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博士学位论文

在 ATLAS 探测器上测量 Z 玻色子的横向动量

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**Measurement of the transverse momentum of Z bosons with
ATLAS Detector**

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By

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Abstract

The Standard Model is so far the best theory to describe and predict the properties and interactions of fundamental particles. It successfully predicted the existence of W and Z bosons, that were discovered at the CERN SPS in 1983, and predicted the Higgs boson, that was observed by A Toroidal LHC Apparatus (ATLAS) and another experiment based on LHC, the Compact Muon Solenoid (CMS), in 2012. It is well known that many questions observed in experiments are not explained by the SM, hence physicists have been searching for the evidence of new physics, but so far no solid evidence has been established. Improving the precision of Standard Model parameters can constraint the properties of possible new physics or phenomena, indicating the right direction to look for new physics.

This thesis presents precise measurements of the W and Z boson transverse momentum using a special dataset collected by the ATLAS experiment from proton-proton collisions at 5 TeV and 13 TeV at the Large Hadron Collider (LHC). These measurements are key ingredients for the next W mass measurement from the ATLAS experiment that is planned to be released in the next few years. In addition, the thesis covers work done in the ATLAS detector upgrade, both in the vertex pixel detector (ITK) and the High Granularity Timing Detector (HGTD), for the HL-LHC planned to start in 2027. These detectors are essential to be able to continue doing this kind of precision physics in ATLAS in the longer term.

The W boson mass, m_W , is one of the most sensitive parameters in the standard model. Significant deviation between the prediction and measurement of the m_W would be a potential indication of new physics. Recently the precision measurement from the CDF II collaboration raised a significant tension between the experiment observations and the standard model expectations. The W mass measurement is obtained from the measurement of the momenta of the leptons and neutrinos from the W boson decay. The neutrino momenta is measured indirectly from the lepton and the energy deposited in the calorimeter from the hadronic recoil produced in p-p collisions against the W

boson. One of the main challenges in W mass measurements is the modeling of the W boson transverse momentum. A precision measurement of the W boson transverse momentum is a key ingredient for precise W mass measurement. Transverse momentum of W boson is measured through the hadronic recoil produced with W . The hadronic recoil is calibrated through the measurement of Z transverse momentum using dilepton measurements. Z and W boson transverse momentum measurements are great probes to explore the parton distribution functions of the proton and quantum chromodynamics, especially at low p_T region where the QCD fails to work in perturbative re-summations. ATLAS took datasets at low overlapping secondary proton-proton collisions condition, namely low pileup. The data corresponds to an integrated luminosity of 335 pb^{-1} at 13 TeV and 257 pb^{-1} at 5 TeV. Low pileup condition allows the hadronic recoil to be measured at much better precision, and QCD multi-jet backgrounds are highly suppressed in the signal region, thus provides great opportunity to make precision measurements on W boson mass and transverse momenta of W and Z bosons. My work on the Z boson transverse momenta measurements at $\sqrt{s} = 5$ and 13 TeV and hadronic recoil calibrations that improve the W transverse momenta measurements are presented in this thesis. The work is an important milestone towards the m_W measurements which should be finalized in around two years. I also worked on the ATLAS phase II upgrade project. For the pixel detector, I studied detector assembly techniques in the endcaps, while for the High Granularity Timing Detector, I measured the electronic properties of Low-Gain Avalanche Diode sensors. These detectors improve the momenta measurement and suppress pileup effects, that allows to make precision measurements on Standard Model parameters on the High Luminosity LHC.

Keywords: LHC, ATLAS, W and Z boson, transverse momentum, low pile-up dataset

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第 1 章 Introduction

The universe is composed of fundamental particles, including fermions and bosons. Particle physicists study the characteristics of fundamental particles and the interactions between those particles. Since 1970s, Murray Gell-Mann, Sheldon Glashow and Steven Weinberg has established Standard Model to explain the fundamental particles and the principles of interactions between them^[1-4].

The standard model has explained most of the phenomenons observed in the experiments. Moreover, the standard model predicted the existence of the Higgs boson, which was discovered by the ATLAS (A Toroidal LHC Apparatus) and CMS (Compact Muon Solenoid) experiments in 2012.^[5,6] In standard model, the universe is composed of fermions, which has spin $\frac{1}{2}$, including quarks (u, d, c, s, t, b) and leptons ($e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau$). A summary of the fundamental particles in the standard model is in Figure 1.1.

Standard Model is a non-abelian gauge theory with the symmetry group $SU(3)_C \otimes SU(2)_L \otimes U(1)_Y$ and has a total of twelve gauge bosons: the photon, three weak bosons and eight gluons. Gluons are the mediators of the strong interaction, which has the strongest coupling constant and shortest interaction length. $\gamma, W^\pm, Z$ are the mediators of electro-weak interactions. The Quantum chromodynamics (QCD) describes the strong interactions between quarks, it has characteristics such as asymptotic freedom and quark confinement. Asymptotic freedom means that when quarks are close enough, the strong forces between them are very small. Quark confinement means that when quarks go apart, the strong forces between them increase fast, so that quarks are always bonded together. The quantum electrodynamics (QED) is the rule for electro-weak force. In QED, the Electromagnetism is mediated by a photon, γ . And the weak interaction is mediated by $W^\pm, Z$. Each type of interactions has different length and power characteristic, so that each interaction dominates in a certain dimension range.

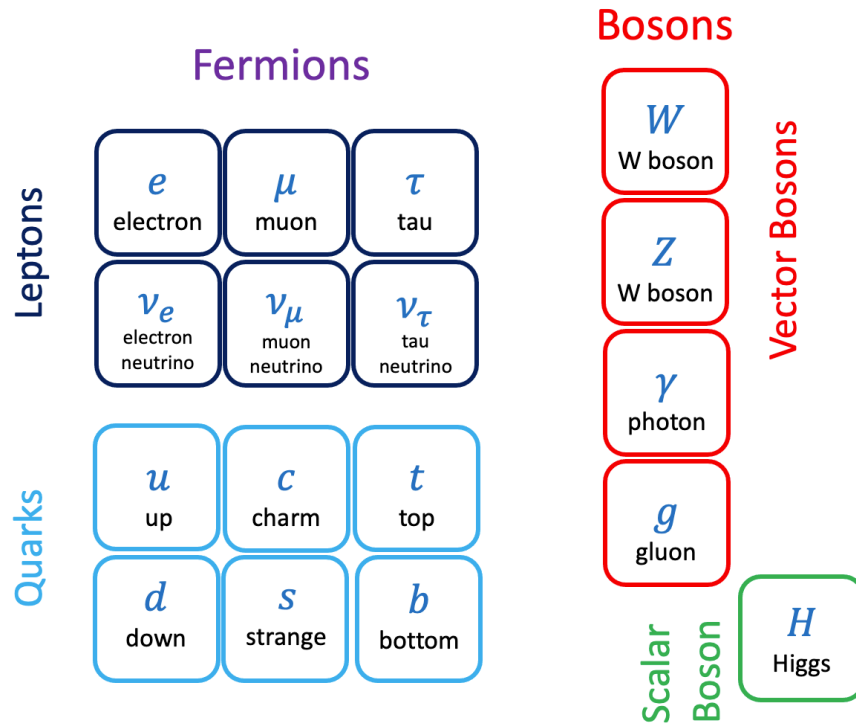


图 1.1 Summary of fundamental particles in standard model. Matters are constituted from quarks and leptons. The Higgs boson gives the mass of particles through Higgs mechanism.

1.1 Weak Interactions And The W Boson Mass In Standard Model

The W and Z bosons are the mediators of the weak interactions. A classical weak interaction vertex is illustrated in the Feynman diagrams in Figure 1.2, where f and f' can be any lepton or any quark. There are typically two categories of the weak interactions, leptonic and quark vertices.

The first observation of the W and Z bosons was established at the CERN SPS in 1983,^[7–10]. Since then, precision measurements on the mass of the W boson has played an important role in testing the Standard Model. Any re-summed new theory induced The mass of W boson, m_W is sensitively correlated to many standard model parameters. At leading order in the electroweak theory, the W-boson mass, m_W , is expressed in a function of the Z boson mass (m_Z), the fine-structure constant (α), and the Fermi constant (G_μ), illustrated in Eq. 1.1.^[11]

$$m_W^2(1 - \frac{m_W^2}{m_Z^2}) = \frac{\pi\alpha}{\sqrt{2}G_\mu}(1 + \Delta r) \quad (1.1)$$

At higher orders, the radiative correction, Δr , includes additional dependence on masses of Higgs boson and heavy particles. The one-loop result of Δr can be written in Eq. 1.2, in which $c_W = M_W/M_Z$, $s_W^2 = 1 - c_W^2$. $\Delta\alpha$ involves contribution from the shift in the fine structure constant due to light fermions, $\Delta\alpha \propto \log m_f$. $\Delta\rho$ depend quadratically on the top quark mass, m_t . The last part, Δr_{rem} , contains the dependence on the Higgs boson mass, M_H . Higher-order QCD corrections to Δr are at $\alpha\alpha_s$, $\alpha\alpha_s^2$, and $\alpha\alpha_s^3$ for $\Delta\rho$. These contributions can be probed by comparing predicted value of m_W to direct measurement. In global fits to the SM parameters, constraints on physics beyond SM are limited by the W-boson mass measurement precision, as in Figure 1.3. Thus, improving the precision of measurement of W boson mass is of high importance to test the overall consistency of the standard model.

$$\Delta r^{(\alpha)} = \Delta\alpha - \frac{c_W^2}{s_W^2}\Delta\rho + \Delta r_{rem}(M_H) \quad (1.2)$$

Δr has been calculated up to two-loop results in^[11]. Beyond two-loop order the results for the pure fermion-loop corrections are calculated to four-loop order. Eq. 1.1

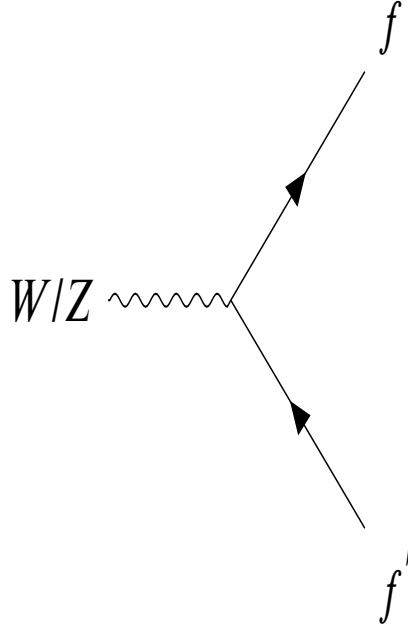


图 1.2 Feymann diagram of weak interaction, while a W or Z boson decay to a pair of fermions.

Z boson decays to two fermions with opposite charge, W boson decayed leptons have total charge ± 1 . There are typically two type of final states, one is hadronic qq' , the other is leptonic $l + l(\nu)$.

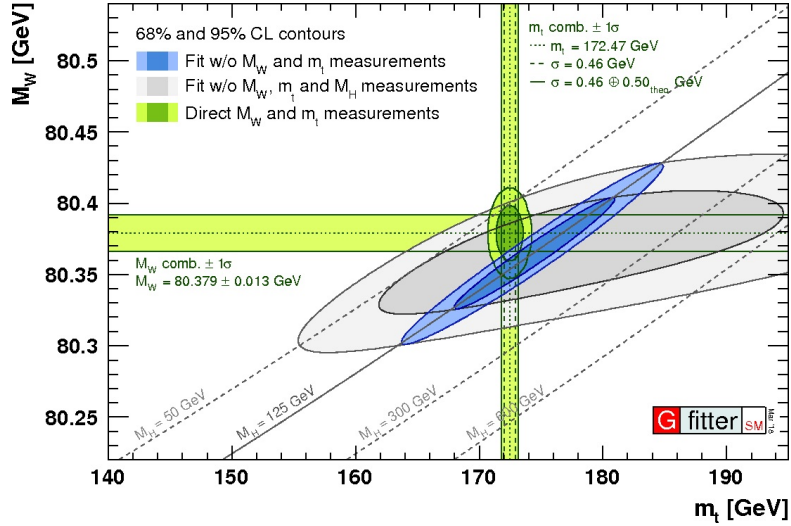


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is usually written in the format in Eq. 1.3 for predicting the W-boson mass.

$$M_W^2 = M_Z^2 \left\{ \frac{1}{2} + \sqrt{\frac{1}{4} - \frac{\pi\alpha}{\sqrt{2}G_\mu M_Z^2} [1 + \Delta r(M_W, M_Z, M_H, m_t, \dots)]} \right\} \quad (1.3)$$

The parameter m_W is strongly correlated to other sensitive parameters such as the Higgs boson mass, M_H , the top boson mass M_t , the fine structure constant α . These constraints are affected both by the experimental error of M_H and by the uncertainty of the theory prediction.

W boson mass is determined from the Jacobian edges of the final state kinematic spectrums, such as W boson transverse mass, $m_T^W = \sqrt{2p_T^l p_T^{miss}(1 - \cos\Delta\phi)}$ and W-decayed lepton transverse momenta, p_T^l . The former method, m_T^W , is sensitive to the average number of interactions per bunch crossing, referred to as pileup ($\langle\mu\rangle$), while the latter method is limited by the imperfect knowledge of the distribution of W boson p_T at initial state. Large fraction of W(or Z)-boson production is induced by at least one second-generation quark, s or c, in the initial state, which implicates the W-boson transverse momentum distribution, and then distorts p_T^l distribution in final state.

1.2 Previous W Mass Measurements And The Challenges

Since the discovery of the W and Z bosons at the CERN SPS, the precision measurement on the W boson mass, m_W , has been a hot topic in particle physics experiments. The UA2 Collaboration reported the first observation of W boson using a dataset corresponding to a total integrated luminosity of 19.0 nb^{-1} at center-of-mass energy $\sqrt{s} = 540 \text{ GeV}$.^[7] Only four W events are observed in the measurement. The first result is $m_W = (80_{-6}^{+10})\text{GeV}$.

Accelerator and detector technology has been developed quickly that the beam energy and detector resolution allow scientists to improve the precision of m_W measurement by many order of magnitudes. The ALEPH, DELPHI, L3, OPAL collaborations performed the m_W measurement with data taken at the electron-positron collider LEP at CERN from 1995 to 2000.^[13] The combined data set considered in this report corresponds to a total luminosity of about 3 fb^{-1} collected by the four LEP experiments,

at centre-of-mass energies ranging from 130 GeV to 209 GeV. At LEP, two methods had been used for the measurement: first is measuring the cross-section of W pairs at the production threshold, second is using the leptonic decay spectrum of the W boson by directly reconstructing W decays. The latter method is the more precise one. The combined results is $m_W = 80.376 \pm 0.033$ GeV.

There are two basically ways to measure the m_W parameter. One use the W -pair production threshold, and the other make direct mass reconstruction from W decayed products. The W -pair production threshold method used in the LEP experiments are illustrated as follows: the SM cross-section of the reaction $e^+e^- \rightarrow W^+W^-$ shows a typical threshold behavior close to a centre-of-mass energy that corresponds to twice the W mass. In the threshold region the cross-section rises in proportion to the velocity of the W bosons produced, which is approximately given by $\beta = \sqrt{1 - 4m_W^2/s}$, neglecting radiative corrections and finite width effects. Thus, a measurement of the production cross-sections at a give center-of-mass energy is directly related to the W boson mass.. The intrinsic precision of this method is similar to the direct-reconstruction method. The measurement of WW production cross section as a function of the center of mass energy, E_{cm} , by ALEPH colloboration, is shown in Figure 1.4.

The other method that directly reconstruct W decayed products is illustrated below: The mass and total decay width of the W boson is determined with high precision by reconstructing directly the decay products of the two W bosons, mainly in the fully hadronic, $W^+W^- \rightarrow q\bar{q}q\bar{q}$, and semi-leptonic, $W^+W^- \rightarrow q\bar{q}l\nu$, decay channels. The $W^+W^- \rightarrow l\nu l\nu$ decay also contains information on m_W when analyzing the leptonic energy spectrum or reconstructing an approximated mass of the decaying W bosons, However, the intrinsic statistical precision dominates the total uncertainty in the experiment. The method compares the $m_T = \sqrt{2p_T^e p_T^\nu [1 - \cos(\Delta\phi)]}$ distributions between data and Monte-Carlo simulations. Figure 1.5 shows an example of this method used in D_0 experiment.

The current world average result $M_W = 80.377 \pm 0.012$ GeV is dominated by the combined Tevatron data from CDF and D0 expirements yielding an average $M_W = 80.387 \pm 0.016$ GeV^[16], the combined LHC data from ATLAS^[2] and LHCb yields

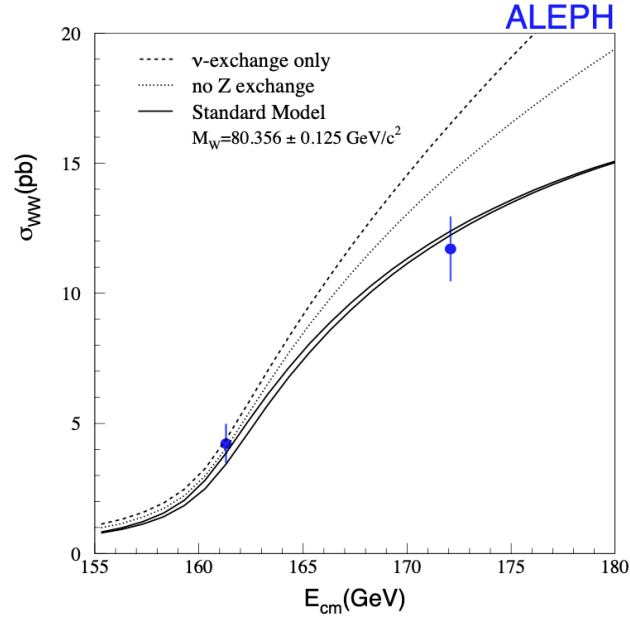


图 1.4 Measurement of the W pair production cross section by ALEPH at the two center of mass energies, compared to the Standard Model prediction from GENTLE for the world average energies, value of the W mass (the two curves correspond to the $\pm 125 \text{ MeV}/c^2$ error on m_W)^[14]

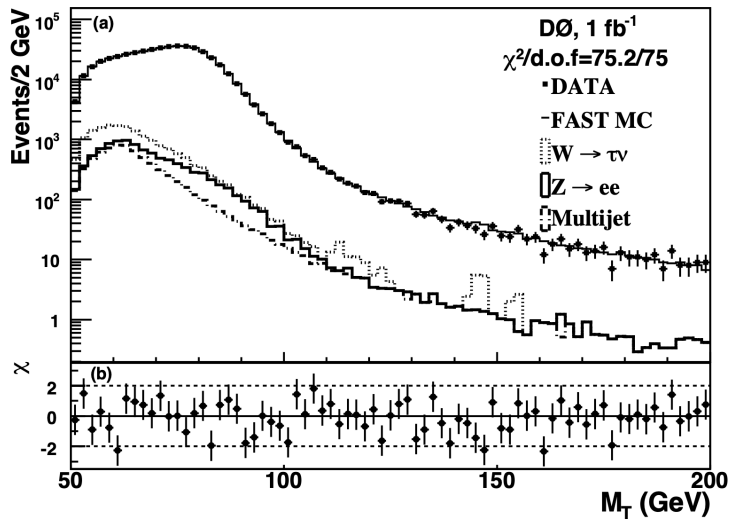


图 1.5 Comparison of the m_T data distribution with its expectation from a fast MC simulation of $W^+ \rightarrow e^+ \nu$ events with D0 experiment.^[15]

an average W mass of $M_W = 80.366 \pm 0.017$ GeV, and LEP-2 average results from ALEPH, DELPHI, L3, OPAL which is $M_W = 80.376 \pm 0.033$ GeV^[13].

ATLAS collaboration performed a measurement of the mass of the W boson based on proton–proton collision data recorded in 2011 at a centre-of-mass energy of 7 TeV at the LHC, corresponding to 4.6 fb^{-1} of integrated luminosity.^[2] The selected data sample consists of 7.8×10^6 candidates in the $W \rightarrow \mu\nu$ channel and $\times 10^6$ candidates in the $W \rightarrow e\nu$ channel. The result is $m_W = 80.370 \pm 0.019$ GeV. The mass of the W boson is extracted from the Jacobian edges of the final-state kinematic distributions, measured in the plane perpendicular to the beam direction. Sensitive observables include the transverse momenta of the charged lepton and neutrino, p_T^ℓ, p_T^ν , and the W -boson transverse mass, m_T , shown in Figure 1.6.

The ATLAS experiment benefit from large signal and calibration samples. The numbers of selected W - events, collected in a sample corresponding to approximately 4.6 fb^{-1} of integrated luminosity at a centre-of-mass energy of 7 TeV, are of the order of 10^7 for the $W \rightarrow \ell\nu$. The available data sample is therefore larger by an order of magnitude compared to the corresponding samples used for the CDF and D0 measurements.

LHCb collaboration published a measurement on m_W on 2022^[18], in which the W boson mass is measured using proton-proton collision data at $\sqrt{s}=13$ TeV corresponding to an integrated luminosity of 1.7 fb^{-1} recorded during 2016 by the LHCb experiment. With a simultaneous fit of the muon q/p_T distribution of a sample of $W \rightarrow \mu\nu$ decays and the ϕ distribution of a sample of $Z \rightarrow \mu\mu$ decays the W boson mass is determined to be $m_W = 80354 \pm 23_{\text{stat}} \pm 10_{\text{exp}} \pm 17_{\text{theory}} \pm 9_{\text{PDF}}$, where uncertainties correspond to contributions from statistical, experimental systematic, theoretical and parton density functions sources.

Many m_W measurements have been performed using Tevatron machine with CDF and D₀ experiments, the combined Tevatron data from CDF and D0 yields an average W mass of 80.387 ± 0.016 GeV.^[16] Besides the combination of CDF and D0 results in 2013, a latest result from the CDF collaboration was done in April 2022.^[19] The based on their full Run-2 dataset of 8.8 fb^{-1} of CDF detector, with much reduced uncertainty:

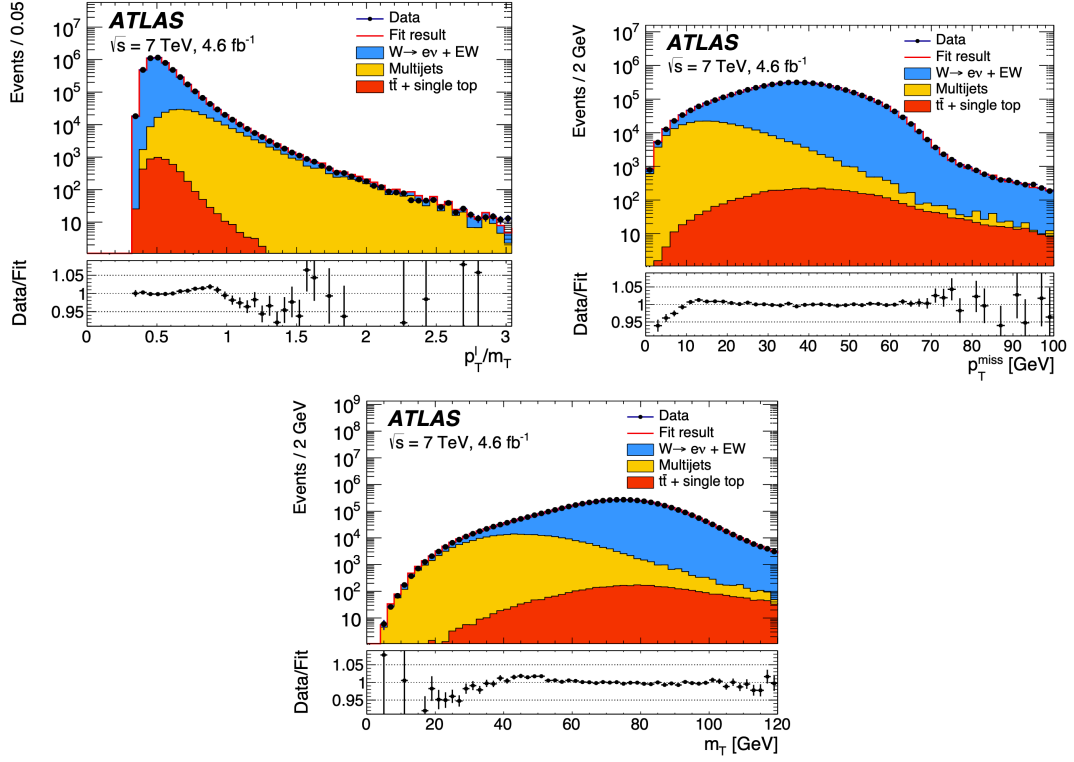


图 1.6 Crucial spectrums in 7 TeV W boson mass measurements. Left top plot is the transverse momentum of lepton decayed from W boson, p_T^ℓ , which is one of the two fit parameters to obtain the W boson mass and is sensitive to the modeling of p_T^W distribution. Right top plot is the missing transverse momentum calculated from the remaining energy of p_T^ℓ and the energy deposited in hadronic calorimeter, denoted as E_T^{miss} . Left bottom plot is transverse mass $m_T = \sqrt{2p_T^\ell E_T^{\text{miss}}(1 - \cos(\theta_{l,E_T^{\text{miss}}}))}$, the other fit parameter to obtain m_W , which is not sensitive to p_T^W but need good resolution of E_T^{miss} measurement.^[17]

Uncertainty source	statistics	experimental systematic	QCD modeling	EW modeling	PDF	total
Uncertainty (MeV)	6.8	10.6	8.3	5.5	9.2	18.5

表 1.1 Uncertainties in ATLAS 7TeV measurement on W boson mass.^[2]

80.4335 ± 0.0094 GeV. This new CDF result, which includes the data of their previous result and thus supersedes it, is of higher precision than the world average quoted above. However, the two determinations disagree significantly, which brings the attention to future measurement on W mass.

A list of the uncertainties in previous ATLAS W boson mass measurement in^[2] is listed in Table 1.1, In the content of overall uncertainty, the statistical uncertainty was 6.8, much smaller than systematic uncertainties like the experimental systematic, QCD modeling uncertainty and the PDF uncertainties. Thus, accumulating more dataset in $p - p$ collisions with LHC without improving the understanding of the systematic uncertainties would not improve the W mass measurement to a satisfactory level.

Recent ATLAS measurements on W mass were performed using template fits methods of two variables, the transverse momentum of lepton decayed from the W boson, p_T^ℓ , and the transverse mass mass of W boson, $m_W = \sqrt{2p_T^\ell p_T^\nu \cos(\theta_{l\nu})}$ the parts related to the modeling of transverse momentum distribution of W boson dominates (including QCD modeling and PDF). Especially the p_T^W disagrees between theoretical calculations and direct measurements at low q_T region, causing a large contribution to the uncertainty in W boson mass measurement. The p_T^W distribution used for this measurement is extrapolated from the p_T^Z measurement. Improving the p_T^W and p_T^Z inputs to the m_W measurements are important to further reduce the uncertainties.

1.3 Measurements Of Transverse Momenta Of Z Bosons

Transverse momentum distribution of W is of significant importance in m_W measurement. In previous ATLAS 7 TeV W mass measurement, the p_T^W distribution is extrapolated from the W and Z differential cross sections, as well as the Z boson transverse momentum and angular distributions, the latter measured at 8 TeV^[17]. The QCD parameters of the parton shower and resummation models are determined by fits to the Z p_T measured as in^[20], Resummed calculations (NNLO) was proceeded to describe W/Z - p_T distribu-

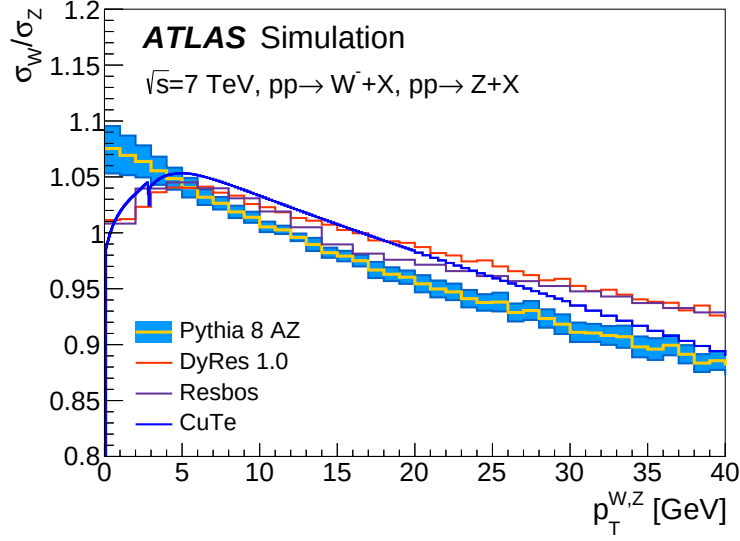


图 1.7 Resummed calculations (NNLO) to describe W/Z p_T ratio doesn't agree with direct measurement (Pythia 8 AZ is tuned with results from LEP and SLD). SLD is a large full-coverage particle physics detector situated at Stanford Linear Collider (SLC) in Stanford, California. The modeling of p_T of W and Z bosons are very difficult to calculate at low- p_T where the perturbative calculation of QCD fails.^[17]

tion, which however, didn't match with AZ tune of the PYTHIA8 parton shower that was derived using an earlier measurement of the Z -boson transverse momentum distribution with LEP and SLD^[21], especially at low p_T region. Figure 1.7. Thus, direct measurements of the p_T^Z and p_T^W will be beneficial to the QCD and PDF modeling uncertainties. On the other hand, the transverse momentum measurements of W and Z bosons in the Drell-Yan process are of great interests because their behaviors are very sensitive to the presence of gauge bosons in the strong interaction. Moreover, p_T^Z measurements are important probe to tested the perturbative QCD and the parton density functions (PDFs).

We consider the inclusive hard-scattering process in p-p collisions: W (or Z) bosons are produced with non-zero p_T due to emission of quarks and gluons from the initial-state partons as well as to the intrinsic transverse momentum of the initial-state partons in the proton. The W or Z decay to two leptons ($W \rightarrow \ell \nu$, $Z \rightarrow \ell \ell$).

$$h_1(P_1) + h_2(P_2) \rightarrow V(q) + X \rightarrow l_3(p_3) + l_4(p_4) + X \quad (1.4)$$

where the collision of the two protons h_1 and h_2 with momenta P_1 and P_2 pro-

duces the vector boson V ($V = W^+, W^-$ and Z/γ^*) with total momentum q^μ , which subsequently decays in the lepton pair $l_3 l_4$, and X denotes the accompanying final-state (hadronic) radiation. Considering the W and Z production cased, the invariant mass M of the lepton pair is high, but differs from the on-shell mass m_V of vector bosons W and Z . Then the colliding hadrons and the final state leptons are approximately massless ($0 \approx P_1^2 = P_2^2 = P_3^2 = P_4^2 \ll m_V^2$). Assuming the colliding hadrons are back-to-back, the momentum of boson q^μ is determined by the invariant M , the two dimensional transverse momentum vector p_T^V and the rapidity $y = \frac{1}{2} \ln \frac{q \cdot P_2}{q \cdot P_1}$ of the boson.

The kinematics of the lepton pair is completely specified by six independent variables including the three-momenta of the two leptons. To better describe the kinematics with respect to p_T^V , the final-state lepton kinematics are described using the vector boson momentum $q^\mu = q_{l_3}^\mu + q_{l_4}^\mu$ and two independent variables that specify the angular distribution of the leptons with respect to the vector boson momentum q^μ . These two angular variables are denoted as $\Omega = \{\Omega_A, \Omega_B\}$. the most general differential hadronic cross section can be written as in Eq. 1.5. [22]

$$\begin{aligned} \frac{d\sigma_{h_1 h_2 \rightarrow l_3 l_4}}{d^2 q_T dM^2 dy d\Omega}(q_T, M, y, s, \Omega) = & \Sigma_{a_1, a_2} \int_0^1 dx_1 \int_0^1 dx_2 f_{a_1/h_1}(x_1, \mu_F^2) f_{a_2/h_2}(x_2, \mu_F^2) \\ & \times \frac{d\hat{\sigma}_{a_1 a_2 \rightarrow l_3 l_4}}{d^2 q_T dM^2 d\hat{y} d\Omega}(q_T, M, \hat{y}, \hat{s}, \Omega; \alpha_s(\mu_R^2), \mu_R^2, \mu_F^2) \end{aligned} \quad (1.5)$$

where the $f_{a/h}(x, \mu_F^2)$ ($a=q_f, \hat{q}_f, g$) are the parton densities (PDF) of the colliding hadron at the factorization scale μ_F . $d\hat{\sigma}_{a_1 a_2 \rightarrow l_3 l_4}$ are the differential partonic cross sections, $\hat{s} = x_1 x_2 s$ is the square of the partonic center-of-mass energy. $\hat{y} = y - \ln \sqrt{x_1/x_2}$ is the vector boson rapidity with respect to the colliding partons. And μ_R is the renormalization scale.

The LO+NLO Feynman diagrams for the production of a Z Boson decaying to two muons are shown in Figure 1.8. At the leading order calculations of the Drell-Yan process, no transverse momenta of the Z is predicted. For the Next-LO and higher orders, additional quarks or gluons are produced recoiling against the Z , which gives Z non-zero p_T . On the other hands, initial state radiations, which are soft gluons emitted from partons, would change the momentum of the partons, thus gives Z small p_T . Moreover,

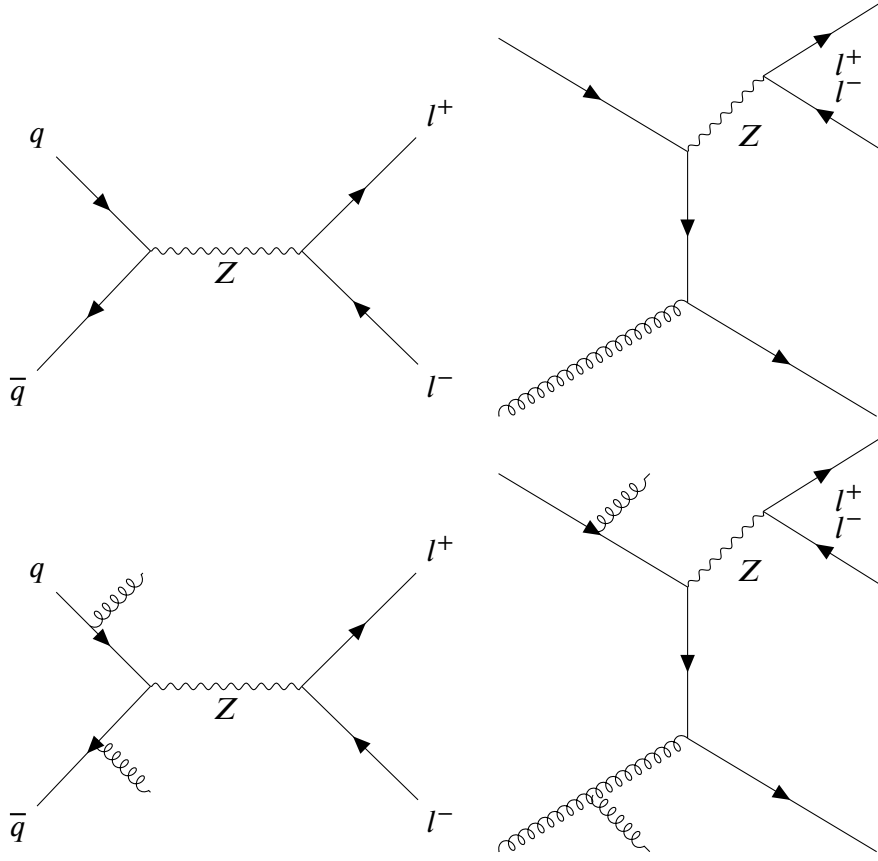


图 1.8 Feynman diagrams for the production of Z decaying to two leptons. Left top plot is the leading order, with Z produced with zero p_T . Right top plot is NLO diagram with one quark recoiling against the Z . Left bottom plot is leading order plus initial state radiated gluons, corrections need to be calculated regarding these soft emissions. Right bottom plot is NLO + ISR radiated gluons.

the momentum carried by partons are not necessarily parallel to the beam axis. Intrinsic transverse momenta of partons and misalignment of proton beam are also sources of the initial state p_T^Z . Phenomenologically, the p_T of Z boson at low region can be described using soft-gluon resummation^[22–27]. With the help of QCD factorization theorem^[28], scientists are able to predict the Drell-Yan cross section at measurement p_T^V in a useful format at large p_T^V , $p_T^V m_V$. However, this factorized form was not useful at $p_T^V \ll m_V$ because the perturbative coefficients contain large logarithms: the coefficient of $\alpha_s^N(p_T^{V^2})$ contains $1/p_T^{V^2}$ times a series of logarithms $\ln^n(m_V^2/p_T^2)$, with $n = 0, 1, \dots, 2N - 1$. In the very low- p_T region, m_V/p_T increase quickly and the theory can not describe that region.

In ATLAS experiment, the W and Z bosons are measured using the leptonic decayed channel ($W \rightarrow l\nu$, $Z \rightarrow l\nu$, where l is an electron or muon), with very small backgrounds contained in the signal region. The transverse momentum of Z boson can be precisely measured by the Z-decayed leptons. However, the W-decayed neutrino escaped from the ATLAS detector, thus it is impossible to measure the p_T^W by lepton products. Given the fact that the X particle in Eq. 1.4 recoiling against the W boson, assuming initial partons h_1 and h_2 are coming from precisely opposite-direction beams, the projections of momenta of the W boson and the X particle are equal (but with opposite direction). So it allows scientists to measure p_T^W indirectly through the *hadronic recoil* reconstruction of transverse momentum of the X particle.

The *hadronic recoil* is used for the measurement of p_T^W , it is defined as the vector sum of the transverse energy of all particles decayed from the X particle in Eq. 1.4. The full procedure of the calibration of the *hadronic recoil* is discussed in Section 3.4. In *hadronic recoil* calculations, all of the energies deposited in the calorimeters in a bunch crossing are summed to estimate the p_T of recoil. The algorithm works well in case that only one event of interest happens per bunch crossing. However, in a standard ATLAS run, a large number of p-p collisions occurs in a bunch crossing. The hadronic state products of those collisions deposit in the same hadronic calorimeters, with the cones of energy depositions overlapping with others. Therefore we cannot distinguish the *hadronic recoil* from a W or Z event to other processes. The measurement of p_T^W is impossible in a standard ATLAS run, neither nor for the p_T^Z measurement using *hadronic recoil*.

The number of interactions of parton collisions per bunch crossing are denoted as pileup, μ . The pileup of LHC accelerator is typically very high (30 - 40) in ATLAS run-II period, which degrades the precision of measurement on the *hadronic recoil*. Fortunately, using special low pileup dataset^[21], the *hadronic recoil* can be precisely measured. A study of the dependence of resolution of *hadronic recoil* on the pileup^[21] is shown in Figure 1.9. Significant improvement on recoil resolution is observed at low pileup conditions. Moreover, with dedicated calorimeter settings, the resolution can be further reduced at the same pileup level.

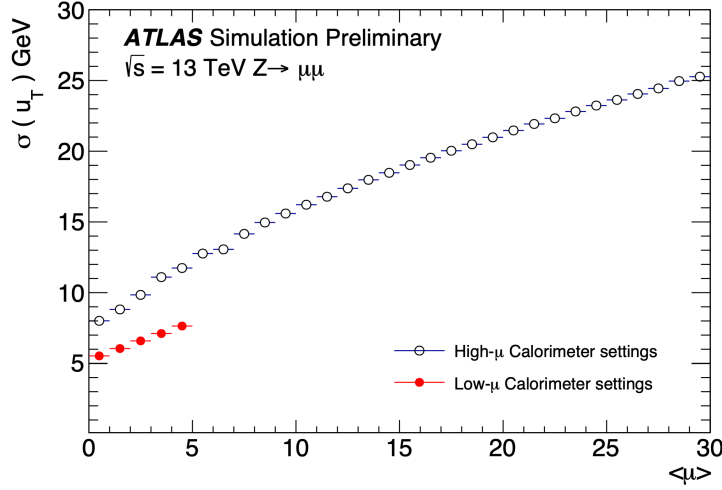


图 1.9 Recoil resolution as a function of μ for simulated $Z \rightarrow \mu\mu$ events with two different calorimeter settings.^[21]

The transverse momentum of W and Z is precisely measured using the low pileup dataset. It is a milestone towards the final W mass measurement, which is expected to be done with uncertainty below 10 MeV.^[21]

A first measurement of the W and Z/γ^* transverse momentum distributions is done by ATLAS proton-proton collisions at $\sqrt{s} = 7 \text{ TeV}$ corresponding to integrated luminosity of approximately 320 nb^{-1} .^[29] With increase of the luminosity of LHC and better understanding of ATLAS detectors, the p_T^Z measurements have been improved a lot. The most recent ATLAS measurement on p_T^Z is published in 2018^[30]. The analysis uses data from 36.1 fb^{-1} of proton-proton collisions at a centre-of-mass energy of $\sqrt{s} = 13 \text{ TeV}$ collected in 2015 and 2016. It reaches a precision of 0.2% for the normalized spectra at low values of $p_T^{\ell\ell}$ in Figure 1.10.

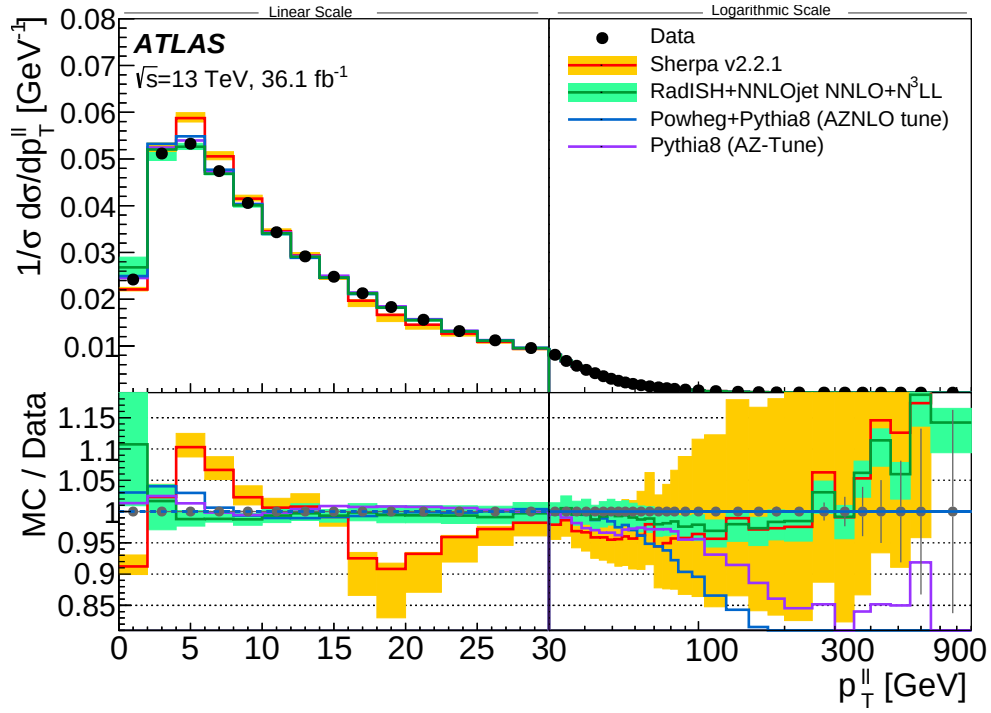


图 1.10 Comparison of the normalized p_T^Z distributions predicted by different computations: Pythia8 with the AZ tune, Powheg+Pythia8 with the AZNLO tune, Sherpa v2.2.1 and RadISH with the Born level combined measurement. The uncertainties of the measurement are shown as vertical bars and uncertainties of the Sherpa and RadISH predictions are indicated by the coloured bands. ^[30]

1.4 Outline of the Thesis

The structure of the thesis is in the following: Chapter 2 describes the detectors of ATLAS used for the analysis. Chapter 3 defines the physics objects, with calibration of the objects, and event selection. Chapter 4 illustrates the methodology of transverse momentum measurement, the calibrations of *hadronic recoil* that I worked on, as well as the p_T^Z measurement results. Chapter 5 is about the detector work that I have been done, including my qualification task that mounting the modules on the endcaps for ATLAS ITk upgrade project, and sensors tests for the High-Granularity-Timing Detector project. Chapter 6 is the summary of my works.

第 2 章 The Large Hadron Collider and ATLAS Detector

The Large Hadron Collider (LHC) at CERN is the world's largest and most powerful particle accelerator. The accelerator sits in a tunnel 100 meters underground at CERN, the European Organization for Nuclear Research. It consists of a ring of 27 kilometers ring consisting of superconducting magnets with a number of accelerating structures that boost the energy of the particles along the way. The LHC pushes protons or ions to near the speed of light and collide at four points on the ring, which are the four main experiments in the LHC, named as A Toroidal LHC Apparatus (ATLAS), Compact Muon Solenoid (CMS), LHC-beauty (LHCb) and A Large Ion Collider Experiment (ALICE). A illustrative figure showing the layout of the LHC is shown in Figure 2.1. Inside the LHC, bunches of up to 10^{11} protons collide 40 million times per second to provide 13 TeV proton-proton collisions at a design luminosity of $10^{34} \text{ cm}^{-2}\text{s}^{-1}$. The brief procedure of a proton accelerated through the accelerator complex is as follows:

- Protons are taken obtained by stripping electrons from hydrogen atoms.
- Protons are injected into the PS Booster (PSB) at an energy of 50 MeV from Linac2.
- The booster accelerates them to 1.4 GeV. The beam is then fed to the Proton Synchrotron (PS) where it is accelerated to 25 GeV.
- Protons are then sent to the Super Proton Synchrotron (SPS) where they are accelerated to 450 GeV.
- They are finally transferred to the LHC (both in a clockwise and an anticlockwise direction) where they are accelerated for 20 minutes to 6.5 TeV. Beams circulate for many hours inside the LHC beam pipes under normal operating conditions.
- Protons arrive at the LHC in bunches, which are prepared for each detector.

The ATLAS detector has been built for probing p-p collisions. The overall ATLAS detector layout is shown in Figure 2.2. It's forward-backward symmetric with respect to the interaction point. The ATLAS detector consists of an inner detector surrounded by a

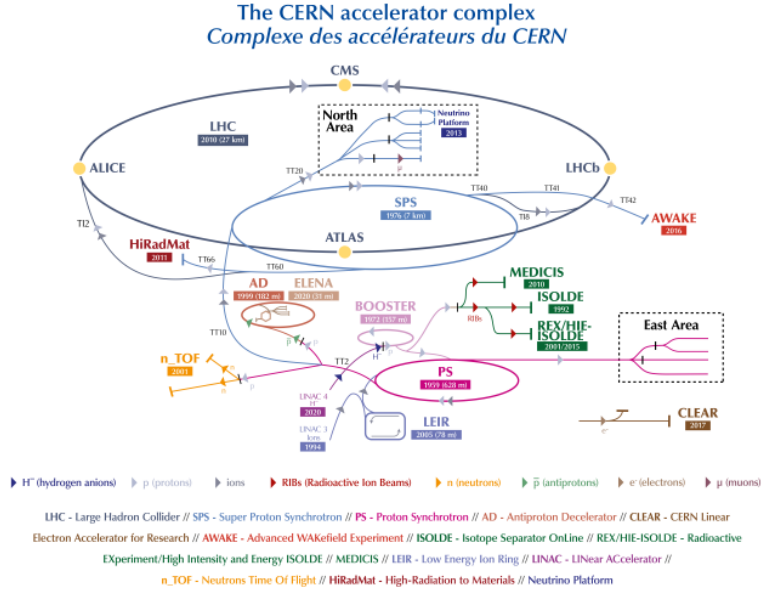


图 2.1 Layout of the LHC accelerator complex. The proton beams are accelerated to 6.5 GeV and injected to LHC rings and collide at four experiments: ATLAS, CMS, LHCb and ALICE. The ring is 27 km long and 100 meters underground at CERN. [31]

thin superconducting solenoid magnet, electromagnetic and hadronic calorimeters and a muon spectrometer incorporating three large superconducting toroidal magnet systems. The rest of this chapter is organized as the following: Section 2.1 introduces the basic coordinates to describing the detector geometry and data condition. Section ?? discusses about the Inner detector. Section 2.3 discusses about the calorimeters. Section 2.4 discusses about the muon chambers. Section 2.5 discusses about the magnets. Section 2.6 discusses about the trigger system.

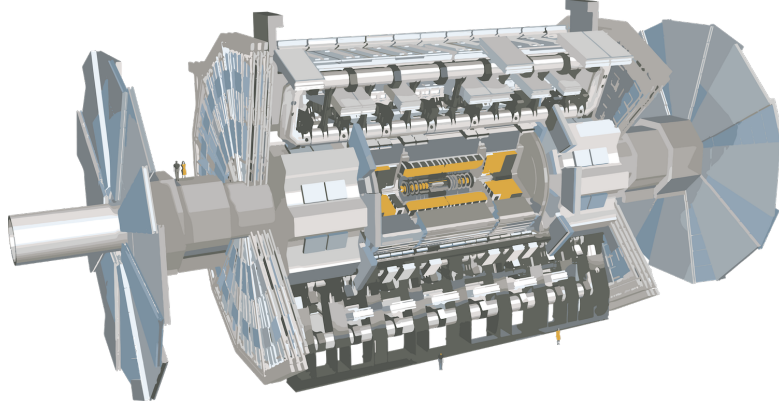


图 2.2 The ATLAS detector consists of a silicon pixel detector, a silicon micro-strip detector, a transition Radiation Tracker and the insertable B-layer. The dimensions of the detector are 25 m in height and 44 m in length.^[32]

2.1 Coordinates in ATLAS Detector and Parameters for Data Conditions

The coordinate system and nomenclature used to describe the ATLAS detector and the particles emerging from the p-p collisions are briefly summarized here. they are used through this paper.

The interaction point is defined as the origin of the coordinate system, and the beam direction defines the z -axis and the $x - y$ plane is transverse to the beam direction, which is also called the transverse plane. The positive x -axis is defined as pointing from the interaction point to the centre of the LHC ring and the positive y -axis is defined as pointing upwards. The azimuthal angle ϕ is measured around the beam axis, and the polar angle θ is the angle from the beam axis. The pseudorapidity is defined as $\eta = -\ln \tan(\theta/2)$ (in the case of massive objects such as W and Z bosons, the rapidity $y = 1/2 \ln[(E + p_z)/(E - p_z)]$ is used). The transverse momentum p_T , the transverse energy E_T , and the missing transverse energy E_T^{miss} are defined in the $x - y$ plane which is perpendicular to the beam axis. The distance ΔR in the pseudorapidity-azimuthal angle space is defined as $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$.

The distribution of the pileup for ATLAS data taken in the years from 2015 to 2018 are displayed in Figure 2.3. The average of μ has been increasing during these years. The data used for my analysis on W and Z precision measurements is in very low pileup conditions, shown in the red circle in the figure.

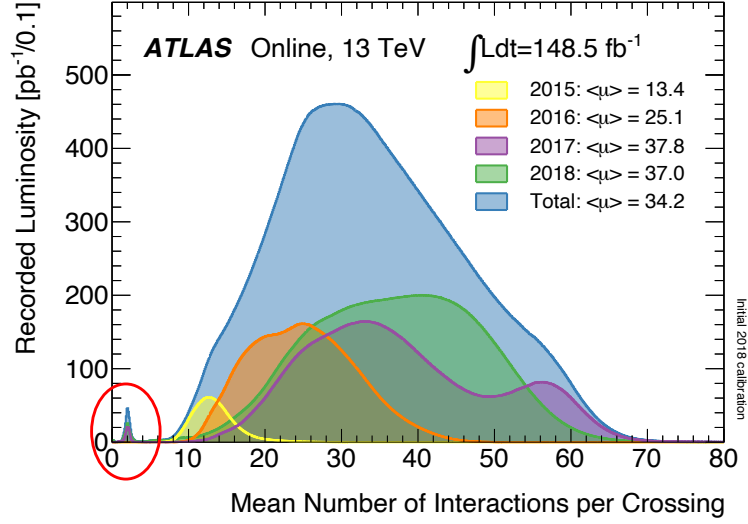


图 2.3 Pileup distributions for ATLAS data taken in the years from 2015 to 2018. The average of pileup is very high, up to 34.2. The data used in the analysis of this thesis is of low pileup conditions, emphasized in the red circle. ^[33]

2.2 Tracking

ATLAS tracking system consists of a silicon pixel detector (Pixel), a Semiconductor Tracker (SCT), a transition-radiation straw-tube tracker (TRT) and the Insertable B-Layer (IBL). It covers the pseudorapidity range $|\eta| < 2.5$. The detector granularity offers high-precision measurements of charged particle momentum and vertex resolution. The layout of the Inner Detector (ID) is illustrated in Figure 2.4. It is immersed in a 2 T magnetic field provided by the magnets, which make charged particles pass in helical traces through the detector. The curvatures of particle traces are measured by reconstructing the hits at different layers in the tracker. With curvatures obtained from tracks, momenta of charged particles are then : $p = B \times Q \times R$. Where B refers to the magnetic field, Q refers to the charge of particle, R represents the radius of the trace.

With the transverse momentum of tracks measured, the primary vertex is defined as the one with the highest sum of p_T of tracks associated to it for each event. Tracks for the signal particles originated from the proton-proton collisions must pass through the primary vertex while tracks of backgrounds do not pass through primary vertex. The distance between primary vertex and a track is used to separate backgrounds. The application is done as cuts on the projection of distance between primary vertex and a

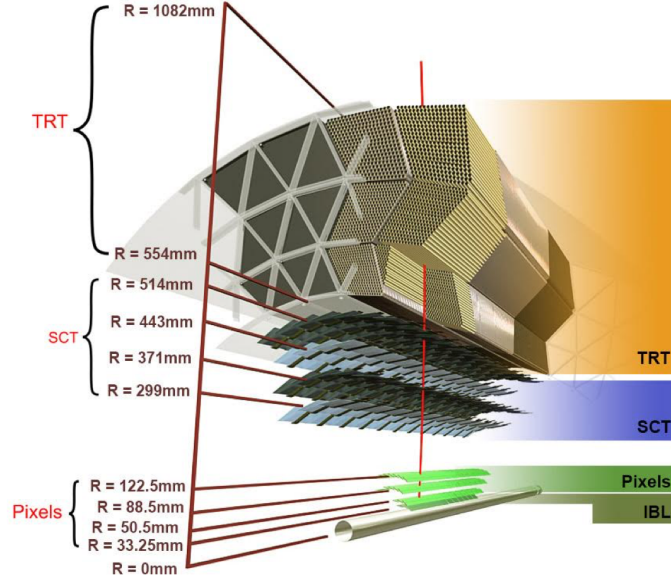


图 2.4 The Inner Detector consists of a silicon pixel detector, a silicon micro-strip detector, a transition Radiation Tracker and Insertable B-layer.^[34]

track to two dimension, one in the transverse plane, denoted as d_0 , and another along the z axis, denoted as z_0 . They are used to estimate the track parameter resolution.

The Pixel Detector is composed of sensors of $50 \times 400 \mu\text{m}^2$ size, except for the innermost layer (IBL) which is $50 \times 250 \mu\text{m}^2$. There are four barrel layers covering the low $|\eta|$ region, and three disks in each end-cap covering high $|\eta|$ region. The Semiconductor Tracker surrounds the Pixel Detector and is used to detect the tracks of charged particles. Its layout is optimized such that each particle crosses at least four layers of silicon. This allows scientists to measure particle hits positioning with a precision of up to $25 \mu\text{m}$. The Pixel Detector and the Semiconductor Tracker provides precision informations of the tracks which are close to the interaction point.

The Transition Radiation Tracker (TRT) is the outmost part of the trackers. It is made up of drift tubes filled with a gas mixture. As charged particles cross through the tubes, they ionize the gas to create a detectable electric signal, which are used to reconstruct the tracks of charged particles such as an electron or pion.

The SemiConductor Tracker (SCT) is a silicon strip detector and forms the intermediate tracking layers of the ATLAS inner detector. The SCT is geometrically divided into a central barrel region and two endcaps. It collects the charge from ionizing parti-

cles, and information is gathered with those from the pixels, IBL, and TRT to reconstruct the full track of charged particles, up to $|\eta| < 2.5$.

2.3 Calorimetry

Calorimeters are designed to absorb most of the particles coming from a collision, forcing them to deposit all of their energy and stop within the detector. Figure 2.5 shows an overview of ATLAS calorimeters. These calorimeters cover the range $|\eta| < 4.9$, using various of techniques met the vary requirements of the physics processes of interest and of the radiation condition over the η -range. The components of the ATLAS calorimetry system include the Liquid Argon (LAr) Calorimeter and the Tile Hadronic Calorimeter.

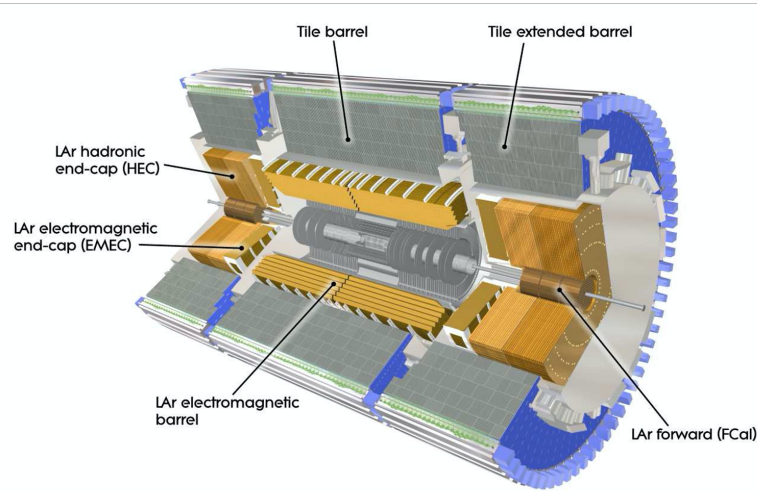


图 2.5 Cut-away view of the ATLAS Calorimeters. It consists of barrel and endcaps. The barrel uses scintillator to measure the energy, and uses steel to absorb energy. ^[35]

2.3.1 The Liquid Argon Calorimeters

The Liquid Argon (LAr) Calorimeter surrounds the ATLAS Inner Detector. It is composed of an electromagnetic calorimeter covering the barrel region for $|\eta| < 1.475$, two endcaps for $1.375 < |\eta| < 3.2$, including a hadronic end-cap and an electromagnetic end-cap, and a LAr forward Calorimeter covers the highest η region from 3.1 to 4.9. The geometry of the LAr calorimeter is shown in Figure 2.6. To keep the argon in liquid form, the calorimeter is kept at -184°C . Specially-designed, vacuum-sealed cylinders of cables bring the electronic signals from the cold liquid argon to the warm area where the readout electronics are located.

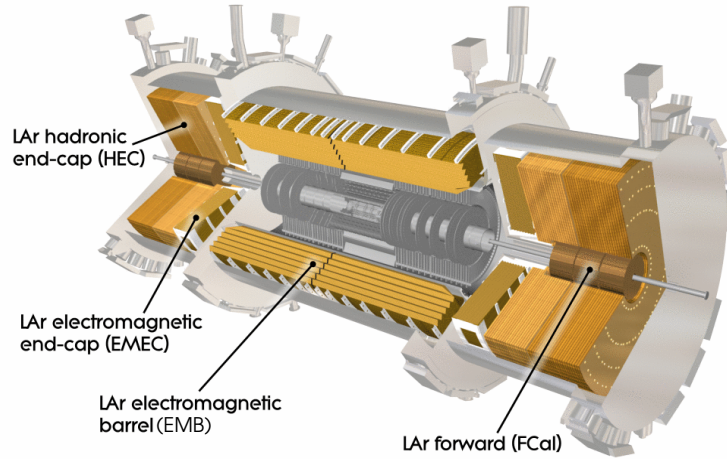


图 2.6 Cut-away view of the liquid Argon calorimeter. Three Electromagnetic LAr Calorimeters cover barrel and endcap region with $|\eta| < 3.2$. LAr hadronic Calorimeter end-cap covers $1.375 < |\eta| < 3.2$. The LAr Forward Calorimeter covers η region from 3.1 to 4.9. ^[35]

The LAr Calorimeter measures the energy of electrons, photons and hadrons. It features layers of metal (either tungsten, copper or lead) that absorb incoming particles, converting them into showing of new particles with lower energy. Electromagnetic forces are the best-understood forces that result in the energy-loss mechanisms inside the electromagnetic calorimeter. There are different processes of electromagnetic interactions happen in the calorimeters, such as:

- Ionization: the incident particles knock out the atomic electrons of the medium by overcoming the Coulomb fields generated by the atomic nuclei.
- Excitation: In some cases, the incoming charged particle instead of ionizing, excite the atoms or molecules of the medium to lose their energy. When the atoms de-excite from these metastable states, they may release scintillation light which can be used as a signal in calorimeters.
- Cerenkov light: Cerenkov light is emitted by the medium if the incoming particles travel faster than the speed of light in the material.
- Nuclear reactions: At very high energies, electromagnetic interactions will also induce nuclear reactions.
- Bremsstrahlung: At high energies, charged particles may lose their energy through

bremsstrahlung.

Charged particles interact with the materials in the LAr Calorimeter, the energies of all particles produced in those interactions are summed to estimate the energy.

2.3.2 Tile Hadronic Calorimeters

The Tile Calorimeters are the hadron calorimeter covering the central region of the ATLAS detector. The Tile Calorimeters surround the LAr calorimeter and contain three sections, one central long barrel section with 5.8 m in length covering $|\eta| < 1.0$, and two extended sections covering $0.8 < |\eta| < 1.7$. Full azimuthal coverage around the beam is covered by the Tile Calorimeter and it is located at an inner radial distance of 2.28 m from the beam and extend to 4.25 m.

The Hadronic End-cap Calorimeter (HEC) consists of two independent wheels in each end-cap, located just behind the EMCal end-cap. To ensure the efficiency in the transition region between the end-cap and the forward calorimeter (around $|\eta| = 3.1$), the HEC extends out to $|\eta| = 3.2$, overlapping with the forward calorimeter consisquently. Similarly, the HEC η range also slightly overlaps that of the tile calorimeter ($|\eta| < 1.7$) by extending to $|\eta| = 1.5$.

The Forward Calorimeter (FCal) is integrated into the end-cap cryostats, because this reduced radiation background levels in the muon spectrometer. The FCal consists of three modules in each end-cap. The first module is made of copper in consideration of improving electromagnetic measurements. And the other two are made of tungsten, which are dedicated to measure the hadronic interactions.

The Tile Calorimeters are made of layers of steel and plastic scintillating tiles. As particles hit the layers of steel, a shower of new particles are generated and collected by the tile calorimeters. Hadronic calorimetry is more complicated than electromagnetic calorimetry mainly due to the involvement of strong forces in the energy deposition process of hadrons. It is a sampling calorimeter using steel as the absorber and scintillating tiles as the active material. In both barrel and extended barrel region, the tile calorimeter consists of three layers. The according thicknesses are approximately 1.5, 4.1 and 1.8 λ for the barrel and 1.5, 2.6, and 3.3 λ for the extended barrel.

2.4 Muon System

Muons are particles that usually pass through the Inner Detector and Calorimeter undetected, which need a muon system to measure the transverse momentum.

The layout of muon spectrometer is shown in Figure 2.7. It consists of four parts: monitored drift tubes (MDT) cover pseudo-rapidity range $|\eta| < 2.7$; cathode strip chambers (CSC) cover range $2.0 < |\eta| < 2.7$; resistive plate chambers (RPC) cover range $|\eta| < 1.05$; and thin gap chambers (TGC) cover $1.05 < |\eta| < 2.7$ (2.4 for triggering);

Thin Gap Chambers are used for triggering the muons and for 2nd coordinate measurement (non-bending direction) at ends of detector. Resistive Plate Chambers are for triggering and 2nd coordinate measurement in central region. Monitored Drift Tubes measure the curves of muon tracks. Cathode Strip Chambers measure precision coordinates at ends of detector. The muon spectrometer is based on the magnetic deflection of muon tracks in the large superconducting air-core toroid magnets, instrumented with separate trigger and high-precision tracking chambers.

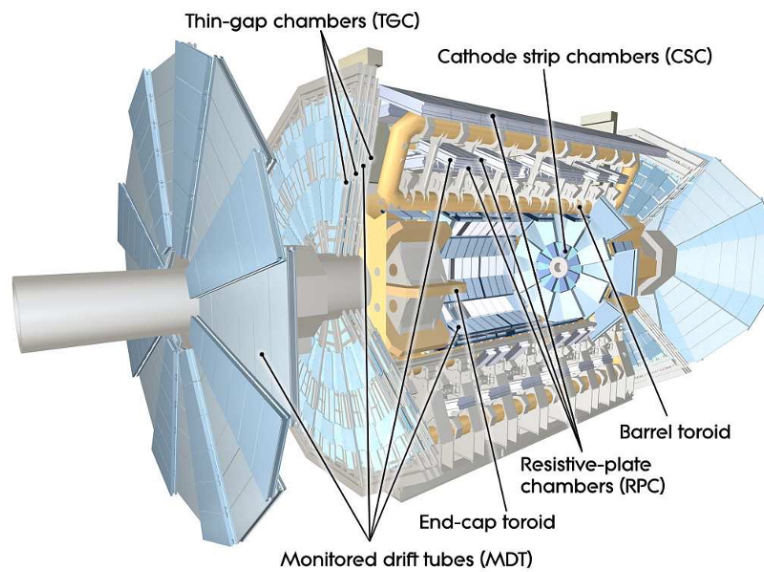


图 2.7 Cut-away view of the ATLAS Muon system. ^[36]

2.5 Magnets

The magnet system is composed of one Central Solenoid Magnet, and three Toroid Magnets. Figure 2.8 shows a picture on the structure of magnets. One of Toroid Magnet

is in the barrel region, surrounding the Solenoid Magnet. The other two Toroid Magnets are at the end-caps. The trajectories of charged particles are bended in the magnet field provides by these magnets, then their momenta and charges could be measured from the curvature of particle tracks

The magnet system generates a stable, precise and predictable magnetic field in an enormous volume and is fully integrated with the detectors in an overall $20 \times 20 \times 25\text{m}^3$ space. The central Solenoid provides 2 Tesla magnetic field in the central tracking volume. The Toroid provides magnetic field of 3 - 8 Tesla which is perpendicular to the magnetic field from the solenoid. The magnet system is cooled to about 4.5 K (-268°C) in order to provide the necessary strong magnetic fields.

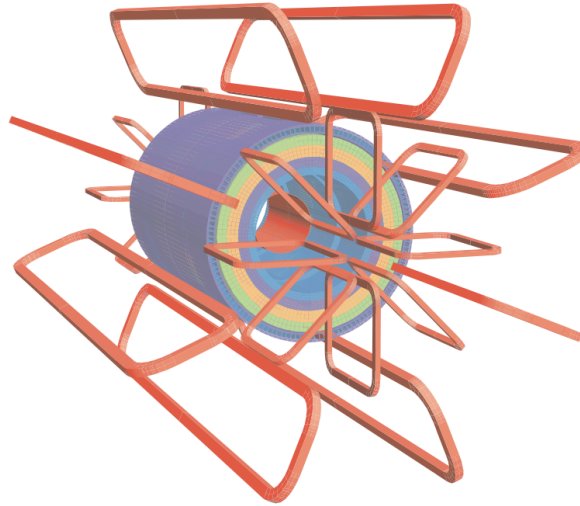


图 2.8 Scope view of Magnet system of ATLAS. It consists of a Solenoid in the central track volume and three Toroids surrounds the solenoid. The solenoid provides a 2 Tesla field in the tracking region^[37]

2.6 Data Acquisition

The beams of the LHC consist of trains of particle bunches. The minimum time interval between passage of successive bunches within a train is 25 ns. Thus collisions can take place every 25 ns within a time interval determined by the lengths of the bunches. At an instantaneous luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and bunch spacing of 25 ns the average number of interactions is about 23 per bunch-crossing, corresponding to about

10^9 interactions per second. Selective triggering is therefore required to select the most interesting collision events for study.

The Data Acquisition (denoted as DAQ collectively) systems are used to collect the data produced by ATLAS, and filter the data offline to lower the data rate down to roughly 200 Hz. The trigger system has contains three levels: L1 and the event filter. Each trigger level refines the decisions made at the previous level and applies additional selection criteria. The first level trigger uses a limited amount of the total detector information to make a decision in less than $2.5 \mu s$, reducing the data rate to about 75kHz. Event filter combine information from more detectors for a final rate of up to 200 Hz.

第3章 Reconstruction And Event Selection

The W and Z events are produced in $q + q' \rightarrow V + X$ in ATLAS with X being a quark or gluon recoiling against the vector boson, W or Z . In final states, W or Z bosons decay through leptonic channels, $W \rightarrow l\nu$, $Z \rightarrow \ell\ell$, where l is an electron or muon, as shown in Figure 3.1 The X particle is a quark or gluon, which decays through strong interactions to a shower of quark and gluon mixture, named as *jets*.

Transverse momenta of W and Z are measured from the electrons, muons, jets and indirectly measured neutrinos. These are achieved using the Trackers, Electro-magnetic and Hadronic Calorimeters, and Muon detector described in Chapter 2. The procedures to identify and reconstruct these particles are discussed in Section 3.1.

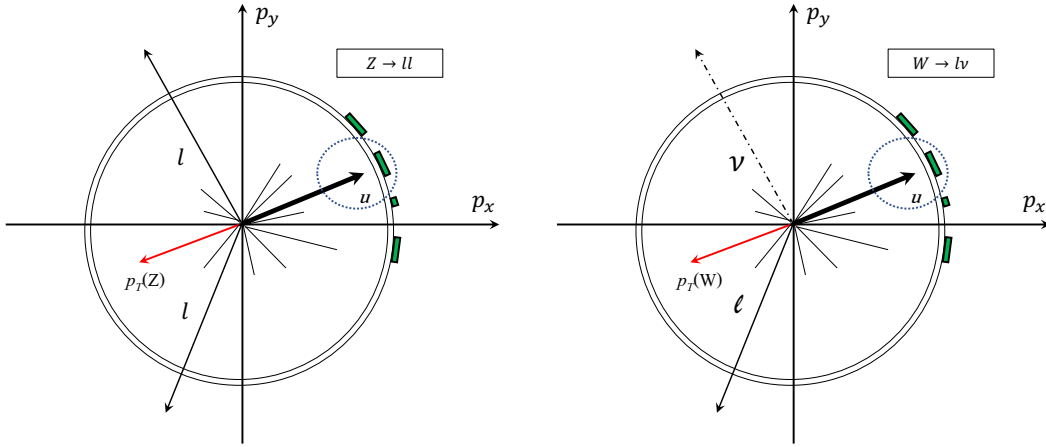


图 3.1 W and Z bosons are produced with recoil u . p_T^Z can be measured through two opposite sign leptons, p_T^W can only be measured using the transverse momentum of recoil.

3.1 Basic Physics Objects Reconstruction

The reconstruction of tracks of charged particles in trackers are described in Section 3.1.1. The identification (ID) and reconstruction of an electron are described in Section 3.1.2. Muon ID and reconstruction is discussed in Section 3.1.3. Jet reconstruction is illustrated in Section 3.1.4. Further calibrations of these objects are discussed in sections Section 3.3. Data and Monte-Carlo simulation samples are presented in Section 3.5. Event selection of signal events are illustrated in Section 3.6.

Further calibrations of these quantities are discussed in sections Section 3.3. The calibration of u_T is significantly important in p_T^W measurement so it is described in a dedicated Section 3.4. Data and Monte-Carlo simulation samples are presented in Section refsec:samples. Event selection of signal events are illustrated in Section 3.6.

3.1.1 Track Reconstruction

A general overview of track reconstruction is described in this section. Roughly, ATLAS tracking is done first “inside out” and then “outside in”, an illustrative picture is shown in Figure 3.2.

Firstly, hits in the inner detector are reconstructed into tracks through this ordered execution of algorithms. The end result is a selection of track collections which are then available for physics analysis. Typically, the information of the tracks includes the distance of the track to primary vertex, projected to the z axis, denoted as z_0 , and the projection to x, y plane, denoted as d_0 , and the primary direction of the particle momentum, described by azimuthal angle ϕ and the polar angle θ , and the ratio q/p of the charge of particle divided by the magnitude of its momentum. Figure 3.3 shows illustrations for these basic track parameters.

The primary track reconstruction starts by forming track seeds consisting of triplets of hits in either the Pixel or SCT sub-detectors which are compatible with originating from a charged particle track. Then search roads, which are sets of detector modules that can be expected to contain clusters compatible with the seed, are built through the remaining detector based on the estimated seed trajectory. Then, these seeds are extended along the search roads through a combinatorial Kalman filter, which searches for

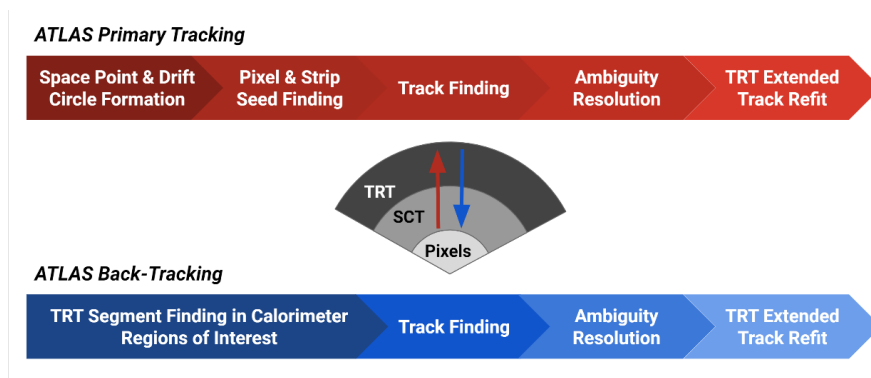


图 3.2 An overview of tracking reconstruction. It is done first "inside out" as in the red arrow, and then "outside in" as in the blue arrow.^[38]

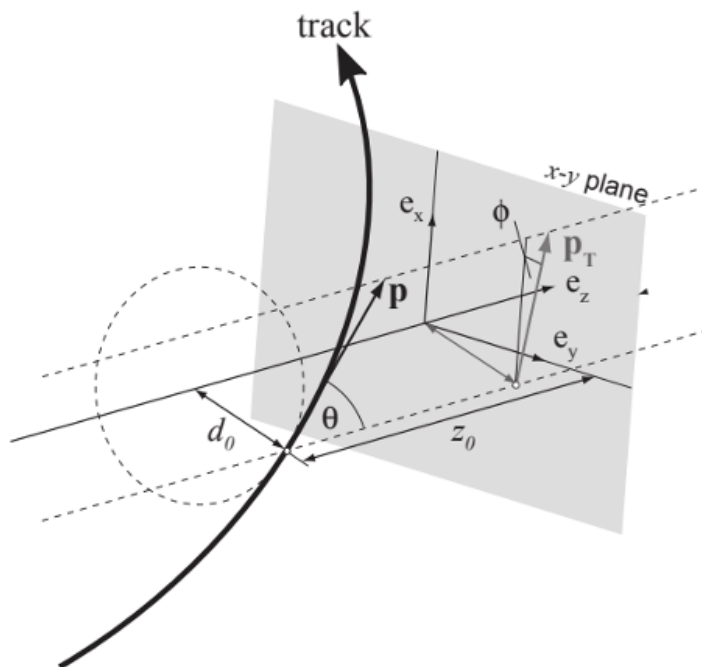


图 3.3 Global track parameters of a charged particle in ITk. These parameters are used for particle identification and momentum measurement. [38]

adjacent clusters both outwards and inwards in r while attempting to smooth the trajectory. Additionally, potential seeds that fail the track finding are checked for calorimeter compatibility, if the seed is within a region of interest (ROI) in the calorimeter the track-finding procedure is redone allowing an additional “kink” in the track. This is known as Bremsstrahlung recovery and helps recover some efficiency for electron reconstruction. The end result of this track finding/pattern recognition process is a set of potential track candidates that then undergoes further refinement. The implementation of the Kalman filter approach in tracking is fast computationally, but is relatively imprecise and doesn't resolve ambiguities. If a hit is selected by several track candidates, these tracks are put in an ambiguity solver to choose the most probably track.

3.1.2 Electron Reconstruction

Electron reconstruction consists in fitting a track using information from the Inner Detector and matching it to an energy cluster in the EM calorimeter. An identification algorithm is applied based on multivariate likelihood discriminant which is built using shower shape, track and track-to-cluster matching discriminating variables, to separate the electrons from the primary vertex to electron produced in photon conversions and hadronization. Three levels of identification operating points are typically provided for electron ID. These are referred to as Loose, Medium, and Tight in order of increasing background rejection. The operating points are defined such that the set of electron candidates with higher background rejection is a subset of the electron candidates with lower background rejection (Tight $\subseteq$ Medium $\subseteq$ Loose). An overview of electron reconstruction is shown in Figure 3.4.

In most analysis, only the electrons from the primary vertex are needed, a cut is required on $|d_0|/\sigma(d_0) < 5$ and $|z_0 \sin\theta| < 0.5$ mm. Electrons should be detected inside the coverage of tracker $|\eta| < 2.47$ and not in the crack.

3.1.3 Muon Reconstruction

The muon reconstruction is exploited with muon track in the ID and Muon Spectrometer tracking detectors. Information from the calorimeters is also used in the determination of track parameters, to account for cases of large energy loss in the calorimeters, and for MS-independent tagging of ID tracks as muon candidates.^[40] In this analysis, the type of combined (CB) muons is used.

Combined muons are identified by matching MS tracks to ID tracks and performing a combined track fit based on the ID and MS hits, taking into account the energy loss in the calorimeters. Based on the particle trajectory from the combined fit, the muon spectrometer hits associated with the track may again be updated and the track fit repeated. For $|\eta| > 2.5$, MS tracks may be combined with short track segments reconstructed from hits in the pixel and SCT detectors.

After reconstruction, muon candidates used for physics analyses are selected by a set of requirements on the number of hits in the different ID subdetectors and different MS stations, on the track fit properties, and on variables that test the compatibility of the individual measurements in the two detector systems. A given set of requirements for each of the muon types are defined referring to as a selection working point (WP). Three standard selection WPs are designed to cover the needs of the majority of physics analyses. In order of increasing purity and decreasing efficiency, these are the Loose, Medium, and Tight WPs. In this analysis, the Medium WP is used.

3.1.4 Jet Reconstruction

Particle Flow algorithm^[41] is used to reconstruct the jet in the analysis. First, inner detector (ID) tracks are selected with the *tight* criteria. These criteria comprise at least nine hits in the silicon detectors and tracks must not have missing hits in the pixel detector when such hits are expected from the trajectory and the operating conditions.

Tracks must be within $|\eta| < 2.5$ and have a transverse momentum of $p_T > 0.5$ GeV. Tracks matching to either an electron or muon with $p_T > 10$ GeV identified using the medium WP are removed. These tracks are then matched to a single calorimeter cluster. The calorimeter clusters are reconstructed with the usual topo-cluster algorithm^[42]

calibrated to the electromagnetic (EM) scale. The energy that the particle belonging to the track is expected to deposit in the calorimeter can then be computed based on the cluster position and the track momentum. It is relatively common that a single particle deposits its energy in multiple clusters, such that additional clusters within a cone around the track are added to the jet. Finally, the difference of the expected calorimeter energy deposited by the track and the sum of the associated clusters is compared with the expected calorimeter noise. If the difference is compatible with zero within 1.5σ , the clusters are removed otherwise the remnant topo-cluster is retained.

The PFOs are thus made from two separate collections: the neutral PFOs (nPFOs) that correspond to topo-clusters not associated to ID tracks (i.e. charged particles) and the charged PFOs (cPFOs) that correspond to the selected ID tracks. The cPFOs coming from vertices other than the primary vertex are removed, by requiring $z_0 \times \sin(\theta)$ to be within 2 mm from the primary vertex.

3.1.5 Missing Transverse Energy

In each collision, the sum of transverse momenta of final state particles are in conservation to zero. In case of particles escape the detection of ATLAS, imbalance of transverse energy are observed. These are typically from neutrinos or other undetectable particles like dark matter. The quantity missing transverse energy, denoted as E_T^{miss} , is used to quantify this effect. It is calculated from the rest of the energy summing over all reconstructed particles, such as photons, electrons, muons and jets.

3.2 Observable Definitions

The transverse plane is defined as perpendicular to the z-axis defined in Section 2.1. Then transverse momentum of a particle of interests is defined as the momentum projection in the transverse plane. The kinematic spectrums of W and Z are the measured through leptonic decay products.

The key parameters to describe kinematics of leptons, which could be electrons or muons in this analysis, are the momentum of lepton projected in the transverse plane, p_T^ℓ , the polar angle defined as the angle between lepton momentum and the z axis, η_l , the azimuthal angle, ϕ_l

In Z events, the invariant mass, m_{ll} , as defined in Eq. 3.2 and the transverse momentum, p_T^{ll} , as defined in Eq. 3.1 are obtained from the spectrums of leptons by combining the four-momenta of the di-lepton pair. Eq. 3.2

$$p_T^{ll} = p_{T,1} + p_{T,2} \quad (3.1)$$

$$m_{ll} = \sqrt{(E_{T,1} + E_{T,2})^2 - (p_{T,1} + p_{T,2})^2} \quad (3.2)$$

The momentum of the partons produced with W or Z , is measured by reconstructing the vector sum of the transverse energy of all clusters deposited in the calorimeters, excluding energy deposits associated with the decay leptons (see Figure 3.5). It is defined in Eq. 3.3.

$$u_T = \sum_i \vec{E}_{T,i} \quad (3.3)$$

where $\vec{E}_{T,i}$ is the vector of the transverse energy of cluster i deposited in hadronic calorimeter. The magnitude of the transverse energy $E_T = E/\cosh\eta$, with E being the energy deposit of the cluster and η being its pseudorapidity. The azimuth angle of a cluster, ϕ , is defined from the coordinates of the cluster in the transverse plane. In W and Z boson events, $-\vec{u}_T$ provides an estimation of the boson transverse momentum. In Z boson events, $u_{||}^Z$ and $u_{\perp}^Z$ represent the parallel and perpendicular projections of the recoil with respect to the direction of Z boson reconstructed from the dilepton pair. Whereas $u_{||}^Z$ could be compared to $-p_T^{ll}$ to probe the detector response in terms of linearity, the $u_{\perp}^Z$ distributions satisfy $\langle u_{\perp}^Z \rangle = 0$ and the width of it is an estimation of the recoil resolution. In W -boson events, $u_{||}^l$ and $u_{\perp}^l$ are the projections of the recoil onto the axes parallel and perpendicular to the reconstructed lepton transverse momentum.

In W events, the transverse momentum of the neutrino is estimated from missing transverse energy in Eq. 3.4.

$$p_T^{\nu} = E_T^{\text{miss}} = -(\vec{u}_T + p_T^{\ell}) \quad (3.4)$$

The resolution of the hadronic recoil is affected by the hadronic activities from underlying events, which quantified by the total reconstructed transverse energy $\sum E_T$, defined as the scalar sum of the transverse energy of all calorimeter clusters, and the

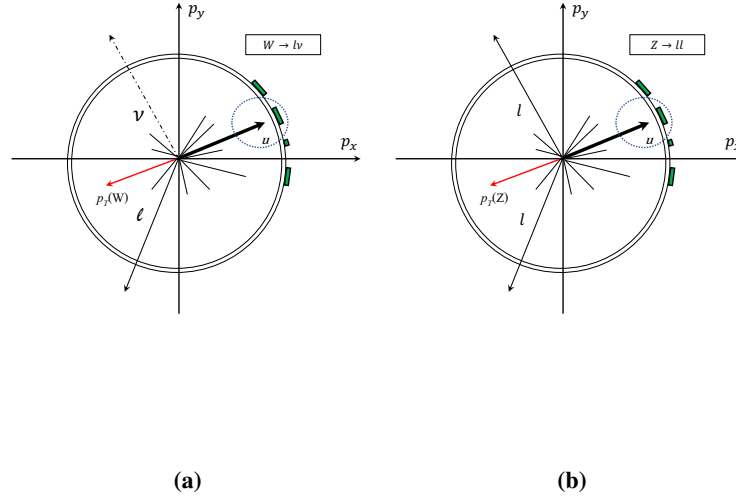


图 3.5 Sketch map displaying the transverse plane of a W/Z + recoil event. (a)W + recoil (b)Z + recoil. Di-lepton decayed from Z is measured by the tracker and EM calorimeter. the transverse momentum of recoil (u) in both W and Z events is evaluated by vector sum of energy deposited in Hadronic calorimeter, excluding energy associated with W/Z-decayed leptons.

quantity $\sum \overline{E}_T \equiv \sum E_T - |\vec{u}_T|$, which correct for the jet or gluon produced in the W and Z events.

Further calibrations of these variables about leptons and *hadronic recoil* are discussed in Sections 3.3 and 3.4

3.3 Calibration Of The Leptons

3.3.1 Electron Calibrations

This section discussed the calibrations and uncertainties applied to the lepton candidates in the analyses of the low pile-up datasets, with an average number of interactions per bunch crossing of $\langle \mu \rangle \approx 2$. Calibrations and uncertainties in electron and muon channels are discussed separately. The electron transverse momenta calibrations and related uncertainties are discussed in this section.

The data and MC samples used to extract the performance corrections are described in Section 3.5. Firstly, the calibration procedure used for the standard ATLAS 13 TeV data used in^[43] is briefly summarized. Then the extraction of the electron and muon

energy scales and resolution corrections for the special low pile-up dataset is discussed. The energy calibration of electrons is performed using $Z \rightarrow \ell\ell$ events from the low pile-up dataset. An alternative approach to extract energy scale corrections based on the extrapolation of the calibration correction computed with high pile-up dataset to low pile-up conditions is also described.

The measurement of electron efficiencies and the corresponding data-to-MC ratios (scale factors, denoted as SFs) for the 5 and 13 TeV low-pileup datasets are discussed afterwards, which includes a description of the methodology and the results for the reconstruction, identification, isolation, and trigger efficiencies and scale factors. The reconstruction scale factors are obtained by extrapolation of the standard high-pileup SFs to the low- μ regime, and apply to both the 13 and 5 TeV datasets. The identification scale factors are measured in-situ separately for the 13 and 5 TeV data. Isolation and trigger efficiencies and SF are measured in-situ for the 13 and 5 TeV data sets.

To select $Z \rightarrow ee$ events in high pile-up data, electron candidates must pass the triggers HLT_2e12_lhloose_L12EM10VH(for the year 2015), HLT_2e17_lhvloose_nod0 (2016), HLT_2e24_lhvloose_nod0 (2017) and HLT_2e24_lhvloose_nod0 (2018). For the low pileup data of the years 2017 and 2018, electron candidates must pass the trigger HLT_e15_lhloose_nod0_L1EM12. The offline selections used for high pile-up data are: both electrons are required to have a transverse momentum $p_T > 27$ GeV and $|\eta| < 2.47$ and satisfy the medium LH selection and to fulfill a loose isolation criteria as described in ^[44]. The same selections are applied to the MC simulation. The number of selected events for standard and low pile-up datasets can be found in Table 3.1.

	Standard runs		Low pile-up runs	
	Data	MC	Data	MC
2015 (13 TeV)	1.62 M	6.53 M (MC16a)	*	*
2016 (13 TeV)	15.6 M	18.5 M (MC16a)	*	*
2017 (5 TeV)	*	*	58.7 k	2.14 M
2017 (13 TeV)	19.2 M	20.2 M (MC16d)	79.9 k	1.38 M
2018 (13 TeV)	25.4 M	28.8 M (MC16e)	107.2 k	1.41 M

表 3.1 The number of $Z \rightarrow ee$ candidate events selected after applying all the selections for standard and low-pileup runs at $\sqrt{s} = 5$ and 13 TeV.

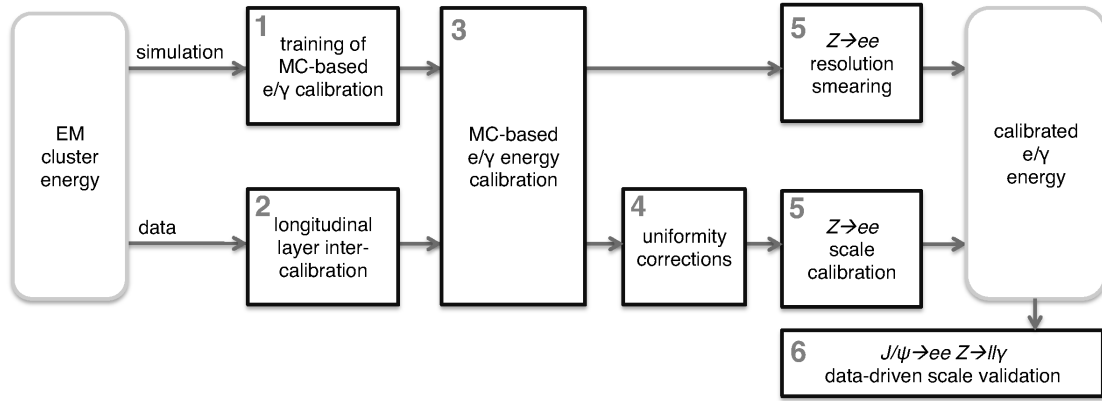


图 3.6 Schematic overview of the procedure used to calibrate the energy response of electrons and photons.

The detailed steps in the procedure to calibrate the energy response of electrons are shown in Figure 3.6. After the MVA-based scale calibration (trained on simulation and applied to both data and MC), BCID-dependent pile-up and uniformity corrections to data (steps 1-4), the overall electron response in data is calibrated using the $Z \rightarrow ee$ resonance (step number 5). The energy response in data is matched to the one in simulation by applying two corrections factors extracted from the calibration procedure: the energy scale factor α and the additional constant term c' . These corrections are extracted with the template method described in details in^[45].

- The energy scale factors α_i corrects the measured energy in data, E^{data} , to the scale of the simulation, E^{MC} , and is typically binned in pseudorapidity of the calorimeter

cluster (referred to with the index i)

$$E^{\text{data}} = E^{\text{MC}}/(1 + \alpha_i)$$

• The relative resolution of the electron energy measurement can be written as quadratic sum $\oplus$ of several terms:

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

where a is the stochastic term describing the fluctuations related to the development of the electromagnetic shower in the calorimeter, b is the electronic and pile-up noise term and c is the constant term. An additional constant term c'_i is used to enlarge the width of the MC mass distribution up to the data one in a given η_{calo} bin i :

$$\left(\frac{\sigma(E)}{E}\right)_i^{\text{data}} = \left(\frac{\sigma(E)}{E}\right)_i^{\text{MC}} \oplus c'_i$$

For the low pile-up runs, the same procedure described above is used to derive α and c' correction factors to match the response and resolution between data and MC. For the standard high-pileup data, the energy scale factors corrections are derived in 68 η bins. Because of the smaller number of $Z \rightarrow ee$ events in the low-pileup runs, combined 24 bins are used to derive the energy scale factors corrections in Table 3.2. The results obtained from these binnings are shown in Figure 3.7.

-2.47	-2.4	-2.1	-1.8	-1.55	-1.37	-1.2	-1	-0.8	-0.6	-0.4	-0.2	0	0.2	0.4	0.6	0.8	1	1.2
1.37 1.55 1.8 2.1 2.4 2.47																		

表 3.2 Values of η_{calo} bin frontiers for energy scale factors for low pile-up runs.

After the extraction of the correction scale factors using the in-situ method for low pileup runs, the m_{ll} distributions in data and MC are compared in Figure 3.8 for the low pile-up data in 2017. The agreement is good in the peak region: the agreement keeps within the uncertainties.

The electron selection efficiencies and uncertainties are discussed in the rest of this section. Electrons used in the analysis are required to be successfully reconstructed, pass certain p_T and η cuts as well as selections for identification (ID), isolation and

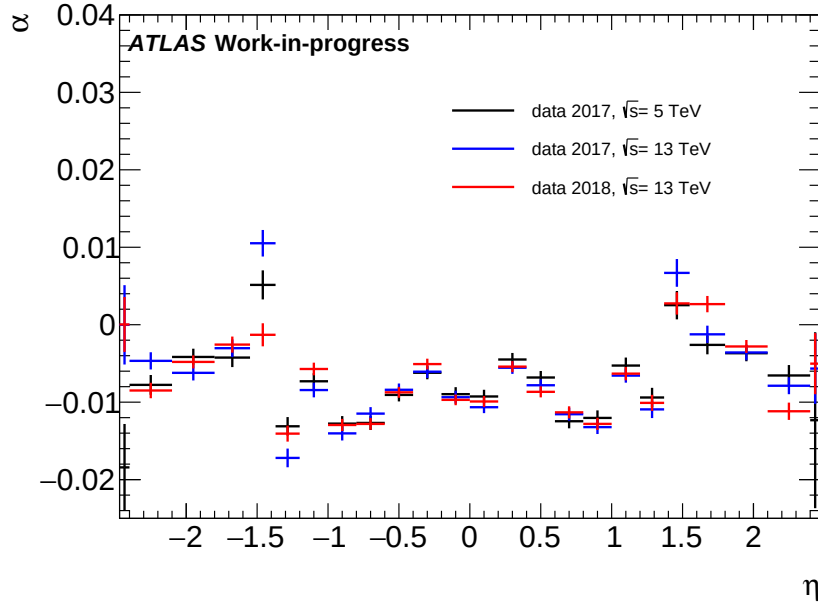


图 3.7 Energy scale factors α for low pile-up runs of 2017 (blue), 2018 (red) and 2017 at 5TeV (black) using 24 η bins.

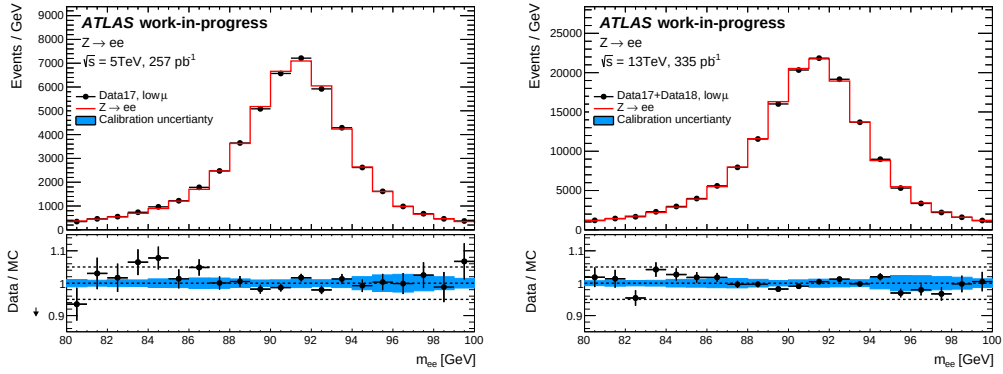


图 3.8 The invariant mass distribution around the Z-mass peak for MC and data in low pile-up runs for 5TeV and 13TeV data. The lower panel shows the data to simulation ratio, with the systematic uncertainty in green band. The 13TeV datasets includes both 2017 and 2018 data.

trigger. This section explains the measurements of the efficiencies associated to these steps for electrons in the central region $|\eta| < 2.47$ of the ATLAS detector for the low-pileup data. The data to MC ratio of the efficiencies measured with “tag-and-probe” methods are extracted with uncertainties to correct in the analysis the MC efficiencies to those measured in data. All procedures to select events and subtract background generally follow what is done for the standard EGamma tag-and-probe analyses during Run2 as documented e.g. in Refs. ^[43] and ^[44].

The definition of efficiencies are defined below:

- The reconstruction efficiency: the efficiency of reconstructing an electron from the combination of a cluster in the electromagnetic calorimeter to its track in the inner detector.
- The identification efficiency is defined as the fraction of reconstructed electrons passing a given working point, in this analysis, Medium electron is used.
- The isolation efficiency is defined as the fraction of reconstructed, MediumLLH-identified electrons that pass the isolation requirement $ptvarcone20/p_T^e < 0.1$.
- The trigger efficiency is of reconstructed, MediumLLH-identified and isolated electrons passing the trigger selection, HLT_e15_lhloose_nod0_L1EM12.

The reconstruction efficiency (ϵ_{reco}) means for the efficiency of reconstructing an electron from the combination of a cluster in the electromagnetic calorimeter to its track in the inner detector. The identification (ϵ_{ID}) and isolation (ϵ_{iso}) criteria use the shapes of EM showers in the calorimeter and track-related quantities to separate prompt, isolated electrons from photons and jets. Moreover, the trigger efficiency ($\epsilon_{trigger}$) relates to the fact that events are recorded online only if they pass the selection of HLT_e15_lhloose_nod0_L1EM12 algorithm.

Efficiencies in simulation are corrected to the data using scale factor (SF), defined as the ratio of the efficiency measured in data to that simulated from Monte Carlo samples. The total efficiency correction weight for a $W \rightarrow e\nu$ event is obtained as the product of different SFs:

$$W_{event}^{W \rightarrow e\nu} = SF_{reco} \times SF_{ID} \times SF_{iso} \times SF_{trigger} \quad (3.5)$$

The total efficiency correction weight for a $Z \rightarrow ee$ event is obtained from the SFs of

two associated electrons:

$$Z_{event}^{Z \rightarrow ee} = SF_{reco}^{e+} \times SF_{reco}^{e-} \times SF_{ID}^{e+} \times SF_{ID}^{e-} \times SF_{iso}^{e+} \times SF_{iso}^{e-} \times \frac{SF_{trig}^{e+}/ef f_{trig}^{e-} + SF_{trig}^{e-}/ef f_{trig}^{e+} - SF_{trig}^{e+} * SF_{trig}^{e-}}{1/ef f_{trig}^{e+} + 1/ef f_{trig}^{e-} - 1} \quad (3.6)$$

Electron efficiencies are measured with the tag-and-probe method in $Z \rightarrow ee$ events: Electrons are required to have $p_T > 15$ GeV (main focus is 20 GeV or the tag) and $|\eta| < 2.47$, excluding the crack region between barrel and endcap $1.37 < |\eta| < 1.52$ and pass a cut-based loose identification quality selection named "is Good Object Quality".

The efficiency scale factor results are shown in Figure 3.9 as function of p_T for different η bins for the 5 and 13 TeV merged data sets. The 5 and 13 TeV reconstruction SFs are compatible within their uncertainties. So the two datasets are merged to improve the measurement by reducing the statistical uncertainties in particular in the background subtraction procedure.

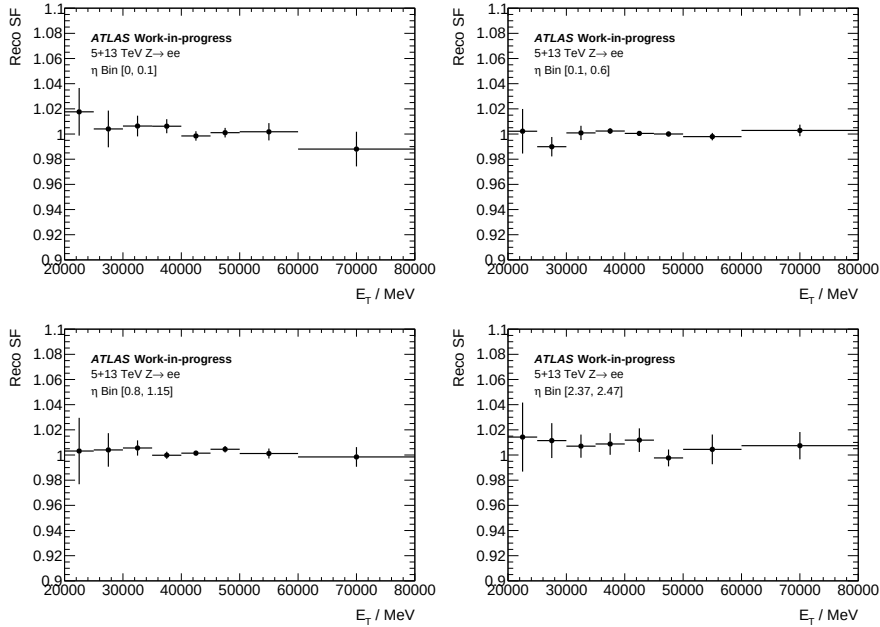


图 3.9 Examples of electron reconstruction SFs with 5+13 TeV combination in η bins as written in the plot legend. The total uncertainties are shown.

The electron identification efficiency is defined as the fraction of reconstructed electrons passing a given working point. For the low-pileup $W \rightarrow e\nu$ and $Z \rightarrow \ell\ell$

measurements, the “medium LH” working point was found to give a good balance of efficiency and background rejection, so all measurements are performed for this working point (MediumLLH_d0z0_DataDriven_Rel21_Smooth_vTest). two different methods are used to perform the background subtraction, called Z_{mass} and Z_{Iso} .

In Z_{mass} -method, the tag electron is required to be matched to the single-electron trigger, pass tight ID and isolation cuts and $p_T > 20$ GeV. Probes are required to be reconstructed as electron with good track (passing the “PassTrackQuality” criteria and the electron/photon ambiguity resolver), p_T and be separated by $\Delta R > 0.4$ from jets with $p_T^{\text{jet}} > 20$ GeV.

Z_{Iso} -method uses the calorimeter energy isolation $E_T^{\text{cone0.3}}$ of the probe electron. The variable $E_T^{\text{cone0.3}}$ is defined as the calorimeter energy deposition in topological clusters within $\Delta R < 0.3$ around the electron candidate. Signal electrons are predominantly expected at small values of $E_T^{\text{cone0.3}} \sim 0$ whereas background should be found mainly at high values.

The final ID SFs and uncertainties are obtained by considering both the Z_{mass} and Z_{Iso} results. The results are shown in Figure 3.10

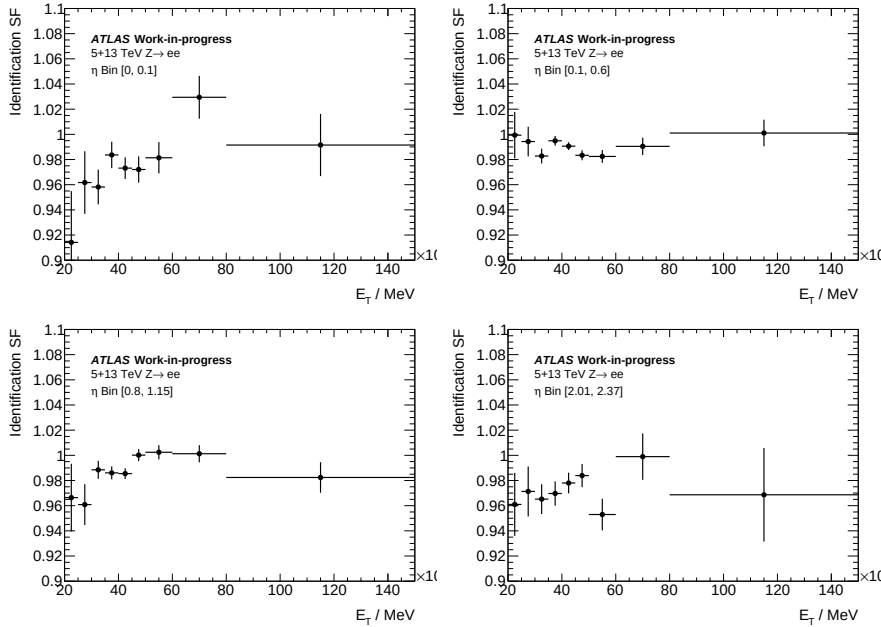


图 3.10 Examples of electron ID SFs at 13 TeV data extracted from the combination of the Z_{mass} and Z_{Iso} methods in four η ranges as indicated in the plot title as a function of p_T^e . The total uncertainties are shown.

The electron isolation efficiency is defined as the fraction of reconstructed, MediumLLH-identified electrons that pass $ptvarcone20/p_T^e < 0.1$. the isolation criterion of interest, $ptvarcone20$, is based on the sum of transverse momenta of tracks in a cone of $\Delta R < 0.2$ around the electron. The efficiencies are determined as function of η in bins of p_T^e . The MC isolation efficiencies are shown in Figure 3.11

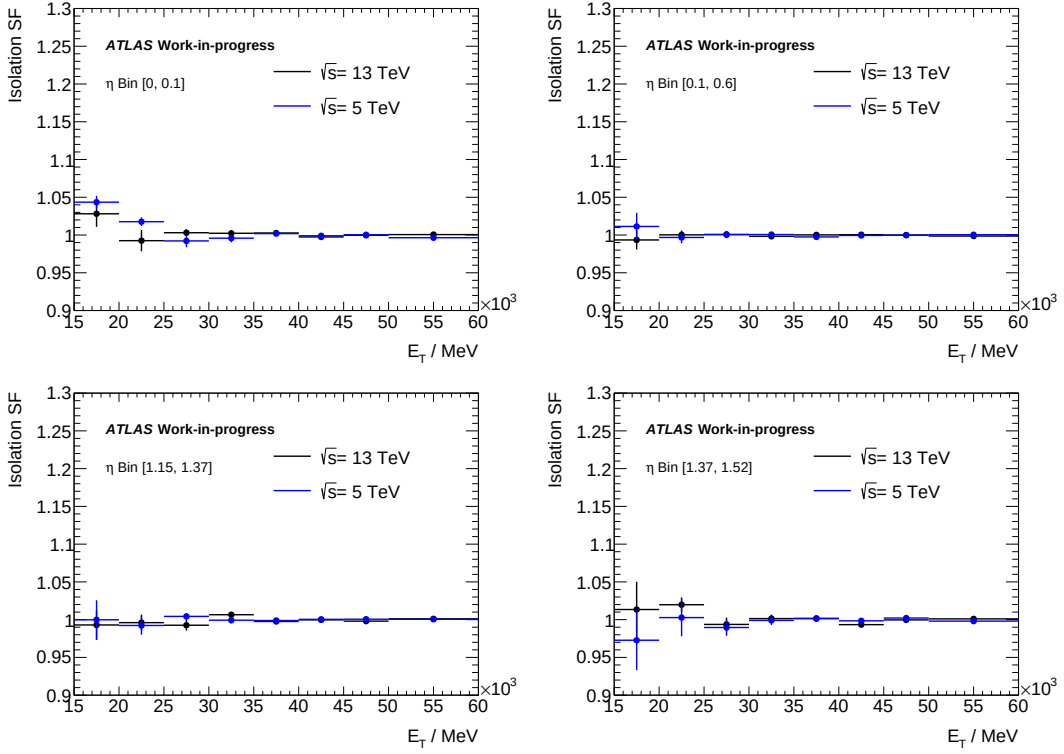


图 3.11 Example electron isolation efficiencies for the $ptvarcone20/p_T^e < 0.1$ working point compared between low-pileup MC at 5 and 13 TeV in several η ranges

During the low-pileup data taking it was possible to run the trigger HLT_e15_lhloose_nod0_L1EM12 unprescaled, which has a low threshold of $p_T > 15$ GeV, loose ID criteria and no isolation requirement. The efficiency of this trigger is defined as the fraction of reconstructed, MediumLLH-identified and isolated electrons passing the trigger selection. Figure 3.12 shows the efficiencies and data-to-MC SFs determined in the 13 TeV low-pileup dataset as function of η in bins of p_T . the efficiency is relatively high with typically 90 – 98% and the SFs are generally close to unity.

The measurements of electron reconstruction, identification, isolation and trigger efficiencies and the corresponding data-to-MC SF in 5 and 13 TeV low-pileup data was discussed. Different ways to improve the SF precision are investigated:

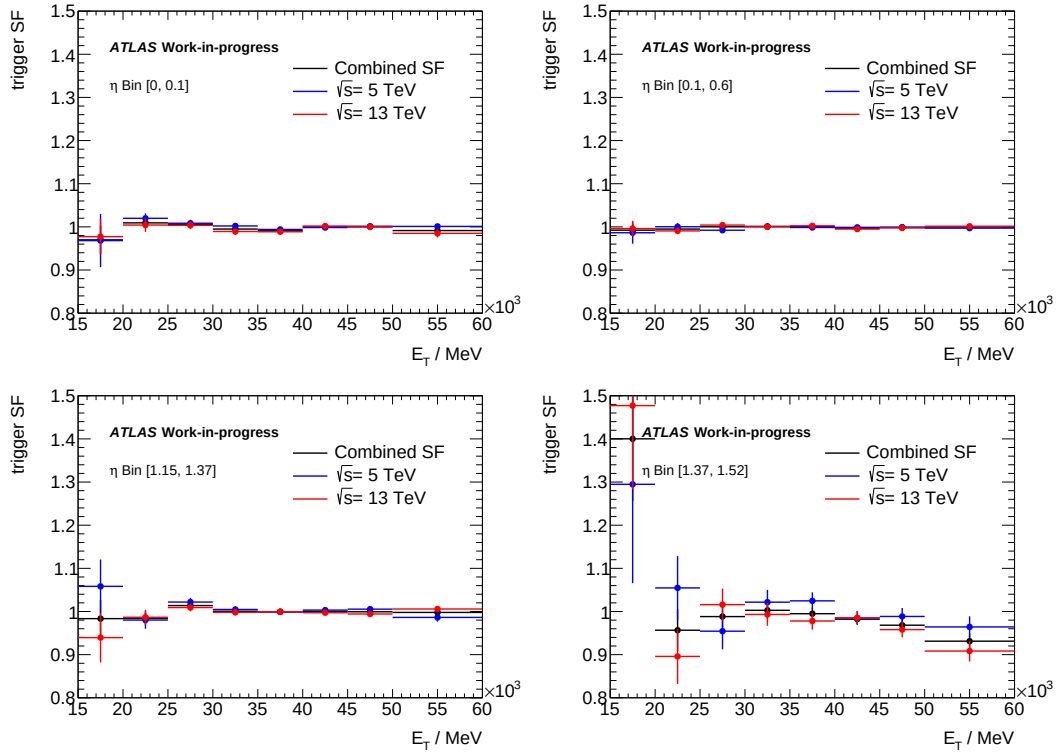


图 3.12 Example of Comparison of electron trigger (HLT_e15_lhloose_nod0_L1EM12) SFs with 5 TeV and 13 TeV data as well as the average in four positive η ranges as written in the plot legend (results were found very similar for negative eta) . Four bins from most central $\eta = 0 - 0.1$ (top left) to most forward $\eta = 2.37 - 2.47$ (bottom right) are show.

Reconstruction: 5 and 13 TeV MC efficiencies and SF measurements are compatible and can be combined to reduce statistical uncertainties. The high-pileup reconstruction SF is found to be compatible with the low-pileup measurement within additional global 0.2% systematic uncertainty. This is eventually the method chosen for the final analyses.

Identification: The 5 TeV and 13 TeV ID SFs are measured individually. Following the high-pileup procedure, the SF are averaged between the ZIso and Zmass methods.

Isolation and Trigger: the SFs are found to be close, but not identical for the 5 TeV and 13 TeV low-pileup data sets, therefore the final SF are used as derived in-situ from the respective datasets.

3.3.2 Muon calibrations

This chapter discusses the extraction of muon efficiency scale factors, and the calibration of muon momentum scale and resolution, considering the special runs taken in low pile-up (low- μ) conditions. These data sets require dedicated studies of the muon performance, since the data conditions are very different from the other ATLAS runs and the standard efficiency scale factors and calibration determined for high-pileup data sets might not be appropriate.

The muon momentum calibration includes corrections to the momentum scale and resolution. These corrections are applied to muons in the MC simulation to bring the scales and resolutions closer to the one measured in data. The corrections are applied separately to muon tracks reconstructed in the inner detector (ID tracks) and in the muon spectrometer (ME tracks). A procedure of reweighting contributions from ID and ME tracks allows to propagate the corrections to combined muon tracks (CB tracks). To derive and validate muon momentum corrections, muons from two resonances are used: $J/\psi \rightarrow \mu\mu$ (for muon transverse momenta $5 < p_T < 30 \text{ GeV}$) and $Z \rightarrow \mu\mu$ ($22 < p_T < 300 \text{ GeV}$). In order to study the muon momentum corrections, fits are made to $J/\psi \rightarrow \mu\mu$ and $Z \rightarrow \mu\mu$ mass peaks. The fit model consist of a sum of a Crystal Ball function (core of the mass peak), a wider Gaussian (accounting for e.g. multiple scattering) and an exponential function describing backgrounds. Two parameters of the Crystal Ball function are considered for the validation of corrections:

- mean of the mass peak, $m_{\mu\mu}$, which is sensitive to the momentum scale
- width of the mass peak, $\sigma_{\mu\mu}$, which is sensitive to the momentum resolution

The $m_{\mu\mu}$ distribution comparisons after muon momentum calibration between data and MC simulations are shown in Figure 3.13. The blue band represents the calibration uncertainty of muon momentum. The agreement is good in the peak region: the agreement keeps within the uncertainties.

The muon reconstruction efficiencies and scaling factors are determined by the ATLAS MCP group using the same procedures as for the full Run 2 analysis. The efficiencies in data and MC are derived from the low- μ data and compared to those derived from the full, high- μ 2017+2018 data sets. The data/MC efficiency ratios are found to

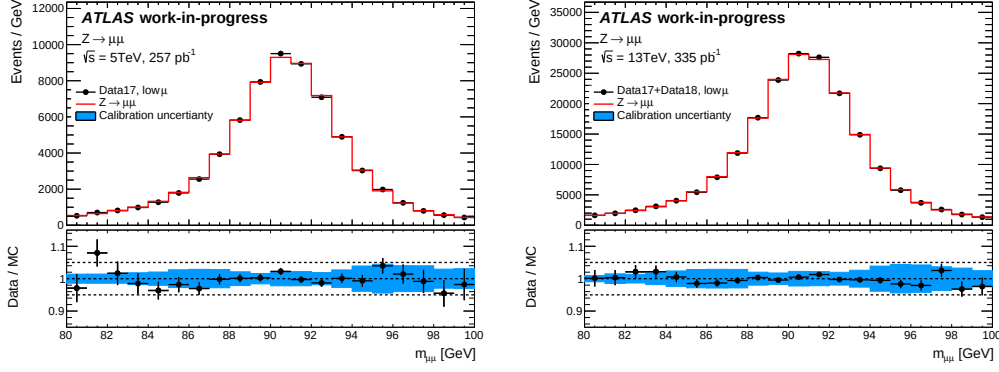


图 3.13 The invariant mass distribution around the Z-mass peak for MC and data in low pile-up runs for 5TeV and 13TeV data. The lower panel shows the data to simulation ratio, with the systematic uncertainty in green band. The 13TeV datasets includes both 2017 and 2018 data.

be in agreement with the ones from high- μ data. To avoid unnecessary statistical fluctuations in the analyses, it was decided to make use of the full high- μ statistics and use high- μ scaling factors with an additional extrapolation correction and systematic to the low- μ conditions. The scale factors are measured in two dimensions, the transverse momentum p_T and pseudorapidity η of the muons.

There are four selection efficiencies taken into account:

- **Reconstruction** : The Medium muon reconstruction working point is used in the analysis, where muons are combined from tracks reconstructed in the inner detector (ID) and muon spectrometer (MS).
- **Track-to-vertex-association**: Muon candidates are required to pass $|z_0| \cdot \sin(\theta) < 0.5$ mm and $|d_0|/\sigma_{d_0} < 3$ in order to make sure that the selected objects are originating from the primary vertex.
- **Trigger** : fraction of muons passing HLT_mu14 trigger requirement.
- **Isolation**: fraction of muons passing $p_T^{\text{varcone20}}/p_T^\mu < 0.1$ requirement.

The Medium muon reconstruction working point is used in the analysis, where muons are combined from tracks reconstructed in the inner detector (ID) and muon spectrometer (MS). This working point provides very good acceptance up to $|\eta| < 2.5$, a small fake rate, and small systematic uncertainties.

The following selection criteria are applied to the tag muon: it is required to satisfy

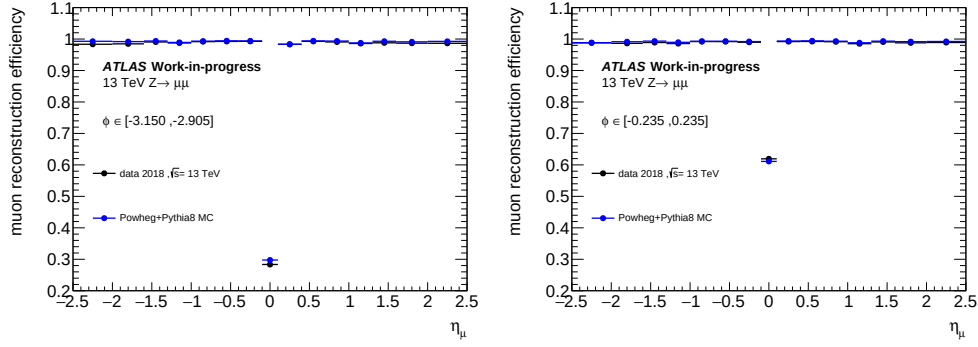


图 3.14 Comparison of reconstruction efficiencies for Medium muons using the low- μ runs of 2018 at a centre-of-mass energy of $\sqrt{s} = 13$ TeV in data and Powheg+Pythia8 simulation. Efficiencies are shown as a function of muon η in slices of muon ϕ . The error bands show only the statistical errors.

the Medium identification criteria, $p_T > 28$ GeV, $|\eta| < 2.5$ and the single muon trigger requirement HLT_mu14 for low- μ data. In order to suppress background, i.e. mostly muons from the decay of hadrons in jets, the tag muon must fulfill the Fix Cut Tight (FCTight) selection criteria. The muon reconstruction efficiency for the 2018 (13 TeV) data sets are shown below. The simulation shown is the one relevant to the data set under consideration, i.e. low- μ data are compared to dedicated low- μ MC, while high- μ (standard) data are compared to the standard ATLAS MC16d/e. The top pads show the measured data and MC efficiencies, while the bottom pads show the data/MC efficiency scale factors for the matching pairs (low- μ data/MC, high- μ data/MC). The one-dimensional projections in relevant muon kinematics (p_T , η , ϕ) are shown. In general, the data efficiencies are slightly below the MC efficiencies, which is corrected in the analysis by applying the data/MC ratio as correction factor. Both the data and MC efficiencies are separately very high and very close between the high- μ and low- μ sets and hence the efficiency scale factors are very similar. When comparing the scale factors, it is important to consider, that the uncertainty component labelled as “systematic” does have a very significant statistical component for the low- μ data, as the methods were developed and tested for large datasets. One should therefore judge the agreement within the total uncertainties. Of special importance for the eventual measurement of the W -boson mass is the dependence of efficiency on the muon p_T .

Muon candidates are required to pass $|z_0| \cdot \sin(\theta) < 0.5$ mm and $|d_0|/\sigma_{d_0} < 3$ in or-

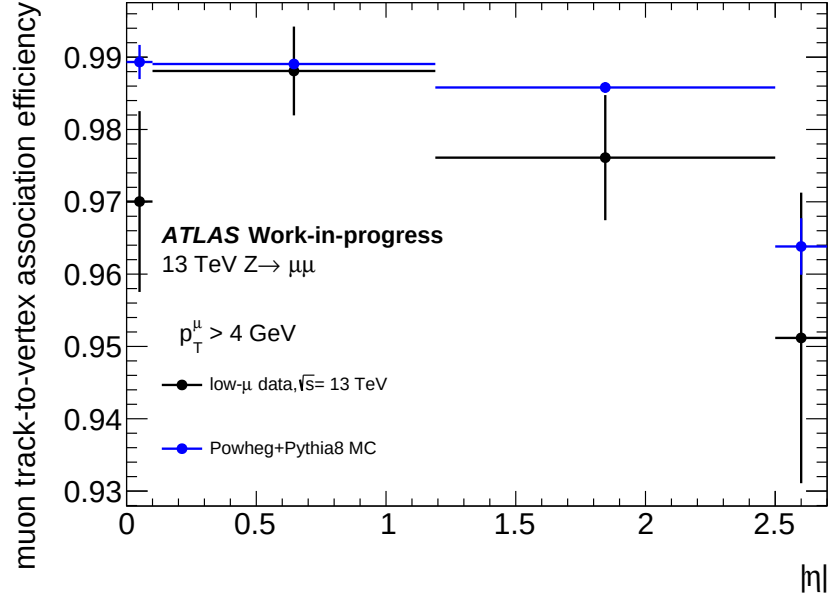


图 3.15 Comparison of TTVA efficiencies for Medium muons using the low- μ runs of 2017+18 at $\sqrt{s} = 13$ TeV. Efficiencies are shown as function of muon η . Red (orange) points correspond to low- μ data (MC), while the black (blue) points are high- μ data (MC).

der to make sure that the selected objects are originating from the primary vertex. These selections are also referred to as *track-to-vertex association* (TTVA) requirements. The *Loose* identification criterion is the default choice for this measurement by the MCP group and the TTVA efficiency is not affected by the choice of identification working point, thus the derived corrections are valid also for the *Medium* working point. The TTVA efficiencies for the low- μ data periods are shown in function of η_μ in Figure 3.15.

The determination of trigger efficiency in data is based on the ‘tag-and-probe’ method. At the high-level trigger the HLT_mu14 chain selects events containing a muon with $p_T > 14$ GeV and is seeded from the level-1 trigger L1_MU10 requiring a muon with $p_T > 10$ GeV. The muon is considered to have fired the trigger, when the reconstructed object can be matched within $\Delta R < 0.1$ to the trigger object. The trigger efficiency is then defined as fraction of all probe candidates and events where the probe candidate was matched to the trigger object.

The efficiencies were examined in three dimensions, p_T , η and ϕ . In contrast to the more common approach which bin the efficiencies and scaling factors in η and ϕ , instead a binning in η and p_T was applied, to meet the needs of the analysis, where the

Systematic	Variation
Tighter Z mass window	$86 < m_{\mu\mu} < 96 \text{ GeV}$
Looser Z mass window	$76 < m_{\mu\mu} < 106 \text{ GeV}$
Tighter isolation	$\text{ptvarcone30}/p_T < 0.1$ and $\text{topoetcone20}/p_T < 0.2$
Looser isolation	$\text{ptvarcone30}/p_T < 0.2$ and $\text{topoetcone20}/p_T < 0.4$
Tighter matching	$\Delta R < 0.08$
Looser matching	$\Delta R < 0.12$
Detector symmetry	$\Delta\phi_{\mu\mu} < 3.0426$
no IP cuts	

表 3.3 Systematic variations of the selection used in the muon trigger efficiency measurements.

p_T^Z and p_T^W spectrums are highly dependent on the proper determination of the lepton p_T distribution but which are inclusive in ϕ . To determine the impact of systematic uncertainties, the selection requirements of the probe objects and the matching window to the trigger object were varied. The systematic variation in considerations can be found in Table 3.3.

Figure 3.16 shows the one-dimensional projections of the efficiencies for 13 TeV data. A feature that is common to muon trigger efficiencies in ATLAS is the lower efficiency in the barrel region (largely due to geometrical reasons) and the lower data/MC ratios in the barrel (due to broken RPCs). The scale factors are determined with typically sub-percent accuracy, dominated by statistical uncertainties.

Muons decayed from W and Z bosons are expected to be isolated. Applying the related selections is a major way to reject backgrounds from QCD multijet production. The requirement $p_T^{\text{varcone20}}/p_T < 0.1$ is used in the analysis.

The isolation selection efficiency is defined as the ratio of the number of probe muons passing this isolation selection to the number of all probe muons (Eq. 3.7). Scale factors (SFs), which are used in the analysis to correct MC events, are derived as the ratio of isolation selection efficiencies in data and simulation (Eq. 3.8). The efficiencies of isolation selections and SFs are measured as a function of the probe muon η and p_T .

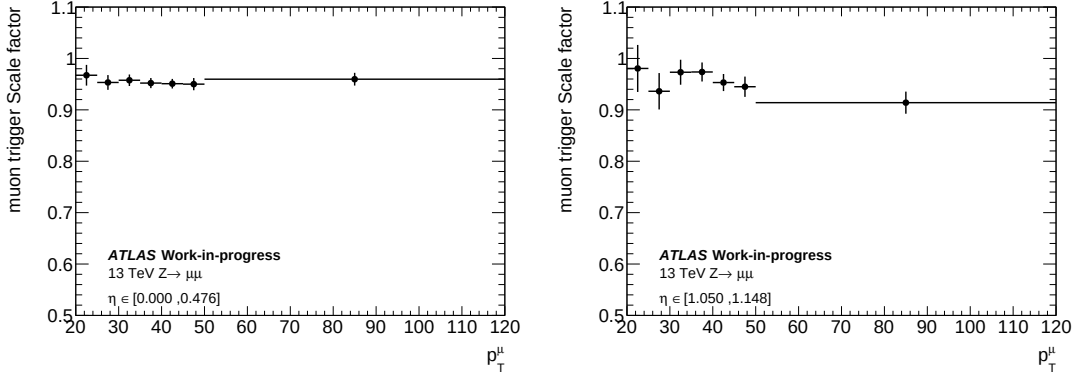


图 3.16 1D trigger efficiency in data and MC at 13 TeV, for probes from the barrel and endcap regions and inclusive p_T distributions. Trigger sectors in the barrel and endcap regions are different and therefore shown in distinct plots. The bin edges correspond to physical edges of the trigger sectors.

$$\epsilon_{\text{iso}} = \frac{N_{\text{probe}}^{\text{isolated}}}{N_{\text{probe}}}. \quad (3.7)$$

$$\text{SF}_{\text{iso}} = \frac{\epsilon_{\text{iso}}^{\text{data}}}{\epsilon_{\text{iso}}^{\text{MC}}}. \quad (3.8)$$

In all cases, the scale factor uncertainties are dominated by the statistical precision of the isolation efficiency measurement in data, while the largest contribution to systematic uncertainties typically comes from the variation of the tag-and-probe pair invariant mass range. The $p_T^{\text{varcone20}}/p_T < 0.1$ isolation cut is selected to be applied in the final analyses results. The summary of one-dimensional efficiencies and SFs for $p_T^{\text{varcone20}}/p_T < 0.1$ working point measured for the 2018 13 TeV datasets is shown in Figure 3.17.

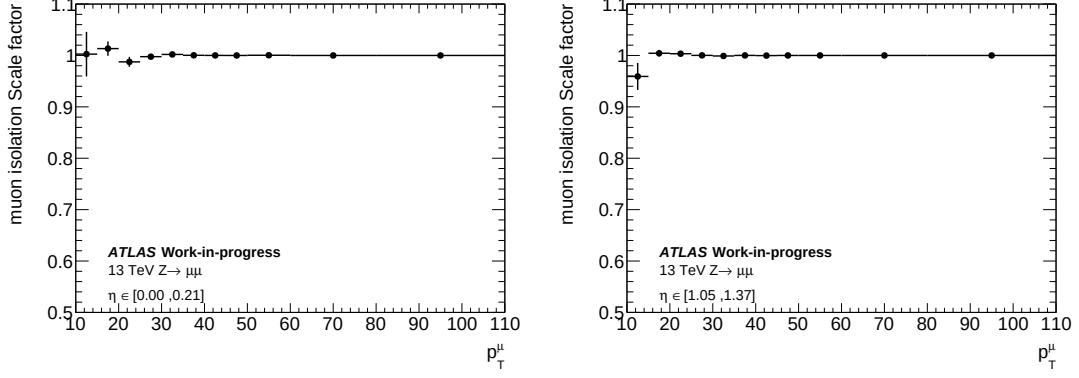


图 3.17 Scale factors for $p_T^{varcone20}/p_T < 0.1$ isolation selections measured in 13 TeV data and MC as a function of muon p_T in slices of η_μ .

3.4 Hadronic Recoil Calibration

The transverse momentum of the neutrino from the $W \rightarrow \ell \nu$ decay can only be determined indirectly through the measurement of all other particles produced in a pp collision. In the context of W -boson measurements the neutrino plays a important role and is crucial to achieve the highest precision possible. The basic methodology to infer the neutrino kinematics is called *hadronic recoil*. The idea is to measure the vectorial and scalar sums of all particles from initial state gluon and quark radiation. As the initial pp collision is balanced in the transverse plane, the transverse momentum of W or Z equal to the magnitude of scalar sum of p_T for all energies deposited on calorimeters excluding the signal electron or muon. Furthermore, the neutrino transverse momentum can be inferred from the *hadronic recoil* and the lepton p_T which decayed from the W .

The relation between the quantities is:

$$\vec{p}_T^V = \vec{p}_T^\ell + \vec{p}_T^\nu = - \sum_{i=\text{ISR } q,g} \vec{p}_{Ti} = -\vec{u}_T. \quad (3.9)$$

where $\vec{p}_T^V$ denotes the transverse momentum of the W boson and $\vec{p}_T^\ell$ and $\vec{p}_T^\nu$ denote the transverse momenta of the charged decay lepton l and the neutrino ν . The hadronic recoil $\sum_{i=\text{ISR } q,g} \vec{p}_{Ti} = \vec{u}_T$ is the quantity which accounts for all transverse momenta of the partons from initial state radiation and thus indirectly measures the transverse momentum of the W boson $\vec{p}_T^V$. Assuming for now that $\vec{u}_T$ can be measured, this allows

to determine indirectly the neutrino transverse momentum $\vec{p}_T^\nu$:

$$E_T^{\text{miss}} = p_T^V = -(\vec{u}_T + \vec{p}_T^\ell) \quad (3.10)$$

where E_T^{miss} is the missing transverse energy as introduced in Section 3.1.5. The angle between the lepton and E_T^{miss} , $\phi_{l\nu}$, is also importance to determine the transverse mass $m_T = \sqrt{2p_T^\ell p_T^\nu(1 - \cos\phi_{l\nu})}$. The same considerations hold also for $Z \rightarrow \ell\ell$ production with the crucial difference that the neutrino transverse momentum p_T^ν is replaced by a very precisely measured p_T^ℓ of the second lepton.

3.4.1 Hadronic Recoil Reconstruction

The hadronic recoil has been used successfully in previous measurements, such as the measurement of the W -boson transverse momentum with 2010 $\sqrt{s} = 7$ TeV data^[20] and the measurement of the W -boson mass with 2011 $\sqrt{s} = 7$ TeV data^[17]. This chapter summarizes the studies done regarding the understanding of how to calculate and calibrate the *hadronic recoil* for the precision measurements on p_T^W and p_T^Z .

The *hadronic recoil* is calculated using an algorithm based on *Particle Flow Objects* (PFO). An important consideration is to make the algorithm fully transparent regarding its application in $W \rightarrow e\nu$ or $W \rightarrow \mu\nu$ events and its calibration with $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ events. This is achieved by the removal of any activity in a cone of $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} < 0.2$ around any identified electron or muon. The bias introduced in this procedure through the removal of energy deposits unrelated to the lepton is compensated for by a replacement with energy in a region away from the lepton. The calibration uses Z -boson events as a standard candle since the (transverse) kinematics of the final state is fully reconstructed through the precise measurement of the two decayed leptons with a resolution better by one order of magnitude than the hadronic recoil measurement.

The input constituents used for the reconstruction of the hadronic recoil include the *Particle Flow Objects* and *topo-clusters*. The *Particle Flow* algorithm is discussed in Section 3.1.4. The Particle Flow Objects (PFOs) are made from two separate collections: the neutral PFOs (nPFOs) that correspond to topo-clusters not associated to ID tracks (i.e. charged particles) and the charged PFOs (cPFOs) that correspond to

the selected ID tracks. The cPFOs coming from vertices other than the primary vertex are removed, by requiring $z_0 \times \sin(\theta)$ to be within 2 mm from the primary vertex.

The energy associated with W – and Z – decayed leptons are removed from the hadronic recoil. The algorithm should be transparent between W –boson and Z –boson as well as electron and muon decay channels to allow for a precise calibration and well-understood correlations. Example for lepton-related differences between the electron and muon channels to be removed are energy deposits from muons in the calorimeter or electrons showering in the material leading to energy deposits away from the main electron cluster. Empirically it has been found, that a cone of radius $\Delta R < 0.2$ around the lepton axis is sufficient to remove these effects, while being small enough to not impact the rest of the event reconstruction. The PFOs inside this cone around identified leptons are therefore removed from the calculation of the recoil. This procedure at the same time removes energy deposits from underlying event and pile-up and thus artificially creates an imbalance in the event. To compensate this, the activity in the removed cone is replaced by the one from a random cone located at the same η and at a random ϕ position such that it is away by $\Delta R > 0.4$ from any lepton and the uncorrected recoil. The replacement cone activity is rotated in ϕ to the removed lepton direction and added vectorially to the recoil. The leptons which are entering this removal procedure should be well measured and pass the following criteria: $p_T > 10$ GeV, $|\eta| < 2.4$ for muons, and $|\eta| < 2.47$ for electrons, excluding the crack, muons pass *medium* and electrons pass *LooseLH + B-Layer hit*.

A critical quantity in the hadronic recoil calibration is $\sum E_T$, defined in Section 3.2. Naturally $\sum E_T$ will be strongly dependent on the vector boson dynamics and grow with $p_T^V = u_T$. To disentangle these effects, an even more important quantity is defined by $\sum \bar{E}_T = \sum E_T - u_T$. $\sum \bar{E}_T$ is thought of the event activity corrected for the directed recoil activity and thus represents the activity from underlying event, pileup, and emissions beyond first hard emission. E.g. a $V + 1$ jet event has $\sum \bar{E}_T \sim 0$ on parton level for any jet p_T and thus a finite $\sum \bar{E}_T > 0$ is due to additional activity.

Due to the large phase space for underlying event, multiple emissions and pileup activity, $\sum \bar{E}_T$ has a typical value of order 100 – 200 GeV in W, Z production events as

shown in Figure 3.18 for the case of $Z \rightarrow \ell\ell$ at $\sqrt{s} = 5, 13$ TeV. Significantly higher values of $\sum \vec{E}_T$ are reached for the higher beam energy. It can also be appreciated in this figure, that the $\sum \vec{E}_T$ quantity has the same distribution in electron and muon channels, demonstrating that the lepton removal works as expected.

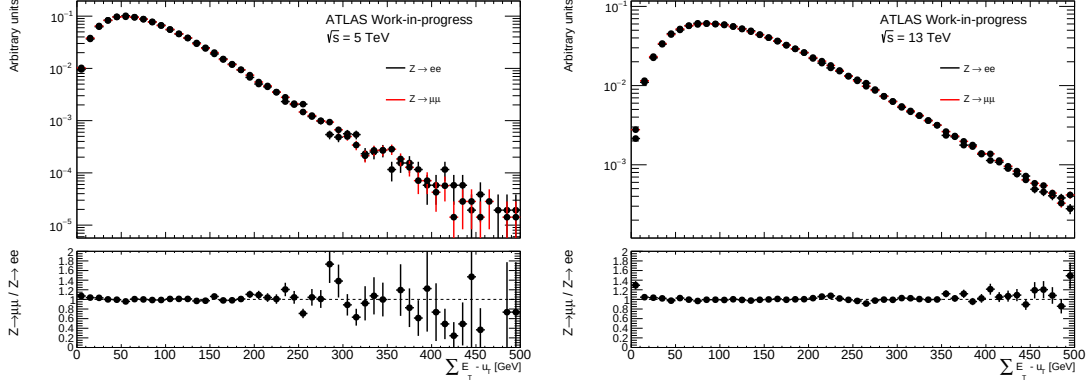


图 3.18 Distributions of $\sum \vec{E}_T$ for data at $\sqrt{s} = 5$ TeV(left) and at $\sqrt{s} = 13$ TeV(right) in $Z \rightarrow \ell\ell$ events. The 13 TeV data taken in 2017 and 2018 were combined. The distributions for the electron and muon channels are compared, showing a good compatibility.

To characterize and calibrate the hadronic recoil, a few additional variables are defined to describing the event activity. Specifically, these variables are independent of the random ϕ direction of the event activity and instead correlate directly with the vector boson kinematics. In Z events, the Z -boson axis in the transverse plane, $\vec{p}_T^{\ell\ell}$, is used to characterize the boson activity, as sketched in Figure 3.19. The scalar quantities employed are formed from projections of $\vec{u}_T$ as follows:

- The component of the hadronic recoil perpendicular to the Z axis¹

$$u_{\perp} = \frac{|\vec{p}_T^{\ell\ell} \times \vec{u}_T|}{p_T^{\ell\ell}}, \quad (3.11)$$

which is zero on average with a width of the distribution reflecting the hadronic recoil resolution (along this direction)

- The component parallel to the Z -boson axis

$$u_{\parallel} = \frac{\vec{p}_T^{\ell\ell} \cdot \vec{u}_T}{p_T^{\ell\ell}}, \quad (3.12)$$

which should in principle balance the boson transverse momentum $u_{\parallel} = -p_T^{\ell\ell}$.

¹The notation uses the usual “cross product $\times$ ” on 2D vectors extended to 3D as $(x, y, 0)$

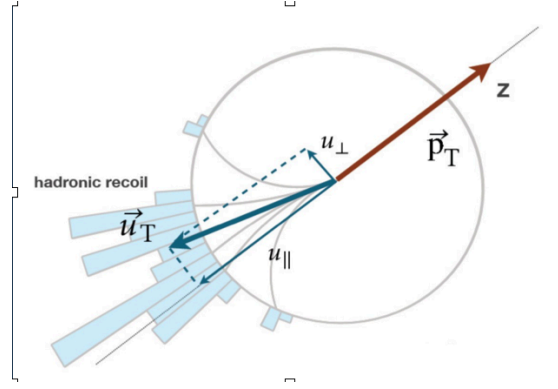


图 3.19 Sketch of an event in the transverse plane of the production of a Z -boson at significant transverse momentum (indicated by the arrow labelled with “Z” and $\vec{p}_T = \vec{p}_T^{\ell\ell}$ and of the projections $u_\perp$ and $u_\parallel$ of the hadronic recoil u_T with respect to the “ Z -boson axis”.

- It is thus more convenient to define the so-called *bias*

$$b = u_\parallel + p_T^{\ell\ell}, \quad (3.13)$$

which is expected to be centred around zero. However, due to particles escaping detection, energy losses in dead material and the non-compensating nature of the calorimeters, one typically finds on average $b > 0$ (and the distribution will have a width reflecting the hadronic recoil resolution along this direction).

Figure 3.20 shows the distributions of $u_\perp$, $u_\parallel$ and the *bias* b in the simulation and in the data in $Z \rightarrow \mu\mu$ selection without any calibration of the hadronic recoil.

In the case of W -boson events, the boson axis $\vec{p}_T^{\ell\ell}$ cannot be reconstructed in data, due to the missing of the neutrino. Thus two alternative projections of hadronic recoil are defined with respect to the W -decayed lepton:

$$u_\perp^\ell = \frac{|\vec{p}_T^\ell \times \vec{u}_T|}{p_T^\ell} \quad (3.14)$$

and

$$u_\parallel^\ell = \frac{\vec{p}_T^\ell \cdot \vec{u}_T}{p_T^\ell}, \quad (3.15)$$

3.4.2 Performance Studies

This section discusses two studies that were performed to optimize the *hadronic recoil algorithm* regarding the u_T resolution as is necessary for an optimal measurement of the W -boson transverse momentum spectrum.

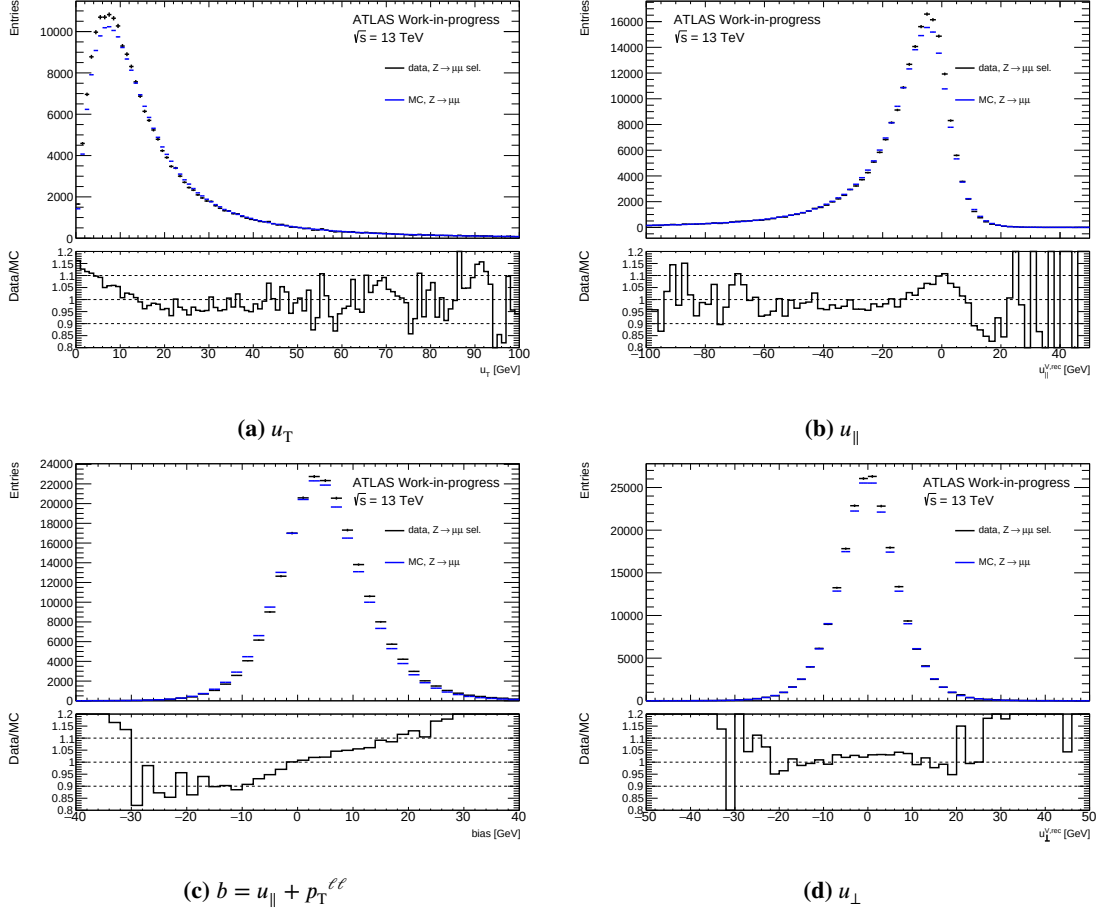


图 3.20 Illustrative recoil distributions in the data and in the simulation, after a $Z \rightarrow \mu\mu$ selection at 13 TeV, using 2017 data. No calibration is applied and the true underlying p_T^V is not necessarily similar in data and simulation. $u_T \sim p_T^{\ell\ell}$ follows the distribution of the Z -boson transverse momentum (broadened by resolution), $u_{||}$ is to first order equal to $-u_T \sim p_T^{\ell\ell}$, which is made more explicit in the b quantity, which is slightly biased to positive values. The transverse projection $u_{\perp}$ is on average equal to zero. The bin size is not constant and the bins contain simply event entries, leading to shapes that are different from what one would obtain using the entries divided by the bin width.

The hadronic recoil algorithm can use different input constituents and the performance of eleven different choices is studied using $Z \rightarrow \mu\mu$ simulation at $\sqrt{s} = 13$ TeV. The topo-clusters reconstructed in the calorimeters are by default calibrated at the electromagnetic (EM) scale, however they may be calibrated at the hadronic scale with the so-called Local Hadronic Calibration (LC)^[46]. Given that the PFOs use generally the track measurements (cPFO) for charged hadrons ($\pi^\pm, \dots$) in the central region, and given that the remaining calorimeter clusters (nPFO) are supposedly dominated by neutral hadron decays such as $\pi^0 \rightarrow \gamma\gamma$, it is best to not use LC weights associated to nPFOs, and simply take the EM scale. On the other hand in the forward region not covered by the tracker, the LC calibration may be useful. The best performance among these algorithm is achieved by the *pfoEM*, that uses both charged and neutral PFOs and the EM scale for the neutral PFOs, which is therefore chosen for further calibration and the eventual analysis.

The key quantity to optimize the response and resolution is the relative resolution $\sigma(u_\perp)/\langle u_T \rangle$ studied as a function of the true boson transverse momentum p_T^V . The resolution $\sigma(u_\perp)$ is determined through a Gauss fit in each bin, and $\langle u_T \rangle$ is the arithmetic mean of the recoil magnitude of the corresponding bin. Smaller values of $\sigma(u_\perp)$ are obviously better and the normalization to the measured u_T ensures that a small resolution is not trivially obtained at the expense of response.

3.4.2.1 Performance Depending On Kinematic Selections On PFOs

In this section, a study is presented if the default performance of the hadronic recoil algorithm can be optimized further by restricting the constitute PFOs with simple kinematic selections on minimum PFO p_T and maximum PFO $|\eta|$. While the default setting is to maximize the acceptance, it could be that low momentum or high rapidity PFOs are primarily noise and neglecting them would improve the resolution. The key quantity to optimize the resolution is the relative resolution $\sigma(u_\perp)/\langle u_T \rangle$, studied as a function of $\sum \bar{E}_T$ defined in Section 3.4.1. A scan is performed on the minimum p_T and maximum η of the neutral PFOs entering the definition of the recoil. This scan cover the range $p_T > 0 \dots 2000$ MeV in steps of 200 MeV, and values of pseudorapidity of $|\eta| < 2.5 \dots 4.9$ in steps of 0.2. The study is performed using the low-pileup $Z \rightarrow \ell\ell$ data.

All the variables of interest related to the hadronic recoil are compatible between $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ channels. So that electron and muon channels are merged to achieve better statistic precision. Several quantities are compared between the two channels in Figures 3.21,3.22,3.23 and 3.24 , including u_T and $u_\perp$ for 5 and 13 TeV. In these plots, the data has been binned in intervals of $\sum \vec{E}_T$, thus softening the dependence of both u_T and $u_\perp$ with total energy.

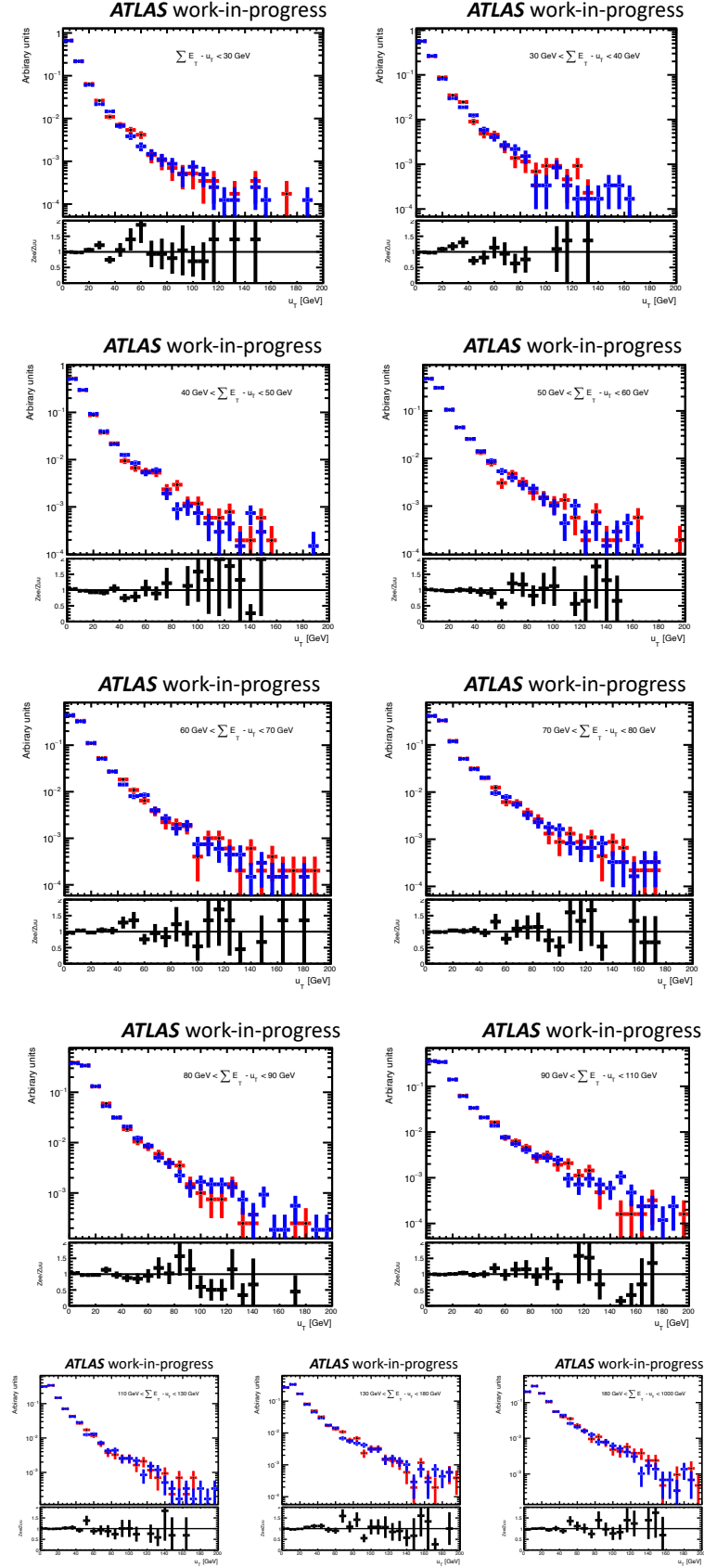


图 3.21 Distributions of the recoil transverse momentum u_T , in different bins of $\sum \bar{E}_T$ at $\sqrt{s} = 5$ TeV. In each subfigure, a comparison of the distributions for each leptonic mode of the Z boson, $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ is shown. Good compatibility is observed between both channels.

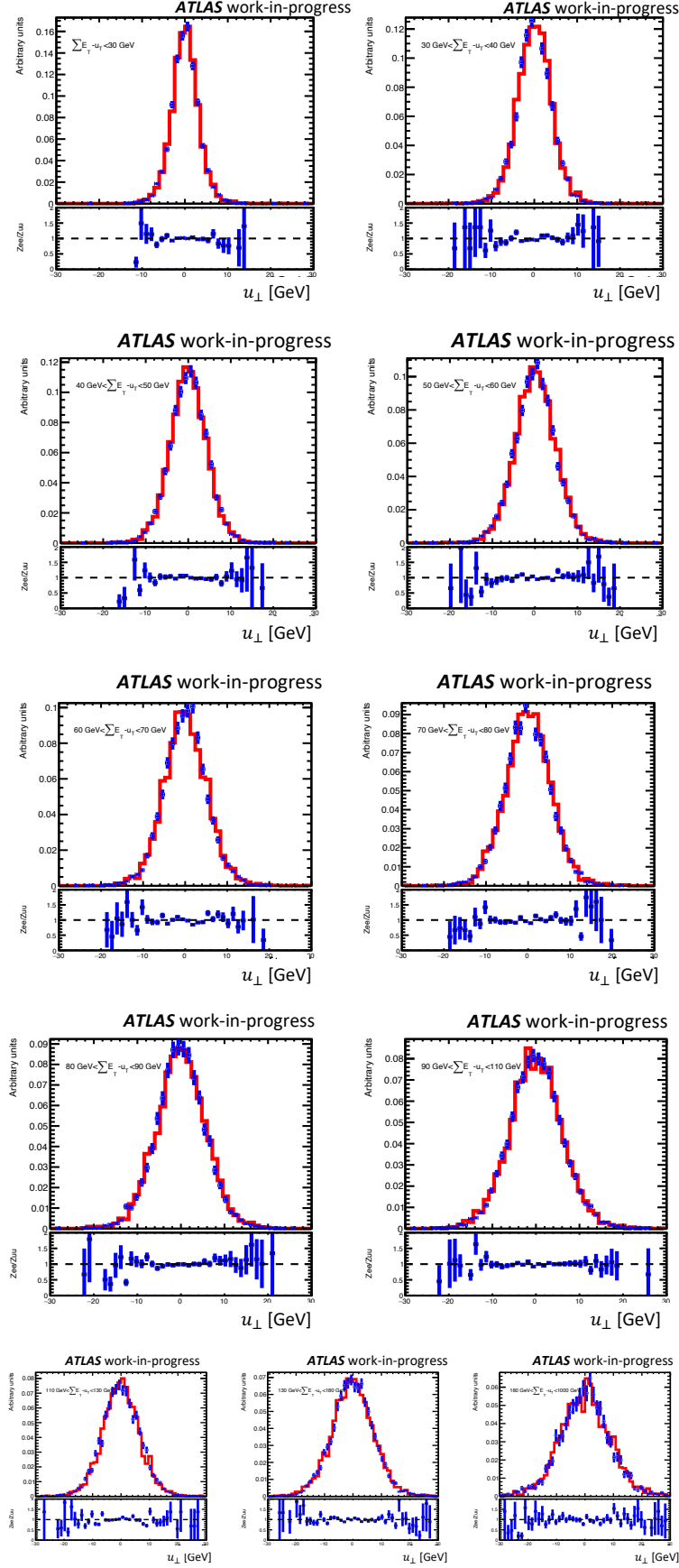


图 3.22 Distributions of the recoil component in the direction orthogonal to the Z boson axis, $u_{\perp}$, in different bins of $\sum \bar{E}_T$ at $\sqrt{s} = 5$ TeV. In each subfigure, a comparison of the distributions for each leptonic mode of the Z boson, $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ is shown. Good compatibility is observed between both channels.

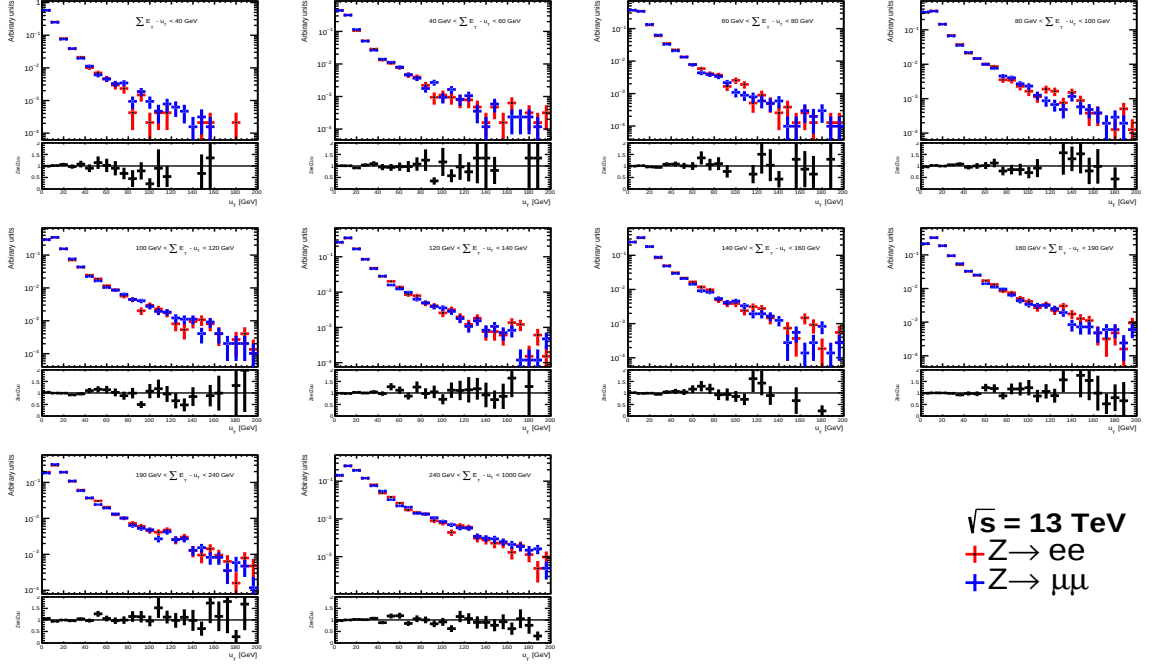


图 3.23 Distributions of the recoil transverse momentum u_T , in different bins of $\sum \bar{E}_T$ at $\sqrt{s} = 13$ TeV. In each subfigure, a comparison of the distributions for each leptonic mode of the Z boson, $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ is shown. Good compatibility is observed between both channels.

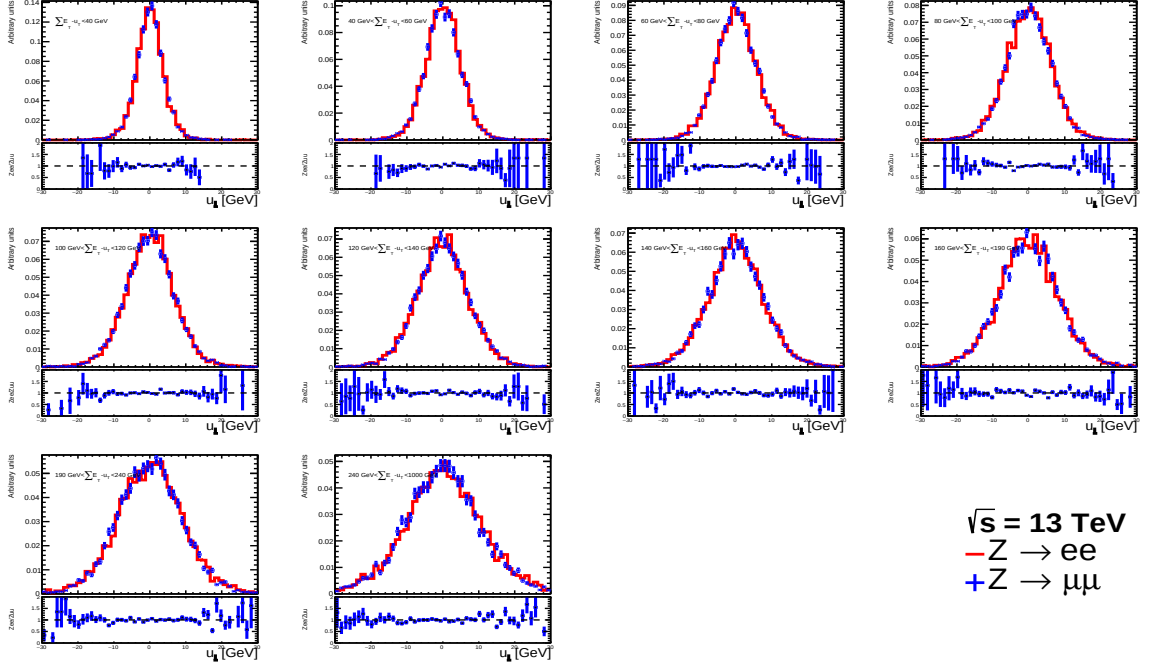


图 3.24 Distributions of the recoil component in the direction orthogonal to the Z boson axis, $u_{\perp}$, in different bins of $\sum \bar{E}_T$ at $\sqrt{s} = 13$ TeV. In each subfigure, a comparison of the distributions for each leptonic mode of the Z boson, $Z \rightarrow ee$ and Zmm is shown. Good compatibility is observed between both channels.

As an additional check of the recoil compatibility of the $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ samples, the recoil resolution, defined as the RMS of a Gaussian fit to the $u_{\perp}$ distribution, is obtained for both channels and both 5 and 13 TeV dataset, summarized in table Tables 3.4 and 3.5 . The RMS of the $u_{\perp}$ distribution is compatible between $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ channels in all intervals of $\sum \bar{E}_T$. This validates that the $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ samples could be combined in the recoil performance study.

Recoil resolution $\sqrt{s} = 5$ TeV		
$\sum \vec{E}_T$ range	$\sigma_{\perp}(Z \rightarrow ee)$	$\sigma_{\perp}(Z \rightarrow \mu\mu)$
(0, 30) GeV	3.05 ± 0.04	3.08 ± 0.03
(30, 40) GeV	3.85 ± 0.05	3.86 ± 0.04
(40, 50) GeV	4.26 ± 0.05	4.29 ± 0.04
(50, 60) GeV	4.70 ± 0.05	4.71 ± 0.05
(60, 70) GeV	5.01 ± 0.06	4.93 ± 0.05
(70, 80) GeV	5.21 ± 0.06	5.23 ± 0.05
(80, 90) GeV	5.59 ± 0.07	5.53 ± 0.06
(90, 110) GeV	6.02 ± 0.06	5.96 ± 0.05
(110, 130) GeV	6.34 ± 0.08	6.51 ± 0.06
(130, 180) GeV	7.19 ± 0.08	7.09 ± 0.07
(180, 1000) GeV	8.45 ± 0.14	8.38 ± 0.13

表 3.4 Results for the recoil resolution $\sigma(u_{\perp})$ for both $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ samples at $\sqrt{s} = 5$ TeV

Recoil resolution $\sqrt{s} = 13$ TeV		
$\sum \vec{E}_T$ range	$\sigma_{\perp}(Z \rightarrow ee)$	$\sigma_{\perp}(Z \rightarrow \mu\mu)$
(0, 40) GeV	3.71 ± 0.05	3.75 ± 0.04
(40, 60) GeV	4.82 ± 0.05	4.92 ± 0.04
(60, 80) GeV	5.63 ± 0.05	5.62 ± 0.04
(80, 100) GeV	6.16 ± 0.05	6.13 ± 0.05
(100, 120) GeV	6.58 ± 0.06	6.65 ± 0.05
(120, 140) GeV	7.10 ± 0.07	7.18 ± 0.06
(140, 160) GeV	7.58 ± 0.08	7.68 ± 0.07
(160, 190) GeV	8.05 ± 0.08	8.14 ± 0.07
(190, 240) GeV	8.90 ± 0.09	8.75 ± 0.07
(240, 1000) GeV	10.7 ± 0.1	10.5 ± 0.1

表 3.5 Results for the recoil resolution $\sigma(u_{\perp})$ for both $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ samples at $\sqrt{s} = 13$ TeV

The values of the recoil resolution $\sigma(u_{\perp})$ are obtained from Gaussian fits to the $u_{\perp}$ distributions in each $\sum \bar{E}_T$ bin, shown in Figure 3.25. The fits are performed based on the assumption that the recoil resolution follows Gaussian distributions, which is approximately correct in each certain $\sum \bar{E}_T$ bin. To make the fit work the best, two aspects are taken into account. The first point is that the resolution changes with $\sum \bar{E}_T$, so in each $\sum \bar{E}_T$ intervals the Gaussian distributions of $u_{\perp}$ is smeared, the smaller $\sum \bar{E}_T$ binning is used, the more like is the distribution a Gaussian. On the other hand, the fit is limited by the statistics of the full dataset, the larger $\sum \bar{E}_T$ binning is used, the less statistic fluctuation is obtained in each bin. To optimize the fit performance, the $\sum \bar{E}_T$ binning is decided based on the distribution of events along its axis, so that each bin contains approximately the same amount of events. Due to the different $\sum \bar{E}_T$ distribution between 5 and 13 TeV, the binning is then different for two energy. The binning for 5TeV data is

$$0, 30, 40, 50, 60, 70, 80, 90, 110, 130, 180, 1000$$

and the binning for 13TeV data is

$$0, 40, 60, 80, 100, 120, 140, 160, 190, 240, 1000$$

Example plots of resolution of $u_{\perp}$ as a function of $\sum \bar{E}_T$ in the simulation and the data are displayed on Figure 3.26. The simulation is not used further in this study, but it can be appreciated that the underlying distributions are generally similar to data. The scan on the PFO kinematics is then performed on data.

The scan of the relative resolution $\sigma(u_{\perp})/\langle u_T \rangle$ with respect to $\sum \bar{E}_T$ for each of the $(p_T, |\eta|)$ thresholds on the neutral PFOs is shown in Figures 3.28 and 3.27 for 13 and 5 TeV, respectively. The main observation is that, for a given minimum p_T threshold, the resolution improves by extending the η coverage. This suggests that the loss of information due to tighter requirement on the PFO pseudorapidity is worse than a potentially higher noise in the forward region.

To find the optimal working point, the values of the relative resolution shown in Figures 3.27 and 3.28 are organized in 2-dimensional maps as a function of the (p_T, η) thresholds applied to the PFOs, which are then shown in Figures 3.29 and 3.30. The

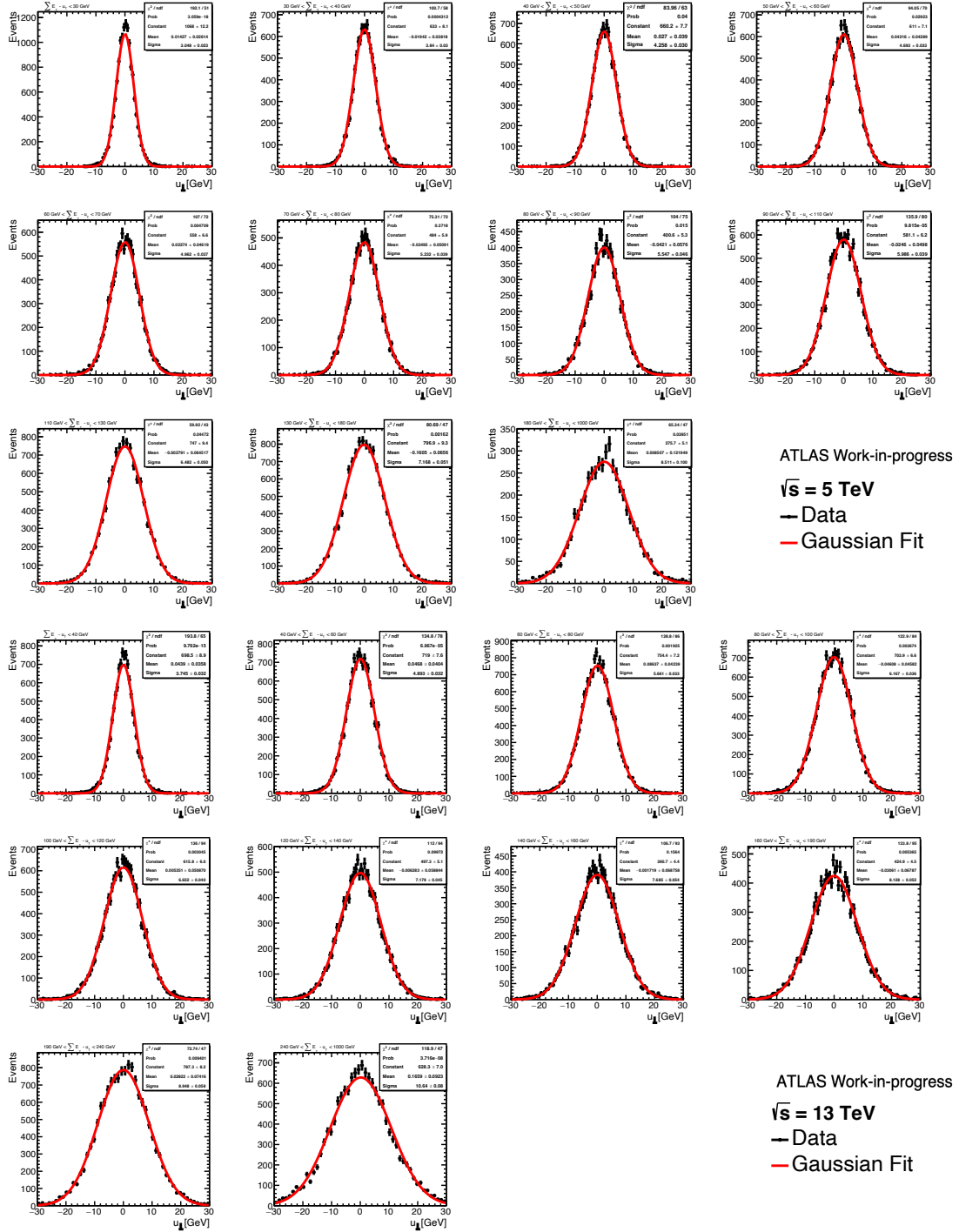


图 3.25 Example Gaussian fits to the $u_{\perp}$ distributions in $\sqrt{s} = 5 \text{ TeV}$ (top) and $\sqrt{s} = 13 \text{ TeV}$ (bottom) $Z \rightarrow \ell\ell$ data events. The resolution is obtained as the “Sigma” parameter of the fit. No cut on the kinematics of PFOs beyond the basic selection is applied.

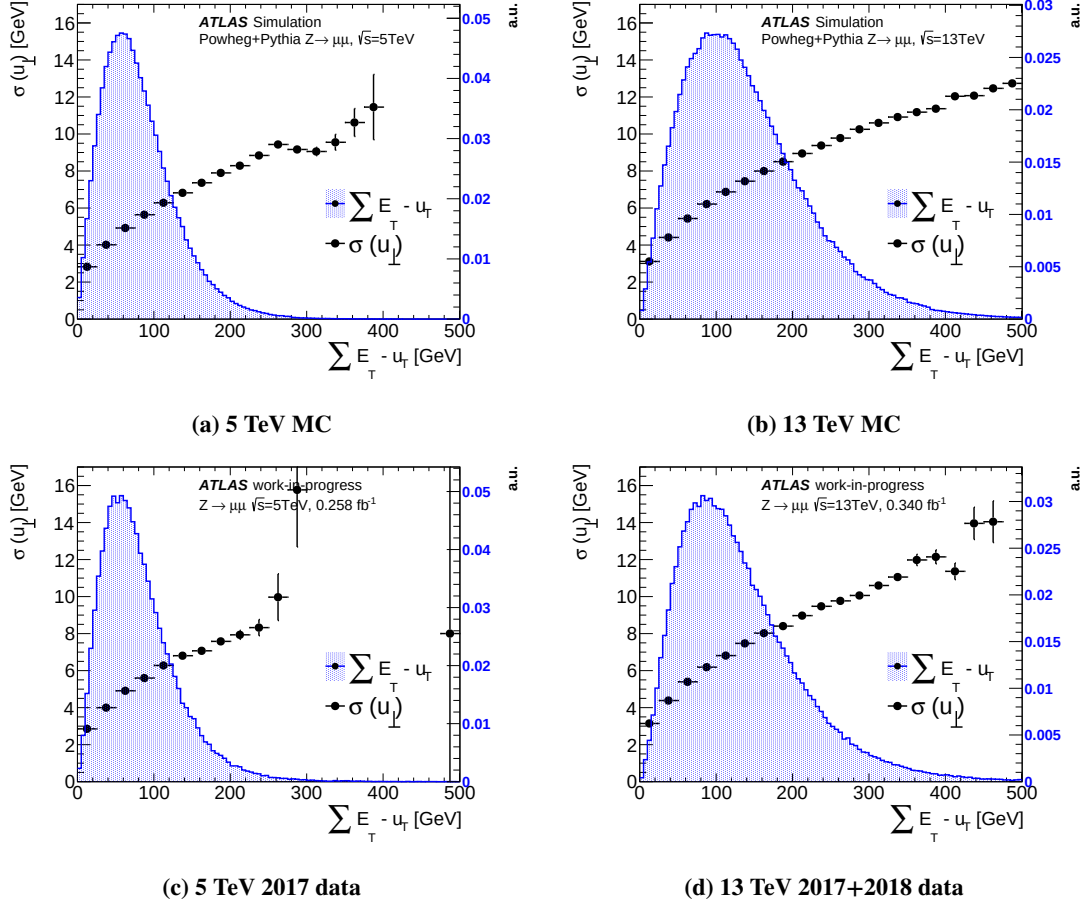


图 3.26 $\sigma(u_{\perp})$ as a function of $\sum \vec{E}_T$ in $Z \rightarrow \mu\mu$ simulated events (top) and data (bottom). No cut on the PFO kinematics is applied beyond the basic selection.

results presented show that the best recoil resolution is obtained by using the constituent PFOs in the largest possible phase space, *i.e.* no additional cuts beyond those implicit in the track reconstruction ($p_T > 500$ MeV) and the maximal coverage of the ATLAS FCAL up to $|\eta| = 4.9$.

3.4.2.2 Recoil Calibration

This section is devoted to the description of the calibration procedure for the hadronic recoil. The relevant variables were previously defined in Section 3.4. Specifically, the scale and resolution of the two projections of $\vec{u}_T$, parallel and perpendicular to the boson direction have to be matched between simulation and the data. The calibration mainly uses Z events with the goal to apply this to W events. Background subtraction is always applied to the data, although it does not have any visible impact on the correction coefficients. The procedure follows the procedure developed in the analysis of the 2011

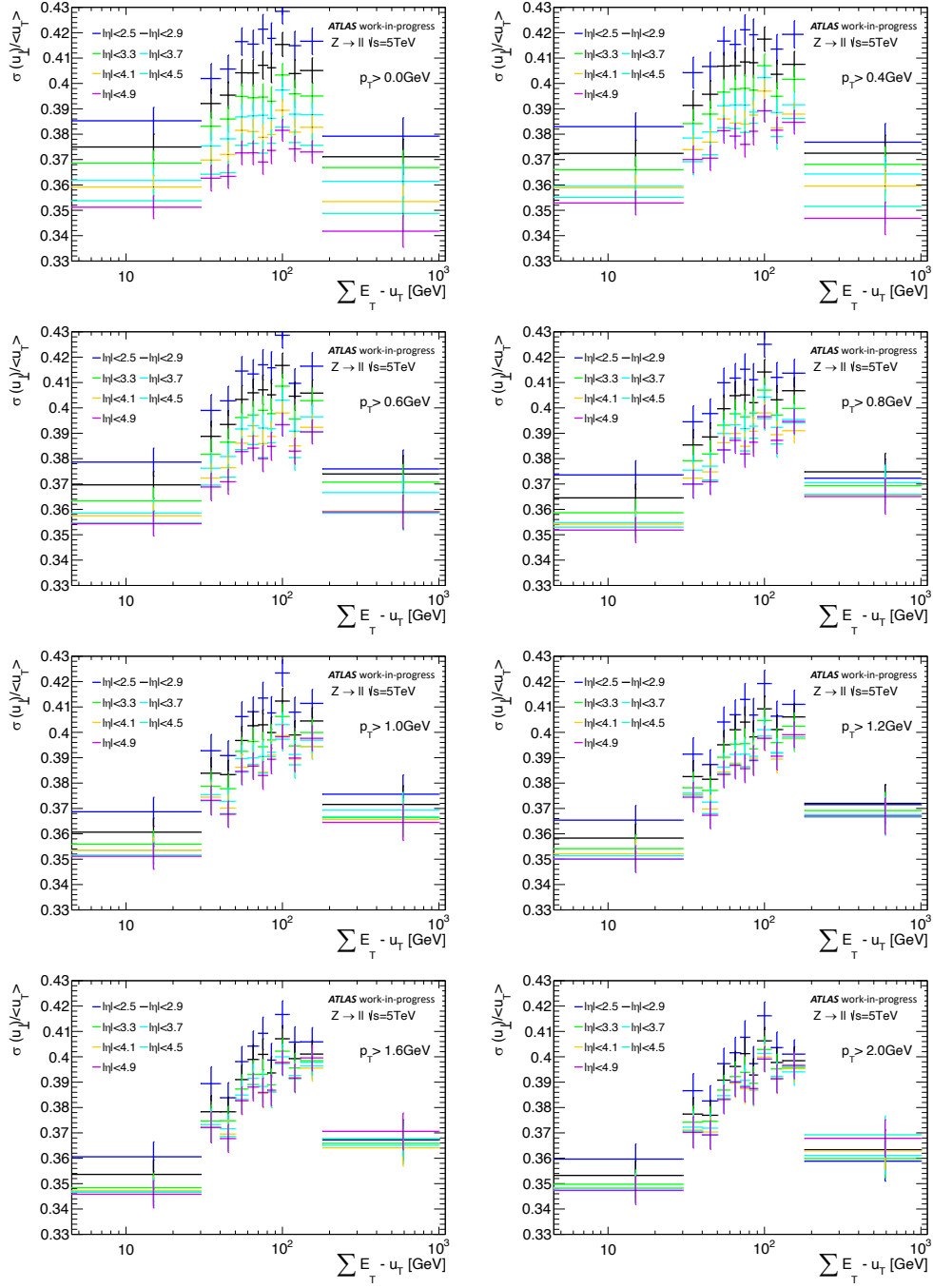


图 3.27 Relative recoil resolution $\sigma(u_{\perp})/\langle u_T \rangle$ as a function of $\sum \bar{E}_T$ for different transverse momentum and pseudorapidity thresholds on the neutral PFOs with 2017 data at $\sqrt{s} = 5$ TeV.

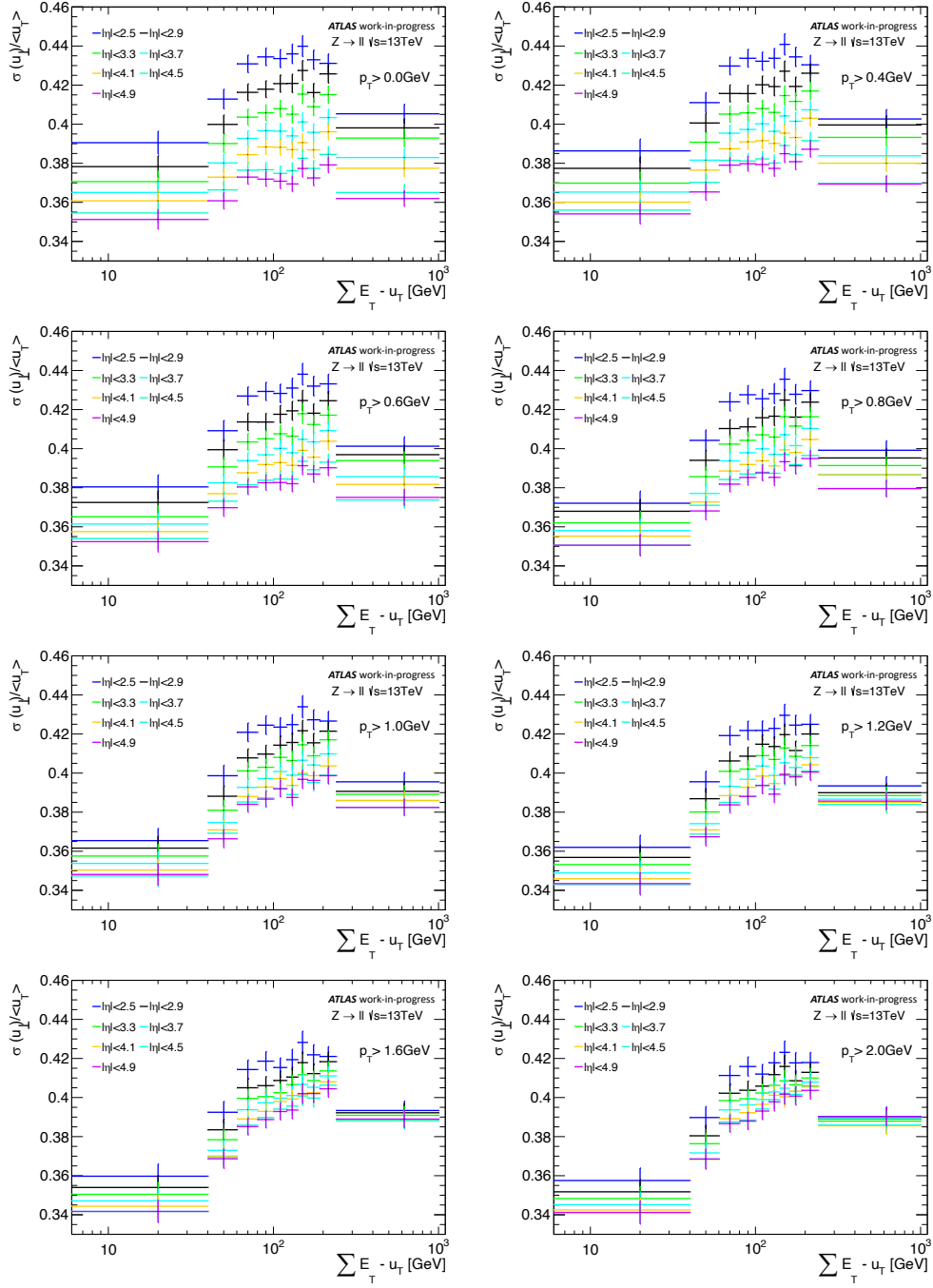


图 3.28 Relative recoil resolution $\sigma(u_{\perp})/\langle u_{\perp} \rangle$ as a function of $\sum \bar{E}_T$ for different transverse momentum and pseudorapidity thresholds on the neutral PFOs at with 2017+2018 data at $\sqrt{s} = 13$ TeV.

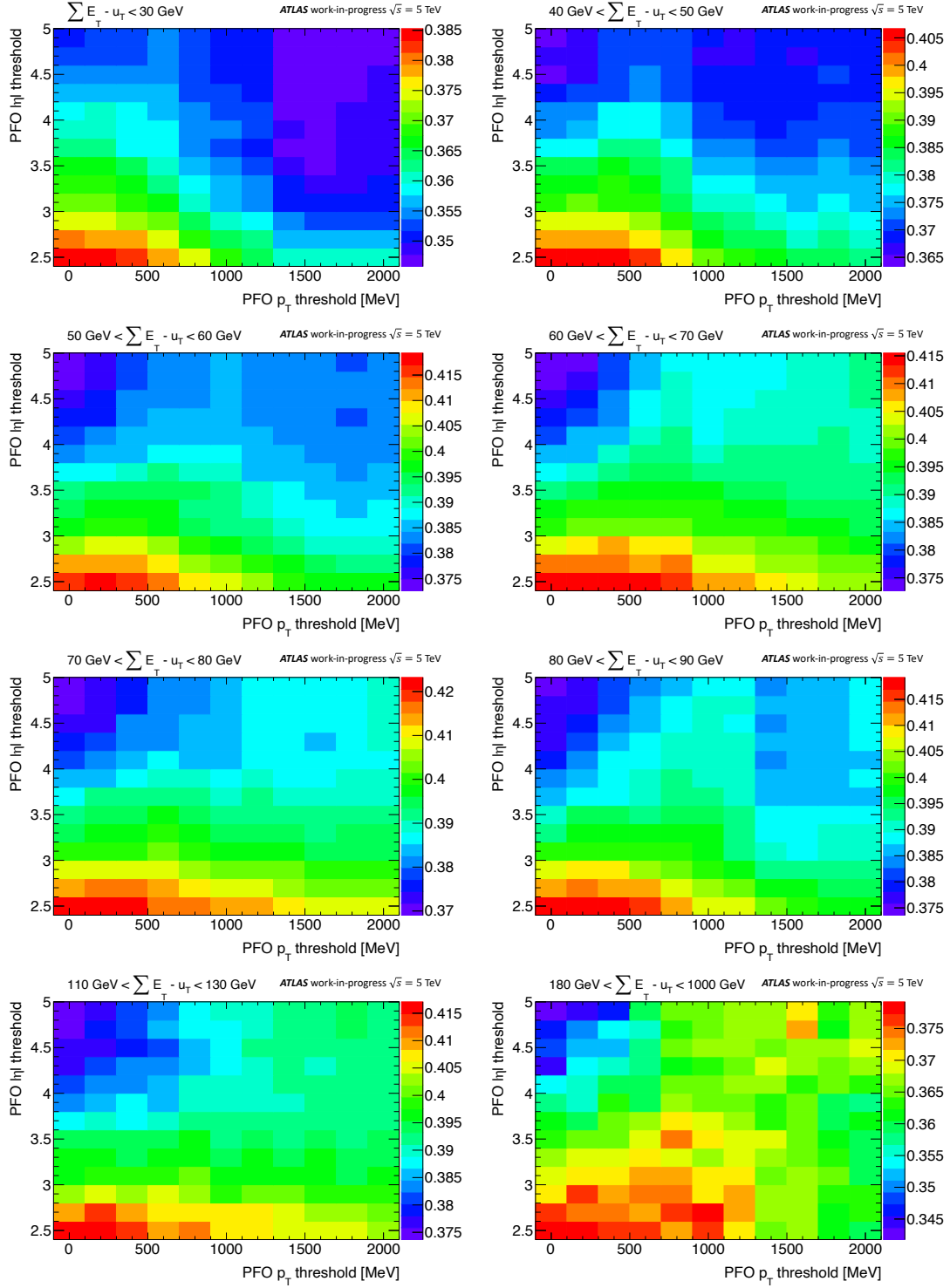


图 3.29 Relative recoil resolution $\sigma(u_{\perp})/\langle u_{\perp} \rangle$ as a function of the transverse momentum and pseudorapidity thresholds for the neutral PFOs at $\sqrt{s} = 5$ TeV with data taken in 2017. Each subfigure shows the data in ranges of $\sum \bar{E}_T$.

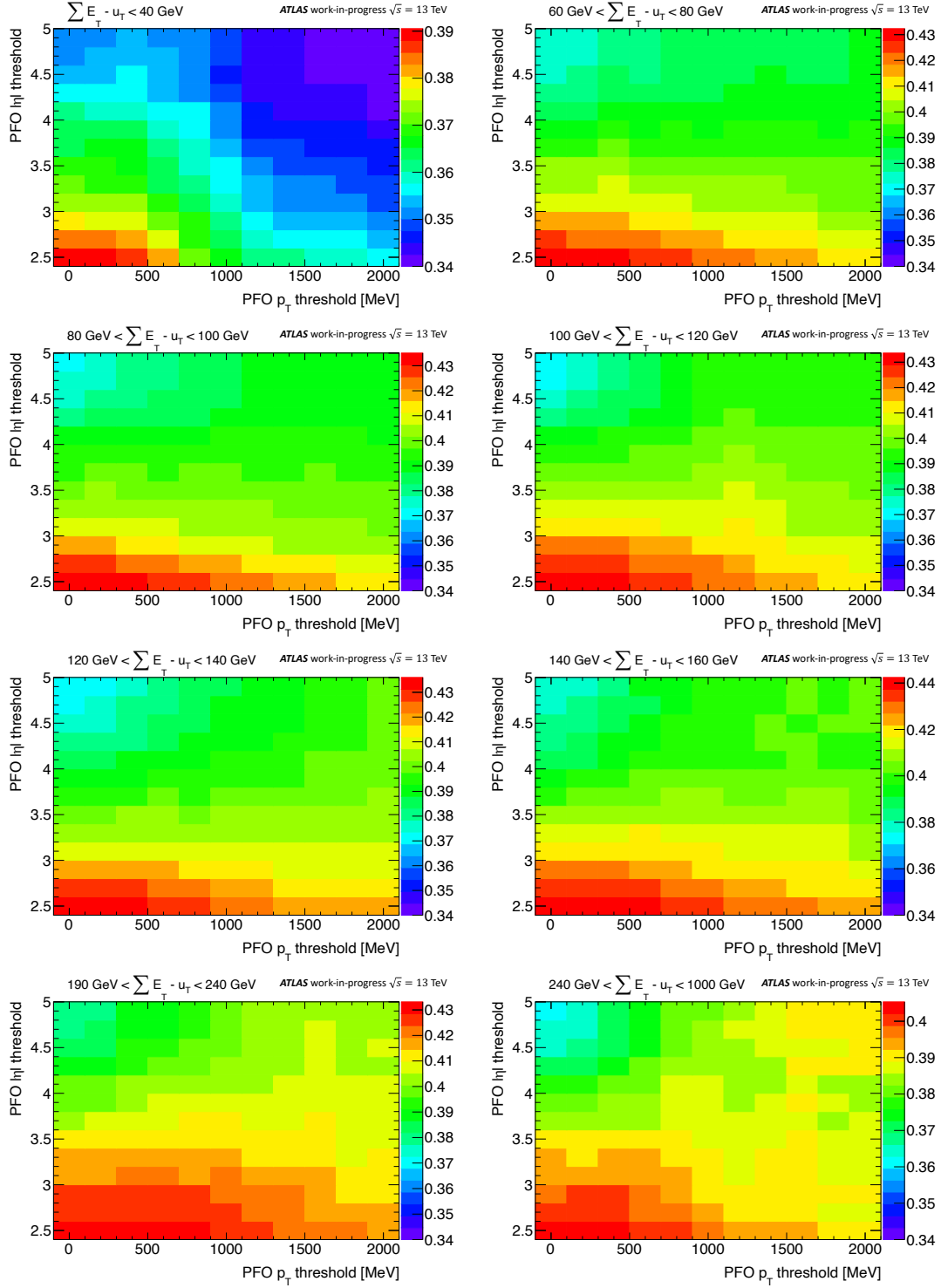


图 3.30 Relative recoil resolution $\sigma(u_{\perp})/\langle u_T \rangle$ as a function of the transverse momentum and pseudorapidity thresholds for the neutral PFOs at $\sqrt{s} = 13$ TeV with 2017+2018 data. Each subfigure shows the data in ranges of $\sum \vec{E}_T$.

7 TeV data documented in [?] with some modifications. The following steps are performed sequentially:

- MC is re-weighted : first, a 2-dimensional re-weighting improves the modeling of the $\sum \bar{E}_T$ distributions as a function of $p_T^{\ell\ell}$. Then a one-dimensional reweighting of $\sum \bar{E}_T$ in slices of u_T improves the closure of the procedure,
- the ϕ distribution of the recoil is corrected,
- the recoil $\vec{u}_T$ is separated into $u_{\parallel}$ and $u_{\perp}$, the resolution and the response of these two projections in MC are corrected to data, finally the corrected $\vec{u}_T$ quantity is formed.

The corrections are obtained separately for 5 and 13 TeV data because of the large Parton Distribution Functions (PDFs) difference and consequently large $\sum \bar{E}_T$ difference. There is only one correction performed for the sum of the 2017 and 2018 data, because the calibration coefficients have been found to be compatible between both channels.

3.4.2.3 Modeling Of $\sum \bar{E}_T$

While Z and W events share many similarities, the calibration could transfer at high accuracy. However, the small differences in the energy scale, the PDFs and others lead to differences in the underlying event activity and the p_T^V spectra. The transfer of the calibration corrections from the Z to the W therefore requires to obtain the calibration as a function of $\sum \bar{E}_T$ and p_T^V . It is essential for the MC to model $\sum \bar{E}_T$ and its correlation to p_T^V well. This is illustrated in Figure 3.31 that shows a data-to-MC comparison of the bias $b = u_{\parallel} + p_T^{\ell\ell}$ and $u_{\perp}$ in $Z \rightarrow \mu\mu$ events after the full calibration chain and after applying all steps except for the modeling correction of $\sum \bar{E}_T$. In this latter case, one can observe a significant non-closure of several percent. Hence, it is crucial to get the correlation between $\sum \bar{E}_T$ and p_T^V correctly modeled in the MC to ensure that in each p_T^V bin the distribution of $\sum \bar{E}_T$ is correct.

Three event weights are obtained to model the event activity $\sum E_T$ and its correlation with p_T^V for the POWHEGMC samples. A first 2D re-weighting of the $(\sum \bar{E}_T, p_T^{\ell\ell})$ distribution is derived from the ratio of the data to Z simulation, adding both electron

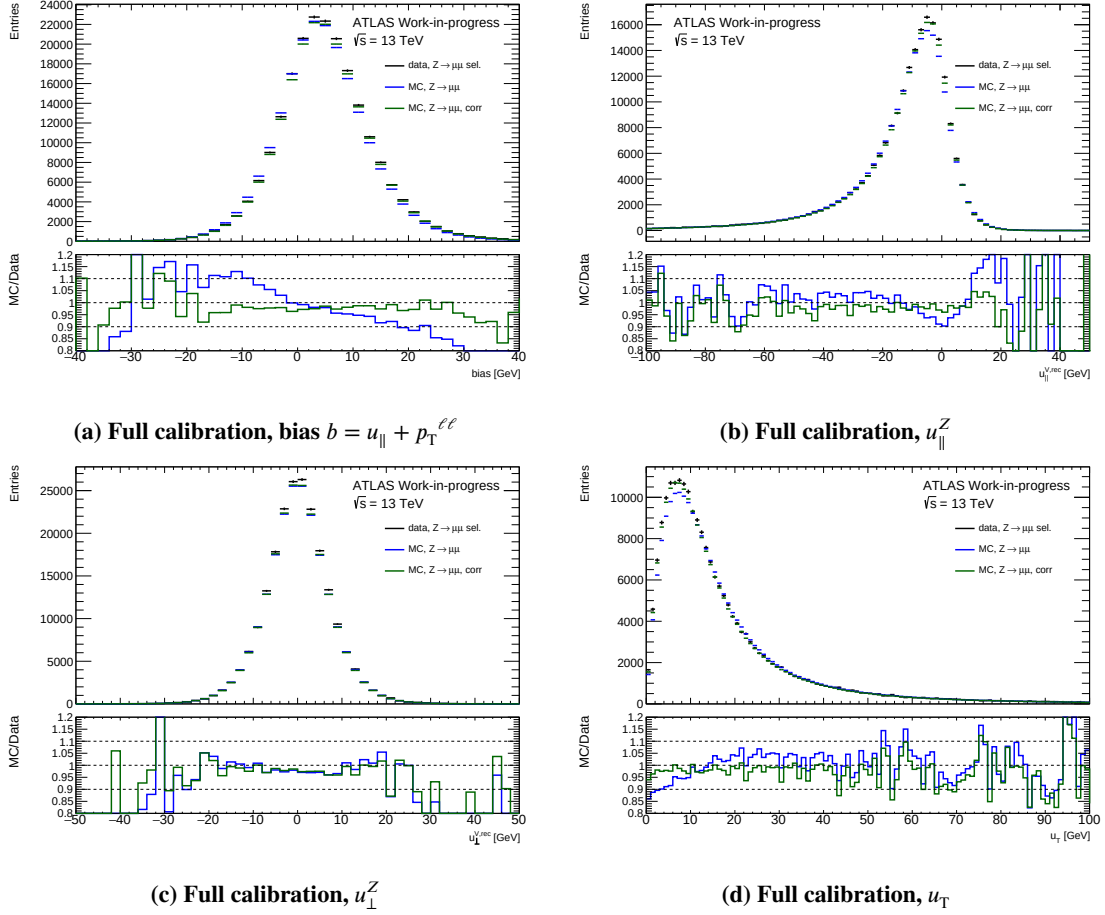


图 3.31 Bias $b = u_{\parallel} + p_T^{\ell\ell}$ and $u_{\perp}, u_{\parallel}, u_T$ distributions in the data and in simulated events before (blue) and after (green) calibration at 13 TeV. The lower panel shows uncorrected and corrected MC to data ratios. The plots show that the agreement between data and MC are much better after calibration applied

and muon channels:

$$w_{2D}^Z(\sum \bar{E}_T, p_T^{\ell\ell}) = \frac{h^{\text{data},Z}(\sum \bar{E}_T, p_T^{\ell\ell})}{h^{\text{MC},Z}(\sum \bar{E}_T, p_T^{\ell\ell})}. \quad (3.16)$$

Here h are normalized 2-dimensional distributions of $(\sum \bar{E}_T, p_T^{\ell\ell})$. In the application to the W simulation, $p_T^{\ell\ell}$ is not available and is replaced by $p_T^{\text{true},V}$ using the re-weighting coefficients obtained in Z events.

The second set of weights is only obtained for and applied to the W process. The $p_T^{\text{true},V}$ is not accessible in the data (and is actually what we want to measure), so we cannot use a similar 2D-weight. However a better modeling of $\sum \bar{E}_T$ can be achieved by looking at $\sum \bar{E}_T$ in bins of u_T , and by re-weighting in this quantity. The weight is

then defined after application of the 2D re-weighting, in u_T bin j , as:

$$w_{j,\text{sliced}}^{W^\pm}(\sum \bar{E}_T) = \frac{h_j^{\text{data},W^\pm}(\sum \bar{E}_T)}{h_j^{\text{MC},W^\pm,Z2D\text{mod}}(\sum \bar{E}_T)}, \quad (3.17)$$

where h_j is the normalized $\sum \bar{E}_T$ distribution for u_T bin j in the data (numerator) or in the predictions, summing the signal and the background (denominator), after the standard W selection.

The application of both re-weightings (2D and 1D, sliced in u_T) unfortunately modifies the transverse momentum spectrum of the boson $p_T^{\text{true},V}$. Since the modeling of $p_T^{\text{true},V}$ is critical in the W and Z boson p_T measurement and in the W boson mass measurement, the initial spectrum in the full phase-space before selection cuts should be recovered. This is achieved by an additional 1D re-weighting (the third weight) in $p_T^{\text{true},V}$, see Eq. 3.18:

$$w_{1D}^{W^\pm}(p_T^{\text{true},V}) = \frac{h^{\text{MC},W^\pm,\text{mod}}(p_T^{\text{true},V})}{h^{\text{MC},W^\pm,\text{orig}}(p_T^{\text{true},V})}. \quad (3.18)$$

Here h is the original (denominator) or modified (numerator) $p_T^{\text{true},V}$ distribution in the W simulated events before any selection cut. The total weight applied to simulated $W^\pm$ events, with a u_T value falling in bin j , is then the product: $w_{2D}^Z(\sum \bar{E}_T, p_T^{\text{true},V}) \times w_{j,\text{sliced}}^{W^\pm}(\sum \bar{E}_T) \times w_{1D}^{W^\pm}(p_T^{\text{true},V})$

3.4.2.4 u_X And u_Y Correction

Similar to the 7 TeV W mass analysis, the direction of the recoil, $\phi(\vec{u}_T)$ is not perfectly modeled in the simulation, which may be due to the beam crossing angle, calorimeter non-uniformity, beam displacement from $(x, y) = (0, 0)$ etc. This is empirically corrected for by an additive offset taken from the differences between the mean values of the x, y components of the recoil in Z events in data and in the simulation ($\langle u_X \rangle$ and $\langle u_Y \rangle$). As a small dependence is seen, the offsets are fitted with a first-order polynomials as function of $\sum \bar{E}_T$. The components of the recoil in the simulation are then corrected as follows:

$$\begin{aligned} u_X^{\text{MC,corr}} &= u_X^{\text{MC}} + [(\langle u_X^{\text{data}} \rangle - \langle u_X^{\text{MC}} \rangle)(\sum \bar{E}_T)] \\ u_Y^{\text{MC,corr}} &= u_Y^{\text{MC}} + [(\langle u_Y^{\text{data}} \rangle - \langle u_Y^{\text{MC}} \rangle)(\sum \bar{E}_T)] \end{aligned} \quad (3.19)$$

3.4.2.5 Resolution And Response Corrections

As in the procedure employed in the 7 TeV W mass analysis, the recoil resolution is derived by comparing the width of $u_{\perp}$ in the data and in the simulation in Z events, adding up electron and muon channels. The recoil response is explored by comparing the hadronic recoil momentum along the boson axis, $u_{\parallel}$, and the boson transverse momentum reconstructed from the di-lepton $p_T^{\ell\ell}$. The $u_{\perp}$ distribution follows in each bin of $(\sum \bar{E}_T, p_T^{\ell\ell})$ a roughly Gaussian distribution centered at 0. The resolution of $u_{\parallel}$ can be estimated from the bias distribution $b = u_{\parallel} + p_T^{\ell\ell}$. To compare both distributions, the bias b should be also centered at 0, which is not the case, because of particles escaping detection and energy losses in dead material. To center the bias, $p_T^{\ell\ell}$ is “corrected” by a factor dependent on $\sum \bar{E}_T$ and $p_T^{\ell\ell}$ (depending on which variable the resolution is plotted against). The scaled bias is referred to as $b' = u_{\parallel} + k \cdot p_T^{\ell\ell}$. Mathematically the resolution is then expressed as :

$$\sigma(b') = \sigma(u_{\parallel} + k \cdot p_T^{\ell\ell}), \quad (3.20)$$

Here k is the scaling factor that transforms the bias distribution $b = u_{\parallel} + p_T^{\ell\ell}$ to b' with $\langle b' \rangle = 0$. k is derived as :

$$k = 1 - \frac{\langle b \rangle}{\langle p_T^{\ell\ell} \rangle} = -\frac{\langle u_{\parallel} \rangle}{\langle p_T^{\ell\ell} \rangle} \quad (3.21)$$

Figure 3.32 shows the comparisons of the recoil resolution $\sigma(u_{\perp})$ and $\sigma(b')$, as a function of $\sum \bar{E}_T$ and $p_T^{\ell\ell}$ in the data and in the simulation. The 2D-reweighting of $(\sum \bar{E}_T, p_T^{\ell\ell})$ of MC to data has been applied, while the u_X and u_Y corrections are not applied here, which plays a negligible role in this study. In these plots, it can be concluded that there is an absolute difference with $\sigma(u_{\perp}) < \sigma(b') = \sigma(u_{\parallel})$. The difference of resolution between $u_{\parallel}$ and $u_{\perp}$ does not depend much on either $\sum \bar{E}_T$ or $p_T^{\ell\ell}$, and the differences between simulation and data for these resolutions is small but visible,

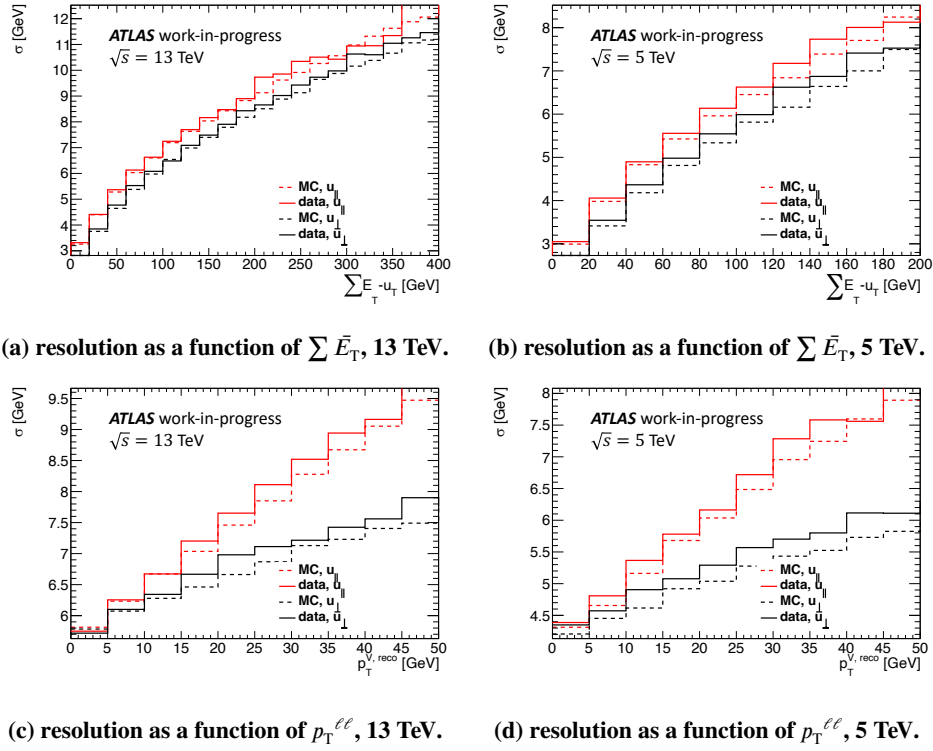


图 3.32 The resolutions in $u_{\perp}$ and $u_{\parallel}$ compared between data and MC for $Z \rightarrow \ell\ell$ events in 5 and 13 TeV data. The top two panels show the absolute resolutions, while the lower two panels show the same quantities as function of $p_T^{\ell\ell}$.

reaching $\approx 2\%$ the resolution correction is derived from $\sigma(u_\perp)$ for the perpendicular component of the recoil, and from $\sigma(b)$ for the parallel component.

The data-to-MC resolution correction for $u_\perp$ is derived as a ratio of $\sigma(u_\perp)$ values is:

$$r(\sum \bar{E}_T, p_T^{\ell\ell}) = \frac{\sigma(u_\perp)^{\text{data}}}{\sigma(u_\perp)^{\text{MC}}}. \quad (3.22)$$

The 2D function $r(\sum \bar{E}_T, p_T^{\ell\ell})$ is constructed in bins of $p_T^{\ell\ell}$ by separate fits to the numerator and denominator $\sigma(u_\perp)^{\text{data}}$ and $\sigma(u_\perp)^{\text{MC}}$ as function of $\sum \bar{E}_T$:

$$\sigma(u_\perp)(\sum \bar{E}_T) = c + d \cdot \sqrt{\sum \bar{E}_T}. \quad (3.23)$$

The corrected value of $u_\perp$ in the simulation is then obtained by a simple scaling to correct the width in the simulation to that in the data.

$$u_\perp^{\text{MC,corr}} = u_\perp^{\text{MC}} \times r\left(\sum \bar{E}_T, p_T^{\text{true},V}\right). \quad (3.24)$$

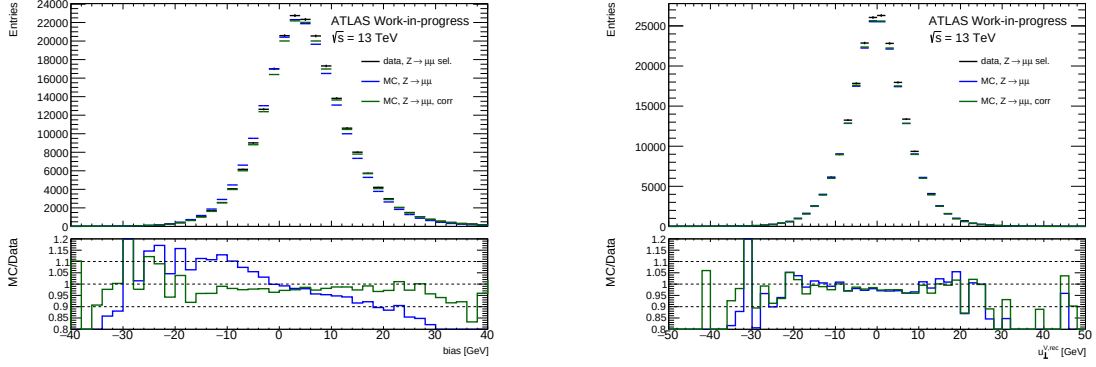
The resolution correction of the bias, $r_\parallel$, is obtained the same way as r , using the standard deviation of the bias instead of $u_\perp$. The correction of $u_\parallel$ in MC contains both a resolution and a scale correction:

$$u_\parallel^{\text{MC,corr}} = \langle u_\parallel^{\text{data}} \rangle + (\langle b^{\text{data}} \rangle - \langle b^{\text{MC}} \rangle) \cdot r_\parallel + (u_\parallel^{\text{MC}} - \langle u_\parallel^{\text{data}} \rangle) \cdot r_\parallel. \quad (3.25)$$

Note there are several reasons why we do not expect the data to corrected MC ratio to be exactly 1 after the calibration is applied.

- the calibration coefficients are fitted summing $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ channels together, since the performance in the two decayed channels are not perfectly the same, small fluctuations within the uncertainty is expected.
- the calibration coefficients are smoothly fitted functions of $\sum \bar{E}_T$ or $p_T^{\ell\ell}$ in bins of the other observable. Therefore even if the binning of the plots matched the initial binning used for fitting, the fits does not go exactly through the points, but waving around the average by 1σ (fit function error).

For all these reasons, considering that no systematic uncertainty (including that of the recoil calibration) is included in the band (only data and MC statistics are), the closure is at a satisfactory level.



(a) bias, 13 TeV, 2017 and 2018 data and calibration.

 (b) $u_{\perp}$, 13 TeV, 2017 and 2018 data and calibration.

图 3.33 Recoil calibration closure test: data and simulated distribution of the bias and of $u_{\perp}$, before and after applying the calibration, in $Z \rightarrow \mu\mu$ events. The $p_T^{\ell\ell}$ spectrum in the corrected MC matches by construction the one in the data. The lower panel shows uncorrected and corrected MC to data ratios.

3.4.2.6 Recoil Calibration Uncertainty

The uncertainties on the recoil calibration are mostly related to the data statistics in the case of the resolution and response corrections, and to the small non-closure due to the extrapolation from the Z to the W .

The non-closure of the $\sum \vec{E}_T$ modeling procedure is obtained from a closure test with Sherpa MC events used as pseudo-data. Reweighting coefficients are derived from Sherpa Z and W events to make POWHEG look like SHERPA using the procedure defined in Section 3.4.2.3. Then the coefficients are applied to POWHEG W events and check how well it resembles Sherpa W events for the 2D $(\sum \vec{E}_T, p_T^{\text{true},V})$ distribution. Any deviation found in this distribution is indicative of a non-closure. This remaining non-closure for the $\sum \vec{E}_T$ distribution in each $p_T^{\text{true},V}$ bin defines a reweighting taken as a systematic variation.

Given the large size of the simulated MC samples with respect to the data statistics (about 10 times for W , and about 20 times for Z , the MC statistical uncertainties are neglected.

In each of the $p_T^{\ell\ell}$ bins, the fitted resolution functions $\sigma(u_{\perp})(\sum \vec{E}_T)$ in the data have uncertainties in the c and d parameters, see Eq. 3.23. The fitting algorithm, ROOT, also provides the full covariance and correlation matrices for these. This allows to per-

form a rotation in the vectorial space defined by the eigenvectors of the covariance matrix, and eventually obtain 2 UP and 2 DOWN uncorrelated variations that are linear combinations of c and d uncertainty variations.

3.4.3 Recoil Calibration Results

Several distributions related to the hadronic recoil performance are shown in Figures 3.34 and 3.35 in $Z \rightarrow \mu\mu$ events after the full calibration chain is applied. Figures 3.36 and 3.37 show the same, but in $Z \rightarrow ee$ events. The ratio panel shows $(\text{data} - \text{MC})/\sigma$, where σ includes data statistics, MC statistics, recoil calibration uncertainties related to Z data statistics. The bias and $u_{\perp}$ distributions are expected to show good data to MC agreement within the uncertainty. For the other distributions, this agreement is dependent on the modeling quality of the boson p_T in POWHEG+PYTHIA8.2.

Table 3.6 gives the number of nuisance parameters for each uncertainty category. In the case of statistical uncertainties, this reflects the number of fitted functions (one per bin), while in the case of systematic uncertainties, the number is simply 1 as the uncertainty is fully correlated in the kinematic space.

Uncertainty name	Number of NPs		Description
	5 TeV	13 TeV	
$\sqrt{s}$			
RESOLUTION_STAT0_UP	12	14	Statistical uncertainty on the resolution correction.
RESOLUTION_STAT0_DOWN	12	14	Statistical uncertainty on the resolution correction.
RESOLUTION_STAT1_UP	12	14	Statistical uncertainty on the resolution correction.
RESOLUTION_STAT1_DOWN	12	14	Statistical uncertainty on the resolution correction.
RESPONSE_STAT0_UP	20	15	Statistical uncertainty on the response correction.
RESPONSE_STAT0_DOWN	20	15	Statistical uncertainty on the response correction.
RESPONSE_STAT1_UP	20	15	Statistical uncertainty on the response correction.
RESPONSE_STAT1_DOWN	20	15	Statistical uncertainty on the response correction.
RESPONSE_SYS_UP	1	1	Systematic uncertainty on the response correction.
RESPONSE_SYS_DOWN	1	1	Systematic uncertainty on the response correction.
SET_SYS	1	1	Systematic uncertainty on the $\sum \vec{E}_T$ reweighting.
EXTRAPOLATION_RESOL_SYS	1	1	Systematic uncertainty on the resolution correction due to the extrapolation from the Z to the W .
EXTRAPOLATION_RESP_SYS	1	1	Systematic uncertainty on the response correction due to the extrapolation from the Z to the W .
Total number of NPs	135	119	

表 3.6 Table of uncertainty categories as implemented in the calibration tool, together with their respective number of nuisance parameters (NPs).

Figures 3.38 and 3.39 show the u_T distribution for selected W events at 5 TeV after

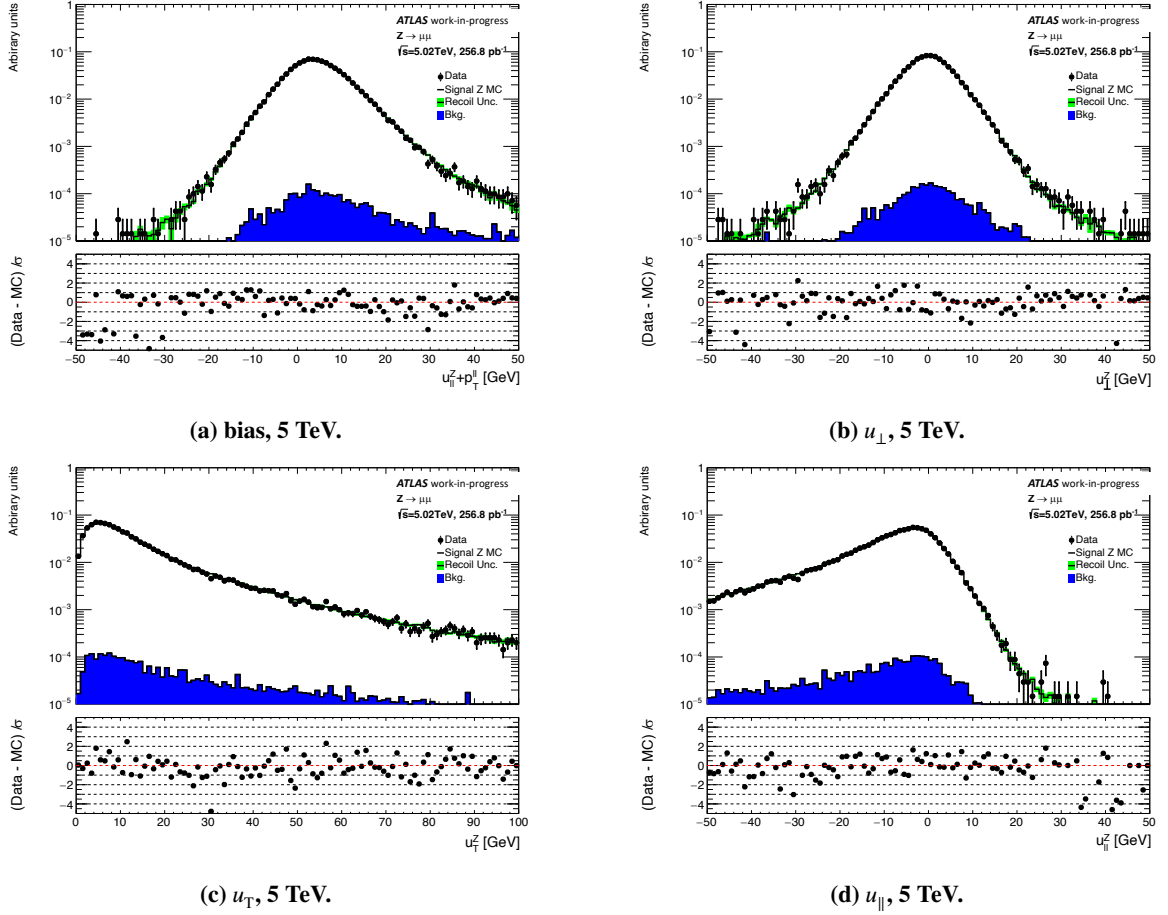


图 3.34 Recoil distributions in $Z \rightarrow \mu\mu$ events at 5 TeV in the data and in the simulation after final calibration. The uncertainty includes statistical uncertainties, and recoil systematic uncertainties of statistical nature.

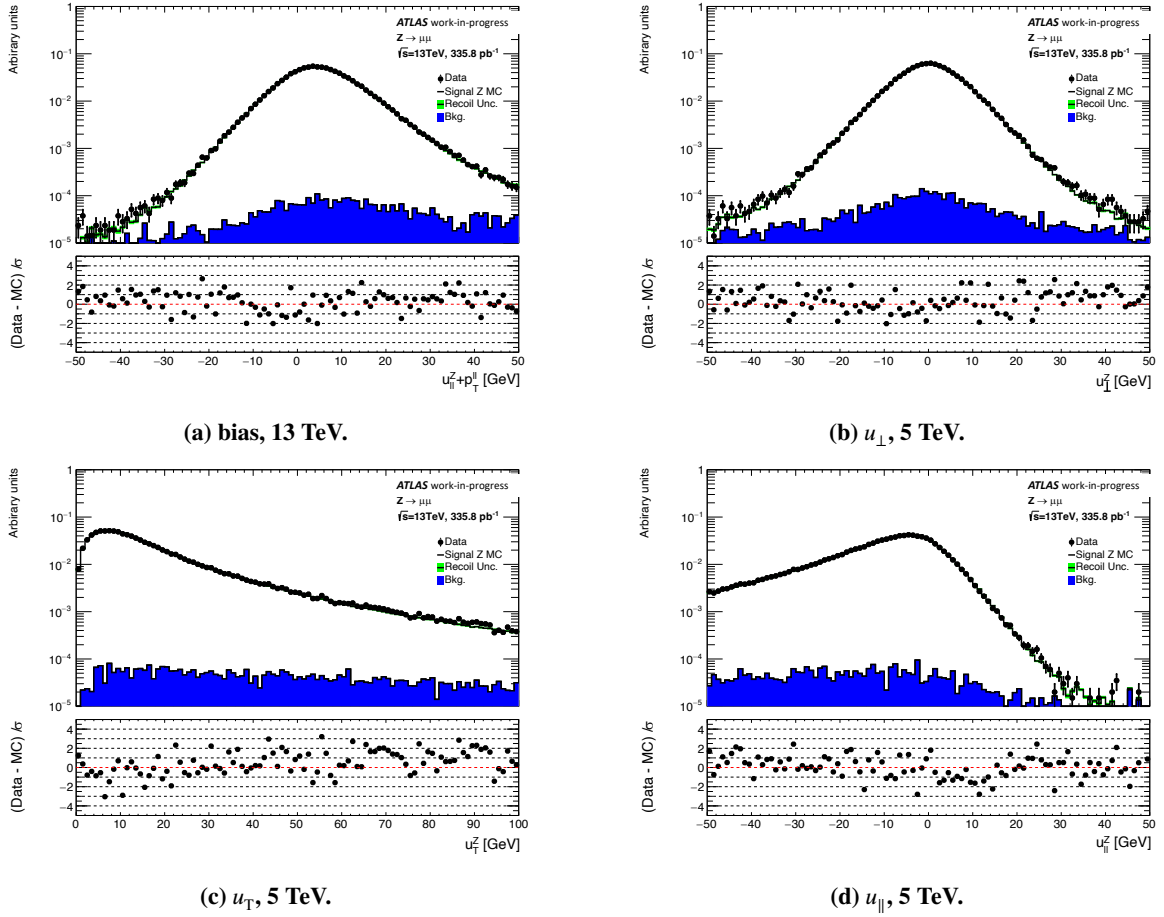


图 3.35 Recoil distributions in $Z \rightarrow \mu\mu$ events at 13 TeV in the data and in the simulation after final calibration. The uncertainty includes statistical uncertainties, and recoil systematic uncertainties of statistical nature.

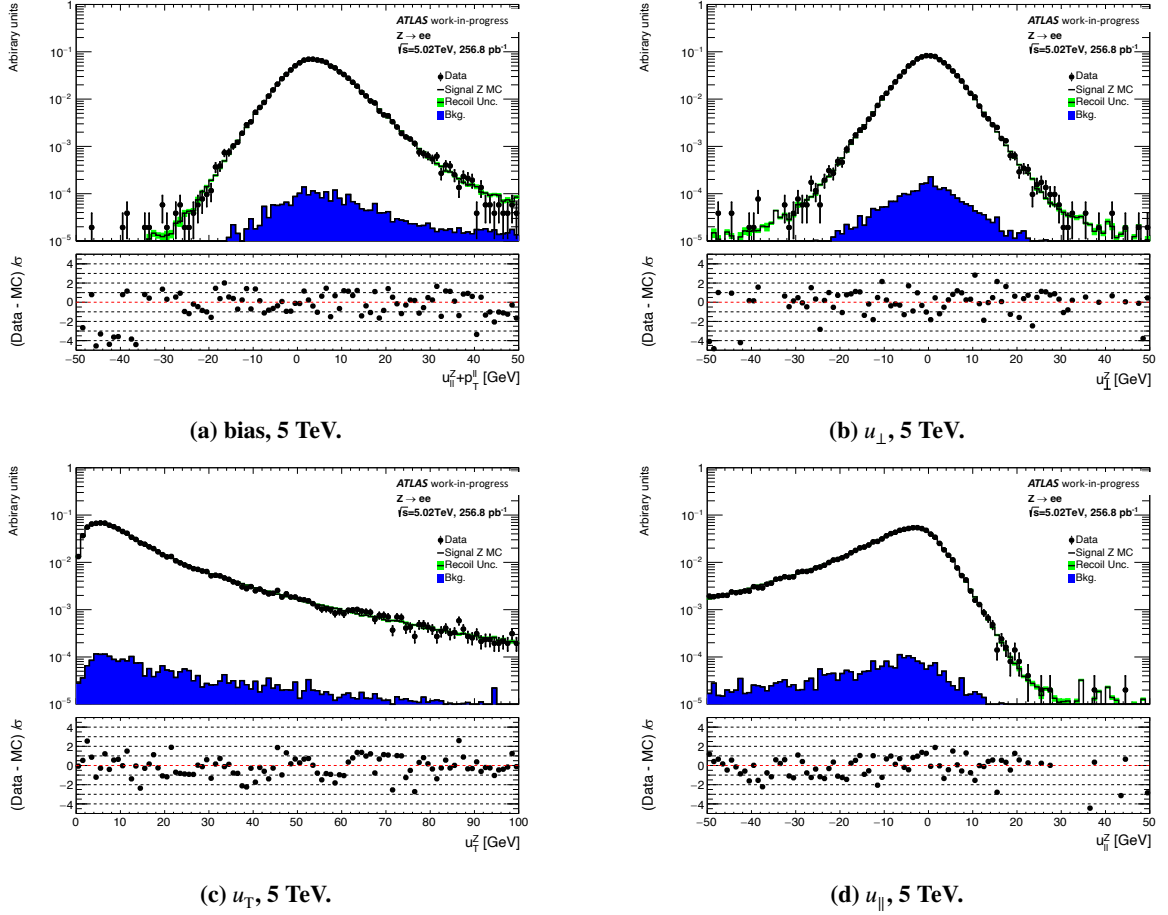


图 3.36 Recoil distributions in $Z \rightarrow ee$ events at 5 TeV in the data and in the simulation after final calibration. The uncertainty includes statistical uncertainties, and recoil systematic uncertainties of statistical nature.

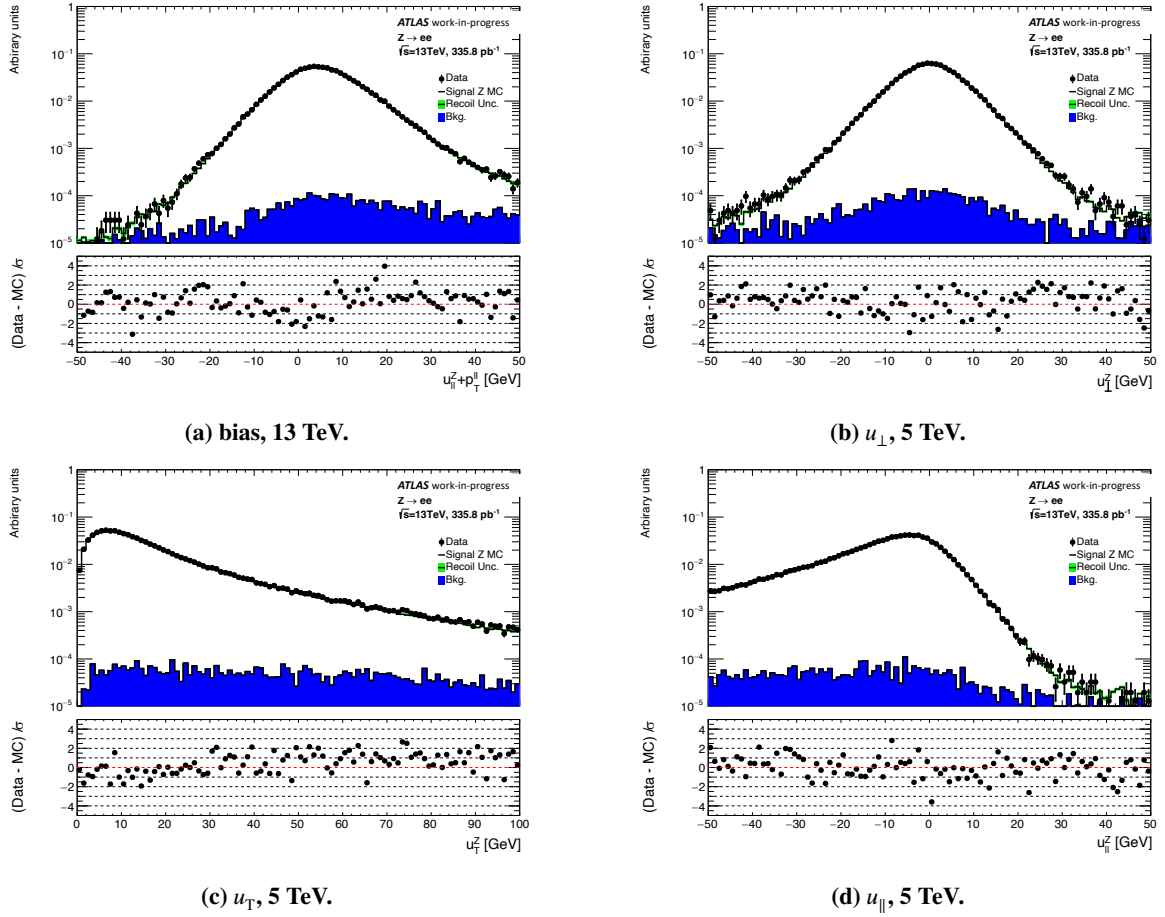


图 3.37 Recoil distributions in $Z \rightarrow ee$ events at 13 TeV in the data and in the simulation after final calibration. The uncertainty includes statistical uncertainties, and recoil systematic uncertainties of statistical nature.

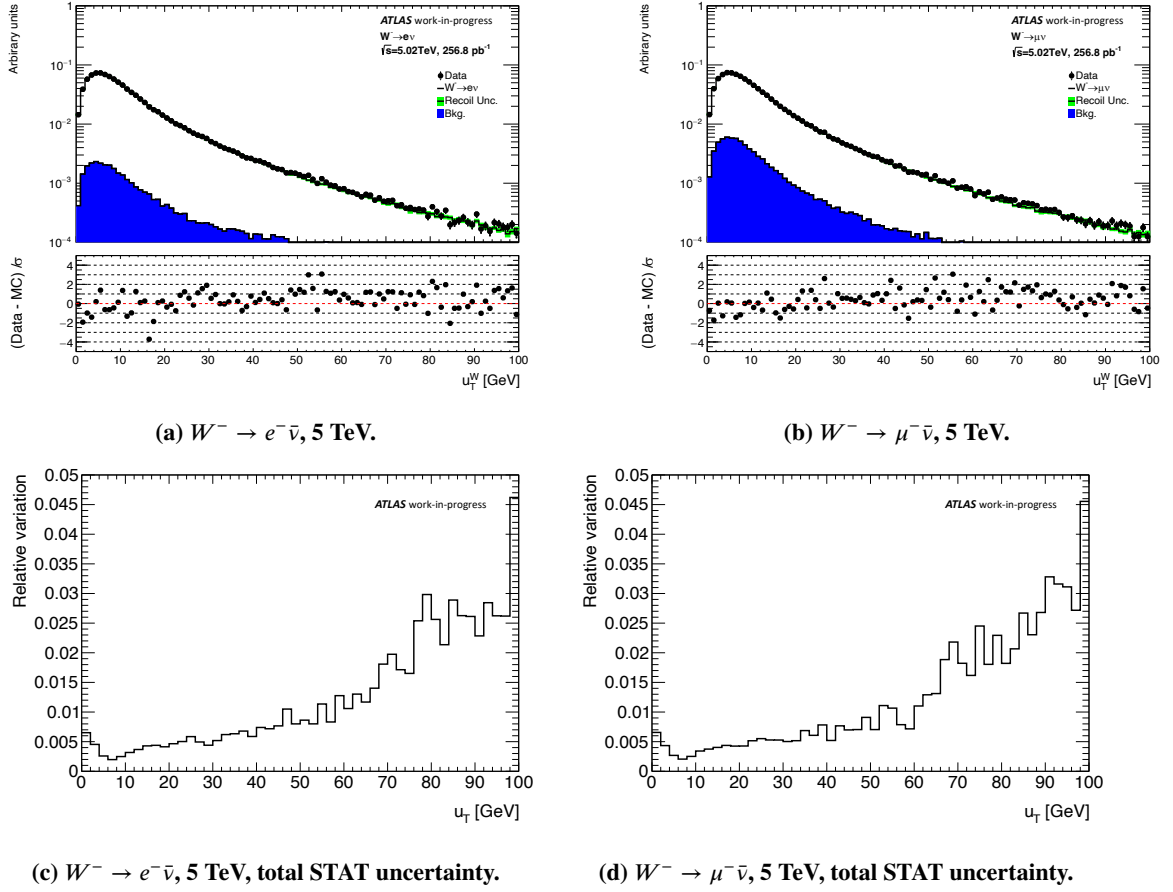


图 3.38 Recoil distributions in W^- events at 5 TeV in the data and in the simulation after final calibration. The uncertainty includes statistical uncertainties, recoil systematic uncertainties related to Z data statistics, to the response systematic and to the extrapolation from the Z to the W in the response and resolution corrections. The total uncertainty related to Z data statistics is also shown separately.

the full calibration chain is applied. The ratio panel shows $(\text{data} - \text{MC})/\sigma$, where σ includes data statistics, MC statistics, recoil calibration uncertainties related to Z data statistics, to the response systematic and to the extrapolation from the Z to the W in the response and resolution corrections. Figures 3.40, 3.41, 3.42 and 3.43 show the impact of each nuisance parameter on the measured u_T spectra.

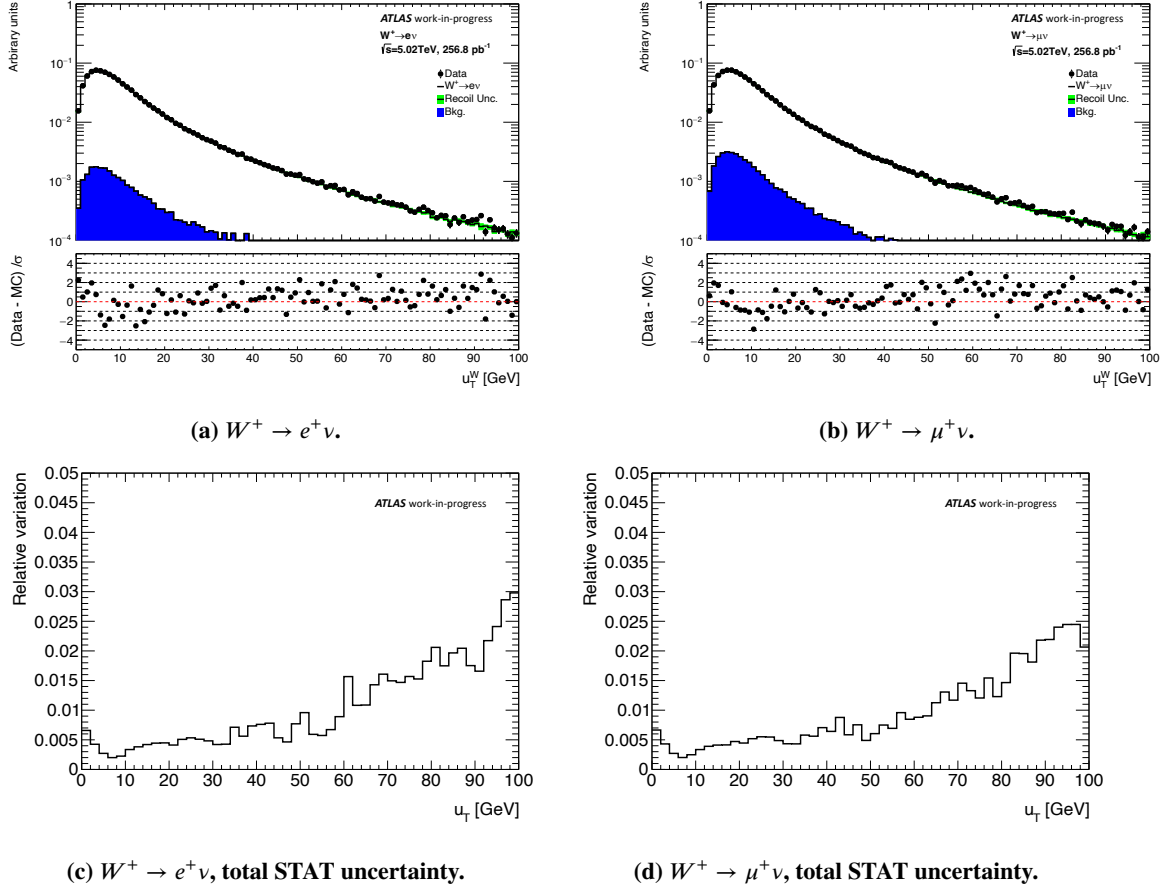


图 3.39 Recoil distributions in W^+ events at 5 TeV in the data and in the simulation after final calibration. The uncertainty includes statistical uncertainties, recoil systematic uncertainties related to Z data statistics, to the response systematic and to the extrapolation from the Z to the W in the response and resolution corrections. The total uncertainty related to Z data statistics is also shown separately.

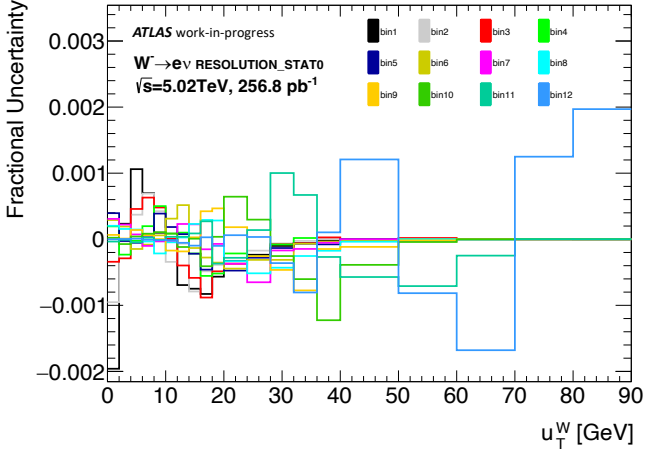
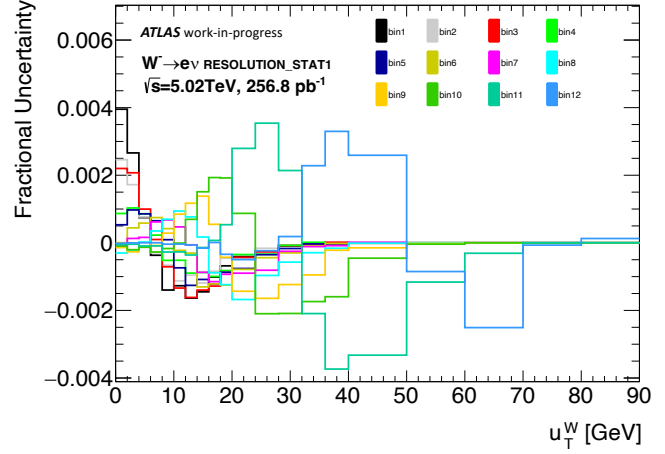
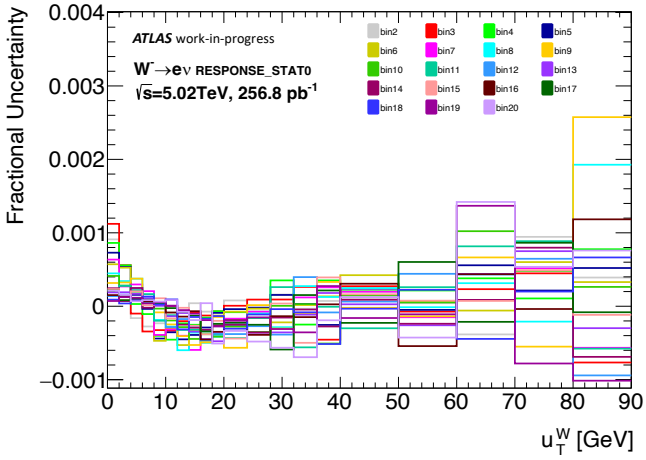
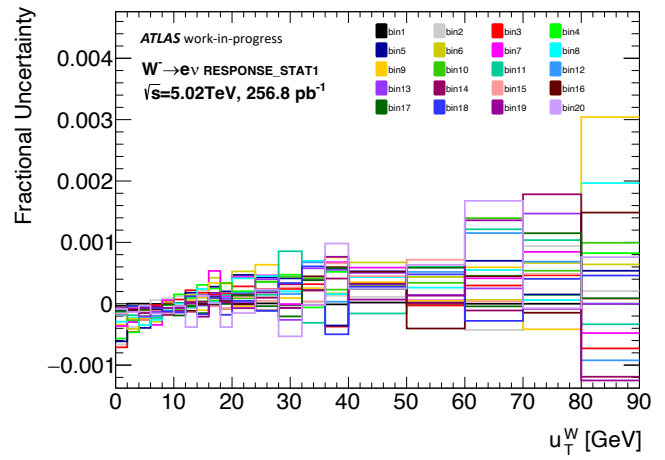

 (a) $W^- \rightarrow e^- \bar{\nu}$, RESOLUTION_STAT0.

 (b) $W^- \rightarrow e^- \bar{\nu}$, RESOLUTION_STAT1.

 (c) $W^- \rightarrow e^- \bar{\nu}$, RESPONSE_STAT0.

 (d) $W^- \rightarrow e^- \bar{\nu}$, RESPONSE_STAT1.

图 3.40 Impact of statistical uncertainty components from the in-situ resolution and response corrections on the measured u_T spectrum in $W^- \rightarrow e^- \bar{\nu}$ events at 5 TeV.

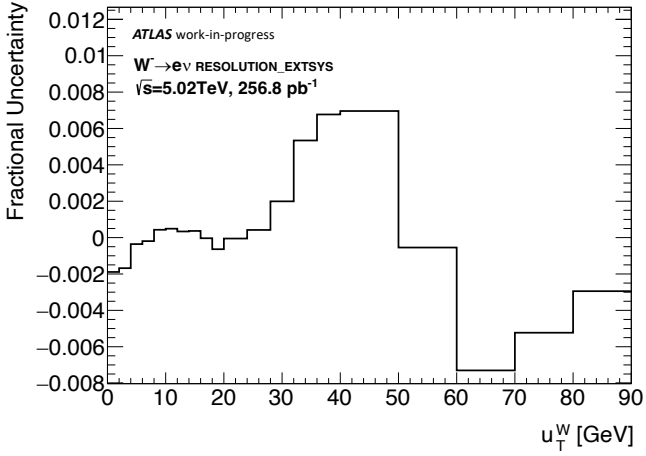
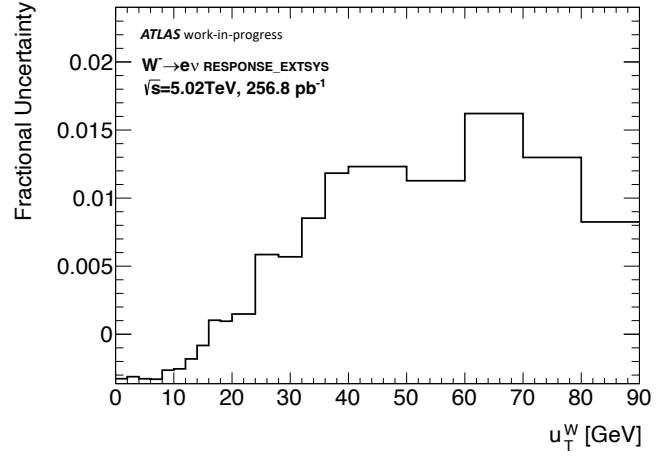
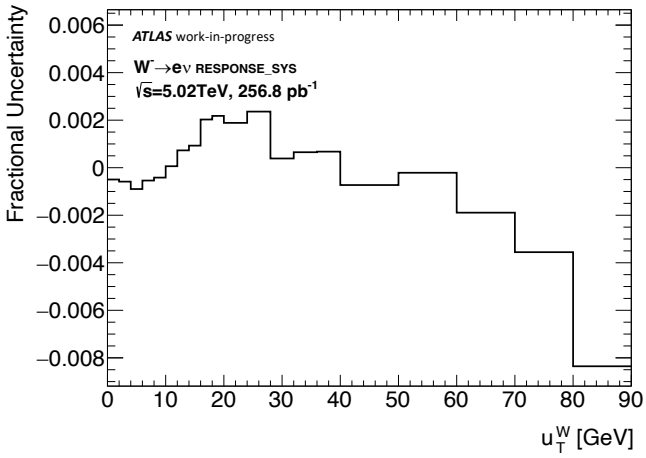
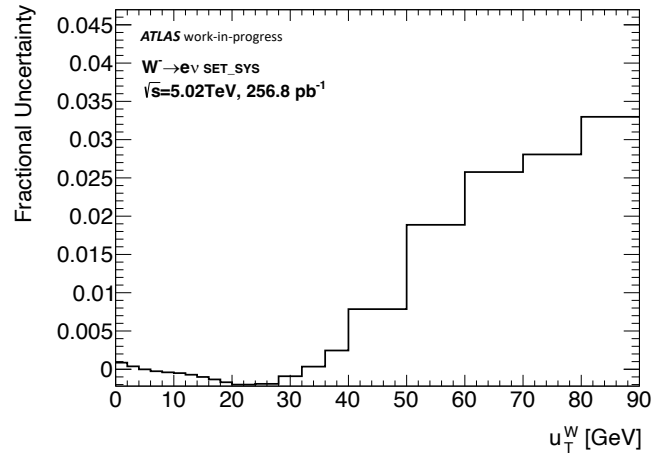

 (a) $W^- \rightarrow e^- \bar{\nu}_e$, RESOLUTION_EXTSYS.

 (b) $W^- \rightarrow e^- \bar{\nu}_e$, RESPONSE_EXTSYS.

 (c) $W^- \rightarrow e^- \bar{\nu}_e$, RESPONSE_SYS.

 (d) $W^- \rightarrow e^- \bar{\nu}_e$, SET_SYS.

图 3.41 Impact of systematic uncertainty components from the in-situ resolution and response corrections on the measured u_T spectrum in $W^- \rightarrow e^- \bar{\nu}_e$ events at 5 TeV.

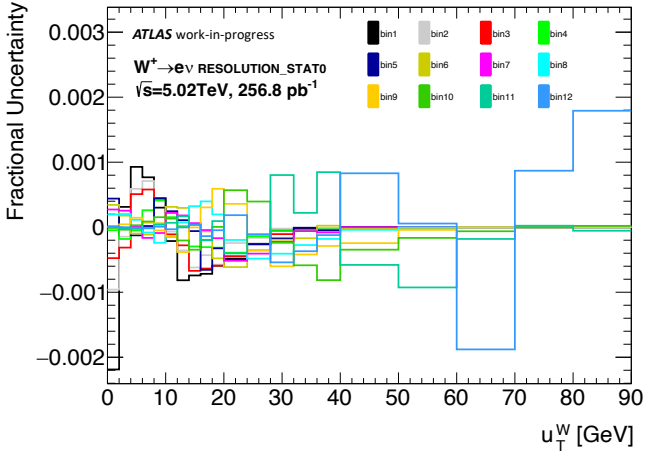
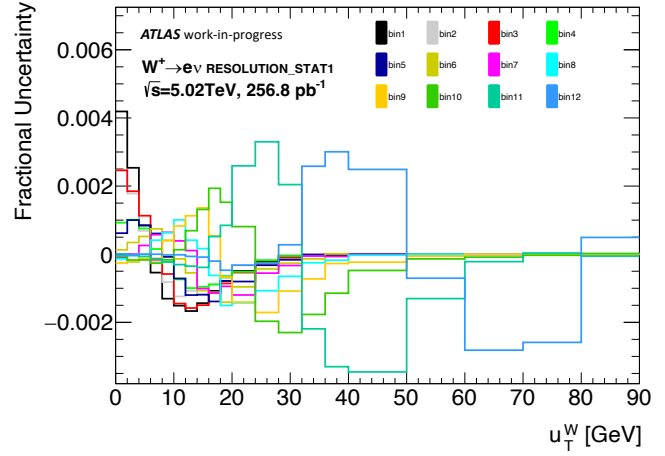
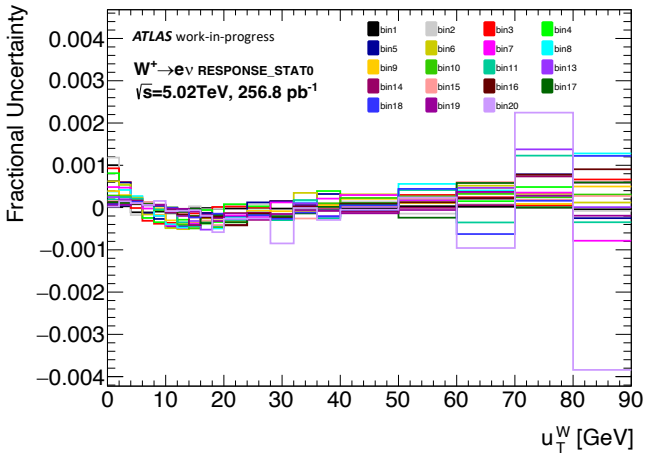
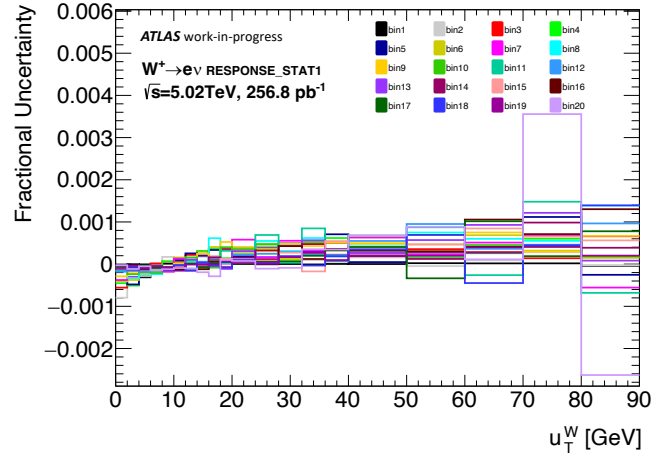

 (a) $W^+ \rightarrow e^+ \nu$, RESOLUTION_STAT0.

 (b) $W^+ \rightarrow e^+ \nu$, RESOLUTION_STAT1.

 (c) $W^+ \rightarrow e^+ \nu$, RESPONSE_STAT0.

 (d) $W^+ \rightarrow e^+ \nu$, RESPONSE_STAT1.

图 3.42 Impact of statistical uncertainty components from the in-situ resolution and response corrections on the measured u_T spectrum in $W^+ \rightarrow e^+ \nu$ events at 5 TeV.

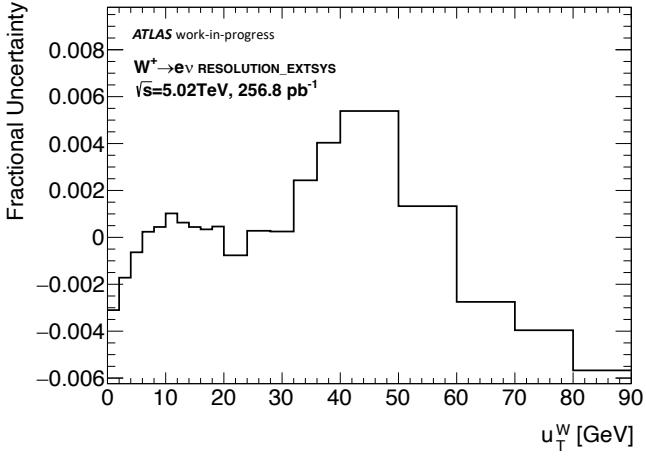
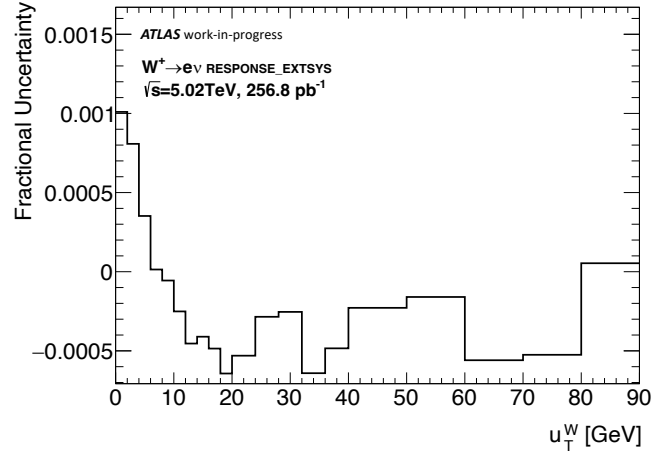
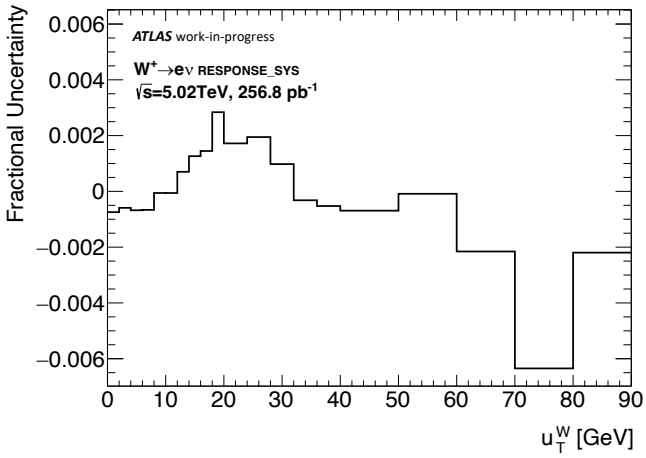
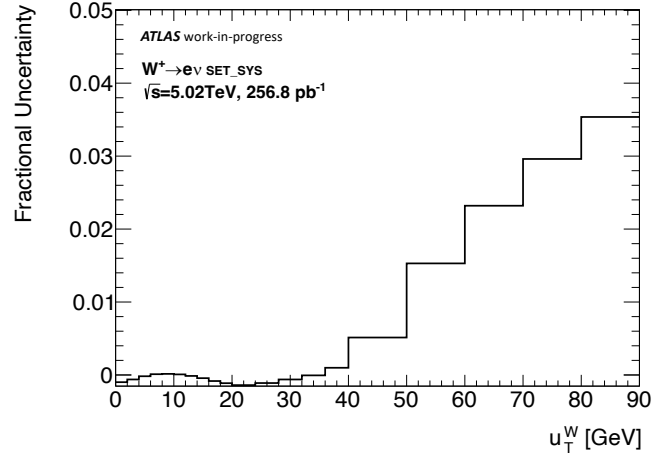

 (a) $W^+ \rightarrow e^+ \nu$, RESOLUTION_EXTSYS.

 (b) $W^+ \rightarrow e^+ \nu$, RESPONSE_EXTSYS.

 (c) $W^+ \rightarrow e^+ \nu$, RESPONSE_SYS.

 (d) $W^+ \rightarrow e^+ \nu$, SET_SYS.

图 3.43 Impact of systematic uncertainty components from the in-situ resolution and response corrections on the measured u_T spectrum in $W^+ \rightarrow e^+ \nu$ events at 5 TeV.

3.5 Low Pileup Dataset And Monte-Carlo Simulations

3.5.1 Low Pileup Dataset

The datasets used in this analysis were taken at $\sqrt{s} = 5$ and 13 TeV in November 2017 and June 2018 at low pileup conditions.

- $\sqrt{s} = 5.02$ TeV data was taken in November 2017, during ATLAS data period M, preliminary calibrated luminosity 256.827 pb^{-1} with an uncertainty of $\pm 1.6\%$, (tag OffLumi-5TeV-003), Runs 340644, 340683, 340697, 340718, 340814, 340849, 340850, 340910, 340925, 340973, 341027, 341123, 341184

- $\sqrt{s} = 13$ TeV data was taken in November 2017, during ATLAS data period N, preliminary calibrated luminosity 144.931 pb^{-1} with an uncertainty of $\pm 2.1\%$, (tag OffLumi-13TeV-010-lowmu), Runs 341294, 341312, 341419, 341534, 341615, 341649

- $\sqrt{s} = 13$ TeV data was taken in June 2018, ATLAS data period G4+J, preliminary calibrated luminosity 190.249 pb^{-1} with an uncertainty of $\pm 1.5\%$. (tag OffLumi-13TeV-010-lowmu), Runs 354396, 355331, 355389, 355416, 355468

The total luminosity for the 13 TeV data amounts to 335.180 pb^{-1} with an uncertainty of 1.5%. The luminosity calibration of the low-pileup datasets is further discussed in^[47].

The 5 TeV runs were taken in a range of pileup μ from around 1 to 5. starting at around $\langle\mu\rangle \approx 5$ and falling in the course of the run to about $\langle\mu\rangle \approx 1$. In contrast, the 13 TeV runs were taken with a fixed leveled luminosity at $\mu = 2$ (with minor exceptions). Figure 3.44. All data is taken at 25 ns bunch spacing, but there is a small difference in the filling scheme where the 2017 data was taken in the $8b4e$ bunch structure and the 2018 data with longer uninterrupted bunch trains.

Some notable differences compared to the standard high μ data are:

- Lower topo-cluster thresholds are used in reconstruction of the hadronic recoil to optimize the response of the topo-clusters; this has also affected the electron response;
- Single electron and muon triggers with significantly lower thresholds and looser identification criteria are used, HLT_e15_lhloose_nod0_L1EM12 is used for electron channel and HLT_mu14 is used for muon channel.

The data of the 2017 runs, both 5 and 13 TeV, was reprocessed using updated

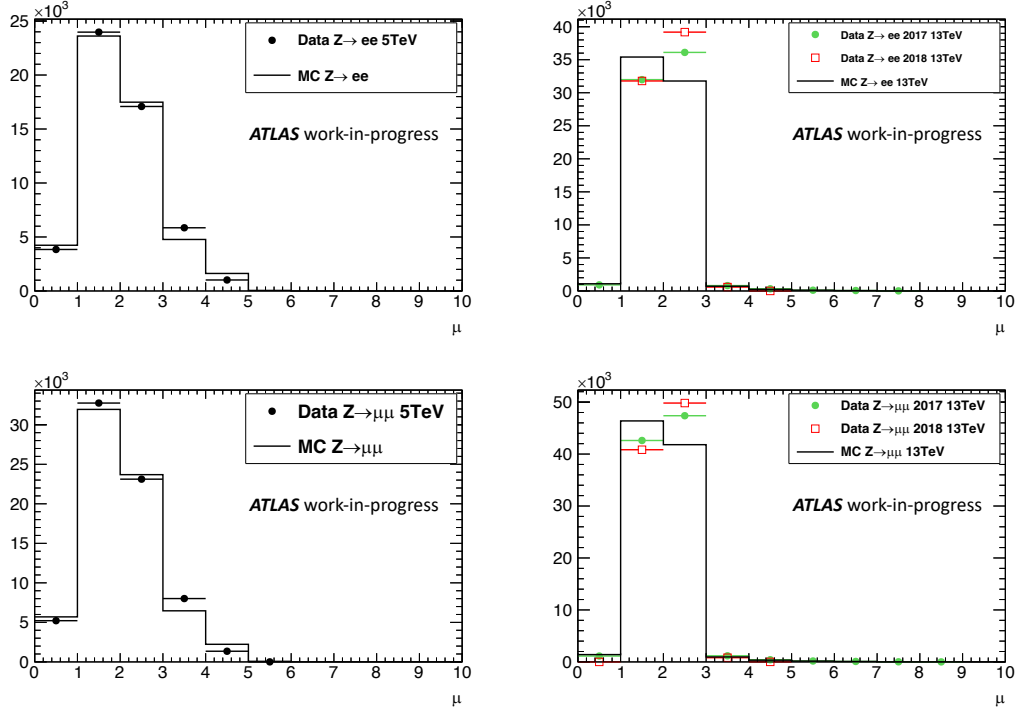


图 3.44 Pileup distributions for the low- μ dataset in a $Z \rightarrow ee$ (top row) and a $Z \rightarrow \mu\mu$ (bottom row) selection.

settings for the ID alignment (r10803) to improve the muon sagitta biases, while the 2018 data relies on the T0-reconstructed data sets. Data is further processed to STDM4 or STDM6 derivations:

- original (T0) 2017 data was processed to STDM4 with p3372
- reprocessed 2017 data was processed to STDM6 with p3653
- 2018 data was processed to STDM6 with p3583

3.5.2 Signal MC Samples

Fully simulated and reconstructed ATLAS Monte Carlo samples ("MC") from the MC16 production are used to estimate the signal and background processes. All MC samples use specific setting for the data conditions, i.e. the pileup overlay, topo-cluster noise thresholds and trigger menu. The main signal samples for W and Z production are generated using POWHEGevent generator^[48?–50] using the CT10 PDF, interfaced to PYTHIA8^[51] using AZNLO tune^[?]. POWHEG+PYTHIA8 samples are interfaced to PHOTOS++^[52] to simulate the effect of final state QED radiation.

Alternative samples are prepared with SHERPA^[53] using 2.2.1 version at 13TeV

process (5TeV)	sample
$W^+ \rightarrow e^+ \nu$	mc16_5TeV.361100.PowhegPythia8EvtGen_AZNLOCTEQ6L1_Wplusenu.e4916_s3238_r10243_r10210_p3665
$W^+ \rightarrow \mu^+ \nu$	mc16_5TeV.361101.PowhegPythia8EvtGen_AZNLOCTEQ6L1_Wplusmunu.e4916_s3238_r10243_r10210_p3665
$W^- \rightarrow e^- \nu$	mc16_5TeV.361103.PowhegPythia8EvtGen_AZNLOCTEQ6L1_Wminusenu.e4916_s3238_r10243_r10210_p3665
$W^- \rightarrow \mu^- \nu$	mc16_5TeV.361104.PowhegPythia8EvtGen_AZNLOCTEQ6L1_Wminusmunu.e4916_s3238_r10243_r10210_p3665
$Z \rightarrow e^+ e^-$	mc16_5TeV.361106.PowhegPythia8EvtGen_AZNLOCTEQ6L1_Zee.e4916_s3238_r10243_r10210_p3374
$Z \rightarrow \mu^+ \mu^-$	mc16_5TeV.361107.PowhegPythia8EvtGen_AZNLOCTEQ6L1_Zmumu.e4916_s3238_r10243_r10210_p3665

表 3.7 Signal MC samples at 5 TeV

process (13TeV)	sample
$W^+ \rightarrow e^+ \nu$	mc16_13TeV.361100.PowhegPythia8EvtGen_AZNLOCTEQ6L1_Wplusenu.e3601_s3126_r10244+r11165_p3665
$W^+ \rightarrow \mu^+ \nu$	mc16_13TeV.361101.PowhegPythia8EvtGen_AZNLOCTEQ6L1_Wplusmunu.e3601_s3126_r10244+r11165_p3665
$W^- \rightarrow e^- \nu$	mc16_13TeV.361103.PowhegPythia8EvtGen_AZNLOCTEQ6L1_Wminusenu.e3601_s3126_r10244+r11165_p3665
$W^- \rightarrow \mu^- \nu$	mc16_13TeV.361104.PowhegPythia8EvtGen_AZNLOCTEQ6L1_Wminusmunu.e3601_s3126_r10244+r11165_p3665
$Z \rightarrow e^+ e^-$	mc16_13TeV.361106.PowhegPythia8EvtGen_AZNLOCTEQ6L1_Zee.e3601_e5984_s3126_r10244+r11165_r10210_p3665
$Z \rightarrow \mu^+ \mu^-$	mc16_13TeV.361107.PowhegPythia8EvtGen_AZNLOCTEQ6L1_Zmumu.e3601_e5984_s3126_r10244+r11165_r10210_p3665

表 3.8 Signal MC samples at 13 TeV

and 2.2.5 version at 5TeV, with the NNPDF3.0 PDFs and merging $V + 0, 1, 2$ jets at NLO accuracy with $V + 3, 4$ jets at LO accuracy. All of the signal MC samples used in the analysis are listed in Table 3.7 for 5 TeV and Table 3.8 for 13 TeV.

For W and Z processes, the samples are normalized to the DYTURBO program, an optimized version of DYNLO^[54,55] using the MMHT2014nnlo PDF set^[56], to Next-to-next-to-leading-order (NNLO). The numbers are taken from the ATLAS publications using 2015 data at 13 TeV^[57] and 5.02 TeV^[58] and are summarized in Table 3.9 and Table 3.10. The uncertainties on those cross-sections arise from the choice of PDF set and PDF set internal uncertainties ($\sim 3 - 4\%$), from factorization and renormalisation scale dependence ($< 1\%$), and the strong coupling constant α_s ($\sim 1 - 2\%$).

3.5.3 Background Processes Estimated Using Monte-Carlo Simulations

Backgrounds from top-quark pair-production $t\bar{t}$ as well as single-top production (Wt , t -channel, s -channel) are generated with POWHEG+PYTHIA8. The 5 TeV $t\bar{t}$ cross section is taken as the top++ prediction reported in the CMS publication^[59]. Various combinations of di-bosons VV , $V = W, Z$ are generated with Sherpa in all decay channels with at least one real lepton in the final state. A conservative total uncertainty of 5% is taken as an uncertainty on any event count predictions normalized using these cross-sections, e.g. for use of subtraction of electroweak backgrounds. Details are in

the provided tables.

Process	Data set	Generator	$\sigma \cdot \text{BR} \cdot \epsilon_{\text{filter}}$ [nb] (th. unc.)	$N_{\text{evt}}^{\text{skim}} [10^6]$	$N_{\text{evt}}^{\text{unskim}} [10^6]$
$W^+ \rightarrow e^+ \nu$	361100	POWHEG+PYTHIA	11.6 (5%)	40	40
$W^+ \rightarrow \mu^+ \nu$	361101	POWHEG+PYTHIA	11.6 (5%)	40	40
$W^+ \rightarrow \tau^+ \nu$	361102	POWHEG+PYTHIA	11.6 (5%)	0.28	5.0
$W^- \rightarrow e^- \bar{\nu}$	361103	POWHEG+PYTHIA	8.63 (5%)	30	30
$W^- \rightarrow \mu^- \bar{\nu}$	361104	POWHEG+PYTHIA	8.63 (5%)	29	29
$W^- \rightarrow \tau^- \bar{\nu}$	361105	POWHEG+PYTHIA	8.63 (5%)	0.24	4.0
$Z \rightarrow ee$	361106	POWHEG+PYTHIA	1.910×1.03 (5%)	10	10
$Z \rightarrow \mu\mu$	361107	POWHEG+PYTHIA	1.910×1.025 (5%)	10	10
$Z \rightarrow \tau\tau$	361108	POWHEG+PYTHIA	1.910×1.025 (5%)	0.12	1.0
$ZZ(q\bar{q}\ell\ell)$	363356	SHERPA 2.2.1	0.01556×0.141 (10%)	0.0064	0.010
$WZ(q\bar{q}\ell\ell)$	363358	SHERPA 2.2.1	0.003433 (10%)	0.0063	0.010
$WW(q\bar{q}\ell\nu)$	363359	SHERPA 2.2.1	0.02472 (10%)	0.0093	0.020
$WW(\ell\nu q\bar{q})$	363360	SHERPA 2.2.1	0.02472 (10%)	0.0093	0.020
$WZ(\ell\nu q\bar{q})$	363489	SHERPA 2.2.1	0.01142 (10%)	0.0047	0.010
$ZZ(4\ell)$	364250	SHERPA 2.2.2	0.001252 (10%)	0.0057	0.010
$WZ(3\ell\nu)$	364253	SHERPA 2.2.2	0.004583 (10%)	0.0062	0.010
$WW(2\ell 2\nu)$	364254	SHERPA 2.2.2	0.01250 (10%)	0.0073	0.010
$WZ(\ell 3\nu)$	364255	SHERPA 2.2.2	0.003235 (10%)	0.0050	0.010
Wt	410013	POWHEG+PYTHIA	0.03582 (10%)	0.0037	0.010
$W\bar{t}$	410014	POWHEG+PYTHIA	0.03399 (10%)	0.0037	0.010
$t\bar{t}$ (nominal)	410470	POWHEG+PYTHIA	0.8318×0.544 (7%)	1.2	2.0
$t(t - \text{chan.}t)$	410642	POWHEG+PYTHIA	0.03699 (10%)	0.016	0.030
$t(t - \text{chan.}\bar{t})$	410643	POWHEG+PYTHIA	0.02217 (10%)	0.011	0.020
$t(s - \text{chan.}t)$	410644	POWHEG+PYTHIA	0.002027 (10%)	0.0050	0.010
$t(s - \text{chan.}\bar{t})$	410645	POWHEG+PYTHIA	0.001268 (10%)	0.0052	0.010
$t\bar{t}$ (syst.)	410480	POWHEG+PYTHIA	0.8318×0.438 (7%)	0.85	1.5
$t\bar{t}$ (syst.)	410482	POWHEG+PYTHIA	0.8318×0.105 (7%)	0.40	0.50
$t\bar{t}$ (syst.)	410557	POWHEG+PYTHIA	0.8318×0.438 (7%)	0.85	1.5
$t\bar{t}$ (syst.)	410558	POWHEG+PYTHIA	0.8318×0.105 (7%)	0.40	0.50

表 3.9 Monte Carlo samples at $\sqrt{s} = 13$ TeV.

Process	Data set	Generator	$\sigma \cdot \text{BR} \cdot \epsilon_{\text{filter}}$ [nb] (th. unc.)	$N_{\text{evt}}^{\text{skim}} [10^6]$	$N_{\text{evt}}^{\text{unskim}} [10^6]$
$W^+ \rightarrow e^+ \nu$	361100	POWHEG+PYTHIA	4.357 (5%)	11	11
$W^+ \rightarrow \mu^+ \nu$	361101	POWHEG+PYTHIA	4.357 (5%)	11	11
$W^+ \rightarrow \tau^+ \nu$	361102	POWHEG+PYTHIA	4.357 (5%)	0.065	0.94
$W^- \rightarrow e^- \bar{\nu}$	361103	POWHEG+PYTHIA	2.902 (5%)	7.0	7.0
$W^- \rightarrow \mu^- \bar{\nu}$	361104	POWHEG+PYTHIA	2.902 (5%)	7.0	7.0
$W^- \rightarrow \tau^- \bar{\nu}$	361105	POWHEG+PYTHIA	2.902 (5%)	0.039	0.59
$Z \rightarrow ee$	361106	POWHEG+PYTHIA	0.6600×1.025 (5%)	6.3	6.3
$Z \rightarrow \mu\mu$	361107	POWHEG+PYTHIA	0.6600×1.025 (5%)	3.4	3.4
$Z \rightarrow \tau\tau$	361108	POWHEG+PYTHIA	0.6600×1.025 (5%)	0.039	0.29
$Z \rightarrow ee$	364381	SHERPA 2.2.5	0.6600×1.12 (5%)	5.0	5.0
$Z \rightarrow \mu\mu$	364382	SHERPA 2.2.5	0.6600×1.12 (5%)	5.0	5.0
$Z \rightarrow \tau\tau$	364383	SHERPA 2.2.5	0.6600×1.12 (5%)	1.5	1.5
$W \rightarrow e\nu$	364384	SHERPA 2.2.5	7.259 (5%)	25	25
$W \rightarrow \mu\nu$	364385	SHERPA 2.2.5	7.259 (5%)	25	25
$W \rightarrow \tau\nu$	364386	SHERPA 2.2.5	7.259 (5%)	6.0	6.0
$ZZ(4\ell)$	361063	SHERPA 2.1	0.004624 (10%)	0.017	0.049
$WZ(\ell\ell\ell^-\nu\text{SF})$	361064	SHERPA 2.1	0.0005324 (10%)	0.0073	0.015
$WZ(\ell\ell\ell^-\nu\text{OF})$	361065	SHERPA 2.1	0.001041 (10%)	0.012	0.030
$WZ(\ell\ell\ell^+\nu\text{SF})$	361066	SHERPA 2.1	0.0008433 (10%)	0.010	0.020
$WZ(\ell\ell\ell^+\nu\text{OF})$	361067	SHERPA 2.1	0.001633 (10%)	0.016	0.039
$WW(2\ell 2\nu)$	361068	SHERPA 2.1	0.003356 (10%)	0.068	0.090
$WW(q\bar{q}\ell\nu)$	361091	SHERPA 2.1	0.006059 (10%)	0.078	0.15
$WW(\ell\nu q\bar{q})$	361092	SHERPA 2.1	0.006082 (10%)	0.14	0.26
$WZ(\ell\nu q\bar{q})$	361093	SHERPA 2.1	0.002503 (10%)	0.039	0.075
$WZ(q\bar{q}\ell\ell)$	361094	SHERPA 2.1	0.0007518 (10%)	0.017	0.025
$ZZ(q\bar{q}\ell\ell)$	361096	SHERPA 2.1	0.003789×0.148 (10%)	0.0070	0.010
$t\bar{t}$	410470	POWHEG+PYTHIA	0.06890×0.544 (7%)	1.8	2.8
$t(\text{s} - \text{chan.}t)$	410644	POWHEG+PYTHIA	0.0005400 (10%)	0.028	0.050
$t(\text{s} - \text{chan.}\bar{t})$	410645	POWHEG+PYTHIA	0.0002751 (10%)	0.028	0.050
Wt	410646	POWHEG+PYTHIA	0.002990 (10%)	0.018	0.050
$W\bar{t}$	410647	POWHEG+PYTHIA	0.002983 (10%)	0.019	0.050
$t(\text{t} - \text{chan.}t)$	410658	POWHEG+PYTHIA	0.005414 (10%)	0.028	0.050
$t(\text{t} - \text{chan.}\bar{t})$	410659	POWHEG+PYTHIA	0.002682 (10%)	0.028	0.050

表 3.10 Monte Carlo samples at $\sqrt{s} = 5\text{TeV}$.

3.6 Event Selection

For measuring p_T^Z , candidate $Z \rightarrow \ell\ell$ events are required to pass the same unprescaled single-lepton triggers in both the 5 and 13 TeV datasets, HLT_e15_lhloose_nod0_L1EM12 or HLT_mu14, and either lepton may trigger the event. Events are required to contain exactly two electron or two muon candidates satisfying the isolation and identification criteria. Events with additional muons (electrons) with transverse momentum greater than 20 GeV and satisfying the medium (loose) ID criteria are rejected. And both electrons or muons have to be $p_T > 25$ GeV. The two electron (muon) candidates are required to be of opposite charge with a dilepton invariant mass of $66 < m_{\ell\ell} < 116$ GeV selecting the resonant region around the Z peak. Summary of the selections of $Z \rightarrow \ell\ell$ events are listed in Table 3.11

Selection	$Z \rightarrow ee$	$Z \rightarrow \mu\mu$
lepton ID working point	Medium LH electron	Medium muon
d_0, z_0	$d_0/\sigma(d_0) < 5, \Delta z_0 \times \sin(\theta) < 0.5$	$d_0/\sigma(d_0) < 3, \Delta z_0 \times \sin(\theta) < 0.5$
$ \eta $	$ \eta < 2.47$, excluding crack (1.37-1.52)	$ \eta < 2.4$
Isolation	$ptvarcone20 / p_T < 0.1$	
lepton charges	two opposite sign leptons	
transverse momentum	$p_T > 25$ GeV	
$m_{\ell\ell}$	$66 \text{ GeV} < m_{\ell\ell} < 116 \text{ GeV}$	

表 3.11 Selections for $Z \rightarrow \ell\ell$ events for both 5 and 13 TeV datasets.

In Tables 3.12 and 3.13 the cut flow numbers for the $Z \rightarrow \ell\ell$ signal selection for the $\sqrt{s} = 13$ low- μ dataset are shown; the equivalent numbers for the $\sqrt{s} = 5$ low- μ dataset are shown in Tables 3.14 and 3.15. A summary of observed compared to expected yields is then provided in Table 3.16.

Cut	Data	Signal	$Z \rightarrow \tau\tau$		$W^\pm \rightarrow l^\pm \nu$		Top	Diboson	MultiJet
No cut	56038636	641084.68 $\pm$ 176.00	86921.61 $\pm$ 275.00		7012291.76 $\pm$ 933.63		108429.73 $\pm$ 145.18	14532.94 $\pm$ 126.84	-
Two electrons	237221	196940.70 $\pm$ 96.72	837.65 $\pm$ 24.58		479.55 $\pm$ 8.61		2304.40 $\pm$ 20.06	599.23 $\pm$ 22.64	-
Electron trig matched	236820	196624.93 $\pm$ 96.64	831.69 $\pm$ 24.49		425.45 $\pm$ 7.81		2300.08 $\pm$ 20.04	599.19 $\pm$ 22.64	-
Isolation	224967	194585.91 $\pm$ 96.15	808.90 $\pm$ 24.17		263.67 $\pm$ 6.14		2047.71 $\pm$ 19.22	585.37 $\pm$ 22.46	-
Opposite charge	222256	192148.48 $\pm$ 95.55	797.68 $\pm$ 24.00		194.86 $\pm$ 5.41		1974.44 $\pm$ 18.99	551.63 $\pm$ 21.93	-
Both $p_T^\mu > 25$ GeV	172651	162035.98 $\pm$ 87.79	168.62 $\pm$ 11.11		37.65 $\pm$ 1.96		1401.94 $\pm$ 16.05	420.09 $\pm$ 18.99	-
$66 < m_{ee} < 116$ GeV	165027	158000.48 $\pm$ 86.70	79.70 $\pm$ 7.54		16.53 $\pm$ 1.42		501.40 $\pm$ 9.91	323.93 $\pm$ 14.65	110 ± 68

表 3.12 Analysis cut flow for $Z \rightarrow ee$ 13 TeV signal selection. The minimum lepton p_T required before the final p_T cut is 15 GeV. Displayed uncertainties on MC background are MC statistics only.

Cut	Data	Signal	$Z \rightarrow \tau\tau$		$W^\pm \rightarrow l^\pm \nu$		Top	Diboson	MultiJet
No cut	56038636	645948.76 $\pm$ 178.06	86921.61 $\pm$ 275.00		6964694.84 $\pm$ 931.38		108429.73 $\pm$ 145.18	14532.94 $\pm$ 126.84	-
Two muons	365843	267039.96 $\pm$ 114.35	801.57 $\pm$ 24.09		886.54 $\pm$ 11.71		3978.45 $\pm$ 25.29	789.92 $\pm$ 26.76	-
Muon trig matched	362610	262178.31 $\pm$ 113.32	783.12 $\pm$ 23.81		866.71 $\pm$ 11.60		3891.49 $\pm$ 24.97	770.30 $\pm$ 26.43	-
Isolation	292967	257409.16 $\pm$ 112.30	755.72 $\pm$ 23.40		101.02 $\pm$ 3.64		2416.77 $\pm$ 19.72	730.10 $\pm$ 25.84	-
Opposite charge	292692	257407.03 $\pm$ 112.30	754.32 $\pm$ 23.38		89.65 $\pm$ 3.40		2369.76 $\pm$ 19.58	712.73 $\pm$ 25.66	-
Both $p_T^\mu > 25$ GeV	223806	213225.71 $\pm$ 102.32	160.32 $\pm$ 10.86		22.39 $\pm$ 1.94		1630.27 $\pm$ 16.41	524.58 $\pm$ 21.71	-
$66 < m_{\mu\mu} < 116$ GeV	214035	207860.18 $\pm$ 101.04	79.67 $\pm$ 7.56		11.92 $\pm$ 1.40		553.90 $\pm$ 9.22	414.20 $\pm$ 17.34	177 ± 44

表 3.13 Analysis cut flow for $Z \rightarrow \mu\mu$ 13 TeV signal selection. The minimum lepton p_T required before the final p_T cut is 15 GeV. Displayed uncertainties on MC background are MC statistics only.

Cut	Data	Signal	$Z \rightarrow \tau\tau$		$W^\pm \rightarrow l^\pm \nu$		Top	Diboson	MultiJet
No cut	11372289	176337.83 $\pm$ 71.97	26629.86 $\pm$ 140.18		1975838.05 $\pm$ 597.63		7638.68 $\pm$ 7.32	3622.07 $\pm$ 8.83	-
Two electrons	72037	63253.88 $\pm$ 41.58	282.09 $\pm$ 13.06		116.85 $\pm$ 4.79		165.93 $\pm$ 0.88	203.38 $\pm$ 3.86	-
Electron trig matched	71412	63107.73 $\pm$ 41.53	280.35 $\pm$ 13.02		99.97 $\pm$ 4.49		165.32 $\pm$ 0.88	202.70 $\pm$ 3.86	-
Isolation	69068	62642.62 $\pm$ 41.38	275.25 $\pm$ 12.91		61.81 $\pm$ 3.17		143.51 $\pm$ 0.81	195.59 $\pm$ 3.69	-
Opposite charge	68229	61827.51 $\pm$ 41.11	273.43 $\pm$ 12.87		45.85 $\pm$ 2.88		137.65 $\pm$ 0.78	185.66 $\pm$ 3.67	-
Both $p_T^\mu > 25$ GeV	53684	52565.65 $\pm$ 37.89	43.04 $\pm$ 4.97		7.83 $\pm$ 0.94		94.26 $\pm$ 0.65	133.85 $\pm$ 2.22	-
$66 < m_{ee} < 116$ GeV	51772	51309.63 $\pm$ 37.43	23.13 $\pm$ 3.67		3.98 $\pm$ 0.63		35.47 $\pm$ 0.40	109.09 $\pm$ 2.04	0^{+87}_{-0}

表 3.14 Analysis cut flow for $Z \rightarrow ee$ 5 TeV signal selection. The minimum lepton p_T required before the final p_T cut is 18 GeV. Displayed uncertainties on MC background are MC statistics only.

Cut	Data	Signal	$Z \rightarrow \tau\tau$		$W^\pm \rightarrow l^\pm \nu$		Top	Diboson	MultiJet
No cut	11372289	170822.37 $\pm$ 94.58	26629.86 $\pm$ 140.18		1936606.79 $\pm$ 589.63		7638.68 $\pm$ 7.32	3622.07 $\pm$ 8.83	-
Two muons	111874	88643.79 $\pm$ 68.03	366.66 $\pm$ 14.71		178.02 $\pm$ 7.07		341.71 $\pm$ 1.30	293.59 $\pm$ 3.06	-
Muon trig matched	111000	86936.15 $\pm$ 67.38	360.34 $\pm$ 14.59		172.17 $\pm$ 7.02		333.68 $\pm$ 1.28	287.31 $\pm$ 3.03	-
Isolation	94735	85728.31 $\pm$ 66.89	354.34 $\pm$ 14.46		25.92 $\pm$ 2.06		178.34 $\pm$ 0.89	257.05 $\pm$ 2.81	-
Opposite charge	94651	85727.80 $\pm$ 66.89	354.34 $\pm$ 14.46		23.23 $\pm$ 1.95		172.50 $\pm$ 0.87	249.95 $\pm$ 2.78	-
Both $p_T^\mu > 25$ GeV	73105	71541.14 $\pm$ 61.10	76.37 $\pm$ 6.73		6.20 $\pm$ 1.40		114.79 $\pm$ 0.71	175.23 $\pm$ 2.28	-
$66 < m_{\mu\mu} < 116$ GeV	70447	69819.41 $\pm$ 60.35	38.56 $\pm$ 4.77		3.70 $\pm$ 1.30		43.97 $\pm$ 0.44	144.93 $\pm$ 2.12	15.9 ± 7.9

表 3.15 Analysis cut flow for $Z \rightarrow \mu\mu$ 5 TeV signal selection. The minimum lepton p_T required before the final p_T cut is 18 GeV. Displayed uncertainties on MC background are MC statistics only.

Selection	Observed	Expected
13 TeV $Z \rightarrow ee$	165027	159032 $\pm$ 112
13 TeV $Z \rightarrow \mu\mu$	214035	209097 $\pm$ 112
5 TeV $Z \rightarrow ee$	51772	51481 $\pm$ 58
5 TeV $Z \rightarrow \mu\mu$	70447	70066 $\pm$ 61

表 3.16 Observed and Expected yield comparison for all signal selections. Displayed uncertainties are MC statistics plus QCD Multijet uncertainties.

3.7 Reconstructed Level Comparisons Between Data And Monte-Carlo Simulation

Data to MC comparisons at reconstructed level for both the $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ channels at 5 and 13 TeV are provided here after applying the event selection described in this chapter. In all of these control plots, the MC signal plus background MC are normalized to the data integral. the χ^2 is computed using the full covariance matrices with all experimental systematics except the luminosity uncertainty.

3.7.1 $\sqrt{s}=13$ TeV Dataset Control Plots

The data/MC comparisons at reconstructed level at 13 TeV are shown in several spectrums of interests in this subsection. All physics processes of the MCs are categorized and shown in different colors: the signal $Z \rightarrow ee$ or $Z \rightarrow \mu\mu$ processed are in white histograms; the top related processes, which are dominated by $t\bar{t}$ channel, are in yellow; $W \rightarrow \tau\nu$, and also possibly $W \rightarrow e/\mu + \nu$ faking into $Z \rightarrow \ell\ell$, are in red stack. $Z \rightarrow \tau\tau$ is shown in green. And the diboson processes, in which each boson could be a Z or W boson, with semi-leptonic decays, are in blue. The QCD multijet backgrounds, as derived in Section 4.2 are shown in purple. The data is plotted in dots with its statistic uncertainty. All experimental systematic uncertainties, including lepton scale factor uncertainties, hadronic recoil calibration uncertainties (Section 3.4) and background uncertainties are summed in quadrature. The background uncertainties are calculated from the uncertainties of cross sections of every MC processes, the MJ uncertainties, and the luminosity uncertainty which take part in the scaling the MC events. Due to the very clean background contamination in $Z \rightarrow \ell\ell$ selections, the background uncertainties are found to be very small.

Figure 3.45,3.46 show the $\sum \vec{E}_T = \sum E_T - u_T$ and $\sum E_T$ spectrums. $\sum \vec{E}_T$ and $\sum E_T$ are the key parameters to estimate the underlying event activities which affect the *Hadronic recoil* performance, as discussed in Figure 3.4. Figure 3.47 refers to the invariant mass of the dilepton pair, which show clear Z -mass resonance. Figures Figure 3.48 to Figure 3.50 correspond to the lepton kinematics including $p_T^\ell, \eta_\ell, \phi_\ell$. Figure Figure 3.51 is the reconstructed Z boson transverse momentum using dilepton kinematics, While Figure 3.52 is that using hadronic recoil system. Figure 3.53 is the rapidity of

Z boson at reco-level. All spectrums are in general well agreed with the Monte-Carlo simulations.

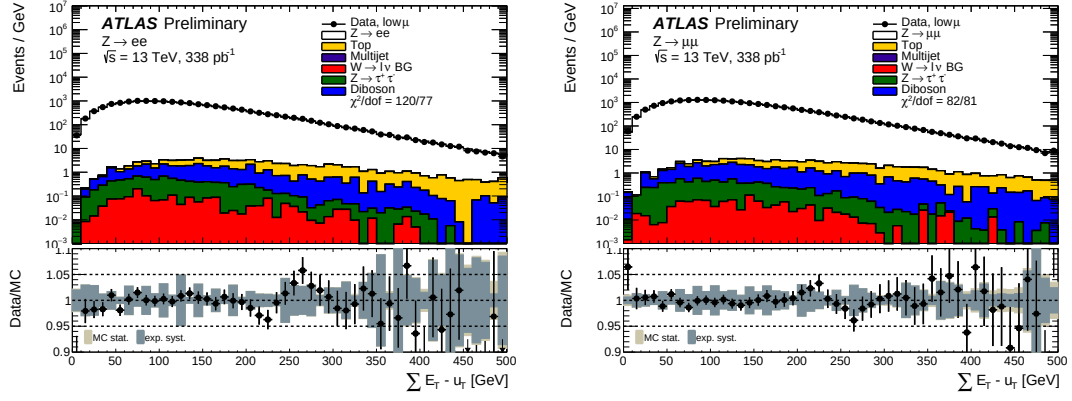


图 3.45 $\Sigma \bar{E}_T$ distribution in the $\sqrt{s} = 13$ TeV $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ analyses.

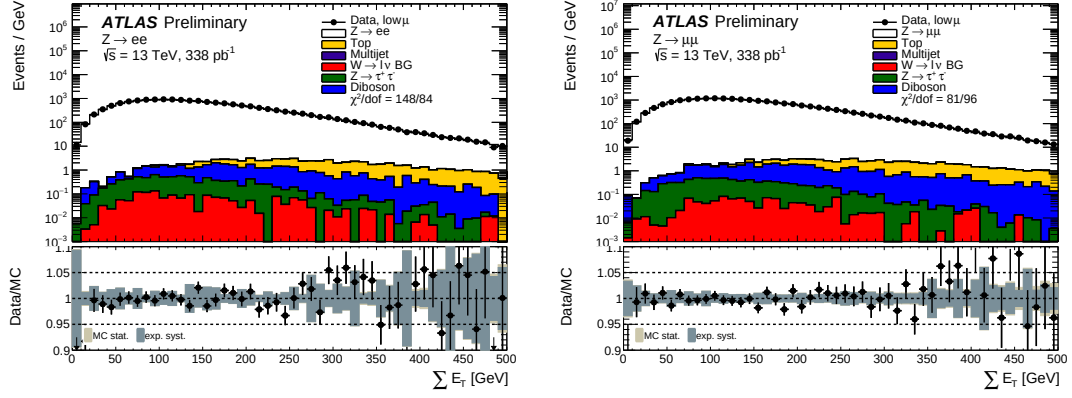
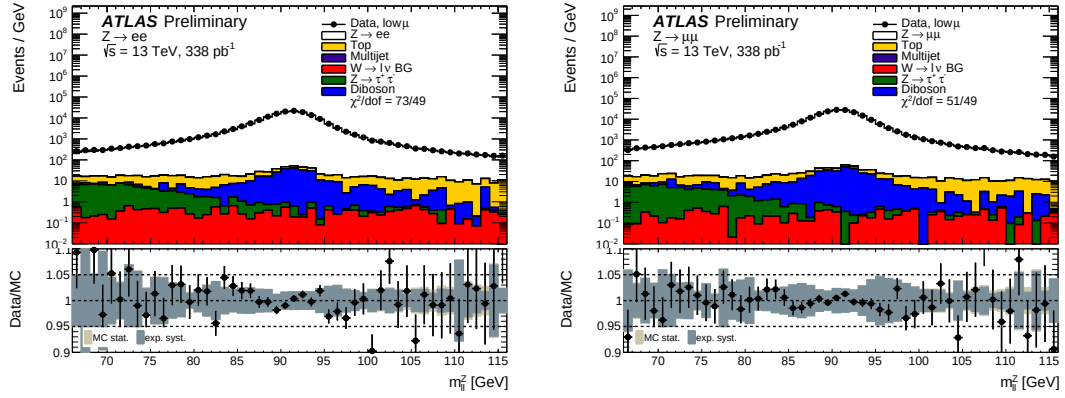
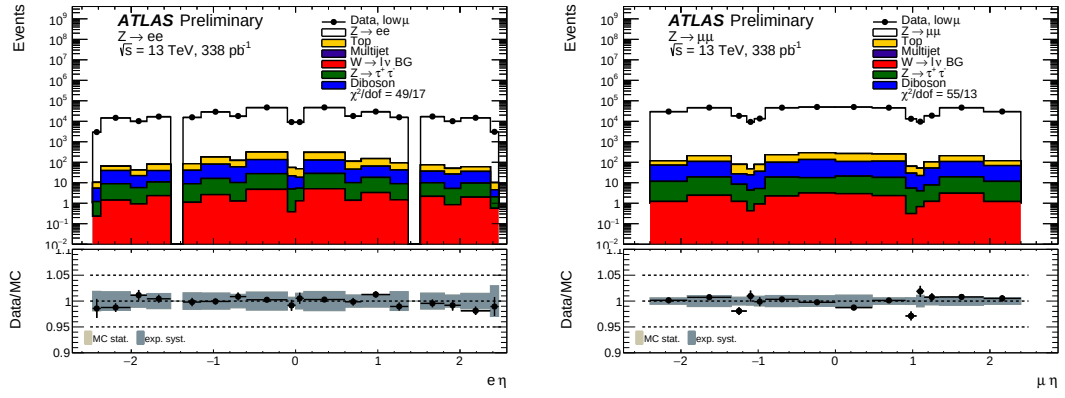
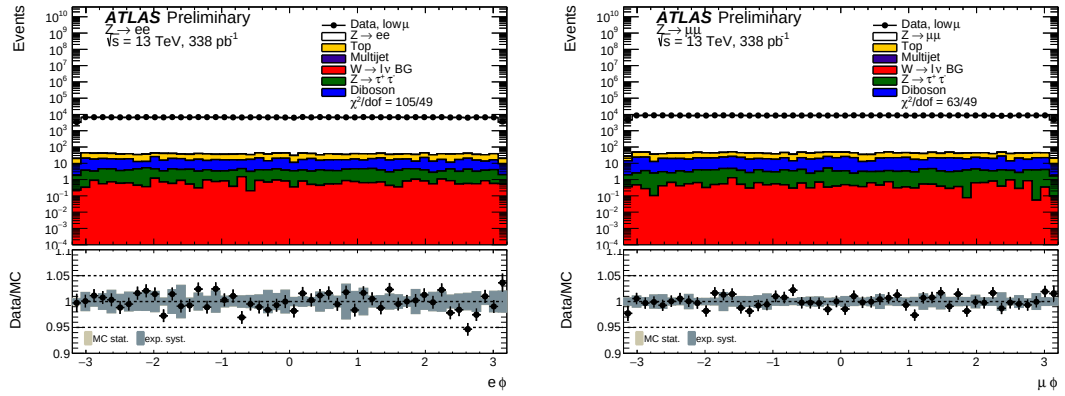


图 3.46 ΣE_T distribution in the $\sqrt{s} = 13$ TeV $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ analyses.


 图 3.47 Dilepton mass distribution in the $\sqrt{s} = 13$ TeV $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ analyses.

 图 3.48 Lepton pseudorapidity distribution in the $\sqrt{s} = 13$ TeV $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ analyses.

 图 3.49 Lepton phi distribution in the $\sqrt{s} = 13$ TeV $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ analyses.

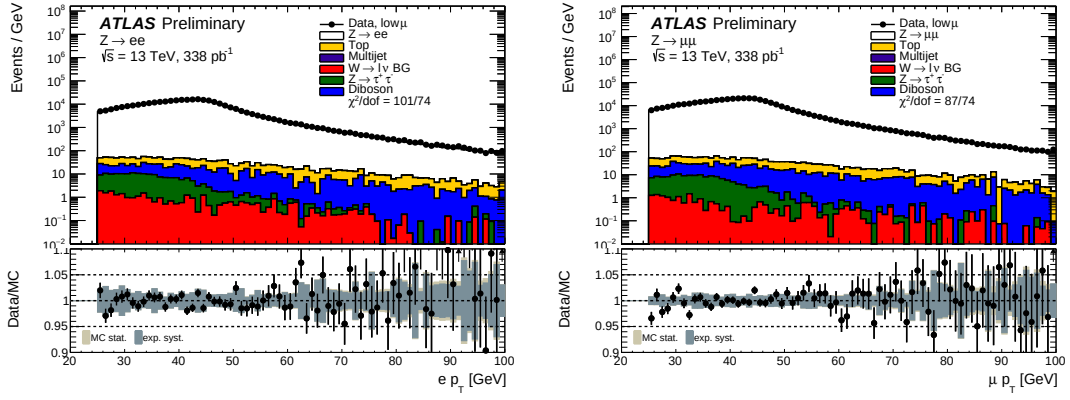


图 3.50 Lepton transverse momentum distribution in the $\sqrt{s} = 13$ TeV $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ analyses.

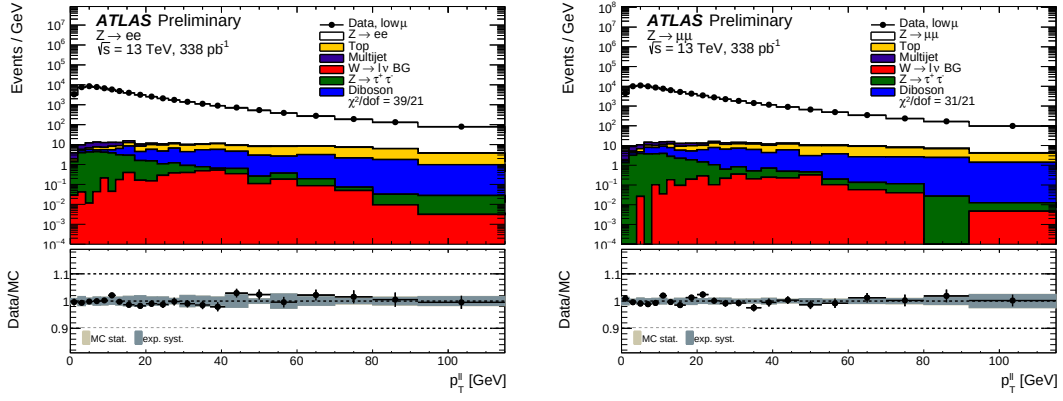


图 3.51 Dilepton pair transverse momentum $p_T^{\ell\ell}$ in the $\sqrt{s} = 13$ TeV $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ analyses.

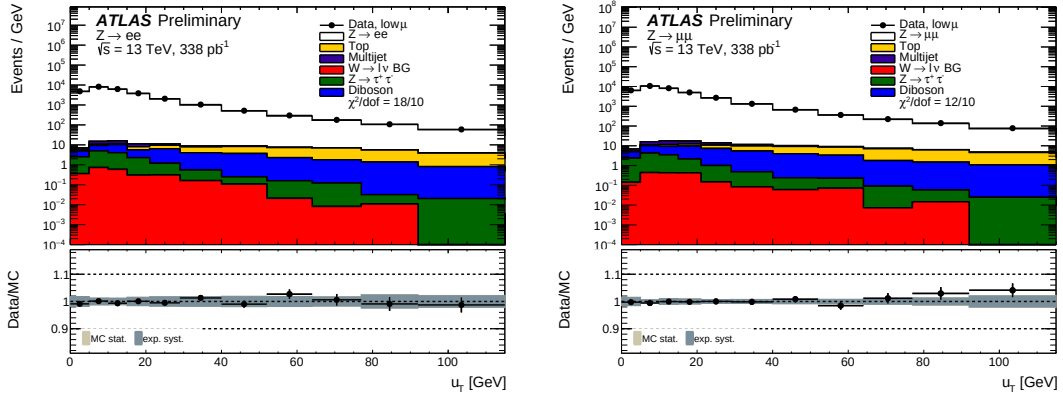


图 3.52 Hadronic recoil u_T distribution in the $\sqrt{s} = 13$ TeV $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ analyses.

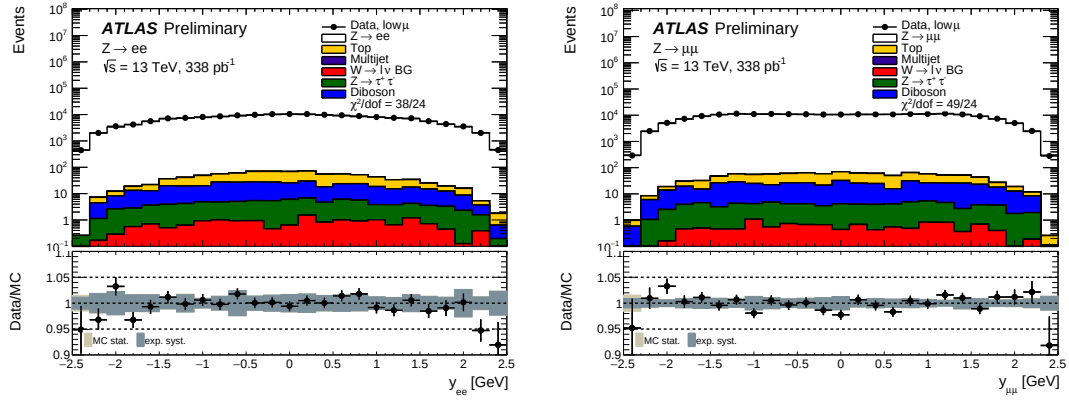


图 3.53 Rapidity of the Z reconstructed from dilepton system in the $\sqrt{s} = 13 \text{ TeV}$ $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ analyses.

3.7.2 $\sqrt{s} = 5$ TeV Control Plots

The plots in the left column show the $Z \rightarrow ee$ channel, whereas the plots in the right column show the $Z \rightarrow \mu\mu$ channel.

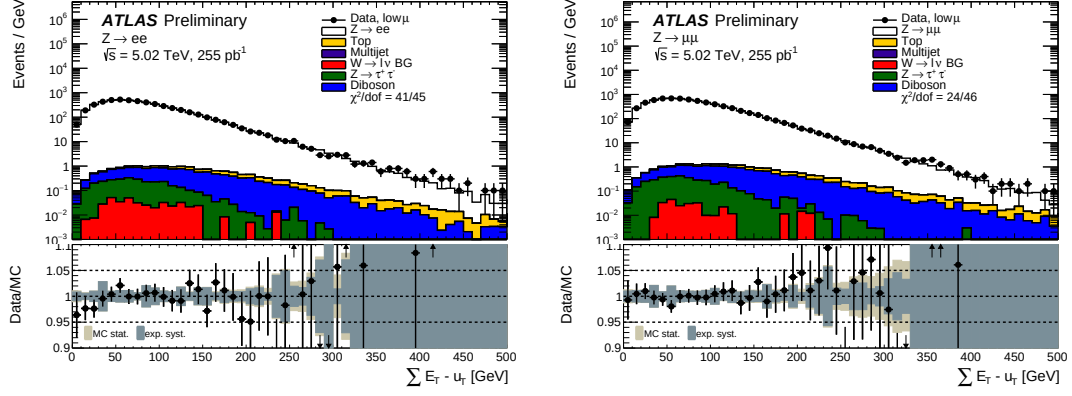


图 3.54 $\sum \bar{E}_T$ distribution in the $\sqrt{s} = 5$ TeV $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ analyses.

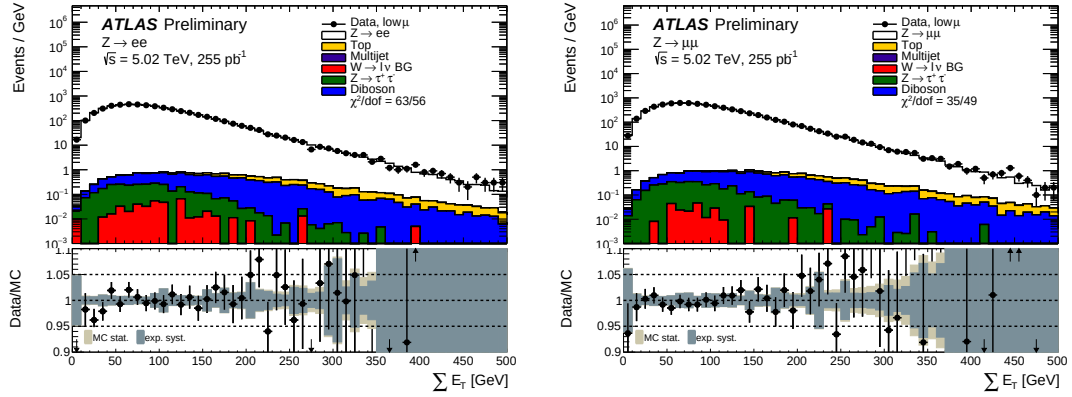
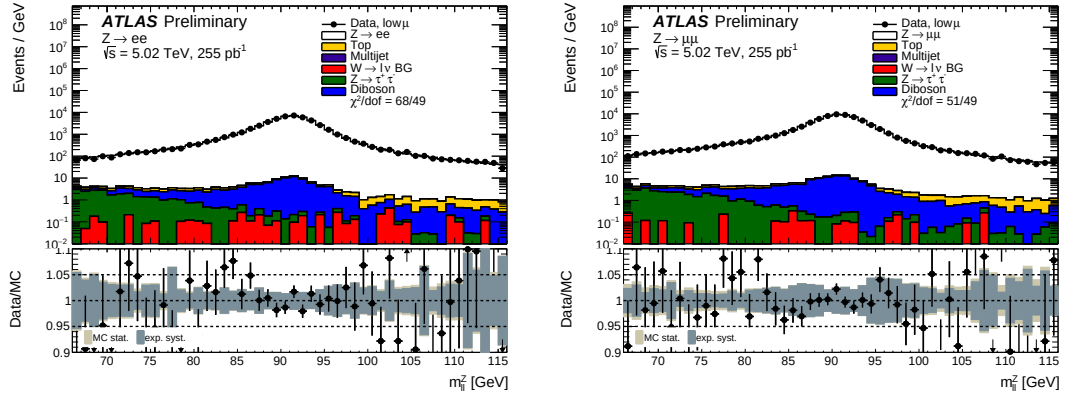
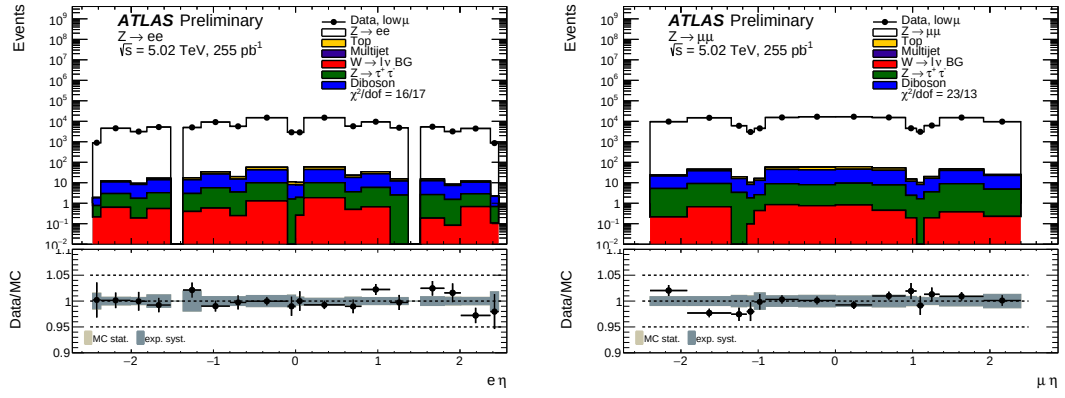
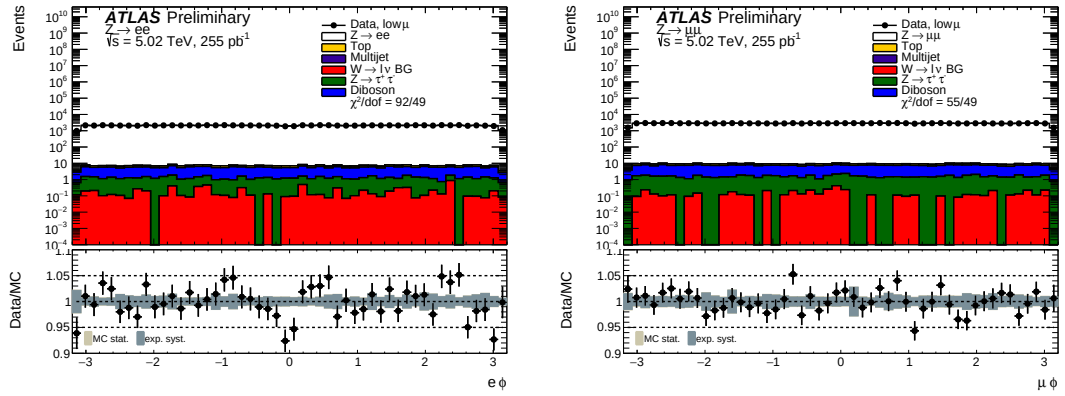


图 3.55 $\sum E_T$ distribution in the $\sqrt{s} = 5$ TeV $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ analyses.


 图 3.56 Dilepton mass distribution in the $\sqrt{s} = 5$ TeV $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ analyses.

 图 3.57 Lepton pseudorapidity distribution in the $\sqrt{s} = 5$ TeV $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ analyses.

 图 3.58 Lepton phi distribution in the $\sqrt{s} = 5$ TeV $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ analyses.

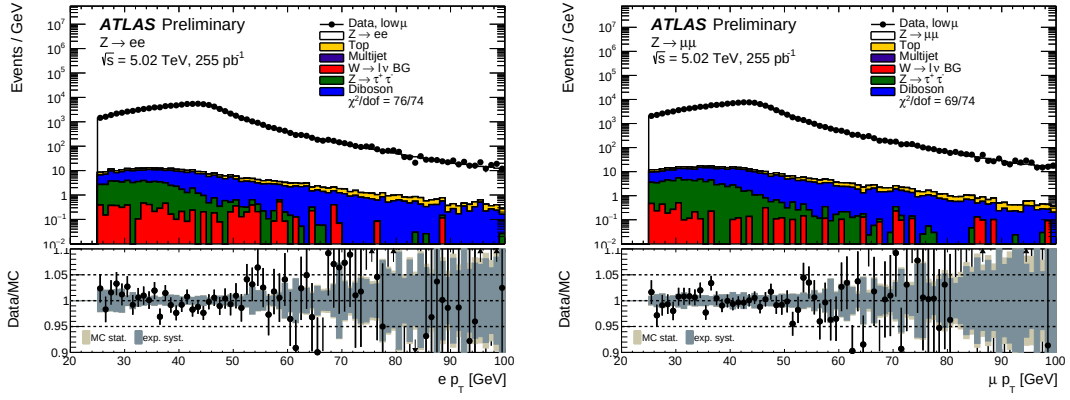


图 3.59 Lepton transverse momentum distribution in the $\sqrt{s} = 5$ TeV $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ analyses.

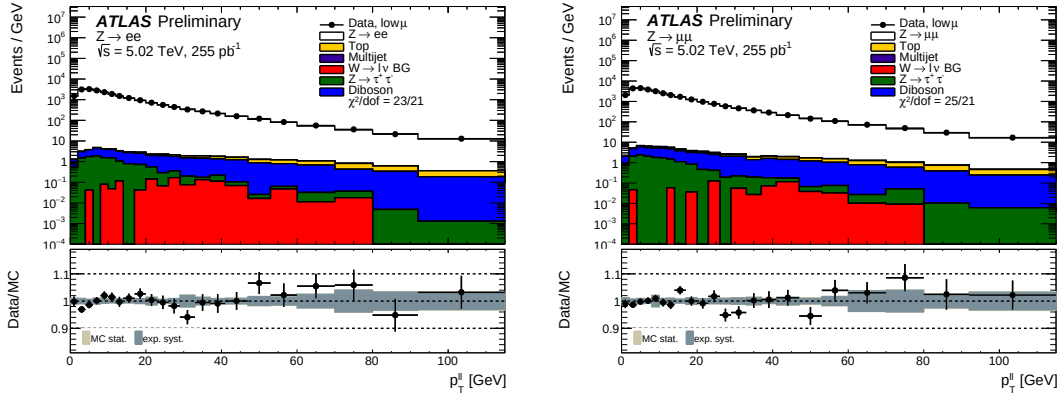


图 3.60 Dilepton pair transverse momentum $p_T^{\ell\ell}$ in the $\sqrt{s} = 5$ TeV $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ analyses.

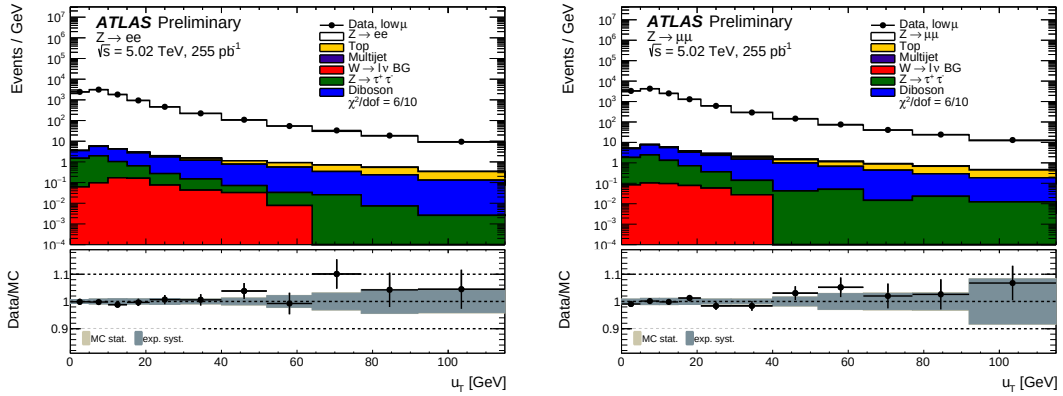


图 3.61 Hadronic recoil u_T distribution in the $\sqrt{s} = 5$ TeV $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ analyses.

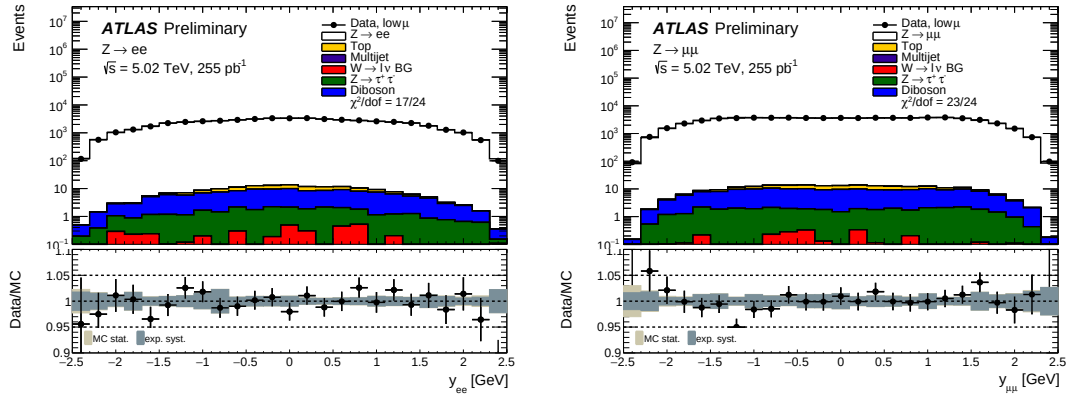


图 3.62 Rapidity of the Z reconstructed from dilepton system in the $\sqrt{s} = 5 \text{ TeV}$ $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ analyses.

第 4 章 Transverse Momenta Of W/Z Bosons In Low Pileup Runs

The measurement of the transverse momenta of W and Z are discussed in this chapter. The measurements are based on the physics objects introduced in Section 3.1. Di-leptons are reconstructed to measure the p_T^Z . The jets decayed from the quark or gluon produced against W are calibrated to measure p_T^W . This chapter is organized as the following: Section 3.2 introduces dedicated physic variables induced in the measurements. Section 4.1 describes the methodology of p_T measurements. The calibration of *hadronic recoil* system, which is the key to measure p_T^W , is discussed in Section 3.4. The estimation of QCD multijets background is illustrated in Section 4.2. Section 4.3 shows the measurement results of p_T^Z and related uncertainties. Section 4.3.5 discusses combination of results of electron and muon channels. Section 4.4 shows comparison of the results to various of predictions.

4.1 Description Of The Measurements

The W-boson differential cross-sections are measured through the u_T , while the Z cross-sections are measured in terms of p_T^{ll} , separately for electron and muon channels. The results are combined between electron and muon channels afterwards.

The measurements are done with a fiducial phase space chosen according to the detector acceptance and to vetoing backgrounds. The fiducial phase space for W cross section measurement is defined by the lepton transverse momentum $p_T^l > 25$ GeV, the missing transverse energy $E_T^{miss} > 25$ GeV, and the transverse mass $m_T > 50$ GeV. And the fiducial phase space for Z events is defined by the transverse momenta of two leptons $p_T^l > 25$ GeV and the invariant mass of the di-lepton pair $66 \text{ GeV} < m_{ll} < 116 \text{ GeV}$.

Backgrounds from top quark and electro-weak processes are estimated with MC samples, the QCD multijets backgrounds are estimated using data-driven method, discussed in Section 4.2.

The kinematics of leptons and had-recoil can be described at different levels regarding the effects of final-state photon radiation. Cross-sections at born level are the physics

parameters of interests to be compared with Standard-Model prediction, which employ the lepton kinematics before quantum electrodynamic final-state-radiation (QED FSR). While the bare-level is defined by leptons after QED FSR. The dress-level is defined by combining bare four-momentum of each lepton with QED FSR photons radiated from the lepton with a cone size of $\Delta R = 0.1$ around the lepton. The results discussed in the paper are at dressed and Born level.

To achieve the p_T -measurement at Born level, the reconstructed level spectrums are "unfolded" using the correlations between reconstructed and truth level information, which is estimated from the Monte Carlo simulations. The application of this approach is discussed in Section 4.3.1.

4.2 QCD Multijets Background Estimation

Two main categories of backgrounds affect single W boson and single Z final states: the electroweak (single and diboson) and top backgrounds, obtained from the appropriate MC samples, and the the so-called multi-jet (MJ) background which can't be reliably simulated and has to be derived from data. Depending on the lepton flavor, the MJ background has significant contributions from real leptons produced in semi-leptonic decays of heavy quarks, pion decays, or photon conversions. Although the multi-jets background process is effectively rejected by the isolation selection and the E_T^{miss} and m_T requirements, it still represents a non-negligible contribution due to the large jet production cross-section, especially in W events. Multijets background contributed up to about 5% of the event yield in previous 7 and 13 TeV W boson measurements in standard, high pile-up running conditions. In Z cases the MJ background is expected to be extremely small because of the Z event selection which requires two opposite-sign, well-identified and isolated leptons and the clean environment of the low- μ dataset.

The data sample discussed in this analysis has a pile-up of $\mu \sim 2$, about a factor of 15–20 smaller than the standard 13 TeV running conditions. Lower pile-up will reduce the MJ background yield for at least two reasons:

- a reduced pile-up contribution to the isolation distributions, improving the dis-

criminating power of the isolation cuts;

- better E_T^{miss} and m_T -resolution, with correspondingly improved discriminating power of the event selection cuts (for W events);

The same methodology is used for the MJ estimation at 5 and 13 TeV. In this chapter, we will discuss the general procedure and the results of the MJ yield extraction and the associated uncertainties for the $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ channels.

The data-driven estimation of the MJ background is based on the so-called ABCD method. In the ABCD method three control regions (CR): B, C, and D are defined inverting or relaxing sequentially two requirements of the definition of good leptons used in the signal region (SR), A, defined in 3.6. These control regions are rich in events produced from background processes with fake leptons, not accurately described by the MC simulation. The key discriminating variable used to define the CR is the isolation variable ($ptvarcone20/p_T$) of the sub-leading lepton. A lepton is defined to be isolated if $ptvarcone20/p_T < 0.1$ and anti-isolated if $ptvarcone20/p_T > 0.1$. In the electron channel, the Electron identification (ID) working point for the sub-leading lepton is also inverted to increase the statistics of the CRs. In regions C and D the sub-leading electrons are required to pass the Loose ID operating point but to fail the Medium ID requirement, and the p_T^e requirement is relaxed to 20 GeV. In the muon channel, the opposite sign of the dimuon is inverted to same sign in the CR.

In the $Z \rightarrow ee$ channel the four regions are defined as the following (note that the leading electron is required to pass the Medium ID working point in each region):

- A (SR): opposite sign, both electrons isolated, both electron pass Medium ID, both $p_T^e > 25$ GeV.
- B: same as A but the sub-leading electron is anti-isolated.
- C: no lepton sign requirement, leading electron isolation requirement removed, sub-leading electron satisfies the Loose not Medium ID, sub-leading electron is isolated, both electron p_T requirement is relaxed to $p_T^e > 20$ GeV.
- D: same as C but the sub-leading electron is anti-isolated.

In the $Z \rightarrow ee$ channel, it was found that the CRs, defined as above, were still very signal-dominated to extract a MJ estimation. Therefore to reduce this signal con-

tamination, the Z mass peak region was excluded for the extraction. Only events with an electron invariant mass in the range between [66, 81] GeV and [101, 116] GeV are considered for the MJ extraction in all the regions A - D; the result of the procedure is then scaled to account for the region of the Z resonance. The scale only works under assumption that MJ background is flat along the invariant mass of dilepton $m_{\ell\ell}$. Due to the small dataset of low pileup run, it is impossible to validate in the data.

Figure 4.1 shows, for data and for all the MC samples, the isolation spectra of the sub-leading lepton in each of the four regions for the $Z \rightarrow ee$ channel for data and signal plus background MCs at 5 and 13 TeV, respectively. Each region is labeled and corresponds to the above list. Similar plots but for the $Z \rightarrow \mu\mu$ channel are shown in Figure 4.2.

Multi-jet events in the B , C and D regions ($N_{MJ}^B, N_{MJ}^C, N_{MJ}^D$) are estimated by subtracting from the data (separately for each region) the contribution from prompt lepton component described with the MC events. Then the total MJ yield is linearly extrapolated to the signal region (region A) using the formula: $N_{MJ}^{SR} = N_{MJ}^B \times \frac{N_{MJ}^C}{N_{MJ}^D}$. In the $Z \rightarrow ee$ channel where the Z mass peak is excluded, N_{MJ}^{SR} is multiplied by 50./30. to scale the MJ yield to the full $m_{\ell\ell}$ range of [66, 116] GeV.

4.2.1 MJ Background Yield Extraction

Due to the low pile-up data and $Z \rightarrow \ell\ell$ event selection, the expected number of MJ events is small, but measurable. The p_T -boson integrated MJ yield estimate using the ABCD method in the SR as well as the number of (data-MC) events in the B, C and D regions is shown in Table 4.1 for $Z \rightarrow ee$ channel, and Table 4.2 for $Z \rightarrow \mu\mu$ channel. More information such as the ratio of MJ events to the number of data events, N_{MJ}/N_{DATA} , which helps to explain the expected percentage of MJ events in each region, and the signal contamination expected from MC ($MC_{sig}/MC_{sig+bkg}$). The error is statistics only, taken as the $\sqrt{N}$ in each bin, and then the final error for the MJ estimate in the SR is calculated via standard error propagation.

In the $Z \rightarrow ee$ channel, it was difficult to find a CR that had a very low signal contamination in both the isolated (C) and anti-isolated (D) regions, because of the low statistics and minimal expected MJ events. While in the $Z \rightarrow \mu\mu$ channel, the control

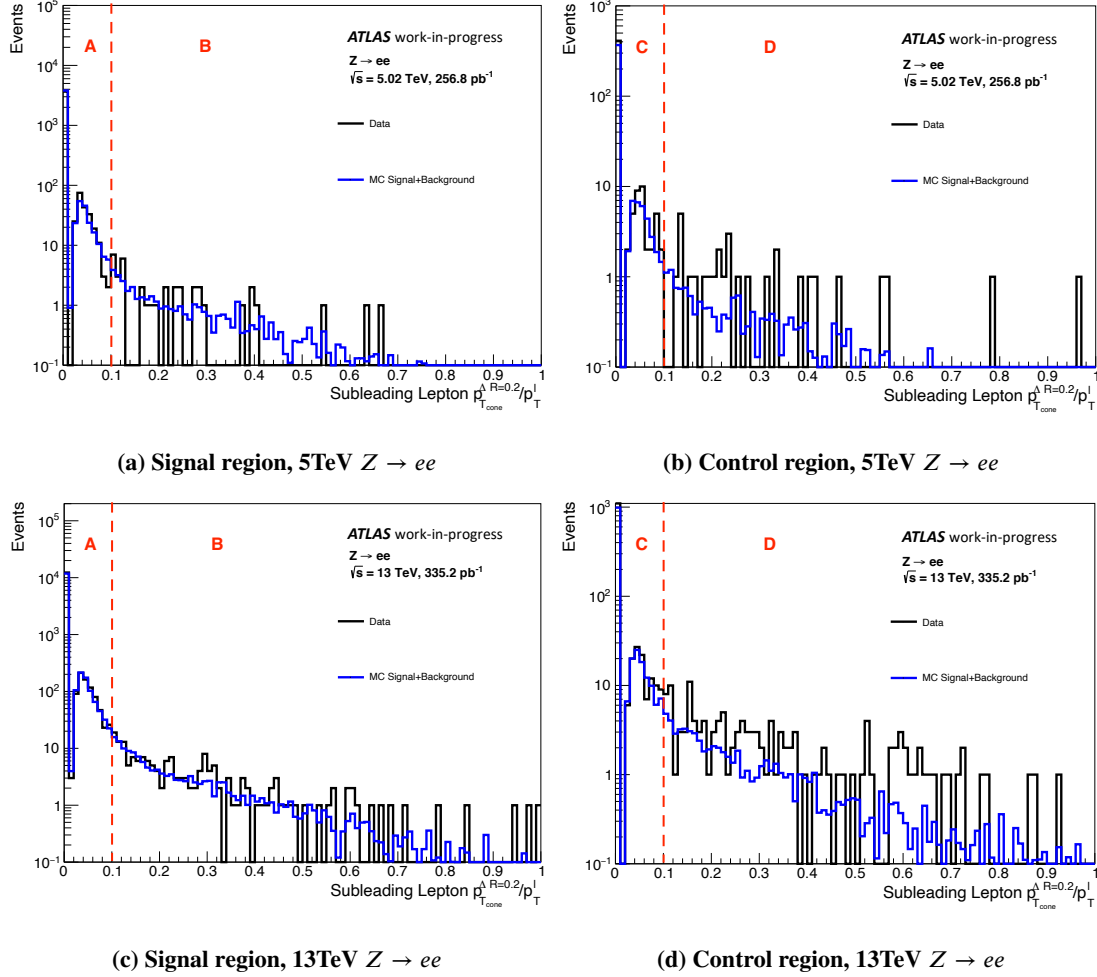


图 4.1 Isolation variable $p_T^{cone \Delta R=0.2}/p_T^e$ for the $Z \rightarrow ee$ channel for the sub-leading electron candidate in Data (black) and MC (blue) at 5 TeV (top) and 13 TeV (bottom). The estimated number of MJ events in the full phase space of the SR is calculated by subtracting the MC events from the Data events in each region to find N_{MJ} , and calculating

$$N_{MJ}^{SR} = N_{MJ}^B \times \frac{N_{MJ}^C}{N_{MJ}^D}.$$

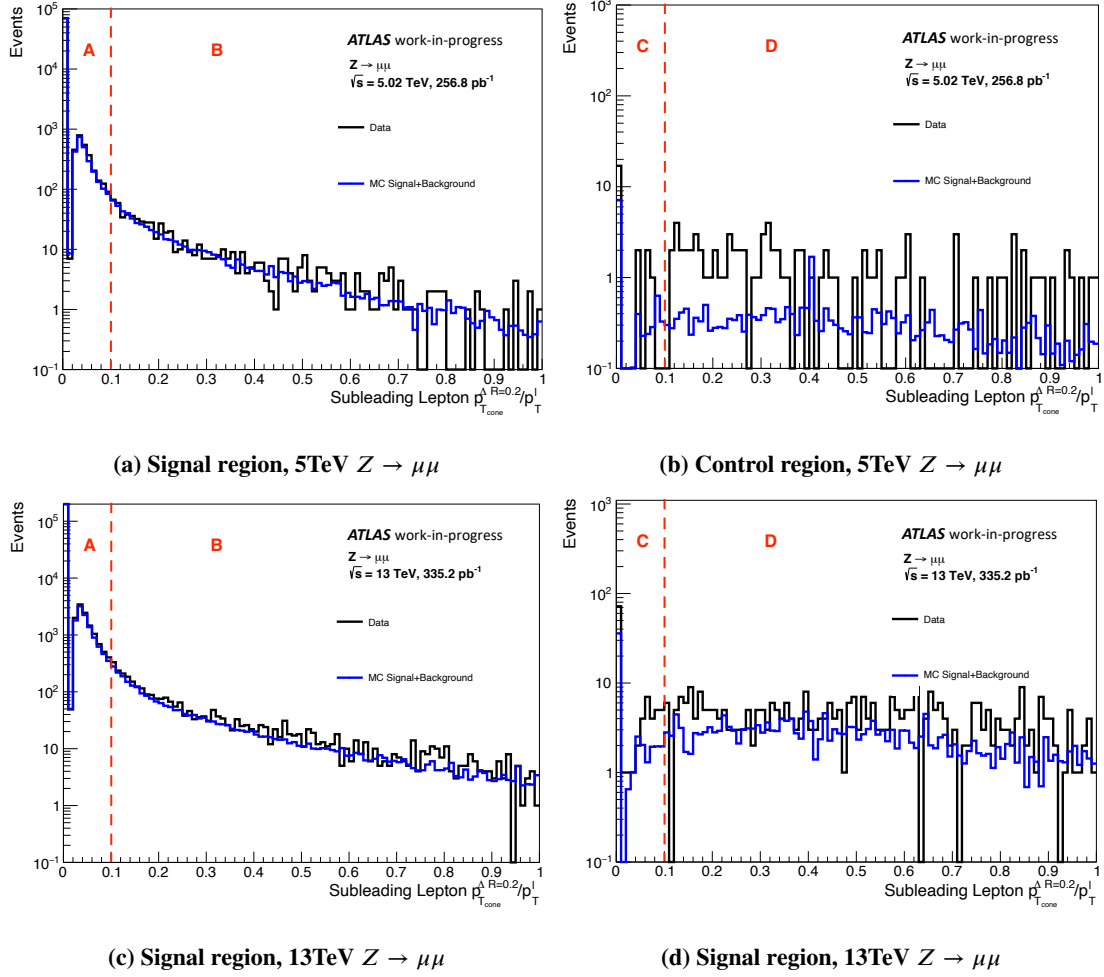


图 4.2 Isolation variable $p_T^{cone \Delta R=0.2}/p_T^\mu$ for the $Z \rightarrow \mu\mu$ channel for the sub-leading muon candidate in Data (black) and MC (blue) at 5 TeV (top) and 13 TeV (bottom). The estimated number of MJ events in the full phase space of the SR is calculated by subtracting the MC events from the Data events in each region to find N_{MJ} , and calculating

$$N_{MJ}^{SR} = N_{MJ}^B \times \frac{N_{MJ}^C}{N_{MJ}^D}.$$

$Z \rightarrow ee$ at 5 TeV	SR	B	C	D
N_{MJ}	0.0^{+23}_{-28}	$0.0^{+6.2}_{-6.5}$	48 ± 21	12.7 ± 5.5
N_{MJ}/N_{Data}	0.0 ± 0.0063	0.0 ± 0.17	0.106 ± 0.048	0.43 ± 0.20
signal contamination	0.9833 ± 0.0038	0.948 ± 0.047	0.973 ± 0.013	0.702 ± 0.059
$Z \rightarrow ee$ at 13 TeV	SR	B	C	D
N_{MJ}	66 ± 41	24 ± 14	192 ± 37	70 ± 12
N_{MJ}/N_{Data}	0.0050 ± 0.0032	0.136 ± 0.078	0.149 ± 0.029	0.492 ± 0.095
signal contamination	0.9661 ± 0.0029	0.867 ± 0.027	0.9577 ± 0.0098	0.575 ± 0.039

表 4.1 Multi-jet events estimated in the SR with the ABCD method, as well as the number of (data - MC) events in the B , C and D regions, MJ event fraction, and MC signal contamination in each of the four regions for $Z \rightarrow ee$ selection at 5 and 13 TeV. Note that these are the numbers obtained in the off peak region, so the nominal N_{MJ} estimate in SR must be multiplied by 50/30. to account for the removed Z mass peak region as explained in section 4.2.

$Z \rightarrow \mu\mu$ at 5 TeV	SR	B	C	D
N_{MJ}	15.9 ± 7.9	97 ± 28	12.6 ± 4.7	77 ± 11
N_{MJ}/N_{Data}	0.00022 ± 0.00011	0.128 ± 0.038	0.57 ± 0.25	0.64 ± 0.11
signal contamination	0.9962 ± 0.0012	0.924 ± 0.013	0.036 ± 0.080	0.029 ± 0.068
$Z \rightarrow \mu\mu$ at 13 TeV	SR	B	C	D
N_{MJ}	177 ± 44	725 ± 60	53 ± 11	216 ± 25
N_{MJ}/N_{Data}	0.00079 ± 0.00020	0.212 ± 0.018	0.52 ± 0.12	0.384 ± 0.047
signal contamination	0.98901 ± 0.00068	0.8525 ± 0.0064	0.02 ± 0.103	0.026 ± 0.030

表 4.2 Multi-jet events estimated in the SR with the ABCD method, as well as the number of (data - MC) events in the B , C and D regions, MJ event fraction, and MC signal contamination in each of the four regions for $Z \rightarrow \mu\mu$ selection at 5 and 13 TeV.

regions C and D have low signal contamination regardless of the isolation requirement, and regions A and B are almost entirely signal MC-dominated. In the $Z \rightarrow ee$ channel at 5 TeV the final MJ event estimate in SR was found to be consistent with 0, because the subtraction of data to MC in control region B is consistent with 0. To estimate an upper limit of MJ yield in this channel, the full size of the statistical uncertainty of the yield in this region is taken as the central value ($N_{MJ}^B = 6.2_{-6.5}^{+0}$). The final nominal MJ event estimates in SR for each channel are summarised in Table 4.3

Channel	Number of selected data	Number of expected Signal	MJ yield
$Z \rightarrow \mu\mu$ at 5 TeV	70447	69804.73 ± 60.34	15.9 ± 7.9
$Z \rightarrow \mu\mu$ at 13 TeV	214035	208006.82 ± 101.12	177 ± 44
$Z \rightarrow ee$ at 5 TeV	51772	51305.74 ± 37.43	0_{-0}^{+87}
$Z \rightarrow ee$ at 13 TeV	165027	158216.41 ± 86.83	110 ± 68

表 4.3 Summary of estimated number of MJ events in the SR for each Z decay channel. The quoted uncertainty on the MJ estimate is only statistical

4.2.2 MJ Shape

Given the good agreement between data and MC predictions in regions A and B that is seen in figs. 4.2 and 4.1, the total MJ event count is small (see table 4.3). Because of this, the total number of MJ events are estimated by integrating over the full analysis selection and distributing throughout the final observables ($p_T^{\ell\ell}$ or u_T) following the shape obtained from the control region C.

All events in the CRs (regions C and D) are used to extract a shape to distribute the number of expected MJ events throughout the $p_T^{\ell\ell}$ and u_T distributions separately. To suppress statistical fluctuations, the $p_T^{\ell\ell}$ and u_T distributions are fitted to a Landau function (Figure 4.3 and 4.4), which peaks at $p_T \approx 10$ GeV. The resulting fitted distributions are then normalised to the inclusive number of MJ events for each channel listed on Table 4.3 and included in the nominal unfolding procedure.

The uncertainty on the yield of the MJ background is propagated through the extrapolation $Unc_{SR} = Unc_B \times \frac{Unc_C}{Unc_D}$. The uncertainty extrapolation is done for the integrated MJ yield in signal and control regions, and the shape in $p_T^{\ell\ell}$ and in u_T is taken

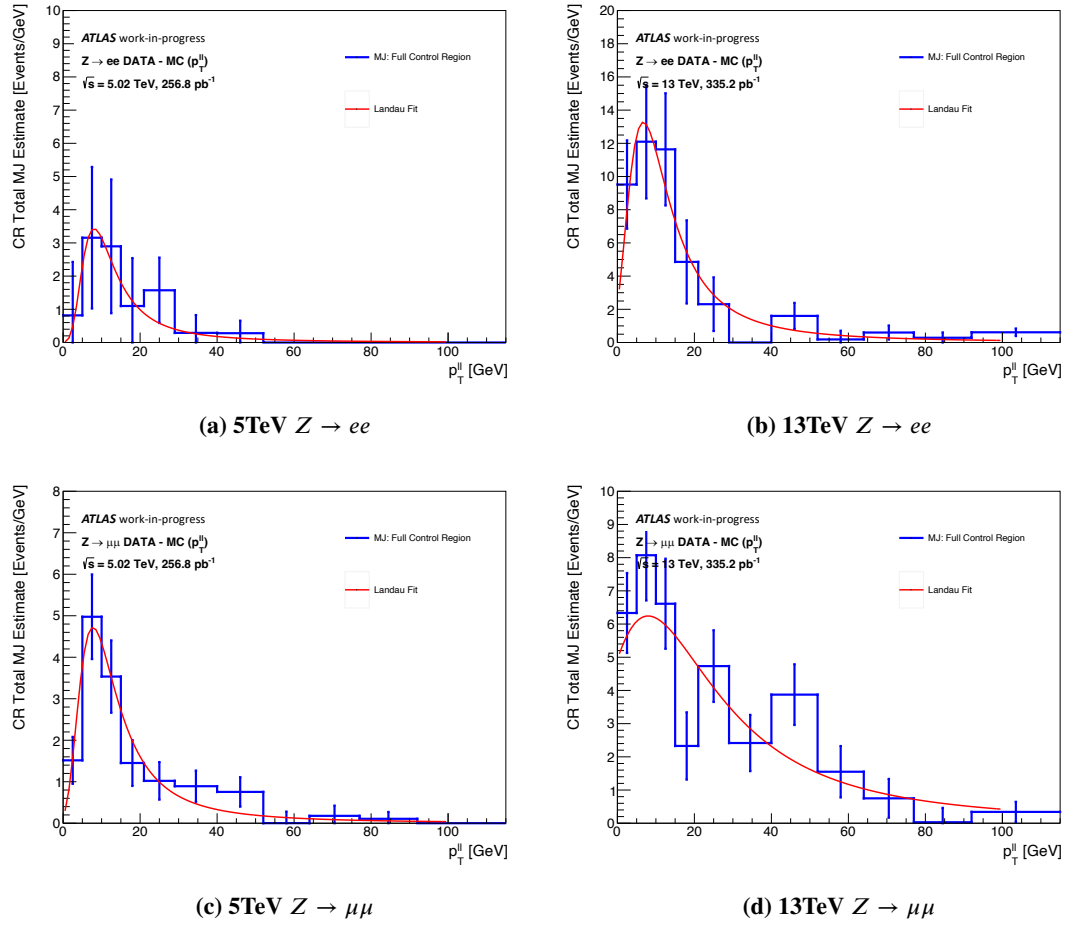


图 4.3 Multi-jet shape fit in the $Z \rightarrow ee$ (top) and $Z \rightarrow \mu\mu$ (bottom) control regions for $p_T^{\ell\ell}$ at 5 (left) and 13 (right) TeV.

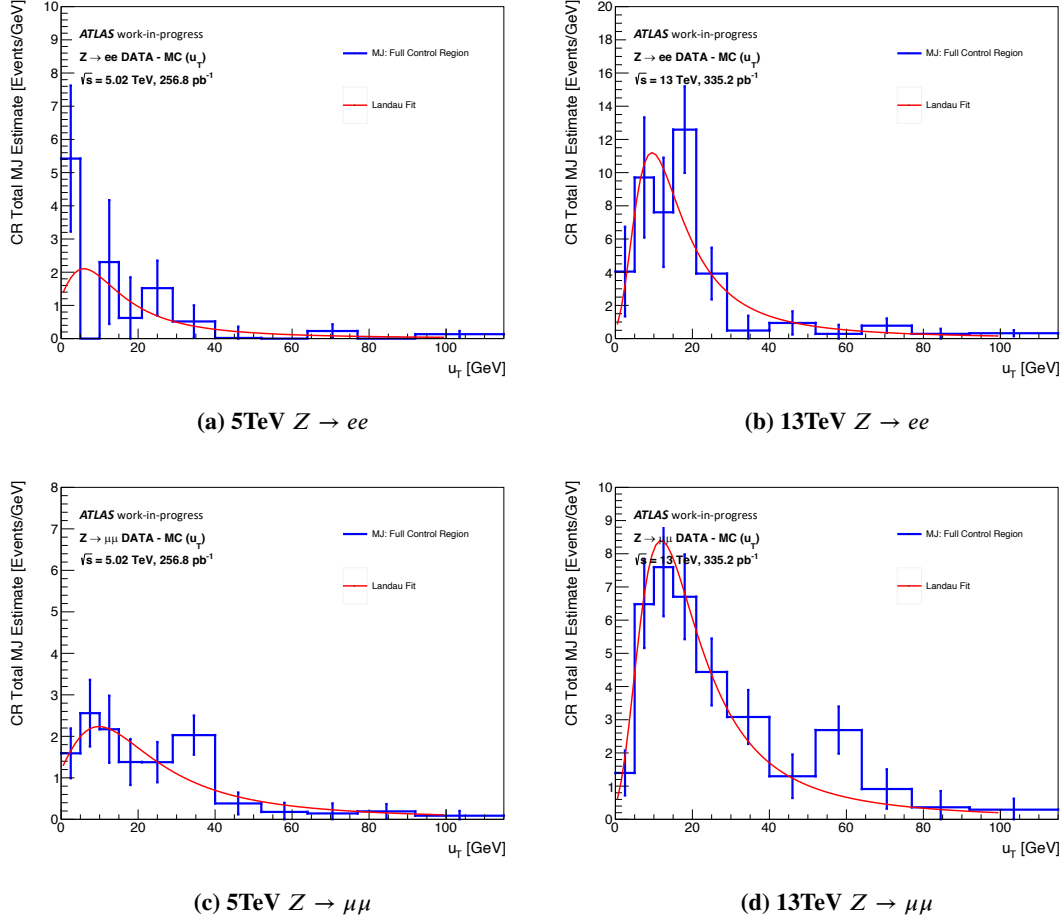


图 4.4 Multi-jet shape fit in the $Z \rightarrow ee$ (top) and $Z \rightarrow \mu\mu$ (bottom) control regions for u_T at 5 (left) and 13 (right) TeV.

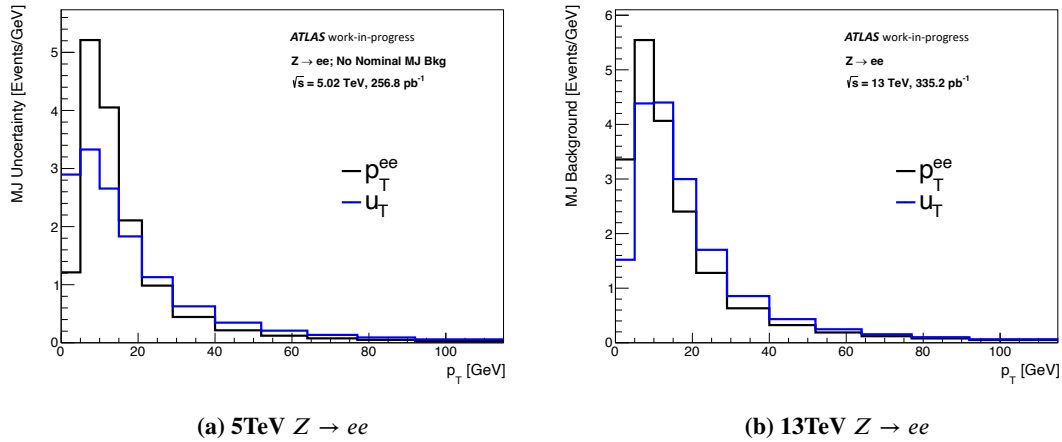


图 4.5 Multi-jet distributions for $Z \rightarrow ee$ at 5 (left) and 13 (right) TeV.

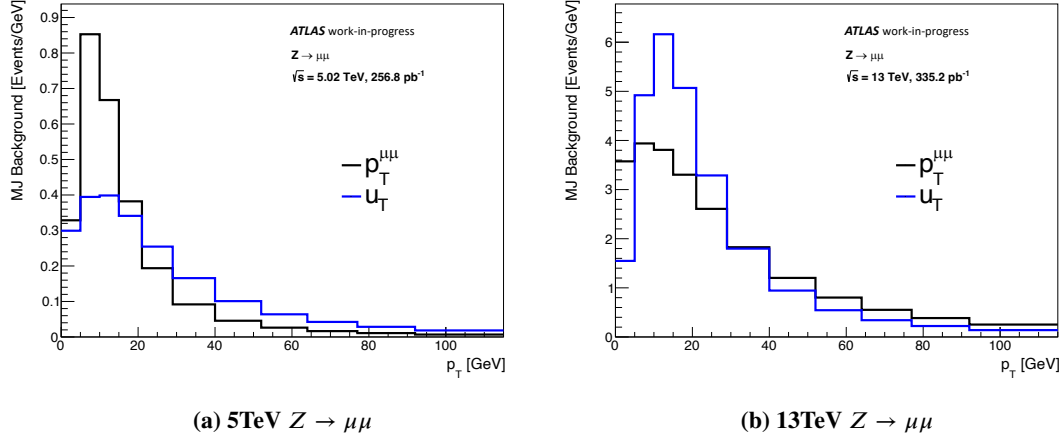


图 4.6 Multi-jet distributions for $Z \rightarrow \mu\mu$ at 5 (left) and 13 (right) TeV.

from the fit in control region and the normalize to the yield. This is because of the high statistic uncertainty in all B,C and D regions that an binned extrapolation is not possible. For the $Z \rightarrow ee$ channel at 5 TeV where there are no nominal MJ events, no nominal MJ background is included (the MJ background is consistent with zero), but the shape fitting method is still needed to provide the distribution when the MJ background yield is varied by its positive uncertainty.

Figure 4.3 shows the MJ $p_T^{\ell\ell}$ spectra and corresponding Landau fit in the control region for the $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ channels. Figure 4.4 shows the same MJ spectra but for u_T . The integrated event numbers are the same in each channel for $p_T^{\ell\ell}$ and u_T because they are measurements of the same MJ events.

Figures 4.5 ($Z \rightarrow \mu\mu$) and 4.6 ($Z \rightarrow ee$) show the shape of the nominal MJ distribution for both Z decay channels in both the $p_T^{\ell\ell}$ and u_T distributions at 5 and 13 TeV. For $Z \rightarrow ee$ at 5 TeV, the distribution is the upper limit on the number of MJ events since the nominal estimate is zero events.

The QCD multijets backgrounds are estimated using ABCD data-driven method in the $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ channels, with estimated background fractions below 0.1. Data to simulation comparisons are in good agreement.

4.3 Results Of Transverse Momentum Measurement

In this section we present the p_T^Z cross section measurement. Section 4.3.3 describes the statistical and experimental systematic uncertainties at reconstructed level. It is observed that the p_T^Z modeling in POWHEG+PYTHIA8 simulation does not agree well with the data. Thus a data-driven method is used to correct for p_T^Z distribution at truth level. The correction and associated uncertainties are discussed in Section 4.3.2. Then the p_T^Z cross section measurements, which are proceeded using Bayesian unfolding method, are discussed in Section 4.3.4, for electron and muon decay channels separately. The combination of p_T^Z cross section measurement in electron and muon decay channels are shown in Section refssec:comb.

4.3.1 Bayesian Unfolding

The p_T^W and p_T^Z are measured from the kinematics of final state particles with each sub-detectors of ATLAS. Due to the finite resolution of the sensors of each detector, the p_T distributions are distorted. To retrieve the "truth" information which corresponding to the best knowledge we could achieve, the response of detector are simulated with a huge amount of work from performance group. Then the reconstructed level measurements are "unfolded" using Bayes' Theorem to estimated the truth distributions. ^[60]

4.3.1.1 Probability And Bayes' Theorem

The degree of randomness can be quantified with the concept of probability. The mathematical theory of probability has a history dating back at least to the 17th century, and several different definitions of probability have been developed. Consider a set S called the sample space consisting of a certain number of elements, to each subset A of S one assigns a real number $P(A)$ called a probability, defined by the following three axioms:

- For every subset A in S , $P(A) \geq 0$.
- For any two subsets A and B that are disjoint (i.e. mutually exclusive, $A \cap B = \emptyset$) the probability assigned to the union of A and B is the sum of the two corresponding probabilities, $P(A \cup B) = P(A) + P(B)$.
- The probability assigned to the sample space is one, $P(S) = 1$.

These axioms and definitions imply the following theorems whose validity is rather obvious.

- $p\{\bar{A}\} = 1 - P\{A\}, P\{0\} = 0$
- $P\{A \cup B\} = P\{A\} + P\{B\} - P\{A \cap B\}$
- if $A \in B$, then $P\{A\} \geq P\{B\}$

We introduce the definition of *conditional probability*, $P\{A|B\}$, as probability of the event A happens under the condition that B applies. It is given by:

$$P\{A|B\} = \frac{P\{A \cap B\}}{P\{B\}}, P\{B\} \neq 0 \quad (4.1)$$

The notation $A|B$ expresses that B is considered as fixed, while A is the random event to which the probability refers. An concept *independent* is defined that if the probability that both A and B happens equals to the product of the probability for each happens $P\{A \cap B\} = P\{A\} \times P\{B\}$, then A and B are *independent*.

From 4.1, we can exchange A and B and thus $P\{A|B\}P\{B\} = P\{A \cap B\} = P\{B|A\}P\{A\}$ and we obtain the famous Bayes' theorem 4.2:

$$P\{A|B\}P\{B\} = P\{B|A\}P\{A\} \quad (4.2)$$

4.3.1.2 Bayesian iterative unfolding

Bayes' theorem offers a natural way to unfold experimental distributions in order to get the best estimates of the true ones. The unfolding procedure consists of correcting detector effects such as the finite detector acceptance, the reconstruction efficiency, and the finite detector resolution, from a measured observable in order to determine the true underlying distribution. The principle is explained in the equation 4.3

$$P(\text{Truth}_i | \text{Reco}_j) = \frac{P(\text{Reco}_j | \text{Truth}_i) P_0(C_i)}{\sum_{l=1}^{n_{\text{truth}}} P(\text{Reco}_j | \text{Truth}_l) P_0(\text{Truth}_l)} \quad (4.3)$$

Where *reco* and *truth* refers to the truth level and reconstructed level measurements. The conditional probability to observe a reconstructed value in the bin i given a truth value in the bin j is defined by the response matrix R_{ij} . It is built from the migration

matrix M_{ij} , corrected for efficiency:

$$R_{i,j} = M_{i,j} \cdot \epsilon_j \quad (4.4)$$

The efficiency in a given $p_T^{\text{true},V}$ bin j , ϵ_j , is defined as :

$$\epsilon_j \equiv \frac{N_j^{\text{reco\&gen}}}{N_j^{\text{gen}}} = \frac{\sum_i N_{ij}}{N_j^{\text{gen}}} \quad (4.5)$$

where $N_j^{\text{reco\&gen}}$ is the number of events in a bin j (here $p_T^{\text{true},V}$ bin j) passing both reconstructed-level and fiducial volume selection cuts ($T\&R$). N_{ij} is the number of events in u_T bin i and $p_T^{\text{true},V}$ bin j . The weights applied to these events comprise both truth (*e.g.* polarisation) and reconstructed level weights (*e.g.* lepton scale factors). Figure 4.7a shows an example of the purity ϵ_j .

The migration matrix can be determined from simulation by filling a two-dimensional histogram for all selected events passing Truth and Reco cuts, normalized to unity in each truth bin j :

$$M_{ij} = \frac{N_{ij}}{\sum_k N_{kj}}. \quad (4.6)$$

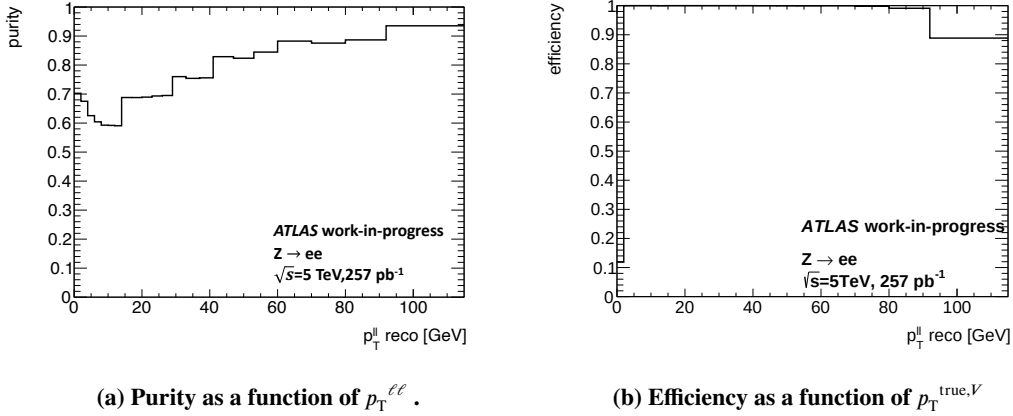


图 4.7 Example of reconstruction purity and efficiency corrections for the $Z \rightarrow ee$ channel at 5 TeV.

Examples of the migration matrix are shown in 4.8 for simulated $Z \rightarrow ee$ events at 5 TeV. It should be noted that these matrices are non-diagonal, not only because of the resolution in $p_T^{\ell\ell}$ and u_T , but also because the detector response in $p_T^{\ell\ell}$ and u_T , i.e. $\langle p_T^{\ell\ell} / p_T^{\text{true},V} \rangle$ and $\langle u_T / p_T^{\text{true},V} \rangle$, is lower than 1 and moreover dependent on

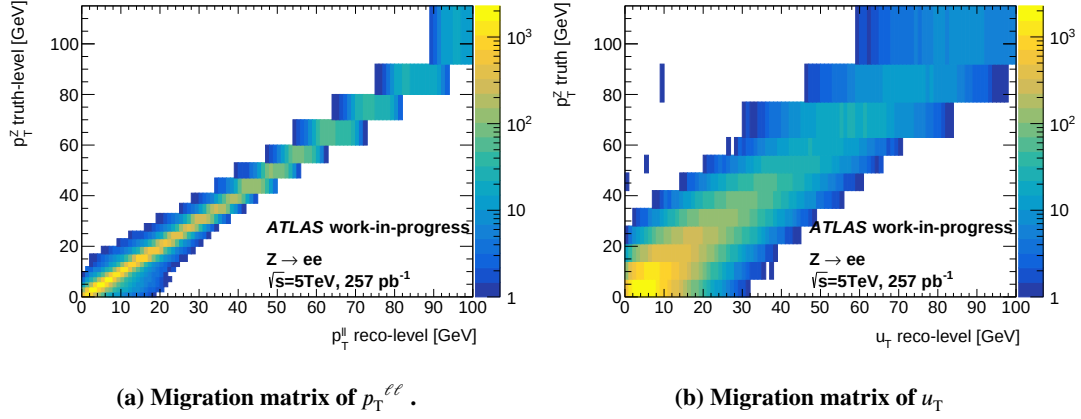


图 4.8 Example of migration matrices for $p_T^{\ell\ell}$ and u_T for the $Z \rightarrow ee$ channel at 5 TeV.

$p_T^{\text{true},V}$. This is reflected in the shape of the dominant bins in the matrices, which is not strictly linear, especially at low $p_T^{\text{true},V}$.

The purity p_i in a given $p_T^{\ell\ell}$ bin i , is defined as :

$$p_i \equiv \frac{N_i^{\text{reco\&gen}}}{N_i^{\text{reco}}} = \frac{\sum_j N_{ij}}{N_i^{\text{reco}}}, \quad (4.7)$$

where N_i^{reco} is the number of reconstructed events in $p_T^{\ell\ell}$ bin i , required only to pass the reconstructed-level selection cuts. 4.7a shows an example of the purity estimate. It should be noted that the purity is defined with respect to the full fiducial volume, not with respect to the correct truth bin. Otherwise, the purity would be much smaller.

In symbolic notation, it can be written that:

$$D_i = \sum_j R_{ij} T_j + B_i \quad (4.8)$$

where T is the physics true distribution obtained after fiducial cuts; R_{ij} is the response matrix with resolution effects estimated using finite-size Monte Carlo samples. D and B are the observed distribution and the sum of all background contributions respectively, obtained after reconstructed-level cuts.

The unfolding procedure determines the best estimate of the underlying distribution following:

$$\tilde{U}_j = \sum_i U_{ij} (D_i - B_i) * p_i \quad (4.9)$$

where $\tilde{U}_j$ is the unfolded spectrum, which estimates the underlying distribution T ; and U_{ij} symbolically represents the unfolding transformation, which in the simplest case is

just the inverse of the response matrix R_{ij} . The background-subtracted data distribution $D_i - B_i$ is multiplied by the purity p_i to account for the reconstructed events not matched with a truth definition. The unfolding can be performed through the following steps:

- choose the initial distribution of $P(\text{Truth})$ from the best knowledge of the process under study, and hence the initial expected distribution p_0 , in the low- μ , analysis, it is the p_T^Z distribution simulated from POWHEG+PYTHIA8 generator.
- calculate the first iterative distribution p_1 ;
- replace the p_0 distribution with p_1 . Repeat the Estimation to get the next iteration distribution p_2 .
- calculate the overall uncertainty $\sqrt{\sigma^2(\text{stat.}) + \sigma^2(\text{sys.}) + \sigma^2(\text{unfoldingunc.})}$, the best iterative number is achieved with the minimization of the overall uncertainty. Typically, the statistic uncertainty increases with number of iterations and the unfolding uncertainty decreases with number of iterations.

The unfolding matrix U_{ij} is determined in this analysis using the iterative Bayesian regularized unfolding approach, described in^[60,61]. Technically, a coded implementation of the D'Agostini iterative scheme is available in RooUnfold using the *RooUnfoldBayes* class. A number of iterations has to be chosen for the implementation of the iterative solution. This number is optimized to minimize the total uncertainty and specifically ensure a small uncertainty related to possible biases induced by the unfolding.

4.3.2 p_T Correction And Uncertainty

The initial agreement between the detector-level transverse momentum distributions in data and MC is found to be not fully satisfactory, i.e. the difference is found to be significantly larger than the experimental sensitivity especially at 13 TeV. It was found that starting the unfolding from this non-optimal initial distribution and considering the full initial data/MC discrepancy as source of unfolding uncertainty leads to not optimal results.

To optimize the analysis results, the MC simulation is reweighted by default in $p_T^{\text{true},V}$ to guarantee the best possible data to MC agreement on the reconstructed u_T (or $p_T^{\ell\ell}$) distributions for W (and Z) analyses. This procedure ensures that the unfold-

ing result is unbiased, and is referred to as the p_T correction. The uncertainties will be discussed in this sections.

For the Z analyses, the agreement between data and simulation is optimized at detector level for the $p_T^{\ell\ell}$ and u_T distribution by minimizing the following χ^2 :

$$\chi^2 = \sum_{ij} \Delta_i^T C_{ij}^{-1} \Delta_j, \Delta_i = (D_i - B_i) - \sum_j R_{ij} \times (w_T(p_T^Z))_j \quad (4.10)$$

Here C_{ij}^{-1} denotes the total covariance matrix, including statistical and systematic uncertainties on the observed and simulated $p_T^{\ell\ell}$ and u_T distributions; Δ is the difference between the background-subtracted data distribution, $(D - B)$, and the corresponding reconstruction-level simulated distribution obtained from the product between a generator-level weighting function and the response matrix, $R(w_T(p_T^Z))$. The weighting function, $w_T(p_T^Z)$, evaluated in each truth bin j , modifies the generated Z -boson p_T distribution in the MC sample used to determine the response matrix for events passing both reconstructed-level and truth selection cuts. The parameters of the $w_T(p_T^Z)$ weighting function are the degrees of freedom in the minimization procedure. A satisfactory agreement is obtained using

$$(w_T(p_T^Z))_j = N_j \left[\left(1 + a p_{T,j}^Z + b p_{T,j}^{Z^2} \right) * \left(1 - c + c * r_{\text{NNPDF/CT10}}(p_{T,j}^Z) \right) \right] \quad (4.11)$$

where $r_{\text{NNPDF/CT10}}(p_T^Z)$ represents the ratio between predictions obtained with NNPDF3.0 and CT10NLO in the full phase space, and the additional terms provide more flexibility to the fit. The reweighting functions are optimized separately for each process and each centre-of-mass energy. They are derived over the range $p_T = 0 - 100 \text{ GeV}$ and the value of the correction is frozen at $p_T^Z = 100 \text{ GeV}$ for any larger p_T . Separate reweightings are derived for the $p_T^{\ell\ell}$ and u_T distributions. Figure 4.9 show the resulting best reweighting functions at $\sqrt{s} = 13 \text{ TeV}$ and 5 TeV . For the u_T measurement, the reweighting function is obtained from a simultaneous fit to the electron and muon channels, while the $p_T^{\ell\ell}$ measurement keeps the averaged reweighting function. The general consistency between the reweighting functions obtained for the u_T and $p_T^{\ell\ell}$ distributions, at both center-of-mass energy, indicates that this method catches genuine physics effects. At

the same time, it's clear that especially at $\sqrt{s} = 13$ TeV the $p_T^{\ell\ell}$ reweighting is able to catch a feature at smallest p_T that is lost in the u_T resolution. Figures 4.10 and 4.11 show the reconstruction-level data/MC ratios obtained from this procedure.

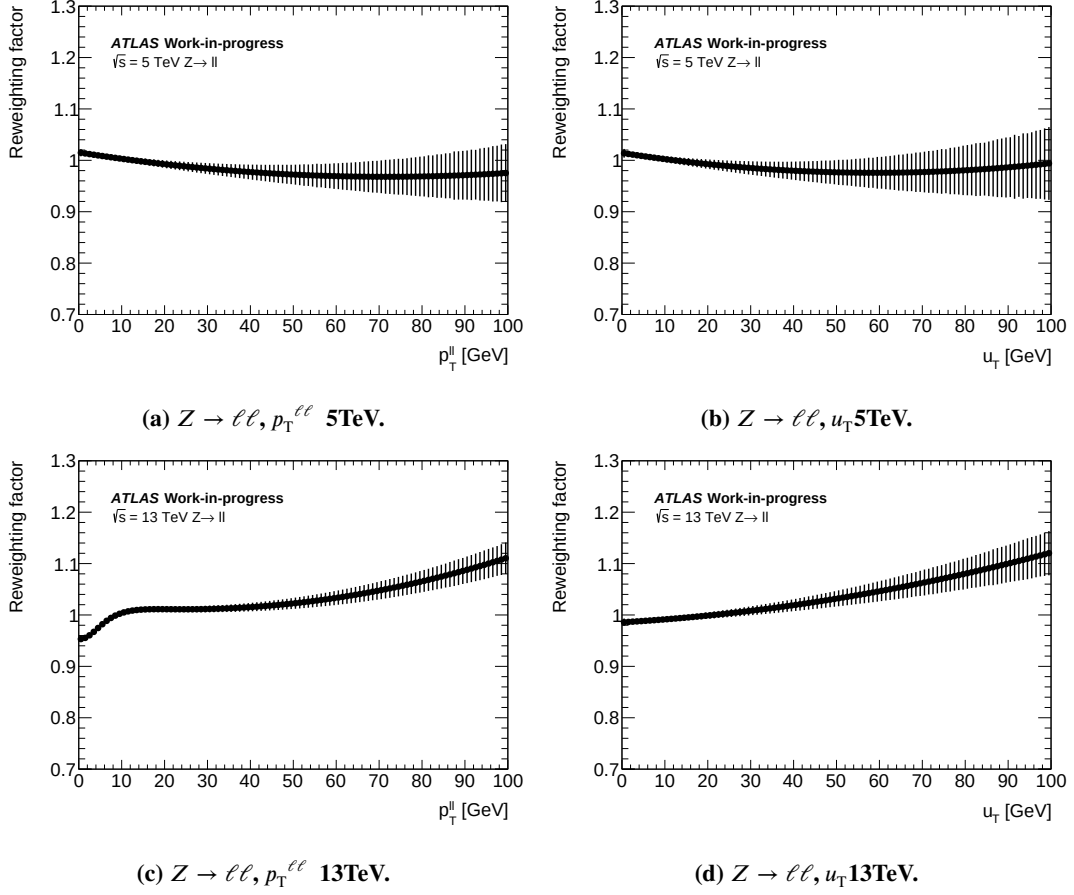


图 4.9 Best reweighting functions for electron and muon combined channels obtained with the $p_T^{\ell\ell}$ and u_T distributions at 13 TeV and 5 TeV, respectively. These functions are used to correct the truth p_T spectrum. The error bars represent the uncertainty in the reweighting functions.

The unfolding bias uncertainty on the unfolded p_T spectrum is estimated following the data driven procedure described above. Three sources of uncertainties are considered : In addition to the uncertainty from the variations of the fit function (fit function uncertainty), the following sources of uncertainties are tested:

- uncertainty from the variations of the fit parameters.
- the variation on the fit parametrization, based on the testing of alternative fit functions (other than the baseline fit)
- the variation over the initial (p_T^Z, y) distribution, based on the testing of different

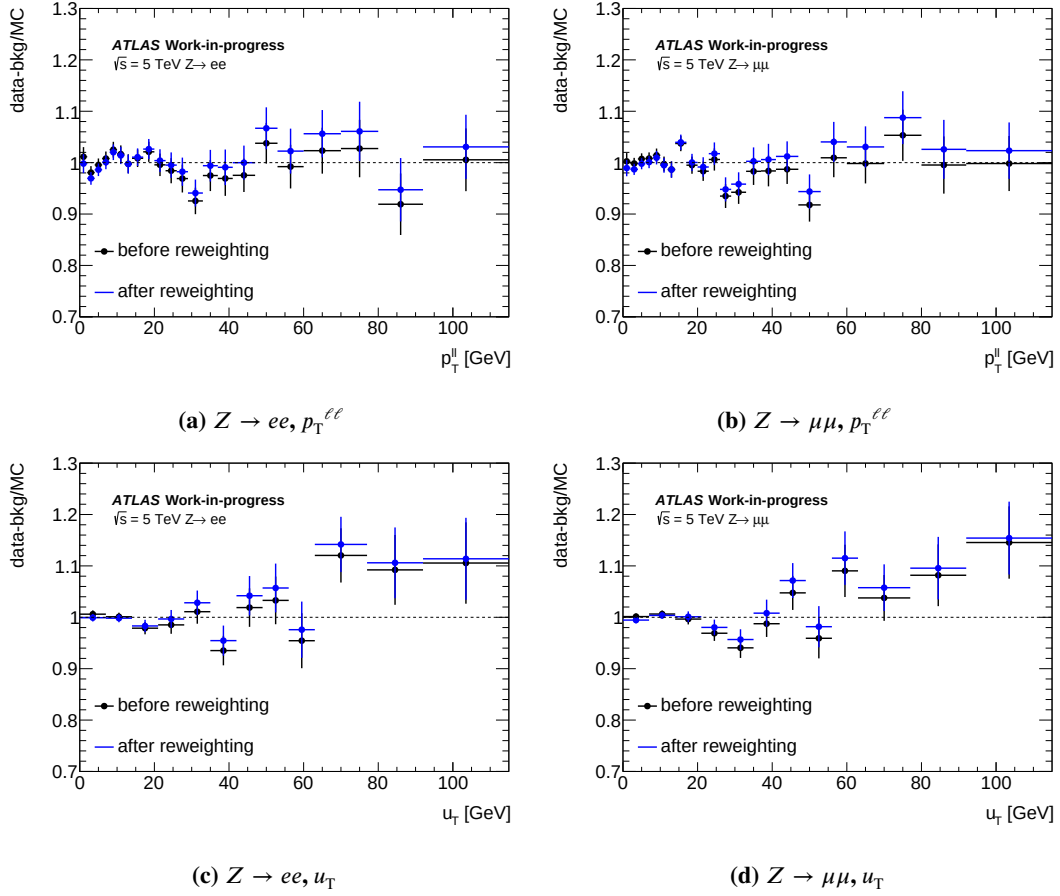


图 4.10 Comparison between the ratio of data and MC simulation at reconstruction level of the $p_T^{\ell\ell}$ and u_T distributions before (black line) and after the p_T reweighting (blue line) for $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ channels at $\sqrt{s} = 5$ TeV. The errors bars represent statistical uncertainty only.

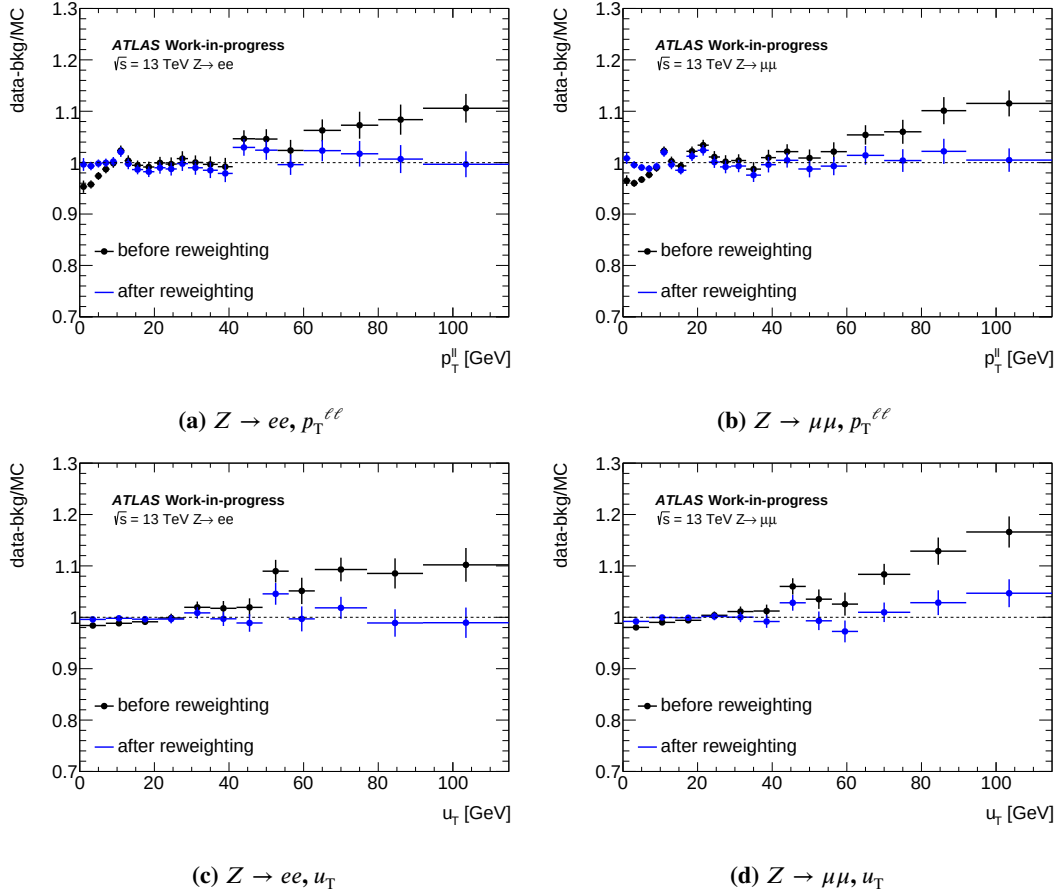


图 4.11 Comparison between the ratio of data and MC simulation at reconstruction level of the $p_T^{\ell\ell}$ and u_T distributions before (black line) and after the p_T reweighting (red line) for $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ channels at $\sqrt{s} = 13$ TeV. The errors bars represent statistical uncertainty only.

MC predictions to Z which the baseline truth-level (p_T^Z, y) distribution is reweighted in 2D.

To test the impact for the choice of reweighting function which the Data/MC ratio is fitted with. The following weighting functions are tried:

$$2nd\text{-}Order\text{ Pol.}: w_T(p_T^Z) = N \left[1 + a p_T^Z + b p_T^{Z^2} \right], \quad (4.12)$$

$$Gaus. + Pol.: w_T(p_T^Z) = N \left[G(p_T^Z; \mu, \sigma) + a p_T^Z + b p_T^{Z^2} \right], \quad (4.13)$$

$$Expo. + Pol.: w_T(p_T^Z) = N \left[1 + a p_T^{Z^2} + \frac{b}{\tau} e^{-p_T^Z/\tau} \right], \quad (4.14)$$

$$NNPDF/CT10: w_T(p_T^Z) = N \left[(1 + a p_T^Z) \times (1 - b(1 - r_{\text{nnpdf30/ct10}}(p_T^Z))) \right] \quad (4.15)$$

these functions contain a second-order polynomial modifying the high- p_T^Z behaviour of the initial p_T^Z distribution, with additional terms providing more flexibility in the low- p_T^Z region: a Gaussian term ($G(p_T^Z; \mu, \sigma)$); a ratio of DYTURBO p_T predictions obtained using the NNPDF3.0 and CT10 PDF sets ($r_{\text{nnpdf30/ct10}}(p_T^Z)$); or an exponential ($e^{-p_T/\tau}$). In addition, a third-order polynomial was tested. All functions are multiplied by a normalization parameter N , ensuring that the integral of $R(w_T)$ stays equal to the integral of $D - B$. The best agreed weighting function is chosen as the reweighting function and the deviation between the chosen reweighting function and the other options are taken as systematic uncertainty.

Several MC predictions are tested for determined the reweighting functions: : PYTHIA, SHERPA, HERWIG7, DYTURBO using the CT10 and NNPDF3.0 PDFs.

4.3.3 Uncertainty Propagation

4.3.3.1 Statistical Uncertainty Estimation Through The Bootstrap Method

The bootstrap method^[62] is used to propagate statistical fluctuations through a re-sampling of the distributions in the analysis. All distributions (in both data and simulation) are produced with a finite number of events, and as such are subject to fluctuations.

The impact of statistical fluctuations on the analysis is evaluated by creating ensembles of pseudo-data sets, both for data and simulation, where the number of events with given characteristics is fluctuated around the actually observed (or generated) number of such events, within the expected statistical uncertainty. For low-dimensional

histograms, the bootstrap can be performed by fluctuating the histogram bin contents around their nominal values, within the statistical uncertainty. For higher-dimensional problems this method can not be applied, and a weighting method is used instead. Technically, for each pseudo-data set, each event is assigned a random weight defined as follows:

$$w = P(n, 1) \quad (4.16)$$

where n is randomly generated according to the Poisson distribution of unit mean, and $P(n, 1)$ is the value of the Poisson probability to observe n events while expecting an average of 1. This procedure naturally accounts for the correlated effect of statistical fluctuations across all observables and distributions of relevance for the analysis. It is repeated a large number of times, to produce an ensemble of data sets that mimics the expected fluctuations with sufficient precision. In practice, 100 pseudo-data sets are often enough for a proper evaluation of statistical uncertainties. In this analysis, 4000 pseudo-data sets are used.

Data statistical uncertainties result from fluctuations in the observed spectrum D . These are propagated to the measurement using the bootstrap method described above, applied to the observed distribution. For each pseudo-data sample α , the unfolded spectrum is

$$\tilde{U}_j^\alpha = \sum_i U_{ij}(D_i^\alpha - B_i) \quad (4.17)$$

When estimating the uncertainty on the normalised cross-section, each $\tilde{U}_j^\alpha$ is scaled such that the total number of events is the same as that of the nominal unfolded spectrum. Assuming N_{bs} pseudo-data samples, the corresponding covariance is estimated as

$$C_{kl}^{\text{stat,Data}} = \frac{1}{N_{\text{bs}} - 1} \sum_{\alpha=1}^{N_{\text{bs}}} (\tilde{U}_k^\alpha - \langle \tilde{U} \rangle_k) (\tilde{U}_l^\alpha - \langle \tilde{U} \rangle_l) \quad (4.18)$$

where $\langle U \rangle_{k,l}$ denotes the average over the bootstrap samples, and the diagonal uncertainty is

$$\delta \tilde{U}_k = \sqrt{C_{kk}^{\text{stat,Data}}} \quad (4.19)$$

Monte Carlo statistical uncertainties result from the finite statistics of the simulation sample used to determine the efficiency correction and the migration matrix. These

are propagated to the measurement using the bootstrap method described above as follows: for each fluctuated MC sample α , the unfolded spectrum is

$$\tilde{U}_j^\alpha = \sum_i U_{ij}^\alpha (D_i - B_i) \quad (4.20)$$

and assuming N_{bs} fluctuated MC samples, the corresponding covariance is estimated as above:

$$C_{kl}^{\text{stat,MC}} = \frac{1}{N_{\text{bs}} - 1} \sum_{\alpha=1}^{N_{\text{bs}}} (\tilde{U}_k^\alpha - \langle \tilde{U} \rangle_k) (\tilde{U}_l^\alpha - \langle \tilde{U} \rangle_l) \quad (4.21)$$

When estimating the uncertainty on the normalised cross-section, each $\tilde{U}_j^\alpha$ is scaled such that the total number of events is the same as that of the nominal unfolded spectrum. Note that in this case the migration matrix as well as the efficiency and purity corrections are changed, contrary to data statistic uncertainty where the reconstructed spectrum is varied.

4.3.3.2 Systematic Uncertainties

Systematic uncertainties are decomposed into a large set of uncorrelated sources of uncertainty, induced by uncertainties in the lepton and recoil calibration corrections, lepton efficiency corrections, the background subtraction, and the physics description of the signal process.

Under a given change in the calibration, efficiency or physics modelling corrections, the unfolding result is

$$\tilde{U}_j^a = \sum_i U_{ij}^a (D_i - B_i) \quad (4.22)$$

where a labels the correction uncertainties (e.g a specific efficiency scale factor or calibration bin).

Background subtraction uncertainties are propagated through variations of B :

$$\tilde{U}_j^a = \sum_i U_{ij} (D_i - B_i^a) \quad (4.23)$$

where B^a represents varied estimates of the total background, under variations of the various background process cross sections and the integrated luminosity.

4.3.4 Measurement Of The p_T^Z Spectrum

The p_T^Z cross section measurement is presented in this section. Following the statistical and experimental systematic uncertainties at reconstructed level as well as at unfolded level, for $p_T^{\ell\ell}$ and u_T spectra. Separate e and μ as well as the combined $e - \mu$ cross sections are reported in common fiducial regions close to the initial experimental selections so as to involve only minimal extrapolations. The kinematic requirements applied for the cross-section measurements are: $p_T^{\ell} > 25$ GeV, $|\eta^l| < 2.5$, and $66 \text{ GeV} < m_{\ell\ell} < 116 \text{ GeV}$

4.3.4.1 Reconstructed Level Uncertainties

The breakdown of the statistical and experimental systematic uncertainties at reconstructed-level for the Z analysis are shown in 4.12 and 4.13 at 13 and 5 TeV, respectively. The generator systematic uncertainties are calculated from the difference of reconstructed-level predictions between POWHEG and SHERPA. The uncertainty breakdowns at reconstructed-level are presented in the finer "1 GeV binning", as the reco-level inputs to the unfolding procedure use this finer binning. A full breakdown of the systematic uncertainties after unfolding is shown in section 4.3.4.2.

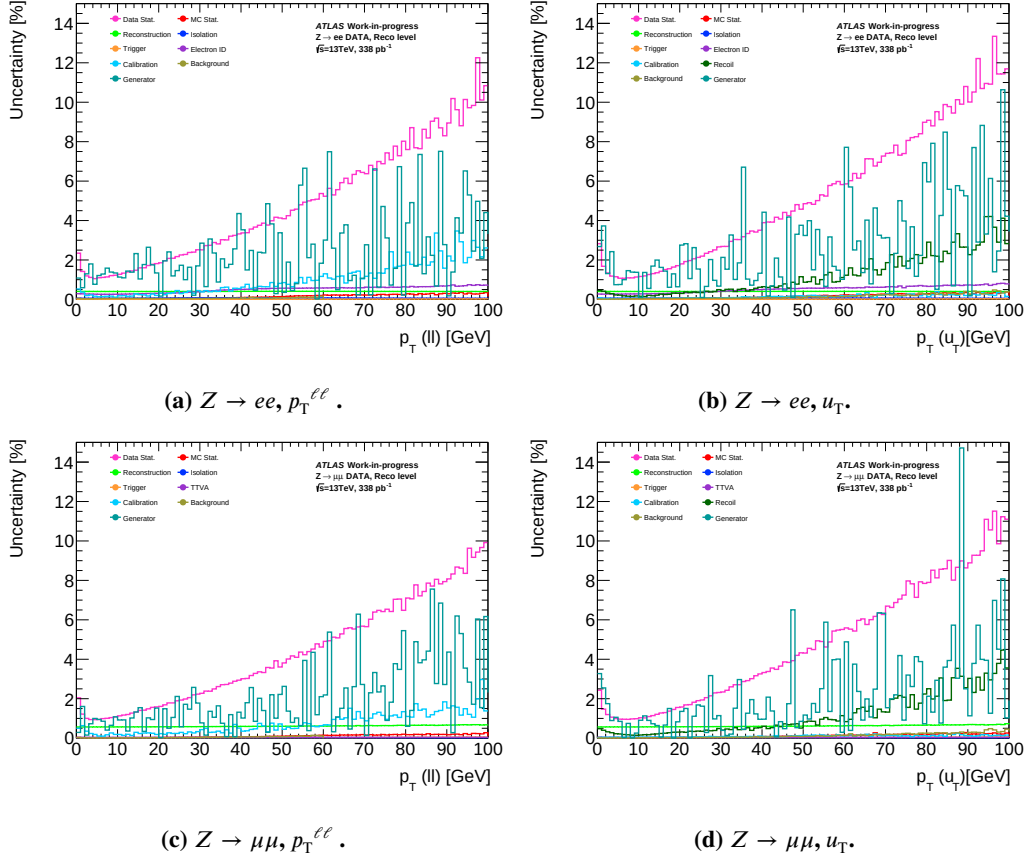


图 4.12 Total statistical and systematic uncertainties for reconstructed-level event yields for the electron and muon channels at 13 TeV. The uncertainties are shown as a percentage with respect to the number of reconstructed data events in each bin of $p_T^{\ell\ell}$ and u_T , respectively.

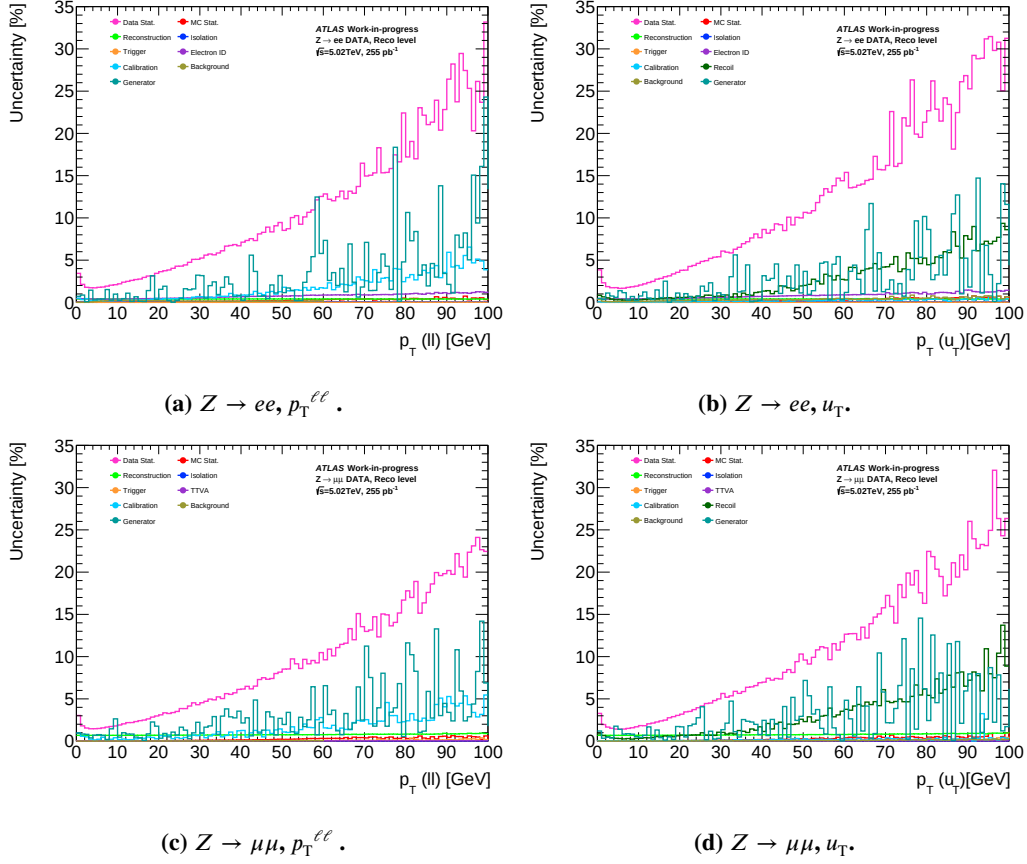


图 4.13 Total statistical and systematic uncertainties for reconstructed-level event yields for the electron and muon channels at 5 TeV. The uncertainties are shown as a percentage with respect to the number of reconstructed data events in each bin of $p_T^{\ell\ell}$ and u_T , respectively.

4.3.4.2 Final Uncertainty Breakdown At Unfolded Level

In the following subsection, the complete breakdown of the unfolded statistical, systematic (including generator systematic), and luminosity uncertainties for the 13 and 5 TeV datasets are presented. Results for $p_T^{\ell\ell}$ are shown with “2 GeV” bins, while the results for u_T are shown “7 GeV” bins. Multijet uncertainties are included as part of the background uncertainties. The generator systematic uncertainty is calculated as the difference of unfolded-level measurements using POWHEG and SHERPA, in the same way as it is done in the p_T^W measurement. The uncertainty breakdowns for the unnormalised (absolute) differential cross section measurements are shown in Fig. 4.14 for 13 TeV and Fig. 4.15 for 5 TeV. The corresponding “shape uncertainties” for the normalised distributions are calculated by normalising each variation and are shown in Fig. 4.16 for 13 TeV and Fig. 4.17 for 5 TeV.

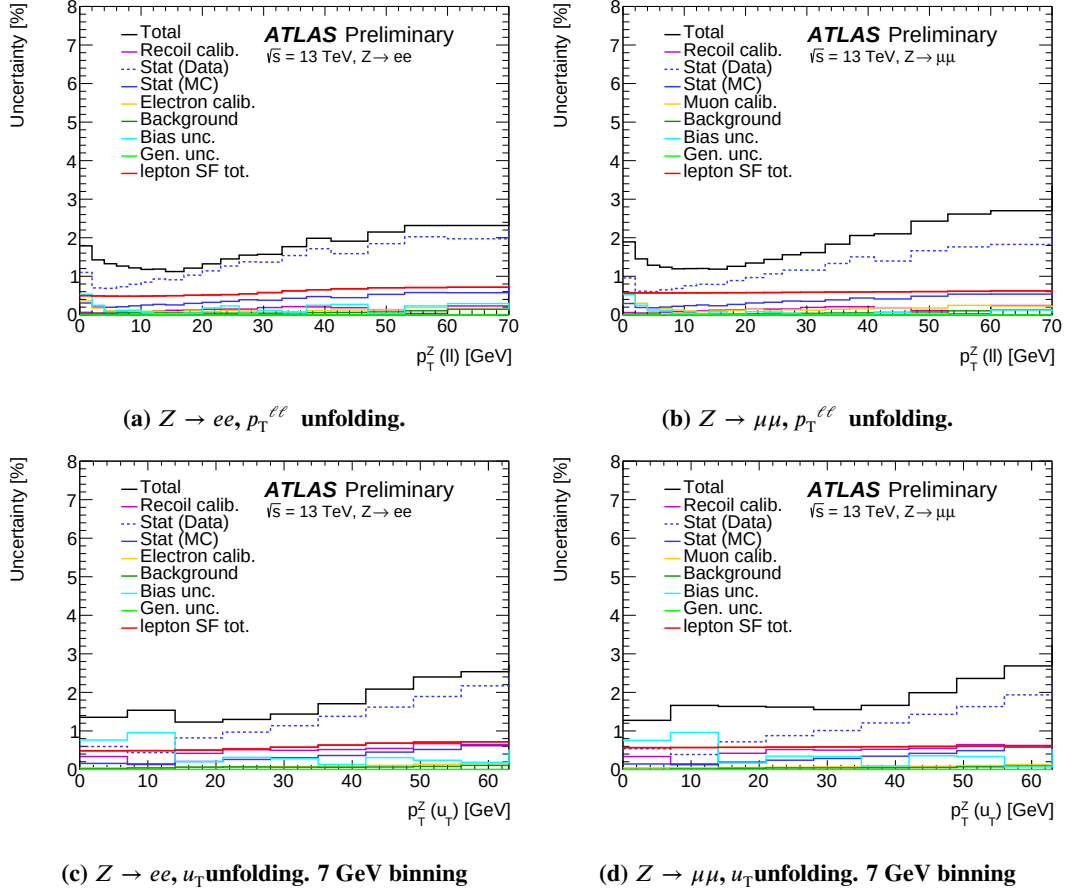


图 4.14 Complete uncertainty breakdown for both Z decay channels and both observables for the $\sqrt{s} = 13$ TeV dataset. The uncertainties are shown as a percentage of the unfolded data per p_T bin. Each uncertainty has been unfolded using Bayesian unfolding with the chosen number of iterations: two for the $p_T^{\ell\ell}$ and ten for the u_T measurements.

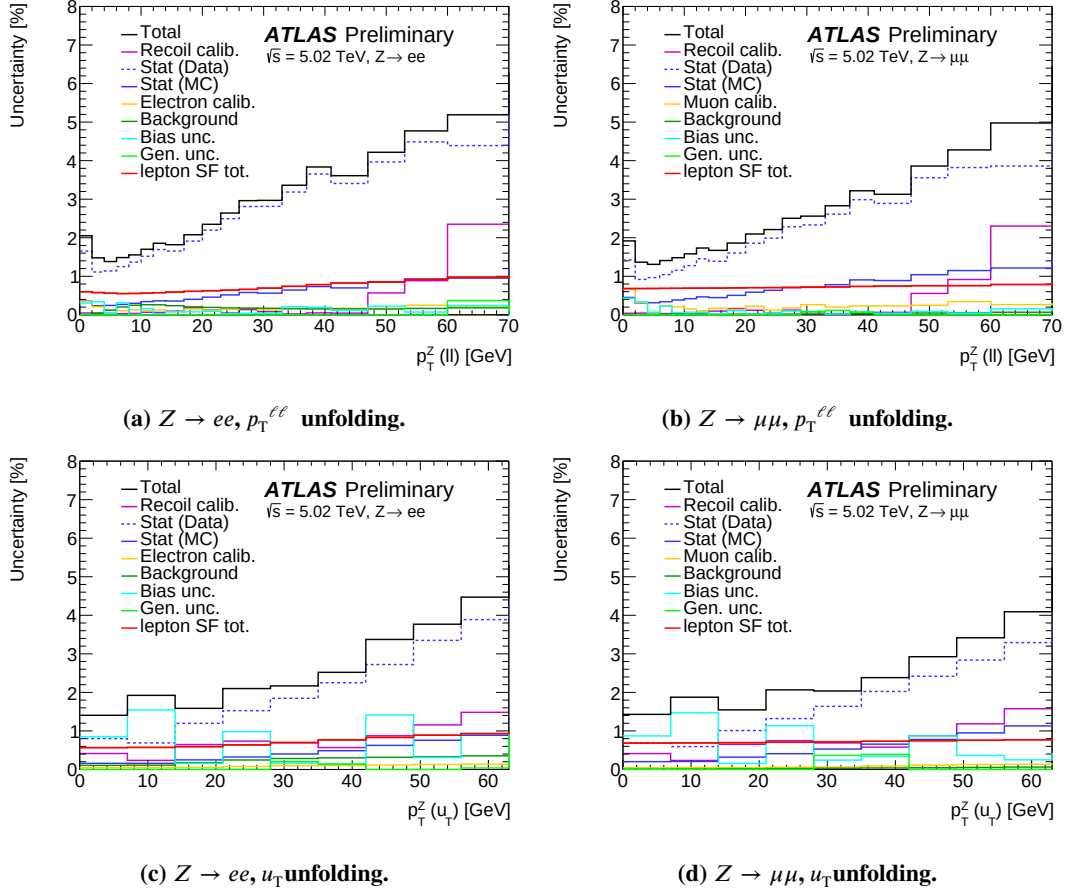


图 4.15 Complete uncertainty breakdown for both Z decay channels and both observables for the $\sqrt{s} = 5$ TeV dataset. The uncertainties are shown as a percentage of the unfolded data per p_T bin. Each uncertainty has been unfolded using Bayesian unfolding with the chosen number of iterations: two for both the $p_T^{\ell\ell}$ and u_T measurements.

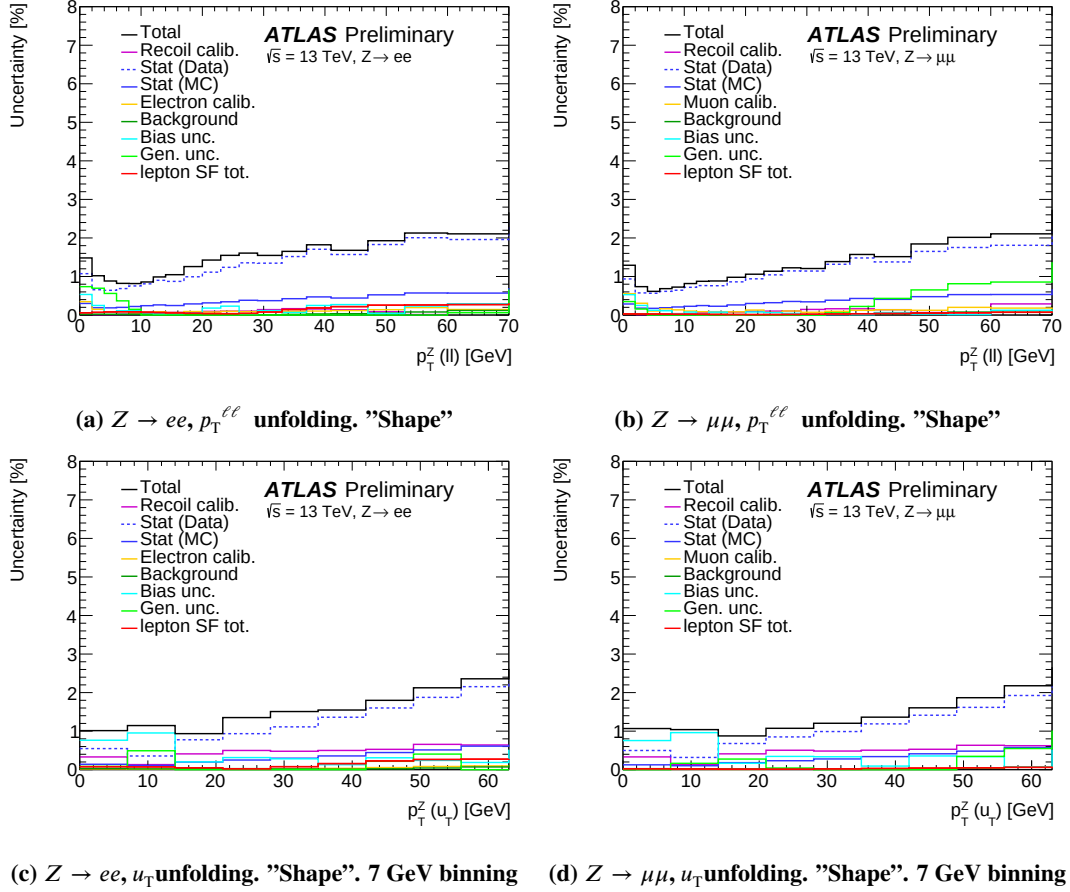


图 4.16 "Shape" uncertainty breakdown plots for both Z decay channels and both observables for the $\sqrt{s} = 13$ TeV dataset. The uncertainties are shown as a percentage of the unfolded data per p_T bin. Each uncertainty has been unfolded using Bayesian unfolding with the chosen number of iterations: two for the $p_T^{\ell\ell}$ measurement and five for the u_T measurement. All variations are normalized to the nominal p_T distribution after efficiency and acceptance corrections.

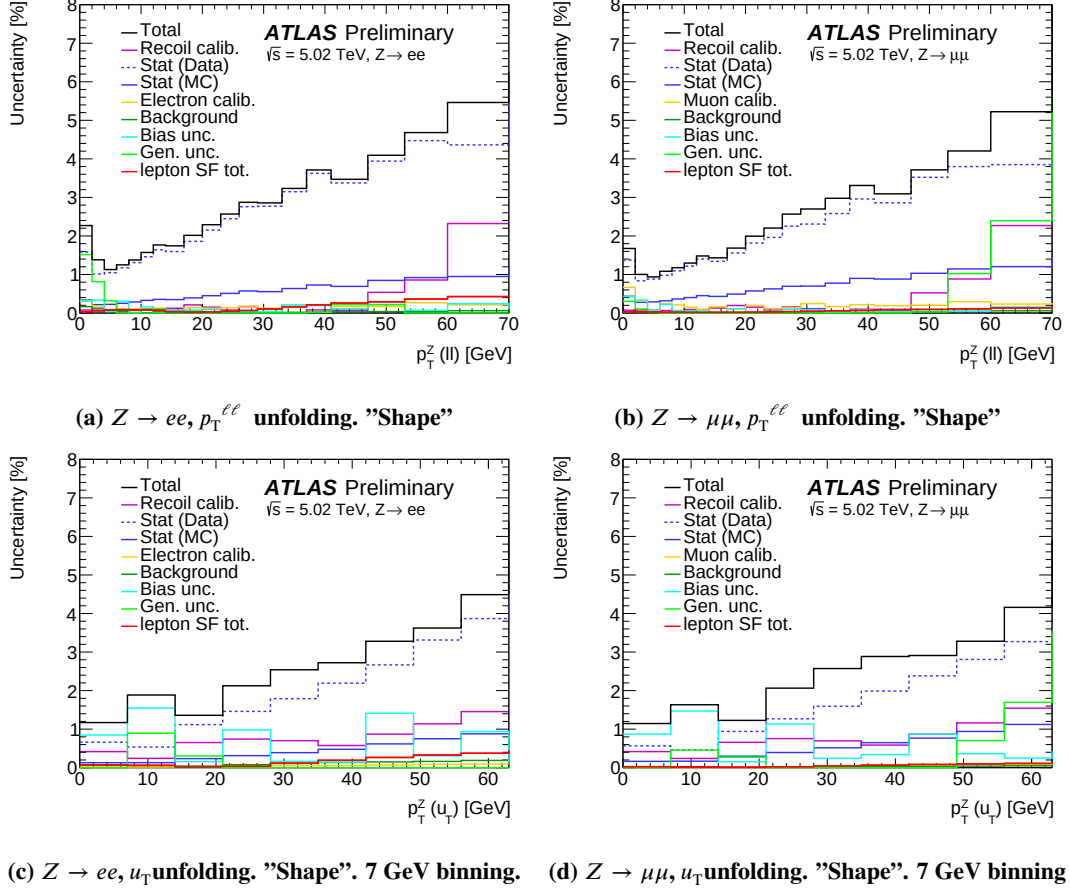


图 4.17 "Shape" uncertainty breakdown plots for both Z decay channels and both observables for the $\sqrt{s} = 13$ TeV dataset. The uncertainties are shown as a percentage of the unfolded data per p_T bin. Each uncertainty has been unfolded using Bayesian unfolding with the chosen number of iterations: two for the $p_T^{\ell\ell}$ and five for the u_T measurements. All variations are normalized to the nominal p_T distribution after efficiency and acceptance corrections.

4.3.4.3 Transverse Momenta Of Z Boson At Unfolded Level

Here we present the unfolded distributions for the Z analysis. We begin with the unfolded differential cross-sections for both the dilepton transverse momentum $p_T^{\ell\ell}$ and the hadronic recoil u_T along with their respective uncertainties in both $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ channels. Results are compared to various Monte Carlo generators. The normalized cross-sections are divided by the integrated cross-section in the fiducial phase space. The results are shown separately for the 13 TeV and 5 TeV datasets. All $p_T^{\ell\ell}$ results are unfolded with 2 iterations. The u_T results are unfolded with 5 iterations at 5 TeV and 10 iterations at 13 TeV, both in the same “7 GeV binning”.

Figures 4.18a and 4.18b show the differential cross section distributions of the dilepton transverse momentum for the $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ channels, respectively. The results are compared to the nominal Monte Carlo generator POWHEG+PYTHIA8, hence the agreement is good at least up to $p_T^{\ell\ell} = 100, \text{ GeV}$ and consistent with what is seen at reconstructed-level Fig. 3.51 up to a small difference in overall normalization. The $Z \rightarrow \mu\mu$ channel (4.18b) shows a positive statistical fluctuation at 20 GeV that is also seen at reconstructed-level (see Fig. 3.51). Figures 4.18c and 4.18d show the differential cross section distributions derived from the hadronic recoil for the $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ channels, respectively. One can see some effect of the correlations introduced by u_T leading to some wave-like pattern in its Bayesian-unfolded result.

Figures 4.19a, 4.19b & 4.19c, 4.19d compare various Monte Carlo generator predictions for the differential p_T^Z cross-section to the data as a function of p_T . The differential cross-sections are normalized by the integrated fiducial cross-section. We use the MCs Sherpa (v2.2.1), DYTURBO (to NNLL+NNLO), POWHEG+PYTHIA8 AZNLO Tune (the nominal MC) and PYTHIA8 with AZ tune. At 13 TeV, the Monte Carlo prediction describing best the data at very low p_T region is PYTHIA8, while the HERWIG7 prediction is the worse with up to 20% deviation from the data. The POWHEG+PYTHIA8 matches the measurement best in the middle range of p_T ($10 \text{ GeV} < p_T < 80 \text{ GeV}$). Above 100 GeV, SHERPA is the prediction most consistent with the data, while all other predictions are well below the data. These conclusions are consistently observed in the electron and muon channels. Similar effects are observed at 5 TeV, but the variations

between the different predictions are less than at 13 TeV.

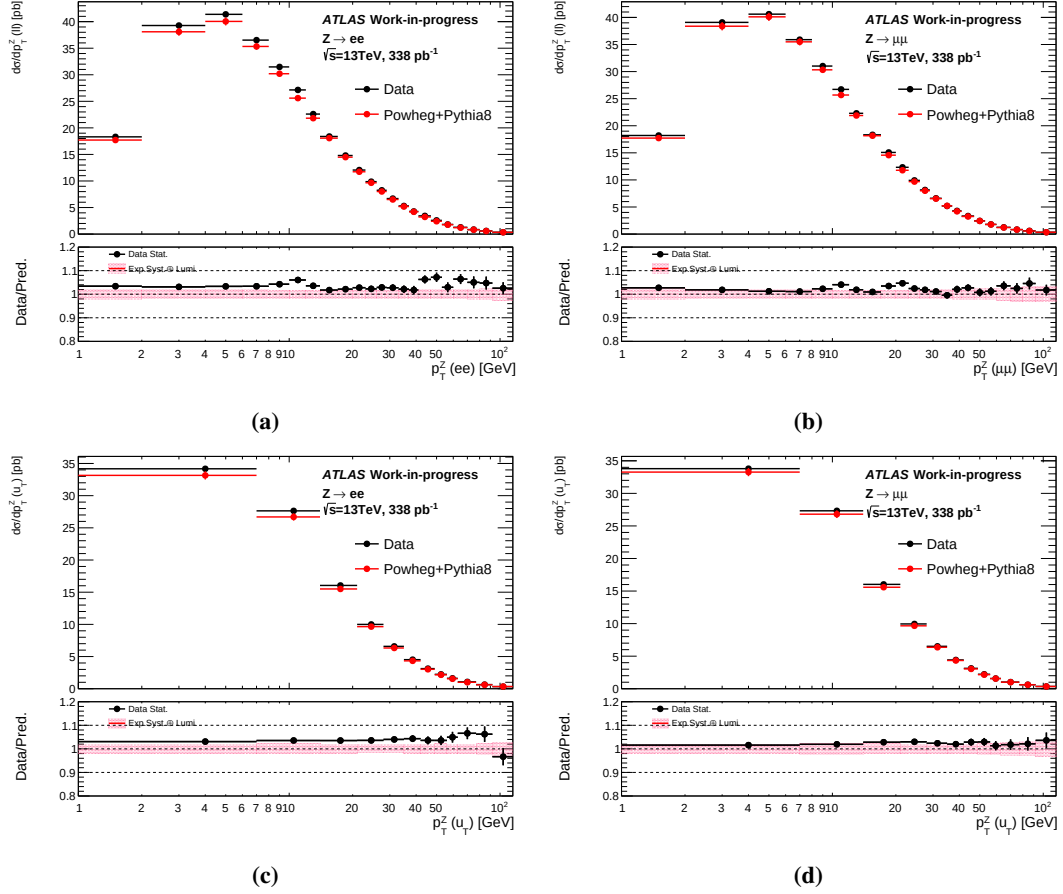


图 4.18 Unfolded dilepton transverse momentum differential cross section distribution in the electron (left) and muon (right) Z decay channels for the $\sqrt{s} = 13$ TeV dataset. The cross section is shown in the upper panel and the lower panel shows the ratio of unfolded data to the nominal (reweighted) Powheg+Pythia8 MC. The uncertainties in the ratio plot are split to show the statistical uncertainty (black error bars), and experimental systematic uncertainties including luminosity (red band). The total uncertainty is the same total uncertainty as that shown in figures 4.14a to 4.14d.

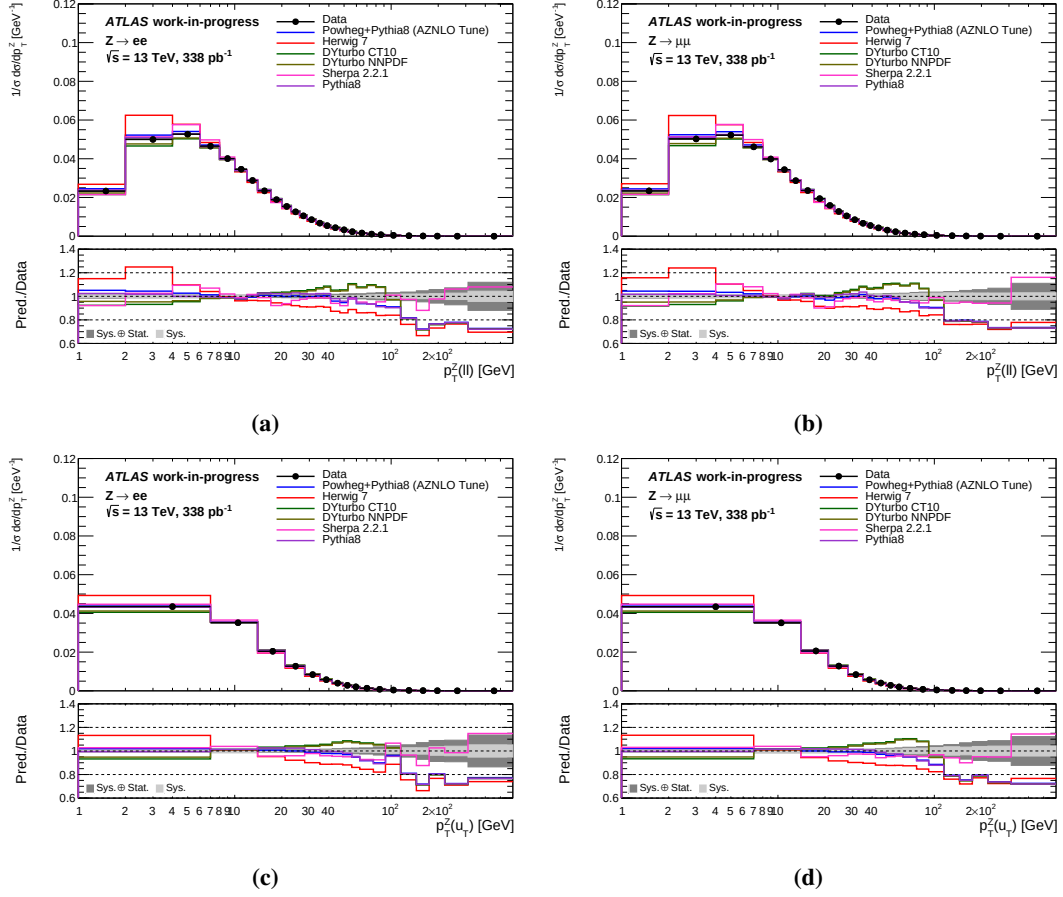


图 4.19 Comparison between various Monte Carlo generator predictions and the unfolded dilepton transverse momentum differential cross-section distribution in the electron (left) and muon (right) Z decay channels for the $\sqrt{s} = 13$ TeV dataset. The differential cross-section has been normalized by the integrated fiducial cross-section. The unfolded data and MC distributions are shown in the upper panel and the lower panel shows the ratio of the various distributions to the data. In the lower panel, the total systematic uncertainties are shown in light grey, and the total overall uncertainty (stat. plus sys.) is shown in dark grey.

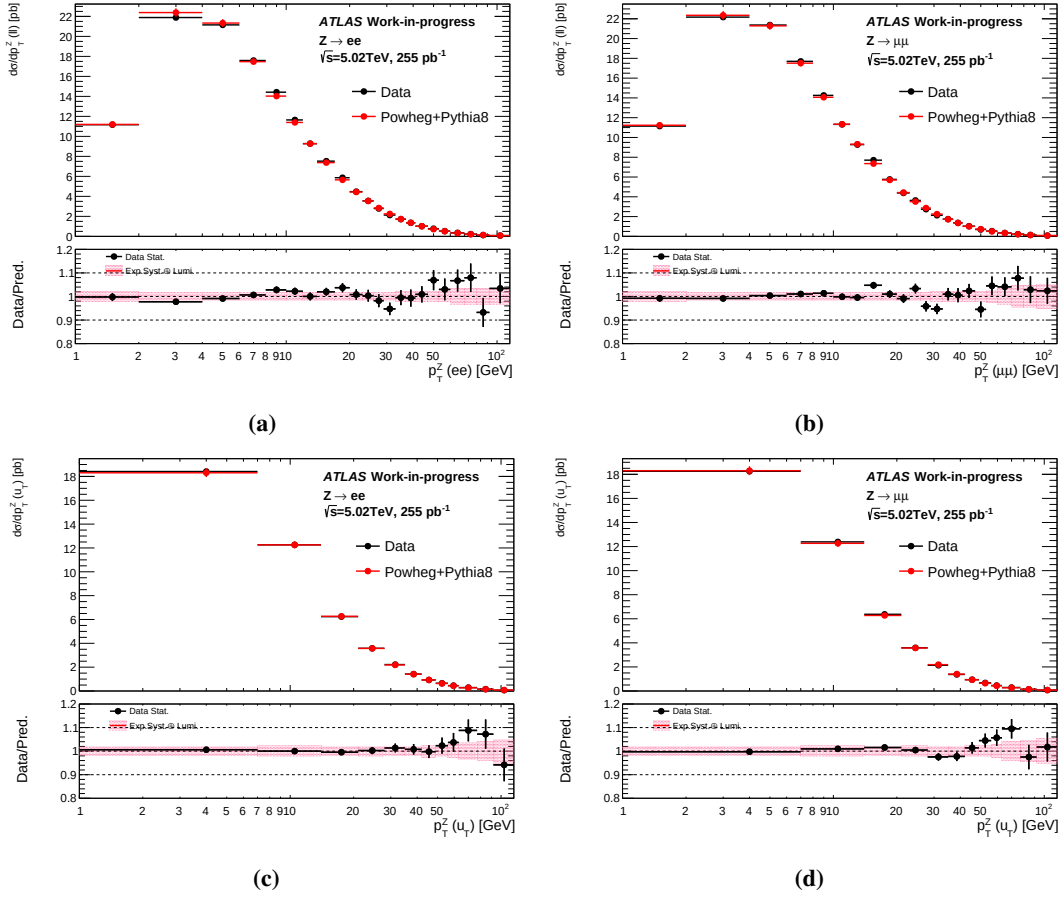


图 4.20 Unfolded dilepton transverse momentum differential cross-section distribution in the electron (left) and muon (right) Z decay channels for the $\sqrt{s} = 5$ TeV dataset. The cross section is shown in the upper panel and the lower panel shows the ratio of unfolded data to the nominal (non-reweighted) Powheg+Pythia8 MC. The uncertainties in the ratio plot are split to show the statistical uncertainty (black error bars), and experimental systematic uncertainties including luminosity (red band). The total uncertainty is the same total uncertainty as that shown in figures 4.15a to 4.15d.

Figures 4.20a and 4.20b show the differential cross-section distributions of the dilepton transverse momentum for the $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ channels, respectively, while figures 4.20c and 4.20d show the differential cross-section distributions of the hadronic recoil for the $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ channels. The unfolded results are consistent with the nominal MC (as to be expected after the nominal MC was reweighed to the data) aside from statistical fluctuations, e.g. at 30 GeV (also seen at reconstructed-level Fig. 3.60). Due to its poorer resolution, the hadronic recoil result once again features stronger bin-to-bin correlations and so the unfolded data is not able to capture the shape

as well as the $p_T^{\ell\ell}$ measurement.

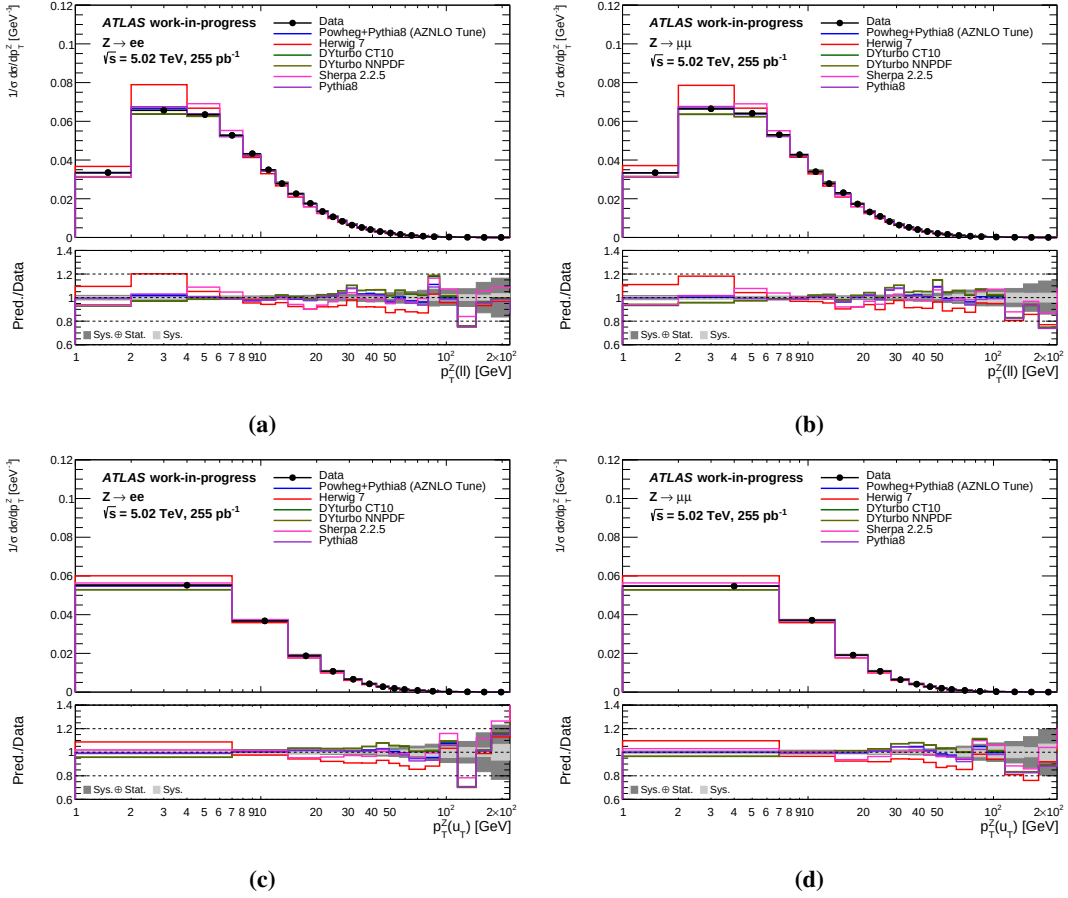


图 4.21 Comparison between various Monte Carlo generator predictions and the unfolded dilepton transverse momentum differential cross-section distribution in the electron (left) and muon (right) Z decay channels for the $\sqrt{s} = 5$ TeV dataset. The differential cross-section has been normalized by the integrated fiducial cross-section. The unfolded data and MC distributions are shown in the upper panel and the lower panel shows the ratio of the various distributions to the data. In the lower panel, the total systematic uncertainties are shown in light grey, and the total overall uncertainty (stat. plus sys.) is shown in dark grey.

Figures 4.21a, 4.21b & 4.21c, 4.21d compare various Monte Carlo generator predictions for the differential p_T^Z cross-section to the data as a function of p_T in the 5 TeV decay channels. The differential cross-sections are normalized by the integrated fiducial cross-section. The predictions at 5 TeV are more consistent with the data than at 13 TeV. At low p_T , both tunings of PYTHIA perform well in contrast to most other predictions. At higher p_T the differences between data and predictions are less clear than at 13 TeV

and most generators are compatible with the data to some extent.

4.3.5 Channel Combination

The electron- and muon-channel transverse momenta measurements are combined using χ^2 minimization, following the best linear unbiased estimator method (BLUE)^[63,64]. Firstly, a covariance matrix (or an error matrix) is needed to describe the variances of the individual estimates, while the off-diagonal elements describe the correlations between pairs of estimates. The combination procedure works under the following principles:

- the combined result is a linear combination of the individual estimates;
- the combined result provides an unbiased estimate of the parameter of interest (PoI)
- it has the minimum possible variance σ^2 .

The combination is that

$$y = \sum \alpha_i y_i, \sum \alpha_i = 1 \quad (4.24)$$

The covariance matrix is defined below:

$$C = \begin{pmatrix} C^e & C^{e\mu} \\ C^{e\mu} & C^\mu \end{pmatrix} \quad (4.25)$$

The $N \times N$ covariance matrices C^e and C^μ are the covariance matrices for each e- or μ - channel, including statistics and systematics uncertainties. $C^{e\mu}$ corresponds to the sources of uncertainties that correlate both channels. The χ^2 minimization and combined uncertainty calculation is performed as:

$$\bar{\mathbf{X}} = (\mathbf{H}^T \mathbf{C}^{-1} \mathbf{H})^{-1} \mathbf{H}^T \mathbf{C}^{-1} \mathbf{X}, \quad (4.26)$$

where $\mathbf{H}$ is a $2N \times N$ matrix specifying the structure of the linear system:

$$\mathbf{H} = \begin{pmatrix} 1 & & 0 \\ & \ddots & \\ 0 & & 1 \\ 1 & & 0 \\ & \ddots & \\ 0 & & 1 \end{pmatrix}. \quad (4.27)$$

The $2N$ lines represent the measured electron and muon distributions; the N columns represent the combined spectrum; $H_{ij} = 1$ when measurement i contributes to the combined value j , and 0 otherwise.

Finally, the covariance matrix of the combined measurement is given by:

$$\bar{\mathbf{C}} = (\mathbf{H}^T \mathbf{C}^{-1} \mathbf{H})^{-1}. \quad (4.28)$$

The above procedure is rigorously correct only in the Gaussian limit, and for a fixed covariance matrix, i.e. when the uncertainties are constant, not depending in particular on the value of the measured quantity. Many sources of uncertainty are actually defined relative to the measurement; for example, luminosity or efficiency uncertainties are fixed fractions of the measured cross section. A given relative source of uncertainty then has a smaller impact for lower measured values; when combining two measurements, this results in a bias towards the lowest measured cross section.

A practical solution to this issue^[65] is to iterate the combination procedure, rescaling the covariance matrix elements according to the combined uncertainties of the previous iteration. In the present analysis, the combination is iterated 4 times and stable results are observed.

A complete table of the correlations of uncertainties between $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ channels are summarized in Table 4.4. Correlation assumptions are used for the combination of electron- and muon-channel results for a given process, and for cross-section ratios and integrals.

Electron calibration refers to the data-driven determination of the energy scale and resolution corrections; electron efficiencies denote scale factors for reconstruction, identification, isolation and trigger. Muon calibration uncertainties include momentum scale and resolution corrections, and the uncertainty in the determination of sagitta bias corrections. There are scale factors for muon reconstruction, isolation and trigger efficiencies. Recoil calibration uncertainties include all corrections to the recoil response and resolution, and uncertainties in $\sum \bar{E}_T$, as described in Section 3.4.

Electroweak and Top background uncertainties cover uncertainties in the predictions of the W , Z , di-boson and top production cross sections. The uncertainty in the

Source of uncertainty	Spectrum	W^+ vs. W^-	W vs. Z	e vs. μ	5 vs. 13 TeV
Data & MC statistics	Partial	No	No	No	No
Lepton calibration & efficiencies	Full	Full	Full	No	No
Recoil calibration (Z -based)	Full	Full	Full	Full	No
Recoil calibration ($\sum \vec{E}_T$)	Full	No	No	Full	No
EW & top backgrounds	Full	Full	Full	Full	Full
Multijet background (statistics)	No	No	No	No	No
Multijet background (method)	Full	Full	No	Full	Full
Unfolding bias	Full	No	No	Full	No
Generator systematic	Full	Full	No	Full	Full
Luminosity	Full	Full	Full	Full	No

表 4.4 Simplified description of the correlation model considered when combining channels and calculating ratios or integrals. Correlations assumptions for W^+ vs. W^- and W vs. Z are listed for a given lepton flavour; e vs. μ refers to a given channel.

Multijet background includes uncertainties on the distribution and the total yield, see Section 3.5.2 for the complete discussions.

The unfolding bias represents the uncertainty induced by the freedom in the p_T^Z distribution assumed in the MC used to determine the migration matrices and selection efficiencies. The 5 NPs correspond to the fit uncertainty(3NPs), the parametrization uncertainty (1NP), and the Initial (p_T, y) distribution (1NP). The generator systematic uncertainty reflects the impact of alternate perturbative and non-perturbative QCD models, for a given p_T^Z distribution.

The complete correlation matrix of the ensemble of measurements discussed in this note is shown in Figure 4.22.

4.3.5.1 Combination of p_T^Z results

Combinations are performed for normalized differential cross section distributions. The combination results are shown in Figure 4.23 for 5 and 13 TeV, respectively. The uncertainty breakdowns of the combined results are shown in Figure 4.24. Summary of the compatibility between the different channels is given in Table 4.5.

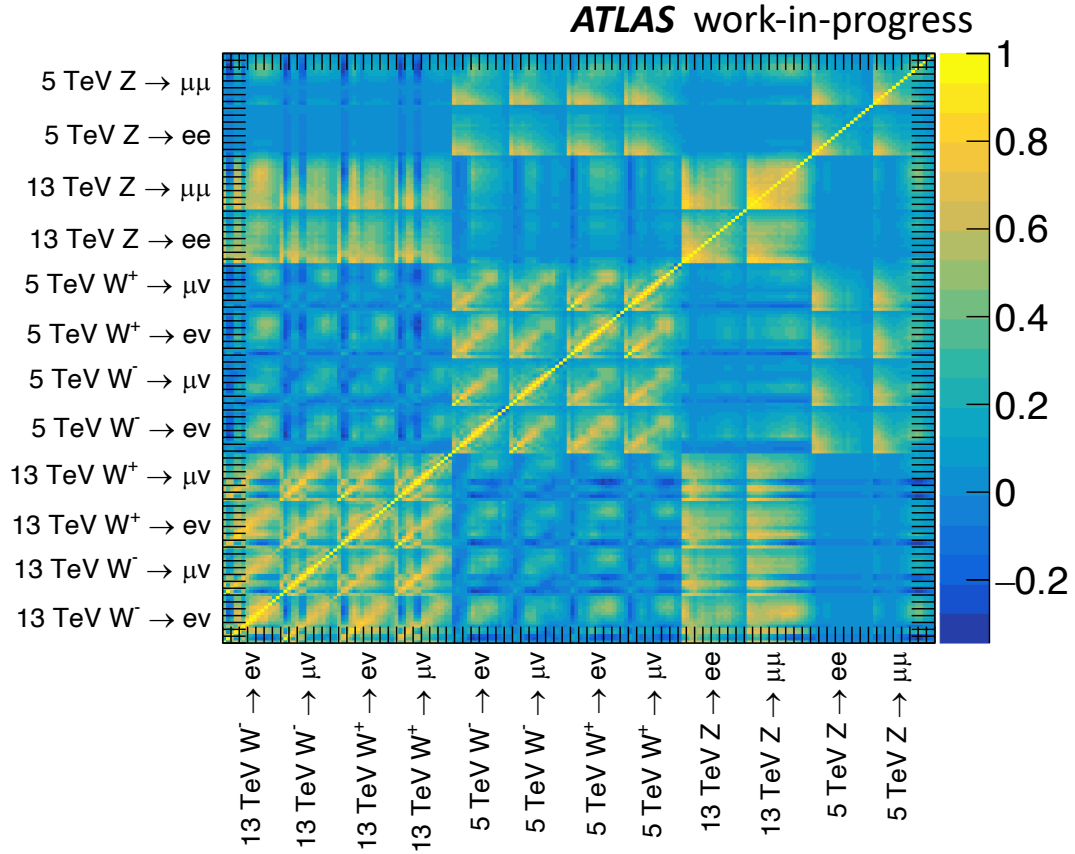


图 4.22 Correlations between the measurements. The blocks visible correspond to the p_T spectrum measured in W^+ , W^- in e/μ channel at 13 TeV (bins 1-60), W^+ , W^- in e/μ channel at 5 TeV (bins 61-120), Z e/μ channel at 13 TeV (bins 121-154), Z e/μ channel at 5 TeV (bins 155-186)

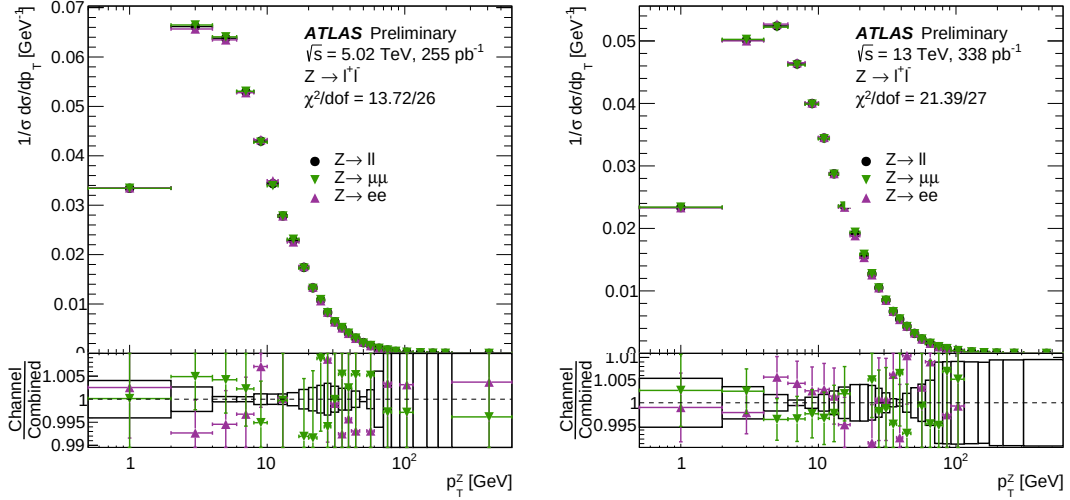


图 4.23 Combination of the normalised Z measurements at 5 TeV (left) and 13 TeV (right).

The error bars of the separate channels include uncorrelated uncertainties across the channels, whereas those of the combined result include only the correlated uncertainties across the channels. The error bars in the ratio panel show the relative uncorrelated uncertainties for the electron and muon channels, while the black boxes show the relative correlated uncertainties for combined results.

Figure 4.23 shows generally very good compatibility of the normalized p_T^Z measurements between the electron and muon channels. The χ^2/dof between electron and muon channel results are 13.53/26 at $\sqrt{s} = 5$ TeV, which corresponds to confidence level of 97.9%. And $\chi^2/dof = 21.21/27$ at $\sqrt{s} = 13$ TeV, corresponds to confidence level of 77.6%. The confidence level at 5 TeV is excellent which demonstrates that the electron and muon channels are well matched. At 13 TeV, the agreement is relatively worse than 5 TeV but still at a satisfactory level. For both 5 and 13 TeV, the compatibility between the p_T results in two channels are very good at $p_T < 10$ GeV, where the statistics of Z events are rich. In [10, 20] GeV range, the measurements do not agree well in two channels. For higher p_T range, in [30, 100] GeV, the ratio of $\sigma(e/\mu)/\sigma(\text{combined})$ is fluctuating up and down. But most of the points are covered by the uncertainties in this region and the points look like in random fluctuations. Thus this behavior is just due to the limit of data statistics.

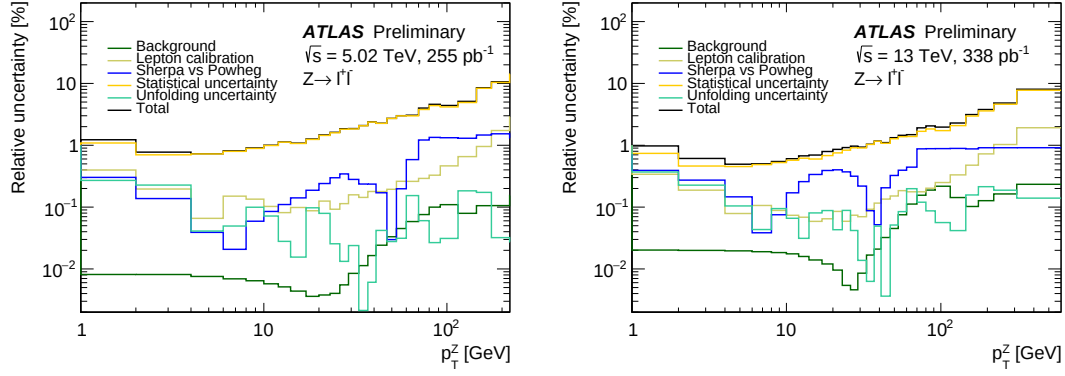


图 4.24 Breakdown of uncertainties for the combined Z measurements at 5 TeV (left) and 13 TeV (right).

Channels		$\sqrt{s}$	$\chi^2 / \text{d.o.f}$
$Z \rightarrow ee$	$Z \rightarrow \mu\mu$	5 TeV	13.5 / 26
$Z \rightarrow ee$	$Z \rightarrow \mu\mu$	13 TeV	21.2 / 27

表 4.5 χ^2 values and numbers of degrees of freedom for the combinations of the normalized differential measurements.

4.3.5.2 Cross-section ratios and integrals

This section presents the W and Z production cross sections at given centre-of-mass energy, and ratios between the 5 TeV and 13 TeV cross sections. Total fiducial cross section are calculated by integrals over the measured transverse momentum distributions. The ratios Z production cross sections between two center-of-mass energies are of physical interest to discriminate between different theoretical calculations or PDFs.

Figure 4.25 shows the ratio of W - and Z - boson cross sections at $\sqrt{s} = 5$ and 13 TeV. The W - cross section results comes from the measurements using low- μ data taken using the *hadronic recoil* calibrations discussed in Section 3.4. The uncertainties of the ratios are extrapolated from each measurement of W - and Z - cross sections and the correlations are taken into account from 4.4. The uncertainties of the ratios are shown in Figure 4.26. The integrated cross-section for each W^+ , W^- and Z channels are displayed in Table 4.6. And the ratios of integrated cross-section between W and Z are in Table 4.7.

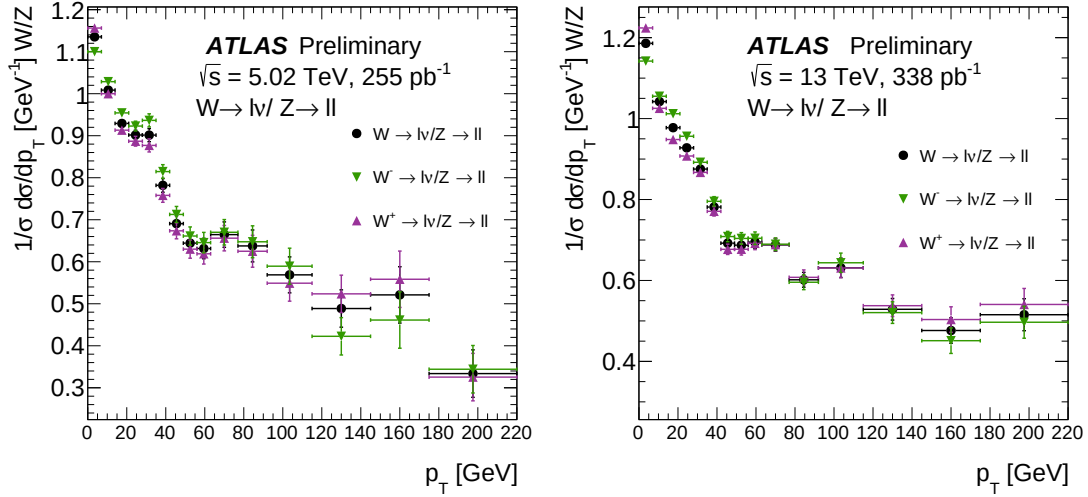


图 4.25 Ratio between the $W^\pm$ and Z transverse-momentum distributions at 5 TeV (left) and 13 TeV (right).

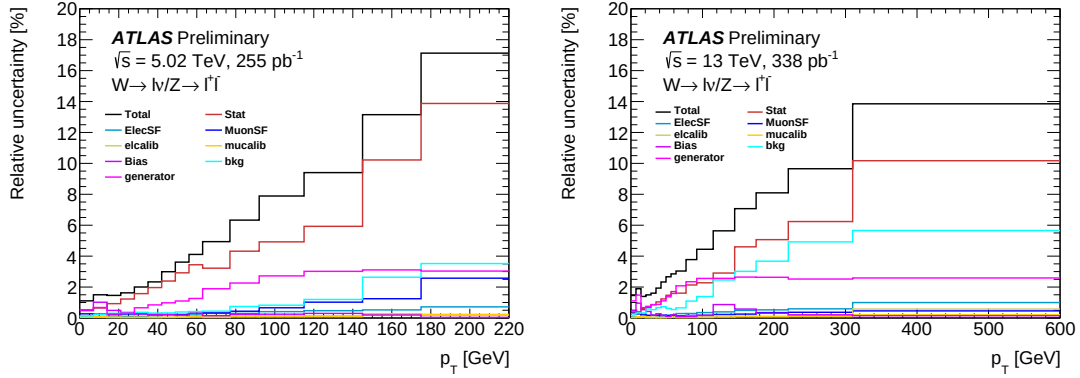


图 4.26 Breakdown of uncertainties for the ratio between the W and Z transverse-momentum distributions at 5 TeV (left) and 13 TeV (right).

Process	Cross section at $\sqrt{s} = 5$ TeV [pb]	Cross section at $\sqrt{s} = 13$ TeV [pb]	13/5 TeV Ratio
$W^+ \rightarrow \ell^+ \nu$	2228 ± 3 (stat.) ± 8 (sys.) ± 23 (lumi.)	4571 ± 3 (stat.) ± 21 (sys.) ± 44 (lumi.)	2.051 ± 0.03
$W^- \rightarrow \ell^- \bar{\nu}$	1385 ± 2 (stat.) ± 5 (sys.) ± 15 (lumi.)	3486 ± 3 (stat.) ± 18 (sys.) ± 34 (lumi.)	2.517 ± 0.04
$Z \rightarrow \ell \ell$	333.0 ± 1.2 (stat.) ± 2.2 (sys.) ± 3.3 (lumi.)	780.3 ± 2.6 (stat.) ± 7.1 (sys.) ± 7.1 (lumi.)	2.343 ± 0.03

表 4.6 Integrated fiducial cross sections for W and Z production in pb as well as the ratio of cross sections at 13 TeV and 5 TeV.

Processes	Cross-section ratio at $\sqrt{s} = 5$ TeV	Cross-section ratio at $\sqrt{s} = 13$ TeV
W^+/Z	6.69 ± 0.08	5.86 ± 0.09
W^-/Z	4.16 ± 0.05	4.47 ± 0.07
$W^\pm/Z$	10.85 ± 0.12	10.33 ± 0.15

表 4.7 Integrated cross-section ratios.

Table 4.6 gives the numbers of $Z \rightarrow \ell\ell$ and $W \rightarrow \ell\nu$ integrated fiducial cross sections at 5 and 13 TeV. The integrated $Z \rightarrow \ell\ell$ (including electron and muon channels) cross sections at 5 TeV is $333 \pm 1.2_{stat.} \pm 2.2_{sys.} \pm 3.3_{lumi.}$ pb. The integrated $Z \rightarrow \ell\ell$ cross sections at 13 TeV is $780.3 \pm 2.6_{stat.} \pm 7.1_{sys.} \pm 7.1_{lumi.}$ pb. In contrast to the differential cross sections, the integration benefits to the statistical uncertainty by merging the limiting dataset of low- μ runs together. So statistical uncertainty is much smaller than systematic and luminosity uncertainties. The luminosity uncertainty is the dominating uncertainty, which is 1% at 5 TeV and 0.9% at 13 TeV, as discussed in Section 3.5.1. This result is measured with slightly better uncertainty compared to fiducial Z boson cross sections measured at 7 TeV in^[66], which corresponding to $0.06\%_{stat} \oplus 0.3\%_{syst} \oplus 1.8\%$. The $W \rightarrow \ell\nu$ cross sections is different for the positive and negative charges of the W boson. Production of W^+ is larger than W^- . The W^+ integrated cross section is $2228 \pm 3_{stat.} \pm 8_{sys.} \pm 23_{lumi.}$ pb at 5 TeV and $(4571 \pm 3_{stat.} \pm 21_{sys.} \pm 44_{lumi.})$ pb at 13 TeV. The ratio of W^+ cross section at 13/5 TeV is 2.051 ± 0.03 . W^- integrated cross section is $(1385 \pm 2_{stat.} \pm 5_{sys.} \pm 15_{lumi.})$ pb at 5 TeV and $(3486 \pm 3_{stat.} \pm 18_{sys.} \pm 34_{lumi.})$ pb at 13 TeV. The ratio of W^- cross section at 13/5 TeV is 2.517 ± 0.04 . Similarly to the Z cross section measurements, the uncertainty in W cross section measurements are dominated by the luminosity uncertainty, the precision of W production cross section is better than the results in^[66] because of better luminosity determination.

Table 4.7 shows the ratios of the integrated cross sections of $W^+, W^-, W^\pm$ over the Z . W^+/Z cross section ratio is 6.69 ± 0.08 for 5 TeV and 5.86 ± 0.09 for 13 TeV results. The negative charged W^-/Z cross section ratio is 4.16 ± 0.05 at 5 TeV 4.47 ± 0.07 at 13 TeV. The $W^\pm$ is the direct sum of the cross section from positive and negative charged boson. The ratio of Summed W over Z cross section is 10.85 ± 0.12 at 5 TeV and 10.33 ± 0.15 at 13 TeV. It is clear that the W^+ cross section is significantly higher than W^- .

4.4 Comparisons To Predictions

In this section, we will compare the final p_T^Z data measurements as obtained in the the electron+muon combination (see Sec. 4.3.5) to an list of predictions.

Generically, predictions of vector boson p_T spectra can be sorted into two classes:

- Monte Carlo generators (MCs) that combine leading order (LO) or next-to-leading order (NLO) matrix elements and match them to parton showers and models for underlying event, hadronisation and particle decay to produce complete particle level events,
- Higher-order analytical calculations that combine fixed-order calculations (typically at NLO or NNLO or even near- N^3 LO) to resummation calculations (characterised by counting of next-to...-leading logarithms from NLL to N^4 LL).

All samples are used as generated without any corrections or modifications. The fiducial predictions following the selections discussed in Sec. 3.6. As the fiducial phase space is defined at Born QED level, either the electron or muon decay channels can be used and it was checked that both provide identical predictions.

The following MC predictions are extracted from official ATLAS MC production:

- POWHEG+PYTHIA8 AZNLO : This is the baseline MC used in this analysis. The POWHEGMC generator^[48–50,67] is used for the simulation at NLO loop of the hard-scattering processes of Z production and leptonic decay, It is interfaced to PYTHIA8.186^[51] for the modeling of the parton shower, hadronization, and underlying event, with the AZNLO set parameters tuned to 7 TeV $p_T^{\ell\ell}$ and ϕ^* measurements^[68]. The CT10 NLO PDF set^[69] is used for the parton shower.
- SHERPA2.2.1/2.2.5 : This is the alternative MC used in this analysis, for p_T reweighting (details in Section 4.3.2) and generator uncertainties. The production of V +jets was simulated with the SHERPA2.2.1 (13 TeV) or SHERPA2.2.5 (5 TeV)^[70].
- POWHEG+HERWIG7.2.1 : this sample follows the setup of POWHEG+PYTHIA8 AZNLO, but employs HERWIG7.2.1^[70,71] for the parton shower, hadronization, underlying event.
- PYTHIA8 AZ : This is the MC used in previous ATLAS W mass measurement^[17]. a LO + parton shower prediction using PYTHIA8 MEs and parton shower with the

CTEQ6L1 PDF set and the AZ set parameters tuned to describe 7 TeV p_T and ϕ^* measurements^[68].

All samples are generated in the full phase space and normalized to common NNLO cross sections. All samples are used as generated without any corrections or modifications. The all samples are propagated to the fiducial phase space as discussed in Section 3.6.

At this stage all comparisons are presented in Figures 4.27 and 4.28 . While the absolute distributions contain the most complete measurement, it is generally easier to factorize the discussion of the integrated fiducial cross sections from the shapes, therefore we anticipate a higher weight will be put on the normalized distributions. Concentrating on those, a few generic features can be observed that are valid across all final states and $\sqrt{s}$:

- The data is precise and discriminating up to about $p_T = 200$ GeV at 13 TeV and $p_T = 100$ GeV at 5 TeV.
- **Powheg+Pythia8 AZNLO** and especially **Pythia8 AZ** describe reasonably well the low- p_T region, but fail for $p_T \gtrsim 30 - 50$ GeV.
- **Powheg+Herwig 7.2.1** performs poorly across the whole spectrum.
- **Sherpa[2.2.1/5]** oscillate around the data in the region $p_T \lesssim 30$ GeV, this behaviour is somewhat improved in **Sherpa[2.2.11]**. SHERPA performs generally better than other predictions. Because

4.4.1 Consistency Checks

The consistency of unfolded p_T^Z results are cross-checked in this section. The first check is the comparison of the measurements using low- μ data with two different methods. One method is though precisely measured lepton quantities, $p_T^{\ell\ell}$. The other method is using the *hadronic recoil* method. Two methods base on the same dataset, event selections, efficiency and acceptance corrections. Thus the two methods should give the same results theoretically. But due to effects such as final state radiations and different detector response to lepton and jet energy, the two methods will not be the same. Moreover, in absence of neutrino in W events, the *hadronic recoil* is the only approach to measure p_T^W . Thus the compatibility of unfolded results using dilepton

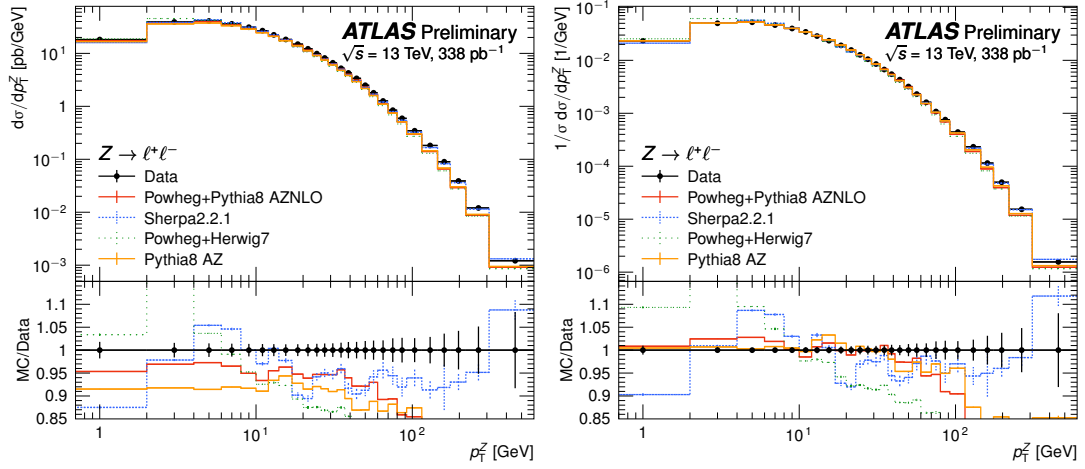


图 4.27 Measurements of absolute differential cross sections (left) and normalised differential distributions (right) at 13 TeV (black points) for Z compared to a set of MC predictions as described in the text.

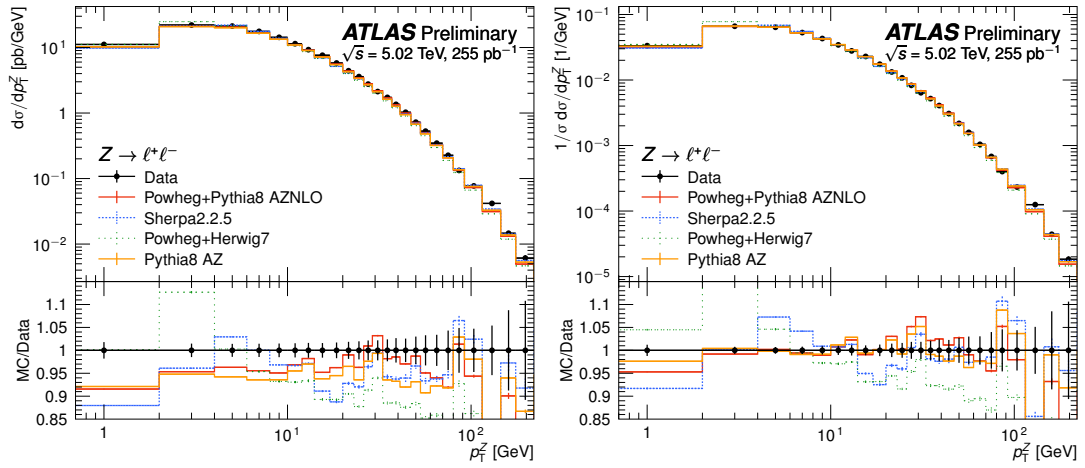


图 4.28 Measurements of absolute differential cross sections (left) and normalised differential distributions (right) at 5 TeV (black points) for Z compared to a set of MC predictions as described in the text.

and *hadronic recoil* methods are crucial validations for the p_T^W measurement. This is disbused in Section 4.4.1.2.

Previous p_T^Z measurement at $\sqrt{s} = 13$ TeV is published in^[72], through the transverse momenta of dilepton system. It would be interesting and meaningful to compare the p_T^Z results using dilepton method between low- μ analysis and standard pileup results. It is shown in Section 4.4.1.1.

4.4.1.1 Compatibility Study Of p_T^Z Measurements Between The Low- μ And The High- μ Analysis

Here we present the comparison of the low pile-up p_T^Z measurement at 13 TeV to the published ATLAS measurement of p_T^Z at 13 TeV using the full high pile-up dataset Ref^[72] shown in 4.29. The electron and muon channels are compared separately. Since the fiducial phase spaces in the two analyses are different (4.8), corresponding corrections must be taken into account.

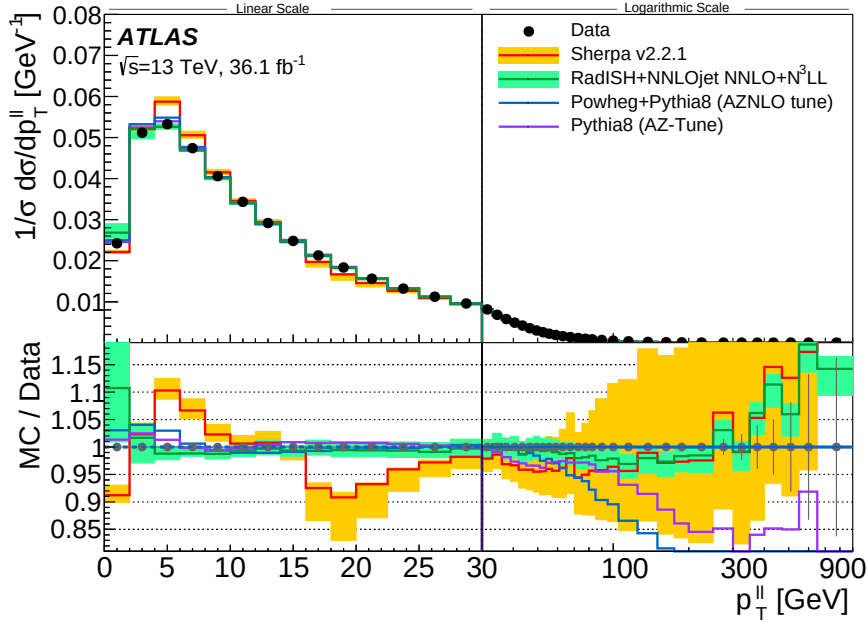


图 4.29 Unfolded p_T^Z results in the high- μ analysis^[72].

The only difference in fiducial phase space is the lepton p_T cut, which is 25 GeV in the low- μ analysis and 27 GeV in the high- μ analysis because in high- μ data, the trigger for p_T^l is 27GeV. A corresponding correction factor is applied to the high- μ distribution before comparison (reff:Correction). This correction factor is derived from the ratio of events in low-mu fiducial phase space to high-mu fiducial phase space, obtained from

MC estimation.

Fiducial	Low- μ Analysis	High- μ Analysis
η_l	$ \eta_l < 2.5$	$ \eta_l < 2.5$
p_T^l	$p_T^l > 25 \text{ GeV}$	$p_T^l > 27 \text{ GeV}$
m_{ll}	$66 \text{ GeV} < m_{ll} < 116 \text{ GeV}$	$66 \text{ GeV} < m_{ll} < 116 \text{ GeV}$

表 4.8 Comparison of fiducial phase space between low- μ and high- μ p_T^Z measurements.

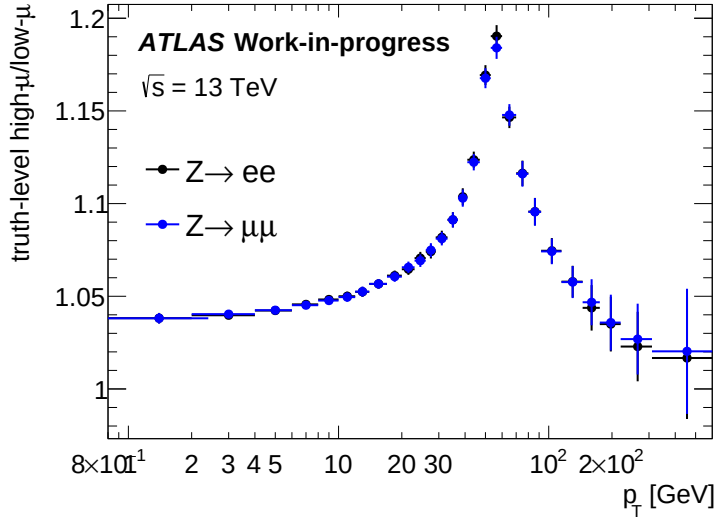


图 4.30 Ratio of truth-level predictions with the different fiducial phase spaces in the low- μ ($p_T^{\ell} > 25 \text{ GeV}$) and high- μ ($p_T^{\ell} > 27 \text{ GeV}$) analyses. The shown factors are to be multiplied to the high- μ cross sections as a function of $p_T^{\ell\ell}$. (Please disregard the flipped y-axis ratio label.)

To calculate the compatibility between the high- μ and low- μ measurements, a bin-by-bin χ^2 can be calculated using 4.29:

$$\chi^2 = \sum_i \frac{(p_{T,low-\mu}^i - p_{T,high-\mu}^i)^2}{\sigma^2(p_{T,low-\mu}^i) + \sigma^2(p_{T,high-\mu}^i) + 2 \times \text{Corr}(\sigma(p_{T,high-\mu}^i), \sigma(p_{T,high-\mu}^i))} \quad (4.29)$$

Generally, some of the uncertainties such as the lepton performance systematics will be correlated. However, in the low- μ analysis calibrations and corrections are mostly derived directly using the low- μ dataset itself^[73,74] while in the high- μ analysis, the calibrations and corrections are derived using standard ATLAS high- μ dataset,

thus the uncertainties can be considered as mostly uncorrelated. Even the high- μ analysis is dominated by the data and MC statistics, with subleading contributions from lepton efficiency and calibration uncertainties^[72]. Therefore, to very good accuracy we can treat the combined uncertainty as the quadratic sum of total uncertainties from each analysis. The bin-by-bin χ^2 is calculated using 4.30:

$$\chi^2 = \sum_i \frac{(p_{T,low-\mu}^i - p_{T,high-\mu}^i)^2}{\sigma^2(p_{T,low-\mu}^i) + \sigma^2(p_{T,high-\mu}^i)}, \quad (4.30)$$

where the uncertainties of the low- μ and high- μ measurements are the quadratic sums of their statistical and systematic uncertainties as is show in 4.31 and 4.32.

$$\sigma^2(p_{T,low-\mu}^i) = \sqrt{\sigma^2(low - \mu, stat.) + \sigma^2(low - \mu, syst.)} \quad (4.31)$$

$$\sigma^2(p_{T,high-\mu}^i) = \sqrt{\sigma^2(high - \mu, stat.) + \sigma^2(high - \mu, syst.)} \quad (4.32)$$

The p_T^Z distribution must also be re-binned in order to compare the two measurements because different binning was used in each analysis. The p_T^Z bins in the high- μ analysis are

[0, 2, 4, 6, 8, 10, 12, 14, 16, 18, 20, 22.5, 25, 27.5, 30, 33, 36, 39, 42, 45, 48, 51, 54, 57, 61, 65, 70,

75, 80, 85, 95, 105, 125, 150, 175, 200, 250, 300, 350, 400, 470, 550, 650, 900, 2500]

while for the low- μ analysis, the binning is

[0, 2, 4, 6, 8, 10, 12, 14, 17, 20, 23, 26, 29, 33, 37, 41, 47, 53, 60, 70, 80, 92,

115.0, 145.0, 175.0, 220.0, 310.0, 600.0]

To account for this difference, the high- μ p_T^Z distribution is re-binned to the low- μ binning. Whenever the rebinning is not trivially possible, the bin values in the new re-binned comparison histograms are weighted by bin width, and the relative uncertainty is the error of the bin in old binning which contains the centre of the low- μ binning. E.G. while re-binning 14,16,18,20 (in high-mu binning) to 14,17,20 (in low-mu binning):

$$\frac{d\sigma^{high-\mu, rebinned}}{dp_T^{bin(14,17)}} = \frac{\frac{d\sigma^{high-\mu}}{dp_T^{bin(14,16)}} \times 2 \text{ GeV} + \frac{d\sigma^{high-\mu}}{dp_T^{bin(16,18)}} \times 1 \text{ GeV}}{3 \text{ GeV}}$$

The relative error is taken from the bin where the centre of new bin is located, e.g. for low- μ bin (14,17) GeV, the centre is 15.5 GeV, which is in the high- μ bin (14,16) GeV, the relative error of bin (14,16) GeV for the re-binned bin (14,17) GeV.

This rebinning method is only approximate as it assumes the cross-section to be flat within a bin, but allows to consider more bins than just taking the smallest common binning, which would force us to e.g. have a big bin between 14 and 20 GeV.

Comparisons between high- μ and low- μ measurements of p_T^Z distributions are shown in 4.31. Very good agreement is observed between the high- μ measurement in red and the low- μ measurement in black. In most of the bins, the ratio is within 1σ . The χ^2 values are $\chi^2/\text{dof} = 11.7/26$ in the $Z \rightarrow ee$ channel and $\chi^2/\text{dof} = 15.3/26$ in the $Z \rightarrow \mu\mu$ channel.

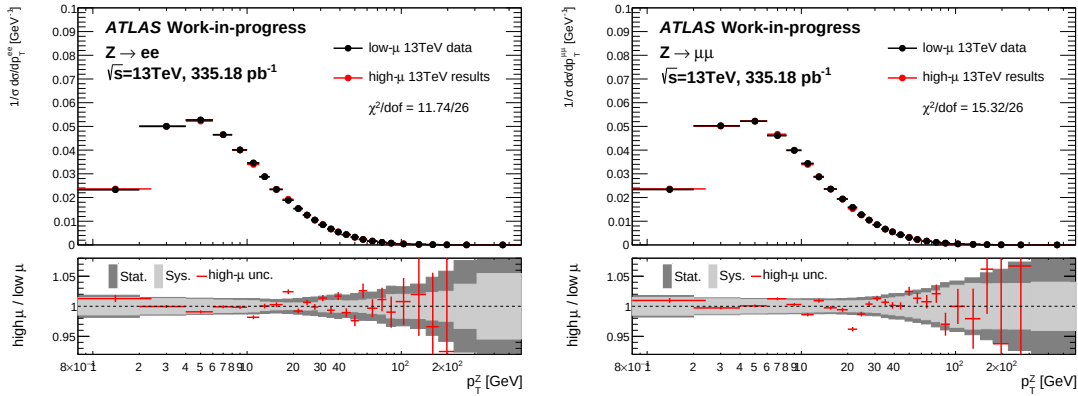


图 4.31 Compatibility of the p_T^Z measurement between the high- μ and low- μ analyses at the unfolded level. The left plot is the $Z \rightarrow ee$ channel and the right plot is the $Z \rightarrow \mu\mu$ channel.

4.4.1.2 Compatibility Between The Dilepton Method And Hadronic Recoil Method For Measuring p_T^Z

Here we present studies on the compatibility of the unfolded p_T^Z spectra using the dilepton system ($p_T^{\ell\ell}$) and the hadronic recoil system (u_T). These studies help validate the p_T^W measurement as the hadronic recoil method can here be directly compared to the dilepton method.

A direct comparison of the unfolded p_T^Z spectrum using $p_T^{\ell\ell}$ and u_T distributions is shown in Figure 4.32. The data here are identical to that shown in Figures 4.19 and 4.21. While this gives a first sense of compatibility, it falls short by not treating the uncertainties in the ratio correctly, as there are correlations in both statistical and systematic uncertainties.

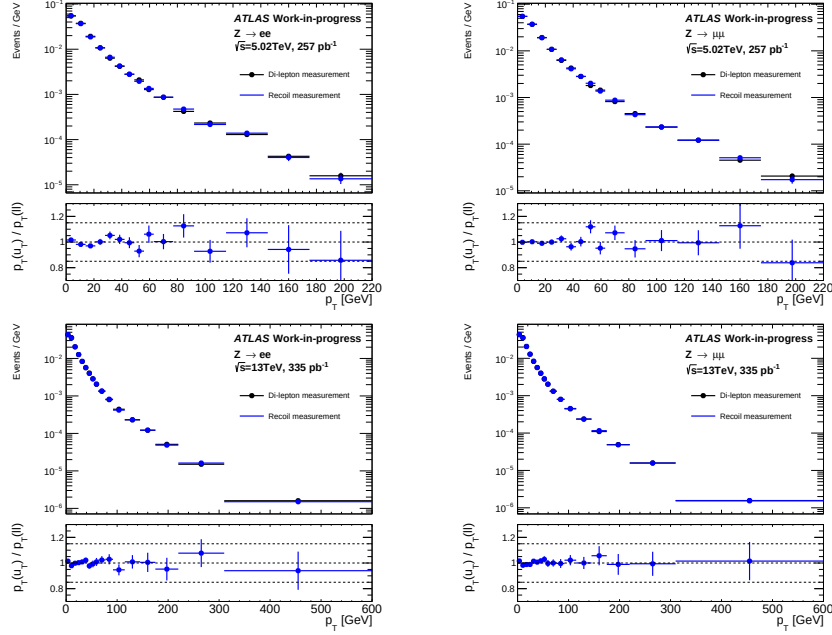


图 4.32 Comparisons of the p_T^Z measurements using the p_T^Z (ll) and p_T^Z (u_T) using only statistical uncertainty without considering the correlations introduced by unfolding the same data events twice. Disregard the highest u_T bin at 5 TeV (top row), which is not part of the recoil-based measurements.

The correlated uncertainties in the unfolded $p_T^Z(\ell\ell)$ and $p_T^Z(u_T)$ measurements are taken into account using the covariances between the two measurements. The statistical uncertainty is found to dominate and estimated through the bootstrap method with 4000 toys around the nominal $p_T^Z(\ell\ell) - p_T^Z(u_T)$. The statistical covariance is therefore estimated as:

$$C_{i,j}^{stat.} = \frac{1}{N_{toys} \times (\int p_T)^2} \sum_k [(p_{T,toy[k]}^i(ll) - p_T^i(ll)) - (p_{T,toy[k]}^i(u_T) - p_T^i(u_T))] \times [(p_{T,toy[k]}^j(ll) - p_T^j(ll)) - (p_{T,toy[k]}^j(u_T) - p_T^j(u_T))]. \quad (4.33)$$

Here, i and j are the bins in p_T , and k loops over all bootstrap toys. The systematic

covariance matrices are built similarly:

$$C_{i,j}^{syst.} = \frac{1}{(\int p_T)^2} \sum_k [(p_{T,NP[k]}^i(l) - p_T^i(l)) - (p_{T,NP[k]}^i(u_T) - p_T^i(u_T))] \times \\ [(p_{T,NP[k]}^j(l) - p_T^j(l)) - (p_{T,NP[k]}^j(u_T) - p_T^j(u_T))]. \quad (4.34)$$

The covariance matrices from statistics and each systematic nuisance parameter are summed directly to the total covariance matrix, and then normalized to the unit by divided by squared of the integral of p_T (or u_T) distribution. Thus the compatibility could be estimated by the χ^2 computed as

$$\chi^2 = \Delta^T(p_T, u_T) C^{-1} \Delta(p_T, u_T), \\ \text{where } \Delta(p_T, u_T)^i = \frac{1}{\int p_T} (p_T^i - u_T^i) \quad (4.35)$$

The leading uncertainties are the data statistical uncertainties, recoil, components of the bias uncertainty, and only at 13 TeV the lepton calibration, and the corresponding covariance matrices are shown in Figs. 4.33, 4.34, 4.35, 4.36.

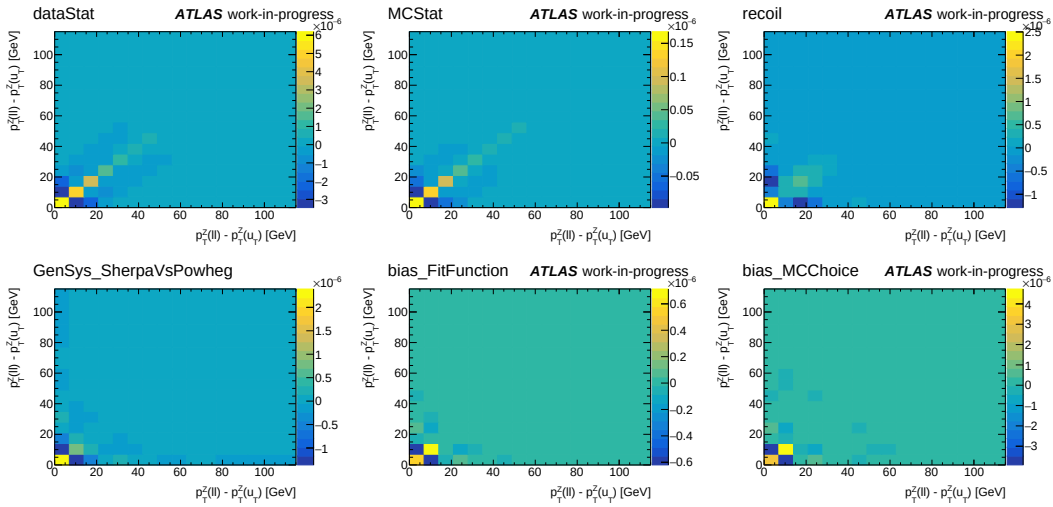


图 4.33 Covariance matrices for $p_T^Z(\ell\ell) - p_T^Z(u_T)$ in the $Z \rightarrow ee$ channel at 5 TeV for the leading uncertainties: data statistics, MC statistics, recoil calibration, generator systematics, unfolding fit function choice, unfolding MC choice. All other uncertainties are also included, but are at least a factor 10 smaller and thus not shown.

The corresponding correlation matrices for $p_T^Z(\ell\ell) - p_T^Z(u_T)$ are shown in Figs 4.37, 4.38, 4.39, 4.40, this time for all components even those that have an almost negligible error magnitude.

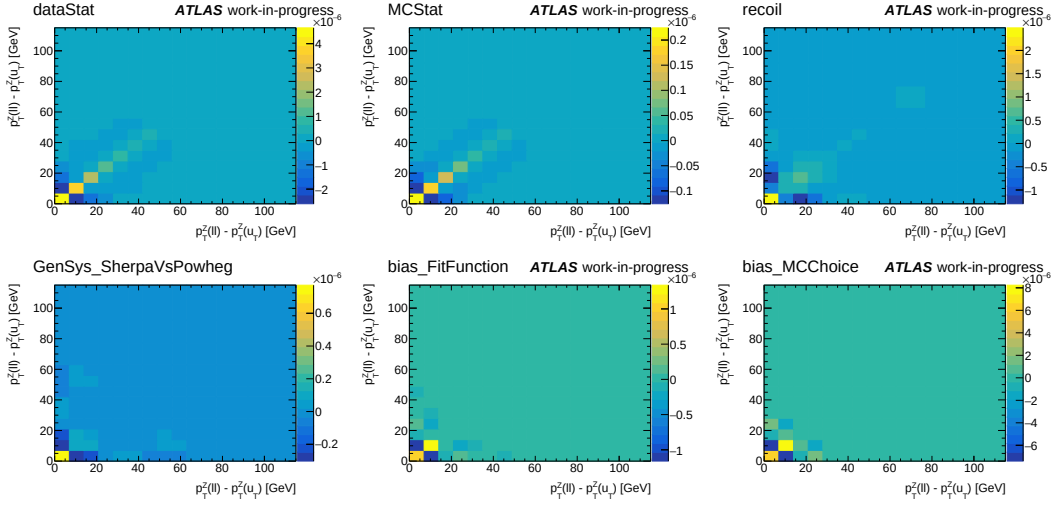


图 4.34 Covariance matrices for $p_T^Z(\ell\ell) - p_T^Z(u_T)$ in the $Z \rightarrow \mu\mu$ channel at 5 TeV for the leading uncertainties: data statistics, MC statistics, recoil calibration, generator systematics, unfolding fit function choice, unfolding MC choice. All other uncertainties are also included, but are at least a factor 10 smaller and thus not shown.

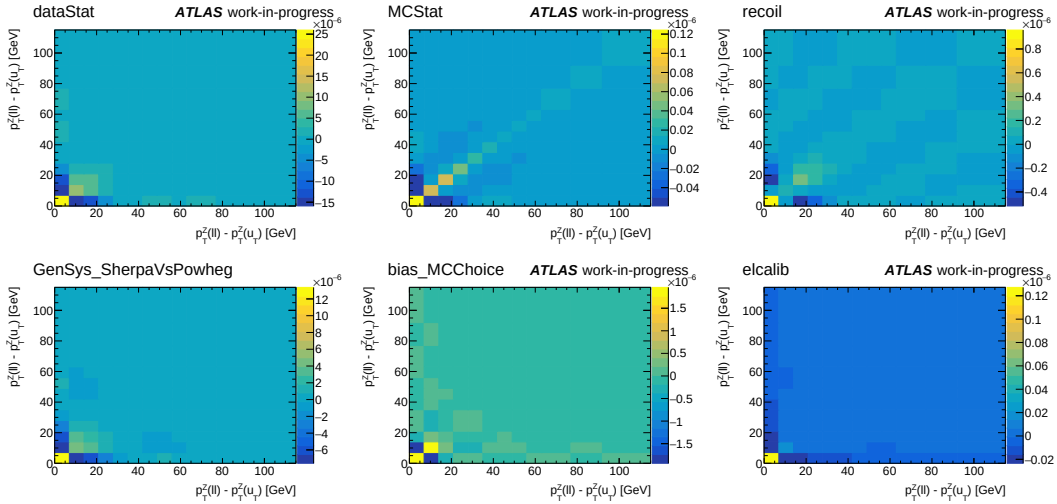


图 4.35 Covariance matrices for $p_T^Z(\ell\ell) - p_T^Z(u_T)$ in the $Z \rightarrow ee$ channel at 13 TeV for the leading uncertainties: data statistics, MC statistics, recoil calibration, generator systematics, unfolding MC choice, electron calibration. All other uncertainties are also included, but are at least a factor 10 smaller and thus not shown.

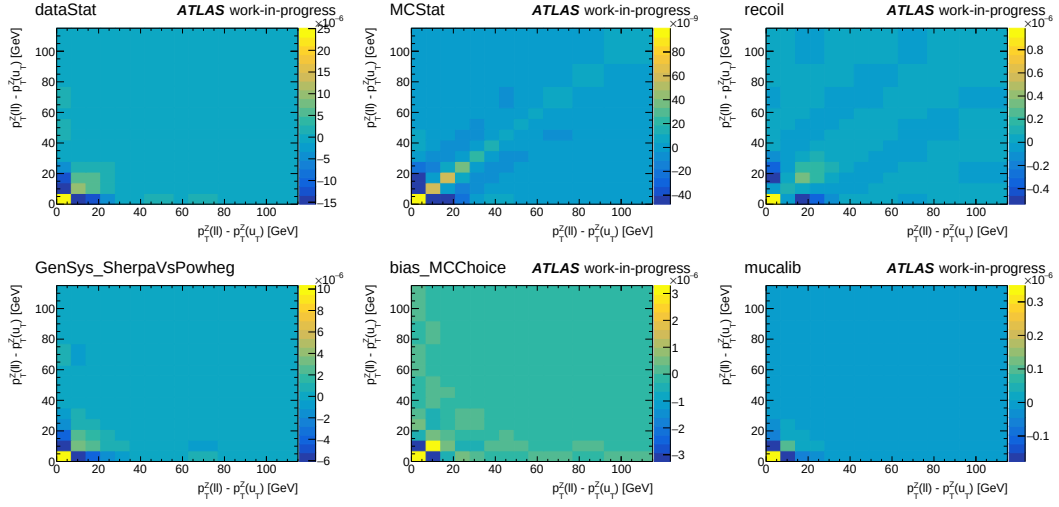


图 4.36 Covariance matrices for $p_T^Z(\ell) - p_T^Z(u)$ in the $Z \rightarrow \mu\mu$ channel at 13 TeV for the leading uncertainties: data statistics, MC statistics, recoil calibration, generator systematics, unfolding MC choice, electron calibration. All other uncertainties are also included, but are at least a factor 10 smaller and thus not shown.

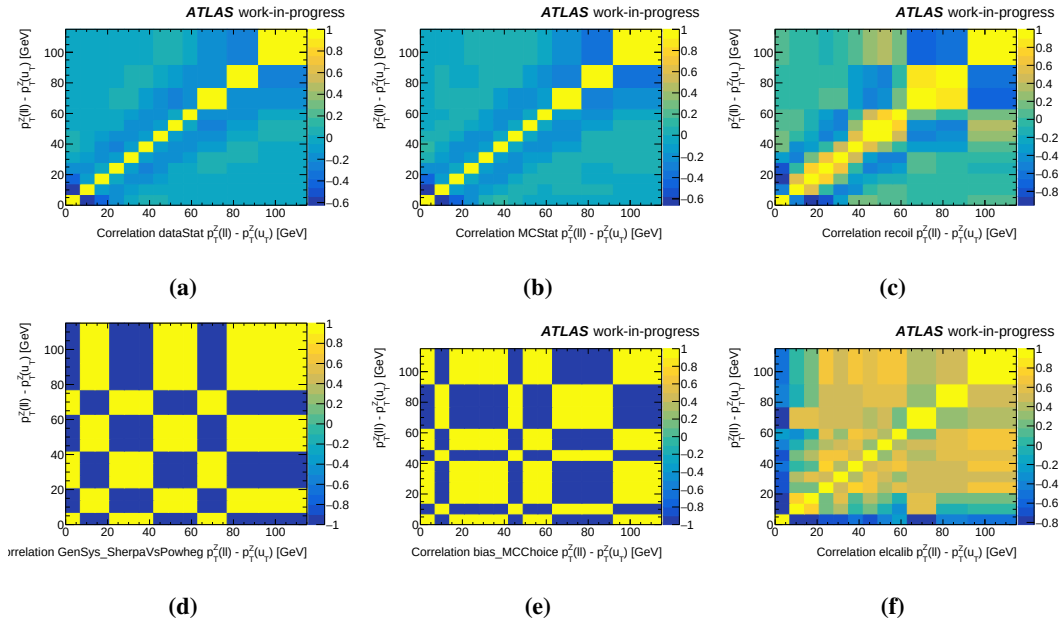


图 4.37 Correlation matrices for each uncertainty in the $Z \rightarrow ee$ channel at 5 TeV. (a) data statistics. (b) MC statistics. (c) recoil calibration. (d) Generator systematics. (e) unfolding MC choice (f) electron calibration

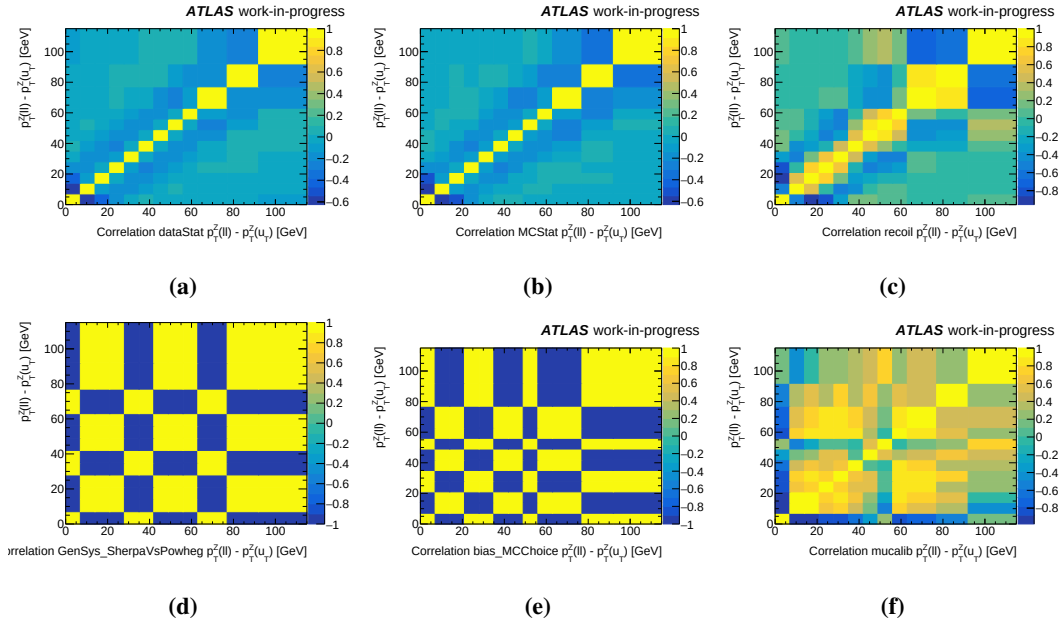


图 4.38 Correlation matrices for each uncertainty in the $Z \rightarrow \mu\mu$ channel at 5 TeV. (a) data statistics. (b) MC statistics. (c) recoil calibration. (d) Generator systematics. (e) unfolding MC choice (f) muon calibration

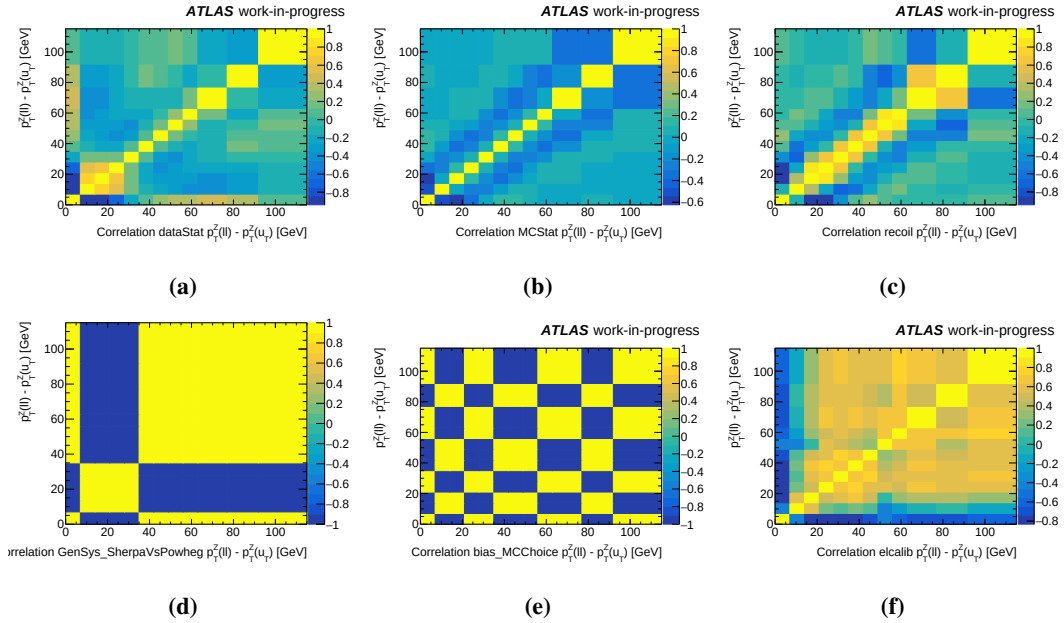


图 4.39 Correlation matrices for each uncertainty in the $Z \rightarrow ee$ channel at 13 TeV. (a) data statistics. (b) MC statistics. (c) recoil calibration. (d) Generator systematics. (e) unfolding MC choice (f) electron calibration

Considering the statistical fluctuations due to the small dataset and the anti-correlations in the recoil calibration in $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ channels, χ^2 compatibility calculations are then computed with $p_T(e) + p_T(\mu)$ combined results for both center-of-mass energies. The combination is considered in the following steps : (This is ONLY for the $p_T(l\bar{l})/p_T(u_T)$ comparibility)

- For $p_T^{\ell\ell} - u_T$, it is directly summed in two channels: $\Delta' = (p_T(l\bar{l})^e + p_T(l\bar{l})^\mu) - (p_T(u_T)^e + p_T(u_T)^\mu)$
- Covariance matrices are re-calculated from the covariances from two channels.
- For statistic covariance, it is considered uncorrelated between electron and muon channels, so they are added directly : $Cov_{i,j} = Cov_{i,j}^e + Cov_{i,j}^\mu$
- For systematic components, correlations are taken into account.

$$Cov_{i,j} = Cov_{i,j}^e + Cov_{i,j}^\mu + \sqrt{Cov_{i,i}^e Cov_{j,j}^\mu} + \sqrt{Cov_{j,j}^e Cov_{i,i}^\mu}$$

the combined results are shown in Table 4.9. The degrees of freedom (dof) is $N_{\text{bins}} - 1 = 14$ at 5 TeV and 16 at 13 TeV due to the additional constraint of same total cross section. As can be seen from the table, the compatibility is generally good at both center-of-mass energies. Better agreements are seen at 13TeV, because of the larger dataset at 13 TeV allows better recoil calibration using the dilepton system.

χ^2	5 TeV	13 TeV
Stat.+ Sys. Uncertainty	14.9 / 14	8.7 / 16
p -value	38.5%	85.0%

表 4.9 χ^2/dof results for the $p_T^Z(\ell\bar{\ell}) - p_T^Z(u_T)$ compatibility at 5 and 13TeV. The last row gives the equivalent χ^2 probability.

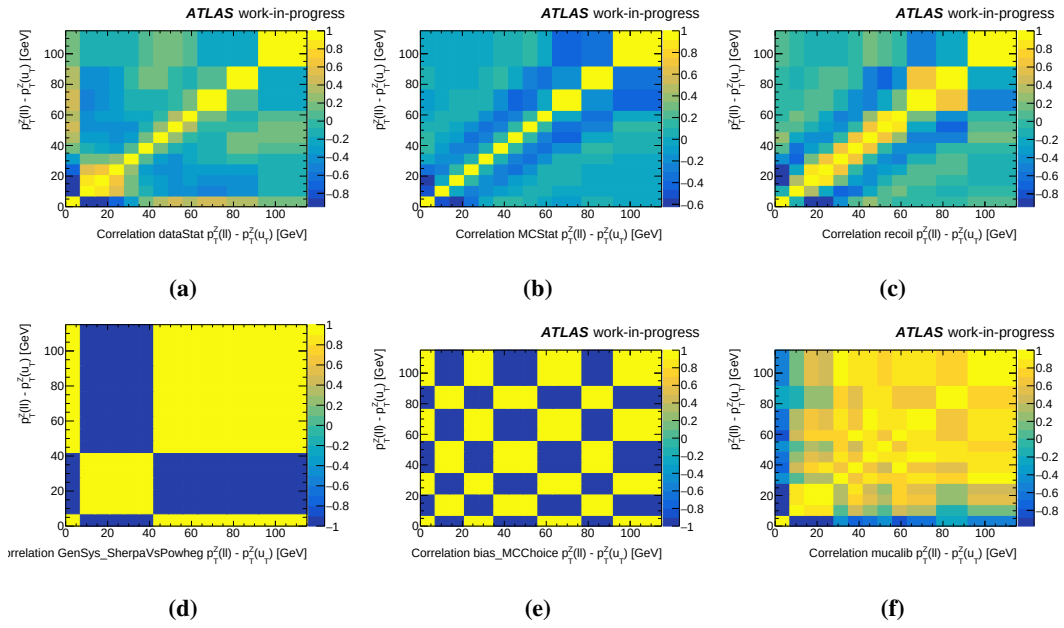


图 4.40 Correlation matrices for each uncertainty in the $Z \rightarrow \mu\mu$ channel at 13 TeV. (a) data statistics. (b) MC statistics. (c) recoil calibration. (d) Generator systematics. (e) unfolding MC choice (f) muon calibration.

4.5 Summary of p_T^Z measurement

The first measurement of the $p_T^{\ell\ell}$ (as well as u_T) Z boson transverse momentum spectrum measurement in proton-proton low-pileup collisions at a center-of-mass energy of $\sqrt{s} = 13$ and 5 TeV is presented. It uses a data set of an integrated luminosity of 335 pb^{-1} at 13 TeV and 257 fb^{-1} at 5 TeV recorded by the ATLAS detector at the LHC in 2017 and 2018, under special data conditions that the pileup μ is approximately 2. The measurements use both muon and electron channel of the $Z \rightarrow \ell\ell$ decay in a fiducial phase space within the detector acceptance. Moreover, the low-pile conditions allow good reconstruction of the hadronic decay products from the soft gluon/quark recoil against the Z. The calibration of the transverse momenta of the recoil, calibrated by the precisely measured di-lepton p_T , provides better measurement on the transverse momenta of W. This measurement is a medium step towards a high-precision measurement on the W boson mass, m_W . This is also the main physics motivation for the dedicated low pileup dataset and the full analysis. Benefit from the p_T^Z and p_T^W measurement, it is promising that the group could achieve a m_W measurement within $\pm 10 \text{ MeV}$ uncertainty, which is better than the world average from all experiments before. It is also close to the precision of the Electro-Weak fit: $\Delta m_W = 8 \text{ MeV}$.

第 5 章 Future of W and Z Precision Analysis

The current precision analysis on the properties of W and Z bosons are limited by many factors, one of which is the statistical uncertainty. As shown in low- μ analysis Section 4.3.4.2, the leading contribution among all uncertainty sources is the statistical uncertainty, especially at 5 TeV. In the future, the upgrade of LHC, namely High-Luminosity LHC, is going to take much more data than what we have for now, so the precision measurements will continue to be done.

This chapter is organized in the following: Section 5.1 shows an overview of the HL-LHC and the potential for m_W measurements using HL-LHC. Section 5.2 presents my qualification task in the ATLAS ITk upgrade project. Section 5.3 discusses my work on the High-Granularity-Timing-Detector, which is a new detector to be installed in ATLAS for LH-LHC period.

5.1 High-Luminosity LHC and the Potential on M_W Measurements

To sustain and extend its discovery potential, CERN has planned to upgraded it, named as High-Luminosity Large Hadron Collider (HL-LHC). The HL-LHC will provide an order of magnitude more data starting from 2027, allowing precision tests of the properties of the Higgs boson and improved sensitivity to a wealth of new-physics scenarios. At that time the LHC will have been upgraded to reach a peak instantaneous luminosity of $7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, which corresponds to an average of about 200 inelastic proton-proton collisions per beam-crossing. This program aims to provide a total integrated luminosity of 3000 fb^{-1} by 2035^[75].

These precision measurements could reveal discrepancies with the SM predictions, which in turn could inform us about the energy scale of beyond-SM physics. In addition to improving SM measurements, the upgraded detectors and trigger systems being developed and constructed for the HL-LHC era will enable direct searches to better target new physics with challenging signatures. To achieve these goals, it will be essential to achieve a detailed understanding of the detector performance as well as to measure the

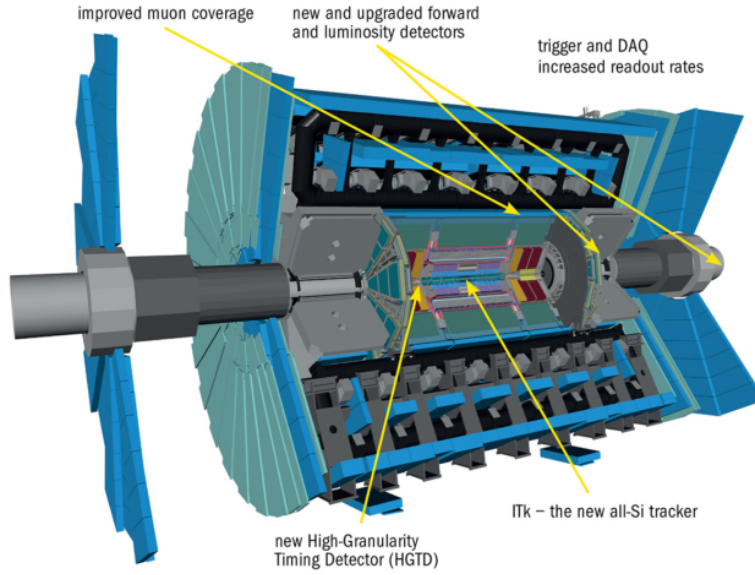


图 5.1 Schematic of the major upgrades to the ATLAS detector for the HL-LHC era. It includes changes to the trigger and data-acquisition systems, a new all-silicon tracker, a new High-Granularity Timing Detector,

integrated luminosity of the collected dataset to 1% precision.

To handle the increased number of interactions when proton bunches collide at the HL-LHC, the ATLAS collaboration is working hard to upgrade its detectors with state-of-the-art instrumentation and technologies. These new detectors will need to cope with challenging radiation levels, higher data rates and an extreme high-occupancy environment. Upgrades will include changes to the trigger and data-acquisition systems, a completely new ITk, as well as a new silicon timing detector, namely the High-Granularity Timing Detector. Figure 5.1. I have worked on both the upgrade for ITk and HGTD.

Proton-proton collision data at low pile-up are of large interest for W precision physics using the upgraded LHC and detectors. Potential of a dedicated dataset collected at low instantaneous luminosity and moderate pile-up for the measurement of the m_W at the HL-LHC is investigated by ATLAS^[76]. The value of such low pileup data lies in the optimal reconstruction of missing transverse momentum allowed by the low detector occupancy, and in the extended pseudorapidity coverage of the upgraded ATLAS detector. Both effects allow a reduction of PDF uncertainties below what can be achieved using data from ATLAS Run 1 and Run 2. With HL-LHC, the W production cross section is large enough to achieve small statistical uncertainties

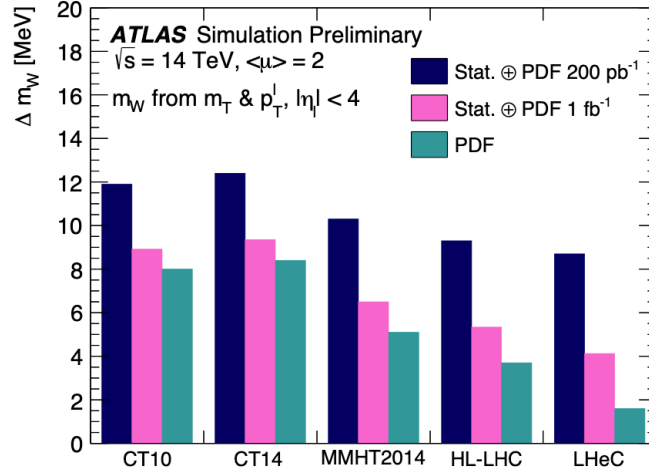


图 5.2 Measurement uncertainty for lepton acceptance regions and centre-of-mass energies, for combined fits to the p_T^ℓ and m_T distributions, using 200 pb^{-1} data collected at each energy in HL-LHC. With the much higher luminosity at HL-LHC, it is easy to collect enough data to make a better m_W measurement than the current world average.^[76]

in a moderate running time. At $\sqrt{s} = 14 \text{ TeV}$ and for an instantaneous luminosity of $L \approx 5 \times 10^{32} \text{ cm}^{-2} \text{ s}^{-1}$, corresponding to two collisions per bunch crossing on average at the LHC, about 2×10^6 W boson events can be collected in one week. Such a sample provides a statistical sensitivity at the percent level for measurements of the W boson transverse momentum distribution, and of about 10 MeV for a measurement of m_W .

Additional potential is provided by the new tracking detector, the ITk, which extends the coverage in pseudorapidity beyond $|\eta| < 2.5$ to $|\eta| < 4$. The increased acceptance allows W-boson measurements to probe a new region in Bjorken x at $p_T^W \approx m_W^2$. This will in turn allow further constraints on the W parton density functions (PDFs) from cross section measurements, and reduce PDF uncertainties in the measurement of m_W . The preliminary estimated uncertainty using 200 pb^{-1} low- μ data collected with HL-LHC is shown in Figure 5.2

5.1.1 ITk Upgrade And The Benefits To Precision W And Z Measurement

One important design goal for the ITk Pixel Detector is to maximize its ability to help rejecting pile-up contributions to jet and missing transverse energy (E_T^{miss}) reconstruction. This can be achieved using the separation along z of primary and pile-up

vertices. During Run 1 and Run 2 ATLAS developed several jet-vertex tagging methods to identify and remove pile-up contributions to jet reconstruction. In addition, ATLAS is further developing a particle flow algorithm^[77] to improve the combination of calorimeter and tracking information for the jet and E_T^{miss} reconstruction. A major limitation of the current detector is that track-based pile-up suppression is only possible for jets inside the Inner Detector acceptance of $|\eta| < 2.5$. The ITk Pixel Detector will significantly extend the tracker acceptance to $|\eta| < 4$.

To meet all of the requirements of a charged particle close to the beamline at the HL-LHC, it presents a unique challenge for the design of an all-silicon system that consists of a Pixel Detector at small radius and a large area Strip Detector surrounding it. The ITk will have to operate over the entire LHC Phase II program. In order to cope with these requirements, and to maintain the same tracking performance as the present ATLAS Inner Detector, the layout of the ITk required a careful optimization.

The layout of ITk is shown in Figure 5.3^[78]. The detector design combines precision central tracking in the presence of an average of 200 pile-up events with the ability to extend the tracking coverage to a pseudorapidity of 4 while maintaining excellent tracking efficiency and performance. The ITk comprises of two subsystems: a Strip Detector surrounding a Pixel Detector. The Strip Detector covers the barrel region up to $|\eta| < 2.7$, and the Pixel Detector extending the coverage to $|\eta| < 4$. My worked is on the Pixel Detector part.

In comparison with the Run 2 configuration, the improved tracking, the absence of the transition radiation detector, and the increased pile-up require a new optimization of the electron identification algorithm. Tracks, and their vertex association information, can be used to mitigate pile-up effects in the jet and E_T^{miss} reconstruction. During Runs 1 and 2, ATLAS developed several jet vertex-tagging methods to identify and remove pile-up jets.^[79,80] A major limitation of the current track-based pile-up suppression methods for jets is that they are not applicable to jets outside the inner tracker detector acceptance. The extension from the current $|\eta| < 2.5$ tracker acceptances to $|\eta| < 4$ of the ITk will enable these techniques to be employed in the forward region to reject jets due to pile-up interactions.

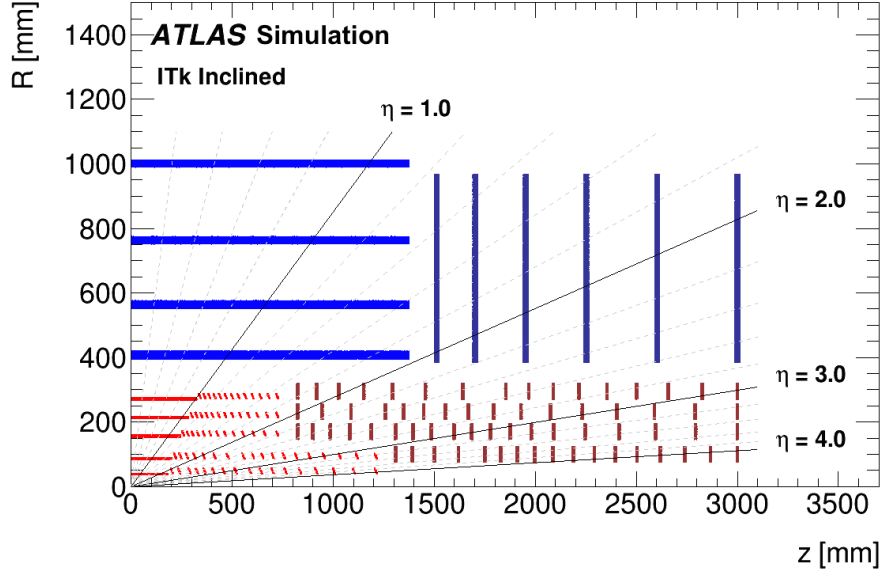


图 5.3 Schematic layout of the ITk for the HL-LHC phase of ATLAS. Here only one quadrant and only active detector elements are shown. The horizontal axis is the axis along the beam line with zero being the interaction point. The vertical axis is the radius measured from the IP. The outer radius is set by the bore of the solenoid.

With new ITk Pixel detectors, the E_T^{miss} reconstruction significantly benefits from the increased tracker acceptance that enables pile-up jet rejection in the forward region. The additional gain in the soft term using tracks between $|\eta|$ of 2.5 and 4 also help in the improvement. Overall the E_T^{miss} performance even at an average of 200 pile-up events benefits from the excellent pile-up control using the new ITk. E_T^{miss} measurement is dominated by the hadronic recoil measurement using the LAr calorimeter. However, the ATLAS LAr calorimeter has the disadvantage that it has a relatively slow response time of 600 ns, and thus the calorimeter signal is integrated over 24 bunch crossings. The high pile-up further degrades the E_T^{miss} resolution, so that it is advantageous to use a track-based E_T^{miss} calculation for the soft-term component. Figure 5.5 shows the resolution of the x- and y-components of the E_T^{miss} as function of the number of primary vertices using track information for $|\eta| < 2.7$ (red) and using this information for $|\eta| < 4.0$ (black) for samples of POWHEG+PYTHIA $\hat{t}\hat{t}$ events with $\langle \mu \rangle = 200$. It is seen that the resolution is about 30% better when using tracks up to $\eta = 4.0$. This improvement is primarily explained by the removal of forward pile-up jets. There is also a small improvement from extending the measurement of the soft-term component of the E_T^{miss}

out to $|\eta| < 4.0$.

Figure 5.4 shows the efficiency for pile-up jets as a function of the efficiency for hard-scatter jets with $20 < p_T < 40$ GeV, in three different $|\eta|$ regions, using PYTHIA8 dijets events with $\langle \mu \rangle = 200$. It is seen that even at high η , beyond the present tracker acceptance, a good discrimination is achieved. In the physics benchmark studies of ITk upgrade, a pile-up jet efficiency of 2% (i.e. a rejection of 50) is assumed, corresponding to a jet selection efficiency of 86% for $|\eta| < 1.5$ and 80% for $|\eta| > 2.9$.

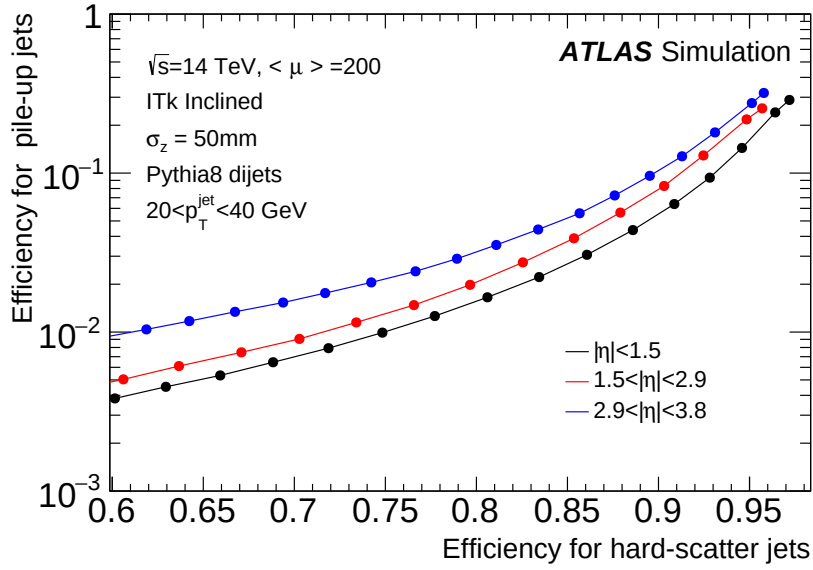


图 5.4 The efficiency for pile-up jets as a function of the efficiency for hard-scatter jets with $20 < p_T < 40$ GeV.

5.1.2 HGTD And The Benefits To Precision W And Z Measurement

A powerful new way to mitigate the effects of pileup is to use high-precision timing information to distinguish between collisions occurring close in space but well-separated in time. Therefore a High-Granularity Timing Detector, based on low gain avalanche detector technology, is studied for the ATLAS Phase-II upgrade. HGTD will improve the detector physics performance in the forward region, covering the pseudo-rapidity region between 2.4 and 4.0. The target average time resolution per track using HGTD detector is 30 ps at the start of lifetime, increasing to 50 ps at the end of HL-LHC operation. The high-precision timing information improve the forward object reconstruction, complementing the capabilities of the upgraded Inner Tracker (ITk) in

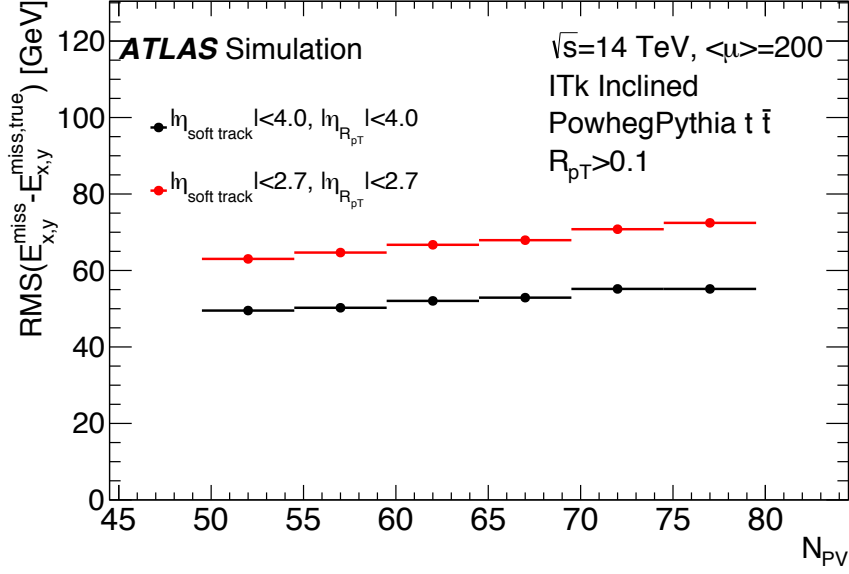


图 5.5 The resolutions of the x and y components of E_T^{miss} for the $|\eta| < 2.7$ (red) and $|\eta| < 4.0$ (black) Inner Tracker acceptance ranges for samples of Powheg+Pythia $t\bar{t}$ events with $\langle \mu \rangle = 200$, as a function of the number of reconstructed primary vertices.

the forward regions of ATLAS and leading to an improved performance for both jet and lepton reconstruction. These improvements benefit the hadronic recoil measurements for W and Z precision analysis at the HL-LHC. In addition, the HGTD offers unique capabilities for the online and offline luminosity determination, an important requirement for cross section measurements.

Taking into account the space constraints of the existing ATLAS Experiment, the HGTD will be located in the gap region between the barrel and the end-cap calorimeters, at a distance in Z of approximately ± 3.5 m from the nominal interaction point. This region lies outside the ITk volume and in front of the end-cap and forward calorimeters. The position of the two vessels for the HGTD within the ATLAS detector is shown in Figure 5.6.

5.1.2.1 Suppression of pileup jets

The reject pile-up jets will allow to use the data from HL-LHC to perform precision physics, otherwise it would not be possible. We expect to be able to measure hadronic recoil with the same precision, as in this thesis but in a situation with higher pile-up, which will allow us to collect larger data samples, reducing the low-statistics problem.

in this analysis.

In the study from^[81], using tracks with $p_T > 1$ GeV, jets are reconstructed from clusters of calorimeter energy deposits with radius parameter $R = 0.4$. Reconstructed hard-scatter jets are required to be within $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\Phi)^2} < 0.3$ of a truth jet with $p_T > 10$ GeV. Figure 5.7 shows the relative pileup-jet rate for relatively low- p_T jets, as a function of pseudorapidity. A significant improvement is observed at larger values of η where the z impact parameter resolution is worse and timing information becomes more important to associate tracks to vertices.

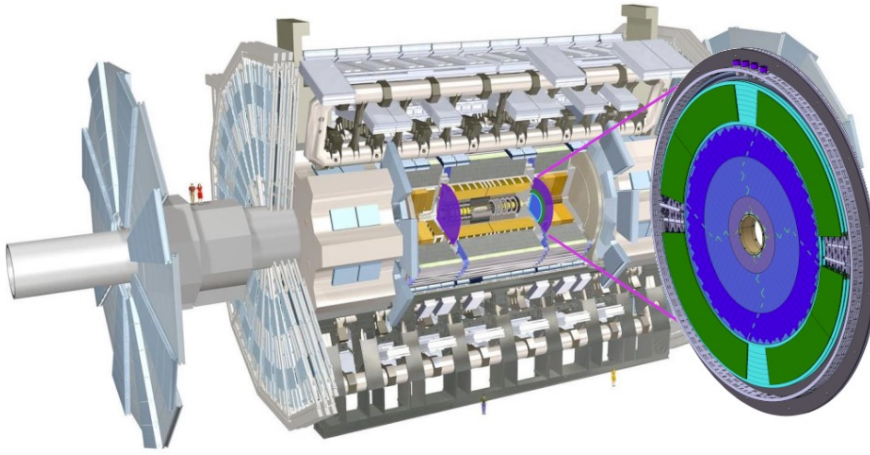


图 5.6 Position of the HGTD within the ATLAS Detector. The HGTD acceptance is defined as the surface covered by the HGTD between a radius of 120 mm and 640 mm at a position of $z = \pm 3.5$ m along the beamline, on both sides of the detector.

5.1.2.2 Improvement On Isolation Efficiency

Another key experimental requirement for the precision measurement of W and Z properties, is the requirement of the lepton isolation, as discussed in Section ???. The HGTD, together with the ITK, can prevent the negative effects of pileup on the isolation of the leptons. Studies show that the isolation efficiency will only slightly degrade, due to pileup, as compared to the results described in this thesis.^[81] In the forward region, the relatively large z window required to associate tracks to the primary vertex results in increased pileup track contamination, which consequently degrades the isolation efficiency. The association of a time to the lepton track can be used to reject tracks within the isolation cone which come from pileup interactions spatially close.

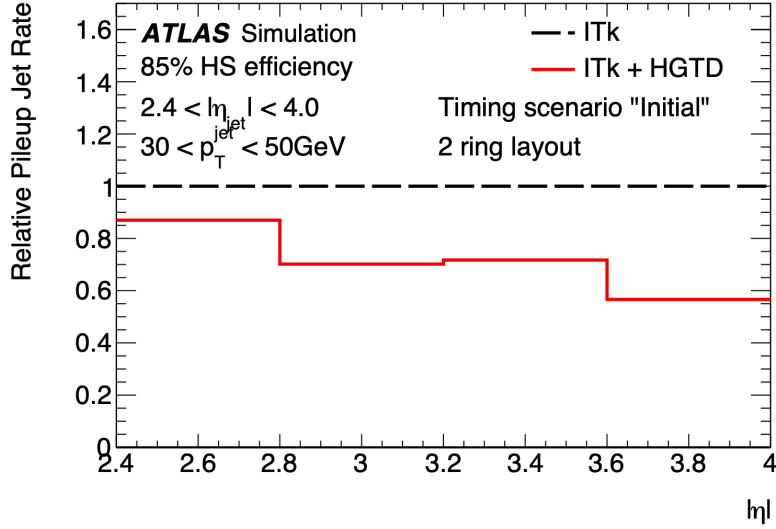


图 5.7 Relative pileup jet rate as a function of jet pseudorapidity, for jets with $30 \text{ GeV} < p_T < 50 \text{ GeV}$.

As studied in^[81], electron decayed from Z bosons in the forward region in acceptance passing the standard ATLAS “medium” identification criteria are selected. The electron track is defined as the track closest to the calorimeter cluster of the electron, out of those that have a ratio of track p_T to transverse cluster energy greater than 0.1. In order to improve the lepton isolation definition, the time of all tracks with $p_T > 1 \text{ GeV}$ which are within the $\Delta R < 0.2$ isolation cone are compared with the time of the electron track. If the time difference between the two is larger than twice the quadratic sum of the timing resolution of both tracks, or if the surrounding track fails to obtain a time, the track is discarded. The isolation efficiency as a function of the pileup density is shown in Figure 5.8 for the ITk-only and HGTD scenarios, where all electrons no matter whether a timing measurement is available or not are included in the denominator. The isolation efficiency of lepton is improved by more than 5% even after working for 4000 fb^{-1} integrated luminosity.

While the efficiency drops with increased pileup vertex density when using only the ITk, the addition of the HGTD timing information reduces this drop, keeping an efficiency above 85% even at high pileup density, i.e. with up to three additional vertices per mm around the hard-scatter vertex on average. For a local pileup density of the order of 1.6 vertices/mm the electron isolation efficiency is improved by about 10%, which

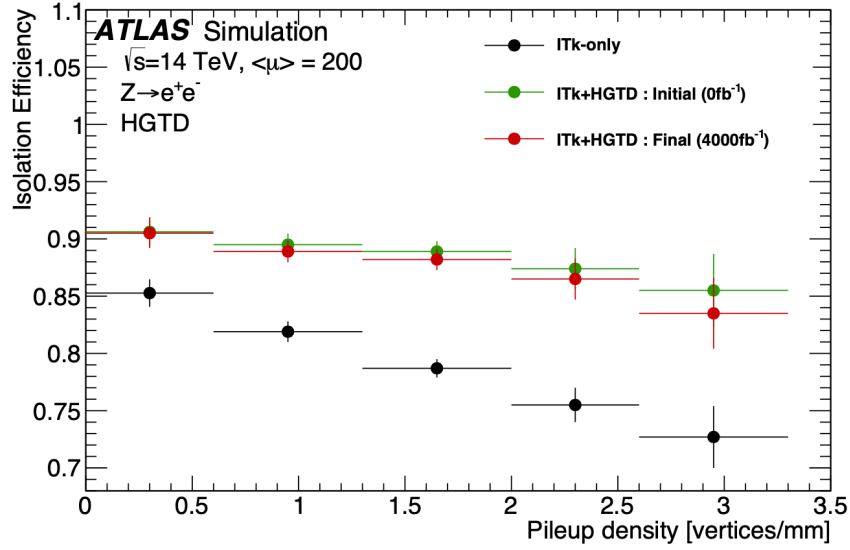


图 5.8 The efficiency for electrons to pass track-isolation criteria, denoted as $\epsilon(p_T^{iso})$, as function of the local vertex density, for the ITk-only and ITk+HGTD scenarios.

corresponds to a factor of two reduction of the inefficiency. These results show that the expected HGTD performance is sufficient to achieve a forward lepton track isolation efficiency essentially independent of the pileup vertex density and at a level similar to that achieved in the central region.

5.1.2.3 Particle-flow Jet Reconstruction And Missing E_T

HGTD detector will also improve other aspects of the W/Z precision measurements, such as Particle-flow jet reconstruction and Missing E_T . The Particle-Flow-Objects algorithm is used in the reconstruction of the transverse energy of the *hadronic recoil* against W and Z bosons in the measurement. While the E_T^{miss} is one of the crucial part in the p_T^W and m_W measurements.

Particle-flow jet reconstruction relies on the ability to match charged particle tracks with calorimeter signals and primary vertices. In particular, a key component of this approach, leading to the improved jet energy resolution, is the removal of calorimeter energy deposited by tracks originating from pileup vertices. The ambiguity to accurately associate forward tracks to nearby vertices is expected to limit the capability of particle-flow algorithms to reduce the impact of energy fluctuations due to pileup within jets in the forward region. This effect can be addressed by the use of timing information to

correctly identify hard-scatter and pileup tracks within the jet. For jets with low track-multiplicities, on the other hand, one may take advantage of the vertex t_0 identification. Improved jet energy resolution can lead to further improvements of sensitivity in many key physics channels, such as Vector Boson Fusion analyses.

There are three ways in which the HGTD can be utilized to potentially enhance the resolution of the E_T^{miss} . The first means is by using the improved jet energy resolution from particle-flow reconstruction using HGTD. Second, by reducing the (forward) pileup contamination in the track-based soft-term of the E_T^{miss} . The soft-term is defined by all charged tracks associated to the primary vertex that do not belong to hard physics objects. The knowledge of the track-time will enable a more pure selection of forward tracks in the soft-term component of the E_T^{miss} . Third, the improved forward pileup jet suppression will directly translate into improvements in the E_T^{miss} resolution, by the rejection of pileup jets that appear to come from the primary vertex but do not belong to the hard interaction.

5.2 Module Mounting For ATLAS ITk Upgrade Project

The layout of the upgraded ITk for the HL-LHC phase of ATLAS is in Figure 5.3. The silicon pixel detectors that I worked on is the the dark red disks in the endcaps on both sides which are perpendicular to the beam axis. A compilation of test results relevant to gluing pixel detector modules to a support structure is presented in this section. This is my qualification task, part of the development work towards the module loading to the support structures for the ALTAS ITk Pixel Endcap. For the ITk Pixel Endcap, the support structure is based on half-rings, each consisting of a carbon foam sandwich with carbon fibre facings. Down the centre of each half-ring runs a titanium pipe, carrying CO₂ coolant. The sensors are fabricated to 2×2 modules, so they are denoted as "quad modules". This section is organized as follows: Section 5.2.1 introduces the techniques on the glue dispensing for the module mounting. Section 5.2.2 shows a study on the glue curing time. Section 5.2.3 illustrates the design for the procedure of the glue dispensing and testing results. Section 5.2.4 shows the measurements on the spatial precision for the module mounting work.

5.2.1 Glue Dispensing

The glue that joint modules to the half-rings must have sufficient mechanical strength to support each module. This mechanical strength must be preserved throughout the lifetime of the experiment, after high levels of radiation damage and through multiple thermal cycles. The adhesive joint between the detector module and the carbon fibre facing also introduces a thermal resistance, which is proportional to the thickness of the glue layer and inversely proportional to its area. It is therefore the case that precise form of the glue joint must be sufficiently reproducible to ensure that each module can be cooled sufficiently, so as to prevent thermal runaway in the sensors for the lifetime of the experiment. Thermal runaway is discussed in [82].

The thermal performance of the half-ring can be characterized by a Thermal Figure of Merit (TFM), used to describe the thermal resistance between the sensor and the coolant. By convention, the thermal resistance per unit sensor area is used: i.e. the difference between sensor and coolant temperature for unit power density over the sensor area. For the endcap half-rings we expect the total TFM to be near $25 \text{ C} \cdot \text{cm}^2/\text{W} \times 1 \pm 20\%$. This is dominated by the foam conductivity, the joint between the foam and the pipe, and the heat transfer between the pipe and the CO_2 coolant. The contribution to the TFM from the glue between the module and the half-ring can be estimated as:

$$\text{TFM}_{\text{glue}} = h_{\text{glue}} / [\sigma_{\text{glue}} \times \eta_{\text{glue}}] \quad (5.1)$$

where h_{glue} refers to the thickness of glue layer, σ_{glue} refers to the conductivity and η_{glue} is the glue coverage in the space between the module and half-ring.

For the glue tested in this work, manufacturer's data for SE4445, a glue layer of conductivity = 1.3 W/mK and thickness 130 micron, with 100% area coverage, the TFM contribution from the glue would be:

$$(0.013 \text{ cm}) / (0.013 \text{ W/cm} \cdot \text{K}) = 1 \text{ C} \cdot \text{cm}^2/\text{W} \quad (5.2)$$

This value is then 4% of the $25 \text{ C} \cdot \text{cm}^2/\text{W} \times 1 \pm 20\%$ total. Later on, we will discuss what thickness, area and reproducibility might reasonably be achievable for the glue layer during production.

The SE4445 material is supplied in a syringe with 2 barrels. The components have been found by experience to settle out with time during storage. The adhesive was therefore decanted from the syringes into two plastic containers. Each component was separately mixed by hand before use. Mixing of the two components was also performed by hand, the material being decanted into a small mixing pot on top of an electronic weighing machine. The manual mixing method was a possible source of small variations in adhesive viscosity and/or curing time.

We consider each readout integrated circuit (ROIC) in a quad module as a separate entity, with its own glue pattern. The ideal finished glue joint will leave a border all around the edge of the chip, into which the glue does not encroach. This is to prevent adhesive from flowing up the edges of the ROICs, where it may contact the sensor, or provide a path for HV discharges. The ROIC used for prototyping on the ITk Pixel Endcap project is the FE-I4B, which has dimensions approximately $19\text{ mm} \times 20\text{ mm}$. The ideal finished glue pattern size is therefore a rectangle near $18\text{ mm} \times 19\text{ mm}$, i.e. the area coverage cannot exceed 90%. The thickness should not be less than $100\mu\text{m}$ for reasons of repeatability. Conversely, the thickness should be kept reasonably small for reasons of thermal resistance. We begin with the starting assumption that a layer thickness in the range $100\text{--}200\text{ }\mu\text{m}$ will be acceptable, with $140 \pm 30\mu\text{m}$ likely to be a reasonable specification to work towards.

We therefore started by aiming to deposit $18\text{ mm} \times 19\text{ mm} \times 140\text{ }\mu\text{m}$ of adhesive below each ROIC, i.e. 0.048 cc . The mass of adhesive required depends on the density of the adhesive in question; for SE4445, with a density of 2.41 g/cc , we require near 115 mg of adhesive per ROIC.

In the work conducted towards module loading, several methods of glue application have been trialled. And the method chosen was to use a syringe of adhesive, mounted on the Aerotech gantry robot. The glue deposition is performed by a Nordson EFD 1500XL dispenser, under the same Labview control as the gantry motion, enabling lines of adhesive to be printed. The glue pattern chosen in the first instance was an 8-pointed star. An example of this pattern, printed using red test gel, is shown in Figure 5.9

The dispense rate through the needle is controlled by the dispense needle internal

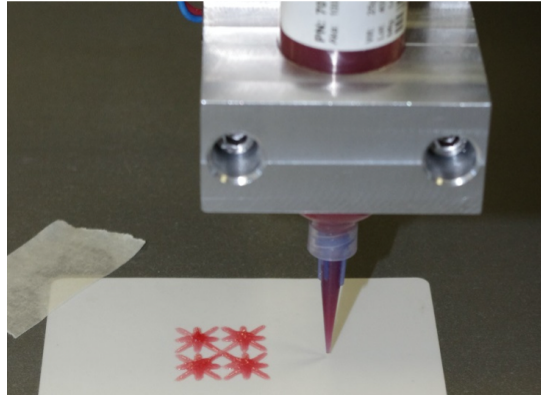


图 5.9 Printing a quad-module glue pattern using red test gel

diameter and the applied air pressure. The dispense unit used also has a vacuum setting, which uses the venturi effect to create a depression in the syringe when material is not being dispensed. This is intended to stop drips from the needle. The philosophy in setting the needle dispense rate was first to consider the speed at which the stages would be moved in order to write the glue pattern. 8 separate bead sections were deposited for each pattern, with a total glue mass near 115 mg. The sections are near 8 mm long for those parallel to the axes and 11 mm long for diagonal sections. Running at 8 mm/s we therefore require near 10 s for the motion and hence the adhesive must be dispensed at a rate near 12 mg/s. This was then used as a starting point for the trials.

5.2.2 Curing Time Testing

It was noted during initial gluing trials with SE4445 that the adhesive required became slower to dispense as time elapsed after mixing the two components. This was explored further with some measurements of adhesive flow rate versus time.

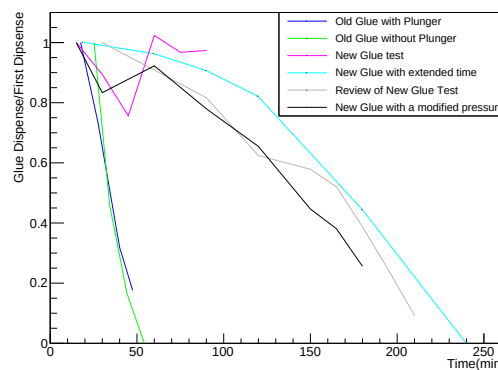


图 5.10 Relative Flow rates versus time after mixing for SE4445 adhesive

Figure 5.10 shows the results of measuring glue flow rate through the dispense needle as a function of time after mixing. The batch of in-date can be safely used for at least an hour after mixing without significant change in its viscosity. It is noted that an out-of-date batch of glue would cure much faster than a new one. More advanced adhesive dispensers than the one used can be programmed to increase the dispense pressure with time in an automated way.

5.2.3 Glue Pattern Tests

Adhesive trials were first conducted by gluing microscope cover slips to microscope slides. The thicknesses and masses of the slides and cover slips were first measured, using a digital micrometer and digital scales.

Three sets of three samples each were made and measured. Sample Group A used an 8-pointed star adhesive pattern of side 18mm before compression with 37g weights. For Sample Group B and C, the pattern size was reduced to 14mm. Group B was compressed with 37g (stainless steel bar) weights, whilst Group C was compressed with 17g (aluminium bar) weights. Examples of the visual appearance of three sets are shown in Figure 5.11. Measurements of glue layer thickness are shown in Table 5.1.

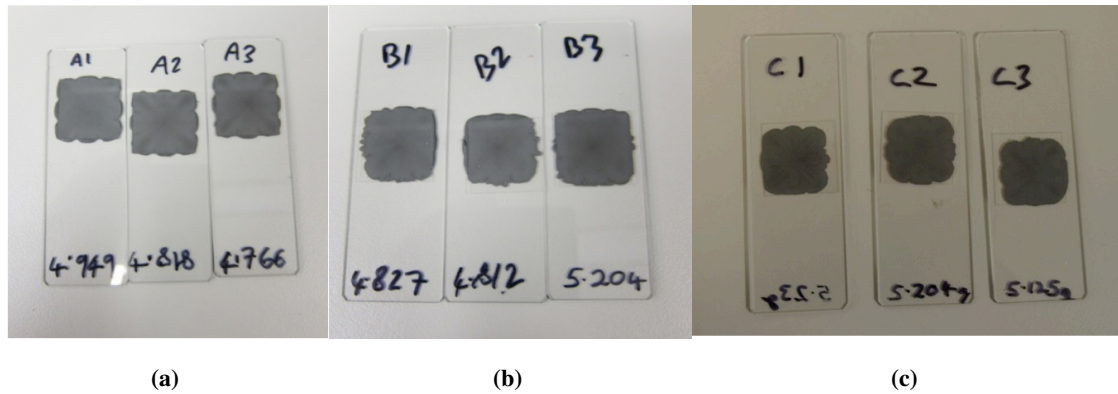


图 5.11 Example of pictures showing the glue patterns and gluing jigs with weights for pressing the gluing cover slips to slides. Group A dispense glue with 8-pointed star pattern of side 18 mm, Groups B and C dispense use star pattern of side 14 mm.

The conclusions from these preliminary trials were as follows:

- For samples compressed using the same weight, the final glue layer thickness appears to be nearly linear with the mass of glue deposited, if no mechanical means is

Sample name	Glue mass (mg)	Center thickness (um)
A1	114	95
A2	101	82
A3	107	107
B1	83	75
B2	86	73
B3	88	73
C1	75	75
C2	76	76
C3	79	79

表 5.1 Glue joint thicknesses for 3 sets of slides + cover slips

used to limit the glue spread.

- Reducing the weight used to compress the joint limits the lateral spread of the adhesive to some extent. Using a mechanical means to stop the compression of the joint (e.g. a spacer) should allow more accurate control of this.
- For a quad module, one might expect a weight near 120g to give adequate spreading of SE4445.

Quad Module Glue Pattern Tests were done using glass dummy modules of size 38.5 x 41.5mm, thickness 300 μ m. A vacuum chuck with feet to define the glue layer thickness is used to set the spacing for glue thickness. (See illustrative picture Figure 5.12)

Figure 5.13 show a series of trials, gluing glass dummy quad modules to glass substrates. Trials 3 and 4 were carried out without any mechanical stop to the chuck motion as the glue layer was compressed. All others were carried out using a chuck with feet and adjustable vacuum cups. The glue thickness are in good flatness in each trial. And the coverages are in general high, except for the 7th trial in which the thickness is adjusted to larger value and the glue amount was kept low.

The most important conclusions from this series of trials are as follows.

- For the samples which were compressed without a mechanical stop (Trial 2 and

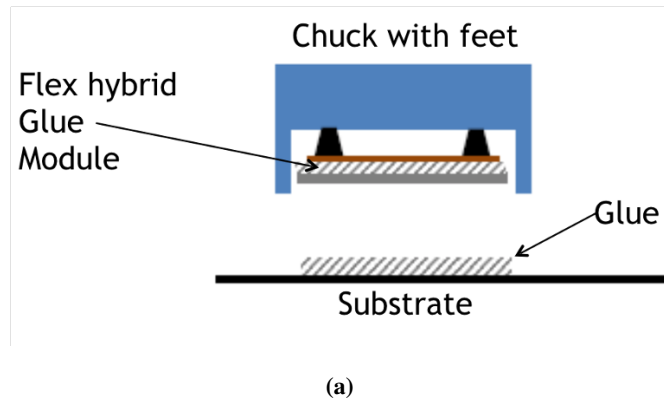


图 5.12 Illustrative picture showing how the chuck with feet and adjustable cups can modify the thickness of glue layer.

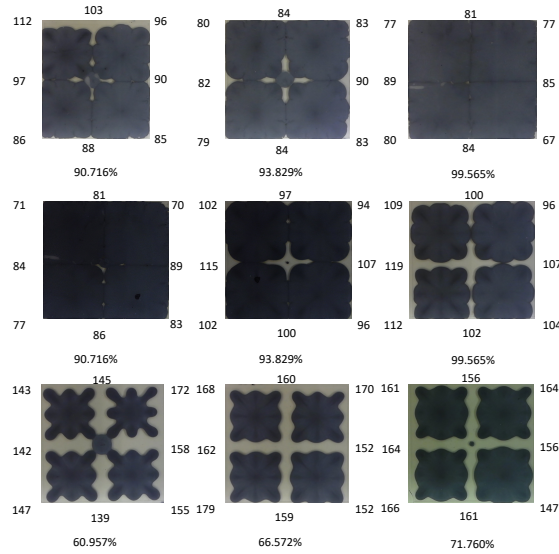
Trial 3), the adhesive flowed out until the voids were filled. At this point, the layer thickness was 80 μm on average. It might in principle be possible to leave lanes clear of adhesive at the ROIC edges by careful tuning of the chuck pressure. However this would imply the necessity of adjusting the chuck pressure with a series of trials after every new adhesive batch. Therefore it is considered that a mechanical spacer should be used if clear areas must be preserved.

- The runout across the glue layer is near 20 microns for the samples assembled without a spacer. This is comparable to, or rather better than, the use of chuck feet as a spacer.

- The first samples assembled using the chuck with feet and the second batch of adhesive (Trial 5 and Trial 6) show an average glue thickness near 105 microns, indicating that the feet were effective in setting the glue thickness above its natural settling point for a given pressure. However the clear lanes at the chip edges were not fully preserved so the chuck feet were adjusted to give a thicker layer and less lateral spread. (Alternatively one could have reduced the quantity of adhesive and kept the same thickness).

- The first sample after adjusting the chuck to give a thicker layer (Trial 7) shows that the adhesive quantity dispensed was no longer sufficient for the desired layer thickness. The dispense pressure was therefore increased for Trial 8 and Trial 9. A minor adjustment to the cups was also made at this stage.

- The last two samples (Trial 8 and Trial 9) are nominally identical. Both have an



(a)

图 5.13 Photos of gluing trials with a vacuum chuck with feet to define the glue layer thickness.

The glue thickness measured at each conner and edge are shown, the glue coverage is written below the pictures. The glue thickness is controllable and the glue coverage is high. The photo 3 and 4 are without chuck feet to mechanically stop the pressure so the glue spread too much. Photo 7 start to use larger space between glasses, but the glue dispense is not adjusted yet. The photos 8 and 9 are using more amount of glue from calculation and the glue coverage is good.

average thickness close to 160 microns, with a measured runout of 27 microns and 19 microns respectively. Lanes are clear of adhesive at the ROIC edges.

As well as the glue thickness, the area covered is important for the thermal resistance of the glue joint. In order to investigate this, an IPEVO Ziggi-HD document camera was used to photograph the finished glue patterns. SE4445 is mid-grey in colour and therefore stands out if the glass dummies are placed against a light background. It also stands out against a black background, which was useful in the photography of glass dummies attached to the carbon fibre facings of dummy half-rings.

Such a photograph can then be read into a suitable image processing program. In this case, image processing tools which are supplied as part of Labview were used. The free program Image-J is also an ideal candidate for this application. A global threshold can be placed on the recorded pixel intensity and a binary image generated. The glue

coverage is then very well approximated by the ratio of the pixels above threshold to the total area of the image. Results from this procedure for the glue patterns in Figure 5.13 are shown in the same figures.

From the figure, it can be seen that the two final patterns give area coverage of 67 and 72% respectively. One can estimate the area coverage that would be achieved using this method during production, by noting that a glue coverage of 83% appears to be unsafe with respect to leaving clear lanes. A coverage of 61% can clearly be increased without risk. So in production, coverages of 65% - 75% are likely to be achievable reproducibly.

5.2.4 Quad Module Dummies On A Half-ring

The same procedure of the glue dispense is then repeated on the half-ring of the supporting framework of the ITk endcaps Figure 5.14. The results of interest are the glue thickness and are coverage achieved, using the 8 pointed star glue pattern and SE4445 adhesive, as in the trials above.

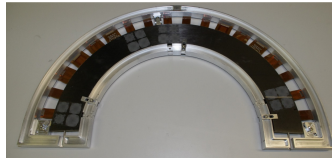


图 5.14 Gluing the dummy module to the supporting endcap half-ring after mounting. Quad glue patterns could be seen in the middle of the half-ring. Good coverage is achieved for the glue layer.

Figure 5.15 shows measurements of the area coverage. The four dummy modules are labelled as 1st, 5th, 6th, 9th, because it was designed for a ring that nine quad modules are to be placed. But in the study of the mounting work it is not needed to make all of them. So four of the places are chosen, while two on the center of the half-ring, and two on the ends. The coverage is 75% on average, but the adhesive has encroached on the lanes at the edge of the ROICs. This means that one would have to reduce the coverage to keep these lanes clear. As the encroachment always occurs at the centre point of the glue pattern sides, a modification of the pattern could help.

The precision of the mounting for the modules are measured with a SmartScope

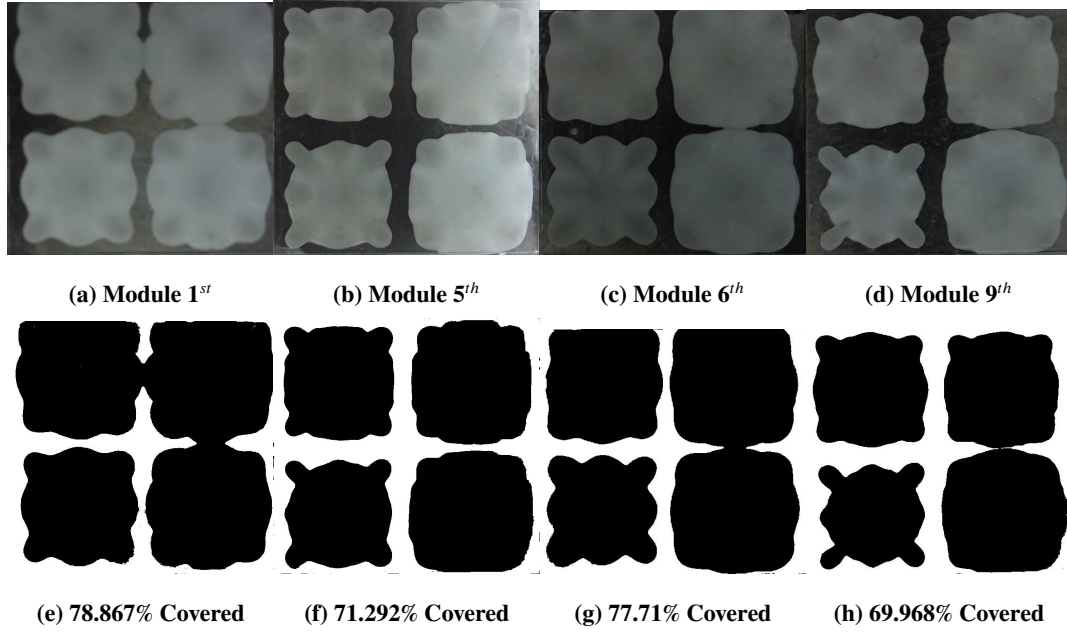


图 5.15 Finished glue patterns achieved on an inner half-ring.

Figure 5.16. The precision is defined by the difference between the measured position from the SmartScope to the designed position that the *Aerotech* stage was set to mount. Different precisions are achieved in the x- and y- directions of the Aerotech stage, because of the intense variation in manufacture.

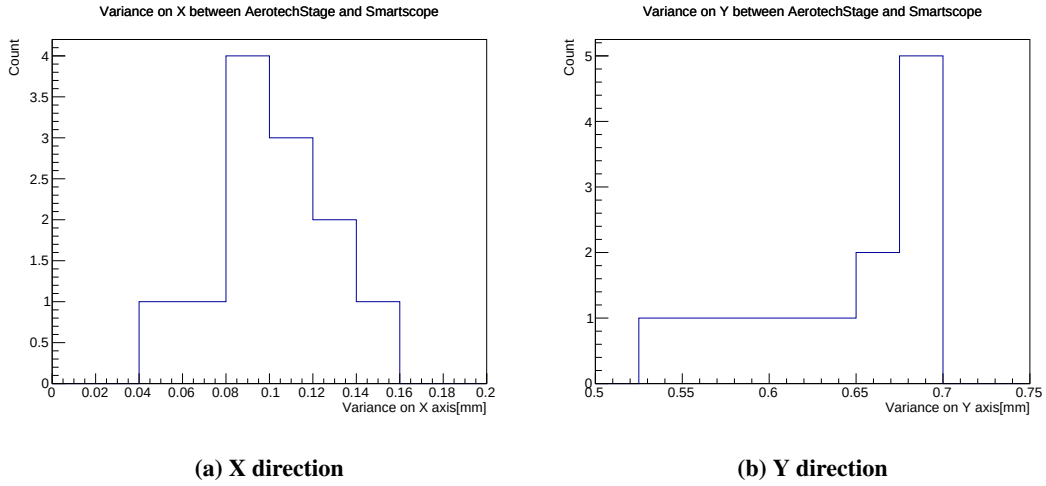


图 5.16 Variation of the module positioning to its designed places.

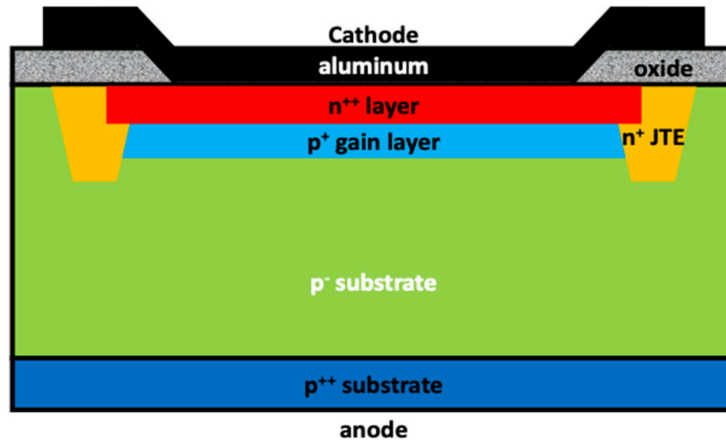


图 5.17 Basic structure of Low Gain Avalanche Detectors (LGAD). The charge multiplication is enabled by the gain layer colored in blue. And the n^+ JTE is implemented to avoid early breakdown at the edge.^[83]

5.3 Sensor Tests for HGTD Project

5.3.1 Low Gain Avalanche Detectors Tests For ATLAS HGTD Project

Figure 5.17 shows the basic structure of Low Gain Avalanche Detectors(LGAD). The most important part of the LGAD sensor is the charge multiplication in the so-called gain layer which is formed by a heavily doped $1\text{--}2\ \mu\text{m}$ thick p^+ layer sandwiched between the n^{++} layer and the p^- substrate. A further important structure in an LGAD is the JTE (Junction Termination Extension), implanted to avoid early breakdown at the edge. The thickness of the p^- substrate is as thin as $50\ \mu\text{m}$ for a superior time resolution of around $35\ \text{ps}$ per detector layer. The negative anode voltages are applied from the backside electrode to make the sensor work at the voltage before breakdown and with a gain larger than 10 for good time resolution, while the signals of each sensor are collected and analyzed from the top cathode electrode. The measurements were done with single pad sensors with one guard ring Figure 5.18.

5.3.2 Current - Bias Voltage Measurements With Physical Damages On The Mask

The 5×5 sensors, which are cut from the left bottom corner of figure Figure 5.18a, are tested using the probe station for its leakage current (I) - bias voltage (V) characteristics. A typically result is shown in Figure 5.19, 21 pads show very good consistency in I-V characteristics out of the total 25 pads. Three pads break down at lower bias

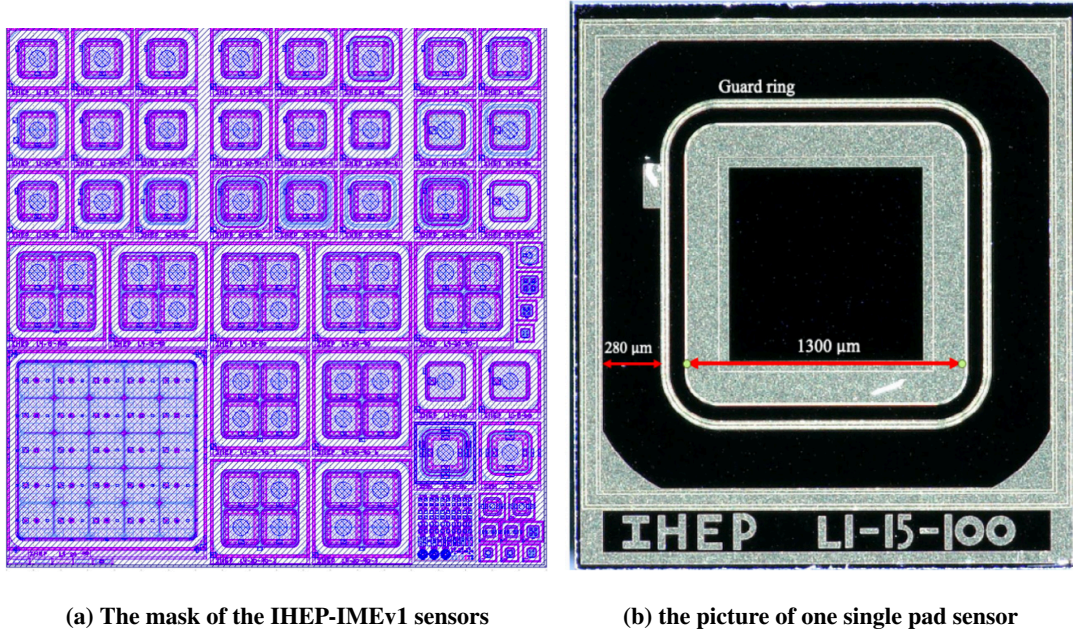


图 5.18 IHEP-IMEv1 sensors structures. The mask is produced with single pad sensors, 2×2 pad sensors and 5×5 pad sensors. In each sensor, a guard ring surrounds the pad.^[83]

voltage, while the rest one pad has very small leakage current than the other.

There are several reasons that could explain the behavior of those with different I-V characteristics.

- The non-uniformity in the production procedure such as doping concentration, the curving of circuits on the pads.
- The variation in the environment of the testing, including the room temperature, humidity.
- The variation in the operation of the testing people. For example, in each time of the testing, one is to re-connect the wires for the voltmeter and amperemeter. The connection between wires to the meters might differ each time, resulting in different resistance.
- The mis-behaves making physical damages on the surface of the sensors during testing, storage and transportation.

第二和第三个原因在测试中无法完全消除。但是传感器表面的物理损伤是可以观察到的，且可以在未来的工作中加以预防。因此，研究物理损伤对 I-V 特性的影响有重要意义。首先，对取自三个晶片（即 W1、W7 和 W8）的单个模块进行显微镜扫描，以确定每个模块的物理损伤情况。考虑到单个模块的结构，物

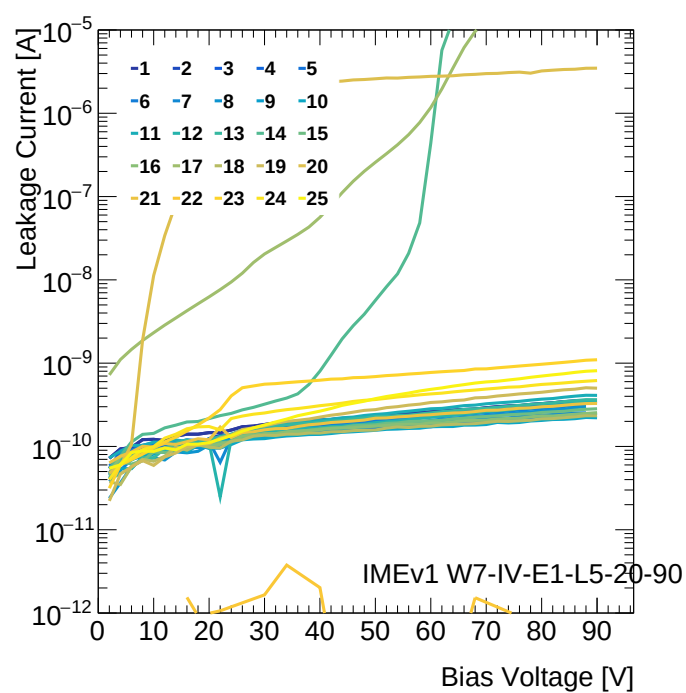


图 5.19 Leakage current - bias voltage result for a 5×5 sensor. For most of the measurements, the leakage current - bias voltage performance shows great repeatability. Three pads breaks down at low bias voltage. For one pad the leakage current is not properly measured.

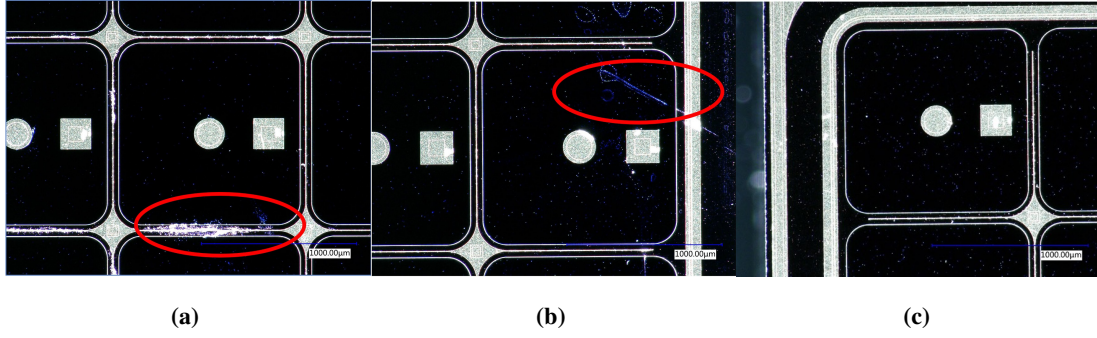


图 5.20 Classification of the physical damage type on sensors depending on the positions. (a) shows damage on the metal ring around pads, (b) shows scratch across the sensor. (c) shows the cases no damage can be observed.

理损伤被分为三类 Figure 5.20:

The second and third bullets cannot be fully removed in a test. But the physical damages on the sensor surface is observable, and could be prevented in future work. So it is studied on the effect of physical damages to the I-V characteristics. Firstly, the single pads of three wafers (namely W1, W7 and W8) were scanned under an microscope, to identify the physical damage condition on each pad. Considering the structure of single pads, the physical damages were divided into three categories Figure 5.20:

- Visible damages on the metal ring around pads.
- Scratch through the pad.
- No visible damages.

The counting for each type of pads are summarized in Table 5.2. It is concluded from the table that the scratch damage takes a much higher fraction in bad pads than in good pads, while the scratch damage takes a much higher fraction in bad pads than in good pads (about 2σ difference).

To study the effects of physical damages on I-V characteristics more directly, a few pads were curved intendedly with the tweezer used to place the sensors on the probe station. One pad is scratched with less power Figure 5.21a and the others are scratched with more power Figures 5.21b, 5.21c and 5.21d .

The measurements on the current-voltage characteristics Figure 5.22 were done exactly before and after the damages were made, so the environment of the testing is regarded as the same. The conclusion is that the leakage current after physical dam-

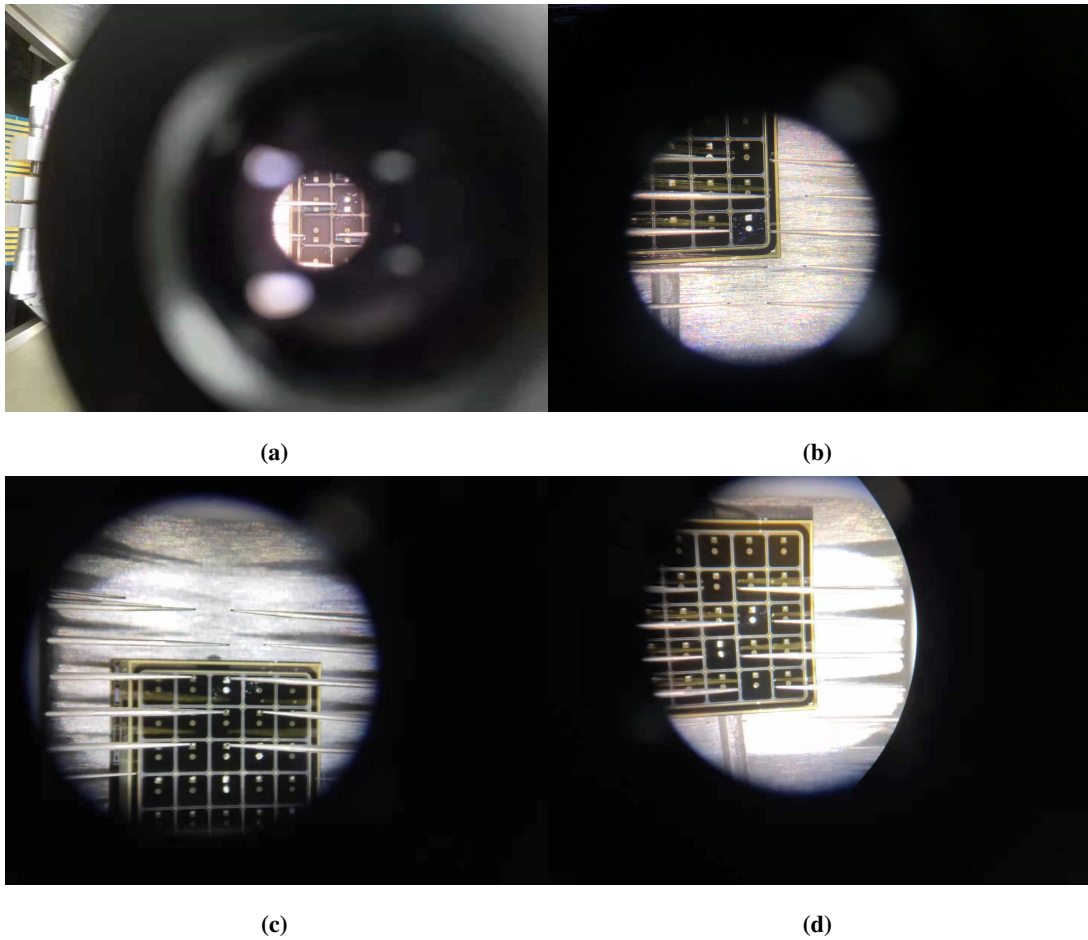


图 5.21 Intended physical damages on the surfaces of single pads made by tweezer, to test the effects of those damages on I-V characteristics.

damage type	scrub	scratch	no obvious damage
pads with abnormal I-V curve	20	21	33
fraction with abnormal I-V curve	0.15 ± 0.04	0.33 ± 0.06	0.52 ± 0.06
pads with good I-V curve	29	167	499
fraction with good I-V curve	0.042 ± 0.008	0.240 ± 0.016	0.718 ± 0.017

表 5.2 Counting of pads with different types of physical damages on the mask and the I-V characteristics

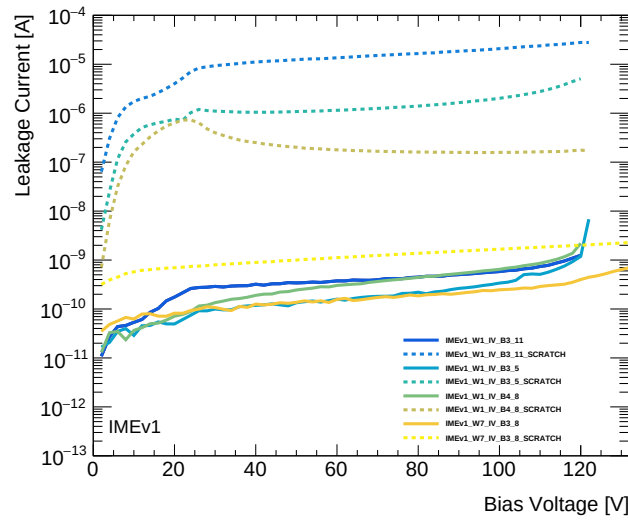


图 5.22 Measurements on leakage current - bias voltage curves before and after physical damage on the mask of sensors. Four pads from two different wafers were tested. W7_IV_B3_8 is scratched with less power and its increasing on leakage current is much less than the other three pads.

ages (dashed lines) are significantly larger than the current before the damages were made (solid lines). Moreover, with harder curving (W1_IV_B3_11, W1_IV_B3_5, W1_IV_B4_8) on the mask of sensors, the increase of the leakage current comparing after and before the damage is much larger than the lighter curving (W7_IV_B3_8). So the conclusion is clear that physical damage on the mask of sensors lead to larger leakage current. And the effect depends on the power of the damaged made. It is noted that the damage is made with a tweezer pressing with hand on millimeter level pads, So the power of the damage is well-controllable, and there is no need to scale the power.

The leakage current - bias voltage characteristic is measured with the IHEP-IME

version 1 sensors, most of the single pads show good consistency in the measurement. Further studies are made on the correlations between the sensor performance and the possible physical damages on the surface. Overall 825 single pads were classified into three types of damages: scrub on the metal ring around the pad; scratches through the pad or no visible damages. The results show that scratches through the pad making significant damages on the I-V properties on the sensors, while the scrub on the metal ring around the pad does not increase the probability of poor I-V properties with the statistical uncertainty. It is indicating that during the tests, transportation and storage procedure of the IHEP-IME sensors, physical damage could destroy the electronic properties so that it is noted to taking better care of the sensors in the future work.

第 6 章 Conclusion

In this paper, we discussed about the vector boson differential cross section measurement in function of transverse momenta of W and Z boson. The measurement uses low pileup dataset taken with ATLAS detector in the year 2017 and 2018, corresponding to integrated luminosity $\int \mathcal{L} dt = 335 \text{ pb}^{-1}$ at 13 TeV and 257 pb^{-1} at 5 TeV. Leptonic decay channels $W \rightarrow \ell \nu$ and $Z \rightarrow \ell \ell$ are used to measure the boson p_T , where ℓ is an electron or muon, and ν is a neutrino. The main backgrounds considered are diboson processes, top, $Z \rightarrow \tau \tau$, $W \rightarrow \tau \nu$ and QCD multijets backgrounds. The selections including fiducial cuts, isolation and impact parameter cuts on leptons could effectively reject the backgrounds in signal region. The remaining backgrounds in signal region are estimated using MC16 samples for top and electroweak processes and data-driven methods for QCD multijets.

The transverse momenta of Z boson can be measured through kinematics of two opposite sign leptons which are precisely measured by ATLAS detector. While the p_T^W can be only measured by the hadronic final states from the initial state radiation against the W boson, which could be a quark or gluon. In this case, the *hadronic recoil* is calibrated using Z events, where the p_T of recoil is calibrated using $p_T^{\ell \ell}$. Full statistic and systematic uncertainties are precisely estimated. To improve the precision of the analysis, the team has put a huge amount of efforts to build dedicated calibrations for the electrons, muons, and the *hadronic recoil*. POWHEG+PYTHIA8 generator at NLO interfaced to CT10 PDF settings are used to simulated the kinematics of signal channels. To remove the bias induced by the difference of initial p_T^Z prior between the MC and data, a data-driven p_T correction is studied to achieve the best data to MC agreement at reconstructed level. The corresponding uncertainty for the correction is estimated.

To retrieve the born level p_T^V , Bayesian iterative unfolding method is used to unfold the p_T measurements from reconstructed level to truth level. Full statistic plus systematic uncertainties are propagated to the unfolding procedure for the final results. Transverse momentum of Z boson is measured with precision of about 1% at low p_T for 5 TeV, and

the uncertainty increases to 3 - 4% at 80 GeV. At 13 TeV, the uncertainty of p_T^Z is below 1% in $[0, 20]$ GeV region, and it increases to 2% at 80 GeV. p_T^Z measurements at both center-of-mass energies are dominated by data statistics. The sub-leading contribution of uncertainties is Monte Carlo statistics at 5 TeV and unfolding bias uncertainty at 13 TeV. In addition to six differential cross sections and distributions for W^+ , W^- and Z final states at two $\sqrt{s}$, presented are integrals, normalized distributions and a variety of ratios.

The comparison to MC sample predictions show a variety of deficits in the low p_T region that are common for all vector bosons. The agreement is better at $\sqrt{s} = 5.02$ TeV and also in good consistency at 13 TeV. POWHEG+PYTHIA8 AZNLO and PYTHIA8 AZ describe the measurements very well at low p_T , because these two generators are next-leading-order predictions tuned to ATLAS previous p_T^Z measurements, and they do not suffer from the problem of QCD re-summation for higher orders at low p_T . But at $p_T > 80$ GeV, POWHEG+PYTHIA8 and PYTHIA8 predictions show large discrepancies to the measurements because the next-leading order predictions are not enough to predict this region. On the contrast, the next-to-next-to leading order prediction, Sherpa, match well with the measurements at high p_T region, but not at low p_T region. In $20 < p_T < 40$ GeV region at 5 TeV, all MCs fluctuated around the data, which is regarded as statistical fluctuations.

In addition to the validation of the results, two compatibility studies are performed: First is the comparison of low- μ p_T^Z measurement to standard pileup measurement at $\sqrt{s} = 13$ TeV. The other is the compatibility between the results from dilepton and *hadronic recoil* measurements. Good consistencies are observed in the two cross checks, indicating that the methodology of the measurements are in general reliable.

This analysis is of crucial importance because the low pileup data condition allows for direct measurements of p_T^W . Precision measurements of p_T^W and p_T^Z are sensitive probes to test QCD and PDF models. Moreover, the precisely measured p_T^W is an important work towards the W mass measurement. p_T^W measurements improve the PDF uncertainties, and hadronic recoil calibrations derived in this analysis would benefit the m_T measurement for m_W . It is promising that a precision of $\Delta m_W \approx 10$ MeV

could be achieved, which could be published in about two years. The CDF collaboration published a most recent measurement on $m_W = 80.4335 \pm 0.0094$ GeV. Surprisingly, the researchers found that the mass of the boson was significantly higher than the SM predicts, with a discrepancy of 7 standard deviations. This measurement is in significant tension with the standard model expectation, and certainly raise the expectation of scientists around the world to the low- μ results on m_W .

Even after the finalization of the W boson mass measurement with low pileup data with ATLAS detector, precision measurements on standard model parameters are still very important. Any improvement on the precision of Standard model parameters could indicate the new physics. ATLAS group will continue works on precision measurements on HL-LHC period, the tracker is going to be upgraded and a new detector, HGTD, will be installed. I have worked on the module mounting for the pixel detectors of upgraded ITk, which could provide identification and precision momenta measurement of charged particles. I also worked for the sensor tests for the LGADs sensors for HGTD detector. The HGTD will provide precision timing information to suppress the pileup effects at the very high data rating. Both of the two detectors will help a lot on the precision measurements in HL-LHC.

Some future accelerators have been investigated to work on this field such as the Circular Electron Positron Collider, designed by Institute of High Energy Physics, Chinese Academy of Science. One of the goals for CEPC is to measure m_W with super clean lepton collision. The W mass measurements at CEPC will not suffer from the PDF uncertainty which is a crucial part in ATLAS measurement. Because CEPC collides elementary particles, electrons and positrons, so the momenta carried by these leptons are precisely determined. At the W threshold scan, the CEPC could produce 10^7 W event in a year, which could provide much better W mass measurement than at LHC.

- -> Appendix -

- -> Backmatter: bibliography, glossary, index -

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作者简历及攻读学位期间发表的学术论文与研究成果

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