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

Chatrchyan, Serguei

2011-07-27


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

Downloaded from Helda, University of Helsinki institutional repository.

This is an electronic reprint of the original article.

This reprint may differ from the original in pagination and typographic detail.

Please cite the original version.
Measurement of $W\gamma$ and $Z\gamma$ production in pp collisions at $\sqrt{s} = 7$ TeV

CMS Collaboration

CERN, Switzerland

A R T I C L E   I N F O

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

Editor: M. Boer

Keywords:
CMS
Physics
Electroweak

A B S T R A C T

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 $E_T > 10$ 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 $Z\gamma$ process. The following cross section times branching fraction values are found: $\sigma(pp \rightarrow W\gamma + X) \times B(W \rightarrow \ell\nu) = 56.3 \pm 5.0$ (stat.) $\pm 5.0$ (syst.) $\pm 2.3$ (lumi.) pb and $\sigma(pp \rightarrow Z\gamma + X) \times B(Z \rightarrow \ell\ell) = 9.4 \pm 1.0$ (stat.) $\pm 0.6$ (syst.) $\pm 0.4$ (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.

© 2011 CERN. Published by Elsevier B.V. All rights reserved.

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 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 $Z\gamma$ 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 $p\overline{p}$ 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 Zγγ 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 \( \Delta R = \sqrt{(\eta_\gamma - \eta_\ell)^2 + (\phi_\gamma - \phi_\ell)^2} \). 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 top 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 SHERPA [16] and further interfaced with PYTHIA [17] for showering and hadronization. The kinematic distributions for these signals 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 top, W+ jets, and Z+ jets. Multijet QCD, \( \gamma + \) 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 by requiring the pseudorapidity of the candidate’s pseudorapidity to 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 Wγ final state, while the looser selection is used for Zγ.

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 Wγ → μγγ 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 → e\( ^+ e^− \) 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+ jets and Z+ jets events are similar to those in multijet 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, \( E_{\text{miss}} \), in the event. The \( E_{\text{miss}} \) 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 calorimeters 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 \( E_{\text{miss}} \) measurement less sensitive to calorimeter miscalibration. The \( E_{\text{miss}} \) 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 \( E_{\text{miss}} \) 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 modeling of \( E_{\text{miss}} \) in the simulation is checked using events with (W \( \rightarrow e\nu\)) and without (Z \( \rightarrow \ell^+\ell^-\)) genuine \( E_{\text{miss}} \) 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 W\(\gamma \rightarrow \ell\nu\gamma \) signal and 98% efficient for W\(\gamma \rightarrow e\nu\gamma \). The trigger efficiency is close to 100% for both Z\(\gamma \rightarrow \ell\nu\gamma \) 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\(\gamma \rightarrow \ell\nu\gamma \) final state is characterized by a prompt, energetic, and isolated lepton, significant \( E_{\text{miss}} \) 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 \( p_T > 20 \text{ GeV} \), which must satisfy the trigger requirements; one photon with transverse energy \( E_T^\gamma > 10 \text{ GeV} \), and the \( E_{\text{miss}} \) 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 \( \ell\nu\gamma \) 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\(\gamma \rightarrow e\nu\) processes. For \( \mu\nu\gamma \), we reject the event if a second muon is found with \( p_T > 10 \text{ GeV} \).

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 Z\(\gamma \) 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\( \pm 0.5 \) and 16.4\( \pm 1.0 \) for W\(\gamma \rightarrow e\nu\gamma \) and W\(\gamma \rightarrow \mu\nu\gamma \), respectively. A larger contribution from Z\(\gamma \) 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 \( E_{\text{miss}} \) determination. The W\(\gamma \rightarrow \tau\nu\gamma \) production, with subsequent \( \tau \rightarrow \ell\nu\ell \) 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 \( E_{\text{T}} \) distribution for photon candidates in events passing the full W\(\gamma \) 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 $Q_1 \times \Delta \eta$ 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 $Q_1 \times \Delta \eta = 0$ 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 $E_T^{\text{miss}}$ to exceed 90 GeV, to reduce the contribution from FSR $W\gamma$ production. The agreement between background-subtracted data and MC prediction is reasonable, with a Kolmogorov–Smirnov test [36,37] result of 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.)

Events in the $Z\gamma$ 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 $E_T^\gamma$ 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 $ee\gamma$ final state and 90 events in the $\mu\mu\gamma$ final state. No events are observed with more than one photon candidate. The $Z + \text{jets}$ 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, $\gamma + \text{jets}$, $t\bar{t}$, 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 $Z\gamma$ candidate events is shown in Fig. 4. The distribution of the $\ell\ell\gamma$ mass as a function of the dilepton invariant 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

$$\sigma = \frac{N_{\text{data}} - N_{\text{bkg}}}{\epsilon \cdot L},$$

where $N_{\text{data}}$ is the number of observed events, $N_{\text{bkg}}$ is the number of estimated background events, $\epsilon$ is the fiducial and kinematic acceptance of the selection criteria, and $L$ 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 $Z\gamma$. 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
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}^{miss}-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 WW and ZZ channels are summarized in Table 1.

We find the cross section for WW production for E_{T}^{miss} > 10 GeV and ΔR(ℓ, γ) > 0.7 to be σ(pp → WW + X) × B(W → eγ) = 57.1 ± 6.9(stat.) ± 5.1(syst.) ± 2.3(lumi.) pb and σ(pp → WW + X) × B(W → μγ) = 55.4 ± 7.2(stat.) ± 5.0(syst.) ± 2.3(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 σ(pp → WW + X) × B(W → eγ) = 56.3 ± 5.0(stat.) ± 5.0(syst.) ± 2.3(lumi.) pb. This result agrees well with the NLO prediction [41] of 49.4 ± 3.8 pb.

The ZZ cross section within the requirements E_{T}^{miss} > 10 GeV, ΔR(ℓ, γ) > 0.7, and m_{jj} > 50 GeV, is measured to be σ(pp → ZZ + X) × B(Z → ee) = 9.5 ± 1.4(stat.) ± 0.7(syst.) ± 0.4(lumi.) pb for the ee final state, and σ(pp → ZZ + X) × B(Z → μμ) = 9.2 ± 1.4(stat.) ± 0.6(syst.) ± 0.4(lumi.) pb for the μμ final state. The combination of the two results yields σ(pp → ZZ + X) × B(Z → eγ) = 9.4 ± 1.0(stat.) ± 0.6(syst.) ± 0.4(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 the measured cross sections and the E_{T}^{miss} distributions with the corresponding SM predictions, we proceed to set limits on anomalous TGCs. The most general Lorentz-invariant Lagrangian that describes the WW coupling has seven independent dimensionless couplings g_1^\gamma, \kappa_\gamma, \lambda_\gamma, g_4^\gamma, g_5^\gamma, \kappa^\gamma, and \lambda^\gamma [42]. By requiring CP invariance and SU(2) x U(1) gauge invariance only two independent parameters remain: κ\gamma and λ\gamma. In the SM, κ\gamma = 1 and λ\gamma = 0. We define aTGCs to be deviations from the SM predictions, so instead of using κ\gamma, we define Δκ\gamma ≡ κ\gamma − 1. While these couplings have no physical meaning as such, they are related to the electromagnetic moments

<table>
<thead>
<tr>
<th>Source</th>
<th>WW → eeγ</th>
<th>WW → μμγ</th>
<th>ZZ → eeγ</th>
<th>ZZ → μμγ</th>
<th>Effect on A · εMC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lepton energy scale</td>
<td>2.3%</td>
<td>1.0%</td>
<td>2.8%</td>
<td>1.5%</td>
<td></td>
</tr>
<tr>
<td>Lepton energy resolution</td>
<td>0.3%</td>
<td>0.2%</td>
<td>0.5%</td>
<td>0.4%</td>
<td></td>
</tr>
<tr>
<td>Photon energy scale</td>
<td>4.5%</td>
<td>4.2%</td>
<td>3.7%</td>
<td>3.0%</td>
<td></td>
</tr>
<tr>
<td>Photon energy resolution</td>
<td>0.4%</td>
<td>0.7%</td>
<td>1.7%</td>
<td>1.4%</td>
<td></td>
</tr>
<tr>
<td>Pile-up</td>
<td>2.7%</td>
<td>2.3%</td>
<td>2.3%</td>
<td>1.8%</td>
<td></td>
</tr>
<tr>
<td>PDFs</td>
<td>2.0%</td>
<td>2.0%</td>
<td>2.0%</td>
<td>2.0%</td>
<td></td>
</tr>
<tr>
<td>Total uncertainty on A · εMC</td>
<td>6.1%</td>
<td>5.2%</td>
<td>5.8%</td>
<td>4.3%</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Effect on ε_{data}/ε_{MC}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trigger</td>
</tr>
<tr>
<td>Lepton identification and isolation</td>
</tr>
<tr>
<td>E_{T}^{miss} selection</td>
</tr>
<tr>
<td>Photon identification and isolation</td>
</tr>
<tr>
<td>Total uncertainty on ε_{data}/ε_{MC}</td>
</tr>
<tr>
<td>Background</td>
</tr>
<tr>
<td>Luminosity</td>
</tr>
</tbody>
</table>

Table 2

One-dimensional 95% CL limits on WWγ, ZZγ, and ZZγ aTGCs.

<table>
<thead>
<tr>
<th>Source</th>
<th>WWγ</th>
<th>ZZγ</th>
<th>ZZγ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Δλγ</td>
<td>−1.11 &lt; Δλγ &lt; 1.04</td>
<td>−0.05 &lt; h_3 &lt; 0.06</td>
<td>−0.07 &lt; h_3 &lt; 0.07</td>
</tr>
<tr>
<td>Δkγ</td>
<td>−0.18 &lt; λγ &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>

of the W boson,

\[ \mu_W = -\frac{e}{2M_W}(2 + \Delta\kappa^\gamma + \lambda^\gamma), \]

\[ Q_W = -\frac{e}{M_W}(1 + \Delta\kappa^\gamma - \lambda^\gamma), \]

where \( \mu_W \) and \( Q_W \) are the magnetic dipole and electric quadrupole moments of the W boson, respectively.

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

The non-SM terms in the effective Lagrangian are scaled with \( \alpha/m_V^2 \), where \( \alpha \) is an aTGC, \( m_V \) is the mass of the gauge boson.
found no evidence for anomalous WWγ production at the NLO predicted value \[19\] of 9. We measured the Wγ cross section times the branching fraction for the leptonic W decay to be \[\sigma(pp\rightarrow W\gamma \rightarrow \ell\nu)\times Br(W\rightarrow \ell\nu) = 56.3 \pm 5.0_{\text{stat}} \pm 5.0_{\text{syst}} \pm 2.3_{\text{lumi}} \text{ pb}\], which agrees well with the NLO prediction of 49.4 \pm 3.8 pb. This result is in good agreement with the LHCb measurement of 49.4 \pm 3.8 pb, 4\text{ aTGC}\text{, where }\Lambda_{\text{NP}}\text{ is the characteristic energy scale of new physics}[44].\text{ We present upper limits on aTGCs for }\Lambda_{\text{NP}}\text{ 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 \(E_T > 10\ GeV\), \(\Delta R(\gamma, \ell) > 0.7\), and for the additional requirement on the dilepton invariant mass to exceed 50 GeV for the Zγ process. We measured the Wγ cross section times the branching fraction for the leptonic W decay to be \(\sigma(pp\rightarrow W\gamma \rightarrow X)\times Br(W\rightarrow \ell(\nu)) = 9.6 \pm 1.0_{\text{stat}} \pm 0.6_{\text{syst}} \pm 0.4_{\text{lumi}} \text{ pb}\), 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 WWγ, WZγ, and Zγγ 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.

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); COCENCIAS (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); IPEM (Iran); SFI (Ireland); INFN (Italy); NRF and WCU (Korea); LAS (Lithuania); CINVESTAV, CONACYT, SEP, and UASLP-FAI (Mexico); MCU (Pakistan); SCSR (Poland); PCT (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).

Open access

This article is published Open Access at sciencedirect.com. It is distributed under the terms of the Creative Commons Attribution License 3.0, which permits unrestricted use, distribution, and reproduction in any medium, provided the original authors and source are credited.

References


Laboratório de Instrumentação e Física Experimental de Partículas, Lisboa, Portugal


Joint Institute for Nuclear Research, Dubna, Russia

V. Golovtsov, Y. Ivanov, V. Kim, P. Levchenko, V. Murzin, V. Oreshkin, I. Smirnov, V. Sulimov, L. Uvarov, S. Vavilov, A. Vorobyev, A. Vorobyev

Petersburg Nuclear Physics Institute, Gatchina (St. Petersburg), Russia


Institute for Nuclear Research, Moscow, Russia

V. Epshteyn, V. Gavrilov, V. Kaftanov, M. Kossov, A. Krokhinot, N. Lychkovskaya, V. Popov, G. Safronov, S. Semenov, V. Stolin, E. Vlasov, A. Zhokin

Institute for Theoretical and Experimental Physics, Moscow, Russia


Moscow State University, Moscow, Russia

V. Andreev, M. Azarkin, I. Dremin, M. Kirakosyan, A. Leonidov, S.V. Rusakov, A. Vinogradov

P.N. Lebedev Physical Institute, Moscow, Russia


State Research Center of Russian Federation, Institute for High Energy Physics, Protvino, Russia

P. Adzic, M. Djordjevic, D. Krpic, J. Milosevic

University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia


Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Madrid, Spain

C. Albajar, G. Codispoti, J.F. de Trocóniz

Universidad Autónoma de Madrid, Madrid, Spain


Universidad de Oviedo, Oviedo, Spain


Instituto de Física de Cantabria (IFCA), CSIC – Universidad de Cantabria, Santander, Spain


CERN, European Organization for Nuclear Research, Geneva, Switzerland


Paul Scherrer Institut, Villigen, Switzerland


Institute for Particle Physics, ETH Zurich, Zurich, Switzerland

E. Aguiló, C. Amsler, V. Chiochia, S. De Visscher, C. Favaro, M. Ivova Rikova, B. Millan Mejias, P. Otiougova, C. Regenfus, P. Robmann, A. Schmidt, H. Snoek

Universität Zürich, Zurich, Switzerland


National Central University, Chung-Li, Taiwan


National Taiwan University (NTU), Taipei, Taiwan


Cukurova University, Adana, Turkey


Middle East Technical University, Physics Department, Ankara, Turkey

Rutgers, the State University of New Jersey, Piscataway, USA

G. Cerizza, M. Hollingsworth, S. Spanier, Z.C. Yang, A. York

University of Tennessee, Knoxville, USA


Texas A&M University, College Station, USA


Texas Tech University, Lubbock, USA


Vanderbilt University, Nashville, USA

M.W. Arenton, M. Balazs, S. Boutle, B. Cox, B. Francis, R. Hirosky, A. Ledovskoy, C. Lin, C. Neu, R. Yohay

University of Virginia, Charlottesville, USA

S. Gollapinni, R. Harr, P.E. Karchin, P. Lamichhane, M. Mattson, C. Milstène, A. Sakharov

Wayne State University, Detroit, USA


University of Wisconsin, Madison, USA

* Corresponding author.
E-mail address: Roberto.Tenchini@cern.ch (R. Tenchini).

1 Also at CERN, European Organization for Nuclear Research, Geneva, Switzerland.
2 Also at Universidade Federal do ABC, Santo Andre, Brazil.
3 Also at Laboratoire Leprince-Ringuet, Ecole Polytechnique, IN2P3–CNRS, Palaiseau, France.
4 Also at Suez Canal University, Suez, Egypt.
5 Also at British University, Cairo, Egypt.
6 Also at Fayoum University, El-Fayoum, Egypt.
7 Also at Soltan Institute for Nuclear Studies, Warsaw, Poland.
8 Also at Massachusetts Institute of Technology, Cambridge, USA.
9 Also at Université de Haute-Alsace, Mulhouse, France.
10 Also at Brandenburg University of Technology, Cottbus, Germany.
11 Also at Moscow State University, Moscow, Russia.
12 Also at Institute of Nuclear Research ATOMKI, Debrecen, Hungary.
13 Also at Eötvös Loránd University, Budapest, Hungary.
14 Also at Tata Institute of Fundamental Research – HECR, Mumbai, India.
15 Also at University of Vissva-Bharati, Santiniketan, India.
16 Also at Sharif University of Technology, Tehran, Iran.
17 Also at Shiraz University, Shiraz, Iran.
18 Also at Isfahan University of Technology, Isfahan, Iran.
19 Also at Politecnico di Torino, Turin, Italy.
20 Also at Università della Basilicata, Potenza, Italy.
21 Also at Laboratori Nazionali di Legnaro dell’INFN, Legnaro, Italy.
22 Also at University degli Studi di Siena, Siena, Italy.
23 Also at California Institute of Technology, Pasadena, USA.
24 Also at Faculty of Physics of University of Belgrade, Belgrade, Serbia.
25 Also at University of California, Los Angeles, Los Angeles, USA.
26 Also at University of Florida, Gainesville, USA.
27 Also at Université de Genève, Geneva, Switzerland.
28 Also at Scuola Normale e Sezione dell’INFN, Pisa, Italy.
29 Also at University of Athens, Athens, Greece.
30 Also at The University of Kansas, Lawrence, USA.
31 Also at Institute for Theoretical and Experimental Physics, Moscow, Russia.
32 Also at Paul Scherrer Institut, Villigen, Switzerland.
33 Also at University of Belgrade, Faculty of Physics and Vinca Institute of Nuclear Sciences, Belgrade, Serbia.
34 Also at Gaziosmanpasa University, Tokat, Turkey.
35 Also at Adiyaman University, Adiyaman, Turkey.
36 Also at Mersin University, Mersin, Turkey.
37 Also at Izmir Institute of Technology, Izmir, Turkey.
38 Also at Kafkas University, Kars, Turkey.
39 Also at Süleyman Demirel University, Isparta, Turkey.
40 Also at Ege University, Izmir, Turkey.
41 Also at Rutherford Appleton Laboratory, Didcot, United Kingdom.
42 Also at School of Physics and Astronomy, University of Southampton, Southampton, United Kingdom.
43 Also at INFN Sezione di Perugia; Università di Perugia, Perugia, Italy.
44 Also at Utah Valley University, Orem, USA.
45 Also at Institute for Nuclear Research, Moscow, Russia.
46 Also at Los Alamos National Laboratory, Los Alamos, USA.
47 Also at Erzincan University, Erzincan, Turkey.
† Deceased.