Measurement of W-gamma and Z-gamma production in pp collisions at sqrt(s) = 7 TeV

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2011-07-27

Chatrchyan , S , Azzolini , V , Eerola , P , Fedi , G , Czellar , S , Härkönen , J , Heikkinen , A , Karimäki , V , Kinnunen , R , Kortelainen , M J , Lampen , T , Lassila-Perini , K , Lehti , S , Linden , T , Luukka , P , Mäenpää , T , Tuominen , E , Tuominiemi , J , Tuovinen , E , Ungaro , D , Wendland , L & The CMS Collaboration 2011 , ' Measurement of W-gamma and Z-gamma production in pp collisions at sqrt(s) = 7 TeV ' , Physics Letters B , vol. 701 , no. 5 , pp. 535-555 . https://doi.org/10.1016/j.physletb.2011.06.034

http://hdl.handle.net/10138/27352
https://doi.org/10.1016/j.physletb.2011.06.034

publishedVersion

Physics Letters B 701 (2011) 535–555

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

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ARTICLE INFO

Article history:
Received 14 May 2011
Received in revised form 6 June 2011
Accepted 12 June 2011
Available online 16 June 2011
Editor: M. Doser

Keywords:
CMS
Physics
Electroweak

ABSTRACT

A measurement of Wγ and Zγ production in proton–proton collisions at $\sqrt{s} = 7$ TeV is presented. Results are based on a data sample recorded by the CMS experiment at the LHC, corresponding to an integrated luminosity of 36 pb^{-1}. The electron and muon decay channels of the W and Z are used. The total cross sections are measured for photon transverse energy $E_T^\gamma > 10$ GeV and spatial separation from charged leptons in the plane of pseudorapidity and azimuthal angle $\Delta R(\ell,\gamma) > 0.7$, and with an additional dilepton invariant mass requirement of $M_{\ell\ell} > 50$ GeV for the Zγ process. The following cross section times branching fraction values are found: $\sigma(\mathrm{pp} \to \mathrm{W}\gamma + X) \times \mathcal{B}(\mathrm{W} \to \ell\nu) = 56.3 \pm 5.0(\mathrm{stat.}) \pm 5.0(\mathrm{syst.}) \pm 2.3(\mathrm{lumi.})$ pb and $\sigma(\mathrm{pp} \to \mathrm{Z}\gamma + X) \times \mathcal{B}(\mathrm{Z} \to \ell\ell) = 9.4 \pm 1.0(\mathrm{stat.}) \pm 0.6(\mathrm{syst.}) \pm 0.4(\mathrm{lumi.})$ pb. These measurements are in agreement with standard model predictions. The first limits on anomalous WWγ, ZZγ, and Z$\gamma\gamma$ trilinear gauge couplings at $\sqrt{s} = 7$ TeV are set.

The study of Zγ and Wγ production in proton–proton collisions is an important test of the standard model (SM) because of its sensitivity to the self-interaction between gauge bosons via trilinear gauge boson couplings (TGCs). These self-interactions are a direct consequence of the non-Abelian $SU(2) \times U(1)$ gauge symmetry of the SM and are a necessary ingredient to construct renormalizable theories involving massive gauge bosons that satisfy unitarity. The values of these couplings are fully fixed in the SM by the gauge structure of the Lagrangian. Thus, any deviation of the observed strength of the TGC from the SM prediction would indicate new physics, for example, the production of new particles that decay to Zγ or Wγ, or new interactions that increase the strength of the TGCs. Previous searches for anomalous TGCs (aTGCs) performed at lower energies by the $\mathrm{e}^+\mathrm{e}^-$ LEP [1–8] and $\mathrm{p}\bar{\mathrm{p}}$ Tevatron experiments [9–14] yielded results consistent with the SM. Testing TGCs at the Large Hadron Collider (LHC) is particularly interesting because it extends the test of the validity of the SM description of interactions in the bosonic sector to substantially higher energies.

We present the first measurement of the Wγ and Zγ cross sections, and of the WWγ, ZZγ, and Z$\gamma\gamma$ TGCs at $\sqrt{s} = 7$ TeV, using data collected with the Compact Muon Solenoid (CMS) detector in 2010, corresponding to an integrated luminosity of 36 pb^{-1}.

Final-state particles in the studied collision events are reconstructed in the CMS detector, which consists of several subdetectors. The central tracking system is based on silicon pixel and strip detectors, which allow the trajectories of charged particles to be reconstructed in the pseudorapidity range $|\eta| < 2.5$, where $\eta = -\ln\tan(\theta/2)$ and θ is the polar angle relative to the counterclockwise proton beam direction. CMS uses a right-handed coordinate system, in which the x axis lies in the accelerator plane and points towards the center of the LHC ring, the y axis is directed upwards, and the z axis runs along the beam axis. Electromagnetic (ECAL) and hadron (HCAL) calorimeters are located outside the tracking system and provide coverage for $|\eta| < 3$. The ECAL and HCAL are finely segmented with granularities $\Delta\eta \times \Delta\phi = 0.0175 \times 0.0175$ and 0.087×0.087, respectively, at central pseudorapidities and with a coarser granularity at forward pseudorapidities; ϕ denotes the azimuthal angle, measured in radians. A preshower detector made of silicon sensor planes and lead absorbers is located in front of the ECAL at $1.653 < |\eta| < 2.6$. The calorimeters and tracking systems are located within the 3.8 T magnetic field of the superconducting solenoid. Muons are measured in gas-ionization detectors embedded in the steel return yoke. In addition to the barrel and endcap detectors, CMS includes extensive calorimetry in the forward regions. A detailed description of CMS can be found elsewhere [15].

The Wγ and Zγ processes are studied in the final states $\ell\nu\gamma$ and $\ell\ell\gamma$, respectively, where ℓ is either an electron or a muon. Leading order (LO) Wγ production can be described by three processes: initial state radiation (ISR), where a photon is radiated by one of the incoming quarks; final state radiation (FSR), where a photon is radiated from the charged lepton from the W boson decay; and finally through the WWγ vertex, where a photon couples directly to the W boson. In the SM, LO Zγ production is described via ISR and FSR processes only, because the ZZγ and Z$\gamma\gamma$ TGCs are not allowed at tree level.

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doi:10.1016/j.physletb.2011.06.034

As at LO the $W\gamma$ and $Z\gamma$ cross sections diverge for soft photons or, in the case of $Z/\gamma^*\gamma$ production, for small values of the dilepton invariant mass, we restrict the cross section measurement to the phase space defined by the following two kinematic requirements: the photon candidate must have transverse energy E_T^γ larger than 10 GeV, and it must be spatially separated from the final-state charged lepton(s) by $\Delta R(\ell,\gamma) > 0.7$, where $\Delta R = \sqrt{(\eta_\ell - \eta_\gamma)^2 + (\phi_\ell - \phi_\gamma)^2}$. Furthermore, for the $Z\gamma$ final state, the invariant mass of the two lepton candidates must be above 50 GeV.

The main background to $W\gamma$ and $Z\gamma$ production consists of $W + \text{jets}$ and $Z + \text{jets}$ events, respectively, where the photon candidate originates from one of the jets. We estimate this background from data. The contribution from other processes, such as $t\bar{t}$ and multijet QCD production, is much smaller and it is estimated from Monte Carlo (MC) simulation studies. All signal samples for $W\gamma + n$ jets and $Z\gamma + n$ jets ($n \leqslant 1$) are generated with SHERPA [16] and further interfaced with PYTHIA [17] for showering and hadronization. The kinematic distributions for these signal processes are further cross-checked with simulated samples generated with MadGraph [18] interfaced with PYTHIA and good agreement is found. The signal samples are normalized using the next-to-leading order (NLO) prediction from the NLO Baur generator [19]. Background processes have been generated with the MadGraph + PYTHIA combination for $t\bar{t}$, $W + \text{jets}$, and $Z + \text{jets}$. Multijet QCD, $\gamma + \text{jets}$ and diboson processes are produced using only the PYTHIA generator. All generated samples are passed through a detailed simulation of the CMS detector based on GEANT4 [20] and the same complete reconstruction chain used for data analysis. All background samples are normalized to the integrated luminosity of the data sample using NLO cross section predictions, except inclusive W and Z production, for which the next-to-next-to-leading order cross section is used [21].

Photon candidates are reconstructed from clusters of energy deposits in the ECAL. We require photon candidates to be in $|\eta| < 1.44$ or $1.57 < |\eta| < 2.5$. Photons that undergo conversion in the material in front of the ECAL are also efficiently reconstructed by the same clustering algorithm. The clustered energy is corrected, taking into account interactions in the material in front of the ECAL and electromagnetic shower containment [22]. The photon candidate's pseudorapidity is calculated using the position of the primary interaction vertex. The absolute photon energy scale is determined using electrons from reconstructed Z boson decays with an uncertainty estimated to be less than 2%, and further verified using an independent FSR $Z \to \mu\mu\gamma$ data sample, selected with similar selection criteria used to select $Z\gamma$ candidates events but with $\Delta R(\gamma,\mu) < 0.7$, by comparing the $\mu\mu\gamma$ invariant mass to the nominal Z boson mass. Both the position and the width of the peak of the $\mu\mu\gamma$ invariant mass distribution in MC simulation are found to be consistent with that observed in data. We estimate the systematic uncertainty due to modeling of the photon energy measurement by varying the photon energy scale and resolution in the MC simulation within the uncertainties of the data-MC simulation agreement of the $\mu\mu\gamma$ invariant mass distribution. To reduce the background from electrons, photon candidates must not have associated hits in the innermost layer of the pixel subdetector. To reduce the background from misidentified jets, photon clusters are required to be isolated from other activity in the ECAL, HCAL, and tracker system. This photon isolation is defined by requiring the scalar sum of transverse energies or momenta reconstructed in the HCAL, ECAL, and Tracker sub-detectors, and spatially separated from the photon candidate by $\Delta R < 0.4$, to be less than 4.2, 2.2, and 2.0 GeV, respectively. Finally, the photon candidate's energy deposition profile in pseudorapidity must be consistent with the shape expected for a photon [22]. The adopted photon selection criteria lead to a signal efficiency of about 90%, while significantly suppressing the major background from misidentified jets.

Electron candidates are reconstructed from clusters of energy deposited in the ECAL that are matched to a charged track reconstructed in the silicon tracker. Similar requirements to those for photon candidates are applied to the ECAL energy cluster. We require electron candidates to have $p_T > 20$ GeV and $|\eta| < 2.5$. Two sets of electron identification criteria based on shower shape and track-cluster spatial matching are applied to the reconstructed candidates. These criteria are designed to reject misidentified jets from QCD multijet production while maintaining at least 80% (95%) efficiency for electrons from the decay of W or Z bosons for the tighter (looser) criteria. This efficiency is defined relative to the sample of reconstructed electrons. The tighter set of criteria is the same as the one used in the CMS measurement of the W and Z boson cross sections [23]. Electrons originating from photon conversions are suppressed by dedicated algorithms [24]. The tighter selection is used for the $W\gamma$ final state, while the looser selection is used for $Z\gamma$.

Muons are reconstructed as charged tracks matched to hits and segments in the muon system. The track associated with the muon candidate is required to have at least 11 hits in the silicon tracker, it must be consistent with originating from the primary vertex in the event, and it must be spatially well-matched to the muon system including a minimum number of hits in the muon detectors. These selection criteria follow the standard muon identification requirements employed in previous analyses [23] that are 95% efficient for muons produced in W and Z boson decays. All muon candidates are required to have $p_T > 20$ GeV and $|\eta| < 2.4$. The muon candidates in $W\gamma \to \mu\nu\gamma$ are further restricted to be in the fiducial volume of the single muon trigger, $|\eta| < 2.1$.

All lepton identification and reconstruction efficiencies of final state particles are measured in data using $Z \to \ell^+\ell^-$ events [23] and are found to be within a few percent of those obtained from MC simulation.

To estimate the background due to jets misidentified as photons, we use a method based on the assumption that the properties of jets misidentified as photons do not depend on the jet production mechanism and that photon candidates originating in jets in $W + \text{jets}$ and $Z + \text{jets}$ events are similar to those in multijet QCD events. We estimate the $W + \text{jets}$ and $Z + \text{jets}$ background contributions by measuring the E_T-dependent probability for a jet to be identified as a photon candidate, and then folding this probability with the nonisolated photon candidate E_T spectrum observed in the $W\gamma$ and $Z\gamma$ samples. The former is measured in a sample of multijet QCD events containing at least one high-quality jet candidate that satisfies the CMS jet trigger requirement [25]. Any photon candidate observed in such a sample is most likely a misidentified jet. We then measure the E_T^γ-dependent ratio of jets passing the full photon identification criteria to those identified as photons but failing the track isolation requirement. As the contribution from genuine photons in the multijet sample from $\gamma + \text{jets}$ processes becomes significant at large values of E_T^γ, we subtract this contribution from the total ratio using a Monte Carlo simulation prediction. The obtained E_T-dependent probability is folded with the nonisolated photon candidates in the $W\gamma$ and $Z\gamma$ candidate events to estimate the number of $W + \text{jets}$ and $Z + \text{jets}$ events, respectively, passing the full selection criteria. The estimation of the background from misidentified jets for the $W\gamma$ and $Z\gamma$ processes is further cross-checked with $W + \text{jets}$ and $Z + \text{jets}$ MC simulation and with the results obtained from an independent study of photon cluster shower shapes following the same approach as in Ref. [26] (shape method). We observe good agreement between all three methods (Fig. 1).

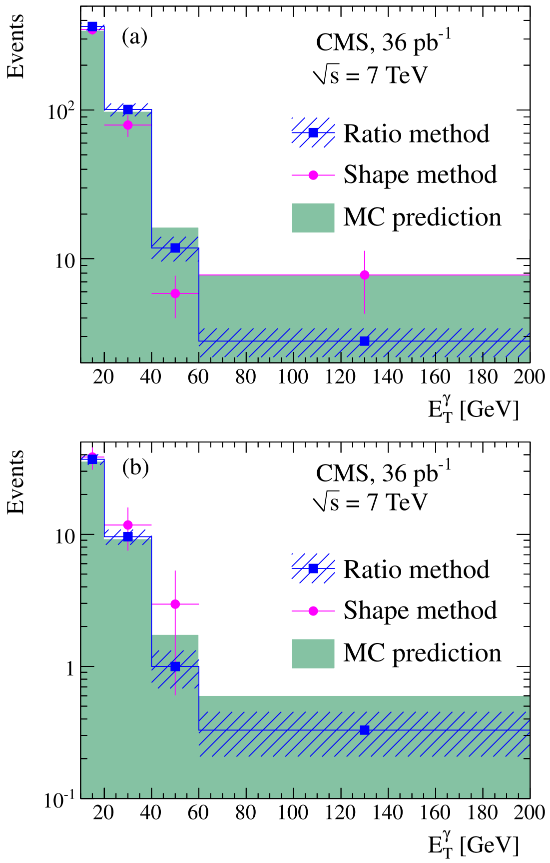

Fig. 1. Background from misidentified jets as a function of the photon candidate E_T, estimated from the ratio method, is shown with blue squares together with an alternative method that uses energy deposition shape templates (magenta circles), and MC simulation (green filled histogram) for (a) Wγ and (b) Zγ channels. Uncertainties include both statistical and systematic sources. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

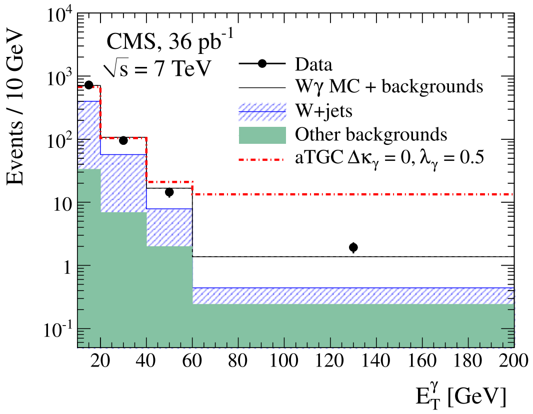

Fig. 2. Transverse energy distribution for the photon candidates for Wγ production. Data are shown with black circles with error bars; expected signal plus background is shown as a black solid histogram; the contribution from misidentified jets is given as a hatched blue histogram, and the background from γ + jets, $t\bar{t}$, and multiboson processes is given as a solid green histogram. A typical aTGC signal is given as a red dot-and-line histogram. The last bin includes overflows. Entries in wider bins are normalized to the ratio of 10 GeV and the bin width. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

A neutrino from leptonic W boson decay does not interact with the detector and results in a significant missing transverse energy, E_T^{miss}, in the event. The E_T^{miss} in this analysis is calculated with the particle-flow method [27]. The algorithm combines information from the tracking system, the muon chambers, and from all the calorimetry to classify reconstructed objects according to their particle type (electron, muon, photon, charged or neutral hadron). This allows precise corrections to particle energies and also provides a significant degree of redundancy, which renders the E_T^{miss} measurement less sensitive to calorimetry miscalibration. The E_T^{miss} is computed as the magnitude of the negative vector sum of transverse energies of all particle-flow objects. Both ECAL and HCAL are known to record anomalous signals that correspond to particles hitting the transducers, or to rare random discharges of the readout detectors. Anomalous noise in the calorimeters can reduce the accuracy of the E_T^{miss} measurement. Algorithms designed to suppress such noise reduce it to a negligible level, as shown in studies based on cosmic rays and control samples [28]. The modeling of E_T^{miss} in the simulation is checked using events with ($W \to \ell\nu$) and without ($Z \to \ell^+\ell^-$) genuine E_T^{miss} and good agreement is found [23,29].

Data for this study are selected with the CMS two-level trigger system by requiring the events to have at least one energetic electron or muon, consistent with being produced from W or Z boson decays. This requirement is about 90% efficient for the $W\gamma \to \mu\nu\gamma$ signal and 98% efficient for $W\gamma \to e\nu\gamma$. The trigger efficiency is close to 100% for both $Z\gamma \to \ell\ell\gamma$ final states. The events are required to contain at least one primary vertex with reconstructed z position within 24 cm of the geometric center of the detector and xy position within 2 cm of the beam interaction region.

The $W\gamma \to \ell\nu\gamma$ final state is characterized by a prompt, energetic, and isolated lepton, significant E_T^{miss} due to the presence of the neutrino from the W boson decay, and a prompt isolated photon. The basic event selection is similar for the electron and muon channels: we require a charged lepton, electron or muon, with $p_T > 20$ GeV, which must satisfy the trigger requirements; one photon with transverse energy $E_T^\gamma > 10$ GeV, and the E_T^{miss} in the event exceeding 25 GeV. As mentioned before, the photon must be separated from the lepton by $\Delta R(\ell, \gamma) > 0.7$. For the $e\nu\gamma$ channel, the electron candidate must satisfy the tight electron selection criteria. If the event has an additional electron that satisfies the loose electron selection, we reject the event to reduce contamination from $Z/\gamma^* \to ee$ processes. For $\mu\nu\gamma$, we reject the event if a second muon is found with $p_T > 10$ GeV.

After the full selection, 452 events are selected in the $e\nu\gamma$ channel and 520 events are selected in the $\mu\nu\gamma$ channel. No events have more than one photon candidate in the final state. The background from misidentified jets estimated in data amounts to $220 \pm 16(\text{stat.}) \pm 14(\text{syst.})$ events for the $e\nu\gamma$ final state, and $261 \pm 19(\text{stat.}) \pm 16(\text{syst.})$ events for the $\mu\nu\gamma$ final state. Backgrounds from other sources, such as the Zγ process in which one of the leptons from the Z boson decay does not pass the reconstruction and identification criteria and diboson processes where one of the electrons is misreconstructed as a photon, are estimated from MC simulation and found to be 7.7 ± 0.5 and 16.4 ± 1.0 for $W\gamma \to e\nu\gamma$ and $W\gamma \to \mu\nu\gamma$, respectively. A larger contribution from Zγ background in the muon channel is due to a smaller pseudorapidity coverage for muons, thus increasing the probability for one of the Z decay muons to be lost, which results also in an overestimated value of the measured missing energy in such events as the lost muon cannot be taken into account in the E_T^{miss} determination. The $W\gamma \to \tau\nu\gamma$ production, with subsequent $\tau \to \ell\nu\nu$ decay, also contributes at the few percent level to the $e\nu\gamma$ and $\mu\nu\gamma$ final states. We rely on MC simulation to estimate this contribution. The E_T distribution for photon candidates in events passing the full Wγ selection is given in Fig. 2.

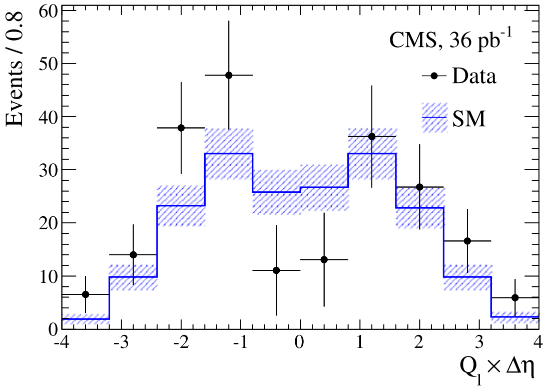

Fig. 3. The background-subtracted charge-signed rapidity difference for the combined electron and muon channels of Wγ production is shown for data (black circles with error bars) and SM simulation (blue hatched region). The results of the Kolmogorov–Smirnov test of the agreement between data and MC prediction is 57%, which indicates a reasonable agreement. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

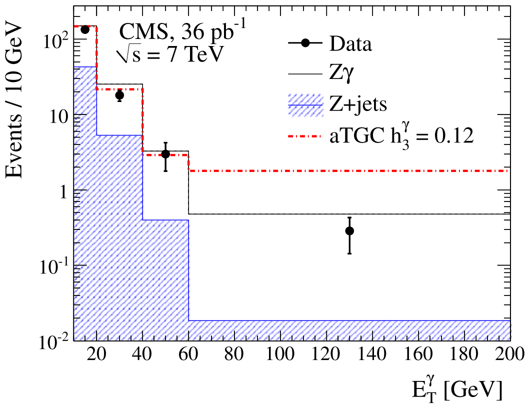

Fig. 4. The transverse energy distribution of photon candidates in the Zγ channel in data is shown with black circles with error bars; the expected signal plus background is shown as a solid black histogram, while the contribution from misidentified jets is given as a hatched blue histogram. A typical aTGC signal is given as a red dot-and-line histogram. The last bin includes overflows. Entries in wider bins are normalized to the ratio of 10 GeV and the bin width. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

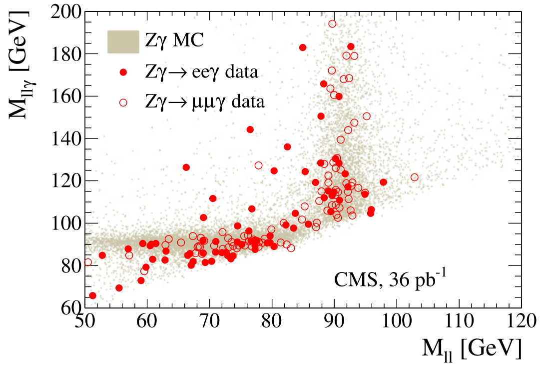

Fig. 5. Distribution of the $\ell\ell\gamma$ invariant mass as a function of the dilepton invariant mass for selected Zγ candidates in the electron (filled circles) and muon (open circles) final states. The data accumulation at $M_{\ell\ell\gamma} \simeq M_Z$ corresponds to FSR events, while the data at $M_{\ell\ell} \simeq M_Z$ correspond to ISR events.

The three tree-level Wγ production processes interfere with each other, resulting in a radiation-amplitude zero (RAZ) in the angular distribution of the photon [30–34]. The first evidence for RAZ in Wγ production was observed by the D0 Collaboration [10] using the charge-signed rapidity difference $Q_\ell \times \Delta\eta$ between the photon candidate and the charged lepton candidate from the W boson decay [35]. In the SM, the location of the dip minimum is located at $Q_\ell \times \Delta\eta = 0$ for pp collisions. Anomalous Wγ production can result in a flat distribution of the charge-signed rapidity difference.

In Fig. 3 we plot the charge-signed rapidity difference in background-subtracted data with an additional requirement on the transverse mass of the photon, lepton, and E_T^{miss} to exceed 90 GeV, to reduce the contribution from FSR Wγ production. The agreement between background-subtracted data and MC prediction is reasonable, with a Kolmogorov–Smirnov test [36,37] result of 57%.

Events in the Zγ sample are selected by requiring a pair of electrons or muons, each with transverse momentum $p_T > 20$ GeV, forming an invariant mass above 50 GeV. One of these leptons must satisfy the trigger requirements. The events are further required to have a photon candidate passing the selection criteria with transverse energy E_T^γ above 10 GeV. The photon must be separated from any of the two charged leptons by $\Delta R(\ell,\gamma) > 0.7$. After applying these selection criteria we observe 81 events in the eeγ final state and 90 events in the $\mu\mu\gamma$ final state. No events are observed with more than one photon candidate. The Z + jets background to these final states is estimated to be $20.5 \pm 1.7(\text{stat.}) \pm 1.9(\text{syst.})$ and $27.3 \pm 2.2(\text{stat.}) \pm 2.3(\text{syst.})$, respectively. Other backgrounds from multijet QCD, γ + jets, $t\bar{t}$, and other diboson processes contribute less than one event in each of the two channels and are therefore neglected in this analysis. The E_T distribution of the photon candidates in the selected Zγ candidate events is shown in Fig. 4. The distribution of the $\ell\ell\gamma$ mass as a function of the dilepton mass is displayed in Fig. 5. We observe good agreement between data and the SM prediction.

The measurement of the cross sections is based on the formula

$$\sigma = \frac{N_{\text{data}} - N_{\text{bkg}}}{A\epsilon\mathcal{L}}, \tag{1}$$

where N_{data} is the number of observed events, N_{bkg} is the number of estimated background events, A is the fiducial and kinematic acceptance of the selection criteria, ϵ is the selection efficiency for events within the acceptance, and $\mathcal{L}$ is the integrated luminosity. The acceptance is determined relative to the phase space defined by the cuts $E_T^\gamma > 10$ GeV and $\Delta R(\ell,\gamma) > 0.7$, and in addition by $M_{\ell\ell} > 50$ GeV for Zγ. We determine the product $A \cdot \epsilon$ from MC simulations and apply correction factors ρ to account for differences in efficiencies between data and simulations. These correction factors come from efficiency ratios $\rho = \epsilon/\epsilon_{\text{sim}}$ derived by measuring ϵ and ϵ_{sim} in the same way on data and simulations, respectively, following the procedure used in the inclusive W and Z measurement [23].

Systematic uncertainties are grouped into three categories. In the first group, we combine the uncertainties that affect the product of the acceptance, reconstruction, and identification efficiencies of final state objects, as determined from Monte Carlo simulation. These include uncertainties on lepton and photon energy scales and resolution, effects from pile-up interactions, and uncertainties in the parton distribution functions (PDFs). Lepton energy scale and resolution effects are estimated by studying the invariant mass of $Z \rightarrow \ell\ell$ candidates, while the photon energy scale and resolution uncertainty comes from ECAL calibration studies which are further cross-checked with the Zγ FSR study. The uncertainty due to the PDFs is estimated following Ref. [38]. The second group includes the systematic uncertainties affecting the data vs. simulation correction factors ρ for the efficiencies of the trigger, reconstruction, and identification requirements. These include lepton trigger, lepton and photon reconstruction and identification, and E_T^{miss} efficiencies for the Wγ process. The lepton efficiencies are

Table 1
Summary of systematic uncertainties.

Source	$W\gamma \to e\nu\gamma$	$W\gamma \to \mu\nu\gamma$	$Z\gamma \to ee\gamma$	$Z\gamma \to \mu\mu\gamma$
	Effect on $A \cdot \epsilon_{MC}$			
Lepton energy scale	2.3%	1.0%	2.8%	1.5%
Lepton energy resolution	0.3%	0.2%	0.5%	0.4%
Photon energy scale	4.5%	4.2 %	3.7%	3.0%
Photon energy resolution	0.4%	0.7%	1.7%	1.4%
Pile-up	2.7%	2.3%	2.3%	1.8%
PDFs	2.0%	2.0%	2.0%	2.0%
Total uncertainty on $A \cdot \epsilon_{MC}$	6.1%	5.2%	5.8%	4.3%
	Effect on $\epsilon_{data}/\epsilon_{MC}$			
Trigger	0.1%	0.5%	$< 0.1\%$	$< 0.1\%$
Lepton identification and isolation	0.8%	0.3%	1.1%	1.0%
E_T^{miss} selection	0.7%	1.0%	N/A	N/A
Photon identification and isolation	1.2%	1.5%	1.0%	1.0%
Total uncertainty on $\epsilon_{data}/\epsilon_{MC}$	1.6%	1.9%	1.6%	1.5%
Background	6.3%	6.4%	9.3%	11.4%
Luminosity	4%			

determined by the "tag-and-probe" method [23] in the same way for data and simulation, and the uncertainty on the ratio of efficiencies is taken as a systematic uncertainty. The third category comprises uncertainties on the background yield. These are dominated by the uncertainties on the data-driven W + jets and Z + jets background estimation. These include systematic uncertainties due to the modeling of the E_T^γ-dependent ratio and the uncertainty due to the γ + jets contribution. Finally, an additional uncertainty due to the measurement of the integrated luminosity is considered. This uncertainty is 4% [39].

All systematic uncertainties for the $W\gamma$ and $Z\gamma$ channels are summarized in Table 1.

We find the cross section for $W\gamma$ production for $E_T^\gamma > 10$ GeV and $\Delta R(\ell,\gamma) > 0.7$ to be $\sigma(pp \to W\gamma + X) \times \mathcal{B}(W \to e\nu) = 57.1 \pm 6.9(\text{stat.}) \pm 5.1(\text{syst.}) \pm 2.3(\text{lumi.})$ pb and $\sigma(pp \to W\gamma + X) \times \mathcal{B}(W \to \mu\nu) = 55.4 \pm 7.2(\text{stat.}) \pm 5.0(\text{syst.}) \pm 2.2(\text{lumi.})$ pb. Taking into account correlated uncertainties between these two results, due to photon identification, energy scale, resolution, data-driven background, and signal modeling, and following the Best Linear Unbiased Estimator method [40], we measure the combined cross section to be $\sigma(pp \to W\gamma + X) \times \mathcal{B}(W \to \ell\nu) = 56.3 \pm 5.0(\text{stat.}) \pm 5.0(\text{syst.}) \pm 2.3(\text{lumi.})$ pb. This result agrees well with the NLO prediction [41] of 49.4 ± 3.8 pb.

The $Z\gamma$ cross section within the requirements $E_T^\gamma > 10$ GeV, $\Delta R(\ell,\gamma) > 0.7$, and $m_{\ell\ell} > 50$ GeV, is measured to be $\sigma(pp \to Z\gamma + X) \times \mathcal{B}(Z \to ee) = 9.5 \pm 1.4(\text{stat.}) \pm 0.7(\text{syst.}) \pm 0.4(\text{lumi.})$ pb for the $ee\gamma$ final state, and $\sigma(pp \to Z\gamma + X) \times \mathcal{B}(Z \to \mu\mu) = 9.2 \pm 1.4(\text{stat.}) \pm 0.6(\text{syst.}) \pm 0.4(\text{lumi.})$ pb for the $\mu\mu\gamma$ final state. The combination of the two results yields $\sigma(pp \to Z\gamma + X) \times \mathcal{B}(Z \to \ell\ell) = 9.4 \pm 1.0(\text{stat.}) \pm 0.6(\text{syst.}) \pm 0.4(\text{lumi.})$ pb. The theoretical NLO prediction [19] is 9.6 ± 0.4 pb, which is in agreement with the measured value.

Given the good agreement of both the measured cross sections and the E_T^γ distributions with the corresponding SM predictions, we proceed to set limits on anomalous TGCs. The most general Lorentz-invariant Lagrangian that describes the $WW\gamma$ coupling has seven independent dimensionless couplings g_1^γ, κ_γ, λ_γ, g_4^γ, g_5^γ, $\tilde{\kappa}_\gamma$, and $\tilde{\lambda}_\gamma$ [42]. By requiring *CP* invariance and $SU(2) \times U(1)$ gauge invariance only two independent parameters remain: κ_γ and λ_γ. In the SM, $\kappa_\gamma = 1$ and $\lambda_\gamma = 0$. We define aTGCs to be deviations from the SM predictions, so instead of using κ_γ we define $\Delta\kappa_\gamma \equiv \kappa_\gamma - 1$. While these couplings have no physical meaning as such, they are related to the electromagnetic moments of the W boson,

$$\mu_W = \frac{e}{2M_W}(2 + \Delta\kappa_\gamma + \lambda_\gamma),$$
$$Q_W = -\frac{e}{M_W^2}(1 + \Delta\kappa_\gamma - \lambda_\gamma), \qquad (2)$$

where μ_W and Q_W are the magnetic dipole and electric quadrupole moments of the W boson, respectively.

Table 2
One-dimensional 95% CL limits on $WW\gamma$, $ZZ\gamma$, and $Z\gamma\gamma$ aTGCs.

$WW\gamma$	$ZZ\gamma$	$Z\gamma\gamma$
$-1.11 < \Delta\kappa_\gamma < 1.04$	$-0.05 < h_3 < 0.06$	$-0.07 < h_3 < 0.07$
$-0.18 < \lambda_\gamma < 0.17$	$-0.0005 < h_4 < 0.0005$	$-0.0005 < h_4 < 0.0006$

For the $ZZ\gamma$ or $Z\gamma\gamma$ couplings, the most general Lorentz-invariant and gauge-invariant vertex is described by only four parameters h_i^V ($i = 1,2,3,4$; $V = \gamma, Z$) [19]. By requiring *CP* invariance, only two parameters, h_3^V and h_4^V, remain. The SM predicts these couplings to vanish at tree level. Simulated samples of $W\gamma$ and $Z\gamma$ signals for a grid of aTGCs values are produced similarly to the SM signal $W\gamma$ and $Z\gamma$ samples described above. A grid of λ_γ and $\Delta\kappa_\gamma$ values is used for the $WW\gamma$ coupling, and a grid of h_3 and h_4 values is used for the $ZZ\gamma$ and $Z\gamma\gamma$ couplings.

Assuming Poisson statistics and log-normal distributions for the generated samples and background systematic uncertainties we calculate the likelihood of the observed photon E_T spectrum in data given the sum of the background and aTGCs E_T^γ predictions for each point in the grid of aTGCs values. To extract limits we parameterize the expected yields as a quadratic function of the anomalous couplings. We then form the probability of observing the number of events seen in data in a given bin of the photon transverse energy using a Poisson distribution with the mean given by the expected signal plus a data driven background estimate and allowing for variations within the systematic uncertainties. The confidence intervals are found using MINUIT, profiling the likelihood with respect to all systematic variations [43]. The resultant two-dimensional 95% confidence level (CL) limits are given in Fig. 6. To set one-dimensional 95% CL limits on a given anomalous coupling we set the other aTGCs to their respective SM predictions. The results are summarized in Table 2.

All the non-SM terms in the effective Lagrangian are scaled with α/m_V^n, where α is an aTGC, m_V is the mass of the gauge

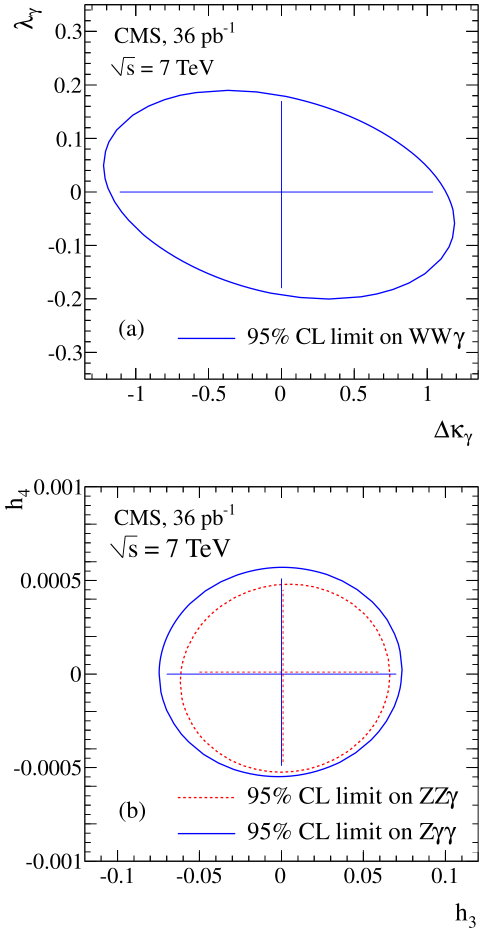

Fig. 6. Two-dimensional 95% CL limit contours (a) for the WWγ vertex couplings λ_γ and $\Delta\kappa_\gamma$ (blue line), and (b) for the ZZγ (red dashed line) and Z$\gamma\gamma$ (blue solid line) vertex couplings h_3 and h_4 assuming no energy dependence on the couplings. One-dimensional 95% CL limits on individual couplings are given as solid lines. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

boson (W boson for the WWγ coupling and Z boson for ZZγ and Z$\gamma\gamma$ couplings), and n is a power that is chosen to make the aTGC dimensionless. The values of n for $\Delta\kappa_\gamma$, λ_γ, h_3, and h_4 are 0, 2, 2, and 4, respectively. An alternative way to scale those new physics Lagrangian terms is with $\alpha/\Lambda_{\text{NP}}^n$, where Λ_{NP} is the characteristic energy scale of new physics [44]. We present upper limits on aTGCs for Λ_{NP} values between 2 and 8 TeV in Fig. 7.

In summary, we have presented the first measurement of the Wγ and Zγ cross sections in pp collisions at $\sqrt{s} = 7$ TeV for $E_{\text{T}}^{\gamma} > 10$ GeV, $\Delta R(\gamma, \ell) > 0.7$, and for the additional requirement on the dilepton invariant mass to exceed 50 GeV for the Zγ process. We measured the Wγ cross section times the branching fraction for the leptonic W decay to be $\sigma(\text{pp} \to \text{W}\gamma + X) \times \mathcal{B}(\text{W} \to \ell\nu) = 56.3 \pm 5.0(\text{stat.}) \pm 5.0(\text{syst.}) \pm 2.3(\text{lumi.})$ pb. This result is in good agreement with the NLO prediction of 49.4 ± 3.8 pb, where the uncertainty includes both PDF and k-factor uncertainties. The Zγ cross section times the branching fraction for the leptonic Z decay was measured to be $\sigma(\text{pp} \to \text{Z}\gamma + X) \times \mathcal{B}(\text{Z} \to \ell\ell) = 9.4 \pm 1.0(\text{stat.}) \pm 0.6(\text{syst.}) \pm 0.4(\text{lumi.})$ pb, which also agrees well with the NLO predicted value [19] of 9.6 ± 0.4 pb. We also searched and found no evidence for anomalous WWγ, ZZγ, and Z$\gamma\gamma$ trilinear gauge couplings. We set the first 95% CL limits on these couplings at $\sqrt{s} = 7$ TeV. These limits extend the previous results [1–4,9–14] on vector boson self-interactions at lower energies.

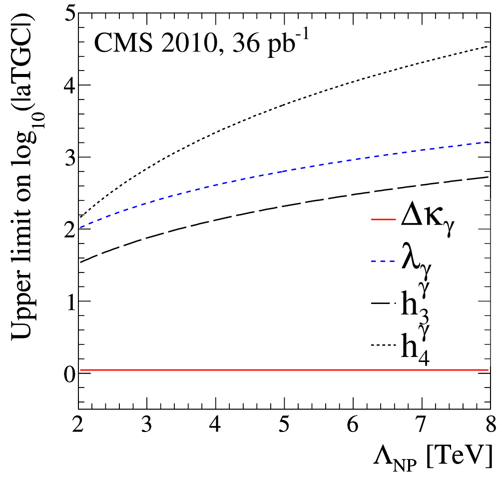

Fig. 7. Upper 95% CL limits on $\log_{10}(|\text{aTGC}|)$ as a function of Λ_{NP} for $\Delta\kappa_\gamma$, λ_γ, h_3^γ, and h_4^γ. Limits on the latter two couplings are similar to those for h_3^Z and h_4^Z. These limits refer to the formulation in which the new physics Lagrangian terms are scaled with $\alpha/\Lambda_{\text{NP}}^n$, where Λ_{NP} is the characteristic energy scale of new physics and α is the aTGC.

Acknowledgements

We wish to congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC machine. We thank the technical and administrative staff at CERN and other CMS institutes, and acknowledge support from: FMSR (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES (Croatia); RPF (Cyprus); Academy of Sciences and NICPB (Estonia); Academy of Finland, ME, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NKTH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); PAEC (Pakistan); SCSR (Poland); FCT (Portugal); JINR (Armenia, Belarus, Georgia, Ukraine, Uzbekistan); MST and MAE (Russia); MSTD (Serbia); MICINN and CPAN (Spain); Swiss Funding Agencies (Switzerland); NSC (Taipei); TUBITAK and TAEK (Turkey); STFC (United Kingdom); DOE and NSF (USA).

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