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UNIVERSITY OF CALIFORNIA
SANTA CRUZ

**MEASUREMENT OF THE INCLUSIVE CROSS SECTIONS FOR
PRODUCTION OF $W^\pm$ AND Z BOSONS DECAYING TO
ELECTRONIC AND MUONIC FINAL STATES IN $\sqrt{s} = 13$ TEV pp
COLLISIONS WITH THE ATLAS DETECTOR**

A dissertation submitted in partial satisfaction of the
requirements for the degree of

Doctor of Philosophy

in

PHYSICS

by

Alexander Thomas Law

March 2016

The Dissertation of Alexander Law
is approved:

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Vice Provost and Dean of Graduate Studies

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Abstract

Measurement of the Inclusive Cross Sections for Production of $W^\pm$ and Z
Bosons Decaying to Electronic and Muonic Final States in $\sqrt{s} = 13$ TeV pp
Collisions with the ATLAS Detector

Alexander Law

Measurements are presented of fiducial and total inclusive cross-sections for $W \rightarrow \ell\nu_\ell$ and $Z \rightarrow l^+l^-$ production, where $\ell = e$ or μ , in pp collisions at center-of-mass energy $\sqrt{s} = 13$ TeV, using the ATLAS Detector at CERN's Large Hadron Collider. Data used in these measurements correspond to 81 inverse picobarns (pb^{-1}) of integrated luminosity, recorded during June and July 2015. Cross-sections are measured in six independent analysis channels, corresponding to the e and μ final states of W^+ , W^- , and Z bosons. Electron and muon channels are combined to obtain fiducial and total cross-sections-times-leptonic-branching-ratios for each of W^+ , W^- , and Z . The measured total cross section values (in picobarns, pb) are $\sigma_{W^+}^{\text{tot}} = 11779 \pm 19$ (stat) ± 319 (syst) ± 589 (lumi), $\sigma_{W^-}^{\text{tot}} = 8751 \pm 16$ (stat) ± 238 (syst) ± 438 (lumi), and $\sigma_Z^{\text{tot}} = 1972 \pm 7$ (stat) ± 38 (syst) ± 99 (lumi). The total $W \rightarrow \ell\nu_\ell$ cross-section is measured to be (in pb) $\sigma_{W^\pm}^{\text{tot}} = 20550 \pm 25$ (stat) ± 553 (syst) ± 1028 (lumi). Lepton universality ratios for $W^\pm$ and Z are calculated and found to be compatible with Standard-Model expectations and global averages. The $W^\pm$ charge ratio is measured to be $\sigma_{W^+}^{\text{fid}}/\sigma_{W^-}^{\text{fid}} = 1.295 \pm 0.003$ (stat) ± 0.010 (syst). The ratio of $W^\pm$ to Z fiducial cross-sections is measured to be $\sigma_{W^\pm}^{\text{fid}}/\sigma_Z^{\text{fid}} = 10.31 \pm 0.04$ (stat) ± 0.20 (syst). All measurements are compared to NNLO(QCD)+NLO(EW) predictions, based on a selection of modern proton parton distribution functions.

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Introduction

The measurement of inclusive cross-sections of the W^+ , W^- , and Z bosons are foundational steps in the campaign of electroweak-sector measurements at any modern hadron collider facility. The decays to leptonic final states are experimentally clean. Theoretical predictions are precise. High event rates and low backgrounds facilitate systematic-uncertainty-limited measurements with relatively early data. Previous measurements from LHC Run-1 provide recent and highly relevant precedents for experimental methods.

For these reasons, the $W^\pm$, Z cross-sections are an ideal proving ground for the upgraded ATLAS detector in LHC Run-2. An active Standard Model analysis with percent-level sensitivities after less than a month of collisions proved valuable to the collaboration at large, as a rapid road-test for important analysis tools which had yet to be fully validated in data studies.

Chapter 1 of this dissertation presents a brief conceptual summary of the Standard Model electroweak interactions which characterize the properties of the $W^\pm$ and Z bosons. To place the work at hand in its scientific and historical context, Chapter 2 surveys prior $W^\pm$ and Z inclusive cross-section measurements at many different collider facilities, with an emphasis on early-run commissioning studies similar in spirit to this one. Chapter 3 provides a description of the Large Hadron Collider and the ATLAS detector, as well as the algorithms employed in

these measurements to reconstruct electrons, jets, muons, and missing energy with ATLAS data. The primary subject of this dissertation is Chapter 4, where the method and results of ATLAS' first measurements of the 13 TeV $W^\pm$, Z inclusive cross-sections are presented in detail.

Chapter 1

Theory

1.1 The Electroweak Sector of the Standard Model

This section presents an abbreviated overview of the mathematical structure of Standard Model electroweak interactions. We begin with a simplified electroweak Hamiltonian, prior to mixing, mass generation, or electroweak symmetry breaking (EWSB).

$$H_{EW} = g J_\mu^i W_\mu^i + g' J_\mu^Y B_\mu^0 \quad (1.1)$$

$J_\mu^i = \bar{\psi}_L \gamma_\mu T_k \psi_L$ is the weak isospin current.

$T_k = \sigma_k/2$ are the SU(2) generators, and σ_k the Pauli matrices.

ψ_L are the *left-handed* weak isospin spinors.

γ_0, γ_i are the Lorentz boost generators in chiral representation.

$J_\mu^Y = (\frac{1}{2}g'Y) \bar{\psi} \gamma_\mu \psi$ is the hypercharge current, with hypercharge operator Y .

g, g' are the weak isospin and hypercharge coupling constants.

B_μ^0 is the U(1) hypercharge gauge boson field.

W_μ^i are the three SU(2) weak isospin gauge boson fields.

The first term defines the interactions of the weak isospin field. This interaction is mediated by three gauge boson fields, denoted W_μ^i . The second term describes the interaction of the same fermions (but coupling to a different charge) with a single gauge boson field, the B_μ^0 .

This is an example of a “chiral” theory, because the weak isospin W_μ^i fields couple only to fermions of left-handed chirality. The hypercharge B_μ^0 field couples equally to left- and right-handed fermions. Note that g , g' are independent coupling constants for the weak isospin and hypercharge fields, respectively.

The gauge symmetry of this interaction is SU(2)×U(1). In this representation, the three weak isospin fields W_μ^i are W^1 , W^2 , and W^3 . The SU(2) generators associated with these fields do not commute, leading to interactions among the W_μ^i 's.

The B_μ^0 field carries neither weak isospin nor hypercharge, but couples equally to left- and right-handed hypercharged fermions. Since the W 's carry no hypercharge, there are no interactions between the B and the W 's.

However, prior to mass generation, the B^0 and W^3 share all quantum numbers. Thus they mix, and the mixtures corresponding to physical mass eigenstates are characterized by the weak mixing angle, θ_W .

$$\begin{aligned} Z^0 &= W^3 \cos \theta_W - B^0 \sin \theta_W \\ A &= W^3 \sin \theta_W + B^0 \cos \theta_W \end{aligned} \tag{1.2}$$

One mixture, the A , couples to a mixture of hypercharge and weak isospin common to all electromagnetically-interacting Standard Model particles. This is

the physical photon, γ .

The orthogonal mixture, Z^0 , couples to weak isospin and hypercharge in such a way that their contributions to the electric charge coupling exactly cancel. This weakly interacting neutral boson is what we know as the Z boson.

We can then rewrite the weak vector boson fields in the basis of this “new” electric charge, and obtain the physical charged eigenstates, W^+ and W^- .

$$\begin{aligned} W^+ &= \frac{1}{\sqrt{2}} (W^1 - iW^2) \\ W^- &= \frac{1}{\sqrt{2}} (W^1 + iW^2) \end{aligned} \tag{1.3}$$

The theory in this form is incomplete, however. Trivial mass terms ($m\bar{\psi}\psi$) break gauge invariance for both fermion and boson interactions. It consequently anticipates long-range electroweak interactions mediated by stable, massless $W^\pm$ and Z bosons. Particle and nuclear experiments are incompatible with any gauge theory of electroweak interaction other than those mediated by short-ranged, massive electroweak bosons. The Higgs mechanism [1, 2] solves these problems, and predicts a new physical resonance, the Higgs boson, which was confirmed experimentally in 2012 by the ATLAS and CMS collaborations at the Large Hadron Collider.[3, 4]

The central supposition of Higgs theory is the existence of a new weakly charged, complex scalar field with uniform, nonzero Vacuum Expectation Value (vev). We know that it can have no color or electric charge, or else it would impart effective masses to the photon and gluon. The charge-weak isospin-hypercharge relations imposed by Eqns. 1.2 tell us that if the Higgs field has a zero-charge isospin projection, then there is a complementary charge-1 projection, as well. We will demand zero vev for this charged isospin projection (“up”) of the Higgs

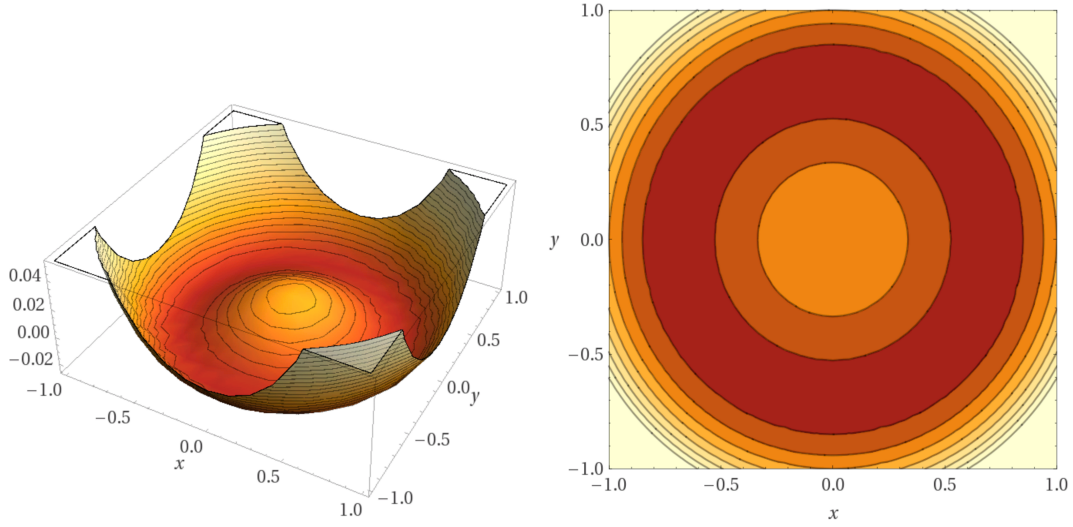


Figure 1.1: The Higgs (or “sombbrero”) potential (not to scale). The x and y axes correspond to the complex magnitudes of the isospin-up and -down projections of the Higgs field ϕ .

field, in order to avoid massive photons. Of course, the field’s interactions should generate mass terms compatible with the observed Standard Model spectrum.

To engineer the desired features, we add to the electroweak Lagrangian and Hamiltonian the potential in Eqns. 1.4, in which ϕ is the complex, scalar Higgs field:

$$V(\phi) = \mu^2 \phi^\dagger \phi + \lambda (\phi^\dagger \phi)^2, \quad \mu^2 < 1 \quad (1.4)$$

$$\phi = \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix}$$

$$(\phi^\dagger \phi)^2 = \{\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2\}$$

$$e^{i\theta(x)} = \begin{pmatrix} 0 \\ v/2 \end{pmatrix}$$

$$\phi^\dagger \phi = v^2 = \frac{-\mu^2}{2\lambda} \text{ defines the vacuum potential minimum, vev.}$$

$$m_H = v\sqrt{2\lambda}$$

With a quadratic polynomial potential in the scalar field strength, and a negative coefficient on the linear term, we get a minimum displaced from zero. Figure 1.1 shows the so-called “sombbrero” potential of the Higgs field, plotted in the two-dimensional space of weak isospin projections. It automatically satisfies the requirement for a nonzero vacuum expectation value, but not yet our need for a zero isospin-up component. We fix this by transforming ϕ to align the “down” direction with wherever we find the field. Now we have our vacuum Higgs field, with magnitude characterized by v .

To generate boson masses, we add to the Lagrangian the term in Eqn. 1.5.

$$L_{HV} = \left| \left(i\partial_\mu - gT_i W_\mu^i - g'\frac{1}{2}Y B_\mu^0 \right) \phi \right|^2 - V(\phi) \quad (1.5)$$

This is the Klein-Gordon equation for a massless scalar field, with the covariant derivative corrected to preserve local $SU(2) \times U(1)$ symmetry. Expanding the first term, we obtain Lorentz-scalar mixtures of $W^\pm$ and Z fields.

$$\frac{1}{2} \left(\frac{gv}{2} \right)^2 \underbrace{\left[(W_\mu^1)^2 + (W_\mu^2)^2 \right]}_{|W^+|^2 + |W^-|^2} + \frac{v^2}{8} \underbrace{\left[gW_\mu^3 - g'B_\mu \right]^2}_{Z^0} \quad (1.6)$$

The term above the left moustache is an even mixture of the $W^\pm$ charge eigenstates. The term above the right moustache is proportional to the zero-electric-charge mixture of the neutral electroweak boson fields (Eqns. 1.2). These are our mass terms for W^+ , W^- , and Z .

These do not, however, represent the whole content of the electroweak boson fields. Eqn. 1.6 does not contain the orthogonal mixture of W^3 and B^0 , which we identified as the photon (Eqn. 1.2). That is fine, of course, because the photon is

massless.

For the sake of thoroughness, we'll address the fermion mass interactions, even though they are not directly relevant to the measurement at hand. For each fermion species, we add a potential

$$\begin{aligned} L_{Hd} &= -g_d \left[(\bar{\psi}_L^u, \bar{\psi}_L^d) \begin{pmatrix} \phi_u \\ \phi_d \end{pmatrix} \psi_R^d + \bar{\psi}_R^d (\phi_u^\dagger, \phi_d^\dagger) \begin{pmatrix} \psi_L^u \\ \psi_L^d \end{pmatrix} \right] \\ L_{Hu} &= -g_u \left[(\bar{\psi}_L^u, \bar{\psi}_L^d) \begin{pmatrix} \phi_u^\dagger \\ \phi_d^\dagger \end{pmatrix} \psi_R^u + \bar{\psi}_R^u (\phi_u, -\phi_d) \begin{pmatrix} \psi_L^u \\ \psi_L^d \end{pmatrix} \right] \end{aligned} \quad (1.7)$$

The form of the fermion interactions is motivated by the Yukawa potential. Note especially that the form of the coupling is different for weak isospin up and down fermions. One might say that up and down fermions “see” the Higgs field differently. Note also that left-chiral fermion fields are isospin doublets, while right-chiral fields, which do not couple to $W^\pm$, are singlets in isospin representations. This is by construction of the original electroweak Lagrangian (Eqn. 1.1).

Expanding these interactions, we obtain independent mass terms, with independent constants, for up and down members of the same weak isospin doublet.

$$\left(\frac{g_d v}{\sqrt{2}} \right) \bar{\psi}^d \psi^d \quad \left(\frac{g_u v}{\sqrt{2}} \right) \bar{\psi}^u \psi^u \quad (1.8)$$

This is how the theory permits light neutrino partners to massive leptons, and large mass differences within quark generations. Further exegesis of these interactions reveals a physical mass eigenstate of the Higgs field, the Higgs boson, with direct couplings to all massive fermions and bosons.

The $SU(2) \times U(1)$ gauge theory of electroweak interactions, with symmetry broken spontaneously via the Higgs mechanism, provides a complete theoretical

picture of the spectrum of Standard Model electroweak interactions observed in experiment. And while the theory does establish concrete relations among the masses of the physical electroweak bosons and the weak mixing angle θ_W , it does not provide *a priori* predictions of these parameters. It has been left to the 60-year campaign of high-energy particle physics experiment to establish these parameters.

1.2 The $W^\pm$ and Z Bosons

1.2.1 Experimental Parameters

All of the free parameters of the $SU(2) \times U(1)$ electroweak Theory have been measured experimentally. Values obtained by the Particle Data Group through global averages of experimental results are listed in Eqns. 1.9.[5]

$$\begin{aligned}
 \sin^2 \theta_W &= \frac{g'^2}{g^2 + g'^2} \approx 0.23 \\
 v &= \frac{|\mu|}{\sqrt{\lambda}} = \frac{2M_W}{g} \approx 246 \text{ GeV} \\
 M_W &= 80.385 \pm 0.015 \text{ GeV} \\
 M_Z &= \frac{M_W}{\cos \theta_W} = 91.1876 \pm 0.0021 \text{ GeV} \\
 M_H &= \lambda v = 125.09 \pm 0.24 \text{ GeV}
 \end{aligned} \tag{1.9}$$

1.2.2 Decays

The decays of the $W^\pm$ and Z are predicted exactly by the full $SU(3) \times SU(2) \times U(1)$ theory, and are independent of the initial-state process by which the particles were

	Branching Ratios (%)	
	$W^\pm$	Z
BR_e	10.71 ± 0.16	3.363 ± 0.004
BR_μ	10.63 ± 0.15	3.366 ± 0.007
BR_τ	11.38 ± 0.21	3.370 ± 0.008
BR_{had}	67.41 ± 0.27	69.91 ± 0.06
invisible	1.4 ± 2.6	20.00 ± 0.06

Table 1.1: Branching ratios for W^+ , W^- , and Z bosons, as percentages.[5]

produced. Hence the $W^\pm$ and Z branching ratios to final states are universal to all collider experiments. The branching ratios to electrons, muons, and tau leptons are tightly constrained ($BR_e \approx BR_\mu \approx BR_\tau$) by the principle of lepton universality, which has been confirmed experimentally to a high degree of precision (including by this analysis). The equivalence is not perfect, even in theory, due to differences in the decay kinematic phase spaces attributable to the different lepton masses. The measured branching ratios are summarized in Table 1.1.

1.2.3 Z/γ^* Interference

The mixing within the $B^0/W^3/\gamma/Z^0$ system described in Section 1.1 has an important consequence for experimental studies of the Z boson. Interference between the Z and off-shell photons (γ^*) means that predictions and simulations of Z production must include the interference with γ^* to obtain accurate predictions. As can be seen from Figure 1.2, analyses that use the dilepton invariant mass $m_{\ell\ell}$ of Z decays must make a somewhat arbitrary choice about their Z fiducial phase space. The choice of limits in $m_{\ell\ell}$ is consequential to predictions and experimental results. For this reason, Z results are typically quoted as a function of the $m_{\ell\ell}$ window in

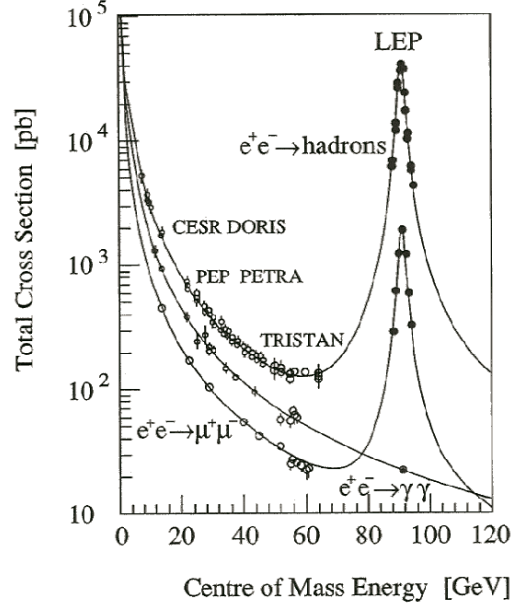


Figure 1.2: Z/γ^* interference. The Z peak in dilepton invariant mass interferes with the exponentially-falling γ^* invariant mass distribution. This plot was obtained from a center-of-mass energy scan in e^+e^- collisions at various lepton colliders.

which they were evaluated. In the measurements described in this dissertation, the chosen dilepton invariant mass range was $66 \text{ GeV} < m_{\ell\ell} < 116 \text{ GeV}$.

1.3 $W^\pm/Z$ Production at 13 TeV

The tree-level processes which dominate $W^\pm$ and Z production at the Large Hadron Collider are pictured in figure 1.3. The predicted approximate cross-sections are summarized in Table 1.2. Decay branching ratios of $W^\pm$ and Z are predicted fully in the Standard Model (with experimental values for m_W , m_Z , and $\sin^2 \theta_W$), and are independent of the initial state from which the bosons were produced.

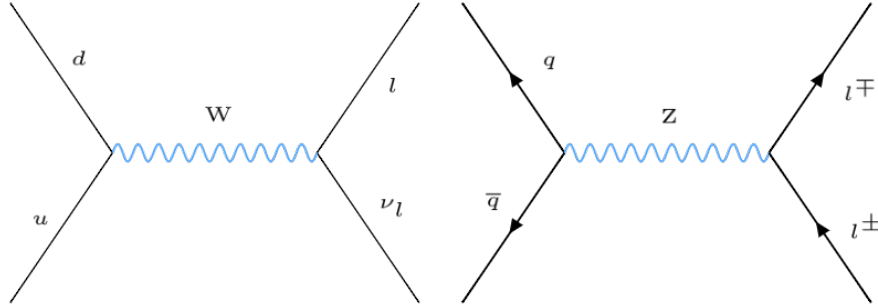


Figure 1.3: Feynman Diagrams of the dominant $W^\pm$ and Z production processes at LHC. The leptonic decays studied in these measurements are illustrated here, though hadronic final states predominate $W^\pm$, Z decays in general (Table 1.1).

	$\sigma(13 \text{ TeV}) \text{ (pb)}$
σ_{W^+}	$11540^{+320}_{-310}(\text{PDF}) \pm 150(\text{scale}) \pm 160(\text{other})$
σ_{W^-}	$8540^{+210}_{-240}(\text{PDF}) \pm 110(\text{scale}) \pm 120(\text{other})$
σ_Z	$1890 \pm 50(\text{PDF}) \pm 30(\text{scale}) \pm 30(\text{other})$

Table 1.2: Predicted cross-sections for $W^+ \rightarrow \ell^+ \nu_\ell$, $W^- \rightarrow \ell^- \bar{\nu}_\ell$, and $Z \rightarrow \ell^+ \ell^-$ at 13 TeV LHC. These predictions were calculated at NNLO(QCD) + NLO(EW). PDF uncertainties are evaluated by variation of the parton distribution functions input to theory calculations. Scale uncertainties are evaluated by varying the factorization and renormalization scales at which the predictions are calculated. The predictions are described in Section 4.6.1.

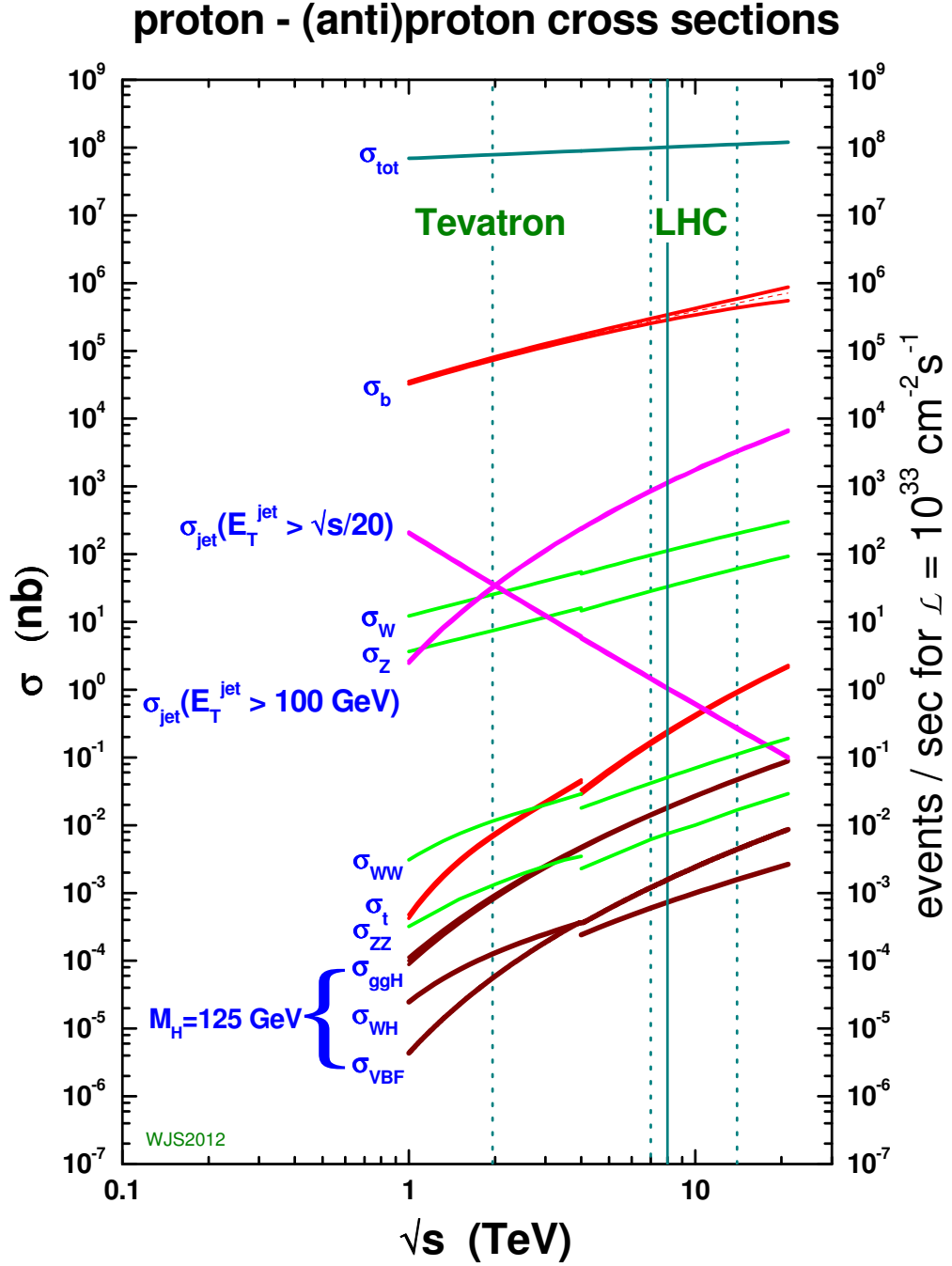


Figure 1.4: Proton-(anti)proton cross-sections for several significant physics processes as a function of $\sqrt{s}$. [6]

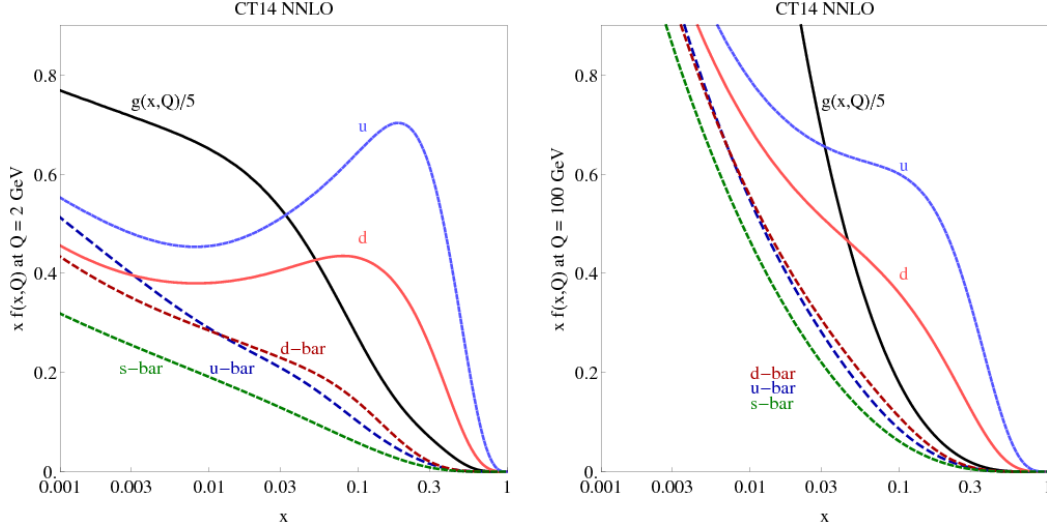


Figure 1.5: Parton Distribution Functions for the proton. Q is the momentum transfer between initial-state partons in the event. x is the fraction of total proton momentum (6.5 TeV at Run-2 LHC) carried by the chosen parton. xf is the population of partons in the initial state at a given (x, Q) . Figure 4 from [7].

1.3.1 The Parton Distribution Function (PDF)

The Parton Distribution Function (PDF) is, essentially, a phenomenological model that describes the abundance and momentum spectra of the quarks, antiquarks, and gluons within the proton. For a given initial state defined by the incoming partons, and the momentum transfer Q^2 between them, the probability of $W^\pm$ or Z production is given by the Standard Model quantum field theory matrix element. The probability for a proton-proton collision at given $\sqrt{s}$ to produce a $q_u \bar{q}_d$, $\bar{q}_u q_d$, or $q \bar{q}$ reaction, with initial state parton momentum fractions x and x' , and momentum transfer Q^2 , is calculated via the use of PDFs. Characteristic x for $W^\pm$ and Z production at 13 TeV LHC is on the order of 0.01. For single- $W^\pm$ and Z production, the momentum-transfer parameter Q^2 is set by the respective boson masses, plus any additional momentum carried by the bosons. Characteristic Q^2 in these events is on the order of $(100 \text{ GeV})^2$.

Due to weaker experimental constraints in some regions of the flavor-momentum space (especially low- x gluons), experimentalists choose from among many “competing” PDFs. All modern PDFs are compatible with the existing body of experimental results, but their predictions can diverge where experimental constraints are not as strong. Differences among alternative proton PDFs correspond to variations of the analytical models of flavor and momentum content, as well as in the fits of those models’ free parameters to the corpus of experimental data. Significant parameters of the PDF model include the number of quark flavors (three-flavor uds versus four-flavor $udsc$ versus five-flavor $udscb$) included in the model, and the order in Quantum Chromodynamics (QCD) calculations (typically next-to-leading-order or next-to-next-to-leading order) at which the model is evaluated. Differences with respect to the fitting include the free parameters of the chosen models, the statistical fitting procedure, and the selection of experimental results included in the fit.

Predictions of the $W^\pm$ and Z cross-sections at LHC are not highly sensitive to PDF choice (among modern NNLO PDFs, at least). However, the experimental uncertainty on ratios among these cross-sections becomes competitive with the theoretical uncertainties on predictions, creating the potential for these precision ratio measurements to provide empirical discrimination among modern proton PDFs. These predictions and their comparisons to theory are described in [Section 4.6](#).

Chapter 2

Prior Measurements

To date, only a handful of experimental facilities worldwide have achieved center-of-mass particle collision energies sufficient to produce electroweak bosons on-mass-shell. These include CERN’s Super Proton Synchrotron, the Tevatron at Fermilab, the Large Electron-Positron collider, also at CERN, the Large Hadron Collider, HERA at the DESY, and the Relativistic Heavy-Ion Collider at Brookhaven. While these accelerators all, in principle, would have produced some real $W^\pm$ and Z bosons, not all were built with any intent to generate rich $W^\pm$ and Z datasets. HERA, in particular, is ill-suited (as an electron-proton collider) for precision measurements of $W^\pm$ and Z properties. Both HERA experiments, ZEUS and H1, have nevertheless published evidence of real (i.e., nonvirtual) $W^\pm$ and Z production consistent with Standard Model expectations at HERA.[\[8–11\]](#)

In terms of integrated luminosity, the total inclusive cross sections of $W^\pm$ and Z bosons, $\sigma_{W,Z}^{\text{tot}}$, are the earliest accessible measurements in the Electroweak physics campaign at any hadron collider. Almost all succeeding measurements of $W^\pm$ and Z properties are, in essence, relations among such cross sections in various final states and differential parameters.

Because the total inclusive cross sections times branching ratios depend on the collision initial state, $\sigma_{W,Z}^{\text{tot}}$ are unique, in general, to every collider facility. The collection of measurements of the same process at many hadron colliders can be used to test the evolution of $\sigma_{W,Z}^{\text{tot}}$ for the respective initial and final states, as seen in Figures 2.1 and 2.2.

Total pp and $p\bar{p}$ cross sections increase with $\sqrt{s}$, as the range in momentum fraction x within which the initial-state quarks carry sufficient energy for the boson reaction increases. For a given process, pp and $p\bar{p}$ cross sections converge at high $\sqrt{s}$. This is due to the convergence of valence and sea (anti)quark content towards the lower- x region of the proton PDF (Figure 1.5).

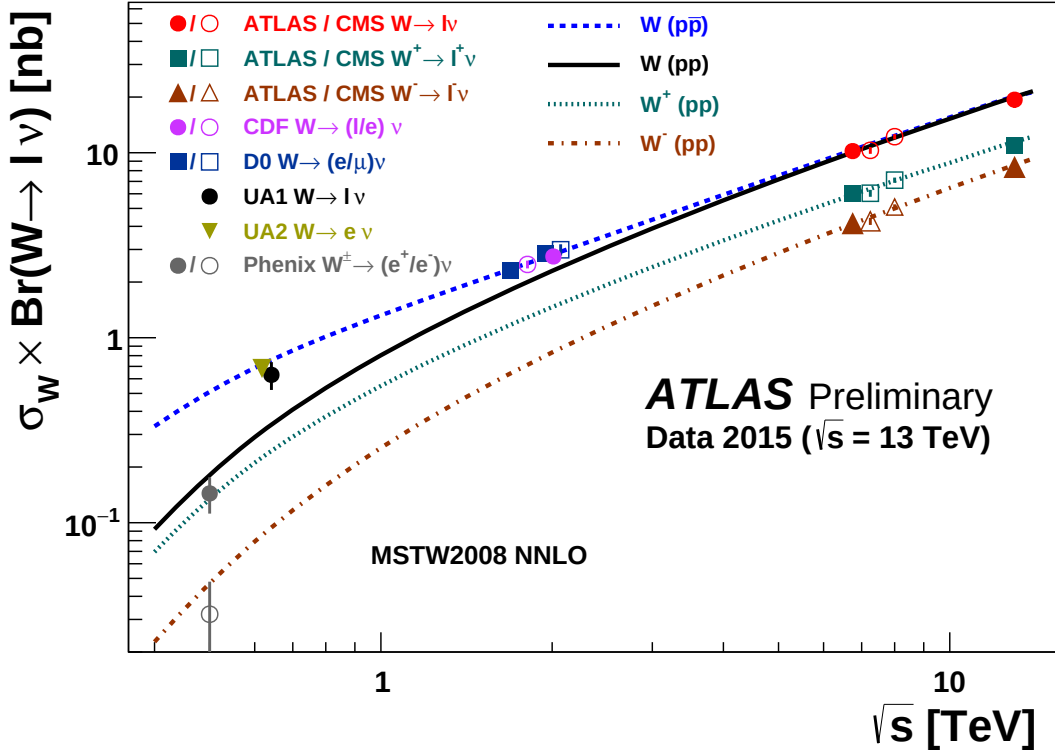


Figure 2.1: σ_W versus $\sqrt{s}$ at proton-(anti)proton colliders. The evolution of $W^\pm$ and Z cross sections with $\sqrt{s}$ tests PDF models of parton-momentum-fraction evolution.

This section will summarize the important prior measurements of the $W^\pm$ and

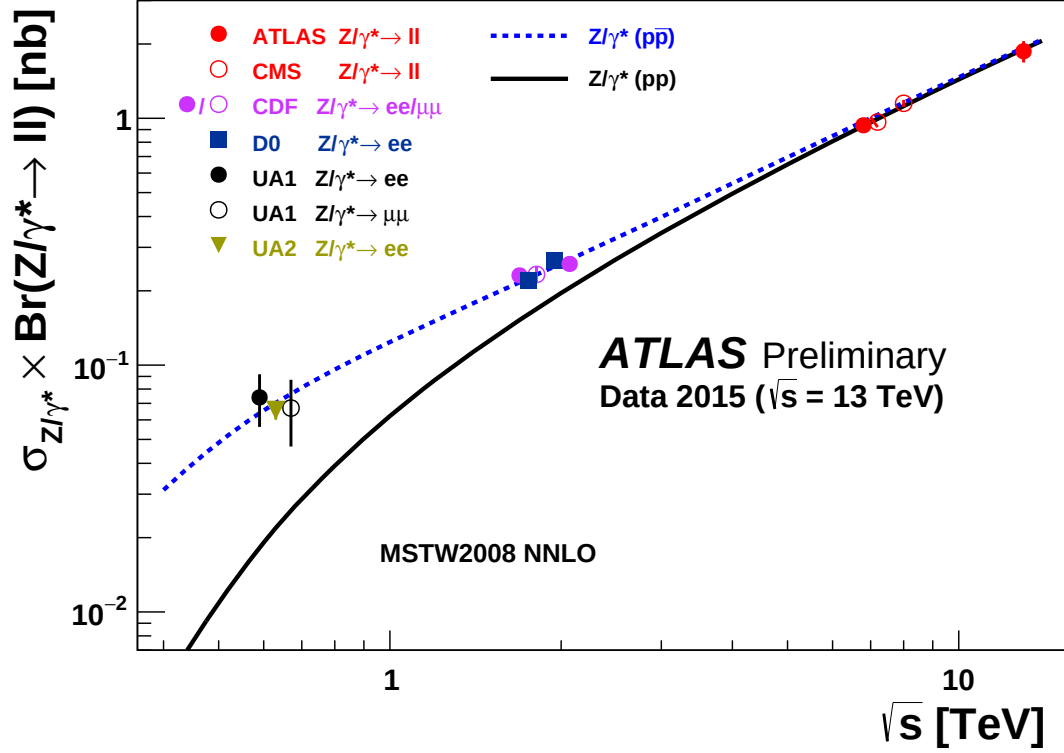


Figure 2.2: σ_Z versus $\sqrt{s}$ at proton-(anti)proton colliders. The evolution of $W^\pm$ and Z cross sections with $\sqrt{s}$ tests PDF models of parton-momentum-fraction evolution.

Z bosons which paved the way for the work at hand, with particular attention to foundational measurements of total inclusive $W^\pm$ and Z cross sections. Prior measurements at Tevatron and LHC are emphasized, being the most closely related in method to the subject of this dissertation.

2.1 SPS Measurements (Discovery)

The W^+ , W^- , and Z bosons were first observed in 1982-1983 with the UA1 (“Underground Area 1”) and UA2 (“Underground Area 2”) detectors, installed at CERN’s Super Proton Synchrotron (SPS). Beginning in 1978, the preexisting SPS was converted from a 450 GeV proton-proton collider, to a 540 GeV proton-

antiproton machine, with the explicit goal of detecting the $W^\pm$ and Z . Its collision energy was upgraded again in 1983-84 to 630 GeV for additional runs through 1990. SPS is still in operation today, back in proton-proton mode, as the final particle injection stage to the Large Hadron Collider.

Measurements of $W^\pm$ and Z properties were performed in the leptonic final states $Z \rightarrow l^+l^-$ and $W \rightarrow \ell\nu_\ell$, since multijet backgrounds arising from the hadronic initial state overwhelmed the hadronic boson decay signals. Despite the high hadronic background, evidence for the hadronic decays of $W^\pm$ and Z was observed as an excess over the smooth dijet background in the (unresolved) W/Z mass range. [12–15]

It is notable that almost all of the $W^\pm$ and Z boson properties measured subsequently at future hadron colliders, including the LHC, were measured first in the UA1 and UA2 datasets. UA1 and UA2 obtained experimental results for the cross sections, masses, and widths of the $W^\pm$ and Z bosons, $\sin^2 \theta_W$, the leptonic branching ratios, $W^\pm$ charge asymmetries, p_T^Z distributions, m_W/m_Z mass ratios, and more. [16–18]

2.2 SLC Measurements

The SLAC Large Detector (SLD) experiment, at the Stanford Linear Collider (SLC), performed many measurements of the Z boson properties between 1989 and 1998. SLC collided electrons and positrons up to a peak center-of-mass energy of approximately 100 GeV. A large dataset was collected at the Z mass resonance in order to characterize many of the Z boson properties. SLC’s dataset was not particularly productive with respect to $W^\pm$ measurements, due to the fact that the neutral e^+e^- initial state could only generate charged $W^\pm$ bosons through

higher-order processes resulting in associated production with oppositely-charged final-state particles.

Low hadronic backgrounds at SLC, and the installation of one of the earliest silicon vertexing detectors, enabled SLD to characterize the hadronic decays of the Z boson with a precision which was not possible at many other colliders. In 2006, many SLC measurements performed at the Z peak in center-of-mass collision energies were combined with corresponding measurements from LEP (Section 2.3) into a global fit of many dependent electroweak parameters.[19]

2.3 LEP Measurements

The Large Electron-Positron collider operated at CERN from 1989-2000, in the underground tunnel which eventually became home to the Large Hadron Collider. LEP collided electrons and positrons at center-of-mass energies up to 209 GeV. Four large detectors were installed at LEP, called ALEPH, L3, DELPHI, and OPAL. These experiments exploited the well-defined initial-state energy of lepton-lepton interactions to collect a large dataset (LEP-1) at the Z mass peak resonance. This dataset was large enough, and the detectors sufficiently precise, to observe and study single- $W^\pm$ production through higher-order processes which were not accessible at the Stanford Linear Collider. Between 1995 and 2000, a dataset (LEP-2) was collected of collisions up to $\sqrt{s} = 209$ GeV. LEP-2's maximum center-of-mass energy was sufficient to access W^+W^- diboson production (in the t-channel via neutrino exchange, or s-channel via virtual Z/γ^*). The W^+W^- cross section was measured as a function of center-of-mass energy, to identify the diboson on-shell resonance mass. The $W^\pm$ mass was also measured as a parameter of distributions of explicitly reconstructed $W^\pm$ boson masses.

The four LEP experiments combined electroweak results at Z -pole energy with corresponding measurements from the Stanford Linear collider. The combinations were published in 2006.[19] A global combination of LEP-2 electroweak measurements, including $W^\pm$ and Z boson properties, from all four LEP experiments, was published in 2013.[20]

2.4 RHIC Measurements

The Relativistic Heavy Ion Collider (RHIC) is located at Brookhaven National Laboratory in Brookhaven, New York, USA. It began operation in 2000 and continues to operate through the present day (2016). RHIC is first and foremost a heavy-ion collider, designed to study long-range correlations (like quark-gluon plasma and Bose-Einstein condensates) in collisions of heavy ions like gold and lead. The extremely high multiplicity of decay products from heavy-ion collisions are an effectively impossible environment in which to identify $W^\pm$ and Z boson decays. RHIC has, however, performed dedicated proton-proton runs at $\sqrt{s} = 500 \text{ GeV}$. In 2010-2011, the two large RHIC detector experiments, STAR and PHENIX, published analyses of $W^\pm$ and Z production in these data, almost contemporaneous to the first LHC results.

The initial state at RHIC in proton-proton mode is essentially similar to that of the SPS *before* it was retrofitted for the $W^\pm$, Z search. Compared to the SPS experiments, however, RHIC experiments enjoy the combined benefits of higher luminosity and decades of additional detector research and development.

RHIC $W^\pm$ and Z cross sections were measured exclusively in the electronic decay channels, as neither STAR nor PHENIX features robust muon ID. The $W^\pm$, Z cross sections measured at RHIC experiments are all compatible with Standard-

model expectations, but exhibit large, statistically-dominated uncertainties (on the order of 30%), owing to the small cross sections at RHIC and low selection efficiencies.[21–23]

2.5 Tevatron Measurements

The Tevatron, located at Fermilab outside of Chicago, USA, was a proton-antiproton synchrotron collider that operated from 1987 to 2011. The peak center-of-mass energy at Tevatron was 1.96 TeV. As at the CERN $Spp\bar{S}$, Z boson production occurred predominantly via valence quark-antiquark annihilation. $W^\pm$ production occurred predominantly via fusion of charged up-down valence quark pairs. Tevatron also achieved sufficient collision energy and integrated luminosity to study multiboson production and interactions, including $p\bar{p} \rightarrow W^+W^-$.

Tevatron delivered collisions to two large, general-purpose detectors: CDF and D0.[24, 25] Tevatron collected two major datasets, Run 1 and Run 2. The first, was at $\sqrt{s} = 1.8$ TeV. The accelerator and detectors were then upgraded for a $\sqrt{s} = 1.96$ TeV dataset (Run 2).[26] The total integrated luminosity of Run 2 was approximately 13 fb^{-1} per detector. CDF measured the inclusive cross sections times branching ratios of $W^\pm$ and Z , in the electron and muon channels, at 1.8 TeV and 1.96 TeV.[27–29] D0 made the same measurements at 1.8 TeV, but not in the muon channel at 1.96 TeV.[30, 31]

CDF and D0, especially after upgrades for Tevatron Run 2, feature all of the same basic detector subsystems and operational principles as CMS and ATLAS - in particular hermetic calorimetry and robust muon ID. Tevatron luminosities were large enough, relative to the $W^\pm$, Z cross sections, that CDF and D0 were able to publish systematic-uncertainty-limited measurements of $\sigma_{W,Z}^{\text{tot}}$ with relatively

small, early subsets of the data from each run. The common hadronic initial states produce nearly identical menus of significant background processes. The leading uncertainties on $W^\pm$ and Z cross sections are similar, as well (luminosity, QCD background contributions).

2.6 LHC Run 1

For the purposes of this summary, the Large Hadron Collider [32] (Section 3.1) is a synchrotron collider capable of generating proton-proton collisions at center-of-mass energies up to 13 TeV. LHC experiments have published measurements of $W^\pm$ and Z properties at center-of-mass energies $\sqrt{s} = 7$ and 8 TeV. This dissertation 4 reports the first measurements of $W^\pm$ and Z boson cross sections in the 13 TeV (Run 2) dataset.

The two general-purpose detectors at LHC best suited to $W^\pm$ and Z physics are ATLAS and CMS.[33, 34] These two experiments have published dozens of results on $W^\pm$, Z production and properties, as well as sophisticated combinations of their datasets. LHCb has also published observations of $W^\pm$ and Z production consistent with Standard Model expectations within that detector’s limited acceptance.[35]

Even though the LHC is a pp collider, instead of $p\bar{p}$ like the SPS and Tevatron, $W^\pm$ and Z production at LHC proceed primarily via the same processes: s-channel $q\bar{q} \rightarrow Z$, and $u\bar{d}(\bar{u}d) \rightarrow W^{+(-)}$, with the initial-state antiquarks drawn from the so-called parton sea characterized by the proton PDF (Section 1.3.1). With respect to precision in measurements of the vector boson properties, the LHC’s energy, luminosity, and resolution more than compensate the suppression of these initial states in the pp PDF (relative to $p\bar{p}$). Note the convergence at high $\sqrt{s}$ of pp and

$p\bar{p}$ cross sections for $W^\pm$, Z production (Figures 2.1 and 2.2). The charged initial state at ATLAS also leads to a difference in the W^+ and W^- cross sections. The ratio $R_{W^+/W^-} = \sigma_{W^+}/\sigma_{W^-}$ is sensitive to the relative populations of quark species in the proton PDF (especially of valence u and d). It also has an experimentally accessible Standard Model value at LHC.

CMS and ATLAS have published many more measurements of $W^\pm$ and Z boson properties and production than are summarized here. Complete, up-to-date bibliographies can be found at the collaborations' websites.[36, 37]

CMS published $W \rightarrow \ell\nu_\ell$ and $Z \rightarrow l^+l^-$ cross sections for the electron and muon decays in 2010 with very early (2.9 pb^{-1}) 7 TeV data. QCD templates for the $W \rightarrow \mu\nu_\mu$ channel were obtained from data control regions. The QCD background to the $W \rightarrow e\nu_e$ signal was modeled analytically, and the model was validated by comparison to Monte-Carlo simulation. Signal normalizations were fit from the missing transverse energy ($\cancel{E}_T$) distributions of $W^\pm$ selections. Total backgrounds to the Z measurement were negligible. Cross sections were established with 2-3% uncertainty in the muon final states, and 5-6% uncertainty in the electron channels. This was followed in 2011 by a 36 pb^{-1} 7 TeV analysis.[38]

The CMS 8 TeV $W^\pm$ analysis, published in 2014, measured cross sections times branching ratios with total uncertainties of approximately 6% for $W^\pm$ bosons, and 3% for Z . Total uncertainties on ratios of cross sections were at the 2% level.[39]

Similarly to CMS, ATLAS published $W^\pm$ and Z cross sections in the $e\nu_e$, $\mu\nu_\mu$, e^+e^- , and $\mu^+\mu^-$ final states with early 7 TeV data recorded in 2010, and then followed up with a revised analysis using a larger subset of the 7 TeV data. As of March 2016, ATLAS has not yet published 8 TeV cross sections for the $W^\pm$ and Z .

The early 7 TeV paper was based on about 320 nb^{-1} of total luminosity, con-

siderably smaller than that of the corresponding CMS measurement. This dataset was distinguished by a very low pileup environment, typically 1, 2, or 3 primary vertices per event passing the high- p_T lepton triggers. The total inclusive boson cross sections were extracted using a method similar to that described in Chapter 4. The precision of this measurement was hampered especially by large (11%) uncertainty on the integrated luminosity at ATLAS during these first data runs.[40]

A succeeding analysis published in 2014 updated these results based on approximately 35 pb^{-1} of data (still a minuscule fraction of the whole 7 TeV dataset, approximately 4 fb^{-1}). Luminosity uncertainties were improved considerably (3.4%). The cross section extraction method differs from that used in the early 7 TeV and 13 TeV measurements. The alternative method was better suited to the evaluation of differential cross sections presented alongside the inclusive results in this study. Total uncertainties on ratios of inclusive cross sections were competitive with theory uncertainties.[41]

Chapter 3

Experimental Facilities

This chapter describes the design and function of the Large Hadron Collider and the ATLAS detector. It is important to note that many technical parameters of the LHC and ATLAS are subject to periodic change. Reasons for changes have historically included planned upgrades, such as installation of new detector hardware during pauses in operation, gradual wear-and-tear due to, e.g., radiation damage, and unanticipated technical failures, such as the infamous 2008 dipole magnet “quench” [42]. The measurements described in this dissertation were performed using data collected by LHC/ATLAS during June and July 2015. Descriptions in this chapter reflect the status of the accelerator and detector during this period of time.

3.1 The Large Hadron Collider

Details of the design and initial construction of the Large Hadron Collider (LHC) are available in the LHC Design Report, volumes 1-3.[43–45] The accelerator is described as of commissioning (2008) in the Large Hadron Collider publication.[32]

The Large Hadron Collider is a charged-particle synchrotron complex capable of colliding proton bunches at center-of-mass energies up to 13 TeV, with collision rates (instantaneous luminosity, L_{inst}) of up to $10^{34} \text{ pb}^{-1}/s$. At the time of writing of this dissertation, the LHC exceeds all other particle-collider facilities worldwide in its peak and nominal values of collision energy and data throughput. Consequently, the LHC, CMS, and ATLAS provide the richest datasets available in which to study many rare and high-energy particle phenomena, including $W^{\pm}$ and Z boson production.

In addition to proton-proton collisions, the LHC periodically performs heavy-ion runs, during which one or both proton beams are replaced by beams of highly ionized heavy nuclei. As of March 2016, heavy-ion runs have included lead-lead, gold-gold, and proton-lead collisions, at varying instantaneous luminosities, bunch spacings, and center-of-mass energies.

3.1.1 Physical Infrastructure

The Large Hadron Collider is located at the European Organization for Nuclear Research (CERN), astride the Swiss-French border near Geneva, Switzerland. LHC beams circulate in an underground tunnel of roughly circular shape, 27 kilometers in circumference (Figure 3.1). The tunnel has a circular cross-section 3.8 meters in diameter, illustrated in Figure 3.2. Its depth varies from 75 to 100 meters, conforming to geological features of the region between Lake Geneva’s southwestern shore and the Jura foothills.

The LHC tunnel was originally excavated in 1983-1988 to house the Large Electron-Positron (LEP) collider complex. LEP collided electron and positron beams at center-of-mass energies up to 209 GeV. Important LEP measurements

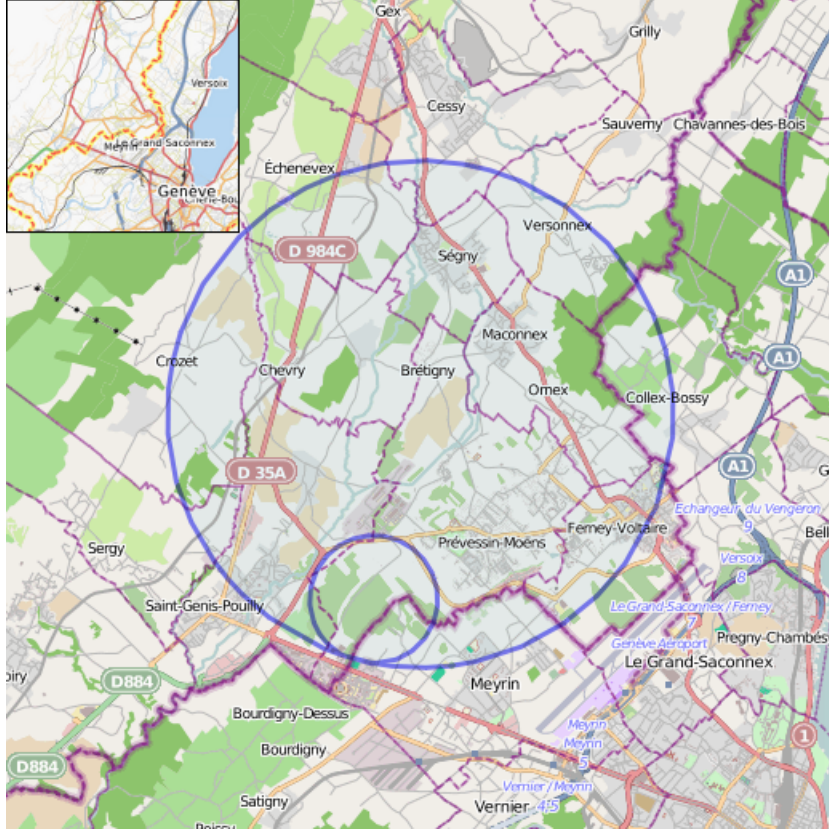


Figure 3.1: Geographical map of the LHC tunnel (larger ring). The smaller ring is the CERN Super Proton Synchrotron.[46]

of $W^\pm$ and Z boson properties are summarized in section 2.3. LEP operated from 1989 through 2000, when it was decommissioned to make way for the Large Hadron Collider.[47]

The majority of the LHC tunnel, approximately 23 km of the total 27 km, is occupied by dipole magnets which steer high-energy charged particles around the ring at a constant curvature radius of approximately 3 km. The dipoles are described in greater detail in section 3.1.4.

The other roughly 4 km of tunnel are accounted for by the eight “long straight sections” (LSS), each approximately 500 m in length, located symmetrically around the ring. Since the large dipole magnets are not required to contain the beams

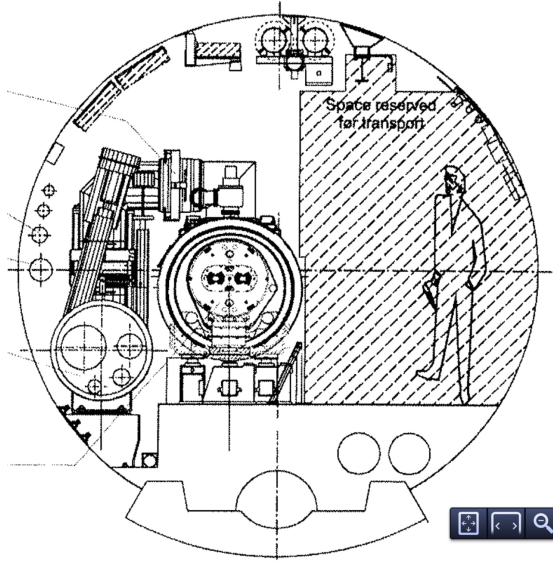


Figure 3.2: Cross-sectional illustration of the LHC tunnel. The tunnel diameter is approximately 3.8 m (note human figure for scale). From Fig. 11-1 of [43]

Point	Occupied by	note
1	ATLAS detector	general-purpose physics
2	ALICE detector	heavy-ion physics
3	Momentum Cleaning	beam quality
4	RF Accelerators	beam quality
5	CMS detector	general-purpose physics
6	Beam Dump	safe disposal of beams
7	Betatron Cleaning	beam quality
8	LHCb detector	charm and beauty physics

Table 3.1: LHC Surface Points and Interaction Regions

through straight sections, these lengths can be instrumented with other accelerator and physics infrastructure. Each long straight section is connected to the surface by wide, vertical access shafts through which large devices and materiel can be lowered and removed. The eight LHC surface points and straight sections are listed in Table 3.1, and illustrated in Figure 3.3.

Vue d'ensemble des ouvrages souterrains du LHC

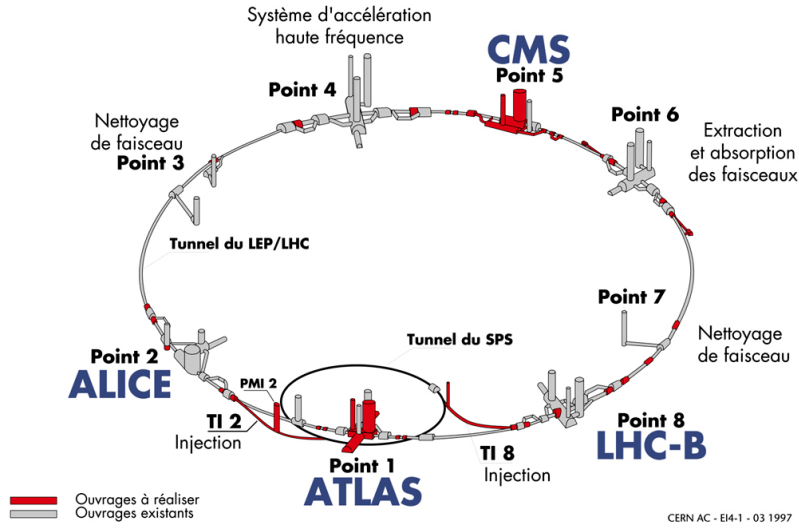


Figure 3.3: LHC caverns and Interaction Points. Tunnels and shafts drawn in red were new excavations, added to the LEP tunnel for the LHC project. [48]

3.1.2 Injection Complex

The CERN-LHC proton injection chain is summarized in Table 3.2 and illustrated in 3.4.

CERN's accelerator complex has evolved over 60 years as a staged injection system, in which successive generations of energy-frontier accelerators have become, each in turn, humble stepping stones on the way to the next big thing. Hence, the LHC receives charged particles from the Super-Proton-Synchrotron (SPS) at an injection energy of 450 GeV. SPS receives protons at 24 GeV from the (evidently less-than-super) Proton Synchrotron (PS). The PS receives particles at 1.4 GeV from the PS Booster. Hydrogen gas at rest is ionized to produce protons and accelerated to 50 MeV inside CERN's LINAC2 linear accelerator.

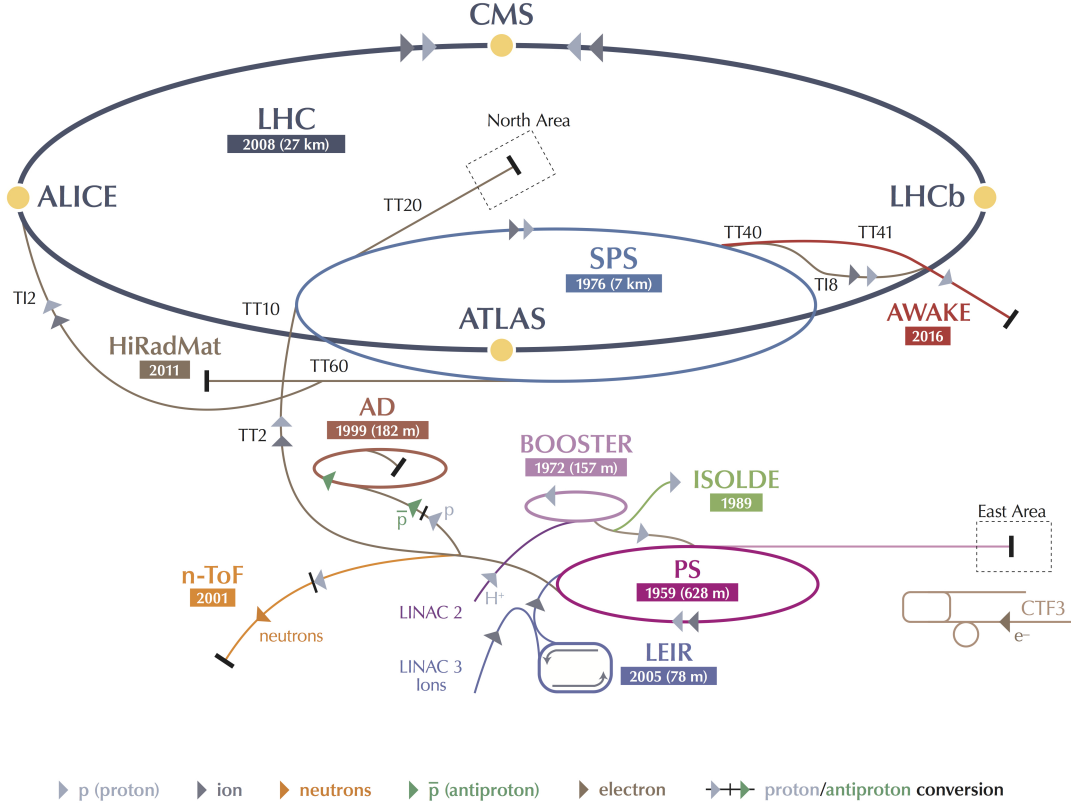


Figure 3.4: Illustration (not to scale) of the CERN-LHC Proton Injection chain. LHC protons begin in the LINAC2 (lower middle), and are injected through the PS BOOSTER (periwinkle), the Proton Synchrotron (PS, mauve), the Super Proton Synchrotron (SPS, blue), and the LHC (dark blue).[\[49\]](#)

3.1.3 RF Acceleration

The basic principle of a synchrotron accelerator is to steer charged particles through a closed loop using applied electromagnetic fields. Tangential electrical gradients oscillating in phase with particles' orbit provide an incremental kick to the particles' total energy upon each revolution. At LHC, the gradients are supplied by a complex of radiofrequency (RF) cavities installed at point 4. The LHC RF system serves several purposes: The first is to accelerate particles from SPS injection energies to LHC collision energies. After the beams have achieved

Acceleration Stage	Energy
LINAC2	50 MeV
Proton Synchrotron Booster	1.4 GeV
Proton Synchrotron	24 GeV
Super Proton Synchrotron	450 GeV
Large Hadron Collider	6.5 TeV

Table 3.2: CERN-LHC proton injection stages.

steady-state collision energies, the cavities continue to compensate for energy lost to synchrotron radiation. The cavities also shape particle bunches in the longitudinal direction, in order to synchronize bunches for crossing and deliver maximum luminosity at the interaction points.

The RF cavities are shaped as a series of hollow elliptical bulbs connected along a straight line through their symmetry axis, as seen in Figure 3.5. When driven by alternating electromagnetic fields applied at one end of the cavity through a perpendicular waveguide, this shape produces standing electromagnetic fields which oscillate in time, and alternate in sign from one bulb to the next. The electrical fields are primarily parallel to the cavity axis. The corresponding magnetic fields are primarily tangential, and vanish towards the cavity axis. Figure 3.6 illustrates the approximate geometry of the RF cavity fields. Particles traversing the cavity on-axis experience high electrical potential gradients parallel to the beam direction, but little magnetic acceleration transverse to the beam direction.

Because the standing EM field in each bulb alternates in time, it is possible to match the geometry, frequency, and phase of the cavities such that a high- β charged particle traversing the cavity on-axis will always experience a forward electrical potential. Because the electrical gradient undulates between positive and negative values over the length of the cavity, particles in a bunch which are sufficiently displaced forward or behind the nominal bunch position will experience

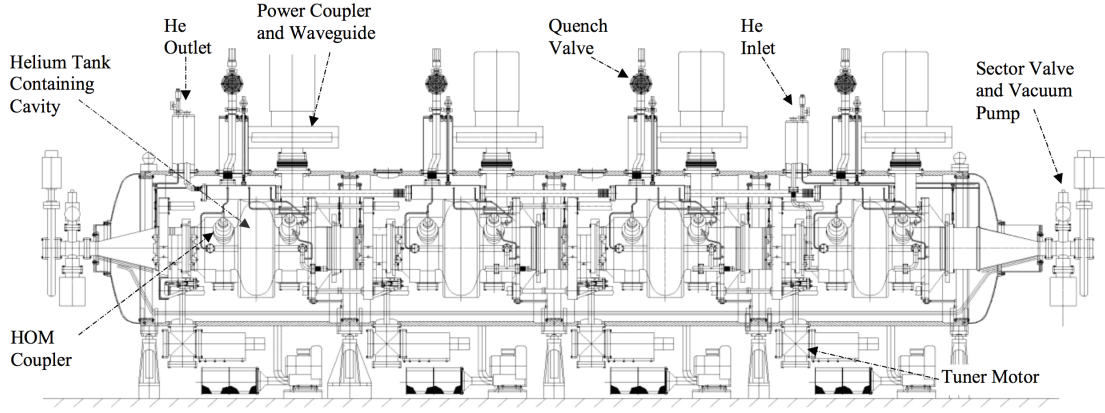


Figure 3.5: Technical Drawing of an LHC RF accelerating cavity assembly. Figure 6.1 from [43].

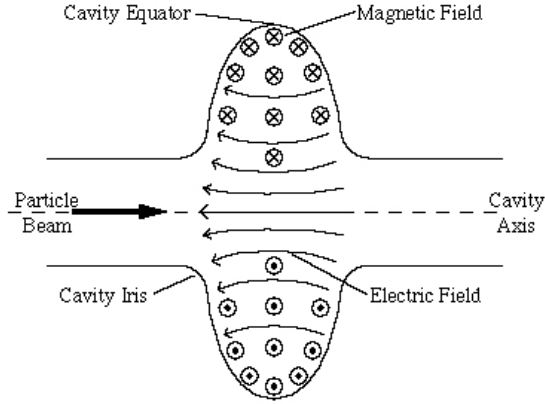


Figure 3.6: Rough illustration of the EM fields within a typical superconducting RF accelerator cavity.[50]

restorative gradients, or be captured by an adjacent RF bunch, leading to a steady-state equilibrium in the longitudinal dispersion of proton bunches.[51]

Because the LHC beams have the same charge but approximately opposite momenta, the two beams require independent RF accelerator systems. Each RF chain has a total of 8 resonant cavities. The effective gradient of each cavity is 2 megavolts, for a (theoretical) total of 16 mega-electron-volts per proton per rotation per beam. Due to practical inefficiencies and the necessity to fine-tune other beam parameters, however, the energy delivered to the beams per revolution

is considerably lower in practice.

Resonant fields of this strength and frequency could not be sustained in cavities fabricated from common conductor materials like copper. Ohmic power losses from interior surface currents could not be sustainably compensated, and the cavities themselves could even warp or melt from resistive heating. To mitigate the problems of power loss and heat dissipation, LHC RF cavities are fabricated with superconducting niobium-on-copper thin films on their interior surfaces. The cavities are maintained below the Ni-Cu superconducting temperature threshold of 9.2 kelvin using liquid helium coolant. [52, 53]

3.1.4 Dipole Steering Magnets

The vast majority of the LHC tunnel is occupied by dipole steering magnets. High-energy particles are bent around the ring by magnetic fields which are nearly uniform over the particles' path. The magnetic fields are generated inside 15-meter long, 35-ton cryodipole assemblies. There are 1232 dipole magnets in the LHC, each providing approximately five-thousandths of a radian of deflection to the beams.

As particles are accelerated from injection energy by the RF cavity system described in the previous section (3.1.3), dipole fields are slowly increased in concert with particle momenta to maintain the curvature which keeps the beams inside the vacuum pipes.

Figure 3.7 illustrates the cross-sectional geometry and magnetic field shape within LHC dipole magnets. Figure 3.8 illustrates the layout of superconducting bus cables that carry the electrical current to generate the magnetic fields. The most unique feature of the LHC cryodipoles is the “twin-bore” design, in which

the two beam pipes are threaded side-by-side through opposite-flux regions of a single, complex magnetic field. This elegant, if slightly baroque, design was needed in order to fit the LHC dipole system into the existing LEP tunnel. The oppositely-charged LEP beams could be steered by the same magnetic field, so the LEP tunnel, which LHC inherited, was not dug wide enough to accommodate independent dipole magnets for the two beams side-by-side. The twin-bore design effectively fits two dipole fields into the cross-sectional space allotted for one at LEP.

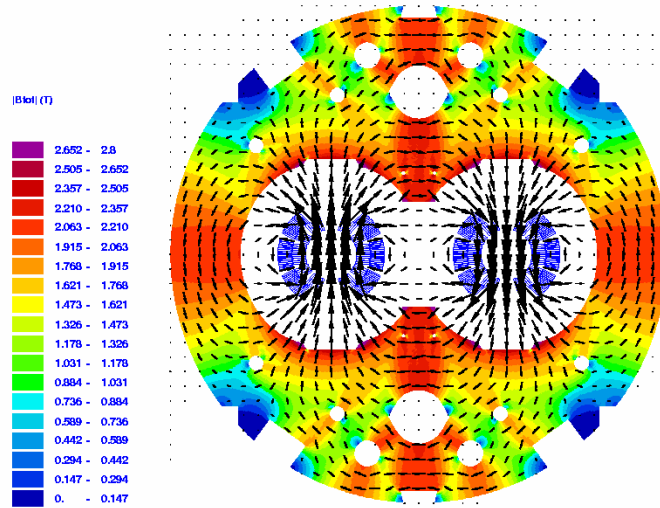


Figure 3.7: Illustration of the LHC steering dipole magnetic field cross-section. Fig. 5 From [54]

As is the case with the accelerating radiofrequency cavities described in section 3.1.3, the currents required to sustain magnetic fields of this strength can only be carried by superconductive media. The dipoles employ bus cables fabricated from niobium-titanium alloy, with a superconducting threshold temperature just below 2 kelvin. Like the accelerating cavities, LHC dipole magnets are cooled using liquid-helium refrigerant. [52]

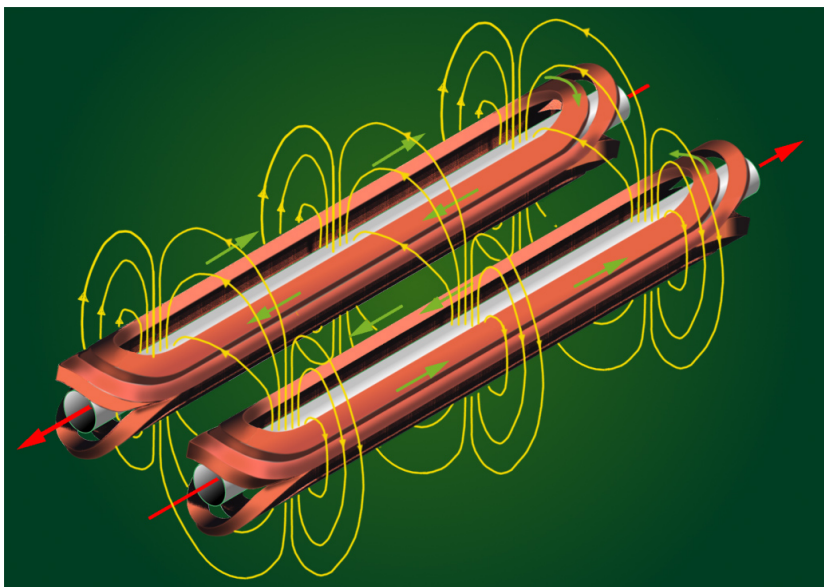


Figure 3.8: Illustration of the superconducting bus cable layout within LHC twin-bore cryodipoles.[\[55\]](#)

Taking the tunnel radius as a fixed constraint, the maximum dipole field strength of approximately 8.3 tesla represents the proximal limitation on LHC collision energies. The LHC’s RF accelerators could, in principle, drive particles to substantially higher energies, but the dipoles could not then contain them in the tunnel. The extraordinary currents and magnetic field strengths sustained by the LHC dipoles represent, especially considering the scale of manufacture, the present state-of-the art in high-field magnet technology. Any future colliders operating at higher energy will have to employ longer tunnels, advanced dipole technology, or likely, both.

3.1.5 Multipole Focusing Magnets

Whereas LHC bunches are shaped in the longitudinal direction by the RF cavities (Section [3.1.3](#)), the transverse beam profiles are sculpted by a network of multipole focusing magnets interspersed with the dipoles in regular patterns called “cells.”

A full taxonomy of multipole magnets and their particular applications within the LHC is beyond the scope of this dissertation. A list of magnet types and populations is provided in reference [56]. The multipole systems are detailed exhaustively in [43], and summarized somewhat more accessibly in [52]. A common magnet cell pattern is illustrated in Figure 3.9.

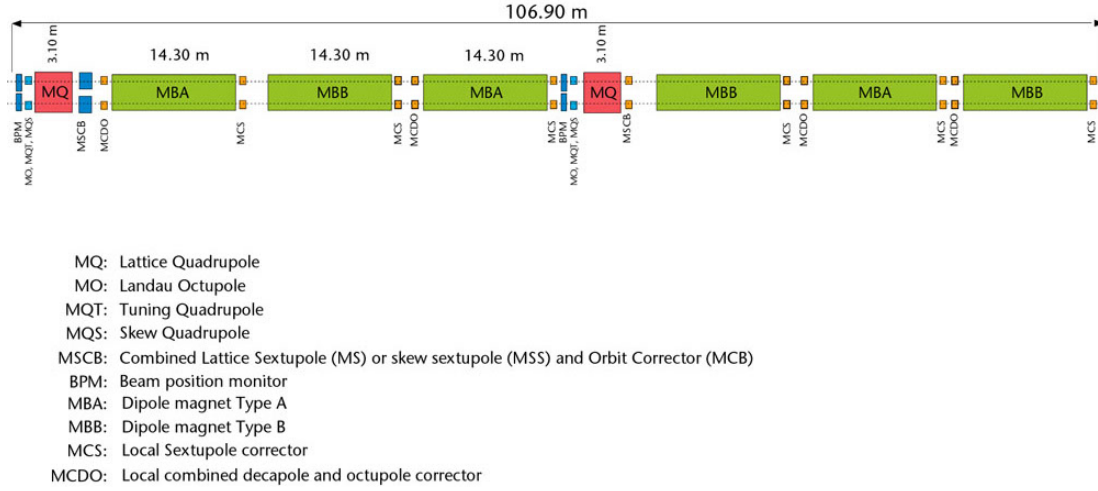


Figure 3.9: Illustration of a typical LHC multipole magnet cell. [57]

Generally, the many sextupole, octupole, and decapole magnets apply fine adjustments to compensate defocusing, steering, and oscillation which occur in the transverse plane as byproducts of the many manipulations performed to regulate the quality and uniformity of LHC beams.

The primary necessity to contain the beams against the electrostatic potential within each bunch is fulfilled by the quadrupole focusing magnets. Quadrupoles are best suited for the heavy lifting of transverse confinement, because practical quadrupoles can realize the highest magnetic field strengths.

The cross-section of a quadrupole field (as “seen” by an incoming charged particle) is illustrated in Figure 3.10. This shows that any single quadrupole field will focus the beam along one axis, but will defocus it along the other. This

dilemma is resolved by rotating alternate quadrupole fields by $\pi/2$. Along each axis, then, the beams are alternately focused and defocused. Because the field strength is larger away from the center, the cumulative effect is focusing on both axes. Through this process, the proton beams achieve an equilibrium emittance which is constrained by the Coulomb repulsion within the proton bunch.

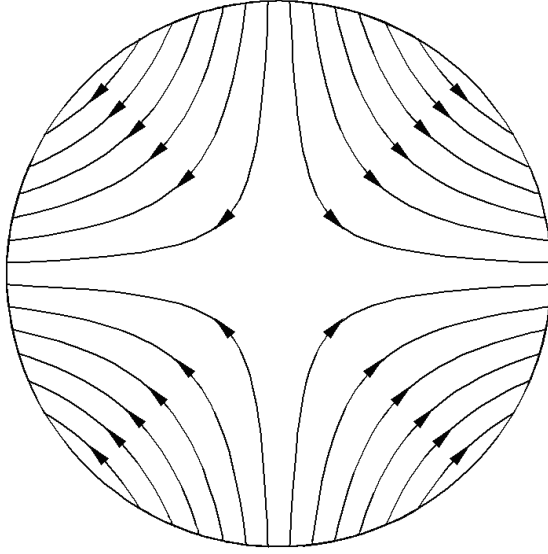


Figure 3.10: Cross-sectional illustration of a quadrupole magnetic field.[58]

3.1.6 Collimation

Particles of different total momentum within a high- β accelerator bunch circulate at effectively the same frequency, but slightly different radii. Consequently, finite momentum distributions within proton bunches map directly onto distributions in the horizontal profile of the bunch. At LHC and many other accelerators, momentum spread as a result of many influences can add up to unacceptable transverse displacements from the nominal beam spot.

By mapping the momentum spread onto the horizontal displacement from the nominal beam spot center, a safe momentum acceptance can be enforced simply

with a physical aperture (collimator) in the horizontal plane. In general, the horizontal spread due to momentum dispersion is convoluted with all other sources of transverse displacement, especially betatron oscillation (see section 3.1.6).

Another source of potentially dangerous excursions which must be controlled in the LHC beam is betatron oscillation. Betatron oscillation arises as a consequence of spatial spread within proton bunches at insertion to the LHC ring, and manifests as oscillations in the horizontal and vertical planes transverse to the nominal bunch center. All particles circulating in a synchrotron exhibit betatron oscillation of some amplitude, so an acceptance must be defined in the betatron phase space which guarantees a comfortable margin of safety for instruments installed near the beam. A pedagogical introduction to betatron oscillation is available in [51].

Filtering betatron oscillations of unacceptable amplitude is similar in practice to momentum cleaning. Like momentum filtering, betatron cleaning is performed by directing the beam through variable apertures in the vertical and horizontal planes. At LHC, betatron cleaning is performed at IR 3, diametrically opposite from IR 7, which contains the momentum cleaning facilities.

3.1.7 Beam Dump

At the end of their useful lifetimes, LHC beams are safely diverted into a large carbon target at IR 6. Carbon is chosen for its high heat capacity and relatively low rates of nuclear activation and secondary emission under proton bombardment. Because the beams can pose extreme ionizing- and penetrating-radiation hazards to delicate accelerator and detector equipment, it must be possible to safely dispose of them at an instant's notice should they drift out of safe operational parameters. To this end, a short, contiguous beam gap of approximately

$3\mu\text{s}$, is preserved in every fill. This guarantees time in every revolution for the beam dump “kicker” magnets, which divert the beams to the dump target, to ramp up to full field, without scattering part of the beams across the path to the target.

3.2 The ATLAS Detector

Details of the design and initial construction of the ATLAS detector are available in the ATLAS Technical Design Report.[59, 60] The detector as of final construction and commissioning is summarized in the 2008 ATLAS Detector publication.[33]

The ATLAS (“A Toroidal LHC ApparatuS”) detector (Figure 3.11) is located in the large cavern beneath LHC Point 1 (Figure 3.1), directly adjacent to CERN’s Meyrin campus (Figure 3.3). ATLAS is a general-purpose particle detector, designed to measure as broad a spectrum of hadronic collision radiation as possible. This is in contrast to, e.g., the ALICE and LHCb detectors, which are optimized to study heavy-ion collisions and heavy-flavor hadron decays, respectively. Notable features of ATLAS include high-precision measurement of charged-particle trajectories and momenta, nearly hermetic calorimetry, and reliable performance under high-pileup conditions, with typically dozens of inelastic collisions per proton-proton bunch crossing.

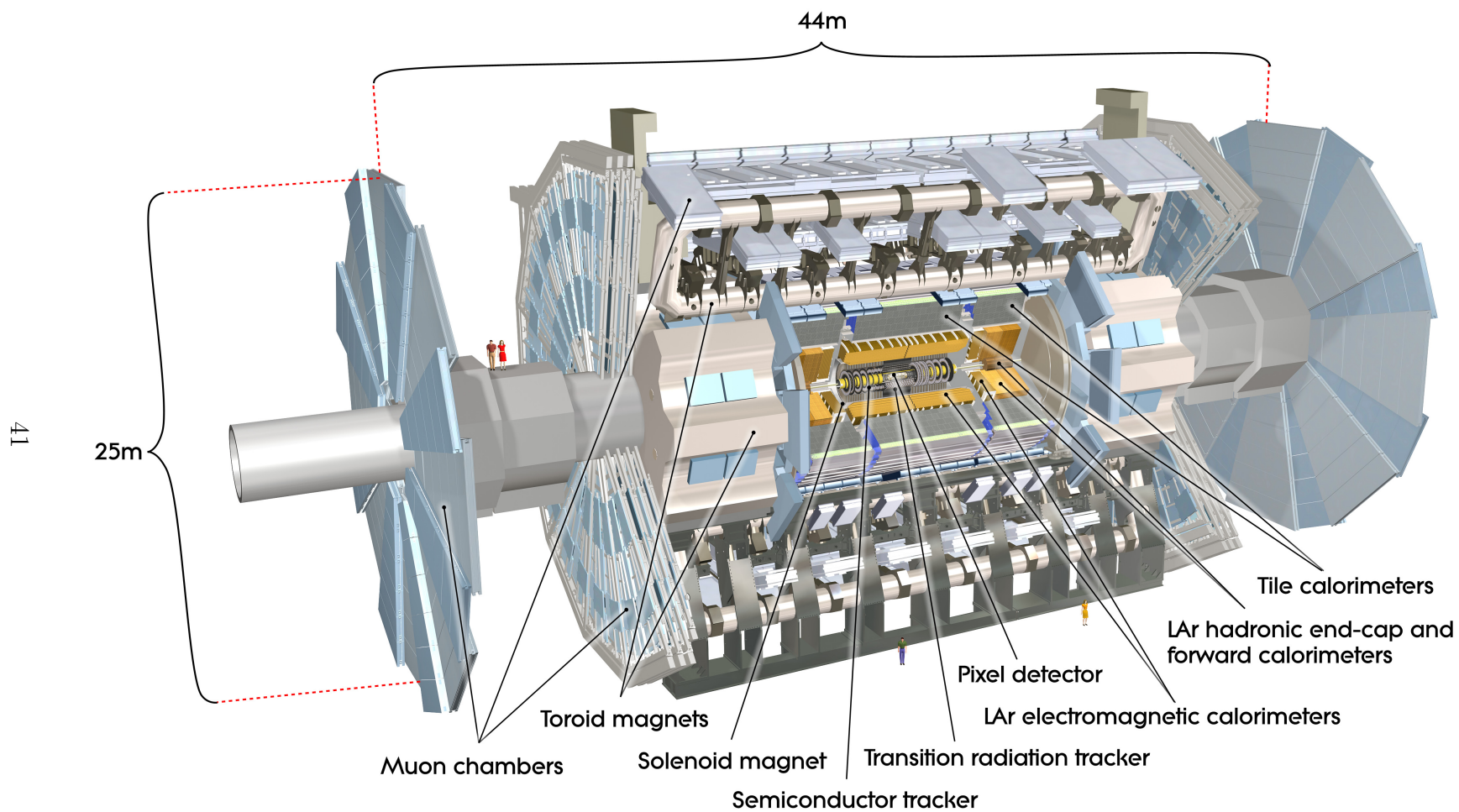


Figure 3.11: Schematic cutaway view of the ATLAS detector.[61]

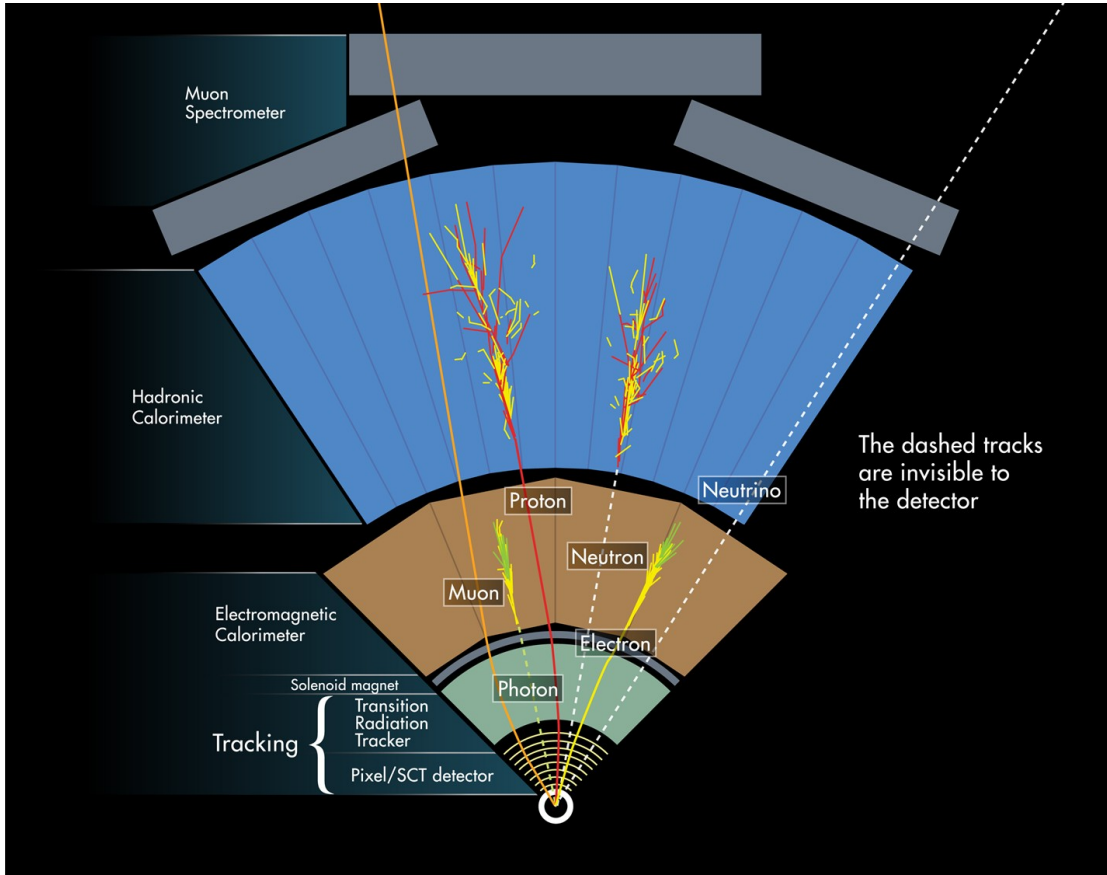


Figure 3.12: Particle interactions with the different ATLAS detector subsystems[62]

The essential design of ATLAS is a system of nested, cylindrical detectors, each measuring different properties of a limited subset of the variety of charged-particle collision radiation. The ATLAS detector subsystems are described individually in subsequent sections.

Because the spectrum of decay products varies strongly as a function of the polar angle in the detector frame, most detectors are further divided into central or “barrel” regions, and forward or “end-cap” regions. Because the intrinsic detector response often varies between these regions due to different designs, as well as different background spectra, analyses frequently utilize the azimuthal boundaries between barrel and end-cap regions of important measurements to define fiducial

regions of the analyses. In the case of the $W^\pm$, Z cross-section measurements, the pixel detector barrel boundaries, the Muon Spectrometer barrel coverage, and the “gap” between the Electromagnetic Calorimeter’s barrel and end-cap regions all contribute to the definition of the experimental fiducial phase-space. These detectors and their features, as they relate to the 13 TeV $W^\pm$, Z cross-section measurements are described in further detail in the following sections.

3.2.1 The Inner Detector

The four innermost detectors in ATLAS are the Insertable B-Layer, the Pixel Detector, the Semiconductor Tracker, and the Transition Radiation Tracker, collectively called the “Inner Detector” (ID). Data from the ID systems are combined to reconstruct the 3-D tracks of charged particles emerging from the interaction region. Properties of these tracks provide information on the charge, momenta, primary vertex association, and species of particles.

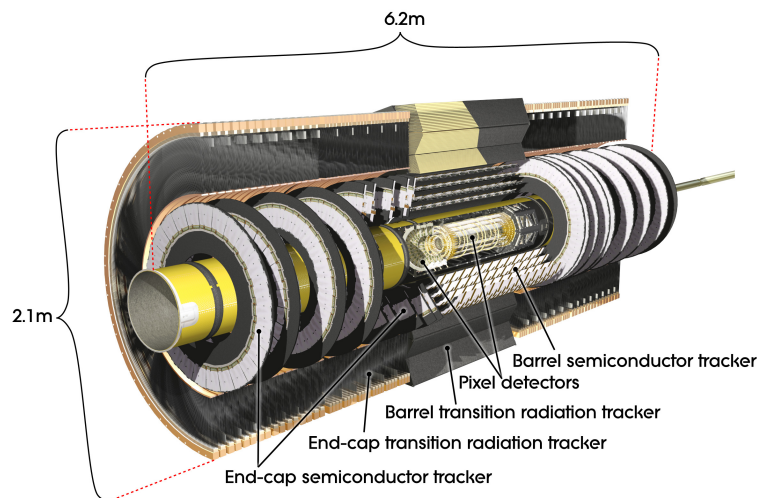


Figure 3.13: Cutaway view of the ATLAS Inner Detector. The IBL is not pictured in this rendering.[63]

The Inner Detector as a whole is illustrated in Figures 3.13 and 3.14. The

design and initial construction of the Inner Detector as a whole is detailed in the ATLAS Inner Detector Technical Design Report.[64, 65] The Inner Detector as of the ATLAS Detector commissioning in 2008 is reported in the ATLAS Detector publication.[33]

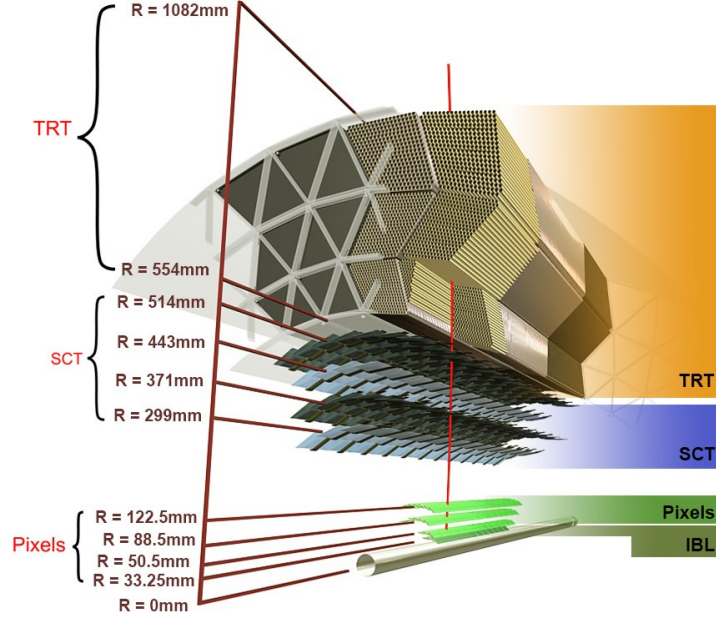


Figure 3.14: Cross-section of the ATLAS Inner Detector, showing the layers and radii of the several tracking sub-detectors.[63]

All four ID systems are based on the common principle of a finely segmented ionization detector. Each employs different technologies to meet the demands and capitalize on the advantages of tracking at different radii from the interaction region. The IBL, Pixel, and SCT detectors employ thin, planar silicon tiles as the ionization-sensitive bulk medium. IBL and Pixel sensors are micropatterned to divide the sensor surfaces into two-dimensional $100\text{ }\mu\text{m}$ -scale pixels. SCT sensors are segmented in one dimension only, defining long, narrow strips. The TRT, by contrast, uses straw tube trackers with gas as the bulk medium to provide dense readings in the $r - \phi$ plane, but only divides η/z in half around the center of

ATLAS.

Charged-particle tracks are reconstructed in analysis by algorithms which “connect the dots” through 3-D voxels corresponding to the known locations and shapes of ID channels which report charged particle “hits” during the same beam crossing. Some of these algorithms are summarized in section 3.3.1.

The Inner Detector is immersed in a high-strength magnetic field of approximately 2 tesla, pointing parallel to the beam axes. The field is generated by a superconducting solenoidal magnet which is wound just outside of the Transition Radiation Tracker (shown in Figure 3.12). The solenoid field bends the trajectories of charged particles according to their transverse momenta. Particle charges and momenta are calculated from measurements of track curvature in the transverse plane.

Vertex association is performed by algorithms which find collections of tracks which all pass close to a plausible common point-of-origin close to the beam line. The region of substantial overlap between the proton beams at the center of ATLAS is actually about 12 cm long. Sorting of tracks and associated calorimeter clusters by primary vertex is an essential handle against pileup noise in event reconstruction algorithms.

The four ID subsystems, and the Solenoidal Magnet, are described in more detail individually in the following sections.

3.2.2 The Solenoid

The ATLAS Solenoidal Magnet generates the magnetic field upon which the Inner Detector’s momentum resolution depends. The field is approximately 2 tesla in magnitude, pointing parallel to the beam in the $+z$ direction. This means that

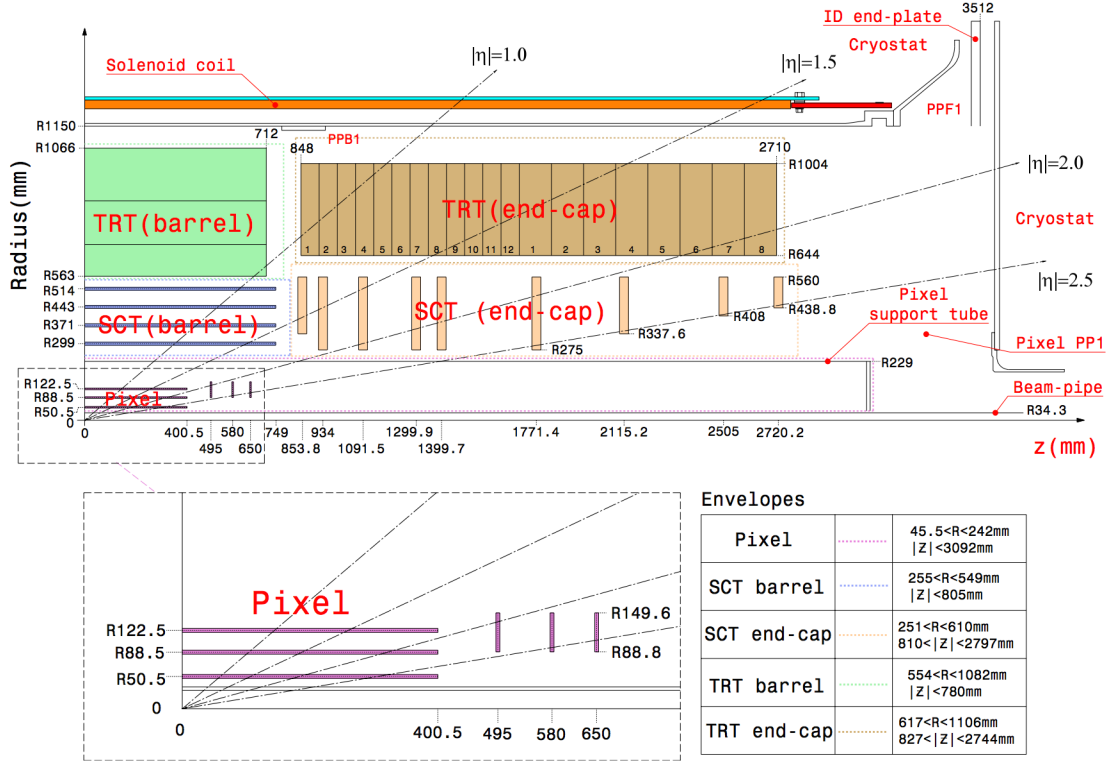


Figure 3.15: $r - \eta$ projection of ATLAS Inner Detector Layout. Figure 4.1 from [33].

viewing the detector along the $+z$ direction (i.e., from the west, standing between Point 2 and Point 1), [33] positrons curve counterclockwise, and electrons curve clockwise.

Like the many high-field magnets used in the LHC accelerator, the ATLAS solenoid is constructed from superconducting bus cables (in this case niobium-titanium), and operated at cryogenic temperatures. [66, 67]

3.2.3 The Insertable B-Layer

The Insertable B-Layer (IBL) was the most significant upgrade to ATLAS performed during the LHC's "Long Shutdown 1" (LS1) in 2012-2015. The IBL is a new layer of silicon pixel tracking tiles integrated directly onto the beryllium beam pipe at the center of ATLAS. Due to the similarity of IBL modules to Pixel

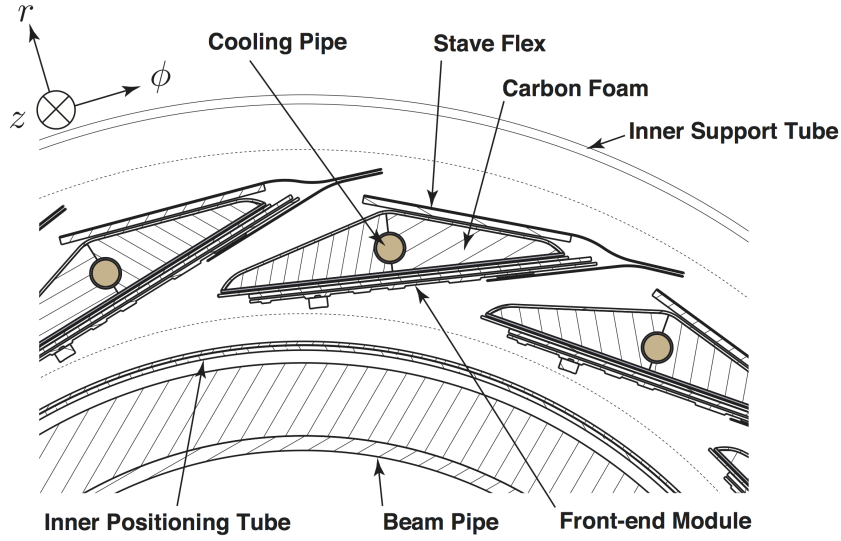


Figure 3.16: Tiling of ATLAS Insertable B-Layer modules. Figure 1a from [68]

Detector modules, the IBL is often considered an upgrade to the Pixel Detector. The name “Insertable B-Layer” even employs the naming convention used to distinguish Pixel Detector layers from one another. On the other hand, the IBL can also be considered a separate detector, because its data is read out asynchronously with the Pixel detector, via an independent DAQ system.

Figure 3.16 illustrates the tiling of IBL modules and mounting on the upgraded beryllium beam pipe. Preliminary plans for the ATLAS Insertable B-Layer are presented in the IBL Technical Design Report and the succeeding Addendum.[69, 70]

The primary benefit of the IBL upgrade is in identification of particle decay vertices displaced from the primary event vertex. The resolution in transverse displacement (d_0) is nearly linear with respect to the radius of the nearest measurement point.[71] IBL also provides a hedge for Run 2 against degradation of the innermost Pixel Detector layer, the (original) B-Layer, which suffers the greatest radiation damage of all ATLAS systems. The Pixel B-Layer exhibited a greater-

than-expected rate of sensor module “death” during Run 1.

The IBL includes two distinct sensor tile designs: planar sensors, which utilize technology proven in the ATLAS Pixel Detector, and the somewhat more experimental 3-D sensors. Until installation in ATLAS, the 3-D technology was not yet proven in practice. However, it has the potential to realize equivalent tracking performance with lower power consumption and improved radiation tolerance.[72] Both designs employ the same $50 \times 250 \mu\text{m}^2$ pixel geometry, preserving compatibility with the same front-end readout electronics.[73]

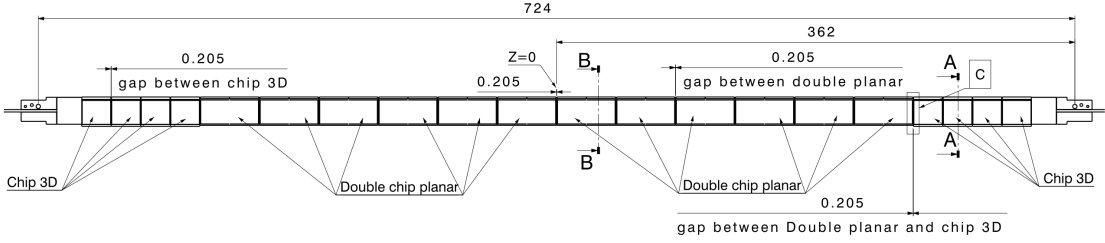


Figure 3.17: Layout of planar and 3D Sensors on IBL staves. Figure 3 from [70]

The IBL barrel is composed of fourteen 72- cm long staves. Each staff includes 12 $4 \times 2 \text{ cm}^2$ planar sensors in the middle, and four $2 \times 2 \text{ cm}^2$ 3-D sensors at each end (Figure 3.17). This design was adopted to provide a practical test of the 3-D sensors, without overreliance on the new technology. Due to the high η coverage of the IBL barrel, as well as the mechanical constraint of threading the detector, along with all of its electronic services, through the Pixel Detector inner radius, the IBL does not include end-cap regions.[74]

During initial operation and alignment studies of the IBL in 2015, it was discovered that a mismatch of thermal expansion properties between laminated staff support layers causes an elliptical distortion of the staves (inward bowing). The distortion was determined to be a source of significant bias in track measurements. The distortion is found to be stable at constant temperature, however, and it is

anticipated that it can be fully characterized and accounted for after detailed alignment studies.[68]

3.2.4 The Pixel Detector

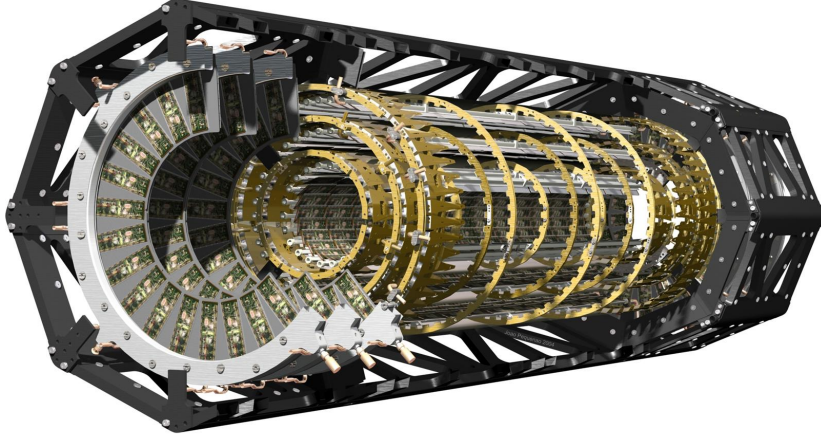


Figure 3.18: Cutaway view of the ATLAS Pixel Detector.[75]

The ATLAS Pixel Detector is detailed in the ATLAS Pixel Detector Technical Design Report [76], as well as the ATLAS Detector publication [33]. The Pixel detector consists of three layers of planar silicon sensor modules, tiled to cover the the entire angular space without gaps (Figure 3.19)

Individual pixel modules consist of thin, planar silicon sensor tiles which are highly segmented in both the x and y directions. The sensors are segmented into pixels $50 \times 400 \mu\text{m}^2$.

The Pixel Detector is responsible primarily for ATLAS' resolution in measuring the impact parameter (d_0) of charged particle tracks, and provides excellent resolving power to distinguish pileup collision vertices from one another.

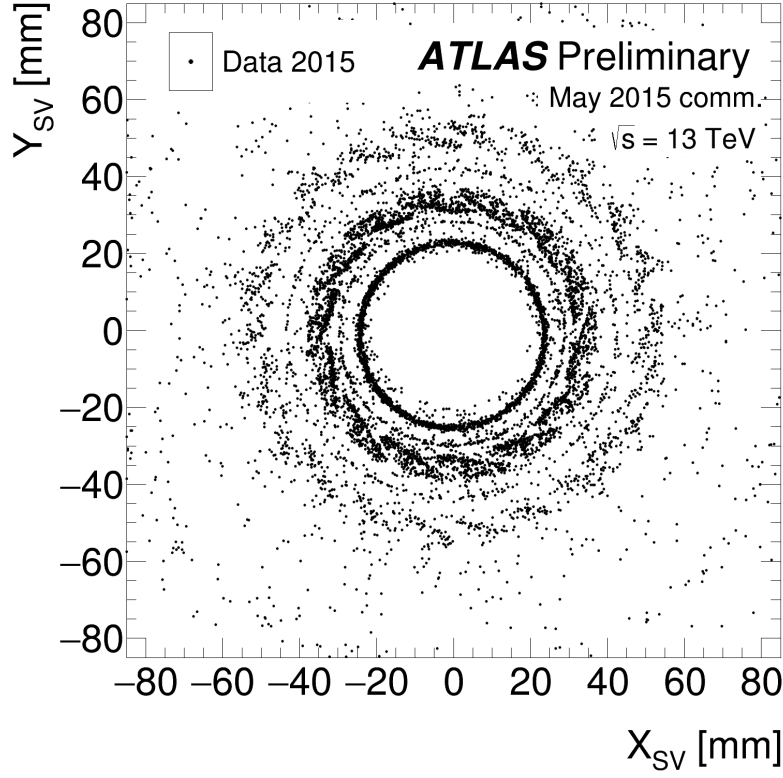


Figure 3.19: Cross-sectional image of the ATLAS IBL and Pixel Detector b-layer, illustrating tiling of planar modules to provide full angular coverage without gaps. This image was generated by mapping the space density of $\gamma \rightarrow e^+e^-$ pair conversion vertices, which occur as the result of particle interactions in detector material.

3.2.5 The Semiconductor Tracker

The ATLAS Semiconductor Tracker is described in the ATLAS Detector Publication.[\[33\]](#). The SCT is highly visible in [Figure 3.13](#).

Like the IBL and the Pixel Detector, The SCT is a multi-layer system of highly segmented silicon sensor tiles. Unlike the IBL and Pixel Detector, SCT sensors have one-dimensional “strip” readout geometries. At higher radii than the pixel systems, the SCT covers a much larger surface, over which decay particles will be separated, on average, by greater absolute distances. Compared to the Pixel

Detector, the SCT represents a compromise between intrinsic resolution on the one hand, and cost, both in terms of money and electronic services like power and data cable, on the other.

In more ways than one, the SCT is the middle child of the ATLAS Inner Tracker. It does not provide the best performance at any single measurement, and yet ATLAS tracking performance would suffer miserably without it. It provides continuity of tracks between the low-radius pixel detector, and the high-radius TRT. Four extra hit layers at intermediate radii reduce combinatorically compatible interpretations of hits, and once hits are sorted into tracks, the SCT points provide additional constraints in fits of track properties.

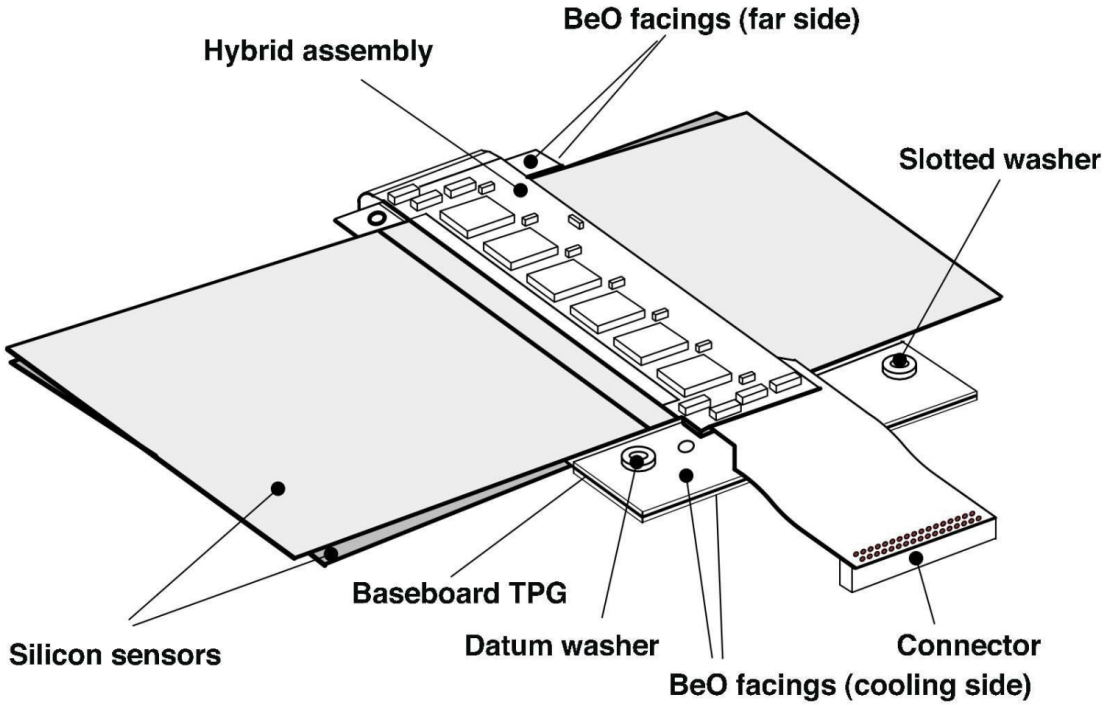


Figure 3.20: Drawing of a double-sided ATLAS SCT Module. From Figure 4.7 in [33]

To strike the appropriate balance, the Semiconductor Tracker uses strip sensors instead of pixels. Strip Sensors are segmented in only one direction. Along the direction of segmentation, the intrinsic resolution of an SCT sensor is comparable

to that of the pixel system ($80\text{ }\mu\text{m}$ in the SCT vs $50\text{ }\mu\text{m}$ for pixels). The resolution is very gross in the perpendicular direction, however, defined by the length of the sensor tile itself.

The gross longitudinal resolution of the pixel sensor is improved somewhat by sandwiching two strip sensors together in each module at a small “stereo angle.” For a single charged particle intersecting the module, the resolution would be minimized by a stereo angle $\pi/2$. However, with two or more hits on the same module in the same beam crossing, this also maximizes the number of compatible interpretations on the 2-D grid of strips (Figure 3.21). Given that the SCT module occupancy is between 2 and 3 hits per beam crossing on average, the SCT stereo angle (40 mrad) represents an optimal compromise between longitudinal resolution and multi-hit combinatorics.

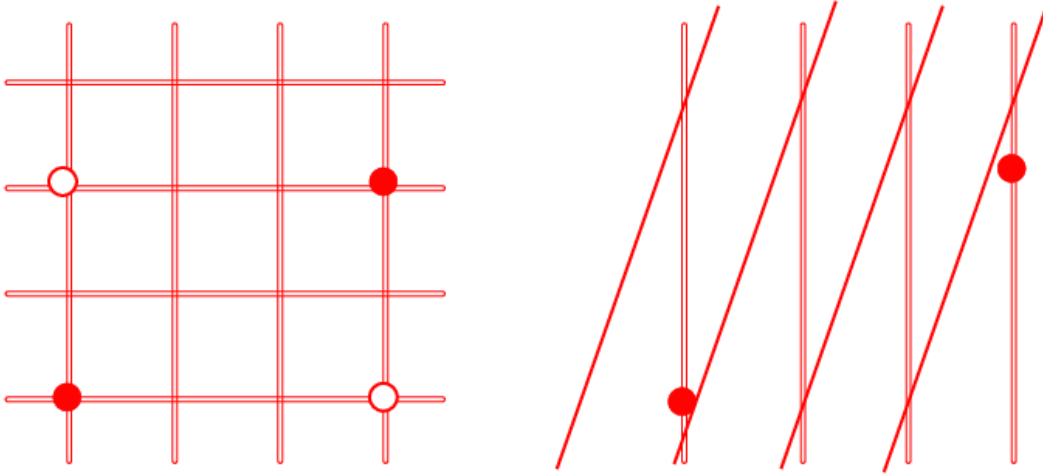


Figure 3.21: Illustration of “ghost hits” in double-layer silicon microstrip tracking modules. Filled circles represent true charged particle hits. Hollow circles represent alternative interpretations of the strip-hit data. The fully orthogonal stereo shown on the left angle maximizes resolution, but also maximizes ghosting. The smaller stereo angle on the right sacrifices resolution to reduce ghosting. Figure 10 from [77]

The SCT stereo scheme means that even though the voxel for a single SCT strip is a rectangle, the voxel of an SCT sandwich module is actually a 40 mrad

trapezoid defined by the overlap of two such rectangular strips (Figure 3.21).

The SCT is laid out in barrel and end-cap regions, with four barrel layers and nine circular end-caps on each side of the interaction region. In order to economize the design and fabrication of the SCT, different, fan-shaped sensors were designed for use in the end-caps. End-cap strips are patterned at an angle to one another, to place each strip at a constant ϕ coordinate.

Together, all SCT layers contain 4088 modules (2112 barrel, and 1976 end-cap). Irrespective of the module type, all modules have 768 strips, for a total of 3,139,584 channels. The total surface area instrumented by the SCT is approximately 63 m².

3.2.6 The Transition Radiation Tracker

The ATLAS Transition Radiation Tracker (TRT) is described in the ATLAS Inner Detector Technical Design Report[64], the ATLAS detector summary publication[33], and two papers describing the barrel and end-cap sections of the detector.[78, 79]

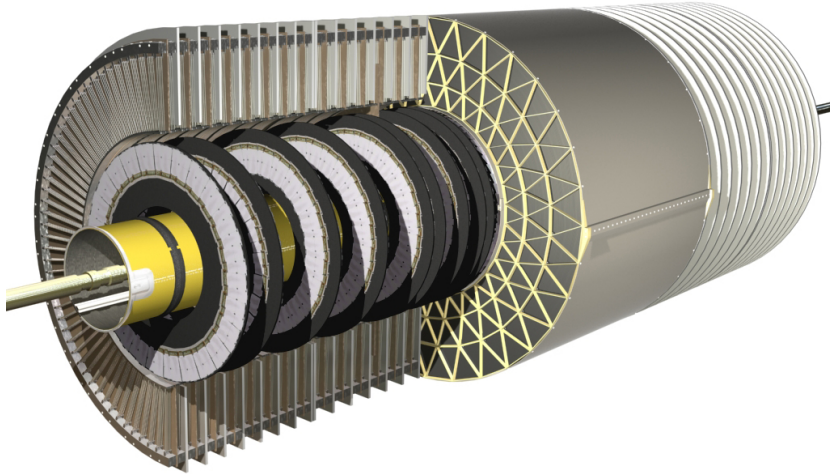


Figure 3.22: Cutaway view of the ATLAS Inner Detector emphasizing the Transition Radiation Tracker barrel and end-cap regions. The SCT endcaps, Pixel detector support tube (yellow), and ATLAS beam pipe are also visible in this rendering.[80]

The TRT is a straw-tube gas drift chamber. It uses mixtures of rare gas as the ionization media. Several gas mixtures have been used in different parts of the TRT, but the primary mixture in the TRT barrel contains xenon, CO_2 and O_2 . Segmentation is provided by dividing the instrumented volume into thousands of thin, hollow straws.

TRT straws are narrow-walled cylinders 4 mm in diameter and 172 cm long. The inner surface of a straw is electrically conductive and held at ground voltage. The anode is a thin gold-tungsten wire $30\text{ }\mu\text{m}$ in diameter, threaded through the center of the straw and held in place by the tension between attachment points at either end of the straw.

The relatively inexpensive straw-tube technology extends the Inner Detector’s instrumented volume to radii which would have been technically and financially prohibitive to cover with silicon. The TRT’s large outer radius contributes considerably to ATLAS’ precision in measuring transverse momenta of charged particles. Because the inner tracker measures p_{T} as the sagitta of tracks in the $r - \phi$ plane, extending the radius over which the sagitta is evaluated increases the significance of the sagitta relative to the ID’s spatial resolution. Even given the TRT’s poor resolution compared to the silicon systems, the effect of doubling the “lever arm” of momentum measurements is dramatic, especially for small sagitta at high p_{T} .

In contrast to the silicon trackers, for which $\text{d}E/\text{d}x$ ionization is the dominant mechanism of charge deposition within the semiconductor bulk, the TRT exploits both $\text{d}E/\text{d}x$ and transition radiation to obtain additional information about particles’ identities. Most charged particles at momenta of interest within ATLAS behave as “minimum ionizing particles,” and exhibit similar $\text{d}E/\text{d}x$ characteristics.[5] Transition radiation intensity has a greater dependence on particle mass. To exploit this difference, TRT readout electronics recognize two distinct voltage

levels - one corresponding to minimum dE/dx ionization, and another, higher, threshold which is typically only triggered by electron transition radiation. This is used primarily to distinguish electrons from other charged long-lived species like muons and pions. This is illustrated in Figure 3.23.

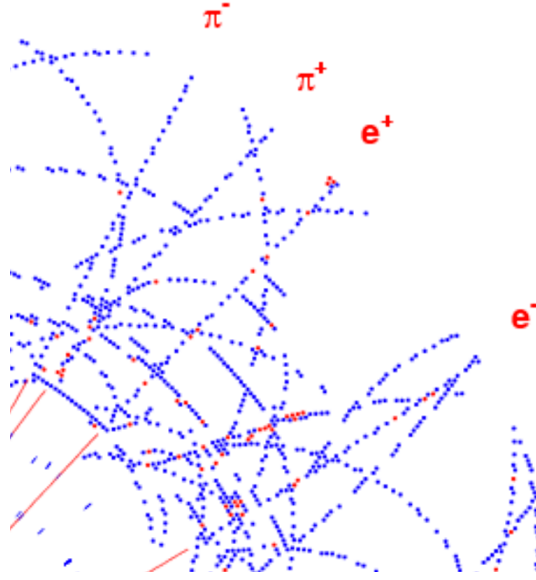


Figure 3.23: Detail of simulated TRT data ($r - \phi$ projection), showing high-threshold electron transition radiation hits in red. From Figure 1 in [81].

To induce transition radiation, gaps between straws are filled with a fibrous polyethylene/polypropylene “radiator” material. The radiator has an index of refraction which differs significantly from that of the straw tube gas and of the air in radiator volumes. When high- γ charged particles cross boundaries between radiator and gas or air, the refractive-index gradient induces transition radiation.

The TRT achieves $r-\phi$ resolution finer than the straw cross-section by measuring drift times of ionized electrons within a straw. Charge carrier drift velocities within TRT gas are low enough that the readout electronics can resolve the pulse shape in time, and extrapolate the incident particle’s distance of closest approach to the anode wire. The resolution in radius about the anode wire is approximately

$120\,\mu\text{m}$. This gives TRT hits the strangest voxel shape of all four tracking detectors: hollow cylinders with walls $120\,\mu\text{m}$ thick, variable outer radii up to 4 mm, and 172 cm long.

Compared to the silicon trackers, the TRT provides position measurements which are dense in the radial coordinate. Charged particles traversing the TRT barrel will register around 35 hits between radii of 56 cm and 108 cm. At the TRT's relatively high radius, this makes it especially useful to identify electron-positron track pairs which originate from conversions of prompt photons within the ID material. Conversions of this type are a leading source of inefficiency in reconstruction of prompt photons, and in erroneous association of conversion electrons to collision event vertices. An event containing a pair-converted prompt photon is shown in Figure 3.24.

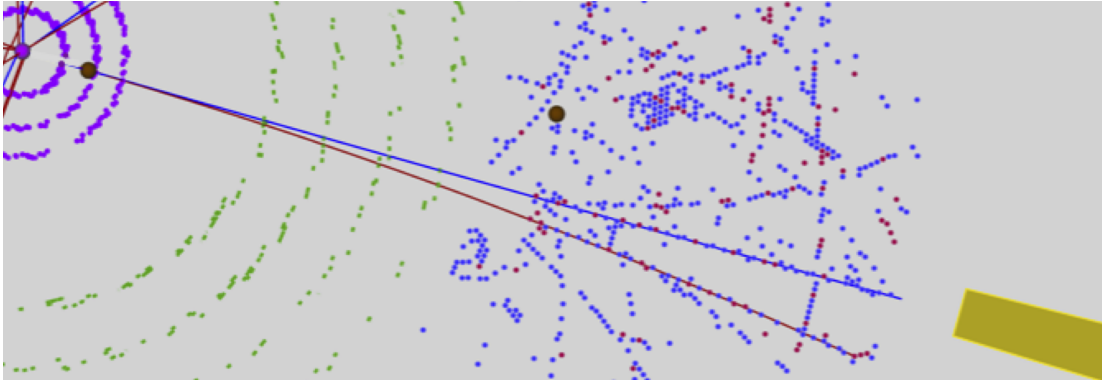


Figure 3.24: ATLAS ID event display with a pair-converted prompt photon (brown dot, top left). The pair conversion vertex originates inside the Pixel Detector material, and spawns two oppositely-charged tracks, both exhibiting high-threshold electron Bremsstrahlung hits in the TRT. From Figure 15 in [82].

Like most detectors in ATLAS, the TRT is laid out in barrel and end-cap regions. The barrel and end-cap regions occupy roughly the same extent in z as the corresponding regions of the SCT, as illustrated in Figures 3.13 and 3.15. There are 10 end-cap wheels on either side of the interaction region. Straws in

TRT wheels are aligned radially, in contrast to the barrel straws which are aligned parallel to the beams.

3.2.7 ATLAS Calorimetry

Measurements of the total energy carried by particles and collimated jets are provided by the ATLAS Calorimetry systems. These include the Electromagnetic Barrel Calorimeter (EMCal), the Electromagnetic End-Cap (EMEC), The Hadronic Tile Calorimeter (TileCal), the Hadronic End-Caps (HEC), and the Forward Calorimeter (FCal). These are all illustrated in Figs. 3.25 and 3.11.

The different calorimeter systems are distinguished functionally by the particle species to which they are sensitive, as well as their different noise, background, and error characteristics. The forward calorimeters, for example, have a unique design which is needed to withstand the enormous fluence of low- p_T diffractive radiation at high $|\eta|$.

Unlike the tracking systems, the calorimeters are continuous in r , and designed to maximize material interactions. The calorimeters are segmented in η , ϕ , and r , though the large volume at high r , and the irreducible spread of calorimeter showers, limits the usefulness of segmentation below the cm scale.

Jets and individual particles are resolved by spatial segmentation of the calorimeters and clustering algorithms. Clusters are associated to primary collision vertices by pointing Inner Detector tracks, or implicitly by association of the highest- p_T vertex to the high- p_T Calorimeter clusters. Clustering and jet reconstruction in the calorimeters is described in more detail in Section 3.3.

Two important particle species to which the calorimeters are largely transparent are muons and neutrinos. The energy of muons is measured as momentum of

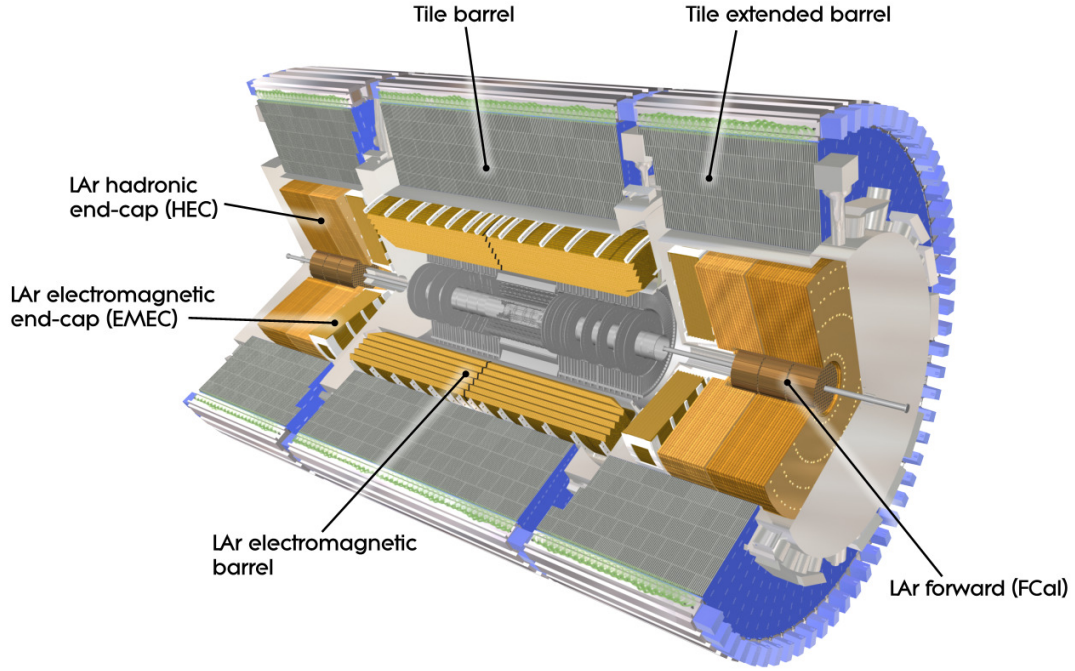


Figure 3.25: Cutaway view of the ATLAS calorimeters, including the hadronic tile calorimeter. Note the Inner Detector in faded gray for comparative scale.[83].

charged tracks in the Muon Spectrometer and Inner Detector. Transverse momentum of neutrinos is inferred from the vector sum of energy deposits in the $r - \phi$ plane. Calculation of Missing Energy and Neutrino p_T are described in greater detail in Section 3.3. Even though the calorimeters are largely blind to muons and neutrinos, the depth of the calorimeters in both radiation and interaction lengths is essential to the performance of muon and missing energy reconstruction. The muon spectrometer is sensitive to all charged particles escaping the calorimeters, so correct association of MS tracks to real muons relies on the assumption that all other charged species would have showered by the calorimeters' outer radius. Similarly, the accuracy of missing energy calculations depends on the full containment of these showers within the calorimeters' instrumented volume.

All ATLAS Calorimeters are sampling calorimeters, meaning they are com-

posed of alternating absorbing and active layers. Absorbing layers are made of highly interacting media which convert the energy of single particles and collimated jets into extensive material interactions, called showers. Active layers convert energy within showers, initiated in upstream absorbing layers, into optical or electronic signals proportional to the collected energy. The efficient division of labor between absorbing and active layers makes sampling calorimeters more compact than conventional calorimeter designs, which employ homogeneous volumes of media like Lead Tungstate (PbWO_4), which are both absorbent and active.

Because some energy within calorimeter showers is inevitably lost in the uninstrumented absorbing layers, the active layers only measure a fraction of the real shower energy. The efficiency and measurement error of each calorimeter system must be meticulously calibrated and parameterized in relevant variables like $|\eta|$, total energy, and shower shape, to obtain reliable estimates of the real energy within calorimeter showers.

3.2.8 The Electromagnetic Calorimeter

The Electromagnetic Calorimeter is designed for precision measurement of electron and photon energies. It employs lead as the absorbing medium, and liquid argon (LAr) as the active material. Lead is a suitable absorber due to its short radiation length, and its relatively long nuclear interaction length. This means that the EMCal is largely opaque to electrons and photons, but mostly transparent to massive species like muons and hadrons. Liquid argon, despite the immense technical overhead imposed by refrigeration infrastructure, is suitable as an absorber in the inner calorimeter due to its high radiation tolerance. The ATLAS liquid argon calorimeters, including the Electromagnetic Barrel and End-Cap Calorime-

ters, are pictured in Figure 3.26.

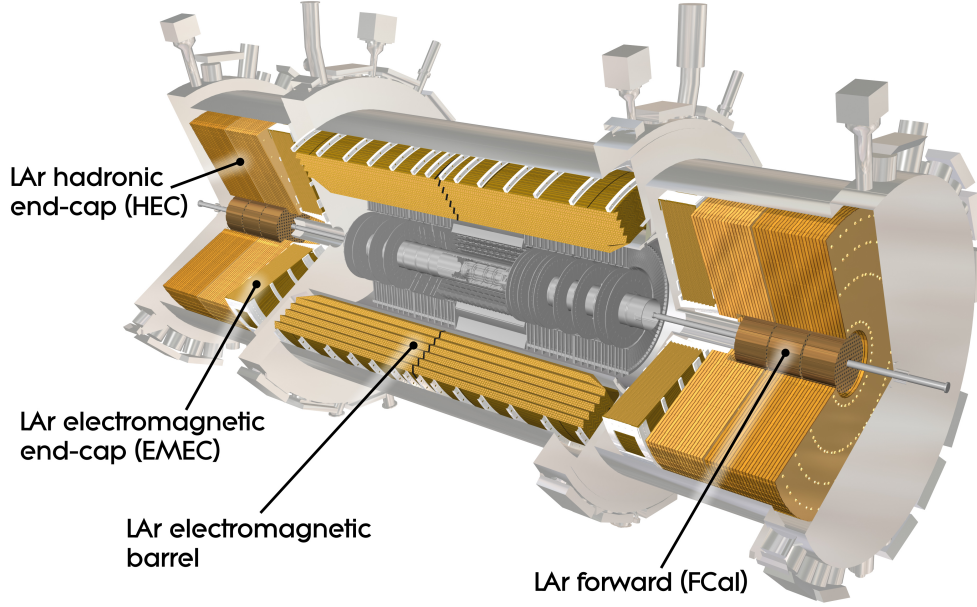


Figure 3.26: Cutaway view of the ATLAS Liquid argon Calorimeters.[84].

The entire EMCal Barrel region, and part of the EMEC, include a thin LAr presampling layer at their inner radii. The presampler is 1.1 cm thick in the barrel region ($|\eta| < 1.475$), and 0.5 cm thick in the EMEC region. The presampler is segmented in η and ϕ . Because the presampler precedes any absorbing media, by interrogating angular shapes of signals in the presampler plane upstream of EMCal clusters, showers initiated in detector material upstream of the calorimeters can be identified, and recalibrated for energy losses prior to reaching the calorimeters.[33]

An EMCal Barrel Module is illustrated in Figure 3.27, showing the three regions in r into which the LAr Barrel is divided. The bulk of the EMCal Barrel and End-Caps are constructed from so-called “accordion” layers. The accordion ge-

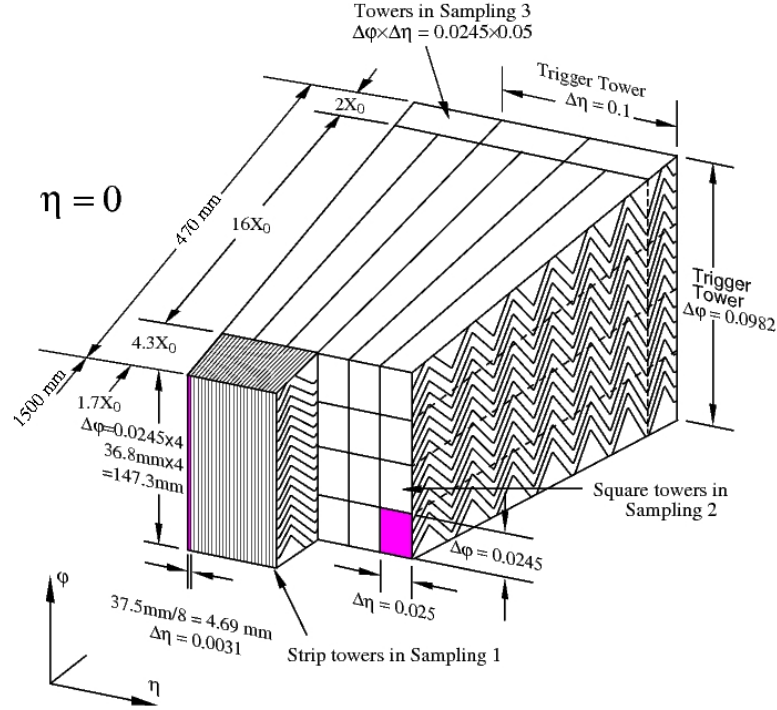


Figure 3.27: Drawing of an EMCAL barrel module. The EMCAL presampling layer is not pictured.[33].

ometry satisfies the technical need to circulate the liquid argon in thin layers (for fast signal extraction), with no radial blind spots in the active medium. Charge deposited in the liquid argon active medium induces current on accordion-layer electrodes, and is read out on front-end planes at constant- r surfaces between EMCAL layers. r resolution is defined by radial depths of the three calorimeter layers. η - ϕ resolution of each layer is defined by the patterning of electrodes on the readout planes.

The readout plane for the first accordion layer in the EMCAL Barrel is patterned with strip-shaped electrodes, which are long in ϕ and thin in η . The “strip” layer provides sufficient segmentation in η to resolve the double-peak structure characteristic of $\pi^0 \rightarrow \gamma\gamma$ decays. In the absence of such a strip layer, diphoton decays of boosted π^0 s would be a large and irreducible source of erroneous reconstruction

of prompt photons.

The middle EMCal Barrel layer is the deepest, and collects the majority of the total energy in EMCal showers. The $\eta - \phi$ segmentation in this layer is approximately 0.025×0.025 , corresponding to the typical angular extent of EMCal showers. The third layer, at the outer radius of the EMCal, is narrow in r . This helps to characterize the radial evolution of the shower, and identify showers that “punch through” the EMCal, leaking energy into the Hadronic Calorimeter. Such showers are often candidates for rejection of the event, or recalibration of the cluster energy measurement.

3.2.9 The Hadronic Calorimeter

The Hadronic Tile Calorimeters and the Liquid argon Hadronic End-Caps are illustrated in Figure 3.25. Both are described in Chapter 5 of the ATLAS Detector Publication.[33]

The Tile calorimeters use steel as the absorber medium, and plastic scintillator as the active media. Nuclear interactions of hadronic radiation inside the steel absorber precipitate showers of low-energy charged particles. Plastic scintillator tiles convert energy of charged showers into light pulses with intensity proportional to the number of charged particles in the shower. Light from the scintillators is transmitted via fiber-optic wires to the HCAL front-end readout circuitry, where the analog light signals are digitized and transmitted off-detector. Tiles are not read out individually. The spatial resolution of the TileCal is defined by the combination of scintillator tiles into readout channels. Scintillator tiles are ganged into three layers in r , and clusters are approximately projective in η (Figure 3.29). As in the EMCal, r segmentation provides information on the shapes of hadronic

showers, which can provide clues to particle identification and warnings of likely punch-through into the Muon Spectrometer. A TileCal barrel module is illustrated in Figure 3.28.

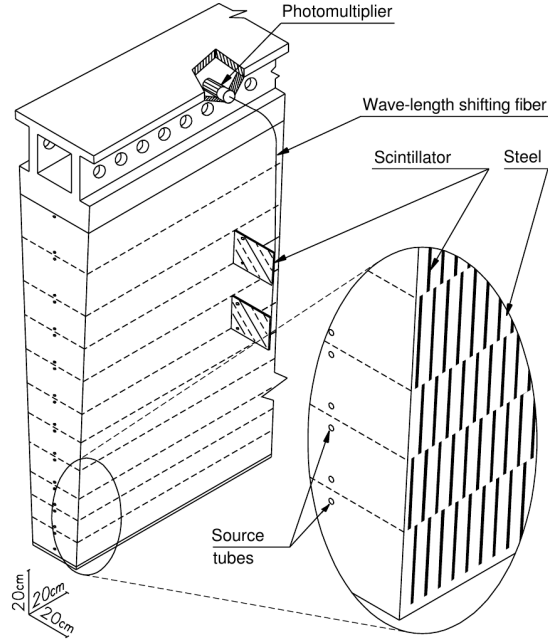


Figure 3.28: Drawing of an ATLAS Tile Calorimeter Barrel Module. Radial orientation of tiles and offset in the tile pattern between radial layers maximizes depth in nuclear interaction lengths (λ), and ensures full coverage in ϕ without gaps.[33]

Because background radiation fluence in ATLAS does not fall off as strongly in z as it does in r , the Hadronic End-Cap calorimeters (visible in Figures 3.25 and 3.26) are subject to fluence of background radiation similar to the Electromagnetic Calorimeters. The plastic-steel combination employed in the Tile Calorimeter could not perform reliably in the background radiation environment at high $|\eta|$, so the Hadronic end-caps employ copper as the absorber material, and liquid argon as the absorber, as in the Electromagnetic Calorimeters. The HEC wheels are composed of planar disc layers alternating among copper absorber, LAr active layers, and readout/service layers. As in the liquid argon EMCal, spatial resolution in HEC measurements is defined by electrode patterning on readout

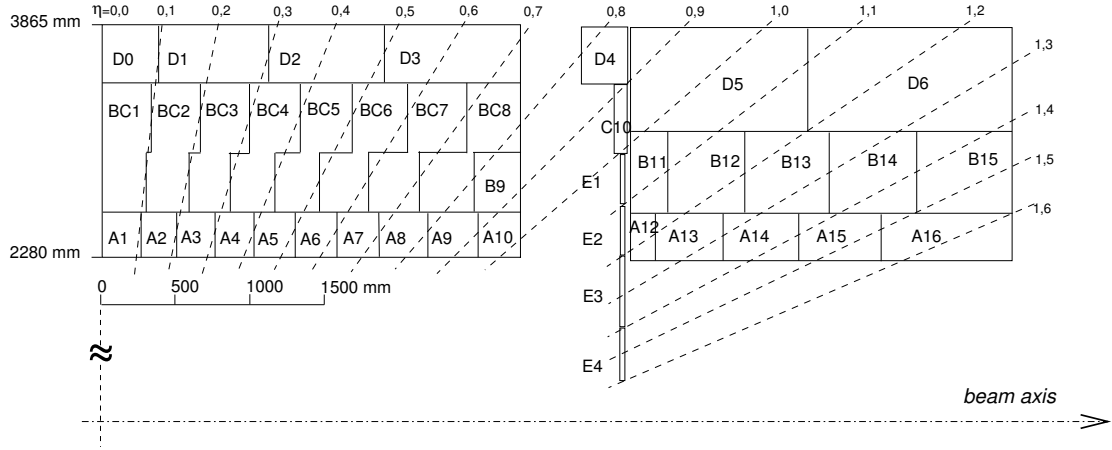


Figure 3.29: $\eta - r$ Geometry of Tile Calorimeter spatial segmentation.[33]

planes. $\eta - \phi$ segmentation in the HEC is approximately 0.1×0.1 for $|\eta| < 2.5$, and approximately 0.2×0.2 at higher $|\eta|$.

3.2.10 The Forward Calorimeter

The ATLAS Forward Calorimeters are visible in Figures 3.25 and 3.26. The Forward Calorimetry system is composed of three cylinders located at very high $|\eta|$ symmetrically on either end of the interaction region (Figure 3.30). The innermost cylinders in z are electromagnetic calorimeters, and the outer two FCal plugs are hadronic. Both employ liquid argon as the active medium. The Electromagnetic FCal (FCal1) uses copper as the absorber, and the hadronic FCals (FCal2,3) use tungsten. The forward calorimeters are designed to measure the same properties (shower shape and total energy) of the same species as the EM and Hadronic systems. However, the extreme background and radiation environment at $3.1 < |\eta| < 4.9$ arising from low- p_T diffraction necessitates distinct designs for the FCals.

The enormous density of energy deposited in the FCals imposes additional constraints on readout signal evolution and extraction times. To meet these constraints, the FCal's use thin, hollow cylinders of liquid argon embedded in the

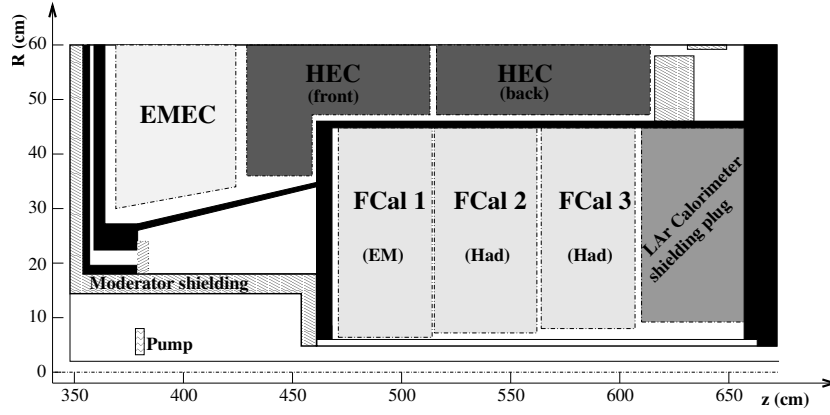


Figure 3.30: $\eta - r$ Geometry of Forward Calorimeters in the $+z$ region. Figure 5-19 from [33].

absorber discs parallel to z (Figure 3.31).

3.2.11 The Toroidal Magnet System

The ATLAS Toroidal Magnet system, pictured in Figure 3.32, is a network of large magnets designed to generate an approximately circumferential (ϕ -pointing) magnetic field in the Muon Spectrometer volume. Measurements of muon track curvature in the Toroidal magnetic field provide measurements of muon momentum.

3.2.12 The Muon Spectrometer

The ATLAS Muon Spectrometer (Figure 3.32) provides identification of muons and measurement of their momenta. The MS is a tiled array of gas ionization tracking chambers. The Muon Spectrometer is described in detail in Chapters 1 and 6 of the ATLAS Detector Publication,[33] and the ATLAS Muon Spectrometer Technical Design Report.[86]

The Muon Spectrometer is sensitive to all charged species. Muon ID is inferred

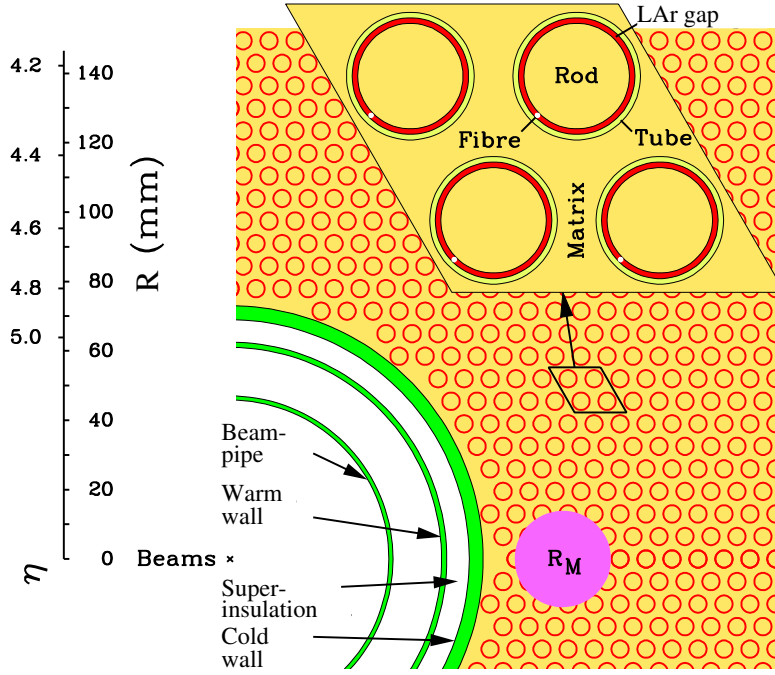


Figure 3.31: Forward Calorimeter $R - \phi$ geometry. Figure 5-20 from [33].

from the opacity of the calorimeters to all other charged, long-lived Standard Model species, as well as matching tracks in the ID. Muon momentum is measured as a parameter of curvature of muon tracks in the Toroidal magnetic field. Due to the predominantly tangentially pointing Toroidal Magnet field geometry, muon trajectories are bent (primarily) in the $r - \eta$ plane.

The Muon Spectrometer is the most technologically heterogeneous subsystem of the ATLAS detector. It includes Monitored Drift Tubes (MDT), Cathode Strip Chambers (CSC), Resistive Plate Chambers (RPC), and Thin Gap Chambers (TGC). All of the Muon Spectrometer subsystems are gas ionization drift chambers, distinguished from one another by gas volume and readout geometries, which are optimized variously for resolution and readout time, and for the different r and $|\eta|$ regions covered by each system.

Of the four distinct MS tracking chamber technologies, two (the TGCs and

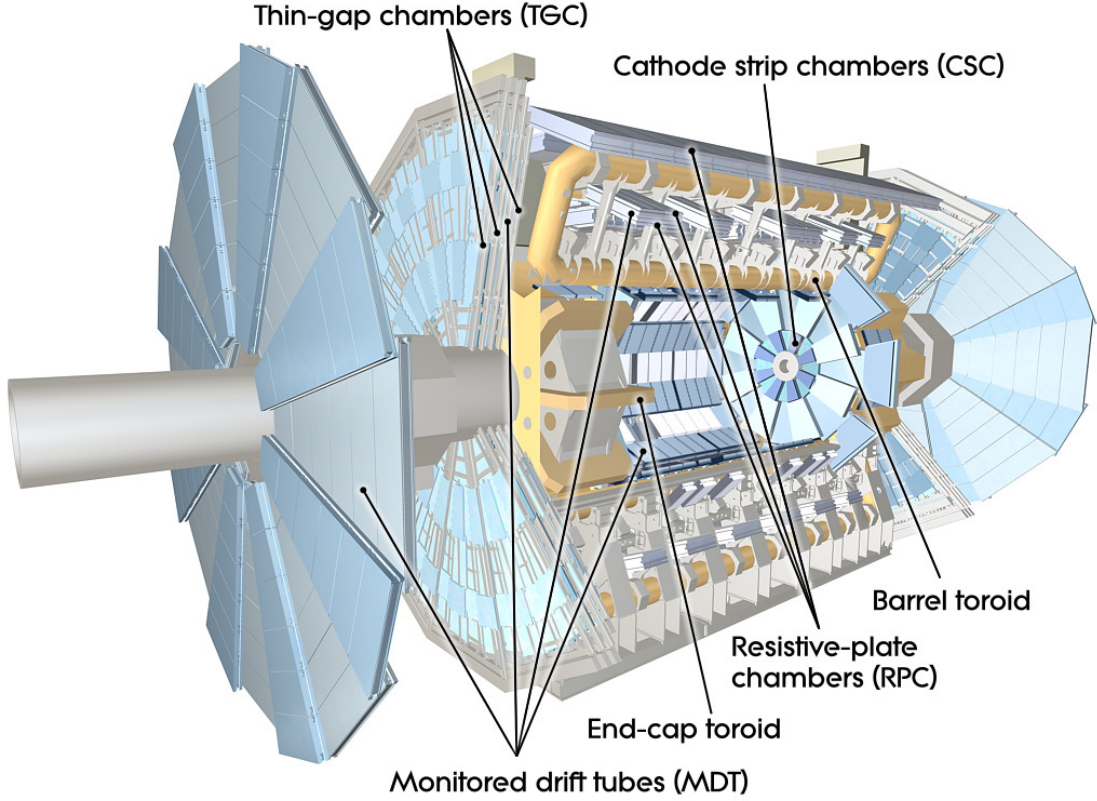


Figure 3.32: Cutaway view of the ATLAS Muon Spectrometer.[85].

RPCs) are optimized for fast signal extraction and readout for input to L1 trigger decisions (see Section 3.2.13). Muons are attractive targets for the L1 trigger, because they are strong evidence for production and decay of electroweak-charged particles at or above the GeV mass scale. Data feeds triggered on high- p_T muons are heavily enriched in tau, top, and $W^\pm/Z$ boson events. The $W^\pm$ and Z cross-section measurements reported in this dissertation used a muon trigger to select $W \rightarrow \mu\nu_\mu$ and $Z \rightarrow \mu^+\mu^-$ events. The $|\eta|$ coverage of the muon trigger systems ($|\eta| < 2.4$) corresponds roughly to the barrel coverage of the Inner Detector.

Due to the muon system's enormous size, and the large real distances between Spectrometer components, monitoring of the relative and absolute alignments of Muon Spectrometer components is a unique challenge. To maintain fine tracking

precision, the Muon Spectrometer’s mechanical structure includes a complicated network of laser interferometers providing continuous metrology and alignment feedback (Figure 3.33).

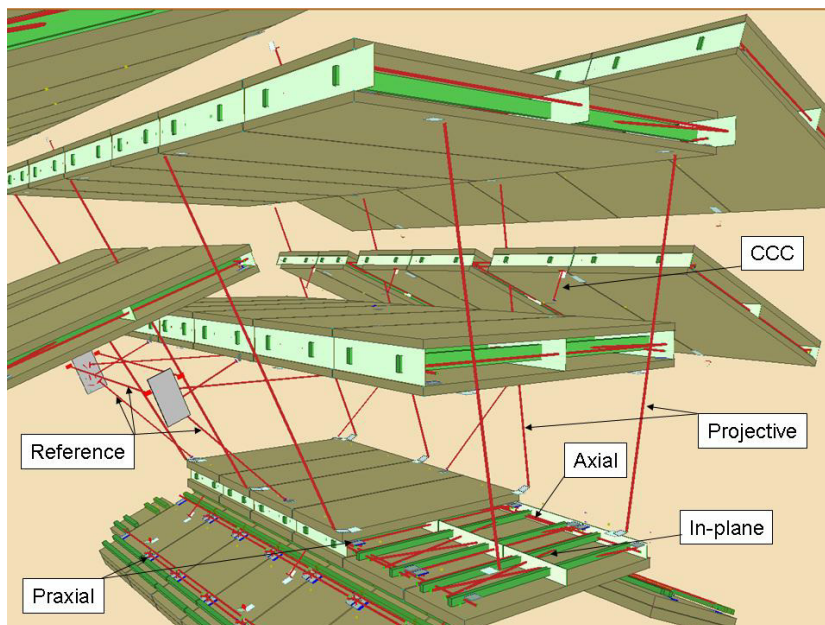


Figure 3.33: Muon Spectrometer Laser Alignment System. Figure 6.25 from [33].

Precision tracking in the Muon Spectrometer Barrel, and in some of the endcaps, is accomplished with Monitored Drift Tube modules. A barrel MDT chamber is illustrated in Figure 3.34. The MDT is a straw-tube gas ionization tracker, similar in principle to the Transition Radiation Tracker described in Section 3.2.6. The “monitoring” in the Monitored Drift Tubes refers to the fiducial laser alignment system built in to the mechanical structure of MDT modules.

In the highly forward region of the muon endcaps, the background rate of charged particles is too high for the MDTs to reliably refresh between hits. Cathode Strip Chambers are chosen to provide precision tracking in the MS endcaps. CSCs are Multiwire Proportional Chambers. Each fan-shaped chamber contains four instrumented gas layers. Anode wires are aligned radially in the center of gas

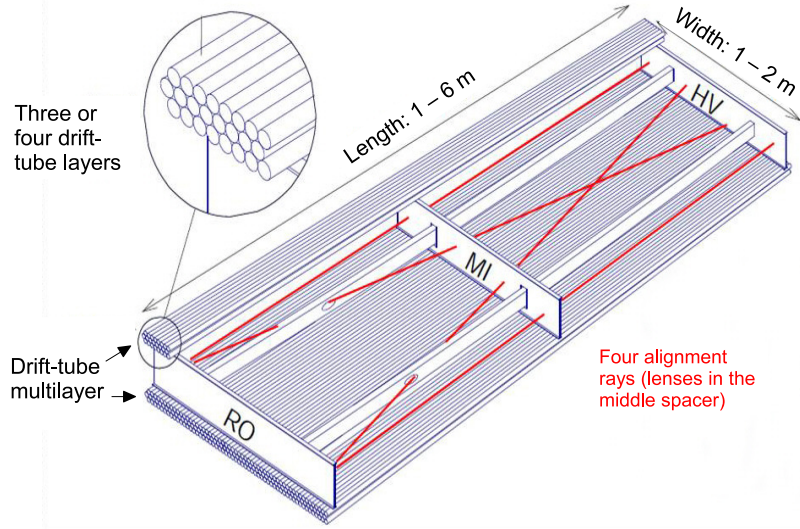


Figure 3.34: Drawing of an MS barrel MDT chamber. Red lines show optical registration lengths. Figure 6.10 from [33].

layers. Each gas layer is instrumented with readout electrode strip arrays, aligned perpendicular to the wires on one face, and parallel to the wires on the opposite face. Each charged particle traversing the muon end-cap is expected to provide four precision measurements of η and four precision measurements of ϕ within the narrow z -extent of the CSC endcaps.

Resistive Plate Chambers (RPCs) are the chosen trigger technology in the Muon Spectrometer barrel region ($|\eta| < 1.05$). RPCs are thin gas drift chambers (no anode wires) with patterned-electrode (strip) readout planes. The thin active gas layer and uniform electric field ensures charge collection times low enough to satisfy the L1 trigger frequency of approximately 100 kHz. RPC chambers are installed on inner or outer faces of MDT modules, as illustrated in Figure 3.37. The RPC system is laid out to provide three layers of full ϕ coverage over the full barrel range in η . Three RPC layers capable of reading out at the rough L1 trigger frequency provide gross momentum resolution sufficient to trigger on muons at selected p_T^μ thresholds.

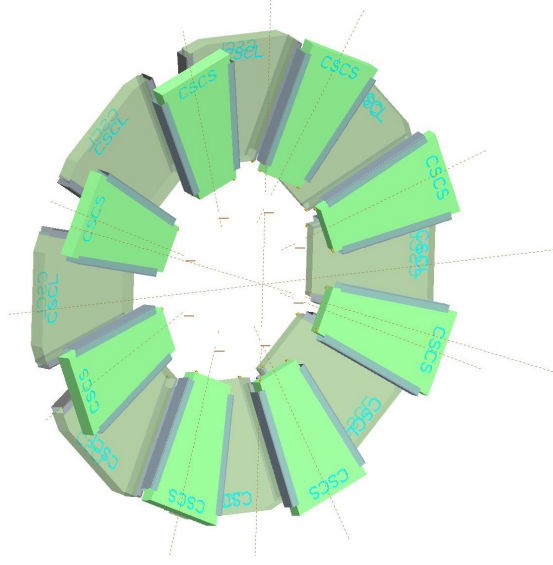


Figure 3.35: Render of a Muon Spectrometer Cathode Strip Chamber end-cap. Figure 6.13 from [33].

The additional constraints on background rejection and readout rates imposed by high backgrounds in the endcap regions require a distinct trigger chamber design from the barrel region RPCs. Trigger events would be lost to readout saturation in the RPCs. In the Muon Spectrometer inner wheels, covering $1.05 < |\eta| < 2.4$, trigger coverage is provided by the Thin Gap Chambers. TGCs are another variation of multiwire gas-ionization proportional chambers.

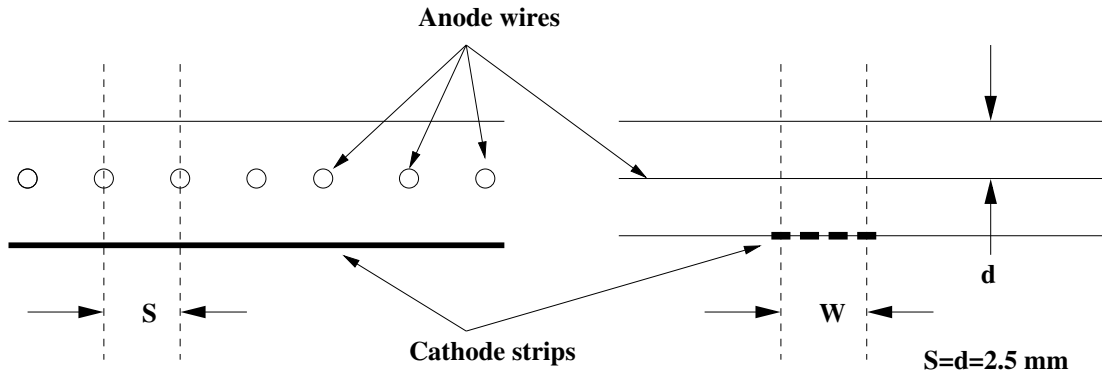


Figure 3.36: Illustration of Muon Spectrometer Cathode Strip Chamber readout geometry. Figure 6.14 from [33].

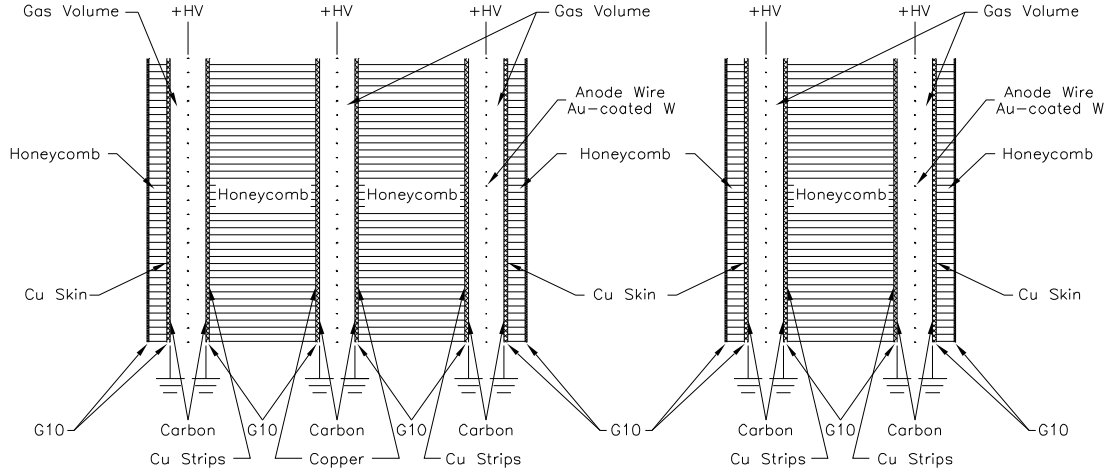


Figure 3.38: Cross-Sectional Illustration of MS Thin Gap Chambers. Figure 6.32 from [33].

out bandwidths.

ATLAS uses a two-stage trigger system, including the Level-1 trigger (L1) and the High-Level trigger (HLT). The level-1 trigger “sees” every beam crossing, and makes a yes/no decision every 50 (or 25) nanoseconds, based on fast on-detector hardware customized to provide very coarse information about the event at high frequency. L1 has access to information from the calorimeters including total energy and coarse topological distributions of energy. L1 can also trigger on signals in the Muon Spectrometer. The enormous number of channels in the Inner Detector prevent ID data from being reported and processed at L1 frequency. The L1 trigger system reduces the event rate from the ATLAS beam crossing rate of 20 (40) MHz, to approximately 100 kHz entering the High-Level Trigger.

The High-Level Trigger receives event data at a rate of approximately 100 kHz from the L1 system. At the L1 output rate, the ATLAS subsystems all have time to read out all data corresponding to the L1 trigger. This means that the HLT has at its disposal all the same data that physics analysts ultimately use offline. The limitation on sophistication of HLT trigger decisions is the high event rate. All

reconstruction and calibration algorithms which constitute input to HLT decisions must execute within approximately 4 seconds per event.

Raw detector data from events passing the HLT trigger decision are written to permanent storage (either tape or hard disks) at CERN, from whence they can be retrieved for processing, offline reconstruction, and analysis.

3.3 Reconstruction of Physics Objects

Identification and measurement of charged tracks, primary vertices, electrons, muons, $\cancel{E}_T$, and jets within ATLAS detector data is performed by standardized reconstruction algorithms. These algorithms are developed and calibrated by dedicated Combined Performance (CP) groups within ATLAS. The outputs of these algorithms are known generically as physics objects, and constitute the bulk of datasets as formatted for physics measurements. Physics objects generally include the measured properties of an object and their uncertainties, as well as detailed information about the reconstruction.

This section summarizes the algorithms used to reconstruct the physics objects (charged tracks, primary vertices, electrons, muons, jets, and $\cancel{E}_T$) whose properties are used to define the leptonic $W^\pm$, Z event selections. The algorithms are described in detail in the publications cited. Here I will present broad functional summaries of the algorithms, in order to motivate and inform later discussions (Section 4.5) of experimental uncertainties on their performance in the $W^\pm$, Z cross-section measurements.

3.3.1 Tracks

High-quality charged tracks reconstructed in the Inner Detector are prerequisite to reconstruction of electrons, muons, and $\cancel{E}_T$. Tracks are inputs to reconstruction and calibration of jets, as well. The paths in space of charged particles are measured in the inner detector (Section 3.2.1). ID Tracks are reconstructed by “connecting the dots” through the known shapes and locations of IBL, pixel, SCT, and TRT ionization volumes (channels) which report signals in the same bunch

crossing.

The IBL and Pixel Detector $z - r\phi$ resolutions are fine enough that charged particles commonly generate signals in several adjacent pixels, resulting in clustered hits on each pixel layer. Typical clusters are 1-4 pixels wide in the shorter pixel dimension, and 1 or 2 pixels in the longer dimension.[88] In order to correctly associate hits resulting from the same particle, and to resolve clusters from nearby, but distinct charged particles, the offline track reconstruction employs an Artificial Neural Network algorithm to cluster pixel hits with optimal accuracy.[89] The performance of the NN clustering algorithm has been studied extensively in Monte-Carlo simulation and evaluated in early 13 TeV data as well.[90]

Hit clustering in the SCT is a simpler exercise. Tracks are generally better-separated at SCT radii. Due to SCT sensors' strip geometry, clustering is a one-dimensional problem, as opposed to the 2-D clustering required in the pixels. SCT data also does not report information on the amount of charge collected on a channel, which prohibits pixel-like calculations of cluster moments and barycenters.

After pixel and strip clusters have been evaluated, the iterative process of “connecting the dots” begins with the construction of track seeds. Seeds are combinations of three hits taken from three different layers of the pixel-SCT system. Three points are required to make a first estimate of all track parameters which are needed to extrapolate the seed to additional tracking layers and look for compatible hits. The number of three-cluster combinations is very large under typical ATLAS pileup conditions. The vast majority of seeds are specious random combinations, and are eventually discarded when they can not be extrapolated to compatible hits at outer or intermediate radii.[91]

Extrapolation of track seeds to outer and intermediate tracking layers is per-

formed by a combinatorial Kalman Filter algorithm. The Kalman filter extrapolates seeds to tracks, iteratively incorporating compatible hits in additional silicon layers, and reoptimizing track parameters on-the-fly. The filter uses spatial resolution in different tracking layers, as well as uncertainties due to multiple scattering and Bremsstrahlung radiation. Tracks extrapolated from specious seeds generated by random combinations of silicon hits generally have fewer compatible hits, more holes along the extrapolated path, and poor quality-of-fit. Seeds from real charged particles generally extrapolate to track candidates with more compatible hits, fewer holes, and higher quality-of-fit.[\[92\]](#)

The collection of track candidates output by the Kalman Filter are then ranked and sorted according to the quality of reconstruction, in order to identify likely fakes, and to resolve conflicts and ambiguities in the allocation of hit clusters to tracks. Quality criteria include number of hits, numbers of holes, numbers of hit clusters shared with other tracks, Kalman fit χ^2 , and others. Tracks passing overall quality thresholds become reconstructed Physics Objects and their parameters are refitted with algorithms optimized for parameter resolution independent of track-finding.

With respect to reconstruction of electrons, muons, jets, and $\cancel{E}_T$, ID tracking performance is excellent. Within the fiducial acceptance of these measurements, tracking efficiency and resolution are not proximal limitations on the performance of client reconstruction algorithms.

3.3.2 Primary Vertices

Primary vertices are measurements of the three-dimensional location of inelastic proton-proton collisions within the beam crossing area at the center of ATLAS.

The vertices are located with ATLAS Inner Detector data by identifying points in space near the beam crossing which are compatible with the intersection of several charged tracks. As with most reconstruction algorithms, primary vertex reconstruction proceeds in finding and fitting stages. In the first stage, charged ID tracks passing loose criteria on p_T , quality of fit, impact parameter, and impact parameter resolution, are selected as inputs to the search for primary proton-proton collision vertices.

For each track, the point of closest approach (POCA) to the nominal beam spot axis is calculated. The density of POCA in z is histogrammed, and the global maximum of $d_{\text{Ntrk}}/d_{z\text{POCA}}$ is taken as the starting point for the first vertex. Nearby tracks are then collected to the vertex by testing the compatibility of the current vertex position with the measured track parameters and uncertainties. If the track is compatible to within a configurable χ^2 confidence level, it is assigned to the vertex and removed from the collection of input tracks. As tracks are collected to the vertex, the best fit to the vertex position is refit, accounting for the possibility that displaced tracks from secondary decays might not point precisely to the primary vertex.

Once the iterative vertex finding algorithm has associated all possible tracks to compatible primary vertex candidates, the vertex positions are re-fit using the parameters and uncertainties of all associated tracks. Beam spot density maps measured in the same run for the current beam condition are input to the fit as prior constraints on the vertex positions, as well. Additional corrections (derived from measurements in data) to the vertex position fit uncertainty are parameterized in $\sqrt{\sum p_T^2}$ and N_{track} . [93]

As with the basic charged track reconstruction, Inner Detector vertexing performance is more than adequate for studies of the $W^\pm$, Z inclusive cross-sections

in the leptonic final states. Only the reconstruction efficiency is of any direct relevance to the $W^\pm$, Z inclusive cross-section measurements. Even this effect is slight, as the very loose vertex identification criteria employed in this measurement did not cut a single event from the data or background simulation samples.

3.3.3 Electrons

Prompt electrons are characterized in the ATLAS detector by Inner Detector tracks pointing to energy clusters in the EM Calorimeter, with no associated signals in the hadronic calorimeter or the Muon Spectrometer (Figure 3.12). The efficiency of underlying track and EM clustering algorithms is very high, but several background processes contaminate prompt electron reconstruction. These include some real electrons from non-prompt sources, such as those emitted in hadronic decay showers and $\gamma \rightarrow e^+e^-$ pair conversions. Most of the hadronic fakes (“jets faking electrons”), however, are due to dense hadronic showers in which a charged pion track closely overlaps a $\gamma\gamma$ deposit in the electromagnetic calorimeter.

There are different algorithms for electron reconstruction in the central and forward regions. “Central” in this context is defined by the Pixel Detector barrel coverage ($|\eta| < 2.47$, Figure 3.15), which is an important boundary in the reconstruction of ID tracks. The entire fiducial region of the $\sigma_{W \rightarrow e\nu_e}$ and $\sigma_{Z \rightarrow e^+e^-}$ measurements lies within this central region of electron reconstruction.

Electron reconstruction is divided generally into three steps: reconstruction, calibration, and identification. Reconstruction scans the event for track-EM cluster pairs. Calibration rebuilds the track-cluster pairs with track and cluster algorithms optimized for electrons. Identification applies additional cuts and al-

gorithms based on fine details of the track and cluster shape, as well as nearby activity in other detectors, in order to discriminate against background processes.

Reconstruction begins with a systematic search of the EM calorimeter via a “sliding-window” algorithm [94] to identify clustered energy deposits above 2.5 GeV. The size of the window in $\eta - \phi$ space corresponds roughly to the Molière radius of electron showers in the EM calorimeter. To reduce the possibility that the clusters found by the sliding window are localized features of larger calorimeter structures, additional cuts are imposed on the ratios R_η and R_{Had} . R_η is the ratio of energy contained in the EM calorimeter $\eta - \phi$ window to a larger window with the same center. R_{Had} is the ratio of energy in the EM Calorimeter window, to the hadronic calorimeter measurement within the corresponding angular area. EM calorimeter clusters with significant leakage outside the $\eta - \phi$ window, or into the hadronic calorimeter, are likely to be products of hadronic jets, rather than prompt photons.

Candidate clusters are then compared to the list of ID tracks reconstructed in the event, looking for cluster-track pairs in which the track points into the cluster. In this search, ATLAS’ general-purpose algorithm for charged track reconstruction is supplemented by an electron-specific algorithm which makes greater allowance for electrons’ high rate of bremsstrahlung radiation inside detector material. This supplementary algorithm is only used when the electron-bremsstrahlung hypothesis is well-motivated, i.e., no fully reconstructed ID track points into an EM cluster, but a 3-point Pixel Detector track seed (Section 3.3.1) does. Compared to generic ATLAS tracking, the supplementary electron-identification tracking algorithm recovers substantial electron reconstruction efficiency.

All candidate tracks are then refit under the explicit electron hypothesis. The refit tracks are used to repeat the cluster-track matching with tighter angular cri-

teria for matches. Within ATLAS' high-pileup environment, it is often necessary to resolve ambiguities in cluster-track association due to the presence of several Inner Detector tracks matched to a given EM calorimeter cluster. The reconstruction quality of the track itself is considered next. Matched tracks which were reconstructed with one or more high-precision Pixel Detector hits are prioritized. If more than one matched track includes pixel hits, the angular compatibility of the tracks with the calorimeter cluster is tested again, this time at higher precision than the initial match. Tracks passing the second ΔR test are finally ranked by their number of Pixel Detector points, with hits in the innermost Pixel Detector Layer counting double. A hit in the IBL or the innermost pixel layer is strong evidence that the track is indeed prompt.

The resultant cluster-refit-track pairs are electron candidates, taken as input to the calibration and identification steps. Calibration/identification begins by rebuilding the 2-dimensional $\eta - \phi$ EM clusters with a 3-dimensional clustering algorithm optimized for electrons, and which accounts for the shower axis predicted by the matched track. The total energy in the electron shower is extracted with a multivariate algorithm that integrates information about the three-dimensional cluster shape with detailed topological maps of detector response. The calibrated cluster energy measurement is taken as the total energy in the four-momentum of the reconstructed electron. The normalized (prompt) momentum vector (i.e., the direction) is obtained from the fitted parameters of the matched track.

The physical properties of the reconstructed electron are fully defined once the four-momentum is calculated in the calibration. It then remains to quantify the degree of certainty that the reconstructed object is a true prompt electron. This is the identification step. Run-1 analyses had a choice between a cut-based electron identification algorithm and a simultaneous multivariate algorithm. Most

of the input variables were common between the two. For Run-2, the cut-based identification has been deprecated, and only the multivariate identification has been updated for the Run-2 analysis software model. Three electron likelihood algorithms are calibrated for use in Run-2 physics measurements (in order of ascending signal purity): Loose, Medium, and Tight. The $W^\pm$, Z cross-section measurements use the Medium likelihood criteria for $W^\pm$ and Z daughter candidates (Section 4.2). The likelihood is defined as

$$d_L = \frac{L_S}{L_S + L_B}, \quad L_n(\vec{x}) = \prod_{i=1}^N P_{n,i}(x_i), \quad (3.1)$$

where $P_{n,i}(x_i)$ are the probability density functions for a signal or background sample n , in the variable x_i . The Loose, Medium, and Tight Likelihood conditions correspond to choices of input variables $\vec{x}$ and cuts on the discriminant d_L . PDFs for each input variable are derived from dedicated studies in data. Samples of electrons passing tighter identification working points are approximately, but not strictly, subsets of looser identification selections.

Two inputs to the electron identification MVA are of particular note: the so-called “isolation variables” $E_T^{\text{cone}}(\Delta R)/p_T$ and $p_T^{\text{cone}}(\Delta R)/p_T$. In the $W^\pm$, Z cross section measurements, these variables are used to define selections for Multijet background templates in data control regions (Section 4.4.2). Of the many electron identification variables, $E_T^{\text{cone}}(\Delta R)/p_T$ and $p_T^{\text{cone}}(\Delta R)/p_T$ exhibit the greatest independent separation between signal electrons and jets faking electrons. $E_T^{\text{cone}}(\Delta R)/p_T$ is the sum (divided by p_T) of transverse energy in calorimeter topoclusters falling within a cone ΔR about the electron cluster’s center, omitting a central angular area associated to the electron itself. $p_T^{\text{cone}}(\Delta R)/p_T$ is similar in principle, but based on Inner Detector tracks instead of calorimeter

cells. $p_T^{\text{cone}}(\Delta R)/p_T$ is defined as the sum (divided by p_T) of transverse momentum of tracks within ΔR of the electron candidate track, excluding the electron track. Only high-quality tracks originating from the same primary vertex as the electron are used.

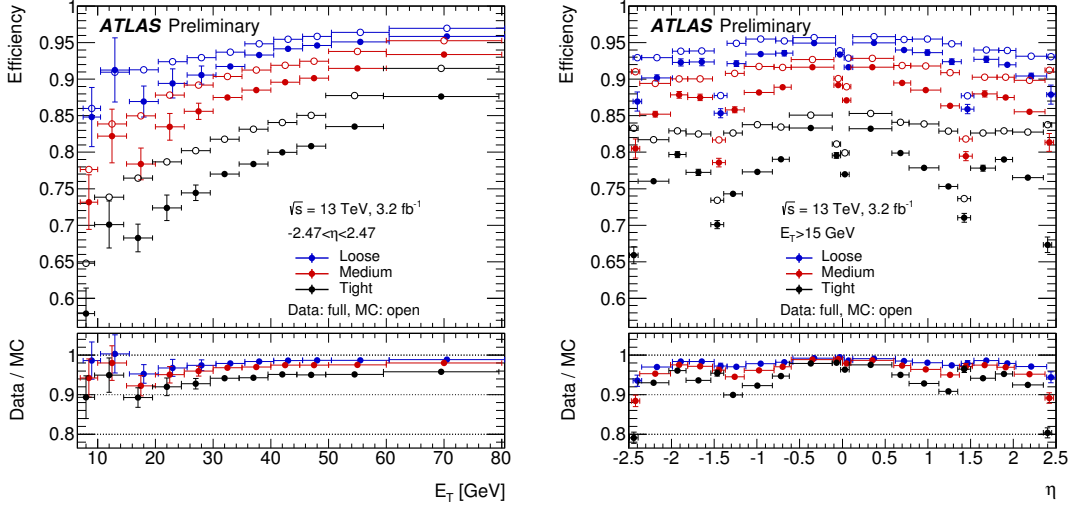


Figure 3.39: Electron reconstruction efficiency versus (left) E_T , and (right) η .[\[95\]](#)

The efficiency to reconstruct electrons is a leading uncertainty on the total inclusive cross-sections in the $W \rightarrow e\nu_e$ and $Z \rightarrow e^+e^-$ channels. The electron reconstruction and identification efficiencies were measured in 2012 data at $\sqrt{s} = 8$ TeV. Reconstruction algorithms were also described in detail in the same publication.[\[96\]](#) Early 2015 measurements of reconstruction identification and efficiency at $\sqrt{s} = 13$ TeV were published in December 2015 (Figure 3.39).[\[95\]](#) The electron efficiency corrections applied to the Monte-Carlo events were based on $Z \rightarrow e^+e^-$ tag-and-probe studies conducted in the 50 ns data.

3.3.4 Muons

Muons generate signals in every ATLAS detector subsystem. They leave tracks in the Inner Detector, minimum-ionizing deposits in the electromagnetic and hadronic calorimeters, and tracks in the Muon Spectrometer. Several algorithms for muon reconstruction at ATLAS have been calibrated for use in physics analyses. These include Standalone, Combined, Segment-Tagged, Calorimeter-Tagged, and High- p_T . They are distinguished functionally by fiducial coverage, reconstruction efficiency, and signal purity; and methodologically by the choice of which subdetectors are interrogated for evidence of muon production. The various reconstruction algorithms are described in [97]. The Combined algorithm achieves the highest signal purity. It requires compatible tracks to be reconstructed independently in the Inner Detector and the Muon Spectrometer. These $W^\pm$ and Z cross-section measurements use exclusively muons reconstructed with the Combined algorithm. The muon identification condition which explicitly defines the physics object selection in these measurements (“medium”) generally admits both Combined and Standalone muons. However, additional fiducial cuts ($|\eta^\mu| < 2.4$) in the analysis object selection logically remove all Standalone muons which fulfill the medium identification criterion.

Since muons are the only long-lived charged species which will not typically decay or shower in either calorimeter system, the presence of recognizable charged tracks in the Muon Spectrometer is the starting point for Muon reconstruction and identification. Track reconstruction in the MS begins with segment finding. Gross regions of activity in the $\eta - \phi$ plane are identified by signals in the resistive-plate trigger chambers. High-precision MDT chambers overlapping the RPC regions-of-activity are then searched for track segments. Segments are collections of 6 or

more hits within small angular areas in individual MDT chambers.

Compatible segments from the three MDT layers are then collected into track candidates. Compatibility is determined by loose angular criteria and goodness-of-fit to a single track. Track candidates are then rebuilt with a global fit to all associated segment hits. The final track fitting algorithm accounts for material interactions, inhomogeneity of the toroid magnetic field, “blind” spots in the MS instrumentation, and ambiguous hit-track associations.

Muon track candidates are extrapolated backwards through the calorimeter volume to the Inner Detector. Minimum-ionizing energy losses (approximately 3 GeV) in the calorimeters can be modeled with detailed three-dimensional material maps, or measured directly from calorimeter readings in cells traversed by the track. To fulfill the Combined muon reconstruction, the extrapolated Muon Spectrometer track must be matched to a charged track reconstructed independently in the Inner Detector. Reconstruction of charged tracks in the Inner Detector is described in Section 3.3.1. Additional tests are applied on compatibility of the associated tracks’ momentum.

Compatible sets of ID, calorimeter, and Muon Spectrometer signals are then refit with an algorithm optimized explicitly for the muon hypothesis. The Combined muon fit measures the momentum of the muon candidate from a global fit through all associated track points. The fit accounts for uncertainties due to multiple scattering in the detector and minimum-ionizing energy loss through the calorimeters, as in the trajectory extrapolation from the Muon Spectrometer track.

Once the reconstruction is complete, classification as a medium quality muon depends on additional criteria on the fiducial acceptance and measurement quality. To pass the medium identification criteria, Combined muons must additionally be

reconstructed with $|\eta^\mu| < 2.5$, and pass additional cuts on the quality of track measurements in the Muon Spectrometer. The independent measurements of p_T from the matched ID and MS tracks are also compared for compatibility, to reduce contamination by unrelated but randomly overlapping MS-ID track segments.

The muon reconstruction efficiencies for a variety of algorithms and fiducial regions, including those employed in these measurements, were measured using tag-and-probe methods in $Z \rightarrow \mu^+\mu^-$, $J/\Psi \rightarrow \mu^+\mu^-$, and $\Upsilon \rightarrow \mu^+\mu^-$ data samples. The efficiency to reconstruct muons with the Combined algorithm within the fiducial acceptance of these measurements was found to be greater than 0.99. The efficiency maps and uncertainties input to the $W^\pm$, Z cross-section calibrations were derived from similar analyses performed in the early 2015 50 ns dataset.[98] These efficiencies were also measured in Run-1 at 7 and 8 TeV [97], and in the later (and much larger) 2015 13 TeV dataset collected with 25 ns bunch spacing.[99, 100]

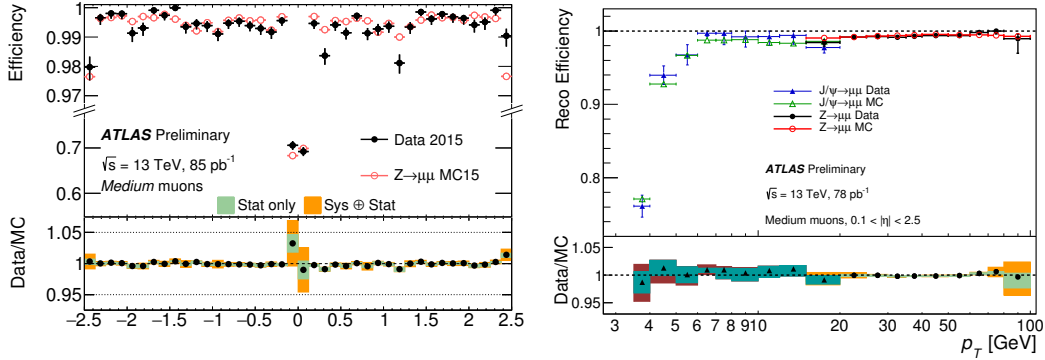


Figure 3.40: Muon reconstruction efficiency versus (left) η and (right) p_T . Figure 2a from [98].

Uncertainties on muon reconstruction efficiencies are linear contributions on the total cross section uncertainties in the $W \rightarrow \mu\nu_\mu$ and $Z \rightarrow \mu^+\mu^-$ channels. Muon p_T resolution propagates into the uncertainty on missing transverse energy. $\cancel{E}_T$ resolution and uncertainties on the shape limit the uncertainty on cross-section

fits performed in the $\cancel{E}_T$ distribution.

3.3.5 Jets

Collimated multi-particle decays of hadronic objects with significant transverse momentum are called jets. Jets are not features of the final state in any of the signal processes measured in these studies. However, they contribute significant backgrounds to electron and muon reconstruction. Jet activity within an event is used to calculate and calibrate missing energy (Section 3.3.6) as well. And jets within the fiducial acceptance of these measurements are used as “veto objects” to exclude signal events in which the $\cancel{E}_T$ could be mismeasured.

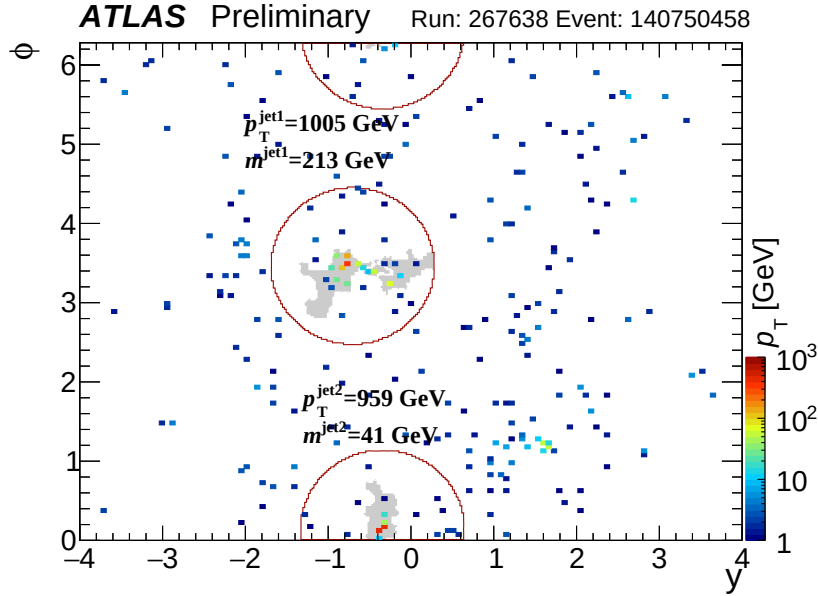


Figure 3.41: Jet Clustering in the Hadronic Calorimeter. y is the proper rapidity, not pseudorapidity (η). Clustering is performed via the $k_t^{-2}(0.4)$ algorithm, with cluster momenta calibrated at the electromagnetic scale. Figure 10c from [101]

There are three primary steps to jet reconstruction in ATLAS. The first step is topological clustering (“topoclustering”), in which the hadronic calorimeter is searched for contiguous 3-dimensional clusters of cells with energy signals signifi-

cantly above noise level. In the second step, the rough momenta of topoclusters are then input to a 2-dimensional iterative jet clustering algorithm. Finally, properties of reconstructed jets are recalibrated according to detailed studies of the instrumental and algorithmic response of the full jet measurement and reconstruction chain.

Several alternative calorimeter cell and jet clustering recipes have been calibrated for ATLAS physics measurements. AntiKtFourEMTopo jets emerged in Run 1 as the default choice for analyses (like this one) which were not extremely sensitive to jet performance. The name “AntiKtFourEMTopo” describes jets constructed from 3D calorimeter cell topoclusters (“Topo”) calibrated at the electromagnetic scale (“EM”), via the Anti- k_t algorithm (“AntiKt”), with radius parameter 0.4 (“Four”). At the time of these measurements in very early Run-2, they were also the best-calibrated for 50 ns crossing-rate conditions.[\[102\]](#)

Calorimeter cell topoclustering proceeds by first searching all 3 layers of the hadronic calorimeter for cells with charge signals 4σ or more above the typical level of electronic noise. These cells become the seeds of clusters. Adjoining cells with signals above 2σ are then added to the cluster cores. Any cells with positive measurements adjoining the 2σ isosurfaces are collected to the clusters. Position-energy moments are calculated to identify the barycenter of each cluster, which becomes the reference for the angle of the cluster’s momentum. The cluster energy measurement is calibrated at the EM scale, and the resultant cluster 4-vector is taken as input to the jet clustering algorithm. Calibrating cluster energies at the EM scale is not a physically realistic choice, but EM-scale topoclusters provide consistent performance with readily quantifiable uncertainties as inputs to higher-level jet clustering algorithms.[\[94\]](#)

The four-momenta derived from calorimeter topoclusters are the input to the

$k_t^{-2}(0.4)$ (“Anti- k_t , four”) jet clustering algorithm. $k_t^{-2}(0.4)$ defines a clever distance measure in y, ϕ, p_T space, and sequentially combines pairs of topocluster momenta according to this measure from least to greatest, summing combined pairs on-the-fly into new input momenta. The distance measure is defined so that relatively soft clusters within a fixed radius ($\Delta R = 0.4$, in our case) of a high- p_T cluster will be collected into a jet with that hard cluster, and that where the radii of jets growing around high- p_T clusters overlap, the allocation of clusters within the overlap is rational, predictable, and stable.[102]

Once the cluster momenta are allocated to jets by the jet clustering algorithm, the topocluster collections are recalibrated for final measurements of jet angle and energy.

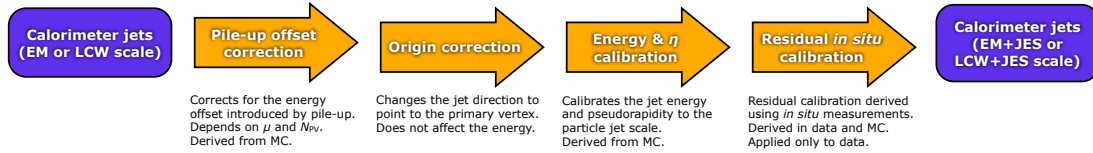


Figure 3.42: Jet Energy Calibration. Figure 3 from [103].

Calibration of the central value of jet energy measurements is known as Jet Energy Scale (JES) correction. Biases and variations of the energy response of the full jet reconstruction, including instrumental and algorithmic effects, are parameterized in many variables via many experimental methods. Significant determinants of ATLAS jet energy response include rapidity, the jet energy itself, in- and out-of-time pileup, and irregularities in the calorimeter instrumentation such as dead cells and uninstrumented volumes.

Calibration of uncertainties on the jet energy, known as Jet Energy Resolution (JER) corrections, are also a major effort within ATLAS. To a first approximation, the intrinsic uncertainty on calorimeter energy measurements is modeled as

$$\frac{\sigma_E^{jet}}{E^{jet}} = \frac{a}{\sqrt{E_{\text{meas}}^{jet}}} + b. \quad (3.2)$$

The first term on the right is derived from Gaussian statistics on the total charge generated in the calorimeter by the hadronic shower. The constant term represents measurement variations due to irreducible electronic noise in the calorimeter cells.

In addition to the intrinsic uncertainty on the jet signal charge, there are many instrumental and algorithmic effects which limit the resolution of the jet energy measurement. Some of these are predicted accurately by the Monte-Carlo models to which data are compared. Others are not modeled accurately, or not anticipated at all. To account for mismodeling of the Jet Energy Resolution in Monte-Carlo, dedicated studies in data measure the JER empirically as a function of many kinematic and shape variables. Where discrepancies are found in JER between Monte-Carlo and data control samples, additional random smearing is applied to jet properties like energy and angle. Uncertainties on the smearing noise functions (the JER uncertainties) are implemented in the jet CP software tools as nuisance parameters.

Because the Jet Energy Scale and Resolution are both sensitive to variable beam conditions, in particular those related to pileup and Luminosity, a special calibration was performed for the early 2015 (50 ns) dataset used for this measurement.

Dozens of uncertainties on the Jet Energy Scale and Resolution have been evaluated in Monte Carlo and data studies and implemented as nuisance parameters in the CP jet tools. Independent effects and intercorrelations among nuisance parameters have also been evaluated in order to provide reduced sets of nuisance

parameters for analyses which are not highly sensitive to these uncertainties. The reduced nuisance parameter sets have been tested to reliably cover the JES/JER uncertainties with many fewer time- and computationally-intensive variations of the analysis.[\[104\]](#) The reduced set of three JES/JER systematic variations is used in the $W^\pm$, Z inclusive cross-section measurements.

3.3.6 Missing Energy

Missing Transverse Energy ($\cancel{E}_T$) is used to infer the presence of a high- p_T neutrino in the leptonic decay of a $W^\pm$ boson. Missing transverse energy is constructed from the negative vector sum of p_T of the high- p_T objects in the event (in our case the electron or the muon), plus an additional “soft” term which is used to account for additional low- p_T activity in the event which was not associated to any of the other physics objects. In the case of signal $pp \rightarrow W \rightarrow l\nu_l$ events, the additional tracks would come primarily from underlying event (UE) activity, i.e., re-hadronization and decay of the primary-event protons’ partonic content which was not consumed in the $W^\pm$ boson reaction. Inclusion of these tracks in the $\cancel{E}_T$ sum helps to account for recoil of hard objects against UE particles with small, but significant p_T .

$\cancel{E}_T$ soft terms may be calculated from calorimeter activity, or based exclusively on ID tracks associated to the event primary vertex. The Track Soft Term (TST) calculation is chosen for this analysis due to its greater stability with respect to in- and out-of-time pileup. Association of ID tracks to the event primary vertex is much more accurate than the vertex association for calorimeter clusters. However, the TST term suffers greater uncertainties arising from p_T carried by neutral hadrons invisible to the Inner Detector. Since this analysis was performed in an

early-Run-2 dataset with unusual (and initially unpredictable) pileup conditions, the TST $\cancel{E}_T$ was preferred on the balance. This choice was further validated by studying the $\cancel{E}_T$ resolution in Z events. In the calculation of the track soft term, all tracks associated to the primary vertex which are not matched (via simple ΔR criteria) to hard analysis objects (electrons or muons, in our case), are included in the TST p_T sum.

Systematic variations of $\cancel{E}_T$ reconstruction are provided through the CP $\cancel{E}_T$ software tools. The $\cancel{E}_T$ software only provides variations related to the $\cancel{E}_T$ soft term calculation. Uncertainties on the momenta of high- p_T $\cancel{E}_T$ sum objects (electrons and muons, in our case) will propagate through the $\cancel{E}_T$ calculation when those parameters are varied independently within their uncertainties.[[105](#), [106](#)]

Chapter 4

Measurement of the $W^\pm$ and Z Boson Cross Sections

This chapter presents the first measurements of the 13 TeV proton-proton cross sections for $W \rightarrow \ell\nu_\ell$ and $Z \rightarrow l^+l^-$, where ℓ are electrons or muons. These measurements have been published at various stages, in part or in whole, in three ATLAS publications: a so-called Publication Note in July 2015, including preliminary kinematic distributions measured in the very first 13 TeV physics data; a Conference Note in September 2015 including the full menu of published cross sections, kinematic distributions, and ratios; and a peer-reviewed publication submitted to Physics Letters B in March of 2015:

Kinematic Distributions of $W^\pm$ and Z Boson Production from pp Collisions at $\sqrt{s} = 13$ TeV in the ATLAS Detector - A collection of plots published 25 July 2015 with the very first 6.4 pb^{-1} of stable collision data. Selected distributions were first presented at the EPS-HEP2015 conference in Vienna, Austria in July 2015, and were among the first physics results to emerge

from the LHC Run-2 dataset.[107]

Measurement of $W^\pm$ and Z Boson Production Cross Sections in pp Collisions at $\sqrt{s} = 13$ TeV in the ATLAS Detector - Preliminary results for the full menu of cross sections and ratios described in this dissertation, using the full 81 pb^{-1} 50 ns dataset, were published as an ATLAS Conference Note on 19 August 2015. These results were presented at the Lepton-Photon conference in Ljubljana, Slovenia, and at the LHCP2015 conference in St. Petersburg, Russia, both in August 2015.[108]

Measurement of $W^\pm$ and Z Boson Production Cross Sections in pp Collisions at $\sqrt{s} = 13$ TeV with the ATLAS Detector - Further work during August 2015 - March 2016 yielded refinements to the background and uncertainty models. Updated measurements of the integrated luminosity were also incorporated. These improvements resulted in dramatic reductions of systematic uncertainties throughout the analysis results. These finalized results are planned to be submitted in a paper to Physics Letters B in March 2016.

My own contribution to the analysis effort was focused on the Summer 2015 Publication and Conference notes, with specific emphasis on kinematic distributions and systematic uncertainties on event selection yields in the $W \rightarrow e\nu_e$ channels. During the subsequent effort leading up to the PLB paper, I provided cross-checks on inputs to the revised $W \rightarrow e\nu_e$ results through event selection comparisons.

The experimental method and results described in this chapter reflect the final analysis as presented in the March 2016 PLB paper. Unless otherwise specified,

details of the analysis in this chapter are referred to this paper.

4.1 Measurement Procedure Overview

The early-2015 $W^\pm/Z$ inclusive cross section analysis measured the quantities listed in Table 4.1. The analysis was organized in six independent channels, corresponding to the electronic and muonic final states of W^+ , W^- , and Z single-boson production. Combinations of electron and muon channels were performed for all 3 bosons. Charge combinations were also performed in the separate electron and muon final states of the W , as well as a total cross section combination of all W charge and lepton channels. All results were compared to the best available theory predictions, described in Section 4.6.1.

Inclusive cross sections are measured both in the total boson decay kinematic phase space (σ^{tot}), and also within limited fiducial phase spaces (σ^{fid}) corresponding loosely to the ATLAS detector’s central acceptance. The total cross sections are interesting as true “pure” physics quantities, ideally independent of the detector parameters. The fiducial cross sections are useful because they do not suffer uncertainties on extrapolation from the detector acceptance to the total event kinematic phase space. This reduction in uncertainties, which is substantial for some quantities like cross section ratios, provides additional sensitivity in comparisons to predictions which can also be calculated within our fiducial acceptance. The calculations of the cross sections and the efficiency factors which relate the fiducial, total, and experimental acceptances are described in this section.

Inclusive fiducial cross sections (σ^{fid}) are calculated from the total signal selection yield in each channel ($N_{W,Z}^{\text{data selected}}$), the experimental signal event selection efficiency ($C_{W,Z}$), the background expectations normalized to luminosity ($B_{W,Z}$),

$\sigma_{W^+ \rightarrow e^+ \nu_e}^{\text{fid}}$	$\sigma_{W^+ \rightarrow e^+ \nu_e}^{\text{tot}}$	$W^+ \rightarrow e^+ \nu_e$ cross section
$\sigma_{W^+ \rightarrow \mu^+ \nu_\mu}^{\text{fid}}$	$\sigma_{W^+ \rightarrow \mu^+ \nu_\mu}^{\text{tot}}$	$W^+ \rightarrow \mu^+ \nu_\mu$ cross section
$\sigma_{W^+ \rightarrow \ell^+ \nu_\ell}^{\text{fid}}$	$\sigma_{W^+ \rightarrow \ell^+ \nu_\ell}^{\text{tot}}$	$W^+ \rightarrow \ell^+ \nu_\ell$ cross section (e, μ combined)
$\sigma_{W^- \rightarrow e^- \bar{\nu}_e}^{\text{fid}}$	$\sigma_{W^- \rightarrow e^- \bar{\nu}_e}^{\text{tot}}$	$W^- \rightarrow e^- \bar{\nu}_e$ cross section
$\sigma_{W^- \rightarrow \mu^- \bar{\nu}_\mu}^{\text{fid}}$	$\sigma_{W^- \rightarrow \mu^- \bar{\nu}_\mu}^{\text{tot}}$	$W^- \rightarrow \mu^- \bar{\nu}_\mu$ cross section
$\sigma_{W^- \rightarrow \ell^- \bar{\nu}_\ell}^{\text{fid}}$	$\sigma_{W^- \rightarrow \ell^- \bar{\nu}_\ell}^{\text{tot}}$	$W^- \rightarrow \ell^- \bar{\nu}_\ell$ cross section (e, μ combined)
$\sigma_{W \rightarrow e \nu_e}^{\text{fid}}$	$\sigma_{W \rightarrow e \nu_e}^{\text{tot}}$	$W \rightarrow e \nu_e$ cross section (both charges)
$\sigma_{W \rightarrow \mu \nu_\mu}^{\text{fid}}$	$\sigma_{W \rightarrow \mu \nu_\mu}^{\text{tot}}$	$W \rightarrow \mu \nu_\mu$ cross section (both charges)
$\sigma_{W \rightarrow \ell \nu_\ell}^{\text{fid}}$	$\sigma_{W \rightarrow \ell \nu_\ell}^{\text{tot}}$	$W \rightarrow \ell \nu_\ell$ cross section (both charges, e, μ combined)
$\sigma_{Z \rightarrow e^+ e^-}^{\text{fid}}$	$\sigma_{Z \rightarrow e^+ e^-}^{\text{tot}}$	$Z \rightarrow e^+ e^-$ cross section
$\sigma_{Z \rightarrow \mu^+ \mu^-}^{\text{fid}}$	$\sigma_{Z \rightarrow \mu^+ \mu^-}^{\text{tot}}$	$Z \rightarrow \mu^+ \mu^-$ cross section
$\sigma_{Z \rightarrow l^+ l^-}^{\text{fid}}$	$\sigma_{Z \rightarrow l^+ l^-}^{\text{tot}}$	$Z \rightarrow l^+ l^-$ cross section (e, μ combined)
$\sigma_{W^+ \rightarrow e^+ \nu_e}^{\text{fid}} / \sigma_{W^+ \rightarrow \mu^+ \nu_\mu}^{\text{fid}}$		W^+ lepton universality ratio
$\sigma_{W^- \rightarrow e^- \bar{\nu}_e}^{\text{fid}} / \sigma_{W^- \rightarrow \mu^- \bar{\nu}_\mu}^{\text{fid}}$		W^- lepton universality ratio
$\sigma_{W \rightarrow e \nu_e}^{\text{fid}} / \sigma_{W \rightarrow \mu \nu_\mu}^{\text{fid}}$		$W^\pm$ lepton universality ratio
$\sigma_{Z \rightarrow e^+ e^-}^{\text{fid}} / \sigma_{Z \rightarrow \mu^+ \mu^-}^{\text{fid}}$		Z lepton universality ratio
$\sigma_{W \rightarrow \ell \nu_\ell}^{\text{fid}} / \sigma_{Z \rightarrow l^+ l^-}^{\text{fid}}$		$W^\pm$ to Z cross section ratio (both charges, e, μ combined)
$\sigma_{W^+ \rightarrow \ell^+ \nu_\ell}^{\text{fid}} / \sigma_{W^- \rightarrow \ell^- \bar{\nu}_\ell}^{\text{fid}}$		W^+ to W^- cross section ratio (e, μ combined)

Table 4.1: Measurements reported in early-2015 $W^\pm, Z$ inclusive cross section analyses. σ^{tot} are total inclusive cross sections. σ^{fid} are fiducial cross sections, measured within a restricted kinematic phase space (Table 4.2). Results are presented and compared to theory predictions in Section 4.6.

and the total integrated luminosity of the dataset ($\mathcal{L}_{\text{lumi}}$), according to Equation 4.1.

$$\begin{aligned}\sigma_{W,Z}^{\text{fid}} &= \frac{N_{W,Z}^{\text{data selected}} - B_{W,Z}}{C_{W,Z} \cdot \mathcal{L}} \\ C_{W,Z} &= \frac{N_{W,Z}^{\text{reco. selected}}}{N_{W,Z}^{\text{truth fiducial}}}\end{aligned}\tag{4.1}$$

$C_{W,Z}$ is the experimental selection efficiency within our fiducial volume. This is measured for each channel in fully simulated and reconstructed signal Monte Carlo as the ratio of the number of events passing our data selection (Tables ??) to the total number of events which satisfy the truth-level fiducial definition.

The event selection algorithms are detailed in Section 4.2 and in Tables 4.4 and 4.6. The various methods of estimating the background yields are detailed in Section 4.4. The measured value and uncertainty on the integrated Luminosity are provided by a dedicated ATLAS Luminosity Working Group.

Extrapolation from fiducial to total inclusive cross sections (σ^{tot}) is calculated from the corresponding fiducial cross section (σ^{fid}), and the fiducial acceptance ($A_{W,Z}$), as in Equation 4.2.

$$\begin{aligned}\sigma_{W,Z}^{\text{fid}} &= A_{W,Z} \cdot \sigma_{W,Z}^{\text{tot}} \\ A_{W,Z} &= \frac{N_{W,Z}^{\text{fiducial}}}{N_{W,Z}^{\text{total}}}\end{aligned}\tag{4.2}$$

The fiducial acceptance $A_{W,Z}$ is the efficiency of the experimental fiducial phase space relative to the total kinematic phase space for signal events. This is measured in generator-level signal Monte-Carlo samples as the fraction of all events falling within the fiducial acceptance (Table 4.2). The common lepton kinematic

	$W \rightarrow \ell \nu_\ell$	$Z \rightarrow l^+ l^-$
leptons	$p_T^\ell > 25 \text{ GeV}$ $ \eta^\ell < 2.5$	
event	$p_T^\nu > 25 \text{ GeV}$ $m_T^{\ell\nu} > 50 \text{ GeV}$	$66 < m_{\ell\ell} < 116 \text{ GeV}$

Table 4.2: Event-level fiducial definitions used in the evaluation of $A_{W,Z}$ and $C_{W,Z}$. All kinematic variables are evaluated at Born-level, prior to the potential emission of final-state photon radiation. $m_{\ell\ell}$ and $m_T^{\ell\nu}$ are calculated from the lepton momenta according to Equation 4.3.

criteria maximize correlations of uncertainties on A_W across analysis channels. The missing-energy cut, which stands in for the p_T of the neutrino in the $W^\pm$ channels, mirrors the electron p_T requirement. The m_T^W region is chosen to optimize signal/background yields. In the Z channel, $m_{\ell\ell}$ isolates a region of the Z/γ^* interference (Figure 1.2) dominated by the Z peak. Equations for the $W^\pm$ transverse mass (m_T^W) and the Z dilepton invariant mass ($m_{\ell\ell}^Z$) with which the fiducial and experimental acceptances are defined are given in Equation 4.3. When m_T^W is calculated in reconstructed physics data, the value of missing transverse energy $\cancel{E}_T$ is used for p_T^ν .

$$\begin{aligned}
m_{\ell\ell} &= \sqrt{2m_\ell^2 + 2E_1 E_2 (1 - \beta_1 \beta_2 \cos \theta_{12})} \approx \sqrt{2E_1 E_2 (1 - \cos \theta_{12})} \\
m_T^{\ell\nu} &= \sqrt{2p_T^\ell p_T^\nu [1 - \cos(\Delta\phi_{\ell\nu})]}
\end{aligned} \tag{4.3}$$

Due to finite detector resolution in the fiducial variables, the possibility exists that some reconstructed events lying just outside the event-level fiducial acceptance can pass the signal selection. This effect was evaluated and found to be a

negligible effect on the value of $C_{W,Z}$.

The W^+ , W^- and Z measurements are performed in as coherent a manner as practical, with identical signal lepton selections and within the same dataset. This maximizes the cancellation of several leading uncertainties (especially luminosity and lepton identification efficiencies) in cross section ratios. Ratios are taken between cross sections evaluated in the restricted fiducial phase space, in order to avoid uncertainties on extrapolation ($A_{W,Z}$) from the detector/selection acceptance to the total physical phase space.

4.2 Event Selection

The selection cuts applied to data and fully reconstructed Monte-Carlo simulation are shown in Tables [4.3](#), [4.4](#), [4.5](#), and [4.6](#).

4.2.1 Trigger Selection

The ATLAS trigger system for Run-2 is described in Section [3.2.13](#). The L1 trigger required in the electron channels promotes events with primitive LArCal clusters of $p_T > 20$ GeV to HLT. The HLT electron trigger applies the full offline electron reconstruction and calibration algorithm described in Section [3.3.3](#), and writes the event if any electron in the event fulfills Medium identification, $p_T^e > 24$ GeV, gradient isolation, and additional loose identification criteria. It will also write events with a Medium identification electron of $p_T^e > 60$ GeV, irrespective of isolation.

In the muon channels, events with L1 Muon Spectrometer segments of $p_T^\mu > 15$ GeV are promoted to HLT. At HLT, offline-reconstructed muons fulfilling Medium identification criteria, $p_T^\mu > 20$ GeV and loose isolation are written out. If $p_T^\mu >$

	e	μ
L1	$p_T^{EMclus} > 20 \text{ GeV}$	$p_T^{MStrk} > 15 \text{ GeV}$
HLT	$p_T^e > 24 \text{ GeV}$	$p_T^\mu > 20 \text{ GeV}$
	loose isolation	loose isolation*
	Likelihood ID Medium	Medium ID
	OR	OR
	$p_T^e > 60 \text{ GeV}$	$p_T^\mu > 50 \text{ GeV}$
	Likelihood ID Medium	Medium ID

Table 4.3: Trigger selection. Trigger instrumentation and algorithms are described in Section 3.2.13. Supplementary trigger feeds were also employed for the selection of multijet background templates, as described in Section 4.4.2. *Due to a bug in ATLAS trigger firmware, the HLT loose isolation requirement was not enforced in the muon channel for more than 90% of this dataset.

50 GeV, the isolation criterion is not enforced.

The loose isolation criteria at HLT are approximately fully efficient with respect to the offline gradient isolation cut applied to leptons. For our purposes, the loose HLT isolation only reduces the trigger frequency/bandwidth below levels which allow it operate without prescaling.

Supplementary trigger feeds were also employed in the selection of data templates for the multijet background in the $W \rightarrow e\nu_e$ channels. These are detailed in Section 4.4.2. Due to a bug in the ATLAS trigger firmware in early Run-2, the HLT loose isolation in the muon trigger was not enforced for more than 90% of the data used in these measurements. This did not create any problems, and in fact came in handy. The trigger bug allowed data-driven multijet background templates in the $W \rightarrow \mu\nu_\mu$ channel to be selected from the same unprescaled trigger feed as signal events. The electron channels were not so lucky, and had to

e	μ
ID Medium	
gradient isolation	
$p_T^\ell > 25 \text{ GeV}$	
$ \eta^e < 2.47$	$ \eta^\mu < 2.4$
$ \eta^e \notin (1.37, 1.52)$	

Table 4.4: Signal lepton selection. The cut on $|\eta^\ell|$ corresponds to the Pixel Detector barrel coverage. The cut on $|\eta^\mu|$ corresponds to the Muon Spectrometer L1 trigger coverage. The $|\eta|$ region (1.37, 1.52) corresponds to the transition region between the EM Calorimeter barrel and end-caps, which is relatively poorly instrumented.

construct multijet data templates from prescaled support triggers (Section 4.4.2).

4.2.2 Lepton Selection

The lepton selection criteria applied to data and Monte-Carlo events are given in Table 4.4. The Medium lepton identification criteria are described in Sections 3.3.3 and 3.3.4. The $|\eta^\ell|$ cuts ensure that the leptons are reconstructed in well-instrumented regions of the detector. The identification criteria are called “Medium” in both the electron and muon cases, though the identification algorithms differ. Lepton identification discriminates against electrons and muons reconstructed erroneously from lepton-like structures in the detector data, and against real leptons from non-prompt sources like electroweak decays within hadronic showers and $\gamma \rightarrow e^+e^-$ pair conversion.

Gradient isolation (described in Section 3.3.3) ensures that the signal leptons are well-separated from hadronic jet activity. Lepton gradient isolation is essential to the early-2015 top quark event selection, and it was included in the $W^\pm$,

	good	bad
reconstruction	anti- $k_t(0.4)$, EM/Topo jets	
p_T^{jet}	$p_T^{\text{jet}} > 20 \text{ GeV}$	
vertex association	$\text{JVT}_{\text{PV}}^{\text{jet}} > 0.64$	
badness	!LooseBad	LooseBad

Table 4.5: Definition of jets for $\cancel{E}_T$ calculation and lepton-jet Overlap Removal. The jet definition is uniform for all six analysis channels. Descriptions of Jet reconstruction (anti- $k_t(0.4)$, EM/Topo) and vertex association (JVT), and badness (LooseBad) are given in Section 3.3.

Z analyses to ensure consistency in lepton selections among early-2015 measurements, with an eye towards facilitating precision ratios among $W^\pm$, Z , and Top cross sections. $W^\pm$ or Z decays at rest would produce leptons of total momentum 40 GeV or greater. The cut $p_T^\ell > 25 \text{ GeV}$ is optimized for the predicted transverse decay kinematics of $W^\pm$ and Z bosons.

The signal lepton counting requirements are strict, not minimal. In the rare case of additional signal leptons in an event, the event is simply rejected, to obviate any uncertainty arising from ambiguity resolution.

4.2.3 Event Selection

All events are required to come from Luminosity Blocks recorded on ATLAS Good Runs Lists (GRL) reflecting full and stable operation of the detector with no significant abnormalities in performance.

A well-reconstructed ($n_{\text{track}} > 2$) primary vertex is required for the calculation of the $\cancel{E}_T$ Track Soft Term (TST, Section 3.3.6) as well as for the Jet Vertex Tagging (JVT) discriminant used to identify jets entering the $\cancel{E}_T$ hard term, and for the muon-jet overlap removal procedure (Table 4.7).

	W	Z
data	ATLAS Good-Runs List (GRL)	
trigger	Table 4.3	
signal leptons	e or μ	e^+e^- or $\mu^+\mu^-$
event	$N_{PrimaryVertex} > 0$	
	0 “bad” Jets	
	ℓ -jet Overlap Removal	
	$\cancel{E}_T > 25 \text{ GeV}$ $m_T^{\ell\nu} > 50 \text{ GeV}$	$66 < m_{\ell\ell} < 116 \text{ GeV}$

Table 4.6: Boson selection. The selection criteria for signal leptons are given in Table 4.4. Jets (both good and bad) used in the event selection, overlap removal, and $\cancel{E}_T$ calculation are defined in Table 4.5. In the $W \rightarrow e\nu_e$ channel, electrons overlapping jets within $\Delta R < 0.4$ are subjected to Overlap Removal (OR) according to the procedure in Table 4.7. $m_T^{\ell\nu}$ and $m_{\ell\ell}$ are calculated with Equations 4.3. In data and fully reconstructed Monte-Carlo selections, value of $\cancel{E}_T$ is used for p_T^ν in the calculation of m_T^W (Equation 4.3).

	e	μ	
		$n_{jet}^{trk} < 2$	$n_{jet}^{trk} \geq 2$
$\Delta R < 0.2$	remove jet	remove jet	remove μ
$0.2 < \Delta R < 0.4$	remove e		
$\Delta R > 0.4$	no overlap removal		

Table 4.7: Lepton-Jet overlap removal (OR) procedure. Candidate jets are defined in Table 4.5. Candidate leptons are defined in Table 4.4.

The lepton-jet overlap removal procedure is applied for the sake of consistency with the $\cancel{E}_T$ calculation, provided via ATLAS CP software tools. Without applying lepton-jet overlap removal according to the ATLAS $\cancel{E}_T$ CP prescription prior to calculation of $\cancel{E}_T$, the $\cancel{E}_T$ CP software can occasionally reconstruct missing energy from objects not as specified by the $W^\pm/Z$ analysis selection.

In the $W^\pm$ channel, the cut $\cancel{E}_T > 25$ GeV is consistent with the lepton p_T cut. $\cancel{E}_T$ is calculated as described in Section 3.3.6, using the Track Soft Term, and including all leptons and jets as defined in Tables 4.4 and 4.5 in the hard-object sum. The requirement $m_T^{\ell\nu} > 50$ GeV incorporates information about the event kinematics, including azimuthal separation of the lepton and missing energy. The cut was raised from 40 to 50 GeV early in the analysis in order to capitalize on this variable’s discrimination against QCD multijet background.

Contamination from background processes in the Z channel is inherently very low due to the distinctive and experimentally clean final state. The coincidence of backgrounds to two opposite-sign, same-flavor, isolated high- p_T leptons is estimated at just 1% of the total Z selection yield. The reconstructed dilepton invariant mass window $66 < m_{\ell\ell} < 116$ GeV isolates a region of the Z/γ^* invariant mass distribution which is dominated by the Z resonance.

4.3 Data and Monte-Carlo Samples

Because the $W \rightarrow \ell \nu_\ell$ and $Z \rightarrow l^+ l^-$ cross sections are predicted to be quite high in 13 TeV proton-proton collisions (approximately 20 and 2 nb^{-1} in each leptonic final state, respectively), these measurements were accessible with just a few weeks of LHC Run-2 data at relatively low instantaneous luminosity (Figure 4.1). The data were recorded between June 13 and July 16, 2015. The proton beams circulated at full Run-2 design energy of 6.5 TeV per beam ($\sqrt{s} = 13 \text{ TeV}$). The proton bunch crossing rate was 20 MHz (50 ns/crossing), half the nominal Run-2 value of 40 MHz (25 ns/crossing). The number of occupied bunches, as well as the charge per bunch, were also limited in order to study the accelerator behavior as the instantaneous luminosity was increased gradually. The maximum instantaneous luminosity from the runs included in this dataset was $1.72 \cdot 10^{33} \text{ cm}^{-2} \text{ s}^{-2}$. The mean average pileup in these data was approximately $\langle \mu \rangle = 19$.

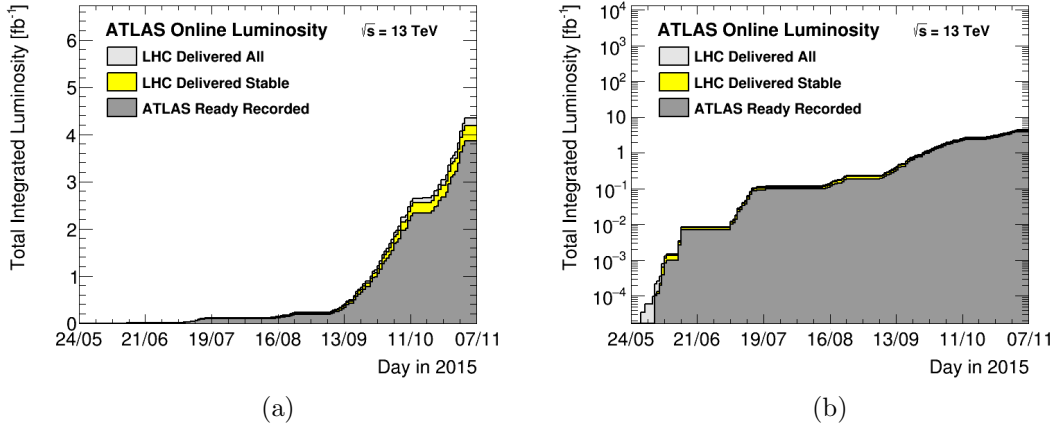


Figure 4.1: LHC and ATLAS integrated luminosity versus time, (a) linear scale, and (b) log scale, for 2015. Data used in these measurements were taken between June 13 and July 16, 2015, and amounted to a total of $[81 \pm 4] \text{ pb}^{-1}$.

The useful ATLAS data approved for physics analysis from this period amounted

to 81 inverse picobarns (pb^{-1}), with an uncertainty on the luminosity measurement of 5% (4pb^{-1}). Before accounting for detector acceptance, reconstruction efficiency, selection efficiency, or background, there would be expected to be about 1.62 million $W \rightarrow e\nu_e$ events, the same number of $W \rightarrow \mu\nu_\mu$ events, and about 162,000 events in each of the $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$ channels.

Special samples of fully-simulated and reconstructed ATLAS Monte-Carlo data were produced for 50 ns analyses, with detector simulation and reconstruction parameters defined to approximate the exceptional accelerator profile (low beam crossing rate and pileup conditions) in the early-2015 run. These samples are described collectively as the “50 ns reconstruction” or the “50 ns reprocessing” campaign. Single-vector-boson signal and background processes were simulated at next-to-leading-order (NLO) precision using the POWHEG BOX event generator software.[109–112] Hadronization and showering subsequent to primary event generation was simulated in these samples with Pythia8 software.[113] Electroweak backgrounds including Top quarks ($t\bar{t}$, Wt , t) were also generated at event-level with POWHEG BOX,[114] but showered using Pythia 6.[115] Diboson samples (ZZ , WZ) in all hadronic and leptonic final states were simulated and showered with Sherpa version 2.1.1.[116] Heavy-flavor dijet samples ($b\bar{b}$, $c\bar{c}$), used in early estimates of the $W \rightarrow \mu\nu_\mu$ multijet contamination, were generated and showered with Pythia8B. In-time soft pileup events were simulated with Pythia 8, and overlaid prior to the GEANT-ATLAS simulation and reconstruction [117, 118], according to a generic pileup distribution, with the expectation that client analyses would reweight the Monte-Carlo data according to observed pileup distributions.

4.3.1 Scale Factors and Reweighting

Monte-Carlo events used in these measurements were reweighted according to measured distributions of several parameters to which the cross section results are sensitive. Some of these distributions were simply not known precisely when the Monte-Carlo was generated, while others exhibited measurable biases when compared to data. These include the pileup conditions of the collision runs, efficiency of the chosen triggers to fire on signal events, and the efficiency of the offline reconstruction and identification algorithms to identify fiducial leptons.

4.3.1.1 Trigger Efficiency

The data readout triggers used in these measurements (Table 4.3) are not fully efficient for signal events which would otherwise pass the signal selection. The trigger efficiency is also nonuniform in lepton kinematic variables. In particular, the L1 electron triggers, which operate with worse energy resolution than the full electron reconstruction, exhibit a noticeable “turn-on” behavior at p_T^e near the lower limit of the offline selection acceptance. Muon triggers have nonuniform response in angular coordinates (η, ϕ) , due to irregularities in the muon barrel trigger hardware.

To correct for the inefficiencies and nonuniformities of the trigger responses, Monte-Carlo events were reweighted in lepton kinematic variables $(\eta^e, p_T^e, \eta^\mu, \phi^\mu)$ to match the measured trigger efficiencies for leptons. This is simple in the $W^\pm$ selection, for which there is only one lepton per signal event which could fire the trigger. The reweighting in the Z channel had to account for the fact there were two leptons in each event, either of which could fire the selected single-lepton trigger. The formula used to reweight $Z \rightarrow l^+l^-$ events based on the measured

single-lepton trigger efficiencies $\epsilon_1(\ell)$ is given in Equation 4.4, where ℓ represents the lepton kinematic variables in which the efficiency was measured, ϵ_1 is the trigger efficiency for a single lepton, ϵ_2 is the trigger efficiency for two same-flavor leptons in the same event, and SF is the data/Monte-Carlo trigger efficiency scale factor.

$$\begin{aligned}
SF_2(\ell_1, \ell_2) &= \frac{\epsilon_2^{\text{data}}(\ell_1, \ell_2)}{\epsilon_2^{\text{MC}}(\ell_1, \ell_2)} \\
\epsilon_2(\ell_1, \ell_2) &= 1 - ([1 - \epsilon_1(\ell_1)][1 - \epsilon_1(\ell_2)]) \\
&= \epsilon_1(\ell_1) + \epsilon_1(\ell_2) - \epsilon_1(\ell_1)\epsilon_1(\ell_2).
\end{aligned}
\tag{4.4}$$

The probabilities to trigger on either lepton are assumed to be uncorrelated. While some correlation could, in principle, arise from detector effects, any such correlation are expected to be very small. This model accurately reproduces the distributions in data, as will be seen in the kinematic distributions in Section 4.6.2.

The single-lepton trigger efficiencies ($\epsilon_1(\ell)$) are measured in data and Monte-Carlo via the “tag-and-probe” method. $Z \rightarrow l^+l^-$ samples are defined with the signal selection described in Section 4.2. The $Z \rightarrow l^+l^-$ selection guarantees an extremely pure collection of fiducial lepton pairs. Because the signal selection only requires that one daughter lepton (the “tag”) fire a signal trigger, the fraction of events in which the second lepton (the “probe”) *also* fires a trigger is an independent measurement of the single-lepton trigger efficiencies.

The electron trigger efficiencies were measured in bins of p_T^e and η^e , while the muon trigger efficiencies were binned in η^μ and ϕ^μ . The 2-dimensional maps of scale factors applied to Monte-Carlo are shown in Figure 4.2.

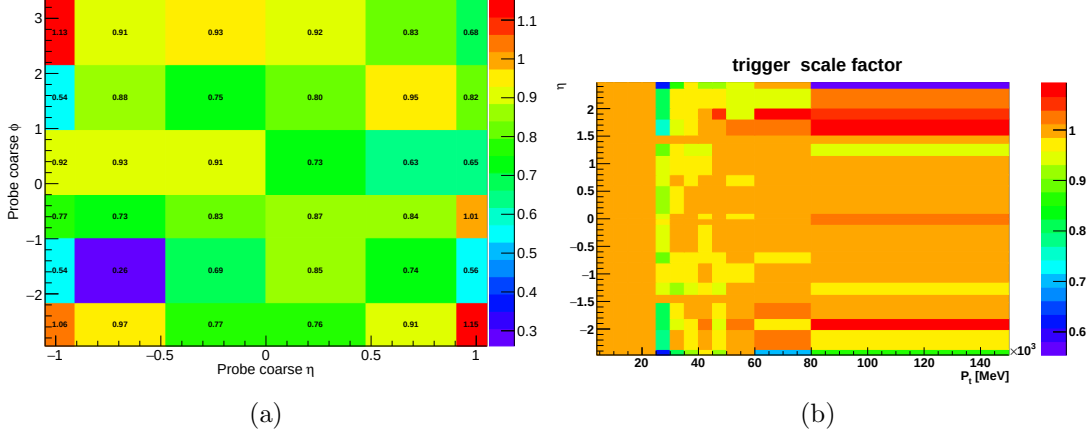


Figure 4.2: Data/Monte-Carlo scale factors for (a) electron, and (b) muon trigger efficiencies.

4.3.1.2 Lepton Reco/ID/Isolation Efficiency

Scale factors for the single-lepton reconstruction and identification efficiencies were provided through the electron and muon CP software interfaces. Offline efficiencies are measured similarly to trigger efficiencies, via tag-and-probe analysis in data using $Z \rightarrow l^+l^-$, $J/\Psi \rightarrow \ell^+\ell^-$, and $W \rightarrow e\nu_e$ selections.

As with the trigger efficiencies, the single-lepton reco/ID efficiency $\epsilon_{\text{reco}}(\eta^\ell, p_T^\ell)$ must be converted to a dilepton reco/ID scale factor for the Z channel. Whereas the trigger condition was *either* lepton, the ID condition is *both*. The Z selection lepton ID scale factor is shown in Equation 4.5.

$$SF_{\text{ID2}}(\ell_1, \ell_2) = \frac{\epsilon_{\text{ID2}}^{\text{data}}(\ell_1, \ell_2)}{\epsilon_{\text{ID2}}^{\text{MC}}(\ell_1, \ell_2)}$$

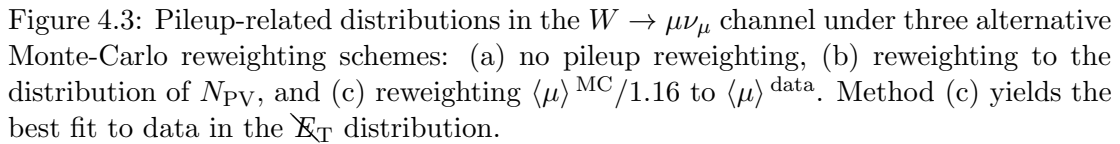
$$\epsilon_{\text{ID2}}(\ell_1, \ell_2) = \epsilon_{\text{ID1}}(\ell_1)\epsilon_{\text{ID1}}(\ell_2) \quad (4.5)$$

4.3.1.3 Pileup

Monte-Carlo events were reweighted so that the pileup distribution in Monte-Carlo matches the distribution in data. The motivation of this reweighting is to produce an accurate model for $\cancel{E}_T$ distributions, which are sensitive to pileup. Accurate modeling of $\cancel{E}_T$ is essential, as the multijet background contribution is extracted in part from fits to the measured $\cancel{E}_T$ distributions. $\cancel{E}_T$ is also an input to the calculation of m_T^W (Equation 4.3), upon which the $W^\pm$ boson event selection criteria depend.

There are two primary measures of pileup activity, the average pileup per luminosity block $\langle\mu\rangle$, and the number of reconstructed primary vertices per event, denoted N_{PV} . $\langle\mu\rangle$ is calculated for each luminosity block from the total luminosity of the block measured during the run by LHC divided by the number of beam crossings. N_{PV} is a simple count of the number of primary vertices reconstructed (as described in Section 3.3.2) in the event. Every event has a value both of $\langle\mu\rangle$ and N_{PV} . N_{PV} values are in general unique to each event. All events from a single luminosity block have the same value of $\langle\mu\rangle$. The $\cancel{E}_T$ reconstruction performance is sensitive to both values, as can be seen in Figure 4.3.

The MC15a (50 ns reprocessing) Monte-Carlo campaign employed a generic $\langle\mu\rangle$ distribution, with the expectation that physics analyses would reweight events to match the $\langle\mu\rangle$ distributions observed in data. $\langle\mu\rangle$ and N_{PV} are correlated, and the relation between them in the MC15a Monte-Carlo samples did not accurately reflect the distributions observed in the early-2015 50 ns dataset. Because the relation between $\langle\mu\rangle$ and N_{PV} in the MC15a samples was fixed at the per-event level at simulation-time, it is impossible to exactly reweight the Monte-Carlo events in both variables simultaneously. Since $\cancel{E}_T$, and by extension m_T^W , are sensitive to



both $\langle\mu\rangle$ and N_{PV} distributions, serious mismodeling in either parameter can be catastrophic for the quality of fits performed in these distributions.

The Monte-Carlo pileup reweighting procedure employed in these measurements represents a compromise between matching the $\cancel{E}_{\text{T}}$ and N_{PV} distributions observed in data. Events were reweighted so that the distribution of the quantity $\langle\mu\rangle^{\text{MC}}/1.16$ exactly matched the distribution observed in data of $\langle\mu\rangle^{\text{data}}$. Conceptually, the factor $1/1.16$ represents an estimate of the degree to which the proportionality between $\langle\mu\rangle$ and N_{PV} was mis-modeled in the MC15a campaign. The value $1/1.16$ was recommended by the ATLAS $\cancel{E}_{\text{T}}$ CP group, based on studies of $\cancel{E}_{\text{T}}$ fit quality under several different reweighting schemes. As Figure 4.3 shows, reweighting based on a scaled value of $\langle\mu\rangle$ represents a compromise between exact reweighting in either variable. Of the three possible schemes compared explicitly for this analysis, this method best reproduces the $\cancel{E}_{\text{T}}$ and m_{T}^W distributions observed in data.

Systematic error on the final measurements due to uncertainties associated with this reweighting procedure were assessed for the $W^{\pm}$ channel measurements. The results and methods by which these uncertainties were assessed are described in Section 4.5.13.

4.3.1.4 p_{T}^Z (not applied)

The effect of reweighting Z -channel Monte-Carlo samples to reproduce the p_{T}^Z distribution observed in data was investigated. The cumulative effect on Z cross sections was determined to be at or below the 0.01% level, which is substantially below the precision on central values and the overall level of systematic uncertainty on these measurements. Because the p_{T}^Z reweighting was determined to have no practical effect, the reweighting was not applied to Monte-Carlo events in the final

measurements.

4.4 Background Estimation

The estimated contributions of each explicitly-evaluated background process to the data selection yield ($B_{W,Z}$) are shown in Table 4.8. The $W \rightarrow \ell\nu_\ell$ and $Z \rightarrow l^+l^-$ analyses benefit from high signal purity overall (approximately 94% and 99%, respectively). Negligible backgrounds are neglected. Dominant backgrounds sort generally into three types: single-boson electroweak, top, and multijet. Single-boson and Top backgrounds are modeled with Monte-Carlo simulations, normalized to the best available NNLO predictions. Multijet contamination in the $W^\pm$ channels is estimated with data-driven methods, via interpolation among fits to distributions in several sideband selections. These backgrounds, and the methods used to estimate their contribution to data selection yields, are described in greater detail in the following sections.

4.4.1 Electroweak Backgrounds

The advanced and experimentally verifiable precision of Standard-Model electroweak Monte-Carlo models enables us to derive background predictions for these processes directly from simulation. Electroweak backgrounds to leptonic $W^\pm$ and Z decays include $W \rightarrow \tau\nu_\tau$, $Z \rightarrow \tau^+\tau^-$, $t\bar{t}$, Wt , W^+W^- , ZZ , and WZ . The Z -channel signal processes $Z \rightarrow e^+e^-$, and $Z \rightarrow \mu^+\mu^-$ were also evaluated as backgrounds to $W \rightarrow e\nu_e$ and $W \rightarrow \mu\nu_\mu$, respectively. The kinematic distributions of interest for these processes have been well-modeled in Monte-Carlo simulations in past experiments, including LHC Run-1 at 7 and 8 TeV. The 13 TeV cross sections to which the simulations are normalized are predicted at NLO or

	channel					
	$e^+\nu_e$	$e^-\bar{\nu}_e$	$\mu^+\nu_\mu$	$\mu^-\bar{\nu}_\mu$	e^+e^-	$\mu^+\mu^-$
data	256,858	206,092	266,592	208,616	35,009	44,898
multijet	21,873	21,014	7149	7199	0	0
$W^+ \rightarrow \tau^+\nu_\tau$	4072	19	4917	-	-	
$W^- \rightarrow \tau^-\bar{\nu}_\tau$	20	3318	-	3939		
$Z \rightarrow \tau^+\tau^-$	318	306	565	558	1	2
diboson	188	196			4	6
single-t	534	402	2551	2431	-	
$t\bar{t}$	2097	2101			8	11
$W^+ \rightarrow e^+\nu_e$	signal	1281	-		0	-
$W^- \rightarrow e^-\bar{\nu}_e$	906	signal				
$W^+ \rightarrow \mu^+\nu_\mu$	-		signal	-	-	0
$W^- \rightarrow \mu^-\bar{\nu}_\mu$			-	signal		
$Z \rightarrow e^+e^-$	2397	2325	-		signal	-
$Z \rightarrow \mu^+\mu^-$	-		11280	10413	-	signal

Table 4.8: Estimated selection yields (in events) of each substantial background process, per analysis channel. The event selection yields in data are given on the top row for comparison. Values in combined cells are sums of the cells. “-” indicates that a background was taken to be negligible in a particular channel. All backgrounds not listed are taken to be negligible. Estimated relative backgrounds to W^+ and W^- selections are approximately equal. An uncertainty on e charge misidentification, which could alter the relative background fractions of W^+ and W^- , is described in Section 4.5.10. Uncertainties on background contributions are described in Section 4.5 and summarized in Table 4.10

NNLO.

The $W^\pm$ and Z final states are inherently distinctive, and with large cross sections that afford the luxury of aggressive event selection cuts. Significant electroweak backgrounds tend to include real leptonic $W^\pm$ or Z bosons.

4.4.1.1 $W \rightarrow \tau\nu_\tau$

$W \rightarrow \tau\nu_\tau$ events in which the τ decays leptonically ($W \rightarrow \tau\nu_\tau \rightarrow \nu_\tau\nu_\tau\nu_\ell\ell$) constitute irreducible backgrounds to the respective $W \rightarrow \ell\nu_\ell$ selections. The common final-state detector signature is an isolated e or μ , plus missing energy. Lepton universality in vector-boson decays dictates that the branching fraction of $W^\pm$ bosons to τ leptons should be equal to the electron and muon branching fractions. The potential contamination is reduced by the leptonic branching fraction of τ decays (about 0.17 for the muonic decay, and 0.18 for the electronic).[5]

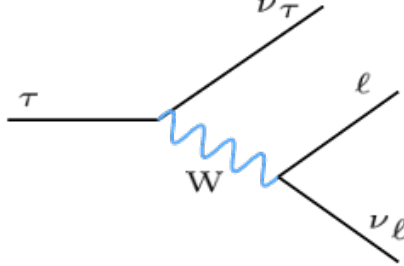


Figure 4.4: Feynman diagram of leptonic τ decay. When the Tau is produced in a $W^\pm$ boson decay ($W \rightarrow \tau\nu_\tau$), its leptonic final states ($\nu_\tau\nu_\tau\ell\nu_\ell$) constitute a small but irreducible background to $W \rightarrow \ell\nu_\ell$.

The 3-body kinematics of leptonic τ decays also reduce the fraction of events falling within the experimental fiducial acceptance. Most commonly, the division of the daughter τ 's transverse momentum among three granddaughters ($\nu_\tau\ell\nu_\ell$) will cause the final state e or μ to fail the signal event selection cut on p_T^ℓ .

In total, the contamination from $W \rightarrow \tau\nu_\tau$ backgrounds, relative to signal

yields in data, is 1.6% in the $e\nu_e$ channel, and 1.9% in the $\mu\nu_\mu$ channel. $W \rightarrow \tau\nu_\tau$ is a negligible background to Z selections.

4.4.1.2 $Z \rightarrow l^+l^-$

$Z \rightarrow l^+l^-$ events can pass the $W \rightarrow \ell\nu_\ell$ selections if the lepton reconstruction and identification algorithms (Section 3.3) fail to identify one electron or muon. In this case, the transverse energy of the lost lepton can be reconstructed as fake $\cancel{E}_T$, imitating the final state of $W \rightarrow \ell\nu_\ell$ events. $Z \rightarrow e^+e^-$ is estimated to contribute approximately 1.0% to the data yield in the $e\nu_e$ channel. $Z \rightarrow \mu^+\mu^-$ is predicted to contribute 4.6% to the $\mu\nu_\mu$ channels. Contamination is higher in the muon channel because the efficiency to reconstruct signal muons is lower than that for electrons, and it is consequently more likely to “miss” a muon than an electron in Z decays.

4.4.1.3 $Z \rightarrow \tau^+\tau^-$

$Z \rightarrow \tau^+\tau^-$ events contribute at low rates to all four channels. In the rare case when both τ daughters decay to the same lepton flavor (about 0.7% of $Z \rightarrow \tau^+\tau^-$ decays), *and* there is sufficient momentum in the system to impart $p_T > 25$ GeV to both granddaughter leptons (likely dependent on a transverse boost of the original Z), $Z \rightarrow \tau^+\tau^-$ can fake $Z \rightarrow e^+e^-$ or $Z \rightarrow \mu^+\mu^-$. As the kinematics of either case are identical, we would expect to see approximately the same level of contamination from this background in both Z final states, and indeed we do.

$Z \rightarrow \tau^+\tau^-$ also contributes at a low rate to the $W^\pm$ channels. There are several possible ways for $Z \rightarrow \tau^+\tau^-$ to fake leptons plus missing energy. The most likely case is for one τ to decay leptonically with real $p_T^\ell > 25$ GeV. If the other τ decays hadronically, much of its transverse energy will be invisible to the

$\cancel{E}_T$ reconstruction. Calorimeter deposits of the pions are not added to the $\cancel{E}_T$ sum unless they are reconstructed in jets with $p_T^{\text{jet}} > 20 \text{ GeV}$ and associated to the event primary vertex. The Track Soft Term is blind to neutral pions, which carry a large average fraction of hadronic τ decay p_T . Another possible mechanism is hadronic τ decays faking electrons, as in the multijet background. However, if this background contained significant contributions from hadronic τ s faking leptons, we would expect the electron channel to have a higher contamination than the muon channel, which is not the case.

4.4.1.4 Diboson

Other than $t\bar{t}$, diboson processes are the only significant background to the $Z \rightarrow l^+l^-$ selection. This background integrates small contributions from a large number of distinct processes (ZZ , WW , WZ , in all permutations of charge and decay channels). The cross sections, selection efficiencies, and mechanisms of contamination vary. All contain some fraction of real electronic and muonic vector boson decays. If the associated boson is somehow not reconstructed, either through hadronic decay or lepton ID inefficiency, the final states observed in the detector can imitate single-boson decay.

4.4.1.5 Top

$t\bar{t}$ events constitute the largest background (at 0.02% in both lepton channels, still quite small) to the Z selections. $t\bar{t}$ contamination in the Z channels works similarly to diboson backgrounds, because nearly every $t\bar{t}$ event decays to two $W^\pm$ bosons plus two b-quark jets. If the $W^\pm$ s decay to same-flavor leptons, the p_T of the associated neutrinos will tend to balance. The jets have little effect on the Z selection, as long as they do not overlap a lepton. These are more hurdles for

$t\bar{t}$ to jump than dibosons in order to pass the Z selection, but the higher cross section at 13 TeV compared to multiboson processes makes $t\bar{t}$ the dominant Z background.

$t\bar{t}$ is also a significant contributor to $W^\pm$ backgrounds. Permutations of the $W^\pm$ decay channels can produce real leptonic $W^\pm$ s, in association with hadronic jets which may or may not balance the leptonic $W^\pm$'s real $\cancel{E}_T$ through the Track Soft Term.

Single-top backgrounds include Wt and QCD single-top processes. Wt contributes to the signal selection yield similarly to $t\bar{t}$ and diboson backgrounds. QCD single-top processes include real leptonically decaying $W^\pm$ bosons. Single-top events are negligible as backgrounds to Z , since the QCD single-top decay contains at most one real isolated lepton.

All top-quark backgrounds contribute approximately 0.57% in the $W \rightarrow e\nu_e$ channels, and 0.53% in the $W \rightarrow \mu\nu_\mu$ channels.

4.4.2 Multijet Backgrounds

Hadronic processes, also called “QCD” and “multijet” events, are the most significant background to the $W^\pm$ boson selection in both the e (9.3%) and μ (3.0%) channels. Weak decays of boosted heavy hadrons can produce real high- p_T electrons and muons. Rarely, hadronic jets can fake electrons by depositing a large fraction of the jet’s energy in an uncharacteristically tight EM calorimeter cluster. At this level of background, photon conversions ($\gamma \rightarrow e^+e^-$) faking single electrons have to be considered, as well. When these fake leptons coincide with significant instrumental $\cancel{E}_T$, they can contaminate the $W \rightarrow \ell\nu_\ell$ selection.

In the context of QCD processes, these conditions are rare, manifesting in just

a tiny fraction of multijet events. The multijet cross section in LHC collisions is so high, however, that even the most implausible jet mis-reconstruction scenarios are explored thoroughly. Even so, the likelihood of *two* such cases coincidentally faking same-flavor, opposite-sign leptons within the Z selection acceptance is negligible. Multijet processes are therefore only evaluated as backgrounds to the $W^\pm$ selections.

Jets and photons faking electrons are considerably more common than fake muons, and the multijet contamination in the $W \rightarrow e\nu_e$ selection is proportionally higher than in the $W \rightarrow \mu\nu_\mu$ channel. This is also the primary culprit for larger uncertainties in the $e\nu_e$ channel, since uncertainties on multijet normalizations are leading contributions to $W^\pm$ cross section errors (Section 4.5).

Estimation of multijet backgrounds is an art unto itself, because no verifiably accurate predictions are available from which to simulate Monte-Carlo data. The multijet background is a heterogeneous catch-all of similar, but distinct, processes which are difficult to model or study precisely. Process composition, normalization, and kinematic distributions of the multijet background are all sensitive to poorly constrained parameters of strong interaction theory, hadronization models, and proton PDFs. These parameters all suffer large theoretical and experimental uncertainties due to the complexity of QCD theory calculations and the challenge of studying hadronic final states experimentally. For this reason, the multijet background is estimated with a data-driven “top-down” approach (contrasted to the electroweak background models constructed “bottom-up” from event-level simulation).

4.4.2.1 Method Summary

Ensembles of independent, multijet-enriched control regions are defined in lepton isolation variables $p_T^{\text{cone}}(\Delta R)/p_T$ and $E_T^{\text{cone}}(\Delta R)/p_T$, which progressively approach the signal definition. Data distributions of several kinematic variables with some multijet-signal shape discrimination are extracted from each lepton isolation control region. Template renormalizations for the signal region are then fit from data in an extended signal region to obtain scale factors useful to translate the control region multijet yields to the signal region.

Estimates of multijet contributions to the signal region in data are extrapolated from trends through control regions of the many individual multijet yield estimates. The extrapolation is performed with two different multijet data template definitions, two different isolation variables, and four different kinematic fit variables. The method is somewhat elaborate, but it crucially does not rely on the accuracy of QCD event simulations.

4.4.2.2 Data Template Definitions

Two multijet-enriched data templates are defined by the $W \rightarrow \ell\nu_\ell$ signal event selection in Section 4.2, with the following changes:

- The requirement of lepton gradient isolation is inverted.
- The cut on (a) m_T^W or (b) $\cancel{E}_T$ is removed
- Supplementary trigger criteria are used, as described below.

The two templates defined by these selections will be called the (a) relaxed- m_T^W and (b) relaxed- $\cancel{E}_T$ templates. They will be referred to generically as the

relaxed, anti-isolated templates/selections. A few words about the motivations of these definitions:

The gradient isolation is one of the strongest discriminants against jets faking leptons available to ATLAS analyses. Inverting this selection cut defines a data sample which is expected to be enriched substantially in multijet background content. Preserving all other kinematic selection cuts keeps the kinematic distributions of the templates as close to those of the selection as possible, while still ensuring that the template samples are fully orthogonal to the signal selection.

Relaxing the m_T^W or $\cancel{E}_T$ cut provides extended kinematic regions over which to fit the multijet distributions. The region $m_T^W < 50$ GeV is especially enriched in multijet background, and adds considerable statistics and shape discrimination to the fits.

The HLT triggers chosen for the signal selection impose loose lepton isolation criteria, which are highly inefficient for the anti-isolated events with which we wish to construct our multijet templates. To obtain sufficient statistics, the multijet templates were selected with supplementary trigger conditions which did not include the lepton isolation at HLT. This was simple in the muon channel, where more than 90% of the data was accidentally triggered without the loose HLT isolation cut. The data sample for the muon multijet templates was simply the subset of signal trigger data for which the HLT isolation was absent.

The supplementary electron HLT trigger had higher intrinsic rate, and was prescaled by as much as 1/7 to regulate its readout bandwidth consumption. This leads to limited sample sizes for the electron multijet templates, and substantial statistical uncertainties. The evaluation of uncertainties on the multijet background estimations are described in Section 4.5.5.

The supplementary electron trigger also had a lower L1 EM cluster p_T thresh-

old, which has an efficiency turn-on curve in p_T that is distinct from the signal selection trigger. The p_T - η efficiency map for the electron multijet support trigger was measured according to the same $Z \rightarrow l^+l^-$ tag-and-probe method used for the signal triggers (Section 4.3.1.1). Hence, Monte-Carlo events used to evaluate electron multijet templates were reweighted according to the correct efficiency map of the electron-multijet support trigger.

4.4.2.3 Isolation Slices

The relaxed- m_T^W and relaxed- $\cancel{E}_T$ data templates are “sliced” on the lepton isolation variables $p_T^{\text{cone}}(\Delta R)/p_T$ and $E_T^{\text{cone}}(\Delta R)/p_T$. This isolates two ensembles of fully independent lepton isolation control regions - one with increasing $E_T^{\text{cone}}(\Delta R)/p_T$ values, and one with increasing $p_T^{\text{cone}}(\Delta R)/p_T$ values. The slicing is different for the muon and electron channels. The slices are defined in Table 4.9, and illustrated cartoonishly in Figure 4.5. The entire gradient-isolated signal region is contained in the template regions defined by the ranges on the top line.

4.4.2.4 Shape Templates

Distributions of several kinematic variables are extracted from each template slice. These distributions are chosen for their shape discrimination between $W^\pm$ signal and multijet background:

- m_T^W
- p_T^ℓ
- $\cancel{E}_T$
- $\Delta\phi(\cancel{E}_T, p_T^\ell)$

Just as the data event selections designed to isolate $W^\pm$ and Z signal events inevitably include background from multijet and other electroweak sources, the

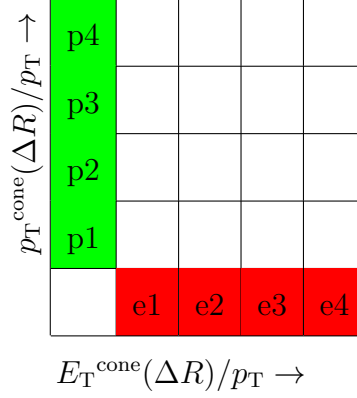


Figure 4.5: Lepton isolation slices for multijet data templates (not to scale). The 5×5 layout corresponds to isolation slicing in the electron channel. Lepton gradient isolation is a p_T/η -dependent cut within the $E_T^{\text{cone}}(\Delta R)/p_T - p_T^{\text{cone}}(\Delta R)/p_T$ plane. Hence, the signal region comprised of all events which pass the gradient isolation cut is concentrated in the bottom, left “slice,” in white. The control regions e1-4, p1-4 are defined in Table 4.9.

μ		e	
$p_T^{\text{cone}}(\Delta R)/p_T$	$E_T^{\text{cone}}(\Delta R)/p_T$	$p_T^{\text{cone}}(\Delta R)/p_T$	$E_T^{\text{cone}}(\Delta R)/p_T$
0.0 - 0.1	0.00 - 0.08	0.0 - 0.08	0.00 - 0.11
0.1 - 0.2	0.08 - 0.14	0.08 - 0.16	0.11 - 0.19
0.2 - 0.3	0.14 - 0.20	0.16 - 0.24	0.19 - 0.27
0.3 - 0.4	0.20 - 0.26	0.24 - 0.32	0.27 - 0.35
0.4 - 0.5	0.26 - 0.32	0.32 - 0.40	0.35 - 0.43
	0.32 - 0.38		
	0.38 - 0.44		

Table 4.9: Lepton isolation control region definitions. Independent control regions are defined in the plane of lepton isolation variables $p_T^{\text{cone}}(\Delta R)/p_T$ and $E_T^{\text{cone}}(\Delta R)/p_T$ by taking the first slice in one variable, and any slice except the first in the other variable. The slicing and choice of control regions is illustrated (cartoonishly) in Figure 4.9.

multijet template selection suffers contamination from the signal and other electroweak backgrounds, as well. The distributions of these variables in each isolation slice are, in principle, “stacks” of contributions from (hypothetical) pure multijet and electroweak samples.

To avoid double-counting the fractions of electroweak processes which are common backgrounds to the signal and multijet data selections, electroweak contamination must be subtracted from the multijet data slice shape templates, and eventually from the estimated signal selection yields. Signal and electroweak distributions of the four fit variables are obtained in each slice by applying the *relaxed* template selections to electroweak Monte-Carlo samples, with the respective isolation cuts for each slice.

An illustration of the shape discrimination between multijet and signal/electroweak processes in the isolation control regions is shown in Figure 4.6. The shapes shown were obtained in the obsolete procedure used to estimate multijet yields, in [108]. However, they can provide a qualitative idea of the shape discrimination between multijet and electroweak processes in the inverted-isolation templates.

While we *could* at this point obtain background-subtracted multijet shape templates by simply subtracting these electroweak Monte-Carlo distributions from data in each isolation slice, we instead postpone the background subtraction to the following step (the normalization fits). Performing the background subtraction inside the normalization fits allows us to correctly correlate the electroweak sample normalizations between signal and multijet templates.

4.4.2.5 Multijet Normalization Fits

Inputs to multijet normalization fits are defined by:

- analysis channel

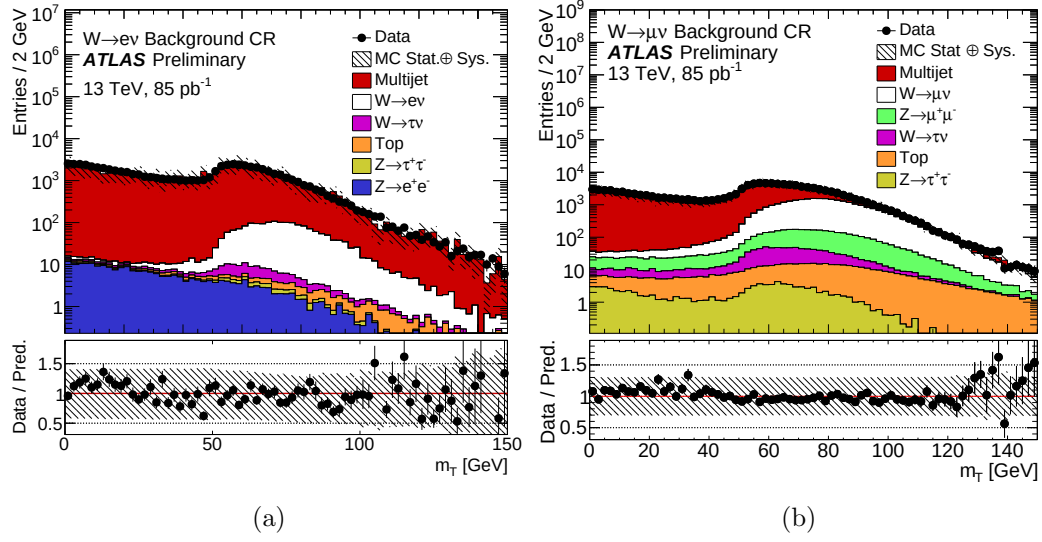


Figure 4.6: An illustration of the shape discrimination between multijet and electroweak processes in the inverted-isolation template region including our isolation slices. These plots are from an *unsliced* inverted-isolation control region used to estimate multijet contamination in an earlier version of this analysis [108], and do not correspond exactly to any of the isolation slices used in this analysis.

- relaxed- m_T^W versus relaxed- $\cancel{E}_T$
- isolation slice
- fit variable

The multijet shape templates are normalized to data using a binned maximum-likelihood fit which compares the value n^i (Equation 4.6) to the number of data events selected with the *relaxed*, *isolated* selection in each bin. i indexes the bin in the chosen fit distribution. n^i is the estimated population based on contributions from all normalized templates. MJ^i is the number of events from the un-renormalized multijet template, *prior to renormalization or subtraction of the electroweak contamination*. b represents one of the electroweak background processes. b^i and W^i are the yields from backgrounds and signal for the *relaxed*, *isolated* signal selection. b_{cont}^i and W_{cont}^i are the contributions to the multijet data template yield from electroweak processes, estimated in the chosen template slice

with background and signal Monte-Carlo. Preserving the electroweak contamination in the multijet template until the normalization fit allows us to vary the electroweak normalizations in the signal selection and in the template selection, which should be fully correlated, simultaneously in the fit.

$$n^i = (\text{MJ}^i - \sum_{b \in \text{BKG}} b_{\text{cont}}^i \times \text{SF}_b - W_{\text{cont}}^i \times \alpha_W) \times \alpha_{\text{MJ}} + \sum_{b \in \text{BKG}} b^i \times \text{SF}_b + W^i \times \alpha_W \quad (4.6)$$

The free parameters of the fit are the normalization of the signal Monte-Carlo template (α_W), the normalizations of each electroweak background Monte-Carlo template (SF_b), and the overall normalization of the multijet data template (α_{MJ}). An example of these fits is illustrated in Figure 4.7. α_{MJ} and α_W are free to float in the fit. The parameters SF_b are also allowed to float, but have additional 5% Gaussian constraints centered on their standard-model normalizations.

Once these re-normalization factors α_W , SF_b , and α_{MJ} are obtained from the likelihood fit, the *non-relaxed* signal selection is applied to both the multijet data template and electroweak Monte-Carlo samples in the chosen isolation slice. The final estimate of the multijet yield (using this distribution, in this isolation slice, using this relaxed template, in this analysis channel) is shown in Equation 4.7. y_x are the (unweighted) yields from data and electroweak Monte-Carlo samples for the *non-relaxed* signal selection *in the chosen isolation slice*.

$$y_{\text{MJ}} = (y_{\text{data}} - \sum_{b \in \text{BKG}} y_b \times \text{SF}_b - y_W \times \alpha_W) \times \alpha_{\text{MJ}} \quad (4.7)$$

Following this procedure, a multijet yield estimate y_{MJ} is computed for every permutation of fit variable ($\mathbb{E}_{\text{T}}$, m_T^W , $\Delta\phi(\ell, \mathbb{E}_{\text{T}})$, and p_T^ℓ) $\times$ isolation slice (Table

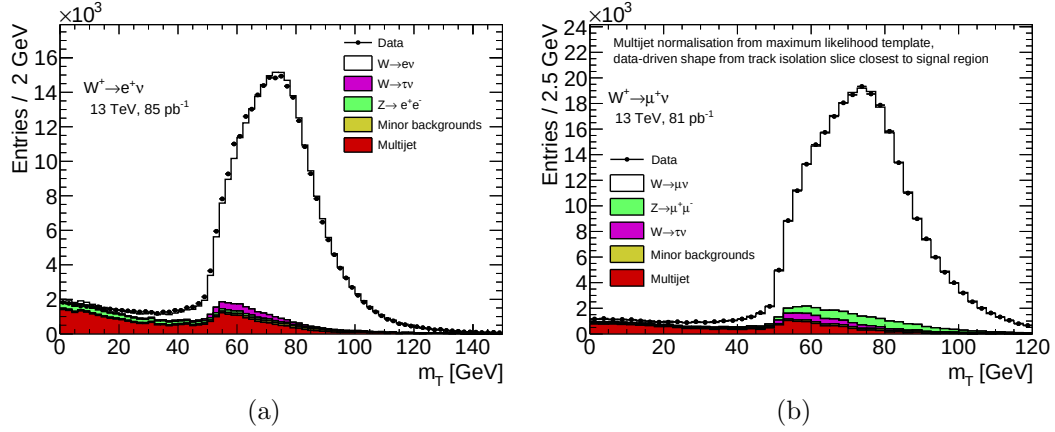


Figure 4.7: Example of multijet normalization fits using m_T^W shapes in the (a) $W^+ \rightarrow e^+ \nu_e$ and (b) $W^+ \rightarrow \mu^+ \nu_\mu$ channels. Data and electroweak template shapes including W^+ signals are from Monte-Carlo simulation, selected with the m_T^W -relaxed, isolated signal selection applied. The multijet template is selected from one lepton-isolation control region, in this case the track isolation slice closest to the signal region ($0.1 < p_T^{\text{cone}}(\Delta R)/p_T < 0.2$, $0.0 < E_T^{\text{cone}}(\Delta R)/p_T < 0.14$). Electroweak templates are also selected from Monte-Carlo in the chosen isolation slice in order to subtract electroweak signal and background contamination from the multijet data template. The electroweak and multijet normalizations are fit to data in a binned maximum-likelihood fit, described in the text. Corollary fits are performed for all permutations of fit variable ($\mathbb{E}_T$, m_T^W , $\Delta\phi(\ell, \mathbb{E}_T)$, and p_T^ℓ) $\times$ isolation slice (Table 4.9) $\times$ template selection (relaxed- m_T^W versus relaxed- $\mathbb{E}_T$).

4.9) $\times$ template selection (relaxed- m_T^W versus relaxed- $\mathbb{E}_T$) $\times$ analysis channel ($e^+ \nu_e$, $e^- \bar{\nu}_e$, $\mu^+ \nu_\mu$, $\mu^- \bar{\nu}_\mu$).

Uncertainties on the multijet yield estimate are the fit uncertainty, further scaled by the fit $\sqrt{\chi^2/N_{\text{DOF}}}$, in order to favor estimates from high-quality fits in the combination of these estimates, described in the following section.

4.4.2.6 Extrapolation and Averaging

The ensemble of multijet yield estimates obtained from the procedure to this point represents a survey over many parameters of the multijet normalization fit which can affect the signal yield estimate. These many values are combined into one best

estimate by first extrapolating the trends in yield estimates through isolation slices back to the signal region, and then by averaging these extrapolations.

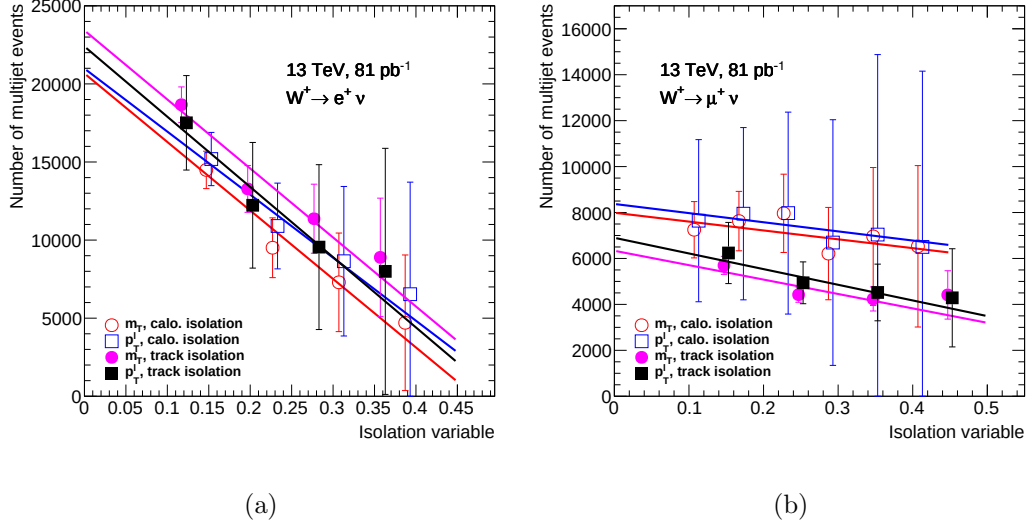


Figure 4.8: Extrapolation of multijet yield. Statistical and fit errors on individual normalization points are further scaled by $\sqrt{\chi^2/\text{N}_{\text{DOF}}}$ for their respective fits, to favor points from isolation control regions with higher-quality fits.

These extrapolations are illustrated in Figure 4.8. For each combination of (analysis channel) $\times$ (relaxation variable) $\times$ (fit variable) $\times$ (isolation variable), the linear trend in multijet yield estimates is extrapolated back to the signal region. The specific points to which the trends are extrapolated are defined by the average values in data of the isolation variables $p_T^{\text{cone}}(\Delta R)/p_T$ (0.002 for both electrons and muons) and $E_T^{\text{cone}}(\Delta R)/p_T$ (0.14 for electrons, and 0.006 for muons) for the *non-relaxed, gradient-isolated* signal selection.

In each analysis channel, the extrapolated yields from all four fit variables, using the same isolation variable, are averaged. This leaves four multijet yield values in each channel, corresponding to choices of (relaxation variable) $\times$ (isolation variable). The average of these four values is taken as the central value of the multijet yield in each channel.

Extensive tests were performed to verify the stability and consistency of the fit procedure. Several sources of systematic uncertainty on the results of these estimates were evaluated. The evaluation of uncertainties on the multijet signal yields is described in Section 4.5.5.

4.5 Uncertainties

Many sources of systematic uncertainty were evaluated in each analysis channel, and propagated through calculations of cross sections, combinations, and ratios. The total uncertainties from each significant source of systematic uncertainty are summarized in Tables 4.10, 4.11, and 4.12. The sources of systematic uncertainty, and the methods employed to estimate the associated measurement errors, are described individually in the following sections. Two recurring concepts, Monte-Carlo systematic variations, and toy Monte-Carlo studies, are described upfront in general terms to avoid repetition among sections devoted to the individual uncertainties.

4.5.1 Monte-Carlo Systematic Variations

In principle, all systematic Monte-Carlo variations and uncertainties applied to reconstructed signal Monte-Carlo in the calculation of $C_{W,Z}$ uncertainties are also applicable to the reconstructed background Monte-Carlo used to evaluate $B_{W,Z}$. However, a baseline expectation on the effect on the background estimates due to reconstruction variations can be estimated from the total uncertainty of about 2% on the signal attributable to the Monte-Carlo variations. Given the low EW background contamination in all six analysis channels, uncertainties on the order of 2% on backgrounds below 7% are taken to be negligible.

	Uncertainty (% $B_{W,Z}$)					
	$e^+\nu_e$	$e^-\bar{\nu}_e$	$\mu^+\nu_\mu$	$\mu^-\bar{\nu}_\mu$	e^+e^-	$\mu^+\mu^-$
MC statistics	-					
MC sys. var.'s	-					
EW Normalization	± 1.66	± 1.58	± 2.86	± 2.79	± 7.33	± 7.26
multijet yield	± 13.36	± 11.28	± 7.00	± 7.87	-	
total	± 13.46	± 11.39	± 7.56	± 8.35	± 7.33	± 7.26

Table 4.10: Itemized uncertainties (in %) on background estimates $B_{W,Z}$ in the six analysis channels. Individual sources of uncertainty are described in the text. “-” indicates that the systematic was taken to be negligible in that channel.

4.5.2 Monte-Carlo Toys

All six analysis channels contain uncertainties on the respective $C_{W,Z}$ due to statistical and systematic uncertainties on the lepton and trigger efficiency maps measured in data (Section 4.5.8 and 4.3.1.2). Statistical uncertainties on scale factors in each bin are uncorrelated, but the propagation of these uncertainties through the event selections and calculations of $C_{W,Z}$ are complex. Such uncertainties are evaluated in this measurement via so-called toy Monte-Carlo procedures. In the toy Monte-Carlo method, an ensemble of variations of the lepton efficiency maps is generated by randomly varying scale factors bin-by-bin, within statistical uncertainty. Variations of the $C_{W,Z}$ calculated with signal Monte-Carlo samples reweighted according to these “toy” efficiency maps define a realistic envelope of statistical uncertainty from lepton efficiency scale factors.

	$e^+\nu_e$	$e^-\bar{\nu}_e$	$\mu^+\nu_\mu$	$\mu^-\bar{\nu}_\mu$	e^+e^-	$\mu^+\mu^-$
central $C_{W,Z}$	0.602	0.614	0.653	0.650	0.552	0.711
uncertainty (%)	+1.949 -1.927	+1.943 -1.902	+1.880 -1.807	+1.801 -1.783	+1.00 -0.99	± 1.05
Itemized Uncertainties ($\%C_{W,Z}$)						
statistics	negligible					
JES/JER	± 1.7	± 1.7	± 1.6	± 1.7	-	
lepton Reco. & ID	± 0.5	± 0.6	± 0.4	± 0.4	± 0.9	± 0.9
lepton isolation	± 0.1	± 0.1	± 0.3	± 0.3	± 0.3	± 0.5
trigger efficiencies	± 0.3	± 0.3	± 0.6	± 0.6	± 0.1	± 0.2
ℓ Energy Scale/Reso.	+0.431 -0.464	+0.411 -0.390	+0.146 -0.143	+0.127 -0.129	+0.22 -0.22	+0.06 -0.07
eCharge Mis-ID	± 0.1		-		± 0.15	-
$\cancel{E}_T$ Soft Term	+0.050 -0.26	+0.025 -0.21	+0.089 -0.31	+0.077 -0.27	-	
Pileup reweighting	+0.33 -0.31	+0.34 -0.37	+0.23 -0.23	+0.20 -0.24	+0.009 -0.006	+0.010 -0.034
PDF	± 0.10	± 0.12	± 0.09	± 0.12	+0.149 -0.089	+0.017 -0.013

Table 4.11: $C_{W,Z}$, with total and itemized relative uncertainties (in %), for each analysis channel. Individual sources of uncertainty are described in the text. “-” indicates that the uncertainty was taken to be negligible in that channel.

	A_{W^+}	A_{W^-}	A_Z
central value	0.383	0.398	0.393
uncertainty (%)	± 1.83	± 1.76	± 1.78

Table 4.12: $A_{W,Z}$, with total relative uncertainties (in %). Uncertainties are dominated by PDF, with subleading contributions from scale and α_s uncertainties. Statistical uncertainties on the generator-level Monte-Carlo samples used to evaluate $A_{W,Z}$ are negligible.

4.5.3 Statistics

Statistical uncertainties enter the fiducial and total inclusive cross sections via the finite size of the data sample used in the measurement of $N_{W,Z}^{\text{data selected}}$. These are assessed analytically as simple Gaussian errors $\sqrt{N_{W,Z}^{\text{data selected}}}$. They are approximately 0.4% in the Z channels, and 0.2% in the $W^\pm$ channels. From Equations 4.1 and 4.2, fractional uncertainties due to statistics on $N_{W,Z}^{\text{data selected}}$ are the same for the total and fiducial cross sections.

Monte-Carlo datasets used in the estimation of electroweak background yields, $C_{W,Z}$, and $A_{W,Z}$ were large enough that statistical uncertainties propagating through to final cross sections were negligible.

There are also statistical uncertainties on the results of data-driven studies used as inputs to these results. These include the fits to the multijet background contribution in the $W^\pm$ channels, and the lepton reco/isolation/ID efficiency studies. The methods of accounting for statistical uncertainty in these parameters are described in their respective sections following. The statistical contributions to the total uncertainty on these parameters are included in the respective line-items in Tables 4.10, 4.11 and 4.12.

4.5.4 Luminosity

Uncertainty on the total integrated luminosity of the early-2015 50 ns dataset is a leading uncertainty on all independent and combined cross sections. Luminosity measurements and uncertainties are provided by the ATLAS luminosity working group. For the early-2015 50 ns dataset, an uncertainty of 5% ($[81 \pm 4.05]$ pb) was determined.

From Equations 4.1, the uncertainty on cross sections due to measurement

error on the integrated luminosity is directly proportional to the luminosity uncertainty. Because the fiducial cross sections are all measured in the same dataset, Δ_{lumi} is fully correlated across the six analysis channels. This means that the fractional uncertainty due to luminosity error is the same for all six independent cross sections and combinations. Furthermore, luminosity uncertainties cancel analytically in cross section ratios. The perfect cancellation of this leading uncertainty is one of the biggest reasons why cross section ratios achieve such improved precision compared to the cross sections themselves.

4.5.5 Multijet Modeling and Normalization

Total uncertainties on multijet background yields (Table 4.10) in the $W^\pm$ analysis channels include contributions from the following sources.

An uncertainty on the accuracy of the multijet fit procedure is assessed for each channel by taking one-half of the difference between the results obtained from the $p_{\text{T}}^{\text{cone}}(\Delta R)$ and $E_{\text{T}}^{\text{cone}}(\Delta R)$ scans. The difference is averaged between results obtained with the two relaxation variables.

An uncertainty on the choice of relaxation variable was assessed by taking half the difference of the yield estimates obtained with either relaxation variable independently.

Statistical uncertainties on the the linear extrapolations ($\sqrt{\chi^2/N_{\text{DOF}}}$) are propagated through all combinations of scan variables, fit variables, and final-state channels, to the final averages for multijet signal yields.

Because the multijet estimates are leading uncertainties on measurements which are input to combinations and ratios, it is important to quantify the correlations among uncertainties on multijet yields in each channel. The uncertainty

correlations are related to the total measured uncertainties by Equation 4.8 (which is essentially just the definition of correlation in this particular context).

$$\delta(N_{mj}^{W^\pm})^2 = \delta(N_{mj}^{W^+})^2 + \delta(N_{mj}^{W^-})^2 - 2\rho\delta(N_{mj}^{W^+})\delta(N_{mj}^{W^-}) \quad (4.8)$$

Here “ δ ” is used for the uncertainties, to avoid confusion with the frequent use of “ σ ” as cross sections. With this definition, independent measurements of the uncertainty in the W^+ , W^- , and W channels provide the correlations ρ , which are used to accurately cancel these uncertainties in the charge ratios (Section 4.5.18).

Systematic variations of the jet energy scale and resolution performance in Monte Carlo samples (Section 4.5.6) are propagated through the multijet fit procedure as well as the signal Monte-Carlo models. Differences in normalization results arising from variations in the JES/JER variations are added as uncorrelated contributions to the total uncertainty on multijet yields. Other Monte-Carlo variations are expected to have negligible effects on the results of multijet fits.

4.5.6 Jet Energy Scale and Resolution

High- p_T jets associated to the event primary vertex are added to the $\cancel{E}_T$ hard-object terms. Biases on the Jet Energy Scale and Resolution therefore sculpt $\cancel{E}_T$ distributions in the $W^\pm$ channels. Neither jets nor $\cancel{E}_T$ are inputs to the Z event selections. JES/JER uncertainties are neglected in Z channels.

JES/JER uncertainties are evaluated as systematic variations of signal Monte-Carlo samples used in the calculation of C_W . The variations are also applied to the signal templates subtracted from the multijet data templates, as described in Section 4.5.5. The JES/JER uncertainties on multijet background estimates are included in the total multijet uncertainties in Table 4.10.

4.5.7 Lepton Reco/Isolation/ID Efficiencies

The error on $C_{W,Z}$ arising from these sources is evaluated via nuisance parameter variation of the Monte-Carlo event scale factors described in Section 4.3.1.2.

For electrons, independent systematics based on many variations of reconstruction performance parameters are available through the e/γ reweighting CP software. However, the available variations as implemented at the time of this analysis included the statistical errors, meaning that simple propagation of the up/down electron efficiency variations would fully correlate the statistical errors on efficiency measurements across all scale factor bins. This would represent a considerable overstatement of the statistical error on electron scale factors. The toy Monte-Carlo analysis which is needed for correct treatment of the statistical uncertainties simultaneously evaluates and combines the correlated systematics, and provides one total error, inclusive of systematics and statistical uncertainties on all electron scale factors.

Scale factor uncertainties in the muon channel are divided into individual systematic nuisance parameters, which are in general fully correlated across all (η, ϕ) bins, and a single, combined statistical error, which represents the combination of uncorrelated statistical contributions from all muon scale factor measurements. This enables analyses to propagate the systematic uncertainties on muon scale factors as simple up/down nuisance parameters, while still achieving proper decorrelation of statistical uncertainties via a separate toy Monte-Carlo analysis.

4.5.8 Trigger Efficiency

Trigger efficiency maps binned in p_T^e , η^e , η^μ , and ϕ^μ were measured via $Z \rightarrow l^+l^-$ tag-and-probe methods as described in Section 4.3.1.1. Systematic uncertainties

on the efficiency in each bin were evaluated and provided as nuisance parameters through the e/γ and muon CP software tools. Generally, individual systematics are modeled as fully correlated across all trigger efficiency bins. Statistical uncertainties on trigger efficiencies are estimated by Toy Monte-Carlo analyses, as described in Section 4.5.2.

Total uncertainties on $C_{W,Z}$ due to trigger efficiency measurements are 0.3% in the $W \rightarrow e\nu_e$ channels, and 0.6% in the $W \rightarrow \mu\nu_\mu$ channels. Z channels suffer lower trigger efficiency uncertainty due to ability to trigger on either of two daughter leptons. $Z \rightarrow e^+e^-$ has 0.1% trigger efficiency uncertainty on its C_Z , and the $Z \rightarrow \mu^+\mu^-$ channel has 0.2%.

4.5.9 Lepton Momentum/Energy Scale and Resolution

Uncertainties on the momentum and energy scale and resolutions in lepton reconstruction were evaluated as systematic variations in reconstructed Monte-Carlo samples, implemented via systematics software tools provided by the ATLAS e/γ and muon CP groups. These variations were applied to reconstructed signal Monte-Carlo, providing lepton scale and resolution uncertainty estimates on $C_{W,Z}$.

In all six analysis channels, the uncertainty on $C_{W,Z}$ from lepton reconstruction nuisance parameters is dominated by the energy scale uncertainty, with much smaller contributions from the energy/momentum resolution.

4.5.10 Electron Charge Mismeasurement

Charge identification of electrons and muons is measured as the sign of the sagitta of the associated Inner Detector track. The sagitta measurement has a finite reso-

lution, leading inevitably to some small rates of charge misidentification, especially for high- p_T tracks with small curvature. The charge misidentification rate for electrons is found to be a nonnegligible source of uncertainty on cross sections. Muon reconstruction suffers a much lower rate of charge errors, owing to the greater sagitta significance relative to spatial precision in the Muon Spectrometer. The muon mis-ID rate is found to be a negligible uncertainty on these measurements, and no uncertainties on q^μ error are assessed.

Charge mis-ID can bias the values of all electron-channel $C_{W,Z}$. In $Z \rightarrow e^+e^-$, events in which one electron charge is flipped can fail the opposite-sign dilepton cut, reducing the experimental efficiency. The different production rates of W^+ and W^- result in asymmetric migration of signal events between electronic $W^\pm$ charge channels. In principle, this would increase the W^- signal yield, at the expense of W^+ .

Charge mismeasurement rates were measured in data using a $Z \rightarrow l^+l^-$ selection with the opposite-lepton-charge criteria relaxed. The fractional number of Z events reconstructed with same-sign lepton charges provides the lepton charge error rates. The resultant uncertainties on the $C_{W,Z}$ were evaluated analytically.

The charge mis-ID variations on $C_{W,Z}$ evaluated in this way are verified to have a small effect, and a conservative, symmetrized uncertainty of 0.1% is assessed for all $C_{W,Z}$ in the electron channels.

4.5.11 Electroweak Background Normalization

The total inclusive cross sections predicted at (N)NLO for single-boson, $t\bar{t}$, diboson, and single-top background processes carry uncertainties between 5% and 6%. These uncertainties are relevant in the estimates of $B_{W,Z}$, and in the sig-

nal/background subtraction applied to multijet data templates. In the background estimates, the electroweak normalization uncertainties are applied as independent variations of the normalizations of the respective Monte-Carlo samples. In the multijet estimation fits, these uncertainties are implemented as Gaussian constraints on the normalization of electroweak (signal+background) templates subtracted from the multijet data templates.

4.5.12 $\cancel{E}_T$ Track Soft Term

Uncertainties on the $\cancel{E}_T$ soft term are evaluated using systematic Monte-Carlo variations of three properties of the $\cancel{E}_T$ TST calculation. These correspond approximately to Inner Detector tracking p_T resolution, and transverse and longitudinal spatial resolution. These variations in $\cancel{E}_T$ TST reconstruction behavior are provided through the ATLAS $\cancel{E}_T$ reconstruction CP software, and were determined from studies in $Z \rightarrow \mu^+\mu^-$ Monte-Carlo data reconstructed with early-2015 (50 ns) accelerator conditions.

$\cancel{E}_T$ is only used in $W^\pm$ -channel analyses, so the TST variations are not applied in the Z channels. $\cancel{E}_T$ reconstruction is an important determinant of $W^\pm$ selection yields, so the TST variations are propagated through the signal Monte-Carlo selections as uncertainties on C_W . The effects on C_W are asymmetric, with upward variations of C_W below +0.09%, and downward variations as large as -0.21%.

4.5.13 Pileup Reweighting

Uncertainties on $C_{W,Z}$ due to pileup reweighting are evaluated via variations of the $\langle\mu\rangle$ scaling constant described in Section 4.3.1.3. Based on comparisons of 50 ns data and MC15a Monte-Carlo simulated and reconstructed with 50 ns con-

ditions, the ATLAS Tracking CP group recommended upper and lower variations of 1.23 and 1.09 (around the nominal value 1.16). These variations of the pileup reweighting factor were propagated through the signal Monte-Carlo event selections as uncertainties on $C_{W,Z}$.

In addition to $\mathbb{X}_T$, and by extension m_T^W , Pileup Reweighting also sculpts the lepton isolation and ID efficiency distributions. Some of the total change in C_W observed from variations of the PURW scaling constant are therefore caused by shifts in the lepton isolation and ID efficiency distributions. Identification and isolation uncertainties are evaluated independently (Section 4.5.7), however.

In order to avoid double-counting the uncertainties on lepton efficiency arising from propagation of pileup reweighting variations, it is necessary to isolate and disregard the variation in $C_{W,Z}$ due to lepton efficiency shifts within PURW nuisance variations.

The shifts in single-lepton efficiencies were measured in Monte-Carlo via Z tag-and-probe studies for the 3 pileup reweighting scenarios. The measured efficiency shifts were then propagated through the $C_{W,Z}$ calculations, and the resultant shifts $\Delta(C_{W,Z})_{\ell\ell}$ were subtracted from the shifts arising from the pileup reweighting variations $\Delta(C_{W,Z})_{\ell\ell}$.

4.5.14 PDF Choice

Uncertainties on the fiducial efficiencies $A_{W,Z}$ arising from the choice of proton PDF are evaluated by reweighting the generator-level events with which the $A_{W,Z}$ are calculated, according to four alternative PDF sets. In addition to the nominal PDF CT14nnlo [7], three other PDFs were used: NNPDF3.0 [119], MMHT14nnlo [120], and ABM12LHC [121]. Each PDF has a set of eigenvector variations to

which events can be reweighted according to the initial-state parton species and momenta. For each of A_{W^+} , A_{W^-} , and A_Z , the envelope of values computed with events reweighted to all eigenvector variations of the four chosen PDF sets was taken as the PDF uncertainty on $A_{W,Z}$.

Z signal Monte-Carlo is produced with the CT10nnlo PDF.[\[122\]](#) To evaluate the PDF uncertainties on the C_Z , signal Monte-Carlo events were reweighted according to the 26 PDF eigenvector variations. The envelope of C_Z values calculated from the reweighted signal Monte-Carlo is taken as the PDF uncertainties.

Conservative estimates of PDF uncertainty on the C_W were adopted from prior ATLAS $W^\pm$, Z analyses which were unpublished at the time of writing this dissertation.

4.5.15 Factorization and Renormalization

To calculate the systematic error on $A_{W,Z}$ due to uncertainty on the factorization and renormalization scales (μ_F and μ_R) defined in the event-generator level, variations of $A_{W,Z}$ were calculated with event samples simulated using alternative μ_R and μ_F values. The standard prescription within ATLAS is to vary μ_F and μ_R up and down independently by factors of 2, excluding combinations for which μ_R/μ_F or μ_F/μ_R exceed 4. i.e., the two cases in which one scale is halved and the other is doubled are excluded. These variations made subdominant contributions to the total uncertainty on $A_{W,Z}$.

4.5.16 α_s

Uncertainty on $A_{W,Z}$ due to the limited precision of α_s measurements is evaluated according to the prescription provided for the PDF used to generate the nominal

event-level simulation sample (CT14nnlo). Two additional samples of event-level signal Monte-Carlo were generated with α_s varied by $\pm 1\sigma$, or ± 0.001 . These variations contributed subdominant uncertainties to $A_{W,Z}$.

4.5.17 Parton Shower

Uncertainties on the hadronization and parton shower models employed in the event-level simulation used to calculate $A_{W,Z}$ were adapted from ATLAS' 7 TeV measurement of $W^\pm$, Z inclusive cross sections. In that analysis, the uncertainty on shower and hadronization modeling was defined by the envelope of $A_{W,Z}$ values derived from event-level samples simulated with two alternative shower simulations (POWHEG and Herwig, as opposed to Pythia used for the nominal sample).[\[41\]](#)

As adapted to the 13 TeV results parton shower uncertainty is also subdominant to the PDF uncertainties on $A_{W,Z}$.

4.5.18 Correlation Model

Correct correlation models among uncertainties on fiducial cross sections facilitate accurate addition of errors in cross section channel combinations, and accurate cancellations in ratios.

Correlations among the lepton trigger, reconstruction, isolation, and ID efficiencies are assessed as part of the Toy Monte-Carlo procedure described in Section [4.5.2](#). Correlations among multijet background yields are described in Section [4.5.5](#). These two sources of uncertainty are the leading sources of uncertainties on fiducial cross sections across all six analysis channels. Unsurprisingly, lepton efficiencies are highly correlated among electronic final states and among

muonic final states, and nearly uncorrelated between e and μ channels.

This method of measuring correlations carries with it a statistical uncertainty arising from the finite number of toys which are practical to generate and evaluate. Since the method is computationally expensive, it is important to quantify how many toys are required to achieve statistical uncertainties below a target threshold. For this analysis, the statistical uncertainty on the correlations among lepton efficiency scale factors is studied as the width of correlation distributions within permutations of the toys engineered to reproduce the measured correlations (on average). The effect on the uncertainties on the cross section ratios established by this method are shown to have negligible effects on the total uncertainty.

Systematic variations of Monte-Carlo used to calculate $C_{W,Z}$ and $B_{W,Z}$ are treated as fully correlated among the six analysis channels. Consistent application of the variations with standardized (and identically configured) CP systematics software guarantees that the algorithmic changes underlying CP Monte-Carlo variations are identical in each channel.

4.6 Measurement Results

4.6.1 Predictions

In this section, measured cross sections and ratios are presented in all tables and plots in comparison to theoretical predictions based on the DYNNLO Monte-Carlo event generator.^[123] Events were generated at next-to-next-to-leading-order (NNLO) with next-to-leading-order (NLO) electroweak corrections. The experimental uncertainty on cross section ratios is anticipated to provide some discriminating power among predictions based on different PDF sets. Results are therefore com-

pared to DYNNLO predictions with several alternative PDFs.

Uncertainties on the predictions are dominated by proton PDF uncertainties, but include many of the same uncertainties assessed for $A_{W,Z}$ efficiencies (Table 4.12). Statistical uncertainties due to finite simulation sample sizes are negligible. Predictions obtained with different PDF sets are generally compatible with one another at the 1σ level.

4.6.2 Kinematic Distributions

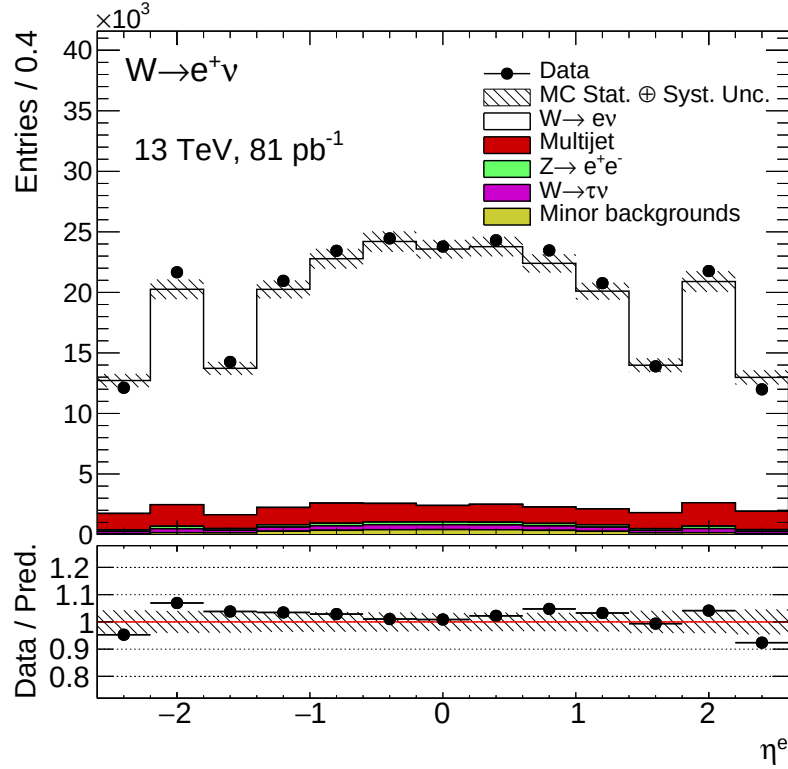
Histogramming event kinematic variables of interest is an important step to validate background models, reconstruction of physics objects and their parameters (like η^ℓ and p_T^ℓ), and derived quantities like $\cancel{E}_T$ and m_T^W . Significant discrepancies between data and Monte-Carlo simulation would draw into question the kinematic modeling of background events in simulation, the composition of our background model, or both.

Error bands include uncertainties on background + signal yields in each bin, evaluated with the full menu of data-driven, analytical, and Monte-Carlo variation uncertainties evaluated for $C_{W,Z}$ and $B_{W,Z}$. The 5% luminosity error and the 5-7% normalization error on electroweak cross sections are excluded from the uncertainty bands. These uncertainties amount to trivial normalizations which are fully correlated across all plots and bins. As such, their inclusion would tend to overstate the uncertainties on kinematic shapes. Black points are data with simple statistical errors.

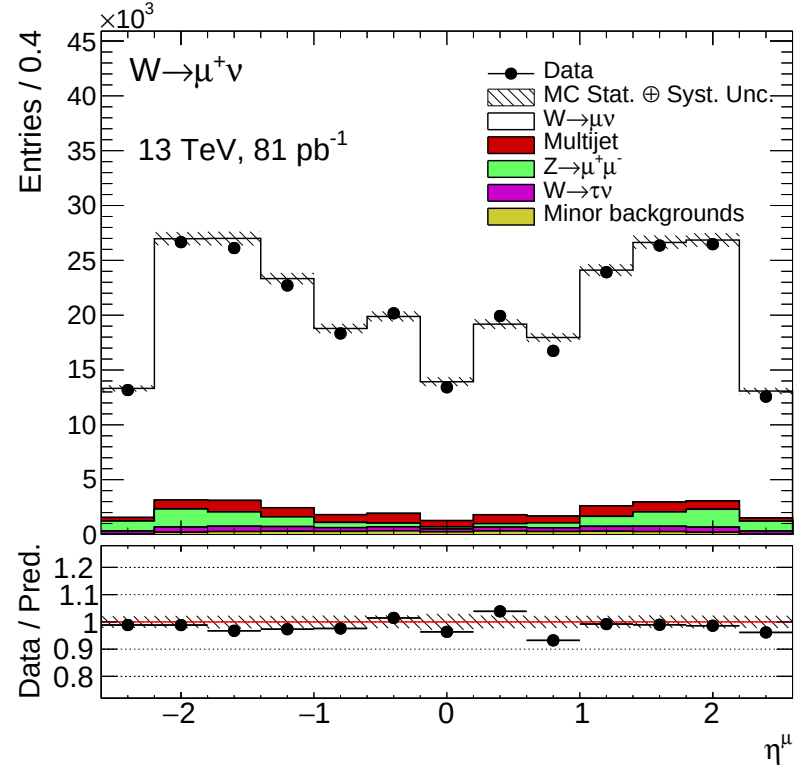
The plots on the following pages show η^ℓ , p_T^ℓ , $\cancel{E}_T$, m_T^W , $m_{\ell\ell}^Z$, p_T^Z , and y^Z . For each variable, the different channels and combinations are presented in the following order: W^+ , W^- , $W^\pm$, Z . Each figure displays the electron channel plot

on the left, and the muon channel plot on the right.

After calibration and reweighting as described in Section 4.3, the analysis background model anticipates these distributions in data well. Differences between data and predictions are generally covered by systematic uncertainties. Few significant trends in data/prediction ratios (such as p_T^μ and p_T^Z) are evident. These distributions show no evidence of significant systematic bias on the inputs to the cross section calculations.

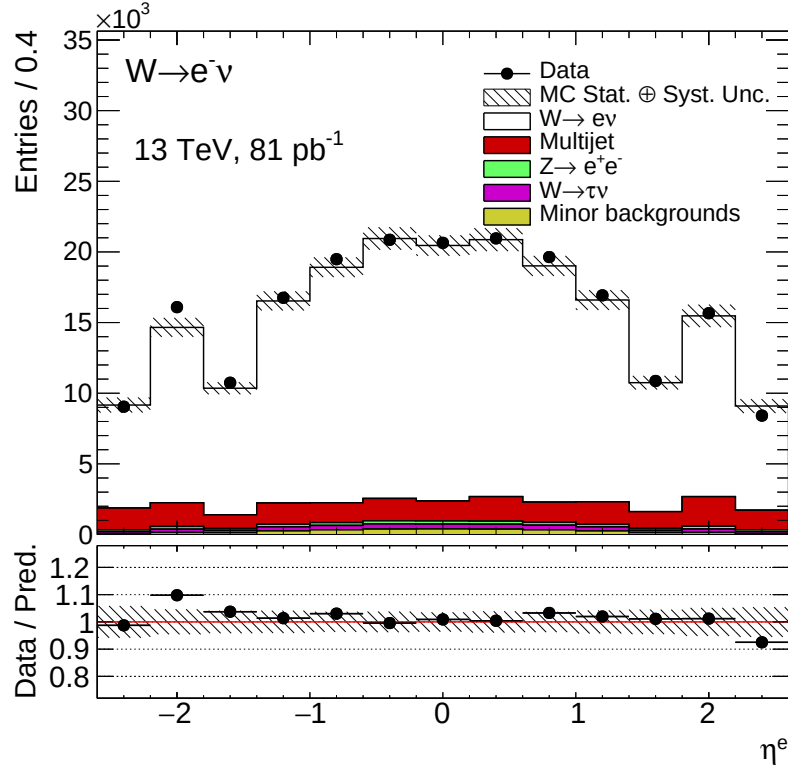


(a)

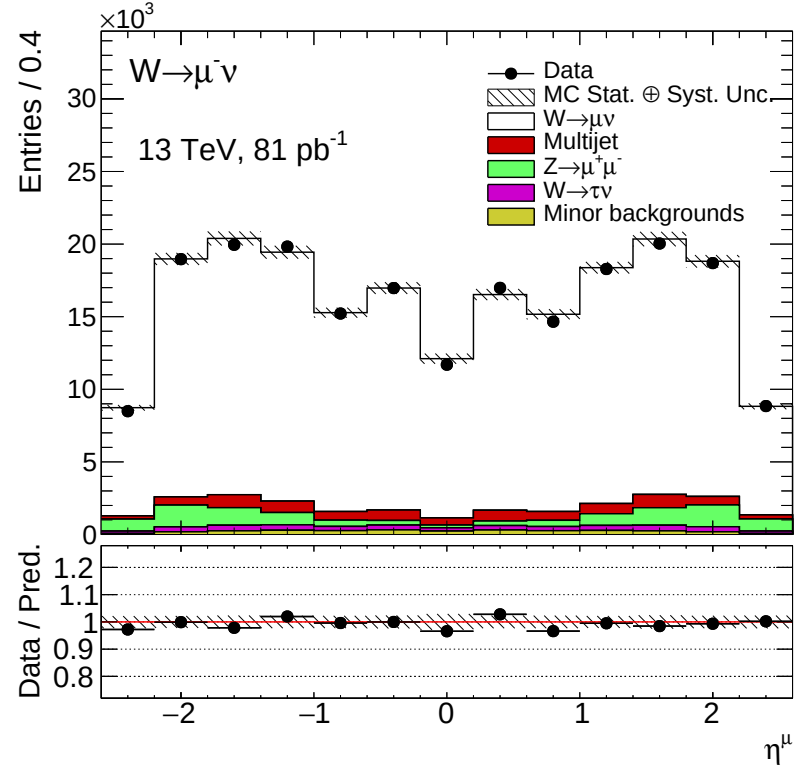


(b)

Figure 4.9: Lepton pseudorapidity, η^ℓ , in the (a) $W^+ \rightarrow e^+ \nu_e$ and (b) $W^+ \rightarrow \mu^+ \nu_\mu$ channels. Distributions are shown after full event selection (Section 4.2). Signal and background predictions other than multijet are derived from Monte-Carlo simulation. Multijet normalization and shape are extrapolated from data control regions, as described in Section 4.4.2. Data points in black include statistical uncertainties. Shaded error bands represent systematic uncertainties on signal + background predictions, as described in Section 4.5, for each bin. A 5% uncertainty on the total integrated luminosity is omitted from these uncertainty bands.

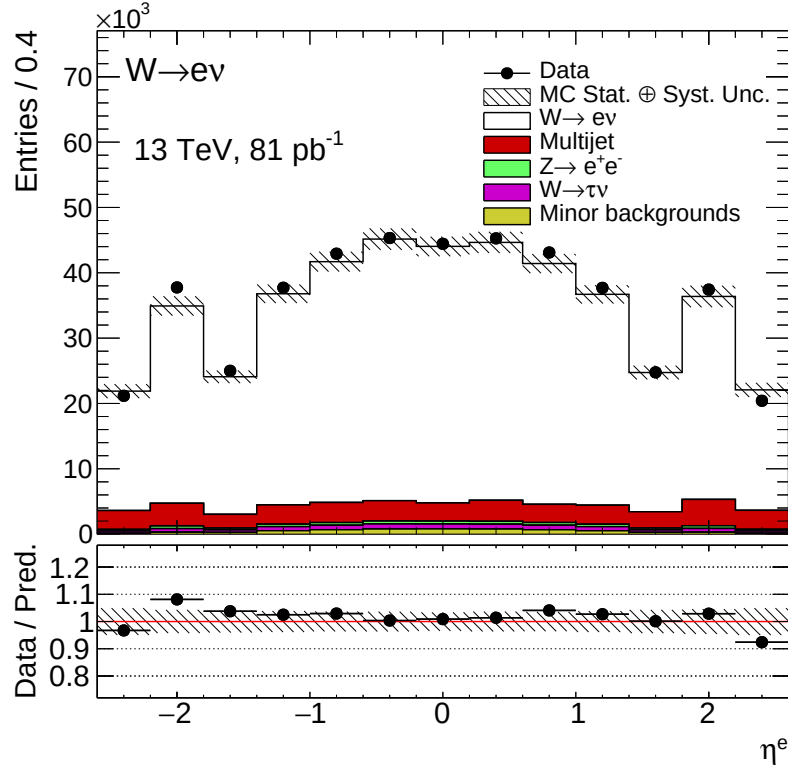


(a)

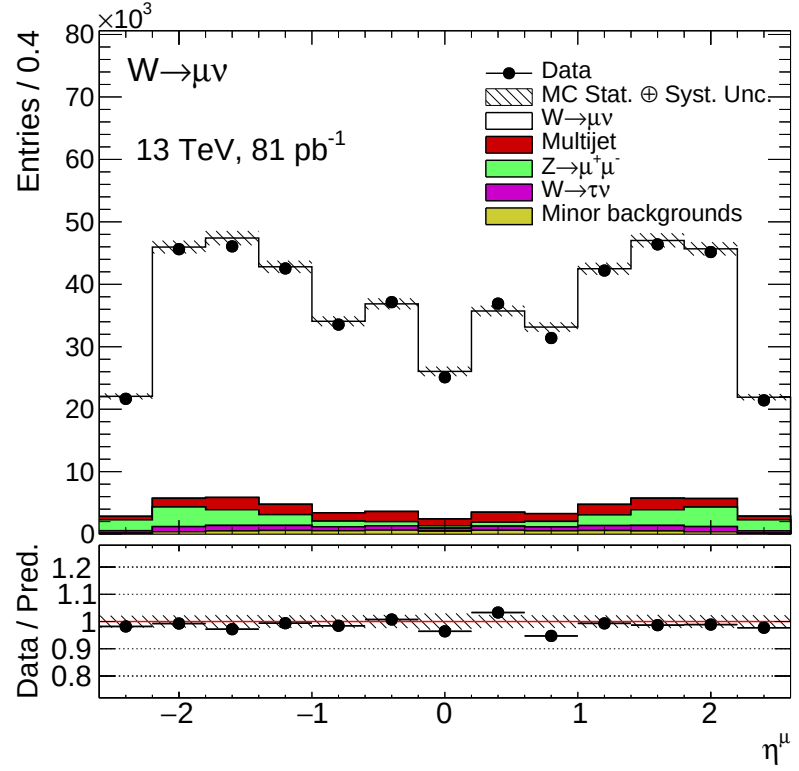


(b)

Figure 4.10: Lepton pseudorapidity, η^ℓ , in the (a) $W^- \rightarrow e^- \bar{\nu}_e$ and (b) $W^- \rightarrow \mu^- \bar{\nu}_\mu$ channels. Distributions are shown after full event selection (Section 4.2). Signal and background predictions other than multijet are derived from Monte-Carlo simulation. Multijet normalization and shape are extrapolated from data control regions, as described in Section 4.4.2. Data points in black include statistical uncertainties. Shaded error bands represent systematic uncertainties on signal + background predictions, as described in Section 4.5, for each bin. A 5% uncertainty on the total integrated luminosity is omitted from these uncertainty bands.

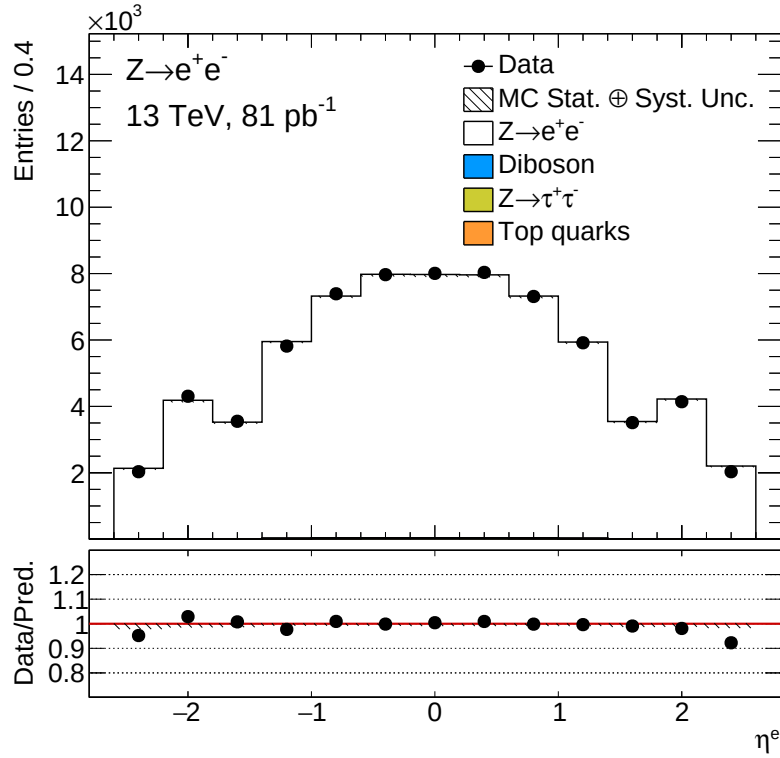


(a)

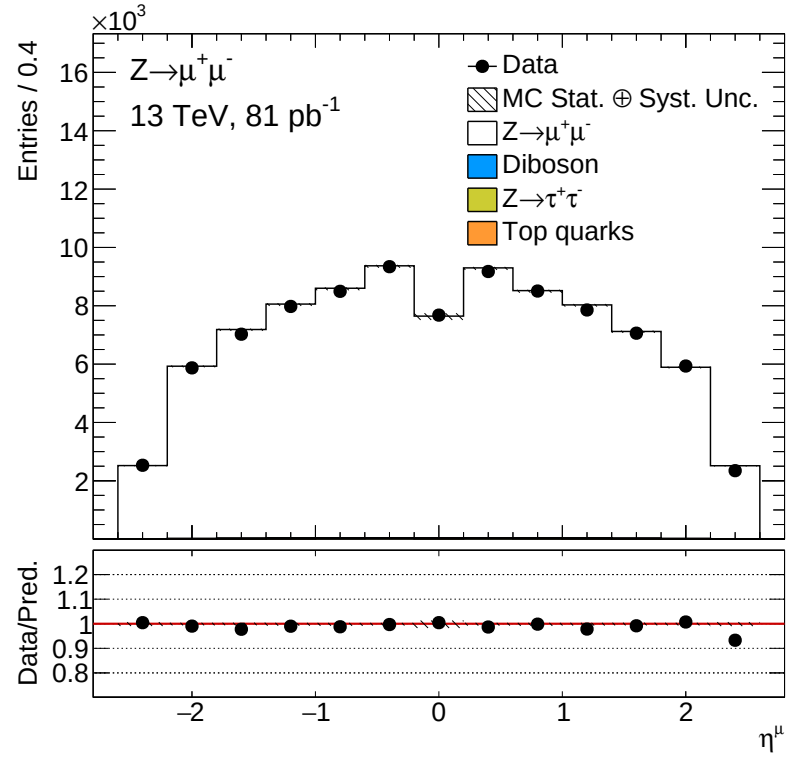


(b)

Figure 4.11: Lepton pseudorapidity, η^ℓ , in the combined $W^\pm \rightarrow \ell^\pm \nu_\ell$ channel. Distributions are shown after full event selection (Section 4.2). Signal and background predictions other than multijet are derived from Monte-Carlo simulation. Multijet normalization and shape are extrapolated from data control regions, as described in Section 4.4.2. Data points in black include statistical uncertainties. Shaded error bands represent systematic uncertainties on signal + background predictions, as described in Section 4.5, for each bin. A 5% uncertainty on the total integrated luminosity is omitted from these uncertainty bands.



(a)



(b)

Figure 4.12: Lepton pseudorapidity, η^ℓ , in the (a) $Z \rightarrow e^+e^-$ and (b) $Z \rightarrow \mu^+\mu^-$ channels. Z -channel plots of lepton variables include two entries per event. Distributions are shown after full event selection (Section 4.2). Signal and background predictions are derived from Monte-Carlo simulation. Data points in black include statistical uncertainties. Shaded error bands represent systematic uncertainties on signal + background predictions, as described in Section 4.5, for each bin. A 5% uncertainty on the total integrated luminosity is omitted from these uncertainty bands.

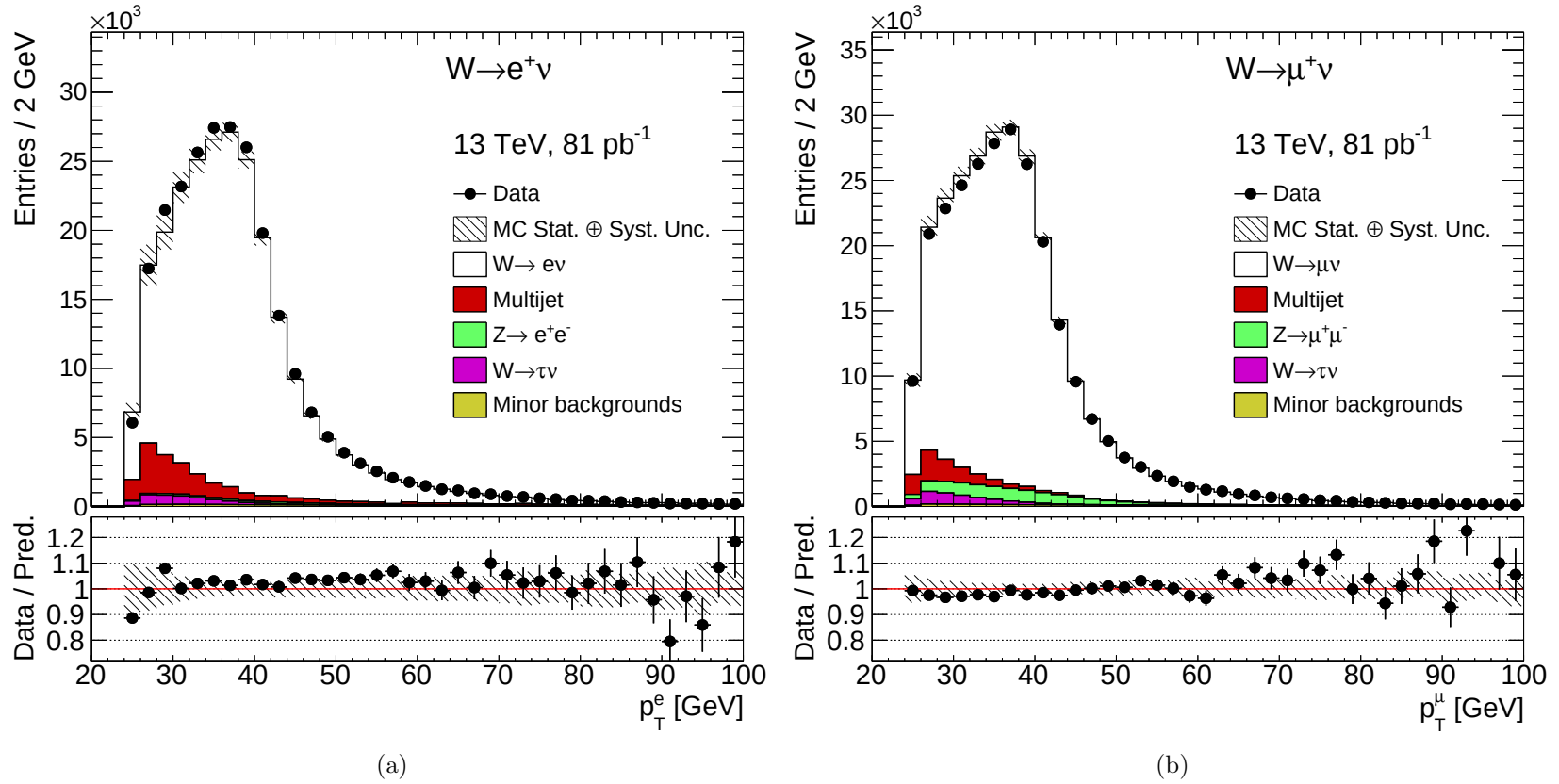


Figure 4.13: Lepton transverse momentum, p_T^ℓ , in the (a) $W^+ \rightarrow e^+ \nu_e$ and (b) $W^+ \rightarrow \mu^+ \nu_\mu$ channels. Distributions are shown after full event selection (Section 4.2). Signal and background predictions other than multijet are derived from Monte-Carlo simulation. Multijet normalization and shape are extrapolated from data control regions, as described in Section 4.4.2. Data points in black include statistical uncertainties. Shaded error bands represent systematic uncertainties on signal + background predictions, as described in Section 4.5, for each bin. A 5% uncertainty on the total integrated luminosity is omitted from these uncertainty bands.

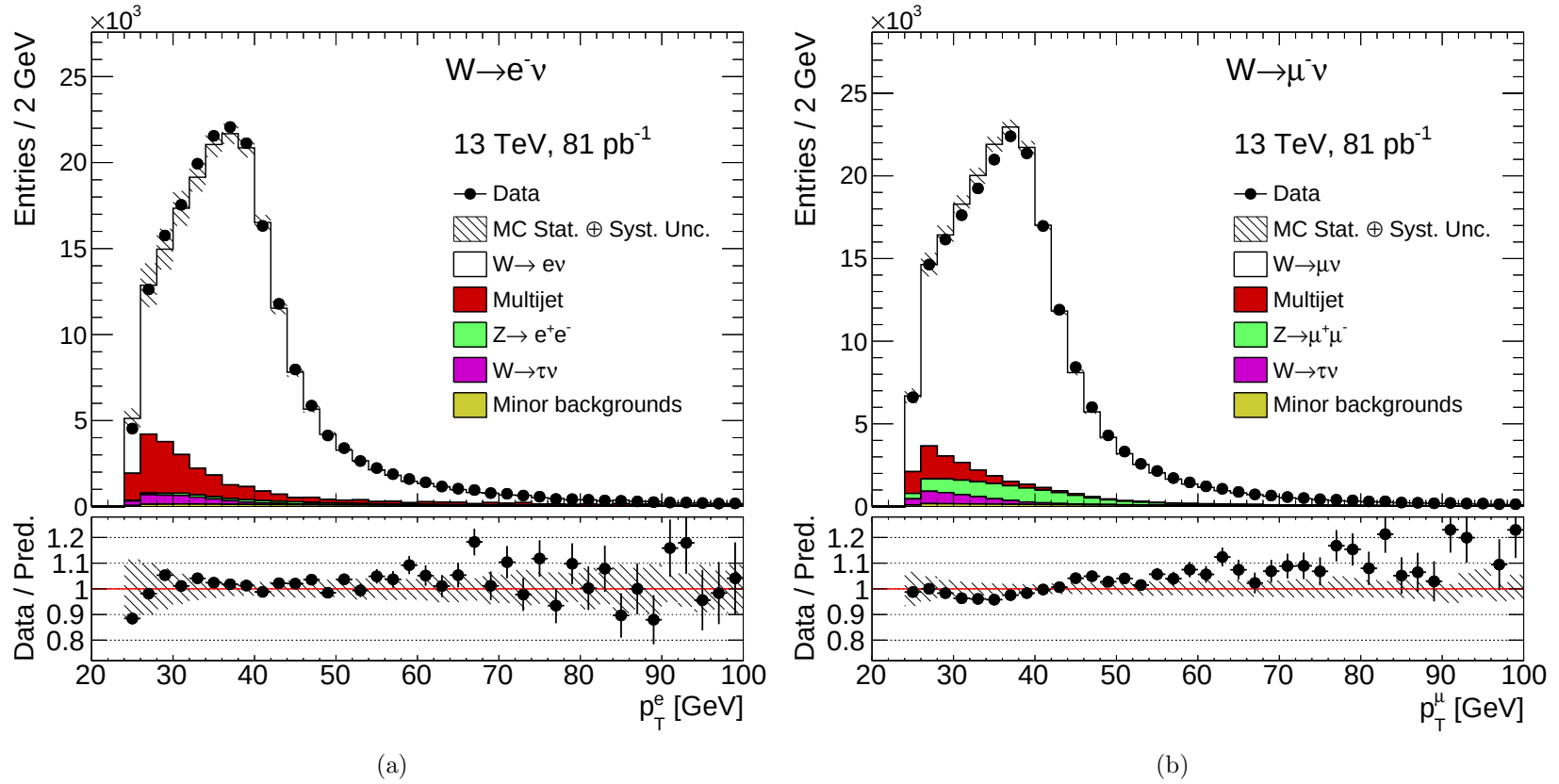
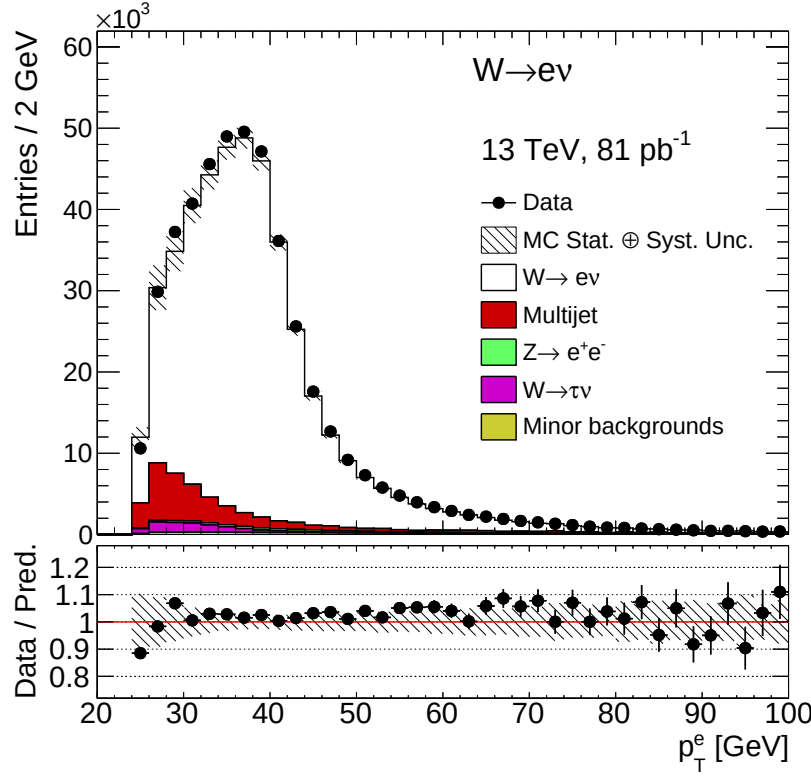
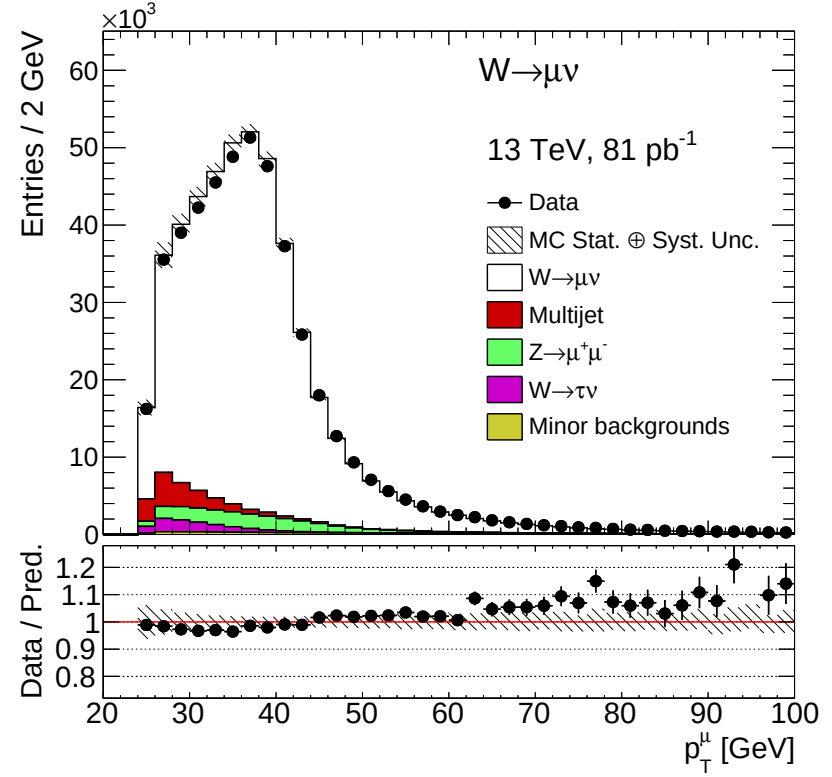


Figure 4.14: Lepton Transverse Momentum, p_T^ℓ , in the (a) $W^- \rightarrow e^- \bar{\nu}_e$ and (b) $W^- \rightarrow \mu^- \bar{\nu}_\mu$ channels. Distributions are shown after full event selection (Section 4.2). Signal and background predictions other than multijet are derived from Monte-Carlo simulation. Multijet normalization and shape are extrapolated from data control regions, as described in Section 4.4.2. Data points in black include statistical uncertainties. Shaded error bands represent systematic uncertainties on signal + background predictions, as described in Section 4.5, for each bin. A 5% uncertainty on the total integrated luminosity is omitted from these uncertainty bands.

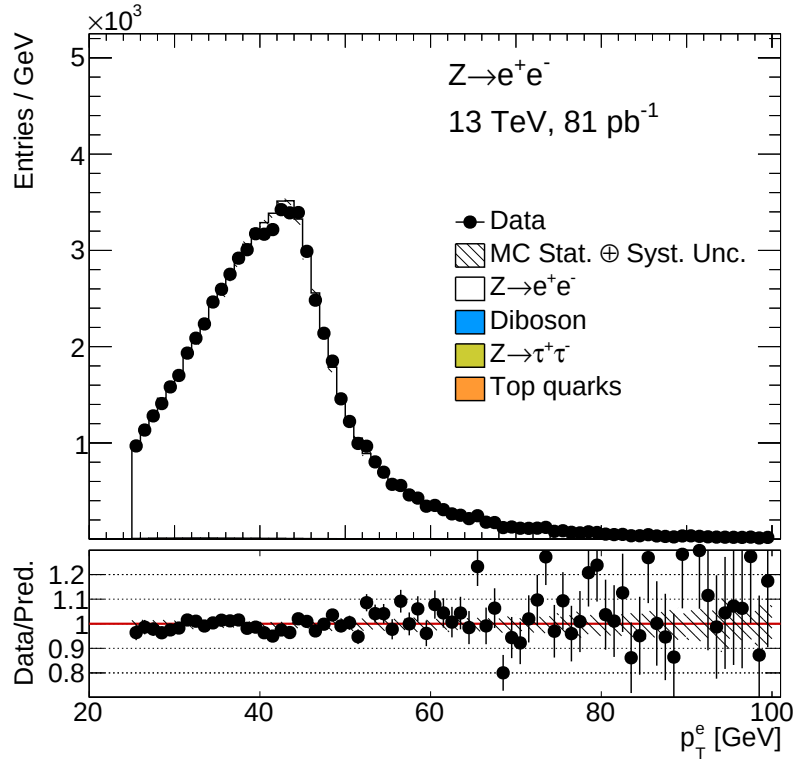


(a)

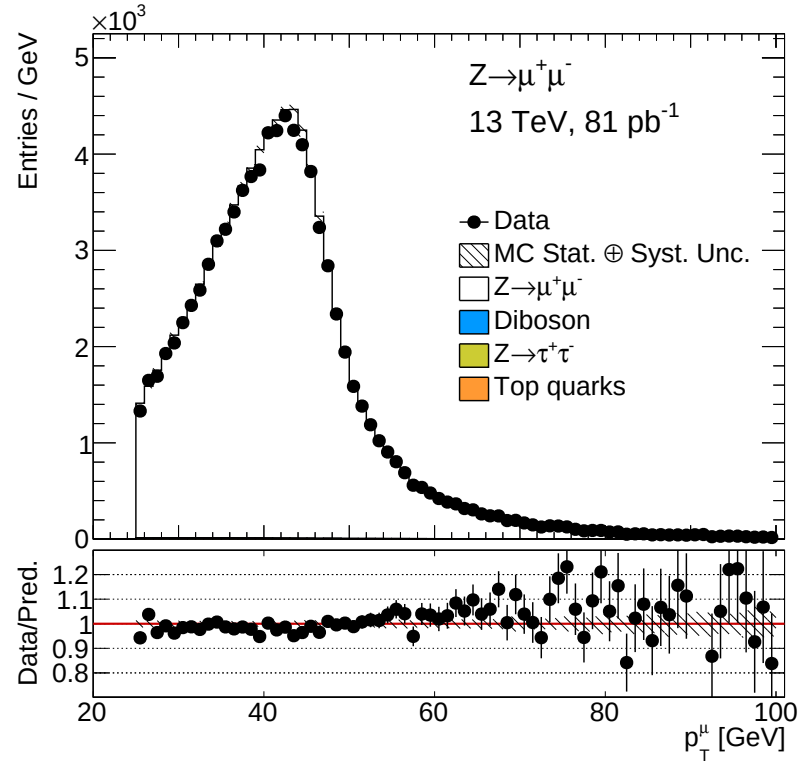


(b)

Figure 4.15: Lepton Transverse Momentum, p_T^ℓ , in the (a) $W^\pm \rightarrow e^\pm \nu_e$ and (b) $W^\pm \rightarrow \mu^\pm \nu_\mu$ channels. Distributions are shown after full event selection (Section 4.2). Signal and background predictions other than multijet are derived from Monte-Carlo simulation. Multijet normalization and shape are extrapolated from data control regions, as described in Section 4.4.2. Data points in black include statistical uncertainties. Shaded error bands represent systematic uncertainties on signal + background predictions, as described in Section 4.5, for each bin. A 5% uncertainty on the total integrated luminosity is omitted from these uncertainty bands.



(a)



(b)

Figure 4.16: Lepton transverse momentum, p_T^ℓ , in the (a) $Z \rightarrow e^+e^-$ and (b) $Z \rightarrow \mu^+\mu^-$ channels. Z -channel plots of lepton variables include two entries per event. Distributions are shown after full event selection (Section 4.2). Signal and background predictions are derived from Monte-Carlo simulation. Data points in black include statistical uncertainties. Shaded error bands represent systematic uncertainties on signal + background predictions, as described in Section 4.5, for each bin. A 5% uncertainty on the total integrated luminosity is omitted from these uncertainty bands.

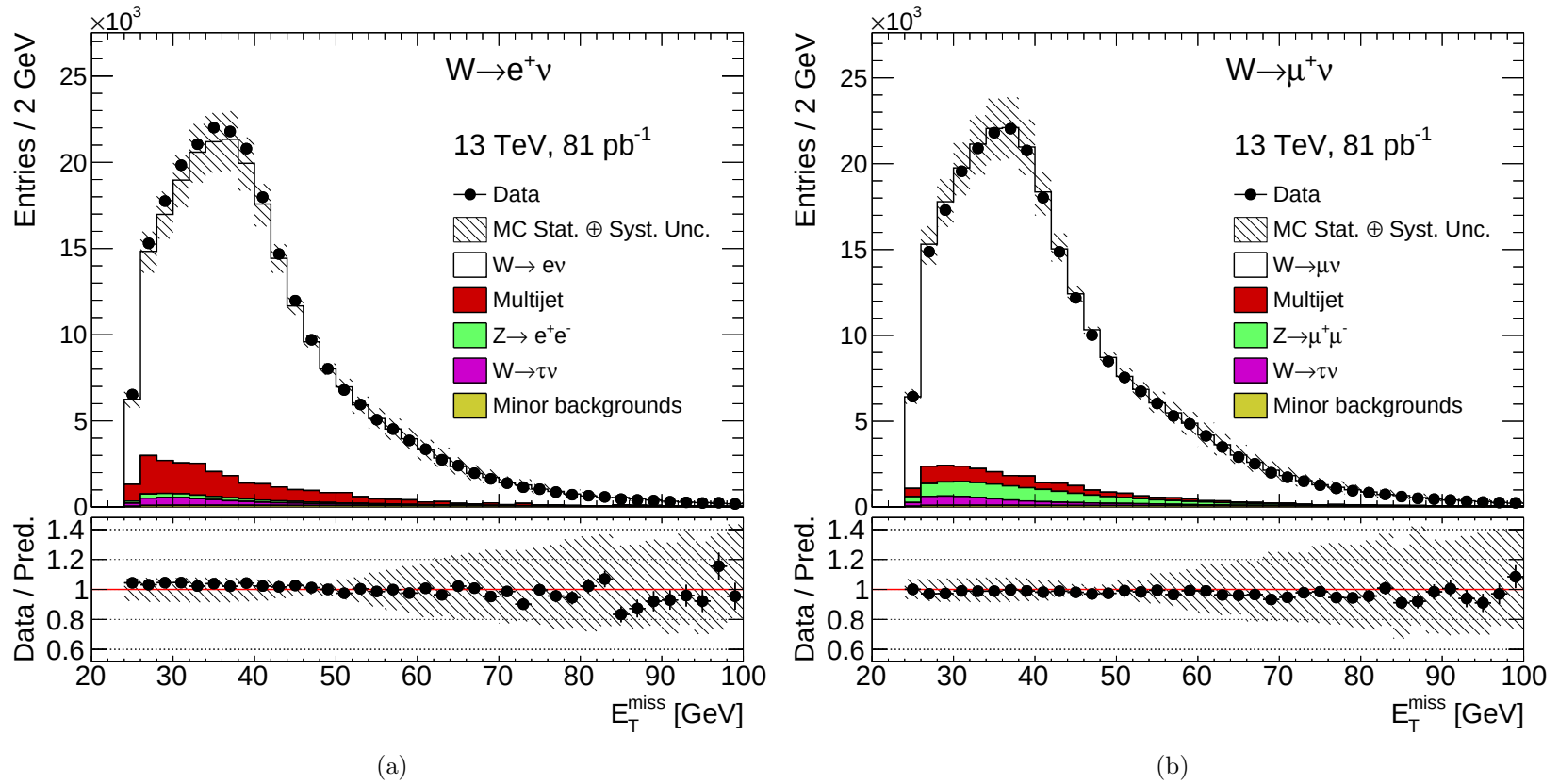


Figure 4.17: Missing Energy, E_T^{miss} , in the (a) $W^+ \rightarrow e^+ \nu_e$ and (b) $W^+ \rightarrow \mu^+ \nu_\mu$ channels. Distributions are shown after full event selection (Section 4.2). Signal and background predictions other than multijet are derived from Monte-Carlo simulation. Multijet normalization and shape are extrapolated from data control regions, as described in Section 4.4.2. Data points in black include statistical uncertainties. Shaded error bands represent systematic uncertainties on signal + background predictions, as described in Section 4.5, for each bin. A 5% uncertainty on the total integrated luminosity is omitted from these uncertainty bands.

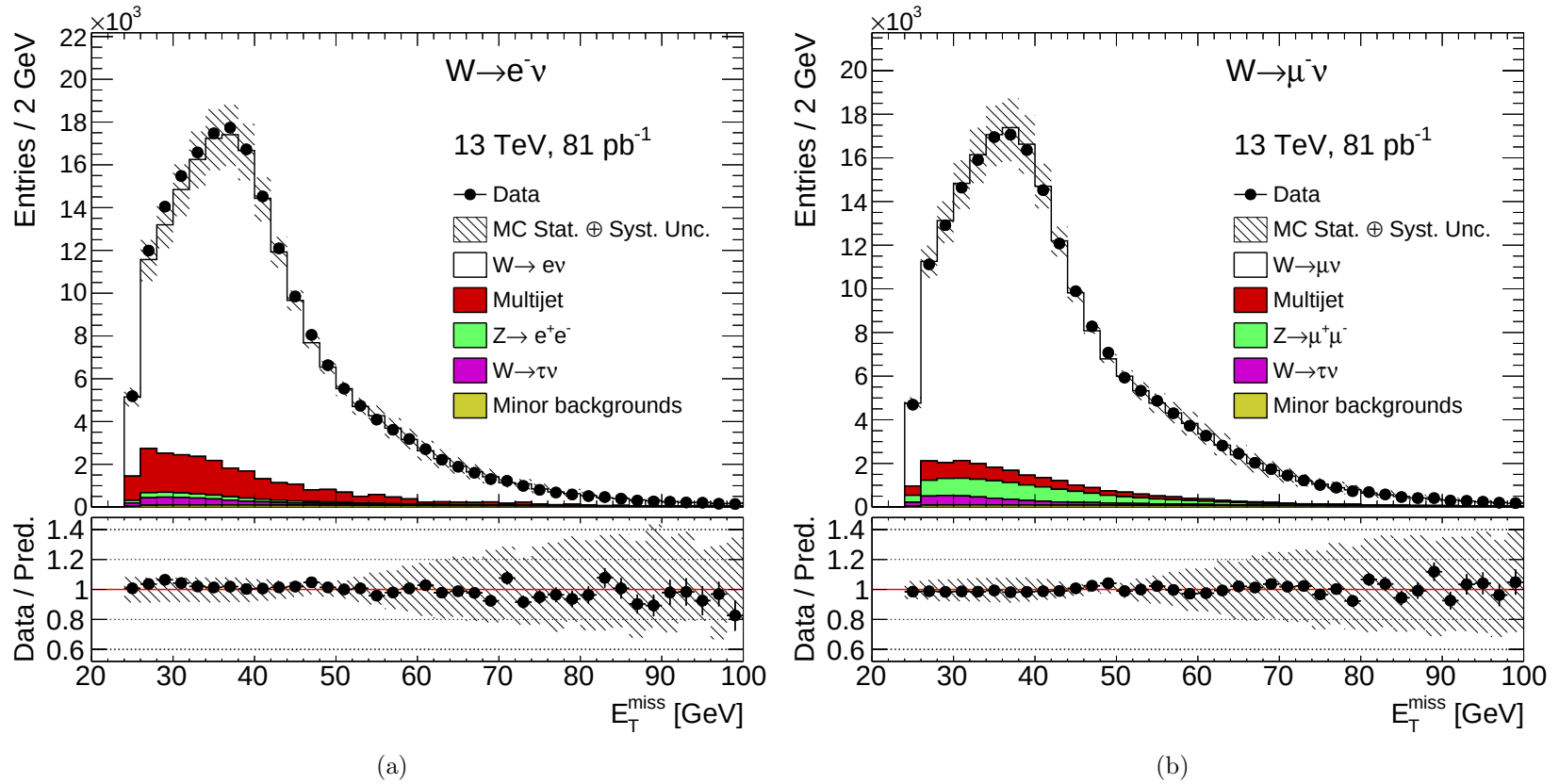


Figure 4.18: Missing Energy, E_T^{miss} , in the (a) $W^- \rightarrow e^- \bar{\nu}_e$ and (b) $W^- \rightarrow \mu^- \bar{\nu}_\mu$ channels. Distributions are shown after full event selection (Section 4.2). Signal and background predictions other than multijet are derived from Monte-Carlo simulation. Multijet normalization and shape are extrapolated from data control regions, as described in Section 4.4.2. Data points in black include statistical uncertainties. Shaded error bands represent systematic uncertainties on signal + background predictions, as described in Section 4.5, for each bin. A 5% uncertainty on the total integrated luminosity is omitted from these uncertainty bands.

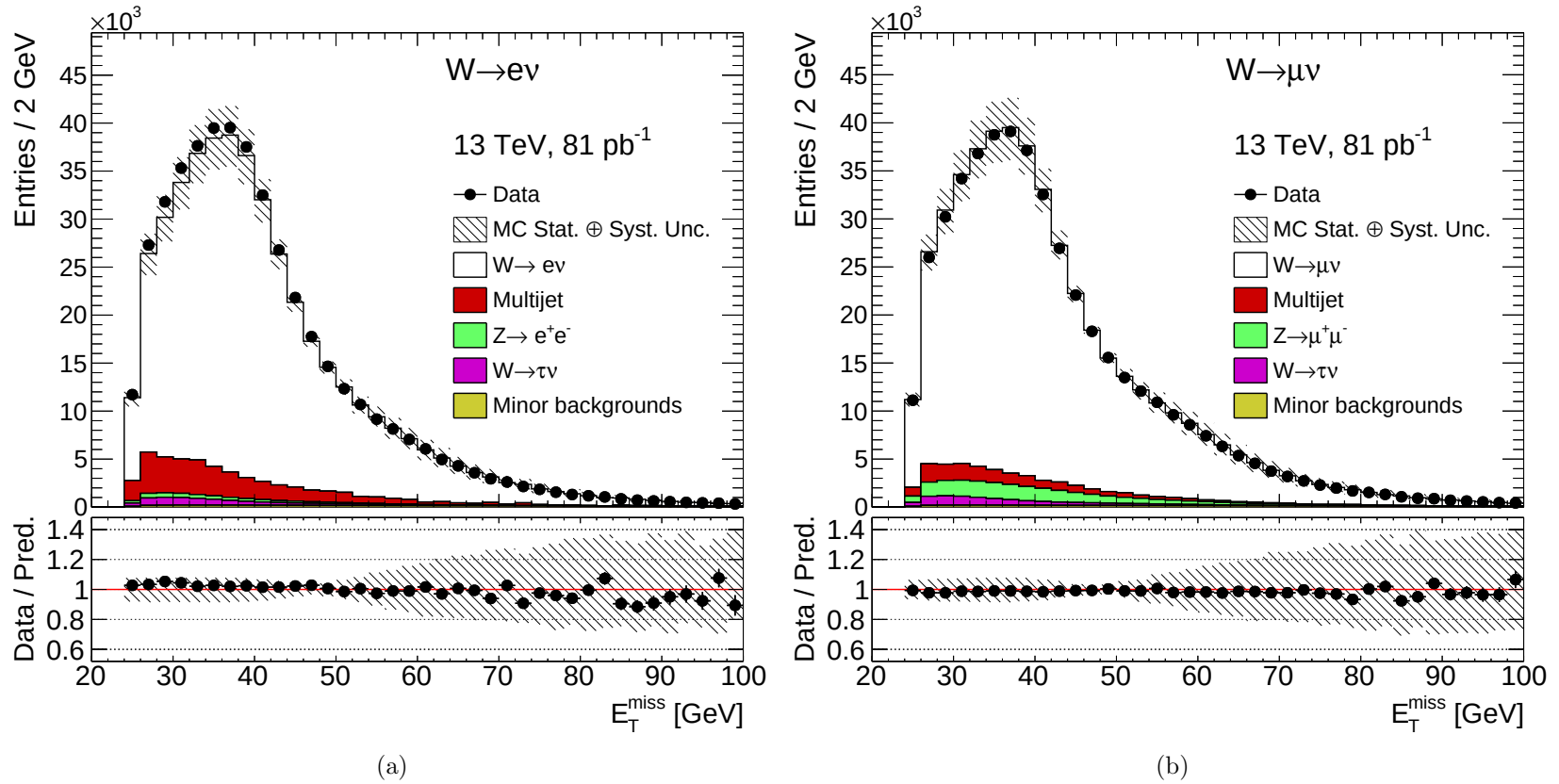
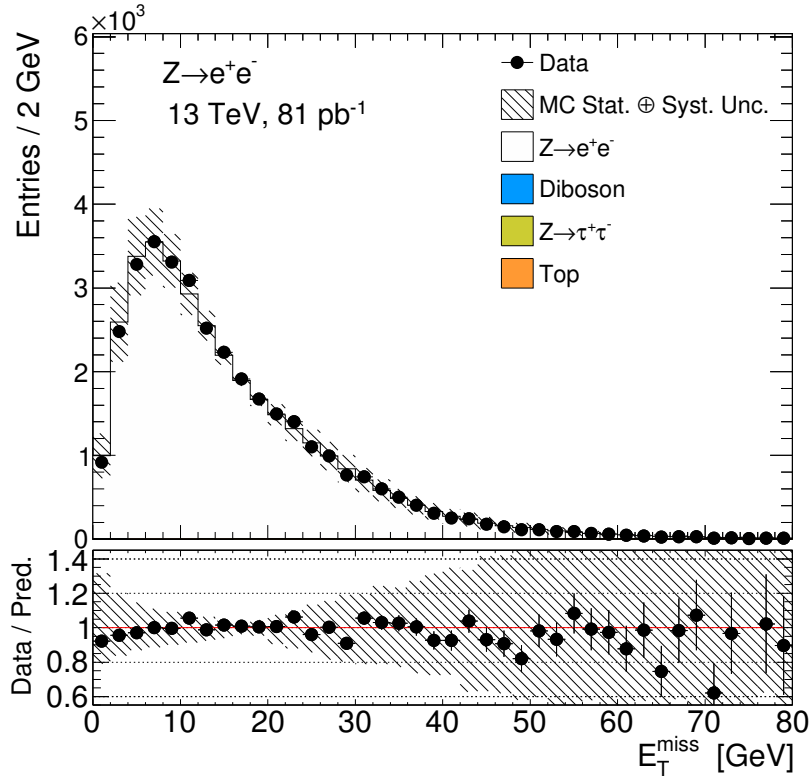
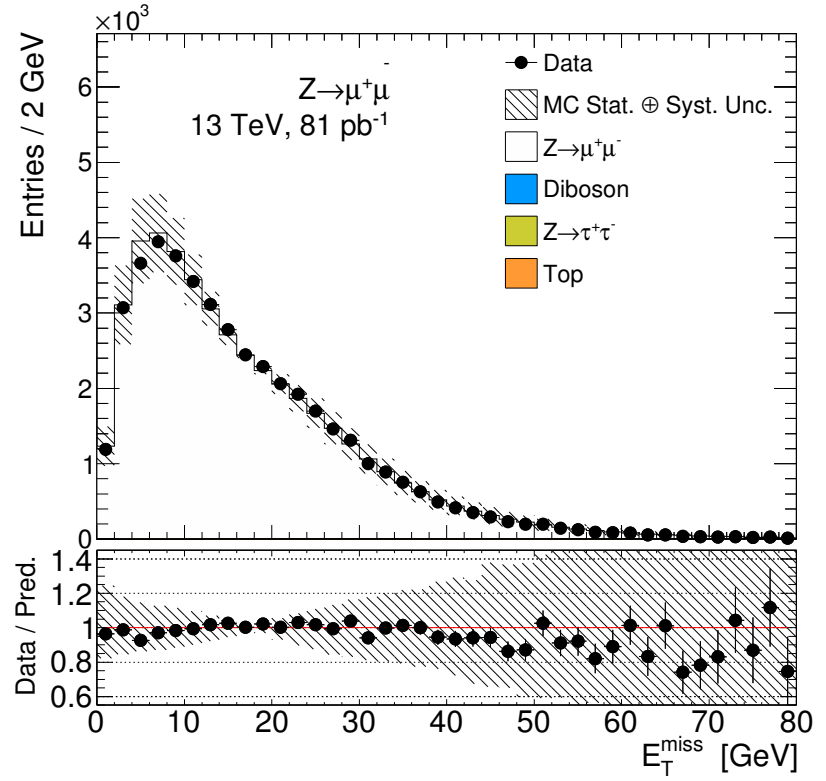


Figure 4.19: Missing Energy, E_T^{miss} , in the (a) $W^\pm \rightarrow e^\pm \nu_e$ and (b) $W^\pm \rightarrow \mu^\pm \nu_\mu$ channels. Distributions are shown after full event selection (Section 4.2). Signal and background predictions other than multijet are derived from Monte-Carlo simulation. Multijet normalization and shape are extrapolated from data control regions, as described in Section 4.4.2. Data points in black include statistical uncertainties. Shaded error bands represent systematic uncertainties on signal + background predictions, as described in Section 4.5, for each bin. A 5% uncertainty on the total integrated luminosity is omitted from these uncertainty bands.

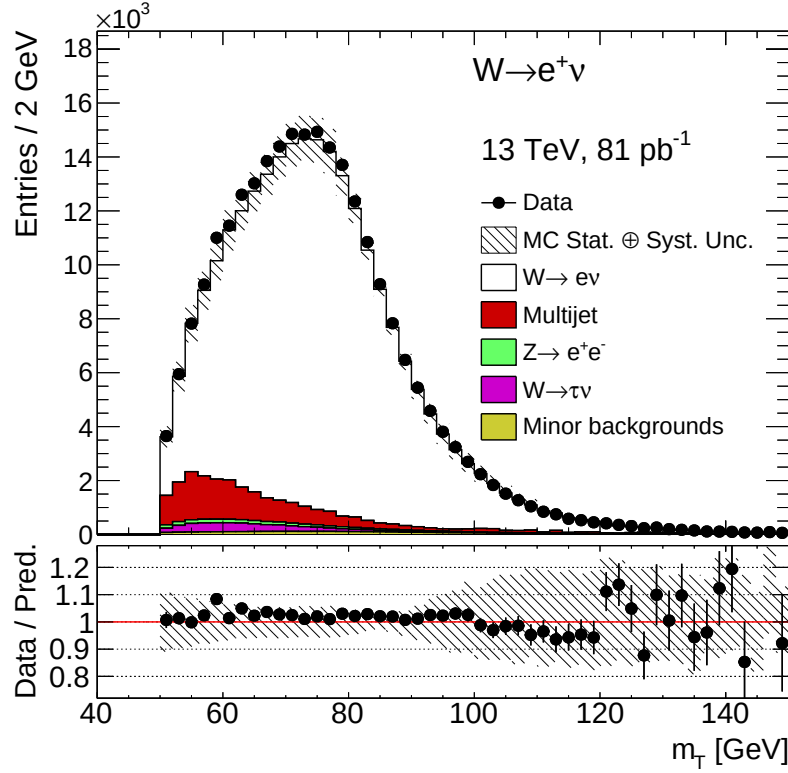


(a)

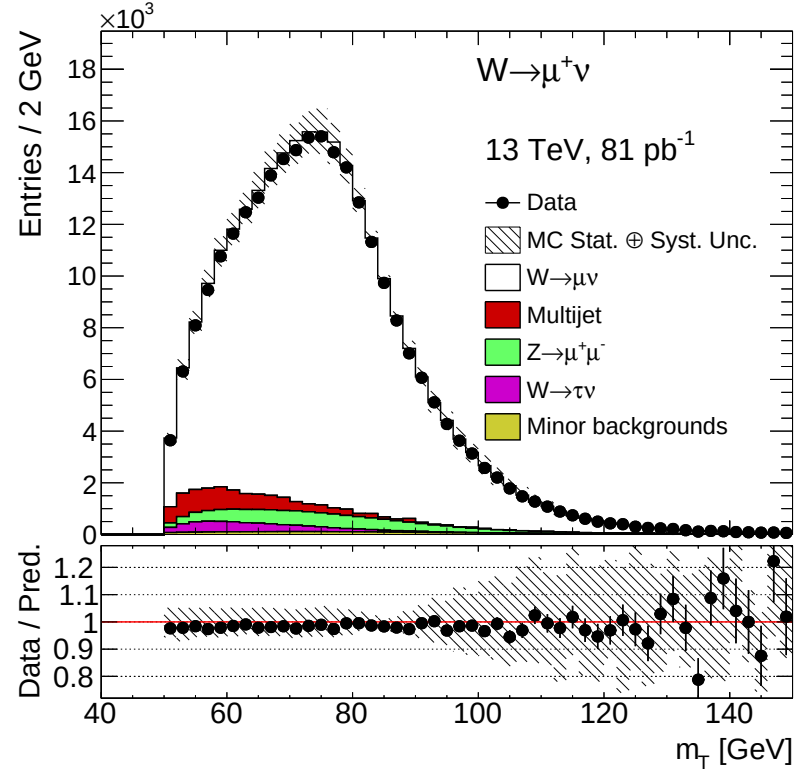


(b)

Figure 4.20: Missing Energy, $\cancel{E}_T$, in the (a) $Z \rightarrow e^+e^-$ and (b) $Z \rightarrow \mu^+\mu^-$ channels. All missing energy in Z signal events is attributable to pileup or resolution of $\cancel{E}_T$ reconstruction. Distributions are shown after full event selection (Section 4.2). Signal and background predictions are derived from Monte-Carlo simulation. Data points in black include statistical uncertainties. Shaded error bands represent systematic uncertainties on signal + background predictions, as described in Section 4.5, for each bin. A 5% uncertainty on the total integrated luminosity is omitted from these uncertainty bands.

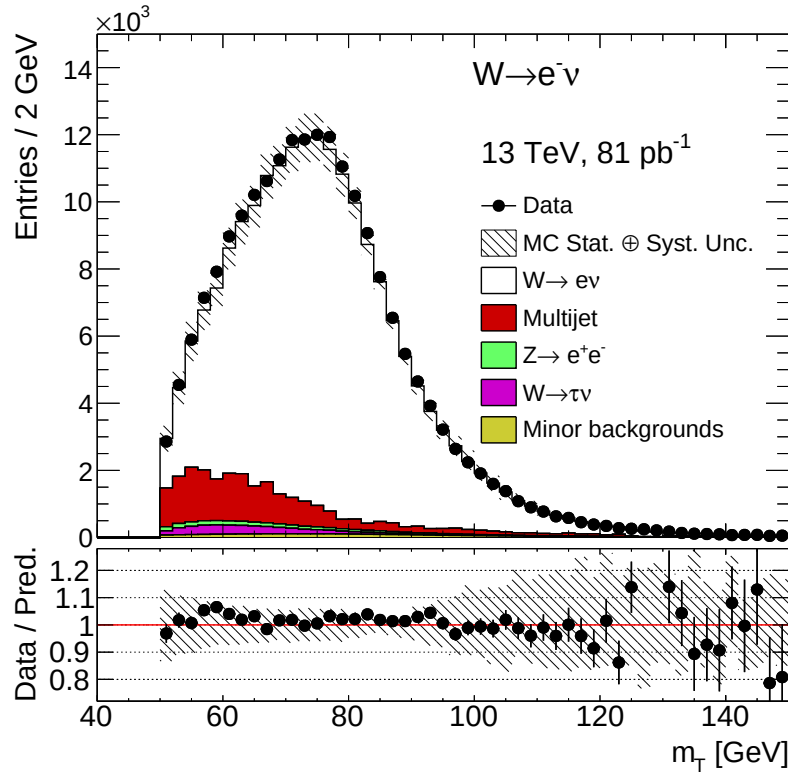


(a)

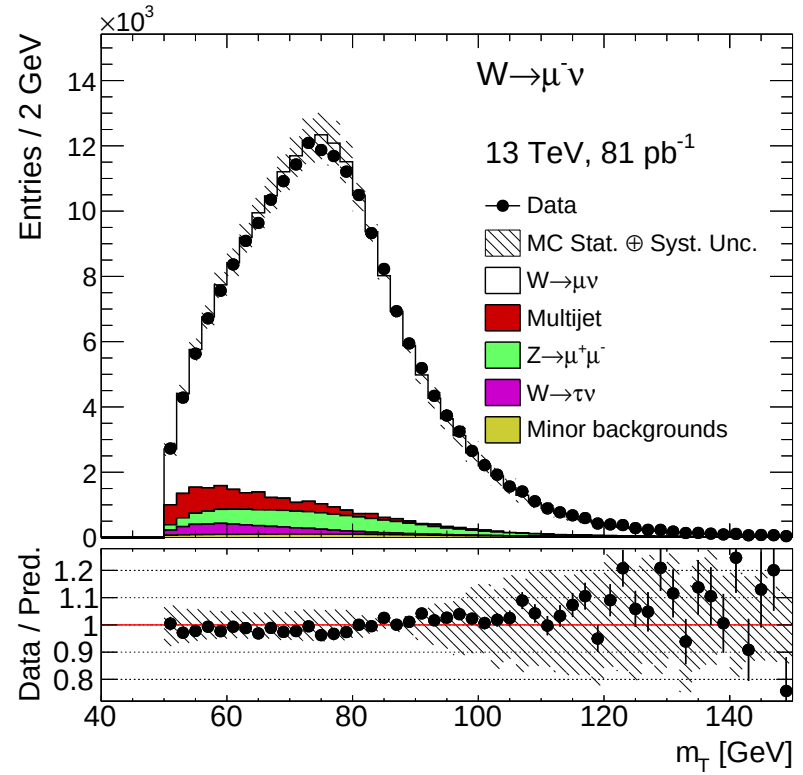


(b)

Figure 4.21: $W^\pm$ transverse mass, m_T^W , in the (a) $W^+ \rightarrow e^+ \nu_e$ and (b) $W^+ \rightarrow \mu^+ \nu_\mu$ channels. Distributions are shown after full event selection (Section 4.2). Signal and background predictions other than multijet are derived from Monte-Carlo simulation. Multijet normalization and shape are extrapolated from data control regions, as described in Section 4.4.2. Data points in black include statistical uncertainties. Shaded error bands represent systematic uncertainties on signal + background predictions, as described in Section 4.5, for each bin. A 5% uncertainty on the total integrated luminosity is omitted from these uncertainty bands.

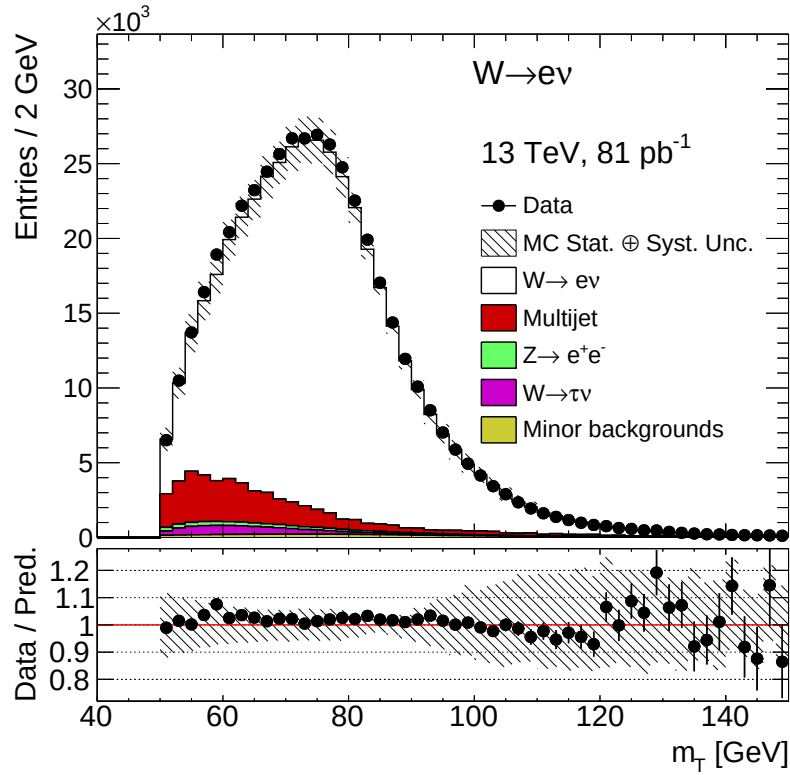


(a)

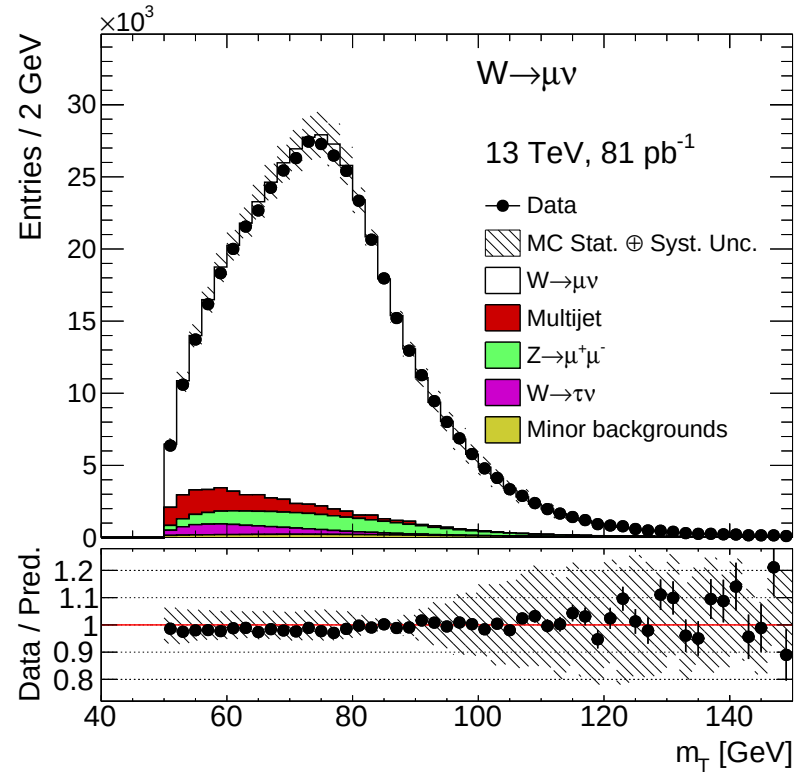


(b)

Figure 4.22: $W^\pm$ transverse mass, m_T^W , in the (a) $W^- \rightarrow e^- \bar{\nu}_e$ and (b) $W^- \rightarrow \mu^- \bar{\nu}_\mu$ channels. Distributions are shown after full event selection (Section 4.2). Signal and background predictions other than multijet are derived from Monte-Carlo simulation. Multijet normalization and shape are extrapolated from data control regions, as described in Section 4.4.2. Data points in black include statistical uncertainties. Shaded error bands represent systematic uncertainties on signal + background predictions, as described in Section 4.5, for each bin. A 5% uncertainty on the total integrated luminosity is omitted from these uncertainty bands.

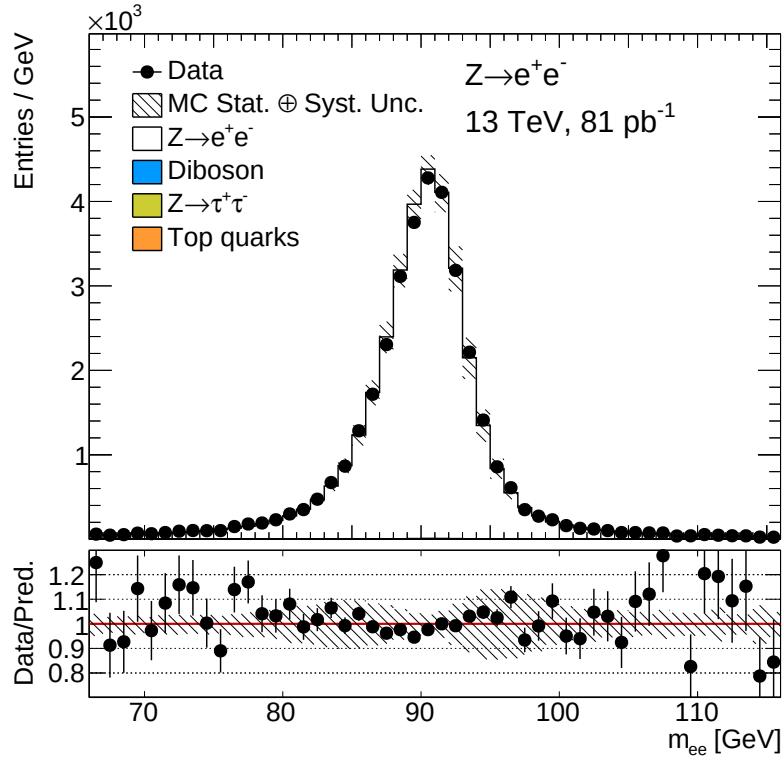


(a)

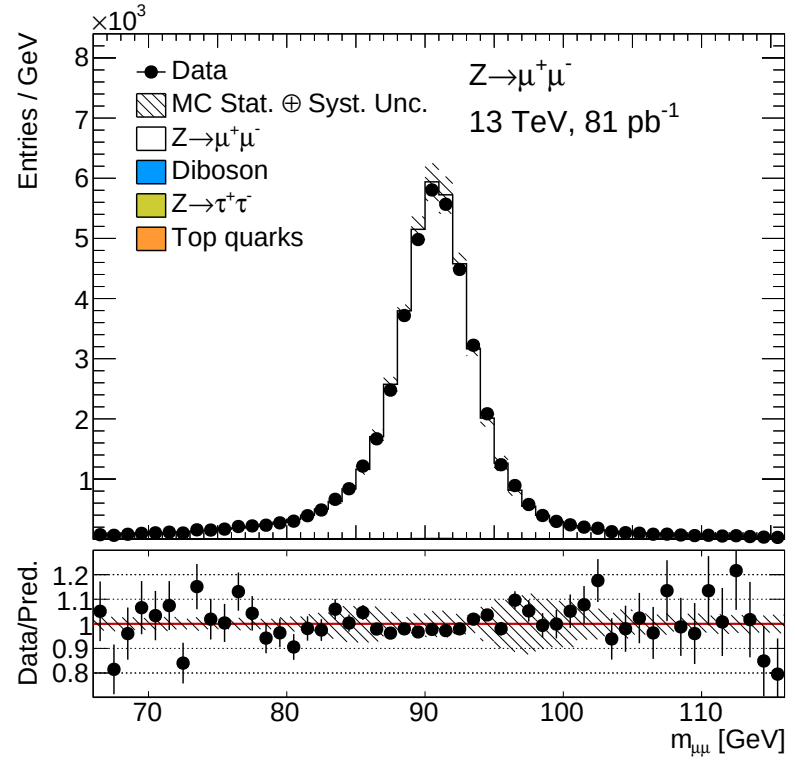


(b)

Figure 4.23: $W^\pm$ transverse mass, m_T^W , in the (a) $W^\pm \rightarrow e^\pm\nu_e$ and (b) $W^\pm \rightarrow \mu^\pm\nu_\mu$ channels. Distributions are shown after full event selection (Section 4.2). Signal and background predictions other than multijet are derived from Monte-Carlo simulation. Multijet normalization and shape are extrapolated from data control regions, as described in Section 4.4.2. Data points in black include statistical uncertainties. Shaded error bands represent systematic uncertainties on signal + background predictions, as described in Section 4.5, for each bin. A 5% uncertainty on the total integrated luminosity is omitted from these uncertainty bands.

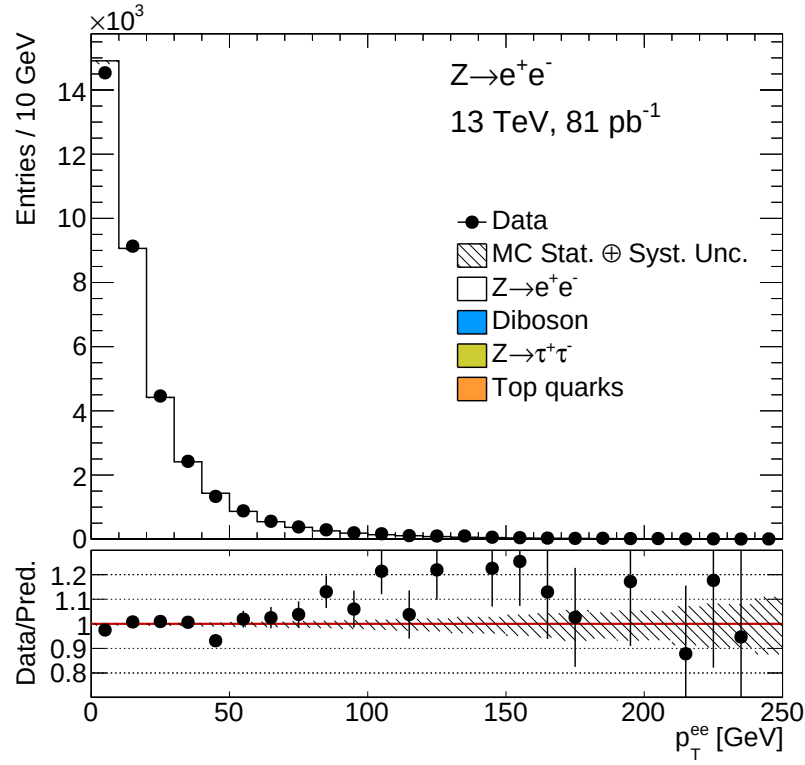


(a)

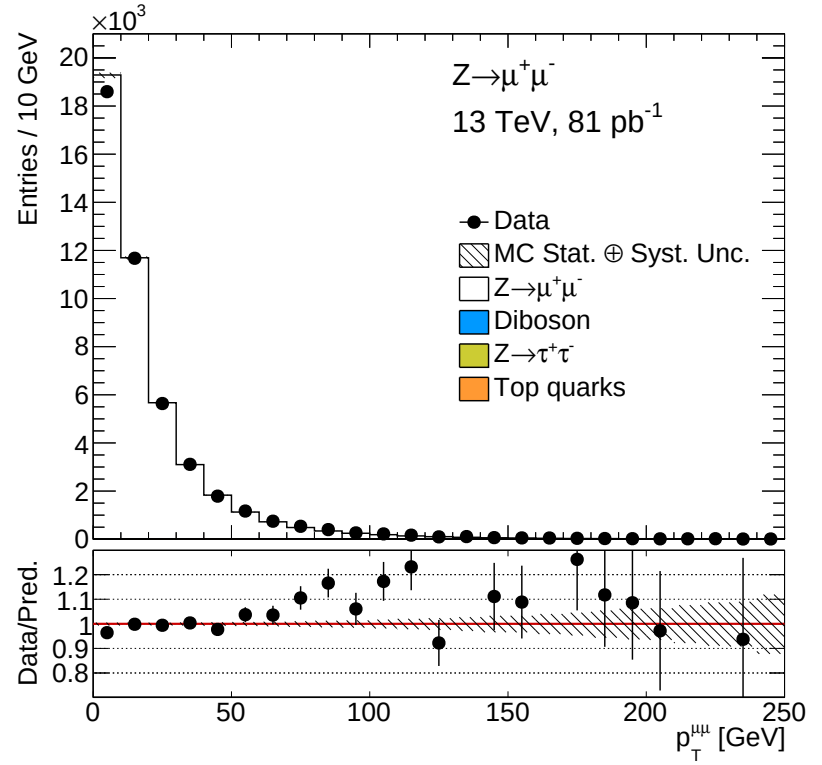


(b)

Figure 4.24: Z dilepton invariant mass, $m_{\ell\ell}^Z$. Distributions are shown after full event selection (Section 4.2). Signal and background predictions are derived from Monte-Carlo simulation. Data points in black include statistical uncertainties. Shaded error bands represent systematic uncertainties on signal + background predictions, as described in Section 4.5, for each bin. A 5% uncertainty on the total integrated luminosity is omitted from these uncertainty bands.

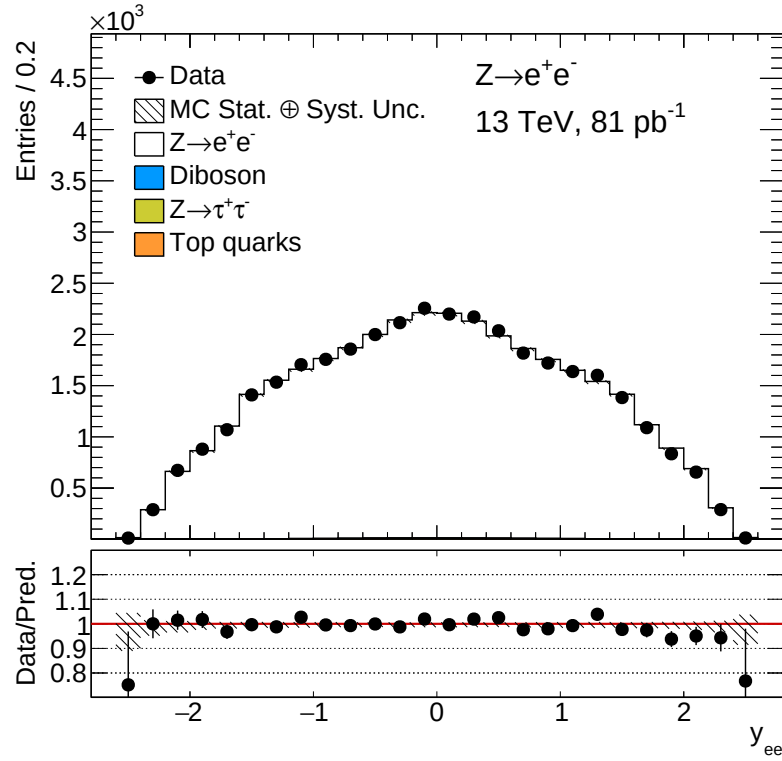


(a)

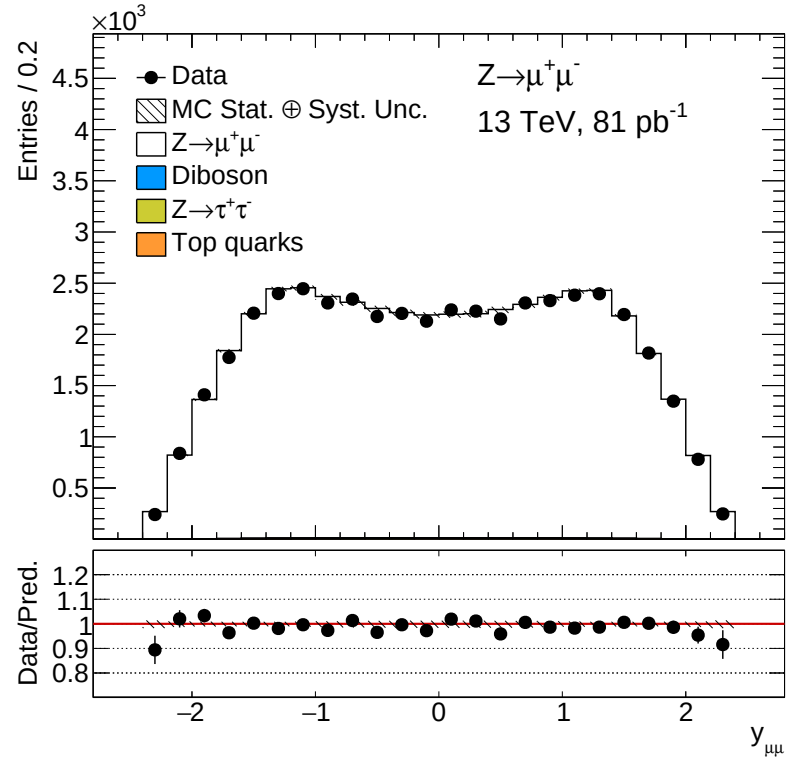


(b)

Figure 4.25: Z transverse momentum, p_T^Z . Distributions are shown after full event selection (Section 4.2). Signal and background predictions are derived from Monte-Carlo simulation. Data points in black include statistical uncertainties. Shaded error bands represent systematic uncertainties on signal + background predictions, as described in Section 4.5, for each bin. A 5% uncertainty on the total integrated luminosity is omitted from these uncertainty bands.



(a)



(b)

Figure 4.26: Z boson rapidity, y^Z . Distributions are shown after full event selection (Section 4.2). Signal and background predictions are derived from Monte-Carlo simulation. Data points in black include statistical uncertainties. Shaded error bands represent systematic uncertainties on signal + background predictions, as described in Section 4.5, for each bin. A 5% uncertainty on the total integrated luminosity is omitted from these uncertainty bands.

4.6.3 Cross Sections

Predictions and measurements for total and fiducial cross sections are summarized in Table 4.13, and shown compared to theory predictions based on several PDFs in Figures 4.27 through 4.33. Measured values and uncertainties in these figures reflect combinations of the electron and muon channel measurements, performed according to the uncertainty correlation model described in Section 4.5.18.

The measured total and fiducial cross sections do not exhibit strong discrimination against any of the selected PDFs. This is due in part to the consistency of the PDF predictions themselves - all predicted cross sections are consistent with one another at the 1σ level. However, a consistent pattern is visible through all channels and combinations, in which the ABM12 and MMHT14nnlo68CL PDFs approach the measured central central cross section values better than CT14nnlo and NNPDF3.0. Cross sections calculated from all four PDFs are consistent with the corresponding measured values at the 1σ level.

	fiducial (pb)	total (pb)
$W^+ \rightarrow e^+ \nu_e$	$4660 \pm 10 \text{ (stat)} \pm 130 \text{ (syst)} \pm 250 \text{ (lumi)}$	$12180 \pm 30 \text{ (stat)} \pm 410 \text{ (syst)} \pm 650 \text{ (lumi)}$
$W^+ \rightarrow \mu^+ \nu_\mu$	$4480 \pm 10 \text{ (stat)} \pm 90 \text{ (syst)} \pm 240 \text{ (lumi)}$	$11700 \pm 20 \text{ (stat)} \pm 320 \text{ (syst)} \pm 620 \text{ (lumi)}$
$W^+ \rightarrow \ell^+ \nu_\ell$	$4511 \pm 7 \text{ (stat)} \pm 90 \text{ (syst)} \pm 226 \text{ (lumi)}$	$11779 \pm 19 \text{ (stat)} \pm 319 \text{ (syst)} \pm 589 \text{ (lumi)}$
	$4420^{+130}_{-140}(\text{PDF}) \pm 50(\text{scale}) \pm 80(\text{other})$	$11540^{+320}_{-310}(\text{PDF}) \pm 150(\text{scale}) \pm 160(\text{other})$
$W^- \rightarrow e^- \bar{\nu}_e$	$3570 \pm 10 \text{ (stat)} \pm 140 \text{ (syst)} \pm 200 \text{ (lumi)}$	$8960 \pm 20 \text{ (stat)} \pm 380 \text{ (syst)} \pm 490 \text{ (lumi)}$
$W^- \rightarrow \mu^- \bar{\nu}_\mu$	$3470 \pm 10 \text{ (stat)} \pm 80 \text{ (syst)} \pm 190 \text{ (lumi)}$	$8710 \pm 20 \text{ (stat)} \pm 250 \text{ (syst)} \pm 470 \text{ (lumi)}$
$W^- \rightarrow \ell^- \bar{\nu}_\ell$	$3483 \pm 6 \text{ (stat)} \pm 72 \text{ (syst)} \pm 174 \text{ (lumi)}$	$8751 \pm 16 \text{ (stat)} \pm 238 \text{ (syst)} \pm 438 \text{ (lumi)}$
	$3400^{+90}_{-110}(\text{PDF}) \pm 40(\text{scale}) \pm 60(\text{other})$	$8540^{+210}_{-240}(\text{PDF}) \pm 110(\text{scale}) \pm 120(\text{other})$
$Z \rightarrow e^+ e^-$	$777 \pm 4 \text{ (stat)} \pm 8 \text{ (syst)} \pm 39 \text{ (lumi)}$	$1978 \pm 11 \text{ (stat)} \pm 40 \text{ (syst)} \pm 99 \text{ (lumi)}$
$Z \rightarrow \mu^+ \mu^-$	$774 \pm 4 \text{ (stat)} \pm 8 \text{ (syst)} \pm 39 \text{ (lumi)}$	$1969 \pm 9 \text{ (stat)} \pm 41 \text{ (syst)} \pm 98 \text{ (lumi)}$
$Z \rightarrow l^+ l^-$	$775 \pm 3 \text{ (stat)} \pm 6 \text{ (syst)} \pm 39 \text{ (lumi)}$	$1972 \pm 7 \text{ (stat)} \pm 38 \text{ (syst)} \pm 99 \text{ (lumi)}$
	$740^{+20}_{-30}(\text{PDF}) \pm 10(\text{scale}) \pm 10(\text{other})$	$1890 \pm 50(\text{PDF}) \pm 30(\text{scale}) \pm 30(\text{other})$

Table 4.13: Measured total and fiducial cross sections with selected predictions (below measurement, where applicable).

4.6.4 Cross Section Ratios

Predictions and measurements of the cross section ratios of interest are shown in Table 4.14, and in Figures 4.35 through 4.38.

The lepton universality ratios $\sigma_{W^\pm \rightarrow e^\pm \nu_e}^{\text{fid}} / \sigma_{W^\pm \rightarrow \mu^\pm \nu_\mu}^{\text{fid}}$ and $\sigma_{Z \rightarrow e^+ e^-}^{\text{fid}} / \sigma_{Z \rightarrow \mu^+ \mu^-}^{\text{fid}}$ are shown in Figure 4.34, as compared to a global average performed by the Particle Data Group [5], and Standard Model theory expectation ($R_W = R_Z = 1$). Within experimental uncertainty, these measurements agree with the global average and theoretical predictions. Compatible experimental values for electronic and muonic branching ratios are an important prerequisite to the combination of electron and muon channels into generic leptonic cross sections $\sigma_{W^+ \rightarrow \ell^+ \nu_\ell}^{\text{fid}}$, $\sigma_{W^- \rightarrow \ell^- \bar{\nu}_\ell}^{\text{fid}}$, and $\sigma_{Z \rightarrow \ell^+ \ell^-}^{\text{fid}}$, as presented in Section 4.6.3.

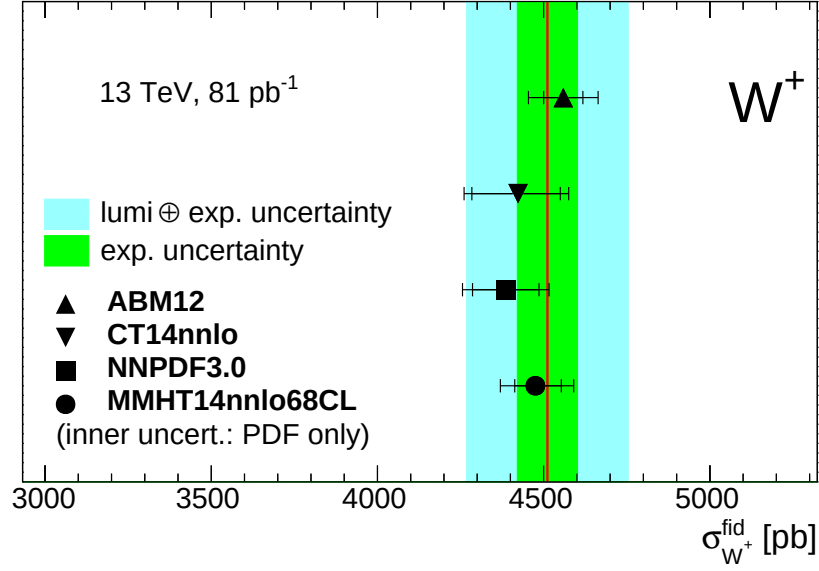
The ratios of greatest physics interest are $R_{W^\pm/Z} = \sigma_{W^\pm}^{\text{fid}} / \sigma_Z^{\text{fid}}$ and $R_{W^+/W^-} = \sigma_{W^+}^{\text{fid}} / \sigma_{W^-}^{\text{fid}}$. Despite the fact that the leading experimental uncertainty on luminosity does cancel in $R_{W^\pm/Z}$, many experimental and theoretical uncertainties are uncorrelated between the $W^\pm$ and Z channels. Consequently differences among the various PDF predictions evaluated for these measurements, and with respect to the measured value of $R_{W^\pm/Z}$, are not significant with respect to the total uncertainties. Within the overall 1σ agreement among the measured and predicted values of $R_{W^\pm/Z}$, a slight but consistent excess, of predictions above measurement is evident.

Because more experimental and theory uncertainties (significantly the multijet background normalization) are correlated between the W^+ and W^- channels, the $W^\pm$ charge ratio R_{W^+/W^-} achieves higher precision in both predictions and measurements (Figures 4.37 through 4.38). Predictions based on the various PDFs are still strictly compatible with one another at the 1σ level. However, 1% total

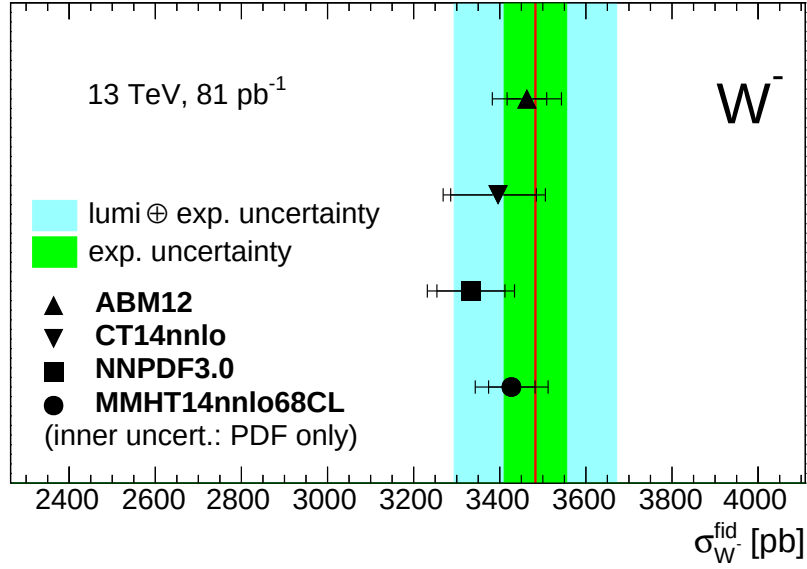
	ratio (theory)
$\sigma_{W^+}^{\text{fid}}/\sigma_{W^-}^{\text{fid}}$	$1.295 \pm 0.003 \pm 0.010$ 1.30 ± 0.01
$\sigma_W^{\text{fid}}/\sigma_Z^{\text{fid}}$	$10.31 \pm 0.04 \pm 0.20$ 10.54 ± 0.12

Table 4.14: Measured and predicted cross section Ratios.

uncertainty on the measured value of R_{W^+/W^-} affords some discrimination among them. As with the total and fiducial cross section measurements, CT14NNLO and MMHT14nnlo68CL are preferred.



(a)



(b)

Figure 4.27: Fiducial Cross Sections $\sigma_{W^+ \rightarrow \ell^+ \nu_\ell}^{\text{fid}}$, $\sigma_{W^- \rightarrow \ell^- \bar{\nu}_\ell}^{\text{fid}}$. Red line shows measured central value. The inner (green) uncertainty band includes all sources of experimental systematic uncertainty (as described in Section 4.5), excluding luminosity. The outer (cyan) band includes the contribution from luminosity error. Filled points are predicted values based on a selection of proton PDFs. The inner error bars on the predictions show uncertainties based on PDF eigenvector variations. The outer error bars include all other sources of theory uncertainty, as well.

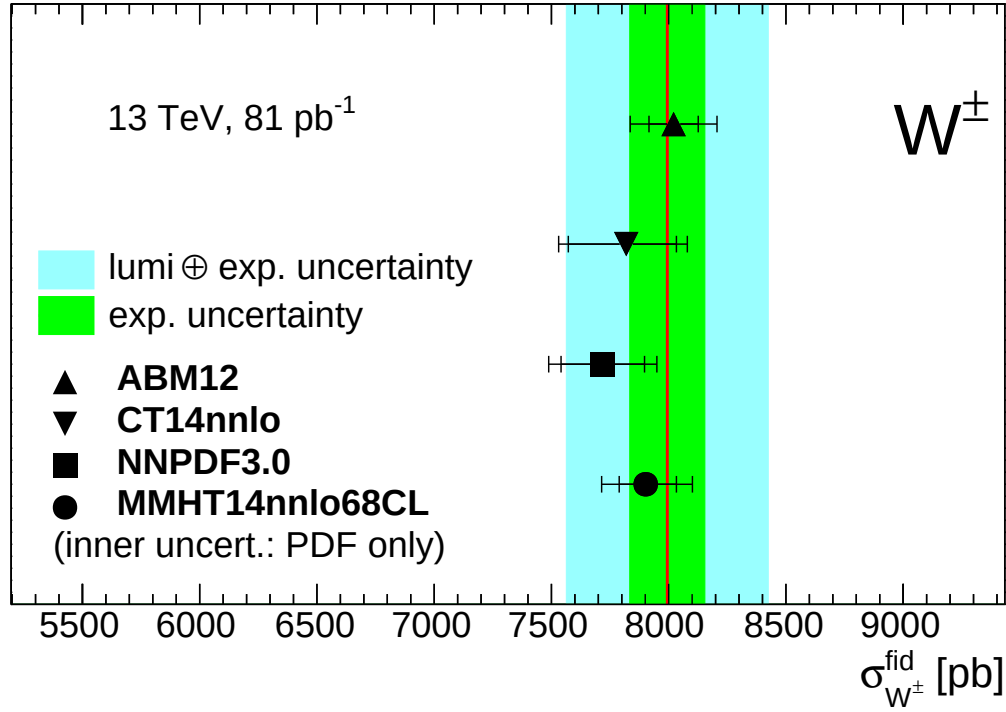
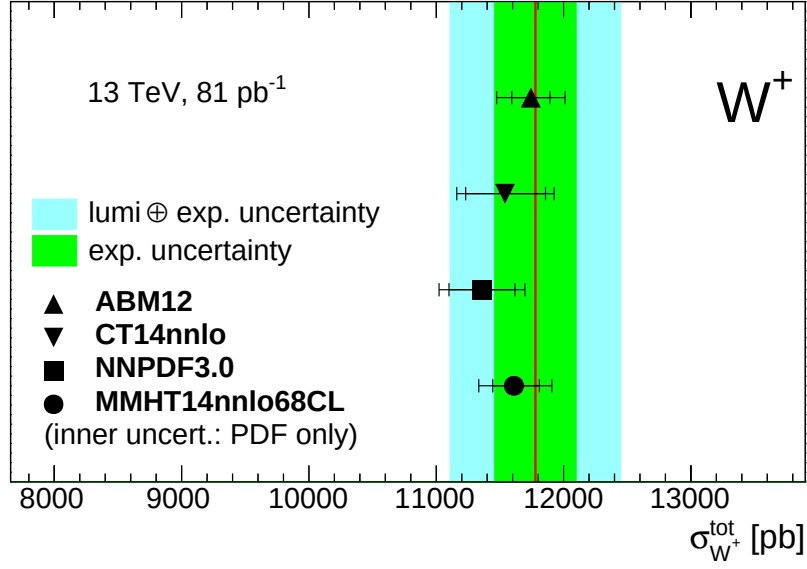
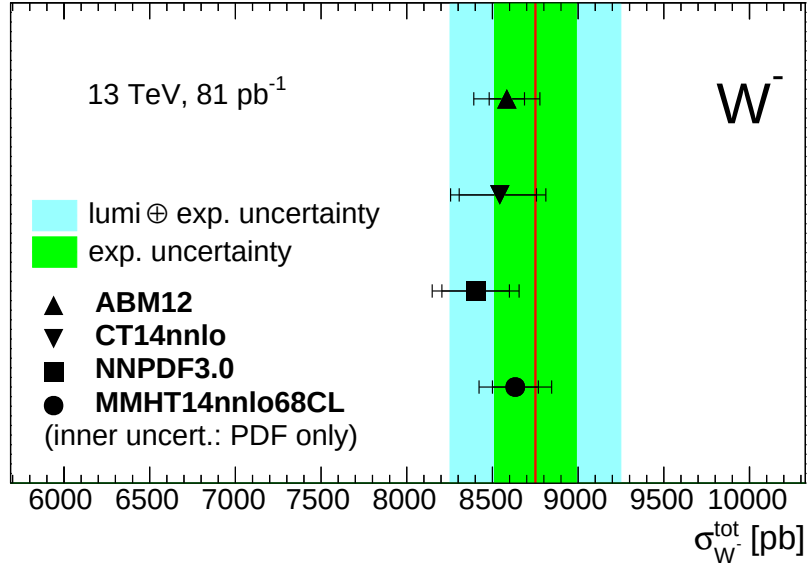


Figure 4.28: Fiducial Cross Section $\sigma_{W^\pm \rightarrow \ell^\pm \nu_\ell}^{\text{fid}}$. Red line shows measured central value. The inner (green) uncertainty band includes all sources of experimental systematic uncertainty (as described in Section 4.5), excluding luminosity. The outer (cyan) band includes the contribution from luminosity error. Filled points are predicted values based on a selection of proton PDFs. The inner error bars on the predictions show uncertainties based on PDF eigenvector variations. The outer error bars include all other sources of theory uncertainty, as well.



(a)



(b)

Figure 4.29: Total Cross Sections $\sigma_{W^+ \rightarrow \ell^+ \nu_\ell}^{\text{tot}}$, $\sigma_{W^- \rightarrow \ell^- \bar{\nu}_\ell}^{\text{tot}}$. Red line shows measured central value. The inner (green) uncertainty band includes all sources of experimental systematic uncertainty (as described in Section 4.5), excluding luminosity. The outer (celeste) band includes the contribution from luminosity error. Filled points are predicted values based on a selection of proton PDFs. The inner error bars on the predictions show uncertainties based on PDF eigenvector variations. The outer error bars include all other sources of theory uncertainty, as well.

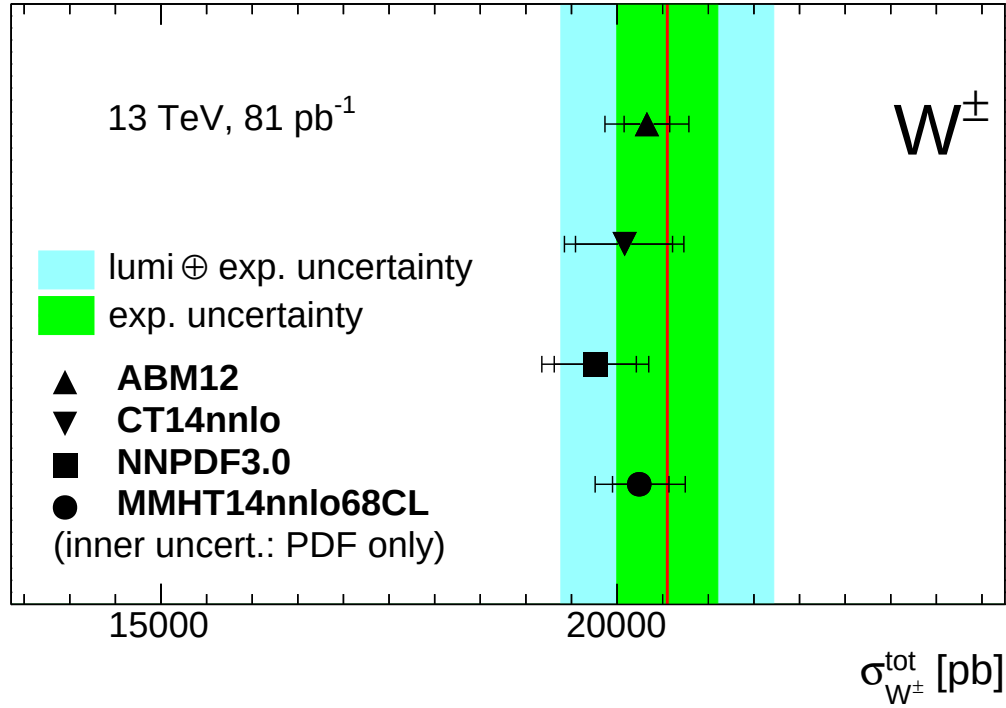


Figure 4.30: Total Cross Section $\sigma_{W^\pm \rightarrow \ell^\pm \nu_\ell}^{\text{tot}}$. Red line shows measured central value. The inner (green) uncertainty band includes all sources of experimental systematic uncertainty (as described in Section 4.5), excluding luminosity. The outer (cyan) band includes the contribution from luminosity error. Filled points are predicted values based on a selection of proton PDFs. The inner error bars on the predictions show uncertainties based on PDF eigenvector variations. The outer error bars include all other sources of theory uncertainty, as well.

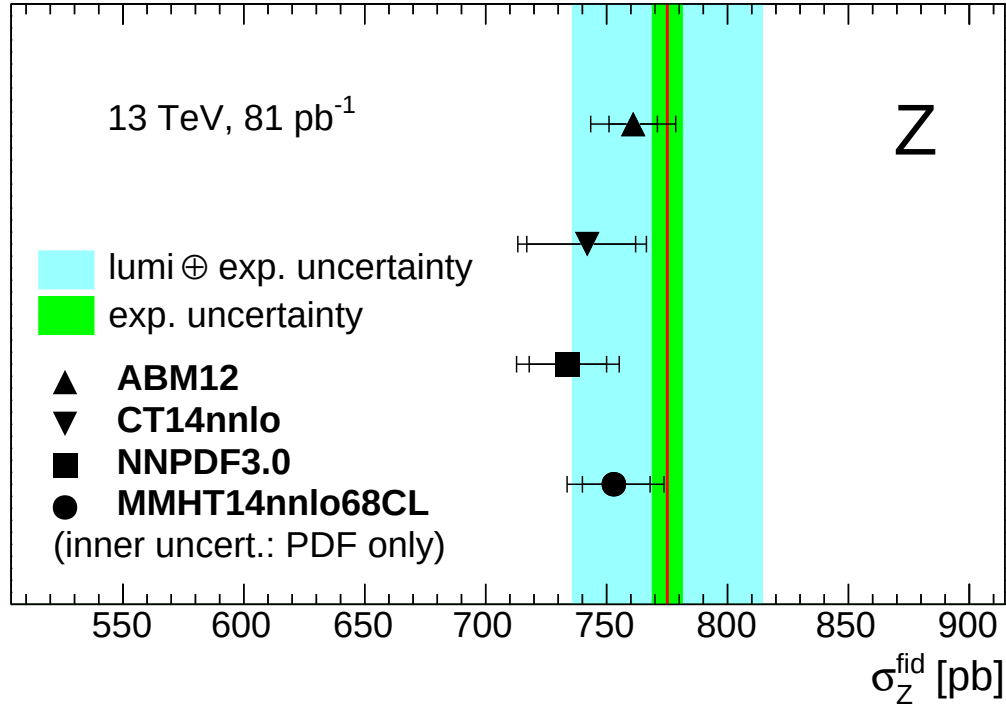


Figure 4.31: Fiducial Cross section $\sigma_{Z \rightarrow l+l-}^{\text{fid}}$. Red line shows measured central value. The inner (green) uncertainty band includes all sources of experimental systematic uncertainty (as described in Section 4.5), excluding luminosity. The outer (celeste) band includes the contribution from luminosity error. Filled points are predicted values based on a selection of proton PDFs. The inner error bars on the predictions show uncertainties based on PDF eigenvector variations. The outer error bars include all other sources of theory uncertainty, as well.

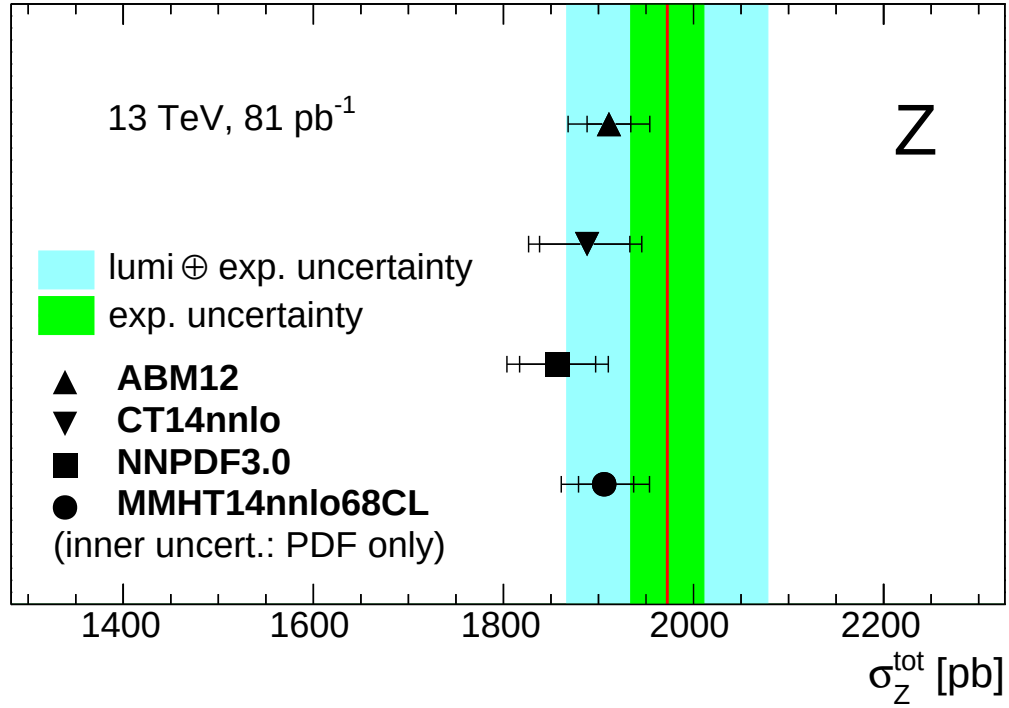
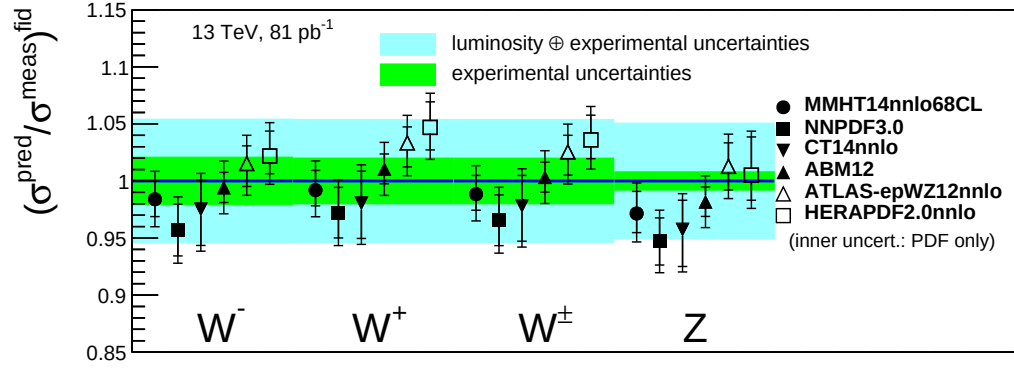
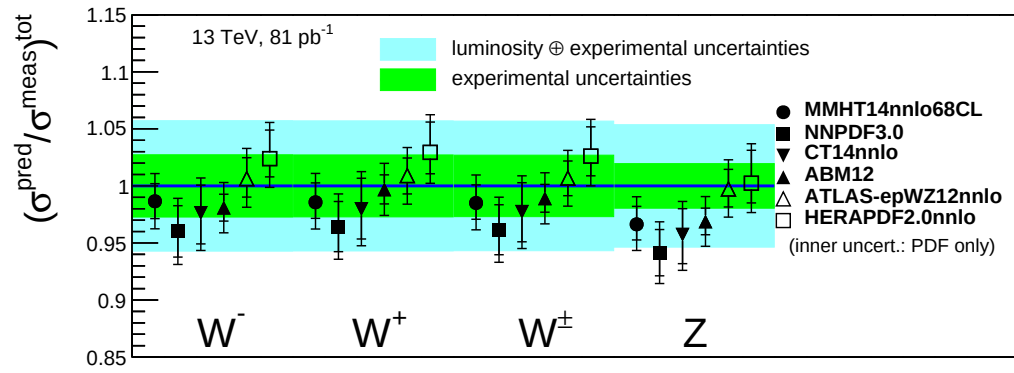


Figure 4.32: Total cross section $\sigma_{Z \rightarrow l+l-}^{\text{tot}}$. Red line shows measured central value. The inner (green) uncertainty band includes all sources of experimental systematic uncertainty (as described in Section 4.5), excluding luminosity. The outer (cyan) band includes the contribution from luminosity error. Filled points are predicted values based on a selection of proton PDFs. The inner error bars on the predictions show uncertainties based on PDF eigenvector variations. The outer error bars include all other sources of theory uncertainty, as well.



(a)



(b)

Figure 4.33: Ratios of predicted to measured (a) fiducial and (b) total cross sections, with predictions based on several PDFs.

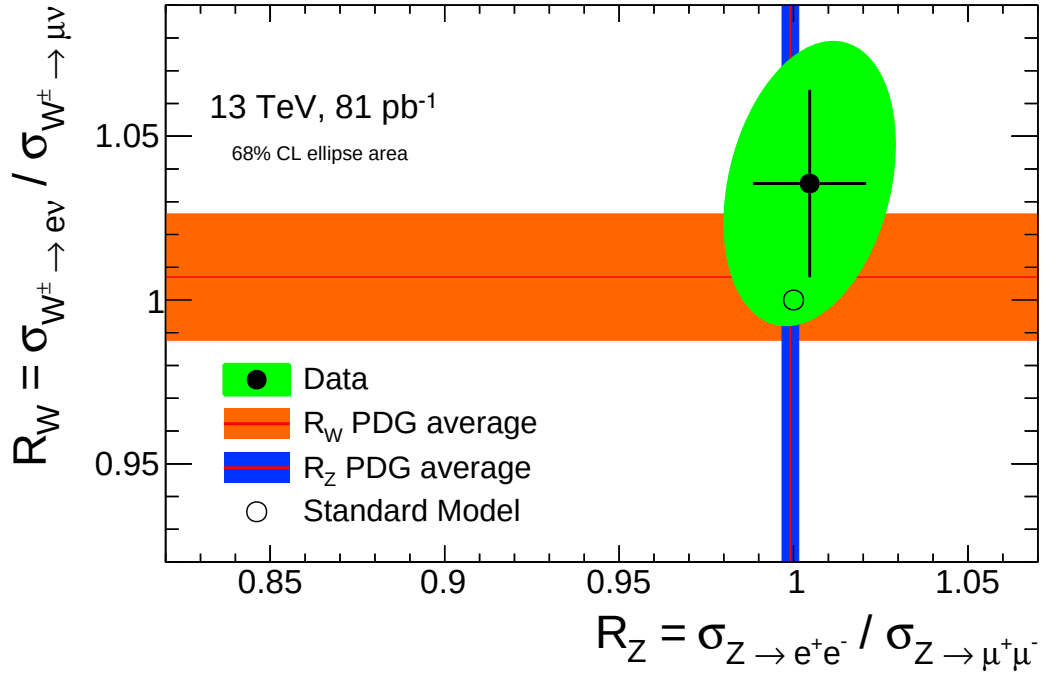
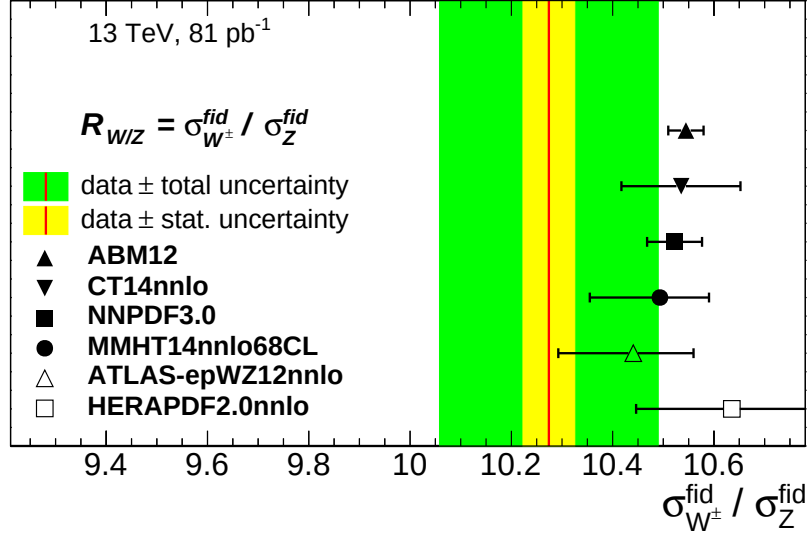
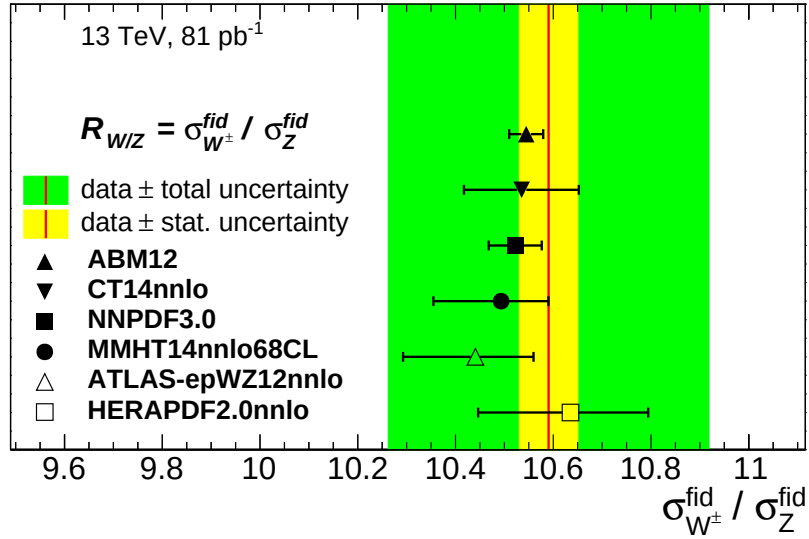


Figure 4.34: Measurement of lepton universality in $W^\pm$ decays (vertical axis) plotted against Z (horizontal) decays. The error bands around the PDG values represent total uncertainties on the global average. The black point shows the central values of this measurement. Orthogonal error bars show independent experimental errors on the universality ratio in the $W^\pm$ and Z channels. The green ellipse shows the correlated 1σ uncertainty in the R_W , R_Z plane.



(a)



(b)

Figure 4.35: $W^\pm/Z$ cross section ratio $R_{W^\pm/Z}$, in the (a) muon and (b) electron channels. The vertical red line shows the measured central value. The inner (yellow) uncertainty band shows experimental statistical uncertainty. The outer (green) uncertainty band includes all sources of experimental uncertainty, as described in Sections 4.5 and 4.5.18. Error bars on points show theory uncertainties based on PDF eigenvector variations.

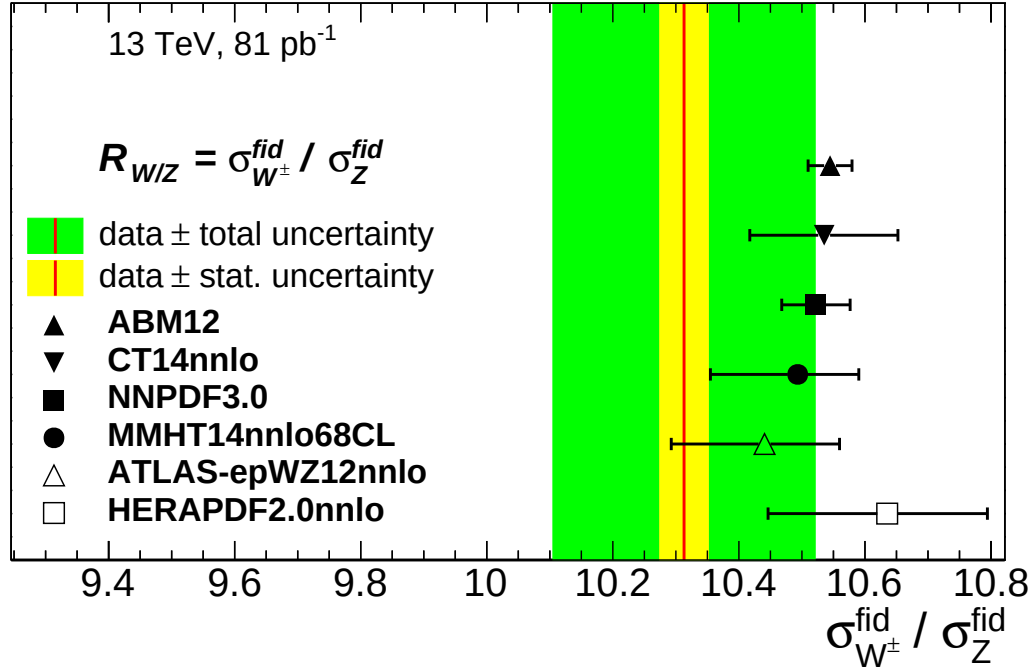
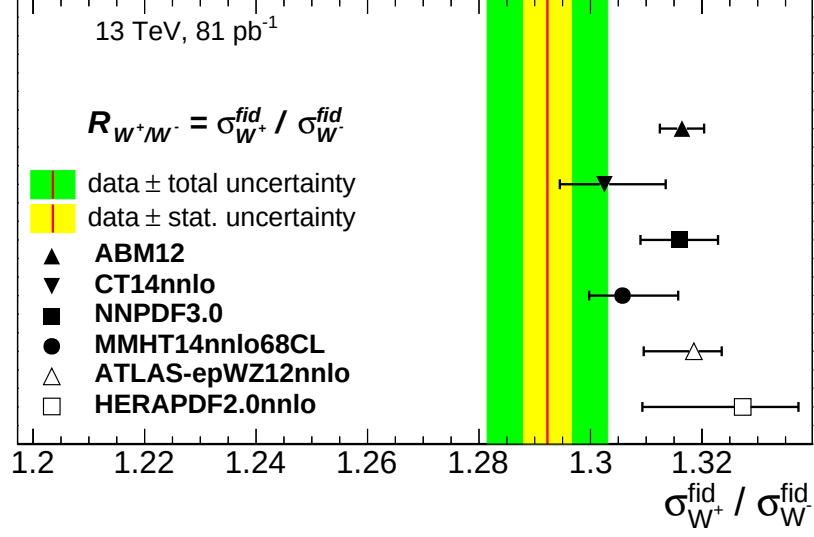
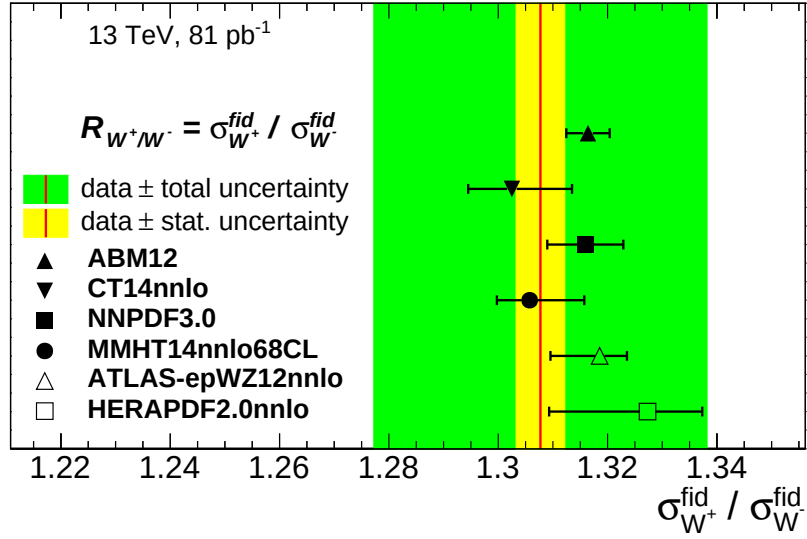


Figure 4.36: Boson cross section ratio $R_{W^\pm/Z}$, combined from the electron and muon analysis channels. The vertical red line shows the measured central value. The inner (yellow) uncertainty band shows experimental statistical uncertainty. The outer (green) uncertainty band includes all sources of experimental uncertainty, as described in Sections 4.5 and 4.5.18. Error bars on points show theory uncertainties based on PDF eigenvector variations.



(a)



(b)

Figure 4.37: $W^\pm$ charge ratio R_{W^+/W^-} , in the (a) muon and (b) electron channels. The vertical red line shows the measured central value. The inner (yellow) uncertainty band shows experimental statistical uncertainty. The outer (green) uncertainty band includes all sources of experimental uncertainty, as described in Sections 4.5 and 4.5.18. Error bars on points show theory uncertainties based on PDF eigenvector variations.

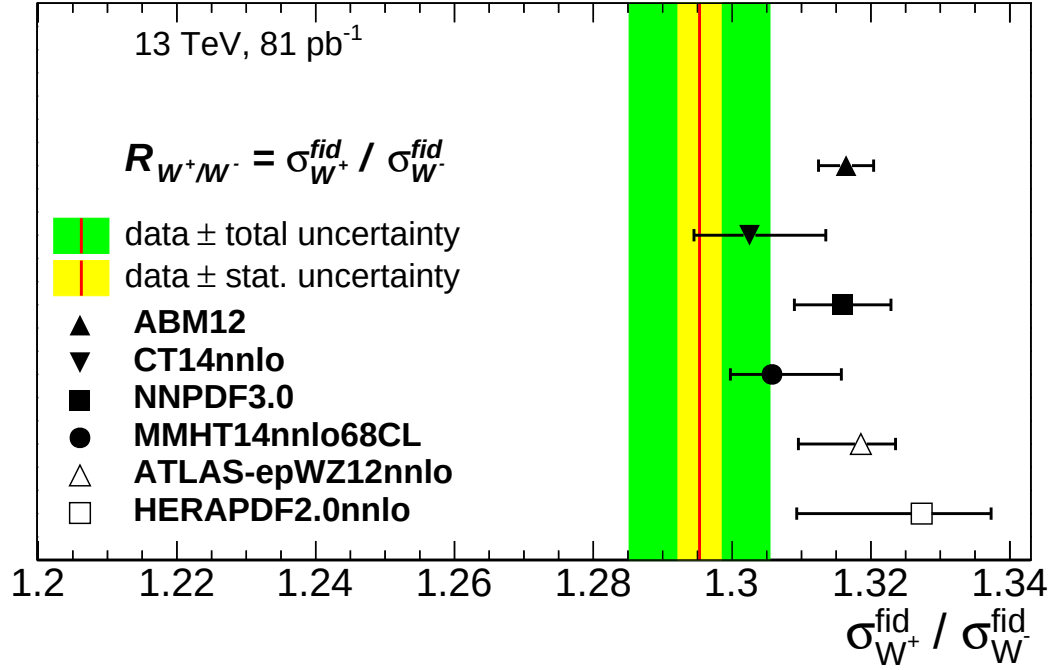


Figure 4.38: $W^\pm$ charge ratio R_{W^+/W^-} , combined from the electron and muon analysis channels. The vertical red line shows the measured central value. The inner (yellow) uncertainty band shows experimental statistical uncertainty. The outer (green) uncertainty band includes all sources of experimental uncertainty, as described in Sections 4.5 and 4.5.18. Error bars on points show theory uncertainties based on PDF eigenvector variations.

Conclusion

Inclusive cross sections for production of $W^\pm$ and Z bosons decaying to electronic and muonic final states were measured in $\sqrt{s} = 13$ TeV pp collisions using the ATLAS detector. Fiducial cross sections were evaluated within a limited experimental phase space. Fiducial acceptance factors $A_{W,Z}$ were calculated based on simulation which relate the fiducial cross sections to the total inclusive cross sections. Experimental uncertainties on fiducial and total cross sections are dominated by luminosity uncertainty (5%) in all analysis channels. Subleading uncertainties in the $W^\pm$ channels arise from multijet background normalizations, and jet energy scale and resolution measurement. The largest non-luminosity uncertainty in the Z channels comes from uncertainties on lepton reconstruction and identification efficiencies (at the sub-percent level).

Distributions in data of kinematic variables to which the cross section results are sensitive were compared to Monte-Carlo simulation as well, to validate the modeling of event-level kinematics and detector response. After experimental calibrations, kinematic distributions of interest are well-modeled by Monte-Carlo simulation.

Cross section measurements are compared to several predictions based on a selection of modern PDFs. All measured cross sections are compatible with all predictions at the 1σ level.

Ratios of interest among fiducial cross sections were evaluated, as well. Ratios benefit from the near-complete cancellation of the dominant uncertainty on luminosity. The lepton-universality ratios $R_{e/\mu}^Z$ and $R_{e/\mu}^W$ are compatible with the Standard-Model prediction of 1. The ratio R_{W^+/W^-} of W^+ and W^- cross sections was measured with less than 1% total experimental uncertainty. The measured value of R_{W^+/W^-} is compatible with Standard-Model prediction. The ratio $R_{W^\pm/Z}$ of $W^\pm$ and Z cross sections was evaluated as well. While almost all experimental ratios are strictly compatible at the 1σ level with all predictions considered, some PDFs were slightly favored.

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