EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2021-111
2021/07/05

CMS-SMP-20-012

Measurements of the electroweak diboson production cross sections in proton-proton collisions at $\sqrt{s} = 5.02$ TeV using leptonic decays

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Abstract

The first measurements of diboson production cross sections in proton-proton interactions at a center-of-mass energy of 5.02 TeV are reported. They are based on data collected with the CMS detector at the LHC, corresponding to an integrated luminosity of 302 pb^{-1}. Events with two, three, or four charged light leptons (electrons or muons) in the final state are analyzed. The WW, WZ, and ZZ total cross sections are measured as $\sigma_{\mathrm{WW}} = 37.0^{+5.5}_{-5.2}\,(\mathrm{stat})^{+2.7}_{-2.6}\,(\mathrm{syst})$ pb, $\sigma_{\mathrm{WZ}} = 6.4^{+2.5}_{-2.1}\,(\mathrm{stat})^{+0.5}_{-0.3}\,(\mathrm{syst})$ pb, and $\sigma_{\mathrm{ZZ}} = 5.3^{+2.5}_{-2.1}\,(\mathrm{stat})^{+0.5}_{-0.4}\,(\mathrm{syst})$ pb. All measurements are in good agreement with theoretical calculations at combined next-to-next-to-leading order quantum chromodynamics and next-to-leading order electroweak accuracy.

Submitted to Physical Review Letters

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The study of diboson production at the CERN LHC is an important test of the standard model (SM) of particle physics because of its sensitivity to the self-interactions between gauge bosons via trilinear gauge couplings [1]. Understanding diboson production is also important for Higgs boson measurements and for a multitude of beyond-the-SM searches where these diboson processes represent irreducible background contributions. The CMS and ATLAS Collaborations have measured diboson production cross sections in proton-proton (pp) collisions at center-of-mass energies of 7, 8, and 13 TeV [2–18]. In this Letter, we present the first measurements of electroweak diboson production cross sections at $\sqrt{s} = 5.02$ TeV. All measurements are performed with pp collision data corresponding to an integrated luminosity of $302\,\mathrm{pb}^{-1}$, collected in November 2017 with the CMS detector [19] at the LHC. The maximum instantaneous luminosity delivered by the LHC during this period was $1.37 \times 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$, and the mean number of pp interactions per bunch crossing, assuming a total inelastic cross section of 65 mb, was 2.0.

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 tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity (η) coverage provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid. A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, is reported in Ref. [19].

Signal and background processes are simulated by using several Monte Carlo (MC) generators. The propagation of the generated particles through the CMS detector and the modeling of the detector response is performed using GEANT4 [20], assuming alignment and calibration from real data. Simulated signal events are generated at next-to-leading order (NLO) in perturbative quantum chromodynamics (QCD) and dynamic renormalization and factorization scales using POWHEG (v2) [21–23]. The WW and WZ signal cross sections are scaled from NLO to next-to-next-to-leading order (NNLO) using MATRIX calculations [24]. The MADGRAPH5_aMC@NLO [25] generator is used to simulate W and Z/γ^*+jets at NLO. The simulation includes up to two extra partons at the matrix element level and uses the FxFx merging scheme [26]. Simulated top quark events—top quark pair production ($\mathrm{t\bar{t}}$) and single top quark processes—are also generated using POWHEG. All the events are then interfaced with PYTHIA 8 (v8.2) [27] for parton showering, hadronization, and the underlying event simulation, using the CP5 tune [28, 29]. The NNPDF3.1 [30] NNLO parton distribution functions (PDFs) are used. The simulated samples include pileup collisions, assuming a cross section of 69.2 mb on the total inelastic pp cross section.

The particle-flow (PF) algorithm [31] reconstructs and identifies each individual particle in an event, with an optimized combination of information from the various elements of the CMS detector. The energy of photons is obtained from the ECAL measurement. The energy of electrons is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The energy of muons is obtained from the curvature of the corresponding track. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies. For each event, hadronic jets are clustered from these reconstructed particles using the anti-k_T algorithm [32, 33] with a distance parameter of 0.4. Jet momentum is determined as the vectorial sum of all particle momenta in the jet, and, based on simulation, is typically within 5 to 10% of the true momentum over the entire transverse momentum (p_{T}) spectrum and detector acceptance. The missing transverse momentum vector $\vec{p}_{\mathrm{T}}^{\text{miss}}$ is computed as the negative vector p_{T} sum of all the PF candidates in an event, and its magnitude is denoted as $p_{\mathrm{T}}^{\text{miss}}$ [34]. The $\vec{p}_{\mathrm{T}}^{\text{miss}}$ is modified to account for corrections to the energy scale of the reconstructed jets in the event [35]. The candidate vertex with the largest value of summed physics-object p_{T}^2 is the primary pp interaction vertex. The physics objects are the jets, clustered using the jet finding algorithm [32, 33] with the tracks assigned to candidate vertices as inputs, and the associated $p_{\mathrm{T}}^{\text{miss}}$, taken as the negative vector p_{T} sum of those jets.

Electrons are identified with a multivariate analysis (MVA) discriminant [36, 37] and are required to have a p_{T} larger than 8 GeV and $|\eta| < 2.5$. Electrons matched to a secondary vertex consistent with a photon conversion or having at least one missing hit in the pixel tracking system are vetoed. Muons are identified as tracks in the central tracker consistent with either a track or several hits in the muon system, and associated with calorimeter deposits compatible with the muon hypothesis. Reconstructed muons are required to have $p_{\mathrm{T}} > 8$ GeV and $|\eta| < 2.4$, and must fulfill criteria on the geometrical matching between the tracker and the muon track, and the quality of the global fit [38]. An upper threshold of 0.4 on the relative isolation (as defined in Ref. [39]), is applied for both electrons and muons. Lepton candidates are selected if the transverse (longitudinal) impact parameter with respect to the primary vertex does not exceed 0.05 (0.1) cm. Identification criteria are specifically designed to separate prompt leptons—electrons and muons from the decay of a W or Z boson either directly or mediated by a leptonic τ decay—from leptons that arise from other sources, such as c or b decays. Two lepton categories, loose and tight, are defined. The loose identification criteria refer to the requirements presented above and are used to provisionally select all leptons in the events. The tight selection is based on an MVA discriminant—a gradient boosted decision tree—trained to separate between prompt and nonprompt lepton sources [40] and includes, in addition to the loose selection, (1) a tighter upper threshold on the relative isolation (0.085 for electrons and 0.325 for electrons and muons), and (2) a threshold on the b-tagging DEEPJET discriminator [41–43] for any jet that contains a lepton to reduce the $\mathrm{t\bar{t}}$ background. Jets with $p_{\mathrm{T}} > 25$ GeV and $|\eta| < 2.4$ which do not overlap ($\Delta R < 0.4$) with a lepton passing the loose criteria are selected.

Events of interest are selected using a two-tiered trigger system [44]. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz. The second level, known as the high-level trigger, consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage. Events that pass at least one single-lepton trigger with p_{T} thresholds of 17 (electrons) or 12 (muons) GeV are selected. Candidate events are further required to have at least two loose leptons (electrons or muons, ℓ) with a minimal invariant mass of any lepton pair greater than 12 GeV.

The WW signal region (SR) requirements are: exactly two tight leptons with opposite charge and different flavor; the p_{T} of the leading (subleading) lepton >20 (10) GeV; the p_{T} of the dilepton system >20 GeV; the azimuthal separation between the two leptons >2.8 radians; and the transverse mass of any lepton and $p_{\mathrm{T}}^{\text{miss}}$ pair >20 GeV. In addition, events with jets are rejected.

For the WZ measurement two SRs are defined: one with three leptons (3ℓ) and another with two muons with the same electric charge (2μss). In the 3ℓ category, events with exactly three loose leptons with at least one opposite-sign same-flavor (OSSF) pair are selected. To exploit the characteristic kinematics of on-shell WZ production, an algorithm is applied to tag the two leptons from the Z boson decay (ℓ_{Z} and ℓ'_{Z}) and that of the W boson decay (ℓ_{W}). If only one OSSF lepton pair occurs in the event, the leptons corresponding to it are tagged as ℓ_{Z} and ℓ'_{Z}, whereas the different flavor one is tagged as ℓ_{W}. If multiple OSSF pairs are found, the OSSF lepton pair with invariant mass closest to that of the Z boson is selected for the ℓ_{Z} ℓ'_{Z} pair. Then, a p_{T} threshold of 8 GeV is imposed. Additional selection criteria are applied to increase the purity of WZ events. The invariant mass of the ℓ_{Z} and ℓ'_{Z} lepton pair must be consistent with the Z boson mass, $|m_{\ell_{\mathrm{Z}}\ell'_{\mathrm{Z}}} - 91.2\,\mathrm{GeV}| < 30\,\mathrm{GeV}$. The two same-sign leptons are required to pass the tight lepton requirements, the p_{T} of ℓ_{W} must be $>$20 GeV, and the invariant mass of the three lepton system must be $>$100 GeV. For the 2μss category, events with two tight muons and zero jets are selected. The p_{T} of the leading (subleading) muon must be $>$20 (10) GeV. To ensure a high-quality charge measurement, the relative uncertainty in the curvature of the muon track must be $<$20%. Additionally, a minimal requirement of $p_{\mathrm{T}}^{\mathrm{miss}} > 25\,\mathrm{GeV}$ is included.

For the ZZ measurement, two categories are defined: one with four leptons (4ℓ) and another with two leptons ($2\ell2\nu$). For the 4ℓ category, exactly four loose leptons with $p_{\mathrm{T}} > 8\,\mathrm{GeV}$ are required. For the $2\ell2\nu$ category, events with exactly two tight OSSF leptons are selected. The p_{T} of the leading (subleading) lepton must be $>$20 (10) GeV. The invariant mass of the leptons must be close to the Z boson peak, $|m_{\ell,\ell'} - 91.2\,\mathrm{GeV}| < 10\,\mathrm{GeV}$. The axial $p_{\mathrm{T}}^{\mathrm{miss}}$ in the event [9], which expresses the p_{T} projection of the neutrino pair of the invisibly decaying Z boson onto the p_{T} direction of the Z boson decaying to charged leptons, must exceed 50 GeV. The relative difference between $p_{\mathrm{T}}^{\mathrm{miss}}$ and the dilepton p_{T} with respect to the dilepton p_{T} must be smaller than 0.3 [9]. Events with jets are rejected.

Most background contributions, including photon conversions, charge mismeasurement, and those processes yielding prompt leptons in the final state, such as $\mathrm{t\bar{t}}$, single top, Drell–Yan (DY), and diboson production, are estimated from simulation. Backgrounds involving one or more nonprompt leptons are estimated from simulation aided by control samples in data in those categories with two leptons in the final state and exclusively from simulation otherwise. Nonprompt-lepton background sources are composed of processes in which at least one of the final-state leptons does not come from the decay of a W or Z boson either directly or mediated by a leptonic τ decay. Dominant SM sources of nonprompt background depend on the specific decay channel: Z+jets and dileptonic $\mathrm{t\bar{t}}$ production for those channels with at least three leptons, W+jets and semileptonic $\mathrm{t\bar{t}}$ for channels with two leptons in the final state. The nonprompt-lepton contribution is estimated using a lepton misidentification rate method [45] based on the misidentification rate measured in a simulated $\mathrm{t\bar{t}}$ sample and applied to control region data. The main background contributions differ in each SR because of the different final states under study. The dominant background contributions for the WW measurement come from nonprompt lepton and top quark production processes. For the WZ 3ℓ, the background is mainly arising from Z+jets. For the WZ 2μss and ZZ $2\ell2\nu$ SRs the main background is nonprompt leptons. The ZZ 4ℓ SR is very clean with a small background contribution of nonprompt leptons.

Although the measurements presented in this Letter are dominated by the statistical limitation of the size of the data set, the impact of different sources of systematic uncertainties is studied.

The lepton identification scale factors are estimated using the tag-and-probe method [46] as a function of the lepton p_{T} and η for loose and tight electrons and muons. These scale factors are close to 1 and have an uncertainty of the order of 1–3%, except for a few bins limited by statistics. Corrections to the jet energy scale are applied to data and simulation separately as

η- and p_T-dependent corrections. Jet energy corrections are derived from simulation to bring the measured response of jets to that of particle-level jets on average. In situ measurements of the momentum balance in dijet, photon+jet, Z+jet, and multijet events are used to correct any residual differences in jet energy scale in data and simulation [35]. The jet energy resolution amounts typically to 15% at 10 GeV and 8% at 100 GeV. During the 2017 data taking, a gradual shift in the input timing of the ECAL L1 trigger in the region of $|\eta| > 2.0$ caused a trigger inefficiency of 1–4%. Correction factors were computed from data and applied to the acceptance evaluated by simulation. For the selected events the trigger efficiency is very close to 1 in all channels, and no further correction is applied to the simulation. The relative difference between the trigger efficiency estimated in the WW, WZ, and ZZ samples and 100% is used as an uncertainty in the respective cross section measurement.

The uncertainty arising from the choice of PDF is determined by reweighting the sample of simulated diboson events according to the 32 replica PDF sets from PDF4LHC15 [47]. The envelope of the variations in the signal yields is used as the estimate of the uncertainty. The systematic bias due to the missing higher-order diagrams in POWHEG is estimated by varying the default renormalization and factorization scale choices independently by a factor of 2 or 1/2. The uncertainty is assigned from the maximum difference in the signal yields for each variation, excluding the two extreme up/down combinations, with the nominal values.

The uncertainty assigned to the nonprompt lepton contribution in the two-lepton categories is based on the differences between the lepton misidentification rate estimated for all flavor jets, and the b-flavor jets and light-flavor jets, separately. The uncertainty affects mostly electrons: a 30% uncertainty is used per electron and 15% per muon in the categories with two leptons in the final state. Normalization uncertainties of 30% for conversions, 20% for nonprompt leptons, charge mismeasurement, and diboson, and 10% for top quark and DY processes are assigned.

An uncertainty of 1.9% in the integrated luminosity, estimated offline using the methodology described in Ref. [48], is applied as a global normalization uncertainty for all processes.

The statistical uncertainties due to the limited size of the MC samples are treated according to the Barlow–Beeston method [49]; individual nuisance parameters (per process and per channel) are used when the corresponding expected amount of events in the bin is smaller than 10 events.

A summary of the expected event yields for signal and each of the background processes, and the observed data in the WW SR is shown in Table 1. For the other SRs, the expected event yields for signal and the total background, and the observed data, are shown in Table 2.

Table 1: Expected event yields in the WW SR and observed number of events. The uncertainties correspond to the statistical and systematic component, respectively.

Source	Number of events
Top quark	$9.0 \pm 0.1 \pm 1.1$
WZ+ZZ	$5.6 \pm 1.0 \pm 1.1$
Drell–Yan	$1.8 \pm 0.5 \pm 0.2$
Conversions	$2.7 \pm 0.7 \pm 0.7$
Nonprompt ℓ	$11.2 \pm 1.3 \pm 3.4$
Background	$30.3 \pm 1.9 \pm 3.9$
WW signal	$55.2 \pm 0.3 \pm 1.8$
Data	101

The cross sections are measured in regions, called total regions, defined to provide a mea-

Table 2: Expected event yields for the signal and total background in the WZ and ZZ SRs, and observed number of events. The uncertainties correspond to the statistical and systematic component, respectively.

SR	Background	Signal	Data
WZ 3ℓ	$4.0 \pm 0.6 \pm 0.4$	$14.8 \pm 0.1 \pm 0.6$	12
WZ 2μss	$0.6 \pm 0.1 \pm 0.1$	$3.2 \pm 0.8 \pm 0.2$	4
ZZ 4ℓ	$0.5 \pm 0.2 \pm 0.1$	$2.7 \pm 0.0 \pm 0.2$	3
ZZ $2\ell 2\nu$	$4.8 \pm 0.3 \pm 0.7$	$4.0 \pm 0.0 \pm 0.2$	12

surement without any detector acceptance requirements. As outlined below, each channel has a different total region defined at generator level with dressed leptons (the momenta of generator-level photons within a cone of $\Delta R(\ell, \gamma) < 0.1$ is added to the lepton momenta). All total regions are defined as excluding events containing any OSSF lepton pair with invariant mass below 4 GeV. For the WW total region, no further requirements are applied. For the WZ total region, an additional kinematic requirement is imposed that selects events consistent with the on-shell Z boson production: $60 < m_{\ell_Z, \ell'_Z} < 120\,\text{GeV}$. For the ZZ total region, this additional kinematic requirement is applied to both Z boson candidates. The lepton tagging algorithm defined above to assign leptons to either the W or Z boson decay is applied. In the case of the ZZ $2\ell 2\nu$ SR, one Z boson is reconstructed from the two leptons and the other from the neutrinos.

The total cross section, σ, is computed as

$$\sigma = \frac{N^{\text{SR}}_{\text{signal}}}{\mathcal{B}(\text{W} \to \ell\nu \text{ or Z} \to \ell\ell)\ \mathcal{B}(\text{W} \to \ell\nu \text{ or Z} \to \ell\ell)\ \epsilon\ \mathcal{L}} \tag{1}$$

where $\mathcal{L}$ is the total integrated luminosity, ϵ is the efficiency of the lepton reconstruction and the additional phase space requirements, and $N^{\text{SR}}_{\text{signal}}$ is the number of obtained signal events, estimated for each SR by performing a maximum likelihood fit to the yields with a single free-floating parameter that corresponds to the normalization of the signal process. The efficiency values are computed using the signal simulated samples as the ratio of the number of events that fulfill the SR requirements over those that only pass the total region ones. An extrapolation from the lepton final state to the total production cross section is done by dividing by the branching fractions ($\mathcal{B}$) of each of the W and/or Z bosons to leptons, which are taken from Ref. [50]. The distributions of the dilepton p_{T} and W boson transverse mass in the WW and WZ 3ℓ signal region, respectively, are shown in Fig. 1. Good agreement between the observed data and prefit and postfit predictions is found in all channels.

The uncertainties derived above are propagated to the final result through the numerator of Eq. (1). The measured values for the WW, WZ, and ZZ total cross sections, shown in Fig. 2, are

$$\begin{aligned}
\sigma_{\text{WW}} &= 37.0^{+5.5}_{-5.2}\,(\text{stat})^{+2.7}_{-2.6}\,(\text{syst}) = 37.0^{+6.2}_{-5.8}\,\text{pb}, \\
\sigma_{\text{WZ}} &= 6.4^{+2.5}_{-2.1}\,(\text{stat})^{+0.5}_{-0.3}\,(\text{syst}) = 6.4^{+2.5}_{-2.1}\,\text{pb}, \\
\sigma_{\text{ZZ}} &= 5.3^{+2.5}_{-2.1}\,(\text{stat})^{+0.5}_{-0.4}\,(\text{syst}) = 5.3^{+2.6}_{-2.1}\,\text{pb},
\end{aligned}$$

respectively. Figure 2 also presents a summary of the diboson production cross section measurements at different center-of-mass energies and a comparison with fixed-order predictions produced via the MATRIX framework [24]. For the WZ measurement, the result is consistent with the SM prediction within two standard deviations. The calculations are performed with the NNPDF31_nnlo_as_0118_luxqed [51] PDF set (NNPDF31_nnlo_as_0118_luxqed_nf4 for WW

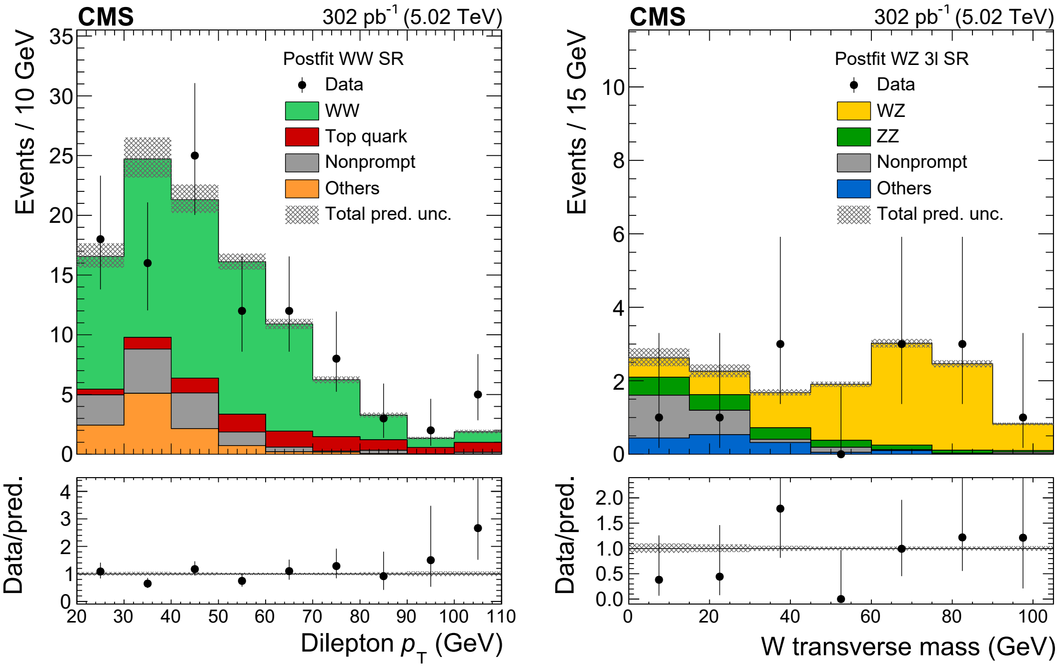

Figure 1: Distribution of the dilepton p_T in the WW signal region (left). Events from DY, conversions, and diboson processes are grouped into the 'Others' category. Distribution of the W boson transverse mass in the WZ 3ℓ signal region (right). Events from conversions, and DY processes are grouped into the 'Others' category. The vertical error bars represent the statistical uncertainty in the data and the shaded band the uncertainty in the prediction. The signal contributions are scaled to the measured cross sections (postfit).

production). The quark-induced processes are calculated at NNLO in QCD and NLO in electroweak (EW) corrections. For the WW and ZZ processes, the gluon induced contribution is calculated at NLO in QCD [52]. Photon-induced contributions are included at up to NLO EW. The quark-induced NNLO QCD and NLO EW contributions are combined multiplicatively (NNLO QCD $\times$ NLO EW), and the gluon- and photon-induced contributions are combined additively, following the procedure described in Ref. [53].

The diboson production cross sections are measured for the first time at a new energy, 5.02 TeV, using data collected with the CMS detector corresponding to an integrated luminosity of 302 pb^{-1}. The analysis is performed in the leptonic decays of the W and Z bosons with at least two leptons in the final state. The measured total cross sections are consistent with theoretical calculations at combined next-to-next-to-leading order quantum chromodynamics and next-to-leading order electroweak accuracy.

Acknowledgments

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid and other centers for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC, the CMS detector, and the supporting computing infrastructure provided by the following funding agencies: BMBWF and FWF (Austria); FNRS and FWO (Belgium); CNPq,

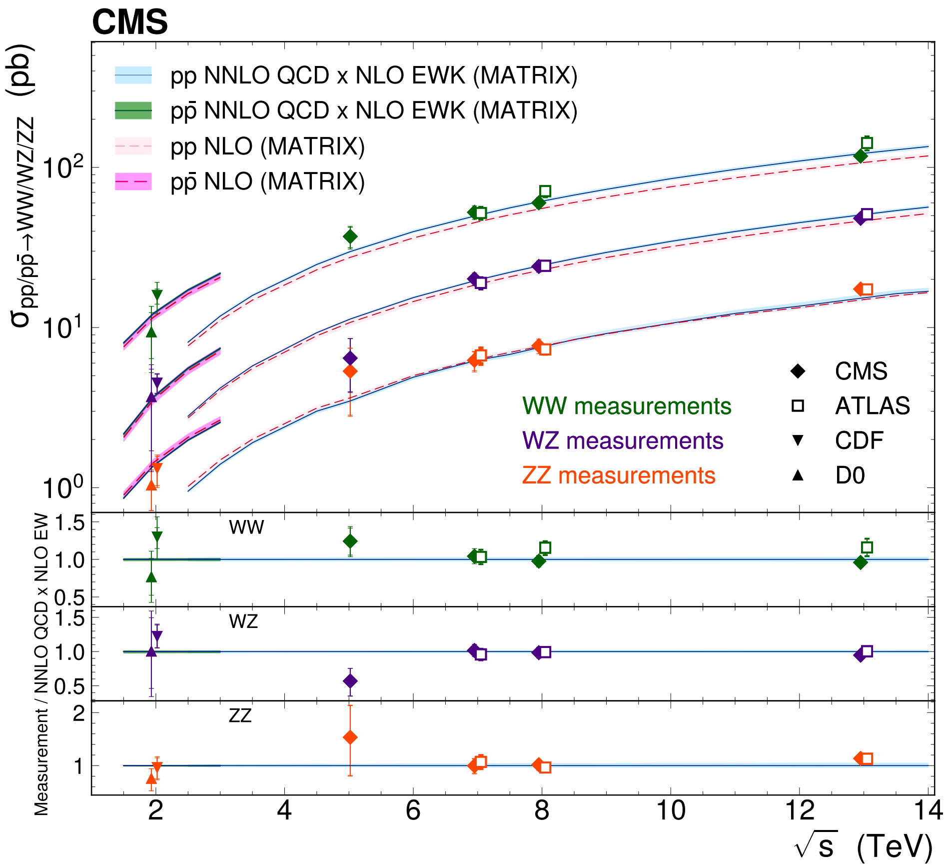

Figure 2: Results obtained in this analysis and other diboson production cross section measurements at different center-of-mass energies for the CMS [11–18], ATLAS [2–10], CDF [54, 55], and D0 [56–58] Collaborations are presented, and compared with the NNLO QCD $\times$ NLO EW and NLO predictions from MATRIX. The vertical error bars represent the uncertainty in the measured cross section.

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

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