Anomalous Quartic $WW\gamma\gamma$ and $ZZ\gamma\gamma$ Couplings in Two-Photon Processes at the LHC

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Two-photon production of WW/ZZ pairs is used to calculate sensitivities to anomalous quartic couplings between photon and massive electroweak bosons at the LHC. We show how the signal can be selected from the diffractive and two-photon backgrounds and that the current sensitivities can be improved by almost two orders of magnitude with early data. Using the full LHC luminosity and the forward detectors installed at 220 m and 420 m from the CMS or ATLAS detectors, sensitivities on anomalous couplings of the order of $10^{-6}\,\mathrm{GeV}^{-2}$ can be achieved.

1 Two-Photon Diboson Production

In the Standard Model (SM), the interaction between the electroweak bosons is dictated by the underlying non-abelian symmetry of the SM Lagrangian. Although the triple gauge boson couplings are measured quite precisely, the constraints of the quartic couplings come from LEP experiments and are less stringent as they required three bosons to be detected. In this work we focus on deriving sensitivities to anomalous quartic vertices involving two photons and a pair of W or Z bosons in exclusive interactions induced by the exchange of two photons at the LHC. Only the fully-leptonic decays of the electroweak bosons are considered. The analysis follows the first investigation [1], but with a broader set of backgrounds considered and also calculated for two different luminosity scenarios.

In two-photon interactions, two almost real photons are emitted from high energetic proton beams, interact with each other and yield various final states such as the pair of leptons, jets, and electroweak bosons, see Figure 1 (left). Since protons leave the interaction intact, and are scattered at small angles, there is no proton remnant, and only the object created from two photons populates the central detector. The fractional momentum loss of the proton is $\xi \equiv 1 - |\mathbf{p}|/|\mathbf{p}_b|$, where $\mathbf{p}_b$ is the beam momentum and $\mathbf{p}$ is the scattered proton momentum. The process is exclusive and can be selected either by tagging the outgoing forward protons or by requiring the detection of the created system from two photons in the central detector and nothing else. The two-photon production is calculated in the framework of the Equivalent Photon Approximation (EPA) which is in detail described in [2].

The two-photon production of W pairs has a total cross section of 95.6 fb (using the value of the fine-structure constant $\alpha_{\mathrm{QED}} = 1/137$ at the scale $Q^2 = 0\,\mathrm{GeV}^2$) whereas the production of Z pairs is forbidden in the SM in the leading order since neither the photon nor the Z boson carry the electric or weak charges.

The sensitivities to potential Beyond Standard Model (BSM) physics is investigated in terms of four anomalous parameters a_0^W/Λ^2, $a_0^Z/\Lambda^2, a_C^W/\Lambda^2$, a_C^Z/Λ^2 using effective anomalous Lagrangians conserving C− and P−parities separately which are added to the SM [3]. They read

$$\begin{aligned}\mathcal{L}_6^0 &= \frac{-e^2}{8}\frac{a_0^W}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}W^{+\alpha}W^-_\alpha - \frac{e^2}{16\cos^2\theta_W}\frac{a_0^Z}{\Lambda^2}F_{\mu\nu}F^{\mu\nu}Z^\alpha Z_\alpha,\\ \mathcal{L}_6^C &= \frac{-e^2}{16}\frac{a_C^W}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}(W^{+\alpha}W^-_\beta + W^{-\alpha}W^+_\beta) - \frac{e^2}{16\cos^2\theta_W}\frac{a_C^Z}{\Lambda^2}F_{\mu\alpha}F^{\mu\beta}Z^\alpha Z_\beta,\end{aligned}$$

where $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ is the electromagnetic stress-energy tensor and θ_W is the Weinberg angle. Λ is a typical scale of new physics (e.g. the mass of new particle) whose exact value is, however, not important since sensitivities to entities including this scale are derived, a_0^W/Λ^2 for instance. The additional Lagrangians are the lowest order operators involving two photons which can be constructed having a correct Lorentz structure and obeying custodial symmetry protecting the value of $\rho = M_W/(M_Z\cos\theta_W)$ to be close to the experimentally measured value 1. They have a dimension six in terms of energy. Notice that in $\mathcal{L}_6^0$ Lorentz indices are decoupled and the operator can be interpreted as a low energy exchange of a massive scalar field. In fact, since anomalous couplings of the order of $10^{-6}\,\mathrm{GeV}^{-2}$ emerge from 1-loop corrections in Higgs-less theories, the measurement proposed in this paper can give us an important information about the symmetry breaking mechanism and mass generation.

Adding these new operators, the total cross section is greatly enhanced as depicted in Figure 1 (right). In the SM, the $\gamma\gamma \to WW$ cross section is constant in the high energy limit due

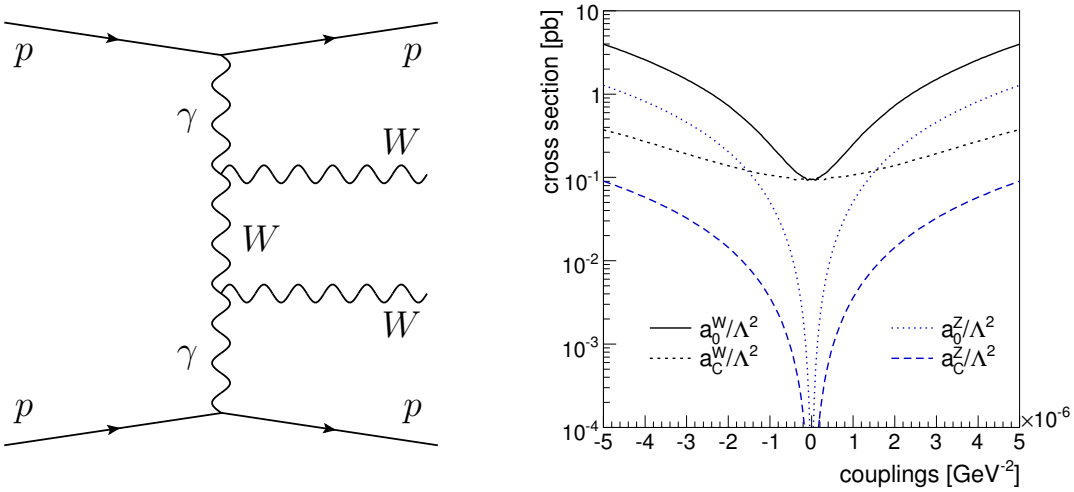

Figure 1: Leading order Feynman diagram of two-photon WW production (left) and enhancement of the total W and Z pair production cross sections in two-photon events from their SM values 95.6 fb and 0 fb, respectively (right). No survival probability which should be 0.9 for two-photon events is applied.

to the cancellation between the involved diagrams ($s-$, $t-$channel, direct four-boson diagrams). Adding new quartic term, the cancellation does not hold any more and the cross section growth

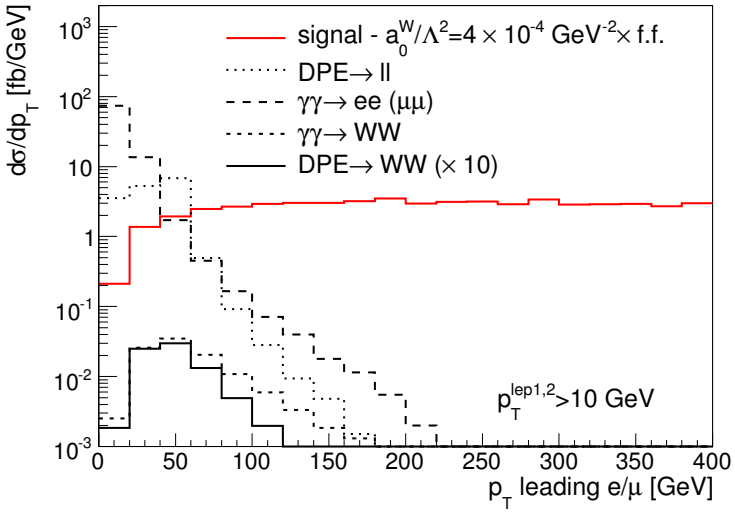

Figure 2: p_T-distribution of the leading electron/muon for signal and background processes. As expected, the signal appears at high p_T. The largest background are two-photon $ee(\mu\mu)$ production and DPE$\rightarrow l\bar{l}$.

as a function of the centre-of-mass energy is driven by diagrams in which the dibosons in the final state are longitudinally polarised. This eventually leads to the violation of unitarity in the process. The main problem is that the unitarity is violated already at the LHC energies which makes the interpretation of new terms as the effective description of new physics impossible. The usual approach in this case is to supplement the anomalous parameters with form factors which weaken the effect of the coupling at high centre-of-mass energy and mimic the exchange of a particle of mass which is beyond the reach of the accelerator. Following the study [1] we use the following parameterisation of the coupling form factor $a \rightarrow a/\left[1 + (W_{\gamma\gamma}/2\,\text{TeV})^2\right]^2$, where $W_{\gamma\gamma} = \sqrt{s\xi_1\xi_2}$ is the invariant mass of two photons and 2 TeV is the scale beyond which the effect of the coupling is suppressed. More detailed discussion on the form factors in our analysis will be given in an up-coming publication.

Since the effect of anomalous parameters on the cross section is large even when form factors are taken into account, the study is divided into two steps. First we present an analysis using the central detector only and limited collected luminosity of 10 (100) pb^{-1} at a reduced centre-of-mass LHC energy $\sqrt{s} = 10$ TeV. To achieve the ultimate sensitivity, the high LHC luminosity 30 (200) fb^{-1} at $\sqrt{s} = 14$ TeV is used in which the two-photon events are selected using very ATLAS Forward Proton (AFP) detectors to be installed at 220 m and 420 m on both sides around the interaction point at few millimetres from the beam. These detectors were recently recognised by the ATLAS management as a potential upgrade of the ATLAS detector and the ATLAS community showed an interest in the diffractive program. The analysis using the CMS detector and the corresponding forward detectors would be similar.

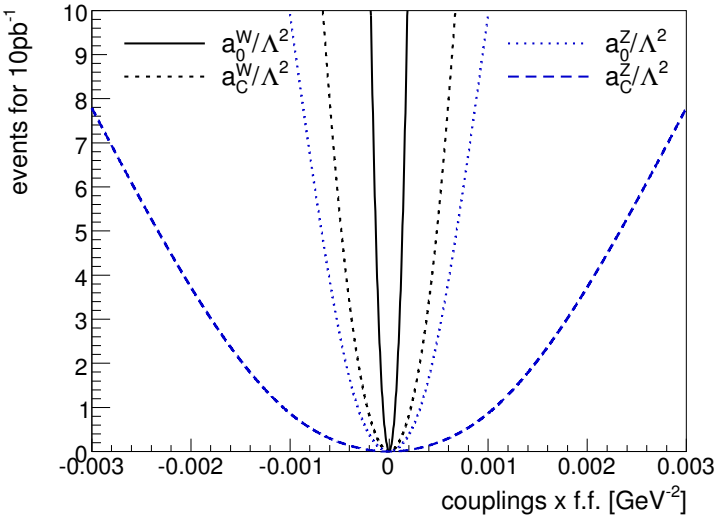

Figure 3: Expected number of signal events due to anomalous quartic couplings for $10\,\mathrm{pb}^{-1}$ after considered cuts (see text).

2 Background

The two-photon WW/ZZ events in which both bosons decay leptonically were studied with respect to the following background: 1) non-diffractive WW/ZZ production which has a large energy flow in the forward region and large number of tracks due to the break-up of the collided protons 2) $\gamma\gamma \to l\bar{l}$ - two-photon dilepton production in which leptons fly exactly back-to-back in the transverse plane 3) DPE$\to l\bar{l}$ - dilepton production through double Pomeron exchange (DPE) in which the partonic structure of the hard diffractive Pomeron is probed in Drell-Yan like process and higher number of tracks is expected due to the Pomeron remnants 4) DPE$\to WW$ - diboson production through double Pomeron exchange, the same production as in the precedent case.

Two-photon or diffractive processes with intact protons were generated using the `FPMC` generator [4] and simulated using `ATLFAST++`, fast standalone simulation of ATLAS inside `ROOT`. The matrix elements with anomalous couplings are calculated using the `CompHEP` program [5] interfaced with `FPMC`. The implemented survival probability factors are 0.9 for the QED two-photon processes and 0.03 for the Pomeron exchanges [6].

The comparison between the anomalous signal and the considered backgrounds with intact protons is shown in Figure 2. The signal is dominant at high transverse lepton momenta and also at large missing mass $W_{\gamma\gamma}$ which sets the analysis strategy.

3 Anomalous Quartic Couplings at Low Luminosity

Let us describe our selection criteria for the low luminosity scenario $10\,(100)\,\mathrm{pb}^{-1}$ in which only one interaction per bunch crossing is present. Such amount of data is expected to be

Couplings	OPAL limits [GeV^{-2}]	Sensitivity @ $\mathcal{L} = 10$ (100) pb^{-1} 95% CL [GeV^{-2}]	Sensitivity @ $\mathcal{L} = 30$ (200) fb^{-1} 95% CL [GeV^{-2}]
a_0^W/Λ^2	[-0.020, 0.020]	1.0×10^{-4} (3.3×10^{-5})	2.6×10^{-6} (1.4×10^{-6})
a_C^W/Λ^2	[-0.052, 0.037]	3.5×10^{-4} (1.1×10^{-4})	9.4×10^{-6} (5.2×10^{-6})
a_0^Z/Λ^2	[-0.007, 0.023]	5.2×10^{-4} (1.7×10^{-4})	6.4×10^{-6} (3.7×10^{-6})
a_C^Z/Λ^2	[-0.029, 0.029]	1.8×10^{-3} (5.9×10^{-4})	35×10^{-6} (14×10^{-6})

Table 1: 95% confidence limits on the anomalous quartic couplings using 10 (100) pb^{-1} of early data (third column) and using 30 (200) fb^{-1} with forward detectors (last column). Coupling form factors are used as described in the text. The OPAL limits [7] can be improved up to four orders of magnitude.

collected during the first months of LHC running. In order to reject non-diffractive and DPE backgrounds with large number of particles due to proton and Pomeron remnants, we require an exclusivity cut $n_{\text{tracks}} \leq 2$. To further suppress the background from two-photon dilepton events, we request large transverse lepton (e, μ) momentum $p_T^{lep1} > 160\,\text{GeV}$, $p_T^{lep2} > 10\,\text{GeV}$ and large missing transverse energy $\not{E}_T > 20\,\text{GeV}$ which is a natural characteristics of W events decaying to leptons and neutrinos.

The ZZ signal is background free because two leptons of the same charge are created when both Zs decay leptonically. The requirement which was used to select the ZZ signal was either to have ≥ 2 leptons of the same charge, or ≥ 3 leptons. Leptons are required to have a transverse momentum p_T^{lep1} >160 GeV and p_T^{lep2} >25 GeV. In addition, no jet can be seen in the event. Such requirements are sufficient to reject all non-diffractive, two-photon or DPE exchange background.

The expected number of signal events for 10 pb^{-1} after the mentioned cuts is shown in Figure 3. The sensitivities to anomalous couplings using low luminosity are shown in Table 1 (third column). They are obtained by varying one of the anomalous parameters while keeping the others to their zero SM values. The sensitivities can be improved by two orders of magnitude with respected to the limits from the OPAL Collaboration [7] with a small amount of data.

4 Anomalous Quartic Couplings at High Luminosity

To obtain sensitivities to anomalous couplings of the order of $10^{-6}\,\text{GeV}^{-2}$ which would allow to test several Higgs-less theories, the full LHC collected luminosity must be used. During the nominal LHC runs about 32 interactions will be present at the peaked luminosity and the number of interactions per bunch crossing will not drop below 13 during one store (the total cross section $\sigma_{\text{tot}} = 100\,\text{mb}$ is assumed). In this case, protons have to be tagged in forward detectors to select the two-photon or diffractive events. Moreover, fast timing detectors will be used to reject the overlap background in which one inelastic event in the central detectors is overlaid with two soft diffractive events giving proton hits in the forward detectors.

In our analysis we select events with fractional momentum loss inside the generic acceptance of the proposed AFP detectors $0.0015 < \xi < 0.15$. To select WW signal we apply the $\not{E}_T > 20\,\text{GeV}$ cut. The corresponding missing mass spectrum $W_{\gamma\gamma}$ for the WW anomalous signal and all backgrounds is shown in Figure 4. To further suppress the contribution of DPE and

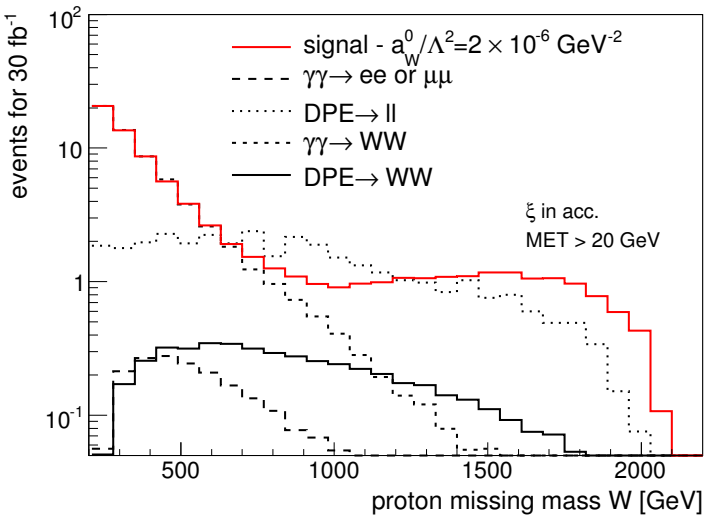

Figure 4: Proton missing mass in the AFP acceptance $0.0015 < \xi < 0.15$ and after $\not{E}_T > 20\,\text{GeV}$ for signal and all backgrounds for $30\,\text{fb}^{-1}$.

two-photon dilepton signal, we require the invariant lepton mass to be far from the Z pole $M_{ll} \notin \langle 80, 100 \rangle\,\text{GeV}$, dileptons not back-to-back $\Delta\phi < 3.13$ and large missing mass $W_{\gamma\gamma} > 800\,\text{GeV}$, $p_T^{lep1} > 160\,\text{GeV}$, $p_T^{lep2} > 10\,\text{GeV}$. After these cuts the total considered background is reduced to ≈ 1 event for $\mathcal{L} = 30\,\text{fb}^{-1}$.

The selection of the ZZ signal is similar to the low luminosity analysis. The complete set of used cuts is ($n_{lep} \geq 2$, 2 of same charge) or $n_{lep} \geq 3, 0.0015 < \xi < 0.15, p_T^{lep1} > 160\,\text{GeV}, p_T^{lep2} > 25\,\text{GeV}, n_{jet} = 0$. The overlaid background is assumed to be negligible with the use of timing detectors which detect the arrival time of the protons and allow to distinguish whether protons in the forward detectors come from the same vertex as the tracks in the central detector.

The calculated sensitivities using integrated luminosity $\mathcal{L} = 30\,(200)\,\text{fb}^{-1}$ are shown in Table 1. The improvement with respect to OPAL limits is almost four orders of magnitude. The charged and neutral terms in the anomalous Lagrangians can partially cancel each other. This effect is seen in two dimensional discovery limits in Figure 5. They are calculated by varying either the pair a_0^W/Λ^2, a_C^W/Λ^2 or the pair a_0^Z/Λ^2, a_C^Z/Λ^2 at the same time.

5 Conclusion

Two-photon interactions at the LHC are exclusive processes which make an important part of the forward physics program. Since heavy mass objects can be created, these events will be used to test the SM in a new ways. The anomalous couplings between photons and pairs of electroweak bosons of the order of $10^{-6}\,\text{GeV}^{-2}$ can be probed which might be used to distinguish between some of the Higgs-less models.

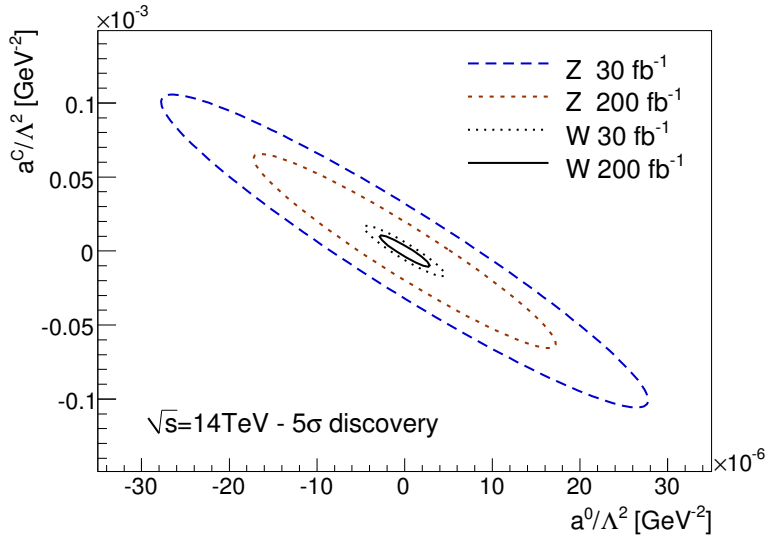

Figure 5: Two dimensional discovery limits using high luminosity and forward detectors. The significance is calculated as $S/\sqrt{B+1}$ where S is the enhancement of the cross section due to anomalous couplings and B is the total background including SM two-photon production. Sensitivities are shown for $30\,\mathrm{fb}^{-1}$ and $200\,\mathrm{fb}^{-1}$ of collected luminosity.

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