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Measurement of the ZZ production cross section and $Z \to \ell^+\ell^-\ell'^+\ell'^-$ branching fraction in pp collisions at $\sqrt{s} = 13$ TeV

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ABSTRACT

Four-lepton production in proton–proton collisions, $pp \to (Z/\gamma^*)(Z/\gamma^*) \to \ell^+\ell^-\ell'^+\ell'^-$, where $\ell, \ell' = e$ or μ, is studied at a center-of-mass energy of 13 TeV with the CMS detector at the LHC. The data sample corresponds to an integrated luminosity of 2.6 fb^{-1}. The ZZ production cross section, $\sigma(pp \to ZZ) = 14.6^{+1.9}_{-1.8}\,(stat)\,^{+0.5}_{-0.3}\,(syst) \pm 0.2\,(theo) \pm 0.4\,(lumi)$ pb, is measured for events with two opposite-sign, same-flavor lepton pairs produced in the mass region $60 < m_{\ell^+\ell^-}, m_{\ell'^+\ell'^-} < 120$ GeV. The Z boson branching fraction to four leptons is measured to be $\mathcal{B}(Z \to \ell^+\ell^-\ell'^+\ell'^-) = 4.9^{+0.8}_{-0.7}\,(stat)^{+0.3}_{-0.2}\,(syst)^{+0.2}_{-0.1}\,(theo) \pm 0.1\,(lumi) \times 10^{-6}$ for the four-lepton invariant mass in the range $80 < m_{\ell^+\ell^-\ell'^+\ell'^-} < 100$ GeV and dilepton mass $m_{\ell^+\ell^-} > 4$ GeV for all opposite-sign, same-flavor lepton pairs. The results are in agreement with standard model predictions.

1. Introduction

Measurements of diboson production at the CERN LHC allow precision studies of the standard model (SM). These measurements are important for testing predictions that were recently made available at next-to-next-to-leading-order (NNLO) in quantum chromodynamics (QCD) [1]. Comparing these predictions to data at a range of center-of-mass energies gives insight into the structure of the electroweak gauge sector of the SM, and new proton–proton collision data at $\sqrt{s} = 13$ TeV allow diboson measurements at the highest energies to date. Any deviations from expected values could be an indication of physics beyond the SM.

Previous measurements of the ZZ production cross section from CMS were performed in the $ZZ \to \ell^+\ell^-\ell''^+\ell''^-$ and $ZZ \to \ell^+\ell^-\nu\nu$ decay channels, where $\ell = e, \mu$ and $\ell'' = e, \mu, \tau$ for both Z bosons produced on-shell, in the dilepton mass range 60–120 GeV [2–4]. These measurements were made with data sets corresponding to integrated luminosities of 5.1 fb^{-1} at $\sqrt{s} = 7$ TeV and 19.6 fb^{-1} at $\sqrt{s} = 8$ TeV, and agree with SM predictions. The ATLAS Collaboration produced similar results at $\sqrt{s} = 7$, 8, and 13 TeV [5–7], which also agree with the SM.

Extending the mass window for the dilepton candidates to lower values allows measurements of $(Z/\gamma^*)(Z/\gamma^*)$ production, where "Z" may indicate an on-shell Z boson or an off-shell Z^* boson. The resulting sample includes Higgs boson events in the "golden channel" $H \to ZZ^* \to \ell^+\ell^-\ell'^+\ell'^-$, where $\ell' = e, \mu$, and rare Z boson decays to four leptons. The $Z \to \ell^+\ell^-\gamma^* \to \ell^+\ell^-\ell'^+\ell'^-$ decay was studied in detail at LEP [8] and was observed in pp collisions by CMS [9] and by ATLAS [10]. Though the branching fraction for this decay is orders of magnitude smaller than that for the $Z \to \ell^+\ell^-$ decay, the precisely known mass of the Z boson makes the four-lepton mode useful for calibrating mass measurements of the nearby Higgs resonance.

This letter reports a study of four-lepton production ($pp \to \ell^+\ell^-\ell'^+\ell'^-$, where ℓ and ℓ' indicate electrons or muons) at $\sqrt{s} = 13$ TeV with a data set corresponding to an integrated luminosity of 2.62 ± 0.07 fb^{-1} recorded in 2015. From this study, cross sections are inferred for nonresonant production of pairs of Z bosons, $pp \to ZZ$, where both Z bosons are produced on-shell, defined as the mass range 60–120 GeV, and resonant $pp \to Z \to \ell^+\ell^-\ell'^+\ell'^-$ production. Discussion of resonant Higgs boson production is beyond the scope of this letter.

2. The CMS detector

A detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [11].

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

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tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), which provide coverage in pseudorapidity $|\eta| < 1.479$ in a barrel and $1.479 < |\eta| < 3.0$ in two endcap regions. Forward calorimeters extend the coverage provided by the barrel and endcap detectors to $|\eta| < 5.0$. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid in the range $|\eta| < 2.4$, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers.

Electron momenta are estimated by combining energy measurements in the ECAL with momentum measurements in the tracker. The momentum resolution for electrons with transverse momentum $p_T \approx 45$ GeV from $Z \to e^+e^-$ decays ranges from 1.7% for nonshowering electrons in the barrel region to 4.5% for showering electrons in the endcaps [12]. Matching muons to tracks measured in the silicon tracker results in a p_T resolution for muons with $20 < p_T < 100$ GeV of 1.3–2.0% in the barrel and better than 6% in the endcaps. The p_T resolution in the barrel is better than 10% for muons with p_T up to 1 TeV [13].

3. Signal and background simulation

Signal events are generated with POWHEG 2.0 [14–16] at next-to-leading-order (NLO) in QCD for quark–antiquark processes and leading-order (LO) for quark–gluon processes. This includes ZZ, $Z\gamma^*$, Z, and $\gamma^*\gamma^*$ production with a constraint of $m_{\ell^+\ell'^-} > 4$ GeV applied between all pairs of oppositely charged leptons at the generator level to avoid infrared divergences. The $gg \to ZZ$ process is simulated at LO with MCFM v7.0 [17]. These samples are scaled to correspond to cross sections calculated at NNLO for $q\bar{q} \to ZZ$ [1] (scaling K factor 1.1) and at NLO for $gg \to ZZ$ [18] (K factor 1.7). The $gg \to ZZ$ process is calculated to $\mathcal{O}(\alpha_s^5)$, where α_s is the strong coupling constant, while the other contributing processes are calculated to $\mathcal{O}(\alpha_s^4)$; this higher-order correction is included because the effect is known to be large [18].

A sample of Higgs boson events is produced in the gluon–gluon fusion process with POWHEG 2.0 in the NLO QCD approximation. The Higgs boson decay is modeled with JHUGEN 3.1.8 [19–21]. The $q\bar{q} \to WZ$ process is generated with POWHEG 2.0.

The PYTHIA v8.175 [22–24] package is used for parton showering, hadronization, and the underlying event simulation, with parameters set by the CUETP8M1 tune [25]. The NNPDF3.0 [26] set is used as the default set of parton distribution functions (PDFs). For all simulated event samples, the PDFs are calculated to the same order in QCD as the process in the sample.

The detector response is simulated using a detailed description of the CMS detector implemented with the GEANT4 package [27]. The event reconstruction is performed with the same algorithms used for data. The simulated samples include additional interactions per bunch crossing, referred to as "pileup." The simulated events are weighted so that the pileup distribution matches the data, with an average of about 11 interactions per bunch crossing.

4. Event reconstruction

All long-lived particles in each collision event — electrons, muons, photons, and charged and neutral hadrons — are identified and reconstructed with the CMS particle-flow (PF) algorithm [28, 29] from a combination of the signals from all subdetectors. Reconstructed electrons [12] and muons [13] are candidates for inclusion in four-lepton final states if they have $p_T^e > 7$ GeV and $|\eta^e| < 2.5$ or $p_T^\mu > 5$ GeV and $|\eta^\mu| < 2.4$. These are designated "signal leptons."

Signal leptons are also required to originate from the event vertex, defined as the proton–proton interaction vertex whose associated charged particles have the highest sum of p_T^2. The distance of closest approach between each lepton track and the event vertex is required to be less than 0.5 cm in the plane transverse to the beam axis, and less than 1 cm in the direction along the beam axis. Furthermore, the significance of the three-dimensional impact parameter relative to the event vertex, SIP_{3D}, is required to satisfy $SIP_{3D} \equiv |IP/\sigma_{IP}| < 4$ for each lepton, where IP is the distance of closest approach of each lepton track to the event vertex and σ_{IP} is its associated uncertainty.

Signal leptons are required to be isolated from other particles in the event. The relative isolation is defined as

$$R_{iso} = \Big[\sum_{\substack{\text{charged} \\ \text{hadrons}}} p_T + \max\big(0, \sum_{\substack{\text{neutral} \\ \text{hadrons}}} p_T + \sum_{\text{photons}} p_T - p_T^{PU}\big) \Big] \Big/ p_T^\ell, \quad (1)$$

where the sums run over the charged and neutral hadrons, and photons, in a cone defined by $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} < 0.3$ around the lepton trajectory, where ϕ is the azimuthal angle in radians. To minimize the contribution of charged particles from pileup to the isolation calculation, charged hadrons are included only if they originate from the event vertex. The contribution of neutral particles from pileup is p_T^{PU}. For electrons, p_T^{PU} is evaluated with the "jet area" method described in Ref. [30]; for muons, it is taken to be half the sum of the p_T of all charged particles in the cone originating from pileup vertices. The factor one-half accounts for the expected ratio of charged to neutral particle energy in hadronic interactions. A lepton is considered isolated if $R_{iso} < 0.35$.

Emission of final-state radiation (FSR) photons by the signal leptons may degrade the performance of the isolation requirements and Z boson mass reconstruction. These photons are omitted from the isolation determination for signal leptons and are implicitly included in dilepton kinematic calculations. Photons are FSR candidates if $p_T^\gamma > 2$ GeV, $|\eta^\gamma| < 2.4$, their relative isolation (defined as in Eq. (1) with $p_T^{PU} = 0$) is less than 1.8, and $\Delta R(\ell, \gamma) < 0.5$ with respect to the nearest signal lepton. To avoid double counting of bremmstrahlung photons that are already included in electron reconstruction, photons are not FSR candidates if there is any signal electron within $\Delta R(\gamma, e) < 0.15$ or within $|\Delta\phi(\gamma, e)| < 2$ and $|\Delta\eta(\gamma, e)| < 0.05$. Because FSR photons have a higher average energy than photons from pileup and are expected to be mostly collinear with the emitting lepton, a photon candidate is accepted as FSR if $\Delta R(\ell, \gamma) / (p_T^\gamma)^2 < 0.012$ GeV^{-2}.

In simulated $ZZ \to \ell^+\ell^-\ell'^+\ell'^-$ events, the efficiency to select generated FSR photons is around 55%, and roughly 85% of selected photons are matched to FSR photons. At least one FSR photon is identified in approximately 2%, 5%, and 8% of simulated events in the 4e, 2e2μ, and 4μ channels, respectively. In data events with two on-shell Z bosons, no FSR photons are selected in the 4e decay channel, while at least one FSR photon is selected in three and five events in the 2e2μ and 4μ decay channels, respectively.

The lepton reconstruction, identification, and isolation efficiencies are measured with a tag-and-probe technique [31] applied to a sample of $Z \to \ell^+\ell^-$ data events. The measurements are performed in several bins of p_T^ℓ and $|\eta^\ell|$. The electron reconstruction and selection efficiency in the ECAL barrel (endcaps) varies from about 85% (77%) at $p_T^e \approx 10$ GeV to about 95% (89%) for $p_T^e \geq 20$ GeV, while in the barrel-endcap transition region this efficiency is about 85% averaged over all electrons with $p_T^e > 7$ GeV. The muons are reconstructed and identified with efficiencies above $\sim$98% within $|\eta^\mu| < 2.4$.

5. Event selection

The primary triggers for this analysis require the presence of a pair of loosely isolated leptons of the same or different flavors. The highest p_T lepton must have $p_T^\ell > 17$ GeV, and the subleading lepton must have $p_T^e > 12$ GeV if it is an electron or $p_T^\mu > 8$ GeV if it is a muon. The dielectron and dimuon triggers require that the tracks corresponding to the leptons originate from within 2 mm of each other in the plane transverse to the beam axis. Triggers requiring a triplet of lower-p_T leptons with no isolation criterion, or a single high-p_T electron without an isolation requirement, are also used. An event is used if it passes any trigger regardless of the decay channel. The total trigger efficiency for events within the acceptance of this analysis is greater than 98%.

A signal event must contain at least two Z/γ^* candidates, each formed from an oppositely charged pair of isolated signal electrons or muons. Among the four leptons, the highest p_T lepton must have $p_T > 20$ GeV, and the second-highest p_T lepton must have $p_T^e > 12$ GeV if it is an electron or $p_T^\mu > 10$ GeV if it is a muon. All leptons are required to be separated by $\Delta R(\ell_1, \ell_2) > 0.02$, and electrons are required to be separated from muons by $\Delta R(e, \mu) > 0.05$.

Within each event, all permutations of leptons giving a valid pair of Z/γ^* candidates are considered separately. Within each $\ell^+\ell^-\ell'^+\ell'^-$ candidate, the dilepton candidate with an invariant mass closest to 91.2 GeV, taken as the nominal Z boson mass, is denoted Z_1 and is required to have a mass greater than 40 GeV. The other dilepton candidate is denoted Z_2. Both m_{Z_1} and m_{Z_2} are required to be less than 120 GeV. All pairs of oppositely charged leptons in the candidate are required to have $m_{\ell\ell'} > 4$ GeV regardless of flavor.

If multiple $\ell^+\ell^-\ell'^+\ell'^-$ candidates within an event pass all selections, the passing candidate with m_{Z_1} closest to the nominal Z boson mass is chosen. In the rare case of further ambiguity, which may arise in events with five or more signal leptons, the Z_2 candidate that maximizes the scalar p_T sum of the four leptons is chosen.

Additional requirements are applied to select events for measurements of specific processes. The $\to$ ZZ cross section is measured using events where both m_{Z_1} and m_{Z_2} are greater than 60 GeV. The $Z \to \ell^+\ell^-\ell'^+\ell'^-$ branching fraction is measured using events with $80 < m_{\ell^+\ell^-\ell'^+\ell'^-} < 100$ GeV, a range chosen to retain most of the decays in the resonance while removing most other processes with four-lepton final states.

6. Background estimate

The major background contributions arise from Z boson and WZ diboson production in association with jets and from $t\bar{t}$ production. In all these cases, particles from jet fragmentation satisfy both lepton identification and isolation criteria, and are thus misidentified as signal leptons.

The probability for such objects to be selected is measured from a sample of $Z + \ell_{candidate}$ events, where Z is a pair of oppositely charged, same-flavor leptons that pass all analysis requirements and satisfy $|m_{\ell^+\ell^-} - m_Z| < 10$ GeV, where m_Z is the nominal Z boson mass. Each event in this sample must have exactly one additional object $\ell_{candidate}$ that passes relaxed identification requirements with no isolation requirements applied. The misidentification probability for each lepton flavor is defined as a ratio of the number of candidates that pass the final isolation and identification requirements to the total number in the sample, measured in bins of lepton candidate p_T and η. The number of $Z + \ell_{candidate}$ events is corrected for contamination from WZ production, or ZZ production in which one lepton is not reconstructed. These events have a third genuine, isolated lepton that must be excluded from the misidentification probability calculation. The WZ contamination is suppressed by requiring the missing transverse energy E_T^{miss} to be below 25 GeV. The E_T^{miss} is defined as the magnitude of the missing transverse momentum vector $\vec{p}_T^{miss}$, the projection onto the plane transverse to the beams of the negative vector sum of the momenta of all reconstructed particles in the event. Additionally, the transverse mass $m_T \equiv \sqrt{(E_T^\ell + E_T^{miss})^2 - (\vec{p}_T^\ell + \vec{p}_T^{miss})^2}$ of $\ell_{candidate}$ and the missing transverse momentum vector is required to be less than 30 GeV. The residual contribution of WZ and ZZ events, which may be up to a few percent of the events with $\ell_{candidate}$ passing all selection criteria, is estimated from simulation and subtracted.

To account for all sources of background events, two control samples are used to estimate the number of background events in the signal regions. Both are defined to contain events with a dilepton candidate satisfying all requirements (Z_1) and two additional lepton candidates $\ell'^+\ell'^-$. In one control sample, enriched in WZ events, one ℓ' candidate is required to satisfy the full identification and isolation criteria and the other must fail the full criteria and instead satisfy only relaxed ones; in the other, enriched in Z+jets events, both ℓ' candidates must satisfy the relaxed criteria, but fail the full criteria. The additional leptons must have opposite charge and the same flavor ($e^\pm e^\mp, \mu^\pm\mu^\mp$). From this set of events, the expected number of background events in the signal region is obtained by scaling the number of observed $Z_1 + \ell'^+\ell'^-$ events by the misidentification probability for each lepton failing the selection. Low-mass dileptons may be sufficiently collinear that their isolation cones overlap, and their misidentification probabilities are therefore correlated. To mitigate the effect of these correlations, only the control sample in which both additional leptons fail the full selection is used if $\Delta R\left(\ell'^+, \ell'^-\right) < 0.6$. The background contributions to the signal regions of $Z \to \ell^+\ell^-\ell'^+\ell'^-$ and $ZZ \to \ell^+\ell^-\ell'^+\ell'^-$ are summarized in Section 8.

Table 1
The contributions of each source of signal systematic uncertainty in the cross section measurements. The integrated luminosity uncertainty and the PDF and scale uncertainties are considered separately. All other uncertainties are added in quadrature into a single systematic uncertainty. Uncertainties that vary by decay channel are listed as a range.

Uncertainty	$Z \to 4\ell$	$ZZ \to 4\ell$
ID efficiency	2–6%	0.4–0.9%
Isolation efficiency	1–6%	0.3–1.1%
Trigger efficiency	2–4%	2%
MC statistics	1–2%	1%
Background	0.7–1.4%	0.7–2%
Pileup	0.4–0.8%	0.2%
PDF	1%	1%
QCD scales	1%	1%
Integrated luminosity	2.7%	2.7%

7. Systematic uncertainties

Systematic uncertainties are summarized in Table 1. In both data and simulated event samples, trigger efficiencies are evaluated with a tag-and-probe technique. The ratio between data and simulation is applied to simulated events, and the size of the resulting change in expected yield is taken as the uncertainty for the determination of the trigger efficiency. This uncertainty is around 2% of the final estimated yield. For $Z \to e^+e^-e^+e^-$ events, the uncertainty increases to 4%.

The lepton identification and isolation efficiencies in simulation are corrected with scaling factors derived with a tag-and-probe method and applied as a function of lepton p_T and η. To estimate the uncertainties associated with the tag-and-probe technique, the total yield is recomputed with the scaling factors varied up and down by the tag-and-probe fit uncertainties. The uncertainties associated with the identification efficiency in the $ZZ \to \ell^+\ell^-\ell'^+\ell'^-$ ($Z \to \ell^+\ell^-\ell'^+\ell'^-$) signal regions are found to be 0.9% (6%) in the 4e final state, 0.7% (4%) in the 2e2μ final state, and 0.4% (2%) in the 4μ final state. The corresponding uncertainties associated with the isolation efficiency are 1.1% (6%) in the 4e final state, 0.7% (3%) in the 2e2μ final state, and 0.3% (1%) in the 4μ final state. These uncertainties are higher for $Z \to \ell^+\ell^-\ell'^+\ell'^-$ events because the leptons generally have lower p_T, and the samples used in the tag-and-probe method have fewer events and more contamination from nonprompt leptons in this low-p_T region.

Uncertainties due to the effect of factorization (μ_F) and renormalization (μ_R) scale choice on the $ZZ \to \ell^+\ell^-\ell'^+\ell'^-$ acceptance are evaluated with POWHEG and MCFM by varying the scales up and down by a factor of two with respect to the default values $\mu_F = \mu_R = m_{ZZ}$. These variations are much smaller than 1% and are neglected. Parametric uncertainties (PDF+α_s) are evaluated using the CT10 [32] and NNPDF3.0 sets and are found to be less than 1%. The largest difference between predictions from POWHEG and MCFM with different scales and PDF sets, 1.5%, is considered to be the theoretical uncertainty in the acceptance calculation. An additional theoretical uncertainty arises from scaling the POWHEG $q\bar{q} \to ZZ$ simulated sample from its NLO cross section to the NNLO prediction, and the MCFM $gg \to ZZ$ samples from their LO cross sections to the NLO predictions. The change in the acceptance corresponding to this scaling procedure is found to be 1.1%. All theoretical uncertainties are added in quadrature.

The largest uncertainty in the estimated background yield arises from differences in sample composition between the $Z + \ell$ control sample used to calculate the lepton misidentification probability and the $Z + \ell^+\ell^-$ control sample. A further uncertainty arises from the limited number of events in the $Z + \ell$ sample. A systematic uncertainty of 40% of the estimated background yield is applied to cover both effects. The size of this uncertainty varies by channel, but is less than 1% of the total expected yield.

The uncertainty in the integrated luminosity of the data sample is 2.7% [33].

8. Cross section measurements

The distributions of the four-lepton mass and the masses of the Z_1 and Z_2 candidates are shown in Fig. 1. The SM predictions include nonresonant ZZ predictions normalized using the NNLO cross section, production of the SM Higgs boson with mass 125 GeV [34], and resonant $Z \to \ell^+\ell^-\ell'^+\ell'^-$ production. The background estimated from data is also shown. The reconstructed invariant mass of the Z_1 candidates, and a scatter plot showing the correlation between m_{Z_2} and m_{Z_1} in data events, are shown in Fig. 2. In the scatter plot, clusters of events corresponding to $ZZ \to \ell^+\ell^-\ell'^+\ell'^-$, $Z\gamma^* \to \ell^+\ell^-\ell'^+\ell'^-$, and $Z \to \ell^+\ell^-\ell'^+\ell'^-$ production can be seen.

The four-lepton invariant mass distribution below 110 GeV is shown in Fig. 3 (top). Fig. 3 (bottom) shows m_{Z_2} plotted against m_{Z_1} for events with $m_{\ell^+\ell^-\ell'^+\ell'^-}$ between 80 and 100 GeV, and the observed and expected event yields in this mass region are given in Table 2.

The reconstructed four-lepton invariant mass is shown in Fig. 4 (top) for events with two on-shell Z bosons. Fig. 4 (bottom) shows the invariant mass distribution for all Z candidates in these events. The corresponding observed and expected yields are given in Table 3.

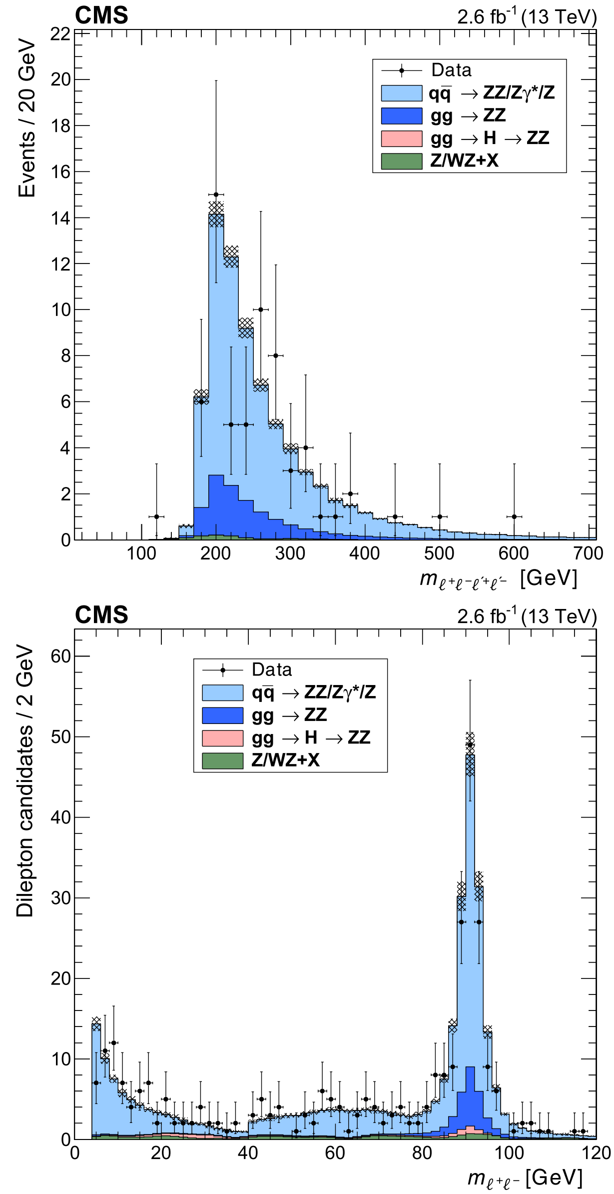

Fig. 1. Distributions of (top) the four-lepton invariant mass $m_{\ell^+\ell^-\ell'^+\ell'^-}$ and (bottom) the invariant mass of the dilepton candidates in all selected four-lepton events, including both Z_1 and Z_2 in each event. Points represent the data, while shaded histograms represent the SM prediction and background estimate. Hatched regions around the predicted yield represent combined statistical, systematic, theoretical, and integrated luminosity uncertainties.

The observed yields are used to evaluate the $pp \to Z \to \ell^+\ell^-\ell'^+\ell'^-$ and $pp \to ZZ \to \ell^+\ell^-\ell'^+\ell'^-$ production cross sections from a combined fit to the number of observed events in all the final states. The likelihood is a combination of individual channel likelihoods for the signal and background hypotheses with the statistical and systematic uncertainties in the form of scaling nuisance parameters. The ratio of the measured cross section to the SM cross section given by this fit including all channels is scaled by the cross section used in the simulation to find the measured fiducial cross section.

The definitions for the fiducial phase spaces for the $Z \to \ell^+\ell^-\ell'^+\ell'^-$ and $ZZ \to \ell^+\ell^-\ell'^+\ell'^-$ cross section measurements are given in Table 4.

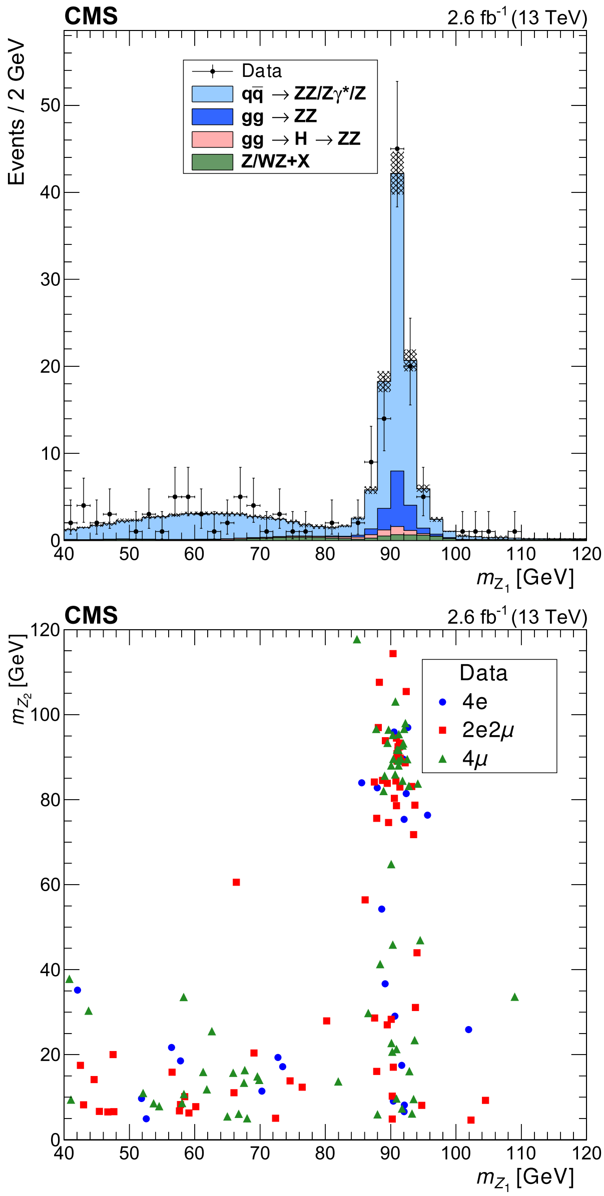

Fig. 2. (top) The distribution of the reconstructed mass of the Z_1 candidate. Points represent the data, while shaded histograms represent the SM prediction and background estimate. Hatched regions around the predicted yield represent combined statistical, systematic, theoretical, and integrated luminosity uncertainties. (bottom) The reconstructed m_{Z_2} plotted against the reconstructed m_{Z_1} in data events, with distinctive markers for each final state.

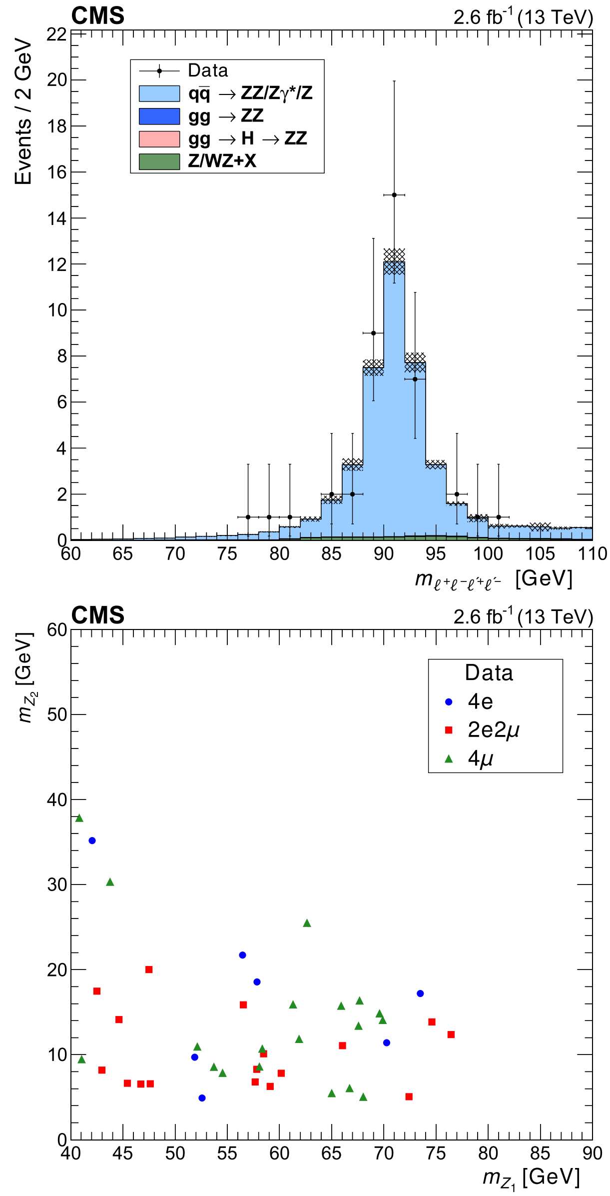

Fig. 3. (top) The distribution of the reconstructed four-lepton mass $m_{\ell^+\ell^-\ell'^+\ell'^-}$ for events selected with $m_{\ell^+\ell^-\ell'^+\ell'^-} < 110$ GeV. Points represent the data, while shaded histograms represent the SM prediction and background estimate. Hatched regions around the predicted yield represent combined statistical, systematic, theoretical, and integrated luminosity uncertainties. (bottom) The reconstructed m_{Z_2} plotted against the reconstructed m_{Z_1} in data events selected with $m_{\ell^+\ell^-\ell'^+\ell'^-}$ between 80 and 100 GeV, with distinctive markers for each final state.

The measured cross sections are

$$\sigma_{\text{fid}}(\text{pp} \to \text{Z} \to \ell^+\ell^-\ell'^+\ell'^-) = 30.5^{+5.2}_{-4.7}\,(\text{stat})\,^{+1.8}_{-1.4}\,(\text{syst}) \pm 0.8\,(\text{lumi})\text{ fb},$$

$$\sigma_{\text{fid}}(\text{pp} \to \text{ZZ} \to \ell^+\ell^-\ell'^+\ell'^-) = 34.8^{+4.6}_{-4.2}\,(\text{stat})\,^{+1.2}_{-0.8}\,(\text{syst}) \pm 0.9\,(\text{lumi})\text{ fb}.$$

The $\text{pp} \to \text{Z} \to \ell^+\ell^-\ell'^+\ell'^-$ fiducial cross section can be compared to $27.9^{+1.0}_{-1.5} \pm 0.6$ fb calculated at NLO in QCD with POWHEG using the same settings as used for the simulated sample described in Section 3, with dynamic scales $\mu_F = \mu_R = m_{\ell^+\ell^-\ell'^+\ell'^-}$. The uncertainties are for scale and PDF variations, respectively. The ZZ fiducial cross section can be compared to $34.4^{+0.7}_{-0.6} \pm 0.5$ fb calculated with POWHEG and MCFM using the same settings as the simulated samples, with dynamic scales $\mu_F = \mu_R = 0.5 m_{\ell^+\ell^-\ell'^+\ell'^-}$ for the contribution from MCFM.

The $\text{pp} \to \text{Z} \to \ell^+\ell^-\ell'^+\ell'^-$ fiducial cross section is scaled to $\sigma(\text{pp} \to \text{Z})\mathcal{B}(\text{Z} \to 4\ell)$ using the acceptance correction factor $\mathcal{A} = 0.122 \pm 0.002$, estimated with POWHEG. This factor corrects the fiducial $\text{Z} \to \ell^+\ell^-\ell'^+\ell'^-$ cross section to the phase space with only the 80–100 GeV mass window and $m_{\ell^+\ell^-} > 4$ GeV requirements, and also includes a correction, 0.96 ± 0.01, for the contribution of nonresonant four-lepton production to the signal region. The measured cross section is

$$\sigma(\text{pp} \to \text{Z})\mathcal{B}(\text{Z} \to \ell^+\ell^-\ell'^+\ell'^-) = 250^{+43}_{-39}\,(\text{stat})\,^{+15}_{-11}\,(\text{syst}) \pm 4\,(\text{theo}) \pm 7\,(\text{lumi})\text{ fb}. \quad (2)$$

The branching fraction for the $\text{Z} \to \ell^+\ell^-\ell'^+\ell'^-$ decay, $\mathcal{B}(\text{Z} \to \ell^+\ell^-\ell'^+\ell'^-)$, is measured by comparing the cross section given by Eq. (2) with the $\text{Z} \to \ell^+\ell^-$ cross section, and is computed as

Table 2
The observed and expected yields of four-lepton events in the mass region $80 < m_{\ell^+\ell^-\ell'^+\ell'^-} < 100$ GeV and estimated yields of background events evaluated from data, shown for each final state and summed in the total expected yield. The first uncertainty is statistical, the second one is systematic.

Final state	Expected $N_{\ell^+\ell^-\ell'^+\ell'^-}$	Background	Total expected	Observed
4μ	$16.88 \pm 0.14 \pm 0.62$	$0.31 \pm 0.30 \pm 0.12$	$17.19 \pm 0.33 \pm 0.63$	17
$2e2\mu$	$15.88 \pm 0.14 \pm 0.87$	$0.37 \pm 0.27 \pm 0.15$	$16.25 \pm 0.31 \pm 0.88$	16
4e	$5.58 \pm 0.08 \pm 0.53$	$0.21 \pm 0.10 \pm 0.08$	$5.78 \pm 0.13 \pm 0.53$	6
Total	$38.33 \pm 0.21 \pm 1.19$	$0.89 \pm 0.42 \pm 0.22$	$39.22 \pm 0.47 \pm 1.21$	39

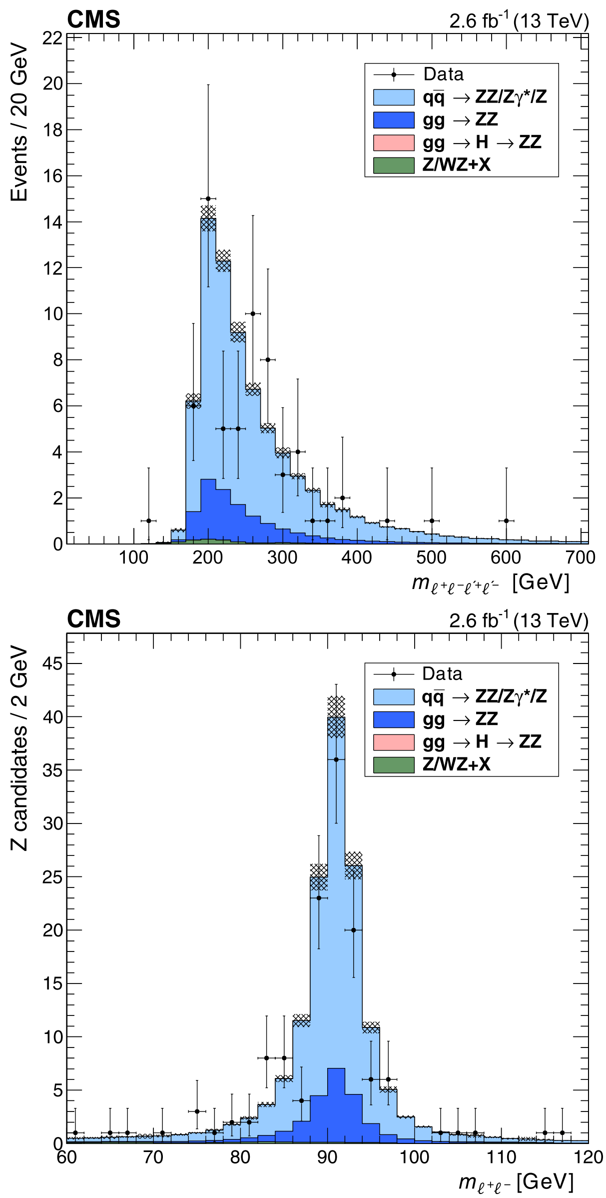

Fig. 4. Distributions of (top) the four-lepton invariant mass $m_{\ell^+\ell^-\ell'^+\ell'^-}$ and (bottom) dilepton candidate mass for four-lepton events selected with both Z bosons on-shell. Points represent the data, while shaded histograms represent the SM prediction and background estimate. Hatched regions around the predicted yield represent combined statistical, systematic, theoretical, and integrated luminosity uncertainties.

$$\mathcal{B}(\mathrm{Z} \to \ell^+\ell^-\ell'^+\ell'^-) = \frac{\sigma(\mathrm{pp} \to \mathrm{Z} \to \ell^+\ell^-\ell'^+\ell'^-)}{\mathcal{C}^{60\text{–}120}_{80\text{–}100}\,\sigma(\mathrm{pp} \to \mathrm{Z} \to \ell^+\ell^-)/\mathcal{B}(\mathrm{Z} \to \ell^+\ell^-)},$$

where $\sigma(\mathrm{pp} \to \mathrm{Z} \to \ell^+\ell^-) = 1870^{+50}_{-40}$ pb is the $\mathrm{Z} \to \ell^+\ell^-$ cross section times branching fraction calculated at NNLO with FEWZ v2.0 [35] in the mass range 60–120 GeV. Its uncertainty includes PDF uncertainties and uncertainties in α_s, the charm and bottom quark masses, and the effect of neglected higher-order corrections to the calculation. The factor $\mathcal{C}^{60\text{–}120}_{80\text{–}100} = 0.926 \pm 0.001$ corrects for the difference in Z mass windows and is estimated using POWHEG. Its uncertainty includes scale and PDF variations. The nominal Z to dilepton branching fraction $\mathcal{B}(\mathrm{Z} \to \ell^+\ell^-)$ is 0.03366 [36]. The measured value is

$$\mathcal{B}(\mathrm{Z} \to \ell^+\ell^-\ell'^+\ell'^-) = 4.9^{+0.8}_{-0.7}\,(\mathrm{stat})\,^{+0.3}_{-0.2}\,(\mathrm{syst})\,^{+0.2}_{-0.1}\,(\mathrm{theo}) \pm 0.1\,(\mathrm{lumi}) \times 10^{-6},$$

where the theoretical uncertainty includes the uncertainties in $\mathcal{A}$, $\mathcal{C}^{60\text{–}120}_{80\text{–}100}$, and $\sigma(\mathrm{pp} \to \mathrm{Z})\mathcal{B}(\mathrm{Z} \to \ell^+\ell^-)$. This can be compared with 4.6×10^{-6}, computed with MADGRAPH5_AMC@NLO [37], and is consistent with the CMS and ATLAS measurements at $\sqrt{s} = 7$ and 8 TeV [9,10].

The total ZZ production cross section for both dileptons produced in the mass range 60–120 GeV and $m_{\ell^+\ell'^-} > 4$ GeV is found to be

$$\sigma(\mathrm{pp} \to \mathrm{ZZ}) = 14.6^{+1.9}_{-1.8}\,(\mathrm{stat})\,^{+0.5}_{-0.3}\,(\mathrm{syst}) \pm 0.2\,(\mathrm{theo}) \pm 0.4\,(\mathrm{lumi})\ \mathrm{pb}.$$

The measured total cross section can be compared to the theoretical value of $14.5^{+0.5}_{-0.4} \pm 0.2$ pb calculated with a combination of POWHEG and MCFM with the same settings as described for $\sigma_{\mathrm{fid}}(\mathrm{pp} \to \mathrm{ZZ} \to \ell^+\ell^-\ell'^+\ell'^-)$. It can also be compared to $16.2^{+0.6}_{-0.4}$ pb, calculated at NNLO in QCD via MATRIX [1,38], or $15.0^{+0.7}_{-0.6} \pm 0.2$ pb, calculated with MCFM at NLO in QCD with additional contributions from LO $\mathrm{gg} \to \mathrm{ZZ}$ diagrams. Both values are calculated with the NNPDF3.0 PDF sets, at NNLO and NLO respectively, and fixed scales set to $\mu_F = \mu_R = m_Z$.

The total ZZ cross section is shown in Fig. 5 as a function of the proton–proton center-of-mass energy. Results from the CMS [2–4] and ATLAS [5–7] experiments are compared to predictions from MATRIX and MCFM with the NNPDF3.0 PDF sets and fixed scales $\mu_F = \mu_R = m_Z$. The MATRIX prediction uses PDFs calculated at NNLO, while the MCFM prediction uses NLO PDFs. The uncertainties are statistical (inner bars) and statistical and systematic added in quadrature (outer bars). The band around the MATRIX predictions reflects scale uncertainties, while the band around the MCFM predictions reflects both scale and PDF uncertainties. The theoretical predictions and all CMS measurements are performed in the dilepton mass range 60–120 GeV. All ATLAS measurements are in the mass window 66–116 GeV. The smaller mass window is estimated to cause a 1.6% reduction in the measured cross section.

9. Summary

Results have been presented for a study of four-lepton final states in proton–proton collisions at $\sqrt{s} = 13$ TeV with the CMS detector at the LHC. The $\mathrm{pp} \to \mathrm{ZZ}$ cross section has been measured to be $\sigma(\mathrm{pp} \to \mathrm{ZZ}) = 14.6^{+1.9}_{-1.8}\,(\mathrm{stat})\,^{+0.5}_{-0.3}\,(\mathrm{syst}) \pm$

Table 3
The observed and expected yields of ZZ events, and estimated yields of background events evaluated from data, shown for each final state and summed in the total expected yield. The first uncertainty is statistical, the second one is systematic.

Final state	Expected $N_{\ell^+\ell^-\ell'^+\ell'^-}$	Background	Total expected	Observed
4μ	$21.80 \pm 0.15 \pm 0.46$	$0.00^{+0.24+0.10}_{-0.00-0.00}$	$21.80^{+0.28+0.47}_{-0.15-0.46}$	26
$2e2\mu$	$36.15 \pm 0.20 \pm 0.81$	$0.60 \pm 0.34 \pm 0.24$	$36.75 \pm 0.34 \pm 0.85$	30
4e	$14.87 \pm 0.12 \pm 0.36$	$0.81 \pm 0.26 \pm 0.33$	$15.68 \pm 0.26 \pm 0.48$	8
Total	$72.82 \pm 0.27 \pm 1.00$	$1.42^{+0.49+0.42}_{-0.43-0.41}$	$74.23^{+0.56+1.08}_{-0.45-1.08}$	64

Table 4
Fiducial definitions for the reported cross sections. The common requirements are applied for both measurements.

Cross section measurement	Fiducial requirements
Common requirements	$p_T^{\ell_1} > 20$ GeV, $p_T^{\ell_2} > 10$ GeV, $p_T^{\ell_{3,4}} > 5$ GeV, $\lvert\eta^\ell\rvert < 2.5$, $m_{\ell^+\ell^-} > 4$ GeV (any opposite-sign same-flavor pair)
$Z \to \ell^+\ell^-\ell'^+\ell'^-$	$m_{Z_1} > 40$ GeV; $80 < m_{\ell^+\ell^-\ell'^+\ell'^-} < 100$ GeV
$ZZ \to \ell^+\ell^-\ell'^+\ell'^-$	$60 < m_{Z_1}, m_{Z_2} < 120$ GeV

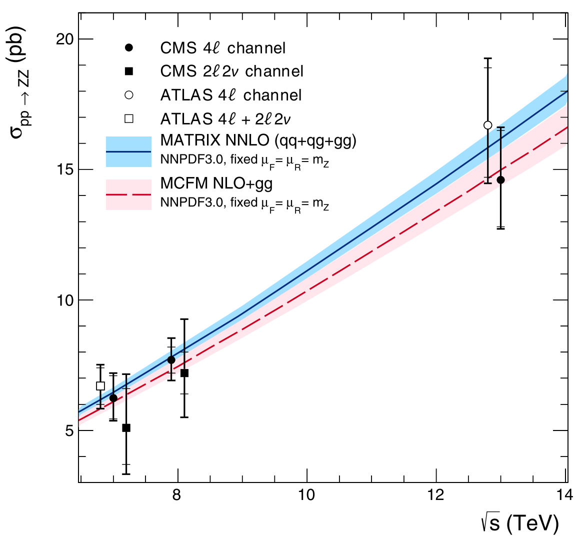

Fig. 5. The total ZZ cross section as a function of the proton–proton center-of-mass energy. Results from the CMS and ATLAS experiments are compared to predictions from MATRIX and MCFM with NNPDF3.0 PDF sets and fixed scales $\mu_F = \mu_R = m_Z$. Details of the calculations and uncertainties are given in the text. Measurements at the same center-of-mass energy are shifted slightly along the x-axis for clarity.

0.2 (theo) $\pm$ 0.4 (lumi) pb for Z boson masses in the range $60 < m_Z < 120$ GeV. The branching fraction for Z boson decays to four leptons has been measured to be $\mathcal{B}(Z \to \ell^+\ell^-\ell'^+\ell'^-) = 4.9^{+0.8}_{-0.7}\,(\text{stat})\,^{+0.3}_{-0.2}\,(\text{syst})\,^{+0.2}_{-0.1}\,(\text{theo}) \pm 0.1\,(\text{lumi}) \times 10^{-6}$ for four-lepton mass in the range $80 < m_{\ell^+\ell^-\ell'^+\ell'^-} < 100$ GeV and dilepton mass $m_{\ell^+\ell^-} > 4$ GeV for all oppositely charged same-flavor lepton pairs. The results are consistent with SM predictions.

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