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Measurement of the production cross section for $Z\gamma \to \nu\bar{\nu}\gamma$ in pp collisions at $\sqrt{s} = 7\,\text{TeV}$ and limits on $ZZ\gamma$ and $Z\gamma\gamma$ triple gauge boson couplings

The CMS Collaboration[*]

Abstract

A measurement of the $Z\gamma \to \nu\bar{\nu}\gamma$ cross section in pp collisions at $\sqrt{s} = 7\,\text{TeV}$ is presented, using data corresponding to an integrated luminosity of $5.0\,\text{fb}^{-1}$ collected with the CMS detector. This measurement is based on the observation of events with an imbalance of transverse energy in excess of 130 GeV and a single photon in the absolute pseudorapidity range $|\eta| < 1.4$ with transverse energy above 145 GeV. The $Z\gamma \to \nu\bar{\nu}\gamma$ production cross section is measured to be $21.1 \pm 4.2\,(\text{stat.}) \pm 4.3\,(\text{syst.}) \pm 0.5\,(\text{lum.})\,\text{fb}$, which agrees with the standard model prediction of $21.9 \pm 1.1\,\text{fb}$. The results are combined with the CMS measurement of $Z\gamma$ production in the $\ell^+\ell^-\gamma$ final state (where ℓ is an electron or a muon) to yield the most stringent limits to date on triple gauge boson couplings: $|h_3^Z| < 2.7 \times 10^{-3}$, $|h_4^Z| < 1.3 \times 10^{-5}$ for $ZZ\gamma$ and $|h_3^\gamma| < 2.9 \times 10^{-3}$, $|h_4^\gamma| < 1.5 \times 10^{-5}$ for $Z\gamma\gamma$ couplings.

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

1 Introduction

The study of the production of pairs of gauge bosons in high-energy particle collisions provides an important test of the electroweak sector of the standard model (SM). The diboson production rate is sensitive to the gauge boson self-interactions that arise as a consequence of the non-Abelian nature of the SU(2)×U(1) symmetry of the SM. The values of these couplings are fixed in the SM, and any observed deviation from the SM predictions would be an indication of new physics at the vertex involving the bosons [1, 2]. In most searches for anomalous triple gauge couplings (TGCs), including this study, the boson transverse energy spectrum is used as a sensitive observable, as new physics is likely to result in an excess of energetic bosons over the SM expectation.

In this paper, a study of the production of a Z boson and a photon, with the Z boson decaying to a pair of neutrinos, is presented. We describe the measurement of the production cross section as well as the extraction of limits on the anomalous couplings for $\mathrm{ZZ}\gamma$ and $\mathrm{Z}\gamma\gamma$.

The $\nu\bar{\nu}\gamma$ final state can be produced through initial-state radiation, where a photon is emitted by an initial-state parton, or through anomalous coupling vertices. The allowed electroweak tree-level diagram in the SM for $\mathrm{Z}\gamma$ production in pp collisions is shown in Fig. 1 (left). The photon produced in the s channel via an anomalous $\mathrm{ZZ}\gamma$ or $\mathrm{Z}\gamma\gamma$ TGC is shown in Fig. 1 (right).

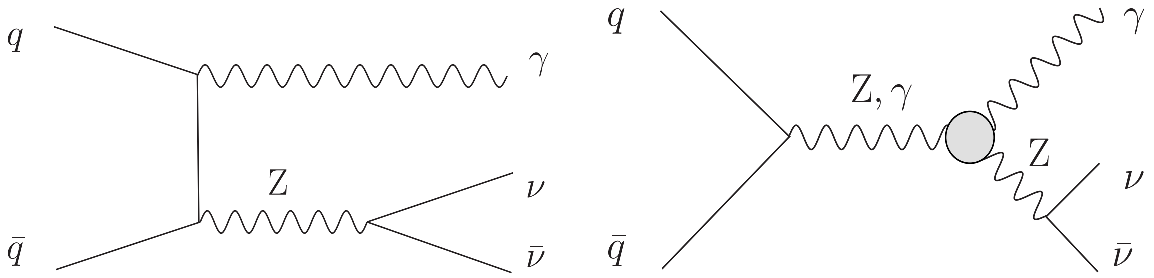

Figure 1: Feynman diagrams of $\mathrm{Z}\gamma$ production via initial state radiation in the SM at tree level (left) and via anomalous $\mathrm{ZZ}\gamma$ and $\mathrm{Z}\gamma\gamma$ triple gauge couplings (right).

The most general Lorentz- and gauge-invariant $\mathrm{ZV}\gamma$ vertex can be described by four coupling parameters h_i^{V} $(i = 1, \ldots, 4)$ [3, 4], where V denotes either a photon or a Z boson. The first two couplings $(i = 1, 2)$ are CP-violating, while the latter two are CP-conserving [4, 5]. At tree level in the SM, the individual values of these TGCs are zero. The photon transverse energy spectrum has similar sensitivity to CP-violating and CP-conserving couplings [6]. Therefore, the results are generally interpreted in terms of CP-conserving TGCs h_3^{V} and h_4^{V}.

The sensitivity to TGCs in $\mathrm{Z}\gamma$ production is higher in the $\mathrm{Z} \to \nu\bar{\nu}$ decay mode than in Z boson decay modes with charged leptons for two reasons. First, the branching fraction for a Z boson decay to a pair of neutrinos is six times higher than for a decay to a particular charged lepton pair. Second, the neutrino channel acceptance is higher.

Searches for anomalous $\mathrm{ZZ}\gamma$ and $\mathrm{Z}\gamma\gamma$ TGCs have been performed at LEP [7–9], the Tevatron [10–12], and the Large Hadron Collider (LHC) [13, 14]. No evidence has been found; the most stringent limits in pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$ were set by the ATLAS Collaboration [14].

2 CMS detector

The measurements reported here are based on a data set corresponding to an integrated luminosity of $5.0\,\mathrm{fb}^{-1}$, collected in 2011 at a center-of-mass energy of $\sqrt{s} = 7\,\mathrm{TeV}$ with the Compact Muon Solenoid (CMS) detector at the LHC. The momenta of charged particles are measured by a silicon pixel and strip tracker. The tracking system is surrounded by a crystal electromagnetic calorimeter and a brass-scintillator hadron calorimeter, which measure particle energies deposited in a barrel and two endcaps. The tracking system and calorimeters are immersed in a 3.8 T magnetic field provided by the superconducting solenoid. Muons are measured in gas-ionization detectors embedded in the steel yoke outside the solenoid. A more detailed description of the CMS detector can be found in Ref. [15]. The trajectory of the particles in the detector can be described by the azimuthal angle ϕ, measured in the x-y plane with respect to the x axis, and the pseudorapidity η, defined as $\eta = -\ln\tan(\theta/2)$, where θ is the polar angle of the trajectory of the particle with respect to counterclockwise beam direction.

3 Data selection and analysis

Candidate events are selected in the experiment using unprescaled single-photon triggers with the lower threshold on photon transverse energy ranging from 75 to 135 GeV as defined by the two-level CMS trigger system. The triggers are fully efficient within 2% statistical uncertainty for photons with pseudorapidity $|\eta| < 1.4$ and transverse energy $E_{\mathrm{T}}^{\gamma} > 145\,\mathrm{GeV}$.

The final state consisting of an energetic photon accompanied by an imbalance of transverse energy can be mimicked by several other processes in the SM with at least one photon in the final state, such as $\mathrm{W}\gamma$, γ+jets, and $\gamma\gamma$ processes, in which only a single energetic photon is reconstructed in the event. Additionally, there are instrumental backgrounds as discussed later in the paper. Characteristics of both the signal and background events have been studied using simulated events. A sample of signal events $\mathrm{Z}\gamma \to \nu\bar{\nu}\gamma$ is obtained using the PYTHIA v6.424 [16] event generator at leading order. The $\mathrm{W}\gamma$ events are generated with the MADGRAPH v5 generator [17], and the cross section is corrected to include next-to-leading-order (NLO) effects through a K factor calculated with the MCFM program [18, 19]. The γ+jets, W boson, and diphoton samples are obtained using PYTHIA. We do not consider final-state radiation $\mathrm{W} \to \ell\nu\gamma$ events in the PYTHIA W boson sample as those are included in the MADGRAPH $\mathrm{W}\gamma$ sample. All leading-order simulation samples are propagated using CTEQ6L1 [20] parton distribution functions (PDFs).

To distinguish photons from misidentified jets, we apply additional calorimetric selection criteria by requiring the shower shape to be consistent with that of an electromagnetic particle [21]. To further reduce the contribution from processes with misidentified jets, the photons are required to be isolated from other activity in the electromagnetic and hadronic calorimeters as well as the tracker. In particular, the scalar sum of the transverse component of the energy deposits (E_{T}) in the electromagnetic calorimeter within an annulus of $0.06 < \Delta R < 0.40$ centered on the photon candidate, where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$, must not exceed 5 GeV, while that in the hadronic calorimeter within an annulus of $0.15 < \Delta R < 0.40$ must be below 2.6 GeV. The scalar sum of the transverse momenta of charged particles, originating from the primary vertex, in an annulus of $0.04 < \Delta R < 0.40$ must be below 2.1 GeV; the central cone around the photon, $\Delta R < 0.04$, is excluded to maintain a high efficiency for photons that initiate electromagnetic showers early in the tracker. Since the high instantaneous luminosity operation of the LHC results in multiple pp interactions in a single bunch crossing (pileup), the track isolation is calculated separately with respect to each vertex in the event; the largest value of this isolation is then required to satisfy the track isolation condition. This procedure reduces the background from jets originating from other vertices in the event corresponding to soft scattering processes.

Beam-halo muons are machine-induced particles that travel parallel to the beam line. When such muons interact with the electromagnetic calorimeter they can undergo a bremsstrahlung process resulting in an electromagnetic energy deposition identified as a photon. To reduce the background due to bremsstrahlung photons from beam-halo and cosmic-ray muons, the timing of the photon measured in the CMS ECAL detector [22] is required to be consistent with that of the beam crossing. To further reduce this background, additional requirements are imposed on the photon candidates in events containing reconstructed muons. Furthermore, to minimize the background due to the electrons from $\mathrm{W} \to \mathrm{e}\nu$ decays that are misidentified as photons, the photons that have a pattern of hits in the pixel detector similar to that expected for electrons are rejected [23].

The imbalance of the transverse energy, $E_{\mathrm{T}}^{\text{miss}}$, in the reconstructed event is defined by the magnitude of the vector sum of the transverse energies of all the reconstructed objects in the event, and is computed using a particle-flow algorithm [24]. The signal events have an $E_{\mathrm{T}}^{\text{miss}}$ comparable in magnitude to the photon transverse energy because the neutrinos from the Z boson decay recoil against the photon. In this study, events are required to have $E_{\mathrm{T}}^{\text{miss}} > 130\,\text{GeV}$, which is less stringent than the 145 GeV requirement on the photon E_{T}. The $E_{\mathrm{T}}^{\text{miss}}$ criterion is fully efficient for signal events and reduces a potential systematic uncertainty related to the modeling of $E_{\mathrm{T}}^{\text{miss}}$ in the simulation.

Finally, events are vetoed if they contain other particles of significant energy or momentum, defined by (i) a track with $p_{\mathrm{T}} > 20\,\text{GeV}$ that is $\Delta R > 0.04$ away from the photon or (ii) a jet, reconstructed with $p_{\mathrm{T}} > 40\,\text{GeV}$ using the particles in the event identified by the particle-flow algorithm and clustered using an anti-k_{T} formalism [25] with a distance parameter of 0.5, within $|\eta| < 3.0$ and $\Delta R < 0.5$ of the axis of the photon. After applying all of the selection criteria, 73 candidate events are selected.

The background from misidentified photons originating in jet fragmentation and decay processes is estimated by constructing a control sample in data, enriched with multijet events. We use this sample to calculate a misidentification ratio, defined as the number of events where the photon candidate satisfies the signal selection criteria to the number of events where the photon candidate satisfies looser selection criteria but fails the isolation condition. Since not all photon candidates in the multijet control sample are from misidentified jets, a correction is applied for genuine photons from direct photon production in the multijet sample. The photon contribution is estimated by means of a fit to the shower shape profile of photon candidates in the control data sample, where the distribution for genuine photons is taken from simulated γ+jets events; this contribution is subtracted from both the numerator and denominator of the misidentification ratio. The corrected ratio is then multiplied by the number of events in the signal data sample that pass the photon selection criteria but fail the isolation requirements. The background contribution due to misidentified jets is estimated to be $11.2 \pm 1.6\,(\text{stat.}) \pm 2.2\,(\text{syst.})$ events. The systematic uncertainty reflects the modeling of the genuine photon shower profile in the simulation, as well as the dependence of the misidentification ratio on the choice of the looser selection criteria and isolation requirements.

The dominant background where an electron is misidentified as a photon is $\mathrm{W} \to \mathrm{e}\nu$ production. The contribution from this process is estimated from a control sample, dominated by $\mathrm{W} \to \mathrm{e}\nu$ events, that is selected by requiring events to pass the full selection criteria except for the requirement of no pixel hits for the photon. Then, the contribution to the $\mathrm{Z}\gamma$ sample from processes with misidentified electrons is estimated by scaling the control sample by $(1 - \epsilon_{\mathrm{ps}})/\epsilon_{\mathrm{ps}}$, where ϵ_{ps} is the probability for an electron to produce hits during its passage through the pixel detector. The value of ϵ_{ps} is estimated from a $\mathrm{Z} \rightarrow \mathrm{ee}$ data sample to be $\epsilon_{\mathrm{ps}} = 0.994 \pm 0.003$. The estimated number of events with misidentified electrons is $3.5 \pm 0.1\,(\text{stat.}) \pm 1.5\,(\text{syst.})$. The systematic uncertainty is dominated by the uncertainty in measuring ϵ_{ps} in $\mathrm{Z} \rightarrow \mathrm{ee}$ events.

The total amount of background from γ+jet, Wγ, and diphoton processes, after the full selection, is estimated from simulation to be $4.4 \pm 1.0\,(\text{stat.}) \pm 0.4\,(\text{syst.})$ events. The uncertainty in the simulated backgrounds takes into account the uncertainty in the scale factor that corrects for the data-simulation difference in the efficiency.

The out-of-time backgrounds, which are not produced via pp interactions, are from beam-halo muons, cosmic rays, and anomalous signals due to neutron interactions with the electromagnetic calorimeter readout system which can produce a final-state signature of a single photon and an imbalance of transverse energy. The contributions from these sources are estimated with data from the timing and the shapes of the shower energy deposition in the ECAL calorimeter using the methods described in Ref. [26]. All contributions are found to be negligible except for the beam-halo muon process, which is estimated to contribute $11.1 \pm 0.6\,(\text{stat.}) \pm 5.5\,(\text{syst.})$ events. The uncertainty in the prediction is calculated by propagating the uncertainty in the shape of the timing distribution for the beam-halo bremsstrahlung shower.

4 Cross section measurement

The expected cross section of the signal process for $E_{\mathrm{T}}^{\gamma} > 145\,\mathrm{GeV}$ and $|\eta| < 1.4$, obtained with the NLO generator WGRAD [4], is $21.9 \pm 1.1\,\mathrm{fb}$. A consistent prediction of $24.6 \pm 2.5\,\mathrm{fb}$ is obtained with MCFM. The quoted uncertainties in both predictions take into account the PDF and scale uncertainties. Based on the WGRAD prediction, the expected number of $\mathrm{Z}(\nu\overline{\nu})\gamma$ signal events is $45.3 \pm 0.3\,(\text{stat.}) \pm 6.9\,(\text{syst.})$. The total number of expected background events is $30.2 \pm 2.0\,(\text{stat.}) \pm 6.2\,(\text{syst.})$. A summary of the backgrounds and data yield is given in Table 1, wherein the uncertainties in the background estimates include both statistical and systematic sources.

Table 1: Summary of estimated backgrounds to the $\mathrm{Z}(\nu\overline{\nu})\gamma$ process. The statistical and systematic uncertainties are added in quadrature.

Source	Number of selected events
Misidentified jets	11.2 ± 2.8
Beam-halo muon processes	11.1 ± 5.6
Misidentified electrons	3.5 ± 1.5
Wγ	3.3 ± 1.0
$\gamma\gamma$	0.6 ± 0.3
γ+jet	0.5 ± 0.2
Total background	30.2 ± 6.5
$\mathrm{Z}\gamma \rightarrow \nu\overline{\nu}\gamma$ (NLO)	45.3 ± 6.9
Data	73

The $\mathrm{Z}\gamma \rightarrow \nu\overline{\nu}\gamma$ cross section for $E_{\mathrm{T}}^{\gamma} > 145\,\mathrm{GeV}$ and $|\eta| < 1.4$ is calculated using the following formulae:

$$\sigma \times \mathcal{B} = \frac{N_{\mathrm{data}} - N_{\mathrm{bg}}}{A \times \epsilon \times L},$$

$$A \times \epsilon = (A \times \epsilon)_{\mathrm{sim}} \times \rho,$$

where N_{data} is the number of observed events, N_{bg} is the estimated number of background events, A is the geometrical and kinematic acceptance of the selection criteria, ϵ is the signal selection efficiency, and L is the integrated luminosity. The product of $A \times \epsilon$ is estimated from the simulation to be 0.452 ± 0.003, where the uncertainty is statistical. The correction factor $\rho = 0.90 \pm 0.11$ takes into account the efficiency difference between data and simulation for the trigger, photon reconstruction and identification, consistency of cluster timing, and jet and track veto requirements [26].

The largest contribution to the systematic uncertainty in $(A \times \epsilon)_{\mathrm{sim}}$ comes from the modeling of the photon energy scale [21], which gives 4.3%. The uncertainties in the PDFs [20, 27, 28] and the pileup each contribute 2.4%. Additionally, there are systematic uncertainties due to the energy scale and resolution in the measurement of $E_{\mathrm{T}}^{\mathrm{miss}}$ [29], the jet energy scale and resolution [30], and the selection of the photon production vertex; each of these contribute less than 3%. All these uncertainties are summarized in Table 2. The systematic uncertainty in the measured integrated luminosity is 2.2% [31].

Table 2: Systematic uncertainties in $(A \times \epsilon)_{\mathrm{sim}}$.

Source	Systematic uncertainty in $(A \times \epsilon)_{\mathrm{sim}}$ (%)
Photon energy scale	$\pm$ 4.3
$E_{\mathrm{T}}^{\mathrm{miss}}$ scale	$+1.6$ -3.1
$E_{\mathrm{T}}^{\mathrm{miss}}$ resolution	$\pm$ 0.03
Jet energy scale	$\pm$ 0.8
Jet energy resolution	$\pm$ 0.2
Identification of photon vertex	$\pm$ 0.3
Pileup modeling	$\pm$ 2.4
PDF modeling	$\pm$ 2.4
Total	$+5.7$ -6.3

The measured production cross section for $Z\gamma \to \nu\bar{\nu}\gamma$ for $E_{\mathrm{T}}^{\gamma} > 145\,\mathrm{GeV}$ and $|\eta| < 1.4$ is $21.1 \pm 4.2\,(\mathrm{stat.}) \pm 4.3\,(\mathrm{syst.}) \pm 0.5\,(\mathrm{lum.})\,\mathrm{fb}$, which is in agreement with the theoretical cross section, predicted at NLO, of $21.9 \pm 1.1\,\mathrm{fb}$.

The distributions of photon transverse energy and $E_{\mathrm{T}}^{\mathrm{miss}}$ are given in Fig. 2, with the signal and background predictions overlaid. The expected contributions from a nonvanishing neutral TGC are also shown. Such a coupling would give rise to more events with large E_{T}^{γ} and $E_{\mathrm{T}}^{\mathrm{miss}}$ than predicted in the SM. No excess of events is observed.

5 Limits on triple gauge couplings

We use the E_{T}^{γ} spectrum to set limits on anomalous TGCs by means of the likelihood formalism. Simulated samples of $Z\gamma$ signal for a grid of TGC values are produced using the SHERPA v1.2.2 generator [32]. In this study, we follow the CMS convention of not suppressing the anomalous TGCs by an energy-dependent form factor.

The probability of observing the number of data events in a given range of E_{T}^{γ} is estimated using a Poisson distribution given by the expected signal and background predictions. The uncertainties in the quoted luminosity, signal efficiency, and background fraction are considered to follow a log-normal distribution. Limits on TGCs are calculated on the basis of a modified frequentist $\mathrm{CL_s}$ method as described in Refs. [33, 34].

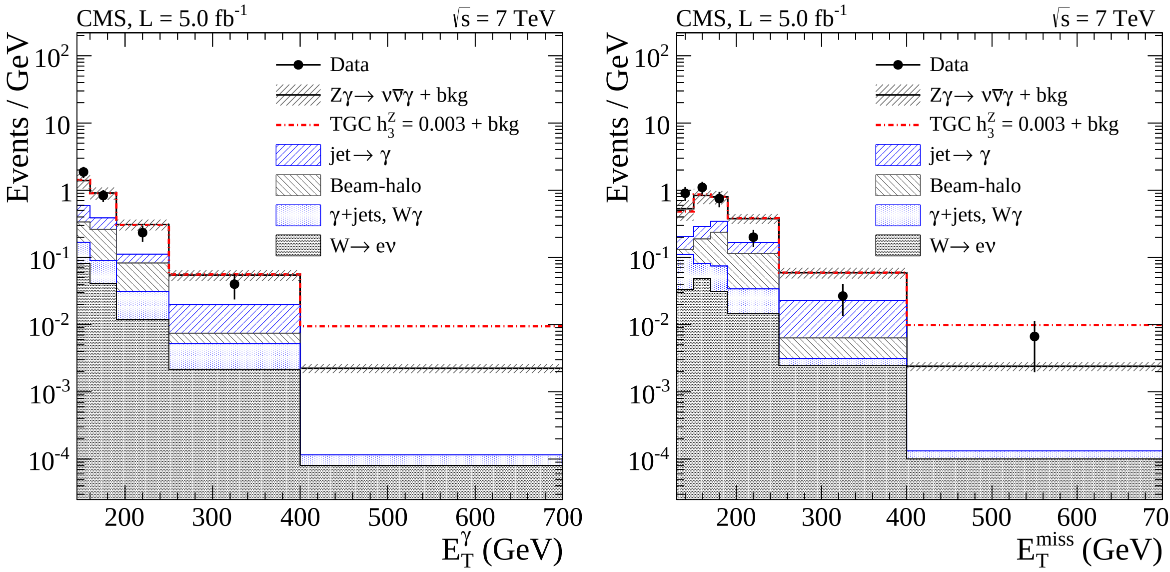

Figure 2: The E_T^γ and E_T^{miss} distributions in data (points with error bars) compared with the SM $Z\gamma \to \nu\bar{\nu}\gamma$ signal and estimated contributions from backgrounds (filled histograms). The shaded band illustrates the total uncertainty in the predicted distribution of the signal plus background hypothesis. A typical anomalous TGC signal would provide an excess, as shown in the dot-dashed histogram. The last bin in the distributions includes overflows.

Limits at 95% CL are set on pairs of TGC parameters (h_3^Z, h_4^Z) and (h_3^γ, h_4^γ), as presented in Fig. 3. Furthermore, one-dimensional 95% CL limits are obtained for a given anomalous TGC while setting the other neutral TGCs to their SM values, i.e., to zero. The results, illustrated in Figs. 4 and 5, are $|h_3^Z| < 3.1 \times 10^{-3}$, $|h_4^Z| < 1.4 \times 10^{-5}$, $|h_3^\gamma| < 3.2 \times 10^{-3}$, and $|h_4^\gamma| < 1.6 \times 10^{-5}$.

We combine the results presented here, based on the Z boson decay to neutrinos, with those obtained by analysis of $Z\gamma$ candidate events where the Z boson decays to a pair of electrons or muons [35]. The combination is performed by summing the negative log-likelihoods at each TGC hypothesis tested. The combined limits are set in the same way as for each individual channel, while also accounting for correlations between the systematic uncertainties in different channels. The resulting two-dimensional 95% CL bounds on TGCs are given in Fig. 6, and one-dimensional limits are as follows: $|h_3^Z| < 2.7 \times 10^{-3}$, $|h_4^Z| < 1.3 \times 10^{-5}$, $|h_3^\gamma| < 2.9 \times 10^{-3}$, and $|h_4^\gamma| < 1.5 \times 10^{-5}$.

6 Summary

In conclusion, we have presented a measurement of the $Z\gamma \to \nu\bar{\nu}\gamma$ production cross section in pp collisions at $\sqrt{s} = 7\,\text{TeV}$ in $5.0\,\text{fb}^{-1}$ of CMS data. The measured $Z(\nu\bar{\nu})\gamma$ cross section for photons with $E_T > 145\,\text{GeV}$ and $|\eta| < 1.4$ is $21.1 \pm 4.2\,(\text{stat.}) \pm 4.3\,(\text{syst.}) \pm 0.5\,(\text{lum.})\,\text{fb}$, in agreement with the SM NLO prediction of 21.9 ± 1.1 fb. No evidence was found for anomalous neutral triple gauge couplings in $Z\gamma$ production and 95% CL limits have been placed on the h_3^V and h_4^V parameters of $ZZ\gamma$ and $Z\gamma\gamma$ couplings: $|h_3^Z| < 3.1 \times 10^{-3}$, $|h_4^Z| < 1.4 \times 10^{-5}$, $|h_3^\gamma| < 3.2 \times 10^{-3}$, and $|h_4^\gamma| < 1.6 \times 10^{-5}$. These results, combined with those obtained from Z boson decays to a pair of electrons or muons, yield the most stringent limits to date on neutral triple gauge couplings: $|h_3^Z| < 2.7 \times 10^{-3}$, $|h_4^Z| < 1.3 \times 10^{-5}$ for $ZZ\gamma$ couplings and $|h_3^\gamma| < 2.9 \times 10^{-3}$, $|h_4^\gamma| < 1.5 \times 10^{-5}$ for $Z\gamma\gamma$. The results from the $\nu\bar{\nu}\gamma$ analysis dominate the sensitivity to anomalous TGCs in $Z\gamma$ production.

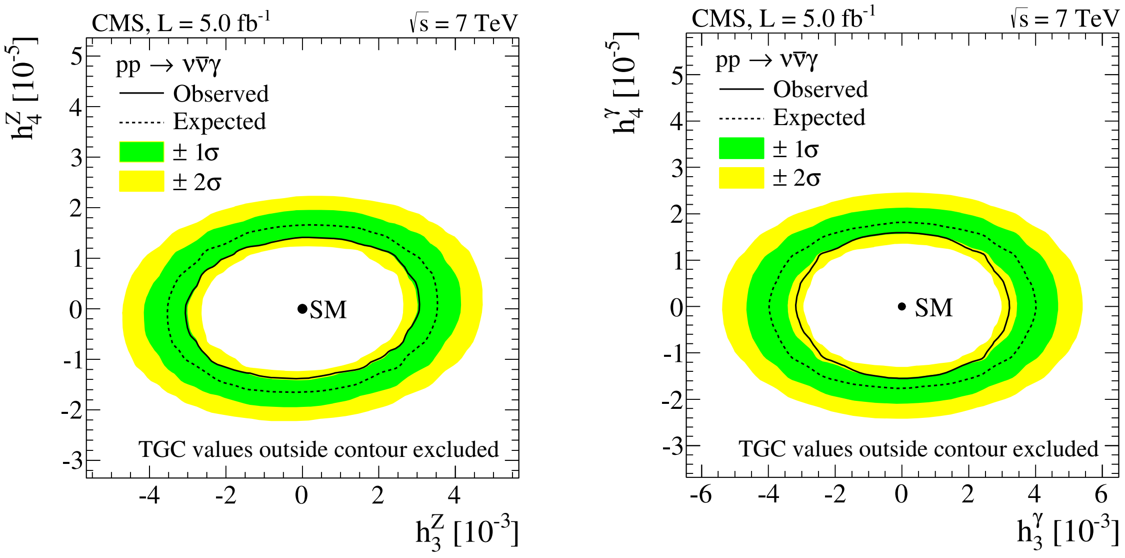

Figure 3: Two-dimensional 95% CL limits on $ZZ\gamma$ couplings (left) and $Z\gamma\gamma$ couplings (right).

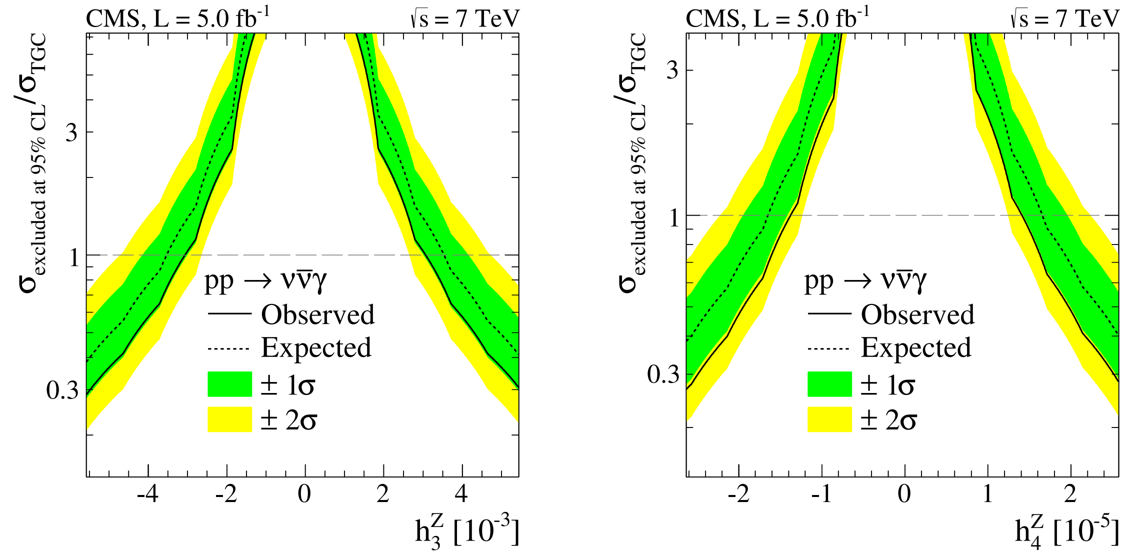

Figure 4: Cross section limits as functions of the $ZZ\gamma$ couplings h_3^Z (left) and h_4^Z (right). The vertical axis represents the ratio of the 95% CL upper limit on the signal contribution from anomalous couplings to the expected contribution for a given TGC hypothesis.

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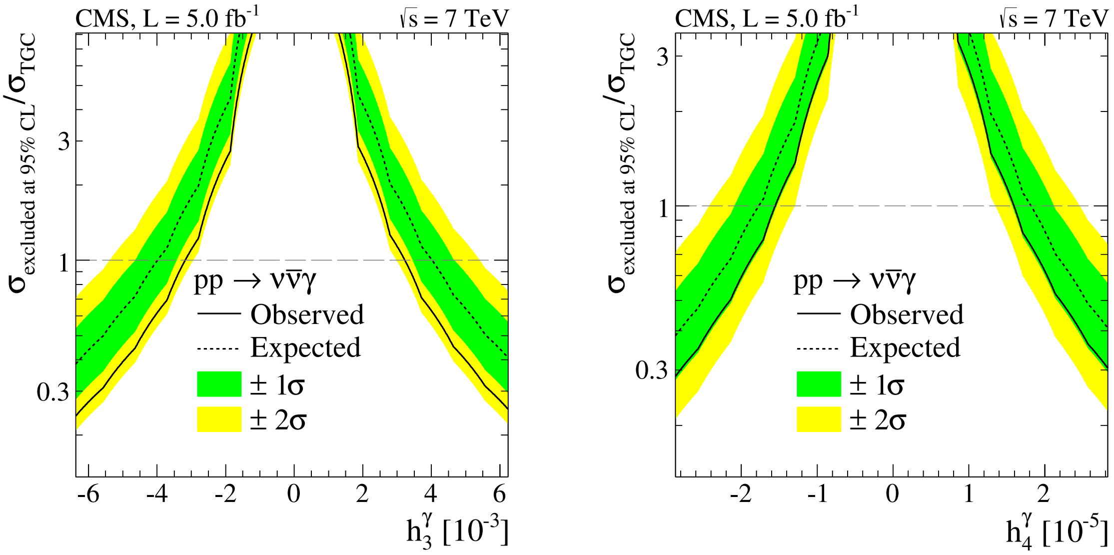

Figure 5: Cross section limits as functions of the $Z\gamma\gamma$ couplings h_3^γ (left) and h_4^γ (right). The vertical axis represents the ratio of the 95% CL upper limit on the signal contribution from anomalous couplings to the expected contribution for a given TGC hypothesis.

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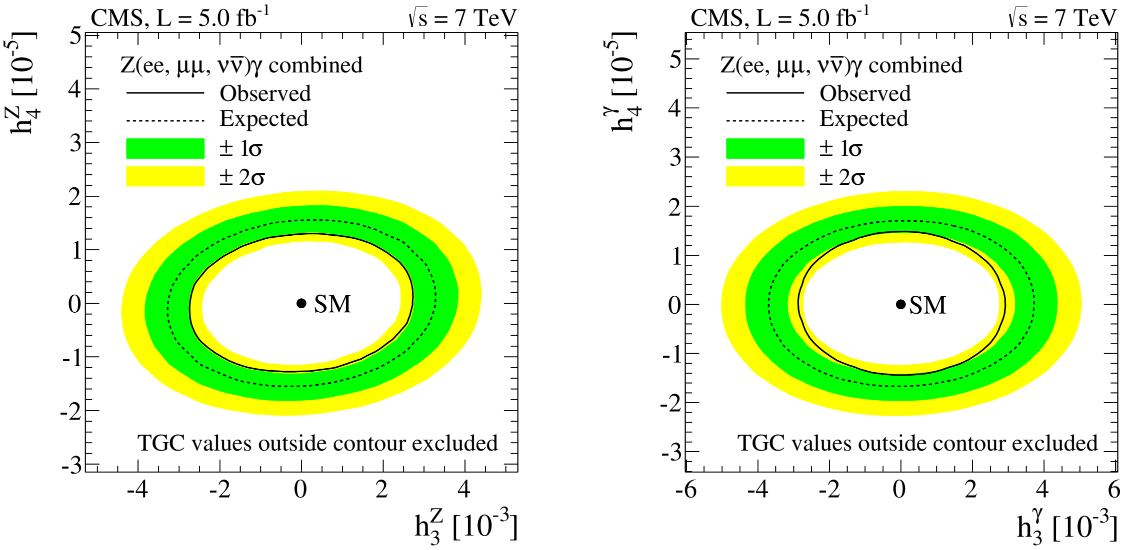

Figure 6: Two-dimensional 95% CL limits on ZZγ couplings (left) and Z$\gamma\gamma$ couplings (right) for combined neutral and charged leptonic channels.

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