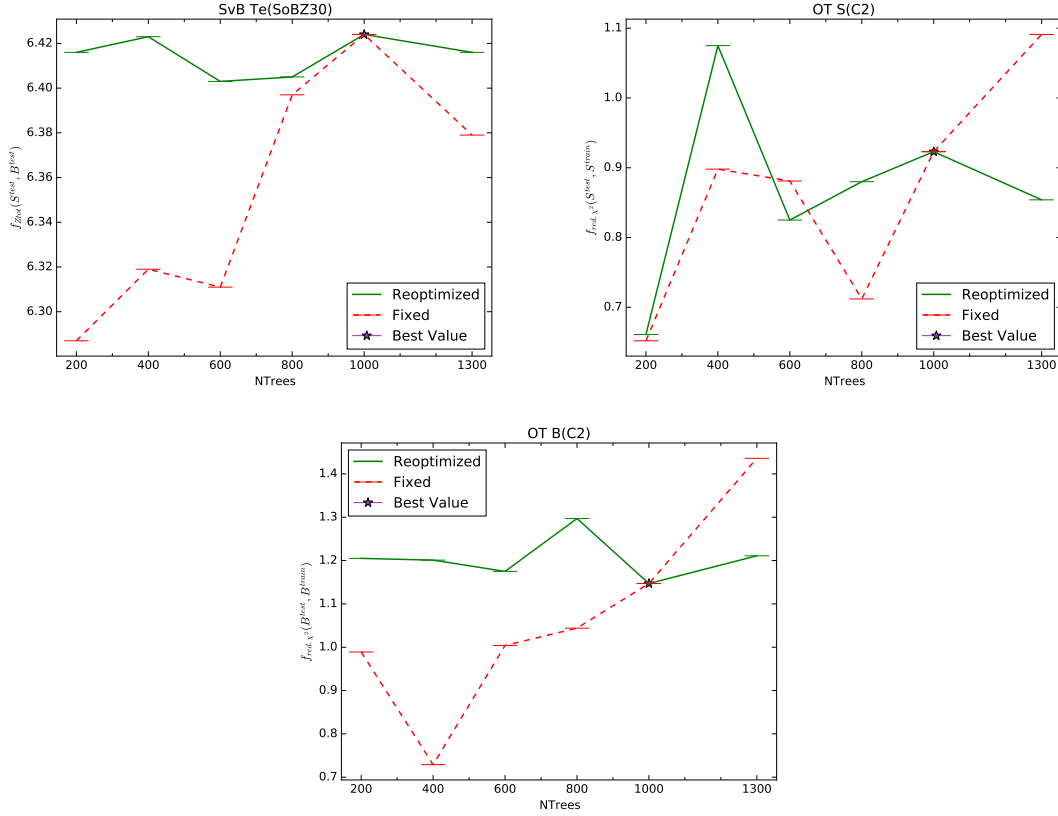


Figure H.1: Values of the significance (top left), χ^2 of signal (top right), and background (bottom) for BDTs with different values for the NTrees meta parameter. For the red dashed line, the other parameters are kept constant while for the green solid line, they are reoptimized. The purple star indicates the position of the overall optimal BDT.

I Signal Region Fitting Results: Plots

The nuisance parameter ranking plots for the three free parameters of the fit are shown in figures I.1 and I.2 for the 00-enriched $p_T^Z > 200$ GeV and $p_T^Z > 100$ GeV signal regions respectively. Only the top 20 systematic uncertainties were included.

The nuisance parameter ranking plots for the two free parameters of the fit are shown in figures I.3 and I.4 for the 00-enriched $p_T^Z > 200$ GeV and $p_T^Z > 100$ GeV signal regions respectively. Only the top 20 systematic uncertainties were included.

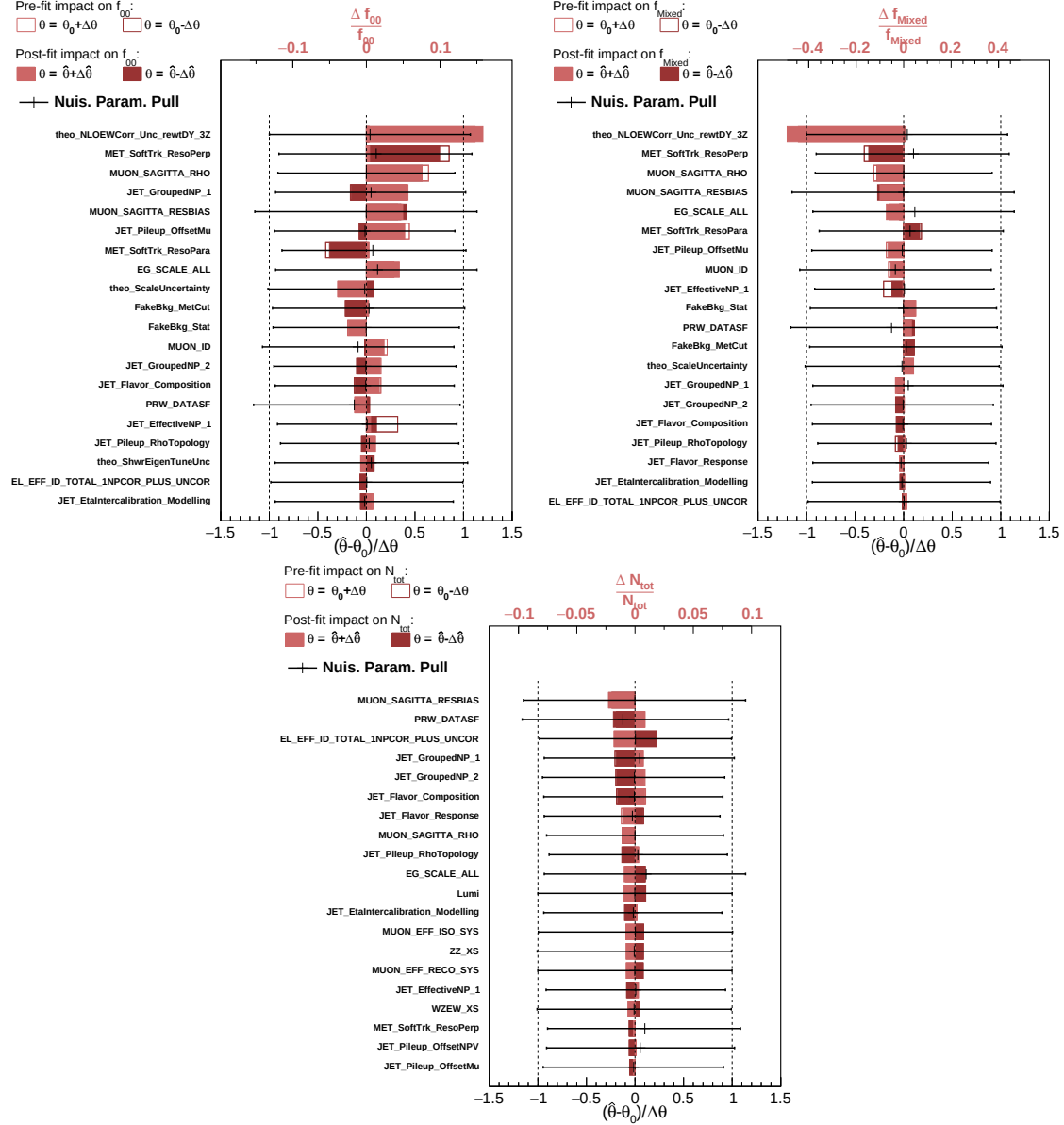


Figure I.1: Ranking of the systematic nuisance parameters included in the fit in the 00-enriched $p_T^Z > 200$ GeV region using the three sample strategy according to their impact on f_{00} (top-left), f_{Mixed} (top-right) and N_{tot} (bottom) using Asimov data obtained with the expected background prediction. Only the top 20 parameters are shown. Nuisance parameters corresponding to MC statistical uncertainties are not considered here. The empty brown rectangles correspond to the pre-fit impact on the respective parameter and the filled brown ones to the post-fit impacts, both referring to the upper scale. The impact of each nuisance parameter, Δf_{00} — Δf_{Mixed} — ΔN_{tot} , is computed by comparing the nominal best-fit value with the result of the fit when fixing the considered nuisance parameter to its best-fit value, $\hat{\theta}$, shifted by its pre-fit (post-fit) uncertainties $\pm\Delta\theta$ ($\pm\Delta\hat{\theta}$). The black points show the pulls of the nuisance parameters with respect to their nominal values, θ_0 . These pulls and their relative post-fit errors, $\Delta\hat{\theta}/\Delta\theta$, refer to the lower scale. For experimental uncertainties which are broken down into several independent sources, the corresponding nuisance parameter (NP) index is reported.

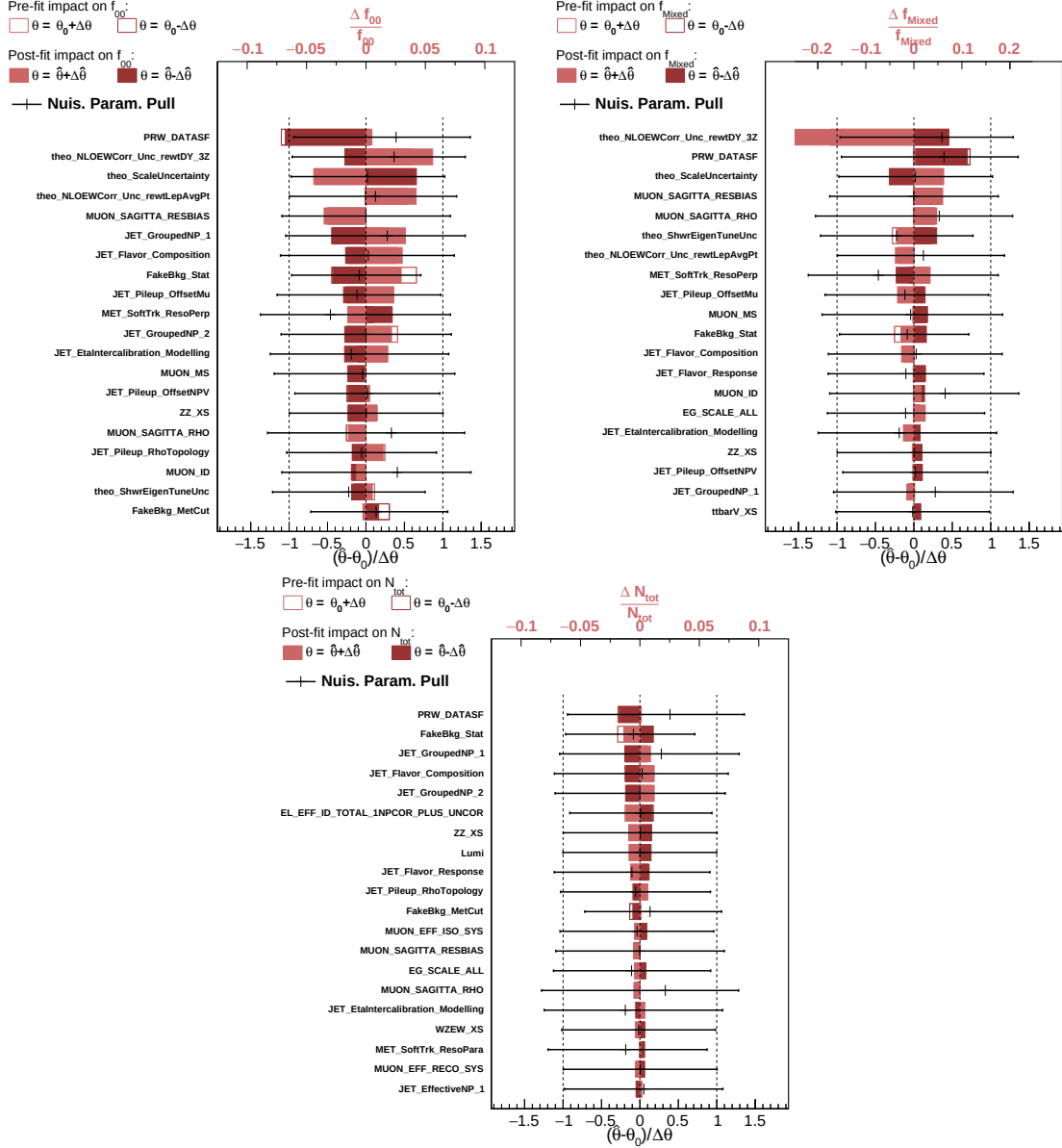


Figure I.2: Ranking of the systematic nuisance parameters included in the fit in the 00-enriched $p_T^Z > 100$ GeV region using the three sample strategy according to their impact on f_{00} (top-left), f_{Mixed} (top-right) and N_{tot} (bottom) using Asimov data obtained with the expected background prediction. Only the top 20 parameters are shown. Nuisance parameters corresponding to MC statistical uncertainties are not considered here. The empty brown rectangles correspond to the pre-fit impact on the respective parameter and the filled brown ones to the post-fit impacts, both referring to the upper scale. The impact of each nuisance parameter, Δf_{00} — Δf_{Mixed} — ΔN_{tot} , is computed by comparing the nominal best-fit value with the result of the fit when fixing the considered nuisance parameter to its best-fit value, $\hat{\theta}$, shifted by its pre-fit (post-fit) uncertainties $\pm\Delta\theta$ ($\pm\Delta\hat{\theta}$). The black points show the pulls of the nuisance parameters with respect to their nominal values, θ_0 . These pulls and their relative post-fit errors, $\Delta\hat{\theta}/\Delta\theta$, refer to the lower scale. For experimental uncertainties which are broken down into several independent sources, the corresponding nuisance parameter (NP) index is reported.

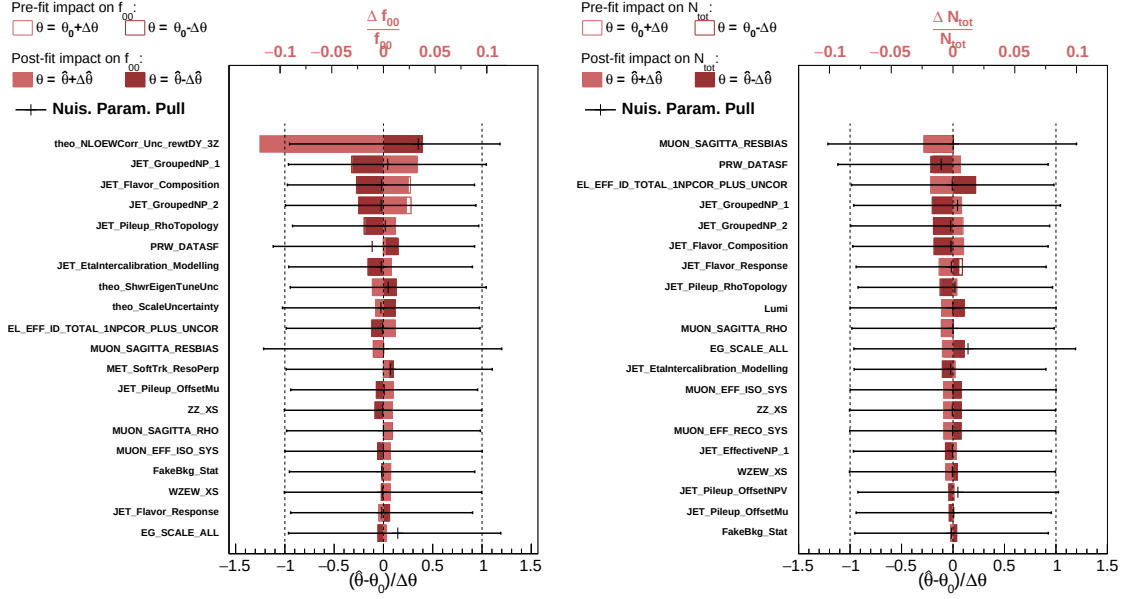


Figure I.3: Ranking of the systematic nuisance parameters included in the fit in the 00-enriched $p_T^Z > 200$ GeV region using the two sample strategy according to their impact on f_{00} (top-left), f_{Mixed} (top-right) and N_{tot} (bottom) using Asimov data obtained with the expected background prediction. Only the top 20 parameters are shown. Nuisance parameters corresponding to MC statistical uncertainties are not considered here. The empty brown rectangles correspond to the pre-fit impact on the respective parameter and the filled brown ones to the post-fit impacts, both referring to the upper scale. The impact of each nuisance parameter, $\Delta f_{00} - \Delta N_{tot}$, is computed by comparing the nominal best-fit value with the result of the fit when fixing the considered nuisance parameter to its best-fit value, $\hat{\theta}$, shifted by its pre-fit (post-fit) uncertainties $\pm\Delta\theta$ ($\pm\Delta\hat{\theta}$). The black points show the pulls of the nuisance parameters with respect to their nominal values, θ_0 . These pulls and their relative post-fit errors, $\Delta\hat{\theta}/\Delta\theta$, refer to the lower scale. For experimental uncertainties which are broken down into several independent sources, the corresponding nuisance parameter (NP) index is reported.

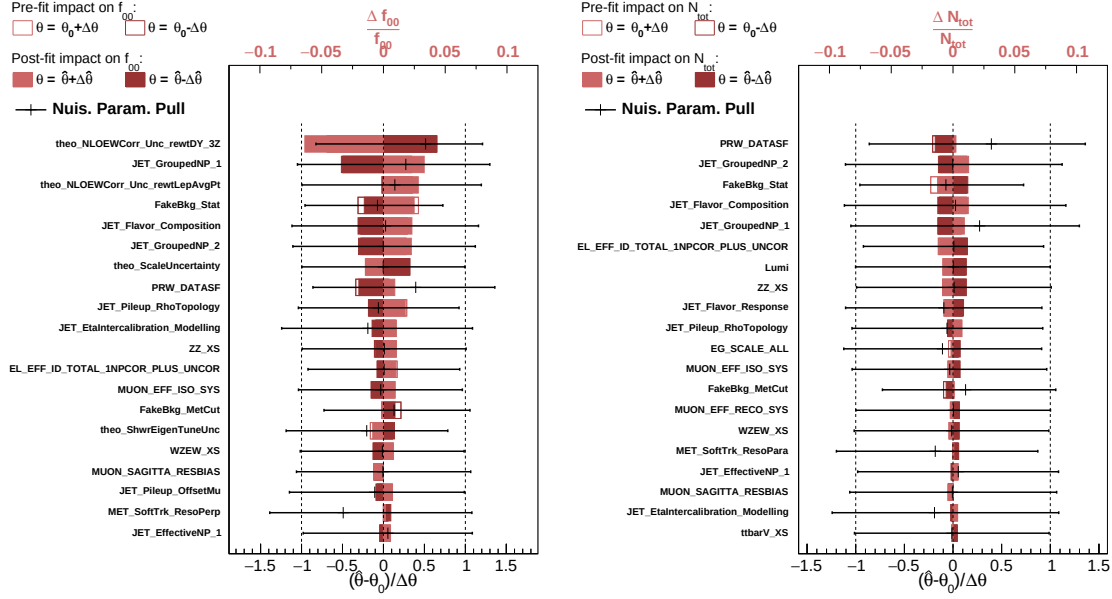


Figure I.4: Ranking of the systematic nuisance parameters included in the fit in the 00-enriched $p_T^Z > 100$ GeV region using the two-sample strategy according to their impact on f_{00} (top-left), f_{Mixed} (top-right) and N_{tot} (bottom) using Asimov data obtained with the expected background prediction. Only the top 20 parameters are shown. Nuisance parameters corresponding to MC statistical uncertainties are not considered here. The empty brown rectangles correspond to the pre-fit impact on the respective parameter and the filled brown ones to the post-fit impacts, both referring to the upper scale. The impact of each nuisance parameter, $\Delta f_{00} - \Delta N_{tot}$, is computed by comparing the nominal best-fit value with the result of the fit when fixing the considered nuisance parameter to its best-fit value, $\hat{\theta}$, shifted by its pre-fit (post-fit) uncertainties $\pm\Delta\theta$ ($\pm\Delta\hat{\theta}$). The black points show the pulls of the nuisance parameters with respect to their nominal values, θ_0 . These pulls and their relative post-fit errors, $\Delta\hat{\theta}/\Delta\theta$, refer to the lower scale. For experimental uncertainties which are broken down into several independent sources, the corresponding nuisance parameter (NP) index is reported.

J Post-Fit Data-MC Comparisons

Figures J.1, J.2, J.3, J.4, J.5 are the post-fit distributions for different variables in $p_T^Z > 100$ GeV region and with the three-parameter fit strategy.

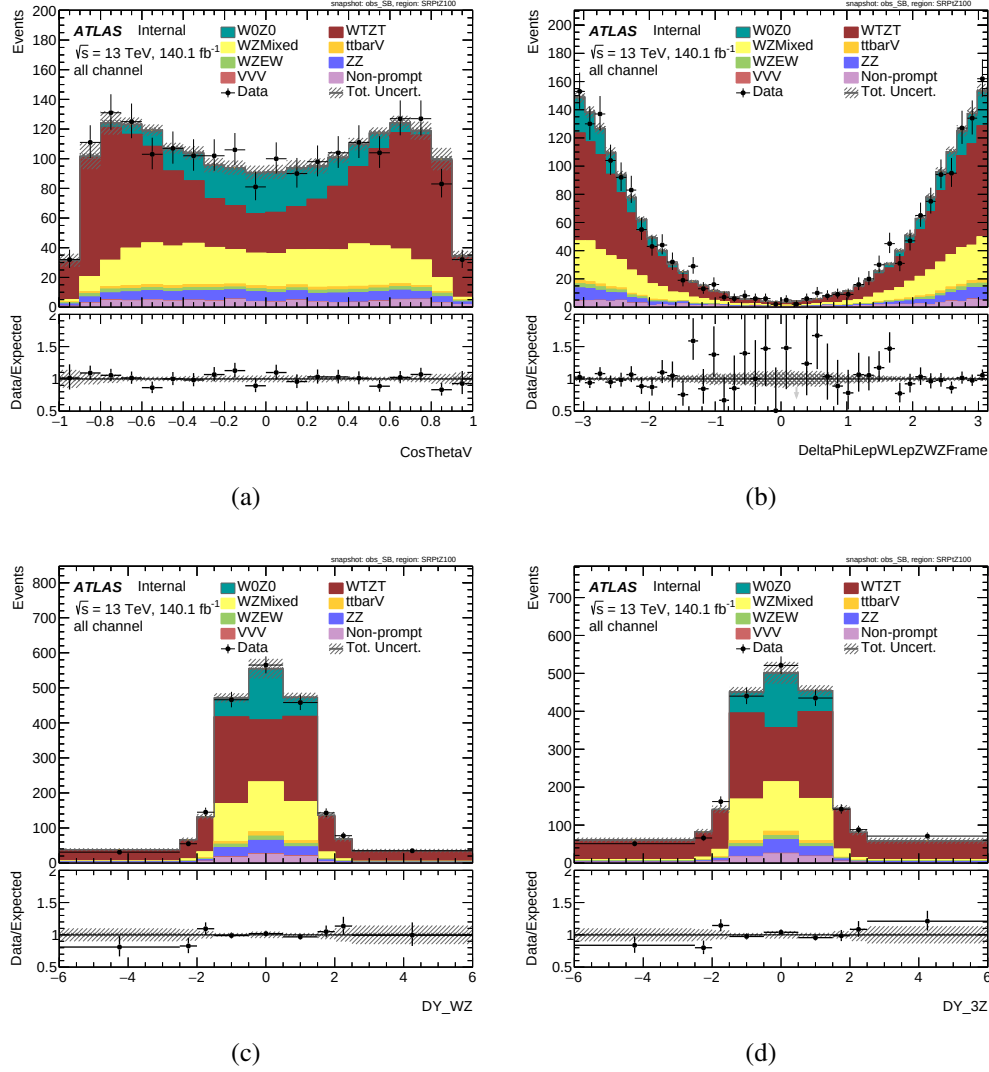


Figure J.1: Post-fit Data-MC Comparison in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 100$ GeV) using three parameter fit strategy for $\cos\theta_V$ (a), $\Delta\phi(\ell_W, \ell_Z)$ in WZ rest frame (b), rapidity difference between W and Z (ΔY_{WZ}) (c) and rapidity difference between W lepton and Z (ΔY_{3Z}) (d).

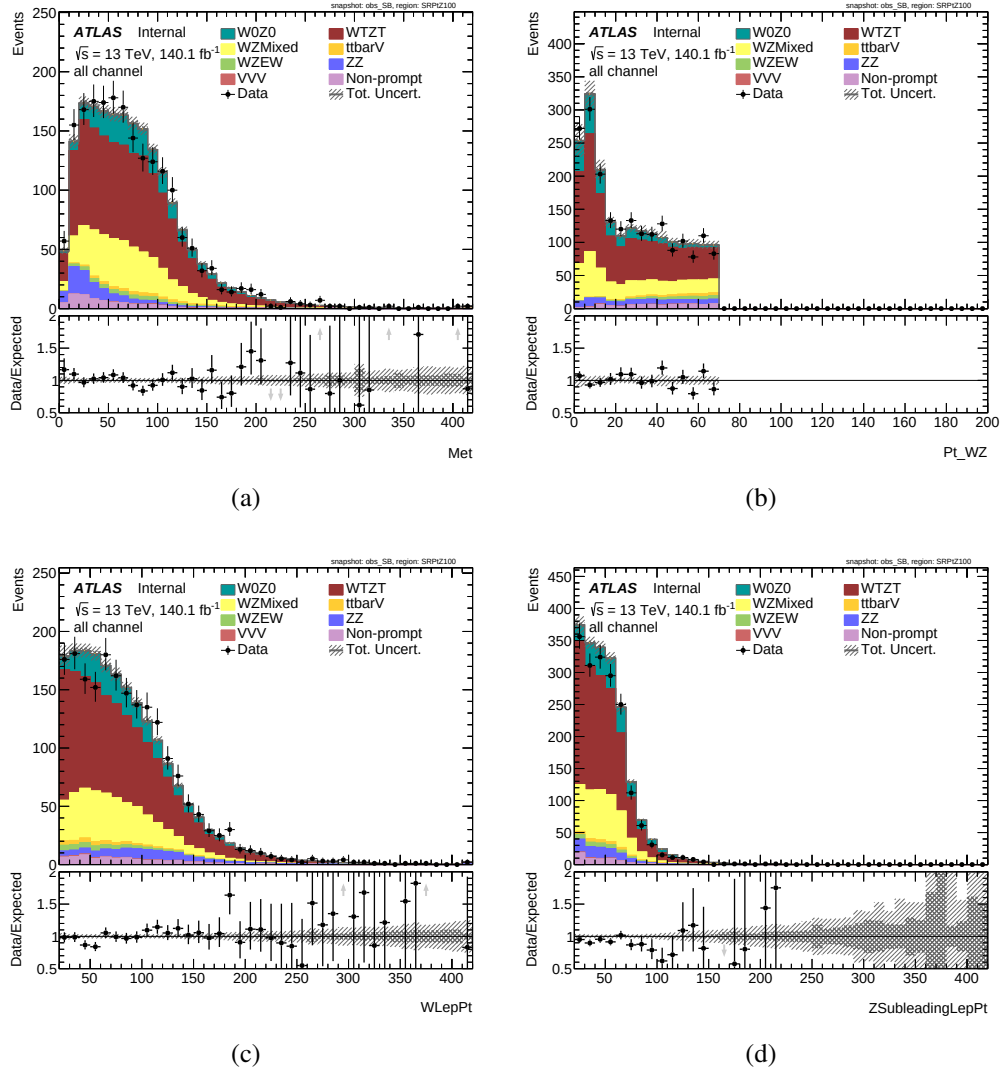


Figure J.2: Post-fit Data-MC Comparison in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 100$ GeV) using three parameter fit strategy for MET (a), p_T^{WZ} (b), p_T of the W lepton (c), and p_T of the subleading Z lepton (d). All variables are calculated at the reconstruction level.

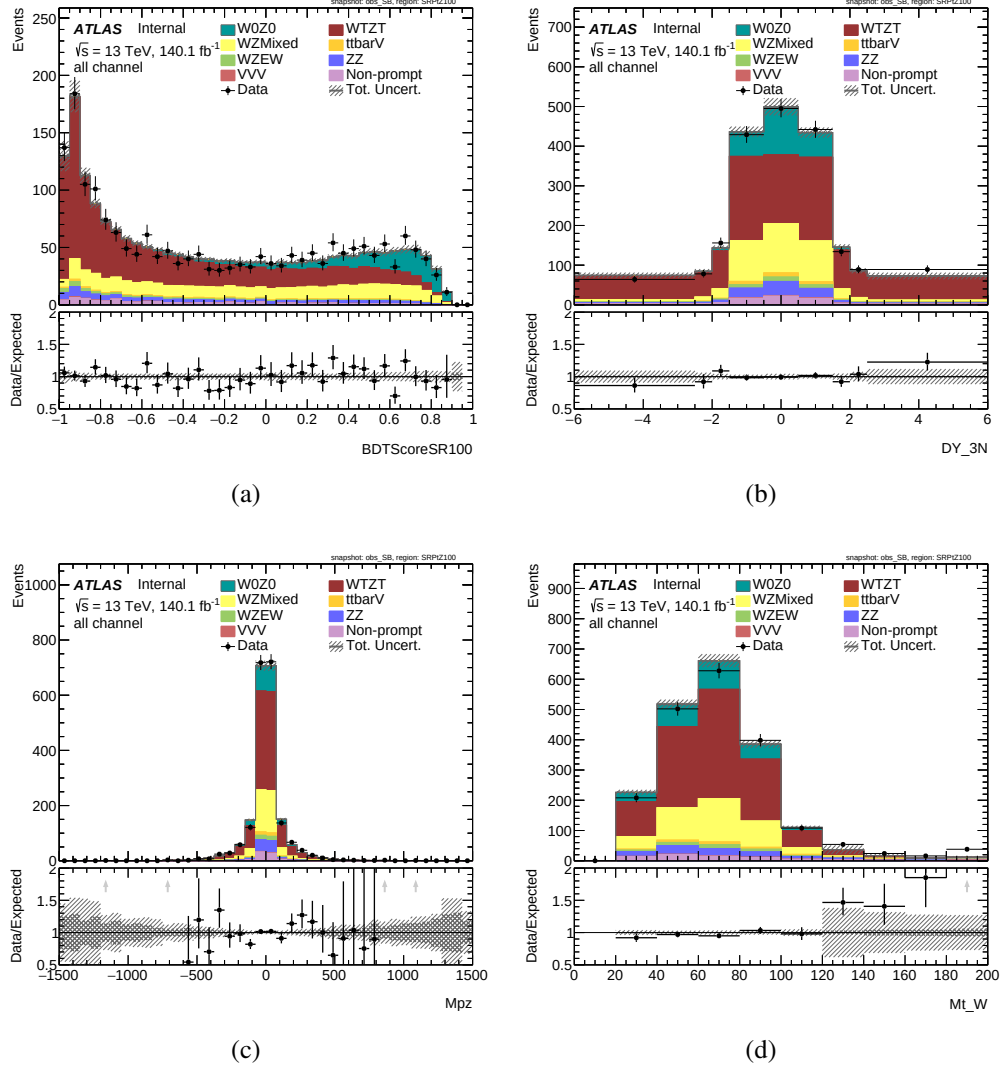
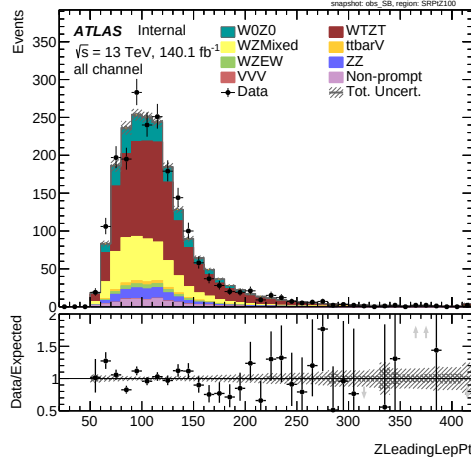
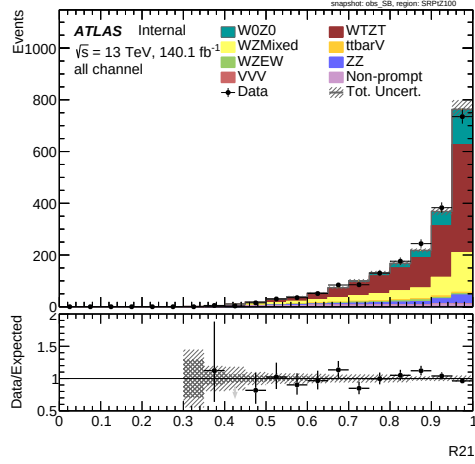


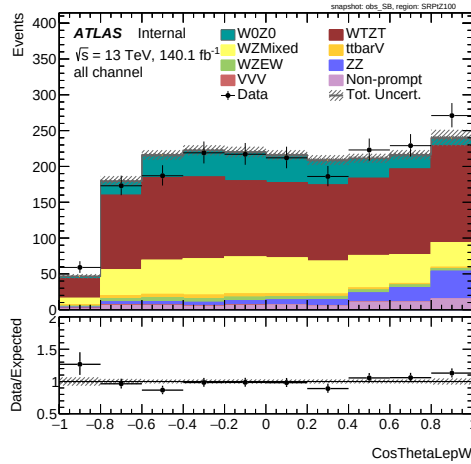
Figure J.3: Post-fit Data-MC Comparison in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 100$ GeV) using the three-parameter fit strategy for the BDT score (a), rapidity difference between the lepton from the W boson and the negatively-charged lepton from the Z boson (b), reconstructed neutrino p_z (c), and m_T^W (d). All variables are calculated at the reconstruction level.



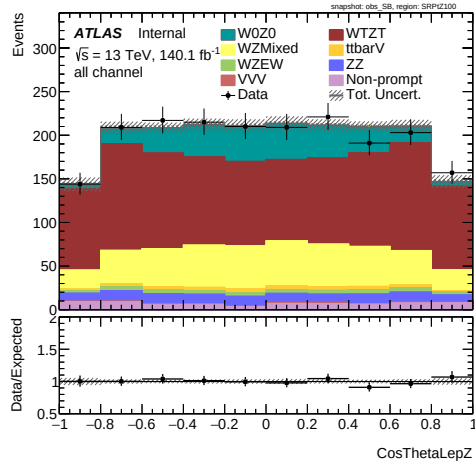
(a)



(b)



(c)



(d)

Figure J.4: Post-fit Data-MC Comparison in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 100$ GeV) using the three-parameter fit strategy for p_T of the leading Z lepton (a), $r_{21} = \frac{p_{T,V_2}}{p_{T,V_1}}$ which is the ratio of the p_T of the subleading vector boson to the p_T of the leading vector boson (b), $\cos\theta_\ell^*(W)$ (c), and $\cos\theta_\ell^*(Z)$ (d). All variables are calculated at the reconstruction level.

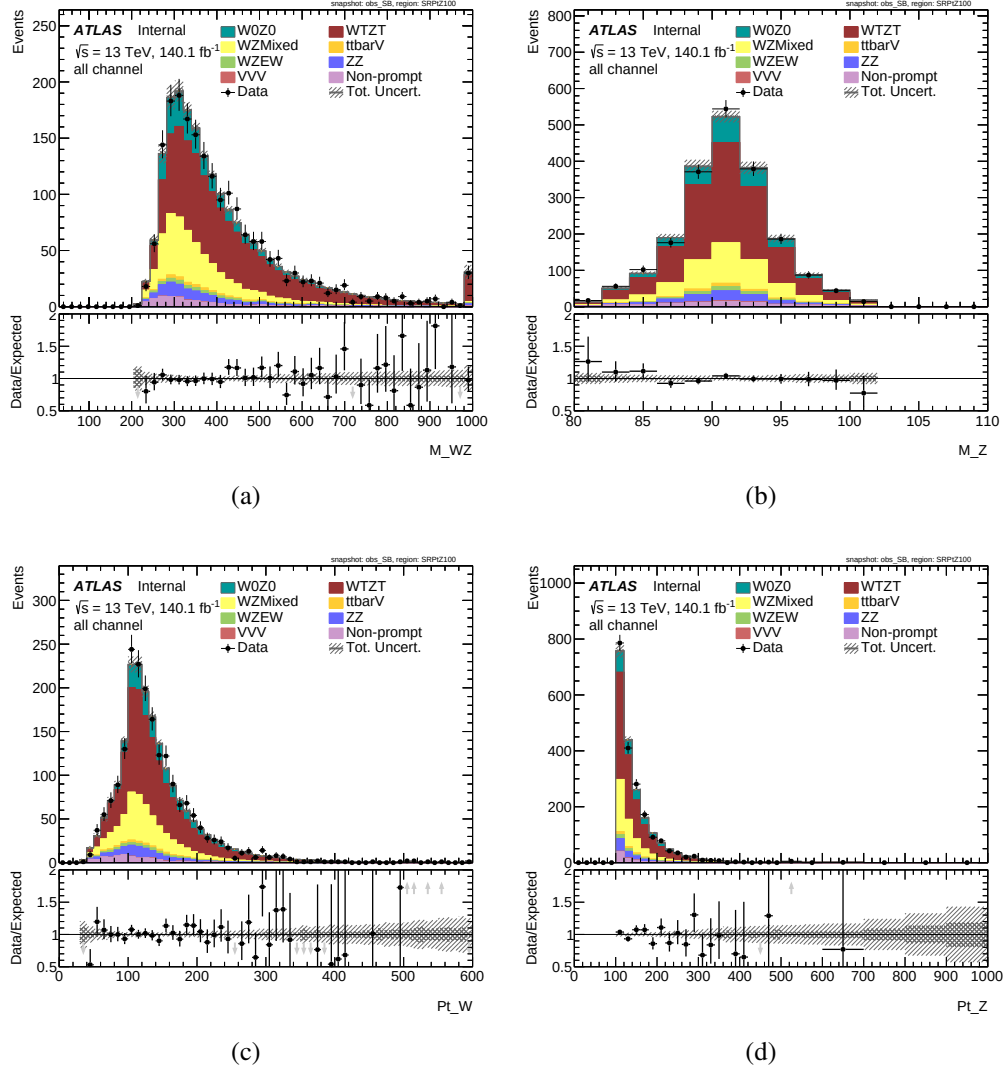


Figure J.5: Post-fit Data-MC Comparison in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 100$ GeV) using the three-parameter fit strategy for M_{WZ} (a), M_Z (b), p_T^W (c), and p_T^Z (d).

Figures J.6, J.7, J.8, J.9, J.10 are the post-fit distributions for different variables in $p_T^Z > 200$ GeV region and with the two-parameter fit strategy.

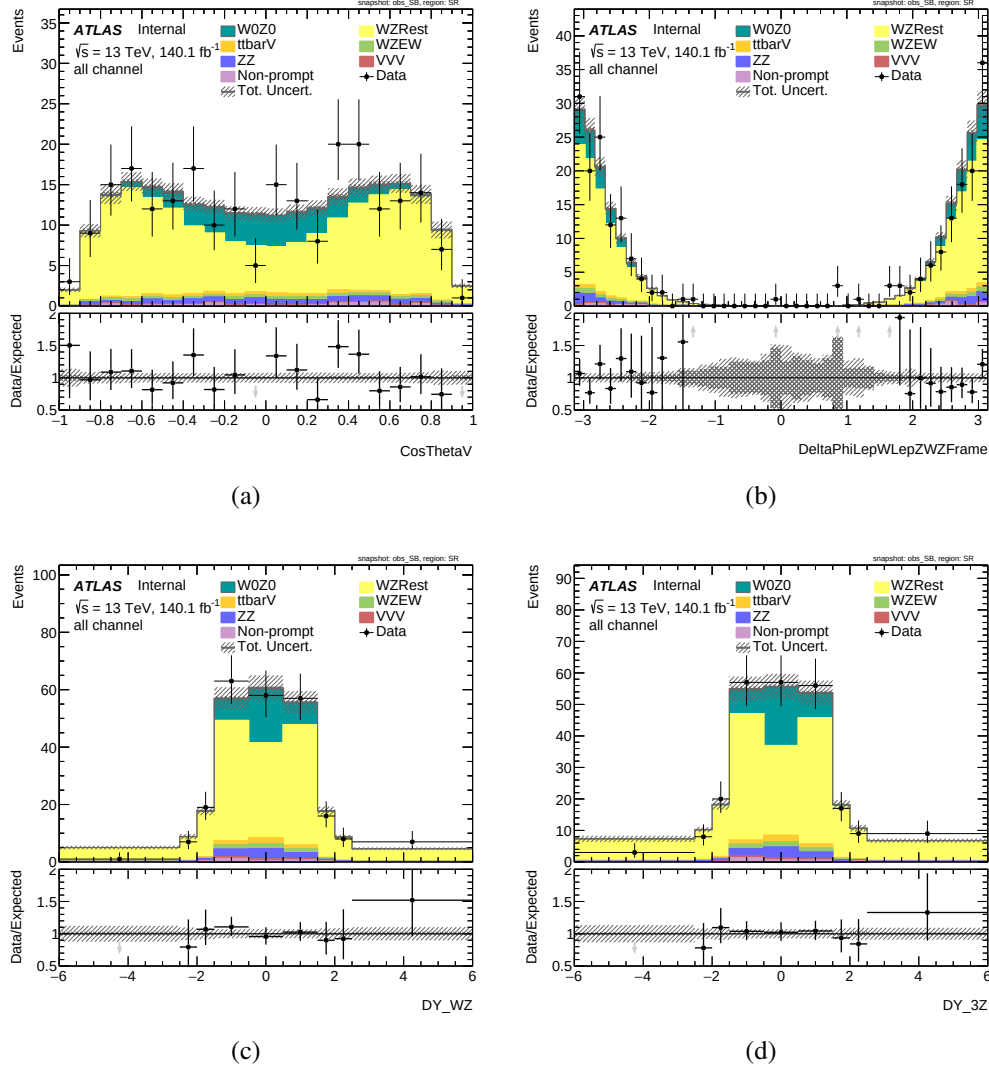


Figure J.6: Post-fit Data-MC Comparison in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 200$ GeV) using two parameter fit strategy for $\cos\theta_V$ (a), $\Delta\phi(\ell_W, \ell_Z)$ in the WZ rest frame (b), rapidity difference between the W and Z bosons (ΔY_{WZ}) (c), and the rapidity difference between the W lepton and the Z boson (ΔY_{3Z}) (d).

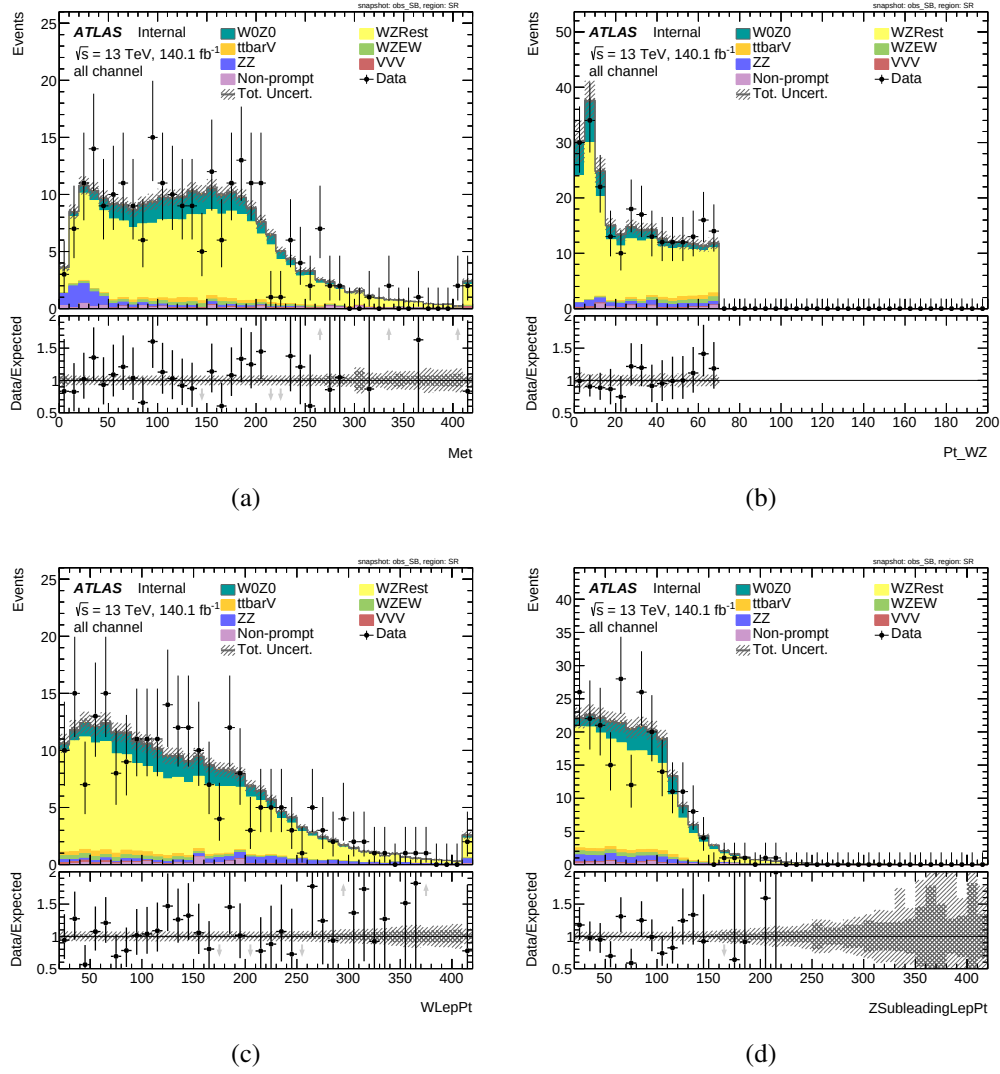
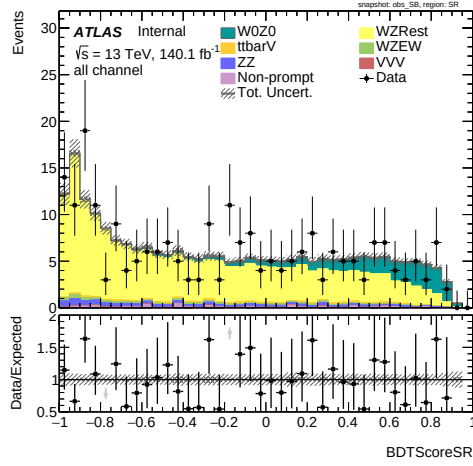
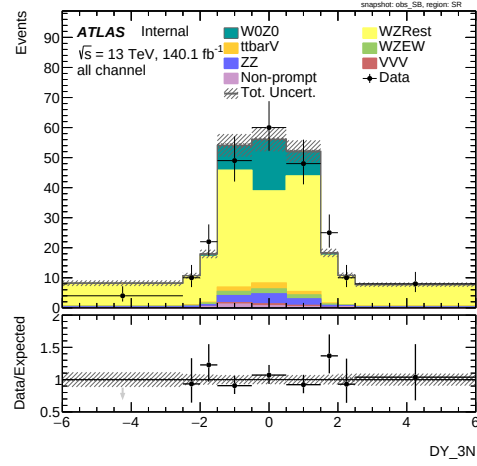


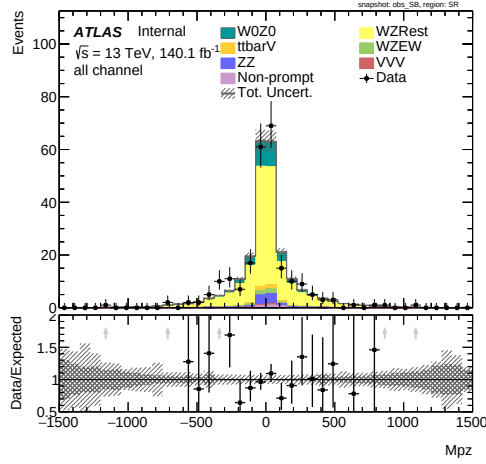
Figure J.7: Post-fit Data-MC Comparison in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 200$ GeV) using two parameter fit strategy for MET (a), p_T^{WZ} (b), p_T of the W lepton (c), and p_T of the subleading Z lepton (d). All variables are calculated at the reconstruction level.



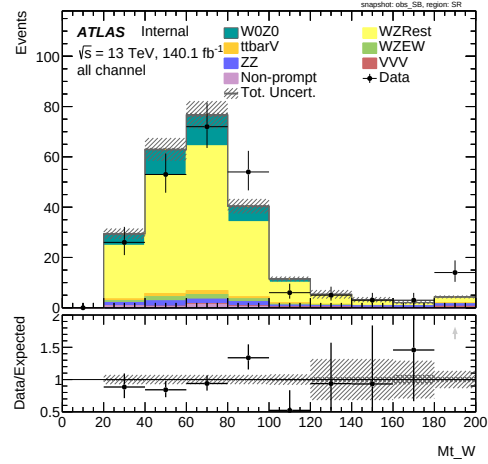
(a)



(b)



(c)



(d)

Figure J.8: Post-fit Data-MC Comparison in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 200$ GeV) using the two-parameter fit strategy for the BDT score (a), rapidity difference between the lepton from the W boson and the negatively charged lepton from the Z boson (b), reconstructed neutrino p_z (c), and m_T^W (d). All variables are calculated at the reconstruction level.

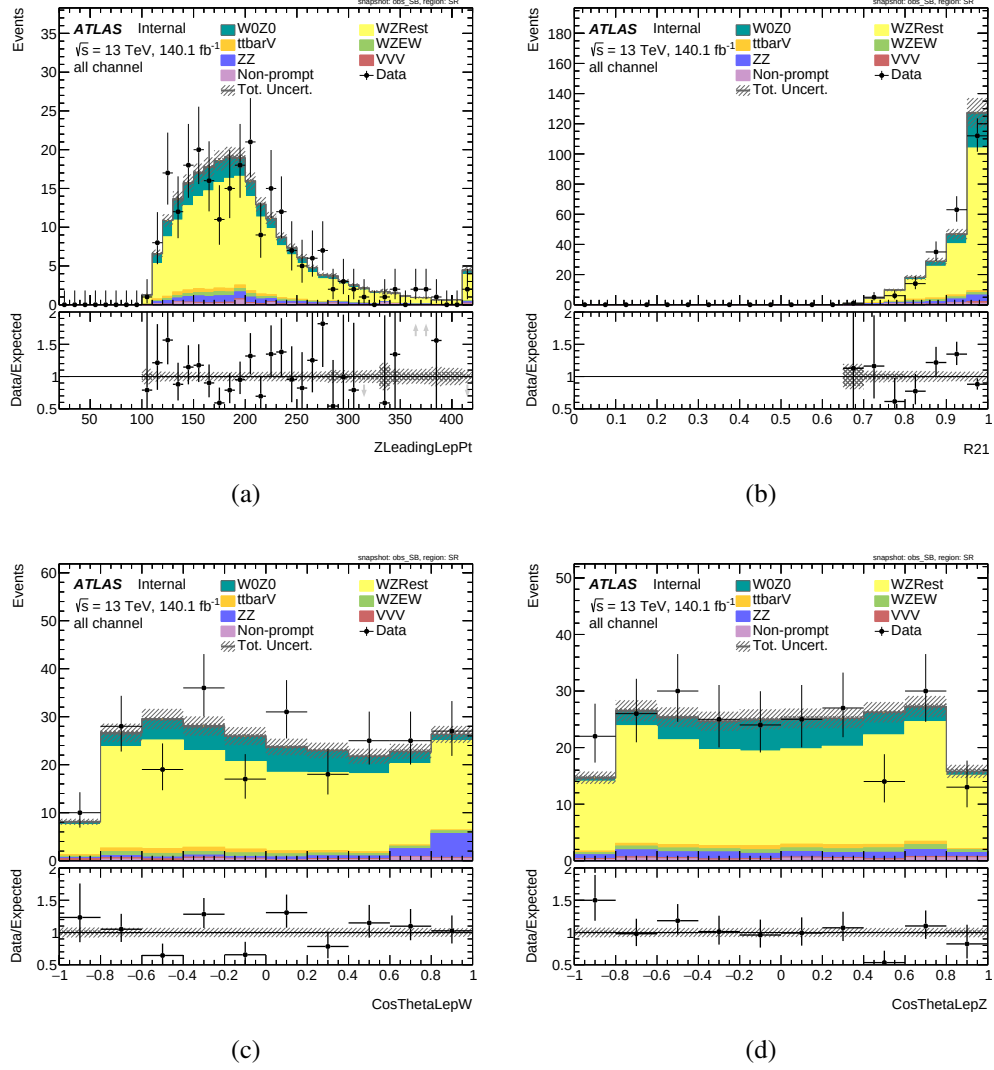


Figure J.9: Post-fit Data-MC Comparison in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 200$ GeV) using the two-parameter fit strategy for p_T of the leading Z lepton (a), $r_{21} = \frac{p_{T,V_2}}{p_{T,V_1}}$ which is the ratio of the p_T of the subleading vector boson to the p_T of the leading vector boson (b), $\cos\theta_{\ell}^*(W)$ (c), and $\cos\theta_{\ell}^*(Z)$ (d). All variables are calculated at the reconstruction level.

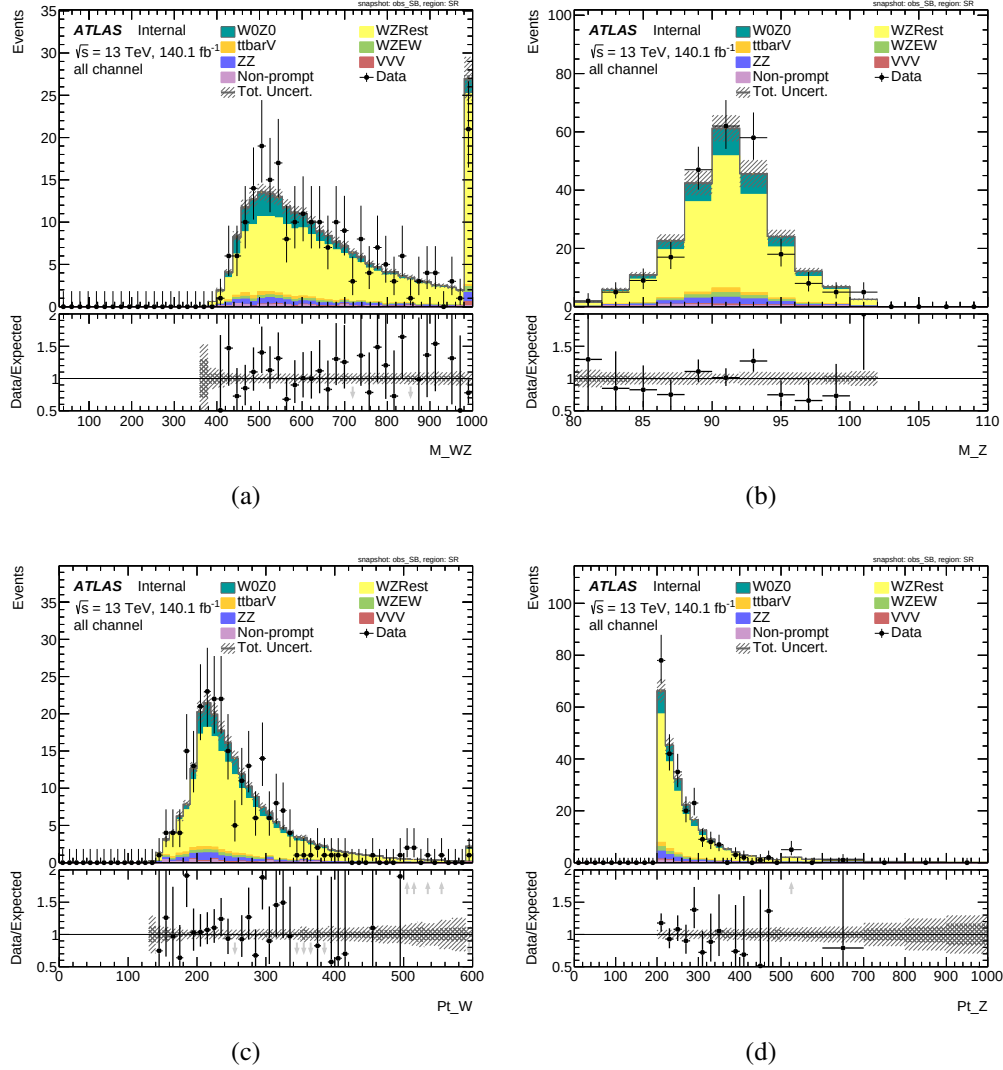


Figure J.10: Post-fit Data-MC Comparison in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 200$ GeV) using the two-parameter fit strategy for M_{WZ} (a), M_Z (b), p_T^W (c), and p_T^Z (d).

Figures J.11, J.12, J.13, J.14, J.15 are the post-fit distributions for different variables in $p_T^Z > 200$ GeV region and with the three-parameter fit strategy.

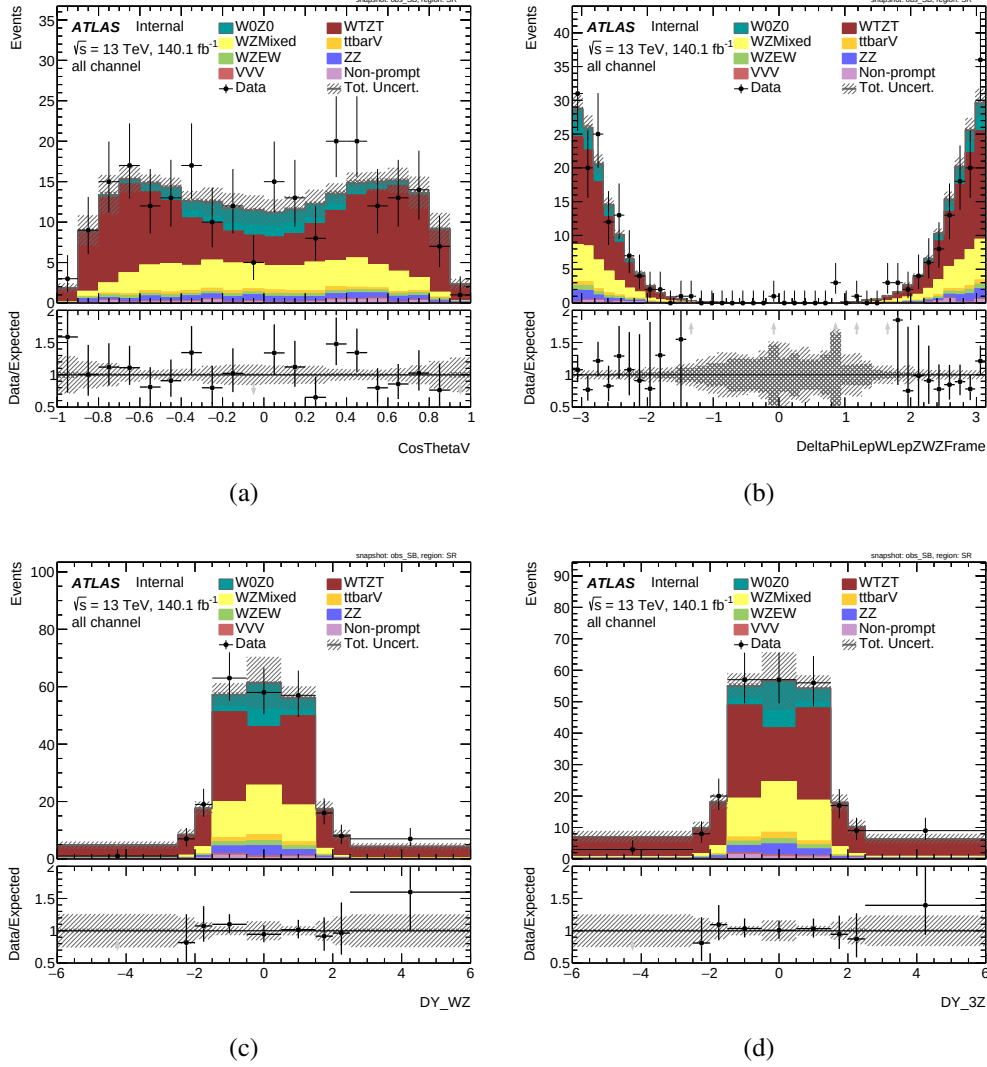


Figure J.11: Post-fit Data-MC Comparison in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 200$ GeV) using three parameter fit strategy for $\cos\theta_V$ (a), $\Delta\phi(\ell_W, \ell_Z)$ in the WZ rest frame (b), the rapidity difference between the W and Z bosons (ΔY_{WZ}) (c), and the rapidity difference between the W lepton and the Z boson (ΔY_{3Z}) (d).

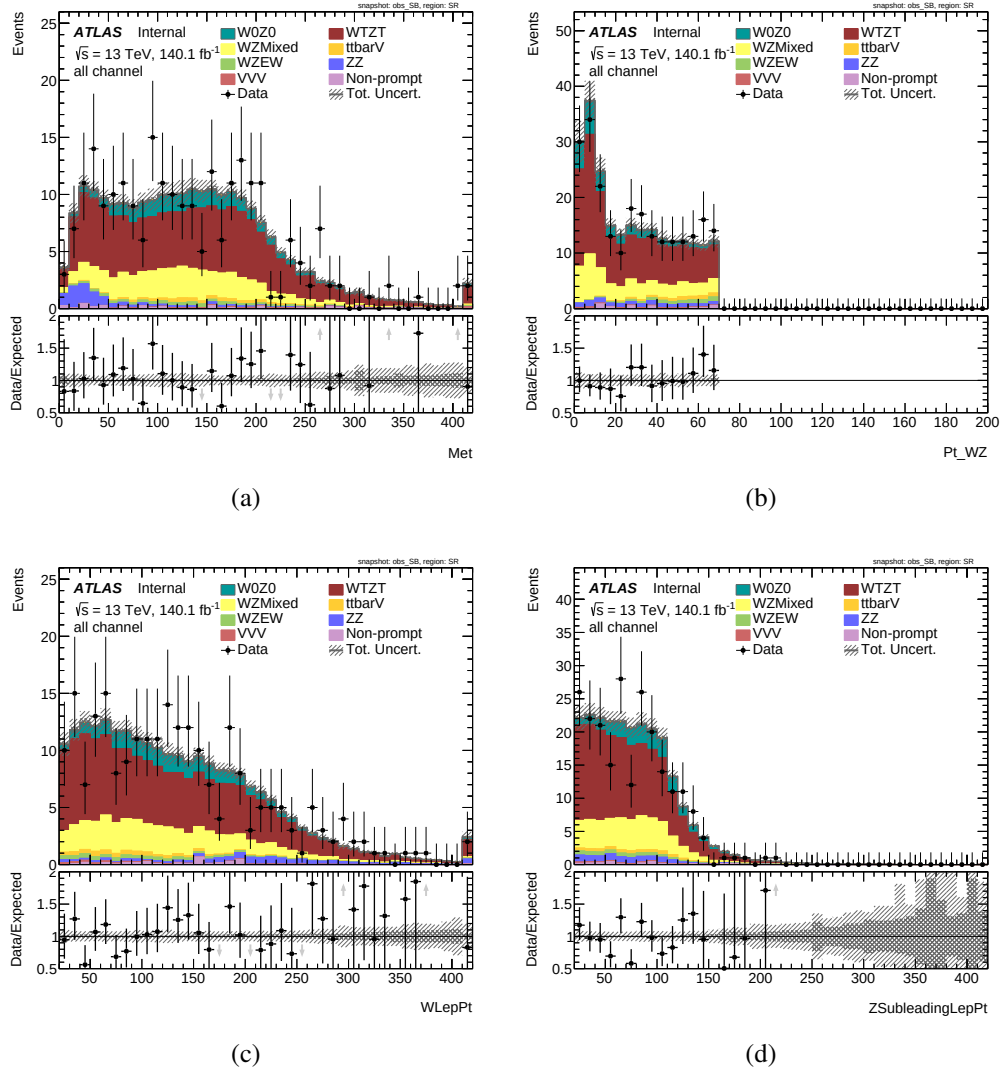


Figure J.12: Post-fit Data-MC Comparison in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 200$ GeV) using three parameter fit strategy for MET (a), p_T^{WZ} (b), p_T of the W lepton (c), and p_T of the subleading Z lepton (d). All variables are calculated at the reconstruction level.

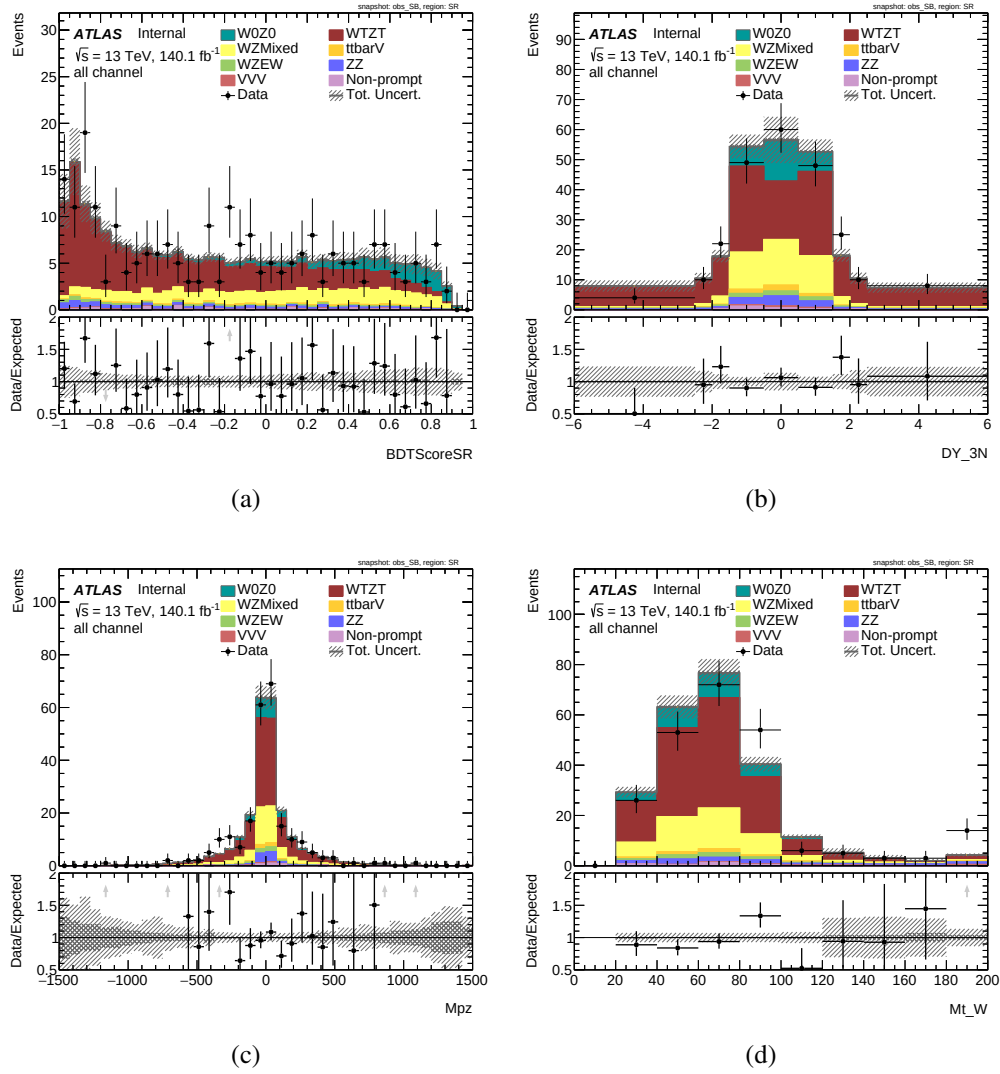
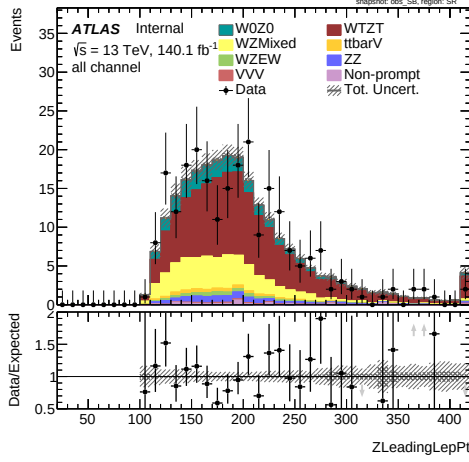
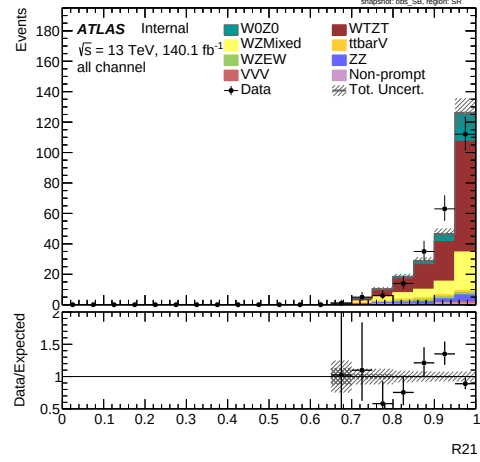


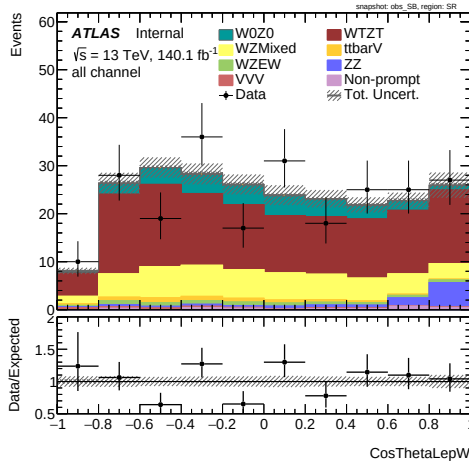
Figure J.13: Post-fit Data-MC Comparison in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 200$ GeV) using the three-parameter fit strategy for the BDT score (a), rapidity difference between the lepton from the W boson and the negatively charged lepton from the Z boson (b), reconstructed neutrino p_z (c), and m_T^W (d). All variables are calculated at the reconstruction level.



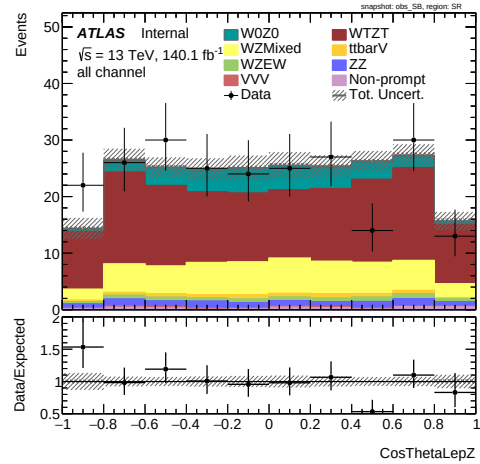
(a)



(b)



(c)



(d)

Figure J.14: Post-fit Data-MC Comparison in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 200$ GeV) using the three-parameter fit strategy for p_T of the leading Z lepton (a), $r_{21} = \frac{p_{T,V_2}}{p_{T,V_1}}$ which is the ratio of the p_T of the subleading vector boson to the p_T of the leading vector boson (b), $\cos\theta_\ell^*(W)$ (c), and $\cos\theta_\ell^*(Z)$ (d). All variables are calculated at the reconstruction level.

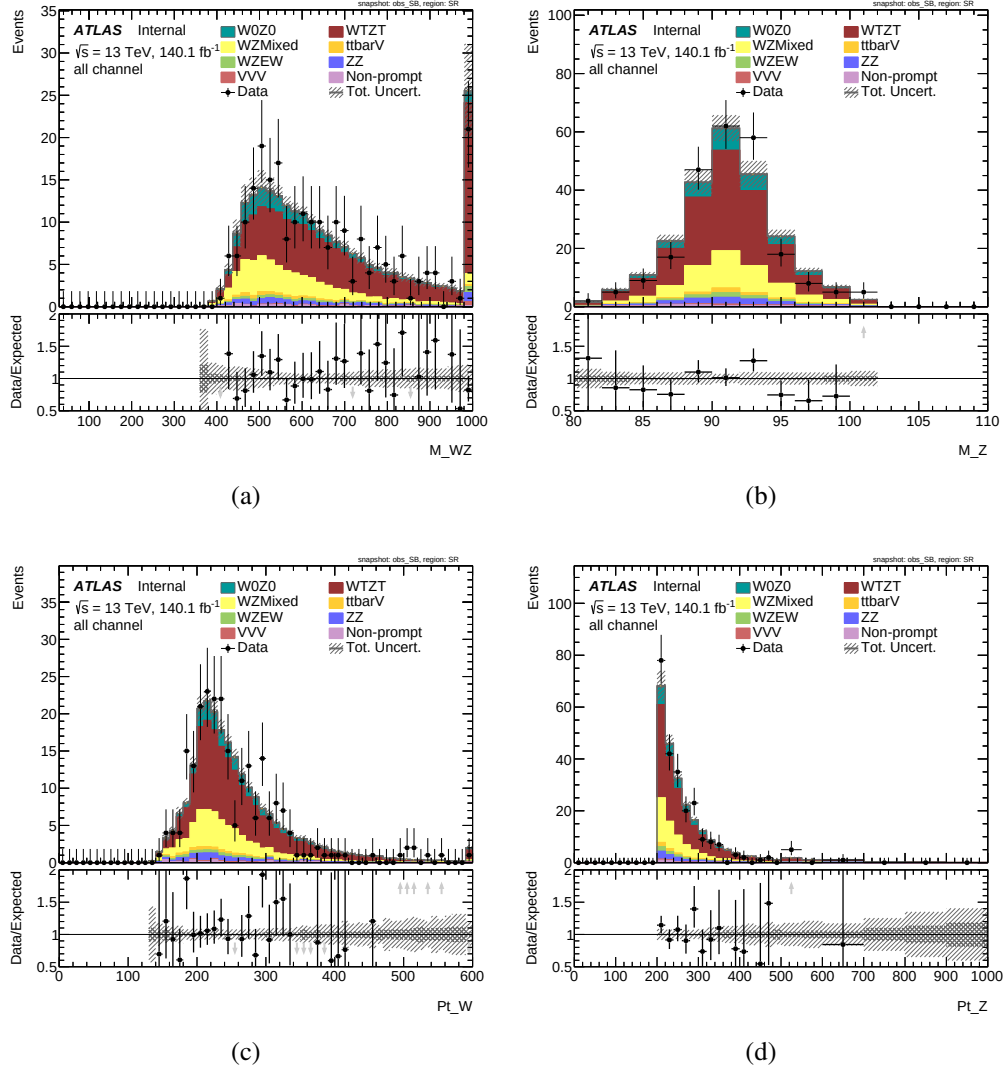


Figure J.15: Post-fit Data-MC Comparison in the signal region ($p_T^{WZ} < 70$ GeV and $p_T^Z > 200$ GeV) using the three-parameter fit strategy for M_{WZ} (a), M_Z (b), p_T^W (c), and p_T^Z (d).

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