Measurement of $W\gamma$ and $Z\gamma$ production in pp collisions at $\sqrt{s} = 7$ TeV

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A measurement of $W\gamma$ and $Z\gamma$ 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 $M_{ll} > 50$ GeV for the $Z\gamma$ process. The following cross section times branching fraction values are found: $\sigma(pp \rightarrow W\gamma + X) \times B(W \rightarrow \ell\nu) = 56.3 \pm 5.0(\text{stat.}) \pm 5.0(\text{syst.}) \pm 2.3(\text{lumi.})$ pb and $\sigma(pp \rightarrow Z\gamma + X) \times B(Z \rightarrow \ell\ell) = 9.4 \pm 1.0(\text{stat.}) \pm 0.6(\text{syst.}) \pm 0.4(\text{lumi.})$ pb. These measurements are in agreement with standard model predictions. The first limits on anomalous $WW\gamma$, $ZZ\gamma$, and $Z\gamma\gamma$ trilinear gauge couplings at $\sqrt{s} = 7$ TeV are set.

The study of $Z\gamma$ and $W\gamma$ production in proton–proton collisions is an important test of the standard model (SM) because of its sensitivity to the self-interaction of gauge bosons (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 fixed in the SM by the gauge structure of the Lagrangian. Thus, any deviation of the observed strength of the TGCs from the SM prediction would indicate new physics, for example, the production of new particles that decay to $Z\gamma$ or $W\gamma$, or new interactions that increase the strength of the TGCs. Previous searches for anomalous TGCs (aTGCs) performed at lower energies by the $e^+e^-$ LEP [1–8] and $p\bar{p}$ 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 $W\gamma$ and $Z\gamma$ cross sections, and of the $WW\gamma$, $ZZ\gamma$, 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 $\theta$ 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 $0.087 \times 0.087$, respectively, at central pseudorapidities and with a coarser granularity at forward pseudorapidities; $\phi$ 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 $W\gamma$ and $Z\gamma$ processes are studied in the final states $\ell\nu\gamma$ and $\ell\ell\gamma$, respectively, where $\ell$ is either an electron or a muon. Leading order (LO) $W\gamma$ 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 $WW\gamma$ vertex, where a photon couples directly to the $W$ boson. In the SM, LO $Z\gamma$ production is described via ISR and FSR processes only, because the $ZZ\gamma$ and $Z\gamma\gamma$ TGCs are not allowed at tree level.
As at LO the Wγ and Zγ cross sections diverge for soft photons or, in the case of Z/γ∗γ∗ 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 \( E_T^\gamma \) 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 Zγ final state, the invariant mass of the two lepton candidates must be above 50 GeV.

The main background to Wγ and Zγ production consists of W + jets and Z + 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 Wγ + n jets and Zγ + n jets \((n \leq 1)\) are generated with \textsc{sherpa} [16] and further interfaced with \textsc{pythia} [17] for showering and hadronization. The kinematic distributions for these signal processes are further cross-checked with simulated samples generated with \textsc{madgraph} [18] interfaced with \textsc{pythia} and good agreement is found. The signal samples are normalized using the next-to-leading order (NLO) prediction from the NLO \textsc{baur} generator [19]. Background processes have been generated with the \textsc{madgraph} + \textsc{pythia} combination for \( t\bar{t} \), W + jets, and Z + jets. Multijet QCD, \( \gamma + \) jets and diboson processes are produced using only the \textsc{pythia} generator. All generated samples are passed through a detailed simulation of the CMS detector based on \textsc{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 depositions 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 the position of the candidate’s pseudorapidity is calculated using the position of the material in front of the ECAL based on \textsc{geant4} and \textsc{mc} simulation. The obtained agreement of the CMS detector based on \textsc{geant4} and \textsc{mc} simulation within the uncertainties of the data-MC simulation is used for Zγ production [23].

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 + jets and Z + jets events are similar to those in multi-jet QCD events. We estimate the W + jets and Z + 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 Wγ and Zγ 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 \( E_T^\gamma \)-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 \( \gamma + \) jets processes becomes significant at large values of \( E_T^\gamma \), 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 Wγ and Zγ candidate events to estimate the number of W + jets and Z + jets events, respectively, passing the full selection criteria. The estimation of the background from misidentified jets for the Wγ and Zγ processes is further cross-checked with W + jets and Z + 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).
A neutrino from leptonic W boson decay does not interact with the detector and results in a significant missing transverse energy, $E_T^\text{miss}$, in the event. The $E_T^\text{miss}$ 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 $E_T^\text{miss}$ measurement less sensitive to calorimetry miscalibration. The $E_T^\text{miss}$ 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 $E_T^\text{miss}$ 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 modelling of $E_T^\text{miss}$ in the simulation is checked using events with (W → ℓν) and without (Z → ℓ⁺ℓ⁻) genuine $E_T^\text{miss}$ 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 Wγ → ℓνγ signal and 98% efficient for Wγ → eγ. The trigger efficiency is close to 100% for both Zγ → ℓ⁺ℓ⁻γ 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 Wγ → ℓνγ final state is characterized by a prompt, energetic, and isolated lepton, significant $E_T^\text{miss}$ 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 $E_T^\text{miss}$ 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 eγ 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 Zγ → ℓ⁺ℓ⁻e processes. For μγ, 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 eγ channel and 520 events are selected in the μγ channel. No events have more than one photon candidate in the final state. The background from misidentified jets estimated in data amounts to 220 ± 16(stat.) ± 14(syst.) events for the eγ final state, and 261 ± 19(stat.) ± 16(syst.) events for the μγ 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 Wγ → eγγ and Wγ → μγγ, 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 $E_T^\text{miss}$ determination. The Wγ → ℓνγ production, with subsequent ℓ → ℓν decay, also contributes at the few percent level to the eγ and μγ final states. We rely on MC simulation to estimate this contribution. The $E_T^\gamma$ distribution for photon candidates in events passing the full Wγ selection is given in Fig. 2.
The three tree-level \( W\gamma \) 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 \( W\gamma \) production was observed by the D0 Collaboration \([10]\) using the charge-signed rapidity difference \( Q_{\gamma} \times \Delta \eta \) 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 \( Q_{\gamma} \times \Delta \eta = 0 \) for pp collisions. Anomalous \( W\gamma \) 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 background-subtracted data with an additional requirement on the transverse energy. The distribution of the rapidity difference 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.) The acceptance is determined relative to the phase space allowed events within the acceptance, and \( \epsilon \) is the selection efficiency for events within the acceptance, and \( L \) is the integrated luminosity. The acceptance is determined relative to the phase space defined by the cuts \( E_T^\gamma > 10 \text{ GeV} \) and \( \Delta R(\ell, \gamma) > 0.7 \), and in addition by \( M_{\ell\ell} > 50 \text{ GeV} \) for \( Z\gamma \). We determine the product \( A \cdot \epsilon \) from MC simulations and apply correction factors \( \rho \) 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 \( \epsilon \) and \( \epsilon_{\text{sim}} \) 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 \( Z\gamma \) 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 \( \rho \) for the efficiencies of the trigger, reconstruction, and identification requirements. These include lepton trigger, lepton and photon reconstruction and identification, and \( E_T^{\text{miss}} \) efficiencies for the \( W\gamma \) process. The lepton efficiencies are...
Table 1
Summary of systematic uncertainties.

<table>
<thead>
<tr>
<th>Source</th>
<th>$W\gamma \rightarrow e\nu\gamma$</th>
<th>$W\gamma \rightarrow \mu\nu\gamma$</th>
<th>$Z\gamma \rightarrow e\nu\gamma$</th>
<th>$Z\gamma \rightarrow \mu\nu\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Effect on $A \cdot \epsilon_{MC}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lepton energy scale</td>
<td>2.3%</td>
<td>1.0%</td>
<td>2.8%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Lepton energy resolution</td>
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<td>0.2%</td>
<td>0.5%</td>
<td>0.4%</td>
</tr>
<tr>
<td>Photon energy scale</td>
<td>4.5%</td>
<td>4.2%</td>
<td>3.7%</td>
<td>3.0%</td>
</tr>
<tr>
<td>Photon energy resolution</td>
<td>0.4%</td>
<td>0.7%</td>
<td>1.7%</td>
<td>1.4%</td>
</tr>
<tr>
<td>Pile-up</td>
<td>2.7%</td>
<td>2.3%</td>
<td>2.3%</td>
<td>1.8%</td>
</tr>
<tr>
<td>PDFs</td>
<td>2.0%</td>
<td>2.0%</td>
<td>2.0%</td>
<td>2.0%</td>
</tr>
<tr>
<td>Total uncertainty on $A \cdot \epsilon_{MC}$</td>
<td>6.1%</td>
<td>5.2%</td>
<td>5.8%</td>
<td>4.3%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Source</th>
<th>$\epsilon_{data}/\epsilon_{MC}$</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
<td>0.1%</td>
<td>0.5%</td>
<td>&lt;0.1%</td>
<td>&lt;0.1%</td>
</tr>
<tr>
<td>Lepton identification and isolation</td>
<td>0.8%</td>
<td>0.3%</td>
<td>1.1%</td>
<td>1.0%</td>
</tr>
<tr>
<td>$E_{T}^{miss}$ selection</td>
<td>0.7%</td>
<td>1.0%</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Photon identification and isolation</td>
<td>1.2%</td>
<td>1.5%</td>
<td>1.0%</td>
<td>1.0%</td>
</tr>
<tr>
<td>Total uncertainty on $\epsilon_{data}/\epsilon_{MC}$</td>
<td>1.6%</td>
<td>1.9%</td>
<td>1.6%</td>
<td>1.5%</td>
</tr>
<tr>
<td>Background</td>
<td>6.3%</td>
<td>6.4%</td>
<td>9.3%</td>
<td>11.4%</td>
</tr>
<tr>
<td>Luminosity</td>
<td></td>
<td></td>
<td></td>
<td>4%</td>
</tr>
</tbody>
</table>

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

<table>
<thead>
<tr>
<th>$WW\gamma$</th>
<th>$ZZ\gamma$</th>
<th>$Z\gamma\gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$-1.11 &lt; \Delta \kappa_{\gamma} &lt; 1.04$</td>
<td>$-0.05 &lt; h_{1} &lt; 0.06$</td>
<td>$-0.07 &lt; h_{3} &lt; 0.07$</td>
</tr>
<tr>
<td>$-0.18 &lt; \lambda_{\gamma} &lt; 0.17$</td>
<td>$-0.0005 &lt; h_{4} &lt; 0.0005$</td>
<td>$-0.0005 &lt; h_{4} &lt; 0.0006$</td>
</tr>
</tbody>
</table>

where $\mu_{W}$ and $Q_{W}$ are the magnetic dipole and electric quadrupole moments of the W boson, respectively.

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 $E_{T}^{\gamma}$ 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 $\alpha/m_{W}^{2}$, where $\alpha$ is an aTGC, $m_{W}$ is the mass of the gauge...
CMS, 36 pb\(^{-1}\) \(\sqrt{s} = 7\) TeV

Fig. 6. Two-dimensional 95% CL limit contours (a) for the WW\(\gamma\) vertex couplings \(\lambda_\gamma\) and \(\Delta\kappa_\gamma\) (blue line), and (b) for the ZZ\(\gamma\) (red dashed line) and ZZ\(\gamma\) (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.)

In summary, we have presented the first measurement of the WW\(\gamma\) and ZZ\(\gamma\) cross sections in pp collisions at \(\sqrt{s} = 7\) TeV for \(E_T > 10\) GeV, \(\Delta R(\gamma, \ell) > 0.7\), and for the additional requirement on the dilepton invariant mass to exceed 50 GeV for the ZZ\(\gamma\) process. We measured the WW\(\gamma\) cross section times the branching fraction for the leptonic W decay to be \(\sigma(pp \rightarrow W\gamma + X) \times B(W \rightarrow \ell\nu) = 56.3 \pm 5.0(\text{stat}) \pm 5.0(\text{syst}) \pm 2.3(\text{lumi})\) pb. This result is in good agreement with the NLO prediction of 49.4 \(\pm 3.8\) pb, where the uncertainty includes both PDF and k-factor uncertainties. The ZZ\(\gamma\) cross section times the branching fraction for the leptonic Z decay was measured to be \(\sigma(pp \rightarrow Z\gamma + X) \times B(Z \rightarrow \ell\ell) = 9.4 \pm 1.0(\text{stat}) \pm 0.6(\text{syst}) \pm 0.4(\text{lumi})\) pb, which also agrees well with the NLO predicted value [19] of 9.6 \(\pm 0.4\) pb. We also searched and found no evidence for anomalous WW\(\gamma\), and ZZ\(\gamma\) 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 \(\log_{10}(a_{TGC})\) as a function of \(\Lambda_{NP}\) for \(\Delta\kappa_\gamma\), \(\lambda_\gamma\), \(h_3\), and \(h_4\). Limits on the latter two couplings are similar to those for \(h_3\) and \(h_4\). These limits refer to the formulation in which the new physics Lagrangian terms are scaled with \(\alpha/\Lambda_{NP}\), where \(\Lambda_{NP}\) is the characteristic energy scale of new physics and \(\alpha\) is the aTGC.

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