Measurement of the ZZ production cross section and search for anomalous couplings in $2\ell2\ell'$ final states in pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$

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ABSTRACT: A measurement is presented of the ZZ production cross section in the ZZ → $2\ell2\ell'$ decay mode with $\ell = \mathrm{e}, \mu$ and $\ell' = \mathrm{e}, \mu, \tau$ in proton-proton collisions at $\sqrt{s} = 7\,\mathrm{TeV}$ with the CMS experiment at the LHC. Results are based on data corresponding to an integrated luminosity of $5.0\,\mathrm{fb}^{-1}$. The measured cross section $\sigma(\mathrm{pp} \to \mathrm{ZZ}) = 6.24\,^{+0.86}_{-0.80}\,(\mathrm{stat.})\,^{+0.41}_{-0.32}\,(\mathrm{syst.}) \pm 0.14\,(\mathrm{lumi.})$ pb is consistent with the standard model predictions. The following limits on ZZZ and ZZγ anomalous trilinear gauge couplings are set at 95% confidence level: $-0.011 < f_4^{\mathrm{Z}} < 0.012$, $-0.012 < f_5^{\mathrm{Z}} < 0.012$, $-0.013 < f_4^{\gamma} < 0.015$, and $-0.014 < f_5^{\gamma} < 0.014$.

The study of diboson production in proton-proton collisions provides an important test of the standard model (SM). Many extensions of the SM predict new scalar, vector, or spin-2 particles that decay into a pair of W or Z bosons. In addition, these final states are sensitive to the self-interactions among the gauge bosons via trilinear gauge couplings (TGCs). These couplings are the direct consequence of the non-Abelian $\mathrm{SU}(2) \times \mathrm{U}(1)$ gauge symmetry of the SM and are a necessary ingredient to construct renormalizable theories. The values of these couplings are fully determined in the SM by the gauge structure of the Lagrangian. Therefore, any deviation of the observed coupling strength from the SM prediction would indicate the presence of new physics. This deviation would be manifested as a change in the production cross section, especially for energetic heavy gauge bosons.

In the SM, ZZ production proceeds via the t- and u-channel $\mathrm{q}\overline{\mathrm{q}}$ scattering diagrams, and via gluon-gluon fusion. The presence of anomalous neutral trilinear couplings (ATGCs) would lead to a sizable enhancement of ZZ final states via s-channel $\mathrm{q}\overline{\mathrm{q}}$ scattering. A model featuring such couplings can be constructed by means of an effective Lagrangian [1]. In this parametrization, two ZZZ couplings and two ZZγ couplings are allowed by electromagnetic gauge invariance and Lorentz invariance for on-shell Z bosons. The couplings are parametrized by two CP-violating ($f_4^{\mathrm{Z},\gamma}$) and two CP-conserving ($f_5^{\mathrm{Z},\gamma}$) complex parameters, which are zero in the SM.

Measurements of the ZZ cross section were previously performed at the Tevatron [2, 3] and the Large Hadron Collider (LHC) [4, 5]. A first measurement of the ZZ cross section at center-of-mass energy $\sqrt{s} = 7\,\mathrm{TeV}$ by the Compact Muon Solenoid (CMS) Collaboration in the decay mode $\mathrm{ZZ} \to 2\ell2\ell$, where ℓ is either e or μ, is presented in ref. [4]. The measured cross section $\sigma(\mathrm{pp} \to \mathrm{ZZ})\mathcal{B}(\mathrm{ZZ} \to 2\ell2\ell) = 28.1^{+4.6}_{-4.0}\,(\mathrm{stat.}) \pm 1.2\,(\mathrm{syst.}) \pm 1.3\,(\mathrm{lumi.})\,\mathrm{fb}$ agrees well with the SM prediction of $27.9 \pm 1.9\,\mathrm{fb}$. In this Letter, we present an extended measurement of the ZZ production cross section based on the decay mode $2\ell2\ell'$, where ℓ' is e, μ, or τ. If a τ is present in the final state, one Z is required to decay into $\mathrm{e}^+\mathrm{e}^-$ or $\mu^+\mu^-$, and the second Z into $\tau^+\tau^-$ in four possible final states: $\tau_{\mathrm{h}}\tau_{\mathrm{h}}$, $\tau_{\mathrm{e}}\tau_{\mathrm{h}}$, $\tau_\mu\tau_{\mathrm{h}}$, and $\tau_{\mathrm{e}}\tau_\mu$, where τ_{h} represents a τ decaying hadronically, while τ_{e} and τ_μ indicate taus decaying into an electron and a muon, respectively. The presence of four leptons in the final state provides a clean signature with only a small contribution from background processes. The background sources include reducible contributions from $\mathrm{Zb}\overline{\mathrm{b}}$ and $\mathrm{t}\overline{\mathrm{t}}$ processes, where the final states contain two isolated leptons and two b jets with secondary leptons, and from Z+jets and ZW+jets processes where the jets are misidentified as leptons.

In this Letter, we also present a search for the neutral ZZZ and ZZγ ATGCs. Previous studies on neutral ZZZ and ZZγ ATGCs were performed at LEP2 [6–10], the Tevatron [11], and the LHC [5]. The most restrictive limits were set in ref. [5], $-0.07 < f_{4,5}^{\mathrm{Z}} < 0.07$ and $-0.08 < f_{4,5}^{\gamma} < 0.08$, with a data set corresponding to an integrated luminosity of $1\,\mathrm{fb}^{-1}$ of pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$.

The measurements presented here are based on data collected in 2010 and 2011 with the CMS experiment at the LHC at $\sqrt{s} = 7\,\mathrm{TeV}$, corresponding to an integrated luminosity of $5.0 \pm 0.1\,\mathrm{fb}^{-1}$. A set of Monte Carlo (MC) event samples is used to simulate signal and background events. The ZZ production via $\mathrm{q}\overline{\mathrm{q}}$ is generated at next-to-leading order (NLO) with POWHEG [12–14], while other diboson processes (WW, WZ, Zγ) are generated with

PYTHIA 6.424 and MADGRAPH [15]. The gg $\to$ ZZ contribution is estimated using events generated with the gg2ZZ code [16]. The Z+jets samples, namely Zb$\bar{\text{b}}$, Zc$\bar{\text{c}}$, and Z+light jets, are generated with MADGRAPH. The t$\bar{\text{t}}$ events are generated at NLO with POWHEG. For leading-order generators, the default set of parton distribution functions (PDFs) used to produce these samples is CTEQ6L [17], while CT10 [18] is used for NLO generators. Finally, for the modeling of ATGCs, the SHERPA generator version 1.2.2 is used [19]. The τ-lepton decays are generated with TAUOLA [20]. All events are processed through a detailed simulation of the CMS detector based on GEANT4 [21] and reconstructed with the same algorithms as used for data.

A detailed description of the CMS detector can be found elsewhere [22]. 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 field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter (ECAL), and the brass/scintillator hadron calorimeter (HCAL). Muons are measured in gas-ionization detectors embedded in the steel flux return yoke of the magnet. CMS uses a right-handed coordinate system, with the origin at the nominal interaction point, the x axis pointing to the center of the LHC ring, the y axis pointing up (perpendicular to the plane of the LHC ring), and the z axis along the counterclockwise-beam direction. The polar angle θ is measured from the positive z axis and the azimuthal angle ϕ is measured in the x-y plane. Variables used in this analysis include the pseudorapidity $\eta = -\ln[\tan(\theta/2)]$ and the transverse momentum $p_{\text{T}} = \sqrt{p_x^2 + p_y^2}$. The ECAL is designed to have both excellent energy resolution and high granularity, properties that are crucial for reconstructing electrons and photons produced in τ-lepton decays. The ECAL is constructed with projective lead tungstate crystals that provide coverage in pseudorapidity $|\eta| < 1.48$ in a barrel region and $1.48 < |\eta| < 3.00$ in two endcap regions (EE). A preshower detector consisting of two planes of silicon sensors interleaved with a total of $3X_0$ of lead is located in front of the EE. The energy resolution is 3% or better for the range of electron energies relevant for this analysis. The tracker measures charged particle tracks within the range $|\eta| < 2.5$. It consists of 1440 silicon pixel and 15 148 silicon strip detector modules, and provides an impact parameter resolution of $\sim$15 μm and a transverse momentum resolution of about 1.5% for 100 GeV particles. The reconstructed tracks are used to measure the location of interaction vertices. The spatial resolution of the reconstruction in the transverse direction is $\sim$25 μm for primary vertices with more than 30 associated tracks [23]. The barrel region of the muon system is instrumented with drift tubes, and the endcap regions with cathode strip chambers. In both regions, resistive-plate chambers provide additional coordinate and timing information. Muons are reconstructed in the range $|\eta| < 2.4$, with a typical p_{T} resolution of $\sim$1% for $p_{\text{T}} = 40$ GeV.

At the trigger level, the selected events are required to have either at least two electrons, one with $p_{\text{T}} > 17$ GeV and the other with $p_{\text{T}} > 8$ GeV, or at least two muons, one with $p_{\text{T}} > 13$ GeV ($p_{\text{T}} > 17$ GeV for high instantaneous luminosity data-taking periods) and the other with $p_{\text{T}} > 8$ GeV.

Electrons are reconstructed within $|\eta^{\text{e}}| < 2.5$ and with $p_{\text{T}}^{\text{e}} > 7$ GeV by combining information from the ECAL and tracker [24, 25]. Electron identification requirements rely on the electromagnetic shower shape and other observables based on tracker and calorimeter

information. The selection criteria depend on p_T^e and $|\eta^e|$, and on a categorization according to observables that are sensitive to the amount of bremsstrahlung emitted along the trajectory in the tracker. Muons are reconstructed [26] within $|\eta^\mu| < 2.4$ and $p_T^\mu > 5\,\text{GeV}$ with information from both the tracker and the muon spectrometer. The track must have more than 10 out of up to 24 possible hits in the silicon tracker [23] to ensure a precise measurement of the momentum. The efficiencies are measured in data, using a tag-and-probe technique [27] based on an inclusive sample of $Z \to \ell^+\ell^-$ events. The measurements are performed in several ranges of p_T^ℓ and $|\eta^\ell|$. The product of reconstruction and identification efficiencies for electrons in the ECAL barrel (endcaps) varies from about 68% (62%) for the p_T^e range 7–10 GeV, to 82% (74%) at $10 < p_T^e < 20\,\text{GeV}$, and reaches up to 90% (89%) at $p_T^e > 20\,\text{GeV}$. The muons are reconstructed and identified with efficiencies above 98%.

Since the ZZ final state is expected to have only a small contribution from background processes, the algorithms are tuned to maximize the lepton-reconstruction efficiency, resulting in an increased lepton-misidentification rate. A particle-flow (PF) technique [28] is used for τ_h reconstruction. In the PF approach, information from all subdetectors is combined to reconstruct and identify particles produced in the collision. The particles are classified into mutually exclusive categories: charged hadrons, photons, neutral hadrons, muons, and electrons. These particles are used to reconstruct the τ_h candidates with the "hadron plus strip" (HPS) algorithm [29], which is designed to optimize the performance of τ_h identification and reconstruction by considering specific τ_h decay modes. The neutrinos produced in all τ decays escape detection and are ignored in the τ_h reconstruction. The algorithm provides high τ_h identification efficiency, approximately 50% for the range of τ_h energies relevant for this analysis, while keeping the misidentification rate for jets at the level of 1%.

Events are required to have at least one $Z \to \ell^+\ell^-$ candidate, denoted by Z_1. The invariant mass of the reconstructed Z_1 is required to be $60 < m_{\ell\ell} < 120\,\text{GeV}$. The two leptons must have opposite charges, one with $p_T > 20\,\text{GeV}$ and the other with $p_T > 10\,\text{GeV}$, and with $|\eta| < 2.5$ for the electrons and $|\eta| < 2.4$ for the muons. If more than one candidate is found, the one with the mass closest to the Z mass is considered as Z_1.

Lepton isolation requirements depend on the ZZ decay mode. For the final states with only electrons and muons, the isolation criteria are based on a combination of the tracker, ECAL, and HCAL information. The standard combined relative isolation is defined as

$$I_{\text{rel}}^{\text{std}} = \left(\sum_i p_{T,\,\text{track}}^i + \max\left(\sum_j E_{T,\,\text{ECAL}}^j + \sum_k E_{T,\,\text{HCAL}}^k - \pi \cdot \Delta R_{\max}^2 \cdot \rho; 0 \right) \right) / p_T^\ell,$$

with the sums running over the charged tracks and the energy deposits in the ECAL and HCAL within a cone around the lepton direction defined by $\Delta R < \Delta R_{\max} = 0.3$, where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, and E_T stands for the transverse energy. The neutral isolation is made largely independent of the pileup of pp collisions by correcting for the average energy density, ρ, calculated in each event using a "jet area" technique [30] and defined as the median of the energy distribution for the neutral particles around all jets. The isolation variable $I_{\text{rel}}^{\text{std}}$ is required to be less than 0.275 for each lepton. The significance of the impact pa-

rameter of each lepton relative to the event vertex (S_{3D}) is required to satisfy $|S_{3D}| < 4$. The primary vertex is chosen as the vertex with the highest sum of p_T^2 of its constituent tracks.

In the $2\ell2\tau$ final states, instead of standard isolation, the leptons from the Z_1 are required to have a combined PF relative isolation $I_{rel}^{PF} < 0.25$. The I_{rel}^{PF} is defined similarly to I_{rel}^{std}, however in this case the sums run over charged hadrons, photons, and neutral hadrons, all measured in the isolation cone of $\Delta R < 0.4$ around the lepton direction.

The selection requirements for the second Z, denoted by Z_2, also depend on the final state. In the final states with electrons and muons only, the isolation requirements are the same as for the leptons from Z_1, but $p_T > 7\,\text{GeV}$ and $p_T > 5\,\text{GeV}$ are required for electrons and muons, respectively. If the final state is $\tau_e\tau_\mu$, the lepton p_T values are required to exceed $10\,\text{GeV}$. The remaining criteria are identical to those for Z_1. Since hadronically decaying τ leptons have much larger misidentification rates than the other leptons, the isolation requirement based on I_{rel}^{PF} for the electrons and muons in the final states $\tau_e\tau_h$ and $\tau_\mu\tau_h$ is changed to 0.15 and 0.1, respectively. A study of inclusive $Z \to \tau^+\tau^-$ production [31] demonstrated that modifying the electron and muon isolation requirements is a more effective way to reduce background in such final states than requiring tighter isolation on τ_h. The τ leptons are required to have $p_T > 20\,\text{GeV}$ and $|\eta| < 2.3$, and to satisfy the requirements of a loose HPS working point. If the Z_2 decays to $\tau_h^+\tau_h^-$, both τ_h are required to satisfy the requirements of a medium working point of the HPS algorithm. The loose (medium) working point requires the scalar sum of the p_T of the charged hadrons and E_T of the neutral hadrons within the isolation cone to be less than $2\,\text{GeV}$ ($1\,\text{GeV}$). The loose (medium) working point corresponds to a probability of approximately 1% (0.5%) for jets to be misidentified as τ_h. Using the medium instead of loose working point leads to a decrease in the τ_h reconstruction efficiency from $\approx 50\%$ to $\approx 40\%$.

The invariant mass of the reconstructed Z_2 is required to satisfy $60 < m_{\ell\ell} < 120\,\text{GeV}$, when Z_2 decays into e^+e^- or $\mu^+\mu^-$. In the $2\ell2\tau$ final states, the visible invariant mass of the reconstructed $Z_2 \to \tau^+\tau^-$ is required to satisfy $30 < m_{\tau\tau}^{vis} < 80\,\text{GeV}$. The upper bound reduces contributions from $Z_2 \to \ell^+\ell^-$, where an electron or a muon is not well reconstructed and is misidentified as a τ_h. For the $Z_2 \to \tau_e\tau_\mu$ final state, the upper bound on $m_{\tau\tau}$ is increased to $90\,\text{GeV}$, as this state is not produced in $Z_2 \to \ell^+\ell^-$ decays. In the final states involving τ_h, leptons from the same Z are required to be separated by $\Delta R > 0.4$ for the Z_1, and by $\Delta R > 0.5$ for the Z_2.

The major contributions to the background are due to Z production in association with jets, WZ production in association with jets, and $t\bar{t}$. In all of these cases, a jet or nonisolated lepton is misidentified as an isolated electron, muon, or τ_h. The relative contribution of each source of background depends on the final state.

The background estimate is performed in two steps. Firstly, the rate for loosely isolated objects to be misidentified as isolated ones is measured in a control region that does not contain any signal contribution. The misidentification rate is estimated with events in which the Z_1 passes all selection requirements, and which contain an additional probe electron, muon, or τ_h. No isolation requirement is applied to the probe. The misidentification rate is defined as the ratio of the number of probe candidates that pass the isolation requirements to the initial number of probe candidates, and is measured as a function of p_T and η for each lepton flavor.

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Decay channel	Expected ZZ	Background	Total expected	Observed
eeee	$10.50 \pm 0.04 \pm 0.95$	$0.25 \pm 0.14 \pm 0.07$	$10.75 \pm 0.14 \pm 0.95$	9
$\mu\mu\mu\mu$	$15.91 \pm 0.05 \pm 1.43$	$0.52 \pm 0.26 \pm 0.25$	$16.43 \pm 0.26 \pm 1.45$	14
ee$\mu\mu$	$26.74 \pm 0.10 \pm 2.41$	$0.58 \pm 0.18 \pm 0.23$	$27.32 \pm 0.21 \pm 2.41$	31
ee$\tau_h\tau_h$	$0.75 \pm 0.01 \pm 0.07$	$0.76 \pm 0.16 \pm 0.05$	$1.51 \pm 0.16 \pm 0.09$	1
$\mu\mu\tau_h\tau_h$	$0.82 \pm 0.02 \pm 0.07$	$0.75 \pm 0.16 \pm 0.08$	$1.57 \pm 0.16 \pm 0.11$	0
ee$\tau_e\tau_h$	$1.17 \pm 0.02 \pm 0.11$	$0.96 \pm 0.34 \pm 0.12$	$2.29 \pm 0.34 \pm 0.16$	3
$\mu\mu\tau_e\tau_h$	$1.15 \pm 0.02 \pm 0.10$	$0.35 \pm 0.34 \pm 0.11$	$1.60 \pm 0.34 \pm 0.15$	3
ee$\tau_\mu\tau_h$	$0.94 \pm 0.02 \pm 0.08$	$0.22 \pm 0.14 \pm 0.04$	$1.17 \pm 0.14 \pm 0.06$	0
$\mu\mu\tau_\mu\tau_h$	$1.08 \pm 0.02 \pm 0.10$	$0.55 \pm 0.24 \pm 0.11$	$1.64 \pm 0.24 \pm 0.15$	2
ee$\tau_e\tau_\mu$	$0.54 \pm 0.01 \pm 0.05$	$0.64 \pm 0.44 \pm 0.16$	$1.22 \pm 0.44 \pm 0.17$	0
$\mu\mu\tau_e\tau_\mu$	$0.60 \pm 0.01 \pm 0.05$	$0.14 \pm 0.30 \pm 0.10$	$0.74 \pm 0.30 \pm 0.11$	2

Table 1. The expected yield of ZZ events obtained from simulation and the estimated yield of background events obtained from data, as described in the text, are shown for each decay channel and are summed in the total expected yield ("Total expected"). They are compared to the number of events observed in the signal region. The first uncertainty is statistical while the second one is systematic.

The second step is to estimate the number of background events in the signal region. The measured misidentification rate is applied to events that pass all selection requirements, including the opposite-charge requirement for the Z_2, but requiring the candidates to not be isolated.

Theoretical uncertainties on the ZZ $\rightarrow 2\ell2\ell'$ acceptance are evaluated using MCFM 6.2 [32], varying QCD scales up and down by a factor of two with respect to the default factorization (μ_F) and renormalization (μ_R) scales $\mu_F = \mu_R = m_Z$, where m_Z is the mass of the Z boson. The variations in the acceptance are 0.1% ($q\overline{q} \rightarrow$ ZZ) and 0.4% (gg $\rightarrow$ ZZ) and can be neglected. The uncertainties related to the PDFs are evaluated following the PDF4LHC prescription [33]. Using the CT10 [18], MSTW08 [34], and NNPDF [35] sets, the uncertainties are estimated to be 4% for $q\overline{q} \rightarrow$ ZZ and and 5% for gg $\rightarrow$ ZZ processes.

The uncertainties on Z+jets, WZ+jets, and $t\overline{t}$ backgrounds reflect the uncertainties on the measured values of the misidentication rates and the limited quantity of data in the control regions in the data and amount to 30–50% depending on the decay channel. The uncertainty on the integrated luminosity is 2.2% [36]. Systematic uncertainties on trigger efficiency (1.5%), lepton identification efficiency, and lepton isolation are evaluated from data. The uncertainties associated with lepton identification and isolation are 1–2% for muons and electrons, and 6–7% for τ_h. Uncertainties on energy scales, 3% for τ_h and 1–2.5% for electrons, contribute to variations in the shape of the mass spectrum.

Table 1 presents the number of observed events in the signal region in each channel, as well as the expected number of signal events and the estimated number of background

events. We observe a total of 54 candidate events in the 4e, 4μ, and 2e2μ channels, compared to the SM expectation of 54.5±0.3 (stat.)±4.8 (syst.) events, which includes 1.4 from background processes. In the 2ℓ2τ channels, 11 candidate events are observed, compared to 11.7±0.8 (stat.)±1.0 (syst.) events expected, including 4.4 from background processes. The reconstructed four-lepton invariant mass distributions are compared to the SM expectations in figures 1 (a) and (b) for the sum of the 4e, 4μ, and 2e2μ channels, and the sum of all the 2ℓ2τ channels. The shapes of the signal and background are taken from the MC simulation, with each component normalized to the corresponding estimated value from table 1. The reconstructed masses in 2ℓ2τ states ($m_{2\ell2\tau}^{\text{vis}}$) are shifted downwards with respect to the generated Z masses by about 30% due to the undetected neutrinos in τ decays. Figures 1 (c) and (d) demonstrate the relationship between the reconstructed Z_1 and Z_2 masses.

To include all the final states in the calculation of the cross section, a simultaneous fit to the numbers of observed events in all the decay channels is performed. The fit is constrained by the requirement that all the measurements come from the same initial state via different decay modes. It allows for combining many decay modes with either very few or no events observed. The joint likelihood is a combination of the likelihoods for the individual channels, which include the signal and background hypotheses. Each τ-lepton decay mode is treated as a separate channel because they are mutually exclusive owing to the methodology adopted for event reconstruction and subsequent event selection. The statistical and systematic uncertainties are introduced in the form of nuisance parameters via log-normal distributions around the estimated central values.

The resulting cross section is measured to be

$$\sigma(\text{pp} \to \text{ZZ}) = 6.24\,{}^{+0.86}_{-0.80}\,(\text{stat.})\,{}^{+0.41}_{-0.32}\,(\text{syst.}) \pm 0.14\,(\text{lumi.})\,\text{pb}.$$

This result is to be compared to the theoretical value of 6.3 ± 0.4 pb calculated with MCFM at NLO for q$\bar{\text{q}}$ → ZZ and LO for gg → ZZ with the MSTW08 PDFs and for both Z bosons in the mass range $60 < m_Z < 120$ GeV. This is the most precise published pp → ZZ cross section measurement to date, which for the first time extends the pp → ZZ → 2ℓ2ℓ measurement to include final states with hadronically decaying τ leptons.

The limits on ATGCs are calculated with the modified frequentist construction CL_s [37–39] based on the shape of the four-lepton invariant mass distributions, including the 4e, 4μ, and 2e2μ channels in the likelihood combination. Figure 2 presents the distribution of the four-lepton reconstructed mass for the sum of the 4e, 4μ, and 2e2μ channels. The dashed and dotted histograms represent the results of the SHERPA simulation for the SM ($f_4^Z = 0$) and in the presence of an ATGC ($f_4^Z = 0.015$), while all the other anomalous couplings are set to zero. The presence of ATGCs would be manifested in an increased yield of events at high four-lepton masses. The invariant mass distributions are interpolated from SHERPA simulation for different values of the anomalous couplings. For each distribution only one or two couplings are varied, while all others are set to zero. The fit is performed to find the maximum likelihood value and limits are calculated. To avoid unitarity violation at energies above the scale Λ of new physics, the ATGCs are often modified with a form-factor parametrization of the type $1/(1 + \hat{s}/\Lambda^2)^2$, where $\sqrt{\hat{s}} \approx m_{2\ell2\ell}$
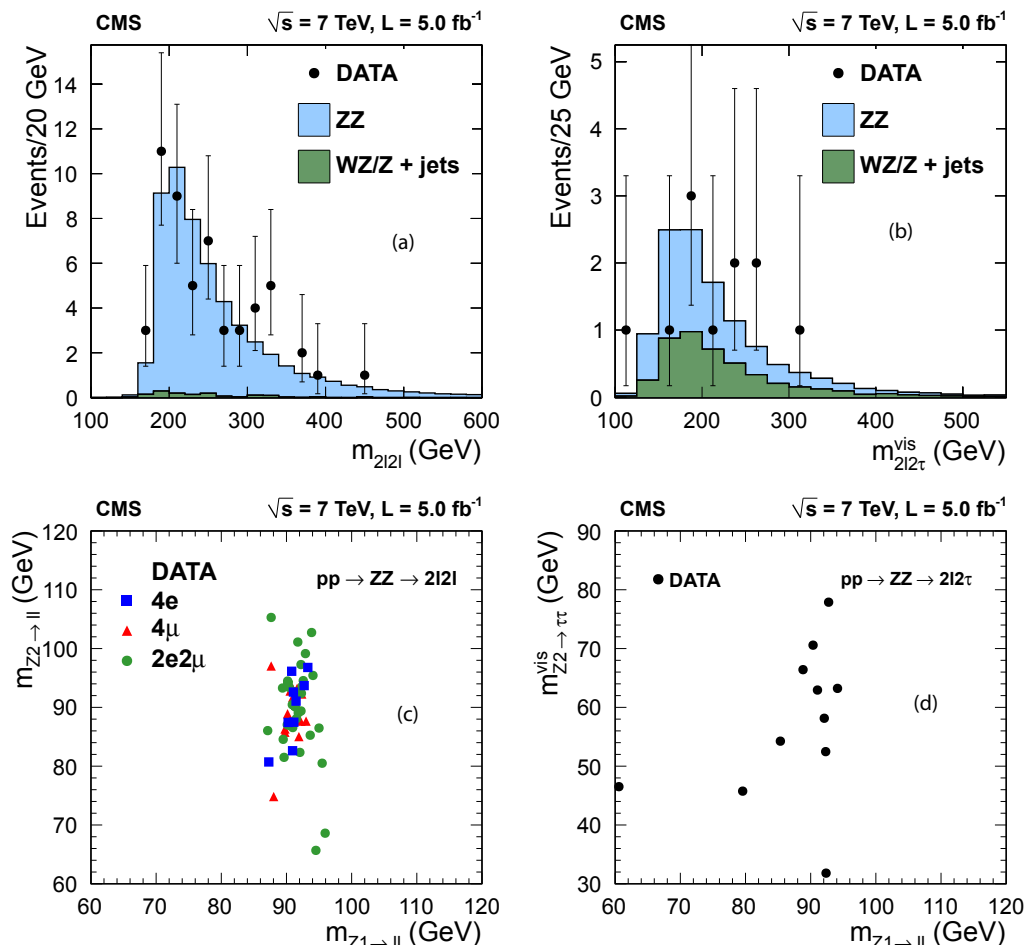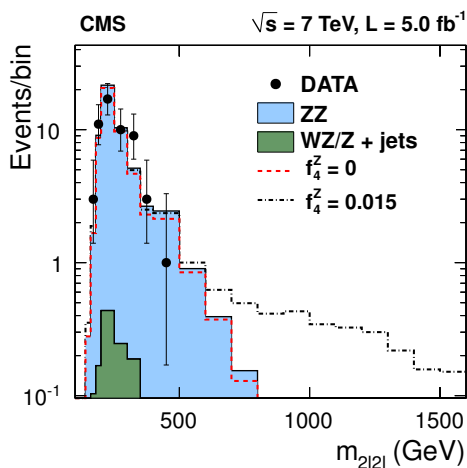
Figure 1. Distributions of the four-lepton reconstructed mass for (a) the sum of the $4e, 4\mu$, and $2e2\mu$ channels and (b) the sum of the $2\ell2\tau$ channels. Points represent the data, and the shaded histograms represent the expected ZZ signal and the reducible background. The shapes of the signal and background are taken from the MC simulation, with each component normalized to the corresponding estimated value from table 1. The distributions (c) and (d) demonstrate the relationship between the reconstructed Z_1 and Z_2 masses.

is the effective center-of-mass energy of the collision. However, no unitarity violations occur in the sensitive region $m_{2\ell2\ell} \lesssim 1.5\,\mathrm{TeV}$ for bare anomalous couplings of order 0.05 or smaller [40], so we calculate the limits without form-factor scaling. This choice has the advantage of avoiding any bias from energy-dependence assumptions and is exact in the limit in which the scale of new physics is much larger than $\sqrt{\hat{s}}$.

Figure 3 presents the expected and observed two-dimensional exclusion limits at 95% confidence level (CL) on the anomalous neutral trilinear ZZZ and ZZγ couplings. The green and yellow bands represent the one and two standard-deviation variations from the expected limit. The present limits are dominated by statistical uncertainties. Systematic uncertainties arising from the uncertainty on the theoretical cross section, PDFs, detector

Figure 2. Distribution of the four-lepton reconstructed mass for the sum of the $4e, 4\mu$, and the $2e2\mu$ channels. Points represent the data, and the shaded histograms represent the expected ZZ signal and the reducible background. The dashed and dotted histograms represent the results of the SHERPA simulation for the SM ($f_4^Z = 0$) and in the presence of an ATGC ($f_4^Z = 0.015$), while all the other anomalous couplings are set to zero.
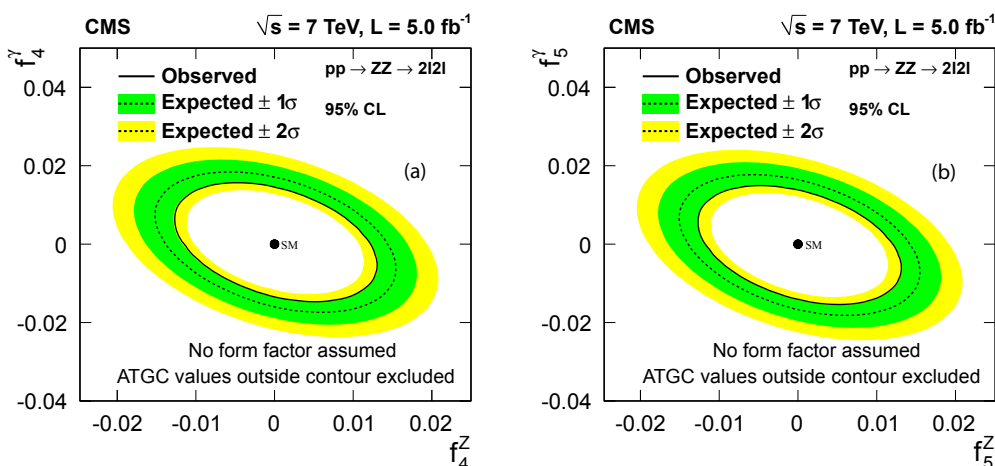
Figure 3. Expected and observed two-dimensional exclusion limits at 95% CL on the anomalous neutral trilinear ZZZ ($f_{4,5}^Z$) and ZZγ ($f_{4,5}^\gamma$) couplings. The green and yellow bands represent the one and two standard-deviation variations from the expected limit. In calculating the limits, the anomalous couplings that are not shown in the figure are set to zero.

efficiencies, and luminosity are introduced in the form of nuisance parameters with log-normal probability density functions. One-dimensional 95% CL limits for the $f_4^{Z,\gamma}$ and $f_5^{Z,\gamma}$ anomalous coupling parameters are measured to be

$$-0.011 < f_4^Z < 0.012, \ -0.012 < f_5^Z < 0.012, \ -0.013 < f_4^\gamma < 0.015, \ -0.014 < f_5^\gamma < 0.014.$$

In the one-dimensional fits, all of the ATGC parameters except the one under study are kept fixed to zero. These values extend previous results on vector boson self-interactions and are currently the most stringent limits established for ZZZ and ZZγ couplings.

In summary, we have presented an updated measurement of the ZZ production cross section in proton-proton collisions at 7 TeV in the ZZ $\rightarrow 2\ell2\ell'$ decay mode, with $\ell = $ e, μ and $\ell' = $ e, μ, τ. The data sample corresponds to an integrated luminosity of $5.0\,\mathrm{fb}^{-1}$. The measured cross section $\sigma(\mathrm{pp} \rightarrow \mathrm{ZZ}) = 6.24\,^{+0.86}_{-0.80}\,(\mathrm{stat.})\,^{+0.41}_{-0.32}\,(\mathrm{syst.}) \pm 0.14\,(\mathrm{lumi.})\,$pb is consistent with the SM prediction and is the most precise published pp $\rightarrow$ ZZ cross section measurement to date. For the first time the pp $\rightarrow$ ZZ $\rightarrow 2\ell2\ell$ measurements are extended to include final states with hadronically decaying τ leptons. Limits on vector-boson self-interactions are established, significantly restricting anomalous ZZZ and ZZγ trilinear gauge couplings.

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