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Measurement of the $Z\gamma \to \nu\overline{\nu}\gamma$ production cross section in pp collisions at $\sqrt{s} = 8$ TeV and limits on anomalous $ZZ\gamma$ and $Z\gamma\gamma$ trilinear gauge boson couplings

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An inclusive measurement of the $Z\gamma \to \nu\overline{\nu}\gamma$ production cross section in pp collisions at $\sqrt{s} = 8$ TeV is presented, using data corresponding to an integrated luminosity of $19.6\,\mathrm{fb}^{-1}$ collected with the CMS detector at the LHC. This measurement is based on the observation of events with large missing energy and with a single photon with transverse momentum above 145 GeV and absolute pseudorapidity in the range $|\eta| < 1.44$. The measured $Z\gamma \to \nu\overline{\nu}\gamma$ production cross section, $52.7 \pm 2.1\,(\mathrm{stat}) \pm 6.4\,(\mathrm{syst}) \pm 1.4\,(\mathrm{lumi})\,\mathrm{fb}$, agrees well with the standard model prediction of $50.0^{+2.4}_{-2.2}$ fb. A study of the photon transverse momentum spectrum yields the most stringent limits to date on the anomalous $ZZ\gamma$ and $Z\gamma\gamma$ trilinear gauge boson couplings.

1. Introduction

The study of the production of boson pairs provides an important test of the electroweak sector of the standard model (SM), since this production is a consequence of the non-Abelian nature of the underlying $SU(2) \times U(1)$ symmetry. Trilinear gauge boson vertices are a consequence of this symmetry, and the values of the self-couplings are fixed in the SM. Any measured deviation would be an indication of physics beyond the standard model at that vertex. For production of a Z boson and a photon, these couplings are zero in the SM. New symmetries or new particles that only become relevant at higher energies could result in a cross section that differs from the SM prediction [1,2], particularly for final-state bosons with high transverse momentum.

In this letter a measurement is presented of the production of a Z boson, which decays into a pair of neutrinos, and a photon in proton–proton collisions, at a centre-of-mass energy of $\sqrt{s} = 8$ TeV, using data collected by the CMS experiment corresponding to an integrated luminosity of $19.6\,\mathrm{fb}^{-1}$. This result extends previous measurements at the LHC [3–5]. We describe a measurement of the production cross section as well as the extraction of limits on anomalous $ZV\gamma$ couplings, where $V = Z, \gamma$. In this search for anomalous trilinear gauge couplings (aTGCs), the final-state boson transverse momentum is used as a sensitive observable.

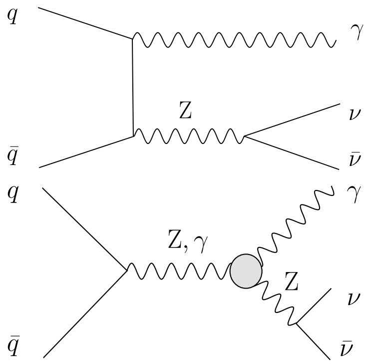

Fig. 1. Feynman diagrams of $Z\gamma$ production via initial-state radiation in the SM at tree level (top), and via anomalous $ZZ\gamma$ or $Z\gamma\gamma$ trilinear gauge couplings (bottom).

The $\nu\overline{\nu}\gamma$ 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 $Z\gamma$ production in pp collisions is shown in Fig. 1 (top). The s-channel production via a $ZZ\gamma$ or $Z\gamma\gamma$ aTGC is shown in Fig. 1 (bottom).

The most general Lorentz-invariant and gauge-invariant $ZV\gamma$ vertex can be described by four coupling parameters h_i^V ($i = 1, \ldots, 4$) [6,7]. The first two couplings ($i = 1, 2$) are CP-violating, while the latter two ($i = 3, 4$) are CP-conserving [7,8]. At tree level in the SM, the individual values of these aTGCs are zero. The

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photon transverse momentum spectrum has similar sensitivity to CP-violating and CP-conserving couplings. The results are generally interpreted in terms of the CP-conserving aTGCs h_3^V and h_4^V.

The sensitivity to aTGCs in $Z\gamma$ production is higher in the $Z \to \nu\overline{\nu}$ decay mode than in Z boson decay modes with charged leptons, because 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, and the acceptance in the neutrino channel is higher.

The fiducial phase space for this measurement is defined by the requirements of photon transverse energy $E_T^\gamma > 145\,\text{GeV}$ and photon pseudorapidity $|\eta^\gamma| < 1.44$, where the contamination from other particles misidentified as photons is lower [9].

2. The 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 ($|\eta| < 1.479$) and two endcap ($1.479 < |\eta| < 3.0$) sections, where η is the pseudorapidity. Extensive forward calorimetry complements the coverage provided by the barrel and endcap detectors. Muons are measured in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. The energy resolution for photons with transverse momentum $\geq 60\,\text{GeV}$ varies between 1% and 2.5% over the solid angle of the ECAL barrel, and from 2.5% to 3.5% in the endcaps [9]. The timing measurement of the ECAL has a resolution better than 200 ps for energy deposits larger than 10 GeV [9]. In the η–ϕ plane, where ϕ is the azimuthal angle and for $|\eta| < 1.48$, the HCAL cells map onto 5×5 arrays of ECAL crystals to form calorimeter towers projecting radially outward from the nominal interaction point.

The event reconstruction is performed using a particle-flow (PF) algorithm [10,11], which reconstructs and identifies individual particles using an optimized combination of information from all subdetectors. Photons are identified as energy clusters in the ECAL. These energy clusters are merged to form superclusters that are five crystals wide in η, centered around the most energetic crystal, and have a variable width in ϕ. The energy of charged hadrons is determined from a combination of the track momentum and the corresponding ECAL and HCAL energies, corrected for the combined response function of the calorimeters. The energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies. For each event, hadronic jets are formed from these reconstructed particles with the infrared- and collinear-safe anti-k_T algorithm [12], using a distance parameter $\Delta R = 0.5$, where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ and $\Delta\eta$ and $\Delta\phi$ are the pseudorapidity and azimuthal angle difference between the jet axis and the particle direction. The missing transverse momentum vector $\vec{\not{E}}_T$ is defined as the projection on the plane perpendicular to the beams of the negative vector sum of the momenta of all reconstructed PF candidates in an event; its magnitude is referred to as $\not{E}_T$.

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. [13].

3. Signal and background modeling

The final state consisting of an energetic photon accompanied by an imbalance in transverse energy can be mimicked by several other processes in the SM. These processes include $W\gamma \to \ell\nu\gamma$ where ℓ is a charged lepton (if the lepton escapes detection), $W \to \ell\nu$ (if the lepton is misidentified as a photon), γ + jets (if the jets are misreconstructed, resulting in $\not{E}_T$), QCD multijet production including $Z(\nu\overline{\nu})$ + jets (if the jet is misidentified as a photon), $Z\gamma \to \ell\ell\gamma$ (if both leptons escape detection), $\gamma\gamma$ events (if one of the photons escapes detection), and also backgrounds from beam halo.

The contributions from the $W\gamma \to \ell\nu\gamma$, γ + jet, $Z\gamma \to \ell\ell\gamma$, and $\gamma\gamma$ processes to the candidate event sample are estimated using Monte Carlo-based (MC) simulations. The $W(\ell\nu)\gamma$ and $Z \to \ell\ell\gamma$ samples are generated with MadGraph5v1.3.30 at leading order (LO) [14] and then processed with the pythia 6.426 event generator [15] for showering and hadronization. The other samples are generated with the pythia 6.426 generator [15] at LO. All the samples are generated using the CTEQ6L1 [16] parton distribution function (PDF) set, processed through the CMS detector simulation based on Geant4 [17,18], and reconstructed in the same manner as collision data.

The cross section for the SM background process $W\gamma \to \ell\nu\gamma$ with at most one jet is corrected with an E_T^γ dependent K factor estimated from mcfm [19] to account for next-to-leading-order (NLO) effects. The PDF4LHC Working Group recommendations [20–22] are used to estimate the uncertainty in the central value of the NLO cross section arising from the PDFs, the strong coupling constant α_s, and its scale dependence. The γ + jet cross section is corrected to include NLO effects.

To determine the efficiency for the SM $Z(\nu\overline{\nu})\gamma$ production cross section measurement, events are produced with the MadGraph5v1.3.30 generator at LO with a maximum of two additional partons and simulated through the full reconstruction chain. Simulated samples of the $Z\gamma$ signal for a grid of aTGC values are produced using the sherpa v1.2.2 generator [23]. The cross section with at most one extra parton is corrected with an E_T^γ dependent K factor estimated from mcfm [19] to account for NLO effects. The inclusive measurement has been compared with a theoretical calculation accurate up to next-to-next-to-leading order (NNLO).

To account for differences arising from imperfect modeling of the data in the simulation, a total correction factor ρ of 0.94 ± 0.06 is applied to all MC-based background estimates. This is the product of individual correction factors defined as ratios of the efficiencies measured in data and in simulation. They include 0.97 ± 0.02 for photon identification measured using $Z \to ee$ events, 0.99 ± 0.03 for timing requirements measured using a sample of electron events, and 0.99 ± 0.02 and 0.99 ± 0.05 for lepton and jet vetoes measured using $W \to e\nu$ events.

4. Event selection

Events are selected using both a single-photon trigger that requires a photon with $E_T^\gamma > 150\,\text{GeV}$, and photon + $\not{E}_T$ triggers with $E_T^\gamma > 70\,\text{GeV}$ and $\not{E}_T > 100\,\text{GeV}$. The combination of these triggers is 96% efficient for events with photon transverse energy $E_T^\gamma > 145\,\text{GeV}$, photon pseudorapidity $|\eta^\gamma| < 1.44$, and $\not{E}_T > 140\,\text{GeV}$. Events are required to have at least one primary vertex reconstructed within a longitudinal distance of $|z| < 24\,\text{cm}$ of the center of the detector and at a distance $<2\,\text{cm}$ from the z axis. The primary vertex is chosen to be the vertex with the highest p_T^2 sum of its associated tracks, where p_T is the transverse momentum.

We impose additional requirements on the energy deposits in the calorimeters to distinguish photons from misidentified jets [9]. The energy in the HCAL associated with the photon supercluster should not exceed 5% of its energy as measured in the ECAL. Moreover, the photon candidates must have a shower distribution in the ECAL consistent with that expected for an electromagnetic (EM) shower [9]. To further reduce photon contamination arising from misidentified jets, isolation requirements on photon candidates are imposed. Energy deposits for isolation are obtained by considering particles in a cone around the axis defined by the supercluster position and the primary vertex [9]. In particular, the scalar sum of transverse momenta (in GeV) of all photons within a cone of $\Delta R = 0.3$ around the supercluster, excluding a strip of width in η of 0.015, is required to be less than $0.7 + 0.005 p_{\mathrm{T}}^{\gamma}$; the scalar sum of the transverse momenta (in GeV) of all charged hadrons, associated with the primary vertex, within a hollow cone of $0.02 < \Delta R < 0.30$ around the supercluster is required to be less than 1.5; and the scalar sum of the transverse momenta (in GeV) of all neutral hadrons within a cone of $\Delta R = 0.3$ around the supercluster is required to be less than $1.0 + 0.04 p_{\mathrm{T}}^{\gamma}$. Due to the large number of additional proton–proton interactions (pileup) in the same bunch crossing at the LHC, it is difficult to know the true origin of the photon for a $\gamma + \not\!\!E_{\mathrm{T}}$ final state (our estimate is correct 50% of the time), which could lead to an underestimation of isolation values. Therefore, an additional PF-based charged particle isolation is calculated for each vertex and the largest value of this isolation sum is required to be smaller than the nominal threshold used for charged particle isolation.

Photon candidates are required to have the energy deposited in the highest energy crystal within the EM cluster to be within ±3 ns of the time expected for particles from a collision. This requirement reduces instrumental background arising from showers induced by bremsstrahlung from muons in the beam halo or in cosmic rays. To further reduce this background, we exploit the characteristic signature of showers from beam halo in the ECAL. A search region is defined around the highest energy crystal of the EM cluster in a narrow ϕ window and over a wide η range, after removal of the EM shower in a 5×5 array. A straight line, parallel to the beam direction, is fitted over the remaining cells within this region. Events are tagged as minimum ionizing particle (MIP tag) if the total energy deposited in the crystals associated with the straight-line fit is greater than 6.3 GeV.

Spurious signals can be embedded within EM showers by direct ionization of the avalanche photodiode sensitive volume by highly ionizing particles. These signals, which would otherwise pass the EM shower selection criteria, are eliminated by requiring consistency among the energy deposition times for all crystals within an EM shower.

Photon candidates are also removed if they are likely to be electrons, as inferred from patterns of hits in the pixel detector, called "pixel seeds", that are matched to the EM clusters [24].

Events containing good photon candidates are then required to have $\not\!\!E_{\mathrm{T}} > 140\,\mathrm{GeV}$. A topological requirement of $\Delta\phi > 2$ rad between the direction of the photon candidate and the vector $\vec{\not\!\!E}_{\mathrm{T}}$ is applied to reduce the contribution from the $\gamma +$jet background.

In order to suppress backgrounds from QCD multijet production and leptonic decay of W/Z + jets, events are vetoed if they contain significant hadronic/leptonic activity defined by: (i) more than one jet with $p_{\mathrm{T}} > 30\,\mathrm{GeV}$ not passing the pileup jet identification criteria [25], separated from the photon by $\Delta R > 0.5$, or (ii) an electron or a muon with $p_{\mathrm{T}} > 10\,\mathrm{GeV}$ and separated from the photon by $\Delta R > 0.5$.

To reduce the contamination from events with $\not\!\!E_{\mathrm{T}}$ arising from instrumental effects, a χ^2 function is constructed and minimized

$$\chi^2 = \sum_{i=\text{photon, jets}} \left(\frac{(p_{\mathrm{T}}^{\mathrm{reco}})_i - (\widetilde{p}_{\mathrm{T}})_i}{(\sigma_{p_{\mathrm{T}}})_i}\right)^2 + \left(\frac{\widetilde{\not\!\!E}_x}{\sigma_{\widetilde{\not\!\!E}_x}}\right)^2 + \left(\frac{\widetilde{\not\!\!E}_y}{\sigma_{\widetilde{\not\!\!E}_y}}\right)^2, \tag{1}$$

where the sum runs over the photon and all the jets in the event. The $(\sigma_{p_{\mathrm{T}}})_i$ are the expected momentum resolutions of the reconstructed (reco) photon and jets, and the $(\widetilde{p}_{\mathrm{T}})_i$ are the free parameters allowed to vary in order to minimize the function. The resolution parametrization associated with the $\not\!\!E_{\mathrm{T}}$ is obtained from Ref. [26]. Lastly, $\widetilde{\not\!\!E}_x$ and $\widetilde{\not\!\!E}_y$ are defined as

$$\begin{aligned} \widetilde{\not\!\!E}_{x,y} &= \not\!\!E_{x,y}^{\mathrm{reco}} + \sum_{i=\text{photon, jets}} (p_{x,y}^{\mathrm{reco}})_i - (\widetilde{p}_{x,y})_i \\ &= - \sum_{i=\text{photon, jets}} (\widetilde{p}_{x,y})_i, \\ \widetilde{\not\!\!E}_{\mathrm{T}} &= \sqrt{\widetilde{\not\!\!E}_x^2 + \widetilde{\not\!\!E}_y^2}. \end{aligned} \tag{2}$$

For events with no true $\not\!\!E_{\mathrm{T}}$, the χ^2 is expected to be small, with values of $\widetilde{\not\!\!E}_{\mathrm{T}}$ close to 0, while for events with significant true $\not\!\!E_{\mathrm{T}}$ the minimization will result in high χ^2 values, with $\widetilde{\not\!\!E}_{\mathrm{T}}$ close to the actual $\not\!\!E_{\mathrm{T}}$ in the event. An additional requirement of $\widetilde{\not\!\!E}_{\mathrm{T}} > 120\,\mathrm{GeV}$ reduces the number of $\gamma +$jet (QCD multijet) events by 80% (35%), while keeping 99.5% of signal events.

After applying these requirements, 630 candidate events are observed in data.

5. Background estimation

The largest contribution is found in the $\mathrm{W}\gamma \to \ell\nu\gamma$ process and is estimated to be 103 ± 21 events. The contributions from other processes, a small fraction of the total background, amount to 36 ± 3 events.

The most significant background contribution estimated using simulation is also validated in a control region dominated by $\mathrm{W}(\ell\nu)\gamma$ events. Events are selected using the full candidate selection but with the lepton veto inverted. In data, 104 events are observed, consistent with an expectation of 126 ± 23 events.

The background originating from jets misidentified as photons is estimated using a data driven method. The method is based on a class of jets, referred to as "photon-like" jets, that have properties similar to electromagnetic objects. Photon-like jets are required to pass a very loose photon selection but at the same time fail one of the isolation requirements. The method also relies on the ratio of jets passing the full photon selection to those identified as photon-like jets. This ratio is measured in a control sample enriched in QCD multijet events. To suppress the contribution of electroweak processes, the missing transverse energy in this control sample is required to be smaller than 30 GeV. Because this sample also contains true isolated photons from QCD direct photon production, this contribution must be subtracted from the numerator of the ratio. The required correction is estimated by performing a fit to the distribution of the candidate shower width variable $\sigma_{\eta\eta}$ [9]. Two shower shape profiles are used in this fit, the shower shape of true photons, obtained from simulated $\gamma +$jet events, and the shower shape of photon-like jets, obtained from the charged hadron isolation sideband in data. This corrected ratio is used to weight a set of data events where the photon candidate passes the photon-like jet selection criteria. The estimated number of background events is found to be 45 ± 14, where the uncertainty reflects an uncertainty in the estimation of the ratio, as well as the statistical uncertainty of the sample scaled for the final estimate.

An instrumental background caused by electrons arises due to the imperfect efficiency for reconstructing and associating pixel seeds with clusters. For our kinematic requirements, this background largely originates from W boson ($\mathrm{W} \to \mathrm{e}\nu$) production, and is estimated from data. The pixel seed efficiency ϵ_{pix} is measured in $\mathrm{Z} \to \mathrm{ee}$ events using the standard "tag-and-probe" method [27] and is estimated to be 0.984 ± 0.002 for electrons with $E_{\mathrm{T}} > 100\,\mathrm{GeV}$. To estimate the final yield of this background, a factor

Table 1
Summary of estimated $\mathrm{Z}(\rightarrow \nu\overline{\nu}) + \gamma$ signal, backgrounds, and observed total number of candidates. Backgrounds listed as "Others" include the small contributions from $\mathrm{W} \rightarrow \mu\nu$, $\mathrm{Z}\gamma \rightarrow \ell\ell\gamma$, $\gamma\gamma$, and γ + jet. Uncertainties include both statistical and systematic contributions.

Process	Estimate
$\mathrm{W}(\rightarrow \ell\nu) + \gamma$	103 ± 21
$\mathrm{W} \rightarrow \mathrm{e}\nu$	60 ± 6
jet $\rightarrow \gamma$ MisID	45 ± 14
Beam halo	25 ± 6
Others	36 ± 3
Total background	269 ± 26
$\mathrm{Z}(\rightarrow \nu\overline{\nu}) + \gamma$	345 ± 43
Data	630
Data – background	361 ± 36

of $(1 - \epsilon_{\text{pix}})/\epsilon_{\text{pix}}$ is applied to a set of events in the data with the same candidate event selection as the signal candidates and with the additional requirement of a pixel seed match. The resulting contribution is estimated to be 60 ± 6 events, where the uncertainty is dominated by the uncertainty in the measurement of ϵ_{pix}.

Since photon candidates are only identified within the ECAL, the candidate sample is susceptible to contamination from noncollision backgrounds. These backgrounds arise from interactions in the calorimeter of accelerator related particles (beam halo), spurious signals in the ECAL itself, and particles originating from cosmic ray interactions. The timing distribution measured from the ECAL for each of these backgrounds is distinctly different from the arrival time distribution for photons produced in collisions. A fit is performed to the candidate time distributions using shapes derived from data. The background distribution are constructed by inverting MIP tag (beam halo) and shower shape (anomalous signal) requirements. The arrival time for photons from the interaction region is modeled using $\mathrm{W} \rightarrow \mathrm{e}\nu$ candidates in data. From the result of the fit, the only significant noncollision background is found to be from beam halo events, and its contribution is estimated to be 25 ± 6 events.

The total number of expected background events is 269 ± 26, as mentioned in Table 1. The number of signal events (data – expected background) is 361 ± 36, where the uncertainty is obtained by adding in quadrature the uncertainty from the data and the background estimation. The expected number of $\mathrm{Z}\gamma \rightarrow \nu\overline{\nu}\gamma$ signal events, obtained using MadGraph5 and corrected for NNLO effects, is 345 ± 43.

6. Cross section measurement

A summary of the backgrounds and data yields is given in Table 1, wherein the uncertainties in the background estimates include both statistical and systematic sources.

The $\mathrm{Z}\gamma \rightarrow \nu\overline{\nu}\gamma$ cross section for $E_{\mathrm{T}}^{\gamma} > 145\,\mathrm{GeV}$ and $|\eta|^{\gamma} < 1.44$ is calculated using the following formulae:

$$\sigma\mathcal{B} = \frac{N_{\text{data}} - N_{\text{bkg}}}{A\epsilon\, L},$$
$$A\epsilon = (A\epsilon)_{\text{sim}}\,\rho,$$

where N_{data} is the number of observed events, N_{bkg} is the estimated number of background events, A is the geometrical acceptance, ϵ is the selection efficiency to select inclusive $\mathrm{Z}(\rightarrow \nu\overline{\nu}) + \gamma$ events offline, and L is the integrated luminosity. The product of $A\epsilon$ is estimated from the simulation to be 0.377 ± 0.001, where the uncertainty is statistical. ρ is the correction factor defined in Section 3.

Table 2
Systematic uncertainties considered in $A\epsilon$ for the $\mathrm{Z}(\nu\overline{\nu})\gamma$ signal sample from various sources.

Source	$\mathrm{Z}(\nu\overline{\nu})\gamma$ [%]
Photon and $\not\!\!E_{\mathrm{T}}$ energy scale	+3.4, −5.0
Jet and $\not\!\!E_{\mathrm{T}}$ energy scale	±2.3
Jet energy resolution	±1.3
Unclustered energy	±1.2
Pileup	±0.3
Luminosity	±2.6
Correction factor ρ	±6.4

The photon, jet and $\not\!\!E_{\mathrm{T}}$ energy scales and resolutions, pileup, correction factor ρ, and the uncertainties in the PDFs are considered as sources of systematic uncertainty in the acceptance calculation. The uncertainty in the photon energy scale is about 1.5%, which translates into an uncertainty in $A\epsilon$ of $^{+3.4}_{-5.0}\%$, where A is the geometrical and kinematic acceptance of the selection criteria, and ϵ is the signal selection efficiency. Additionally, there are systematic uncertainties due to the jet energy scale and jet resolution in the measurement of $\not\!\!E_{\mathrm{T}}$, which give $^{+2.3}_{-2.3}\%$ and $^{+1.2}_{-1.4}\%$, respectively, and the unclustered energy scale, which gives $^{+1.9}_{-0.6}\%$. For pileup, a central value for the total inelastic cross section of 69.4 mb [28,29] is used. A variation of ±5% in the number of interactions is used to cover the uncertainty in $A\epsilon$ due to pileup modeling, which is 0.3%. The uncertainty in the integrated luminosity [30] is 2.6%. Other sources include the uncertainty in the correction factor ρ, which contributes 6.4%.

A summary of the systematic uncertainties in $A\epsilon$ for the $\mathrm{Z}(\nu\overline{\nu})\gamma$ signal sample is shown in Table 2.

The measured production cross section $\sigma(\mathrm{pp} \rightarrow \mathrm{Z}\gamma)\,\mathcal{B}(\mathrm{Z} \rightarrow \nu\overline{\nu})$ for $E_{\mathrm{T}}^{\gamma} > 145\,\mathrm{GeV}$ and $|\eta| < 1.44$ is $52.7 \pm 2.1\,(\text{stat}) \pm 6.4\,(\text{syst}) \pm 1.4\,(\text{lumi})\,\text{fb}$.

The expected cross section of the signal process for $E_{\mathrm{T}}^{\gamma} > 145\,\mathrm{GeV}$ and $|\eta|^{\gamma} < 1.44$, obtained with the NLO generator MCFM, is $40.7 \pm 4.9\,\text{fb}$. The quoted uncertainty in the prediction takes into account the PDF and scale uncertainties. The NNLO theoretical prediction [31,32] is $50.0^{+2.4}_{-2.2}\,\text{fb}$, where the uncertainty includes only scale variations.

The distributions of photon transverse energy and $\not\!\!E_{\mathrm{T}}$ are shown in Fig. 2, with the signal and background predictions overlaid. The expected contribution from a $\mathrm{Z}\gamma\gamma$ aTGC signal with $h_3^{\gamma} = -0.001$, $h_4^{\gamma} = 0.0$ is also shown. No significant excess of events over the SM expectation is observed.

7. Limits on trilinear gauge couplings

We use the E_{T}^{γ} spectrum to set limits on aTGCs by means of a likelihood formalism. In this study, we follow the CMS convention of not suppressing the aTGCs 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. Limits on aTGCs are calculated on the basis of a profile likelihood method as described in Ref. [33]. In the fit to the observed spectra, systematic uncertainties are represented by nuisance parameters with log-normal prior probability density functions. The changes in shape of the observed spectra that result from varying the photon energy scale and the theoretical differential cross section within their respective uncertainties are treated using a morphing technique [34].

The best fit value from data for the aTGCs is very close to the SM values.

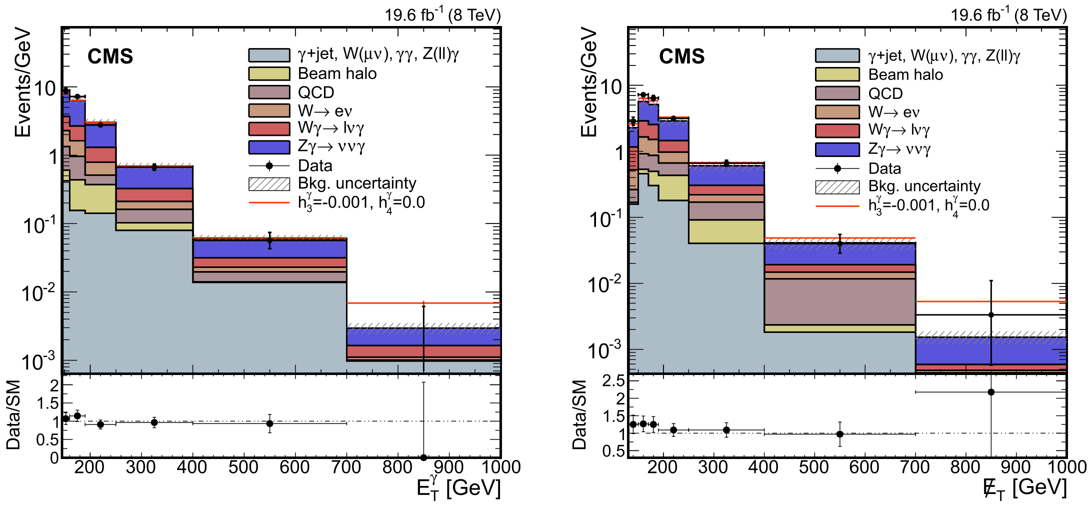

Fig. 2. The E_{T}^{γ} and $\not\!\!E_{\mathrm{T}}$ distributions in data (points with error bars) compared with the SM $\mathrm{Z}\gamma \to \nu\overline{\nu}\gamma$ signal and estimated contributions from backgrounds. A typical aTGC signal from $\mathrm{Z}\gamma\gamma$ with $h_3^{\gamma} = -0.001$, $h_4^{\gamma} = 0.0$ would provide an excess, as shown in the dot-dashed histogram. The background uncertainty includes statistical and systematic components.

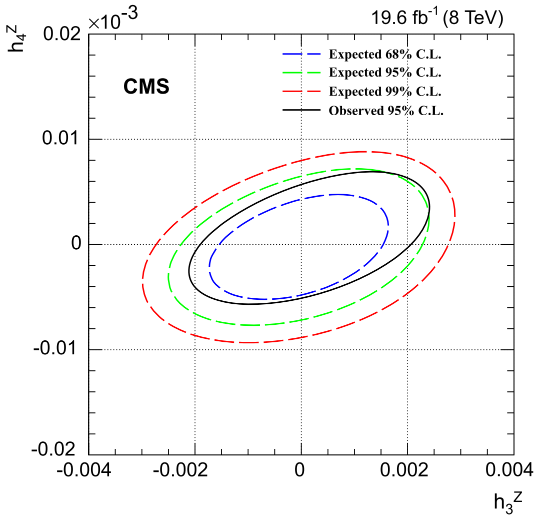

Fig. 3. Two-dimensional 95% CL limits on $\mathrm{ZZ}\gamma$ couplings.

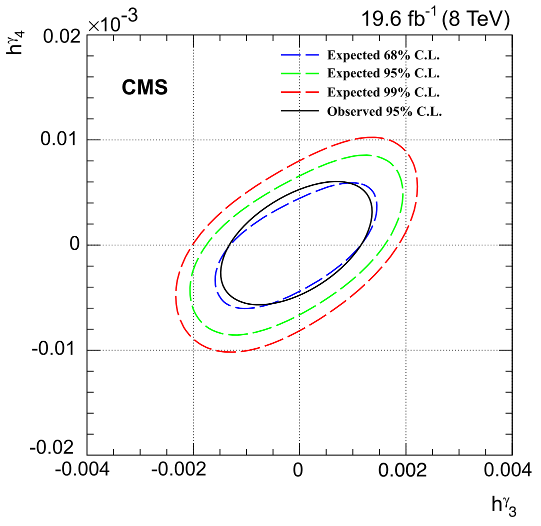

Fig. 4. Two-dimensional 95% CL limits on $\mathrm{Z}\gamma\gamma$ couplings.

Table 3
One-dimensional 95% CL limits on $\mathrm{ZV}\gamma$ anomalous trilinear gauge couplings from the $\mathrm{Z}\gamma \to \nu\overline{\nu}\gamma$ channel. The limits obtained from data with $\sqrt{s} = 7\,\mathrm{TeV}$ are also shown.

Coupling	$\sqrt{s} = 8\,\mathrm{TeV}$	$\sqrt{s} = 7\,\mathrm{TeV}$
h_3^{Z}	$[-1.5, 1.6] \times 10^{-3}$	$[-2.7, 2.7] \times 10^{-3}$
h_4^{Z}	$[-3.9, 4.5] \times 10^{-6}$	$[-1.3, 1.3] \times 10^{-5}$
h_3^{γ}	$[-1.1, 0.9] \times 10^{-3}$	$[-2.9, 2.9] \times 10^{-3}$
h_4^{γ}	$[-3.8, 4.3] \times 10^{-6}$	$[-1.5, 1.5] \times 10^{-5}$

Limits at 95% confidence level (CL) are set on pairs of aTGC parameters $(h_3^{\mathrm{Z}}, h_4^{\mathrm{Z}})$ and $(h_3^{\gamma}, h_4^{\gamma})$, as presented in Fig. 3 and Fig. 4, respectively. Furthermore, one-dimensional 95% CL limits are obtained for a given aTGC while setting the other neutral aTGCs to their SM values, i.e., to zero. A summary of the one-dimensional limits along with 7 TeV is given in Table 3.

8. Summary

We have presented an inclusive measurement of the $\mathrm{Z}\gamma \to \nu\overline{\nu}\gamma$ production cross section in pp collisions at $\sqrt{s} = 8\,\mathrm{TeV}$ using data collected with the CMS experiment in 2012, corresponding to an integrated luminosity of $19.6\,\mathrm{fb}^{-1}$. The measured cross section $\sigma(\mathrm{pp} \to \mathrm{Z}\gamma)\,\mathcal{B}(\mathrm{Z} \to \nu\overline{\nu})$ for photons with $E_{\mathrm{T}}^{\gamma} > 145\,\mathrm{GeV}$ and $|\eta^{\gamma}| < 1.44$ is $52.7 \pm 2.1\,(\mathrm{stat}) \pm 6.4\,(\mathrm{syst}) \pm 1.4\,(\mathrm{lumi})\,\mathrm{fb}$, in agreement with the NNLO prediction [31,32] of $50.0^{+2.4}_{-2.2}\,\mathrm{fb}$. No evidence was found for anomalous neutral trilinear gauge couplings in $\mathrm{Z}\gamma$ production. Limits at 95% CL were placed on the h_3^{V} and h_4^{V} parameters of $\mathrm{ZZ}\gamma$ and $\mathrm{Z}\gamma\gamma$ couplings:

$$-1.5 \times 10^{-3} < h_3^{\mathrm{Z}} < 1.6 \times 10^{-3}$$

$$-3.9 \times 10^{-6} < h_4^{\mathrm{Z}} < 4.5 \times 10^{-6}$$

$$-1.1 \times 10^{-3} < h_3^{\gamma} < 0.9 \times 10^{-3}$$

$$-3.8 \times 10^{-6} < h_4^{\gamma} < 4.3 \times 10^{-6}.$$

These results yield the most stringent limits to date on anomalous neutral trilinear gauge couplings.

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References

[1] J. Ellison, J. Wudka, Study of trilinear gauge-boson couplings at the tevatron collider, Annu. Rev. Nucl. Part. Sci. 48 (1998) 33, http://dx.doi.org/10.1146/annurev.nucl.48.1.33.

[2] K. Hagiwara, R.D. Peccei, D. Zeppenfeld, Probing the weak boson sector in $e^+e^- \to W^+W^-$, Nucl. Phys. B 282 (1987) 253, http://dx.doi.org/10.1016/0550-3213(87)90685-7.

[3] CMS Collaboration, Measurement of the production cross section for $Z\gamma \to \nu\bar{\nu}\gamma$ in pp collisions at $\sqrt{s} = 7$ TeV and limits on $ZZ\gamma$ and $Z\gamma\gamma$ triple gauge boson couplings, J. High Energy Phys. 10 (2013) 164, http://dx.doi.org/10.1007/JHEP10(2013)164, arXiv:1309.1117.

[4] ATLAS Collaboration, Measurements of $W\gamma$ and $Z\gamma$ production in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector at the LHC, Phys. Rev. D 87 (2013) 112003, http://dx.doi.org/10.1103/PhysRevD.87.112003, arXiv:1302.1283; http://dx.doi.org/10.1103/PhysRevD.91.119901 (Erratum).

[5] CMS Collaboration, Measurement of the $Z\gamma$ production cross section in pp collisions at 8 TeV and search for anomalous triple gauge boson couplings, J. High Energy Phys. 04 (2015) 164, http://dx.doi.org/10.1007/JHEP04(2015)164, arXiv:1502.05664.

[6] G.J. Gounaris, J. Layssac, F.M. Renard, Signatures of the anomalous $Z\gamma$ and ZZ production at the lepton and hadron colliders, Phys. Rev. D 61 (2000) 073013, http://dx.doi.org/10.1103/PhysRevD.61.073013.

[7] U. Baur, E.L. Berger, Probing the weak boson sector in $Z\gamma$ production at hadron colliders, Phys. Rev. D 47 (1993) 4889, http://dx.doi.org/10.1103/PhysRevD.47.4889.

[8] U. Baur, S. Errede, J. Ohnemus, Ratio of $W^{\pm}\gamma$ and $Z\gamma$ cross sections: new tools in probing the weak boson sector at the Tevatron, Phys. Rev. D 48 (1993) 4103, http://dx.doi.org/10.1103/PhysRevD.48.4103.

[9] CMS Collaboration, Performance of photon reconstruction and identification with the CMS detector in proton–proton collisions at $\sqrt{s} = 8$ TeV, J. Instrum. 10 (2015) P08010, http://dx.doi.org/10.1088/1748-0221/10/08/P08010, arXiv:1502.02702.

[10] CMS Collaboration, Particle-flow event reconstruction in CMS and performance for jets, taus, and $E_{\mathrm{T}}^{\mathrm{miss}}$, CMS Physics Analysis Summary CMS-PAS-PFT-09-001, http://cdsweb.cern.ch/record/1194487, 2009.

[11] CMS Collaboration, Commissioning of the particle-flow reconstruction in minimum-bias and jet events from pp collisions at 7 TeV, Technical report CMS-PAS-PFT-10-002, Geneva, http://cds.cern.ch/record/1279341, 2010.

[12] M. Cacciari, G.P. Salam, G. Soyez, The anti-k_t jet clustering algorithm, J. High Energy Phys. 04 (2008) 063, http://dx.doi.org/10.1088/1126-6708/2008/04/063, arXiv:0802.1189.

[13] CMS Collaboration, The CMS experiment at the CERN LHC, J. Instrum. 3 (2008) S08004, http://dx.doi.org/10.1088/1748-0221/3/08/S08004.

[14] J. Alwall, M. Herquet, F. Maltoni, O. Mattelaer, T. Stelzer, MadGraph 5: going beyond, J. High Energy Phys. 06 (2011) 128, http://dx.doi.org/10.1007/JHEP06(2011)128, arXiv:1106.0522.

[15] T. Sjöstrand, S. Mrenna, P.Z. Skands, Pythia 6.4 physics and manual, J. High Energy Phys. 05 (2006) 26, http://dx.doi.org/10.1088/1126-6708/2006/05/026, arXiv:hep-ph/0603175.

[16] J. Pumplin, D.R. Stump, J. Huston, H.-L. Lai, P. Nadolsky, W.-K. Tung, New generation of parton distributions with uncertainties from global QCD analysis, J. High Energy Phys. 07 (2002) 012, http://dx.doi.org/10.1088/1126-6708/2002/07/012, arXiv:hep-ph/0201195.

[17] S. Agostinelli, et al., GEANT4 Collaboration, GEANT4—a simulation toolkit, Nucl. Instrum. Methods Sect. A 506 (2003) 250, http://dx.doi.org/10.1016/S0168-9002(03)01368-8.

[18] J. Allison, et al., GEANT4 developments and applications, IEEE Trans. Nucl. Sci. 53 (2006) 270, http://dx.doi.org/10.1109/TNS.2006.869826.

[19] J. Campbell, R. Ellis, C. Williams, MCFM v6.1: a Monte Carlo for FeMtobarn processes at hadron colliders, http://mcfm.fnal.gov/mcfm.pdf, 2011.

[20] S. Alekhin, et al., The PDF4LHC Working Group interim report, arXiv:1101.0536, 2011.

[21] M. Botje, J. Butterworth, A. Cooper-Sarkar, A. de Roeck, J. Feltesse, S. Forte, A. Glazov, J. Huston, R. McNultỹ, T. Sjöstrand, R. Thorne, The PDF4LHC Working Group interim recommendations, arXiv:1101.0538, 2011.

[22] R.D. Ball, V. Bertone, F. Cerutti, L. Del Debbio, S. Forte, A. Guffanti, J.I. Latorre, J. Rojo, M. Ubiali, NNPDF Collaboration, Impact of heavy quark masses on parton distributions and LHC phenomenology, Nucl. Phys. B 849 (2011) 296, http://dx.doi.org/10.1016/j.nuclphysb.2011.03.021, arXiv:1101.1300.

[23] T. Gleisberg, S. Höche, F. Krauss, M. Schönherr, S. Schumann, F. Siegert, J. Winter, Event generation with SHERPA 1.1, J. High Energy Phys. 02 (2009) 007, http://dx.doi.org/10.1088/1126-6708/2009/02/007, arXiv:0811.4622.

[24] CMS Collaboration, Performance of electron reconstruction and selection with the CMS detector in proton–proton collisions at $\sqrt{s} = 8$ TeV, J. Instrum. 10 (2015) P06005, http://dx.doi.org/10.1088/1748-0221/10/06/P06005, arXiv:1502.02701.

[25] CMS Collaboration, Pileup jet identification, CMS Physics Analysis Summary CMS-PAS-JME-13–005, http://cdsweb.cern.ch/record/1581583, 2013.

[26] CMS Collaboration, Performance of the CMS missing transverse momentum reconstruction in pp data at $\sqrt{s} = 8$ TeV, J. Instrum. 10 (2015) P02006, http://dx.doi.org/10.1088/1748-0221/10/02/P02006, arXiv:1411.0511.

[27] CMS Collaboration, Measurement of the inclusive W and Z production cross sections in pp collisions at $\sqrt{s} = 7$ TeV with the CMS experiment, J. High Energy Phys. 10 (2011) 132, http://dx.doi.org/10.1007/JHEP10(2011)132, arXiv:1107.4789.

[28] G. Antchev, et al., First measurement of the total proton–proton cross section at the LHC energy of $\sqrt{s} = 7$ TeV, Europhys. Lett. 96 (2011) 21002, http://dx.doi.org/10.1209/0295-5075/96/21002, arXiv:1110.1395.

[29] CMS Collaboration, Measurement of the inclusive production cross sections for forward jets and for dijet events with one forward and one central jet in pp collisions at $\sqrt{s} = 7$ TeV, J. High Energy Phys. 06 (2012) 036, http://dx.doi.org/10.1007/JHEP06(2012)036, arXiv:1202.0704.

[30] CMS Collaboration, CMS luminosity based on pixel cluster counting – summer 2013 update, CMS Physics Analysis Summary CMS-PAS-LUM-13–001, http://cdsweb.cern.ch/record/1598864, 2013.

[31] M. Grazzini, S. Kallweit, D. Rathlev, A. Torre, $Z\gamma$ production at hadron colliders in NNLO QCD, Phys. Lett. B 731 (2014) 204, http://dx.doi.org/10.1016/j.physletb.2014.02.037, arXiv:1309.7000.

[32] M. Grazzini, S. Kallweit, D. Rathlev, Wgamma and Zgamma production at the LHC in NNLO QCD, in: Proceedings, 12th International Symposium on Radiative Corrections (Radcor 2015) and LoopFest XIV (Radiative Corrections for the LHC and Future Colliders), https://inspirehep.net/record/1416850/files/arXiv:1601.06751.pdf, 2016.

[33] K.A. Olive, et al., Particle Data Group, Review of particle physics, Chin. Phys. C 38 (2014) 090001, http://dx.doi.org/10.1088/1674-1137/38/9/090001.

[34] J.S. Conway, Nuisance parameters in likelihoods for multisource spectra, in: H.B. Prosper, L. Lyons (Eds.), Proceedings of PHYSTAT 2011 Workshop on Statistical Issues Related to Discovery Claims in Search Experiments and Unfolding, CERN, Geneva, Switzerland, 2011, p. 115.

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