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Anomalous quartic $\gamma\gamma\gamma\gamma$ coupling studies using proton tagging at the LHC

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We describe the sensituvity to anomalous $\gamma\gamma\gamma\gamma$ couplings at the LHC using proton tagging and we show that LHC data can be sensitive to anomalous coupling values predicted by extra-dimension and composite Higgs models. Tagging intact protons in the final state ensures that one selects a background free sample produced by γ exchanges only.

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We describe briefly the search for $\gamma\gamma\gamma\gamma$ quartic anomalous couplings using proton tagging at the LHC that regained interest after the excess observed in diphoton production by the CMS and ATLAS experiments [1, 2] (we will not mention here the search for $WW\gamma\gamma$ and $ZZ\gamma\gamma$ couplings is given in [3]).

1. Standard Model exclusive $\gamma\gamma$ production at the LHC: Photon and gluon induced processes

In Fig. 1, we show the leading processes leading to two photons and two intact protons in the final state. The first diagram (Fig. 1, left) corresponds to exclusive QCD diphoton production via gluon exchanges (the second gluon ensures that the exchange is colorless leading to intact protons in the final state) and the second one (Fig. 1, right) via photon exchanges. It is worth noticing that quark, lepton and W loops need to be considered in order to get the correct SM cross section for diphoton production [4, 1, 5] as shown in Fig 2. The QCD induced processes from the Khoze Martin Ryskin model [6] are dominant at low masses whereas the photon induced ones (QED processes) dominate at higher diphoton masses [4]. This is the first time that we put all terms inside a MC generator, FPMC [7].

The first conclusion of our study is that, if we observe high mass diphoton production at the LHC with two intact protons, we are certain that this is a QED process (at high mass, the QCD production is negligible).

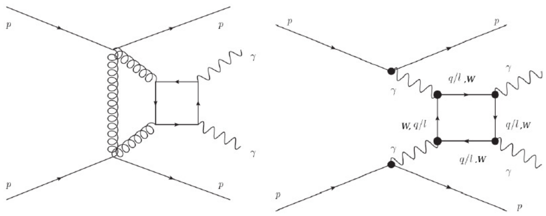

Figure 1: Exclusive diphoton productions - QCD (left) and QED processes (right)

2. Theoretical motivations for anomalous coupling studies

Four-photon (4γ) interactions through diphoton production via photon fusion with intact outgoing protons are considered. The pure photon dimension-eight operators read

$$\mathcal{L}_{4\gamma} = \zeta_1^{\gamma} F_{\mu\nu}F^{\mu\nu}F_{\rho\sigma}F^{\rho\sigma} + \zeta_2^{\gamma} F_{\mu\nu}F^{\nu\rho}F_{\rho\lambda}F^{\lambda\mu} \tag{2.1}$$

and they can induce the $\gamma\gamma\gamma\gamma$ process, highly suppressed in the SM [4]. We discuss here possible new physics contributions to $\zeta_{1,2}^{\gamma}$ that can be probed and discovered at the LHC using the forward proton detectors.

Loops of heavy charged particles contribute to the 4γ couplings [4] as $\zeta_i^{\gamma} = \alpha_{\rm em}^2 Q^4 m^{-4} N c_{i,s}$, where $c_{1,s}$ is related to the spin of the heavy particle of mass m running in the loop and Q its

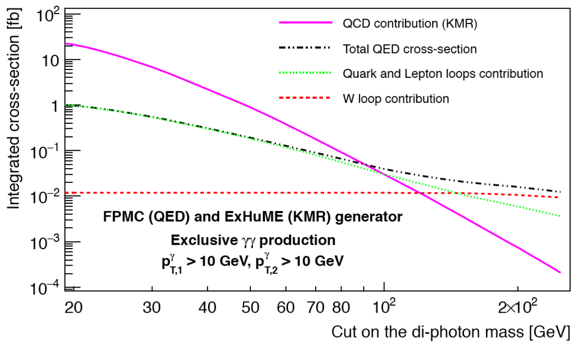

Figure 2: Diphoton production cross section as a function of the diphoton mass requesting two intact protons in the final state and the photons to have a transverse momentum larger than 10 GeV. The QCD exclusive processes (Khoze Martin Ryskin) in full line dominate at low masses while QED diphoton production dominates at higher masses (dashed lines). The QED production corresponds to diphoton production via lepton/fermion loops (dotted line) and W boson loops (dashed-dotted line).

electric charge. These couplings scale as $\sim Q^4$ and are enhanced in presence of particles with large charges. For a 500 GeV vector (fermion) resonance with $Q = 3$ (4), large couplings ζ_i^γ of the order of $10^{-13} - 10^{-14}$ Gev^{-4} can be reached.

Beyond perturbative contributions to ζ_i^γ from charged particles, non-renormalizable interactions of neutral particles are also present in common extensions of the SM. Such theories can contain scalar, pseudo-scalar and spin-2 resonances that couple to the photon and generate the 4γ couplings by tree-level exchange as $\zeta_i^\gamma = (f_s m)^{-2} d_{i,s}$, where $d_{1,s}$ is related to the spin of the particle.

When one is able to detect both the intact protons and the photons in CMS or ATLAS, one reaches unprecedented precision on quartic $\gamma\gamma\gamma\gamma$ anomalous couplings reaching the values predicted by sone extra-dimension or composite Higgs models as we will see in the following.

3. Experimental sensitivity to quartic four photon couplings

The $\gamma\gamma\gamma\gamma$ process can be probed via the detection of two intact protons in the forward proton detectors and two energetic photons in the corresponding electromagnetic calorimeters. In the following, we assume the intact protons to be detected in the proton detectors installed by the CMS-TOTEM Precision Proton Spectrometers (CT-PPS) or ATLAS Forward Physics detectors (AFP). The acceptance of those detectors range from a diffractive mass of about 0.4 to 1.6 TeV.

The photon identification efficiency is expected to be around 75% for $p_T > 100$ GeV, with jet rejection factors exceeding 4000 even at high pile-up (>100). In addition, about 1% of the electrons are mis-identified as photons. These numbers are used in the phenomenological study presented below.

The anomalous $\gamma\gamma\gamma\gamma$ process has been implemented in the Forward Physics Monte Carlo (FPMC) generator [7]. The FPMC generator was also used to simulate the background processes giving rise to two intact protons accompanied by two photons, electrons or jets that can mimic the photon signal. Those include exclusive SM production of $\gamma\gamma\gamma\gamma$ via lepton and quark boxes

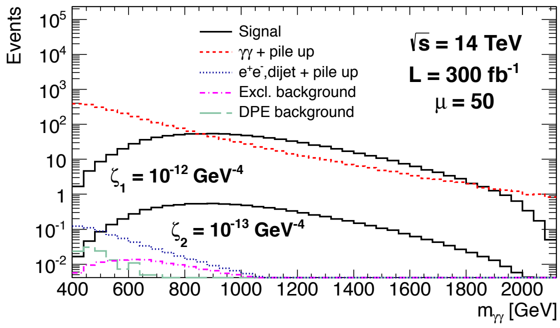

Figure 3: Diphoton invariant mass distribution for the signal ($\zeta_1 = 10^{-12},\ 10^{-13}$ Gev^{-4}) and for the backgrounds (dominated by $\gamma\gamma$ with protons from pile-up), requesting two protons in the forward detectors and two photons of $p_T > 50$ GeV with at least one converted photon in the central detector, for a luminosity of 300 fb^{-1} and an average pile-up of $\mu = 50$.

Cut / Process	Signal (full)	Signal with/without f.f. (EFT)	Excl.	DPE	DY dijet+ pile up	$\gamma\gamma$+ pile up
$[0.015 < \xi_{1,2} < 0.15$, $p_{\mathrm{T1,(2)}} > 200$ (100) GeV]	65.	18. (187.)	0.13	0.2	1.6	2968
$m_{\gamma\gamma} > 600$ GeV	64.	17. (186.)	0.10	0	0.2	1023
$[p_{\mathrm{T2}}/p_{\mathrm{T1}} > 0.95$, $\lvert\Delta\phi\rvert > \pi - 0.01]$	64.	17. (186.)	0.10	0	0	80.2
$\sqrt{\xi_1\xi_2 s} = m_{\gamma\gamma} \pm 3\%$	61.	12. (175.)	0.09	0	0	2.8
$\lvert y_{\gamma\gamma} - y_{pp}\rvert < 0.03$	60.	16. (169.)	0.09	0	0	0

Table 1: Number of signal for $Q_{\mathrm{eff}} = 4$, $m = 340$ GeV and background events after various selections for an integrated luminosity of 300 fb^{-1} and $\mu = 50$ at $\sqrt{s} = 14$ TeV. Values obtained using the corresponding EFT couplings with and without form factors are also displayed. Excl. stands for exclusive backgrounds and DPE for double pomeron exchange backgrounds.

and $\gamma\gamma \to e^+e^-$. This series of backgrounds is called "Exclusive" in Table 1. FPMC was also used to produce $\gamma\gamma$, Higgs to $\gamma\gamma$ and dijet productions via double pomeron exchange (called DPE background in Table 1 and Fig. 4). Such backgrounds tend to be softer than the signal and can be suppressed with requirements on the transverse momenta of the photons and the diphoton invariant mass. In addition, the final-state photons of the signal are typically back-to-back and have about the same transverse momenta. Requiring a large azimuthal angle $|\Delta\phi| > \pi - 0.01$ between the two photons and a ratio $p_{T,2}/p_{T,1} > 0.95$ greatly reduces the contribution of non-exclusive processes.

Additional background processes include the quark and gluon-initiated production of two photons, two jets and Drell-Yan processes leading to two electrons. The two intact protons arise from pile-up interactions (these backgrounds are called $\gamma\gamma$ + pile-up and DY, dijet + pile-up in Table 1). In Fig. 3 we show the diphoton mass distribution for the signal for two different values of anomalous couplings and the different backgrounds. For a diphoton mass above 600 GeV, all standard model backgrounds are negligible and only the non-diffractive diphoton background with two protons originating from pile up remains.

The pile-up background is further suppressed by requiring the proton missing invariant mass to match the diphoton invariant mass within the expected resolution and the diphoton system rapidity and the rapidity of the two protons to be similar, as illustrated in Fig. 4. This is due to the fact that the diphoton system is not related to the diproton one for pile up events.

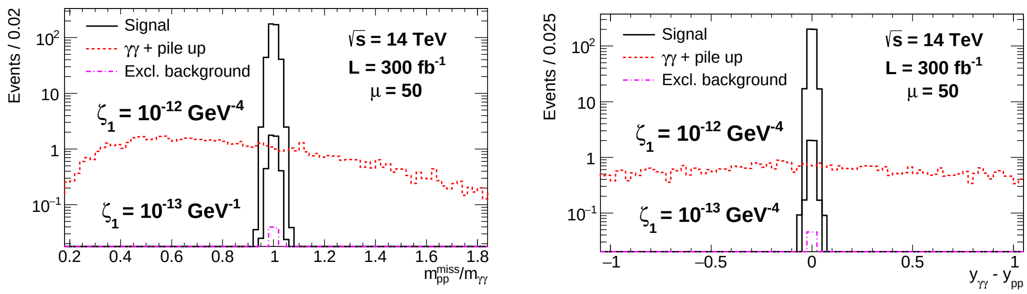

Figure 4: Diphoton to missing proton mass ratio (left) and rapidity difference (right) distributions for signal and backgrounds.

The number of expected signal and background events passing respective selections is shown in Table 1 for an integrated luminosity of 300 fb^{-1} for a center-of-mass energy of 14 TeV. Exploiting the full event kinematics with the forward proton detectors allows to completely suppress the background with a signal selection efficiency after the acceptance cuts exceeding 70%. Tagging the protons is absolutely needed to suppress the $\gamma\gamma$ + pile-up events. Further background reduction is even possible by requiring the photons and the protons to originate from the same vertex that provides an additional rejection factor of 40 for 50 pile-up interactions, showing the large margin on the background suppression. A similar study at a higher pile-up of 200 was performed and led to a very small background. The sensitivity extends up to $7 \cdot 10^{-15}$ GeV^{-4} allowing us to probe further the models of new physics described above, as shown in Table 3. This is the second conclusion of our study: if we observe a high mass diphoton togeeher with two intact protons, it can only be a beyond standard model event since the background is completely suppressed.

Let us now comment briefly about the diphoton excess that was observed in 2015 by the ATLAS and CMS collaborations [2] but which was not confirmed by new data shown in 2016 at ICHEP [8]. It is clear that a resonance decaying into two photons is now disfavoredand the 2015 result was interpreted as a statistical fluctuation. However, there could still be some anomalous diphoton production at high diphoton masses. Without detecting intact protons in the final state, it would be very difficult to analyze such events since they appear as a threshold effect in diphoton production [1]. This potential effect might be included while fitting the background. On the contrary, tagging protons in the final state together with the photons allows to get a background free sample and thus to probe anomalous production with high precision.

We also performed a full amplitude calculation in Ref. [4, 1] that avoids the dependence on the choice of form factors needed in order to avoid quadratic divergences of scattering amplitudes.

[1]Note thst this effect might appear as a local statistical fluctation as observed in 2015 since we are dealing with very small statitsics.

Luminosity	300 fb^{-1}	300 fb^{-1}	300 fb^{-1}	300 fb^{-1}	3000 fb^{-1}
pile up (μ)	50	50	50	50	200
coupling (GeV^{-4})	$\geq$ 1 conv. γ 5 σ	$\geq$ 1 conv. γ 95% CL	all γ 5 σ	all γ 95% CL	all γ 95% CL
ζ_1 f.f.	$1.5 \cdot 10^{-13}$	$7.5 \cdot 10^{-14}$	$6 \cdot 10^{-14}$	$4 \cdot 10^{-14}$	$3.5 \cdot 10^{-14}$
ζ_1 no f.f.	$3.5 \cdot 10^{-14}$	$2.5 \cdot 10^{-14}$	$2 \cdot 10^{-14}$	$1 \cdot 10^{-14}$	$1 \cdot 10^{-14}$
ζ_2 f.f.	$2.5 \cdot 10^{-13}$	$1.5 \cdot 10^{-13}$	$1.5 \cdot 10^{-13}$	$8.5 \cdot 10^{-14}$	$7 \cdot 10^{-14}$
ζ_2 no f.f.	$7.5 \cdot 10^{-14}$	$4.5 \cdot 10^{-14}$	$4 \cdot 10^{-14}$	$2.5 \cdot 10^{-14}$	$2.5 \cdot 10^{-14}$

Table 2: 5 σ discovery and 95% CL exclusion limits on ζ_1 and ζ_2 couplings in GeV^{-4} with and without form factor (f.f.), requesting at least one converted photon ($\geq$ 1 conv. γ) or not (all γ). All sensitivities are given for 300 fb^{-1} and $\mu = 50$ pile up events (medium luminosity LHC) except for the numbers of the last column which are given for 3000 fb^{-1} and $\mu = 200$ pile up events (high luminosity LHC).

Sensitivities were found to be similar leading to possible discoveries of vector or fermions at high masses and high effective charges.

Let us now conclude by stressing the advantages of detecting two photons and two protons in the final state:

- This process is photon-induced (the QCD contribution being very small)
- This process is due to beyond standard model physics at high mass (we have zero background after selection.

In addition, many other channels can be studied using two tagged protons in addition to $\gamma\gamma$ in the final state: ZZ, WW, $Z\gamma$, dijet... The advantage of tagging the protons in the final state is that we have a background free sample at high mass whatever the produced object (one can look for instance at more complicated channels such as $\gamma\gamma$, $\gamma\gamma ll$, $\gamma\gamma jet\,jet$, etc.

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