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Measurements of differential Z boson production cross sections in proton-proton collisions at $\sqrt{s} = 13$ TeV

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Abstract: Measurements are presented of the differential cross sections for Z bosons produced in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$ and decaying to muons and electrons. The data analyzed were collected in 2016 with the CMS detector at the LHC and correspond to an integrated luminosity of $35.9\,\text{fb}^{-1}$. The measured fiducial inclusive product of cross section and branching fraction agrees with next-to-next-to-leading order quantum chromodynamics calculations. Differential cross sections of the transverse momentum p_{T}, the optimized angular variable ϕ^*_η, and the rapidity of lepton pairs are measured. The data are corrected for detector effects and compared to theoretical predictions using fixed order, resummed, and parton shower calculations. The uncertainties of the measured normalized cross sections are smaller than 0.5% for $\phi^*_\eta < 0.5$ and for $p_{\mathrm{T}}^{\mathrm{Z}} < 50\,\text{GeV}$.

Keywords: Hadron-Hadron scattering (experiments), Particle and resonance production

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1 Introduction

The measurement of the production of lepton pairs via the Z boson is important for the physics program of the CERN LHC. The large cross section and clean experimental signature allow precision tests of the standard model (SM), as well as constraints on the parton distribution functions (PDFs) of the proton. In addition, a measurement of the Z production process can set stringent constraints on physics beyond the standard model. Moreover, dilepton events are valuable for calibrating the detector and monitoring the LHC luminosity. The $\mathrm{Z}/\gamma^* \to \ell^+\ell^-$ process, where ℓ is a muon or an electron, is referred to as the Z boson process in this paper.

The Z boson production, identified via its decays into pairs of muons and electrons, can have nonzero transverse momentum, p_{T}, to the beam direction. This is due to the intrinsic p_{T} of the initial-state partons inside the proton, as well as initial-state radiation of gluons and quarks. Measurements of the p_{T} distribution of the Z boson probe various aspects of the strong interaction. In addition, an accurate theoretical prediction of the p_{T} distribution is a key ingredient for a precise measurement of the W boson mass at the Tevatron and LHC.

Theoretical predictions of both the total and the differential Z boson production cross section are available at next-to-next-to-leading order (NNLO) accuracy in perturbative quantum chromodynamics (QCD) [1, 2]. Complete NNLO calculations of vector boson production in association with a jet in hadronic collisions have recently become available at $\mathcal{O}(\alpha_S^3)$ accuracy in the strong coupling [3–5]. These calculations significantly reduce the factorization (μ_F) and renormalization (μ_R) scale uncertainties, which in turn reduce theoretical uncertainties in the prediction of the p_T distribution in the high p_T region to the order of one percent. Electroweak corrections are known at next-to-leading order (NLO) and play an important role at high p_T [6, 7].

However, the fixed-order calculations are unreliable at low p_T due to soft and collinear gluon radiation, resulting in large logarithmic corrections [8]. Resummation of the logarithmically divergent terms at next-to-next-to-leading logarithmic (NNLL) accuracy has been matched with the fixed-order predictions to achieve accurate predictions for the entire p_T range [9, 10]. Fixed-order perturbative calculations can also be combined with parton shower models [11–13] to obtain fully exclusive predictions [14–17]. Transverse momentum dependent (TMD) PDFs [18] can also be used to incorporate resummation and nonperturbative effects.

The Z boson p_T and rapidity y^Z distributions were previously measured, using $\mathrm{e}^+\mathrm{e}^-$ and $\mu^+\mu^-$ pairs, by the ATLAS, CMS, and LHCb Collaborations in proton-proton (pp) collisions at $\sqrt{s} = 7$, 8, and 13 TeV at the LHC [19–32], and in $\mathrm{p\overline{p}}$ at $\sqrt{s} = 1.8$ and 1.96 TeV by the CDF and D0 Collaborations at the Fermilab Tevatron [33–37]. The y^Z distribution in pp collisions is strongly correlated with the longitudinal momentum fraction x of the initial partons and provides constraints on the PDFs of proton. The precision of the Z boson p_T measurements is limited by the uncertainties in the p_T measurements of charged leptons from Z boson decays. The observable ϕ^*_η [38, 39] is defined by the expression

$$\phi^*_\eta = \tan\left(\frac{\pi - \Delta\phi}{2}\right)\sin(\theta^*_\eta), \quad \cos(\theta^*_\eta) = \tanh\left(\frac{\Delta\eta}{2}\right), \tag{1.1}$$

where $\Delta\eta$ and $\Delta\phi$ are the differences in pseudorapidity and azimuthal angle, respectively, between the two leptons. In the limit of negligible lepton mass rapidity and pseudorapidity are identical. The variable θ^*_η indicates the scattering angle of the lepton pairs with respect to the beam in the boosted frame where the leptons are aligned. The observable ϕ^*_η follows an approximate relationship $\phi^*_\eta \sim p_\mathrm{T}^\mathrm{Z}/m_{\ell\ell}$, so the range $\phi^*_\eta \leq 1$ corresponds to p_T^Z up to about 100 GeV for a lepton pair mass close to the nominal Z boson mass. The measurement resolution of ϕ^*_η is better than that of p_T since it depends only on the angular direction of the leptons and benefits from the excellent spatial resolution of the CMS inner tracking system. The Z boson ϕ^*_η distribution was previously measured by the D0 [37], ATLAS [21], CMS [40], and LHCb [32] Collaborations.

We present inclusive fiducial and differential production cross sections for the Z boson as a function of p_T, ϕ^*_η, and $|y^\mathrm{Z}|$. The data sample corresponds to an integrated luminosity of $35.9 \pm 0.9\,\mathrm{fb}^{-1}$ collected with the CMS detector [41] at the LHC in 2016.

2 The CMS detector

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume there are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and

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a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the η coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in ref. [41].

The first level of the CMS trigger system, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events of interest in a fixed time interval of less than 4 μs. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to $\mathcal{O}(1\,\text{kHz})$ before data storage [42].

3 Signal and background simulation

Monte Carlo event generators are used to simulate the signal and background processes. The detector response is simulated using a detailed specification of the CMS detector, based on the GEANT4 package [43], and event reconstruction is performed with the same algorithms used for data.

The simulated samples include the effect of additional pp interactions in the same or nearby bunch crossings (pileup), with the distribution matching that observed in data, with an average of about 23 interactions per crossing.

WZ and ZZ production, via $q\overline{q}$ annihilation, are generated at NLO with POWHEG 2.0 [14–16, 44]. The gg → ZZ process is simulated with MCFM 8.0 [45] at leading order. The Zγ, $t\overline{t}$Z, WWZ, WZZ, and ZZZ processes are generated with MADGRAPH5_aMC@NLO 2.3.3 [17]. The signal samples are simulated using MADGRAPH5_aMC@NLO and POWHEG at NLO. The MADGRAPH5_aMC@NLO generator is used to compute the response matrix in the data unfolding procedure. The PYTHIA 8.226 [11] package is used for parton showering, hadronization, and the underlying-event simulation, with tune CUETP8M1 [46, 47]. The NNPDF 3.0 [48] set of PDF, with the perturbative order matching used in the matrix element calculations, is used in the simulated samples.

4 Event selection and reconstruction

The CMS particle-flow event algorithm [49] aims to reconstruct and identify each individual particle in an event, with an optimized combination of all subdetector information. Particles are identified as charged and neutral hadrons, leptons, and photons.

The reconstructed vertex with the largest value of summed physics-object p_{T}^2 is the primary pp interaction vertex. The physics objects are the objects returned by a jet finding algorithm [50, 51] applied to all charged particle tracks associated with the vertex plus the corresponding associated missing transverse momentum, which is the negative vector sum of the p_{T} of those jets.

Muons are reconstructed by associating a track reconstructed in the inner silicon detectors with a track in the muon system. The selected muon candidates must satisfy a set of requirements based on the number of spatial measurements in the silicon tracker and in the muon system, and the fit quality of the combined muon track [52, 53]. Matching muons to tracks measured in the silicon tracker results in a relative p_{T} resolution of 1% for muons in the barrel and better than 3% in the endcaps, for p_{T} ranging from 20–100 GeV. The p_{T} resolution in the barrel is less than 10% for muons with p_{T} up to 1 TeV.

Electrons are reconstructed by associating a track reconstructed in the inner silicon detectors with a cluster of energy in the ECAL [54]. The selected electron candidates cannot originate from photon conversions in the detector material, and they must satisfy a set of requirements based on the shower shape of the energy deposit in the ECAL. The momentum resolution for electrons from $\mathrm{Z} \to \mathrm{e^+e^-}$ decays ranges from 1.7% in the barrel region to 4.5% in the endcaps [54].

The lepton candidate tracks are required to be consistent with the primary vertex of the event [55]. This requirement suppresses the background of electron candidates from photon conversion, and lepton candidates originating from in-flight decays of heavy quarks. The lepton candidates are required to be isolated from other particles in the event. The relative isolation for the lepton candidates with transverse momentum p_{T}^{ℓ} is defined as

$$R_{\mathrm{iso}} = \left[\sum_{\substack{\text{charged}\\ \text{hadrons}}} p_{\mathrm{T}} + \max\left(0, \sum_{\substack{\text{neutral}\\ \text{hadrons}}} p_{\mathrm{T}} + \sum_{\text{photons}} p_{\mathrm{T}} - 0.5\, p_{\mathrm{T}}^{\mathrm{PU}}\right)\right] \Big/ p_{\mathrm{T}}^{\ell}, \tag{4.1}$$

where the sums run over the charged and neutral hadrons, and photons, in a cone defined by $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ (0.3) around the muon (electron) trajectory. The $p_{\mathrm{T}}^{\mathrm{PU}}$ denotes the contribution of charged particles from pileup, and the factor 0.5 corresponds to an approximate average ratio of neutral to charged particles [52, 54]. Only charged hadrons originating from the primary vertex are included in the sum.

Collision events are collected using single-electron and single-muon triggers that require the presence of an isolated lepton with p_{T} larger than 24 GeV, ensuring a trigger efficiency above 96% for events passing the offline selection. The event selection aims to identify either $\mu^+\mu^-$ or $\mathrm{e^+e^-}$ pairs compatible with a Z boson decay. Therefore, the selected Z boson candidates are required to have two oppositely charged same-flavor leptons, muons or electrons, with a reconstructed invariant mass within 15 GeV the nominal Z boson mass [56]. In addition, both leptons are required to have $|\eta| < 2.4$ and $p_{\mathrm{T}} > 25$ GeV. To reduce the background from multiboson events with a third lepton, events are rejected if an additional loosely identified lepton is found with $p_{\mathrm{T}} > 10$ GeV.

5 Background estimation

The contribution of background processes in the data sample is small relative to the signal. The background processes can be split into two components, one resonant and the other nonresonant. Resonant multiboson background processes stem from events with genuine Z bosons, e.g., WZ diboson production, and their contributions are estimated from simulation.

Nonresonant background stems from processes without Z bosons, mainly from leptonic decays of W boson in $\mathrm{t\bar{t}}$, tW, and WW events. Small contributions from single top quark

Final state	Data	$Z \to \ell\ell$	Resonant background	Nonresonant background
$\mu\mu$	20.4×10^6	20.7×10^6	30×10^3	41×10^3
ee	12.1×10^6	12.0×10^6	19×10^3	26×10^3

Table 1. Summary of data, expected signal, and background yields after the full selection. The predicted signal yields are quoted using MadGraph5_aMC@NLO. The statistical uncertainties in the simulated samples are below 0.1%.

events produced via s- and t-channel processes, and $Z \to \tau\tau$ events are also present. The contribution of these nonresonant flavor-symmetric backgrounds is estimated from events with two oppositely charged leptons of different flavor, $e^{\pm}\mu^{\mp}$, that pass all other analysis requirements. The method assumes lepton flavor symmetry in the final states of these processes [57]. Since the W boson leptonic decay branching fractions are well-known, the number of eμ events selected inside the Z boson mass window can be used to predict the nonresonant background in the $\mu\mu$ and ee channels.

A summary of the data, signal, and background yields after the full selection for the dimuon and dielectron final states is shown in table 1. The contribution of the background processes is below 1%.

6 Analysis methods

The fiducial region is defined by a common set of kinematic selections applied to both the $\mu^+\mu^-$ and e^+e^- final states at generator level, emulating the selection performed at the reconstruction level. Leptons are required to have $p_T > 25\,\text{GeV}$ and $|\eta| < 2.4$, and a dilepton invariant mass $|m_{\ell\ell} - 91.1876\text{ GeV}| < 15\,\text{GeV}$. A small fraction (3%) of selected signal events do not originate from the fiducial region because of detector effects. This contribution is treated as background and subtracted from the data yield. The measured distributions, after subtracting the contributions from the background processes, are corrected for detector resolution effects and inefficiencies due to so-called dressed lepton kinematics. The dressed leptons at generator level are defined by combining the four-momentum of each lepton after the final-state photon radiation (FSR) with that of photons found within a cone of $\Delta R = 0.1$ around the lepton. By using this definition, the measured kinematic distributions for Z boson decays to the muon final state and to the electron final state agree to better than 0.1%. The rapidity measurement is restricted to $|y^Z| < 2.4$. The p_T and ϕ^*_η measurements are restricted to $p_T < 1500\,\text{GeV}$ and $\phi^*_\eta < 50$, respectively. There are less than 0.001% of events with $p_T > 1500\,\text{GeV}$ and less than 0.02% with $\phi^*_\eta > 50$.

The efficiencies for the reconstruction, identification, and isolation requirements on the leptons are obtained in bins of p_T and η using the “tag-and-probe” technique [58]. Scale factors are applied as event weights on the simulated samples to correct for the differences in the efficiencies measured in the data and the simulation. The combined scale factor for the reconstruction, identification, and isolation efficiencies for leptons ranges from 0.9 to 1.0, with an uncertainty of about 0.4 (0.7)% for muons (electrons). Momentum scale corrections are applied to the muons and electrons in both data and simulated events [59].

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The detector effects are expressed through a response matrix, calculated from the simulated MadGraph5_aMC@nlo Z boson sample by associating dressed and reconstructed objects for each observable independently. To account for selection efficiencies and bin migrations, an unfolding procedure based on a least squares minimization with Tikhonov regularization, as implemented in the TUnfold framework [60], is applied. The regularization reduces the effect of the statistical fluctuations present in the measured distribution on the high-frequency content of the unfolded spectrum. The regularization strength is chosen to minimize the global correlation coefficient [61].

7 Systematic uncertainties

The sources of systematic uncertainty in the measurement include the uncertainties in the integrated luminosity, lepton efficiencies (reconstruction, identification, and trigger), unfolding, lepton momentum scale and resolution, and background estimation. A summary of the total uncertainties for the absolute cross section measurements in bins of $p_{\mathrm{T}}^{\mathrm{Z}}$, $|y^{\mathrm{Z}}|$, and ϕ^{*}_{η} is shown in figure 1. The uncertainty in the trigger efficiency is included as part of the lepton identification efficiency uncertainty.

Most of the sources of systematic uncertainty are considered fully correlated between bins in all variables. The statistical uncertainties due to the limited size of the data and simulated samples are considered uncorrelated between bins. Some sources of systematic uncertainty have a significant statistical component, such as the statistical uncertainties in the lepton efficiency measurement. This statistical component is considered as uncorrelated between the lepton p_{T} and η bins used for the determination of the lepton efficiencies.

Measurements of the normalized differential cross sections $(1/\sigma)\mathrm{d}\sigma/\mathrm{d}p_{\mathrm{T}}^{\mathrm{Z}}$, $(1/\sigma)\mathrm{d}\sigma/\mathrm{d}|y^{\mathrm{Z}}|$, and $(1/\sigma)\mathrm{d}\sigma/\mathrm{d}\phi^{*}_{\eta}$ are also performed. Systematic uncertainties are largely reduced for the normalized cross section measurements. A summary of the total uncertainties for the normalized cross section measurements in bins of $p_{\mathrm{T}}^{\mathrm{Z}}$, $|y^{\mathrm{Z}}|$, and ϕ^{*}_{η} is shown in figure 2. Because of the binning in ϕ^{*}_{η}, the uncertainty in this observable in the region around 1 is expected to follow a sharper behavior.

The largest source of uncertainty in the inclusive total cross section measurement comes from the measurement of the integrated luminosity and amounts to 2.5% [62]. That uncertainty is relevant only for the absolute cross section measurements. The leading uncertainties for the normalized cross section measurements are related to the momentum scale and the reconstruction efficiency.

A potential bias in the measurement of the reconstruction, identification, and isolation efficiencies with the tag-and-probe technique is estimated by studying the modeling of the background and signal parameterization in the dilepton invariant mass fit. The uncertainty in the modeling of the electromagnetic FSR in the tag-and-probe fits is obtained by weighting the simulation to reflect the differences between pythia [11] and PHOTOS 3.56 [63] modeling of the FSR. The exponentiation mode of PHOTOS is used. The tag selection in the tag-and-probe technique can also bias the efficiency measurement. An additional uncertainty is considered by varying the tag selection requirements in the efficiency measurement.

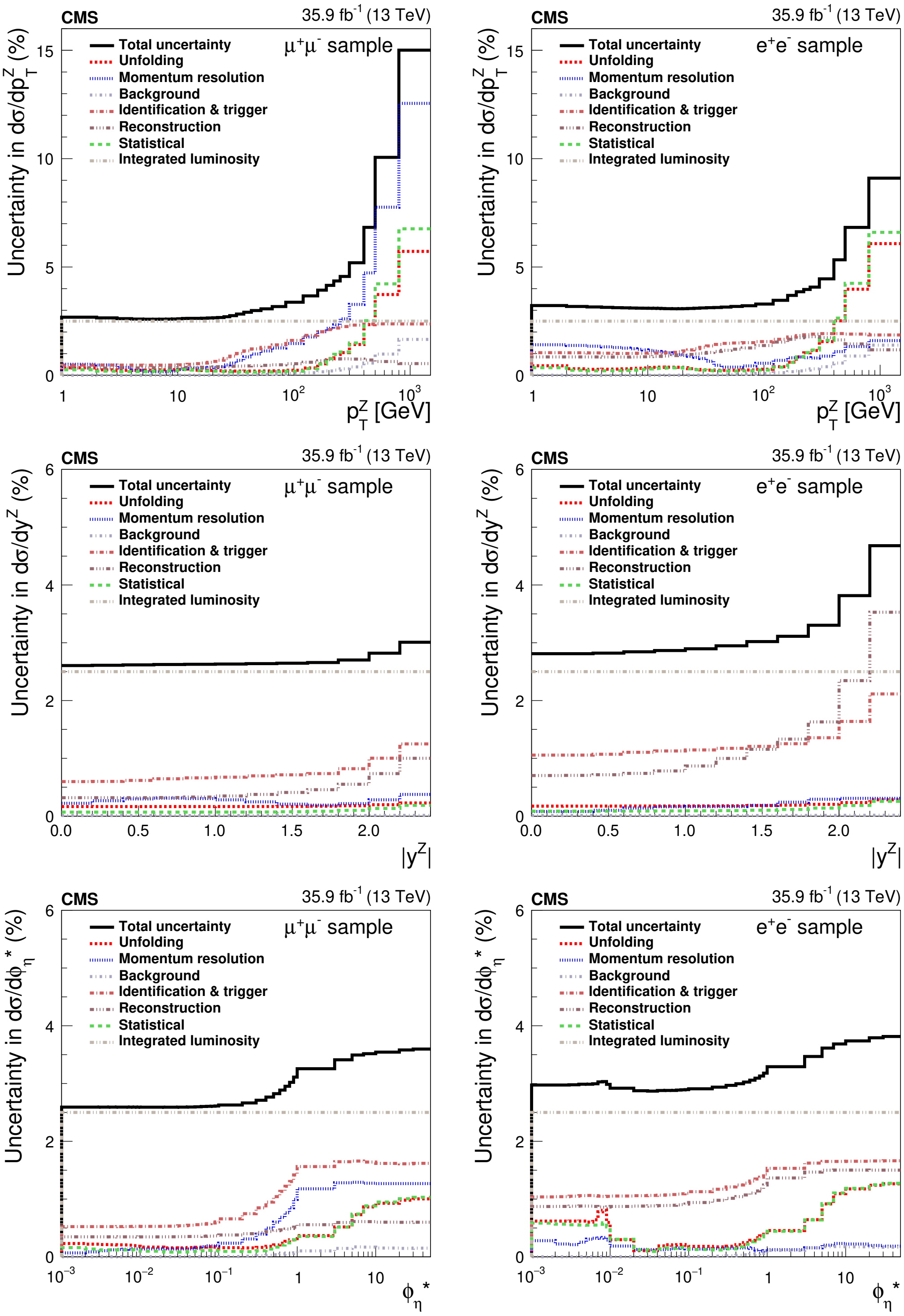

Figure 1. The relative statistical and systematic uncertainties from various sources for the absolute cross section measurements in bins of p_T^Z (upper), $|y^Z|$ (middle), and ϕ^*_η (lower). The left plots correspond to the dimuon final state and the right plots correspond to the dielectron final state. The uncertainty in the trigger efficiency is included as part of the lepton identification uncertainty.

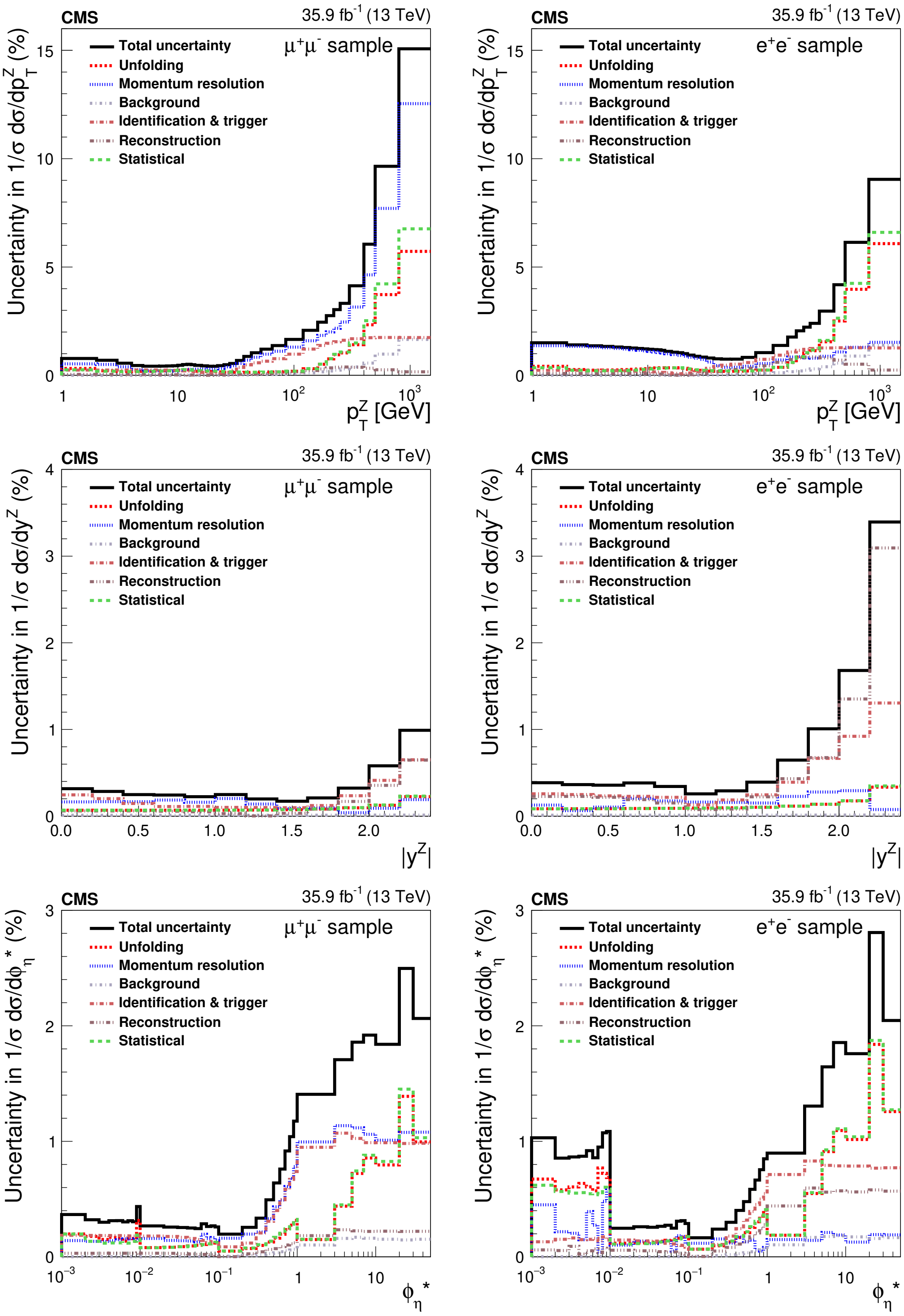

Figure 2. The relative statistical and systematic uncertainties from various sources for the normalized cross section measurements in bins of $p_{\mathrm{T}}^{\mathrm{Z}}$ (upper), $|y^{\mathrm{Z}}|$ (middle), and ϕ_η^* (lower). The left plots correspond to the dimuon final state and the right plots correspond to the dielectron final state.

The uncertainty in the trigger and lepton reconstruction and selection efficiency is about 0.8 (1.3)% in dimuon (dielectron) final states with a sizable dependence on $p_{\mathrm{T}}^{\mathrm{Z}}$, $|y^{\mathrm{Z}}|$, and ϕ_{η}^{*}.

The uncertainty in the dimuon (dielectron) reconstruction efficiency varies between 0.1 (0.2)% in the central part of the detector and 0.5 (2.5)% at large $|y^{\mathrm{Z}}|$ values. The reconstruction efficiency uncertainty also includes the effect of partial mistiming of signals in the forward region in the ECAL endcaps, leading to a one percent reduction in the first-level trigger efficiency. The effect of statistical uncertainties in the measured data-to-simulation scale factors is estimated by varying them within the uncertainties in a series of pseudo-experiments.

The systematic uncertainty due to the choice of the Z boson simulated sample used to determine the response matrices is evaluated by repeating the analysis using POWHEG as the signal sample. The dependence of the measurements on the shapes of $p_{\mathrm{T}}^{\mathrm{Z}}$, $|y^{\mathrm{Z}}|$, and ϕ_{η}^{*} are about 0.3 and 0.5% for the dimuon and dielectron final states, respectively. The uncertainty due to the finite size of the simulated signal sample used for the unfolding reaches about 5% at large $p_{\mathrm{T}}^{\mathrm{Z}}$, and the variation with $p_{\mathrm{T}}^{\mathrm{Z}}$, $|y^{\mathrm{Z}}|$, and ϕ_{η}^{*} closely resembles the statistical uncertainty in data. The systematic uncertainties in the absolute cross section measurement arising from the uncertainties in the lepton momentum scale and resolution are at a level of 0.1 (0.5)% for the dimuon (dielectron) final state. These uncertainties also affect event selection and, because of the correlation between ϕ_{η}^{*} and $p_{\mathrm{T}}^{\mathrm{Z}}$, follow a similar trend for both observables. The muon and electron momentum scales are corrected for the residual misalignment in the detector and the uncertainty in the magnetic field measurements.

The uncertainty in the nonresonant background contribution is estimated conservatively to be about 5%, leading to an uncertainty in the total cross section measurement below 0.1%. The relative contribution of the nonresonant background processes increases with $|y^{\mathrm{Z}}|$ and p_{T}, resulting in an uncertainty of 2% at high p_{T}. The resonant background processes are estimated from simulation and the uncertainties in the background normalization are derived from variations of μ_{R}, μ_{F}, α_{S}, and PDFs [45, 48, 64–67] resulting in uncertainties below 0.1% for the absolute cross section measurement.

When combining the muon and electron channels, the luminosity, background estimation, and modeling uncertainties are treated as correlated parameters, all others are considered as uncorrelated.

Summaries of the uncertainties of the absolute double-differential cross section measurements in $p_{\mathrm{T}}^{\mathrm{Z}}$ and $|y^{\mathrm{Z}}|$ are shown in figures 3 and 4. The statistical uncertainties in the data and the systematic uncertainties with a statistical component are large compared to the single-differential cross section measurements. The statistical uncertainty starts to dominate the total uncertainty in the high $p_{\mathrm{T}}^{\mathrm{Z}}$ regions.

8 Results

The inclusive fiducial cross section is measured in the dimuon and dielectron final states, using the definition described in section 6. The combined cross section is obtained by treating the systematic uncertainties, except the uncertainties due to the integrated luminosity and background estimation, as uncorrelated between the two final states. The integrated

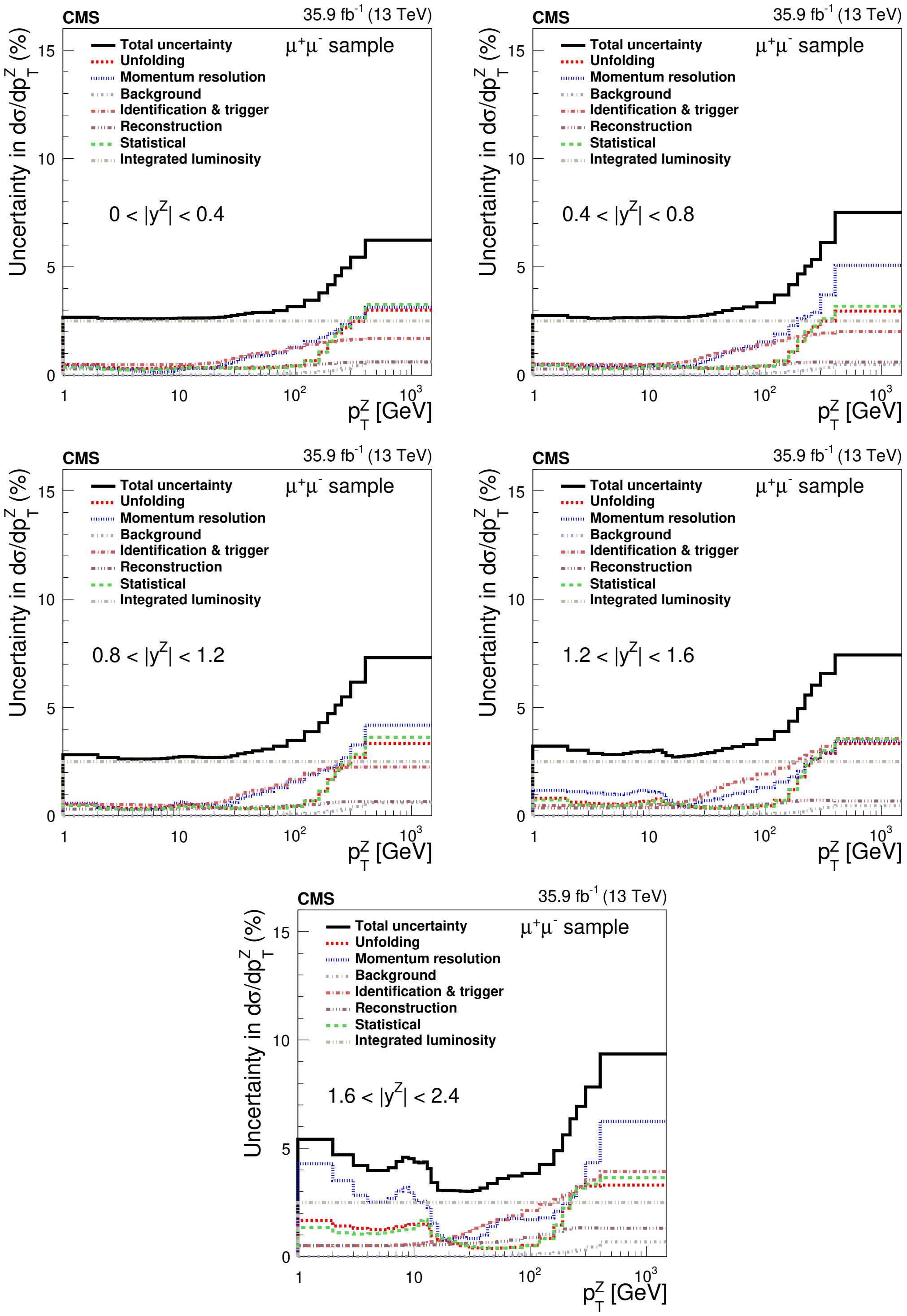

Figure 3. The relative statistical and systematic uncertainties from various sources for the absolute double-differential cross section measurements in bins of p_T^Z for the $0.0 < |y^Z| < 0.4$ bin (upper left), $0.4 < |y^Z| < 0.8$ bin (upper right), $0.8 < |y^Z| < 1.2$ bin (middle left), $1.2 < |y^Z| < 1.6$ bin (middle right), and $1.6 < |y^Z| < 2.4$ bin (lower) in the dimuon final state.

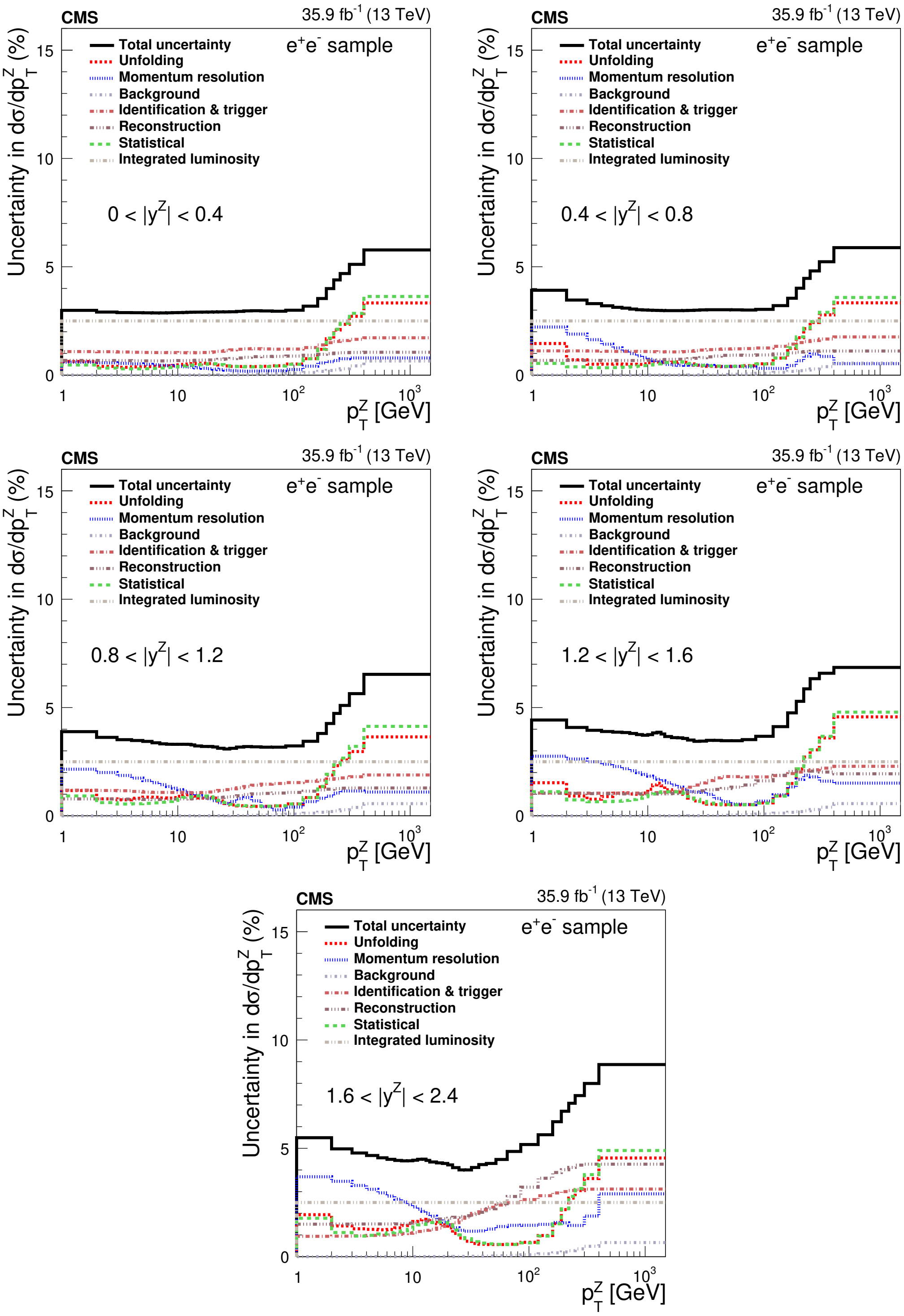

Figure 4. The relative statistical and systematic uncertainties from various sources for the absolute double-differential cross section measurements in bins of p_T^Z for the $0.0 < |y^Z| < 0.4$ bin (upper left), $0.4 < |y^Z| < 0.8$ bin (upper right), $0.8 < |y^Z| < 1.2$ bin (middle left), $1.2 < |y^Z| < 1.6$ bin (middle right), and $1.6 < |y^Z| < 2.4$ bin (lower) in the dielectron final state.

Source	$Z \to \mu\mu$ (%)	$Z \to ee$ (%)
Luminosity	2.5	2.5
Muon reconstruction efficiency	0.4	—
Muon selection efficiency	0.7	—
Muon momentum scale	0.1	—
Electron reconstruction efficiency	—	0.9
Electron selection efficiency	—	1.0
Electron momentum scale	—	0.2
Background estimation	0.1	0.1
Total (excluding luminosity)	0.8	1.4

Table 2. Summary of the systematic uncertainties for the inclusive fiducial cross section measurements.

Cross section	$\sigma\mathcal{B}$ [pb]						
$\sigma_{Z\to\mu\mu}$	694	±	6	(syst)	±	17	(lumi)
$\sigma_{Z\to ee}$	712	±	10	(syst)	±	18	(lumi)
$\sigma_{Z\to\ell\ell}$	699	±	5	(syst)	±	17	(lumi)

Table 3. The measured inclusive fiducial cross sections in the dimuon and dielectron final states. The combined measurement is also shown. $\mathcal{B}$ is the $Z \to \ell\ell$ branching fraction.

luminosity and background estimation uncertainties are treated as fully correlated in the combined measurement. The combined cross section is obtained by unfolding simultaneously the dimuon and dielectron final states. The uncertainties are dominated by the uncertainty in the integrated luminosity and the lepton efficiency. A summary of the systematic uncertainties is shown in table 2. The measured cross sections are shown in table 3.

The measured cross section values agree with the theoretical predictions within uncertainties. The predicted values are $\sigma_{Z\to\ell\ell} = 682 \pm 55\,\text{pb}$ with MadGraph5_aMC@NLO using the NNPDF 3.0 [48] NLO PDF set, and $\sigma_{Z\to\ell\ell} = 719 \pm 8\,\text{pb}$ with fixed order FEWZ [68–71] at NNLO accuracy in QCD using the NNPDF 3.1 [72] NNLO PDF set. The theoretical uncertainties for MadGraph5_aMC@NLO and FEWZ include statistical, PDF, and scale uncertainties. The scale uncertainties are estimated by varying μ_R and μ_F independently up and down by a factor of two from their nominal values (excluding the two extreme variations) and taking the largest cross section variations as the uncertainty.

The measured differential cross sections corrected for detector effects are compared to various theoretical predictions. The measured absolute cross sections in bins of $|y^Z|$ are shown in figure 5 for dimuon and dielectron final states, and their combination. The measurement is compared to the predictions using parton shower modeling with both MadGraph5_aMC@NLO and POWHEG at NLO accuracy in QCD using the NNPDF 3.0 PDF set. The MadGraph5_aMC@NLO prediction includes up to two additional partons at Born level in the matrix element calculations, merged with the parton shower description using the FxFx scheme [73].s A comparison with a fixed order prediction at NNLO accuracy with FEWZ using the NNPDF 3.1 NNLO PDF set is also shown. The MadGraph5_aMC@NLO and POWHEG predictions are consistent with the data within the theoretical uncertainties. The FEWZ prediction with the NNPDF 3.1 PDF set is within 5% of the measurement over the entire $|y^{\mathrm{Z}}|$ range, which is roughly within the uncertainties.

Figure 6 shows the measured absolute cross sections in bins of $p_{\mathrm{T}}^{\mathrm{Z}}$ for dimuon and dielectron final states, and their combination. The measurement is compared to the predictions using parton shower modeling with both MadGraph5_aMC@NLO and POWHEG. A comparison with POWHEG using the MINLO procedure [74] and using the NNPDF 3.1 NLO PDF set is also shown. The predictions are consistent with the measurements within the theoretical uncertainties. The scale uncertainties for the POWHEG-MINLO predictions are evaluated by simultaneously varying μ_{R} and μ_{F} up and down by a factor of two [74]. The POWHEG predictions at high p_{T}, above 100 GeV, disagree with data. The better accuracy of the MadGraph5_aMC@NLO and POWHEG-MINLO predictions at high p_{T} lead to an improved agreement with data.

Figure 7 (left) shows comparisons to the resummed calculations with both RESBOS [75–77] and GENEVA [78]. A comparison to the predictions with TMD PDFs obtained [79] from the parton branching method (PB TMD) [80, 81] and combined with MadGraph5_aMC@NLO at NLO is also shown [82]. The RESBOS predictions are obtained at NNLL accuracy with the CT14 NNLO PDF set and are consistent with the data within the uncertainties at low p_{T} but disagree with the measurements at high p_{T}. The GENEVA predictions include resummation to NNLL accuracy where the resulting parton-level events are further combined with parton showering and hadronization provided by PYTHIA. The GENEVA predictions with the NNPDF 3.1 PDF set and $\alpha_S(m_{\mathrm{Z}}) = 0.114$ are generally consistent with data within the theoretical uncertainties, but disagree with data at p_{T} below 30 GeV. The PB TMD predictions include resummation to NLL accuracy and fixed-order results at NLO, and take into account nonperturbative contributions from TMD parton distributions through fits [79] to precision deep inelastic scattering data. The theoretical uncertainties come from variation of scales and from TMD uncertainties. The PB TMD prediction describes data well at low p_{T}, but deviates from the measurements at high p_{T} because of missing contributions from Z+jets matrix element calculations.

The $p_{\mathrm{T}}^{\mathrm{Z}}$ distribution for $p_{\mathrm{T}} > 32$ GeV is compared to fixed order predictions, as shown in figure 7 (right). A comparison to the MadGraph5_aMC@NLO prediction is included as a reference. The data is compared to the FEWZ predictions at NNLO in QCD and to the complete NNLO predictions of vector boson production in association with a jet [4, 5]. The comparison is performed for $p_{\mathrm{T}} > 32$ GeV because the Z + 1 jet at NNLO prediction does not exist below that value.

The central values of the μ_{F} and μ_{R} are chosen to be $\mu_{\mathrm{F/R}} = \sqrt{(p_{\mathrm{T}}^{\mathrm{Z}})^2 + m_{\ell\ell}^2}$ for the FEWZ and Z+1 jet at NNLO predictions. The scale uncertainties are estimated by simultaneously varying the μ_{F} and μ_{R} up and down together by a factor of two. The CT14 [83] NNLO PDF set is used for the Z+1 jet at NNLO predictions. The predictions

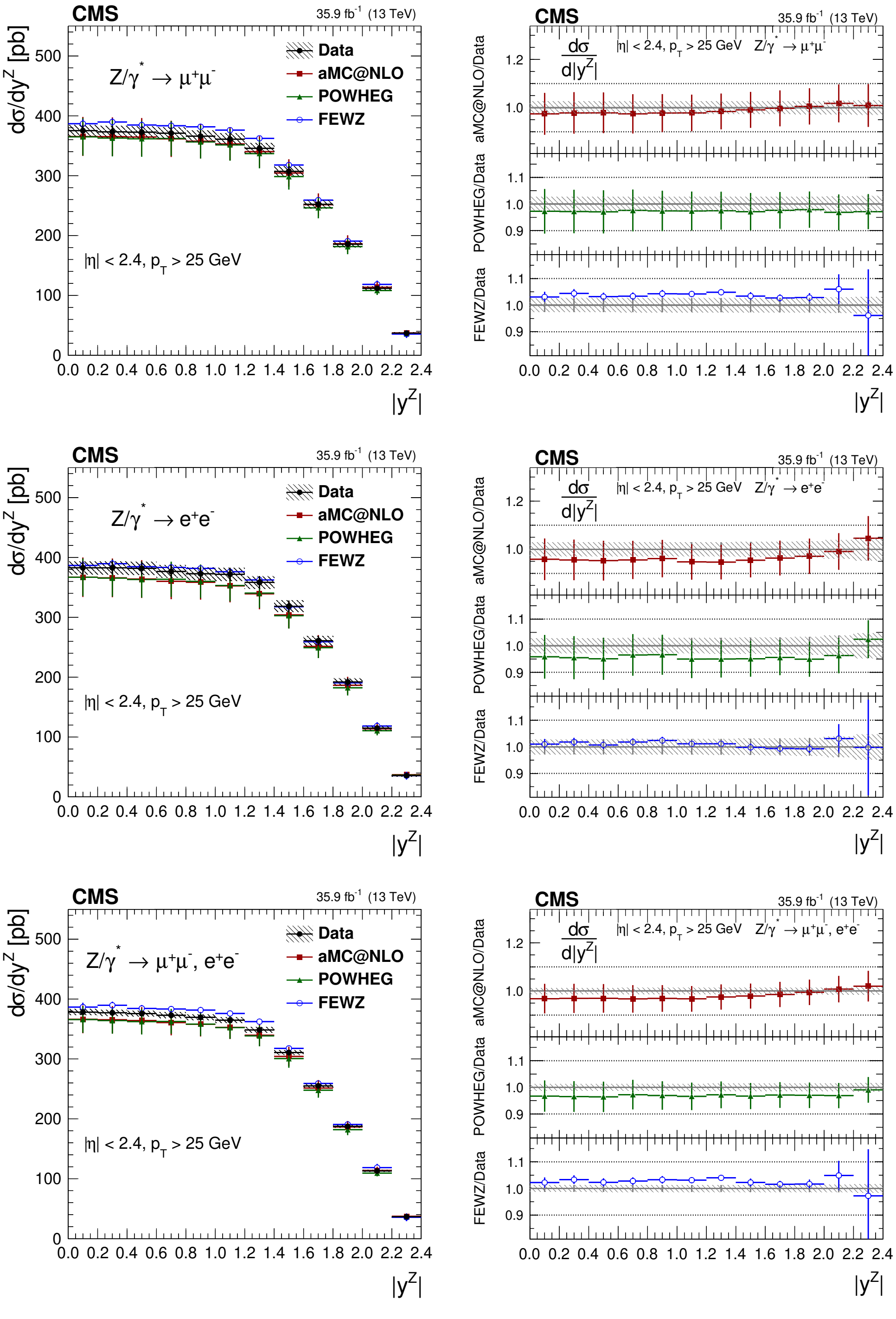

Figure 5. The measured absolute cross sections (left) in bins of $|y^Z|$ for the dimuon (upper) and dielectron (middle) final states, and for the combination (lower). The ratios of the predictions to the data are also shown (right). The shaded bands around the data points (black) correspond to the total experimental uncertainty. The measurement is compared to the predictions with MadGraph5_aMC@NLO (square red markers), POWHEG (green triangles), and FEWZ (blue circles). The error bars around the predictions correspond to the combined statistical, PDF, and scale uncertainties.

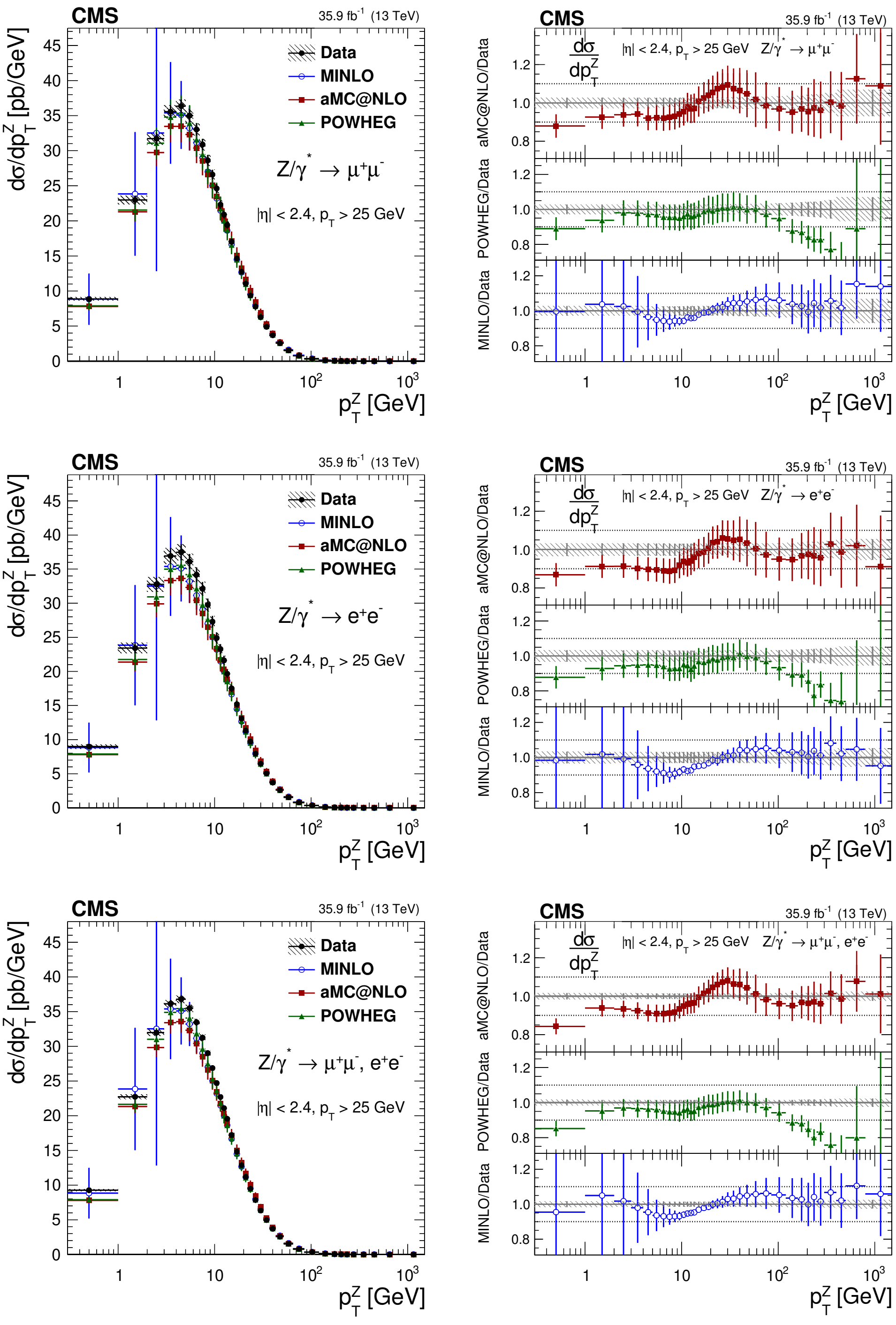

Figure 6. The measured absolute cross sections (left) in bins of p_T^Z for the dimuon (upper) and dielectron (middle) final states, and for the combination (lower). The ratios of the predictions to the data are also shown (right). The shaded bands around the data points (black) correspond to the total experimental uncertainty. The measurement is compared to the predictions with MadGraph5_aMC@NLO (square red markers), POWHEG (green triangles), and POWHEG-MINLO (blue circles). The error bars around the predictions correspond to the combined statistical, PDF, and scale uncertainties.

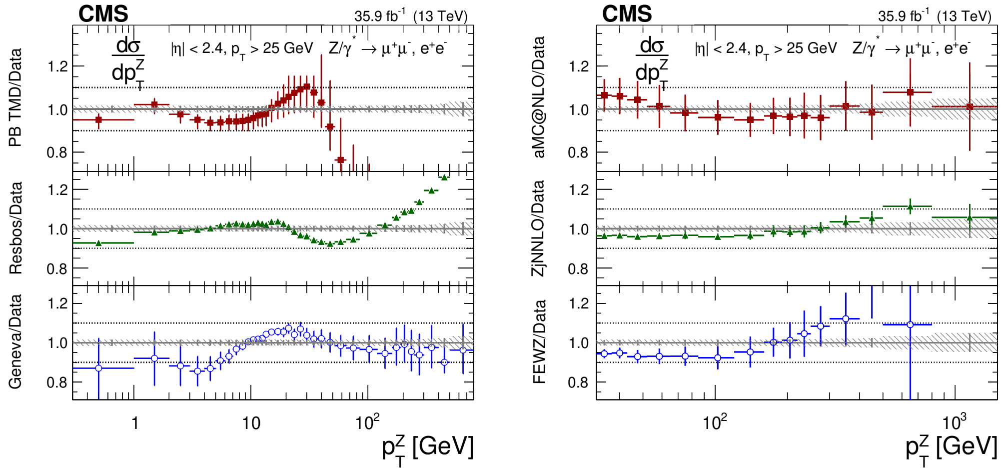

Figure 7. The ratios of the predictions to the data in bins of $p_{\mathrm{T}}^{\mathrm{Z}}$ for the combination of the dimuon and dielectron final states. The shaded bands around the data points (black) correspond to the total experimental uncertainty. The left plot shows comparisons to the predictions with PB TMD (square red markers), RESBOS (green triangles), and GENEVA (blue circles). The right plot shows the $p_{\mathrm{T}}^{\mathrm{Z}}$ distribution for $p_{\mathrm{T}} > 32\,\mathrm{GeV}$ compared to the predictions with MADGRAPH5_aMC@NLO (square red markers), Z + 1 jet at NNLO (green triangles), and FEWZ (blue circles). The error bars around the predictions correspond to the combined statistical, PDF, and scale uncertainties. Only the statistical uncertainties are shown for the predictions with RESBOS.

are consistent with the measurements within the theoretical uncertainties. As can be seen, the Z+1 jet at NNLO calculations significantly reduce the scale uncertainties. The electroweak corrections are important at high p_{T} with expected correction factors of up to 0.9 at $p_{\mathrm{T}} = 500\,\mathrm{GeV}$ and 0.8 at $p_{\mathrm{T}} = 1000\,\mathrm{GeV}$ [6, 7]. They are not included in the predictions shown in figure 7.

Figure 8 shows the measured absolute cross sections in bins of ϕ_η^*. The measurements are compared to the predictions from MADGRAPH5_aMC@NLO, PB TMD, and POWHEG-MINLO. The predictions are consistent with the measurements within the theoretical uncertainties and describe data well at low p_{T}. As expected the PB TMD predictions deviate from data at high p_{T}.

Summaries of the absolute double-differential cross section measurements in $p_{\mathrm{T}}^{\mathrm{Z}}$ and $|y^{\mathrm{Z}}|$ are shown in figures 9–13. The normalized cross section measurements in bins of $p_{\mathrm{T}}^{\mathrm{Z}}$, ϕ_η^*, and $|y^{\mathrm{Z}}|$ are shown in figure 14. The measured normalized cross section uncertainties are smaller than 0.5% for $\phi_\eta^* < 0.5$ and for $p_{\mathrm{T}}^{\mathrm{Z}} < 50\,\mathrm{GeV}$. Summaries of the normalized double-differential cross section measurements in $p_{\mathrm{T}}^{\mathrm{Z}}$ and $|y^{\mathrm{Z}}|$ are shown in figures 15–19. The cross sections are individually normalized in each $|y^{\mathrm{Z}}|$ region. The measurements are compared to the predictions using parton shower modeling with MADGRAPH5_aMC@NLO, POWHEG, and POWHEG-MINLO. The predictions are consistent with the measurements within the theoretical uncertainties, although there is a trend of discrepancy of about 10% in the range $20 < p_{\mathrm{T}}^{\mathrm{Z}} < 60\,\mathrm{GeV}$.

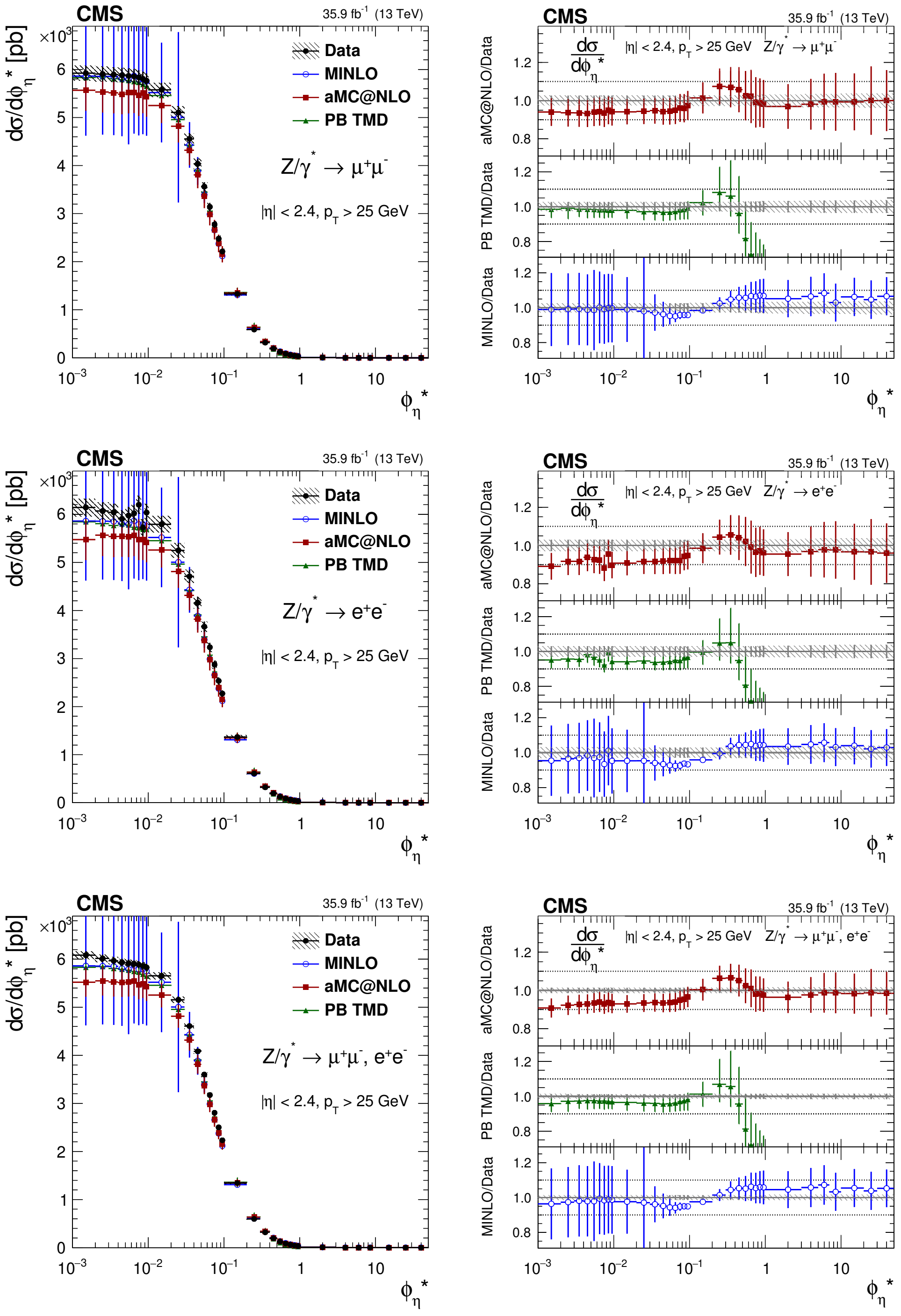

Figure 8. The measured absolute cross sections (left) in bins of ϕ^*_η for the dimuon (upper) and dielectron (middle) final states, and for the combination (lower). The ratios of the predictions to the data are also shown (right). The shaded bands around the data points (black) correspond to the total experimental uncertainty. The measurement is compared to the predictions with MadGraph5_aMC@NLO (square red markers), PB TMD (green triangles), and powheg-MINLO (blue circles). The error bars around the predictions correspond to the combined statistical, PDF, and scale uncertainties.

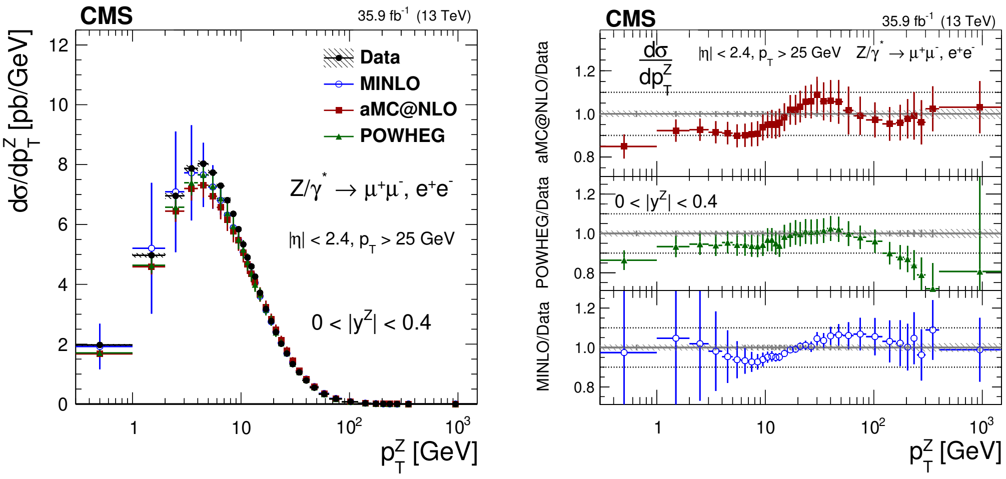

Figure 9. The measured absolute cross sections (left) in bins of $p_{\mathrm{T}}^{\mathrm{Z}}$ for the $0.0 < |y^{\mathrm{Z}}| < 0.4$ region. The ratios of the predictions to the data are also shown (right). The shaded bands around the data points (black) correspond to the total experimental uncertainty. The measurement is compared to the predictions with MadGraph5_aMC@NLO (square red markers), POWHEG (green triangles), and POWHEG-MINLO (blue circles). The error bands around the predictions correspond to the combined statistical, PDF, and scale uncertainties.

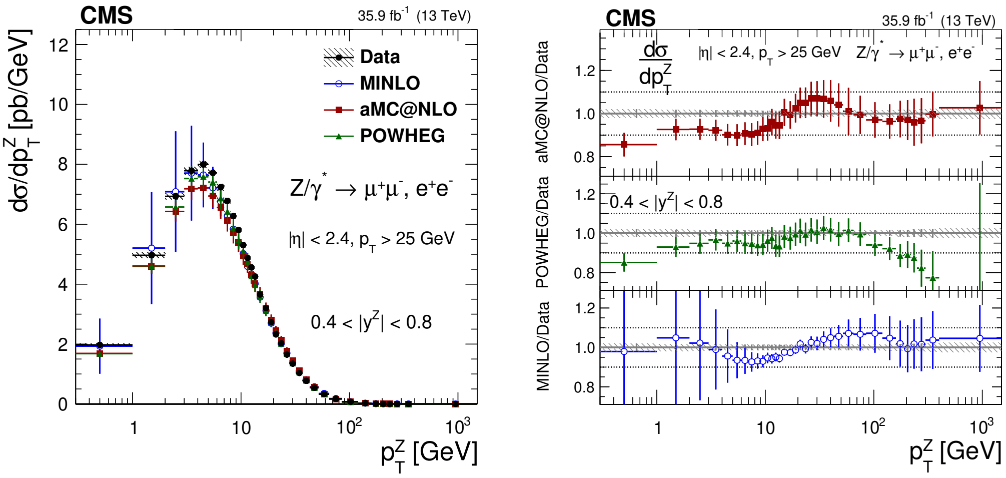

Figure 10. The measured absolute cross sections (left) in bins of $p_{\mathrm{T}}^{\mathrm{Z}}$ for the $0.4 < |y^{\mathrm{Z}}| < 0.8$ region. The ratios of the predictions to the data are also shown (right). The shaded bands around the data points (black) correspond to the total experimental uncertainty. The measurement is compared to the predictions with MadGraph5_aMC@NLO (square red markers), POWHEG (green triangles), and POWHEG-MINLO (blue circles). The error bands around the predictions correspond to the combined statistical, PDF, and scale uncertainties.

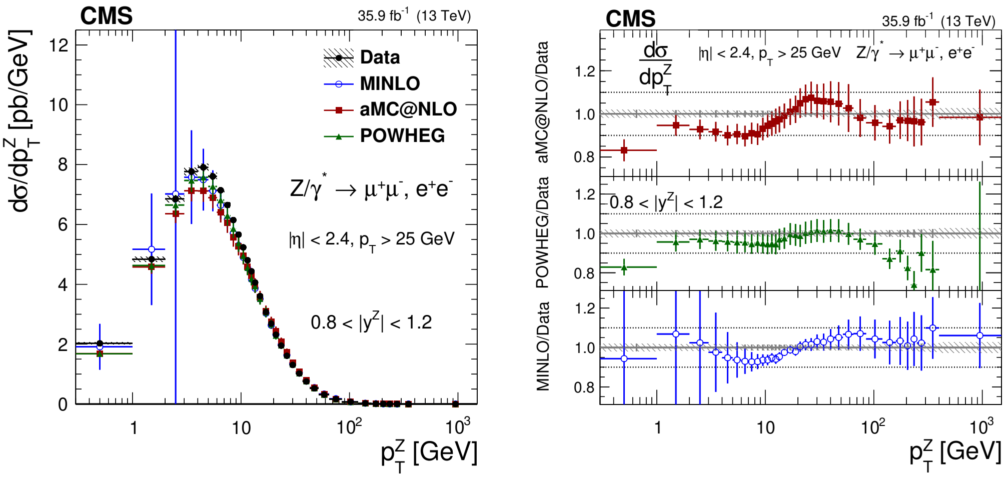

Figure 11. The measured absolute cross sections (left) in bins of p_T^Z for the $0.8 < |y^Z| < 1.2$ region. The ratios of the predictions to the data are also shown (right). The shaded bands around the data points (black) correspond to the total experimental uncertainty. The measurement is compared to the predictions with MadGraph5_aMC@NLO (square red markers), POWHEG (green triangles), and POWHEG-MINLO (blue circles). The error bands around the predictions correspond to the combined statistical, PDF, and scale uncertainties.

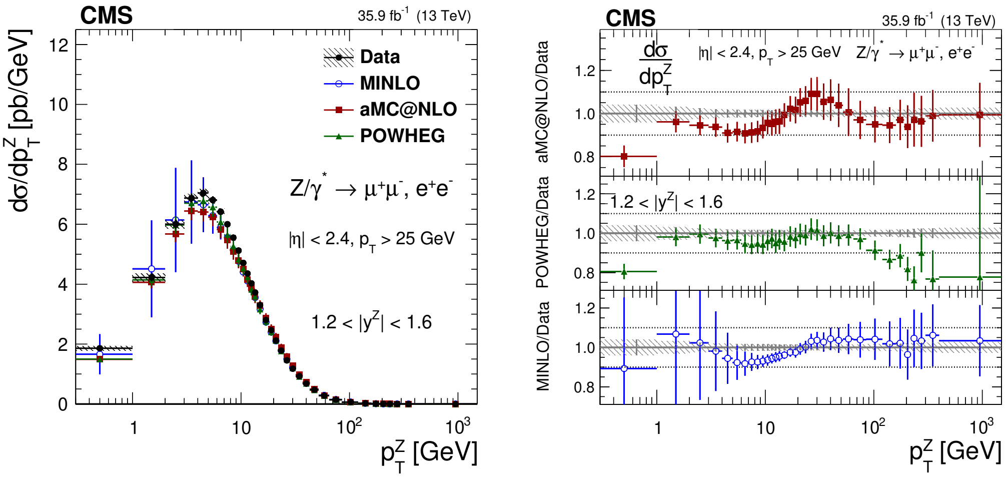

Figure 12. The measured absolute cross sections (left) in bins of p_T^Z for the $1.2 < |y^Z| < 1.6$ region. The ratios of the predictions to the data are also shown (right). The shaded bands around the data points (black) correspond to the total experimental uncertainty. The measurement is compared to the predictions with MadGraph5_aMC@NLO (square red markers), POWHEG (green triangles), and POWHEG-MINLO (blue circles). The error bands around the predictions correspond to the combined statistical, PDF, and scale uncertainties.

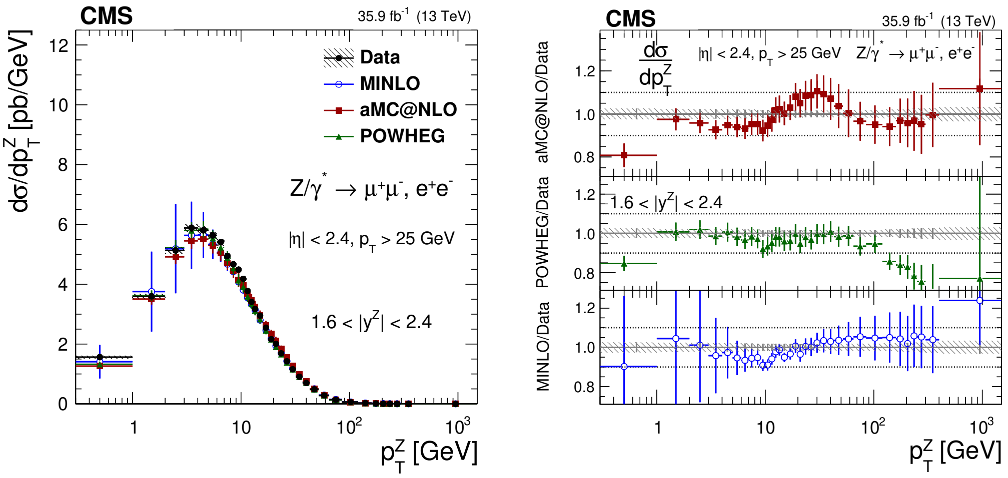

Figure 13. The measured absolute cross sections (left) in bins of $p_{\mathrm{T}}^{\mathrm{Z}}$ for the $1.6 < |y^{\mathrm{Z}}| < 2.4$ region. The ratios of the predictions to the data are also shown (right). The shaded bands around the data points (black) correspond to the total experimental uncertainty. The measurement is compared to the predictions with MadGraph5_aMC@NLO (square red markers), POWHEG (green triangles), and POWHEG-MINLO (blue circles). The error bands around the predictions correspond to the combined statistical, PDF, and scale uncertainties.

9 Summary

Measurements are reported of the differential cross sections for Z bosons produced in proton-proton collisions at $\sqrt{s} = 13$ TeV and decaying to muons and electrons. The data set used corresponds to an integrated luminosity of 35.9 fb^{-1}. Distributions of the transverse momentum p_{T}, the angular variable ϕ^*, and the rapidity of lepton pairs are measured. The results are corrected for detector effects and compared to various theoretical predictions. The measurements provide sensitive tests of theoretical predictions using fixed-order, resummed, and parton shower calculations. The uncertainties in the normalized cross section measurements are smaller than 0.5% for $\phi^*_\eta < 0.5$ and for $p_{\mathrm{T}}^{\mathrm{Z}} < 50$ GeV.

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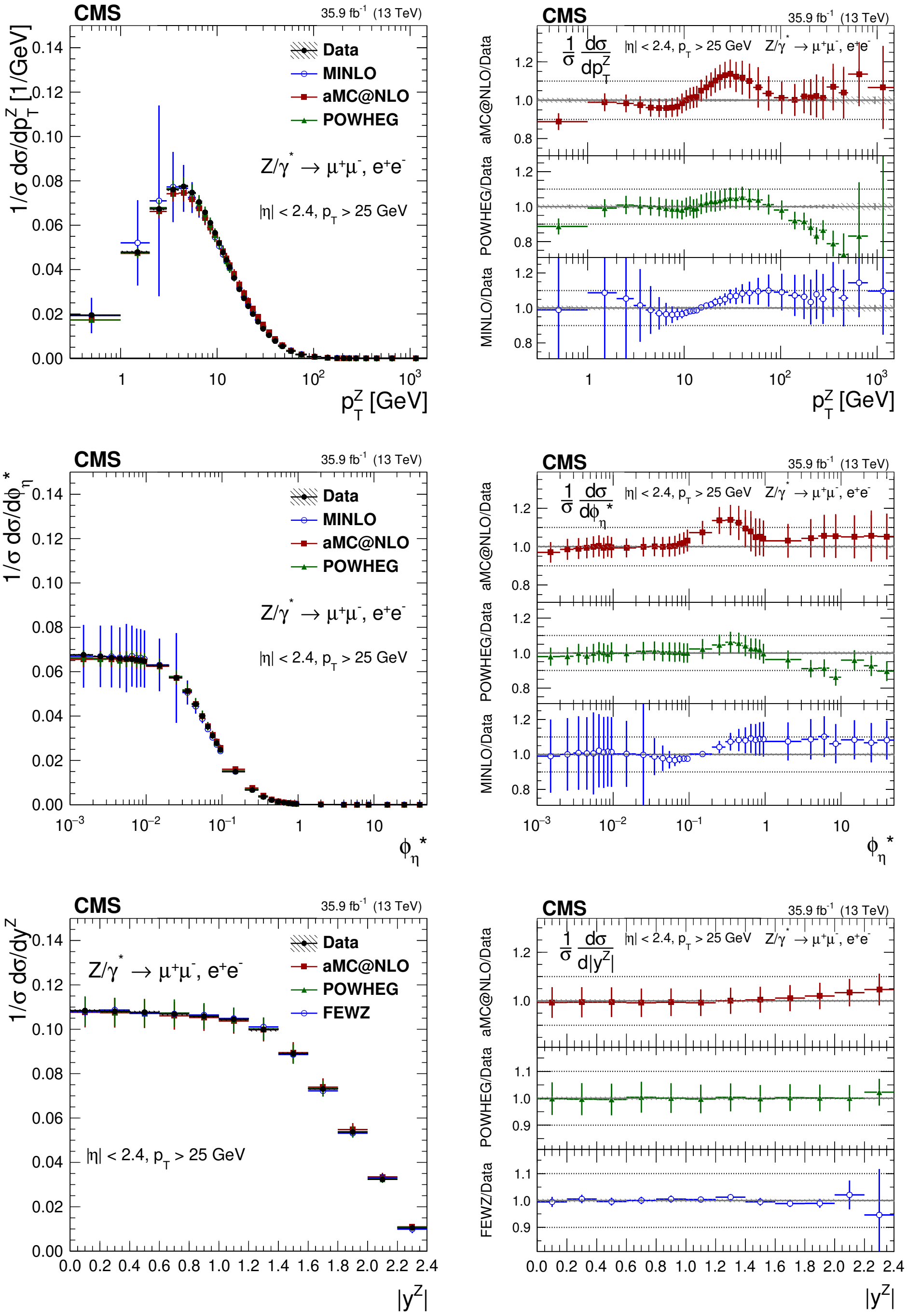

Figure 14. The measured normalized cross sections (left) in bins of p_T^Z (upper), ϕ^*_η (middle), and $|y^Z|$ (lower) for the combined measurement. The ratios of the predictions to the data are also shown (right). The shaded bands around the data points (black) correspond to the total experimental uncertainty. The p_T^Z and ϕ^*_η measurements are compared to the predictions with MadGraph5_aMC@NLO (square red markers), POWHEG (green triangles), and POWHEG-MINLO (blue circles). The $|y^Z|$ measurement is compared to the predictions with MadGraph5_aMC@NLO (square red markers), POWHEG (green triangles), and FEWZ (blue circles). The error bars around the predictions correspond to the combined statistical, PDF, and scale uncertainties.

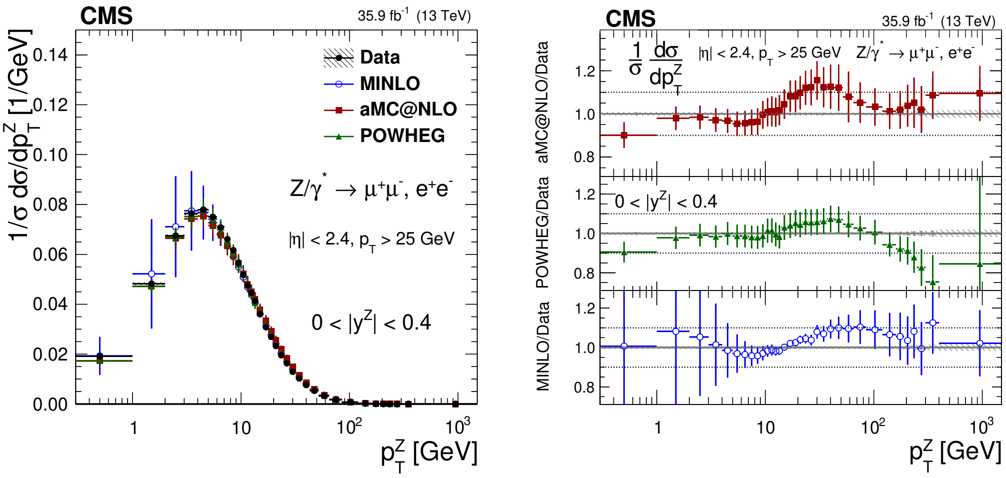

Figure 15. The measured normalized cross sections (left) in bins of $p_{\mathrm{T}}^{\mathrm{Z}}$ for the $0.0 < |y^{\mathrm{Z}}| < 0.4$ region. The ratios of the predictions to the data are also shown (right). The shaded bands around the data points (black) correspond to the total experimental uncertainty. The measurement is compared to the predictions with MadGraph5_aMC@NLO (square red markers), POWHEG (green triangles), and POWHEG-MINLO (blue circles). The error bands around the predictions correspond to the combined statistical, PDF, and scale uncertainties.

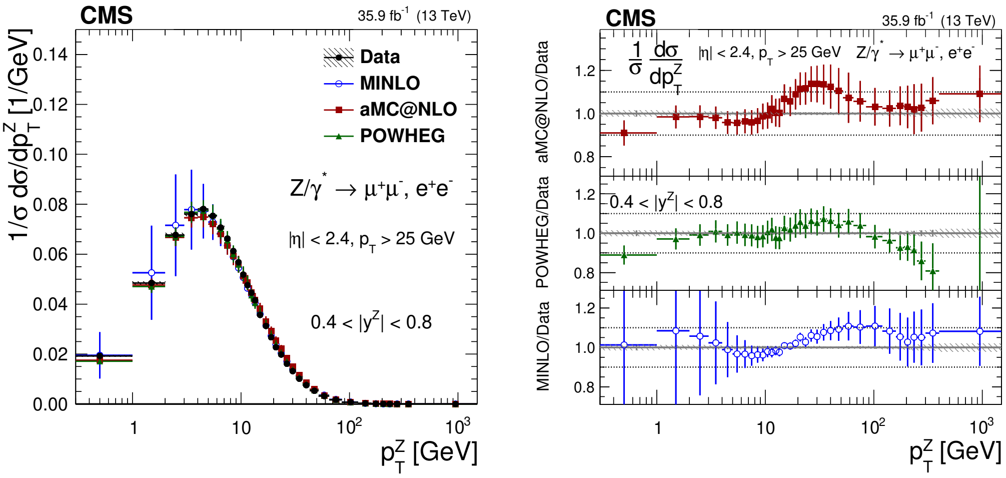

Figure 16. The measured normalized cross sections (left) in bins of $p_{\mathrm{T}}^{\mathrm{Z}}$ for the $0.4 < |y^{\mathrm{Z}}| < 0.8$ region. The ratios of the predictions to the data are also shown (right). The shaded bands around the data points (black) correspond to the total experimental uncertainty. The measurement is compared to the predictions with MadGraph5_aMC@NLO (square red markers), POWHEG (green triangles), and POWHEG-MINLO (blue circles). The error bands around the predictions correspond to the combined statistical, PDF, and scale uncertainties.

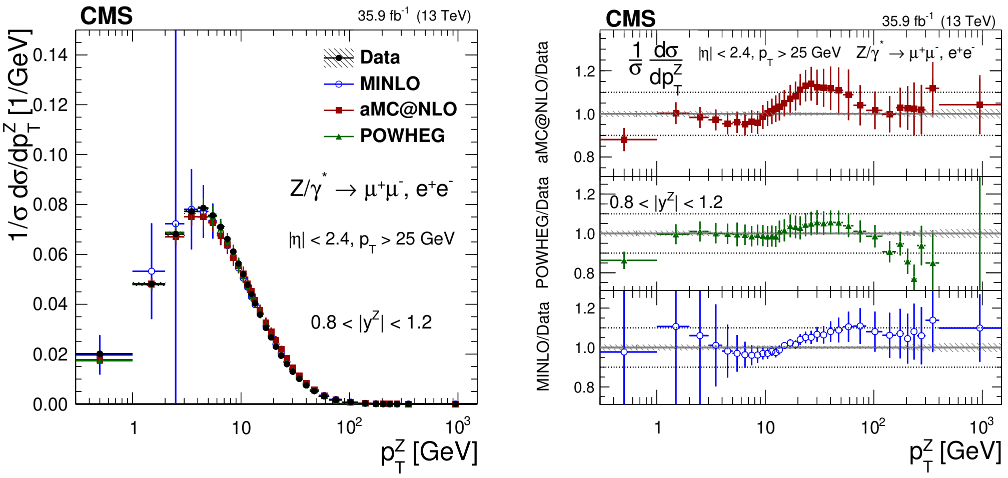

Figure 17. The measured normalized cross sections (left) in bins of p_T^Z for the $0.8 < |y^Z| < 1.2$ region. The ratios of the predictions to the data are also shown (right). The shaded bands around the data points (black) correspond to the total experimental uncertainty. The measurement is compared to the predictions with MadGraph5_aMC@NLO (square red markers), POWHEG (green triangles), and POWHEG-MINLO (blue circles). The error bands around the predictions correspond to the combined statistical, PDF, and scale uncertainties.

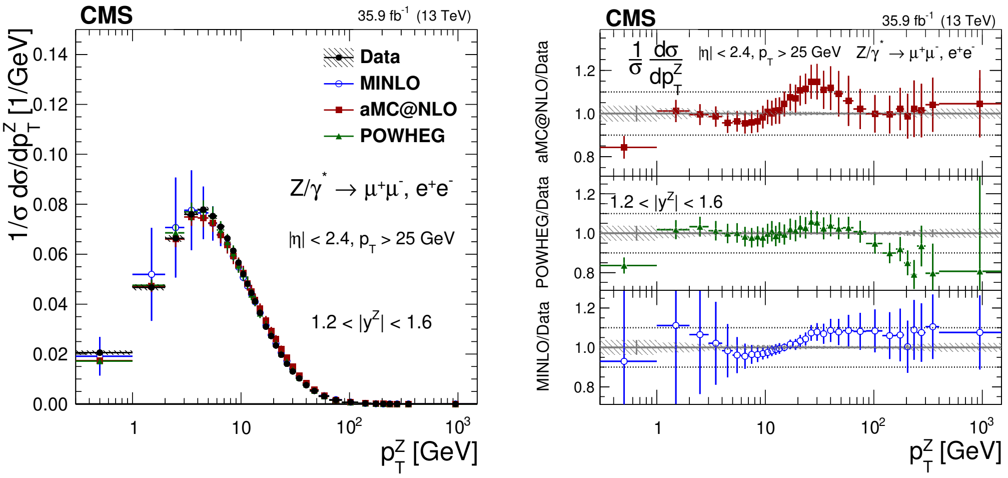

Figure 18. The measured normalized cross sections (left) in bins of p_T^Z for the $1.2 < |y^Z| < 1.6$ region. The ratios of the predictions to the data are also shown (right). The shaded bands around the data points (black) correspond to the total experimental uncertainty. The measurement is compared to the predictions with MadGraph5_aMC@NLO (square red markers), POWHEG (green triangles), and POWHEG-MINLO (blue circles). The error bands around the predictions correspond to the combined statistical, PDF, and scale uncertainties.

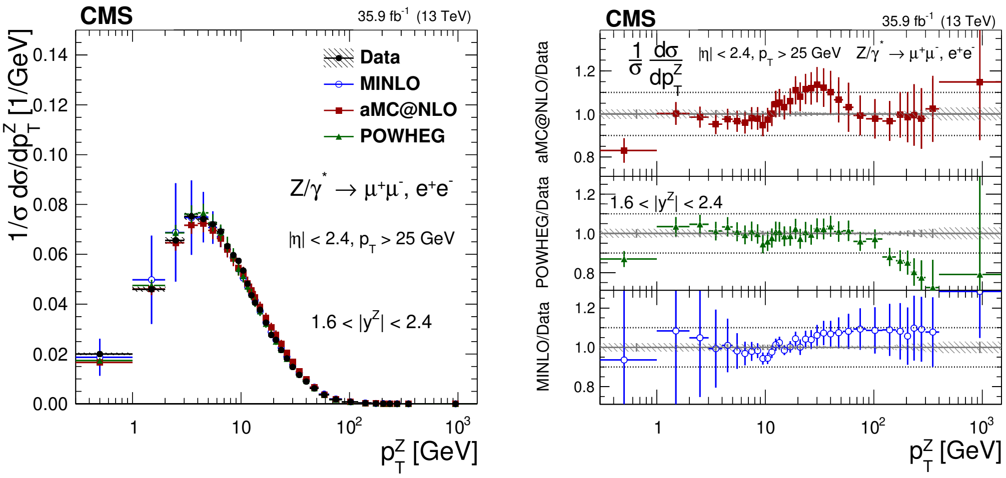

Figure 19. The measured normalized cross sections (left) in bins of p_T^Z for the $1.6 < |y^Z| < 2.4$ region. The ratios of the predictions to the data are also shown (right). The shaded bands around the data points (black) correspond to the total experimental uncertainty. The measurement is compared to the predictions with MadGraph5_aMC@NLO (square red markers), POWHEG (green triangles), and POWHEG-MINLO (blue circles). The error bands around the predictions correspond to the combined statistical, PDF, and scale uncertainties.

MoER, ERC IUT, PUT and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); NKFIA (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); MES (Latvia); LAS (Lithuania); MOE and UM (Malaysia); BUAP, CINVESTAV, CONACYT, LNS, SEP, and UASLP-FAI (Mexico); MOS (Montenegro); MBIE (New Zealand); PAEC (Pakistan); MSHE and NSC (Poland); FCT (Portugal); JINR (Dubna); MON, RosAtom, RAS, RFBR, and NRC KI (Russia); MESTD (Serbia); SEIDI, CPAN, PCTI, and FEDER (Spain); MOSTR (Sri Lanka); Swiss Funding Agencies (Switzerland); MST (Taipei); ThEPCenter, IPST, STAR, and NSTDA (Thailand); TUBITAK and TAEK (Turkey); NASU and SFFR (Ukraine); STFC (United Kingdom); DOE and NSF (U.S.A.).

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