ANOMALOUS COUPLING STUDIES WITH PROTON TAGGING AT THE LHC*

Christophe Royon

Department of Physics and Astronomy, The University of Kansas, Lawrence, USA

We discuss the sensitivities to photon quartic anomalous couplings and to axion-like particles using tagged intact protons at the LHC.

1. Introduction

After describing the Roman Pot detectors in order to measure intact protons in the final state by the CMS-TOTEM and ATLAS experiments at the LHC, we describe new methods to look for quartic photon and W/Z bosons anomalous couplings that could lead to a sign of the existence of extra-dimensions, axion-like particles (ALP) at high masses or composite Higgs bosons. This is definitely complementary to the low-energy experiments that are sensitive to lower masses of ALPs as an example.

2. Detecting intact protons in the final state at the LHC

The ATLAS and CMS-TOTEM collaborations (respectively the ATLAS Forward Proton and CMS-TOTEM Precision Proton Spectrometer) installed some Roman Pots equipped with silicon (strips or pixel) and fast timing (quartz, diamond or silicon) detectors located at about 220 meters from the interaction point [1] in order to measure intact protons in the final state. The basic idea is simple: we use the magnets from the LHC as a spectrometer in order to scatter the protons that lost part of their energy at small angles. The mass acceptance of these detectors depends on how close to the beam the detectors are inserted, but varies typically between 400 GeV and 2 TeV for standard running at the LHC (low β^*). It is possible to reach lower mass diffractive production using high β^* special runs

---

* Presented at the Diffraction and Low-x 2018 Workshop, August 26–September 1, 2018, Reggio Calabria, Italy.

at the LHC. Both sets of detectors were installed at the end of 2016, and respectively about 15 and 40 fb^{-1} of data have been accumulated in 2016 and 2017. Before the long shutdown starting at the end of 2018, more than 100 fb^{-1} of data should be available.

3. Looking for $\gamma\gamma\gamma\gamma$ anomalous couplings

3.1. Motivation

Quartic anomalous production of photon pairs can happen via loops of new charged particles or via production of new resonances. We introduce two effective operators at low energies involving the coupling of four photons, ζ_1 and ζ_2

$$L_{4\gamma} = \zeta_1^\gamma F_{\mu\nu} F^{\mu\nu} F_{\rho\sigma} F^{\rho\sigma} + \zeta_2^\gamma F_{\mu\nu} F^{\nu\rho} F_{\rho\lambda} F^{\lambda\mu} \,. \tag{1}$$

In the case of loops of new particles, the effective coupling can be modified as $\zeta_1 = \alpha_{\mathrm{em}}^2 Q^4 m^{-4} N c_{1,s}$, where m, Q and $c_{1,s}$ are respectively the mass, charge and spin of the particle in the loop. In the case of a resonance X, one gets $\zeta_1 = (f_s m)^{-2} d_{1,s}$, where f_s is the $\gamma\gamma X$ coupling of the new particle to the photon. Typical values of ζ_1 are of the order of 10^{-14}–10^{-13} GeV^{-4} for 2 TeV dilatons as an example.

These couplings are motivated by the existence of warped extra-dimensions that solves the hierarchy problem of the Standard Model of particle physics. Typically, our usual 4D brane contains the SM fields, whereas gravitation happens via the extra-dimensions.

In the following, all SM or anomalous coupling events were generated using the Forward Physics Monte Carlo (FPMC) [2].

3.2. Standard model exclusive di-photon production

In Fig. 1, left there are displayed the two different diagrams contributing to the SM exclusive di-photon production, namely the QCD diagram [3] and the QED one. In Fig. 1, right there are shown the contributions of these two diagrams in the exclusive di-photon cross section for a value of the di-photon mass larger than the value in abscissa. The QCD contribution drops very fast as a function of the di-photon mass and the QED contribution dominates for masses above 150 GeV (the contributions from quark, leptons and W bosons in the loop are also shown). In the acceptance of the forward proton detectors (masses above 400 GeV), the only relevant contributions are photon-induced processes. Observing two photons in CMS or ATLAS and two intact protons in CT-PPS or AFP ensures that this is a photon-induced process [4, 5].
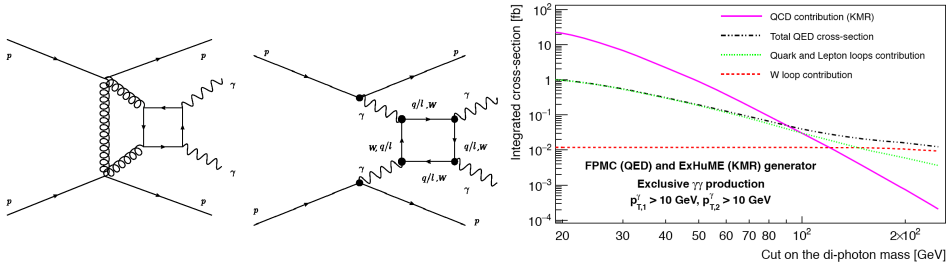
Fig. 1. Left: SM diagrams contributing to exclusive di-photon events. Right: Cross section of the different processes for a di-photon mass larger than the value in abscissa.

3.3. Search for quartic $\gamma\gamma\gamma\gamma$ anomalous couplings

Quartic anomalous photon couplings might lead to the appearance of two photon and two proton events at high di-photon masses. For a di-photon mass above 600 GeV, the exclusive di-photon SM cross section is very small and can be neglected. The only relevant background is due to pile-up. At the LHC, bunches of protons collide and in order to look for rare events, many protons collide within the same bunch crossing. Pile-up backgrounds correspond in our case as two photons originating from the main hard interactions and intact protons coming from additional soft interactions (additional proton–proton interactions). Additional backgrounds originate from leptons misidentified as photons associated with the pile-up.

The fact that we detect all particles in the final state for our signal (two photons and two protons) is crucial in order to suppress the pile-up background as shown in Fig. 2. We display the ratio of the missing di-proton mass to the di-photon mass (left) and the difference between the di-photon and di-proton rapidities (right). In the case of signal, the two protons system is obviously related to the two photons and this is why the signal peaks at 1.0 or 0.0 in Fig. 2, left and right respectively. For pile-up background, the protons are not correlated to the di-photons and this is why we get a flatter distribution.

The number of signal and background events after each requirement (in the acceptance of the forward detectors, high photon transverse momentum, high di-photon mass, two photons well balanced in transverse momentum and azimuthal angle) for a luminosity of 300 fb^{-1} is shown in Table I. The two last lines of the table show the effect of the requirements to reject pile-up events, and less than 0.1 event of background is expected. Any observed event would be a signal event. The expected sensitivity on the anomalous $\gamma\gamma\gamma\gamma$ quartic anomalous coupling is expected to be about 10^{-14} GeV^{-4}, reaching the values predicted by some extra-dimension or composite Higgs models (we gain about two orders of magnitude on sensitivities with respect to the "standard" methods at the LHC).

Let us note that we used in this study an effective approach but we performed another study using a full amplitude calculation that led to similar results [4, 5].
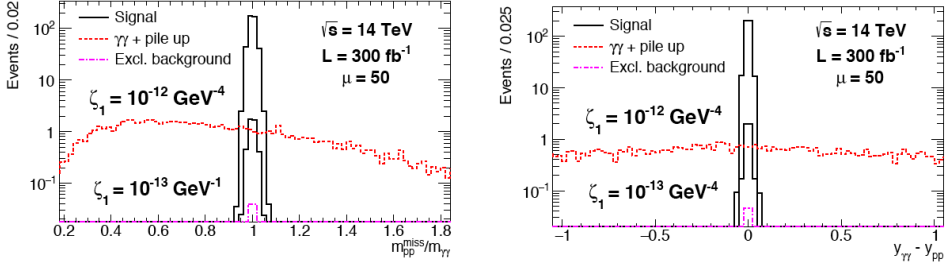

Fig. 2. Ratio of the di-photon and di-proton masses and difference in rapidity between the two systems allowing to select signal *versus* pile-up background.

TABLE I

Selection of diphoton signal events with respect to backgrounds.

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

3.4. Application to the search for axion-like particles at the LHC

The search for exclusive di-photon production is directly applicable to the search for the axion-like particles (ALPs) at the LHC [6]. The ALP is produced as a resonance and decays into two photons. Exclusive di-photon production can increase the sensitivity to ALPs at high mass at the LHC by more than one order of magnitude and even cover a new domain at very high mass [6].

It is worth noticing that the same method allows looking for polarizable dark matter candidates with unprecedented precision [7].

4. Search for quartic anomalous $\gamma\gamma\gamma Z$, $\gamma\gamma WW$ and $\gamma\gamma ZZ$ anomalous couplings

Using the same method as described above in order to reject pile-up backgrounds, one can look for $\gamma\gamma\gamma Z$, $\gamma\gamma WW$ and $\gamma\gamma ZZ$ anomalous couplings [4, 8]. The signals will be $Z\gamma$. WW or ZZ in the main central detectors and two intact protons in CT-PPS or AFP. In the case of WW exclusive production where both Ws decay leptonically, the matching method described above does not work because of the presence of neutrinos. Additional detectors can be used in order to measure the time-of-flight of the protons with a typical precision of 15 to 20 ps [9] and ensure that they originate from the same interaction as the Ws. This additional method allows reducing the pile-up background. At the University of Kansas, we take part in developing and testing, for instance, Ultra-Fast Silicon detectors for CMS-TOTEM and for applications in medicine, chemistry and cosmic-ray experiments. Typical resolutions of 35 ps per layer of Si detectors have been achieved in beam tests.

In the case of γZ production, we studied the cases when the Z boson decays either leptonically or hadronically [8]. In the case when the Z boson decays into hadrons, the matching plots in mass and rapidity are shown in Fig. 3. The distributions are wider than in the di-photon case due to the worse resolution on di-jet mass and rapidity. Combining both decays of the Z bosons allows us to gain about three orders of magnitude on quartic anomalous couplings with respect to more standard methods at the LHC as shown in Table II. The studies of WW and ZZ productions when one or two of the W or Z bosons decay hadronically are still in progress and might allow to observe the SM exclusive production of W pairs at high masses.
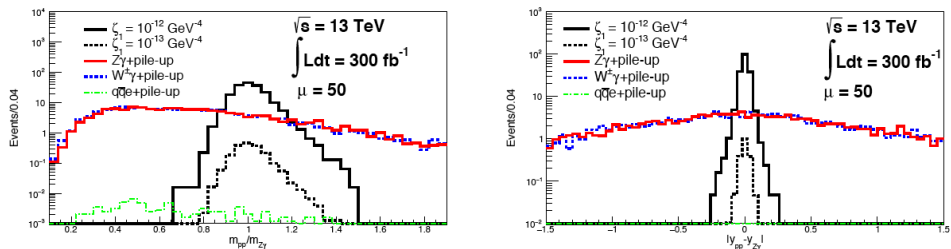

Fig. 3. Ratio of the $Z\gamma$ and di-proton masses and difference in rapidity between the two systems allowing to select signal *versus* pile-up background when the Z boson decays hadronically.

Reach on $\gamma\gamma\gamma Z$ anomalous coupling at the LHC with 300 fb^{-1} and a pile-up of 50. Compared to usual methods at the LHC looking for $Z \to \gamma\gamma\gamma$, the gain on sensitivity is about three orders of magnitude using the leptonic and hadronic decay modes of the Z boson.

Coupling [GeV^{-4}]	ζ ($\tilde{\zeta} = 0$)		$\zeta = \tilde{\zeta}$	
Luminosity	300 fb-1		300 fb-1	
Pile-up (μ)	50		50	
Channels	5σ	95% C.L.	5σ	95% C.L.
$\ell\tilde{\ell}\gamma$	2.8×10^{-13}	1.8×10^{-13}	2.5×10^{-13}	1.5×10^{-13}
$jj\gamma$	2.3×10^{-13}	1.5×10^{-13}	2×10^{-13}	1.3×10^{-13}
$jj\gamma \oplus \ell\tilde{\ell}\gamma$	1.93×10^{-13}	1.2×10^{-13}	1.7×10^{-13}	1×10^{-13}

5. Conclusion

In this brief report, we described the search for extra-dimensions, composite Higgs models or polarizable dark particles at the LHC using a new method based on detecting intact protons in the final state. This allows obtaining a negligible background after the event selection and leads to a better sensitivity by two or three orders of magnitude (depending on the channels) compared to more traditional methods at the LHC.

REFERENCES

[1] CMS and TOTEM collaborations, CERN-LHCC-2014-021; ATLAS Collaboration, CERN-LHCC-2015-009.

[2] M. Boonekamp *et al.*, `arXiv:1102.2531 [hep-ph]`.

[3] V.A. Khoze, A.D. Martin, M.G. Ryskin, *Eur. Phys. J. C* **23**, 311 (2002); L.A. Harland Lang, V.A. Khoze, M.G. Ryskin, *Eur. Phys. J. C* **79**, 39 (2019) [`arXiv:1810.06567 [hep-ph]`].

[4] S. Fichet *et al.*, *J. High Energy Phys.* **1502**, 165 (2015); S. Fichet *et al.*, *Phys. Rev. D* **89**, 114004 (2014); E. Chapon, O. Kepka, C. Royon, *Phys. Rev. D* **81**, 074003 (2010); O. Kepka, C. Royon, *Phys. Rev. D* **78**, 073005 (2008).

[5] S. Fichet, G. von Gersdorff, C. Royon, *Phys. Rev. Lett.* **116**, 231801 (2016); *Phys. Rev. D* **93**, 075031 (2016).

[6] C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon, *J. High Energy Phys.* **1806**, 131 (2018).

[7] S. Fichet, *J. High Energy Phys.* **1704**, 088 (2017).

[8] C. Baldenegro, S. Fichet, G. von Gersdorff, C. Royon, *J. High Energy Phys.* **1706**, 142 (2017).

[9] N. Minafra *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **867**, 88 (2017); D. Breton *et al.*, *Nucl. Instrum. Methods Phys. Res. A* **835**, 51 (2016); **895**, 158 (2018).