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Exclusive production of W pairs in CMS

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Abstract. We report the results on the search for exclusive production of W pairs in the LHC with data collected by the Compact Muon Solenoid detector in proton-proton collisions at $\sqrt{s} = 7$ TeV. The analysis comprises the two-photon production of a W pairs, $pp \to p\,W^+W^-\,p \to p\,\nu e^\pm \nu\mu^\mp\,p$. Two events are observed in data for $p_T(\ell) > 4$ GeV, $|\eta(\ell)| < 2.4$ and $m(\mu^\pm e^\mp) > 20$ GeV, in agreement with the standard model prediction of 2.2 ± 0.4 signal events with 0.84 ± 0.15 background events. Moreover, a study of the tail of the lepton pair transverse momentum distribution is performed to search for an evidence of anomalous quartic gauge couplings in the $\gamma\gamma \to W^+W^-$ vertex. As no events are observed in data, it results in a model-independent upper limits for the anomalous quartic gauge couplings $a^W_{0,C}/\Lambda^2$, which are of the order of 10^{-4}.

1 Introduction

Lepton and boson pairs can be produced in elastic and inelastic collisions of two colliding protons at high energies by electromagnetic interaction, which can be described with the use of electroweak theory. The production mechanism by the exchange of two photons in proton-proton collisions, $pp \to (\gamma\gamma) \to p + X + p$, has particular signatures that allow its identification among other non-exclusive processes, namely, no hadronic activity in the final state apart of the particles in central rapidity and the forward protons. The latter are scattered at small angles and leave a large rapidity gap with respect to the central system. The $\gamma\gamma$ interaction provides the possibility to produce lepton pairs $\gamma\gamma \to \ell^+\ell^-$ [1], well-known processes in the framework of electroweak theory with accuracy higher than 1%, or boson pairs $\gamma\gamma \to \gamma\gamma, W^+W^-$ [2, 3]. In this report, the final state of interest is the two-photon signal $\gamma\gamma \to W^+W^-$, presented in Fig. 1, with W bosons decaying into leptons and neutrinos.

The elastic (or fully exclusive) events are selected using the silicon tracker information in order to reject events with a vertex containing extra tracks other than the two lepton tracks. On the other hand, the two-photon production of W pairs is also accessible in collisions where one or both protons dissociate into a hadronic system, labeled here as $pp \to p^*\,W^+W^-\,p^* \to p^*\,e^\pm\mu^\mp\,p^*$. The search will include these proton dissociative, or quasi-exclusive, events as part of the $\gamma\gamma \to W^+W^-$ signal. Considering that the average number of simultaneous interaction per bunch crossing (pileup) was 9 during the data-taking period of 2011 in the LHC, we look for events with two lepton tracks from the same vertex to have a high efficiency in runs at high luminosities.

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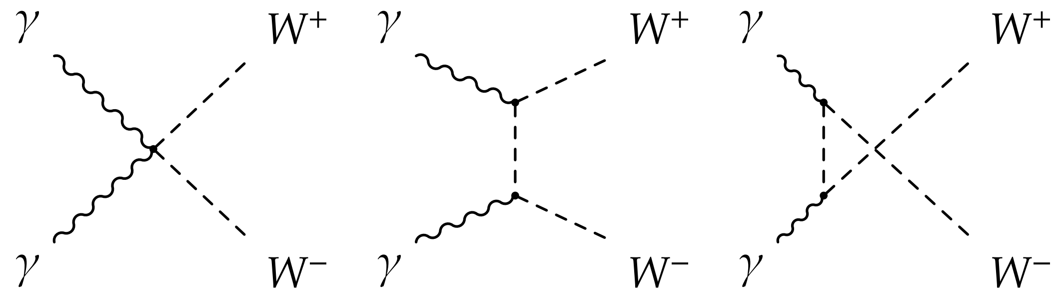

Figure 1. Diagrams contributing to the $\gamma\gamma \to W^+W^-$ in the SM: quartic coupling (left), W-boson exchange in the t-channel (center), and in the u-channel (right).

Since we search for a W pair decaying into leptons, the backgrounds will be larger in case of a same-flavor decay like e^+e^- and $\mu^+\mu^-$, especially due to the Drell-Yan (DY) production. In this case, we choose to select events with a W pair decaying into leptons with opposite-charge and opposite-flavor, $W^+W^- \to e^\pm\mu^\mp$ and undetected neutrinos. In view of validating the event selection, a control sample containing events from exclusive two-photon production of $\mu^+\mu^-$ is used, since it has small theoretical uncertainties. Also, due to the lack of a Monte Carlo (MC) generator accounting for the proton dissociation in $pp \to p\,W^+W^-\,p$, we employ this control sample to extract such contribution from data. The selection of leptons in the final state comprises the lepton pairs with large transverse momentum $p_T(\mu^\pm e^\mp)$ and large invariant mass $M(\mu^\pm e^\mp)$ coming from a vertex with no extra tracks apart of the two lepton tracks. The result will be then compared to the the standard model (SM) expectation for the signal and background events.

Apart of the SM searches, we perform a search for any evidence of new physics regarding the quartic coupling, since any deviation from the SM prediction can potentially be a signal of new physics. Then, the tail of the $p_T(\mu^\pm e^\mp)$ distribution are investigated to look for events consistent with the predictions for anomalous quartic gauge couplings [4].

Therefore, we report the results on the central exclusive production of W pairs [3] in proton-proton collisions at $\sqrt{s} = 7$ TeV obtained with the Compact Muon Solenoid (CMS) detector at CERN.

2 Event selection

Regarding the data-taking period of 2011 with collisions at $\sqrt{s} = 7$ TeV, the CMS detector has collected a total of 5.05/fb of data for events in the $e^\pm\mu^\mp$ channel and 5.24/fb in the $\mu^+\mu^-$ channel. The online algorithms of the high-level trigger (HLT) select leptons with asymmetric thresholds: events with muons with $p_t > 17$ GeV and electrons/muons with $p_t > 8$ GeV and events with electrons/muons with $p_t > 17$ GeV and muons with $p_t > 8$ GeV are selected.

Next, an offline preselection is applied to all leptons in the $e^\pm\mu^\mp$ sample and in the control sample:

- Reconstructed muon and electron/muon with opposite charge;
- Transverse momentum of single leptons: $p_T(\ell) > 20$ GeV;
- Pseudorapidity, η, of single leptons: $|\eta(\ell)| < 2.4$;
- Number of Extra Tracks: nExtTrk<15;
- Invariant mass of lepton pairs: $m(\ell^+\ell'^-) > 20$ GeV.

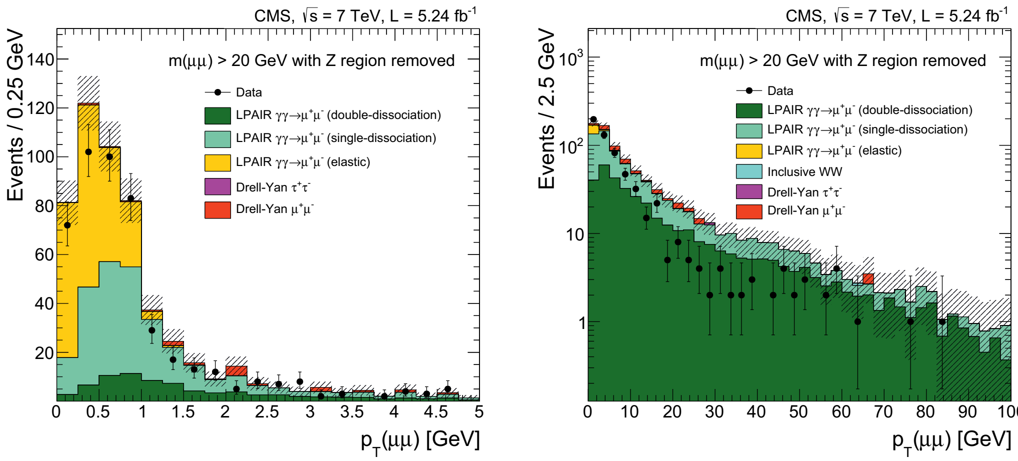

Figure 2. Transverse momentum distributions for muon pairs with the Z-peak region removed ($70 < m(\mu^+\mu^-) < 106$ GeV) in both elastic (left) and dissociation (right) regions with no extra tracks from the muon pair vertex. The hatched bands indicate the statistical uncertainties in the MC samples.

The kinematic region of interest in this search is defined as events having no extra tracks associated to the $e^\pm\mu^\mp$ vertex, with pairs having a transverse momentum larger than 30 GeV in order to reduce the effect of background from $\gamma\gamma \to \tau^+\tau^-$ events. Control plots are produced for events outside this region to check for the proper modeling of the background events, as detailed in Sec. 4.

3 Control sample with $\gamma\gamma \to \mu^+\mu^-$ events

Considering the accuracy in the measurement of lepton pairs in two-photon processes, we use the $\gamma\gamma \to \mu^+\mu^-$ sample to validate the selection of lepton pairs with high mass. In this case, the selection is divided into two regions defined in terms of the p_T balance ($|\Delta p_T(\mu^+\mu^-)|$) and acoplanarity ($1 - |\Delta\phi(\mu^+\mu^-)/\pi|$). The first region, labeled as elastic region, is defined as $|\Delta p_T(\mu^+\mu^-)| < 1$ GeV an acoplanarity smaller than 0.1 GeV, consistent with the elastic process where both protons remain intact in the final state. Besides, the second region, related to the proton dissociation, is defined by $|\Delta p_T(\mu^+\mu^-)| > 1$ GeV and acoplanarity larger than 0.1 GeV. The second region is then used to estimate the contribution from the proton dissociation in order to be scale the sample of $\gamma\gamma \to W^+W^-$ events.

To confirm that the MC predictions are properly describing the data for high-mass lepton pairs. Hence, control plots show that data is well described by the theoretical predictions for the two-photon production of $\mu^+\mu^-$ in the region with no extra tracks. Moreover, the Z peak can be used as a cross-check considering the large contribution of DY processes, since exclusive and photoproduction of the Z bosons are negligible [5–7]. Then, any residual background from inclusive DY production can be investigated in the two regions defined above. Based on simulation, the Z peak region is defined as $70 < m(\mu^+\mu^-) < 106$ GeV, with the DY $\mu^+\mu^-$ production being dominant. The distributions considering events outside the Z-peak region show that the effects of the DY processes are well modeled in this analysis, which allows to perform the search for $\gamma\gamma \to W^+W^-$ events outside this region. Figure 2 presents the transverse momentum distribution of the muon pairs in the elastic and dissociation regions.

Table 1. Background event yields for each of the three control regions.

Region	Background	Data	Sum of backgrounds	$\gamma\gamma \to W^+W^-$ signal
1	Inclusive W^+W^-	43	46.2 ± 1.7	1.0
2	Inclusive DY $\tau^+\tau^-$	182	256.7 ± 10.1	0.3
3	$\gamma\gamma \to \tau^+\tau^-$	4	2.6 ± 0.8	0.7

The agreement between MC and data is good in the elastic region, showing that the LPAIR [8, 9] prediction is ∼10% greater than observed in data. However, the dissociation region presents a large deficit at large $p_T(\mu^+\mu^-)$, which correspond to 28% in comparison to data. This region is significantly affected by rescattering corrections when the protons dissociate due to the inelastic interaction. This effect can be then estimated from data in order to be used to scale the MC predictions for $\gamma\gamma \to W^+W^-$ events. We select the events corresponding to the exclusive muon pair production with invariant mass higher than 160 GeV and divide by the numbers of expected events from theory obtained with LPAIR:

$$F = \left.\frac{N_{\mu\mu\,\mathrm{data}} - N_{DY}}{N_{\mathrm{LPAIR}}}\right|_{m(\mu^+\mu^-)>160\,\mathrm{GeV}} = 3.23 \pm 0.53. \quad (1)$$

Then, this proton-dissociation contribution is included to the predictions of exclusive production of W pairs, assuming that the kinematics of the lepton pairs are the same.

4 Description of data in the signal region

The $\gamma\gamma \to W^+W^-$ signal region is defined for $p_T(\mu^\pm e^\mp) > 30$ GeV and no extra tracks from the vertex. As described in Sec. 3, the expectation from SM should be scaled to take into account the contribution from proton dissociation. The predicted cross section by theory after including the branching ratio for leptonic W decays, and it is scaled by the F factor is:

$$\sigma_{\mathrm{th}}(pp \to p^{(*)}W^+W^-p^{(*)} \to p^{(*)}e^\pm\mu^\mp p^{(*)}) = 4.0 \pm 0.7\,\mathrm{fb}. \quad (2)$$

Since the background reasonably well described, the events in the signal region are selected within two lepton tracks with no extra tracks from the vertex and $p_T(\mu^\pm e^\mp) > 30$ GeV. Table 2 shows the number of events passing each stage in the selection chain with the visible cross section. We employ the event sample to estimate the detector acceptance in the region with $|\eta(\ell)| < 2.4$ and $p_T(\ell) > 20$ GeV, finding an acceptance in the signal region of 55%.

Due to the large contribution to the elastic region from background events, we defined three control regions for each background processes:

- Region 1: Inclusive W^+W^-: $p_T(\mu^\pm e^\mp) > 30$ GeV and nExtTrk = 1-6;
- Region 2: Inclusive DY $\tau^+\tau^-$: $p_T(\mu^\pm e^\mp) < 30$ GeV and nExtTrk = 1-6;
- Region 3: $\gamma\gamma \to \tau^+\tau^-$: $p_T(\mu^\pm e^\mp) < 30$ GeV and nExtTrk = 0.

We observe a good overall agreement in all regions, where Table 1 presents the observed backgrounds event yields for the three control regions. The theoretical predictions overshoot data in the case of DY production of $\tau^+\tau^-$, however no events survive in the signal region. the signal region. Figure 3 presents the invariant mass distribution for each of the three control regions, showing a good description of the data by the MC predictions. As a result, the background is estimated as 0.84 ± 0.15 events, considering the systematic uncertainty on the backgrounds.

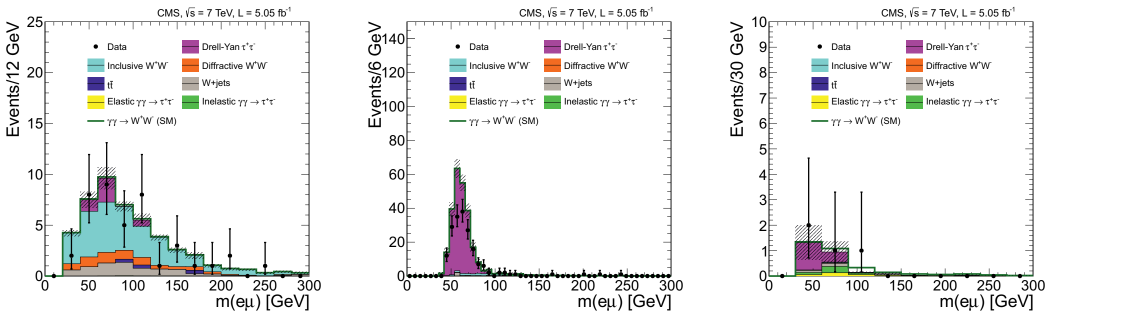

Figure 3. Invariant mass distribution for each of the three control regions: Region 1 (left), Region 2 (center) and Region 3 (right). The shaded bands represent the statistical uncertainty in the MC samples. The signal is stacked to the other histograms.

Table 2. Events passing each step in the selection chain, presented with the signal efficiency × acceptance ($\epsilon \times A$) and the visible cross section. These events contain reconstructed leptons with opposite charge and flavor, each having $p_T(\ell) > 20$ GeV and $|\eta(\ell)| < 2.4$.

Selection step	Signal $\epsilon \times A$	Visible cross section (fb)	Events in data
Trigger and preselection	28.5%	1.1	9086
$m(\mu^\pm e^\mp) > 20$ GeV	28.0%	1.1	8200
Muon ID and Electron ID	22.6%	0.9	1222
$\mu^\pm e^\mp$ vertex with zero extra tracks	13.7%	0.6	6
$p_T(\mu^\pm e^\mp) > 30$ GeV	10.6%	0.4	2

5 Results for the SM searches

As a result, two events pass all the selection criteria, which is in agreement with the theoretical expectation of 2.2 ± 0.4 of signal events and 0.84 ± 0.15 background events. Based on the estimated efficiency × acceptance ($\epsilon \times A$) and luminosity (L), the best fit signal cross section times branching ratio is:

$$\sigma(pp \to p^{(*)}W^+W^-p^{(*)} \to p^{(*)}e^\pm\mu^\mp p^{(*)}) = 2.2^{+3.3}_{-2.0}\,\text{fb}, \tag{3}$$

with $p_T(\ell) > 20$ GeV and $|\eta(\ell)| < 2.4$ with no extra tracks. Applying the Feldman-Cousins method [10], we estimate the observed upper limit in 2.6 times the expect SM yield at 95% confidence level (CL), which results in the limit on the cross section as:

$$\sigma(pp \to p^{(*)}W^+W^-p^{(*)} \to p^{(*)}e^\pm\mu^\mp p^{(*)}) < 10.6\,\text{fb}. \tag{4}$$

The invariant mass, the acoplanarity and the transverse momentum distributions are presented in Fig. 4 with the two events in the signal region observed in data.

6 Beyond SM

It is possible to investigate effects arising from new physics in case that any deviation is observed from the SM expectation in the $\gamma\gamma \to W^+W^-$ vertex. Thus, there are models available in the literature

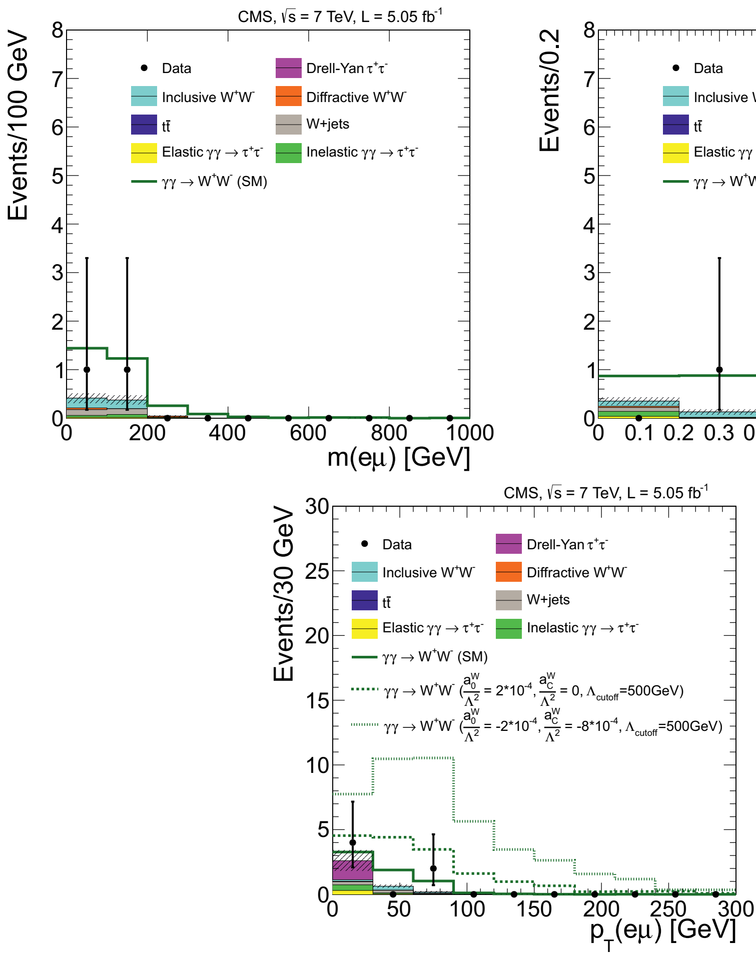

Figure 4. The $e^{\pm}\mu^{\mp}$ invariant mass (top-left), acoplanarity (top-right) and transverse momentum (bottom) distributions in the signal region with no extra tracks. Events are selected with $p_T(\ell) > 20$ GeV, $|\eta(\ell)| < 2.4$ and $p_T(\mu^{\pm}e^{\mp}) > 30$ GeV.

that account for anomalous quartic gauge couplings via an effective Lagrangian [4], which includes the $a^{W,Z}_{0,C}$ anomalous parameters. Since we expect not enough sensitivity to study anomalous triple gauge couplings [11], we focus the current study in the anomalous quartic gauge couplings (aQGC), for which there exist limits obtained at LEP [12–15] and at the Tevatron [2], which report anomalous parameters of the order of 10^{-2} and 10^{-3}, respectively. Moreover, new results from CMS on the tri-boson production[16], $W \to Z\gamma W$, are reported with limits on the anomalous quartic gauge couplings, which shows similar results as the ones found in the exclusive production of W pairs.

Regarding the effective Lagrangian for the aQGC, the resulting cross section rises with center-of-mass energy, consequently violating unitarity at higher energies. An alternative to tame this rise is apply a dipole form factor to each of the anomalous parameters as follows:

$$a_{0,C}^{W}(W_{\gamma\gamma}^{2}) = \frac{a_{0,C}^{W}}{\left(1+\frac{W_{\gamma\gamma}^{2}}{\Lambda^{2}}\right)^{p}},$$

with $p = 2$ for the dipole form factor and $W_{\gamma\gamma}$ is the center-of-mass energy of the $\gamma\gamma$ system. The Λ parameter is related to the energy scale for new physics and play an important role to regulate the cross section. We report results regarding both possibilities of assuming a scale $\Lambda_{\mathrm{cutoff}} = 500$ GeV and no form factor.

7 Results for the searches beyond SM

In order to look for signals of aQGC, we study the tail of the $p_T(\mu^{\pm}e^{\mp})$ distribution for events with no extra tracks. For this purpose, we produce event samples with different anomalous parameters by including the effective Lagrangian to an event generator. By studying the generator-level distributions for $p_T(\mu^{\pm}e^{\mp})$ for various anomalous parameters, we observe that the SM contribution can be neglected for $p_T(\mu^{\pm}e^{\mp}) > 100$ GeV, where the anomalous contribution dominates. Figure 4 present the $p_T(\mu^{\pm}e^{\mp})$ distribution with the MC samples for the anomalous couplings. No excess is observed in the transverse momentum distribution above 100 GeV.

In this case, we report an upper limit to the cross section based on the Feldman-Cousins method:

$$\sigma(pp \to p^{(*)}W^{+}W^{-}p^{(*)} \to p^{(*)}e^{\pm}\mu^{\mp}p^{(*)}) < 1.9\,\mathrm{fb}.$$

for $|\eta(\ell)| < 2.4$, $p_T(\ell) > 20$ GeV and $p_T(e^{\pm}\mu^{\mp}) > 100$ GeV. Besides, new limits to the anomalous parameters are reported considering a form factor with $\Lambda_{\mathrm{cutoff}} = 500$ GeV and without form factors:

$$-0.00015 < a_0^W/\Lambda^2 < 0.00015\ \mathrm{GeV}^{-2}\ (a_C^W/\Lambda^2 = 0, \Lambda = 500\ \mathrm{GeV}),$$
$$-0.0005 < a_C^W/\Lambda^2 < 0.0005\ \mathrm{GeV}^{-2}\ (a_0^W/\Lambda^2 = 0, \Lambda = 500\ \mathrm{GeV}),$$

$$-4.0\times10^{-6} < a_0^W/\Lambda^2 < 4.0\times10^{-6}\ \mathrm{GeV}^{-2}\ (a_C^W/\Lambda^2 = 0, \text{no form factor}),$$
$$-1.5\times10^{-5} < a_C^W/\Lambda^2 < 1.5\times10^{-5}\ \mathrm{GeV}^{-2}\ (a_0^W/\Lambda^2 = 0, \text{no form factor}).$$

In comparison to the existing limits, the limits presented here are nearly two orders of magnitude more stringent than those obtained at LEP and 20 times more stringent than the results reported by the Tevatron. Figure 5 shows the two-dimensional 95% confidence region for limits including a form factor with $\Lambda_{\mathrm{cutoff}} = 500$ GeV.

8 Summary

Results on the search for the exclusive two-photon W pair production in the $e^{\pm}\mu^{\mp}$ decay channel are reported. The studies are performed using 5.05/fb of data collected by the CMS detector in 2011 for proton-proton collisions at $\sqrt{s} = 7$ TeV. Two events are observed in data, which are in agreement with the theoretical prediction of 2.2 ± 0.4 signal events and 0.84 ± 0.15 background events, obtained in the region of $|\eta(\ell)| < 2.4$, $p_T(\ell) > 20$ GeV and $p_T(e^{\pm}\mu^{\mp}) > 30$ GeV.

Besides, further studies regarding the anomalous quartic gauge couplings are performed for the region with $p_T(e^{\pm}\mu^{\mp}) > 100$ GeV. No events are observed in data and limits on the anomalous parameters are addresses, which are two orders of magnitude more stringent than those obtained at LEP and 20 times more stringent than the results obtained at the Tevatron. Reclent results from CMS on the tri-boson production show similar results for these limits.

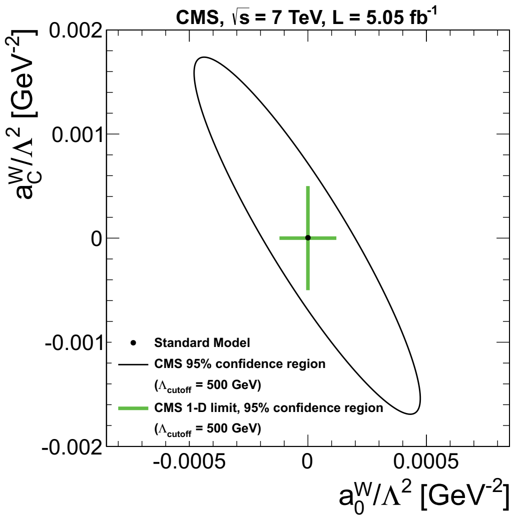

Figure 5. Limits on the anomalous couplings a_0^W and a_C^W for aQGC with Λ_{cutoff} = 500 GeV. The region outside the ellipsis is excluded with 95% CL, obtained with $|\eta(\ell)| < 2.4$, $p_T(\ell) > 20$ GeV and $p_T(e^{\pm}\mu^{\mp}) > 100$ GeV.

9 Acknowledgements

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