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Search for $WW\gamma$ and $WZ\gamma$ production and constraints on anomalous quartic gauge couplings in pp collisions at $\sqrt{s} = 8$ TeV

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A search for $WV\gamma$ triple vector boson production is presented based on events containing a W boson decaying to a muon or an electron and a neutrino, a second V (W or Z) boson, and a photon. The data correspond to an integrated luminosity of 19.3 fb^{-1} collected in 2012 with the CMS detector at the LHC in pp collisions at $\sqrt{s} = 8$ TeV. An upper limit of 311 fb on the cross section for the $WV\gamma$ production process is obtained at 95% confidence level for photons with a transverse energy above 30 GeV and with an absolute value of pseudorapidity of less than 1.44. This limit is approximately a factor of 3.4 larger than the standard model predictions that are based on next-to-leading order QCD calculations. Since no evidence of anomalous $WW\gamma\gamma$ or $WWZ\gamma$ quartic gauge boson couplings is found, this paper presents the first experimental limits on the dimension-eight parameter $f_{T,0}$ and the CP-conserving $WWZ\gamma$ parameters κ_0^W and κ_C^W. Limits are also obtained for the $WW\gamma\gamma$ parameters a_0^W and a_C^W.

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I. INTRODUCTION

The standard model (SM) of particle physics provides a good description of the existing high-energy data [1]. The diboson WW and WZ production cross sections have been precisely measured at the Large Hadron Collider (LHC) and are in agreement with SM expectations [2–6]. This paper presents a search for the production of three gauge bosons $WW\gamma$ and $WZ\gamma$, together denoted as $WV\gamma$. It represents an extension of the measurement of diboson production presented in Ref. [3], with the additional requirement of an energetic photon in the final state. Previous searches for triple vector boson production, when at least two bosons are massive, were performed at LEP [7–11].

The structure of gauge boson self-interactions emerges naturally in the SM from the non-Abelian $SU(2)_L \otimes U(1)_Y$ gauge symmetry. Together with the triple $WV\gamma$ gauge boson vertices, the SM also predicts the existence of the quartic $WWWW$, $WWZZ$, $WWZ\gamma$, and $WW\gamma\gamma$ vertices. The direct investigation of gauge boson self-interactions provides a crucial test of the gauge structure of the SM and one that is all the more significant at LHC energies [12].

The study of gauge boson self-interactions may also provide evidence for the existence of new phenomena at a higher energy scale [13–16]. Possible new physics beyond the SM, expressed in a model independent way by higher-dimensional effective operators [17–22], can be implemented with anomalous triple gauge and quartic gauge couplings (AQGC), both of which contribute in triple gauge boson production. A deviation of one of the couplings from the SM prediction could manifest itself in an enhanced production cross section, as well as a change in the shape of the kinematic distributions of the $WV\gamma$ system. CMS recently obtained a stringent limit on the anomalous $WW\gamma\gamma$ quartic coupling via the exclusive two-photon production of W^+W^- [23].

This paper presents a search for $WV\gamma$ production in the single lepton final state, which includes $W(\to \ell\nu)W(\to jj)\gamma$ and $W(\to \ell\nu)Z(\to jj)\gamma$ processes, with $\ell = e, \mu$. The data used in this analysis correspond to a total integrated luminosity of 19.3 ± 0.5 (19.2 ± 0.5) fb^{-1} [24] collected with the CMS detector in the muon (electron) channel in pp collisions at $\sqrt{s} = 8$ TeV in 2012. The hadronic decay mode is chosen because the branching fraction is substantially higher than that of the leptonic mode. However, the two production processes $WW\gamma$ and $WZ\gamma$ cannot be clearly differentiated since the detector dijet mass resolution ($\sigma \sim 10\%$) [25] is comparable to the mass difference between the W and Z bosons. Therefore, $WW\gamma$ and $WZ\gamma$ processes are treated as a single combined signal.

II. THEORETICAL FRAMEWORK

An effective field theory approach is adopted in which higher-dimensional operators supplement the SM Lagrangian to include anomalous gauge couplings. Within this framework, anomalous boson interactions can be parametrized using two possible representations. The first is a nonlinear realization of the $SU(2) \otimes U(1)$ gauge symmetry that is broken by means other than the conventional Higgs scalar doublet [18,19]. The quartic boson interactions involving photons appear as dimension-six operators. The second is a linear realization of the symmetry that is broken by the conventional Higgs scalar

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doublet [18,20]. The quartic interactions involving photons appear as dimension-eight operators.

Some of the operators within one realization share similar Lorentz structures with operators from the other, so that their parameters can be expressed simply in terms of each other, whereas others cannot. While the discovery of the SM Higgs boson makes the linear realization more appropriate for AQGC searches [13,20], it contains 14 such operators that can contribute to the anomalous coupling signal. In addition, all published AQGC limits to date are expressed in terms of dimension-six parameters. To bridge this divide, we select four dimension-six parameters, two of which have not been previously measured, and the other two are used to compare with previous results [8,18]. These parameters also have dimension-eight analogues. Finally, we include a representative parameter from the linear realization, $f_{T,0}$, which has no dimension-six analogue.

The Feynman diagrams for the quartic vertices are shown in Fig. 1, and the *CP*-conserving, anomalous interaction Lagrangian terms chosen for this analysis are written in Eq. (1).

$$\begin{aligned}\mathcal{L}_{\mathrm{AQGC}} = &-\frac{e^2}{8}\frac{a_0^W}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}W^{+\alpha}W^-_\alpha \\ &-\frac{e^2}{16}\frac{a_C^W}{\Lambda^2}F_{\mu\nu}F^{\mu\alpha}(W^{+\nu}W^-_\alpha + W^{-\nu}W^+_\alpha) \\ &-e^2g^2\frac{\kappa_0^W}{\Lambda^2}F_{\mu\nu}Z^{\mu\nu}W^{+\alpha}W^-_\alpha \\ &-\frac{e^2g^2}{2}\frac{\kappa_C^W}{\Lambda^2}F_{\mu\nu}Z^{\mu\alpha}(W^{+\nu}W^-_\alpha + W^{-\nu}W^+_\alpha) \\ &+\frac{f_{T,0}}{\Lambda^4}\mathrm{Tr}[\hat{W}_{\mu\nu}\hat{W}^{\mu\nu}]\times\mathrm{Tr}[\hat{W}_{\alpha\beta}\hat{W}^{\alpha\beta}]. \qquad (1)\end{aligned}$$

The energy scale of possible new physics is represented by Λ, $g = e/\sin(\theta_W)$, θ_W is the Weinberg angle, e is the unit of electric charge, and the usual field tensors are defined in Refs. [18–20]. The dimension-six parameters a_0^W/Λ^2 and a_C^W/Λ^2 are associated with the $WW\gamma\gamma$ vertex and the κ_0^W/Λ^2 and κ_C^W/Λ^2 parameters are associated with the $WWZ\gamma$ vertex. The dimension-eight parameter $f_{T,0}/\Lambda^4$ contributes to both vertices. The $a_{0,C}^W/\Lambda^2$ coupling parameters have dimension-eight analogues, the $f_{M,i}/\Lambda^4$ coupling parameters. The relationship between the two is as follows [18] [Eq. (3.35)],

$$\begin{aligned}\frac{a_0^W}{\Lambda^2} &= -\frac{4M_W^2}{g^2}\frac{f_{M,0}}{\Lambda^4} - \frac{8M_W^2}{g'^2}\frac{f_{M,2}}{\Lambda^4}, \\ \frac{a_C^W}{\Lambda^2} &= \frac{4M_W^2}{g^2}\frac{f_{M,1}}{\Lambda^4} + \frac{8M_W^2}{g'^2}\frac{f_{M,3}}{\Lambda^4}, \qquad (2)\end{aligned}$$

where $g' = e/\cos(\theta_W)$ and M_W is the invariant mass of the W boson. The expressions listed in Eq. (2) are used to translate the AQGC limits obtained for $a_{0,C}^W/\Lambda^2$, into limits on $f_{M,i}/\Lambda^4$. It is also required that $f_{M,0} = 2\times f_{M,2}$ and $f_{M,1} = 2\times f_{M,3}$, which results in the suppression of the contributions to the $WWZ\gamma$ vertex in Eq. (2), as can be seen from [19] Eq. (22) and Eq. (23).

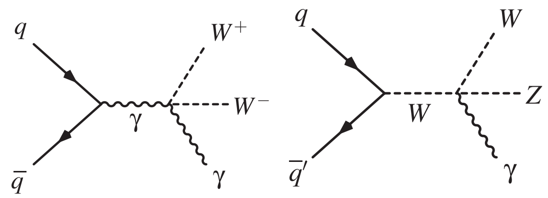

FIG. 1. Feynman diagrams that involve a quartic vector boson vertex. Both diagrams are present in the SM.

Any nonzero value of the AQGCs will lead to tree-level unitarity violation at sufficiently high energy. We find that the unitarity condition [26] cannot be generally satisfied by the addition of a dipole form factor; however, unitarity conserving new physics with a structure more complex than that represented by a dipole form factor is possible. Since the structure of new physics is not known *a priori*, the choice is made to set limits without using a form factor.

III. THE CMS DETECTOR

The central feature of the Compact Muon Solenoid (CMS) apparatus is a superconducting solenoid of 6 m internal diameter and 13 m length, providing a magnetic field of 3.8 T. Within the superconducting solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter (ECAL), and a brass and scintillator hadron calorimeter (HCAL). Muons are reconstructed in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid. Extensive forward calorimetry complements the coverage provided by the brass and scintillator section of the hadronic calorimeter.

The CMS experiment uses a right-handed coordinate system, with the origin at the nominal interaction point, the x axis pointing to the center of the LHC ring, the y axis pointing up (perpendicular to the LHC plane), and the z axis along the counterclockwise beam direction. The polar angle θ is measured from the positive z axis and the azimuthal angle ϕ is measured in radians in the x-y plane. The pseudorapidity η is defined as $\eta = -\ln[\tan(\theta/2)]$.

The energy resolution for photons with transverse energy (E_T) of 60 GeV varies between 1.1% and 2.6% in the ECAL barrel, and from 2.2% to 5% in the end caps [27]. The HCAL, when combined with the ECAL, measures jets with a resolution $\Delta E/E \approx 100\%/\sqrt{E[\mathrm{GeV}]}\oplus 5\%$ [28]. To improve the reconstruction of jets, the tracking and calorimeter information is combined using a particle flow (PF) reconstruction technique [29]. The jet energy resolution typically amounts to 15% at 10 GeV, 8% at 100 GeV, and 4% at 1 TeV.

A more detailed description of the CMS detector can be found in Ref. [30].

IV. EVENT SIMULATION

All Monte Carlo (MC) simulation samples, except for the single-top-quark samples, are generated with the MadGraph 5.1.3.22 [31] event generator using the CTEQ6L1 parton distribution functions (PDF). Single-top-quark samples are generated with powheg (v1.0, r1380) [32–36] with the CTEQ6M PDF set [37,38]. The matrix element calculation is used, and outgoing partons are matched to parton showers from pythia 6.426 [39] tune Z2* [40] with a matching threshold of 20 GeV and a dynamic factorization (μ_F) and renormalization (μ_R) scale given by $\sqrt{m^2_{W/Z} + p^2_{T,W/Z}}$. The next-to-leading-order/leading-order (NLO/LO) QCD cross section correction factors (K factors) for $WV\gamma$ and AQGC diagrams are derived using the NLO cross sections calculated with aMC@NLO [41]. The MSTW2008nlo68cl [42] PDF set is used to calculate the PDF uncertainty following the prescription of Ref. [43]. The K factor obtained for $WV\gamma$ is consistent with a constant value of 2.1 for photons with $E_{\mathrm{T}} > 30$ GeV and $|\eta^\gamma| < 2.5$. The K factor for AQGC diagrams is found to be close to 1.2. A summary of the contributing processes and their cross section is given in Table I.

To simulate the signal events for a given AQGC parameter set, several samples are generated with a range of parameter values and the other AQGC parameters are set to zero.

A Geant4-based simulation [44] of the CMS detector is used in the production of all MC samples. All simulated events are reconstructed and analyzed with the same algorithms that are used for the LHC collision events. Additional corrections (scale factors) are applied to take into account the difference in lepton reconstruction and identification efficiencies observed between data and simulated events. For all simulated samples, the hard-interaction collision is overlaid with the appropriate number of simulated minimum bias collisions. The resulting events are weighted to reproduce the distribution of the number of inelastic collisions per bunch crossing (pileup) inferred from data.

TABLE I. Cross sections used to normalize the simulated samples. All cross sections are given for a photon $E_{\mathrm{T}} > 10$ GeV, $|\eta^\gamma| < 2.5$. The order of the cross section calculation is also indicated. The normalization for the $W\gamma +$ jets sample is derived from data.

Process		Cross section [pb]
SM $WW\gamma$	(NLO)	0.090 ± 0.021
SM $WZ\gamma$	(NLO)	0.012 ± 0.003
$W\gamma +$ jets	(Data)	10.9 ± 0.8
$Z\gamma +$ jets	(LO)	0.63 ± 0.13
$t\bar{t}\gamma$	(LO)	0.62 ± 0.12
Single $t + \gamma$(inclusive)	(NLO)	0.31 ± 0.01

V. EVENT RECONSTRUCTION AND SELECTION

The data used in this analysis corresponds to a total integrated luminosity of 19.3 ± 0.5 (19.2 ± 0.5) fb^{-1} [24] collected with the CMS detector in the muon (electron) channel in pp collisions at $\sqrt{s} = 8$ TeV in 2012. The data were recorded with single-lepton triggers using p_{T} thresholds of 24 GeV for muons and 27 GeV for electrons. The overall trigger efficiency is about 94% (90%) for muon (electron) data, with a small dependence (a few percent) on p_{T} and η. Simulated events are corrected for the trigger efficiency as a function of lepton p_{T} and η.

The events used in this analysis are characterized by the production of a photon plus a pair of massive gauge bosons (WW or WZ), where one W boson decays to leptons and the other boson (W or Z) decays to quarks. To select leptonic W boson decays, we require either one muon ($p_{\mathrm{T}} > 25$ GeV, $|\eta| < 2.1$) or one electron ($p_{\mathrm{T}} > 30$ GeV, $|\eta| < 2.5$, excluding the transition region between the ECAL barrel and end caps $1.44 < |\eta| < 1.57$ because the reconstruction of an electron in this region is not optimal). The off-line lepton p_{T} thresholds is set in the stable, high-efficiency region above the corresponding trigger thresholds. Events with additional leptons with $p_{\mathrm{T}} > 10(20)$ GeV for muons(electrons) are vetoed in order to reduce backgrounds. The escaping neutrino results in missing transverse energy ($\not{E}_{\mathrm{T}}$) in the reconstructed event. Therefore a selection requirement of $\not{E}_{\mathrm{T}} > 35$ GeV is applied to reject the multijet backgrounds. The reconstructed transverse mass of the leptonically decaying W, defined as $\sqrt{p^\ell_{\mathrm{T}} \not{E}_{\mathrm{T}}[1 - \cos(\Delta\phi_{\ell,\not{E}_{\mathrm{T}}})]}$, where $\Delta\phi_{\ell,\not{E}_{\mathrm{T}}}$ is the azimuthal angle between the lepton and the $\not{E}_{\mathrm{T}}$ directions, is then required to exceed 30 GeV [45]. At least two jet candidates are required to satisfy $p_{\mathrm{T}} > 30$ GeV and $|\eta| < 2.4$. The highest p_{T} jet candidates are chosen to form the hadronically decaying boson with mass m_{jj}. The photon candidate must satisfy $E_{\mathrm{T}} > 30$ GeV and $|\eta| < 1.44$. Events with the photon candidate in one of the end caps ($|\eta| > 1.57$) are excluded from the selection because their signal purity is lower and systematic uncertainties are larger.

Jets and $\not{E}_{\mathrm{T}}$ [45,46] are formed from particles reconstructed using the PF algorithm. Jets are formed with the anti-k_{T} clustering algorithm [47] with a distance parameter of 0.5. Charged particles with tracks not originating from the primary vertex are not considered for jet clustering [48,49]. The primary vertex of the event is chosen to be the vertex with the highest $\sum p^2_{\mathrm{T}}$ of its associated tracks. Jets are required to satisfy identification criteria that eliminate candidates originating from noisy channels in the hadron calorimeter [50]. Jet energy corrections [25] are applied to account for the jet energy response as a function of η and p_{T}, and to correct for contributions from event pileup. Jets from pileup are identified and removed using the trajectories of tracks associated with the jets, the topology of the jet shape and the constituent multiplicities [48,49].

The azimuthal separation between the highest p_T jet and the $\not{E}_T$ direction is required to be larger than 0.4 radians. This criterion reduces the QCD multijet background where the $\not{E}_T$ can arise from a mismeasurement of the leading jet energy. To reduce the background from $W\gamma + \text{jets}$ events, requirements on the dijet invariant mass $70 < m_{jj} < 100$ GeV, and on the separation between the jets of $|\Delta\eta_{jj}| < 1.4$, are imposed. In order to reject top-quark backgrounds, the two jets are also required to fail a b quark jet tagging requirement. The combined secondary vertex algorithm [51] is used, with a discriminator based on the displaced vertex expected from b hadron decays. This algorithm selects b hadrons with about 70% efficiency, and has a 1% misidentification probability. The anti-b tag requirement suppresses approximately 7% of the $WW\gamma$ and 10% of the $WZ\gamma$ signal via the $W \to c\bar{s}, Z \to b\bar{b}$ and $Z \to c\bar{c}$ decays. These effects are taken into account in the analysis.

Muon candidates are reconstructed by combining information from the silicon tracker and from the muon detector by means of a global track fit. The muon candidates are required to pass the standard CMS muon identification and the track quality criteria [52]. The isolation variables used in the muon selection are based on the PF algorithm and are corrected for the contribution from pileup. The muon candidates have a selection efficiency of approximately 96%.

Electrons are reconstructed from clusters [27,53–55] of ECAL energy deposits matched to tracks in the silicon tracker within the ECAL fiducial volume, with the exclusion of the transition region between the barrel and the end caps previously defined. The electron candidates are required to be consistent with a particle originating from the primary vertex in the event. The isolation variables used in the electron selection are based on the PF algorithm and are corrected for the contribution from pileup. The electron selection efficiency is approximately 80%. To suppress the $Z \to e^+e^-$ background in the electron channel, where one electron is misidentified as a photon, a Z boson mass veto of $|M_Z - m_{e\gamma}| > 10$ GeV is applied. The impact on the signal efficiency from applying such a suppression is negligible.

TABLE II. Expected number of events for each process. The predicted number of events for the $W\gamma + \text{jets}$ and $WV + \text{jet}$ processes, where the jet is reconstructed as a photon, are derived from data. The "Total prediction" item represents the sum of all the individual contributions.

Process	Muon channel number of events	Electron channel number of events
SM $WW\gamma$	6.6 ± 1.5	5.0 ± 1.1
SM $WZ\gamma$	0.6 ± 0.1	0.5 ± 0.1
$W\gamma + \text{jets}$	136.9 ± 10.5	101.6 ± 8.5
$WV + \text{jets, jet} \to \gamma$	33.1 ± 4.8	21.3 ± 3.3
MC $t\bar{t}\gamma$	12.5 ± 3.0	9.1 ± 2.2
MC single top quark	2.8 ± 0.8	1.7 ± 0.6
MC $Z\gamma + \text{jets}$	1.7 ± 0.1	1.5 ± 0.1
Multijets	$\cdots$	7.2 ± 5.1
Total prediction	194.2 ± 11.5	147.9 ± 10.7
Data	183	139

Photon candidates are reconstructed from clusters of cells with significant energy deposition in the ECAL. The candidates are required to be within the ECAL barrel fiducial region ($|\eta| < 1.44$). The observables used in the photon selection are isolation variables based on the PF algorithm and they are corrected for the contribution due to pileup, the ratio of hadronic energy in the HCAL that is

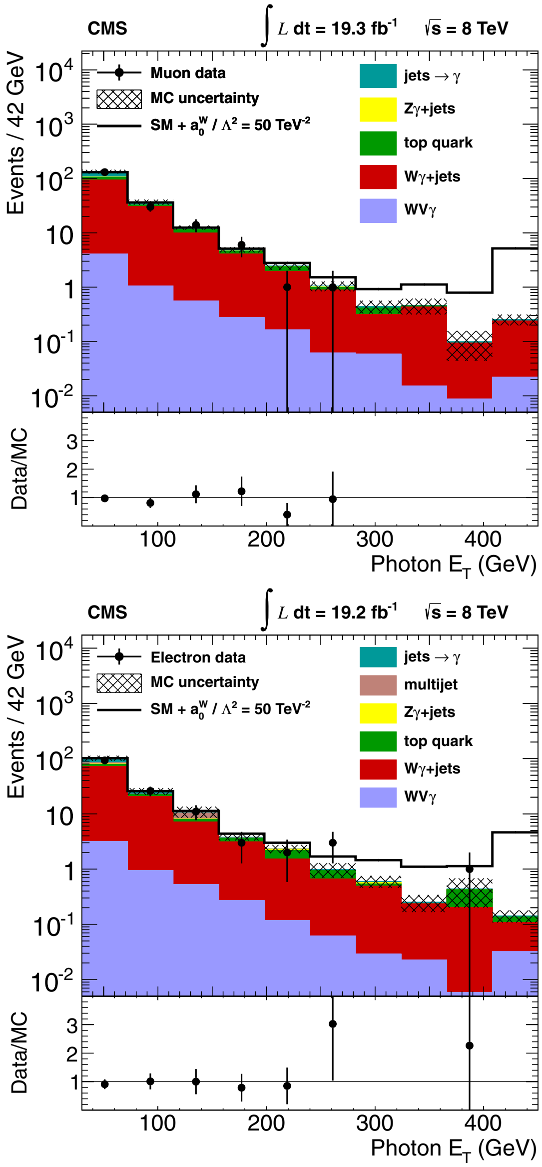

FIG. 2 (color online). Comparison of predicted and observed photon E_T distributions in the (left) muon and (right) electron channels. The rightmost bin includes the integral of events above 450 GeV for each process. The solid black line depicts a representative signal distribution with anomalous coupling parameter $a_0^W/\Lambda^2 = 50\ \text{TeV}^{-2}$.

matched in (η, ϕ) to the electromagnetic energy in the ECAL, the transverse width of the electromagnetic shower, and an electron track veto.

VI. BACKGROUND MODELING

The main background contribution arises from $W\gamma +$ jets production. After imposing the requirements described above, a binned maximum likelihood fit to the dijet invariant mass distribution m_{jj} of the two leading jets is performed. The signal region corresponding to the W and Z mass windows, $70 < m_{jj} < 100$ GeV, is excluded from the fit. The contamination from $WV\gamma$ processes outside of the signal region is less than 1%. The shape of the $W\gamma +$ jets m_{jj} distribution is obtained from simulation, and the normalization of this background component is unconstrained in the fit. The normalization of the contribution from misidentified photons is allowed to float within a Gaussian constraint of 14% (Sec. VII). The post-fit ratio $K = \sigma_{\text{fit}}/\sigma_{\text{LO}}$ for the W$\gamma +$ jets background is 1.10 ± 0.07 (1.07 ± 0.09) in the muon (electron) channel.

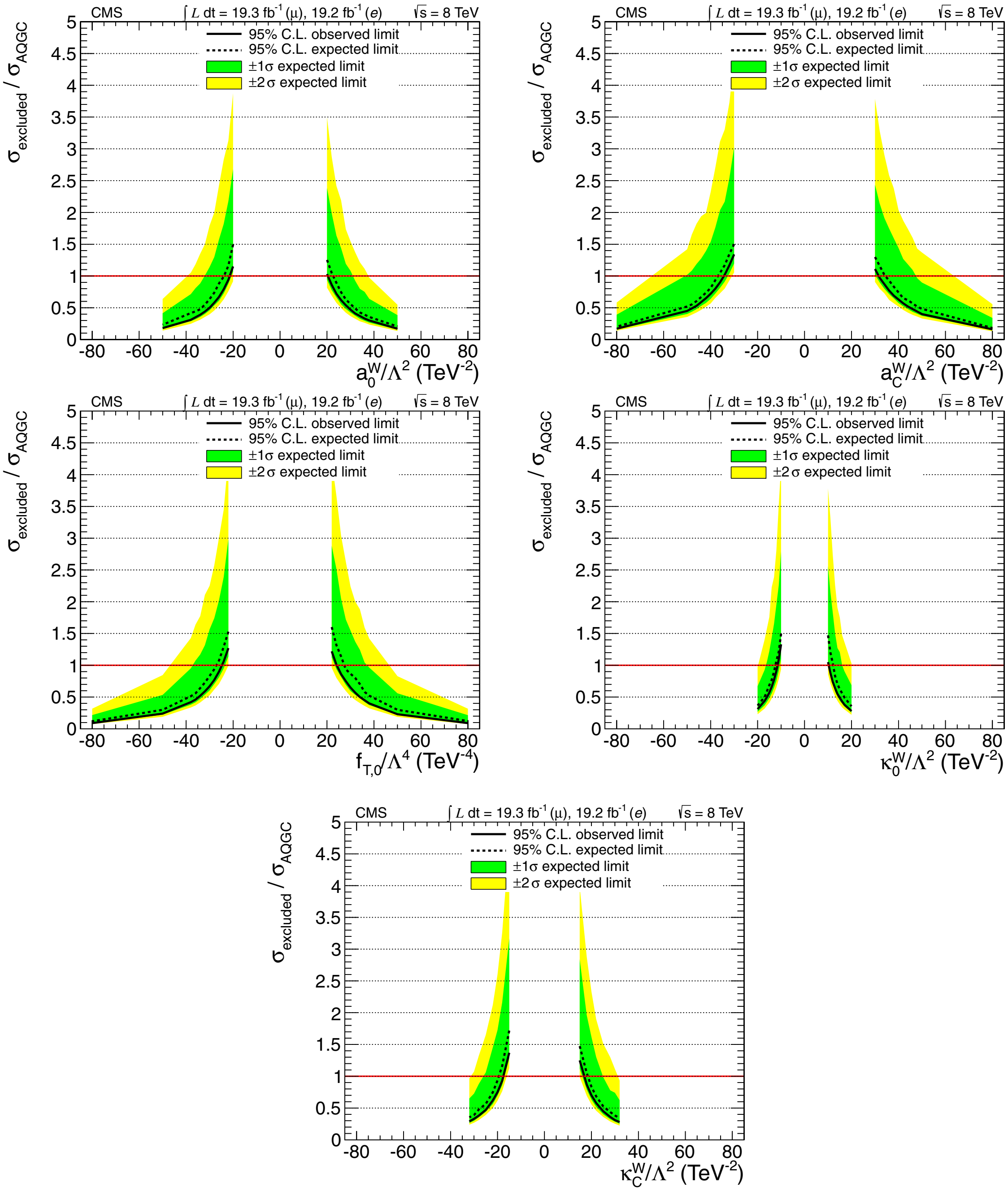

FIG. 3 (color online). 95% C.L. exclusion limits for (upper left) a_0^W/Λ^2, (upper right) a_C^W/Λ^2, (middle left) $f_{T,0}/\Lambda^4$, (middle right) κ_0^W/Λ^2, and (bottom) κ_C^W/Λ^2.

The background from misidentified photons arises mainly from the $W + 3$ jets process, where one jet passes the photon identification criteria. The total contribution from misidentified photons is estimated using a data control sample, where all selection criteria except for the isolation requirement are applied. The shower shape distribution is then used to estimate the total rate of misidentified photons. Details on the method can be found in Ref. [56]. The fraction of the total background from misidentified photons decreases with photon E_T from a maximum of 23% ($p_T = 30$ GeV) to 8% ($p_T > 135$ GeV).

The multijet background is due to misidentified leptons from jets that satisfy the muon or electron selection requirements. It is estimated by using a two component fit to the $\not{E}_T$ distribution in data. The procedure is described in [3], and was repeated for the 8 TeV data. The multijet contribution is estimated to be 6.2% for the electron channel, with a 50% uncertainty, and is negligible for the muon channel.

Other background contributions arise from top-quark pair production, single-top-quark production, and $Z\gamma +$ jets. These are taken from simulation and are fixed to their SM expectations, with the central values and uncertainties listed in Table I. The top-quark pair process contribution comes from the presence of two W bosons in the decays. The $Z\gamma +$ jets background can mimic the signal when the Z decays leptonically and one of the leptons is lost, resulting in $\not{E}_T$. The sum of the top-quark pair, single-top-quark, and $Z\gamma +$ jets backgrounds represent about 8% of the expected SM background rate.

VII. SYSTEMATIC UNCERTAINTIES

The uncertainties contributing to the measured rate of misidentified photons arise from two sources. First, the statistical uncertainty is taken from pseudo experiments drawn from the data control sample described in Sec. VI and is estimated to be 5.6% rising to 37% with increasing photon E_T. The second arises from a bias in the shower shape of $W + 3$ jets simulation due to the inverted isolation requirements. This uncertainty is estimated to be less than 11%. The combined uncertainty on the photon misidentification rate, integrated over the E_T spectrum, is 14%.

TABLE III. The 95% C.L. exclusion limits for each AQGC parameter from the combination of the muon and electron channels.

Observed limits	Expected limits
$-21 < a_0^W/\Lambda^2 < 20$ TeV^{-2}	$-24 < a_0^W/\Lambda^2 < 23$ TeV^{-2}
$-34 < a_C^W/\Lambda^2 < 32$ TeV^{-2}	$-37 < a_C^W/\Lambda^2 < 34$ TeV^{-2}
$-25 < f_{T,0}/\Lambda^4 < 24$ TeV^{-4}	$-27 < f_{T,0}/\Lambda^4 < 27$ TeV^{-4}
$-12 < \kappa_0^W/\Lambda^2 < 10$ TeV^{-2}	$-12 < \kappa_0^W/\Lambda^2 < 12$ TeV^{-2}
$-18 < \kappa_C^W/\Lambda^2 < 17$ TeV^{-2}	$-19 < \kappa_C^W/\Lambda^2 < 18$ TeV^{-2}

TABLE IV. The 95% C.L. exclusion limits for each dimension-eight AQGC parameter from the combination of the muon and electron channels.

Observed limits (TeV^{-4})	Expected limits (TeV^{-4})
$-77 < f_{M,0}/\Lambda^4 < 81$	$-89 < f_{M,0}/\Lambda^4 < 93$
$-131 < f_{M,1}/\Lambda^4 < 123$	$-143 < f_{M,1}/\Lambda^4 < 131$
$-39 < f_{M,2}/\Lambda^4 < 40$	$-44 < f_{M,2}/\Lambda^4 < 46$
$-66 < f_{M,3}/\Lambda^4 < 62$	$-71 < f_{M,3}/\Lambda^4 < 66$

The uncertainty in the measured value of the luminosity [24] is 2.6% and it contributes to the signal and those backgrounds that are taken from the MC prediction. Jet energy scale uncertainties contribute via selection thresholds on the jet p_T and dijet invariant mass by 4.3%. The small difference in $\not{E}_T$ resolution [46] between data and simulation affects the signal selection efficiency by less than 1%. Systematic uncertainties due to the trigger efficiency in the data (1%) and lepton reconstruction and selection efficiencies (2%) are also accounted for. Photon reconstruction efficiency and energy scale uncertainties contribute to the signal selection efficiency at the 1% level. The uncertainty from the b jet tagging procedure is 2% on the data/simulation efficiency correction factor [51]. This has an effect of 11% on the $t\bar{t}\gamma$ background, 5% on the single-top-quark background, and a negligible effect on the signal. The theoretical uncertainty in the $t\bar{t}\gamma$ and $Z\gamma +$ jets production is 20%.

The theoretical uncertainties in the $WW\gamma$, $WZ\gamma$, and AQGC signal cross sections are evaluated using aMC@NLO samples. We vary the renormalization and factorization scales each by factors of 1/2 and 2, and require $\mu_R = \mu_F$, as described in Ref. [43]. We find that the scale-related uncertainties are 23%, and that the uncertainty due to the choice of PDF is 3.6%.

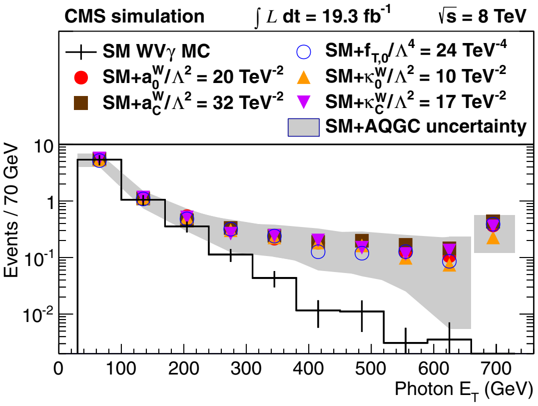

FIG. 4 (color online). Expected photon E_T distributions after the selection for the muon channel is applied: SM prediction, SM plus AQGC prediction for a_0^W/Λ^2, a_C^W/Λ^2, $f_{T,0}/\Lambda^4$, κ_0^W/Λ^2, and κ_C^W/Λ^2. Systematic and statistic uncertainties are shown. The last bin includes the overflow.

VIII. UPPER LIMIT ON THE STANDARD MODEL $WV\gamma$ CROSS SECTION

The SM $WV\gamma$ search is formulated as a simple counting experiment. The selected numbers of candidate events in the data are 183 (139) in the muon (electron) channel. The predicted number of background plus signal events is 194.2 ± 11.5 (147.9 ± 10.7) in the muon (electron) channel, where the uncertainty includes statistical, systematic and luminosity related uncertainties. The event yield per process is summarized in Table II.

Since there is no sign of an excess above the total background predictions, it is possible to set only an upper limit on $WW\gamma$ and $WZ\gamma$ cross sections, given the size of the current event sample. The limit is calculated from the event yields in Table II using a profile likelihood asymptotic approximation method (Appendix A.1.3 in Refs. [57,58]). An observed upper limit of 311 fb is calculated for the inclusive cross section at 95% confidence level (C.L.), which is about 3.4 times larger than the standard model prediction of 91.6 ± 21.7 fb (with photon $E_T > 30$ GeV and $|\eta| < 1.44$), calculated with AMC@NLO. The expected limit is 403 fb (4.4 times the SM).

IX. LIMITS ON ANOMALOUS QUARTIC COUPLINGS

The photon E_T distribution is sensitive to AQGCs and is therefore used to set limits on the anomalous coupling parameters. Following the application of all selection criteria, the photon E_T distributions for data, the total background, and the individual signal models for the muon and electron channels are binned over the range 30–450 GeV. The photon E_T distributions for muon and electron channels are shown in Fig. 2, along with the predicted signal from $WW\gamma\gamma$ AQGC for $a_0^W/\Lambda^2 = 50\ \text{TeV}^{-2}$. The last bin includes the overflow.

The upper limits are set utilizing a profile likelihood asymptotic approximation method (Appendix A.1.3 in Refs. [57,58]), which takes the distributions from the two channels as independent inputs to be combined statistically into a single result. Each coupling parameter is varied over a set of discrete values, keeping the other parameters fixed to zero; this causes the signal distribution to be altered accordingly. The expected and observed signal strengths $\sigma_{\text{excluded}}/\sigma_{\text{AQGC}}$ are then calculated and plotted against the corresponding coupling parameter values.

Figure 3 shows the observed and expected exclusion limits for the combination of muon and electron channels. Some positive/negative asymmetry is noticeable in the plots because of SM/AQGC interference terms in the Lagrangian. Exclusion limits for a_0^W/Λ^2, a_C^W/Λ^2, $f_{T,0}/\Lambda^4$, κ_0^W/Λ^2, and κ_C^W/Λ^2 are computed at 95% C.L. and are listed in Table III. Table IV reports the transformed dimension-eight limits from the limits on the a_0^W and a_C^W parameters.

Figure 4 shows the photon E_T distributions for a signal in the muon channel corresponding to AQGC parameters that are set to the limits we have obtained. The distributions for

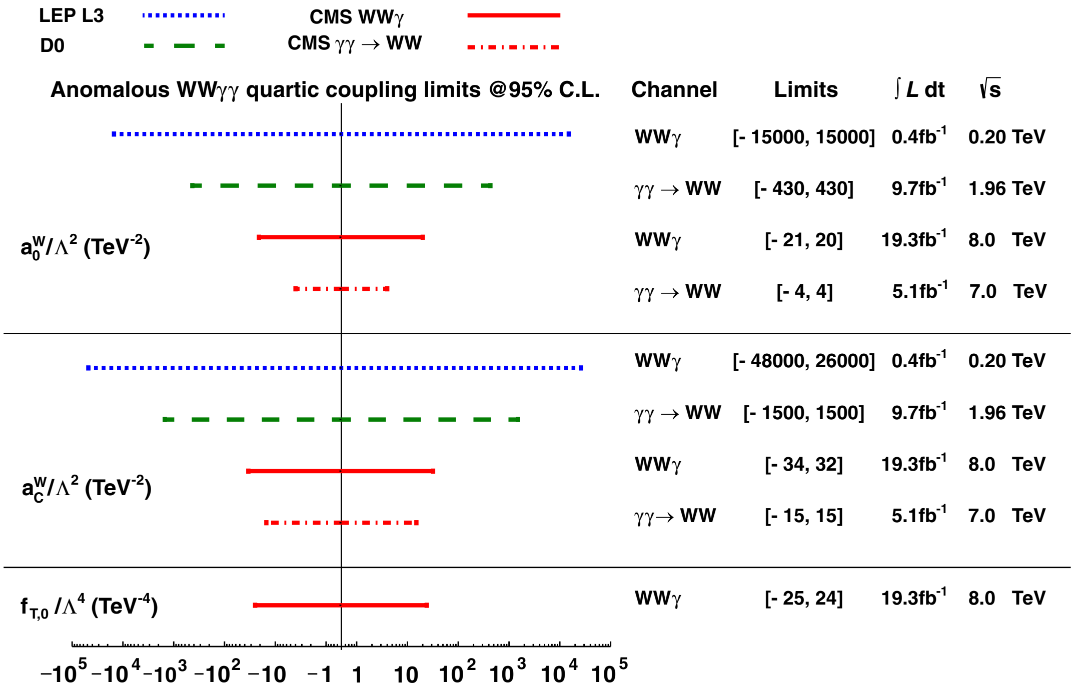

FIG. 5 (color online). Comparison of the limits on the $WW\gamma\gamma$ AQGC parameter obtained from this study, together with results from exclusive $\gamma\gamma \to WW$ production at CMS [23] and results from the L3 [8] and the D0 [59] Collaborations. All limits on AQGC are calculated without a form factor.

the various AQGC values are similar. The contribution from AQGC is prominent in the region $E_{\mathrm{T}} > 240$ GeV, where the expected number of signal events is approximately 1.4. The corresponding distributions for the electron channel are similar.

A comparison of several existing limits on the $WW\gamma\gamma$ AQGC parameter is shown in Fig. 5. Existing limits include the result from exclusive $\gamma\gamma \to WW$ production at CMS [23], in addition to results from the L3 [8] and the D0 [59] Collaborations. All of the limits shown on AQGC are calculated without a form factor.

X. SUMMARY

A search for $WV\gamma$ triple vector boson production that results in constraints on anomalous quartic gauge boson couplings has been presented using events containing a W boson decaying to leptons, a second boson V ($V = W$ or Z) boson, and a photon. The data analyzed correspond to an integrated luminosity of 19.3 fb^{-1} collected in pp collisions at $\sqrt{s} = 8$ TeV in 2012 with the CMS detector at the LHC. An upper limit of 311 fb at 95% C.L. is obtained for the production of $WV\gamma$ with photon $E_{\mathrm{T}} > 30$ GeV and $|\eta| < 1.44$. No evidence for anomalous $WW\gamma\gamma$ and $WWZ\gamma$ quartic gauge couplings is found. The following constraints are obtained for these couplings at 95% C.L.:

$$\begin{aligned} &-21 < a_0^W/\Lambda^2 < 20\ \mathrm{TeV}^{-2}, \\ &-34 < a_C^W/\Lambda^2 < 32\ \mathrm{TeV}^{-2}, \\ &-25 < f_{T,0}/\Lambda^4 < 24\ \mathrm{TeV}^{-4}, \\ &-12 < \kappa_0^W/\Lambda^2 < 10\ \mathrm{TeV}^{-2}, \quad \text{and} \\ &-18 < \kappa_C^W/\Lambda^2 < 17\ \mathrm{TeV}^{-2}. \end{aligned}$$

These are the first experimental limits reported on $f_{T,0}$ and the CP-conserving couplings κ_0^W and κ_C^W. Figure 5 compares the constraints on the $WW\gamma\gamma$ AQGC parameter obtained from this study with those obtained in previous analyses.

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