

# Search for ZZ resonances in the $2\ell 2\nu$ final state in proton-proton collisions at 13 TeV



## The CMS collaboration

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**ABSTRACT:** A search for heavy resonances decaying to a pair of Z bosons is performed using data collected with the CMS detector at the LHC. Events are selected by requiring two oppositely charged leptons (electrons or muons), consistent with the decay of a Z boson, and large missing transverse momentum, which is interpreted as arising from the decay of a second Z boson to two neutrinos. The analysis uses data from proton-proton collisions at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of  $35.9 \text{ fb}^{-1}$ . The hypothesis of a spin-2 bulk graviton (X) decaying to a pair of Z bosons is examined for  $600 \leq m_X \leq 2500 \text{ GeV}$  and upper limits at 95% confidence level are set on the product of the production cross section and branching fraction of  $X \rightarrow ZZ$  ranging from 100 to 4 fb. For bulk graviton models characterized by a curvature scale parameter  $\tilde{k} = 0.5$  in the extra dimension, the region  $m_X < 800 \text{ GeV}$  is excluded, providing the most stringent limit reported to date. Variations of the model considering the possibility of a wide resonance produced exclusively via gluon-gluon fusion or  $q\bar{q}$  annihilation are also examined.

**KEYWORDS:** Beyond Standard Model, Hadron-Hadron scattering (experiments)

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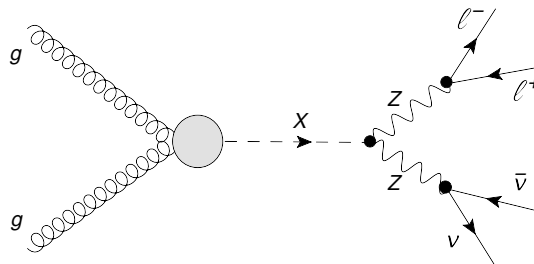
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**1 Introduction**

The standard model (SM) of particle physics has successfully described a wide range of high energy phenomena investigated over the decades. The discovery of a particle compatible with SM predictions for the Higgs boson [1–6] by the ATLAS and CMS experiments [7–9] at the CERN LHC marks an important milestone in the history of particle physics, providing substantive verification of the SM. However, the SM lacks a natural means to accommodate the large hierarchy between gravity and electroweak (EW) scales. Large loop corrections are necessary to stabilize the SM Higgs boson mass at the EW scale. One possible interpretation is that the measured Higgs boson mass is the result of fine-tuned constants of nature within the SM. Alternatively, new physics at the TeV scale can be invoked to stabilize the mass of the Higgs boson far below the Planck scale ( $M_{\text{Pl}} \approx 10^{19}$  GeV). The spontaneous breaking of EW symmetry in the SM has also been associated with new dynamics appearing at the TeV scale. Examples of theoretical extensions include the description of a new strongly interacting sector [10–12] or the introduction of a composite Higgs boson [13–15].

Models extending the number of spatial dimensions can also address the observed difference between the EW and gravitational scales. A solution postulating the existence of multiple and potentially large extra spatial dimensions, accessible only for the propagation of gravity [16, 17], was advanced as a way to eliminate the hierarchy between the EW scale and  $M_{\text{Pl}}$ . The model of Randall and Sundrum [18] introduced an alternative hypothesis,



**Figure 1.** Leading order Feynman diagram for the production of a generic resonance  $X$  via gluon-gluon fusion decaying to the  $ZZ$  final state.

with a single compactified extra dimension and a modification to the space-time metric by an exponential “warp” factor. Standard model particles reside on a  $(3+1)$  dimensional TeV brane, while the graviton propagates through the extra dimensional bulk, thereby generating two effective scales. These models predict the existence of a tower of massive Kaluza-Klein (KK) excitations of a spin-2 boson, the KK graviton, which couples to SM fields at energies on the order of the EW scale. Such states could be produced at a hadron collider. However, limits on flavor-changing neutral currents and EW precision tests place strong constraints on this model. The bulk graviton ( $G_{\text{bulk}}$ ) model extends the Randall-Sundrum model, by addressing the flavor structure of the SM through localization of fermions in the warped extra dimension [19–21], only confining the Higgs field to the TeV brane. The coupling of the graviton to light fermions is highly suppressed in this scenario and the decays into photons are negligible. On the other hand, the production of gravitons from gluon-gluon fusion and their decays into a pair of massive gauge bosons can be sizable at hadron colliders, while precision EW and flavor constraints are relaxed to allow graviton masses in the TeV range. The model has two free parameters: the mass of the first mode of the KK bulk graviton,  $m_G$ , and the ratio  $\tilde{k} = k/\overline{M}_{\text{Pl}}$ , where  $k$  is the unknown curvature scale of the extra dimension, and  $\overline{M}_{\text{Pl}} \equiv M_{\text{Pl}}/\sqrt{8\pi}$  is the reduced Planck mass. For values of  $\tilde{k} < 1$ , the width of the KK bulk graviton relative to its mass is less than  $\approx 6\%$  for  $m_G$  as large as 2 TeV, and therefore a narrow resonance is expected. Previous direct searches at ATLAS and CMS have set limits on the cross section for the production of  $G_{\text{bulk}}$  as a function of  $m_G$  [22–27] using LHC data taken at center-of-mass energies of 7, 8, and 13 TeV.

We present a new search for resonances  $X$  decaying to a pair of  $Z$  bosons, in which one of the  $Z$  bosons decays into two charged leptons and the other into two neutrinos  $2\ell 2\nu$  (where  $\ell$  represents either  $e$  or  $\mu$ ), as illustrated in figure 1. The analysis uses data from proton-proton collisions at a center-of-mass energy of 13 TeV collected in 2016 and corresponding to an integrated luminosity of  $35.9 \text{ fb}^{-1}$ . The results are compared to expectations for the bulk graviton model of refs. [19–21]. We also examine variations of the model considering the possibility of a wide resonance, which is produced exclusively via gluon-gluon fusion or  $q\bar{q}$  annihilation processes.

The characteristic signature of the  $2\ell 2\nu$  final state includes two charged leptons with large transverse momenta ( $p_T$ ) and an overall imbalance in  $p_T$  due to the presence of the undetected neutrinos. The imbalance in transverse momentum ( $\vec{p}_T^{\text{miss}}$ ) is the negative of

the vector sum of the  $p_T$  of all final-state particles; its magnitude is referred to as  $p_T^{\text{miss}}$ . We refer to the observable final states  $ee+p_T^{\text{miss}}$  and  $\mu\mu+p_T^{\text{miss}}$  as the electron and muon channels, respectively.

The search is performed using the transverse mass ( $m_T$ ) spectrum of the two leptons and  $p_T^{\text{miss}}$ , where a kinematic edge is expected from the putative heavy resonance and depends on its invariant mass. The  $m_T$  variable is calculated as:

$$m_T^2 = \left[ \sqrt{(p_T^{\ell\ell})^2 + m_{\ell\ell}^2} + \sqrt{(p_T^{\text{miss}})^2 + m_{\ell\ell}^2} \right]^2 - \left[ \vec{p}_T^{\ell\ell} + \vec{p}_T^{\text{miss}} \right]^2, \quad (1.1)$$

where  $\vec{p}_T^{\ell\ell} \equiv \vec{p}_T^Z$  is the  $p_T$  of the two lepton system associated with the leptonic decay of a Z boson. The decay of the second Z boson to two invisible neutrinos is represented by  $p_T^{\text{miss}}$  and  $m_{\ell\ell}$  in the middle term provides an estimator of the mass of the invisibly decaying Z boson. This choice has negligible impact on the expected signal at large  $m_T$ , but is found to preferentially suppress backgrounds from  $t\bar{t}$  and WW decays.

The most significant background to the  $2\ell 2\nu$  final state is due to Z+jets production, where the Z boson or recoiling hadrons are not precisely reconstructed. This can produce a signal-like final state with  $p_T^{\text{miss}}$  arising primarily from instrumental effects. Other important sources of background include the nonresonant production of  $\ell\ell$  final states and  $p_T^{\text{miss}}$ , primarily composed of  $t\bar{t}$  and WW production, and the resonant background from SM production of diboson (ZZ and WZ) events.

Compared to fully reconstructed final states, the branching fraction for the  $2\ell 2\nu$  decay mode is approximately a factor of six larger than that of the four charged-lepton final state, and has less background than semileptonic channels such as  $2\ell+2\text{quark}$  ( $2\ell 2q$ ). For the  $2\ell 2q$  channel, the hadronic recoil in the Z+jets background is kinematically similar to the  $2q$  system from Z boson decay. For events with large  $p_T^{\text{miss}}$ , as expected for a high-mass signal, high  $p_T$  jets in the corresponding Z+jets background are more accurately reconstructed. This effectively suppresses the background in the  $2\ell 2\nu$  channel and the signal purity is enhanced relative to the  $2\ell 2q$  channel.

## 2 The CMS detector

The central feature of the CMS detector is a 3.8 T superconducting solenoid with a 6 m internal diameter. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the pseudorapidity coverage ( $\eta$ ) provided by the barrel and endcap detectors. Muons are detected in gas-ionization chambers embedded in the steel magnetic flux-return yoke outside the solenoid. Events of interest are selected using a two-tiered trigger system [28]. 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 time interval of less than 4  $\mu\text{s}$ . 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 less than 1 kHz before data storage. 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. [29].

### 3 Event selection and reconstruction

The signal consists of two Z bosons, one decaying into a pair of oppositely charged leptons and the other to two neutrinos, which escape direct detection. The final state is thus characterized by a pair of oppositely charged electrons or muons that are isolated from large deposits of hadronic energy, having an invariant mass consistent with that of a Z boson, and large  $p_T^{\text{miss}}$ . A single-electron or a single-muon trigger has to be satisfied. Thresholds on the  $p_T$  of the leptons are 115 (50) GeV in the electron (muon) channel. Electron events are triggered by clusters of energy depositions in the ECAL that are matched to reconstructed tracks within a range  $|\eta| < 2.5$ . Cluster shape requirements, as well as isolation criteria based on calorimetric and track information, are also applied. An additional sample of photon plus jet(s) ( $\gamma$ +jets) events is collected for background modeling based on control samples in data and is discussed below. The photon trigger is similar to the electron trigger, except that a veto is applied on the presence of a matching track. For muon events the trigger begins with track fitting in the outer muon spectrometer. The outer track is used to seed track reconstruction in the inner tracker and matching inner-outer track pairs are included in a combined fit that is used to select muon candidates in a range  $|\eta| < 2.4$ .

#### 3.1 Event reconstruction

The global event reconstruction (also called particle-flow event reconstruction [30]) consists of reconstructing and identifying each individual particle with an optimized combination of all subdetector information. In this process, the identification of the particle type (photon, electron, muon, charged hadron, neutral hadron) plays an important role in the determination of the particle direction and energy. Photons (e.g. coming from  $\pi^0$  decays or from electron bremsstrahlung) are identified as ECAL energy clusters not linked to the extrapolation of any charged particle trajectory to the ECAL. Electrons (e.g. coming from photon conversions in the tracker material or from b-hadron semileptonic decays) are identified as a primary charged particle track and potentially many ECAL energy clusters corresponding to this track extrapolation to the ECAL and to possible bremsstrahlung photons emitted along the way through the tracker material. Muons (e.g. from b-hadron semileptonic decays) are identified as a track in the central tracker consistent with either a track or several hits in the muon system, associated with an energy deficit in the calorimeters. Charged hadrons are identified as charged particle tracks neither identified as electrons, nor as muons. Finally, neutral hadrons are identified as HCAL energy clusters not linked to any charged hadron trajectory, or as ECAL and HCAL energy excesses with respect to the expected charged hadron energy deposit.

The energy of photons is directly obtained from the ECAL measurement, corrected for zero-suppression effects. The energy of electrons is determined from a combination of the track momentum at the main interaction vertex, the corresponding ECAL cluster energy, and the energy sum of all bremsstrahlung photons attached to the track. The energy of muons is obtained from the corresponding track momentum. The energy of charged hadrons is determined from a combination of the track momentum and the corresponding ECAL and HCAL energy, corrected for zero-suppression effects and 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 energy.

Events are required to have at least one reconstructed interaction vertex. In case of the existence of multiple vertices, the reconstructed vertex with the largest value of summed physics-object  $p_{\text{T}}^2$  is taken to be the primary pp interaction vertex. The physics objects are the jets, clustered using the jet finding algorithm [31, 32] with the tracks assigned to the vertex as inputs, and the associated missing transverse momentum, taken as the negative vector sum of the  $p_{\text{T}}$  of those jets.

To reduce the electron misidentification rate, we require the candidates to satisfy additional identification criteria that are based on the shape of the electromagnetic shower in the ECAL [33]. Electron candidates within the transition region between the ECAL barrel and endcap ( $1.479 < |\eta| < 1.566$ ) are rejected, because instrumental effects degrade the performance of the reconstruction. Candidates that are identified as coming from photon conversions in the detector material are removed. Photon reconstruction uses the same approach as electrons, except that photon candidates must not have an assigned track or be identified as a bremsstrahlung photon from an electron [34].

Muon candidate reconstruction at CMS utilizes several standard algorithms [35], two of which are employed in this analysis. In the first, tracks are reconstructed in the muon system and propagated inward to the tracker. If a matching track is found, a global fit is performed to hits in both the silicon tracker and the muon system. In the second, tracks in the silicon tracker are matched with at least one muon segment in any detector plane of the muon system, but only silicon tracking data are used to reconstruct the trajectory of the muon. To improve efficiency for highly boosted events where the separation between the two muons is small, we require only one muon to satisfy the global fit requirement. This results in an efficiency improvement of 4–18% for identifying Z bosons having  $p_{\text{T}}$  in the range of 200–1000 GeV. The muon misidentification rate is reduced by applying additional identification criteria based on the number of spatial points measured in the tracker and in the muon system, the fit quality of the muon track, and its consistency with the event vertex location.

Leptons produced in the decay of Z bosons are expected to be isolated from hadronic activity in the event. Therefore, an isolation requirement is applied based on the sum of the momenta of either charged hadron PF candidates or additional tracks found in a cone of radius  $\Delta R = 0.3$  around each electron or muon candidate, respectively. The isolation sum is required to be smaller than 10% of the  $p_{\text{T}}$  of the electron or muon. For each electron, the mean energy deposit in the isolation cone coming from other pp collisions in the same bunch crossing, is estimated following the method described in ref. [33], and subtracted from the isolation sum. For muon candidates, only charged tracks associated with the primary vertex are included and any additional muons found in the isolation cone are removed from this sum to prevent rejection of a highly boosted Z boson decay.

Jets produced by initial state radiation may accompany signal events and are also expected to arise from background sources. The jets are reconstructed from all the PF candidates using the anti- $k_{\text{T}}$  algorithm [31, 32] with a radius parameter of  $R = 0.4$ . Charged hadron candidates that are not associated with the primary vertex are excluded. Jet

energy corrections are derived from the simulation, and are confirmed with in situ measurements using the energy balance of dijet, multijet,  $\gamma$ +jets, and leptonically decaying Z+jets events [36].

The  $p_{\text{T}}^{\text{miss}}$  is calculated from all the PF candidates, with momentum scale corrections applied to the candidates.

### 3.2 Sample selection

Events are selected if they include a pair of same-flavor, oppositely charged leptons that pass the identification and isolation criteria. The leading (subleading) leptons are required to have  $p_{\text{T}} > 120$  (35) GeV for the electron channel and  $p_{\text{T}} > 60$  (20) GeV for the muon channel. Electrons (muons) are required to be reconstructed in the range  $|\eta| < 2.5$  (2.4). To suppress backgrounds that do not include a Z boson, the lepton pair is required to have an invariant mass compatible with the Z boson mass [37]  $70 < m_{\ell\ell} < 110$  GeV. If more than one such pair is identified, the pair with invariant mass closest to the Z boson is selected.

The signal region (SR) is defined by additionally requiring that the  $p_{\text{T}}$  of the Z boson candidate satisfies  $p_{\text{T}}^{\text{Z}} > 100$  GeV,  $p_{\text{T}}^{\text{miss}} > 50$  GeV, and the angular difference between  $\vec{p}_{\text{T}}^{\text{Z}}$  and  $\vec{p}_{\text{T}}^{\text{miss}}$  satisfies  $|\Delta\phi(\vec{p}_{\text{T}}^{\text{Z}}, \vec{p}_{\text{T}}^{\text{miss}})| > 0.5$  radians. The SR selection largely suppresses the backgrounds, which are primarily concentrated at low  $p_{\text{T}}^{\text{Z}}$  and low  $p_{\text{T}}^{\text{miss}}$ . In the case of a signal we expect two highly boosted Z bosons, therefore, the  $|\Delta\phi(\vec{p}_{\text{T}}^{\text{Z}}, \vec{p}_{\text{T}}^{\text{miss}})|$  distribution is correspondingly peaked around  $\pi$  in contrast to a relatively flat distribution in the Z+jets background where  $\vec{p}_{\text{T}}^{\text{miss}}$  arises from instrumental effects.

## 4 Signal and background models

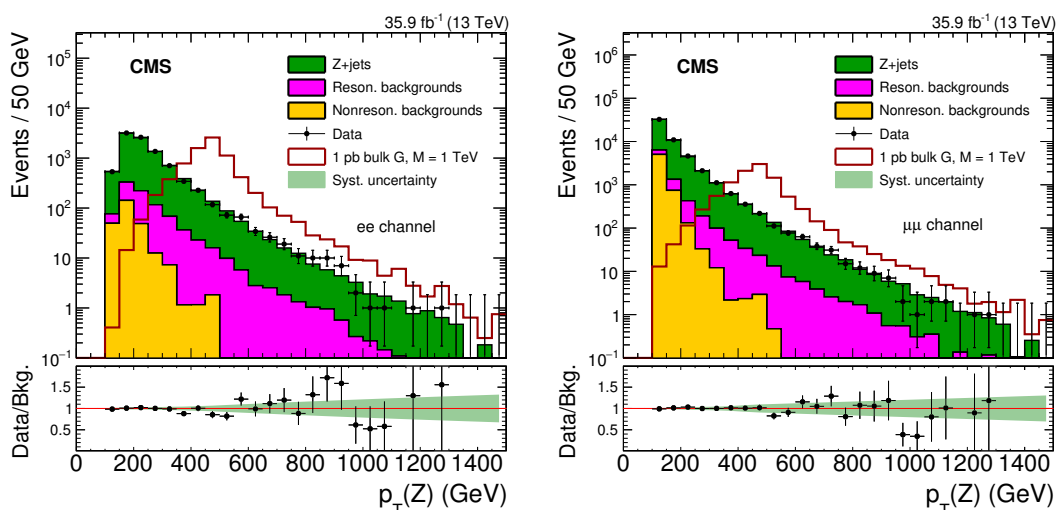
Two versions of the signal model are examined. For our benchmark model, signal events are generated at leading order for the bulk graviton model of refs. [19–21] using the MADGRAPH5\_aMC@NLO 2.3.3 event generator [38]. Because the expected width is small compared to detector resolution for reconstructing the signal, we use a zero width approximation [39] for generating signal events. A more general version of the bulk graviton decaying to ZZ is generated using JHU Generator 7.0.2 [40–42]. We model a bulk graviton as in refs. [43, 44] and introduce variable decay widths up to 30% of  $m_{\text{X}}$ . Production of the wide resonance via gluon fusion and  $q\bar{q}$  annihilation are generated separately. Generated events are interfaced to PYTHIA 8.212 [45] for parton showering and hadronization. The renormalization and factorization scales are set to the resonance mass. Parton distribution functions (PDFs) are modeled using the NNPDF 3.0 [46] parametrization. Signal samples are generated in the mass range 600–2500 GeV for each tested model. We simulate both signal and background using a GEANT4-based model [47–49] of the CMS detector and process the Monte Carlo (MC) events using the same reconstruction algorithms as for data. All MC samples include an overlay of additional minimum bias events (also called “pileup”), generated with an approximate distribution for the number of expected additional pp interactions, and events are reweighted to match the distribution observed in data.



The largest source of background arises from the production of Z+jets events, characterized by a transversely boosted Z boson and recoiling hadrons. The observation of  $p_T^{\text{miss}}$  in these events primarily results from the mismeasurement of jet or lepton  $p_T$ . While this process may be modeled exclusively using simulated events, the description of detector instrumental effects can be improved by constructing a background estimate based on control samples in data. We use a sample of  $\gamma$ +jets data with a reweighting procedure to reproduce the kinematics of the Z boson in Z+jets events, exploiting the intrinsic similarity of the recoiling hadrons balancing the  $p_T$  of the Z boson or the photon. The procedure also employs a sample of Z+jets events generated using the MADGRAPH5\_aMC@NLO framework with next-to-leading order (NLO) matrix elements for final states with up to two additional partons. The merging scheme of Frederix and Frixione is employed for matching to parton showers using a merging scale  $\mu_Q = 30$  GeV [50]. The inclusive cross section is recalculated to include next-to-next-to-leading order (NNLO) QCD and EW corrections from FEWZ 3.1 [51]. We use the Z+jets differential cross section measurement as a function of  $p_T^Z$  in CMS data to reweight each event in the MC sample at the generator level to match the dependence observed in data. The differential cross section measured in  $\gamma$ +jets data is first corrected for backgrounds producing physical  $p_T^{\text{miss}}$ , such as W+jets events. The reconstructed  $\gamma$ +jets events in data are then reweighted as a function of  $p_T^\gamma$  and  $|\eta^\gamma|$  to match the corrected Z+jets spectra in simulation for electron and muon channels separately. This procedure transfers the lepton trigger and identification efficiencies from Z+jets, into the  $\gamma$ +jets data sample. For calculation of the  $m_T$  variable in eq. (1.1), the photon is randomly assigned a mass based on the measured Z boson mass distribution as a function of the Z boson  $p_T$ . Finally to account for small energy scale and resolution differences in the  $p_T^{\text{miss}}$  between  $\gamma$ +jets and Z+jets events, we fit the parallel and perpendicular components of the hadronic recoil relative to the reconstructed boson in both samples using a Gaussian model in bins of boson  $p_T$ . The differences are used to correct the  $\gamma$ +jets data as a function of photon  $p_T$ .

The nonresonant backgrounds can be significant in regions of large  $p_T^{\text{miss}}$  due to the presence of neutrinos in the final state. A method based on control samples in data is used to more precisely model this background. The method uses dilepton samples consisting of  $e\mu$  pairs to describe the expected background in  $\ell\ell$  ( $ee$  or  $\mu\mu$ ) events. This utilizes the fact that  $e\mu$  pairs in the nonresonant background have very similar kinematic behavior and cross sections compared to the  $\ell\ell$  final states. Events with at least one  $e\mu$  pair are selected. If more than one pair is present, the pair having an invariant mass closest to that of the Z boson is selected. The normalization of event yields between  $\ell\ell$  and  $e\mu$  events is estimated using events outside the Z boson mass selection window. Because of effects due to different trigger requirements and identification efficiencies, variances are observed in the lepton  $p_T$  distributions compared to the single-flavor samples. Therefore when modeling the electron (muon) channel, event-based weighting factors are applied to correct the  $p_T$  distribution of the muon (electron) in the  $e\mu$  data for these observed differences. The trigger efficiency is also applied in the background sample to simulate the single-lepton trigger efficiency. The correction corresponding to either the electron or muon channel is applied based on the  $p_T$  and  $|\eta|$  of both leptons.





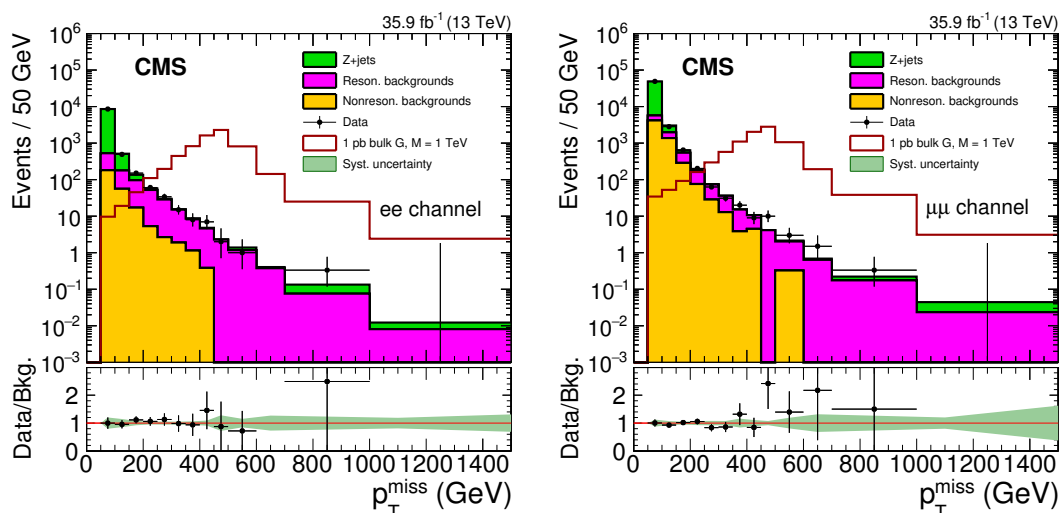
**Figure 2.** The  $p_T^Z$  distributions for electron (left) and muon (right) channels comparing the data and background model based on control samples in data. The lower panels give the ratio of data to the prediction for the background. The shaded band shows the systematic uncertainties in background, while the statistical uncertainty in the data is shown by the error bars. The expected distribution for a zero width bulk graviton resonance with a mass of 1 TeV is also shown for a value of 1 pb for the product of cross section and branching fraction  $\sigma(pp \rightarrow X \rightarrow ZZ) \mathcal{B}(ZZ \rightarrow 2\ell 2\nu)$ .

The irreducible (resonant) background arises mainly from the SM  $q\bar{q} \rightarrow ZZ \rightarrow 2\ell 2\nu$  process and is modeled using MC samples generated by POWHEG 2.0 [52, 53], at NLO in QCD and leading order in EW calculations. We also apply NNLO QCD [54] and NLO EW corrections to the production processes [55, 56]. These are applied as a function of  $m_{ZZ}$  and on average are 1.11 and 0.95 for the NNLO QCD and NLO EW corrections, respectively. Smaller contributions from WZ and  $t\bar{t}Z$  decays are modeled at NLO using MADGRAPH5\_aMC@NLO.

Figure 2 shows the comparison of background models and data for the  $p_T$  distribution of the reconstructed Z boson after all corrections are applied. Figure 3 shows the data and background prediction of the  $p_T^{\text{miss}}$  distribution after all corrections are applied. The  $p_T^{\text{miss}}$  is an essential variable to examine the quality of the background modeling and the understanding of the systematic uncertainties. All the systematic uncertainties are propagated to the  $p_T^{\text{miss}}$  distributions and shown as the uncertainty band on the ratio plots in the lower panels of the figure. Also shown in figures 2 and 3 is the expected signal distribution assuming a bulk graviton with 1 TeV mass and an arbitrary product of the cross section and branching fraction  $\sigma(pp \rightarrow X \rightarrow ZZ) \mathcal{B}(ZZ \rightarrow 2\ell 2\nu)$  of 1 pb.

## 5 Systematic uncertainties

Systematic uncertainties can affect both the normalization and differential distributions of signal and background. Individual sources of systematic uncertainties are evaluated by studying the effects of parameter variations within one standard deviation relative to their nominal values and propagating the result into the  $m_T$  template distributions that are used



**Figure 3.** The  $p_T^{\text{miss}}$  for electron (left) and muon (right) channels comparing the data and background model based on control samples in data. The expected distribution for a zero width bulk graviton resonance with a mass of 1 TeV is also shown for a value of 1 pb for the product of cross section and branching fraction  $\sigma(\text{pp} \rightarrow X \rightarrow \text{ZZ}) \mathcal{B}(\text{ZZ} \rightarrow 2\ell 2\nu)$ . The lower panels show the ratio of data to the prediction for the background. The shaded band shows the systematic uncertainties in background, while the statistical uncertainty in the data is shown by the error bars.

to evaluate signal cross section limits. The various categories of systematic uncertainties affecting these distributions are described below and summarized in table 1 for both electron and muon channels.

Uncertainties from trigger efficiencies, lepton identification and isolation requirements, and tracking efficiency can affect signal and background estimates obtained from both simulation and from control samples in data. The combined effect of these uncertainties on the normalizations of the various samples is found to be 0.4–3.6%.

Uncertainties of 6.8 (3.2)% for the electron (muon) channel are assigned to the reweighting procedure for the Z+jets background. For the nonresonant background, modeling of trigger and lepton identification efficiencies relative to the Z boson data and the size of the sideband samples contribute the major uncertainties in the expected event yields. These are estimated to affect the normalization by 10 (2.4)% for the electron (muon) channel.

The lepton momenta, and photon and jet energies are recalculated by varying their respective corrections within scale uncertainties. These uncertainties affect event selection and the detector response corrected  $p_T^{\text{miss}}$ , contributing a variation of 4.6 (7.4)% to the template normalizations for the MC-generated resonant backgrounds in the electron (muon) channel. Their corresponding effect on acceptance for the signal is negligible. The modeling of jet resolution and the correction applied to unclustered energy are similarly considered for the MC samples and found to contribute an uncertainty of  $\approx 6\%$  each to the resonant background normalization. The effect of variations in corrections to the modeling of recoil in the Z+jets background is found to be 3.4% and 2.0% for the electron and muon channel, respectively.

	Source	Signal (%)	Z+jets (%)	Resonant (%)	Nonresonant (%)
Electron channel	Integrated luminosity	2.5	2.5	2.5	2.5
	PDF: cross section	—	2.3	1.7	—
	Scale: cross section	—	3.5	3.0	—
	EW NLO correction	—	—	3.0	—
	PDF: acceptance	1.0	3.4	1.0	—
	Scale: acceptance	(—)	22.7	2.9	—
	Trigger/identification eff.	2.1	—	0.4	—
	$p_T^Z$ reweighting	—	6.8	—	—
	Nonresonant norm.	—	—	—	10.0
	$p_T$ /energy scale	(—)	—	4.6	—
	Jet energy resolution	(—)	—	6.8	—
	Unclustered energy	(—)	—	5.5	—
	Hadronic recoil	—	3.4	—	—
	Muon channel	PDF: acceptance	1.0	3.4	1.0
Scale: acceptance		(—)	13.1	2.9	—
Trigger/identification eff.		3.6	1.0	1.0	1.0
$p_T^Z$ reweighting		—	3.2	—	—
Nonresonant norm.		—	—	—	2.4
$p_T$ /energy scale		(—)	—	7.4	—
Jet energy resolution		(—)	—	5.6	—
Unclustered energy		(—)	—	6.3	—
Hadronic recoil		—	2.0	—	—

**Table 1.** Summary of the normalization uncertainties that are included in the statistical procedure for the electron and muon channels. All values are listed in percentage units and similar categories are grouped for brevity. Sources that do not apply or are found to be negligibly small are marked “—” or “(—),” respectively. Integrated luminosity and theoretical uncertainties are evaluated separately for effects on normalizations, while all the other uncertainties are considered simultaneously with shape variations in the statistical analysis. Values in the signal column refer to the hypothetical spin-2 bulk graviton signal with a mass of 1 TeV.

Uncertainties arising from the PDF model and renormalization and factorization scales in fixed-order calculations affect signal and simulated backgrounds, modifying predictions for both the production cross-section and the acceptance. We estimate the effect of PDF uncertainties by evaluating the complete set of NNPDF 3.0 PDF eigenvectors, following the PDF4LHC prescription [46, 57]. This contributes a variation of 1.0–3.4% to the MC background models. The production of bulk gravitons is modeled by a fusion process with gluons having large Björken- $x$ , where parton luminosities are generally not well-constrained by existing PDF models. The PDF uncertainties in the signal production cross section depend on  $m_X$  and range from 10–50%, but modify the acceptance by only about 1%.

	Electron channel	Muon channel
Data	9336	52806
Z+jets	8421±203	44253±336
Resonant	637±38	2599±164
Nonresonant	271±28	5961±211
Total background	9329±208	52813±439

**Table 2.** Event yields for different background contributions and those observed in data in the electron and muon channels.

The effect of scale variations is assessed by varying the original factorization and renormalization scales by factors of 0.5 or 2.0. The scale uncertainties are estimated to be about 3–3.5% each in the production cross section and acceptance for the resonant background. For the Z+jets background, the scale choice modifies the normalization by 3.5%. The acceptance varies by 23 (13)% in the electron (muon) channel and the corresponding effect is negligibly small for the signal. An uncertainty of 3.0% is estimated for the (N)NLO correction to the resonant background. The uncertainty assigned to the integrated luminosity measurement is 2.5% [58] and is applied to the signal and simulated backgrounds.

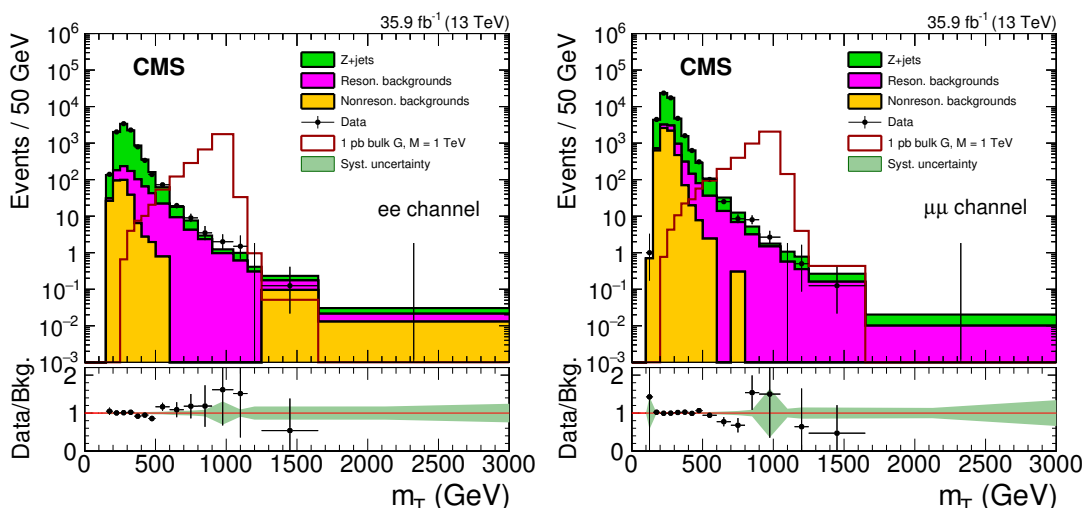
In the treatment of systematic uncertainties, both normalization effects, which only alter the overall yields of individual contributions, as well as shape variations, which also affect their distribution, are taken into account for each source individually.

## 6 Statistical interpretation

The  $m_T$  distribution is used as the sensitive variable to search for a new resonance decaying to ZZ with the subsequent decay  $ZZ \rightarrow 2\ell 2\nu$ . For both the electron and muon channels, a binned shape analysis is employed. The expected numbers of background and signal events scaled by a signal strength modifier are combined to form a binned likelihood calculated using each bin of the  $m_T$  distribution.

The results of a simultaneous fit of the predicted backgrounds to data, combining electron and muon channels, and including the estimated systematic uncertainties are summarized in table 2. Figure 4 shows the post-fit  $m_T$  distributions in the SR using only the background models. The expected distribution for a bulk graviton signal with a mass of 1 TeV and an arbitrary product of cross section and branching fraction  $\sigma(\text{pp} \rightarrow X \rightarrow ZZ) \mathcal{B}(ZZ \rightarrow 2\ell 2\nu)$  of 1 pb is also shown. The observed distributions are in agreement with fitted SM background predictions.

Upper limits on the product of cross section and branching fraction for the resonance production  $\sigma(\text{pp} \rightarrow X \rightarrow ZZ)$  are evaluated using the asymptotic approximation [59] of the modified frequentist approach  $\text{CL}_s$  [60–62]. The same simultaneous combined fit is performed using signal and background distributions after application of the SR selection, to extract the upper limits for a given signal hypothesis. Statistical uncertainties in the background modeling are taken into account by fluctuating the predicted background his-



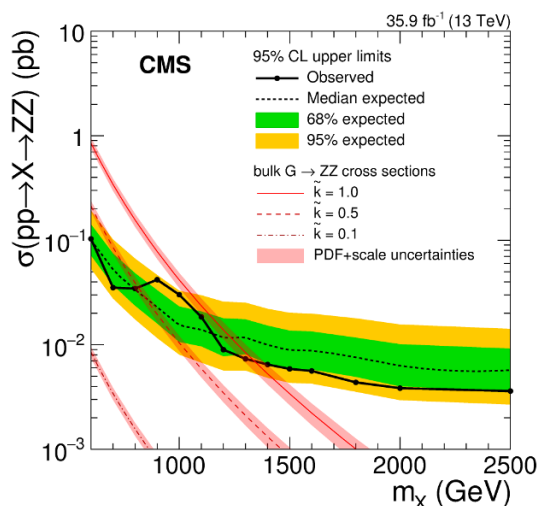
**Figure 4.** The  $m_T$  distributions for electron (left) and muon (right) channels comparing the data and background model based on control samples in data, after fitting the background-only model to the data. The expected distribution for a zero width bulk graviton resonance with a mass of 1 TeV is also shown for a value of 1 pb for the product of branching fraction and cross section  $\sigma(\text{pp} \rightarrow X \rightarrow ZZ) \mathcal{B}(ZZ \rightarrow 2\ell 2\nu)$ . The lower panels show the ratio of data to the prediction for the background. The shaded bands show the systematic uncertainties in the background, while the statistical uncertainty in the data is shown by the error bars.

tograms within an envelope according to uncertainties in each bin. Systematic uncertainties are treated as nuisance parameters, constrained with Gaussian or log-normal probability density functions in the maximum likelihood fit. For the signal, only uncertainties related to luminosity and acceptance contribute in the limit setting procedure. When the likelihoods for electron and muon channels are combined, the correlation of systematic effects is taken into account.

## 7 Results

The expected and observed upper limits on the product of the resonance cross section and the branching fraction for  $X \rightarrow ZZ$  are determined at the 95% confidence level (CL) for the zero width benchmark model as a function of  $m_X$  and shown in figure 5 for the ee and  $\mu\mu$  channels combined. Expectations for  $\sigma(\text{pp} \rightarrow X \rightarrow ZZ)$  are also normalized to the calculations of ref. [39] and shown as a function of the bulk graviton mass for three values of the curvature scale parameter  $\tilde{k} = (1.0, 0.5, 0.1)$ . The hypothesis of  $\tilde{k} = 0.5$  can be excluded for masses below 800 GeV at 95% CL, while the current data are not yet sensitive to the hypothesis of  $\tilde{k} = 0.1$ .

The observed limits are within 2 standard deviations of expectations from the background-only model. The largest upward fluctuations in the data are observed for  $m_X \approx 900$  GeV and weaken the corresponding exclusions in this region. To explore this region in more detail, upper limits are shown separately for the electron and muon channels



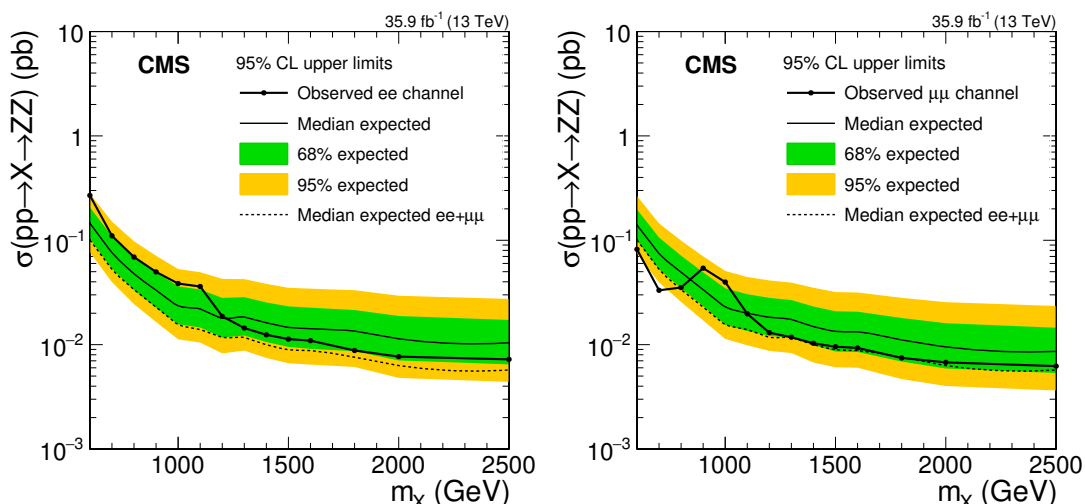
**Figure 5.** Expected and observed limits on the product of cross section and branching fraction of a new spin-2 heavy resonance  $X \rightarrow ZZ$ , assuming zero width, based on the combined analysis of the electron and muon channels. Expectations for the production cross section  $\sigma(pp \rightarrow X \rightarrow ZZ)$  are also shown for the benchmark bulk graviton model for three values of the curvature scale parameter  $\tilde{k}$ .

in figure 6. The upward fluctuations at  $m_X \approx 900$  GeV appear mainly in the muon channel, and additional fluctuations below this  $m_X$  can also be observed.

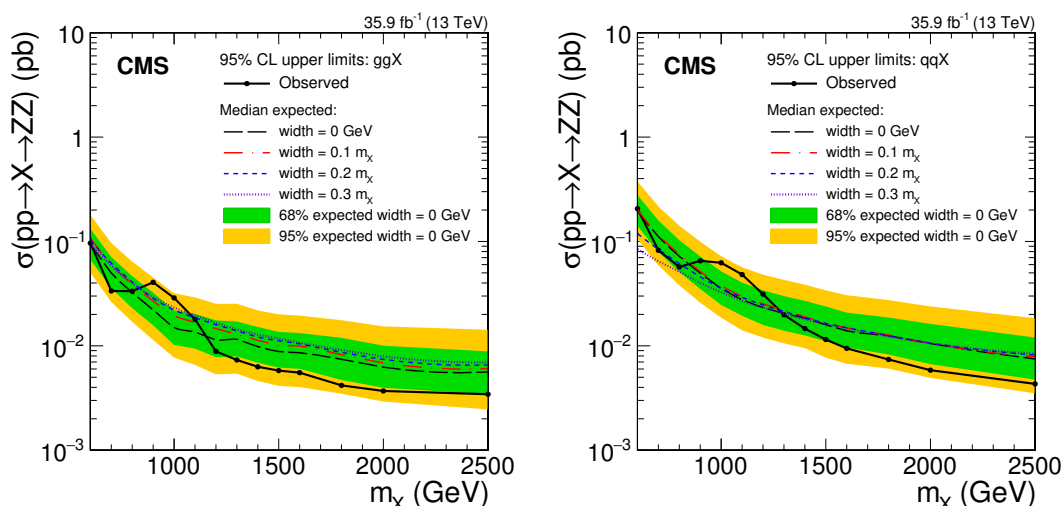
The analysis is repeated comparing to the more general wide width version of the bulk graviton model described above. The initial state is fixed purely to either a gluon–gluon fusion or  $q\bar{q}$  annihilation process and the width of the resonance varied between 0 and  $0.3m_X$ . The 95% CL limits for these models are shown in figure 7. Differences in the limits between the gluon fusion and  $q\bar{q}$  production processes arise from spin and parity effects, which broaden the  $m_T$  peak in  $q\bar{q}$  production [41].

## 8 Summary

A search for the production of new resonances has been performed in events with a leptonically decaying  $Z$  boson and missing transverse momentum, using data corresponding to an integrated luminosity of  $35.9 \text{ fb}^{-1}$  of proton-proton collisions at a center-of-mass energy of 13 TeV. The data are consistent with expectations from standard model processes. The hypothesis of a spin-2 bulk graviton,  $X$ , decaying to a pair of  $Z$  bosons is examined for  $600 \leq m_X \leq 2500$  GeV, and upper limits are set at 95% confidence level on the product of the cross section and branching fraction  $\sigma(pp \rightarrow X \rightarrow ZZ)$  ranging from 100 to 4 fb. For bulk graviton models characterized by a curvature scale parameter  $\tilde{k} = 0.5$  in the extra dimension, the region  $m_X < 800$  GeV is excluded, providing the most stringent limit reported to date. The analysis is repeated considering variations of the bulk graviton model to include a large mass-dependent width. Exclusion limits are provided separately for gluon-gluon fusion and  $q\bar{q}$  annihilation production processes.



**Figure 6.** Expected and observed limits on the product of cross section and branching fraction of a new spin-2 bulk heavy resonance  $X \rightarrow ZZ$ , assuming zero width, shown separately for searches  $X \rightarrow ZZ \rightarrow \ell\nu\nu$  in the electron (left) and muon (right) final states. The median expected 95% CL limits from the combined analysis (figure 5) are also shown.



**Figure 7.** Expected and observed limits on the product of cross section and branching fraction of a new spin-2 heavy resonance  $X \rightarrow ZZ$  based on a combined analysis of the electron and muon channels. The more generic version of the bulk graviton model is considered, assuming either gluon-gluon fusion (left) or  $q\bar{q}$  annihilation (right) processes. Expected limits are also shown for models having various decay widths relative to the mass of the resonance.

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