

Anomalous quartic and triple gauge couplings in γ -induced processes at the LHC

Christophe Royon*

CEA/IRFU/Service de physique des particules, CEA/Saclay, 91191 Gif-sur-Yvette cedex, France

E-mail: christophe.royon@cea.fr

Emilien Chapon

CEA/IRFU/Service de physique des particules, CEA/Saclay, 91191 Gif-sur-Yvette cedex, France

E-mail: emilien.chapon@cea.fr

Oldřich Kepka

IPNP, Faculty of Mathematics and Physics, Charles University, Prague

Center for Particle Physics, Institute of Physics, Academy of Science, Prague

E-mail: kepka@fzu.cz

We study the W/Z pair production via two-photon exchange at the LHC and give the sensitivities on trilinear and quartic gauge anomalous couplings between photons and W/Z bosons for an integrated luminosity of 30 and 200 fb^{-1} . For simplicity and to obtain lower backgrounds, only the leptonic decays of the electroweak bosons are considered. The intact protons in the final states are detected in the ATLAS Forward Proton detectors. The high energy and luminosity of the LHC and the forward detectors allow to probe beyond standard model physics and to test the higgsless and extra dimension models in an unprecedented way.

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*Speaker.

In the Standard Model (SM) of particle physics, the couplings of fermions and gauge bosons are constrained by the gauge symmetries of the Lagrangian. The measurement of W and Z boson pair productions via the exchange of two photons allows to provide directly stringent tests of one of the most important and least understood mechanism in particle physics, namely the electroweak symmetry breaking [1]. The non-abelian gauge nature of the SM predicts the existence of quartic couplings $WW\gamma\gamma$ between the W bosons and the photons which can be probed directly at the Large Hadron Collider (LHC) at CERN. The quartic coupling to the Z boson $ZZ\gamma\gamma$ is not present in the SM.

The quartic couplings test more generally new physics which couples to electroweak bosons. Exchange of heavy particles beyond the SM might manifest itself as a modification of the quartic couplings appearing in contact interactions [2]. It is also worth noticing that in the limit of infinite Higgs masses, or in Higgs-less models [2], new structures not present in the tree level Lagrangian appear in the quartic W coupling. For example, if the electroweak breaking mechanism does not manifest itself in the discovery of the Higgs boson at the LHC or supersymmetry, the presence of anomalous, non SM like, couplings might be the first evidence of new physics in the electroweak sector of the SM.

1. Photon exchange processes in the SM

The process that we intend to study is the W pair production shown in Fig. 1 induced by the exchange of two photons [3, 4]. It is a pure QED process in which the decay products of the W bosons are measured in the central detector and the scattered protons leave intact in the beam pipe at very small angles, contrary to inelastic collisions. Since there is no proton remnant the process is purely exclusive; only W decay products populate the central detector, and the intact protons can be detected in dedicated detectors located along the beam line far away from the interaction point.

The cross section of the $pp \rightarrow pWWp$ process which proceeds through two-photon exchange is calculated as a convolution of the two-photon luminosity and the total cross section $\gamma\gamma \rightarrow WW$. The total two-photon cross section is 95.6 fb.

All considered processes (signal and background) were produced using the Forward Physics Monte Carlo [7] (FPMC) generator. The aim of FPMC is to produce different kinds of processes such as inclusive and exclusive diffraction, photon-exchange processes. FPMC was interfaced to as fast simulation of the ATLAS detector [5]. To reduce the amount of considered background, we only use leptonic (electrons and muons) decays of Z and W bosons. The clean two-leptonic signature of the two boson signal process $\gamma\gamma \rightarrow W^+W^- \rightarrow l\bar{l}\nu\bar{\nu}$ can be mimicked by several background processes which all have two intact protons in the final state. They are the following:

1. $\gamma\gamma \rightarrow l\bar{l}$ - two-photon dilepton production
2. $DPE \rightarrow l\bar{l}$ - dilepton production through double pomeron exchange
3. $DPE \rightarrow W^+W^- \rightarrow l\bar{l}\nu\bar{\nu}$ - diboson production through double pomeron exchange

After simple cuts to select exclusive W pairs decaying into leptons, such as a cut on the proton momentum loss of the proton ($0.0015 < \xi < 0.15$) — we assume the protons to be tagged in the ATLAS Forward Physics detectors [6] — on the transverse momentum of the leading and

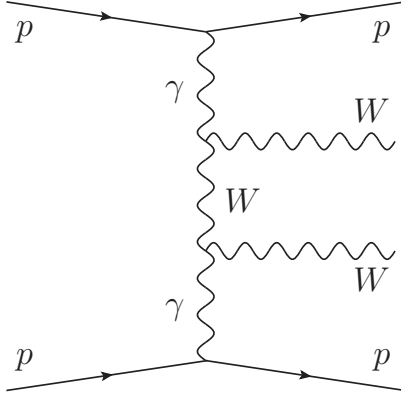


Figure 1: Sketch diagram showing the two-photon production of a central system.

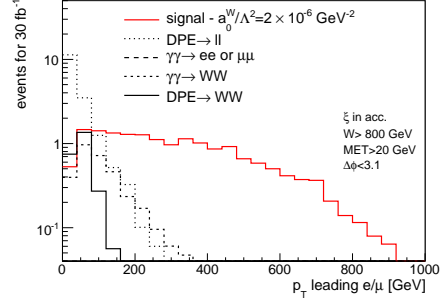


Figure 2: Distribution of the transverse momentum of the leading lepton for signal and background after the cut on W , \cancel{E}_T , and $\Delta\phi$ between the two leptons.

second leading leptons at 25 and 10 GeV respectively, on $\cancel{E}_T > 20$ GeV, $\Delta\phi > 2.7$ between leading leptons, and $160 < W < 500$ GeV, the diffractive mass reconstructed using the forward detectors, the background is found to be less than 1.7 event for 30 fb^{-1} for a SM signal of 51 events. In this channel, a 5σ discovery of the Standard Model $pp \rightarrow pWWp$ process is possible after 5 fb^{-1} .

2. Quartic anomalous couplings

The parameterization of the quartic couplings based on [8] is adopted. We concentrate on the lowest order dimension operators which have the correct Lorentz invariant structure and obey the $SU(2)_C$ custodial symmetry in order to fulfill the stringent experimental bound on the ρ parameter. The lowest order interaction Lagrangians which involve two photons are dim-6 operators. The following expression for the effective quartic Lagrangian is used

$$\begin{aligned} \mathcal{L}_6^0 &= \frac{-e^2 a_0^W}{8 \Lambda^2} F_{\mu\nu} F^{\mu\nu} W^{+\alpha} W_{\alpha}^{-} - \frac{e^2}{16 \cos^2 \theta_W} \frac{a_0^Z}{\Lambda^2} F_{\mu\nu} F^{\mu\nu} Z^{\alpha} Z_{\alpha} \\ \mathcal{L}_6^C &= \frac{-e^2 a_C^W}{16 \Lambda^2} F_{\mu\alpha} F^{\mu\beta} (W^{+\alpha} W_{\beta}^{-} + W^{-\alpha} W_{\beta}^{+}) - \frac{e^2}{16 \cos^2 \theta_W} \frac{a_C^Z}{\Lambda^2} F_{\mu\alpha} F^{\mu\beta} Z^{\alpha} Z_{\beta} \end{aligned} \quad (2.1)$$

where a_0 , a_C are the parametrized new coupling constants and the new scale Λ is introduced so that the Lagrangian density has the correct dimension four and is interpreted as the typical mass scale of new physics. In the above formula, we allowed the W and Z parts of the Lagrangian to have specific couplings, i.e. $a_0 \rightarrow (a_0^W, a_0^Z)$ and similarly $a_C \rightarrow (a_C^W, a_C^Z)$.

The WW and ZZ two-photon cross sections rise quickly at high energies when any of the anomalous parameters are non-zero. The cross section rise has to be regulated by a form factor which vanishes in the high energy limit to construct a realistic physical model of the BSM theory. We therefore modify the couplings by form factors that have the desired behavior, i.e. they modify the coupling at small energies only slightly but suppress it when the center-of-mass energy $W_{\gamma\gamma}$

Couplings	OPAL limits [GeV ⁻²]	Sensitivity @ $\mathcal{L} = 30$ (200) fb ⁻¹	
		5 σ	95% CL
a_0^W/Λ^2	[-0.020, 0.020]	5.4 10 ⁻⁶ (2.7 10 ⁻⁶)	2.6 10 ⁻⁶ (1.4 10 ⁻⁶)
a_C^W/Λ^2	[-0.052, 0.037]	2.0 10 ⁻⁵ (9.6 10 ⁻⁶)	9.4 10 ⁻⁶ (5.2 10 ⁻⁶)
a_0^Z/Λ^2	[-0.007, 0.023]	1.4 10 ⁻⁵ (5.5 10 ⁻⁶)	6.4 10 ⁻⁶ (2.5 10 ⁻⁶)
a_C^Z/Λ^2	[-0.029, 0.029]	5.2 10 ⁻⁵ (2.0 10 ⁻⁵)	2.4 10 ⁻⁵ (9.2 10 ⁻⁶)

Table 1: Reach on anomalous couplings obtained in γ induced processes after tagging the protons in the final state in the ATLAS Forward Physics detectors compared to the present OPAL limits. The 5 σ discovery and 95% C.L. limits are given for a luminosity of 30 and 200 fb⁻¹

increases. The form of the form factor that we consider is the following

$$a \rightarrow \frac{a}{(1 + W_{\gamma\gamma}^2/\Lambda^2)^n} \quad (2.2)$$

where $n=2$, and $\Lambda \sim 2$ TeV.

The cuts to select quartic anomalous gauge coupling WW events are similar as the ones we mentioned in the previous section, namely $0.0015 < \xi < 0.15$ for the tagged protons, $\cancel{E}_T > 20$ GeV, $\Delta\phi < 3.13$ between the two leptons. In addition, a cut on the p_T of the leading lepton $p_T > 160$ GeV and on the diffractive mass $W > 800$ GeV are requested since anomalous coupling events appear at high mass. Fig 2 displays the p_T distribution of the leading lepton for signal and the different considered backgrounds. After these requirements, we expect about 0.7 background events for an expected signal of 17 events if the anomalous coupling is about four order of magnitude lower than the present LEP limit ($|a_0^W/\Lambda^2| = 5.4 \cdot 10^{-6}$) for a luminosity of 30 fb⁻¹. The strategy to select anomalous coupling ZZ events is analogous and the presence of three leptons or two like sign leptons are requested. The expected number of events for a luminosity of 30 fb⁻¹ as a function of the anomalous coupling is displayed in Fig 3 and the 5 σ discovery countours for W and Z quartic anomalous couplings are displayed for two different integrated luminosities of 30 and 200 fb⁻¹ in Fig. 4. Table 1 gives the reach on anomalous couplings at the LHC for the same luminosities compared to the present OPAL limits [9]. We note that we can gain almost four orders of magnitude in the sensitivity to anomalous quartic gauge couplings compared to LEP experiments, and it is possible to reach the values expected in Higgsless or extra-dimension models. The tagging of the protons using the ATLAS Forward Physics detectors is the only method at present to test so small values of quartic anomalous couplings and thus to probe the higgsless models in a clean way.

3. Triple anomalous gauge couplings

In Ref. [10], we also studied the sensitivity to triple gauge anomalous couplings at the LHC.

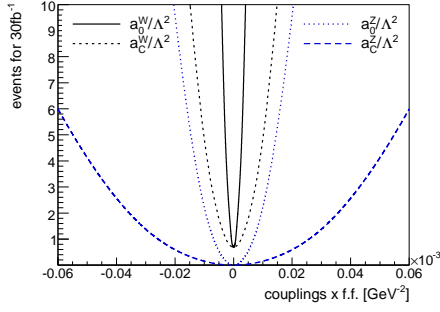


Figure 3: Number of events for signal due to different values of anomalous couplings after all cuts (see text) for a luminosity of 30 fb^{-1} .

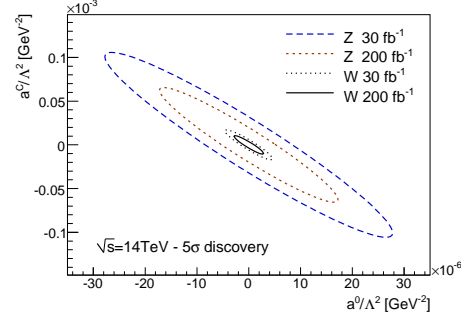


Figure 4: 5σ discovery contours for all the WW and ZZ quartic couplings at $\sqrt{s} = 14 \text{ TeV}$ for a luminosity of 30 fb^{-1} and 200 fb^{-1} .

The Lagrangian including anomalous triple gauge couplings λ^γ and $\Delta\kappa^\gamma$ is the following

$$\mathcal{L} \sim (W_{\mu\nu}^\dagger W^\mu A^\nu - W_{\mu\nu} W^{\dagger\mu} A^\nu) + (1 + \Delta\kappa^\gamma) W_\mu^\dagger W_\nu A^{\mu\nu} + \frac{\lambda^\gamma}{M_W^2} W_{\rho\mu}^\dagger W^\mu{}_\nu A^{\nu\rho}. \quad (3.1)$$

The strategy is the same as for quartic couplings: we first implement this lagrangian in FPMC and we select the signal events when the Z and W bosons decay into leptons. The difference is that the signal appears at high mass for λ^γ and $\Delta\kappa^\gamma$ only modifies the normalisation and the low mass events have to be retained. The sensitivity on triple gauge anomalous couplings is a gain of about a factor 3 with respect to the LEP limits, which represents one of the best reaches before the LHC.

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