Anomalous Gauge Couplings in Photon-Photon Interactions at the LHC

Émilien Chapon, Oldřich Kepka, Christophe Royon

IRFU-SPP, CEA Saclay, 91191 cedex Gif-sur-Yvette, France

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We show that the expected sensitivity to triple and quartic gauge couplings at the LHC with the ATLAS or the CMS detector, in photon-photon interactions, can be improved by 3 orders of magnitude with respect to LEP results. In particular we study anomalous $WW\gamma$, $WW\gamma\gamma$ and $ZZ\gamma\gamma$ couplings.

We first present the results obtainable with early data (10 to 100 pb^{-1}). We discuss finally the sensitivity reached with higher integrated luminosity (30 fb^{-1} and more) using the forward proton detectors foreseen for an upgrade of the ATLAS/CMS detector.

1 Introduction

A lot of new physics analyses at the LHC need a significant amount of data to be carried out. Nevertheless, even with early data, some new results are achievable, for example on anomalous gauge couplings in photon induced processes. A dramatic improvement on the current knowledge of those anomalous couplings is possible even with very few data (from 10 pb^{-1}).

2 Two-photon interactions and anomalous couplings

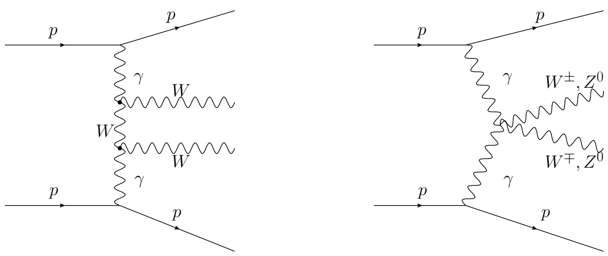

Figure 1: Feynman diagrams for the signal (triple gauge couplings on the left, quartic on the right)

The process we studied is $pp \to p(\gamma\gamma)p \to ppWW$ (see Figure 1). In this photon-induced process, the two photons interact through the exchange of a virtual W, giving a pair of Ws in the final state. The main particularity of this process is that nothing else is produced in the central detectors, and we only detect the products of the decay of the Ws, namely two leptons (including taus if they decay leptonically) as we only studied the leptonic channel.

Even though we would have had more statistics, we did not consider the case when the Ws decay hadronically. In this case one would have to face the high QCD background and thus a more refine analysis would be needed. The protons loose little transverse momentum and fly into the beam pipe, they are therefore left undetected (unless forward proton detectors are installed at ATLAS or CMS, e.g. ATLAS Forward Physics detectors: see below). So we have a very clean signature for our events: only two reconstructed leptons in the central detectors *and nothing else*.

2.1 W pair production through two-photon interaction

The cross section of this process in the Standard Model is well known, since it is a pure Quantum Electrodynamics process. This cross section is $\sigma_{pp\to ppWW} = 95.6\,\text{fb}$ at $\sqrt{s} = 14\,\text{TeV}$, $\sigma_{pp\to ppWW} = 62\,\text{fb}$ at $\sqrt{s} = 10\,\text{TeV}$ ($\alpha_{EM} = 1/137$).

In our study we used the equivalent photon approximation (Budnev flux), which predicts exchanges of quasi-real (low virtuality Q^2) photons whose energy can be substantially large. In particular we can have a high missing mass $M_{\gamma\gamma} = \sqrt{s\xi_1\xi_2}$ (where ξ is the momentum fraction loss of the proton). Therefore photon interactions allow to probe new physics even at the terascale.

2.2 Anomalous couplings

We studied two types of effective Lagrangians of anomalous gauge couplings extending the Standard Model. The first one corresponds to quartic couplings.

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

Anomalous $WW\gamma\gamma$ couplings are parametrised by dimensionless parameters a_0^W and a_C^W, and anomalous $ZZ\gamma\gamma$ couplings by a_0^Z and a_C^Z. We studied the effect of each of these parameters independently, varying only one while the other ones were set to their Standard Model value: 0.

The second Lagrangian, corresponding to triple couplings, reads:

$$\mathcal{L}/ig_{WW\gamma} = \left(W^\dagger_{\mu\nu}W^\mu A^\nu - W_{\mu\nu}W^{\dagger\mu}A^\nu\right) + (1+\Delta\kappa^\gamma)\,W^\dagger_\mu W_\nu A^{\mu\nu}. + \frac{\lambda^\gamma}{M_W^2}W^\dagger_{\rho\mu}W^\mu_\nu A^{\nu\rho}$$

Similarly, the parameters λ^γ and $\Delta\kappa^\gamma$ are 0 in the Standard Model, and were studied independently. See [1] for a study of these couplings at the LHC.

2.3 Signal and backgrounds

The signal we study is characterised by two high-p_T leptons reconstructed in the central detector, and the absence of any other reconstructed object or energy flow. We have a very clear signature for the signal and we can easily reject potential inclusive backgrounds, such as inclusive W pair production. Of course, this is only true at low luminosity: otherwise, electronic pile-up and multiple interactions will add additional activity in the central detector.

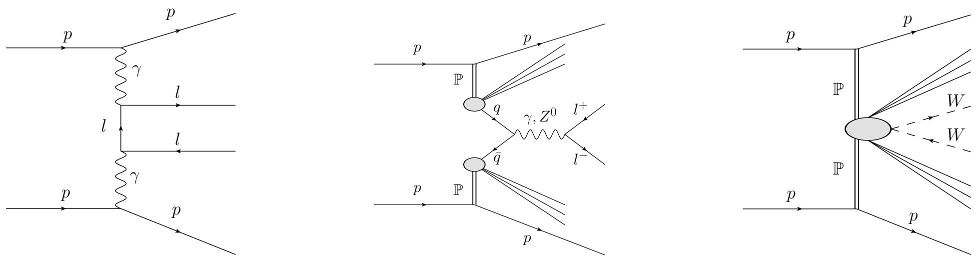

Figure 2: Feynman diagrams for the different background processes.

The backgrounds taken into account for this study are the following (see diagrams on Figure 2):

Non-diffractive W pairs: completely suppressed by requiring two rapidity gaps (regions of the detector devoid of energy) and at most two tracks (not shown).

Dilepton production through photon exchange: suppressed by asking at least one lepton with $p_T > 160\,\text{GeV}$ and missing transverse energy $> 20\,\text{GeV}$.

Dilepton production through pomeron exchange: suppressed by the same cuts as above and by the cut on the number of tracks.

W **pair through pomeron exchange:** low background, mainly suppressed by the cut on tracks.

All those processes (except inclusive production of W pairs) were generated using Forward Physics Monte Carlo (FPMC) [2], a generator based on Herwig, dedicated to the study of forward physics processes. The matrix elements were generated with CompHEP [3]. The events were then reconstructed with ATLFast++ [4], a ROOT standalone package that performs a fast simulation of the ATLAS detector in a parametrised way.

3 Sensitivity using low integrated luminosity at the LHC

In this part, we studied the expected sensitivity on anomalous couplings with a low integrated luminosity at the LHC ($10-100\,\text{pb}^{-1}$ depending on the LHC running scenario), without pile-up and with proton-proton collisions at $\sqrt{s} = 10\,\text{TeV}$.

3.1 Event Selection

The event selection is as follows:

2 reconstructed leptons with $p_T > 10\,\text{GeV}$ where a 'reconstructed lepton' is an electron or a muon. Tau lepton reconstruction was not taken into account: therefore final states involving a tau lepton are kept if the tau decayed leptonically, but not if the tau decayed hadronically.

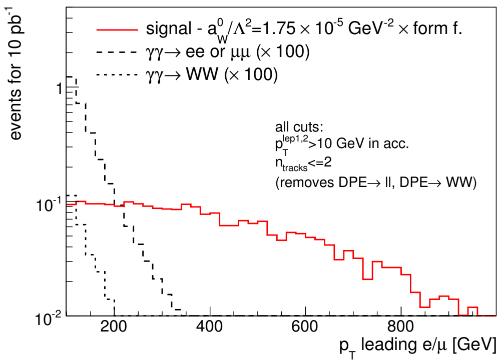

Figure 3: Leading lepton p_T spectrum of the signal and different backgrounds, after all cuts.

Exclusivity In practise, we required that the event does not contain any other reconstructed object than the two reconstructed leptons. This means at most two tracks, no unused calorimeter cluster, and no other reconstructed object (muon, electron, jet or photon). With real data, one would also have to ask for two rapidity gaps[1], one on each side of the detector. This exclusivity requirement is important to reject non-diffractive events, whose production cross section is much higher but in which the proton remnants lead to a large energy flow in the forward region. It also allows to reject processes involving double pomeron exchange, in which the pomeron remnants lead to additional energy flow and higher number of tracks.

1 lepton with $p_T > 160\,\text{GeV}$ With this requirement, we suppress most of the dilepton background. Indeed, this background produces mostly low-p_T leptons, whereas our signal produces much higher p_T leptons, especially with anomalous couplings which mostly enhance the cross section at high $M_{\gamma\gamma}$.

Missing transverse energy $> 20\,\text{GeV}$ This cut further suppresses the dilepton background. The final state for the signal is two leptons and two neutrinos, which leads to a much higher MET than the dilepton background, which does not produce any neutrino (except in the case of a tau decay, but the corresponding cross section is low).

Such event selection has a moderate effect on the signal, and it cuts almost all the background (see Figure 3). The main background, as seen on this plot, is two-photon dilepton production.

3.2 Results

The expected results are presented in Table 1. We see that we can gain a factor 1 000 with respect to the current limits from the OPAL collaboration [5] from as little as $10\,\text{pb}^{-1}$ of data. No similar study has been performed so far at the Tevatron, but the expected sensitivity would be one order of magnitude better than the present LEP limits.

[1] A rapidity gap is a section of the detector, in pseudo-rapidity η, with no deposited energy (with respect to the expected noise). The detailed study of rapidity gaps requires the use of the full detector simulation and is not possible with fast simulation. Nevertheless it is reasonable to assume that the rapidity gap requirement suppresses all of the inclusive background but keeps all of the signal.

Couplings	OPAL limits [GeV^{-2}]	Limits @ 10 TeV [GeV^{-2}] $\mathcal{L} = 10\,\mathrm{pb}^{-1}$	Limits @ 10 TeV [GeV^{-2}] $\mathcal{L} = 100\,\mathrm{pb}^{-1}$	Limit @ 2 TeV [GeV^{-2}] $\mathcal{L} = 100\,\mathrm{pb}^{-1}$
a_0^W/Λ^2	[-0.020, 0.020]	1.41×10^{-5}	4.52×10^{-6}	7×10^{-4}
a_C^W/Λ^2	[-0.052, 0.037]	5.44×10^{-5}	1.68×10^{-5}	2.6×10^{-3}
a_0^Z/Λ^2	[-0.007, 0.023]	1.05×10^{-4}	3.30×10^{-5}	4.25×10^{-3}
a_C^Z/Λ^2	[-0.029, 0.029]	4.54×10^{-4}	1.23×10^{-4}	1.5×10^{-2}

Table 1: Sensitivity at low luminosity

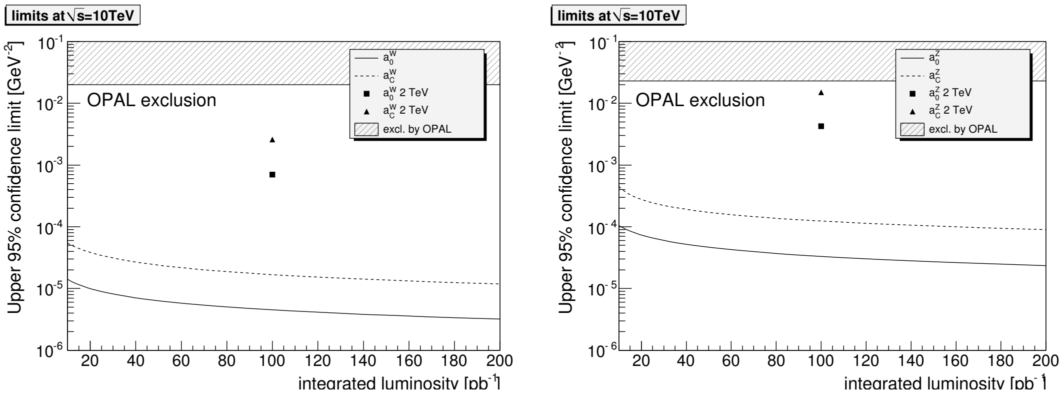

Figure 4: Upper 95% C.L. confidence limits on a_0^W and a_C^W (*left*) and a_0^Z and a_C^Z (*right*). The exclusion from the OPAL collaboration and the estimated limits at 2 TeV are also represented.

NB: the effective Lagrangians as such violate the unitarity at high energy. If we introduce a form-factor ($a \to \frac{a}{1+W_{\gamma\gamma}^2/\Lambda^2}$ where we set $\Lambda = 2\,\mathrm{TeV}$) the actual limits are about 5-6 times worse.

We also studied anomalous $\gamma\gamma ZZ$ couplings (see results in Table 1), which were also implemented in our model. The analysis is much simpler in this case, since the corresponding process ($pp \to ppZZ$ through photon exchange) is forbidden in the Standard Model. The gain of sensitivity is this time of 2 orders of magnitude on the sensitivity from the OPAL collaboration.

Once again, we limit ourselves to the pure leptonic channel, with both Zs decaying to two leptons. To select the events, we required at least 3 reconstructed leptons (or at least 2 of the same generation and sign, e.g. $\mu^+\mu^+$) with $p_T > 10\,\mathrm{GeV}$, at most 4 tracks, and no reconstructed jet.

4 Sensitivity using high integrated luminosity at the LHC

This part of the study, now assuming collisions at 14 TeV, comprises high luminosity runs, with multiple interactions per bunch crossing and pile-up. These will spoil the rapidity gaps on which we relied at low luminosity, and we can no longer use them.

Nevertheless, we use the forward detectors to select the exclusive events with forward protons in the final state. They are currently under development by the AFP collaboration [8], foreseen to be installed at 220 and 420 meters on both sides of the CMS and/or ATLAS detectors. These detectors, installed in the LHC tunnel very close to the beam, will detect diffracted protons with an acceptance on the momentum fraction loss of the proton of $0.0015 < \xi < 0.15$.

To reject the inclusive background, we now ask for two deflected protons to be tagged in those detectors. In practice, it will be necessary to check that these tagged protons come from the main vertex, which will actually be possible with the picosecond time of flight detectors enabling to associate the tagged proton with a vertex in the central detector.

Other changes in the cuts are necessary, mainly because we suppose now a higher integrated luminosity (at least a few tens of fb^{-1}). Therefore we are sensitive to smaller values of the anomalous parameters, but we have more background events.

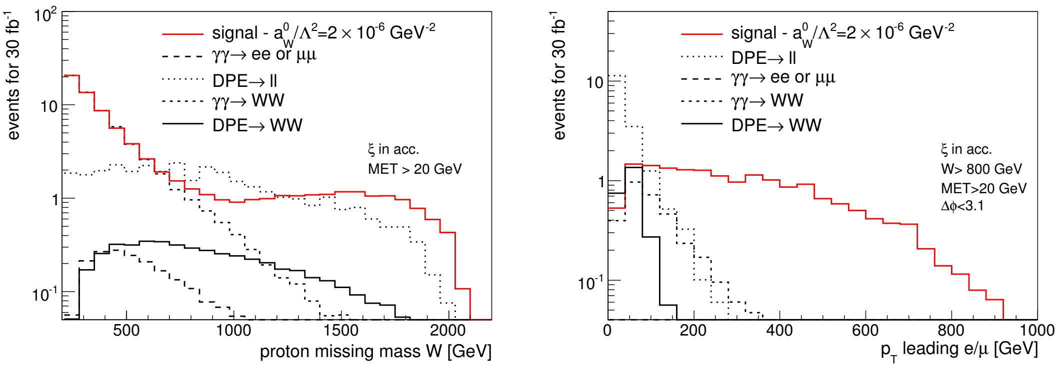

Figure 5: *Left:* W distribution for signal and background. *Right:* p_T distribution of the leading lepton.

The new event selection, motivated by the higher luminosity and the pile-up background, is as follows:

2 reconstructed leptons with $p_T > 10\,\text{GeV}$;

2 tagged protons $(0.0015 < \xi_{1,2} < 0.15)$**, coming from the same vertex** ;

1 lepton with $p_T > 160\,\text{GeV}$;

Missing mass $M_{\gamma\gamma} = \sqrt{s\xi_1\xi_2} > 800\,\text{GeV}$ (This cut enhances the signal / noise ratio, because anomalous couplings only enhance the cross section at high missing mass, as we can see on the left plot of Figure 5.);

Angle difference between the two leptons $\Delta\phi < 3.13$ (This further suppresses the dilepton background (especially from $\gamma\gamma$ interaction), for which the leptons are emitted back-to-back.);

Missing transverse energy $> 20\,\text{GeV}$.

The main remaining backgrounds after these cuts are the double pomeron exchange dilepton production, and the standard model two-photon W pair production, as seen on the right plot of Figure 5.

The expected limits in this scenario are presented in Table 2. We see that we gain an additional factor about 10 with respect to the limits presented in Table 1. The form-factor introduced in Section 3.2 has a smaller impact here, it changes the limits by about a factor 2.

Couplings	Limits from LEP $[\mathrm{GeV}^{-2}]$	Limits @ 14 TeV $\mathcal{L} = 30\,\mathrm{fb}^{-1}$	$\mathcal{L} = 200\,\mathrm{fb}^{-1}$
a_0^W/Λ^2	$[-0.020, 0.020]$	$2.3 \times 10^{-6}\,\mathrm{GeV}^{-2}$	$1.5 \times 10^{-6}\,\mathrm{GeV}^{-2}$
a_C^W/Λ^2	$[-0.052, 0.037]$	$8.7 \times 10^{-6}\,\mathrm{GeV}^{-2}$	$5.5 \times 10^{-6}\,\mathrm{GeV}^{-2}$
λ^γ	[-0.098, 0.101]	[-0.033,0.026]	[-0.024,0.017]
$\Delta\kappa^\gamma$	[-0.044, 0.047]	[-0.034,0.029]	[-0.013,0.012]

Table 2: Sensitivity at high luminosity

5 Conclusion

We studied anomalous $WW\gamma$, $WW\gamma\gamma$ and $ZZ\gamma\gamma$ couplings, considering not only the photon-induced backgrounds but also double pomeron exchange ones, and we found that dilepton production through double pomeron exchange is one of the dominant backgrounds to this study.

With that, we showed that even with only $10\,\mathrm{pb}^{-1}$ of data at the LHC, we can set limits more than 2 orders of magnitude better (form-factor taken into account) than the ones from the OPAL collaboration. With $30\,\mathrm{fb}^{-1}$, and thanks to the AFP proton taggers, we can even reach an additional factor 10 of improvement, leading to a total improvement by factor of 10 000 for $WW\gamma\gamma$ couplings and 1 000 for $ZZ\gamma\gamma$ couplings.

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