EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

FERMILAB-PUB-15-114-CMS

CERN-PH-EP/2015-029
2015/03/19

CMS-SMP-12-016

Measurements of the ZZ production cross sections in the $2\ell 2\nu$ channel in proton-proton collisions at $\sqrt{s} = 7$ and 8 TeV and combined constraints on triple gauge couplings

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Abstract

Measurements of the ZZ production cross sections in proton-proton collisions at center-of-mass energies of 7 and 8 TeV are presented. Candidate events for the leptonic decay mode $\mathrm{ZZ} \rightarrow 2\ell 2\nu$, where ℓ denotes an electron or a muon, are reconstructed and selected from data corresponding to an integrated luminosity of 5.1 (19.6) fb^{-1} at 7 (8) TeV collected with the CMS experiment. The measured cross sections, $\sigma(\mathrm{pp} \rightarrow \mathrm{ZZ}) = 5.2^{+1.5}_{-1.4}\,(\mathrm{stat})\,^{+1.4}_{-1.1}\,(\mathrm{syst}) \pm 0.2\,(\mathrm{lumi})\,\mathrm{pb}$ at 7 TeV, and $6.9^{+0.8}_{-0.8}\,(\mathrm{stat})\,^{+1.8}_{-1.4}\,(\mathrm{syst}) \pm 0.3\,(\mathrm{lumi})\,\mathrm{pb}$ at 8 TeV, are in good agreement with the standard model predictions with next-to-leading-order accuracy. The selected data are analyzed to search for anomalous triple gauge couplings involving the ZZ final state. In the absence of any deviation from the standard model predictions, limits are set on the relevant parameters. These limits are then combined with the previously published CMS results for ZZ in 4ℓ final states, yielding the most stringent constraints on the anomalous couplings.

Submitted to the European Physical Journal C

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[*] See Appendix 10 for the list of collaboration members

1 Introduction

The production of pairs of Z bosons in proton-proton collisions is one of the rarest diboson processes in the Standard Model (SM). The measurement of the cross section and properties of this process probe the self-interaction of electroweak gauge bosons. The ZZ final state is also an important background for other interesting processes, such as the production of high-mass Higgs bosons and their subsequent decay to pairs of bosons [1], and in searches for processes beyond the SM, such as supersymmetry [2]. Because of the non-Abelian structure of the electroweak gauge theory, vector bosons can interact among themselves and can couple in triplets (e.g. WWZ) or quartets (e.g. WWZZ). All couplings involving only bosons without electric charge are expected to be null at tree level, leading to the absence of triple gauge couplings for $Z\gamma\gamma$, $ZZ\gamma$, and ZZZ. An enhancement in the measured rate of ZZ production compared to the expectation from the SM would indicate the existence of anomalous boson couplings.

This paper presents measurements of the ZZ production cross sections in proton-proton collisions at the LHC at two different center-of-mass energies, 7 and 8 TeV, in the decay channel with two charged leptons, electrons (e^+e^-) or muons ($\mu^+\mu^-$), and a neutrino-antineutrino pair of any flavor ($\nu\bar{\nu}$). The data were collected with the CMS detector at 7 (8) TeV, corresponding to 5.1 (19.6) fb^{-1} of integrated luminosity.

At tree level, ZZ pairs are primarily produced in the SM via the t- and u-channels, following the annihilation of a quark-antiquark pair in proton-proton collisions. Because of the high gluon-gluon parton luminosity, the gluon-induced box diagram contributes about 8% to the total ZZ production rate. The production cross section calculated up to next-to-leading order (NLO) accuracy in strong coupling constant (α_S) is expected to be $6.46^{+0.30}_{-0.21}$ ($7.92^{+0.37}_{-0.24}$) pb at 7 (8) TeV [3], where the uncertainties stem from the missing higher orders in the computation. Recently, NLO electroweak (EW) corrections to massive vector boson pair production have been computed [4, 5]. The consequences of these corrections for ZZ production are that the transverse momentum (p_T) spectrum of the Z bosons falls more rapidly and, in addition, the overall cross section decreases by about 4% at LHC center-of-mass energies.

The production of ZZ pairs has been studied at the LHC by the ATLAS experiment, which analyzed the decay modes $2\ell2\ell'$ and $2\ell2\nu$ ($\ell, \ell' = e, \mu$) at 7 TeV [6], and by the CMS experiment, which considered $2\ell2\ell'$ final states ($\ell = e, \mu$ and $\ell' = e, \mu, \tau$) at 7 TeV [7] and 8 TeV [8]. Both experiments measured ZZ production cross sections in good agreement with the SM predictions and set limits on anomalous triple gauge couplings (ATGCs).

The branching fraction for the $2\ell2\nu$ decay mode (where ℓ denotes only e and μ) is approximately six times larger than that of the four-charged-lepton final state. The characteristic signature is an overall imbalance in the transverse momentum of the event between the initial and the final states, which consequently appears as missing transverse energy (E_T^{miss}) in the final state. Although the branching fraction is large, this channel is rather challenging due to the large contamination from background processes, in particular the Drell–Yan (DY) process, which has a cross section nearly five orders of magnitude larger than the signal. If the Z boson or the hadrons recoiling against it are not reconstructed correctly, then an apparent E_T^{miss} results and these events can resemble the signal. Other important sources of background are diboson processes, WW and WZ, with fully leptonic decays, and $t\bar{t}$ production.

This paper presents a measurement of the ZZ production cross section in the $2\ell2\nu$ channel as a function of the transverse momentum (p_T) of the charged lepton pair. The distribution of the dilepton p_T is sensitive to the presence of ATGCs. Limits are computed and finally combined with existing results obtained in the four-charged-lepton final state.

2 CMS detector

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 superconducting 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. The silicon tracking system is used to measure the momentum of charged particles and covers the pseudorapidity range $|\eta| < 2.5$, where $\eta = -\ln(\tan(\theta/2))$, and θ is the polar angle of the trajectory of the particle with respect to the counterclockwise-beam direction. The ECAL and HCAL extend to a pseudorapidity range of $|\eta| < 3.0$. A steel/quartz-fiber Cherenkov forward detector extends the calorimetric coverage to $|\eta| < 5.0$. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid.

The $E_{\mathrm{T}}^{\text{miss}}$ is defined as the magnitude of the missing transverse momentum or momentum imbalance, $\vec{p}_{\mathrm{T}}^{\text{miss}}$, which is the negative vector sum of the momenta in the plane transverse to the beam of all reconstructed particles (photons, electrons, muons, charged and neutral hadrons) in the event.

A more 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. [9].

3 Simulation

Several Monte Carlo (MC) event generators are used to simulate the signal and background processes. The $\mathrm{ZZ} \to 2\ell 2\nu$ signal and the $\mathrm{WW} \to 2\ell 2\nu$ and $\mathrm{WZ} \to 3\ell\nu$ background processes are simulated using MADGRAPH 5 [10], as well as Z +jets, W+jets, and $\mathrm{t\bar{t}}$ +jets processes. Single top-quark processes are simulated with POWHEG [11]. In the simulation, vector bosons are allowed to decay to leptons of any flavor (e, μ, τ), since τ leptons can contribute to dielectron and dimuon final states through $\tau \to \mathrm{e}$ and $\tau \to \mu$ decays. For all these processes, the parton showering is simulated with PYTHIA 6 [12] with the Z2 (Z2*) tune for 7 (8) TeV simulations [13].

The cross section of the ZZ signal is computed with the NLO generator MCFM [3], which includes contributions from gluon-gluon initial states. Since the present cross section measurement and ATGC analysis rely on the p_{T} distribution of Z bosons, a precise prediction of this distribution is required. The charged dilepton p_{T} spectrum of $\mathrm{ZZ} \to 2\ell 2\nu$ generated with MADGRAPH is found to be in good agreement with the corresponding spectrum computed at NLO in QCD with MCFM, therefore no differential correction for NLO QCD effects is applied to the MADGRAPH simulated sample. In addition, the effect of NLO EW corrections [4, 5] is taken into account by reweighting the ZZ and the WZ events as a function of the partonic kinematic variables, and applying weights derived from the calculations described in Ref. [4]. These corrections yield an overall reduction of 4.1% of the ZZ cross section, as well as a softening of the boson p_{T} spectra that results in a reduction of the differential cross section of about 25% at Z p_{T} of 400 GeV.

Simulated samples of the $\mathrm{ZZ} \to 2\ell 2\nu$ process that include contributions from ATGCs (see Section 8) are produced using the leading-order (LO) generator SHERPA [14]. These samples are based on a LO matrix-element simulation including up to two additional jets, matched to parton showers.

The parton distribution functions (PDF) are modeled through the CTEQ6L [15] parametrization at LO, and the CT10 parametrization [16] at NLO. The detector response to the simulated events is modeled with GEANT4 [9, 17].

4 Event selection

The signal consists of two Z bosons, one decaying into a pair of oppositely charged leptons and the other to two neutrinos (ν) that escape direct detection. The final state is thus characterised by: a pair of oppositely charged, isolated electrons or muons, with an invariant mass within a Z-boson mass window, no additional leptons, and large $E_{\mathrm{T}}^{\mathrm{miss}}$.

Events are selected using triggers that require the presence of two electrons or two muons, with minimum p_{T} thresholds on each lepton that depend on the dataset. The highest trigger thresholds in the 8 TeV dataset are 17 GeV and 8 GeV for the leptons with higher and lower p_{T}, respectively. The 8 TeV data sample also includes events that satisfy a single isolated muon trigger, to ensure the highest efficiency. In addition, single-photon triggers or electron-muon triggers are used to select control samples for the background determinations.

Electrons are selected inside the fiducial region of ECAL. The electron candidates must have a minimum p_{T} of 20 GeV, and satisfy standard identification criteria, based on shower shape, track quality, cluster track matching, in order to reject misidentified hadrons [18].

The muons are selected inside the fiducial region of the muon spectrometer, with a minimum p_{T} of 20 GeV, and satisfy standard identification criteria based on track information and isolation [19].

Events are selected if they include a pair of same-flavor, oppositely charged leptons that pass the identification and isolation criteria. In order 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, between 83.5 and 98.5 GeV. The p_{T} of the dilepton pair is required to be greater than 45 GeV. This requirement is particularly effective at reducing the DY background because the Z bosons produced in ZZ events have, on average, larger p_{T} than those from single Z-boson production.

Since the ZZ pair is produced in the collision of two hadrons, additional jets may occur in the event. We use jets reconstructed from particle-flow (PF) candidates, using the anti-k_{T} algorithm [20] with a distance parameter of 0.5. The jet transverse energy is corrected using the CMS standard prescriptions for jet energy scale (JES) calibration [21]. Only jets with a corrected p_{T} greater than 10 GeV and reconstructed within $|\eta| < 5$ are used in this analysis. Further corrections are applied to reduce the effect of secondary proton-proton collisions overlapping with the primary interaction (pileup). An extra correction is applied to jets in the MC samples to match the resolution observed in data. In order to reject jets dominated by instrumental and beam-related noise, loose identification criteria are applied, based on the multiplicity and energy fraction of charged and neutral particles.

In order to suppress background coming from top quarks, events are vetoed if they have a jet identified as a b-tagged jet. A requirement based on a combined secondary vertex discriminator [22] is applied to b-tagged jets with $p_{\mathrm{T}} > 20$ GeV within the tracker fiducial region ($|\eta| < 2.4$). The misidentification probability for light-parton jets is about 10%, whereas the efficiency for b-jets is more than 80%. To further reduce top-quark and other backgrounds with hadronic activity, events are rejected if they contain any jet with $p_{\mathrm{T}} > 30$ GeV.

A good $E_{\mathrm{T}}^{\mathrm{miss}}$ measurement is critical for the extraction of the $\mathrm{ZZ} \to 2\ell 2\nu$ signal given that the $E_{\mathrm{T}}^{\mathrm{miss}}$ distinguishes this process from the DY background. Since the average $E_{\mathrm{T}}^{\mathrm{miss}}$ of the signal is moderate ($\sim$50 GeV), we cannot simply require a high-$E_{\mathrm{T}}^{\mathrm{miss}}$. We follow the approach of constructing a “reduced $E_{\mathrm{T}}^{\mathrm{miss}}$” variable, as done in the D0 [23, 24] and OPAL [25] experiments. The concept behind a reduced $E_{\mathrm{T}}^{\mathrm{miss}}$ is to reduce the instrumental contribution to mismeasured

$E_{\mathrm{T}}^{\mathrm{miss}}$ by considering possible contributions to fake $E_{\mathrm{T}}^{\mathrm{miss}}$. In each event, $p_{\mathrm{T}}^{\mathrm{miss}}$ and jet momenta are decomposed along an orthogonal set of axes in the transverse plane of the detector. One of the axes is defined by the p_{T} of the charged dilepton system, the other perpendicular to it. We define the recoil of the $\ell^{+}\ell^{-}$ system in two different ways: (i) the clustered recoil ($\vec{R}_{\mathrm{c}}$) is the vectorial sum of the momenta of the PF jets reconstructed in the event, and (ii) the unclustered recoil ($\vec{R}_{\mathrm{u}}$) is the vectorial sum of the transverse momenta of all PF candidates in the event, with the exception of the two leptons. On each axis ($i =$ parallel/orthogonal to the dilepton system p_{T}), the reduced $E_{\mathrm{T}}^{\mathrm{miss}}$ projection is defined as

$$\text{reduced } E_{\mathrm{T}}^{\mathrm{miss}\,i} = -p_{\mathrm{T}}^{\ell\ell,i} - R_{\mathrm{c/u}}^{i},$$

where $R_{\mathrm{c/u}}$ represents the choice of R_{c} or R_{u} that minimizes the absolute value of that reduced $E_{\mathrm{T}}^{\mathrm{miss}}$ component, and $p_{\mathrm{T}}^{\ell\ell}$ is the transverse momentum of the Z boson. The presence of genuine $E_{\mathrm{T}}^{\mathrm{miss}}$ in the recoil of the charged dilepton system is expected to be evident in the parallel projection, while the component perpendicular to the $\ell^{+}\ell^{-}$ system is mostly dominated by jet and $E_{\mathrm{T}}^{\mathrm{miss}}$ resolution. The absolute reduced $E_{\mathrm{T}}^{\mathrm{miss}}$ variable is the sum in quadrature of the two components. The reduced $E_{\mathrm{T}}^{\mathrm{miss}}$ shows better DY background suppression than the standard PF $E_{\mathrm{T}}^{\mathrm{miss}}$ at the same signal efficiency. It is also found to be more stable than the PF $E_{\mathrm{T}}^{\mathrm{miss}}$ under variations in pileup conditions and JES.

The $E_{\mathrm{T}}^{\mathrm{miss}}$ balance variable is defined as the ratio between the PF $E_{\mathrm{T}}^{\mathrm{miss}}$ and the transverse momentum of the leptonically decaying Z boson, namely $E_{\mathrm{T}}^{\mathrm{miss}}/p_{\mathrm{T}}^{\ell\ell}$. Values of this variable far from unity identify events in which the leptonic Z-boson candidate is not well balanced by genuine $E_{\mathrm{T}}^{\mathrm{miss}}$ from neutrinos, but recoils against mismeasured jets or leptons. The selected sample can still be contaminated by events with jets with p_{T} below the veto threshold.

A mismeasurement of the jet energy can produce mismeasured $p_{\mathrm{T}}^{\mathrm{miss}}$ aligned with the jet direction in the transverse plane. These events are characterized by a small azimuthal angle between the $p_{\mathrm{T}}^{\mathrm{miss}}$ vector and the closest jet, $\Delta\phi(p_{\mathrm{T}}^{\mathrm{miss}}, \text{jet})$. This distribution is used to reject Z+jets events that have a small $\Delta\phi$ angle. The mismeasurement of a lepton p_{T} can also produce mismeasured $E_{\mathrm{T}}^{\mathrm{miss}}$. Although this effect is usually negligible, given the good lepton momentum resolution in CMS, events are found where a large $E_{\mathrm{T}}^{\mathrm{miss}}$ value (>60 GeV) is accompanied by a small angle between the $p_{\mathrm{T}}^{\mathrm{miss}}$ and the p_{T} of a lepton. Events with $E_{\mathrm{T}}^{\mathrm{miss}} > 60\,\mathrm{GeV}$ and $\Delta\phi(p_{\mathrm{T}}^{\mathrm{miss}}, \text{lepton}) < 0.2\,\mathrm{rad}$ are therefore rejected.

In order to suppress the WZ background, with both bosons decaying leptonically, events are required to have no additional leptons. To improve the rejection power, the p_{T} threshold is lowered to 3 GeV for additional muons, and 10 GeV for electrons. Furthermore, these muons and electrons are selected with looser criteria than those used to reconstruct the Z-boson candidate.

The variables described above are used to extract the signal sample for the cross section measurement. We optimize the requirements in the final selection in order to minimize the total uncertainty in the measured cross section at 8 TeV (see Section 7). The same selection is applied to the 7 TeV data. For this purpose, we scan a series of possible analysis selections, in which we vary the dilepton mass window and p_{T} threshold, the minimum p_{T} of jets used in the computation of the reduced $E_{\mathrm{T}}^{\mathrm{miss}}$ variable, and the reduced $E_{\mathrm{T}}^{\mathrm{miss}}$ requirement. We optimize the selection using MC estimates of the background processes, or using predictions based on control samples in data from the DY, top-quark, and WW backgrounds, as described in Section 5, and we find similar results for the optimal requirements and for the measured cross section. For the final optimization we choose the selection obtained using background estimates from data. The requirements are summarized in Table 1. With this selection, the acceptance for the ZZ signal is about 10% both for the ee and $\mu\mu$ channels, at 7 and 8 TeV.

Table 1: Summary of the optimal signal selection.

Variable	Value
Dilepton invariant mass	$\lvert m(\ell\ell) - 91\rvert < 7.5\,\text{GeV}$
Dilepton p_{T}	$p_{\mathrm{T}}^{\ell\ell} > 45\,\text{GeV}$
b-tagged jets	based on vertex info (for jet with $p_{\mathrm{T}} > 20\,\text{GeV}$)
Jet veto	no jets with $p_{\mathrm{T}} > 30\,\text{GeV}$
Reduced $E_{\mathrm{T}}^{\text{miss}}$	$>65\,\text{GeV}$
$E_{\mathrm{T}}^{\text{miss}}$ balance	$0.4 < E_{\mathrm{T}}^{\text{miss}}/p_{\mathrm{T}}^{\ell\ell} < 1.8$
$\Delta\phi(p_{\mathrm{T}}^{\text{miss}}$, jet)	>0.5 rad
$\Delta\phi(p_{\mathrm{T}}^{\text{miss}}$, lepton)	>0.2 rad
Lepton veto	no additional leptons (e/μ) with $p_{\mathrm{T}} > 10/3\,\text{GeV}$

5 Background estimation

Although the DY process does not include genuine $E_{\mathrm{T}}^{\text{miss}}$ from neutrinos, the tail of the reduced $E_{\mathrm{T}}^{\text{miss}}$ distribution can be contaminated by these events due to detector energy resolution, jet energy mismeasurements, pileup energy fluctuations, and instrumental noise. Given that the simulation may not fully reproduce detector and pileup effects on the reduced $E_{\mathrm{T}}^{\text{miss}}$ distribution, especially in the tails, and that the simulation is limited in statistical precision, we build a model of DY background from control samples in data. For this purpose we use a process that has similar jet multiplicity, underlying event, and pileup conditions as the DY process for the region of interest at high boson p_{T}: the production of prompt isolated photons in association with jets (γ + jets) [26]. We expect that an accurate description of the $E_{\mathrm{T}}^{\text{miss}}$ distribution and other related kinematic variables can be obtained from this photon + jets sample. However, some corrections must be applied to the photon + jets sample to ensure a good modeling of the DY process. The yield of photon events is scaled to the observed charged dilepton system yield as a function of the boson p_{T} after applying the jet veto to both samples. This accounts for the differences in the selection efficiency of the dilepton and photon candidates and corrects for the trigger prescales, which are applied to the low-p_{T} photon triggers.

Only photons in the barrel region are used because the purity and resolution are better than in other regions. Following Ref. [1], the selection of photon events is based on shower shape, isolation in the tracker, and energy deposits in ECAL, and HCAL. After this selection, several processes with instrumental $E_{\mathrm{T}}^{\text{miss}}$ contribute to the photon sample: single γ events, double γ events where one photon escapes detection or fails the identification, and QCD events with a jet misidentified as a photon. Processes with genuine $E_{\mathrm{T}}^{\text{miss}}$ can also contaminate this sample: W/Z+γ with the W/Z boson decaying to $\ell\nu/\nu\nu$, or W+jets with the W boson decaying to eν and the electron misreconstructed as a photon. Although these processes have generally lower cross sections, they are characterized by large $E_{\mathrm{T}}^{\text{miss}}$ values, and thus contribute to the tails of the distribution, where it is most important to measure the residual instrumental background. In order to reduce these background contributions, specific selections are applied. The event must have exactly one photon and no leptons. Only jets with $\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} > 0.4$ from the photon are used for all the jet-related selections (jet veto, reduced $E_{\mathrm{T}}^{\text{miss}}$, etc.). To avoid misreconstruction of the photon energy, a conversion veto is applied using the number of missing expected tracker hits and the distance of closest approach between the reconstructed conversion tracks.

The remaining contribution from W+jets and W/Z + γ events after this selection is estimated from simulation and subtracted from the photon data model. For this purpose, a set of simulated photon samples is used, including γ + jets, QCD with fake photons, electroweak processes with misidentified photons, and EW processes with genuine $E_{\mathrm{T}}^{\text{miss}}$. The full set of MC samples is reweighted and corrected following the same procedure as that used for the photon data sample. Finally, the photon data are corrected as a function of $E_{\mathrm{T}}^{\text{miss}}$ by multiplying them by unity minus the fraction of electroweak processes in the simulation.

We apply a different data-based method to estimate the total number of background events from processes that do not involve a Z boson: i.e. WW and top-quark production. We denote these events as nonresonant background (NRB). In order to measure this contribution, a control sample based on eμ candidate events is selected by applying the same requirements as in the main analysis. The NRB yields in the same-flavor channels (ee and $\mu\mu$) are obtained by scaling the number of events in the control sample. The rescaling is done by means of correction factors, measured from the sidebands (SB) of the Z-boson mass peak, i.e. in the regions 55–70 and 110–200 GeV. The scale factors are measured in a looser selection region in order to improve the statistical precision. We require the reduced $E_{\mathrm{T}}^{\text{miss}} > 65\,\text{GeV}$ in order to suppress the DY contribution from $\tau^+\tau^-$. We also require at least one b-tagged jet with $p_{\mathrm{T}} > 20\,\text{GeV}$, to further reduce DY and other backgrounds, and increase the fraction of top-quark events. The scale factors are defined as follows:

$$\alpha_{\mathrm{ee}/\mu\mu} = N^{\mathrm{SB}}_{\mathrm{ee}/\mu\mu} / N^{\mathrm{SB}}_{\mathrm{e}\mu}, \tag{1}$$

and the NRB contamination in the Z-peak region is:

$$N^{\text{peak}}_{\mathrm{ee}/\mu\mu} = \alpha_{\mathrm{ee}/\mu\mu}\, N^{\text{peak}}_{\mathrm{e}\mu}. \tag{2}$$

The validity of the method is tested in simulation by comparing the predicted background to the expected number of WW and top-quark events.

Figure 1 shows the reduced $E_{\mathrm{T}}^{\text{miss}}$ distributions in dilepton data and simulation, using the photon model to describe the DY background and the data-driven estimation for NRB. A good agreement is found in the region dominated by the DY process, up to about 80 GeV, while the higher part of the spectrum is dominated by diboson production. The error bands shown in Fig. 1 represent the statistical uncertainty in the predicted yields. A systematic uncertainty in the final DY event yield estimated with this method is computed as the relative difference between dilepton yields in data and simulation, in a control region with $E_{\mathrm{T}}^{\text{miss}} < 60\,\text{GeV}$, and it has been found to be 25% (40%) at 7 (8) TeV. This systematic uncertainty is not shown in Figure 1.

6 Systematic uncertainties

Different sources of systematic uncertainty are associated with the expected yields and distributions of signal and background processes and of the data. The uncertainties reported in the following paragraphs affect the final event yields of the relevant processes.

Statistical uncertainty of the simulated and control samples. For the processes estimated from simulation, ZZ and WZ, the limited size of the MC sample affects the precision of the modeling, and is therefore taken as a systematic uncertainty in the shape of the kinematic distributions used in the cross section measurement and ATGC limit setting. Similarly, the backgrounds estimated from data are limited by the size of the control samples described

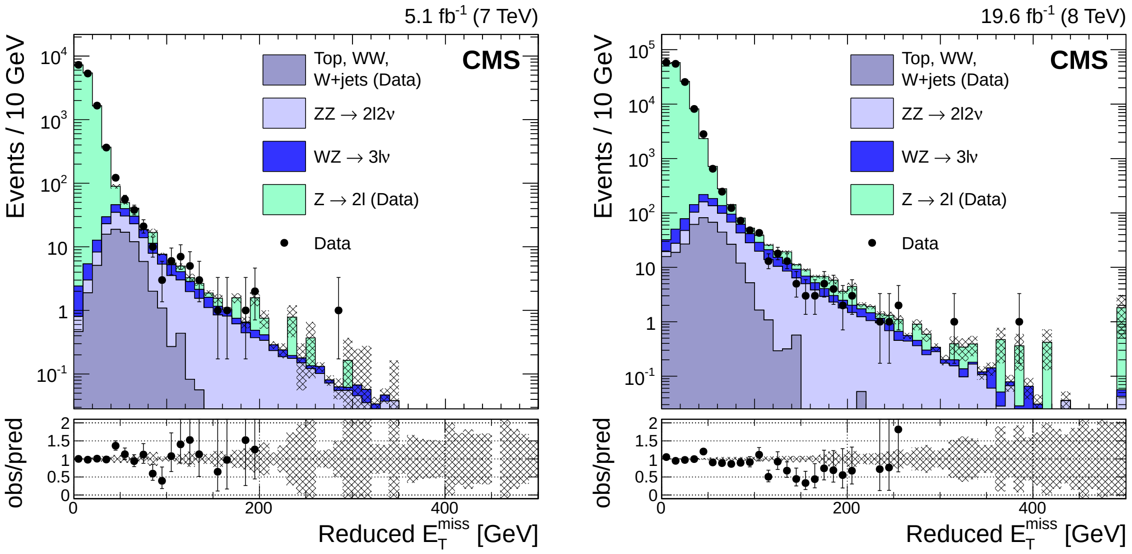

Figure 1: Reduced $E_{\mathrm{T}}^{\mathrm{miss}}$ spectrum in the inclusive $\ell\ell$ ($\ell = \mathrm{e}, \mu$) channel at 7 TeV (left) and 8 TeV (right), using the photon model to describe the DY contribution and NRB modeling for WW, W + jets, and top production at the preselection level. The gray error band represents the statistical uncertainty in the predicted yields.

in Section 5: the eμ sample for nonresonant backgrounds and the γ+jets sample for DY background. These uncertainties are treated in the same way as those backgrounds that are estimated from simulation. This systematic uncertainty has been computed in different reduced $E_{\mathrm{T}}^{\mathrm{miss}}$ bins or different p_{T} bins and is used as shape errors in the fit.

Cross sections of ZZ and WZ. The cross sections for $\mathrm{pp} \rightarrow \mathrm{ZZ} + \mathrm{X} \rightarrow 2\ell 2\nu + \mathrm{X}$ and $\mathrm{pp} \rightarrow \mathrm{WZ} + \mathrm{X} \rightarrow 3\ell\nu + \mathrm{X}$ processes are calculated using MCFM version 6.2 [3], and using PDFs from the Les Houches accord PDF (LHAPDF) program, version 5.8.7 [27]. The PDF+α_S uncertainty in the WZ cross section is evaluated as the maximum spread of the cross sections computed at $\mu_R = \mu_F = m_Z$ with three PDF sets, including the corresponding uncertainties from one standard deviation variation of the PDF parameters and the α_S value [28]. It is found to be 3.1% (4.2%) at 7 (8) TeV.

The uncertainty from the renormalization and factorization scales is evaluated as the maximum difference between the central value of the cross section at $\mu_R = \mu_F = m_Z$ and the central values computed at $\mu_R = \mu_F = m_Z/2$ and $2\,m_Z$, using each of the three PDFs recommended in Ref. [28]. An uncertainty of 5.9% (5.4%) at 7 (8) TeV is found for the WZ background. For the ZZ signal, we evaluate this theoretical uncertainty in the case of the exclusive production with 0 jets, to take into account the jet-veto applied in the signal selection, following the prescription described in Refs. [29, 30]. The exclusive cross section for ZZ+0 jets is $\sigma_{0j} = \sigma_{\geq 0j} - \sigma_{\geq 1j}$, where $\sigma_{\geq nj}$ is the inclusive cross section of ZZ + at least n jets, where $n = 0, 1$. According to Ref. [29], $\sigma_{\geq 0j}$ and $\sigma_{\geq 1j}$ are essentially uncorrelated, thus the uncertainty in σ_{0j} can be computed as $\epsilon_{0j} = \sqrt{\epsilon^2_{\geq 0j} + \epsilon^2_{\geq 1j}}$, where $\epsilon_{\geq 0j}$ and $\epsilon_{\geq 1j}$ are the uncertainties in $\sigma_{\geq 0j}$ and $\sigma_{\geq 1j}$, respectively. The cross sections are computed with MCFM, including the acceptance requirements on lepton p_{T} and η, charged dilepton mass, and $E_{\mathrm{T}}^{\mathrm{miss}}$, as well as the jet veto, when relevant. The cross section uncertainties are estimated by varying the renormalization and factorization scales, as explained above. Since the charged dilepton p_{T} spectrum is the observable from which limits on ATGCs are derived, the uncertainty in σ_{0j} is computed in different intervals of charged dilepton p_{T}.

The uncertainty in the NLO EW correction to ZZ production, corresponding to missing higher-order terms in the computation, is estimated as the product of the NLO QCD and EW corrections [4]. The uncertainty in the EW correction to WZ production is estimated as 100% of the correction, to account for the poorly known fraction of photon+quark-induced events [5] passing the jet veto.

Acceptance. The kinematic acceptance for the signal is computed using MCFM. Kinematic requirements, based on those used in the signal selection, are applied to the charged leptons and neutrinos at the generator level. The acceptance is determined by comparing the cross sections with and without the kinematic requirements. The systematic uncertainty is evaluated as the variation in the acceptance resulting from varying the renormalization and factorization scales from m_Z to $m_Z/2$ and $2\,m_Z$, summed in quadrature with the variation obtained from using different PDF sets and from varying the PDF parameters and the α_S value by one standard deviation. The result is 2.8% at both 7 TeV and 8 TeV.

Luminosity. The uncertainty in the luminosity measurement is 2.2% in 2011, and 2.6% in 2012 [31].

Lepton Trigger and Identification efficiency. Lepton trigger and identification efficiencies are determined from data, using the tag-and-probe technique with $Z \rightarrow \ell\ell$ events [32], and used to correct the simulated samples. The total uncertainty in the lepton efficiency amounts to about 3% for ee events, and 4% for $\mu\mu$ events.

Lepton Momentum Scale. The systematic uncertainty in the lepton momentum scale is computed by shifting the nominal momenta by $\pm 1\sigma$ and propagating the variations to the reduced E_T^{miss}. We assume an uncertainty of 2% (3.5%) in the energy of electrons reconstructed in the ECAL barrel (endcap), and 1% in the muon momentum. The resulting variations of the final yields are 2.5% for the ee channel, and 1.0% for the $\mu\mu$ channel and they are treated as a shape uncertainty.

Jet Energy Scale and Resolution. The uncertainty in the calibration of the jet energy scale directly affects the jet veto, the calculation of reduced E_T^{miss}, and the selection of the balance variable. The JES uncertainty is estimated by shifting the jet energies by $\pm 1\sigma$ and propagating the variations to the reduced E_T^{miss} and all the other relevant observables. Uncertainties in the final yields of 3–4 (7–8)% are found for both the ee and $\mu\mu$ final states at 7 (8) TeV.

Similarly, a systematic uncertainty in jet energy resolution (JER) is computed. As explained above, the energy of jets in simulation is corrected to reproduce the resolution observed in data. Such corrections are varied according to their uncertainties and these variations are propagated to all the observables and selections dependent on jet energy. An uncertainty in the final yields of less than 1% is found in both ee and $\mu\mu$ final states: 0.4% (0.8%) at 7 (8) TeV.

Since the shapes of the distributions are expected to be affected by variations in the JES and the JER, these sources are treated as shape uncertainties in the extraction of the cross section.

b-Jet Veto. The b-tagging efficiency is taken from Ref. [33]. In simulation, the nominal working point for this b-tagger is shifted to reproduce the efficiency observed in data. The uncertainty in the measured efficiency is propagated to the event yields of the processes estimated from simulation by applying further shifts to the discriminator threshold. A very small uncertainty in the final yields of the MC samples is found: 0.1–0.15% at both 7 and 8 TeV.

Pileup. Simulated samples are reweighted to reproduce the pileup conditions observed in data. To compute the uncertainty related to this procedure, we shift the number of interactions by 8% when reweighting the simulated samples. The variation of the final yields induced by this procedure is less than 1% in ZZ and WZ processes. However, the shapes of the kinematic distributions can vary in this procedure, so the varied distributions are used as shape uncertainties in the cross section fit.

Drell–Yan. The uncertainty in the DY contribution is propagated from the uncertainty in the reweighted photon spectrum that is used in the estimate of DY background from data, and is dominated by the subtraction of backgrounds due to EW processes. As explained in Section 5, the DY background estimate is assigned an uncertainty of 25% (40%) at 7 (8) TeV, evaluated from the relative difference between dilepton yields in data and simulation in a control region.

Top-quark and WW Backgrounds. The uncertainty in the estimate of the NRB is derived from the statistical uncertainties in the scale factors in Eq. (1), and from a closure test of the data-driven method for the measurement of this background performed on simulated data. It is found to be about 20% at both 7 and 8 TeV.

A summary of all the systematic uncertainties can be found in Table 4, with the corresponding contributions to the final systematic uncertainty in the cross section measurement.

7 Measurement of the ZZ production cross section

We extract the ZZ production cross section using a profile likelihood fit [34] to the reduced-$E_{\mathrm{T}}^{\mathrm{miss}}$ distribution, shown in Fig. 2. The fit takes into account the expectations for the different background processes and the ZZ signal. Each systematic uncertainty is introduced in the fit as a nuisance parameter with a log-normal prior. For the signal we consider a further multiplicative factor, which is the ratio of the cross section measured in data to the expected theoretical value, i.e. the signal strength $\mu = \sigma/\sigma_{\mathrm{th}}$. Maximizing the profile likelihood, we obtain the ZZ production cross section from the signal strength parameter, as well as optimal fits of the background yields by varying nuisance parameters within their constraints. Table 2 shows the expected signal and background yields, and the corresponding values after the fit. The uncertainties include both the statistical and systematic components.

The cross sections are extracted from individual fits to the ee and $\mu\mu$ channels and from a simultaneous fit to both channels. Table 3 reports the measured $\mathrm{pp} \to \mathrm{ZZ} \to 2\ell 2\nu$ exclusive cross section, i.e. the production cross section of ZZ pairs with mass $60 < M_{\mathrm{Z}} < 120\,\mathrm{GeV}$, with no restrictions on lepton acceptance nor jet number, times the branching fraction to final states with two charged leptons of a given flavor and two neutrinos of any flavor. This is obtained by rescaling the theoretical prediction for the exclusive cross section in the same kinematic range by the fitted signal strength. These theoretical predictions are computed at NLO in QCD with MCFM and corrected for NLO EW effects: 79^{+4}_{-3} (97^{+4}_{-3}) fb at 7 (8) TeV.

The measured inclusive ZZ cross section is obtained by rescaling the theoretical inclusive cross section computed in the zero-width approximation [3] and corrected for NLO EW effects [4] (see Section 1), by the same fitted signal strength. This procedure properly accounts for the contribution of virtual photon decays to the charged-lepton pair production, and yields a measured cross section that can be compared directly with theoretical calculations of inclusive pure ZZ production in the zero-width approximation. The results are:

$$7\,\mathrm{TeV}: \quad \sigma(\mathrm{pp} \to \mathrm{ZZ}) = 5.2^{+1.5}_{-1.4}\,(\mathrm{stat})\,^{+1.4}_{-1.1}\,(\mathrm{syst}) \pm 0.2\,(\mathrm{lumi})\,\mathrm{pb},$$

Table 2: Predicted signal and background yields at 7 and 8 TeV, and corresponding values obtained from the maximum likelihood fit. The uncertainties include both the statistical and systematic components.

Dataset	Process	Channel	Predicted yield	Fitted yield
7 TeV	$ZZ \to 2\ell 2\nu$	ee	14.0 ± 1.9	12.0 ± 4.7
		$\mu\mu$	21.7 ± 3.2	18.4 ± 6.8
	$WZ \to 3\ell\nu$	ee	7.7 ± 0.9	7.9 ± 1.0
		$\mu\mu$	11.5 ± 1.6	11.5 ± 1.3
	Z+ jets	ee	5.0 ± 2.7	4.8 ± 3.2
		$\mu\mu$	8.3 ± 4.8	4.8 ± 4.1
	Non resonant	ee	7.7 ± 3.1	7.4 ± 2.4
		$\mu\mu$	11.2 ± 4.8	9.2 ± 2.9
8 TeV	$ZZ \to 2\ell 2\nu$	ee	77 ± 16	69 ± 12
		$\mu\mu$	109 ± 23	99 ± 17
	$WZ \to 3\ell\nu$	ee	45 ± 6	44.6 ± 5.4
		$\mu\mu$	64 ± 8	64.9 ± 7.2
	Z+ jets	ee	36 ± 12	27.4 ± 8.1
		$\mu\mu$	63 ± 21	52 ± 14
	Non resonant	ee	31 ± 9	34.2 ± 7.7
		$\mu\mu$	50 ± 14	54 ± 12

Table 3: Cross sections [fb] for process $pp \to ZZ \to 2\ell 2\nu$ (where ℓ denotes a charged lepton of a given flavor, ν a neutrino of any flavor) at 7 and 8 TeV, with both Z boson masses in the range 60 to 120 GeV, measured in the ee and $\mu\mu$ channels and the two channels combined.

Channel	$\sqrt{s} = 7\,\text{TeV}$	$\sqrt{s} = 8\,\text{TeV}$
ee	$99^{+35}_{-31}\,\text{(stat)}\,^{+27}_{-22}\,\text{(syst)} \pm 3\,\text{(lumi)}$	$80^{+17}_{-16}\,\text{(stat)}\,^{+25}_{-18}\,\text{(syst)} \pm 3\,\text{(lumi)}$
$\mu\mu$	$48^{+24}_{-21}\,\text{(stat)}\,^{+20}_{-19}\,\text{(syst)} \pm 2\,\text{(lumi)}$	$97^{+14}_{-14}\,\text{(stat)}\,^{+29}_{-22}\,\text{(syst)} \pm 4\,\text{(lumi)}$
Combined	$67^{+20}_{-18}\,\text{(stat)}\,^{+18}_{-14}\,\text{(syst)} \pm 2\,\text{(lumi)}$	$88^{+11}_{-10}\,\text{(stat)}\,^{+24}_{-18}\,\text{(syst)} \pm 4\,\text{(lumi)}$
Theory	$79^{+4}_{-3}\,\text{(theo)}$	$97^{+4}_{-3}\,\text{(theo)}$

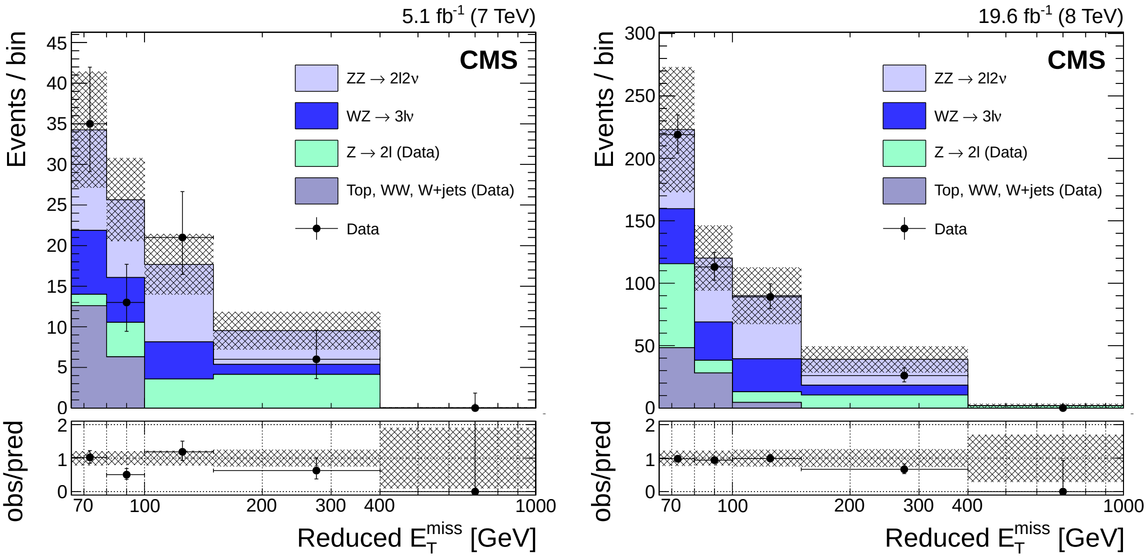

Figure 2: Reduced $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution in $\ell\ell$ ($\ell = \mathrm{e}, \mu$) channels, after the full selection, at 7 TeV (left) and 8 TeV (right). The DY and WW, W+jets, and top backgrounds are estimated with data-driven methods. The gray error band includes statistical and systematic uncertainties in the predicted yields. In the bottom plots, vertical error bars and bands are relative to the total predicted yields. In all plots, horizontal error bars indicate the bin width.

$$8\,\mathrm{TeV}: \quad \sigma(\mathrm{pp} \to \mathrm{ZZ}) = 6.9^{+0.8}_{-0.8}\,(\mathrm{stat})\,^{+1.8}_{-1.4}\,(\mathrm{syst}) \pm 0.3\,(\mathrm{lumi})\,\mathrm{pb}.$$

These are the most precise measurements of the ZZ cross section in the $2\ell 2\nu$ channel and the first measurement in this channel at 8 TeV. The measurements are less than one standard deviation from the SM predictions at both 7 and 8 TeV. The uncertainties are approximately twice as large as those from the CMS measurement in the 4ℓ channel [7, 8], and the channels agree within uncertainties.

The p-values of the simultaneous fit to the ee and $\mu\mu$ channels are 0.335 (0.569) at 7 (8) TeV. The data are also consistent with the reduced $E_{\mathrm{T}}^{\mathrm{miss}}$ spectra uncorrected for NLO EW effects, with only slightly smaller p-values of 0.322 (0.477) at 7 (8) TeV.

Table 4 shows a summary of the sources of systematic uncertainty described in Section 6, with the corresponding contributions to the total systematic uncertainty in the cross sections.

8 Anomalous couplings

The existence of neutral trilinear gauge couplings is forbidden at the tree level, but allowed in some extensions of the SM [35]. The ZZ production process provides a way to probe the existence of such anomalous couplings at the ZZZ and γZZ vertices.

Neutral couplings $V^{(*)}\mathrm{ZZ}$ ($V = \mathrm{Z}, \gamma$) can be described using the following effective Lagrangian [36]:

$$\mathcal{L}_{VZZ} = -\frac{e}{M_{\mathrm{Z}}^2}\left\{\left[f_4^{\gamma}\left(\partial_{\mu}F^{\mu\alpha}\right) + f_4^{Z}\left(\partial_{\mu}Z^{\mu\alpha}\right)\right] Z_{\beta}\left(\partial^{\beta}Z_{\alpha}\right) - \left[f_5^{\gamma}\left(\partial^{\mu}F_{\mu\alpha}\right) + f_5^{Z}\left(\partial^{\mu}Z_{\mu\alpha}\right)\right]\tilde{Z}^{\alpha\beta}Z_{\beta}\right\}, \tag{3}$$

where Z represents the Z boson and $F_{\mu\alpha}$ represents the electromagnetic field tensor. The coefficients f_i^{γ} and f_i^{Z} correspond to couplings $\gamma^{(*)}\mathrm{ZZ}$ and $\mathrm{Z}^{(*)}\mathrm{ZZ}$, respectively. All the operators in Eq. (3) are Lorentz-invariant and $\mathrm{U}(1)_{\mathrm{EM}}$ gauge-invariant, but not invariant under

Table 4: Systematic uncertainties in the cross sections due to each source separately, after the maximum likelihood fit to extract the ZZ cross section. The uncertainties marked with an asterisk ($*$) are used as shape uncertainties in the fit.

Source of uncertainty	Uncertainty [%]	
	7 TeV	8 TeV
($*$) MC statistics: ZZ (ee)	0.8	0.9
($*$) MC statistics: ZZ ($\mu\mu$)	1.3	1.0
($*$) MC statistics: WZ (ee)	1.7	0.8
($*$) MC statistics: WZ ($\mu\mu$)	1.7	1.0
($*$) Control sample statistics: DY (ee)	6.5	4.3
($*$) Control sample statistics: DY ($\mu\mu$)	5.8	5.0
($*$) Control sample statistics: NRB (ee)	6.3	3.0
($*$) Control sample statistics: NRB ($\mu\mu$)	8.2	4.4
WZ cross section: PDF+α_S	1.9	2.6
($*$) ZZ+WZ cross section: scales	14	17
($*$) ZZ+WZ cross section: NLO EW corr.	2.4	2.3
Signal acceptance	2.8	2.8
Luminosity	3.6	4.2
($*$) Pileup	0.5	1.0
Muon trigger, ID, isolation	4.1	3.6
Electron trigger, ID, isolation	1.7	2.0
($*$) Lepton momentum scale	2.7	3.7
($*$) JES	6.0	12
($*$) JER	0.8	1.4
($*$) Unclustered $E_{\mathrm{T}}^{\mathrm{miss}}$	2.0	3.2
($*$) b-jet veto	0.3	0.3
Drell–Yan bkg. normalization	6.6	8.5
Top-quark & WW bkg. normalization	7.7	7.1
Total systematic uncertainty	24.0	24.3
Statistical uncertainty	28.0	12.1

$\mathrm{SU(2)_L} \times \mathrm{U(1)_Y}$ gauge symmetry. The terms corresponding to f_4^V parameters violate the CP symmetry, while the terms corresponding to f_5^V parameters conserve CP.

To avoid unitarity violation at energies above the scale (Λ) of new physics, the Lagrangian of Eq. (3) can be modified with form factors of the type $1/\left(1+\hat{s}/\Lambda\right)^n$, where $\sqrt{\hat{s}}$ is the effective center-of-mass energy of the collision. No form-factor scaling is used in this analysis. This allows to provide results without any bias that can arise due to a particular choice of the form-factor energy dependence.

Previous studies of neutral anomalous triple gauge couplings were performed at LEP2 [37], Tevatron [38], and LHC [6–8]. No deviation from the SM expectation has been observed so far, and the best limits were set by the LHC measurements based on integrated luminosities of about 5 (19.6) fb^{-1} at 7 (8) TeV.

8.1 Limits from the $\mathrm{ZZ} \to 2\ell 2\nu$ channel

In the following, we extract limits on the neutral triple gauge couplings $V^{(*)}\mathrm{ZZ}$ with the same datasets at 7 and 8 TeV as used for the ZZ cross section measurement described in the previous section. Limits on the four f_i^V parameters are set by comparing the data with theoretical predictions.

Figure 3 shows the charged dilepton p_{T} distribution after the full selection described in Table 1, in data and simulation, including SHERPA samples with different values of the f_4^Z parameter. The contribution from the anomalous couplings enhances the high-p_{T} region of the distribution. The charged dilepton p_{T} is thus a good observable to probe for the presence of ATGCs. The DY and nonresonant backgrounds are estimated from data as described above. The SM ZZ process is simulated here using the MADGRAPH sample described in Section 2, with NLO QCD corrections computed with MCFM and NLO EW corrections from Ref. [4]. The contribution of the ATGCs is obtained from the SHERPA samples mentioned above, by subtracting the SM SHERPA contribution to the charged dilepton p_{T}, and is summed to the MADGRAPH ZZ distribution. The interference of the ATGC signal and the SM ZZ production is included, except for $p_{\mathrm{T}}(\mathrm{Z}) < 200\,\mathrm{GeV}$, which has a negligible impact on the limits. The expected signal yields in each p_{T} bin are interpolated between different values of the ATGC coupling parameters using a second-degree polynomial, since the signal cross section depends quadratically on such parameters.

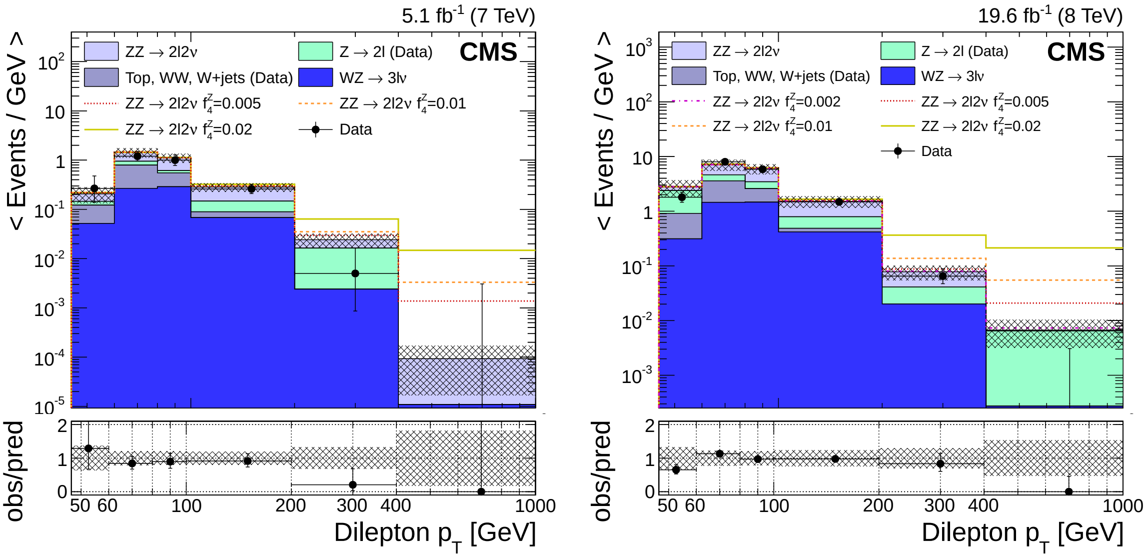

Figure 3: Dilepton ($\ell = \mathrm{e}, \mu$) transverse momentum distributions at 7 TeV (left) and 8 TeV (right). The DY and WW, W+jets, and top backgrounds are estimated from control samples in data. The gray error band includes statistical and systematic uncertainties in the predicted yields. In the bottom plots, vertical error bars and bands are relative to the total predicted yields. In all plots, horizontal error bars indicate the bin width.

The limits are calculated with a profile likelihood method. We set one-dimensional limits on the four parameters, i.e. varying independently a single parameter at a time, while fixing the other three to zero. The 95% CL one-dimensional limits on the four parameters are reported in Table 5 for 7 TeV, 8 TeV, and combined datasets. The observed exclusion limits are about one standard deviation tighter than the expected ones, which is attributed primarily to the observed deficit of events in the highest bin of dilepton p_{T}. The limits set are of comparable sensitivity to those previously obtained by CMS in the 4ℓ channel [7, 8] because the branching fraction in the $2\ell 2\nu$ channel is approximately six times larger than that of the 4ℓ final state, and the signal purity is enhanced at large values of the boson p_{T}, where there is the greatest sensitivity to ATGC effects.

8.2 Combined limits from the $ZZ \to 4\ell$ and $\to 2\ell 2\nu$ channels

We proceed with the combination of the results of the previously published $\mathrm{ZZ} \to 4\ell$ analyses [7, 8] with the present results. In doing this, the published analysis of the 4ℓ ($\ell = \mathrm{e}, \mu$)

Table 5: Summary of 95% CL intervals for the neutral ATGC coefficients, set by the $2\ell2\nu$ final states using the 7 and 8 TeV CMS datasets. The expected 95% CL intervals obtained using the 7 and 8 TeV simulated samples are also shown. No form factor is used.

Dataset	f_4^Z	f_4^γ	f_5^Z	f_5^γ
7 TeV	[-0.010; 0.011]	[-0.012; 0.013]	[-0.010; 0.010]	[-0.013; 0.013]
8 TeV	[-0.0032; 0.0037]	[-0.0043; 0.0037]	[-0.0032; 0.0034]	[-0.0038; 0.0043]
Combined	[-0.0027; 0.0032]	[-0.0036; 0.0032]	[-0.0029; 0.0030]	[-0.0033; 0.0036]
Expected (7 and 8 TeV)	[-0.0048; 0.0052]	[-0.0060; 0.0054]	[-0.0048; 0.0051]	[-0.0058; 0.0062]

channel is unchanged, except that NLO EW corrections to the SM ZZ → 4ℓ background are included in the same way as in the present analysis. We use a profile likelihood method to calculate the 95% CL one-dimensional intervals for the four parameters, combining the data in the 4ℓ and $2\ell2\nu$ channels, at 7 and 8 TeV. The systematic uncertainties in the signal and diboson background cross sections, in the integrated luminosity, and in the lepton efficiencies are treated as fully correlated between the two channels. Table 6 shows the intervals obtained by combining the four separate data sets. The combined analysis improves the sensitivity of the two separate channels, and the limits are more stringent than all the results published to date.

Table 6: Summary of 95% CL intervals for the neutral ATGC coefficients, set by the combined analysis of 4ℓ and $2\ell2\nu$ final states. The intervals obtained separately by the two analyses using the 7 and 8 TeV CMS data sets are shown, as well as their combination. The expected 95% CL intervals obtained using the 7 and 8 TeV simulated samples of both analyses are also shown. No form factor is used.

Dataset	f_4^Z	f_4^γ	f_5^Z	f_5^γ
7 TeV, 4ℓ	[-0.010; 0.011]	[-0.012; 0.013]	[-0.011; 0.011]	[-0.013; 0.013]
7 TeV, $2\ell2\nu$	[-0.010; 0.011]	[-0.012; 0.013]	[-0.010; 0.010]	[-0.013; 0.013]
8 TeV, 4ℓ	[-0.0041; 0.0044]	[-0.0052; 0.0048]	[-0.0041; 0.0040]	[-0.0048; 0.0045]
8 TeV, $2\ell2\nu$	[-0.0032; 0.0037]	[-0.0043; 0.0037]	[-0.0032; 0.0034]	[-0.0038; 0.0043]
Combined	[-0.0021; 0.0026]	[-0.0030; 0.0026]	[-0.0022; 0.0023]	[-0.0026; 0.0027]
Expected (4ℓ and $2\ell2\nu$, 7 and 8 TeV)	[-0.0036; 0.0039]	[-0.0045; 0.0041]	[-0.0036; 0.0036]	[-0.0042; 0.0043]

9 Summary

We have measured the ZZ production cross section in the $2\ell2\nu$ channel in proton-proton collisions at center-of-mass energies of 7 and 8 TeV. The data samples selected for the study correspond to an integrated luminosity of 5.1 (19.6) fb^{-1} at 7 (8) TeV. We have measured

$$\sigma(\mathrm{pp} \to \mathrm{ZZ}) = 5.2^{+1.5}_{-1.4}\,(\mathrm{stat})\,^{+1.4}_{-1.1}\,(\mathrm{syst}) \pm 0.2\,(\mathrm{lumi})\,\mathrm{pb}$$

at 7 TeV, and

$$\sigma(\mathrm{pp} \to \mathrm{ZZ}) = 6.9^{+0.8}_{-0.8}\,(\mathrm{stat})\,^{+1.8}_{-1.4}\,(\mathrm{syst}) \pm 0.3\,(\mathrm{lumi})\,\mathrm{pb}$$

at 8 TeV, in agreement with theory calculations, $6.2^{+0.3}_{-0.2}$ pb ($7.6^{+0.4}_{-0.3}$ pb) at 7 (8) TeV, which include NLO QCD corrections [3] and NLO EW corrections [4, 5]. The selected data have also been analyzed to search for ATGCs involving the ZZ final state. In the absence of any observation of new physics, we have set the most stringent limits to date on the relevant ATGC parameters. In addition, by combining the selected data with the CMS data for the four-charged-lepton final state we have set even tighter constraints.

Acknowledgments

We wish to thank our theoretician colleague Tobias Kasprzik for providing the numerical calculations of the next-to-leading order electroweak corrections to the ZZ and WZ processes.

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: the Austrian Federal Ministry of Science, Research and Economy and the Austrian Science Fund; the Belgian Fonds de la Recherche Scientifique, and Fonds voor Wetenschappelijk Onderzoek; the Brazilian Funding Agencies (CNPq, CAPES, FAPERJ, and FAPESP); the Bulgarian Ministry of Education and Science; CERN; the Chinese Academy of Sciences, Ministry of Science and Technology, and National Natural Science Foundation of China; the Colombian Funding Agency (COLCIENCIAS); the Croatian Ministry of Science, Education and Sport, and the Croatian Science Foundation; the Research Promotion Foundation, Cyprus; the Ministry of Education and Research, Estonian Research Council via IUT23-4 and IUT23-6 and European Regional Development Fund, Estonia; the Academy of Finland, Finnish Ministry of Education and Culture, and Helsinki Institute of Physics; the Institut National de Physique Nucléaire et de Physique des Particules / CNRS, and Commissariat à l'Énergie Atomique et aux Énergies Alternatives / CEA, France; the Bundesministerium für Bildung und Forschung, Deutsche Forschungsgemeinschaft, and Helmholtz-Gemeinschaft Deutscher Forschungszentren, Germany; the General Secretariat for Research and Technology, Greece; the National Scientific Research Foundation, and National Innovation Office, Hungary; the Department of Atomic Energy and the Department of Science and Technology, India; the Institute for Studies in Theoretical Physics and Mathematics, Iran; the Science Foundation, Ireland; the Istituto Nazionale di Fisica Nucleare, Italy; the Ministry of Science, ICT and Future Planning, and National Research Foundation (NRF), Republic of Korea; the Lithuanian Academy of Sciences; the Ministry of Education, and University of Malaya (Malaysia); the Mexican Funding Agencies (CINVESTAV, CONACYT, SEP, and UASLP-FAI); the Ministry of Business, Innovation and Employment, New Zealand; the Pakistan Atomic Energy Commission; the Ministry of Science and Higher Education and the National Science Centre, Poland; the Fundação para a Ciência e a Tecnologia, Portugal; JINR, Dubna; the Ministry of Education and Science of the Russian Federation, the Federal Agency of Atomic Energy of the Russian Federation, Russian Academy of Sciences, and the Russian Foundation for Basic Research; the Ministry of Education, Science and Technological Development of Serbia; the Secretaría de Estado de Investigación, Desarrollo e Innovación and Programa Consolider-Ingenio 2010, Spain; the Swiss Funding Agencies (ETH Board, ETH Zurich, PSI, SNF, UniZH, Canton Zurich, and SER); the Ministry of Science and Technology, Taipei; the Thailand Center of Excellence in Physics, the Institute for the Promotion of Teaching Science and Technology of Thailand, Special Task Force for Activating Research and the National Science and Technology Development Agency of Thailand; the Scientific and Technical Research Council of Turkey, and Turkish Atomic Energy Authority; the National Academy of Sciences of Ukraine, and State Fund for Fundamental Researches, Ukraine; the Science and Technology Facilities Council, UK; the US Department of Energy, and the US National Science Foundation.

Individuals have received support from the Marie-Curie program and the European Research Council and EPLANET (European Union); the Leventis Foundation; the A. P. Sloan Foundation; the Alexander von Humboldt Foundation; the Belgian Federal Science Policy Office; the

Fonds pour la Formation à la Recherche dans l'Industrie et dans l'Agriculture (FRIA-Belgium); the Agentschap voor Innovatie door Wetenschap en Technologie (IWT-Belgium); the Ministry of Education, Youth and Sports (MEYS) of the Czech Republic; the Council of Science and Industrial Research, India; the HOMING PLUS program of Foundation for Polish Science, cofinanced from European Union, Regional Development Fund; the Compagnia di San Paolo (Torino); the Consorzio per la Fisica (Trieste); MIUR project 20108T4XTM (Italy); the Thalis and Aristeia programs cofinanced by EU-ESF and the Greek NSRF; and the National Priorities Research Program by Qatar National Research Fund.

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