Latest results on anomalous gauge couplings from CMS

Ekaterina Avdeeva for the CMS Collaboration

Abstract

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Abstract. The paper presents results from CMS for limits on anomalous triple and quartic
gauge couplings using data collected at the LHC at center-of-mass energies 7 and 8 TeV and
corresponding to integrated luminosities of 5 fb$^{-1}$ and 19.5 fb$^{-1}$ respectively. All results are
consistent with the Standard Model predictions.

1. Introduction
Studies of diboson and triboson productions are important tests of the Standard Model (SM). A discrepancy between a measured distribution of a kinematic variable and the SM distribution or between measured and the SM theoretically predicted cross section would be an indication of a new physics. To date, no deviations from the SM predictions are observed in any diboson or triboson production studies. The CMS analyses discussed in this paper are motivated by the searches for anomalous gauge couplings as the SM extension.

Figure 1. TGC/QGC vertices. First three vertices are allowed in the SM at tree level, and the last two vertices are not allowed in the SM at tree level.

To study anomalous triple and quartic gauge couplings (aTGC and aQGC), we consider vertices which involve three or four bosons, at least one of which is massive (Fig. 1). Charged TGC and QGC (the first three diagrams) are present in the SM at the tree level and can be described by a set of constants predicted by the theory. Several measurements presented in this paper search for deviations of these constants from their SM predicted values. Neutral TGC and QGC are not present in the SM at the tree level and any deviation of neutral TGC and
QGC constants from zero would indicate a presence of an anomalous gauge coupling.

The general strategy employed by CMS in searches for anomalous gauge couplings is to measure a spectrum of a kinematic variable of a process which might involve an anomalous gauge coupling, and compare it with the SM prediction and with aTGC/aQGC predictions with different values of aTGC/aQGC constants. If a process has a photon in its final state, then photon transverse momentum $P_T^\gamma$ is as a rule the most sensitive to aTGC/aQGC and easiest to reconstruct observable and therefore is used to probe for aTGC/aQGC. If there is no photon in the final state, this variable could be the transverse momentum of a final state lepton $P_T^l$, the transverse momentum or an invariant mass of a final state dilepton system ($P_{ll}^T$ or $M_{ll}$). Spectra with non-zero aTGC/aQGC constants would have an excess over the SM prediction at the high end of the spectrum of the kinematic variable of choice.

We study diboson and triboson production where at least one of the bosons is a W or a Z boson. W and Z bosons have different decay modes and therefore different final states are possible. Z boson decay modes include $Z \to l^+l^-$ with a branching fraction $B = 3.4\%$ per lepton flavor, $Z \to \nu\bar{\nu}$ with $B = 20.0\%$, and $Z \to$ hadrons with $B = 69.9\%$ [1]. W boson decay modes include $W \to l\nu$ with $B \simeq 11\%$ per lepton flavor, and $W \to$ hadrons with $B = 67.4\%$ [1]. While the hadronic modes of both Z boson and W boson decays and the invisible mode of a Z boson decay have higher branching ratios than the leptonic modes, selected samples of the hadronic and invisible modes have higher background contamination which lowers the accuracy of such analyses.

The following processes based on LHC Run I data have been recently analyzed and published by CMS:

- $Z\gamma \to l^+l^-\gamma$ at 8 TeV [2] and 7 TeV [3] (probes for neutral TGC)
- $W\gamma \to l\nu\gamma$ at 7 TeV [3] (charged TGC)
- $Z\gamma \to \nu\bar{\nu}\gamma$ at 7 TeV [4] (neutral TGC)
- $ZZ \to 4l$ at 8 TeV [5] (neutral TGC)
- $ZZ \to 2l2\nu$ at 8 TeV and 7 TeV [6] (neutral TGC)
- $WW \to l\nu\nu\nu$ at 8 TeV [7] (charged TGC)
- $WW + WZ \to l\nu j\bar{j}$ at 7 TeV [8] (charged TGC)
- $WZ\gamma + WW\gamma \to l\nu j\bar{j}\gamma$ at 8 TeV [9] (charged QGC)
- $W\pm W\pm + jj \to l\nu\nu\nu + jj$ at 8 TeV [10] (charged QGC)
- VBS (Vector Boson Scattering) $\gamma\gamma \to WW \to l\nu\nu$ at 7 TeV [11] (charged QGC)

The analyses of $Z\gamma \to l^+l^-\gamma$ [2, 3], $Z\gamma \to \nu\bar{\nu}\gamma$ [4], $WW \to l\nu\nu\nu$ [7], and $WZ\gamma + WW\gamma \to l\nu j\bar{j}\gamma$ [9] are discussed in this paper in more detail.

2. $Z\gamma$ Production and Neutral aTGC

Study of $Z\gamma$ production is one of the possible ways to search for aTGC associated with the $ZZ\gamma$ and $Z\gamma\gamma$ vertices. The signature of the $Z\gamma$ production process with further decay of a Z boson to muons or electrons is a charged lepton pair, and a photon. In case of a Z boson decaying to neutrinos, the process signature is a significant missing transverse energy ($E_T^{miss}$), and a photon. Feynman diagrams of $Z\gamma$ production are shown in Fig. 2. The process $q\bar{q} \to l^+l^-\gamma$ can proceed through FSR (final state radiation) or ISR (initial state radiation) while $q\bar{q} \to \nu\bar{\nu}\gamma$ can proceed through ISR only. TGC Feynman diagrams for either process are not allowed in the SM.

In the analysis of the $Z\gamma \to l^+l^-\gamma$ process electron and muon channels are considered separately. The selection requirements are:
• a well identified photon with a transverse momentum of \( P_T^\gamma > 15 \) GeV and pseudorapidity of \( |\eta^\gamma| < 1.44 \) or \( 1.57 < |\eta^\gamma| < 2.50 \) which correspond to barrel and endcap regions of the CMS electromagnetic calorimeter;

• two isolated well-identified muons or electrons with a transverse momentum of \( P_T^l > 20 \) GeV and an invariant mass \( m_{ll} > 50 \) GeV;

• a separation between each lepton and the photon \( \Delta R(l, \gamma) = \sqrt{\Delta \phi^2 + \Delta \eta^2} > 0.7 \).

The major background is due to jets misidentified as photons. This background can not be reduced by additional requirements without losing in signal efficiency, therefore, this background is estimated using a template method. Jets templates are taken from a jet-enriched dataset. Real photon templates in 7 TeV analysis are extracted from signal Monte Carlo (MC) and in 8 TeV analysis from FSR events of \( Z\gamma \) and using a special Random Cone Isolation technique described in [2]. Other backgrounds are estimated using MC predictions.

Spectra of \( P_T^\gamma \) for \( Z\gamma \) production at 7 TeV and 8 TeV for the muon and electron channels are shown in Fig. 3 and 4. Data are well described by the predictions. The differential cross section as a function of \( P_T^\gamma \) is shown in Fig. 5.
Figure 4. Spectra of $P_T^{\gamma}$ of the $Z\gamma$ production process at 8 TeV. Left to right: $Z\gamma \rightarrow \mu\mu\gamma$, $Z\gamma \rightarrow ee\gamma$.

Figure 5. Left: the differential cross section $d\sigma/dP_T^{\gamma}$ (left) of $Z\gamma \rightarrow l^+l^-\gamma$ at 8 TeV. Right: the ratio plot of the measured differential cross section over the next-to-next-to-leading order (NNLO), NLO and LO theory predictions.

The process $Z\gamma \rightarrow \nu\bar{\nu}\gamma$ has a higher branching ratio than $Z\gamma \rightarrow l^+l^-\gamma$ in the muon and electron channels combined but a $\nu\bar{\nu}\gamma$-selected sample is more contaminated by different backgrounds. Event selection for $Z\gamma \rightarrow \nu\bar{\nu}\gamma$ include:

- at least one well identified photon with $P_T^{\gamma} > 145$ GeV, $|\eta^{\gamma}| < 1.4$ must present;
- missing transverse energy must be high due to neutrinos $E_T^{miss} > 130$ GeV;
- events which contain other particles (satisfying certain quality criteria and $P_T$ threshold) are vetoed;
- timing of photons measured in the electromagnetic calorimeter must be consistent with the beam crossing.

Several types of backgrounds are present in the selected sample. Background from jets$\rightarrow\gamma$ misidentification is estimated using a jet-enriched control sample. Machine-induced background is estimated from a sample prepared under the condition that timing is not consistent with the beam crossing. The background of $e \rightarrow \gamma$ is estimated from a control sample dominated by...
**Figure 6.** Summary plot with limits on neutral aTGC constants.

$W \to e\nu$ events. The simulation is used to estimate other contributions. The estimated background plus the prediction for the signal are in a good agreement with data as shown in Fig. 3.

Spectra of $P_\gamma$ are used to set limits on constants of a neutral aTGC Lagrangian (Eq. 1) [2].

\[
L_{V Z \gamma} = L_{V Z \gamma(h_3)} + L_{V Z \gamma(h_4)}
\]

where

\[
L_{V Z \gamma(h_3)} = \frac{e}{m_Z^2} \left[ - [h_3^\gamma (\partial_\rho F^{\rho\sigma}) + h_3^Z (\partial_\rho Z^{\rho\sigma})] Z^\alpha \hat{F}_{\rho\sigma} \right]
\]

\[
L_{V Z \gamma(h_4)} = \frac{e}{m_Z^2} \left[ [h_4^\gamma (\partial_\rho \partial^\rho F^{\rho\alpha}) + h_4^Z (\partial_\rho \partial^\rho Z^{\rho\alpha})] Z_\rho \hat{F}_{\rho\sigma} \right]
\]

The analyses of the $Z\gamma$ production [2, 3, 4] set limits on $h_3^\gamma$, $h_3^Z$, $h_4^\gamma$, $h_4^Z$ constants. These constants are equal to zero in the SM. Limits on the constants measured in an assumption of the other constants to be zero are shown in Fig. 6. The result of the 7 TeV measurement is a combination of measurements in muon, electron, and neutrino channels, this result provides the most stringent limit to date. The result of the $Z\gamma \to \nu\bar{\nu}\gamma$ analysis dominates the sensitivity to aTGC.

Simultaneous two-dimensional limits on the $h_3^\gamma/h_3^Z$ and $h_4^\gamma/h_4^Z$ constants are also set and can be found in original analysis papers [2, 3, 4]. No deviations from the SM are observed.

3. **WW Production and Charged aTGC**

In addition to setting limits on the neutral aTGC constants, CMS also performs analyses which set limits on the charged aTGC constants. CMS has recently published a paper on $WW \to l\nu l\nu$ production at 8 TeV [7]. Feynman diagrams of $WW \to l\nu l\nu$ are shown in Fig. 7. The right diagram shows WW production through TGC. This diagram is present in the SM. The process signature is two leptons ($e^+ e^-$, $\mu^+ \mu^-$, $e^\pm \mu^\mp$), and a significant missing transverse energy $E_T^{miss}$ due to neutrinos in the final state.

Event selection for the process includes:
• two well identified leptons which satisfy kinematic requirements of $P_T^l > 20$ GeV, $|\eta^l| < 2.4$, $|\eta^\nu| < 2.5$;
• requirements on dilepton pairs of $M^{ll} > 12$ GeV, $P_T^{\mu\mu/ee} > 45$ GeV, $P_T^{\mu e} > 30$ GeV;
• requirement on missing transverse energy due to neutrinos $E_T^{miss} > 20$ GeV;
• veto on events which contain the third lepton with $P_T > 10$ GeV and satisfying certain quality criteria.

Figure 7. Feynman diagrams of $WW \to l\nu l\nu$ process.

Figure 8. Spectra of different kinematic variables of $WW \to l\nu l\nu$ process at 8 TeV.

Table 1. Limits on $C_{WW}/\Lambda^2$, $C_{W}/\Lambda^2$ and $C_{B}/\Lambda^2$ coupling constants. 95% confidence interval.

<table>
<thead>
<tr>
<th>Coupling constant</th>
<th>This result (TeV$^{-2}$)</th>
<th>World average (TeV$^{-2}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_{WW}/\Lambda^2$</td>
<td>$[-5.7, 5.9]$</td>
<td>$-5.5 \pm 4.8$</td>
</tr>
<tr>
<td>$C_{W}/\Lambda^2$</td>
<td>$[-11.4, 5.4]$</td>
<td>$-3.9 \pm 3.9$</td>
</tr>
<tr>
<td>$C_{B}/\Lambda^2$</td>
<td>$[-29.2, 23.9]$</td>
<td>$-1.7 \pm 13.9$</td>
</tr>
</tbody>
</table>
Figure 9. Differential cross sections in bins of different kinematic variables of $WW \rightarrow l\nu l\nu$ process at 8 TeV.

Figure 10. Spectrum of $m_\ell\ell$ of $WW \rightarrow l\nu l\nu$ analysis.

Figure 11. Summary plots with limits on neutral aTGC constants.

Dilepton channels ($e^+e^-, \mu^+\mu^-, e^\pm\mu^\mp$) are combined. After the criteria listed above are applied, the selected sample is dominated by the signal with purity of 74%. Major backgrounds in the selected sample are $t\bar{t}$ and $tW$. The background is estimated using top-tagged events and a top-tagging efficiency determined from a top-enriched dataset.

The distributions of the invariant mass and the transverse momentum of a dilepton system $m_\ell\ell$ and $p_T^{\ell\ell}$ and differential cross sections in bins of these variables are shown in Fig. 8-9. The cross sections are compatible with the theory NNLO prediction.
The $m_{ll}$ spectrum is used to probe for aTGC. The simulation indicates that the presence of aTGC would cause an excess at high $m_{ll}$ (Fig. 10). In an interpretation of effective field theory, the aTGC C- and P-conserving operators can be expressed as Eq. 2 [7]:

\[
O_{WWW} = \frac{C_{WWW}}{\Lambda^2} Tr[W_{\mu\nu} W_{\rho\sigma} W^{\mu\rho}], \\
O_{W} = \frac{C_{W}}{\Lambda^2} (D^\mu \Phi)^\dagger W_{\mu\nu} (D^\nu \Phi), \\
O_{B} = \frac{C_{B}}{\Lambda^2} (D^\mu \Phi)^\dagger B_{\mu\nu} (D^\nu \Phi).
\]

The analysis sets limits on constants $C_{WWW}/\Lambda^2$, $C_{W}/\Lambda^2$ and $C_{B}/\Lambda^2$. Limits derived from this analysis compared to other aTGC experimental results are shown in Tab. 1. Limits shown in the table are set assuming that all other constants are equal to zero. Simultaneous limits on pairs of constants are also set and can be found in [7]. All results are consistent with the SM predictions.

4. **WV\gamma Production and Charged aQGC**

Several analyses have been performed in CMS to investigate aQGC. One of the latest results with 8 TeV data comes from an analysis of the $WV\gamma$ final state. Feynman diagrams of the $WV\gamma$ production are shown in Fig. 12. There are two jets, one charged lepton, one neutrino and one photon in the final state. Electron and muon channels of a W boson decay are considered. The second boson, Z or W, decays to two jets. It is not possible to distinguish between jets coming from a W boson and a Z boson decay, therefore $WW\gamma$ and $WZ\gamma$ modes are analyzed together. The process can proceed through radiation of all three bosons (W,W/Z and \gamma) from the quark lines, can involve one or two charged TGC vertices, or can proceed through the charged QGC diagram. All diagrams involving TGC and QGC shown in Fig. 12 are allowed in the SM. Constants of aQGC couplings are probed in this analysis while constants of aTGC couplings are not.

The CMS analysis of $WV\gamma$ process is described in [9]. The following selection criteria are used for $WV\gamma$ event selection:

- one well identified lepton with $P_T^{\ell}(P_T^{\nu}) > 25(30)$ GeV and $\eta^\ell(\eta^\nu) < 2.1(2.5)$;
- two well identified jets with dijet invariant mass close to a W or Z boson mass, 70 GeV < $m_{jj} < 100$ GeV;
- $E_T^{miss} > 35$ GeV due to a neutrino in the final state;
- one well identified photon with $P_T^\gamma > 30$ GeV and $\eta^\gamma < 1.44$.

Muon and electron channels are considered separately with respective final states of $(\mu\nu_\mu)(jj)\gamma$ and $(e\nu_e)(jj)\gamma$. The $P_T^\gamma$ spectra for the muon and electron channels of selected events are shown in Fig. 13. The selected sample is dominated by the W+jets background which is estimated by taking the shape from the MC prediction and the normalization from fit of data outside the dijet invariant mass window. The total uncertainty on the yields is larger than the signal and therefore the cross section can not be measured, only upper limits on cross section are set. It is illustrated in Fig. 13 that presence of aQGC would cause an excess at high $P_T^\gamma$.

Eq. 3 is the charged aQGC Lagrangian [9].
\[ L_{aQGC} = L_1 + L_2 + L_3 \]

where

\[
L_1 = -\frac{e^2}{8} \frac{\alpha_W}{\Lambda^2} F_{\mu
u} F^{\mu\nu} W^+ W^- + \frac{e^2}{16} \frac{\alpha W}{\Lambda^2} W^\pm W^\mp \alpha W^\pm W^- + W^\pm W^- \\
L_2 = -e^2 g^2 \frac{\alpha_W}{\Lambda^2} F_{\mu
u} Z^{\mu\nu} W^+ W_- - \frac{e^2 g^3}{2} \frac{\alpha_W}{\Lambda^2} F_{\mu\nu} Z^{\mu\nu} (W^\pm W^- + W^- W^+) \\
L_3 = \frac{f_{\mu,0}}{\Lambda^4} Tr[W_{\mu\nu} W_{\mu\nu}] \times Tr[\hat{W}_{\alpha\beta} \hat{W}_{\alpha\beta}] 
\]

Limits on the constants \( \frac{\alpha_W}{\Lambda^2} \), \( \frac{\alpha_W^2}{\Lambda^2} \), \( \frac{\kappa_W}{\Lambda^2} \), \( \frac{\kappa_W}{\Lambda^2} \), \( \frac{f_{\mu,0}}{\Lambda^4} \) from Eq. 3 are set in this analysis. The constants \( \frac{\alpha_W}{\Lambda^2} \) and \( \frac{\alpha_W^2}{\Lambda^2} \) are associated with the \( WW\gamma\gamma \) vertex. \( \frac{\kappa_W}{\Lambda^2} \) and \( \frac{\kappa_W}{\Lambda^2} \) are associated with the \( WWZ\gamma \) vertex, and \( \frac{f_{\mu,0}}{\Lambda^4} \) is associated with both the \( WW\gamma\gamma \) and the \( WWZ\gamma \) vertices. This analysis is the first to report limits on \( \frac{\alpha_W}{\Lambda^2} \), \( \frac{\alpha_W^2}{\Lambda^2} \), \( \frac{\kappa_W}{\Lambda^2} \), \( \frac{\kappa_W}{\Lambda^2} \), \( \frac{f_{\mu,0}}{\Lambda^4} \) at 95% confidence level are summarized in Fig. 14. Limits on the other two constants are \(-12 < \frac{\kappa_W}{\Lambda^2} < 10 \) and \(-12 < \frac{f_{\mu,0}}{\Lambda^4} < 10 \).
TeV$^{-2}$ and $-18 < \frac{\kappa_{W}}{\lambda_{W}} < 17$ TeV$^{-2}$. No deviations from the Standard Model are observed.

5. Other aTGC Results
Several other analyses have been performed in CMS which set limits on aTGC and aQGC coupling constants. Eq. 4 [6])

\begin{equation}
L_{VZZ} = -\frac{e}{m_{Z}^2} \left[ f_{4}^{4}(\partial_{\mu}F_{\mu\alpha}) + f_{2}^{Z}(\partial_{\mu}Z_{\mu\alpha}) \right] Z_{\beta}^{(\partial^{3}_{\alpha}Z_{\alpha})} - \left[ f_{5}^{4}(\partial_{\mu}F_{\mu\alpha}) + f_{5}^{Z}(\partial_{\mu}Z_{\mu\alpha}) \right] Z_{\alpha}^{\beta}Z_{\beta}
\end{equation}

is a neutral aTGC Lagrangian which describes aTGC of $ZZZ$ and $ZZ\gamma$ couplings. Analyses of $ZZ$ production set limits on $f_{4}^{4}$, $f_{2}^{Z}$, $f_{5}^{4}$, $f_{5}^{Z}$ constants. Limits on constants from charged aTGC Lagrangian Eq. 5 [12])

\begin{equation}
L_{WWV} = g_{WWV} \left[ g_{1}^{V} (W_{\mu\nu}W_{\mu\nu}^{+} - W_{\mu\nu}W_{\mu\nu}^{-}) + \kappa_{V} (W_{\mu\nu}^{+}W_{\mu\nu}^{V} + \frac{\lambda_{V}}{m_{W}^{2}} V^{\mu\nu}W_{\rho\nu}^{+}W_{\rho\nu}^{-}) \right]
\end{equation}

are set from analyses involving a W boson. Fig. 15 summarizes limits on charged and neutral aTGC constants derived from $W\gamma \rightarrow l\nu\gamma$ [3], $ZZ \rightarrow 4l$ [5], $ZZ \rightarrow 2l2\nu$ [6], $WW \rightarrow l\nu l\nu$ [7], and $WV \rightarrow l\nu+2j$ analyses. All results are consistent with the Standard Model predictions.

Figure 15. Summary plots with limits on charged aTGC constants (left) and neutral aTGC constants (right).

6. Conclusions
The latest results on aTGC and aQGC searches with diboson and triboson productions with 7 TeV and 8 TeV data from CMS are summarized. CMS provides the most stringent limits to date on constants associated with $ZZ\gamma$ and $Z\gamma\gamma$ couplings. The first ever limits on constants associated with the $WWZ\gamma$ aQGC coupling are set by the $WV\gamma$ analysis with the semileptonic final state. Limits on constants associated with $WWZ$, $WW\gamma$, $WW\gamma\gamma$ couplings are also set. There are CMS measurements on the subject that have not been included in this report due to space restrictions. A more complete list of the CMS measurements can be found in [13]. All results are consistent with the SM predictions and with the measurements from the other experiments. There are several more 7 TeV and 8 TeV analyses ongoing in CMS. Higher statistics
and energy of Run II will allow the analysis of spectra in higher $P_T^\gamma$, $P_T^l$, $M_{ll}$ bins and therefore increase sensitivity to anomalous gauge couplings.

References