SEARCHING FOR AXION-LIKE PARTICLES WITH PROTON TAGGING AT THE LHC*

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The existence of an axion-like particle (ALP) would induce anomalous scattering of light-by-light. This process can be probed at the LHC in central exclusive production of photon pairs in p–p collisions by tagging the surviving protons using forward proton detectors. We show that the proposed search in central exclusive production of photon pairs is competitive and complementary to other collider bounds for masses above 600 GeV, especially for resonant ALP production between 600 GeV and 2 TeV.

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1. Introduction

The presence of light (pseudo) scalars coupled to particles of the Standard Model (SM) of particle physics would have numerous consequences from the subatomic to the cosmological scale. These particles might address the longstanding question of why quantum chromodynamics seems to not break the CP symmetry, as well as explain a possible component of dark matter. Axion-like particles (ALPs) appear in many extensions of the SM. In these proceedings, we are primarily interested in the ALP coupling to photons. For more details regarding this study, we refer to the original publication in Ref. [1]. We propose to search for ALPs in central exclusive diphoton production in p–p collisions (see Fig. 1)

$$pp \to p(\gamma\gamma \to \gamma\gamma)p\,, \tag{1}$$

where the photon pair is measured in the central detector and the scattered intact protons are tagged with dedicated forward proton detectors, which are installed symmetrically at a distance of about 210 m (220 m) with respect to the interaction points of the CMS (ATLAS) experiment (see Fig. 2). Using proton tagging, we can reach diphoton-invariant masses between 350 GeV and 2 TeV.

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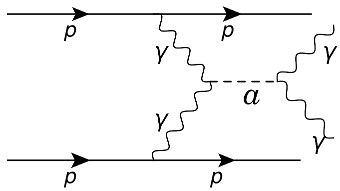

Fig. 1. Schematic diagram of an axion-like particle production in two-photon coherent emission in proton–proton collisions.

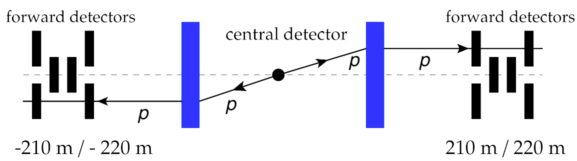

Fig. 2. (Color online) Schematic diagram of the proton tagging method at the LHC. The central detector (circle) collects the photon pair. The LHC magnets (gray/blue) act as a precise momentum spectrometer on the outgoing intact protons. The dashed line represents the beamline.

The LHC magnets around the interaction points of CMS and ATLAS act as a precise longitudinal momentum spectrometer on the protons that have lost a fraction of their original momentum due to the photon exchange. The proton fractional momentum loss $\xi = \Delta p/p$ is reconstructed offline.

2. The $pp \to p(\gamma\gamma \to \gamma\gamma)p$ process

We compute the production rates for light-by-light scattering in proton–proton collisions using the equivalent photon approximation. In this approximation, the electromagnetic field generated by the fast moving protons can be considered as an intense photon beam. The photons exchanged by the colliding protons are almost on their mass shell. The hadronic cross section can be calculated as a convolution of the effective photon fluxes and the $\gamma\gamma \to \gamma\gamma$ subprocess matrix elements. We use the photon flux computed from the proton elastic electromagnetic form factor.

In order to describe the interaction of the (pseudo) scalar a with photons, we use the effective interaction models

$$\mathcal{L}^+ = \frac{1}{f} a F_{\mu\nu} F^{\mu\nu} \quad (\text{CP-even}) , \qquad \mathcal{L}^- = \frac{1}{f} a F_{\mu\nu} \tilde{F}^{\mu\nu} \quad (\text{CP-odd}) , \tag{2}$$

where f^{-1} is the ALP–photon coupling and $\tilde{F}^{\mu\nu} = \frac{1}{2}\epsilon^{\mu\nu\rho\sigma} F_{\rho\sigma}$. The effective operator induces anomalous light-by-light scattering. The pseudoscalar being coupled to photons has a minimal decay width of $\Gamma(a \to \gamma\gamma) = \frac{m_a^3}{4\pi f^2}$.

In our projections, the decay width of a is a free parameter satisfying $\Gamma \geq \Gamma(a \rightarrow \gamma\gamma)$. The decay width is parametrized via the branching ratio into photons $\mathcal{B}(a \rightarrow \gamma\gamma) = \Gamma(a \rightarrow \gamma\gamma)/\Gamma$.

3. Analysis

We consider proton–proton collisions at a center-of-mass energy of 13 TeV and an integrated luminosity of 300 fb^{-1}. We look for photons reconstructed in $|\eta| < 2.5$, where the reconstruction efficiency is $\sim 80\%$ for energetic photons. We ask for the leading (subleading) photon to have a minimum transverse momentum of 200 (100) GeV. To better isolate exclusive production of photon pairs, we apply a cut on the azimuthal angle separation between the two photons $|\Delta\phi^{\gamma\gamma} - \pi| < 0.01$ and their transverse momentum ratio $p^{\gamma}_{\mathrm{T},2}/p^{\gamma}_{\mathrm{T},1} > 0.95$. The resulting invariant mass distribution is shown in Fig. 3. Finally, we apply a cut on the invariant mass of the photon pair of 600 GeV for background suppression purposes, as depicted in Fig. 4. We use the nominal acceptance on the protons fractional momentum loss, $0.015 \leq \xi \leq 0.15$. We assume that ξ is known to 5% precision.

The backgrounds for exclusive photon pair production in p–p collisions can be classified in reducible and irreducible backgrounds. The irreducible background comes from the SM light-by-light scattering process. This background is greatly reduced within the mass acceptance of the forward proton detectors. Finally, we consider central exclusive production of e^+e^-, where the dielectron is misidentified as a photon pair.

The dominating background is the overlap of a non-exclusive photon pair and uncorrelated protons coming from soft diffractive interactions. Protons originating from soft diffractive processes can have fractional momentum losses ξ populating the signal region, and can lead to fake signals. The cross section for diffractive interactions is very large (order 1 mb), and the number of secondary interactions per bunch crossing at the current instantaneous luminosity at the LHC in p–p collisions enhances the likelihood of faking the signal. Central exclusive production events satisfy $m_{\gamma\gamma} = \sqrt{\xi_1\xi_2 s}$ and $y_{\gamma\gamma} = \frac{1}{2}\log(\frac{\xi_1}{\xi_2})$. Thus, we apply a cut $|\sqrt{\xi_1\xi_2 s}/m_{\gamma\gamma} - 1| < 0.03$ and $|y_{\gamma\gamma} - \frac{1}{2}\log(\frac{\xi_1}{\xi_2})| < 0.03$. Non-exclusive photon pairs and protons arising from diffractive processes are kinematically uncorrelated. After applying the offline event selection described in this section, we end up with an almost background-free probe for light-by-light scattering in p–p collisions at high diphoton invariant masses, sensitive to cross sections as small as a fraction of fb.

The signal $\gamma\gamma \rightarrow a \rightarrow \gamma\gamma$ subprocess was implemented and generated with the Forward Physics Monte Carlo event generator (FPMC). FPMC is an event generator for diffractive and photon-induced processes in hadronic

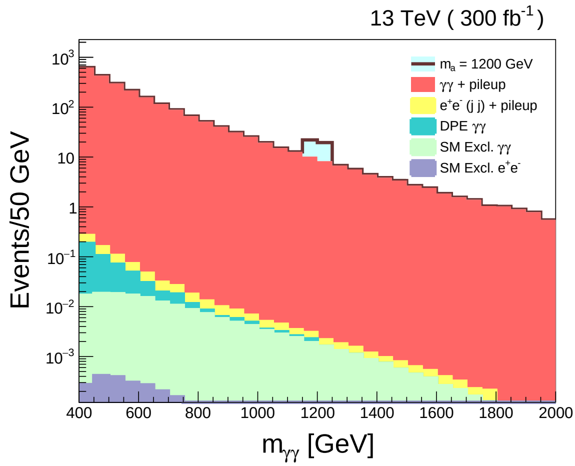

Fig. 3. Differential yield as a function of the photon pair invariant mass for exclusive diphoton candidates with two tagged protons within the acceptance $0.015 < \xi_{1,2} < 0.15$. We assume there are in average 50 secondary interactions per bunch crossing. For illustrative purposes, we show an instance of a resonant ALP production with $m_a = 1200$ GeV and a coupling value $f^{-1} = 0.1$ TeV^{-1}.

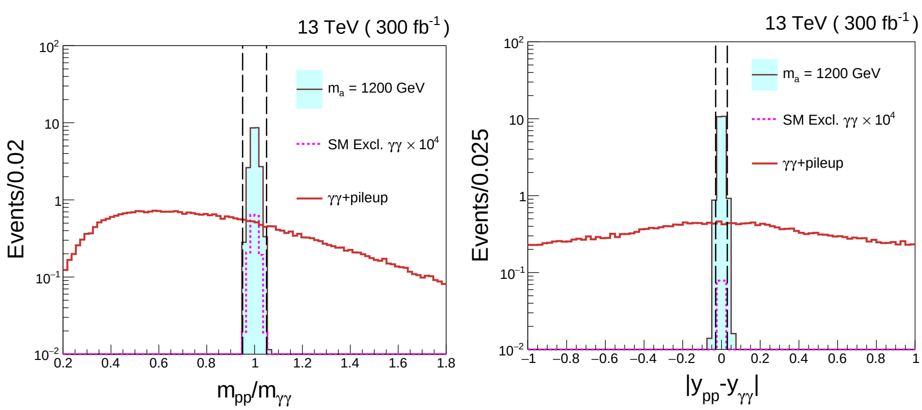

Fig. 4. (Color online) Distributions of the ratio of the diphoton mass reconstructed with the forward detectors $m_{pp} = \sqrt{\xi_1 \xi_2 s}$ to the reconstructed diphoton mass $m_{\gamma\gamma}$ (left), and the difference of the diphoton rapidity $y_{\gamma\gamma}$ and the rapidity reconstructed with the forward detectors $y_{pp} = \frac{1}{2}\log(\frac{\xi_1}{\xi_2})$ distribution (right). A strong correlation between the forward–backward and central information can be seen for the signal (shaded gray/light blue), while for the background (thick solid/red line) the variables are uncorrelated. We select events inside the dashed vertical lines.

collisions. The SM light-by-light scattering process is also simulated in FPMC. We also simulated exclusive dielectron production with this generator. Non-exclusive backgrounds, which include diphoton production, dijet production and e^+e^- in Drell–Yan, are simulated in PYTHIA 8. For the misidentified jets, we use the anti-k_{T} algorithm with a cone radius $R = 0.4$. The probability of tagging at least one proton per diffractive interaction is estimated from the minimum bias library of PYTHIA 8. We assume that the number of secondary interactions per bunch crossing at the interaction points of the LHC follow a Poisson distribution with mean $\mu = 50$.

4. Results

The expected sensitivity from the exclusive diphoton search can be represented in the m_a–f plane. The expected bound is displayed in Fig. 5 in the ALP–photon coupling and mass plane for a centrally produced ALP with branching ratio $\mathcal{B}(a \to \gamma\gamma) = 1$. The lowest coupling values range between 0.02 TeV^{-1} and 0.06 TeV^{-1} for masses between 600 GeV to 1.5 TeV. The bound increases rapidly from 1.5 TeV to 2 TeV and follows a power-law-like behavior for masses larger than 2 TeV independently of the particle width.

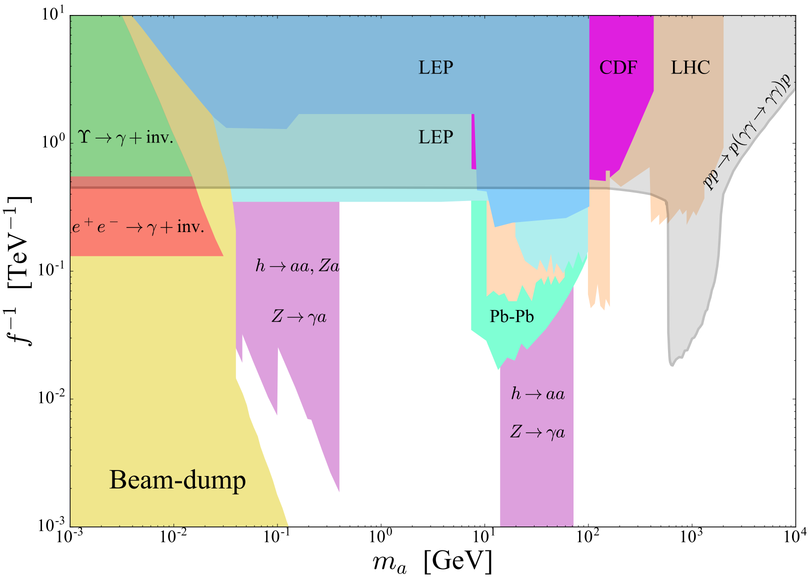

Fig. 5. Exclusion regions on the ALP–photon coupling f^{-1} and mass of the ALP m_a plane. On light-shaded gray, we have the expected 95% C.L. exclusion limit in central exclusive diphoton production events assuming $\mathcal{B}(a \to \gamma\gamma) = 1$ for 300 fb^{-1} in Run-2 of the LHC. Existing bounds are represented by the filled regions and were extracted from Ref. [2], and can depend on additional assumptions.

A subset of the existing bounds were extracted from Ref. [2] and are displayed in Fig. 5. Beam dump searches probe resonant production of neutral pseudoscalar mesons in photon interactions with nuclei. Different beam dump runs at SLAC collectively yield the exclusion region from $10^{-3} < m_a < 10^{-1}$ GeV and $10^{-3} < f^{-1} < 1$ TeV^{-1}. Υ decays searched at the CLEO and BaBar experiments exclude the region in the upper-left corner. Bounds from collider searches for ALPs include measurements of mono-photons with missing transverse energy at the LEP (left-most region), tri-photon searches on and off the Z pole at the LEP for masses of $10^{-1} < m_a < 10^2$ GeV and $f^{-1} > 10^{-1}$ TeV^{-1} (upper region), and searches for the same final states in p–$\bar{p}$ collisions at CDF for masses above 10 GeV but lower than 500 GeV and in p–p collisions at the LHC from 1 GeV to 2 TeV. The region labelled "Pb–Pb" was based on the measurement of light-by-light scattering in ultraperipheral heavy-ion collisions by the ATLAS Collaboration. These collider-based bounds assume $\mathcal{B}(a \to \gamma\gamma) = 1$. We also include recent constraints based on Higgs boson and Z boson exotic decays $h \to Za$, $h \to aa$ and $Z \to \gamma a$, where a decays into a pair of charged leptons or a photon pair. Unlike our bounds, these constraints assume a given coupling value of the ALP to the Higgs boson and Z boson.

5. Conclusion

We examined the possibility of searching for axion-like particles in central exclusive production in proton–proton collisions at the c.o.m. energy of 13 TeV for an integrated luminosity of 300 fb^{-1}. We have found that the bounds on the ALP–photon coupling for masses above 600 GeV can be improved significantly in the central exclusive photon pair production channel. These regions are constrained by standard LHC bump searches. In the 0.6–2 TeV range, we expect that our exclusive diphoton search does better than existing bump searches extrapolated for 300 fb^{-1} and $\sqrt{s} = 13$ TeV by a factor of ~ 3–4 in the ALP–photon coupling.

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