Anomalous gauge interactions in photon collisions at the LHC and the FCC

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Abstract

The forward proton detectors recently installed and operating at the LHC open the possibility to observe photon collisions with high precision, providing a novel window on physics beyond the Standard Model. We review recent simulations and theoretical developments about the measurement of anomalous $\gamma\gamma\gamma\gamma$ and $Z\gamma\gamma\gamma$ interactions. The searches for these anomalous gauge interactions are expected to set bounds on a wide range of particles including generic electroweak particles, neutral particles with dimension-5 coupling to gauge bosons, polarizable dark particles, and are typically complementary from new physics searches in other channels.

Keywords

CERN report; photon collisions, anomalous gauge couplings

1   Forward proton detectors and photon collisions

The new forward detectors have been installed at both ATLAS (ATLAS Forward Proton detector [1]) and CMS (CT-PPS detector [2]) and have started to take data since the 2017 run. The purpose of these detectors is to measure intact protons arising from diffractive processes at small angle, giving access to the so-called central exclusive processes

$$pp \rightarrow p \oplus X \oplus p\,, \tag{1}$$

where the $\oplus$ denote gaps with no hadronic or electromagnetic activity between the central system X and the outgoing protons, see Fig. 1. These central exclusive processes can potentially provide a new window on physics beyond the Standard Model (SM) at the LHC. The special role of the forward detectors is to characterize the outgoing intact protons, hereby giving access to the complete kinematics of the event. Such information can then be used to drastically reduce the backgrounds.

The forward detectors are installed at ~ 200 m on both sides of CMS and ATLAS and host tracking stations. Their acceptance in the fractional momentum loss of the intact protons ξ is approximately $0.015 < \xi < 0.15$ at the nominal accelerator magnetic lattice and beam conditions, which corresponds to an acceptance of 300 to 1900 GeV in the invariant mass of the central system for the nominal LHC beam optics when both protons stay intact. The CMS and TOTEM collaborations presented the first results of said system at the LHC by measuring the central semi-exclusive production of high-mass muon pairs at 13 TeV with an integrated luminosity of 10 fb^{-}1 collected in high-luminosity fills [3], which proves the feasibility of the search for New Physics in the exclusive channel. Timing detectors are scheduled to be installed in both CT-PPS and ATLAS to measure the protons time-of-flight of protons with an expected precision of ~ 15 ps, which would allow to determine the primary vertex with a ~ 1 mm precision [4]. Timing detectors will not be used in the estimations presented today, however they
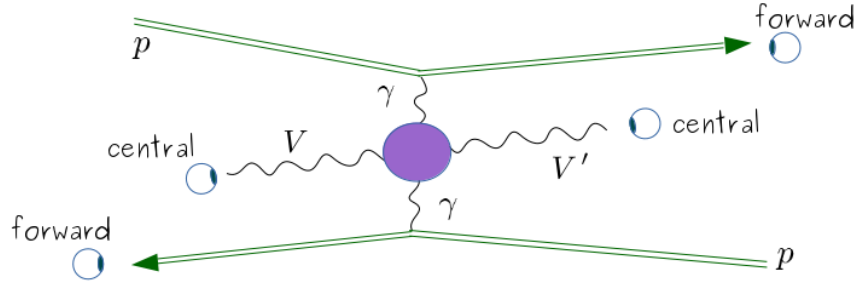
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Fig. 1: Central exclusive photon collision with gauge boson final states. The protons remain intact and are seen by the forward detectors. The outgoing gauge bosons have high p_T and are seen in the central detectors.

are absolutely necessary for final states with missing transverse energy (for example, W^+W^- in the leptonic channel).

Central exclusive processes with intermediate photons – *i.e.* photon collisions – are especially interesting as the equivalent photon flux from the protons is large and well understood. In terms of an effective theory description of the new physics effects, one can for instance test operators like $|H|^2 F_{\mu\nu} F^{\mu\nu}/\Lambda^2$ which induce anomalous single or double Higgs production (for the MSSM case, see [5,6]). Our focus is on quartic gauge couplings, which leads to diboson final states as shown in Fig. 1. Such self-interactions of neutral gauge bosons are particularly appealing to search for new physics, because the SM irreducible background is small. The neutral quartic gauge interactions constitute smoking gun observables for new physics. Studies using proton-tagging at the LHC for new physics searches can be found in [7–24].

2 Searching for anomalous $\gamma\gamma\gamma\gamma$ and $Z\gamma\gamma\gamma$ interactions

Given the promising possibilities of forward detectors, realistic simulations of the search for $\gamma\gamma \to \gamma\gamma$, $\gamma\gamma \to Z\gamma$ have been carried out in [15,21,25]. The search for light-by-light scattering at the LHC without proton tagging has been first thoroughly analyzed in [26]. Let us review the setup, the backgrounds and the event selection for $\gamma\gamma$ and $Z\gamma$ final states.

The Forward Physics Monte Carlo generator (FPMC, [27]) is designed to produce within a same framework the double pomeron exchange (DPE), single diffractive, exclusive diffractive and photon-induced processes. The emission of photons by protons is correctly described by the Budnev flux [28,29], which takes into account the proton electromagnetic structure. The SM $\gamma\gamma \to \gamma\gamma$ process induced by loops of SM fermions and W boson, the exact contributions from new particles with arbitrary charge and mass, and the anomalous vertices described by the effective operators of Eq. (3) have been implemented into FPMC.

The main background for the signals $\gamma\gamma \to \gamma\gamma, Z(ll, jj)\gamma$ is the detection of central final states (including misidentified jet or electrons) originating from a non-exclusive process, occurring *simultaneously* with the forward detection of two protons from pile-up. The probability to detect at least one proton in each of the forward detectors is estimated to be 32%, 66% and 93% for 50, 100 and 200 additional interactions respectively. Other backgrounds include double Pomeron exchange and central exclusive QCD production.

The knowledge of the full event kinematics is a powerful constraint to reject the huge background from pile-up. The key requirements consist in matching the missing momentum (rapidity difference) of the di-proton system with the invariant mass (rapidity difference) of the central system ($XY \equiv \gamma\gamma, (jj)\gamma$, $(\ell\bar{\ell})\gamma$), with $m_{XY}/m_{pp} < 5 - 10\%$ and $|y_{XY} - y_{pp}| < 3 - 10\%$ depending on the channel. Extra cuts rely on the event topology, using the fact that the XY states are typically back-to-back with similar p_T.

Table 1: $5\,\sigma$ sensitivity to the effective quartic gauge couplings of Eq. (3) in GeV^{-4}.

Assumptions	$\gamma\gamma$ final state	γjj, γll final state
13 TeV, 300 fb^{-1}, $\mu = 50$	$\zeta^\gamma(\tilde{\zeta}^\gamma) < 9 \cdot 10^{-15}$	$\zeta^{\gamma Z}(\tilde{\zeta}^{\gamma Z}) < 1.9 \cdot 10^{-13}\ [\gamma jj + \gamma ll]$ $\zeta^{\gamma Z}(\tilde{\zeta}^{\gamma Z}) < 2.8 \cdot 10^{-13}\ [\gamma ll]$ $\zeta^{\gamma Z}(\tilde{\zeta}^{\gamma Z}) < 2.3 \cdot 10^{-13}\ [\gamma jj]$
13 TeV, 3000 fb^{-1}, $\mu = 200$	$\zeta^\gamma(\tilde{\zeta}^\gamma) < 1 \cdot 10^{-14}$	$\zeta^{\gamma Z}(\tilde{\zeta}^{\gamma Z}) < 1.8 \cdot 10^{-13}\ [\gamma ll]$
100 TeV, 3000 fb^{-1}, $\mu = 200$	$\zeta^\gamma(\tilde{\zeta}^\gamma) < 1.1 \cdot 10^{-16}$	
100 TeV, 3000 fb^{-1}, $\mu = 1000$	$\zeta^\gamma(\tilde{\zeta}^\gamma) < 2 \cdot 10^{-16}$	

This translates to cuts of the form $|\Delta\phi_{X,Y} - \pi| < 0.02$, $p_{TX}/p_{TY} > 0.90 - 0.95$. The signal is harder than the background hence one cuts on the invariant mass typically as $m_{XY} > 600 - 700$ GeV. Further background reduction could be possible by measuring the protons time-of-flight, which would allow to constrain the event vertex.

3 Sensitivity to heavy new particles at LHC and FCC

In a scenario where new particles are too heavy to be produced on-shell at the collider, the presence of these new states is best studied using effective field theory methods. The low-energy effects of the new particles are parametrized by higher dimensional operators made of SM fields. For the quartic gauge interactions of our interest we use the basis of operators

$$\begin{aligned}
\mathcal{L}_{4\gamma} &= \zeta^\gamma F_{\mu\nu}F^{\mu\nu}F_{\rho\sigma}F^{\rho\sigma} + \tilde{\zeta}^\gamma F_{\mu\nu}\tilde{F}^{\mu\nu}F_{\rho\sigma}\tilde{F}^{\rho\sigma} \\
\mathcal{L}_{3\gamma Z} &= \zeta^{\gamma Z} F_{\mu\nu}F^{\mu\nu}F_{\rho\sigma}Z^{\rho\sigma} + \tilde{\zeta}^{\gamma Z} F_{\mu\nu}\tilde{F}^{\mu\nu}F_{\rho\sigma}\tilde{Z}^{\rho\sigma} \,.
\end{aligned} \tag{2}$$

Other operators like $\mathcal{O}_2^\gamma = F_{\mu\nu}F^{\nu\rho}F_{\rho\sigma}F^{\sigma\mu}$ are sometimes used. They are linearly dependent of the ones above, with $4\mathcal{O}_2 = 2\mathcal{O} + \tilde{\mathcal{O}}$.

These expected sensitivities are given in Table 1 for different scenarios corresponding to medium luminosity (300 fb^{-1}) and to high luminosity (3000 fb^{-1}) at the LHC. The background being small, statistical significance grows quickly with the event number. Typically $O(10)$ events are enough to reach 5σ significance. We also provide an estimation for FCC with proton collisions, assuming 3000 fb^{-1} and average pile-up of $\mu = 200 - 1000$. We assume the forward proton detectors properties at FCC to be similar to those at the LHC, including the acceptance range.

The ATLAS Collaboration has set a bound on the $Z \to \gamma\gamma\gamma$ decay of $\mathcal{B}(Z \to \gamma\gamma\gamma) < 2.2 \cdot 10^{-6}$ [30], beating the ones from LEP. This bound translates as a limit [25]

$$\sqrt{\zeta^2 + \tilde{\zeta}^2 - \frac{\zeta\tilde{\zeta}}{2}} < 1.3 \cdot 10^{-9}\ \text{GeV}^{-4}\ (95\%\text{CL}) \,. \tag{3}$$

Imagining the same search is done at 13 TeV data with 300 fb^{-1} in the same conditions, we expect very roughly an improvement by an order of magnitude of the bound of Eq. 3. In addition, the current number of pile-up interactions at 13 TeV sets a challenge to the measurement of 3γ final states. This remains far away from the expected sensitivities obtained from photon collisions at the same luminosity by roughly three orders of magnitudes.

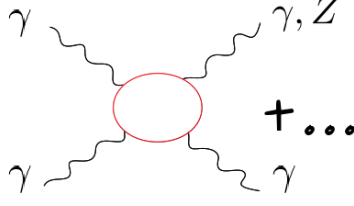## 4   Sensitivity to new electroweak particles

Fig. 2: A loop of electroweak particles inducing a quartic gauge interaction.

New EW charged particles contribute to anomalous gauge couplings at one-loop (Fig. 2). Because of gauge invariance, these contributions can be parametrized in terms of the mass and quantum numbers of the new particle [14]. Using the heat kernel calculation of [14], we obtain the effective couplings

$$\left(\zeta^{\gamma Z}, \tilde{\zeta}^{\gamma Z}\right) = \left(c_s, \tilde{c}_s\right) \frac{\alpha_{\rm em}^2}{s_w c_w m^4} N d \left(c_w^2 \frac{3d^4 - 10d^2 + 7}{240} + (c_w^2 - s_w^2)\frac{(d^2-1)Y^2}{4} - s_w^2 Y^4 \right)$$

$$\equiv \left(c_s, \tilde{c}_s\right) \frac{\alpha_{\rm em}^2}{s_w c_w m^4} \frac{Q_{\rm eff}^4}{4}, \tag{4}$$

$$\left(\zeta^{\gamma}, \tilde{\zeta}^{\gamma}\right) = \left(c_s, \tilde{c}_s\right) \frac{\alpha_{\rm em}^2}{m^4} N d \left(\frac{3d^4 - 10d^2 + 7}{960} + \frac{(d^2-1)Y^2}{8} + \frac{Y^4}{4} \right). \tag{5}$$

We have evaluated the sensitivities using the exact amplitudes. For example, the sensitivity for the case of a charged vector is shown in Fig. 3 for a luminosity of 300 fb^{-1} and $\mu = 50$.

Certain candidates like the typical vector-like quarks arising in Composite Higgs models are already excluded by stronger bounds. On the other hand, our expected bounds from photon collisions are completely model-independent. They apply to any quantum number, are independent of the amount of mixing with the SM quarks, and even apply to vector-like leptons.
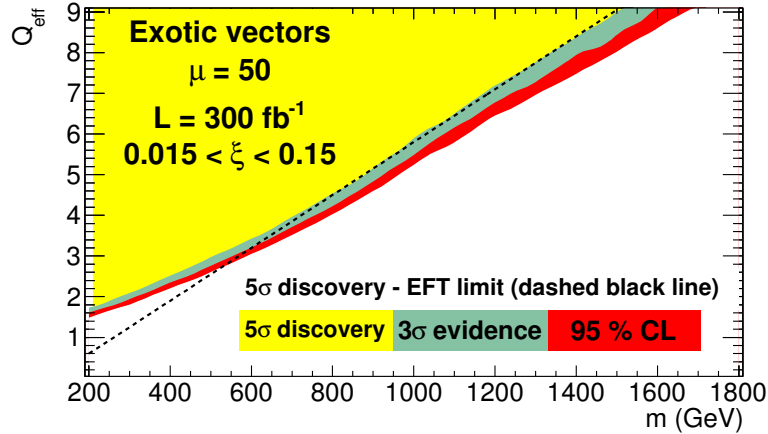

Fig. 3: Expected sensitivity on a spin-1 particle as a function of its mass and of its effective charge $Q_{\rm eff}$.
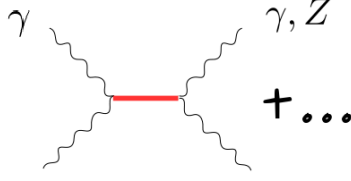
5 Sensitivity to new neutral particles

Fig. 4: The exchange of a neutral particle inducing a quartic gauge interaction.

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, respectively denoted by φ, $\tilde{\varphi}$ and $h^{\mu\nu}$ [15], that can potentially be strongly-coupled to the SM. The full effective theory for such neutral resonances is given in [31].

$$
\begin{aligned}
\mathcal{L}_{\gamma\gamma} =&\, \varphi \left[\frac{1}{f_{0^+}^{\gamma\gamma}} (F_{\mu\nu})^2 + \frac{1}{f_{0^+}^{\gamma Z}} F_{\mu\nu} Z_{\mu\nu} \right] + \tilde{\varphi} \left[\frac{1}{f_{0^-}^{\gamma\gamma}} F_{\mu\nu}\tilde{F}_{\mu\nu} + \frac{1}{f_{0^-}^{\gamma Z}} F_{\mu\nu}\tilde{Z}_{\mu\nu} \right] \\
&+ h^{\mu\nu} \left[\frac{1}{f_2^{\gamma\gamma}}(-F_{\mu\rho}F_\nu{}^\rho + \eta_{\mu\nu}(F_{\rho\lambda})^2/4) + \frac{1}{f_2^{\gamma Z}}(-F_{\mu\rho}Z_\nu{}^\rho + \eta_{\mu\nu}F_{\rho\lambda}Z_{\rho\lambda}/4) \right] ,
\end{aligned}
\tag{6}
$$

where the f_S have mass dimension one. Such neutral particle induces quartic gauge couplings (Fig.4) given by

$$
(\zeta^\gamma, \tilde{\zeta}^\gamma) = \frac{1}{(f_s^{\gamma\gamma})^2\, m^2}(d_s, \tilde{d}_s), \quad (\zeta^{\gamma Z}, \tilde{\zeta}^{\gamma Z}) = \frac{1}{f_s^{\gamma\gamma} f_s^{\gamma Z}\, m^2}(d_s, \tilde{d}_s), \quad (d_s, \tilde{d}_s) = \begin{cases} 1, 0 & s = 0^+ \\ 0, 1 & s = 0^- \\ \frac{1}{4}, \frac{1}{4} & s = 2. \end{cases}
\tag{7}
$$

For example, at 13 TeV, 300 fb^{-1}, $\mu = 50$, the expected 5σ sensitivities on the scalar are

$$
m < 4.5\,\text{TeV} \cdot \left(\frac{1\,\text{TeV}}{f^{\gamma\gamma}} \right), \quad m < 2.3\,\text{TeV} \cdot \left(\frac{1\,\text{TeV}}{\sqrt{f^{\gamma\gamma} f^{\gamma Z}}} \right).
\tag{8}
$$

Following [15, 21], the bounds on a dilaton mass can reach 4260 GeV (5σ) and those on a KK graviton with IR gauge fields can reach 5670 GeV (5σ). Interestingly, the $Z\gamma$ coupling vanishes($f_{Z\gamma} \to \infty$) when the particle couples universally to the $SU(2) \times U(1)_Y$ field strengths $(B^{\mu\nu})^2$, $(W^{I,\mu\nu})^2$, hence the γZ channel provides a powerful piece of information.

6 Sensitivity to a polarizable dark sector

It is very plausible that a new particle be *almost dark* in the sense that it interacts with light only via higher-dimensional operators. Let us focus on self-conjugate particles, which have no dipole – our approach applies very similarly if the dark particle is polarized. For concreteness we focus on a real scalar. Its interactions with light have the form $\frac{1}{\Lambda^2}\phi^2(F^{\mu\nu})^2$, $\frac{1}{\Lambda^4}\partial_\mu\phi\partial_\nu\phi F^{\mu\rho}F_\rho{}^\nu$, ... The property of polarizability can be either induced by mediators, or arise from the inner structure of the particle (intrinsic polarizability) [24]. The latter happens in particular if the dark particle is a composite made of electrically charged constituents. As a matter of fact, many models of dark sectors can feature this kind of composite dark particles (see for instance vectorlike confinement, stealth DM [32]).

The polarizable dark particle can induce quartic gauge interactions at one-loop as shown in Fig. 5. This contribution is potentially dominant in the scenario of intrinsic polarizability. The photon collision
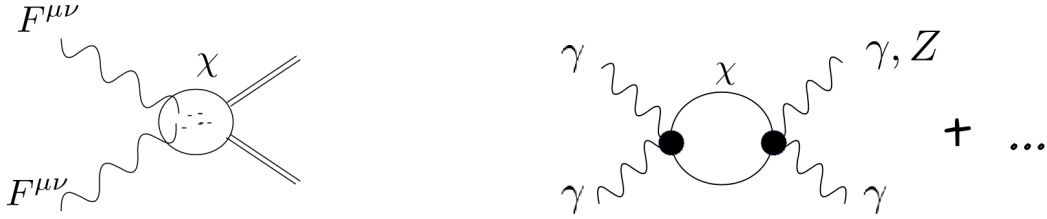
Fig. 5: *Left:* Sketch of a composite polarizable dark particle. *Right:* Sketch of the quartic gauge interaction induced by the polarizable dark particle.

then quite literally sheds light on the dark particle. In a simulation at 13 TeV, 300 fb^{-1} $\mu = 50$, the sensitivities in mass and in Λ go typically up to the TeV scale – details depend on which polarizability operator is considered.

Searching for dark sectors via their virtual effects is a recent trend [33, 34], and many interesting developments are yet to be done. An advantage of such searches is they do not rely on the hypothesis of stability of the dark particle. When the dark particle is stable it is a dark matter candidate, in which case the search in photon collisions turns out to be complementary to monojet+ missing energy searches. The search in photon collisions gets favored by larger multiplicities in the loop ($\propto N^2$ versus $\propto N$) and for large dark particle mass as it is not constrained by the kinematic threshold of DM pair production.

Acknowledgements

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