Observation of the electroweak production of $W\gamma$ in association with two jets in proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration

Abstract

A measurement of the electroweak (EW) production of a W boson and a photon in association with two jets in proton-proton collisions, where the W boson decays leptonically, is presented. Events are selected by requiring one identified electron or muon, missing transverse momentum, one photon, and two jets with a large dijet mass and a large rapidity separation. The measurement is based on data collected with the CMS detector in 2016 at a center-of-mass energy of 13 TeV, corresponding to an integrated luminosity of 35.9 fb$^{-1}$. The observed (expected) significance for this process is 4.9 (4.6) standard deviations. After combining with previously reported CMS results based on 8 TeV data, the observed (expected) significance is 5.3 (4.8) standard deviations. This constitutes the first observation of EW $W\gamma$ production in pp collisions. The cross section measured in the fiducial region is $20.4 \pm 4.5$ fb and the total cross section for EW + QCD $W\gamma$ production in association with 2 jets in the same fiducial region is measured to be $108 \pm 16$ fb. All measurements are in good agreement with recent theory predictions. We set the most stringent limits to date on the anomalous quartic gauge coupling parameters $F_{M,2-5}$ and $F_{T,6-7}$. 
1 Introduction

One of the primary goals of high energy physics after the Higgs boson discovery at the CERN LHC [1–3] is to examine in detail the mechanism of electroweak (EW) symmetry breaking, for example through measurements of the properties of the Higgs boson. Measurements of vector boson scattering (VBS) processes are an important complement and independent method to study EW symmetry breaking. The non-Abelian nature of gauge interactions in the standard model (SM) leads to a rich variety of VBS processes with unique features and possible connections to physics beyond the SM.

It only became possible to study VBS processes in detail recently thanks to the high energy and high luminosity of the LHC. VBS events reconstructed with the CMS detector have several distinguishing characteristics, including two widely separated jets with large dijet invariant mass. The first observation of a VBS process, the EW production of same-sign $W^\pm W^\pm j j$ with a significance of 5.5 standard deviations ($\sigma$), was reported by the CMS Collaboration based on data collected in 2016 [4]. There have been several additional VBS results from both ATLAS and CMS. Notably, ATLAS observed same-sign $W^\pm W^\pm j j$ EW production with a significance of 6.5 $\sigma$ [5]. CMS recently reported an observation of WZ VBS with a significance of 6.8 $\sigma$ [6], along with further studies in the same-sign $W^\pm W^\pm j j$ channel, based on the data sample collected during 2016–2018. Moreover, VBS involving a photon in the final state, $W\gamma$ and $Z\gamma$ scattering, was also reported by the ATLAS and CMS Collaborations, based on data collected at $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of approximately 20 fb$^{-1}$ [7–9]. The observed (expected) significance for $W\gamma$ scattering from CMS was 2.7 (1.5) $\sigma$. For $Z\gamma$ scattering, the observed significance was 2.0 (3.0) $\sigma$ for the ATLAS (CMS) study, where a significance of 1.8 (2.1) $\sigma$ was expected based on the SM prediction. A recent update on $Z\gamma$ scattering from CMS, based on the 13 TeV collision data collected during 2016 and combined with 8 TeV results [10], reported an observed (expected) significance of 4.7 (5.5) $\sigma$.

This note presents a study of VBS in the $W\gamma$ final state at $\sqrt{s} = 13$ TeV. The data sample corresponds to an integrated luminosity of 35.9 ± 0.9 fb$^{-1}$ collected using the CMS detector [11] in 2016. Candidate events are selected by requiring one identified lepton (electron or muon), one identified photon, two jets with a large rapidity separation and a large dijet mass, and moderate missing transverse momentum. This selection reduces the contribution from the strong production of jets associated with $W\gamma$, making the experimental signature an ideal topology for VBS $W\gamma$ studies. The interference of the VBS diagrams ensures the unitarity of the VBS cross section in the SM at high energy, and large interference is known from the EW diagrams [12, 13].

As shown in Fig. 1, the signal process includes both VBS diagrams and non-VBS EW diagrams, such as EW process with triple and quartic gauge couplings. Quantum chromodynamics (QCD)-induced production of $W\gamma j j$ can also occur, demonstrated in the diagram on the right, with both jets originating from QCD vertices. The diagrams shown are representative of the many possibilities in the SM. The effects of beyond the standard model (BSM) physics, such as anomalous quartic gauge couplings (aQGC), can also appear [14].

2 The CMS detector

The central feature of the CMS [11] apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL), each composed of a barrel and two endcap sections. Forward calorimeters extend the coverage provided by the barrel and endcap detectors up to
Figure 1: Representative diagrams for $\ell\nu\gamma jj$ production at the LHC: EW production (left), EW production with triple gauge boson coupling (middle left) and with quartic gauge boson coupling (middle right), and QCD-induced processes (right).

a pseudorapidity of $|\eta|=5$. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid.

Events of interest are selected using a two-tiered trigger system [15]. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of around 100 kHz within a time interval of less than 4 $\mu$s. The second level consists of a farm of processors running a version of the full event reconstruction software optimized for fast processing, and reduces the event rate to around 1 kHz before data storage.

A more detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [11].

3 Signal and background simulation

The signal and background processes are simulated using the Monte Carlo (MC) generator MadGraph5_aMC@NLO 2.4.2 and 2.6.0 [16]. The EW $W\gamma jj$ signal is simulated at leading order (LO) and the main background, QCD $W\gamma$, is simulated with zero and one jets at next-to-leading order (NLO) with the FxFx merging scheme [17]. The interference between the EW and QCD processes is 1–3% in the signal region and is treated as a systematic uncertainty. Other background contributions that are considered include diboson processes (WW, WZ, ZZ) simulated with Pythia 8 [18], single top processes simulated with Powheg 2.0 [19], and top simulated using MadGraph 5 interfaced to Pythia 8 with the FxFx scheme. NLO QCD cross sections are used to normalize these simulated samples.

The Pythia 8.212 package, with the CUETP8M1 [20, 21] tune, is used for parton showering, hadronization, and the underlying event simulation. The NNPDF 3.0 [22] set is considered as the default set of parton distribution functions. All simulated events are processed through a Geant4 [23] simulation of the CMS detector. The tag-and-probe technique [24] is used to correct the differences between data and simulation in the trigger efficiency, as well as the reconstruction and selection efficiencies. Additional proton-proton interactions (pileup) are superimposed over the hard scattering interaction with a distribution of primary vertices matching that obtained from the collision data.

4 Event reconstruction

The particle-flow (PF) algorithm [25] aims to reconstruct and identify each individual particle in an event, with an optimized combination of information from the various elements of the CMS detector. The energy of photons is obtained from the ECAL measurement. The energy of
electrons is determined from a combination of the electron momentum at the primary interaction vertex as determined by the tracker, the energy of the corresponding ECAL cluster, and the energy sum of all bremsstrahlung photons spatially compatible with originating from the electron track. The energy of muons is obtained from the curvature of the corresponding track. The energy of charged hadrons is determined from a combination of their momentum measured in the tracker and the matching ECAL and HCAL energy deposits, corrected for the response function of the calorimeters to hadronic showers. Finally, the energy of neutral hadrons is obtained from the corresponding corrected ECAL and HCAL energies. The PF particle collection is used for a variety of purposes in this analysis, such as evaluating electron, muon, and photon isolation variables, reconstructing jets, and computing the missing transverse momentum ($p_T^{\text{miss}}$) in the event, as described in more detail below.

The reconstructed vertex with the largest value of summed physics-object $p_T^2$ is taken to be the primary pp interaction vertex [26]. The physics objects are the jets, clustered using the anti-$k_T$ jet finding algorithm [27, 28] with the tracks assigned to candidate vertices as inputs, and the associated missing transverse momentum, taken as the negative vector sum of the $p_T$ of those jets.

Electron candidates are reconstructed within $|\eta| < 2.5$ for $p_T > 25$ GeV. To reduce electron misidentification, these candidates are required to pass additional identification criteria based on the relative amount of energy deposited in the HCAL, a match of the trajectory in the inner tracker with that in the supercluster [29] of the ECAL, the number of missing hits in the inner tracker, the consistency between the track and the primary vertex, and $\sigma_{\eta\eta}$, a parameter that quantifies the spread in $\eta$ of the electromagnetic shower in the ECAL, as discussed in Section 6. Electron candidates identified as originating from photon conversions are rejected [29, 30]. A high-quality identification selection (ID) is used to identify electrons in the final state, and a loose selection is used to identify electrons for vetoing events containing additional leptons.

Muons are reconstructed from information in the muon system and the inner tracker for $|\eta| < 2.4$ and $p_T > 20$ GeV [31]. Muon candidates must satisfy identification criteria based on the number of hits in the muon system and the inner tracker, the quality of the combined fit to the track, the number of matched muon-detector planes, and the consistency between the track and the primary vertex. A high-quality ID is used to identify muons in the final state, and a loose ID is used to identify muons for vetoing events with additional leptons.

An additional selection on a relative isolation variable is applied for both electrons and muons. This variable is defined relative to the object $p_T$ by summing the $p_T$ of the charged hadrons and neutral particles in geometrical cones of $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.3$ (0.4) about the electron (muon) trajectory:

$$\text{Iso} = \left( \sum p_T^{\text{charged}} + \max \left[ 0, \sum p_T^{\text{neutral}} + \sum p_T^\gamma - p_T^{\text{PU}} \right] \right) / p_T.$$

Here $\sum p_T^{\text{charged}}$ is the scalar $p_T$ sum of charged hadrons originating from the primary vertex, and $\sum p_T^{\text{neutral}}$ and $\sum p_T^\gamma$ are, respectively, the scalar $p_T$ sums of neutral hadrons and photons. In order to mitigate pileup (PU) effects, only charged hadrons originating at the primary vertex are included. For the neutral hadron and photon components, an estimate of the expected PU contribution ($p_T^{\text{PU}}$) is subtracted. For electrons, $p_T^{\text{PU}}$ is evaluated using the “jet area” method described in Ref. [32], while for muons, $p_T^{\text{PU}}$ is assumed to be one half of the scalar $p_T$ sum deposited in the isolation cone by charged particles not associated with the primary vertex. The factor of one half corresponds approximately to the ratio of neutral to charged hadrons produced in the hadronization of PU interactions. Electrons passing the high-quality (loose)
Photon reconstruction [33] is similar to that of electrons, and is performed in the region of $|\eta| < 2.5$ and for $p_T > 20$ GeV, excluding the ECAL transition region of $1.444 < |\eta| < 1.566$. To minimize photon misidentification, photon candidates are required to pass an electron veto, satisfy criteria based on the distribution of energy deposited in the ECAL and in the HCAL, and on the isolation variables constructed from the kinematic inputs of the charged and neutral hadrons, and other photon candidates present near the photon of interest. A high-quality ID is used to identify prompt photons (i.e., not from hadron decays) in the final state, and a loose ID is used to identify nonprompt photons, which are mainly products of neutral pion decay [33].

Jets are reconstructed from PF objects using the anti-$k_T$ jet clustering algorithm [27] with a distance parameter of 0.4. To reduce the contamination from PU, charged PF candidates in the tracker acceptance of $|\eta| < 2.4$ are excluded from jet clustering when they are associated with PU vertices [25]. The contribution from neutral PU particles to the jet energy is corrected based on the projected area of the jet on the front face of the calorimeter. For this analysis, jets are required to have $|\eta| < 4.7$ and $p_T > 30$ GeV. A jet energy correction, similar to the one developed for 8 TeV collisions [34], is obtained from a dedicated set of studies performed on both data and simulated events (typically involving dijet, $\gamma$+jet, Z+jet, and multijet production). Other residual corrections are applied to the data as functions of $p_T$ and $\eta$ to correct for the small differences between data and simulation. Additional quality criteria are applied to jet candidates to remove spurious jet-like features originating from isolated noise patterns in the calorimeters or in the tracker.

The missing transverse momentum vector $\vec{p}_T^{\text{miss}}$ is computed as the negative vector sum of the $p_T$ of all the PF candidates in an event [35], and its magnitude is denoted as $p_T^{\text{miss}}$. The $p_T^{\text{miss}}$ is modified to account for corrections to the energy scale of the reconstructed jets in the event.

5 Event selection

Candidate events are selected by requiring exactly one electron (muon) with $p_T > 30$ GeV and $|\eta| < 2.5$ (2.4), and transverse mass of the W boson $m_T(W) > 30$ GeV. We define $m_T(W)$ as $\sqrt{2 p_T^e p_T^{miss} [1 - \cos(\Delta\phi_{e,miss})]}$, where $\Delta\phi_{e,miss}$ is the azimuthal angle between the lepton and the $p_T^{miss}$ directions. Events are required to contain a well-identified and isolated photon with $p_T > 25$ GeV, at least two jets with $|\eta| < 4.7$ and $p_T > 40$ (30) GeV separately, and $p_T^{miss} > 30$ GeV. To separate different candidates properly, a separation of $\Delta R > 0.5$ is required between photon, lepton, and jet. In the electron channel we further require the invariant mass of the selected photon and electron to be outside the Z boson mass peak, $|m_{ee} - 91| > 10$ GeV, to suppress the $Z \rightarrow e^+e^-$ background where one electron is misidentified as a photon.

In the analysis two regions are defined: the control region and the signal region. The control region is constructed with the aim of validating our simulated samples and our background estimation methods. It extends the common selection defined above with the additional requirement that the dijet invariant mass $m_{jj}$ is in the range 200 to 400 GeV.

The signal region is defined as the common selection mentioned above with the additional requirements that $m_{jj} > 500$ GeV, $|\Delta y_{jj}| > 2.5$, $m_{W\gamma} > 100$ GeV, $|y_{W\gamma} - (y_{j1} + y_{j2})/2| < 1.2$ [36], and $|\phi_{W\gamma} - \phi_{j1,j2}| > 2$. Here $m_{W\gamma}$ and $\phi_{W\gamma}$ are the invariant mass and azimuthal angle of the photon, charged lepton, and neutrino system, and $y$ is the rapidity. The longitudinal compo-
The dominant source of background to the EW signal is QCD $W\gamma$+jets production. The shape of this background is taken from MC simulation and it is constrained to the theoretical prediction with an uncertainty.

Reconstructed photons and leptons that do not arise from outgoing particles in the hardest interaction in the event are denoted as misidentified photons and misidentified leptons. This
category includes physical photons and leptons, as well as those of purely instrumental origins. Because of the variety of sources of misidentified photons and leptons, and the difficulty of modeling instrumental effects, the MC modeling of these backgrounds is poor and data-driven methods are used to estimate their contribution.

The background from misidentified photons arises mainly from W+jets or top+jets events where one jet is misreconstructed as a photon. The data-driven method used to estimate this background involves measuring and applying a per-photon extrapolation factor, in which the denominator is chosen to be orthogonal to the full photon selection but similar enough that the systematic uncertainties due to the extrapolation are well understood. The photon in the denominator is required to fail the high-quality ID and pass the loose ID [8, 39]. The extrapolation factor is determined from a template fit to the photon $\sigma_{\eta\eta}$ distribution, which is small for prompt photons and large for nonprompt photons. The nonprompt template used in the fit is obtained from a sideband of the photon isolation variable in W+jets data events. More details can be found in Ref. [10].

The background from jets misidentified as electrons (muons) is estimated in a similar fashion. To extrapolate from the loose electrons (muons) to the high-quality electrons (muons), an extrapolation factor is defined as:

$$\frac{f_{e(\mu)}}{1 - f_{e(\mu)}}$$

where $f_{e(\mu)}$ is the electron (muon) fake rate, defined as the ratio of the number of events in the signal region in which the electron (muon) passes the high-quality ID, to the total number of events passing the loose ID. In order to remove further contamination from real electrons (muons), the W+jets and Z+jets samples are subtracted from both the numerator and denominator. The extrapolation factor is measured as a function of the $\eta$ and $p_T$ of the lepton in a control region dominated by dijet events in which one jet is misreconstructed. The dijet control region is defined by selecting exactly one electron (muon), one jet that is well separated from the electron (muon), and low $p_T^{\text{miss}}$. Instead of performing a template fit to extract the real and misidentified contributions in this region, the real contribution is subtracted using simulated samples. This technique is also used and described in Ref. [4].

The background category “double fake” is defined as those events containing both a misidentified photon and a misidentified lepton, and is estimated using data events that contain a photon passing the misidentified photon denominator selection and a lepton passing the misidentified lepton denominator selection. These events are then assigned a weight equal to the product of the misidentified photon extrapolation factor and the misidentified lepton extrapolation factor. Double fake events contaminate the single misidentified background estimate because the second object is assumed to be real, consequently, each time a weight is added to the double fake estimate, the same weight is subtracted from both the single lepton and single photon estimate. In addition, events in which real leptons and photons pass the denominator selection contaminate both the single and double fake estimates, and this source of contamination is estimated and removed using simulated samples with reconstructed objects matched to generator-level objects.

Other backgrounds, including top quark and diboson processes, are estimated from MC simulations and normalized to the integrated luminosity of the data sample using inclusive cross sections calculated at NLO in QCD. The $e \rightarrow \gamma$ background includes events with an electron misidentified as a photon, we apply $|m_{l\gamma} - 91| > 10$ GeV to remove most of the contribution, the remaining contribution is estimated using simulated Drell-Yan and $t\bar{t}\gamma$ events which have
7. Systematic uncertainties

7.1 Photon matched to the electron in generator level with $\Delta R = 0.3$. An example plot comparing the data and prediction of the photon $p_T$ is shown in Fig. 2; the data and the prediction show good agreement.

7 Systematic uncertainties

Systematic uncertainties that affect the measurements arise from experimental inputs, such as detector effects and the methods used to compute higher-level quantities, e.g., efficiencies, and from theoretical inputs, such as the choice of the renormalization ($\mu_R$) and factorization ($\mu_F$) scales and the choice of the PDF set. Each source of systematic uncertainty is quantified by evaluating its effect on the yield of the relevant signal or background categories. The uncertainties are propagated to the final distribution and are calculated bin-by-bin for the different bins described in Section 8. The log-normal distribution is used to model all the systematic uncertainties.

The systematic uncertainties in the lepton trigger, reconstruction, and selection efficiencies, measured using the tag-and-probe technique, are 2–3%. The jet energy scale (JES) uncertainties have the largest impact on the measurement. The JES and jet energy resolution (JER) uncertainties are calculated in simulated events by scaling and smearing the relevant observables and propagating bin-by-bin the effects to the variables used for the signal extraction and for the aQGC search. The uncertainties due to the JES and the JER vary in the ranges 0.9–78% and 0.7–21%, respectively, corresponding to different processes and different $m_{jj}$-$m_{\ell\gamma}$ bins. An uncertainty of 2.5% in the integrated luminosity determination [40] is considered for all processes estimated from simulation and for the fiducial cross section. The statistical uncertainties due to the finite sizes of both the simulated and data samples used in our background and signal prediction are taken into account assuming Poisson statistics. The uncertainties related to the finite number of simulated events, or to the limited number of events in the data control sample, are 7–11% for the EW $W\gamma jj$ signal, 6–36% for the QCD-induced $W\gamma$ background, 43–72% for the nonprompt lepton, and 7–36% for the nonprompt photon background with increasing $m_{jj}$ and $m_{\ell\gamma}$, and they are uncorrelated across different processes and bins of a single distribution.

An overall systematic uncertainty in the nonprompt photon background estimate is defined as the quadratic sum of the systematic uncertainties from several distinct sources. An uncertainty due to the choice of the isolation variable sideband is evaluated by estimating the nonprompt photon fraction with alternative choices of the isolation variable sideband [8]. A nonclosure uncertainty is defined by performing the nonprompt photon fraction fits on simulated samples and comparing the fit results with the known fractions. The nonclosure in the endcap region is worse than in the barrel region, and worsens with increasing photon $p_T$. The overall nonprompt photon background systematic uncertainty is in the range 12–22%, dominated by the nonclosure uncertainty. Similarly, the dominant uncertainty in the nonprompt lepton estimate is the one associated with the nonclosure, which is calculated by comparing two yields: one is from the $\gamma$+jets sample, the other is from the $\gamma$+jets samples where the misidentified lepton rates are applied to loose-but-not-high-quality lepton events. The selection that is used is the same as the main event selection, except that the $m_T$ and $p_T^{\text{miss}}$ requirements are removed in order to increase the statistical power. The uncertainty associated to the nonprompt lepton is 30%.

The scale uncertainty is estimated by simultaneously varying $\mu_R$ and $\mu_F$ up and down by a factor of two from their nominal value in each event, with the condition that $1/2 \leq \mu_R/\mu_F \leq 2$. The maximal differences from the nominal values are taken to be the uncertainties. The PDF uncertainties are estimated by combining the predictions from the members of the NNPDF 3.0
set, according to the procedure described in Refs. [41–43]. For the signal process, the scale
uncertainty varies within the range of 1.5–11% and the PDF uncertainty varies within the range
3.2–5.6% with increasing $m_{jj}$ and $m_{\ell\gamma}$. The scale uncertainty of the QCD-induced $W\gamma$
process, which has a very large impact on the measurement, varies in the range 6.1–20%. It is
constrained by the simultaneous fit to the low $m_{jj}$ control regions. The PDF uncertainty of
QCD-induced $W\gamma$ is in the range of 1–2%.

The interference term between the EW and QCD-induced processes, i.e., $O(a^4\alpha_S)$ at tree level, is
estimated at particle level using MADGRAPH5_aMC@NLO. The contribution of the interference
is calculated as the difference between the inclusive $W\gamma jj$ production, including the interference
term, and the sum of the pure EW-induced $W\gamma jj$ and pure QCD-induced $W\gamma jj$. The interference
is positive, and the ratio of the interference to the EW $W\gamma jj$ decreases with increasing $m_{jj}$, and
is in the range 2–4%. These values are used as a systematic uncertainty in the signal process.

All of the systematic uncertainties described are applied in both the signal significance mea-
surement and the aQGC search. They are also propagated to the uncertainty in the measured
fiducial cross section, with the exception of the theoretical uncertainties associated with the
signal cross section. All the systematic uncertainties except those that arise from the trigger
efficiency and lepton identification are considered to be correlated between the electron and
muon channels. All the uncertainties are summarized in Table 1.

Table 1: Relative systematic uncertainties in the estimated signal and background yields in
units of percent. The range of the uncertainty when varying $m_{jj}$ and $m_{\ell\gamma}$ is shown for the
systematic uncertainty sources.

<table>
<thead>
<tr>
<th>Source</th>
<th>EW $W\gamma$</th>
<th>QCD $W\gamma jj$</th>
<th>VV</th>
<th>$t\bar{t}\gamma$</th>
<th>QCD $Z\gamma$</th>
<th>Single top</th>
<th>Mis-ID photon</th>
<th>Mis-ID lepton</th>
<th>Interference</th>
<th>Cross section of $t\bar{t}\gamma$</th>
<th>Cross section of VV</th>
<th>Pileup modeling</th>
<th>Statistics</th>
<th>L1 prefire correction</th>
<th>b-tagging veto</th>
<th>Muon ID/ISO</th>
<th>Muon trigger</th>
<th>Electron reconstruction</th>
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<th>Photon ID</th>
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<tr>
<td>Cross section of $t\bar{t}\gamma$</td>
<td>—</td>
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</tbody>
</table>

8 EW $W\gamma$ measurement

The simulated signal and background yields as well as the observed data yields are shown in
Table 2. In order to quantify the significance of the observation of the EW production of
$W\gamma$ boson pairs, a statistical analysis of the event yields is performed with a fit to the ($m_{jj}$,$m_{\ell\gamma}$)
two-dimensional distributions. Both $m_{jj}$ and $m_{\ell\gamma}$ are powerful variables for distinguishing be-
tween the signal and QCD $W\gamma$ background, and the two-dimensional fit was found to result in a
larger expected signal significance than either variable individually. The data in the low $m_{jj}$
control region are fit simultaneously with the data in the signal region. The low $m_{jj}$ control
region and the signal region are divided into four bins for the different channels (electron barrel,
electron endcap, muon barrel and muon endcap), but only one overall $m_{jj}$ bin for the control
region. Figure 3 shows the post-fit (i.e., after the simultaneous fit) 2D distributions.
Table 2: Signal, background, and data yields after the final selection for the SM measurement. The pre-fit statistical and systematic uncertainties are added in quadrature.

<table>
<thead>
<tr>
<th></th>
<th>electron barrel</th>
<th>electron endcap</th>
<th>muon barrel</th>
<th>muon endcap</th>
</tr>
</thead>
<tbody>
<tr>
<td>Misidentified photon</td>
<td>81.0 ± 5.2</td>
<td>48.1 ± 4.9</td>
<td>134.8 ± 8.2</td>
<td>52.1 ± 4.8</td>
</tr>
<tr>
<td>Misidentified lepton</td>
<td>63.7 ± 12.3</td>
<td>27.8 ± 7.2</td>
<td>46.8 ± 10.6</td>
<td>23.1 ± 6.5</td>
</tr>
<tr>
<td>e \rightarrow γ</td>
<td>1.5 ± 0.6</td>
<td>2.1 ± 0.8</td>
<td>1.7 ± 0.7</td>
<td>1.1 ± 0.6</td>
</tr>
<tr>
<td>QCD Zγ</td>
<td>18.0 ± 3.1</td>
<td>1.9 ± 0.9</td>
<td>16.2 ± 3.0</td>
<td>4.9 ± 1.3</td>
</tr>
<tr>
<td>Single top</td>
<td>4.9 ± 0.8</td>
<td>2.5 ± 0.5</td>
<td>6.8 ± 0.9</td>
<td>2.4 ± 0.5</td>
</tr>
<tr>
<td>VV</td>
<td>4.2 ± 1.6</td>
<td>0.6 ± 0.6</td>
<td>7.5 ± 2.1</td>
<td>1.4 ± 0.7</td>
</tr>
<tr>
<td>ttγ</td>
<td>20.6 ± 1.6</td>
<td>5.1 ± 0.6</td>
<td>28.3 ± 1.8</td>
<td>6.9 ± 0.8</td>
</tr>
<tr>
<td>QCD Wγjj</td>
<td>154.2 ± 12.0</td>
<td>41.1 ± 4.4</td>
<td>221.2 ± 15.8</td>
<td>72.1 ± 6.2</td>
</tr>
<tr>
<td>Total background</td>
<td>348.3 ± 18.4</td>
<td>129.1 ± 9.9</td>
<td>463.4 ± 21.2</td>
<td>163.8 ± 10.4</td>
</tr>
<tr>
<td>EW Wγjj</td>
<td>48.8 ± 2.2</td>
<td>16.1 ± 1.0</td>
<td>74.5 ± 2.8</td>
<td>24.4 ± 1.3</td>
</tr>
<tr>
<td>Data</td>
<td>393</td>
<td>159</td>
<td>565</td>
<td>201</td>
</tr>
</tbody>
</table>

The data excess is quantified based on a profile likelihood ratio test statistic [44]. This test statistic involves the ratio of two Poisson likelihood functions, one in which the signal strength is fixed to 0 and one in which the signal strength is allowed to be any non-negative value, where the signal strength is the ratio of observed signal to expected signal. Systematic uncertainties are considered by adding parameters to the likelihood function that scale the relevant process(es) and are constrained by log-normal functions. The test statistic distribution is assumed to be in the asymptotic regime in which there is a simple relationship between its value and the significance. The observed (expected) signal strength parameter is extracted to be $\hat{\mu} = 1.20^{+0.26}_{-0.24}$ ($\hat{\mu} = 1.00^{+0.27}_{-0.25}$), corresponding to an observed (expected) statistical significance of 4.9 (4.6) $\sigma$ with the 2016 data set.

This result can be combined at a statistical level with the previous CMS result described in Ref. [9] assuming the signal strength is the same for both analyses. There are two uncertainties that are correlated between the 8 and 13 TeV analyses. The theory uncertainties on the signal and QCD Wγ background of the 8 TeV analysis include multiple sources of theoretical uncertainty but are dominated by the QCD scale uncertainties, so they are correlated with the QCD scale uncertainties on the signal and QCD Wγ background of the 13 TeV analysis. All other uncertainties are left uncorrelated between the 8 and 13 TeV analyses.

After combining with the 8 TeV result using this correlation scheme, the observed (expected) significance is 5.3 (4.8) $\sigma$.

9 Fiducial EW $W\gamma jj$ cross section measurement

A fiducial cross section is extracted using the same $m_{jj}$-m$_{\ell\gamma}$ binning as for the calculation of the significance, and through the same simultaneous fit used in the control region. The fiducial region is defined using MC generator quantities: one electron (muon) with $p_T^{\ell} > 30$ GeV and $|\eta_{\ell}| < 2.4$, $p_T^{miss} > 30$ GeV, $p_T^{g} > 25$ GeV, $|\eta_g| < 1.4442$ or $1.566 < |\eta_g| < 2.5$, $m_T(W) > 30$ GeV, two jets with $p_T^{j} > 40$ (30) GeV and $|\eta_j| < 4.7$, $m_{jj} > 500$ GeV, and $|\Delta\eta_{jj}| > 2.5$. The leptons are defined at particle level with final state radiation recovered. The acceptance is defined as the fraction of the generated signal events passing the fiducial region selection, which is extracted using MADGRAPH 5. The theoretical uncertainty due to the extrapolation between the fiducial
Figure 3: The 2D distributions used in the fit for the signal strength of EW Wγ+2 jets in the electron barrel (top left), electron endcap (top right), muon barrel (bottom left), and muon endcap (bottom right).

region and the signal region was found to be negligible (< 1%). We define the cross section as

$$\sigma_{\text{fid}} = \sigma_g \hat{\mu} \alpha_{gf},$$

where the cross section for the generated signal events is $\sigma_g = 0.776 \text{ pb}$, the signal strength parameter $\hat{\mu} = 1.20^{+0.26}_{-0.24}$, and the acceptance $\alpha_{gf} = 0.02195$. The observed fiducial cross section is

$$\sigma_{\text{EW}}^{\text{fid}} = 20.4 \pm 0.4 \text{ (lumi)} \pm 2.8 \text{ (stat)} \pm 3.5 \text{ (syst)} \text{ fb} = 20.4 \pm 4.5 \text{ fb}.$$

10 **Fiducial cross section of EW+QCD Wγ+2 jets**

In addition to the EW Wγ+2 jets process, we also calculate a cross section for the inclusive EW+QCD Wγ+2 jets process. The fiducial region is the same as that for EW Wγ+2 jets and the
The 2D distributions used in the fit for the signal strength of EW+QCD $W\gamma+2$ jets in the electron barrel (top left), electron endcap (top right), muon barrel (bottom left) and muon endcap (bottom right).

The settings used for the fit are similar to the ones for EW $W\gamma+2$ jets, the difference being that EW and QCD $W\gamma+2$ jets are combined as the signal. The cross section for QCD $W\gamma+2$ jets is $178.6\,\text{pb}$, and $a_{QCD}^{gf}$ is calculated to be $0.0004068$. The measured signal strength for inclusive $W\gamma+2$ jets is $1.21^{+0.17}_{-0.16}$, and the observed fiducial cross section is

$$\sigma_{\text{fid}}^{\text{EW+QCD}} = 108 \pm 2\,\text{(lumi)} \pm 5\,\text{(stat)} \pm 15\,\text{(syst)}\,\text{fb} = 108 \pm 16\,\text{fb}.$$
Figure 4 shows the post-fit results.

11 Limits on anomalous quartic gauge couplings

Figure 5: The $m_{W\gamma}$ distribution of events satisfying the aQGC region selection, which is used to set constraints on the anomalous coupling parameters. The orange line represents a nonzero $F_{T,0}$ setting. All events with $m_{W\gamma} > 990$ GeV are included in the last bin.

The effects of BSM physics can be modeled in a generic way through a collection of linearly independent higher dimensional operators in effective field theory [14]. Reference [45] proposes nine independent charge-conjugate and parity-conserving dimension-eight effective operators by assuming the SU(2)×U(1) symmetry of the EW gauge field, and includes a Higgs doublet to incorporate the presence of a SM Higgs boson. A contribution from aQGCs would enhance the production of events with large $W\gamma$ mass. The operators affecting the $W\gamma jj$ channel can be divided into two categories. The operators $\mathcal{L}_{M,0} - \mathcal{L}_{M,7}$ contain an SU(2) field strength, the U(1) field strength, and the covariant derivative of the Higgs doublet. The operators $\mathcal{L}_{T,0} - \mathcal{L}_{T,2}$ and $\mathcal{L}_{T,5} - \mathcal{L}_{T,7}$, contain only the two field strengths. The coefficient of the operator $\mathcal{L}_{X,Y}$ is denoted by $F_{X,Y}/\Lambda^4$, where $\Lambda$ is the unknown scale of BSM physics.

A simulation is performed that includes the effects of the aQGCs in addition to the SM EW $W\gamma$ process, as well as any interference between the two. We use the $m_{W\gamma}$ distribution to extract limits on the aQGC parameters. To obtain a continuous prediction for the signal as a function of the anomalous coupling, a quadratic fit is performed to the SM+aQGC yield as a function of the aQGC coefficient, separately in each $m_{W\gamma}$ bin in the aQGC region, which is defined based on the common selection in Section 5, and further requiring $m_{jj} > 800$ GeV, $|\Delta\eta_{jj}| > 2.5$, $m_{W\gamma} > 150$ GeV, and $p_T^{\gamma} > 100$ GeV.
11. Limits on anomalous quartic gauge couplings

Figure 5 shows no statistically significant excess of events relative to the SM prediction.

The following profile likelihood test statistic is used in the aQGC limit setting procedure:

\[ t_{\alpha_{\text{test}}} = -2 \log \frac{L(\hat{\alpha}_{\text{test}}, \hat{\theta})}{L(\hat{\alpha}, \hat{\theta})}. \]

The likelihood function is the product of Poisson distributions and a normal constraining term with nuisance parameters representing the sources of systematic uncertainties in any given bin. The final likelihood function is the product of the likelihood functions of the electron and muon channels. The main constraint on the aQGC parameters is from the last bin. The parameter \( \alpha_{\text{test}} \) represents the aQGC point being tested, and the symbol \( \theta \) represents a vector of nuisance parameters assumed to follow log-normal distributions. The parameter \( \hat{\theta} \) corresponds to the maximum of the likelihood function at the point \( \alpha_{\text{test}} \). The \( \hat{\alpha} \) and \( \hat{\theta} \) parameters correspond to the global maximum of the likelihood function.

This test statistic is assumed to follow a \( \chi^2 \) distribution [46]. It is therefore possible to extract the limits immediately from the difference in the log-likelihood function \( \Delta \text{NLL} = t_{\alpha_{\text{test}}}/2 \) [47]. The 95% confidence level (CL) limit on a one-dimensional aQGC parameter corresponds to \( 2\Delta \text{NLL} = 3.84 \). Figure 6 shows the likelihood scan of parameter \( F_{T,0} \) in the calculation of the observed limits.

![Figure 6: Observed 95% CL interval on the aQGC parameter \( F_{T,0} \).](image)

The observed and expected 95% CL limits on the coefficients of these operators, shown in Table 3, are obtained by varying the coefficient of one operator at a time with all others set to 0, the value corresponding to the SM. The yield of the EW signal in any bin is a quadratic function of the coefficient, whose minimum in general does not occur at a coefficient value of 0 due to interference with the SM operators. Therefore, we set upper and lower limits on the operator coefficients. The limit setting procedure involves first obtaining the global maximum of the profile likelihood function, and then the maximum of the profile likelihood function at fixed coefficient values, which can be compared to the global maximum and converted to confidence...
levels. The unitarity bound is defined as the scattering energy at which the aQGC coupling strength, when set equal to the observed limit, would result in a scattering amplitude that violates unitarity. The value of the unitarity bound is determined using the VBFNLO 2.7.1 framework [48], taking into account the difference between VBFNLO and MADGRAPH5_aMC@NLO. These are the most stringent limits to date on the aQGC parameters $F_{M,2-5}/\Lambda^4$ and $F_{T,6-7}/\Lambda^4$.

Table 3: Parameterized by the $W\gamma$ mass, 95% CL shape-based exclusion limits on each aQGC parameter, no form factor is applied. The unitarity bounds are also listed. All coupling parameter limits are in TeV$^{-4}$, while the unitarity bounds are in TeV.

<table>
<thead>
<tr>
<th>Observed limits [TeV$^{-4}$]</th>
<th>Expected limits [TeV$^{-4}$]</th>
<th>Unitarity bound [TeV]</th>
</tr>
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<tbody>
<tr>
<td>$-8.07 &lt; F_{M,0}/\Lambda^4 &lt; 7.99$</td>
<td>$-7.67 &lt; F_{M,0}/\Lambda^4 &lt; 7.55$</td>
<td>1.0</td>
</tr>
<tr>
<td>$-11.8 &lt; F_{M,1}/\Lambda^4 &lt; 12.1$</td>
<td>$-10.8 &lt; F_{M,1}/\Lambda^4 &lt; 11.3$</td>
<td>1.2</td>
</tr>
<tr>
<td>$-2.81 &lt; F_{M,2}/\Lambda^4 &lt; 2.81$</td>
<td>$-2.68 &lt; F_{M,2}/\Lambda^4 &lt; 2.68$</td>
<td>1.3</td>
</tr>
<tr>
<td>$-4.41 &lt; F_{M,3}/\Lambda^4 &lt; 4.49$</td>
<td>$-4.04 &lt; F_{M,3}/\Lambda^4 &lt; 4.10$</td>
<td>1.5</td>
</tr>
<tr>
<td>$-4.99 &lt; F_{M,4}/\Lambda^4 &lt; 4.95$</td>
<td>$-4.70 &lt; F_{M,4}/\Lambda^4 &lt; 4.67$</td>
<td>1.5</td>
</tr>
<tr>
<td>$-8.27 &lt; F_{M,5}/\Lambda^4 &lt; 8.31$</td>
<td>$-7.85 &lt; F_{M,5}/\Lambda^4 &lt; 7.73$</td>
<td>1.8</td>
</tr>
<tr>
<td>$-16.2 &lt; F_{M,6}/\Lambda^4 &lt; 16.0$</td>
<td>$-15.4 &lt; F_{M,6}/\Lambda^4 &lt; 15.1$</td>
<td>1.0</td>
</tr>
<tr>
<td>$-20.8 &lt; F_{M,7}/\Lambda^4 &lt; 20.2$</td>
<td>$-19.4 &lt; F_{M,7}/\Lambda^4 &lt; 18.7$</td>
<td>1.3</td>
</tr>
<tr>
<td>$-0.62 &lt; F_{T,0}/\Lambda^4 &lt; 0.64$</td>
<td>$-0.60 &lt; F_{T,0}/\Lambda^4 &lt; 0.62$</td>
<td>1.4</td>
</tr>
<tr>
<td>$-0.35 &lt; F_{T,1}/\Lambda^4 &lt; 0.39$</td>
<td>$-0.34 &lt; F_{T,1}/\Lambda^4 &lt; 0.38$</td>
<td>1.5</td>
</tr>
<tr>
<td>$-0.99 &lt; F_{T,2}/\Lambda^4 &lt; 1.18$</td>
<td>$-0.98 &lt; F_{T,2}/\Lambda^4 &lt; 1.16$</td>
<td>1.5</td>
</tr>
<tr>
<td>$-0.45 &lt; F_{T,5}/\Lambda^4 &lt; 0.46$</td>
<td>$-0.43 &lt; F_{T,5}/\Lambda^4 &lt; 0.44$</td>
<td>1.8</td>
</tr>
<tr>
<td>$-0.36 &lt; F_{T,6}/\Lambda^4 &lt; 0.38$</td>
<td>$-0.34 &lt; F_{T,6}/\Lambda^4 &lt; 0.36$</td>
<td>1.7</td>
</tr>
<tr>
<td>$-0.87 &lt; F_{T,7}/\Lambda^4 &lt; 0.93$</td>
<td>$-0.83 &lt; F_{T,7}/\Lambda^4 &lt; 0.89$</td>
<td>1.8</td>
</tr>
</tbody>
</table>

12 Summary

The production cross sections of electroweak production of $W\gamma$ in association with two jets are measured in proton-proton collisions at a center-of-mass energy of 13 TeV. The data sample corresponds to an integrated luminosity of 35.9 fb$^{-1}$ collected at $\sqrt{s} = 13$ TeV with the CMS detector. Events are selected by requiring exactly one identified lepton (electron or muon), a moderate missing transverse momentum, one photon, and two jets with a large rapidity separation and a large dijet mass. The observed significance is 4.9 standard deviations ($\sigma$), where a significance of 4.6 $\sigma$ is expected based on the standard model. After combining with previously reported CMS results based on 8 TeV data, the observed (expected) signal significance is 5.3 (4.8) $\sigma$. This constitutes the first observation of electroweak $W\gamma$ production in pp collisions. A cross section measurement in a fiducial region is reported and is consistent with standard model predictions. Constraints are placed on anomalous quartic gauge couplings in terms of dimension-8 effective field theory operators. Results are competitive with or more stringent than previous results.

References

References


