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Measurement of WWZ and ZH production cross sections at $\sqrt{s} = 13$ and 13.6 TeV

The CMS Collaboration*

Abstract

A measurement is presented of the cross section in proton-proton collisions for the production of two W bosons and one Z boson. It is based on data recorded by the CMS experiment at the CERN LHC at center-of-mass energies $\sqrt{s} = 13$ and 13.6 TeV, corresponding to an integrated luminosity of $200\,\mathrm{fb}^{-1}$. Events with four charged leptons (electrons or muons) in the final state are selected. Both nonresonant WWZ production and ZH production, with the Higgs boson decaying into two W bosons, are reported. For the first time, the two processes are measured separately in a simultaneous fit. Combining the two modes, signal strengths relative to the standard model (SM) predictions of $0.75^{+0.34}_{-0.29}$ and $1.74^{+0.71}_{-0.60}$ are measured for $\sqrt{s} = 13$ and 13.6 TeV, respectively. The observed (expected) significance for the triboson signal is 3.8 (2.5) standard deviations for $\sqrt{s} = 13.6$ TeV, thus providing the first evidence for triboson production at this center-of-mass energy. Combining the two modes and the two center-of-mass energies, the inclusive signal strength relative to the SM prediction is measured to be $1.03^{+0.31}_{-0.28}$, with an observed (expected) significance of 4.5 (5.0) standard deviations.

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*See Appendix A for the list of collaboration members

The standard model (SM) of particle physics predicts interactions between massive gauge bosons (W and Z bosons) via triple and quartic gauge couplings. The existence of these couplings can result in the production of multiple massive gauge bosons in proton-proton (pp) interactions. Studies of these processes at the CERN LHC test the SM predictions and probe for new physics, whose contributions could lead to enhancements or reductions of the multiboson production rates with respect to the expectations.

Using pp data at $\sqrt{s} = 13\,\text{TeV}$, corresponding to an integrated luminosity of $137\,\text{fb}^{-1}$, the CMS Collaboration [1, 2] has previously observed the VVV production process (where V refers to a W or Z boson) and also obtained evidence for WWZ individually [3]; these final states include contributions from processes with an on-shell Higgs (H) boson. Additionally, the ATLAS Collaboration [4] has observed at $\sqrt{s} = 13\,\text{TeV}$ the VVZ production process and reported evidence for WWZ using a data set of $140\,\text{fb}^{-1}$ [5].

The analysis described in this Letter uses data collected by the CMS Collaboration in two separate running periods at slightly different center-of-mass energies. The 2016–2018 period (corresponding to $138\,\text{fb}^{-1}$ at $\sqrt{s} = 13\,\text{TeV}$) is referred to as "Run 2", and the 2022–2023 period (corresponding to $62\,\text{fb}^{-1}$ at $\sqrt{s} = 13.6\,\text{TeV}$) is referred to as "Run 3". With the two combined data sets, and concentrating on final states with four charged leptons (e or μ), we are now reporting the most sensitive measurement of the WWZ process to date, which also results in the first evidence for triboson production at 13.6 TeV. We also report the first simultaneous study that separates nonresonant WWZ production from ZH ($\text{H} \to \text{WW}$) production. Representative Feynman diagrams for these two processes are displayed in Fig. 1.

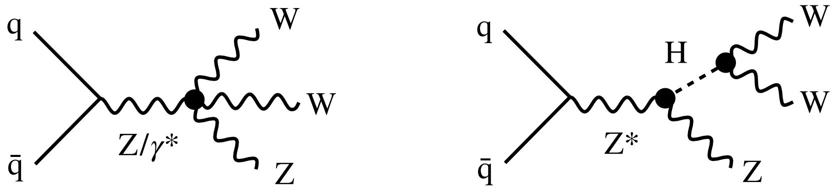

Figure 1: Example Feynman diagrams for nonresonant WWZ (left) and ZH (with $\text{H} \to \text{WW}$) production (right). The quartic gauge coupling is indicated in the left diagram, and the gauge-Higgs couplings are indicated in the right diagram.

The $\text{pp} \to \text{ZH}$ process has been studied in a variety of final states by the CMS and ATLAS Collaborations. The Run 2 measurements result in signal strengths $\mu(\text{ZH}) = 1.29^{+0.22}_{-0.25}$ by CMS [6], and $0.96^{+0.22}_{-0.21}$ by ATLAS [7]. Signal strengths are defined as the ratios of the measured cross sections to the central value of their SM prediction [3, 8, 9]; the uncertainty in the cross section prediction is not included.

The CMS apparatus is a multipurpose, nearly hermetic detector, designed to trigger on [10, 11] and identify electrons, muons, photons, and (charged and neutral) hadrons [12–14]. A global "particle-flow" (PF) algorithm [15] aims to reconstruct all individual particles in an event, combining information provided by the all-silicon inner tracker and by the crystal electromagnetic (ECAL) and brass-scintillator hadron calorimeters (HCAL), operating inside a 3.8 T superconducting solenoid, with data from the gas-ionization muon detectors embedded in the flux-return yoke outside the solenoid. The reconstructed particles are used to build τ-leptons and jets, as well as to measure the missing transverse momentum vector ($\vec{p}_{\mathrm{T}}^{\text{miss}}$) [16–18], defined as the negative of the vector sum of the transverse momenta (p_{T}) of all particles.

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 and direction 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.

Jets are reconstructed from PF candidates, using the anti-k_{T} algorithm with a distance parameter of 0.4 [19, 20]. Jet energies are corrected for instrumental effects and contributions from additional pp interactions within the same or nearby bunch crossings (pileup) [21]. The pileup per particle identification algorithm (PUPPI) [21, 22] can be used to mitigate the effect of pileup at the reconstructed particle level, combining local shape information, event pileup properties, and tracking information. For the study described in this Letter, the PUPPI algorithm is used to improve the reconstruction of jets in the Run 3 data set and $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ in both the Run 2 and Run 3 data sets.

The four-lepton data set used in this study is collected with dilepton triggers, resulting in a trigger efficiency of 100% for events with all four leptons within the p_{T} and pseudorapidity (η) acceptance specified below. Simulated Monte Carlo (MC) samples are used to estimate the SM predictions for the yields of signal processes. The WWZ signal process is generated with the MADGRAPH5_aMC@NLO version 2.6 (Run 2) and 2.9 (Run 3) [8, 23, 24] program at next-to-leading order (NLO) precision. The W bosons for this sample are on-shell; the minimum invariant mass for the pair of leptons from the Z boson is 30 GeV. The quark- and gluon-initiated contributions to the ZH signal process are modeled separately with the POWHEG v2 generator at NLO in perturbative quantum chromodynamics (QCD) [25–29]. The ZH samples require the invariant mass for the pair of leptons from the Z boson to be greater than 10 GeV. Background processes are also estimated with MC simulations, as well as with dedicated data control regions, as discussed below. Some of the background processes (WW, ZZ, $\mathrm{t\bar{t}}$, single top, and $\mathrm{H} \to \mathrm{ZZ}$) are produced with POWHEG to NLO accuracy in QCD, whereas others (WZ, WWW, WZZ, ZZZ, $\mathrm{t\bar{t}V}$, $\mathrm{t\bar{t}H}$, WH, tWZ, tZq, and W+jets) are simulated to NLO accuracy in QCD using MADGRAPH5_aMC@NLO. The $\mathrm{gg} \to \mathrm{ZZ}$ process is produced with the MCFM v7.0.1 program [30]. The NNPDF3.1 next-to-NLO (NNLO) [31] sets of parton distribution functions are used in the simulations. The parton showering and hadronization are modeled with PYTHIA [32, 33] (version 8.240 for the Run 2 samples, and version 8.306 for the Run 3 samples) with the CP5 underlying event tune [34]. Finally, the detector response is simulated with the GEANT4 [35] package. The cross sections for all VVV processes are normalized to the NLO values obtained from the MADGRAPH5_aMC@NLO generator [8, 23, 24]. For each contribution to the ZH signal process, the cross sections recommended by the LHC Higgs Working Group [36] are used.

The main physics objects used in the analysis are leptons (e and μ), escaping particles ($\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$), and jets. We target final states where the two W bosons and the Z boson decay to leptons, either directly or via intermediate tau-lepton decays, and thus we select events with exactly four isolated leptons in the final state. The leading (subleading) lepton in the event is required to have $p_{\mathrm{T}} > 25$ (15) GeV, and the p_{T} of the third and fourth lepton is required to have $p_{\mathrm{T}} > 10$ GeV. Muons and electrons are required to have $|\eta| < 2.4$ and 2.5, respectively. We demand that two of the four leptons be consistent with originating from the decay of an on-shell Z boson: These two leptons, referred to as "Z candidate leptons", are required to be of the same flavor, to have opposite charges, and to form an invariant mass within 10 GeV of the known Z boson mass [37]. The remaining two leptons must have opposite charges, and are referred to as

"W candidate leptons". To minimize background processes that include top quarks, e.g., $\mathrm{pp} \to \mathrm{t\bar{t}Z}$, we reject events with at least one jet of $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ and $|\eta| < 2.4$ if the jet is consistent with originating from bottom quarks, as determined by the DEEPJET discriminator [38–40].

Events are categorized according to the flavors of the W candidate leptons as "opposite flavor" (OF: $\mathrm{e}\mu$) or "same flavor" (SF: ee or $\mu\mu$). This separation is performed because of the different background compositions in the SF and OF channels. Selected events in the SF channel are predominantly ZZ events that decay fully leptonically, with one of the two Z bosons being off-shell. On the other hand, the OF channel selection includes sizable contributions from $\mathrm{pp} \to \mathrm{t\bar{t}Z}$, $\mathrm{pp} \to \mathrm{tWZ}$, and $\mathrm{pp} \to \mathrm{ZZ}$ where in this last case one of the two Z bosons decays to τ leptons that subsequently decay to e or μ.

In the SF channel, the W candidate leptons are required to form an invariant mass more than 10 GeV away from the known mass of the Z boson; additionally, the m_{T2} variable [41, 42] (which is constructed from the transverse momenta of the W candidate leptons and the $\vec{p}_{\mathrm{T}}^{\text{miss}}$) must be greater than 25 GeV. This last requirement is effective at reducing the ZZ background, which tends to produce events with softer leptons, less $p_{\mathrm{T}}^{\text{miss}}$, and smaller m_{T2} values (compared to the non-resonant WWZ signal). Contributions from events with low-mass resonances are suppressed by rejecting events where a pair of opposite-charge leptons forms an invariant mass below 12 GeV. The event selection efficiency including branching fractions into electrons and muons is about 14 and 12% for nonresonant WWZ and ZH, respectively, with some dependence on the run period due to small variations in the run conditions and reconstruction algorithms.

To better distinguish signal processes from background processes, and to distinguish the two signal processes from each other, a boosted decision tree (BDT) multiclassifier [43] is trained on signal and background MC events. The multiclassifier is based on 27 event kinematic properties, such as invariant masses of combinations of leptons, $p_{\mathrm{T}}^{\text{miss}}$, lepton p_{T}, angular separations between objects (leptons and combinations of leptons, $p_{\mathrm{T}}^{\text{miss}}$, jets). The multiclassifier assigns three scores to each event: a WWZ score, a ZH score, and a background score. The three scores are transformed using the `softmax` function in such a way that the sum of all scores for a given event is equal to one. This then allows the individual scores to be interpreted as probabilities of the event to originate from one of the three sources. The most important variables in separating signals from backgrounds and the two signals from each other are the invariant masses of the four leptons and of the W leptons, the $p_{\mathrm{T}}^{\text{miss}}$, the azimuthal angle between the four-lepton system and $\vec{p}_{\mathrm{T}}^{\text{miss}}$, and the η-ϕ separation between the two W leptons.

Signal regions (SRs) are then constructed by binning in the three BDT scores. For Run 2, we define eight SR bins per channel (OF or SF), and for Run 3, which has about one half the integrated luminosity of Run 2, the number of bins per channel is reduced to four.

We use dedicated control regions (CRs) to aid in the estimate of the leading background contributions, which consist of ZZ, $\mathrm{t\bar{t}Z}$, and tWZ production. For the ZZ process, we define one CR per run period, with requirements identical to the SF signal selection except that the invariant mass of both pairs of leptons are required to be within the Z boson mass window and the m_{T2} requirement is not applied. We construct CRs for $\mathrm{t\bar{t}Z}$ and tWZ (referred to as the tXZ CR) by requiring the presence of at least one b-tagged jet, defining a total of eight CR bins by splitting events by SF/OF channels, run period, and b-tagged jet multiplicity (one or more than one). In addition, for the SF tXZ CRs, we replace the $m_{\mathrm{T2}} > 25\,\mathrm{GeV}$ requirement with a $p_{\mathrm{T}}^{\text{miss}} > 80\,\mathrm{GeV}$ requirement, since the latter is more effective at reducing the contributions from the ZZ process in these dedicated CRs.

Smaller background contributions include triboson processes (WWW, WZZ, ZZZ), as well as events with at least one lepton candidate that is not from W or Z boson decay. These backgrounds originate from diboson production (WZ, same- and opposite-sign WW), top quark+X, Higgs boson, $t\bar{t}$, single top, and V+jets processes, and are estimated with MC simulation with appropriate cross section uncertainties applied in the fitting procedure described below. The event yields and the SM prediction for signal and background in the CRs and SRs are displayed in Fig. 2, separately for the two run periods.

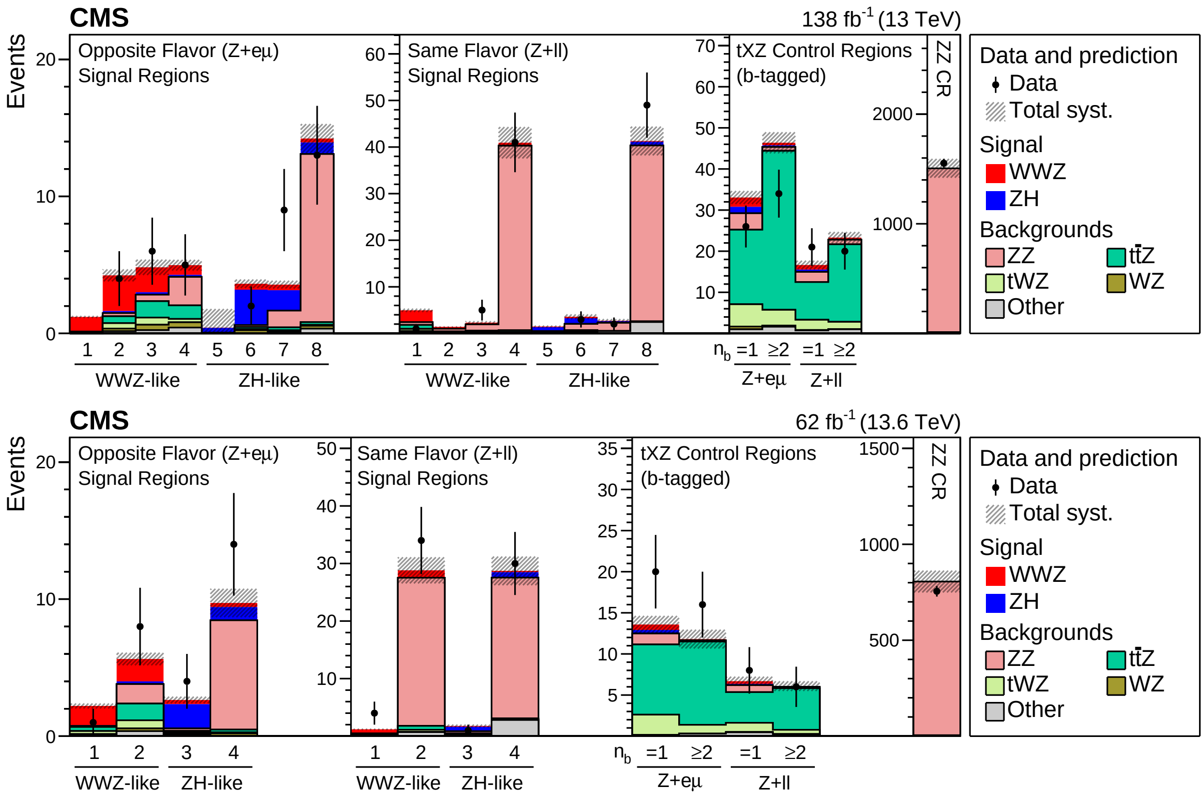

Figure 2: Comparison of the numbers of observed to SM-predicted events for each of the bins included in the fit for Run 2 (upper row) and Run 3 (lower row). The SM expectations are shown before performing the fit. The horizontal axis legend also indicates “WWZ-like” and “ZH-like” bins defined based on whether the WWZ BDT score is higher or lower than the ZH score. The error bars on the data points represent the statistical uncertainties. The shaded bands represent the total contributions of the systematic uncertainties.

The yields for signal (WWZ and ZH) and background are extracted from a simultaneous extended maximum likelihood fit to the bins of Fig. 2. The ZZ normalization and the $t\bar{t}$Z+tWZ normalization are allowed to float freely in the fit, since they are quite effectively constrained by the control regions. The normalizations of the other backgrounds are taken from standard model MC expectations, with appropriate systematic uncertainties. In the simultaneous fit, uncertainties and correlations are handled automatically by the statistical analysis tool, COMBINE [44], with a consistent handling of signal contributions to the control regions.

We account for uncertainties in the fit arising from experimental sources, as well as those associated with the theoretical modeling, by including nuisance parameters in the likelihood. Amongst these uncertainties, the most important ones are those associated with the extraction of the normalization of the main background processes from the control regions and the efficiency of the lepton identification requirements (about 2% per electron and 1% per muon). Other experimental sources of uncertainties include the uncertainty associated with the CMS integrated luminosity measurements for Run 2 (1.6%) [45–47] and Run 3 (1.4%) [48], the simulation of pileup (2%), the uncertainty in the jet energy scale and resolution and its impact on $p_{\mathrm{T}}^{\mathrm{miss}}$ (2%), and the uncertainty in the b tagging efficiency (1%). For theoretical modeling, we include uncertainties in the acceptances of the various processes associated with the MC modeling of parton showers and initial and final state radiation, as well as the assumptions on the renormalization and factorization scales used in the MC generation of the various samples (typically 2%). Finally, we assign a 30% uncertainty to the normalization of the small subleading background processes whose normalizations are not extracted from the fit to the CRs.

The fitted yields are used to compute the signal strength and statistical significance of the two signal processes, WWZ and ZH, in both data-taking periods, separately by process and period, inclusive across processes, and inclusive across periods. Signal strengths and cross sections are shown in Table 1; for the ZH signal process, we report the cross section times the H $\to$ WW branching fraction [49]. A one-dimensional profile likelihood scan of the inclusive total (WWZ and ZH) signal strength and a two-dimensional scan of the WWZ and ZH signal strengths are shown in Fig. 3. From the one-dimensional scan, we measure the inclusive total signal strength to be $1.03^{+0.31}_{-0.28}$, with an observed (expected) significance of 4.5 (5.0) standard deviations.

Table 1: Measured signal strengths and cross sections for the WWZ, ZH (with H $\to$ WW) and inclusive (WWZ+ZH) processes at $\sqrt{s}$ = 13 and 13.6 TeV. For the ZH process, the cross section times the H $\to$ WW branching fraction [49] is reported. The last column shows the SM expectation; the WWZ cross sections are calculated to NLO precision while the ZH cross sections are calculated at NNLO. In the signal strengths reported here, the uncertainty of the predicted cross section is not included.

Era	Process	$\mu = \sigma_{\mathrm{obs}}/\sigma_{\mathrm{SM}}$	σ_{obs} (fb)	σ_{SM} (fb)
Run 2 ($\sqrt{s}$ = 13 TeV)	WWZ only	$0.52^{+0.50}_{-0.41}$ (stat)$^{+0.13}_{-0.12}$ (syst)	97^{+91}_{-75} (stat)$^{+24}_{-21}$ (syst)	184 [8]
	ZH only	$1.01^{+0.62}_{-0.51}$ (stat)$^{+0.14}_{-0.08}$ (syst)	190^{+120}_{-100} (stat)$^{+30}_{-20}$ (syst)	189 [9]
	Inclusive	$0.75^{+0.32}_{-0.28}$ (stat)$^{+0.10}_{-0.08}$ (syst)	280^{+120}_{-110} (stat)$^{+40}_{-30}$ (syst)	373
Run 3 ($\sqrt{s}$ = 13.6 TeV)	WWZ only	$1.91^{+1.12}_{-0.94}$ (stat)$^{+0.25}_{-0.16}$ (syst)	380^{+220}_{-190} (stat)$^{+50}_{-30}$ (syst)	200 [8]
	ZH only	$1.57^{+1.12}_{-0.89}$ (stat)$^{+0.29}_{-0.14}$ (syst)	320^{+230}_{-180} (stat)$^{+60}_{-30}$ (syst)	202 [36]
	Inclusive	$1.74^{+0.67}_{-0.58}$ (stat)$^{+0.22}_{-0.15}$ (syst)	700^{+270}_{-230} (stat)$^{+90}_{-60}$ (syst)	402

Since the BDT is very effective in separating ZH from nonresonant WWZ, fixing the ZH cross section to its measured value [6] does not appreciably change the fitted value of the WWZ signal strength and its uncertainty (less than 1% for the signal strength and about 2% for the uncertainty).

The results are summarized in Tables 1 and 2. In Fig. 4, the measured signal strengths are displayed by process and run period. We note that with the size of the currently available data set, the statistical uncertainties are much larger than the systematic ones; comparing the statistical-only uncertainty to the total uncertainty (i.e., statistical and systematical in quadrature) in each of the signal strength measurements, the inclusion of the systematic uncertainty increases the total uncertainty by less than 5%. Numerical values for figures are provided in the HEPData record for this analysis [50].

In summary, in this Letter we have presented a measurement of the WWZ production cross section in proton-proton collisions in the four charged lepton (e, μ) final state with a data set

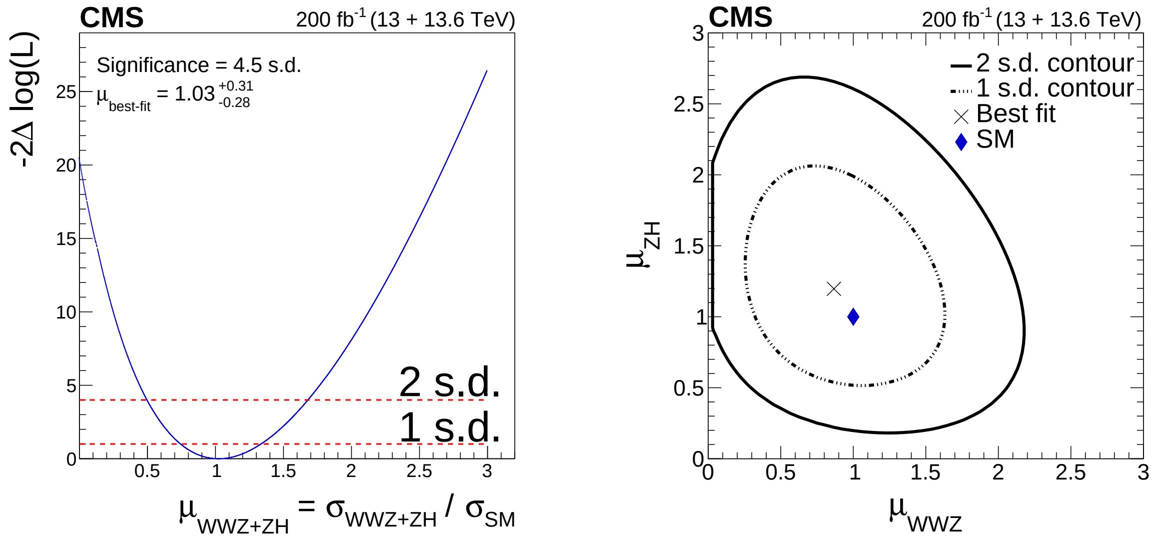

Figure 3: Likelihood scans for the combined Run 2 and Run 3 data sets. Left: One-dimensional likelihood scan as a function of the inclusive WWZ and ZH signal strength parameter ($\mu_{\mathrm{WWZ+ZH}}$). Right: Two-dimensional scan as a function of the individual WWZ and ZH signal strength parameters. For the two-dimensional scan, the one and two standard deviation (s.d.) contours are indicated by the dotted and solid lines, respectively. The correlation coefficient is -0.23. In the signal strengths reported here, the uncertainty of the predicted cross section is not included.

Table 2: Observed (expected) significance of the signal strength in units of standard deviations. The WWZ-only and ZH-only values are obtained by profiling the other signal process, together with all other nuisances.

Era	Total	WWZ	ZH
Run 2	2.9 (4.4)	1.3 (3.1)	2.0 (2.6)
Run 3	3.8 (2.5)	2.5 (1.3)	2.5 (1.7)
Total	4.5 (5.0)	2.4 (3.3)	3.1 (3.1)

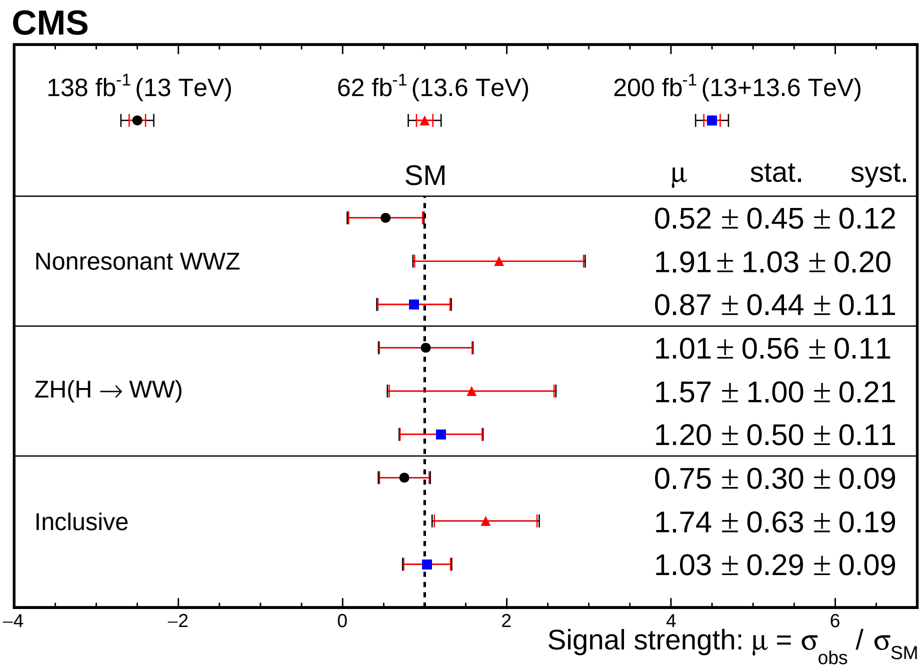

Figure 4: Measured values of the WWZ, ZH, and inclusive signal strength parameters. Results are shown separately by run period as well as after combining the two data sets. The red error bars on the signal strengths represent the statistical uncertainty, and the black error bars represent the total uncertainty. In the signal strengths reported here, the uncertainty of the cross section prediction is not included.

corresponding to an integrated luminosity of 200 fb^{-1} collected by the CMS Collaboration at center-of-mass energies of 13 and 13.6 TeV. The cross section relative to the standard model prediction is measured to be $1.03^{+0.31}_{-0.28}$, representing the most precise measurement of this process to date. The result also provides the first evidence for a triboson production process at 13.6 TeV. Additionally, the nonresonant and ZH (with the Higgs boson H decaying to W bosons) contributions are studied simultaneously for the first time. Within the current uncertainties, our results are in agreement with standard model predictions.

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