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Anomalous coupling studies with forward protons at the LHC

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Abstract

We describe the gain on sensitivities to quartic $\gamma\gamma\gamma\gamma$, $\gamma\gamma WW$ and $\gamma\gamma\gamma Z$ anomalous couplings and to the search for Axion-Like Particles by two or three orders of magnitude with respect to standard methods at the LHC by tagging intact protons in the final state.

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1 Introduction: photon induced processes and measurement of intact protons in CMS/ATLAS

The LHC allows us to study photon-induced processes as shown in Fig. 1 with unprecedented precision. These events is especially clean since we can measure all particles in the final state (intact protons are detected in dedicated detectors located close to the beam) like at LEP. As an example, we can produce exclusively pairs of photons and W bosons in addition of the two intact protons in the final state (see Fig. 1). In the same way, one can look for the exclusive production of ZZ, γZ, $t\bar{t}$ events via photon induced processes. We produce for instance two γ's in the central ATLAS or CMS detectors, and two intact protons that can be detected and measured in roman pot detectors located at about 220 m from the interaction point. Both the ATLAS and CMS-TOTEM collaborations installed roman pots detectors that can measure intact protons at high luminosity at the LHC, the so-called ATLAS Forward Proton (AFP) and CMS-TOTEM Precision Proton Spectrometer (PPS) [1, 2]. At high luminosity (standard runs with $\beta^* \sim 0.5$ at the LHC), the acceptance in mass of the two photons or the two W bosons (see Fig. 1) with intact protons tagged in the roman pot detectors typically covers the domain 400-2300 GeV. We can thus get sensitivity to beyond standard model physics since we can produce high mass objects.

As an example, quartic photon couplings ζ_1 can be modified via loops of new particles or new resonances that couple to photons [3, 4]. In the case of loops of new heavy particles, we get $\zeta_1 = \alpha_{em}^2 Q^4 m^{-4} N c_{1,s}$ where the coupling depends only on $Q^4 m^{-4}$ (charge and mass of the charged particle) and on spin, $c_{1,s}$. This leads to ζ_1 of the order of 10^{-14} -10^{-13} GeV^{-4}

depending on models. ζ_1 can also be modified by neutral particles at tree level (extensions of the SM including scalar, pseudo-scalar, and spin-2 resonances that couple to the photon), $\zeta_1 = (f_s m)^{-2} d_{1,s}$ where f_s is the $\gamma\gamma X$ coupling of the new particle to the photon, and $d_{1,s}$ depends on the spin of the particle. For instance, 2 TeV dilatons lead to $\zeta_1 \sim 10^{-13}$ GeV^{-4}. All these couplings were implemented in the FPMC generator [5] that will be used in the following for all predictions. In the following, we will see if we can be sensitive to these values of anomalous couplings by measuring the γ's in the main detectors of ATLAS and CMS and tagging the intact protons in the final state.

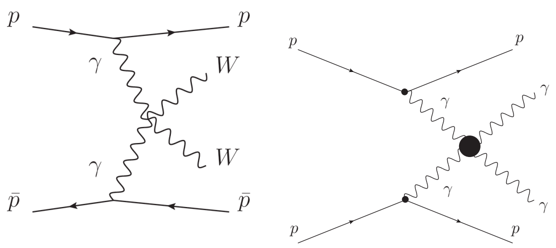

Figure 1: Example of WW and $\gamma\gamma$ exclusive production by photon exchanges.

2 Diphoton exclusive production: SM and BSM contributions

In this section, we will concentrate on diphoton exclusive production as an example and the conclusions can be generalized to exclusive WW, ZZ, γZ, and $t\bar{t}$ production via photon exchanges. Let us start by examining the standard model (SM) production of exclusive diphotons as shown in Fig. 2. Diphotons can be produced exclusively either via QCD processes (Fig. 2, left) or QED processes (Fig. 2, right). The cross sections in fb for a diphoton mass above the value in abscissa are shown in Fig. 3. In purple full line, we display the QCD contribution and in black dashed dotted line the sum of the three QED photon-induced contributions (in green dotted lines, the quarks and leptons loop contribution, and in red dashed line the W loop contribution) [6–9]. We note that above a diphoton mass of 200 GeV, the QCD contribution becomes negligible. Recalling the fact that the acceptance of the roman pot detectors starts at about 400 GeV for standard running at the LHC, it is clear that observing two photons in ATLAS/CMS and two tagged protons means a photon-induced process.

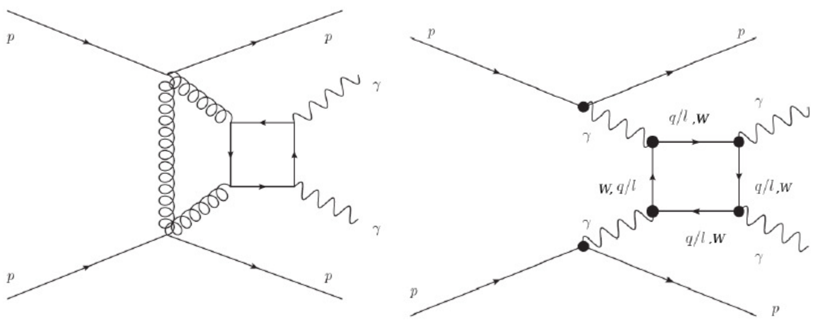

Figure 2: Exlusive production of diphoton vis QCD processes (left) and QED photon exchanges (right).

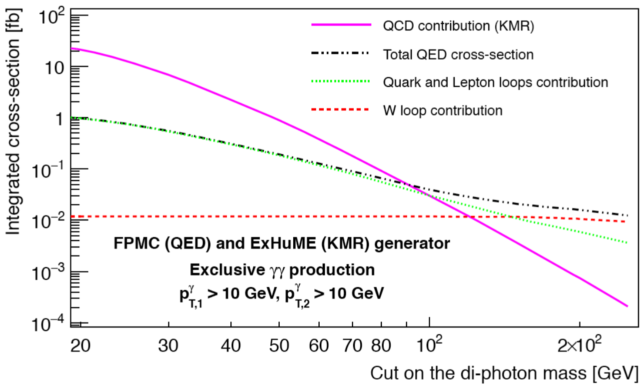

Figure 3: Cross section of exclusive diphoton production above a given diphoton mass given in abscissa for QCD (full line) and QED (dashed dotted line) processes.

Let us new give some details about the exclusive diphoton production analysis for a luminosity of 300 fb^{-1} at the LHC. The number of events is shown in Fig 4. The number of signal events is shown as a black line for two values of anomalous couplings. We also notice that the number of SM exclusive diphotons (red dashed dotted line) or exclusive dileptons with leptons misidentified as photons (blue dotted line) is quite low and can be neglected. The only background that matters is shown in red dashed lines, and correspond to the diphoton production (standard non exclusive production with protons destroyed in the final state) superimposed with intact protons originating from secondary interactions. These events are called pile up since they correspond to the fact that we have up to 50 interactions per bunch crossing at the LHC at standard luminosities. This is basically the only background that we have to consider.

Measuring intact protons is crucial in order to suppress the pile up background. The method is quite simple. Since, for signal, we detect and measure all particles in the final state (namely the two photons, and the two intact protons), we can match the kinematical information as measured by the two photons with the one using the two protons, namely the rapidity and mass defined as

$$\begin{aligned} M_{pp} &= \sqrt{\xi_1 \xi_2 s} = M_{\gamma\gamma} \\ y_{pp} &= \frac{1}{2}\log\left(\frac{\xi_1}{\xi_2}\right) = y_{\gamma\gamma}\,, \end{aligned}$$

where ξ_1 and ξ_2 are the proton fractional momentum loss. The results are shown in Fig. 5, left, for the mass ratio and in Fig. 5, right for the rapidity difference between the pp and $\gamma\gamma$ information for signal in black full line and for pile up background in red dashed lines. It is clear that this variable can reject most of the pile up background and we obtain indeed less than 0.1 event of background for 300 fb^{-1}. The sensitivity on quartic photon anomalous coupling is thus up to a few 10^{-15} GeV^{-4}, which is better by more than two orders of magnitude with respect to “standard" methods at the LHC [3, 4]. Let us note that exclusivity cuts using proton tagging are crucial to suppress backgrounds since, without matching mass and rapidity requirements, the background would be about 80.2 events for 300 fb^{-1}. Running roman pot detectors at high luminosity at the LHC both in ATLAS and CMS-TOTEM was indeed motivated by the gain that we obtain on the reach on anomalous couplings [6–9]. This is now becoming a reality and both CMS-TOTEM and ATLAS reported recently some observation of QED exclusive dilepton production [10, 11] and CMS-TOTEM the first limits on quartic photon anomalous couplings with about 9.4 fb^{-1} of data [12]. The analysis with the total accumulated luminosity (about 110 fb^{-1}) is underway.

This method can be applied directly to the search for axion-like particles (ALP) as an example. ALP can be produced as a resonance via photon induced processes, and we can detect them using the method described above if they decay into two photons as an example. The sensitivity plot (coupling versus mass of the ALP) is shown in Fig. 6 for pp interactions with 300 fb^{-1} of data as a grey region at high ALP masses [13, 14]. We gain about two orders of magnitude on sensitivity for ALP masses of the order of 1 TeV with respect to standard LHC methods and we reach a new domain at high mass that cannot be reached without tagging the protons. In addition, we also show for reference the complementarity with $PbPb$ runnings that cover the region at lower masses (typically ALP masses in the range 10-500 GeV) since the cross section is enhanced by a factor of Z^4 for $PbPb$ runs [13, 14].

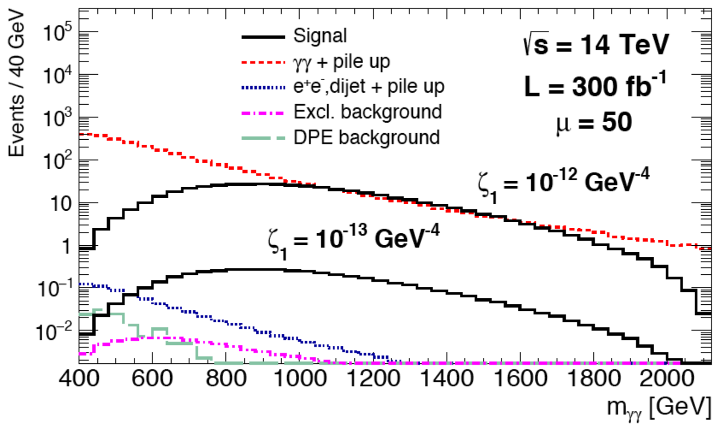

Figure 4: Number of events as a function of the diphoton mass for signal and background for exclusive $\gamma\gamma$ production.

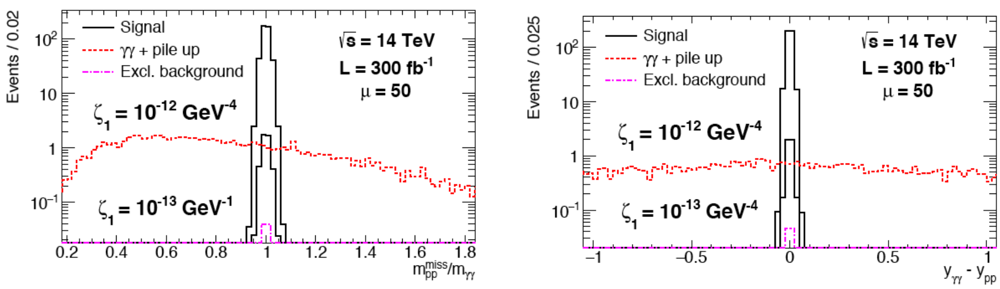

Figure 5: Mass ratio and rapidity difference between the pp and $\gamma\gamma$ information for signal (in full line) and pile up background (dashed line).

3 Anomalous production of $Z\gamma$ and WW vis photon-induced processes

Our previous study can be extended to other exclusive productions via photon exchanges and we will discuss briefly the production of $Z\gamma$ and WW events. Exactly, the same method of matching the mass and rapidity measurements of the $Z\gamma$ system with the tagged proton information can be used. The new aspect of this study is that we can consider both leptonic

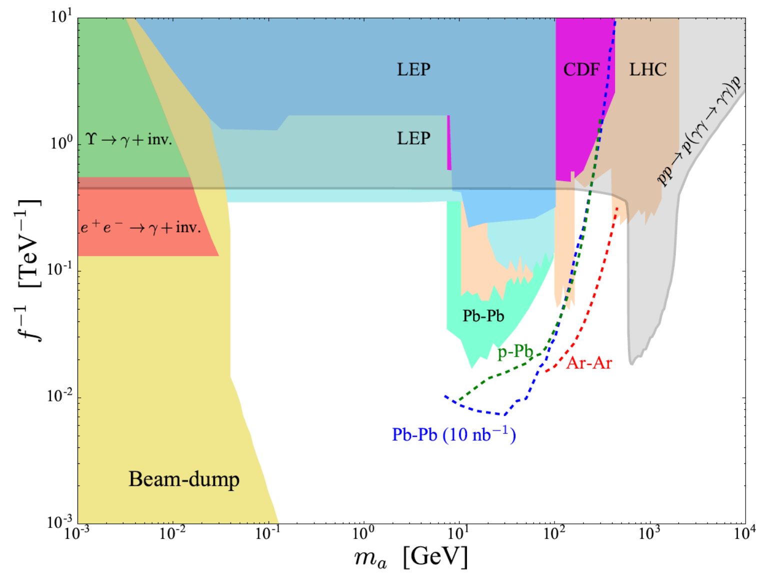

Figure 6: Coupling vs ALP mass sensitivity plot. The reach using the measurement of two intact protons and the two photons for photon-induced processes is shown as a grey area.

and hadronic decays of the Z boson. Of course the resolution on mass and rapidity is worse since the jet resolution is worse than for leptons, but it leads to unprecedented sensitivities to $\gamma\gamma\gamma Z$ anomalous couplings, up to 10^{-13}, better by three orders of magnitude [15] than the sensitivities without tagging the protons at the LHC (the usual method being to look for the three photon decay of the Z boson).

The same study can be used to observe the SM exclusive production of WW bosons via photon exchanges and also to increase our sensitivity to quartic $\gamma\gamma WW$ anomalous couplings. Recent studies [16] showed that the strategy is somewhat different for SM and BSM studies. To measure the SM exclusive WW production (the cross section is of the order of 95.6 fb at the LHC), the best sensitivity originates from the leptonic decays of the Ws where we can obtain about 50 events with 2 events of background for 300 fb^{-1}. The non-zero background originates from the fact that the neutrinos originating from the leptonic decay of the W bosons cannot be obviously measured and this is why the mass and rapidity matching is not working so nicely. Fast timing detectors are needed to suppress further the background in this case. The strategy to look for $\gamma\gamma WW$ quartic anomalous couplings is slightly different since the anomalous coupling events appear at high WW mass as shown in Fig. 7. The best sensitivity to quartic $\gamma\gamma WW$ couplings appear by looking at the hadronic decay of the W bosons even if the dijet background is quite high. The sensitivity with 300 fb^{-1} is of the order of 3.7 10^{-7} GeV^{-2}, better by almost three orders of magnitude that the present LHC sensitivity. This can be further improved by using more advanced jet variables such as subjettiness in order to reject further the dijet background.

4 Conclusion

In this report we considered the exclusive production of $\gamma\gamma$, WW and $Z\gamma$ via photon induced processes, considering the LHC as a $\gamma\gamma$ collider. Tagging the protons in dedicated ATLAS-AFP or CMS-TOTEM-PPS roman pot detector as well as the $\gamma\gamma$, WW, $Z\gamma$ in the main ATLAS or CMS

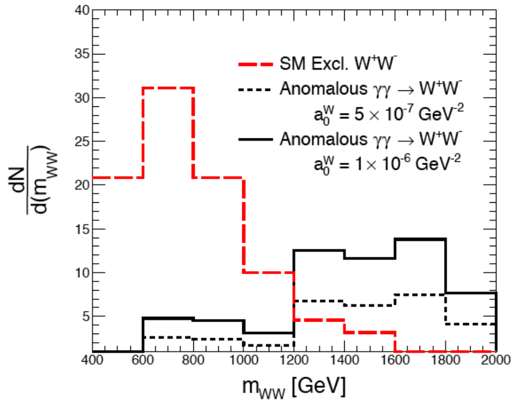

Figure 7: WW mass distribution for exclusive WW production (SM is red dashed line and anomalous couplings in full ball line).

detector ensures that we have a photon-induced process since gluon exchanges are suppressed at high masses in the acceptance of the roman pot detectors. Matching the kinematical information of the central system with the tagged protons ensures that we have a background-free experiment and any observed event is a signal. This leads to better sensitivities to quartic anomalous coupling by two or three order of magnitude with respect to the standard methods at the LHC depending on the process.

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