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Measurement of the Z boson differential cross section in transverse momentum and rapidity in proton–proton collisions at 8 TeV

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ABSTRACT

We present a measurement of the Z boson differential cross section in rapidity and transverse momentum using a data sample of pp collision events at a centre-of-mass energy $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of 19.7 fb^{-1}. The Z boson is identified via its decay to a pair of muons. The measurement provides a precision test of quantum chromodynamics over a large region of phase space. In addition, due to the small experimental uncertainties in the measurement the data has the potential to constrain the gluon parton distribution function in the kinematic regime important for Higgs boson production via gluon fusion. The results agree with the next-to-next-to-leading-order predictions computed with the FEWZ program. The results are also compared to the commonly used leading-order MadGraph and next-to-leading-order POWHEG generators.

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1. Introduction

The production of lepton pairs in proton–proton collisions is dominated by the Drell–Yan (DY) process, i.e. the production of an intermediate γ^*/Z boson by the incoming partons. Measurements of the cross sections as a function of the mass of the intermediate boson (hereafter referred to as the 'Z boson'), rapidity, and transverse momentum provide a very sensitive test of quantum chromodynamics (QCD). Precise measurement of the differential cross section also allows comparisons to calculations employing different parton distribution functions (PDF) and underlying theoretical models. Finally, the understanding of DY lepton pair production is important in the study of several physics processes, such as diboson and $t\bar{t}$ production, as well as in searches for new resonances decaying to dileptons in models of physics beyond the standard model. Differential measurements of Z boson production at the LHC have already been performed [1–8].

In this Letter we present the first measurement of the DY cross section at a centre-of-mass energy of 8 TeV for dimuon pairs in the vicinity of the Z boson peak, doubly differential in the transverse momentum q_T and in the rapidity y of the Z boson. The analysis uses the data sample of pp collisions collected with the CMS detector at the LHC in 2012, corresponding to an integrated luminosity of 19.7 fb^{-1}. We present the absolute fiducial cross section and the fiducial cross section normalised to the inclusive fiducial cross section. The measurement probes the production of Z bosons up to high transverse momenta, $q_T \sim 100$ GeV, a kinematic regime where the production is dominated by gluon–quark fusion. The precision of this measurement leads to experimental uncertainties smaller than or similar to the uncertainties of the gluon PDF in the kinematic region that is relevant to the production of the Higgs boson via the gluon fusion mechanism. Using the Z boson production process to constrain the gluon PDF [9] in the future would be complementary to other processes such as direct photon production [10] and top-quark pair production [11] that constrain the gluon PDF in this regime. Moreover, several of the experimental systematic uncertainties in the DY measurement are uncorrelated with these other processes. The latter have more complex topologies and thus have complementary and potentially larger systematic uncertainties.

2. The CMS detector

A more detailed description of the CMS detector, together with a definition of the coordinate system and the relevant kinematic variables, can be found in Ref. [12]. 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 are a silicon pixel and strip tracker, a lead tungsten crystal electromagnetic calorimeter (ECAL), and a brass/scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Muons are measured in gas-ionisation detectors embedded in the steel flux-return yoke outside the solenoid. Extensive forward

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calorimetry complements the coverage provided by the barrel and endcap detectors. Muons are measured in the pseudorapidity range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive-plate chambers. Matching muons to tracks measured in the silicon tracker results in a relative p_T resolution of 1.3–2.0% in the barrel and better than 6% in the endcaps, for muons with $20 < p_T < 100$ GeV. The p_T resolution in the barrel is better than 10% for muons with p_T up to 1 TeV [13]. The particle-flow event reconstruction [14,15] is used in this analysis. It works by reconstructing and identifying each particle with an optimised combination of all subdetector information. The energy of photons is directly obtained from the ECAL measurement, corrected for zero-suppression effects. The energy of electrons is determined from a combination of the track momentum at the main interaction vertex, the corresponding ECAL cluster energy, and the energy sum of all bremsstrahlung photons. The energy of muons is obtained from the corresponding track momentum. The energy of charged hadrons is determined from a combination of the track momentum and the corresponding ECAL and HCAL energies, corrected for zero-suppression effects, and calibrated for the nonlinear response of the calorimeters. Finally, the energy of neutral hadrons is obtained from the corresponding calibrated ECAL and HCAL energies. The first level of the CMS trigger system, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select the most interesting events in a fixed time interval of less than 4 μs. The high-level trigger processor farm further decreases the event rate from around 100 kHz to around 400 Hz before data storage.

3. Simulation

The signal process is simulated using the leading-order (LO) MadGraph 1.3.30 [16] generator with 0–4 additional jets, interfaced with pythia [17] v6.4.24 with the Z2* tune [18]. The matching between matrix element calculation and parton shower is performed with the k_T-MLM algorithm [19]. Multiple-parton interactions are accounted for via pythia. The LO CTEQ6L1 [20] PDF set is used for the generation. As a cross-check, a second signal sample is simulated using the next-to-leading-order (NLO) powheg [21–24] generator interfaced with pythia. For this generation the NLO CT10 [25] PDF set is used.

The backgrounds are generated with MadGraph (W + jets, $t\bar{t}$, $\tau\tau$), powheg (single top quark [26,27]), and pythia (dibosons, WW, WZ, ZZ). The inclusive cross sections of DY, W + jets [28], and $t\bar{t}$ [29] processes are normalised to next-to-next-to-leading-order (NNLO) predictions. In addition, for the single top quark a higher-order (approximate NNLO [30]) inclusive cross section is used. The generated events are passed through a detector simulation based on Geant4 [31]. The simulated processes are overlaid with minimum bias collisions in order to reproduce the distribution of the number of additional proton–proton interactions per bunch crossing (pileup) present in data.

In addition, for comparison with the final result the double differential cross section is computed with fewz 3.1.b2 [32] at NNLO. The electroweak corrections are computed at NLO and initial-state photon radiation and photon-induced processes are included in the generation. The computation is done for each q_T bin separately. The factorisation and renormalisation scales are chosen as $\sqrt{M_Z^2 + q_T^2}$, where M_Z is the mass of the Z boson and q_T is the value of the lower edge of the corresponding bin in q_T. For the computation the NNLO NNPDF23 PDF set with radiative corrections [33] is used.

4. Event selection

An isolated single-muon trigger is used with a threshold of $p_T > 24$ GeV and a requirement of $|\eta| < 2.1$. The standard CMS baseline offline muon selection [13] is applied. It requires that the muon candidate is reconstructed both in the muon detectors and in the inner tracker, with $\chi^2/n_{\mathrm{dof}} < 10$ for the track fit. In addition, requirements are placed on the minimum number of pixel and tracker layers that are hit and on detailed matching criteria between the trajectories reconstructed in the inner tracker and the muon system. The distance between the muon candidate trajectory and the primary vertex is required to be smaller than 2 mm in the transverse plane and smaller than 5 mm in the longitudinal direction. The vertex with the highest sum of p_T^2 of associated tracks is selected as the primary vertex. The leading reconstructed muon in p_T is required to be the one selected by the trigger. In order to be within the trigger acceptance, the leading muon is selected with $p_T > 25$ GeV and $|\eta| < 2.1$. The second muon is required to have $p_T > 10$ GeV and $|\eta| < 2.4$. The relative isolation is defined to be the scalar sum of the transverse momenta of charged hadrons, neutral hadrons, and photons in a cone of $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.4$ around the muon direction, divided by p_T. After correction for pileup, the value of the relative isolation is required to be less than 0.12 (0.5) for the leading (second) muon. A pair of oppositely charged muons is required to have an invariant mass $M(\mu\mu)$ between 81 and 101 GeV. In the rare case of ambiguity among several reconstructed muons, the muon pair with the invariant mass closest to the Z boson mass is selected. The absolute rapidity $|y|$ of the muon pair must be less than 2.

Scale factors are applied to account for known differences between data and simulation. The efficiencies for the tracking, the trigger, the muon isolation and identification are determined via a "tag-and-probe" method [34]. The tracking efficiency is measured in bins of η. The trigger efficiency is measured in bins of muon p_T and η for positive and negative muons separately. The identification efficiency is measured in bins of p_T and η. In particular phase space regions, especially for higher q_T, the second muon can often point opposite to the Z boson in the azimuthal plane. In that direction, the hadronic activity from the recoil of the Z boson is enhanced. Thus the second muon is often less isolated than the leading muon and the isolation depends on the event kinematics. For that reason, the requirement for the isolation of the second muon is looser than the requirement for the leading muon, and the efficiency is measured in variables reflecting the second muon direction with respect to the Z boson. Three variables for the second muon are chosen to measure this effect on the efficiency in data: the transverse momentum of the dimuon system q_T, the cosine of the polar angle $\cos\theta^*$ and the azimuthal angle ϕ^*. The two angles are measured in the Z boson rest frame, where the z axis is the Z boson flight direction. For $\cos(\theta^*) = -1$ the leptons are more likely to be close to the hadronic recoil. The azimuthal angle is chosen to be zero for the proton closest to the z axis in this frame. The isolation efficiency for the leading muon is measured in bins of p_T and η. These efficiencies are measured in data and simulation, and scale factors are applied to the simulation to account for differences with respect to the data.

The backgrounds are small relative to the signal (at the percent level or smaller) and can be divided into two categories: those where the leptons come from Z boson decays and those where the leptons stem from other sources. The backgrounds from $t\bar{t}$, $\tau\tau$, WW, tW, and W + jets are estimated from specific data samples. Backgrounds typically have two prompt leptons, although not necessarily of the same lepton flavor: flavor universality is used for the background estimation. The estimation consists of two steps. First, the oppositely charged mixed lepton eμ yields are measured in both data and MC. Then the ratio of the yields in data and simulation in this data sample (eμ channel) is used to normalise the simulation in the muon channel. The eμ-channel selection uses the same trigger as the final sample, thus the same trigger efficiency scale factor is used. In addition, the tracking, the identification, and the isolation efficiency scale factors for the leading muon are applied. Electrons are selected if they have $p_T(e) > 20$ GeV and $|\eta(e)| < 2.1$, which is similar to the fiducial regions of the muon selection. No data-to-simulation correction factors are applied to the electron identification since the effect on the final results is negligible. In order to enhance the statistical precision, the invariant mass range of the eμ pairs is increased to [60, 120] GeV. Within the uncertainties, no significant trend in q_T and $|y|$ is observed in the ratio of the eμ yields in data and simulation, and a constant scale factor of 0.987 ± 0.008 is used. The WZ and ZZ backgrounds, which include a true $Z \to \mu\mu$ decay, are taken from simulation.

5. Measured observables and granularity

The reconstructed and background-corrected double differential distribution in q_T and $|y|$ is unfolded to pre-final-state radiation (FSR) lepton kinematics. The unfolding is performed to the kinematic region $81 \le M(\mu\mu) < 101$ GeV and within the kinematic selection of the leading (second) muon, $p_T > 25(10)$ GeV and $|\eta| < 2.1\,(2.4)$. The unfolding is done using an iterative unfolding technique [35] implemented in the RooUnfold package [36]. The bins in q_T are [0, 20], [20, 40], [40, 60], [60, 80], [80, 100], [100, 120], [120, 140], [140, 170], [170, 200], [200, 1000]. In $|y|$ a constant bin width of 0.4 is used and the binning ends at 2.

MadGraph is used as simulation input to the unfolding. The unfolding is validated by treating the simulated powheg signal sample as data. The unfolded powheg distribution is found to be compatible with the distribution at the generator level within unfolding uncertainty.

6. Systematic uncertainties

The sources of systematic uncertainty are ordered by their average size starting with the largest one. The full covariance matrix is computed for both the normalised and the absolute cross section.

- Luminosity uncertainty:
  The uncertainty in the measurement of the integrated luminosity is 2.6% [37].
- Tracking, muon trigger, isolation, and identification efficiency correction factors:
  A potential bias in the measurement of the efficiencies with the tag-and-probe technique is estimated by varying the most sensitive components: the background in simulation is removed and doubled; the signal is parametrised with the sum of two Voigtian functions instead of the sum of a Crystal Ball and a Gaussian function; the efficiencies are parametrised only in η but with finer bins; and, only tags with a single available probe are selected for the measurement instead of all possible pairs. For each contribution a 100% correlation is assumed in the covariance matrix. The effect of statistical uncertainties in the measured data-to-simulation scale factors is estimated by their variation within the uncertainties in a series of pseudo-experiments. Combining the effects extracted from these variations, the systematic uncertainties are typically between 1% and 1.6%, depending on the bin, and increase with q_T.
- Pileup uncertainty:
  The cross section of minimum bias events is varied by ±5% and the impact of the pileup multiplicity in the simulation on the measurement is used as correlated uncertainty for all bins. This uncertainty is at maximum around 0.5% and is negligible compared to the leading uncertainties.
- Statistical uncertainties of the simulation:
  The uncertainty due to the limited number of events in simulation is estimated via pseudo-experiments by varying the response matrix and the efficiency within the statistical uncertainties.
- FSR:
  The simulation is reweighted to reflect the difference between a soft-collinear approach and the exact O(α) result, similar to what was done in Ref. [34]. It also reflects effects from higher-order contributions. The difference between the measurements with and without the reweighting is assigned as an uncertainty and is assumed to be fully correlated for the covariance matrix.
- Backgrounds:
  - $t\bar{t}$, tW, WW, W + jets, and $\tau\tau$ backgrounds:
    A 10% uncertainty is assigned to the scale factor derived in the eμ method. This accounts for the statistical uncertainty of the scale factor and for the uncertainties in the lepton efficiencies. For the covariance matrix full correlation is assumed.
  - WZ and ZZ backgrounds:
    The diboson backgrounds that include a Z boson are determined from simulation. The cross sections are varied by 50% to estimate the systematic uncertainty. While the inclusive cross sections have been measured to agree reasonably well [38–40], we assign conservatively 50% to account for the fact that we use the q_T and $|y|$ shapes from LO calculations.
- Muon momentum resolution:
  The muon momentum resolution is measured in data and simulation, and corresponding corrections are applied. The covariance accounting for the statistical uncertainty of the muon momentum correction measurements is calculated via pseudo-experiments. In addition, an uncertainty is assigned to take into account possible correlated offsets.
- Z boson polarisation:
  The lepton angular distribution of the Drell–Yan process can be described at LO through the coefficients, A_0–A_4 [41]. However, inaccuracies in the way this is modelled in the simulation can affect the result of the unfolding. The angular coefficients A_0–A_4 are inferred in bins of q_T and $|y|$ in [42] for both data and simulation we use. For each parameter A_i the simulation is independently reweighted to correspond to the data as measured in [42]. In case the difference in A_i is smaller than the typical theoretical uncertainty of 10% [43] A_i is varied by 10%. The full difference between the default polarisation and the changed polarisation is assigned as systematic uncertainty. Full correlation is assumed between the bins.
- q_T and y shapes:
  The dependence of the results on the q_T and y shapes of the simulation is studied by repeating the analysis using powheg as the signal sample. The results obtained using MadGraph or powheg for the unfolding are compatible with each other within the statistical uncertainties. In addition, the MadGraph simulation is weighted in fine bins in q_T and y to match the background-corrected data. The effect on the result using the reweighted simulation for the unfolding is much smaller than the uncertainties assigned to the limited statistics of simulation and is neglected.

The contributions of the uncertainties to the normalised cross section measurement are presented in Fig. 1. The systematic uncer-

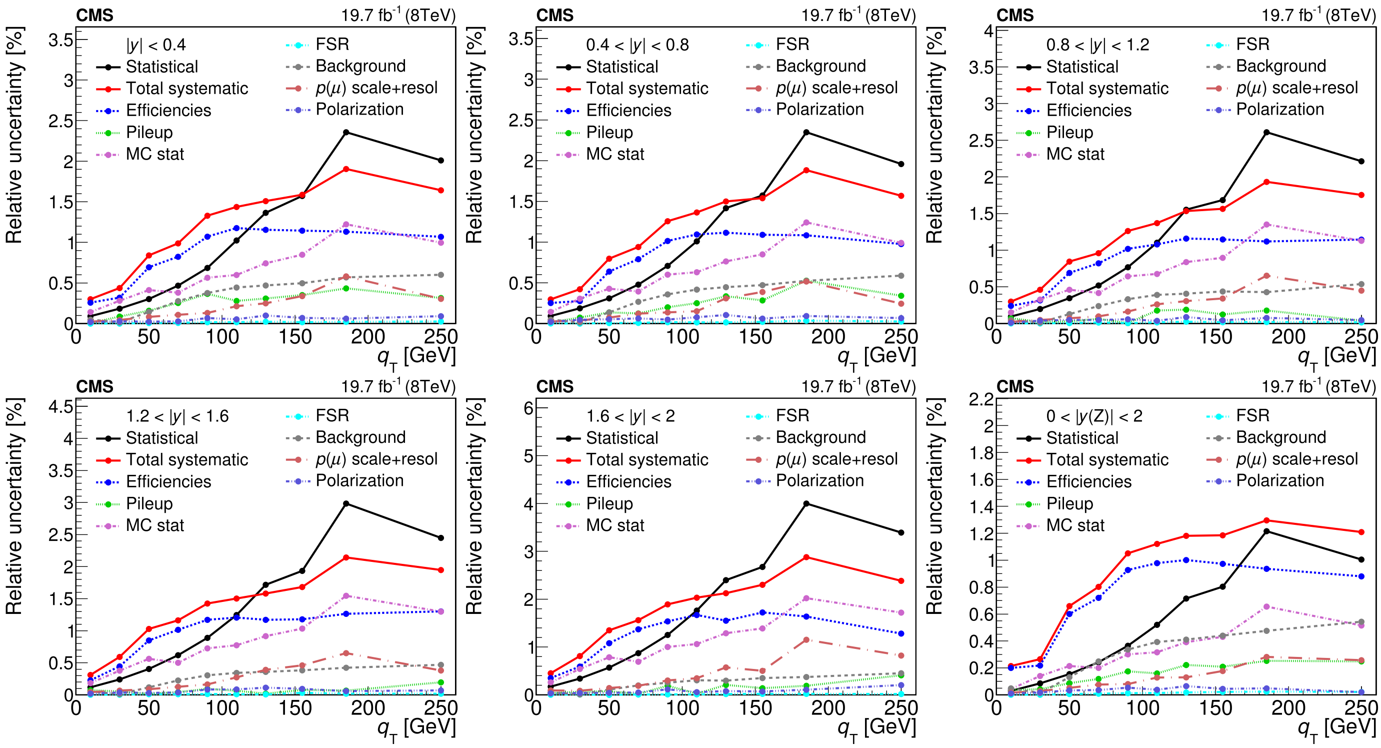

Fig. 1. Relative uncertainties in percent of the normalised fiducial cross section measurement. Each plot shows the q_T dependence in the indicated ranges of $|y|$.

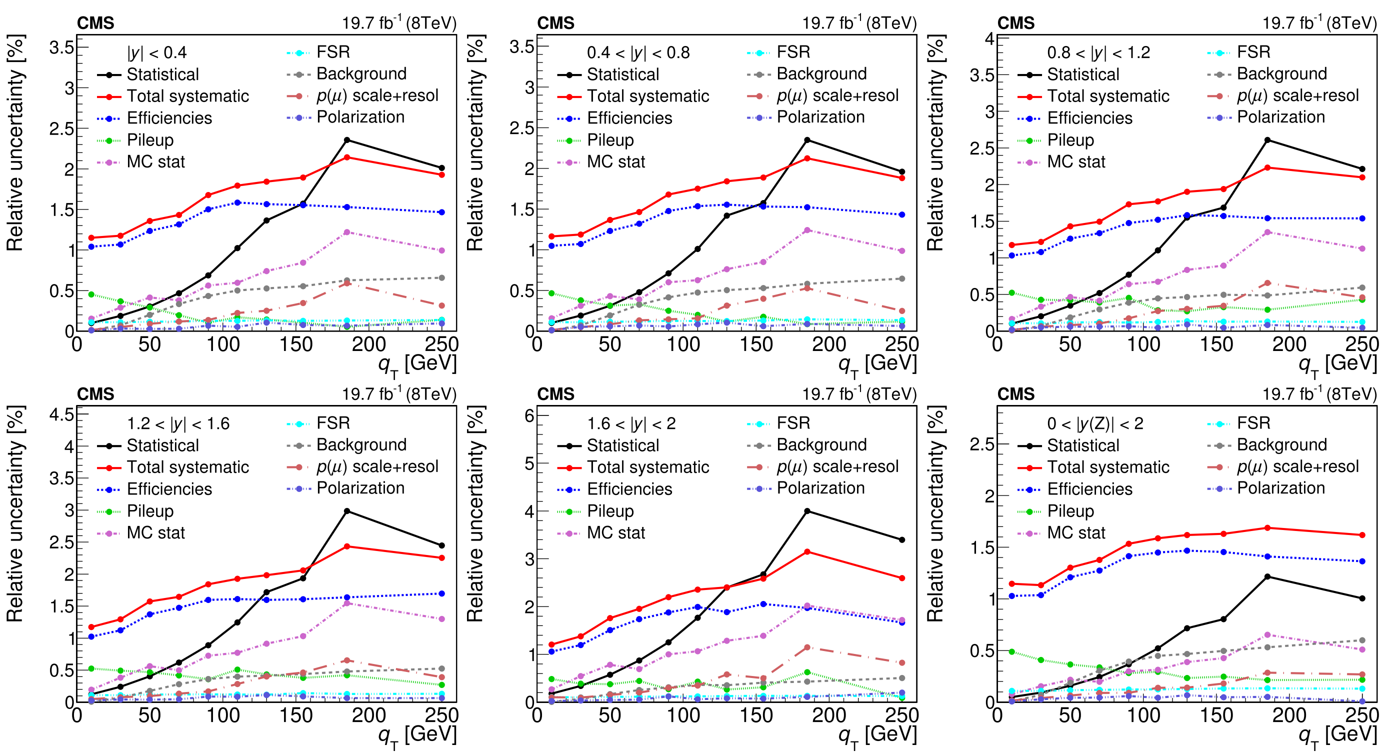

Fig. 2. Relative uncertainties in percent of the absolute fiducial cross section measurement. The 2.6% uncertainty in the luminosity is not included. Each plot shows the q_T dependence in the indicated ranges of $|y|$.

tainty is dominated by the uncertainty in the efficiency correction. In the highest bins of q_T the measurement is dominated by the statistical uncertainties. The uncertainty contributions to the absolute cross section measurement are presented in Fig. 2.

7. Results

The double differential cross section normalised to the inclusive cross section for Z bosons decaying to muons is presented

Table 1
Measured double differential fiducial cross section normalised to the inclusive fiducial cross section in units of GeV^{-1}.

q_T [GeV]	$0 \le \vert y\vert < 0.4$			$0.4 \le \vert y\vert < 0.8$			$0.8 \le \vert y\vert < 1.2$			$1.2 \le \vert y\vert < 1.6$			$1.6 \le \vert y\vert < 2$		
	$d^2\sigma/\sigma_{inc}$	δ_{stat} [%]	δ_{syst} [%]	$d^2\sigma/\sigma_{inc}$	δ_{stat} [%]	δ_{syst} [%]	$d^2\sigma/\sigma_{inc}$	δ_{stat} [%]	δ_{syst} [%]	$d^2\sigma/\sigma_{inc}$	δ_{stat} [%]	δ_{syst} [%]	$d^2\sigma/\sigma_{inc}$	δ_{stat} [%]	δ_{syst} [%]
[0, 20]	2.10×10^{-2}	0.09	0.30	2.10×10^{-2}	0.09	0.30	1.96×10^{-2}	0.10	0.30	1.47×10^{-2}	0.12	0.31	7.88×10^{-3}	0.17	0.45
[20, 40]	6.20×10^{-3}	0.18	0.44	6.08×10^{-3}	0.19	0.42	5.50×10^{-3}	0.20	0.46	4.11×10^{-3}	0.24	0.59	2.17×10^{-3}	0.34	0.81
[40, 60]	2.28×10^{-3}	0.30	0.84	2.22×10^{-3}	0.31	0.80	1.99×10^{-3}	0.35	0.85	1.53×10^{-3}	0.40	1.03	8.11×10^{-4}	0.57	1.35
[60, 80]	9.79×10^{-4}	0.47	0.99	9.48×10^{-4}	0.48	0.94	8.85×10^{-4}	0.52	0.96	6.82×10^{-4}	0.62	1.16	3.75×10^{-4}	0.87	1.56
[80, 100]	4.73×10^{-4}	0.69	1.33	4.56×10^{-4}	0.71	1.26	4.23×10^{-4}	0.77	1.26	3.42×10^{-4}	0.89	1.43	1.92×10^{-4}	1.25	1.89
[100, 120]	2.33×10^{-4}	1.02	1.44	2.34×10^{-4}	1.01	1.36	2.19×10^{-4}	1.10	1.37	1.80×10^{-4}	1.25	1.50	1.01×10^{-4}	1.76	2.03
[120, 140]	1.31×10^{-4}	1.37	1.51	1.24×10^{-4}	1.42	1.50	1.15×10^{-4}	1.55	1.53	1.01×10^{-4}	1.72	1.58	6.03×10^{-5}	2.40	2.13
[140, 170]	6.42×10^{-5}	1.57	1.59	6.34×10^{-5}	1.57	1.54	6.05×10^{-5}	1.68	1.56	5.13×10^{-5}	1.93	1.68	3.00×10^{-5}	2.67	2.30
[170, 200]	2.88×10^{-5}	2.36	1.91	2.93×10^{-5}	2.35	1.88	2.90×10^{-5}	2.61	1.93	2.40×10^{-5}	2.98	2.14	1.49×10^{-5}	4.00	2.88
[200, 1000]	1.31×10^{-6}	2.01	1.64	1.30×10^{-6}	1.96	1.57	1.17×10^{-6}	2.21	1.75	9.90×10^{-7}	2.45	1.95	5.54×10^{-7}	3.39	2.39

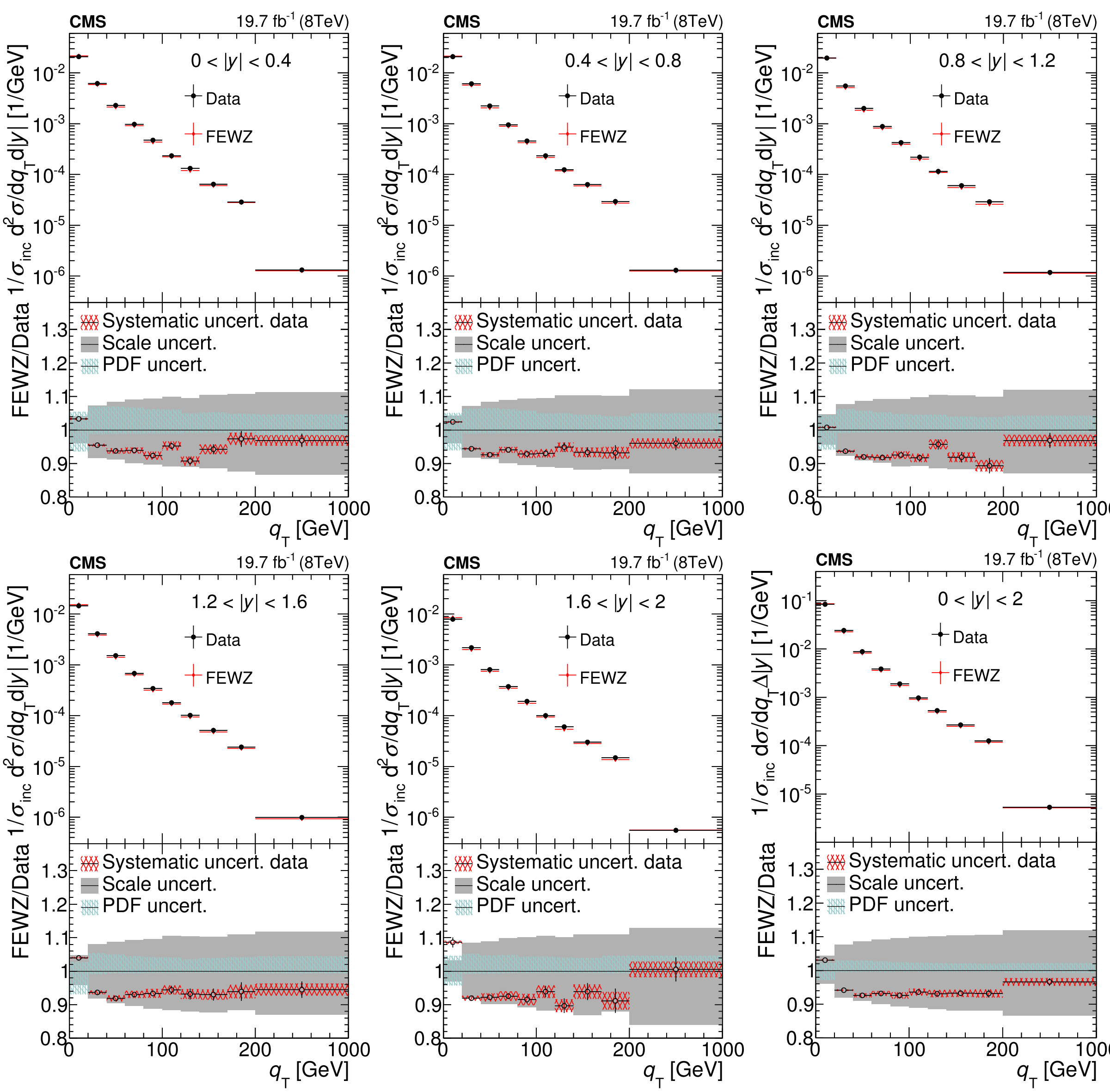

Fig. 3. The measured fiducial Z boson differential cross section, normalised to the inclusive fiducial cross section compared to the NNLO prediction of FEWZ. The first five plots show the q_T dependence in the five bins of $|y|$ and the last plot shows the q_T dependence integrated over $|y|$. The NNLO NNPDF23 PDF set with radiative corrections is used for the generation. We include data in q_T up to 1 TeV, but have shortened the bin for presentation purposes.

in Table 1. A comparison of the measurement with the NNLO FEWZ computation is shown in Fig. 3, where the first five plots show the q_T dependence in the five bins in $|y|$ and the last plot shows the q_T dependence integrated over $|y|$. In the bottom panels the ratio of the FEWZ prediction to data is shown. The vertical error bars represent the statistical uncertainties of data and sim-

Table 2
Measured absolute double differential fiducial cross section in units of pb/GeV.

q_T [GeV]	$0 \le \lvert y\rvert < 0.4$ $d^2\sigma$	δ_{stat} [%]	δ_{syst} [%]	$0.4 \le \lvert y\rvert < 0.8$ $d^2\sigma$	δ_{stat} [%]	δ_{syst} [%]	$0.8 \le \lvert y\rvert < 1.2$ $d^2\sigma$	δ_{stat} [%]	δ_{syst} [%]	$1.2 \le \lvert y\rvert < 1.6$ $d^2\sigma$	δ_{stat} [%]	δ_{syst} [%]	$1.6 \le \lvert y\rvert < 2$ $d^2\sigma$	δ_{stat} [%]	δ_{syst} [%]
[0, 20]	9.87	0.10	2.84	9.86	0.10	2.85	9.20	0.10	2.85	6.89	0.12	2.85	3.71	0.18	2.87
[20, 40]	2.92	0.19	2.85	2.86	0.19	2.86	2.59	0.20	2.87	1.93	0.24	2.90	1.02	0.34	2.94
[40, 60]	1.07	0.30	2.93	1.05	0.31	2.94	9.35×10^{-1}	0.35	2.97	7.19×10^{-1}	0.41	3.04	3.82×10^{-1}	0.57	3.14
[60, 80]	4.61×10^{-1}	0.47	2.97	4.46×10^{-1}	0.48	2.98	4.16×10^{-1}	0.52	3.00	3.21×10^{-1}	0.62	3.08	1.77×10^{-1}	0.87	3.25
[80, 100]	2.23×10^{-1}	0.69	3.09	2.15×10^{-1}	0.71	3.09	1.99×10^{-1}	0.77	3.12	1.61×10^{-1}	0.89	3.19	9.05×10^{-2}	1.25	3.40
[100, 120]	1.10×10^{-1}	1.02	3.16	1.10×10^{-1}	1.01	3.13	1.03×10^{-1}	1.10	3.15	8.46×10^{-2}	1.25	3.24	4.74×10^{-2}	1.76	3.51
[120, 140]	6.18×10^{-2}	1.36	3.19	5.81×10^{-2}	1.42	3.19	5.41×10^{-2}	1.55	3.22	4.76×10^{-2}	1.72	3.27	2.84×10^{-2}	2.40	3.54
[140, 170]	3.02×10^{-2}	1.57	3.22	2.98×10^{-2}	1.57	3.21	2.84×10^{-2}	1.69	3.24	2.41×10^{-2}	1.93	3.32	1.41×10^{-2}	2.67	3.67
[170, 200]	1.36×10^{-2}	2.36	3.37	1.38×10^{-2}	2.35	3.36	1.36×10^{-2}	2.61	3.43	1.13×10^{-2}	2.99	3.56	7.00×10^{-3}	4.00	4.08
[200, 1000]	6.18×10^{-4}	2.01	3.24	6.12×10^{-4}	1.96	3.21	5.52×10^{-4}	2.21	3.34	4.66×10^{-4}	2.45	3.44	2.60×10^{-4}	3.40	3.67

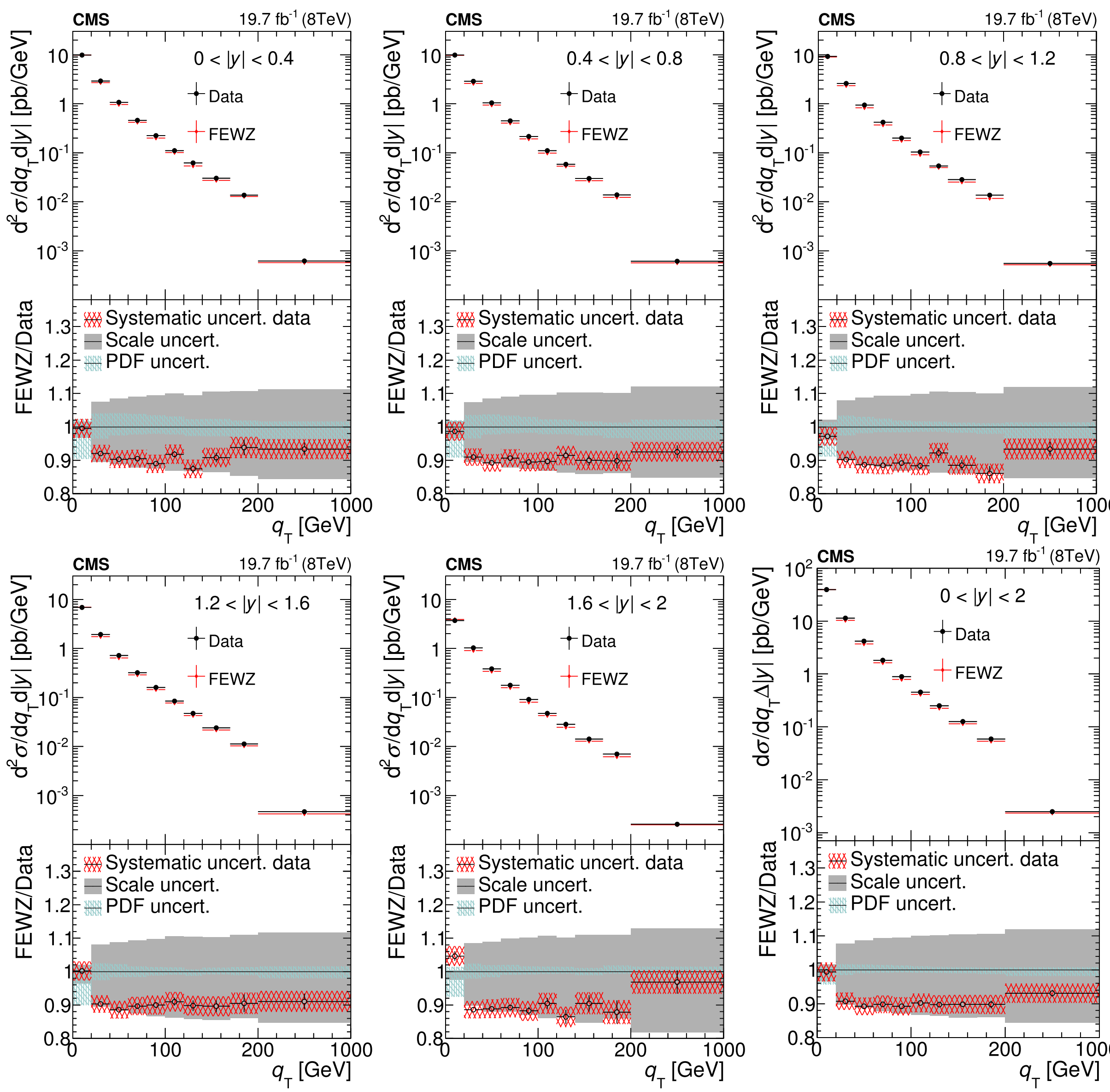

Fig. 4. The measured absolute fiducial Z boson differential cross section compared to the NNLO prediction of FEWZ. The first five plots show the q_T dependence in the five bins of $|y|$ and the last plot shows the q_T dependence integrated over $|y|$. We include data in q_T up to 1 TeV, but have shortened the bin for presentation purposes.

ulation. The red-hatched bands drawn at the points represent the systematic uncertainties of the measurement only. The scale uncertainties are indicated by the grey-shaded areas and the PDF uncertainties by the light-hatched bands. The scale uncertainties are estimated from the envelope of the following combinations of variations of the factorisation μ_F and the renormalisation μ_R scales: $(2\mu_F, 2\mu_R)$, $(0.5\mu_F, 0.5\mu_R)$, $(2\mu_F, \mu_R)$, $(\mu_F, 2\mu_R)$, $(0.5\mu_F, \mu_R)$, and $(\mu_F, 0.5\mu_R)$. The PDF uncertainties are evaluated as the en-

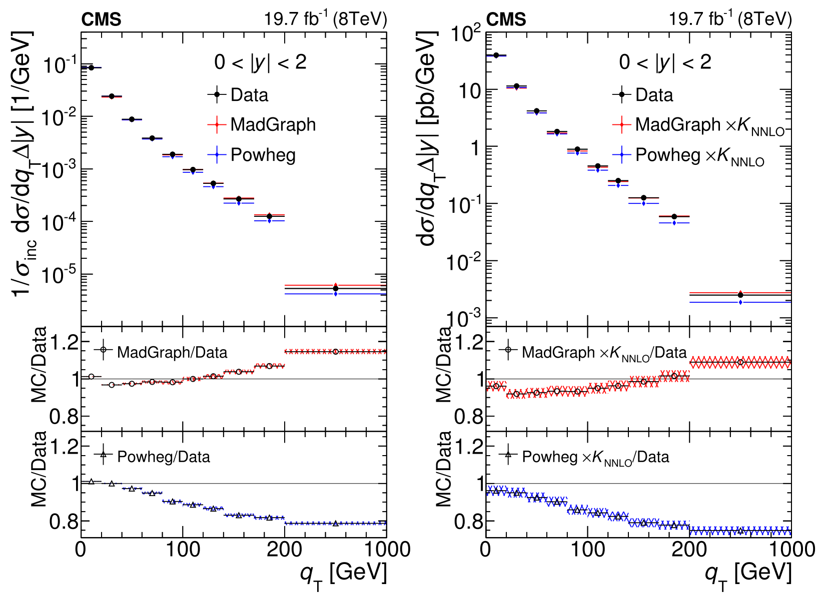

Fig. 5. Normalised (left) and absolute (right) fiducial Z boson cross section, as a function of q_T, compared to predictions from MadGraph (red symbols) and powheg (blue symbols). MadGraph uses the LO CTEQ6L1 PDF set and powheg the NLO CT10 PDF set. The inclusive LO MadGraph and the inclusive NLO powheg cross sections are scaled to the inclusive NNLO cross section calculated with fewz by applying scale factors K^{FEWZ}_{NNLO}. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

velope of the uncertainties of the NNLO NNPDF23 and the NNLO CT10 [44] PDF sets. The scale uncertainty is about 4% for the lowest q_T bin. In the second q_T bin it is about 8% and increases up to about 14% in the highest q_T bin. The jump in the size of the scale uncertainty between the first and the second bins in q_T can be understood as a consequence of reducing the order of the calculation to NLO when the Z boson is produced in combination with a jet, which is the dominant process for $q_T > 20$ GeV. While the scale uncertainties are smaller at low q_T, the shape is not expected to match the data well since multiple soft gluon emissions are not modelled. At very high q_T QED corrections could reach a few percent [45,46].

The PDF uncertainties in the region $q_T > 20$ GeV range between $+1\%$ and -4%. The uncertainty is asymmetric because the inclusive cross section computed using the NNLO CT10 PDF set is about 2.5% larger than the one obtained using the NNLO NNPDF23 PDF set.

The NNLO fewz computation predicts the shape correctly, within scale uncertainties of order 6–12%, where the default scale has the general feature of underestimating the relative abundance of high-q_T (>20 GeV) events at the 7% level. The shape in $|y|$ is well described by fewz.

The absolute double differential cross section is presented in Table 2. The comparison with the NNLO computation of the fewz program is shown in Fig. 4. The scale uncertainties range from 10–16% for $q_T > 20$ GeV. The PDF uncertainties are of the order of 3% in the central rapidity region and decrease to about 1% in the forward region. The absolute cross section predicted by the NNLO program fewz agrees within the uncertainties with the measurement.

A comparison of the measurements with the MadGraph and the powheg generators is shown in Fig. 5. The statistical uncertainties are smaller than the symbol size. The hatched bands represent the systematic uncertainties of the measurement only. The two generators show opposite trends in q_T. The MadGraph generator overestimates the data in the highest q_T bins, whereas the powheg generator underestimates the data up to 20% in this region. Also shown are the absolute differential cross section predictions of MadGraph and powheg after normalising their inclusive cross sections to the NNLO cross section by K factors, which are independent of q_T and $|y|$.

8. Summary

For Z bosons decaying to muons the double differential Z boson fiducial cross section in q_T and $|y|$ has been measured in pp collisions at 8 TeV. The results are compared to the next-to-next-to-leading-order predictions computed with the fewz program and they agree within the scale uncertainties. Deviations from the data of up to 20% at high transverse momentum are observed in the MadGraph and powheg generators. The results are presented along with the full covariance matrix in order to enable their use in future fits of the PDF. The experimental uncertainties are significantly smaller than the current theoretical and PDF uncertainties.

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[59] Also at Texas A&M University at Qatar, Doha, Qatar.
[60] Also at Kyungpook National University, Daegu, South Korea.