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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 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 $60 < m_{\ell \ell'} < 120 \text{ GeV}$ is $\sigma(\text{pp} \rightarrow WZ) = 39.9 \pm 3.2 \text{ (stat)}^{+2.9}_{-3.1} \text{ (syst)} \pm 0.4 \text{ (theo)} \pm 1.3 \text{ (lumi)} \text{ pb}$, 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 nonabelian $SU(2)_L \times U(1)_Y$ gauge group. The nonabelian nature of the electroweak gauge group leads to gauge boson self-interactions via triple gauge couplings (TGCs) and quartic gauge couplings (QGCs). In this framework, massive diboson production primarily occurs through weak interactions involving the radiation of pairs of massive vector bosons or through the radiation of a single gauge boson followed by TGC interactions. In addition, weak gauge boson pairs can be produced through QGCs in vector boson scattering interactions. Thus, the study of diboson production can directly test both the weak interaction and the nonabelian nature of the electroweak gauge group.

The observation of WZ production in proton-antiproton collisions at the Tevatron collider was reported by the CDF [1, 2] and D0 [3] experiments. Results on diboson production in e^+e^- collisions at LEP can be found in Refs. [4–7]. The WZ production cross section in proton-proton collisions has been measured at the CERN LHC by the CMS experiment at $\sqrt{s} = 8$ TeV [8] and the ATLAS experiment at $\sqrt{s} = 7, 8$, and 13 TeV [9–11]. 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 [12]. 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 end-cap 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.

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 fb^{-1} . Several Monte Carlo (MC) event generators are used to simulate the signal and background processes.

The WZ signal is generated at next-to-leading-order (NLO) with POWHEG 2.0 [13–16]. The ZZ production via $q\bar{q}$ annihilation is generated at NLO using POWHEG 2.0, while the $gg \rightarrow ZZ$ process is simulated at leading-order with MCFM 7.0 [17]. The $Z\gamma$, $t\bar{t}V$ ($t\bar{t}W$, $t\bar{t}Z$), and triboson events VVV (WWZ, WZZ, ZZZ) are generated at NLO with MADGRAPH5_AMC@NLO

[18]. The ZZ samples are scaled to the cross section calculated at next-to-next-to-leading-order (NNLO) for $q\bar{q} \rightarrow ZZ$ [19] (k factor 1.1) and at NLO for $gg \rightarrow ZZ$ [20] (k factor 1.7). The PYTHIA 8.175 [21] program is used for parton showering, hadronization, and underlying event simulation using the CUETP8M1 tune [22]. The NNPDF3.0 [23] 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 [24], and the event reconstruction is performed with the same algorithms used for data. The simulated samples include additional interactions per bunch crossing (pileup). 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 [25, 26]. 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 [27]. Electron identification relies on the electromagnetic shower shape and other observables based on tracker and calorimeter information. The selection criteria depend on 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 $|\eta^\mu| < 2.4$ [28]. 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 requirements on the track components in the muon system and taking into account matching with small energy deposits in the calorimeters.

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. 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 (0.02) cm for muons with p_T less (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 [29] with $R = 0.4$ is used. The standard method for jet energy corrections [30] is applied. These include corrections that improve the reconstruction efficiency as a function of the number of pileup interactions. To exclude electrons and muons from the jet sample, the jets are required to be separated from the selected leptons by $\Delta R > 0.3$. In order to reject jets coming from pileup collisions (pileup jets), a multivariate-based jet identification algorithm [31] is applied. This algorithm takes advantage of differences in the shape of energy deposits in a jet cone. 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 [32] with the *tight* working point is used [33]. The

efficiency for selecting b quarks is $\approx 49\%$ with a misidentification probability of $\approx 4\%$ for c quarks and $\approx 0.1\%$ for light quarks.

The isolation of individual electrons or muons is defined relative to their transverse momentum p_T^ℓ 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:

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

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^{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 ρ is calculated in each event using the “jet area” method [34], which defines ρ 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_{eff} is the geometric area of the isolation cone times an η -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^{miss} .

The overall efficiencies of the reconstruction, identification, and isolation requirements for the prompt e or μ are measured in data in several bins of p_T^ℓ and $|\eta^\ell|$ using a “tag-and-probe” technique [35] 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 pairs must be greater than 4 GeV. The trilepton invariant mass $m_{3\ell}$ is required to be more than 100 GeV.

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 non-prompt 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 non-prompt 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 η as the ratio of the number of leptons that pass the final isolation and identification requirements to the number of 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 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 in the event: 20 GeV for muons and 35 GeV for electrons.

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 other 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^{miss} in the signal region, 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. 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 25% 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^{miss} reconstruction. The uncertainty in the E_T^{miss} reconstruction is estimated by varying the energies of the PF objects within their uncertainties. The energy of each PF object is varied within its uncertainty to determine the uncertainty of E_T^{miss} reconstruction. The uncertainty in the integrated luminosity of the data sample is 2.7% [36]. This uncertainty affects both the signal and the simulated portion of the background estimation and does not affect the data driven background estimation; the total effect on the cross section is 3.2%.

Theoretical uncertainties in the $WZ \rightarrow \ell\nu\ell'\ell'$ acceptance are evaluated using POWHEG and MCFM by varying dynamic renormalization and factorization scales up and down by a factor of two with respect to the default values $\mu_R = \mu_F = m_{WZ}$, where m_{WZ} is the true mass of the WZ system at the generator level. The variations in the acceptance due to the scale variations can be neglected. Phenomenological uncertainties (PDF+ α_s) are evaluated using CT14 [37] and NNPDF sets and found to be <1%. The MCFM generator program is also used with the CT14 and MMHT2014 [38] PDF sets instead of NNPDF3.0. The largest difference from all possible sources, 1%, is taken as the theoretical uncertainty in the measured total cross section.

Uncertainties in prompt background sources are estimated from the theoretical uncertainties in the cross sections. For the ZZ background the uncertainty is 4% [39], and it contributes to the total WZ cross section with an uncertainty of 0.4%. The uncertainties are 15% for $t\bar{t}V$ and 6% for triboson and $Z\gamma$; 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 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).

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

Table 1: The contributions of each systematic uncertainty source to the final uncertainty in the cross section measurement. The integrated luminosity as well as the PDF and scale uncertainties are reported separately while the other uncertainties are combined into a single systematic uncertainty.

Source of uncertainty	Uncertainty in the cross section
Background with nonprompt μ	5.4%
Background with nonprompt e	3.9%
b tagging	2.1%
E_T^{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
VVV cross section	negligible
Integrated luminosity	3.2%
PDF and scales	1.0%

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.

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 from a data driven method, compared to the number of observed events for each decay channel.

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 μ	$50.2 \pm 0.8^{+2.4}_{-2.4}$	$14.8 \pm 3.6^{+3.9}_{-3.0}$	$8.3 \pm 0.5^{+0.6}_{-0.6}$	$73.3 \pm 3.7^{+4.8}_{-4.1}$	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	$226.1 \pm 1.6^{+9.5}_{-9.3}$	$66.9 \pm 7.1^{+14.4}_{-11.1}$	$36.6 \pm 1.1^{+2.6}_{-2.4}$	$329.5 \pm 7.3^{+18.3}_{-15.6}$	318

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 lepton from W boson decay to have $p_T > 20$ GeV, all leptons to be within $|\eta| < 2.5$, and $60 < m_{\ell'\ell'} < 120$ GeV. All the leptons are considered before final-state radiation.

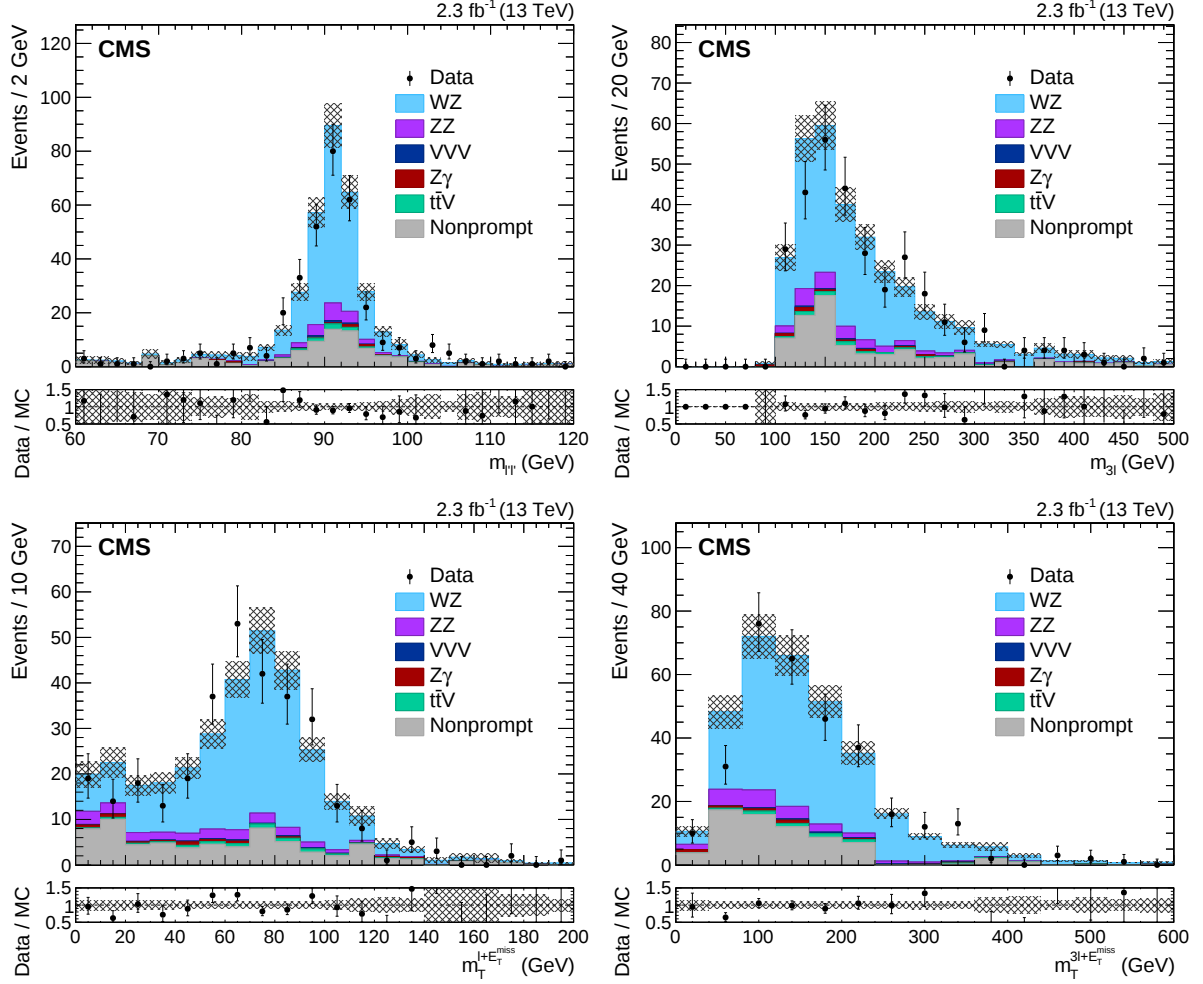


Figure 1: (upper left) Distribution of the reconstructed $\ell'\ell'$ pair mass summed for all decay channels with the $m_{\ell'\ell'}$ selection extended to 60–120 GeV. (upper right) Distribution of the $\ell\ell'\ell'$ reconstructed mass summed for all decay channels with the $m_{3\ell} > 100$ GeV selection requirement removed. (lower left) The transverse mass of the lepton from the W boson and the E_T^{miss} system. (lower right) The transverse mass of the three leptons and the E_T^{miss} system. Solid symbols represent the data with statistical uncertainty, while histograms represent the expected WZ signal and backgrounds. Uncertainties in the signal and background yields include experimental 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.

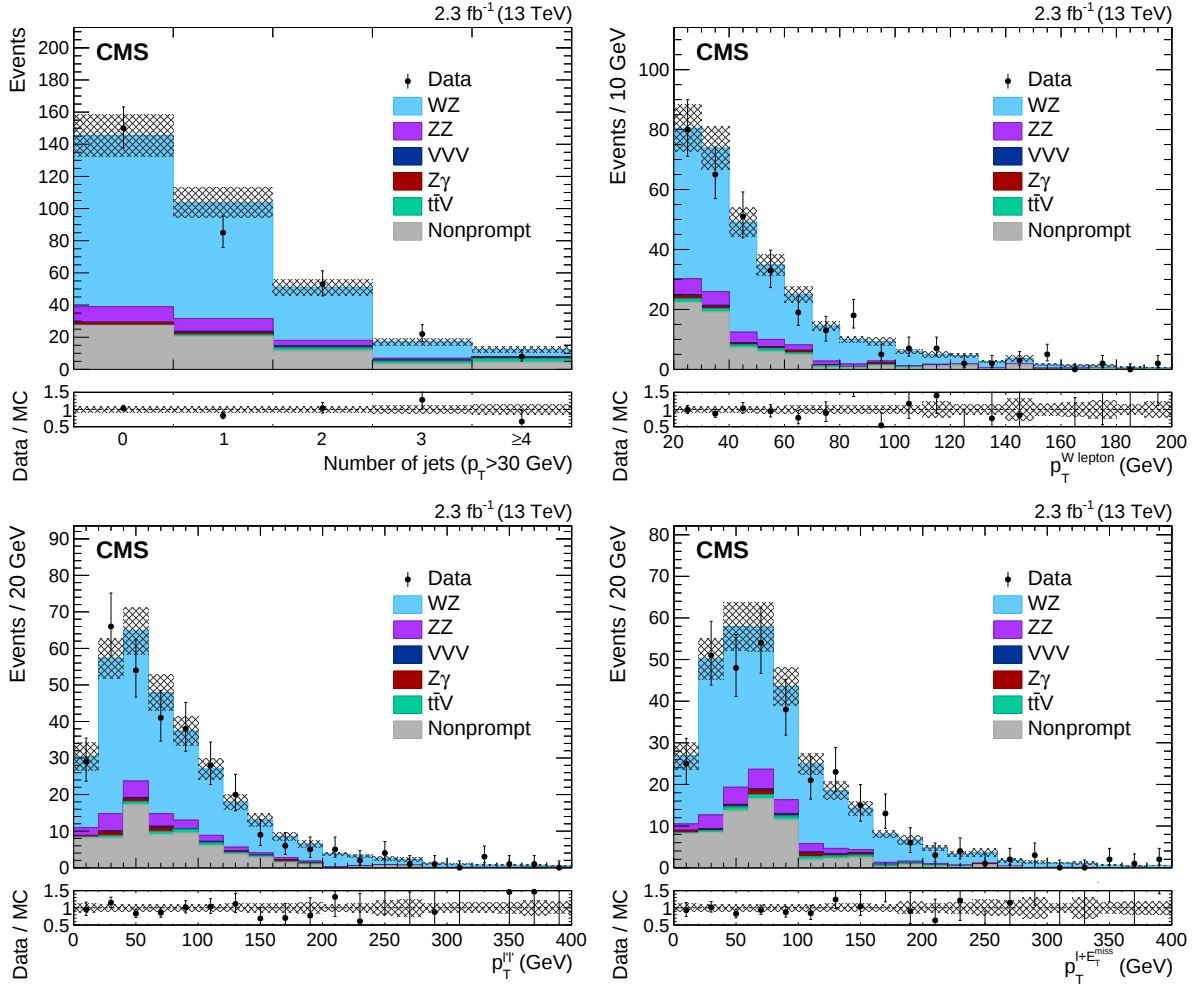


Figure 2: (upper left) Distribution of the number of jets with $p_T > 30$ GeV in the event. (upper right) Transverse momentum of the lepton associated with the W boson. (lower left) Transverse momentum of selected Z boson candidates. (lower right) Transverse momentum of selected W boson candidates. Solid symbols represent the data with statistical uncertainty, while histograms represent the expected WZ signal and backgrounds. Uncertainties in signal and background yields include experimental 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.

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 . The major difference between the channels is the tighter identification and isolation requirements on the electrons. The efficiency correction also takes into account the effect of the E_T^{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 τ into an electron or muon is considered as signal at the detector level, but not at the generator level. Thus the correction for τ lepton decays is also taken into account in the selection efficiency.

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 with the statistical and systematic uncertainties included as scaling nuisance parameters.

The fiducial $WZ \rightarrow \ell\nu\ell'\ell'$ cross section for $p_T^{\ell'} > 20, 10 \text{ GeV}$, $p_T^\ell > 20 \text{ GeV}$, all leptons within $|\eta| < 2.5$, and $60 < m_{\ell'\ell'} < 120 \text{ GeV}$ is

$$\sigma_{\text{fid}}(\text{pp} \rightarrow WZ \rightarrow \ell\nu\ell'\ell') = 258 \pm 21 \text{ (stat)}_{-20}^{+19} \text{ (syst)} \pm 8 \text{ (lumi)} \text{ fb}, \quad (1)$$

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

$$\sigma(\text{pp} \rightarrow WZ) = 39.9 \pm 3.2 \text{ (stat)}_{-3.1}^{+2.9} \text{ (syst)} \pm 0.4 \text{ (theo)} \pm 1.3 \text{ (lumi)} \text{ pb}. \quad (2)$$

The acceptance of the fiducial phase space, $(45.0 \pm 0.4)\%$, is calculated with POWHEG. The nominal Z to dilepton branching fraction $\mathcal{B}(Z \rightarrow \ell'\ell')$ is $(3.3658 \pm 0.0023)\%$ for each lepton flavor, while for the W boson the average branching fraction to leptons is $(10.67 \pm 0.16)\%$: $(10.71 \pm 0.16)\%$ for the electron channel and $(10.63 \pm 0.15)\%$ for the muon channel [40].

The measured cross sections can be compared to 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 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 up and down by a factor of two. 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 $50.0_{-1.0}^{+1.1} \text{ (scale)} \text{ pb}$, available at NNLO via MATRIX [41] with fixed QCD scales set to $\mu_R = \mu_F = \frac{1}{2}(m_Z + m_W)$ and NNPDF3.0 PDFs. Uncertainties for this calculation take into account only renormalization and factorization scale variations. The values from MCFM with this scale choice are $291_{-13}^{+16} \text{ (scale)} \pm 4 \text{ (PDF)} \text{ fb}$ for the fiducial and $44.9_{-1.8}^{+2.2} \text{ (scale)} \pm 0.7 \text{ (PDF)} \text{ pb}$ for the total cross sections.

9 Summary

The WZ production cross section in proton-proton collisions at $\sqrt{s} = 13 \text{ TeV}$ has been measured with the CMS experiment at the LHC using a data sample corresponding to an integrated luminosity of 2.3 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 lepton from the W boson decay with

$p_T > 20$ GeV, all leptons within $|\eta| < 2.5$, and $60 < m_{\ell'\ell'} < 120$ GeV is $\sigma_{\text{fid}}(\text{pp} \rightarrow \text{WZ} \rightarrow \ell\nu\ell'\ell') = 258 \pm 21$ (stat) $^{+19}_{-20}$ (syst) ± 8 (lumi) fb. The corresponding total cross section is $\sigma(\text{pp} \rightarrow \text{WZ}) = 39.9 \pm 3.2$ (stat) $^{+2.9}_{-3.1}$ (syst) ± 0.4 (theo) ± 1.3 (lumi) pb for the dilepton mass range $60 < m_{\ell'\ell'} < 120$ GeV. This measurement is consistent with the theoretical values of 274^{+11}_{-8} (scale) ± 4 (PDF) fb for the fiducial cross section and $42.3^{+1.4}_{-1.1}$ (scale) ± 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 $\mu_R = \mu_F = m_{\text{WZ}}$, and with the NNLO prediction.

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