



# Measurement of the WZ production cross section in pp collisions at $\sqrt{s} = 13$ TeV

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## ABSTRACT

The WZ production cross section in proton–proton collisions at  $\sqrt{s} = 13$  TeV is measured with the CMS experiment at the LHC using a data sample corresponding to an integrated luminosity of  $2.3 \text{ fb}^{-1}$ . The measurement is performed in the leptonic decay modes  $WZ \rightarrow \ell\nu\ell'\ell'$ , where  $\ell, \ell' = e, \mu$ . The measured cross section for the range  $60 < m_{\ell'\ell'} < 120$  GeV is  $\sigma(\text{pp} \rightarrow WZ) = 39.9 \pm 3.2(\text{stat})^{+2.9}_{-3.1}(\text{syst}) \pm 0.4(\text{theo}) \pm 1.3(\text{lumi})$  pb, consistent with the standard model prediction.

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## 1. Introduction

Measurements of the cross sections for massive gauge boson pair production in proton–proton collisions provide an essential test of the electroweak sector of the standard model (SM). The electroweak interaction in the SM is determined by the non-Abelian  $SU(2)_L \times U(1)_Y$  gauge group. The non-Abelian nature of the electroweak gauge group leads to gauge boson self-interactions via triple gauge couplings (TGCs) and quartic gauge couplings (QGCs). The weak gauge boson pair production includes TGC interactions as well as QGC interactions via vector boson scattering. Thus, the study of diboson production can directly test both the weak interaction and the non-Abelian nature of the electroweak gauge group. The next-to-leading order (NLO) and next-to-next-to-leading order (NNLO) perturbative QCD corrections for the boson pair production have substantial impact on the predicted cross sections due to the addition of the gluon-initiated processes that are enhanced at energies available at the CERN LHC. The increase in the cross section is significant compared to the experimental uncertainties, allowing LHC boson pair cross section measurements to directly validate higher-order perturbative QCD calculations.

The observation of WZ production in proton–antiproton collisions at the Tevatron collider was reported by the CDF [1,2] and D0 [3] experiments. The WZ production cross section in proton–proton collisions has been measured at the LHC by the CMS ex-

periment at  $\sqrt{s} = 8$  TeV [4] and the ATLAS experiment at  $\sqrt{s} = 7, 8,$  and  $13$  TeV [5–7]. All measurements are in good agreement with SM predictions.

This paper reports the CMS measurement of the WZ production cross section in proton–proton collisions at  $\sqrt{s} = 13$  TeV. The measurement is performed using the leptonic decay modes  $WZ \rightarrow \ell\nu\ell'\ell'$ , where  $\ell, \ell' = e, \mu$ .

## 2. The CMS detector

The CMS detector is described in detail elsewhere [8]. The key components for this analysis are summarized here. 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 superconducting solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter, which provide the pseudorapidity coverage  $|\eta| < 1.479$  in a barrel section and  $1.479 < |\eta| < 3.0$  in two endcap sections. Forward calorimeters extend the coverage to  $|\eta| < 5.0$ . Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid.

The first level of the CMS trigger system, composed of custom hardware processors, is designed to select the most interesting events in less than  $4 \mu\text{s}$  using information from the calorimeters and muon detectors. The high-level-trigger processor farm decreases the event rate from almost 100 kHz to around 1 kHz, before data storage.

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### 3. Data and Monte Carlo samples

This measurement uses a sample of proton–proton collisions collected in 2015 at  $\sqrt{s} = 13$  TeV. The integrated luminosity of the sample is  $2.3 \text{ fb}^{-1}$ . Several Monte Carlo (MC) event generators are used to simulate the signal and background processes.

The WZ signal is generated at NLO in perturbative QCD with POWHEG2.0 [9–12]. The ZZ production via  $q\bar{q}$  annihilation is generated at NLO using POWHEG2.0, while the  $gg \rightarrow ZZ$  process is simulated at leading-order with MCFM 7.0 [13]. The  $Z\gamma$ ,  $t\bar{t}W$ ,  $t\bar{t}Z$ ,  $tZ$ , and triboson events  $VVV$  (WWZ, WZZ, ZZZ) are generated at NLO with MADGRAPH5\_AMC@NLO [14]. The ZZ samples are scaled to the cross section calculated at NNLO for  $q\bar{q} \rightarrow ZZ$  [15] (scaling  $k$  factor 1.1) and at NLO for  $gg \rightarrow ZZ$  [16] (scaling  $k$  factor 1.7). The PYTHIA 8.175 [17] program is used for parton showering, hadronization, and underlying event simulation using the CUETP8M1 tune [18]. The NNPDF3.0 [19] set of parton distribution functions (PDFs) is used, unless otherwise specified.

For all processes, the detector response is simulated using a detailed description of the CMS detector, based on the GEANT4 package [20], and the event reconstruction is performed with the same algorithms used for data. The simulated samples include additional interactions per bunch crossing (pileup) taken from minimum-bias events generated with PYTHIA. The simulated events are weighted so that the pileup distribution matches the measured one, with an average of about 11 pileup interactions per bunch crossing.

### 4. Event reconstruction

Using the information from all CMS subdetectors, a particle-flow (PF) technique is employed to identify and reconstruct the individual particles emerging from each collision event [21,22]. The particles are classified into mutually exclusive categories: charged hadrons, neutral hadrons, photons, muons, and electrons.

Electrons are reconstructed within the geometrical acceptance  $|\eta^e| < 2.5$ . The reconstruction combines the information from clusters of energy deposits in the ECAL and the trajectory in the tracker [23]. Electron identification relies on the electromagnetic shower shape and other observables based on tracker and calorimeter information. The selection criteria depend on the transverse momentum,  $p_T$ , and  $|\eta|$ , and on a categorization according to observables that are sensitive to the amount of bremsstrahlung emitted along the trajectory in the tracker. Two working points are defined: *tight* and *very tight*.

Muons are reconstructed within  $|\eta^\mu| < 2.4$  [24]. The reconstruction combines the information from both the tracker and the muon spectrometer. The muons are selected from among the reconstructed muon track candidates by applying minimal quality requirements on the track components in the muon system and by ensuring that muons are associated to small energy deposits in the calorimeters. A single *tight* working point is defined.

The electrons and muons are required to originate from the primary vertex, which is chosen to be the vertex with the highest sum of  $p_T^2$  of its constituent tracks [25]. For each lepton track the distance of closest approach to the primary vertex in the transverse plane,  $d_{xy}$ , is required to be less than 0.01 (0.07) cm for electrons in the barrel (endcap) region and 0.01 cm for muons with  $p_T$  less than 20 GeV and 0.02 cm for muons with  $p_T$  greater than 20 GeV. The distance along the beamline,  $d_z$ , must be less than 0.4 (0.6) cm for electrons in the barrel (endcap) and 0.1 cm for muons. For the *very tight* electron working point, electrons must pass  $d_{xy} \leq 0.01$  (0.04) cm and  $d_z \leq 0.05$  (0.4) cm in the barrel (endcap) region.

Jets are reconstructed using PF objects. The anti- $k_T$  jet clustering algorithm [26] with  $R = 0.4$  is used. The standard method for

jet energy corrections [27] is applied. These include corrections to the pileup contribution that keep the jet energy correction and the corresponding uncertainty almost independent of the number of pileup interactions. To exclude electrons and muons from the jet sample, the jets are required to be separated from the identified leptons by  $\Delta R > 0.3$ . In order to reject jets coming from pileup collisions (pileup jets), a multivariate-based jet identification algorithm [28] is applied. This algorithm takes advantage of differences in the shape of energy deposits in a jet cone between hard-scatter and pileup jets. The jets are required to have  $p_T > 20$  GeV and  $|\eta| < 5.0$ . To identify the top quark background contribution in its decay to  $b$  quarks, the CSVv2  $b$  tagging algorithm [29] with the *tight* working point is used [30]. The efficiency for selecting  $b$  quark jets is  $\approx 49\%$  with a misidentification probability of  $\approx 4\%$  for  $c$  quark jets and  $\approx 0.1\%$  for light quark jets.

The isolation of individual electrons or muons is defined relative to their transverse momentum  $p_T^\ell$  by summing over the transverse momenta of charged hadrons and neutral particles within a cone with radius  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.4$  around the lepton direction at the interaction vertex:

$$I^\ell = \left( \sum p_T^{\text{charged}} + \max \left[ 0, \sum p_T^{\text{neutral}} + \sum p_T^\gamma - p_T^{\text{PU}} \right] \right) / p_T^\ell. \quad (1)$$

Here,  $\sum p_T^{\text{charged}}$  is the scalar sum of the transverse momenta of charged hadrons originating from the primary vertex. The  $\sum p_T^{\text{neutral}}$  and  $\sum p_T^\gamma$  are the scalar sums of the transverse momenta for neutral hadrons and photons, respectively. The neutral contribution to the isolation from pileup events,  $p_T^{\text{PU}}$ , is estimated differently for electrons and muons. For electrons,  $p_T^{\text{PU}} \equiv \rho A_{\text{eff}}$ , where the average transverse momentum flow density  $\rho$  is calculated in each event using the “jet area” method [31], which defines  $\rho$  as the median of the ratio of the jet transverse momentum to the jet area,  $p_T^{\text{jet}}/A_{\text{jet}}$ , for all pileup jets in the event. The effective area  $A_{\text{eff}}$  is the geometric area of the isolation cone times an  $\eta$ -dependent correction factor that accounts for the residual dependence of the isolation on the pileup. For muons,  $p_T^{\text{PU}} \equiv 0.5 \sum_i p_T^{\text{PU},i}$ , where  $i$  runs over the charged hadrons originating from pileup vertices and the factor 0.5 corrects for the ratio of charged to neutral particle contributions in the isolation cone. Electrons are considered isolated if  $I^e < 0.08$  (0.07) for the barrel (endcap) region, while muons are considered isolated if  $I^\mu < 0.15$ . For the *very tight* electron working point, the electrons must pass  $I^e < 0.04$  (0.06) for the barrel (endcap) region.

The missing transverse momentum vector  $\vec{p}_T^{\text{miss}}$  is defined as the projection onto the plane perpendicular to the beams of the negative vector sum of the momenta of all reconstructed PF objects in an event, corrected for the pileup contribution. Its magnitude is referred to as  $E_T^{\text{miss}}$ .

The overall efficiencies of the reconstruction, identification, and isolation requirements for the prompt  $e$  or  $\mu$  are measured in data in several bins of  $p_T^\ell$  and  $|\eta^\ell|$  using a “tag-and-probe” technique [32] applied to an inclusive sample of  $Z$  events. The efficiency for selecting electrons in the ECAL barrel (endcaps) varies from about 85% (77%) at  $p_T^e \approx 10$  GeV to about 95% (89%) for  $p_T^e > 20$  GeV. It is about 85% in the transition region between the ECAL barrel and endcaps,  $1.44 < |\eta| < 1.57$ , averaging over the whole  $p_T$  range. Muons are reconstructed and identified with efficiency above 98% in the full  $|\eta^\mu| < 2.4$  range. These efficiencies are measured in data and simulation. The data/MC efficiency ratios are used as scale factors to correct the simulated event yields.

## 5. Event selection

Collision events are selected by triggers that require the presence of one or two electrons or muons. The  $p_T$  threshold for the single lepton is 23 (20) GeV for the electron (muon) trigger. For the dilepton triggers, with the same or different flavors, the minimum  $p_T$  of the leading and subleading leptons are 17 (17) and 12 (8) GeV for electrons (muons), respectively. The trigger efficiency for events within the acceptance of this analysis is greater than 99%.

A selected event is required to have three lepton candidates  $\ell\ell'\ell'$ . The  $\ell\ell'$  pair has two leptons with opposite charge and the same flavor, as expected for a Z boson candidate. One of the leptons from the Z boson candidate is required to have  $p_T > 20$  GeV and the other  $p_T > 10$  GeV. If more than one combination is possible, the one with invariant mass closest to the Z boson mass is selected. The lepton associated with the W boson must have  $p_T > 20$  GeV. All leptons must pass the *tight* identification and isolation requirements. To further reduce the contribution from Z+jets in events with an electron associated with the W boson, this electron must pass the requirements of the *very tight* working point.

There must be no other isolated leptons with  $p_T > 10$  GeV in the events. To reduce contributions from  $t\bar{t}$  events, the two leptons constituting the Z boson candidate are required to have an invariant mass satisfying  $76 < m_{\ell\ell} < 106$  GeV, and there must be no jets with  $p_T > 20$  GeV and  $|\eta| < 2.4$  that pass a b tagging requirement. The WZ events are expected to have missing transverse energy consistent with the presence of a neutrino in the final state, therefore  $E_T^{\text{miss}} > 30$  GeV is required. The invariant mass of any dilepton pair must be greater than 4 GeV. This requirement prevents problems with collinear emission of same-flavor opposite-sign dilepton pairs in theoretical calculations. The selection is extended to all dilepton pairs at the detector level to reduce backgrounds from low mass resonances with a negligible effect on signal efficiency. The trilepton invariant mass,  $m_{3\ell}$ , is required to be more than 100 GeV to exclude a region where production of Z bosons with final-state radiation is expected to contribute.

## 6. Background estimation

The background contributions in this analysis are divided into two categories: background processes with prompt isolated leptons, e.g., ZZ, Z $\gamma$ ,  $t\bar{t}Z$ ; and background processes from nonprompt leptons from hadrons decaying to leptons inside jets or jets misidentified as isolated leptons, primarily Z+jets and  $t\bar{t}$ . The background processes with prompt leptons are estimated from simulation. The processes with at least one nonprompt lepton are estimated from data.

The major background contributions with nonprompt leptons arise from the production of Z bosons in association with jets and from  $t\bar{t}$ , whereas smaller contributions come from W boson production in association with jets and multijet processes. The nonprompt background contribution is evaluated using the “*tight-to-loose*” method. The method estimates the probability that a *loose* candidate is misidentified as a *tight* lepton and applies this probability to control regions with *loose* candidates to estimate the resulting contribution to the signal region. These *loose* candidates are selected with relaxed lepton identification and isolation requirements.

The misidentification probability is measured from a sample of dijet events enriched in nonprompt leptons. The sample is selected with one jet passing the relaxed lepton identification requirements matched to a single lepton trigger, defined as the probe lepton. The probe lepton and the second jet must be separated by  $\Delta R > 1$ . The misidentification ratio for each lepton flavor is defined in bins of

lepton  $p_T$  and  $\eta$  as the ratio of the number of probe leptons that pass the final isolation and identification requirements to the number of probe leptons that do not pass the *tight* requirements. The contamination from W+jets is suppressed by requiring a transverse mass  $m_T < 20$  GeV, where  $m_T = \sqrt{2E_T^{\text{miss}}p_T^\ell(1 - \cos(\Delta\phi))}$  and  $\Delta\phi$  is the azimuthal angle between the vectors  $\vec{p}_T^{\text{miss}}$  and  $\vec{p}_T^\ell$ . The contamination from Z boson events is suppressed by requiring the invariant mass of each pair of leptons composed of the probe lepton and of any other lepton candidate in the event to be outside of the window 60–120 GeV. Contributions from low mass resonances decaying into pairs of leptons are suppressed by requiring the dilepton mass to be greater than 20 GeV. The transverse momentum spectrum of the probe lepton in dijet events is different from the spectrum in Z and  $t\bar{t}$  events. We have verified in data that one can make them similar with a requirement on the minimum transverse momentum of the second jet of 20 (35) GeV for the dijet events with one probe muon (electron).

A set of control regions with events containing three leptons is then used to estimate the background from nonprompt leptons. Zero, one, or two leptons are required to pass the signal region requirements, while the remaining leptons must pass the *loose* requirements and fail the signal region requirements. The misidentification ratio is applied to the *loose* leptons failing the *tight* identification requirements to estimate the corresponding contribution to the signal region. The total background is calculated as a sum of contributions from different regions. This method is validated in nonoverlapping data samples enriched in Drell–Yan and  $t\bar{t}$  contributions. The Drell–Yan region is defined by inverting the selection requirement in  $E_T^{\text{miss}}$  and the  $t\bar{t}$  region is defined by requiring at least one b-tagged jet and rejecting events with  $76 < m_{\ell\ell} < 106$  GeV while keeping all other requirements for the signal region. The overall yield predicted with the “*tight-to-loose*” method agrees with that measured in the control region within 5%, with a maximum deviation of 30% in a single decay channel. The observed deviations are used as systematic uncertainties in the predicted background yields in the signal region.

## 7. Systematic uncertainties

Systematic uncertainties are less than 1% for the trigger efficiency and 2–4% for the lepton identification and isolation requirements, depending on the lepton flavors. Other systematic uncertainties are related to the use of simulated samples: 1% for the effects of pileup and 1–2% for the  $E_T^{\text{miss}}$  reconstruction, which is estimated by varying the energies of the PF objects within their uncertainties. The uncertainty in the b quark jet content in WZ events is 2% and accounts for differences in b-tagging efficiencies between data and MC as well as differences in b quark jet content between Z+jets and WZ+jets events. The uncertainty in the integrated luminosity of the data sample is 2.7% [33]. This uncertainty affects both the signal and the simulated portion of the background estimation and does not affect the background estimation from data; the total effect of the luminosity uncertainty on the cross section is 3.2%.

Uncertainties in prompt background sources are estimated from the theoretical uncertainties in the cross sections. For the ZZ background the uncertainty is 4% [15,34], and it contributes to the WZ cross section with an uncertainty of 0.4%. The uncertainties are 15% for  $t\bar{t}V$  [14,35,36] and 6% for triboson and Z $\gamma$  [13]; their contribution to the uncertainty in the WZ cross section is much less than 1%.

The uncertainties in background contributions from both flavors of nonprompt leptons are determined by combining the uncertainties in the measured values of the misidentification probabilities and the statistical uncertainties due to the limited number

**Table 1**

The contributions of each systematic uncertainty source to the combined uncertainty in the cross section measurement. The integrated luminosity as well as the PDF and scale uncertainties are reported separately in Equations (2) and (3) as (lumi) and (theo), respectively, while the other uncertainties are combined into a single systematic uncertainty (syst).

Source of uncertainty	Uncertainty in the cross section
Background with nonprompt $\mu$	5.4%
Background with nonprompt e	3.9%
b tagging	2.1%
$E_T^{\text{miss}}$	2.0%
Electron efficiency	1.9%
Muon efficiency	1.5%
Pileup	0.8%
ZZ cross section	0.4%
$t\bar{t}V$ cross section	negligible
Z $\gamma$ cross section	negligible
VV cross section	negligible
Integrated luminosity	3.2%
PDF and scales	1.0%

of events in the control regions. The systematic uncertainty in the misidentification probability is 30% for both electrons and muons. It covers the largest difference observed between the estimated and measured numbers of events in data control samples enriched in  $t\bar{t}$  and Drell–Yan contributions. The uncertainties are uncorrelated between electrons and muons. The contribution to the uncertainty in the cross section measurement is 5.4% (3.9%) from muons (electrons).

Theoretical uncertainties in the  $WZ \rightarrow \ell\nu\ell'\ell'$  acceptance are evaluated using POWHEG and MCFM by varying dynamic renormalization and factorization scales independently up and down by a factor of two with respect to the default values  $\mu_R = \mu_F = m_{WZ}$  with the condition that  $0.5 \leq \mu_R/\mu_F \leq 2$ , where  $m_{WZ}$  is the mass of the WZ system at the generator level. The uncertainty in the acceptance due to the scale variations can be neglected. Phenomenological uncertainties (PDF+ $\alpha_s$ ) are estimated using the CT14 [37], NNPDF3.0, and MMHT2014 [38] PDF sets according to their individual prescriptions. The largest variation among the sets defines an envelope of about 1%, which is taken as the theoretical uncertainty in the measured cross section.

A summary of each systematic uncertainty and its contribution to the final uncertainty in the cross section measurement is presented in Table 1.

## 8. Results

The observed and expected event yields for all decay channels are summarized in Table 2. The invariant mass distributions for all channels combined are shown in Fig. 1 and compared to the SM

expectations and to the backgrounds estimated from data. The two upper plots show distributions for events after all the selection requirements are applied except the one displayed. The two lower plots show distributions with the full WZ selection requirements. Kinematic distributions of the selected events are shown in Fig. 2. Overall, the simulated signal combined with the background contributions are in agreement with the data within uncertainties.

The measured yields, corrected for the efficiency of the event selections and the acceptance of the fiducial phase space, are used to evaluate the WZ production cross section.

The fiducial  $WZ \rightarrow \ell\nu\ell'\ell'$  phase space is defined by the requirement of two leptons from the Z boson decay to have  $p_T > 20$  and 10 GeV, the charged lepton from W boson decay to have  $p_T > 20$  GeV, all leptons to be within  $|\eta| < 2.5$ ,  $60 < m_{\ell'\ell'} < 120$  GeV, and invariant mass of any same-flavor opposite-sign lepton pair is above 4 GeV. All the leptons are considered before final-state radiation (FSR). The difference between the cross section calculation with leptons before FSR and the cross section with “dressed” leptons, which are obtained by summing the lepton momentum and the momenta of radiated photons within a cone of  $\Delta R < 0.1$  around the lepton, is found to be less than 1%.

The correction between the fiducial definition and the selection requirements takes into account the effect of the  $E_T^{\text{miss}}$  requirement, the reduced  $m_{\ell'\ell'}$  mass window in the selection with respect to the fiducial definition, and the requirements of exactly three isolated leptons and no b-tagged jets in the event. A small contribution from WZ events where the W or Z boson decays via  $\tau$  into an electron or muon is considered as signal at the detector level, but not at the generator level. Thus the correction for  $\tau$  lepton decays is also taken into account in the selection efficiency.

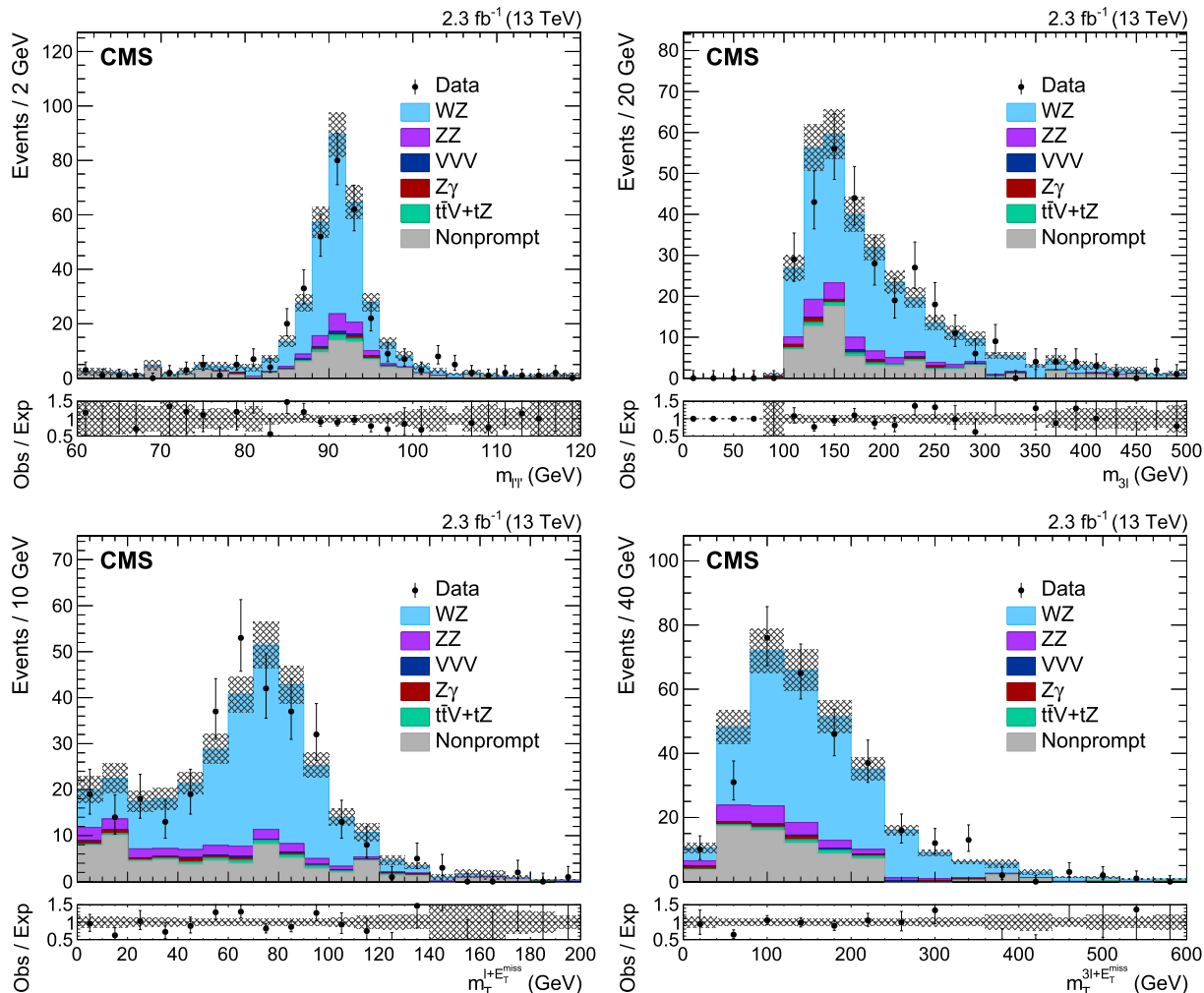
The efficiency of the selection requirements with respect to the fiducial requirements varies with the channel, from 55% in  $\mu\mu\mu$  to 25% in eee. It includes a 70% correction for the  $E_T^{\text{miss}}$  requirement at the reconstruction level, a 7% correction for the contribution from tau decays and the effects of the lepton identification requirements. The difference in the Z boson mass window definition at the selection level and in the fiducial definition has a 2% effect. The theoretical uncertainties in these corrections are estimated by checking differences between the various POWHEG, MADGRAPH, and MCFM predictions and are found to be much less than 1% so they are neglected in the fiducial cross section measurement. The major difference between the channels is the tighter identification and isolation requirements on the electrons.

To include all final states in the cross section calculation, the number of expected signal and background events is fitted to the number of observed events simultaneously in all decay channels. The likelihood is written as a combination of individual channel likelihoods for the signal and background hypotheses. The statistical and systematic uncertainties are included as scaling nuisance parameters and the correlation between different sources of uncertainties across channels is taken into account.

**Table 2**

The expected yields of WZ events and the estimated yields of background events, consisting of the prompt leptons estimated from simulation and nonprompt background from data, compared to the number of observed events for each decay channel. The first uncertainty is statistical and the second is systematic.

Decay channel	Expected WZ	Background		Total expected	Observed
		Nonprompt	Prompt		
eee	$35.9 \pm 0.6^{+1.8}_{-1.8}$	$10.6 \pm 1.7^{+3.2}_{-2.5}$	$6.6 \pm 0.6^{+0.5}_{-0.5}$	$53.1 \pm 1.9^{+3.9}_{-3.3}$	49
ee $\mu$	$50.2 \pm 0.8^{+2.4}_{-2.4}$	$14.8 \pm 3.6^{+3.9}_{-3.0}$	$8.3 \pm 0.5^{+0.6}_{-0.6}$	$73.3 \pm 3.7^{+4.8}_{-4.1}$	78
$\mu\mu e$	$56.0 \pm 0.8^{+2.5}_{-2.4}$	$21.5 \pm 3.2^{+5.0}_{-3.9}$	$9.3 \pm 0.6^{+0.8}_{-0.7}$	$86.8 \pm 3.4^{+5.8}_{-4.8}$	83
$\mu\mu\mu$	$84.0 \pm 1.0^{+3.4}_{-3.3}$	$20.0 \pm 4.9^{+6.1}_{-4.7}$	$12.4 \pm 0.5^{+0.8}_{-0.7}$	$116.3 \pm 5.0^{+7.2}_{-6.0}$	108
Total	$226 \pm 2^{+10}_{-9}$	$67 \pm 7^{+14}_{-11}$	$37 \pm 1^{+3}_{-2}$	$330 \pm 7^{+18}_{-16}$	318



**Fig. 1.** (upper left) Distribution of the reconstructed  $l'l'$  pair mass summed for all decay channels with the  $m_{l'l'}$  selection extended to 60–120 GeV. (upper right) Distribution of the  $l'l'l'$  reconstructed mass summed for all decay channels with the  $m_{3l} > 100$  GeV selection requirement removed. (lower left) The transverse mass of the lepton from the W boson and the  $E_T^{\text{miss}}$  system. (lower right) The transverse mass of the three leptons and the  $E_T^{\text{miss}}$  system. Solid symbols represent the data with Poisson statistical uncertainties, while histograms represent the expected WZ signal and backgrounds. The shaded band represents the uncertainties in the signal and background estimated yields and includes systematic, theoretical, and integrated luminosity uncertainties in addition to the statistical uncertainty. The background shapes are taken from simulation or data, as described in the text. A ratio of the observed (Obs) and expected (Exp) distributions is also included.

The fiducial  $WZ \rightarrow \nu l'l'$  cross section for  $p_T^{l'} > 20, 10$  GeV,  $p_T^l > 20$  GeV, all leptons within  $|\eta| < 2.5$ ,  $60 < m_{l'l'} < 120$  GeV, and invariant mass of any same-flavor opposite-sign lepton pair above 4 GeV is

$$\sigma_{\text{fid}}(\text{pp} \rightarrow WZ \rightarrow \nu l'l') = 258 \pm 21 \text{ (stat)} \\ \pm_{-20}^{+19} \text{ (syst)} \pm 8 \text{ (lumi) fb,} \quad (2)$$

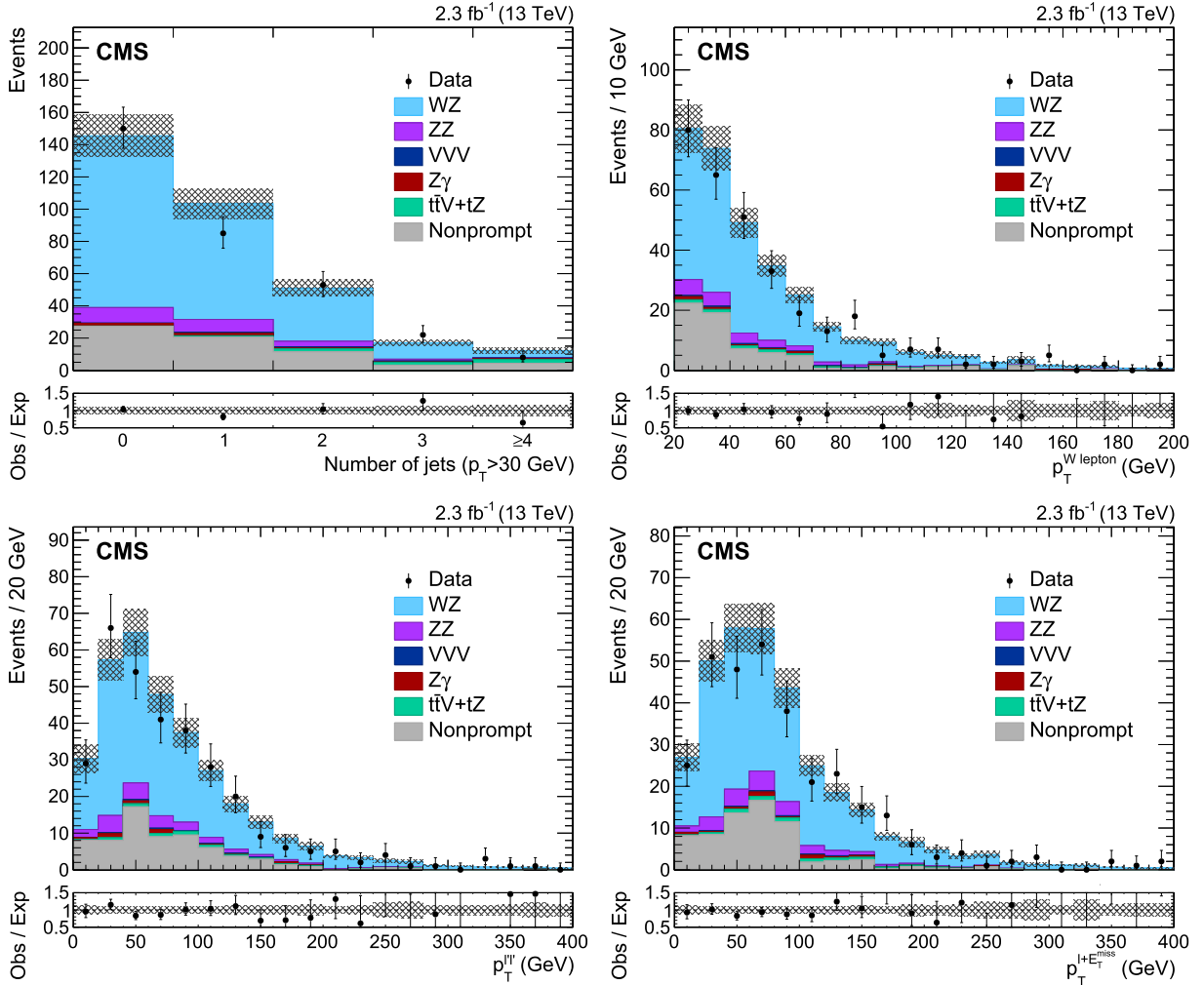
corresponding to a total cross section for the range  $60 < m_{l'l'} < 120$  GeV of

$$\sigma(\text{pp} \rightarrow WZ) = 39.9 \pm 3.2 \text{ (stat)} \\ \pm_{-3.1}^{+2.9} \text{ (syst)} \pm 0.4 \text{ (theo)} \pm 1.3 \text{ (lumi) pb.} \quad (3)$$

The acceptance of the fiducial phase space,  $(45.0 \pm 0.4)\%$ , is calculated with POWHEG. The nominal Z to dilepton branching fraction  $\mathcal{B}(Z \rightarrow l'l')$  is  $(3.3658 \pm 0.0023)\%$  for each lepton flavor, while for the W boson the average branching fraction to each lepton flavor,  $(10.67 \pm 0.16)\%$ , is derived from  $(10.71 \pm 0.16)\%$  for the electron channel and  $(10.63 \pm 0.15)\%$  for the muon channel [39].

The measured cross sections can be compared to the theoretical values of  $274_{-8}^{+11}$  (scale)  $\pm 4$  (PDF) fb for the fiducial cross section and  $42.3_{-1.1}^{+1.4}$  (scale)  $\pm 0.6$  (PDF) pb for the total cross section calculated with MCFM at NLO with NNPDF3.0 PDFs, with dynamic renormalization and factorization scales set to  $\mu_R = \mu_F = m_{WZ}$ . The uncertainty is obtained by varying the factorization and renormalization scales independently up and down by a factor of two with the condition that  $0.5 \leq \mu_R/\mu_F \leq 2$ . The MCFM and POWHEG predicted cross sections agree within the statistical uncertainties of the generated samples.

The measured total cross section can also be compared to the theoretical value of  $50.0_{-1.0}^{+1.1}$  (scale) pb, available at NNLO via MATRIX [40] with fixed QCD scales set to  $\mu_R = \mu_F = \frac{1}{2}(m_Z + m_W)$  and NNPDF3.0 PDFs. Uncertainties in this calculation take into account only renormalization and factorization scale variations. The variations are done independently with the condition that  $0.5 \leq \mu_R/\mu_F \leq 2$ . The values from MCFM with this scale choice are  $291_{-13}^{+16}$  (scale)  $\pm 4$  (PDF) fb for the fiducial and  $44.9_{-1.8}^{+2.2}$  (scale)  $\pm 0.7$  (PDF) pb for the total cross sections.



**Fig. 2.** (upper left) Distribution of the number of jets with  $p_T > 30$  GeV in the event. (upper right) Transverse momentum of the lepton associated with the W boson. (lower left) Transverse momentum of selected Z boson candidates. (lower right) Transverse momentum of selected W boson candidates. Solid symbols represent the data with Poisson statistical uncertainties, while histograms represent the expected WZ signal and backgrounds. The shaded band represents the uncertainties in the signal and background estimated yields and includes systematic, theoretical, and integrated luminosity uncertainties in addition to the statistical uncertainty. The background shapes are taken from simulation or data, as described in the text. A ratio of the observed (Obs) and expected (Exp) distributions is also included.

## 9. Summary

The WZ production cross section in proton–proton collisions at  $\sqrt{s} = 13$  TeV has been measured with the CMS experiment at the LHC using a data sample corresponding to an integrated luminosity of  $2.3 \text{ fb}^{-1}$ . The measurement is performed in the leptonic decay modes  $WZ \rightarrow \ell\nu\ell'\ell'$ , where  $\ell, \ell' = e, \mu$ . The measured fiducial  $WZ \rightarrow \ell\nu\ell'\ell'$  cross section for two leptons from the Z boson decay with  $p_T > 20$  and 10 GeV, the charged lepton from the W boson decay with  $p_T > 20$  GeV, all leptons within  $|\eta| < 2.5$ , and  $60 < m_{\ell\nu} < 120$  GeV is  $\sigma_{\text{fid}}(\text{pp} \rightarrow WZ \rightarrow \ell\nu\ell'\ell') = 258 \pm 21(\text{stat})_{-20}^{+19}(\text{syst}) \pm 8(\text{lumi}) \text{ fb}$ . The corresponding total cross section is  $\sigma(\text{pp} \rightarrow WZ) = 39.9 \pm 3.2(\text{stat})_{-3.1}^{+2.9}(\text{syst}) \pm 0.4(\text{theo}) \pm 1.3(\text{lumi}) \text{ pb}$  for the dilepton mass range  $60 < m_{\ell\nu} < 120$  GeV. For both cross sections, the invariant mass of any same-flavor opposite-sign lepton pair is required to be above 4 GeV. This measurement is compared with the theoretical values of  $274_{-8}^{+11}(\text{scale}) \pm 4(\text{PDF}) \text{ fb}$  for the fiducial cross section and  $42.3_{-1.1}^{+1.4}(\text{scale}) \pm 0.6(\text{PDF}) \text{ pb}$  for the total cross section calculated with  $\text{MCFM}$  at NLO with NNPDF3.0 PDFs, with dynamic renormalization and factorization scales set to  $\mu_R = \mu_F = m_{WZ}$ , and with the NNLO prediction from  $\text{MATRIX}$ .

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