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Measurement of differential ZZ + jets production cross sections in pp collisions at $\sqrt{s} = 13$ TeV

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Abstract: Diboson production in association with jets is studied in the fully leptonic final states, $\mathrm{pp} \to (\mathrm{Z}/\gamma^*)(\mathrm{Z}/\gamma^*) + \text{jets} \to 2\ell 2\ell' + \text{jets}$, ($\ell, \ell' = \mathrm{e}$ or μ) in proton-proton collisions at a center-of-mass energy of 13 TeV. The data sample corresponds to an integrated luminosity of 138 fb^{-1} collected with the CMS detector at the LHC. Differential distributions and normalized differential cross sections are measured as a function of jet multiplicity, transverse momentum p_T, pseudorapidity η, invariant mass and $\Delta\eta$ of the highest-p_T and second-highest-p_T jets, and as a function of invariant mass of the four-lepton system for events with various jet multiplicities. These differential cross sections are compared with theoretical predictions that mostly agree with the experimental data. However, in a few regions we observe discrepancies between the predicted and measured values. Further improvement of the predictions is required to describe the ZZ+jets production in the whole phase space.

Keywords: Hadron-Hadron Scattering , Vector Boson Production

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Contents

1 Introduction

Measurements of diboson production at the CERN LHC are relevant for precision studies of the standard model (SM). In the SM, ZZ production proceeds mainly through processes represented by the quark-antiquark t- and u-channel scattering diagrams (figure 1 left). In calculations at higher order in quantum chromodynamics (QCD), gluon-gluon fusion also contributes via box diagrams involving quark loops (figure 1 right). The electroweak (EW) and QCD vertices result in the production of Z pairs and of associated jets, and the measurement of this process is the goal of this analysis.

Previously pairs of on-shell Z bosons, produced in the dilepton mass range 60–120 GeV, were studied by the CMS Collaboration using data sets with integrated luminosities of $5.1\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 7\,\mathrm{TeV}$ [1], $19.6\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 8\,\mathrm{TeV}$ [2, 3] in the $\mathrm{ZZ} \to 2\ell 2\ell'$, $\mathrm{ZZ} \to 2\ell 2\tau$ and $\mathrm{ZZ} \to 2\ell 2\nu$ decay channels, where $\ell, \ell' = \mathrm{e}$ or μ, and with integrated luminosities of $2.6\,\mathrm{fb}^{-1}$ [4] and $35.9\,\mathrm{fb}^{-1}$ [5] at $\sqrt{s} = 13\,\mathrm{TeV}$ in the $\mathrm{ZZ} \to 2\ell 2\ell'$ decay channel. The ZZ cross section was also measured at $\sqrt{s} = 5.02\,\mathrm{TeV}$ based on the $\mathrm{ZZ} \to 2\ell 2\ell'$ and $\mathrm{ZZ} \to 2\ell 2\nu$ decay channels [6]. The differential cross sections for Z boson pair production in association with jets were measured at $\sqrt{s} = 8$ and 13 TeV with integrated luminosities of 19.7 and $35.9\,\mathrm{fb}^{-1}$, respectively, using the $\mathrm{ZZ} \to 2\ell 2\ell'$ decay channel [7]. The most recent measurement of ZZ production cross sections with the full Run 2 data set with an integrated luminosity of $137\,\mathrm{fb}^{-1}$ at $\sqrt{s} = 13\,\mathrm{TeV}$ performed by the CMS Collaboration was published in ref. [8], and

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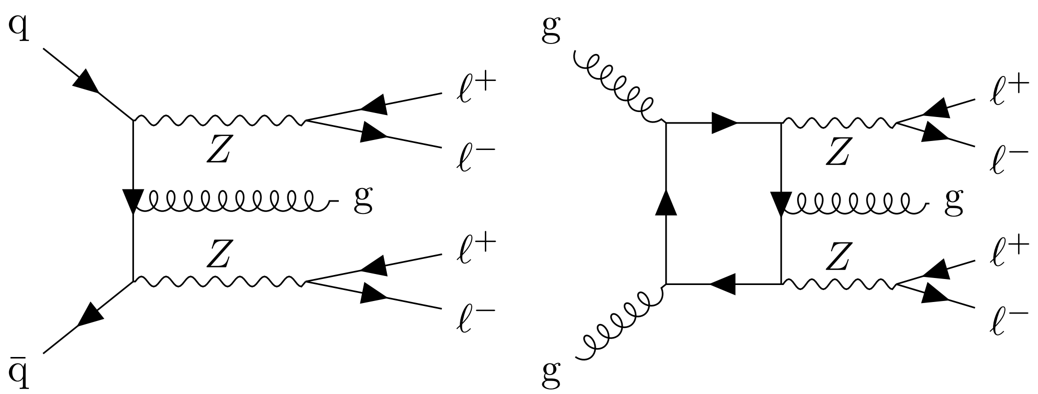

Figure 1. Example Feynman diagrams of ZZ production associated with jets via (left) quark-initiated production and (right) loop-induced gluon fusion production.

results on the EW production of ZZ+2jets were published in ref. [9]. All measurements agree with SM predictions. The ATLAS Collaboration published similar results at $\sqrt{s} = 7$, 8, and 13 TeV [10–15], which also agree with the SM. These measurements are important to test predictions recently made available at next-to-next-to-leading order (NNLO) in QCD [16]. Comparing measurements at the highest collision energies to theoretical predictions tests the ability of the most advanced higher order QCD and EW calculations to predict the cross sections of complex final states with jets and multiple vector bosons, and the full Run 2 proton-proton (pp) collision data at $\sqrt{s} = 13$ TeV allow diboson measurements at the highest energies and integrated luminosities to date.

This paper reports a measurement of the four-lepton production ($\mathrm{pp} \to 2\ell 2\ell'$, where 2ℓ and $2\ell'$ indicate oppositely charged pairs of electrons or muons, and Z/γ^* interference is included) in association with jets at $\sqrt{s} = 13$ TeV using a data set with an integrated luminosity of 138 fb^{-1} recorded in 2016–2018 by the CMS experiment. Cross sections are reported for the nonresonant production of pairs of Z bosons, $\mathrm{pp} \to \mathrm{ZZ}$, in association with jets, where both Z bosons are produced on-shell, defined as Z bosons with mass in the range 60–120 GeV. The effect of the presence of jets on the four-lepton mass ($m_{4\ell}$) distribution is also studied with and without the on-shell requirement. Differential distributions and cross sections are measured with respect to jet multiplicity ($\mathrm{N_{jets}}$), transverse momentum p_{T}, pseudorapidity η, invariant mass and $\Delta\eta$ of the dijet system composed of the highest-p_{T} and second-highest-p_{T} jets, and with respect to $m_{4\ell}$ for events with different jet multiplicities. The results are compared with predictions of theoretical models. This analysis is an extension to that of ref. [8] with a focus on jet variables. The two analyses, ref. [8] and this paper, use the same events with a few minor differences: (i) a 0.3% update in the estimated luminosity of the data set; (ii) the simulation program MadGraph5_aMC@NLO [17] is used instead of POWHEG [18–21] as the nominal $\mathrm{q\overline{q}} \to \mathrm{ZZ}$ sample; and (iii) a regularized unfolding method is used instead of a simple matrix inversion. Therefore, the ZZ fiducial cross section measured in ref. [8] is directly valid for this analysis. The results are also compared with recent nNNLO+PS predictions [22, 23], where PS is parton shower.

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. [24].

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, which provide coverage in pseudorapidity $|\eta| < 1.48$ in a cylindrical barrel and $1.48 < |\eta| < 3.00$ in two endcap regions. Forward calorimeters extend the coverage provided by the barrel and endcap detectors to $|\eta| < 5.0$. Muons are detected 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 $p_{\mathrm{T}} \approx 45\,\mathrm{GeV}$ from $\mathrm{Z} \to \mathrm{e}^+\mathrm{e}^-$ decays ranges from 1.7% for nonshowering electrons in the barrel region to 4.5% for showering electrons in the endcaps [25]. Matching muons to tracks identified in the silicon tracker results in a p_{T} resolution for muons with $20 < p_{\mathrm{T}} < 100\,\mathrm{GeV}$ 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 [26, 27].

Events of interest are selected using a two-tiered trigger system. The first level, composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a fixed latency of $4\,\mu\mathrm{s}$ [28]. 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 [29].

3 Data and Monte Carlo samples

The data sample used in this analysis was recorded by the CMS experiment in 2016, 2017, and 2018, corresponding to 36.3, 41.5, and $59.7\,\mathrm{fb}^{-1}$ of integrated luminosities, respectively. The details of the luminosity measurement are described in refs. [30–32].

The Monte Carlo (MC) simulation used for this analysis can be divided into signal and background samples. The ZZ signal production via quark-antiquark annihilation is simulated at next-to-leading order (NLO) in QCD with MadGraph5_aMC@NLO v2.4.2 [17] and POWHEG 2.0 [18–21]. The MadGraph5_aMC@NLO sample is used as the nominal $\mathrm{q\bar{q}} \to \mathrm{ZZ}$ sample in reconstruction-level distributions and for unfolding, because this sample is expected to describe data better than POWHEG since it merges the 0-jet and 1-jet NLO processes, whereas the POWHEG sample is simulated at NLO accuracy for 0-jet and LO accuracy for 1-jet processes. The $\mathrm{gg} \to \mathrm{ZZ}$ process is simulated at leading order (LO) with MCFM v7.0 [33]. The cross sections of these samples are normalized to the cross sections calculated at NNLO in QCD for $\mathrm{q\bar{q}} \to \mathrm{ZZ}$ (K factor of 1.1) [16] and at NLO in QCD for $\mathrm{gg} \to \mathrm{ZZ}$ (K factor of 1.7) [34]. The production processes via SM Higgs boson production and decay (specifically $\mathrm{gg} \to \mathrm{H} \to \mathrm{ZZ}$) are simulated with POWHEG at NLO. Electroweak ZZ production in association with two jets is simulated with MadGraph5_amc@nlo [17] at LO. The nominal SM signal predictions are derived from the MadGraph5_amc@nlo $q\bar{q} \to ZZ$ sample, the mcfm $gg \to ZZ$ sample, and the MadGraph5_amc@nlo EW production sample, which includes vector boson fusion Higgs boson contributions and their interference with non-Higgs boson EW production, and the powheg $H \to ZZ$ sample.

Simulated events for the irreducible background processes containing four prompt leptons in the final state, such as $t\bar{t}Z$, WWZ, WZZ, and ZZZ, where the last three are combined and denoted as VVV, are simulated with MadGraph5_amc@nlo at LO ($t\bar{t}Z$) and NLO (VVV).

Parton showering, hadronization and fragmentation are simulated in all samples with pythia 8.226 and 8.230 [35], with parameters set by the CUETP8M1 [36] (CP5 [37]) tune for the 2016 (2017 and 2018) data-taking period, and the NNPDF3.0 (3.1) set of parton distribution functions, PDFs, [38] is used.

Results are also compared with the very recent nNNLO+PS predictions [22, 23], which consist of NNLO predictions for the quark-initiated production combined with parton showers using the MiNNLO$_{PS}$ method, and NLO predictions for the loop-induced gluon fusion production matched to parton showers, with event generators for the two channels implemented in the powheg framework. Spin correlations, interferences, and off-shell effects are included by calculating the full process $pp \to \ell^+\ell^-\ell'^+\ell'^-$ and considering all contributions to the four-lepton final state. The contribution mediated by a Higgs boson is included in the gluon fusion production mode.

As part of the nNNLO+PS predictions, the $q\bar{q} \to ZZ$ predictions from the MiNNLO$_{PS}$ method are accurate at NNLO for inclusive production and accurate at NLO for Z+1-jet production. The combination of the two jet multiplicities does not require any unphysical merging scale [39]. These predictions are expected to be more accurate at high jet multiplicities than: (i) the powheg $q\bar{q} \to ZZ$ predictions, which are accurate at NLO in inclusive production; (ii) the MadGraph5_amc@nlo predictions, which are simulated at NLO with the 0- and 1-jet processes, and merged using the FxFx scheme [40].

The detector response is simulated using a detailed description of the CMS detector implemented with the Geant4 package [41]. The simulated samples include additional interactions per bunch crossing, referred to as pileup. Simulated events were weighted so that the pileup distribution reproduces that observed in the data.

4 Event reconstruction

Standard CMS reconstruction and identification (ID) algorithms, referred to as particle-flow (PF) [42], are used to reconstruct and identify stable particles arising from collisions — electrons, muons, photons, and charged and neutral hadrons — by combining the signals from all subdetectors. Electrons and muons are considered candidates for the reconstruction of ZZ final states ("signal leptons") if their $p_T^\ell > 7\,(5)$ GeV and their $|\eta^\ell| < 2.5\,(2.4)$ for electrons (muons).

Signal leptons are required to originate from the primary interaction vertex of the event, which is taken to be the vertex corresponding to the hardest scattering in the event, evaluated using tracking information alone, as described in section 9.4.1 of ref. [43]. The distance of the lepton track origin from the primary vertex is required to be <1 cm along the beam line, and <0.5 cm in the transverse plane. Furthermore, the significance of the three-dimensional impact parameter relative to the event vertex, $\mathrm{SIP_{3D}}$, is required to satisfy $\mathrm{SIP_{3D}} \equiv |\frac{\mathrm{IP}}{\sigma_{\mathrm{IP}}}| < 4$ for each lepton, where IP is the distance of closest approach of the lepton track to the primary vertex and σ_{IP} is its associated uncertainty.

Loose and tight ID requirements are defined for each lepton. The tight IDs are used for signal leptons, whereas the loose IDs are used in control regions to define objects that might be spuriously identified as a signal lepton. An electron satisfies the loose ID if it satisfies the p_{T}, η, and vertex requirements above. It satisfies the tight ID if it satisfies the loose ID and the multivariate discriminator described in ref. [44]. A muon satisfies the loose ID if it satisfies the above p_{T}, η, and vertex requirements, and provides a good track-matching between the tracker and the muon detectors. It satisfies the tight ID if it satisfies the loose ID, and either is tagged as a muon by the PF algorithm for the years 2016–2017 (satisfies a multivariate discriminator for the year 2018 [45]), or is a high p_{T} (> 200 GeV) muon and satisfies a set of requirements on the quality of the associated track.

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

$$R_{\mathrm{Iso}} = \left(\sum_{\text{charged}} p_{\mathrm{T}} + \max\left[0, \sum_{\text{neutral}} p_{\mathrm{T}} + \sum_{\text{photons}} p_{\mathrm{T}} - p_{\mathrm{T}}^{\mathrm{PU}}(\ell)\right]\right) \Big/ p_{\mathrm{T}}^{\ell} \tag{4.1}$$

where the sums run over the p_{T} of hadrons and photons in a cone of size $\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ around the lepton momentum direction, where ϕ is the azimuthal angle in radians. To mitigate the contribution of pileup interactions to the isolation, charged hadrons are included only if they originate from the primary vertex [46]. The estimated neutral contribution to the isolation from pileup, $p_{\mathrm{T}}^{\mathrm{PU}}(\ell)$, is defined differently for electrons and muons. For electrons, $p_{\mathrm{T}}^{\mathrm{PU}}(\mathrm{e}) \equiv \rho\, A_{\mathrm{eff}}$ where the average p_{T} flow density ρ is calculated for each event using a "jet area" method [47], and is defined as the median of the $p_{\mathrm{T}}^{\mathrm{jet}}/A_{\mathrm{jet}}$ distribution for all pileup jets in the event. The effective area A_{eff} is the geometric area of the isolation cone projection on the face of the calorimeter multiplied by an η-dependent correction factor that accounts for the residual dependence of the isolation value on pileup. For muons, $p_{\mathrm{T}}^{\mathrm{PU}}(\mu) \equiv 0.5 \sum_i p_{\mathrm{T}}^{\mathrm{PU},i}$, where i runs over the momenta of the charged hadron PF candidates originating from pileup vertices, and the factor of 0.5 corrects for the ratio of charged to neutral particles in the isolation cone. For the years 2016–2017, muons are considered isolated if their $R_{\mathrm{Iso}} < 0.35$, whereas for 2018 and for electrons the isolation requirement is included in the multivariate discriminator used for the selection.

The efficiencies for the reconstruction, identification, and isolation of signal leptons are measured in data and simulation using a tag-and-probe technique [48] based on inclusive samples of Z boson events, with an additional sample of J/ψ events for low-p_{T} muons. The measurements are performed in bins of p_{T}^{ℓ} and $|\eta^{\ell}|$, where for electrons the supercluster η is used. The electron selection efficiency in the ECAL barrel (endcaps) varies from ∼85 (77)% at $p_{\mathrm{T}}^{\mathrm{e}} \approx 10$ GeV, to ∼95 (89)% for $p_{\mathrm{T}}^{\mathrm{e}} \geq 20$ GeV, and is ∼85% in the barrel-endcap transition region. The muons are reconstructed and identified with efficiencies above ∼98% within $|\eta^{\mu}| < 2.4$. The ratio between the data and simulation efficiencies in each p_{T}-$|\eta|$ bin is applied as a correction factor to leptons in simulated events. If the correction factor for a given lepton is $f_{\rm eff}^{\ell}(p_{\rm T}{}^{\ell}, \eta^{\ell})$, the efficiency correction for each event is $\prod_{\ell} f_{\rm eff}^{\ell}(p_{\rm T}{}^{\ell}, \eta^{\ell})$, where the product index runs over the four leptons of the ZZ candidate.

Jets are reconstructed based on PF candidates, rejecting the charged hadrons associated to a pileup vertex, with the anti-$k_{\rm T}$ clustering algorithm [49, 50] using a distance parameter $R = 0.4$. To reduce the instrumental background, tight identification criteria based on the multiplicities and energy fractions carried by charged and neutral hadrons are imposed on jets [51]. Jets from pileup are rejected using pileup jet identification criteria based on the compatibility of the associated tracks with the primary vertex, when inside the tracker acceptance, and on the jet topology [46]. Jet energy corrections are applied to the reconstructed jets [52, 53].

5 Event selection

The data samples used in this analysis are selected by the trigger system that requires the presence of a pair of loosely isolated leptons or a triplet of leptons, with minimum-$p_{\rm T}$ thresholds for leptons depending on the lepton combination. Further triggers include a set of single-electron and single-muon triggers, and triggers on leptons of different flavors. The trigger efficiency within the acceptance is greater than 98%.

Events are required to have at least four leptons. Each event should contain at least one lepton with $p_{\rm T} > 20$ GeV, two leptons with $p_{\rm T} > 10$ GeV, and four leptons with $p_{\rm T} > 7\,(5)$ GeV for electrons (muons). All leptons must pass the "tight" lepton identification and isolation requirements described in section 4.

The 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 $\Delta R(\mathrm{e}, \mu) > 0.05$, to remove spurious "ghost" leptons arising from ambiguities in track reconstruction. Lepton pairs originating from hadronic decays are removed by requiring that all oppositely charged lepton pairs in the ZZ candidate have $m_{\ell_1\ell_2} > 4$ GeV regardless of lepton flavor.

Z candidates are built from two oppositely-charged leptons of the same flavor. The pair is retained if it satisfies $4 < m_{\ell^+\ell^-} < 120$ GeV. All possible four-lepton candidates in an event are then considered. For each ZZ candidate, the dilepton pair with invariant mass closest to the nominal Z mass $m_{\rm Z}$ (91.1876 GeV [54]) is designated Z_1, and the other is designated Z_2. The event is kept if $40 < m_{\mathrm{Z}_1} < 120$ GeV and $4 < m_{\mathrm{Z}_2} < 120$ GeV.

In the case of multiple ZZ candidates satisfying all requirements, the ambiguity is resolved by selecting the candidate where m_{Z_1} is closest to the nominal Z mass. If more than one lepton combination is still possible, the Z_2 candidate is chosen as the one that maximizes the scalar $p_{\rm T}$ sum of the leptons.

In this analysis, the jets are required to have a $p_{\rm T} > 30$ GeV and $|\eta| < 4.7$. In addition, jets are required to be well separated from any isolated lepton by requiring $\Delta R(\text{jet,lepton}) > 0.4$, where the lepton here satisfies all the tight requirements except for the lower $p_{\rm T}$ requirement (> 5 GeV instead of > 7 GeV for electrons, > 3 GeV instead of > 5 GeV for muons) and a relaxed $\mathrm{SIP_{3D}}$ requirement (<10 instead of <4 for electrons).

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6 Background estimates

The requirement of four well-reconstructed and isolated lepton candidates strongly suppresses any background; therefore, this analysis has very low background contributions, dominated by Z boson and WZ diboson production in association with jets, and $\mathrm{t\bar{t}}$ production.

In a small fraction of cases, particles from jet fragmentation satisfy both lepton identification and isolation criteria, and thus are misidentified as signal leptons. This background is estimated using control data samples. The probability for jets to be misidentified and selected as leptons is measured from a sample of $\mathrm{Z}+\ell_{\text{candidate}}$ events, where Z denotes a pair of oppositely charged, same-flavor leptons that pass the selection requirements and satisfy $|m_{\ell^+\ell^-} - m_\mathrm{Z}| < 7\,\mathrm{GeV}$. Each event in this sample must have exactly one additional lepton candidate $\ell_{\text{candidate}}$ that satisfies the loose identification requirements with no isolation requirements applied. The misidentification probability for each lepton flavor, measured in bins of p_T and η of the $\ell_{\text{candidate}}$, is defined as the ratio between the number of candidates that pass the final isolation and identification requirements to the total number of candidates in the sample. The number of $\mathrm{Z}+\ell_{\text{candidate}}$ events is corrected for the contamination from WZ production and for ZZ events 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 momentum $p_\mathrm{T}^\text{miss} < 25\,\mathrm{GeV}$. The p_T^miss is defined as the magnitude of the missing transverse momentum vector $\vec{p}_\mathrm{T}^\text{miss}$, the projection onto the plane transverse to the beams of the negative vector momentum sum of all reconstructed PF candidates in the event, corrected for the jet energy scale (JES). The transverse mass, calculated as $m_\mathrm{T} \equiv \sqrt{(p_\mathrm{T}^\ell + p_\mathrm{T}^\text{miss})^2 - (\vec{p}_\mathrm{T}^{\,\ell} + \vec{p}_\mathrm{T}^\text{miss})^2}$, is required to be $<30\,\mathrm{GeV}$. The residual contribution of WZ and ZZ events, which can be up to a few percent of the $\ell_{\text{candidate}}$ events passing all selection criteria, is estimated from simulation and subtracted.

Two control samples are used to estimate the number of background events in the signal region. Both are defined as samples that contain events with a dilepton candidate satisfying all requirements (as Z_1) and two additional lepton candidates $\ell^+\ell^-$. In one control sample, enriched in WZ+jets events, one ℓ candidate is required to satisfy the tight identification and isolation criteria and the other must fail this selection and instead satisfy only the loose requirements; in the other control sample, enriched in Z+jets events, both ℓ candidates must satisfy the loose criteria, but fail the full criteria. The additional leptons must have opposite charges and the same flavor ($\mathrm{e}^\pm\mathrm{e}^\mp$ and $\mu^\pm\mu^\mp$). The expected number of background events in the signal region, denoted "Z+X" in the figures, is obtained by scaling the number of observed $\mathrm{Z}_1 + \ell^+\ell^-$ events by the misidentification probability for each lepton failing the selection. The procedure is described in more detail in ref. [55].

In addition to this reducible background, which contributes to approximately 1–2% of the expected $\mathrm{ZZ} \to 2\ell2\ell'$ event yield, the yields from the $\mathrm{t\bar{t}Z}$ and VVV processes with four prompt leptons are estimated from simulated samples to be around 1.0–1.5% of the expected $\mathrm{ZZ} \to 2\ell2\ell'$ yield.

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7 Unfolding and systematic uncertainties

To obtain differential cross sections normalized to the ZZ fiducial cross sections (for the on-shell ZZ region and for the full four-lepton invariant mass range as defined by the kinematic requirements) and compare CMS data to theoretical predictions, the data are "unfolded" to remove detector resolution, efficiency, and acceptance effects. For each distribution to be unfolded, a response matrix is obtained from simulated signal samples. The response matrix represents the correlation map between the distributions obtained after the full detector simulation, reconstruction, and selection, and the generated distributions they originate from. It is used in unfolding to obtain true physical distributions from observed data. The data are unfolded using the iterative D'Agostini's method [56] including correction for background contributions, with the `RooUnfold` toolkit as described in ref. [57], and compared with the theoretical predictions from MadGraph5_aMC@NLO $q\overline{q} \to ZZ$ and POWHEG $q\overline{q} \to ZZ$, where MCFM $gg \to ZZ$, POWHEG $H \to ZZ$, and MadGraph5_aMC@NLO EW ZZ predictions are also added to these two sets of predictions. The unfolded results are also compared with the nNNLO+PS predictions.

The measured on-shell ZZ fiducial cross section from ref. [8] is $40.5 \pm 0.7\,(\text{stat}) \pm 1.1\,(\text{syst}) \pm 0.7\,(\text{lumi})$ fb, which agrees well with the expected value of $39.3^{+0.8}_{-0.7} \pm 0.6$ fb. As explained in the introduction, this fiducial cross section is valid for the current analysis. The fiducial phase space selections are similar to the reconstruction-level selections and detailed in table 1. We use the notation m_{Z_1,Z_2} to refer to both m_{Z_1} and m_{Z_2}. The MC particle-level distributions use generator-level leptons "dressed" by adding the momenta of generator-level photons within $\Delta R(\ell,\gamma) < 0.1$ from the direction of the lepton.

In constructing the response matrix, there are MC events that pass the reconstruction-level selections, but do not have corresponding events at particle level that pass the fiducial selections. In the unfolding method used, these out-of-fiducial events are treated as background events that equivalently propagate from an additional particle-level bin to the reconstruction-level bins. The size of the contribution of these out-of-fiducial events can be up to 15% for events with at least one jet. In addition, the nonprompt and VVV background events are also added to the out-of-fiducial events.

The systematic uncertainties are propagated through the unfolding by reevaluating the response matrix with the sample used in building the matrix shifted or reweighted to reflect a one standard deviation variation in the quantity of interest. The resulting difference in the final normalized unfolded distributions is taken as the uncertainty related to that quantity.

The systematic uncertainty in the trigger efficiency is estimated to be 2%, and cancels out in normalized differential cross sections. To evaluate uncertainties associated with lepton efficiencies, the response matrix is reevaluated using lepton efficiency correction factors varied up and down by the tag-and-probe [48] fit uncertainties. Electrons and muons are treated separately, and all leptons of the same type are treated as correlated. For the uncertainties associated with the JES and jet energy resolution, the jet p_T is varied by shifting the JES and the spreading up and down by their uncertainties, and the response matrix is reevaluated.

The uncertainty in lepton fake rates is 40%, and is dominated by the statistical uncertainty but also includes systematic uncertainties associated with the underlying physics processes between events in the 3ℓ and 4ℓ control regions. The reducible background is varied up and

Particle type	Selection
	ZZ base selection
Leptons	$p_T(\ell_1) > 20\,\text{GeV}$ $p_T(\ell_2) > 10\,\text{GeV}$ $p_T(\ell) > 5\,\text{GeV}$ $\lvert\eta(\ell)\rvert < 2.5$
Z and ZZ	$40 < m_{Z_1} < 120\,\text{GeV}$, $4 < m_{Z_2} < 120\,\text{GeV}$ $m_{\ell\ell} > 4\,\text{GeV}$ (any oppositely charged same-flavor pair)
Jets	$p_T(j) > 30\,\text{GeV}$ $\lvert\eta(j)\rvert < 4.7$ $\Delta R(\ell, j) > 0.4$ for each ℓ, j
	On-shell ZZ region
Z and ZZ	ZZ base selection + $60 < m_{Z_1,Z_2} < 120\,\text{GeV}$
	Full $m_{4\ell}$ range
Z and ZZ	ZZ base selection + $m_{4\ell} > 80\,\text{GeV}$

Table 1. Particle-level selections used to define the fiducial phase space.

down by the lepton fake rate uncertainty (40%) and the unfolding is repeated to estimate the associated uncertainty from the difference between the normalized distributions.

The pileup uncertainty is evaluated by recomputing the response matrix with the total inelastic cross section [58], which defines the pileup weights applied to MC, varied up and down by 4.6%. The uncertainty associated with the luminosity is evaluated by reevaluating the response matrix with the simulation normalized to the integrated luminosity varied up and down by its total uncertainty, which is 1.2, 2.3 and 2.5% for 2016, 2017 and 2018, respectively. It is small as expected due to the cancellation from the normalization by the fiducial cross section.

The uncertainty arising from generator-specific modeling differences is evaluated from the difference between the measurements unfolded with the response matrix based on the $q\overline{q} \to ZZ$ sample simulated by MadGraph5_aMC@NLO and the POWHEG sample.

The PDF and related strong coupling (α_S) uncertainties are evaluated by reweighting the MadGraph5_aMC@NLO sample to PDF and α_S variations, and then redoing the unfolding and combining the results according to the procedure described in ref. [59]. For the renormalization (μ_R) and factorization (μ_F) scales (QCD scales) uncertainties, the response matrix is reevaluated with the MadGraph5_aMC@NLO $q\overline{q} \to ZZ$ sample reweighted to reflect the distribution with μ_F and μ_R independently varied up and down by a factor of

Systematic source	Uncertainty range
Electron efficiency	0.13–0.30%
Muon efficiency	0.02–0.08%
Jet energy resolution	1.65–3.85%
JES correction	0.93–5.32%
Reducible background	0.05–0.43%
Pileup	0.04–1.08%
Luminosity	$<0.03\%$
$q\overline{q} \to ZZ$ MC choice	0.52–4.52%
$gg \to ZZ$ cross section	0.01–0.19%
QCD scales	0.16–0.82%
PDF	0.05–0.12%
PDF α_S	0.01–0.10%

Table 2. Contributions of each source of systematic uncertainty to the normalized differential cross section measurements of jet variables. Uncertainties depend on the distributions and are listed as a range.

2. All combinations are considered except those in which μ_F and μ_R differ by a factor of four, and the envelope of all variations is used.

The normalization of the MCFM sample ($gg \to ZZ$) is varied by the scale and PDF uncertainties of its cross section ($^{+18\%}_{-14\%}$), and the resulting difference between the normalized distributions is used.

The contributions of each source of systematic uncertainty to the final results are summarized in tables 2–4. The numbers in these tables are only indicative. They are estimated by varying each source and obtaining the difference in the normalized unfolded distributions. Each number in the tables is not showing an estimate of uncertainty per bin, but an estimate of the portion of the uncertainty contribution per distribution, given by

$$\frac{\sum_{i=1}^{N_{\text{bins}}} |h_{\text{central}}(i) - h_{\text{varied}}(i)|}{\sum_{i=1}^{N_{\text{bins}}} h_{\text{central}}(i)} \tag{7.1}$$

where h_{central} and h_{varied} are the central and varied histograms, respectively, both with sum of bin contents normalized to 1, and N_{bins} is the total number of bins. There are, in general, two estimates from up/down variations and the larger one is used.

Systematic source	$m_{4\ell}$ with all jets	0 jet	1 jet	2 jets	3 and more jets
Electron efficiency	0.42%	0.38%	0.66%	0.36%	0.26%
Muon efficiency	0.05%	0.06%	0.07%	0.09%	0.08%
Jet energy resolution	—	0.07%	1.72%	1.65%	0.80%
JES correction	—	0.17%	1.77%	1.95%	0.97%
Reducible background	0.18%	0.18%	0.32%	0.33%	0.96%
Pileup	0.02%	0.05%	0.11%	0.13%	0.35%
Luminosity	0.01%	0.01%	0.02%	0.02%	0.05%
$q\overline{q} \to ZZ$ MC choice	0.35%	0.65%	0.94%	0.48%	0.35%
$gg \to ZZ$ cross section	0.02%	0.03%	0.09%	0.06%	0.09%
QCD scales	0.15%	0.16%	0.58%	0.54%	0.62%
PDF	0.05%	0.05%	0.15%	0.15%	0.21%
PDF α_S	0.02%	0.01%	0.05%	0.03%	0.02%

Table 3. The contributions of each source of systematic uncertainty in the normalized differential cross sections measurements as a function of $m_{4\ell}$ with jet multiplicity from 0 to 3 and more, in events satisfying $60 < m_{Z_1,Z_2} < 120\,\text{GeV}$.

Systematic source	$m_{4\ell}$ with all jets	0 jet	1 jet	2 jets	3 and more jets
Electron efficiency	2.12%	2.55%	2.28%	1.77%	1.46%
Muon efficiency	0.71%	0.78%	0.92%	0.79%	0.42%
Jet energy resolution	—	0.11%	1.73%	2.63%	2.32%
JES correction	—	0.33%	1.64%	3.01%	2.02%
Reducible background	2.22%	2.19%	2.88%	3.40%	5.09%
Pileup	0.21%	0.28%	0.19%	0.32%	0.52%
Luminosity	0.12%	0.12%	0.16%	0.17%	0.25%
$q\overline{q} \to ZZ$ MC choice	0.57%	0.48%	1.22%	3.07%	4.21%
$gg \to ZZ$ cross section	0.10%	0.18%	0.61%	0.80%	0.46%
QCD scales	0.27%	0.25%	0.67%	1.25%	1.86%
PDF	0.07%	0.09%	0.20%	0.23%	0.28%
PDF α_S	0.08%	0.08%	0.15%	0.20%	0.28%

Table 4. The contributions of each source of systematic uncertainty in the normalized differential cross sections measurements as a function of $m_{4\ell}$ with jet multiplicity from 0 to 3 and more, in events from the full $m_{4\ell}$ range.

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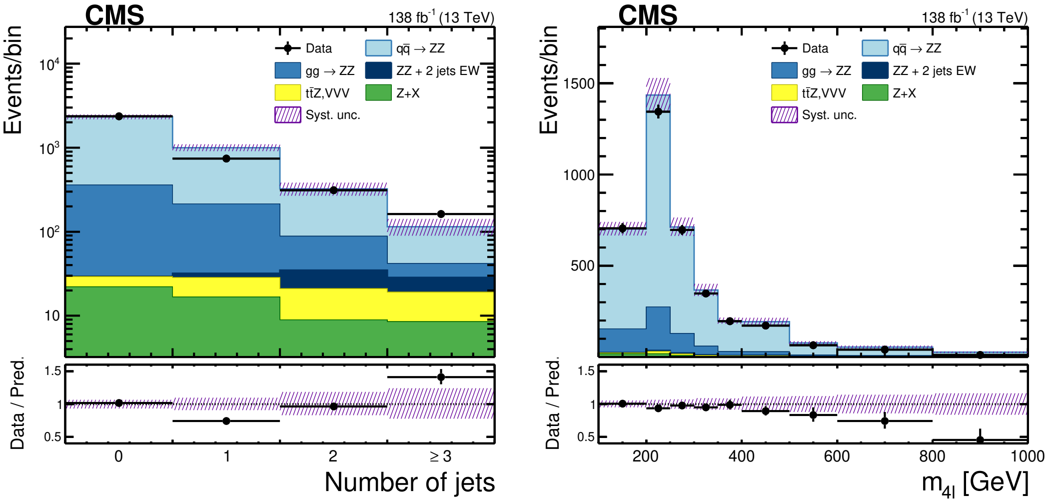

Figure 2. Distribution of the number of jets with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ (left) and of m_{ZZ} (right) for ZZ+jets events with $60 < m_{\mathrm{Z}_1,\mathrm{Z}_2} < 120\,\mathrm{GeV}$ for the combined 4e, 4μ, and 2e2μ decay channels. Points represent the data, vertical bars the statistical uncertainties, and shaded histograms represent the expected standard model predictions and reducible background estimated from data. The purple band of slashes represents the systematic uncertainties in the predictions, which includes systematic uncertainties associated with trigger efficiency, lepton efficiencies, jet energy correction and jet energy resolution, pileup, luminosity, Monte Carlo generator choice, $gg \to ZZ$ cross section, and reducible background. The overflow is included in the last bin of the distributions.

8 Results

8.1 Differential distributions

Differential distributions for various reconstructed quantities are presented in this subsection. We proceed with unfolding the data to compare directly with particle-level theoretical predictions, and the results are presented in the next subsection. Figure 2 (left) shows the number of reconstructed jets with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ for the ZZ+jets events with $60 < m_{\mathrm{Z}_1,\mathrm{Z}_2} < 120\,\mathrm{GeV}$. The last bin includes all events with three or more jets. The description of events with three and more jets requires NNLO and even higher corrections, but there are not enough hard jets from the matrix element in the MC samples used, therefore the difference between data and predictions at high jets multiplicity is expected. The 0 and 2 jet bins are well described by the predictions, whereas in the 1 jet bin the predictions significantly overestimate the measured event yield. The $m_{4\ell}$ distribution is shown in figure 2 (right), inclusive in the number of jets. This distribution is well described by the predictions, except for the increasing discrepancy between data and MC towards high masses; this can be mitigated by adding the EW corrections, as demonstrated in ref. [22] and in the next subsection.

Figure 3 shows the p_{T} and $|\eta|$ distributions for the highest- and second-highest-p_{T} jet in events with at least one and two jets, respectively. As expected from the distribution of the number of jets, the predictions overestimate the measurements in the highest-p_{T} jet distributions. The largest difference is observed for highest-p_{T} jets with $p_{\mathrm{T}} < 100\,\mathrm{GeV}$, whereas the second-highest-p_{T} distributions are better described. Apart from the difference

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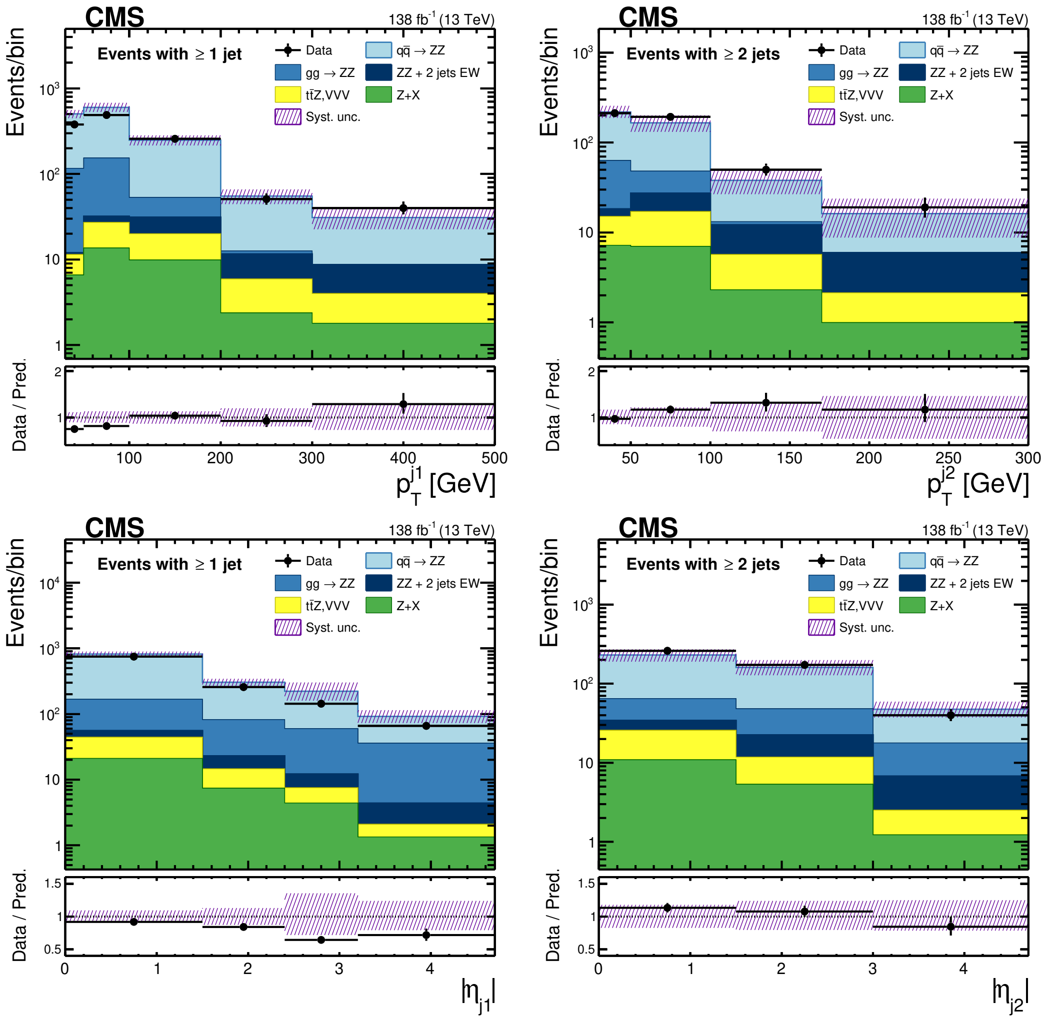

Figure 3. Distribution of the p_T of the highest-p_T jet (upper left) in events with at least one jet, and of the p_T of the second-highest-p_T jet (upper right) in events containing at least two jets. The $|\eta|$ distribution of the highest-p_T (lower left) and second-highest-p_T (lower right) jets. Events are required to have $60 < m_{Z_1,Z_2} < 120\,\text{GeV}$. Other details are as in the caption of figure 2.

in the yield, the p_T distributions of both the highest-p_T and second-highest-p_T jets show similar differential behavior with respect to the predictions (similar trend up to 300 GeV), which is demonstrated in the lower panels of the figures, where data-to-prediction ratios are presented. Similar conclusions are valid also for the $|\eta|$ distributions.

The invariant mass of the dijet system and $\Delta\eta$ between two jets with highest p_T are among the most important dijet distributions. The dijet mass distribution is well described by predictions, as shown in figure 4 (left), whereas in the $|\Delta\eta|$ distribution there is a small trend between data and predictions that can be seen in the lower panel of figure 4 (right). As expected, the contribution of the EW ZZ production is increasing towards the high jet separation and dijet mass, but still remains a small part of the total ZZ cross section.

The effect of the presence of jets in ZZ events is also studied using the $m_{4\ell}$ distribution for different jet multiplicities (figures 5, 6). Each distribution contains only events with exactly

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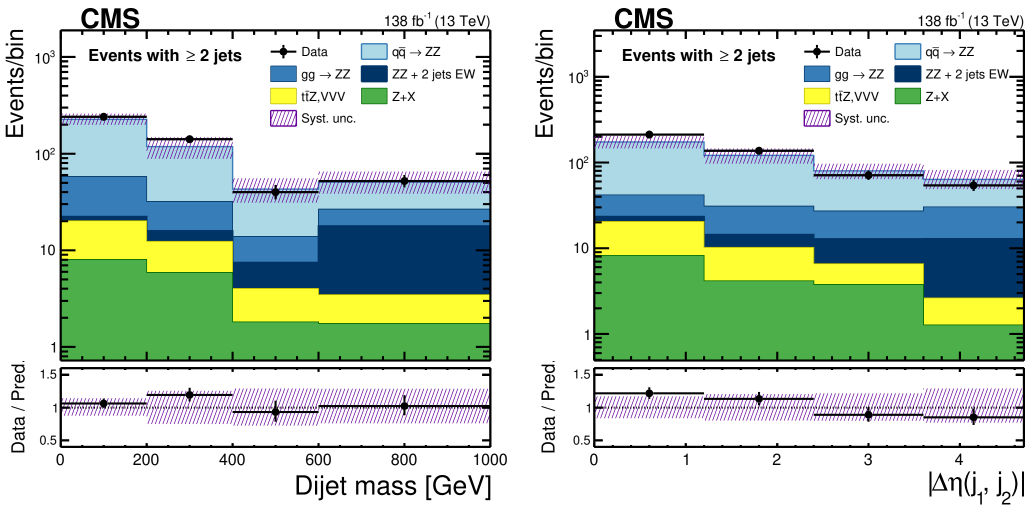

Figure 4. The dijet mass (left) and $|\Delta\eta|$ (right) between the two highest-p_T jets in events with at least two jets. Events are required to have $60 < m_{Z_1,Z_2} < 120\,\text{GeV}$. Other details are as in the caption of figure 2.

0, 1, 2, 3 jets or ≥4 jets. The predictions describe well the normalized differential behavior, but fail to describe the event yield in the 1-jet case. With increasing jet multiplicities the predicted yields decrease much faster than the measured ones. In the case of 4 or more jets, the data yields are significantly larger than predicted. All distributions in figure 5 are presented for events with on-shell Z bosons, $60 < m_{Z_1,Z_2} < 120\,\text{GeV}$.

The same analysis is repeated in the full $m_{4\ell}$ range and the results are presented in figure 6. The data and MC predictions are compared in three mass regions: Z boson region, Higgs boson region, and nonresonant ZZ production region. It is important to note that the Higgs boson sample is simulated using the POWHEG NLO predictions, whereas a similar contribution in the ZZ sample has the $gg \to ZZ$ process simulated at LO and normalized to NLO prediction (see section 3 for detail). As shown in figure 6 (upper left), the predictions describe well the data that are inclusive in jet multiplicity. In figure 6 (middle left), the predictions do not describe the event yield of the ZZ nonresonant part, but agree well with data in the Z and Higgs boson production regions. With increasing jet multiplicity, the agreement between data and predictions for ZZ and Z production regions becomes worse, whereas the predictions for the Higgs boson region are compatible with the data within large statistical uncertainties.

The measured and expected event yields for all decay channels and jet multiplicities in different mass ranges are summarized in tables 5 and 6.

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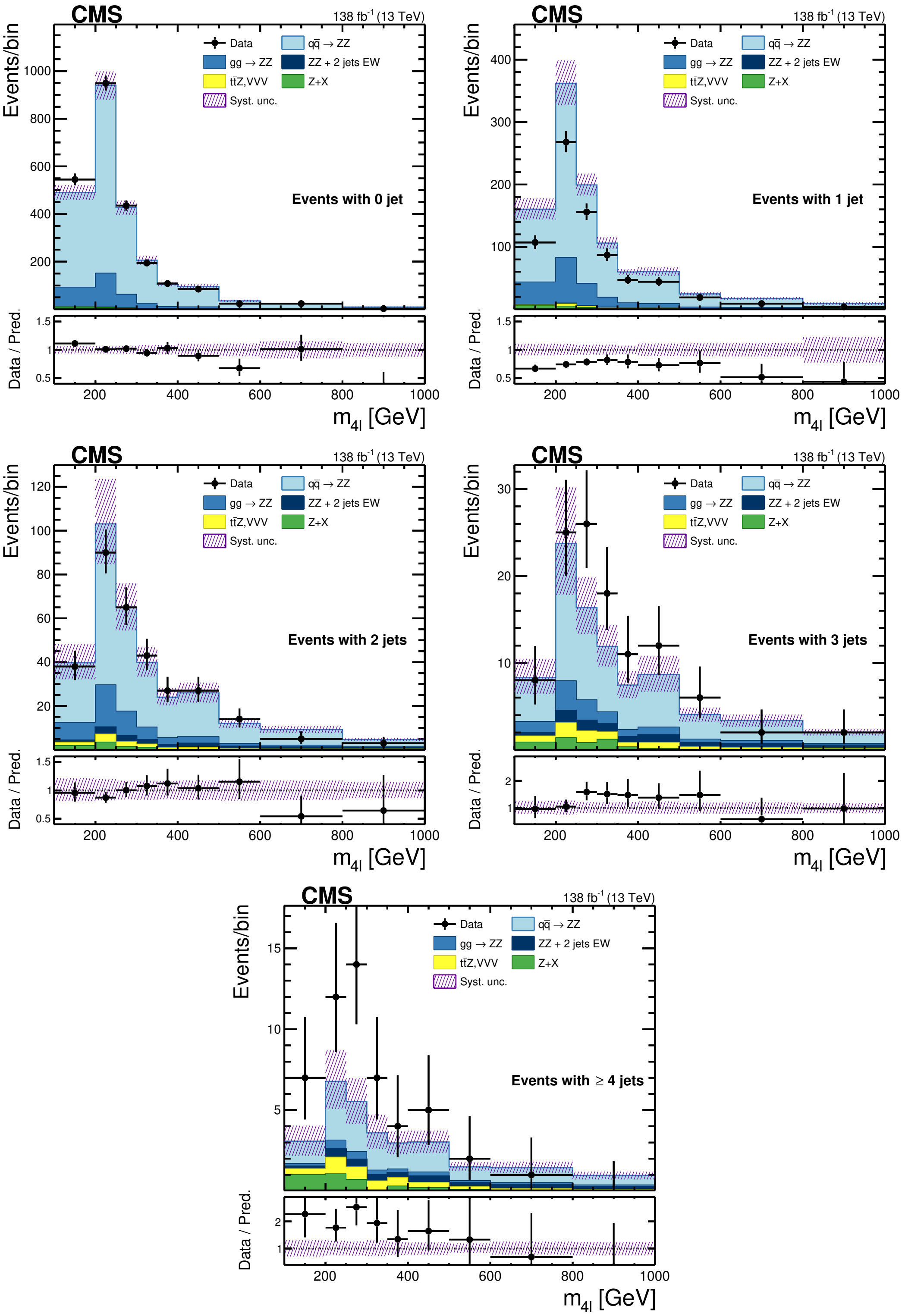

Figure 5. The $m_{4\ell}$ distributions for events with $60 < m_{Z_1,Z_2} < 120$ GeV and different jet multiplicities. Other details are as in the caption of figure 2.

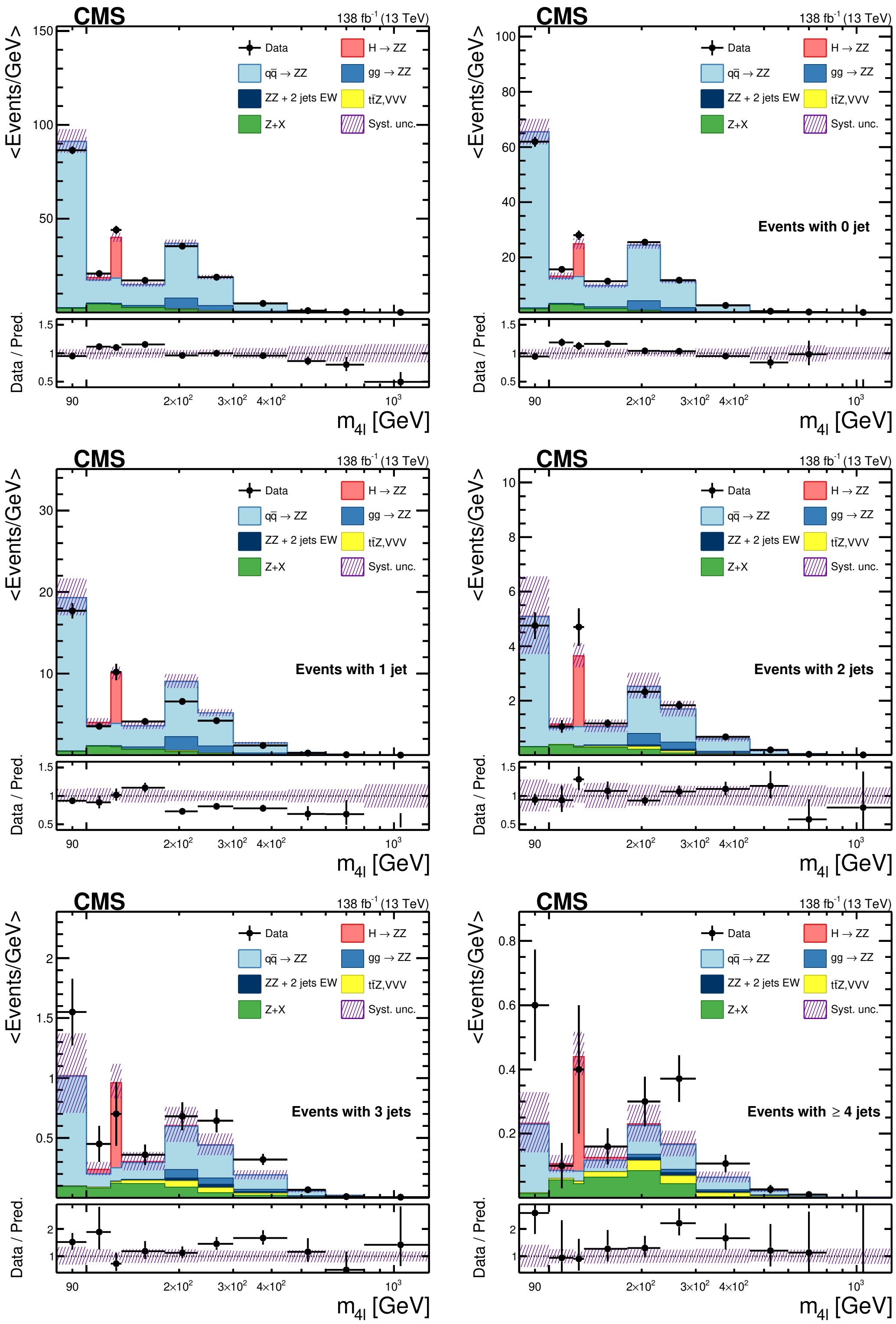

Figure 6. The $m_{4\ell}$ distributions in the full four-lepton invariant mass range for events with different jet multiplicities, normalized by bin width. Other details are as in the caption of figure 2.

Process	eeee	eeμμ	μμμμ	$2\ell 2\ell'$
		$80 < m_{4\ell} < 100\,\text{GeV}$		
Background	$4.6 \pm 0.5 \pm 1.8$	$15.5 \pm 1.6 \pm 6.2$	$22.8 \pm 2.1 \pm 9.1$	$43 \pm 3 \pm 17$
Signal	$216 \pm 1^{+40}_{-36}$	$731 \pm 2^{+66}_{-64}$	$841 \pm 2^{+59}_{-57}$	$1790 \pm 3^{+140}_{-140}$
Total expected	$220 \pm 1^{+40}_{-36}$	$747 \pm 3^{+66}_{-64}$	$864 \pm 3^{+59}_{-58}$	$1830 \pm 4^{+140}_{-140}$
Data	194	698	838	1730
		$60 < m_{Z_1,Z_2} < 120\,\text{GeV}$		
Background	$22.9 \pm 0.9 \pm 5.7$	$46 \pm 2 \pm 10$	$28.9 \pm 1.3 \pm 6.5$	$98 \pm 2 \pm 23$
Signal	$716 \pm 2^{+63}_{-60}$	$1830 \pm 3^{+140}_{-140}$	$1138 \pm 3^{+85}_{-82}$	$3680 \pm 5^{+280}_{-270}$
Total expected	$739 \pm 2^{+63}_{-60}$	$1870 \pm 4^{+140}_{-140}$	$1167 \pm 3^{+85}_{-82}$	$3780 \pm 5^{+280}_{-270}$
Data	671	1805	1106	3582

Table 5. The observed and expected yields of ZZ events in different mass ranges, and estimated yields of background events, shown for each final state and for the sum. The first uncertainty is statistical, and the second one is systematic. (Due to rounding, the sum of individual entries may not match the total value shown.)

Process	0 jet	1 jet	2 jets	3 jets	≥4 jets
			$80 < m_{4\ell} < 100\,\text{GeV}$		
Background	$25 \pm 2 \pm 10$	$9.1 \pm 1.3 \pm 3.6$	$6.1 \pm 1.0 \pm 2.4$	$1.9 \pm 0.6 \pm 0.8$	$0.4 \pm 0.3 \pm 0.1$
Signal	$1300 \pm 3^{+100}_{-100}$	$371 \pm 2^{+48}_{-45}$	$95 \pm 1^{+29}_{-28}$	$18.7 \pm 0.4^{+7.1}_{-6.2}$	$4.5 \pm 0.2^{+1.9}_{-1.8}$
Total expected	$1320 \pm 3^{+100}_{-100}$	$381 \pm 2^{+48}_{-45}$	$101 \pm 1^{+29}_{-28}$	$20.6 \pm 0.7^{+7.1}_{-6.2}$	$4.9 \pm 0.3^{+2.0}_{-1.8}$
Data	1238	354	95	31	12
			$60 < m_{Z_1,Z_2} < 120\,\text{GeV}$		
Background	$29.3 \pm 1.4 \pm 8.9$	$28.6 \pm 1.2 \pm 6.7$	$21.2 \pm 0.9 \pm 3.7$	$11.6 \pm 0.7 \pm 2.0$	$7.6 \pm 0.5 \pm 1.5$
Signal	$2320 \pm 3^{+160}_{-170}$	$960 \pm 3^{+100}_{-90}$	$303 \pm 1^{+60}_{-56}$	$75 \pm 1^{+20}_{-19}$	$21.9 \pm 0.3^{+7.9}_{-7.2}$
Total expected	$2350 \pm 4^{+160}_{-170}$	$990 \pm 3^{+100}_{-100}$	$324 \pm 2^{+60}_{-56}$	$87 \pm 1^{+21}_{-19}$	$29.5 \pm 0.7^{+8.1}_{-7.4}$
Data	2367	741	312	110	52

Table 6. The observed and expected yields of ZZ events in different mass ranges, and estimated yields of background events, shown for each jet multiplicity. The first uncertainty is statistical, and the second one is systematic. (Due to rounding, the sum of individual entries may not match the total value shown.)

8.2 Differential cross sections

The unfolded differential distributions normalized to the ZZ fiducial cross section are presented in figures 7–10. Figure 7 (left) shows the normalized $d\sigma/dm_{4\ell}$ cross section. The MadGraph5_aMC@NLO, POWHEG and nNNLO+PS predictions demonstrate similar behavior and describe well the differential behavior at low $m_{4\ell}$, whereas they overestimate the measured values in the moderate to high $m_{4\ell}$ regions. This discrepancy can be mitigated with EW corrections as discussed in ref. [22]. To estimate the effect of the corrections, a differential K factor from [22] for the NLO EW corrections was applied to the nNNLO+PS predictions as a function of $m_{4\ell}$. The EW-corrected nNNLO+PS predictions describe the measured values better than those without the corrections, although at high values of $m_{4\ell}$ only within large statistical uncertainties of the measurements. The EW corrections are only significant in $m_{4\ell}$ and have negligible effect on any other normalized distribution presented in

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this paper; therefore in all other non-$m_{4\ell}$ distributions only nominal nNNLO+PS predictions are shown. For the $m_{4\ell}$ distributions for various jet multiplicities the EW corrections are not available and therefore these distributions do not contain EW corrections.

Figure 7 (right) shows the differential cross sections as a function of the number of jets in the events. The MadGraph5_aMC@NLO and POWHEG predictions show similar distributions. Similar to the discussion in the previous section, neither of the two MC simulations describes the 1-jet cross section, and both simulations predict too low cross sections for high jet multiplicities. On the other hand, the nNNLO+PS prediction describes the high jet multiplicity bin better than the other two predictions, whereas the agreement in the 1-jet bin is also improved. In general, the nNNLO+PS prediction describes the N_{jets} distribution better than MadGraph5_aMC@NLO and POWHEG.

Figure 8 shows the differential cross sections in bins of p_T and $|\eta|$ for the highest- and the second highest-p_T jet in events with at least one and two jets. The p_T distributions show moderate differences between data and predictions, whereas the $|\eta|$ distributions are well described within uncertainties.

Figure 9 shows the differential cross sections for dijet events as a function of (left) $|\Delta\eta|$ and (right) the dijet mass between two highest-p_T jets. Within uncertainties the dijet mass is described by the predictions, whereas $|\Delta\eta|$ measurements show a small trend with respect to the predictions.

Finally, the $\mathrm{d}\sigma/\mathrm{d}m_{4\ell}$ differential cross section is presented in figure 10 for the full four-lepton invariant mass range and inclusive in jet multiplicity. The measured normalized differential cross section is well described by the predictions. Additional $\mathrm{d}\sigma/\mathrm{d}m_{4\ell}$ differential cross sections with different jet multiplicities for the on-shell Z bosons and for the full four-lepton invariant mass range are presented in figures 11 and 12. The comparison with the theoretical predictions shows the same behavior than for the measurements presented in the previous section.

9 Summary

The four-lepton production in association with jets, $\mathrm{pp} \to (\mathrm{Z}/\gamma^*)(\mathrm{Z}/\gamma^*) + \text{jets} \to 2\ell 2\ell' + \text{jets}$, where $\ell, \ell' = \mathrm{e}$ or μ, was studied in proton-proton collisions at a center-of-mass energy of 13 TeV. The data sample corresponds to an integrated luminosity of $138\,\mathrm{fb}^{-1}$ collected with the CMS detector at the LHC during 2016–2018. Differential distributions and differential cross sections normalized to the ZZ fiducial cross section were measured with respect to various kinematic variables: number of jets, jet transverse momentum (p_T) and pseudorapidity (η), invariant mass of the dijet system and η difference between the highest-p_T and second-highest-p_T jets, and invariant mass of the four leptons ($m_{4\ell}$) for different jet multiplicities. Tabulated results are provided in HEPData [60]. In general, predictions of theoretical models agree with the data, but in some regions significant discrepancies between predicted and measured values were observed. The recent nNNLO+PS prediction improves the data/prediction agreement in the 1-jet and high jet multiplicity regions, and describes the distribution of jet multiplicities better than NLO samples generated with the event generators MadGraph5_aMC@NLO and POWHEG. The inclusion of electroweak corrections improves the description of the $m_{4\ell}$ distribution. These measurements demonstrate the necessity for better Monte Carlo modeling

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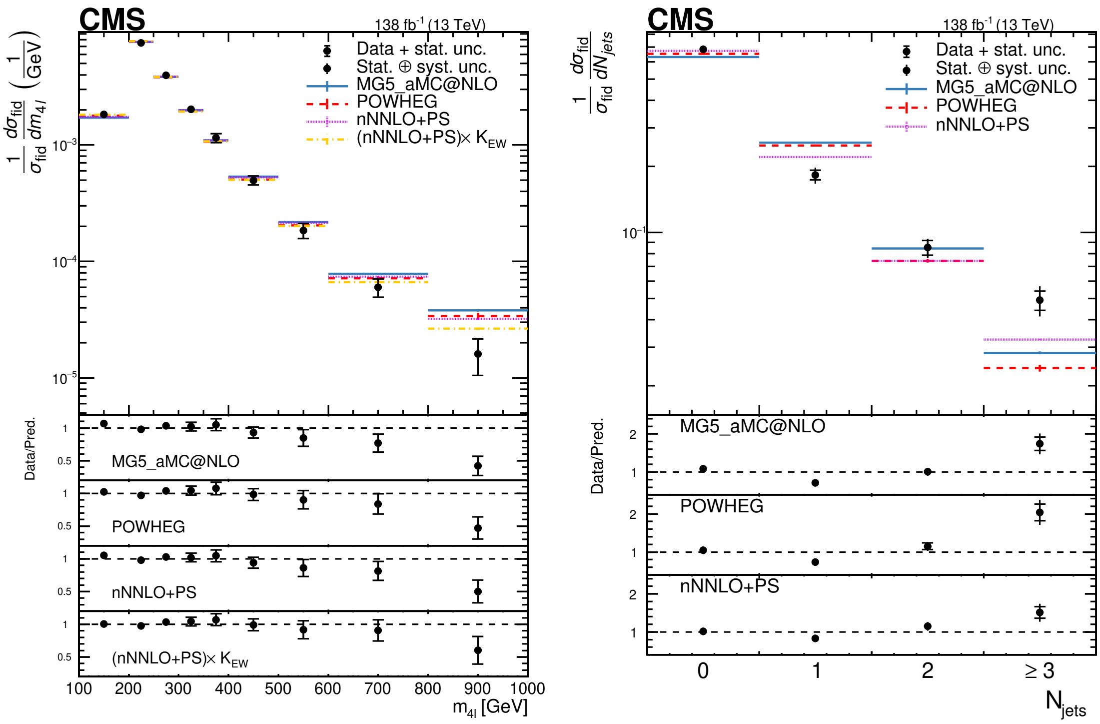

Figure 7. Differential cross sections normalized to the fiducial cross section as a function of (left) $m_{4\ell}$, (right) the number of jets with $p_T > 30$ GeV. The on-shell Z requirement $60 < m_{Z_1,Z_2} < 120$ GeV is applied. Points represent the unfolded data, solid histograms the MadGraph5_aMC@NLO $q\bar{q} \to ZZ$ predictions, and red dashed histograms the POWHEG $q\bar{q} \to ZZ$ predictions. MCFM $gg \to ZZ$, POWHEG $H \to ZZ$, and MadGraph5_aMC@NLO EW ZZ predictions are included in these two sets of predictions. The purple dashed histograms represent the nNNLO+PS predictions, and the yellow dashed histogram represents the nNNLO+PS prediction with EW corrections applied. Vertical bars on both MC predictions represent the statistical uncertainties. The lower panels show the ratio of the measured to the predicted cross sections. The vertical bars on data points with horizontal lines at the ends represent the statistical uncertainties only, whereas the vertical bars without horizontal lines at the ends represent the total uncertainties calculated as the sum in quadrature of the statistical and systematic uncertainties. The overflow is included in the last bin of the distributions.

in events with complex multiboson final states and extra jets. Further improvement of the predictions is required to describe the ZZ+jets production in the whole phase space.

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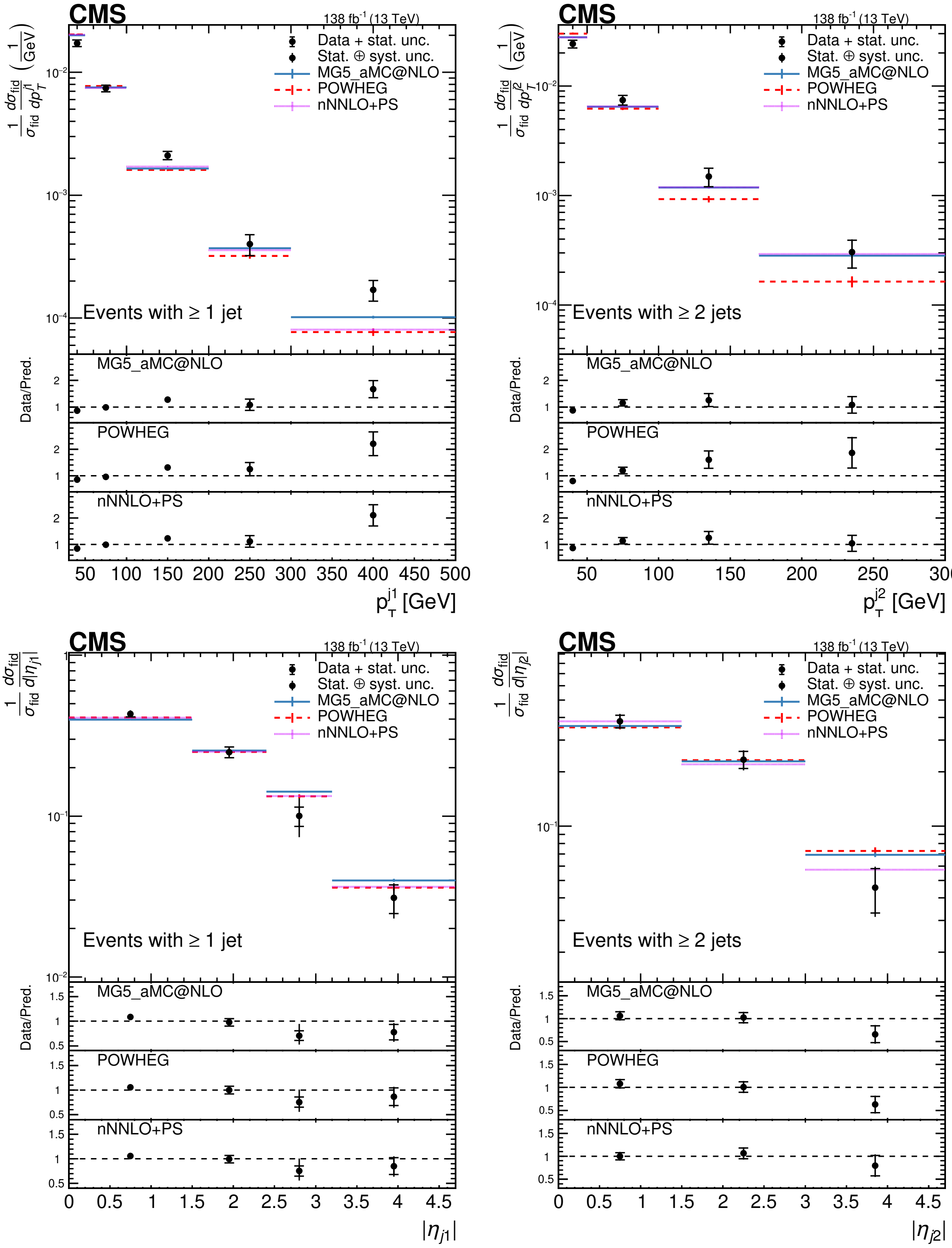

Figure 8. Differential cross sections normalized to the fiducial cross section as a function of p_T and $|\eta|$ of the highest- and the second-highest-p_T jet in events containing at least one or two jets, respectively. The on-shell Z requirement $60 < m_{Z_1,Z_2} < 120\,\text{GeV}$ is applied. Other details are as in the caption of figure 7.

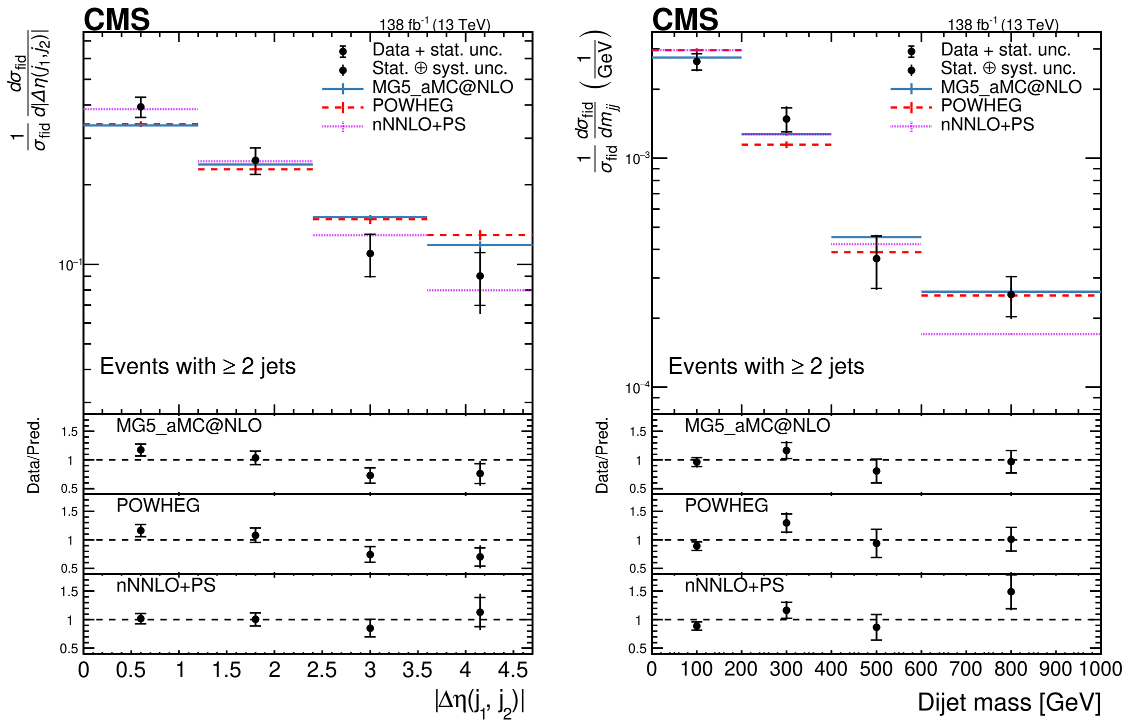

Figure 9. Differential cross sections normalized to the fiducial cross section as a function of (left) $|\Delta\eta|$ and (right) dijet mass between highest-p_T jets in events with at least two jets. Events with $60 < m_{Z_1,Z_2} < 120\,\text{GeV}$ requirement. Other details are as in the caption of figure 7.

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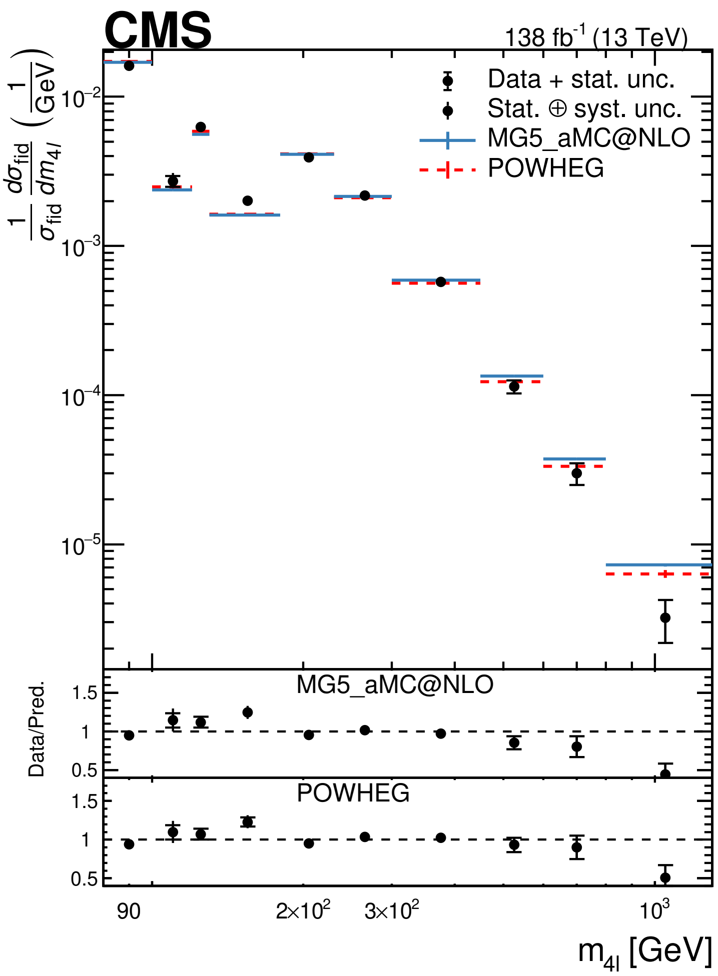

Figure 10. Differential cross sections normalized to the fiducial cross section as a function of $m_{4\ell}$ for the full four-lepton invariant mass range. Other details are as in the caption of figure 7.

Science — EOS" — be.h project n. 30820817; the Beijing Municipal Science & Technology Commission, No. Z191100007219010 and Fundamental Research Funds for the Central Universities (China); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Shota Rustaveli National Science Foundation, grant FR-22-985 (Georgia); the Deutsche Forschungsgemeinschaft (DFG), under Germany's Excellence Strategy — EXC 2121 "Quantum Universe" — 390833306, and under project number 400140256 - GRK2497; the Hellenic Foundation for Research and Innovation (HFRI), Project Number 2288 (Greece); the Hungarian Academy of Sciences, the New National Excellence Program - ÚNKP, the NKFIH research grants K 131991, K 133046, K 138136, K 143460, K 143477, K 146913, K 146914, K 147048, 2020-2.2.1-ED-2021-00181, and TKP2021-NKTA-64 (Hungary); the Council of Science and Industrial Research, India; ICSC — National Research Center for High Performance Computing, Big Data and Quantum Computing, funded by the EU Nex-Generation program (Italy); the Latvian Council of Science; the Ministry of Education and Science, project no. 2022/WK/14, and the National Science Center, contracts Opus 2021/41/B/ST2/01369 and 2021/43/B/ST2/01552 (Poland); the Fundação para a Ciência

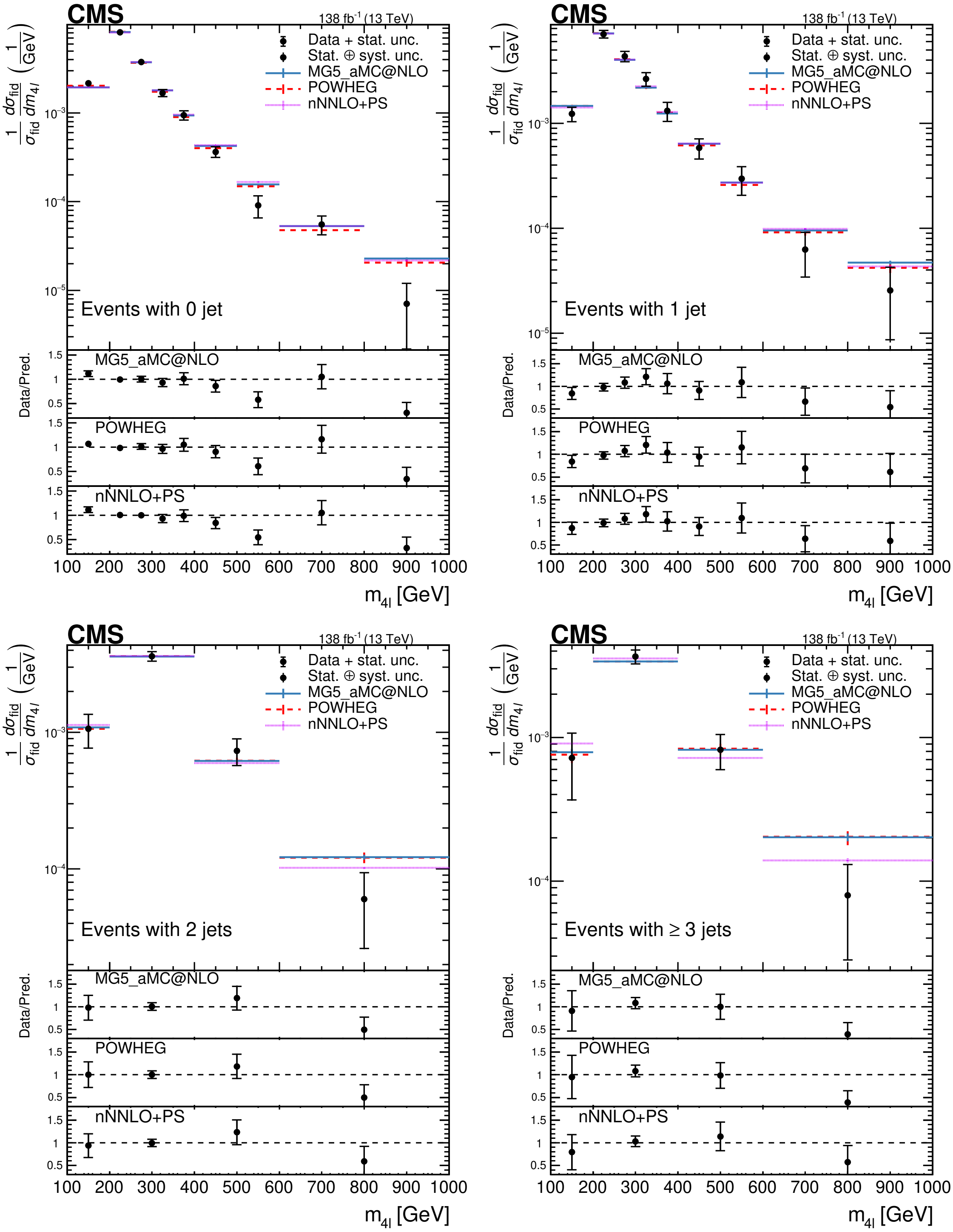

Figure 11. Differential cross sections normalized to the fiducial cross section as a function of $m_{4\ell}$ for $60 < m_{Z_1,Z_2} < 120\,\text{GeV}$ and for different jet multiplicities. Other details are as in the figure 7 caption.

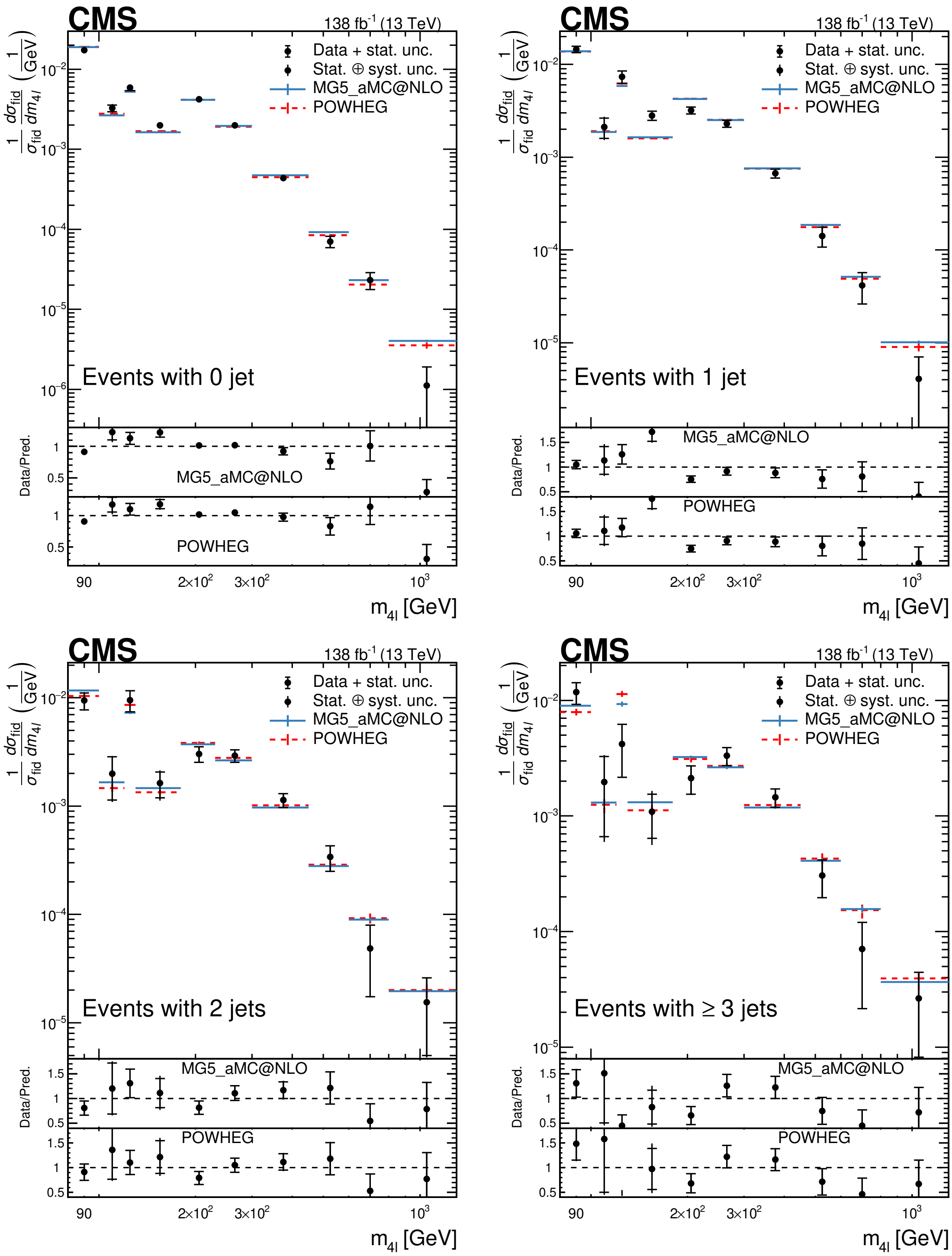

Figure 12. Differential cross sections normalized to the fiducial cross section as a function of $m_{4\ell}$ for the full four-lepton invariant mass range and different jet multiplicities. Other details are as in the figure 7 caption.

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