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Looking for New Strategies to Probe Low-Mass Axion-like Particles in Ultraperipheral Heavy-Ion Collisions at the LHC

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Abstract: The possibility to search for long-lived axion-like particles (ALPs) decaying into photons is investigated in ultraperipheral PbPb collisions at the Large Hadron Collider (LHC). We propose a search strategy for low-mass ALPs using the LHCb and ALICE experiments. The ALP identification is performed by requiring the decay vertex be reconstructed outside the region where a primary vertex is expected, which strongly suppress the contribution associated with the decay of light mesons. We also use the fact that a fraction of the photons convert into electron–positron pairs, allowing the reconstruction of the particle decay position. We present the predictions for the pseudorapidity and transverse momentum distributions of the ALPs and photons. Moreover, predictions for the fiducial cross-sections, derived considering the characteristics of the ALICE and LHCb detectors, are presented for different values of the ALP mass and the ALP—photon coupling.

Keywords: axion-like particles; ultraperipheral heavy-ion collisions; new physics

1. Introduction

The description of dark matter (DM) is one of the main current theoretical challenges in particle physics. Among the compelling DM candidates are axion-like particles (ALPs), which arise in beyond the standard model (BSM) theories as a pseudo-Nambu–Goldstone boson resulting from the breaking of a U(1) symmetry and are expected to couple to standard model (SM) fields with model-dependent couplings (for reviews, see, e.g., Refs. [1–3]). In the particular case where the ALP couples to the SM particles only electromagnetically, the Lagrangian is given by

$$\mathcal{L} = \frac{1}{2}(\partial_\mu a)^2 - \frac{1}{2}m_a^2 - \frac{1}{4}g_{a\gamma\gamma}F_{\mu\nu}\tilde{F}^{\mu\nu}, \tag{1}$$

where a is the ALP field, m_a is the ALP mass, and $g_{a\gamma\gamma}$ is the ALP–photon coupling. In recent years, the search for ALPs has been performed in e^+e^-, ep, pp, pA, and AA collisions (see, e.g., Refs. [4–20]), and the experimental results have imposed important constraints on the allowed values for m_a and $g_{a\gamma\gamma}$ [21,22]. However, the probing of ALPs with small masses ($\leq$1.0 GeV) is still a challenge, mainly due to the large background associated with the light meson decays, which also decay into two photons (for a more detailed discussion, see, e.g., Refs. [15,16,19]). Such studies indicate that a new search strategy is needed in order to separate the signal from the background in this kinematic region. One possible strategy has been proposed in Ref. [23], which considered the identification of photons converted into electron–positron pairs inside the tracking detector as a way to improve the signal/background ratio in the searching of ALPs produced in pp collisions. Our goal in

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this paper is to extend this proposal for ultraperipheral heavy-ion collisions (UPCs) [24], using the fact that in this case the decay vertex can be selected to be outside the region where a primary vertex is expected (luminosity region) and estimate the associated cross-sections. Such a requirement strongly suppresses the background contribution, since in this case the primary vertex occurs inside the luminosity region. This study is motivated by the higher photon luminosity present in PbPb collisions, which implies a smaller statistical uncertainty in comparison to the searches performed in pp collisions [25,26]. Moreover, UPCs allow us to probe low-mass ALPs, in contrast with pp collisions, where the tagging of the final state protons only is possible when the invariant mass of the produced state is larger than 200 GeV [25,26]. Furthermore, neither LHCb nor ALICE were designed to reconstruct such high-energy photons but are well-suited for lower-energy photons. Finally, as we will focus on low-transverse-energy photons, this study will provide predictions for the ALICE and LHCb experiments, which are the current detectors able to probe these photons.

This paper is organized as follows. In the next section, we present a brief review of the formalism needed to describe the ALP production in UPCs and describe the search strategy considered in our analysis. In Section 3, we will present initially our predictions at the generator level for the pseudorapidity and transverse momentum distributions of an ALP produced in ultraperipheral PbPb collisions at $\sqrt{s_{NN}} = 5.5$ TeV. The associated distributions for the photons resulting from ALP decays will also be presented. In addition, the results for the fiducial cross-sections, derived by considering the kinematical range covered by the ALICE and LHCb detectors and the implementation of the proposed search strategy, will be shown and discussed. Finally, in Section 4, our main conclusions will be summarized.

2. Search Strategy

The production of axion-like particles in UPCs and its decay into a two-photon system is represented in Figure 1. The associated cross-section can be estimated using the equivalent photon approximation [24,27], which implies that the total cross-section can be factorized as follows:

$$\begin{aligned} \sigma(PbPb \to Pb \otimes \gamma\gamma \otimes Pb; s_{NN}) &= \int \mathrm{d}^2\mathbf{r}_1 \mathrm{d}^2\mathbf{r}_2 \mathrm{d}W \mathrm{d}y \frac{W}{2}\, \hat{\sigma}(\gamma\gamma \to a \to \gamma\gamma; W) \\ &\times \; N(\omega_1, \mathbf{r}_1) N(\omega_2, \mathbf{r}_2) S^2_{abs}(\mathbf{b}) \;, \end{aligned} \quad (2)$$

where $N(\omega_i, \mathbf{r}_i)$ is the number of photons with energy ω_i at a transverse distance $\mathbf{r}_i$ from the center of nucleus, defined in the plane transverse to the trajectory, which is determined by the charge form factor of the nucleus (for a more detailed discussion see, e.g., Ref. [28]). Moreover, $\hat{\sigma}$ is the cross-section of the $\gamma\gamma \to a \to \gamma\gamma$ process, $\sqrt{s_{NN}}$ is the center-of-mass energy of the PbPb collision, $\otimes$ characterizes a rapidity gap in the final state and $W = \sqrt{4\omega_1\omega_2}$ is the invariant mass of the $\gamma\gamma$ system. Finally, in order to exclude the overlap between the colliding nuclei and insure the dominance of the electromagnetic interaction, it is useful to include in Equation (2) the absorptive factor $S^2_{abs}(\mathbf{b})$, which depends on the impact parameter $\mathbf{b}$ of the PbPb collision. The resulting final state is then very clean, consisting of the diphoton system, two intact nuclei, and two rapidity gaps, i.e., empty regions in pseudorapidity that separate the intact very forward nuclei from the $\gamma\gamma$ system. For heavy-ion collisions, the large photon–photon luminosity ($\propto Z_1^2 Z_2^2$, where Z_i are the atomic numbers of the incident particles) implies a large enhancement of the two-photon cross-sections, which allows probing the production of rare SM processes, as, e.g., the light-by-light scattering, as well the search of new physics such as ALPs coupled to photons [2]. In recent years, ATLAS and CMS collaborations reported limits on the ALPs properties considering the diphoton production in UPCs, providing the strongest limits to date in the mass region 5 GeV $\leq m_a \leq$ 100 GeV [21,22].

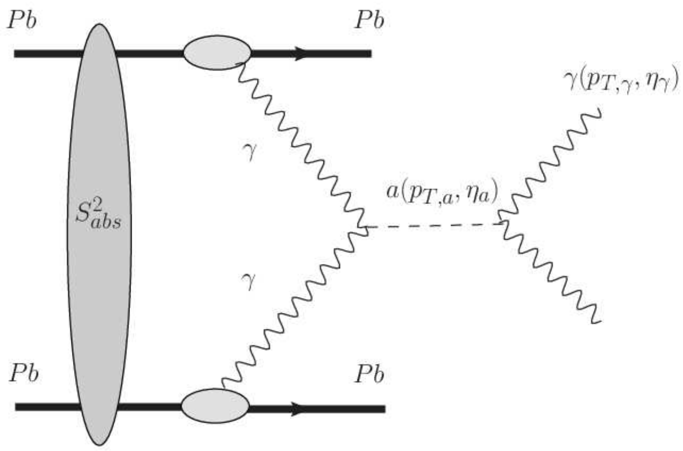

Figure 1. ALP production and decay into a two-photon system through the $\gamma\gamma \to a \to \gamma\gamma$ subprocess in PbPb collisions.

As discussed in the introduction, our focus in this paper is on ALPs with small masses, which generate a diphoton system in their decay. A shortcoming to separate the ALP signal in this region is associated with the fact that the diphoton low-mass spectrum has several standard model background sources such as π^0, η and $\eta'(958)$ [15]. Given the values for the cross-section associated with the ALP production, these sources of background obscure the ALP signal in this kinematical region. To address this challenge and establish a distinct signal region, one promising strategy involves probing ALPs that decay into photons outside the primary vertex luminous region (PV), followed by their conversion into an electron–positron pair. Figure 2 depicts this search strategy. The basic idea is that the reconstructed converted photons can subsequently identify a displaced secondary vertex situated beyond the lead–lead luminous region, differently from the SM light mesons that decay inside the luminous region. In this scenario, the decay rate of an ALP into two photons is determined by its mass and the magnitude of the ALP–photon coupling as follows [4]:

$$\Gamma(a \to \gamma\gamma) = \frac{g^2_{a\gamma\gamma} m_a^3}{64\pi}. \quad (3)$$

Additionally, the ALP decay length is determined by the inverse of the decay rate. As a consequence, ALPs with small masses imply, for a fixed value of $g_{a\gamma\gamma}$, a larger decay length. Accounting for a relativistic boost p_a/m_a and considering an ALP with $p_a = 0.4$ GeV, $m_a = 0.2$ GeV, and $g_{a\gamma\gamma} = 0.1$ TeV^{-1}, the decay length l_{decay} can be written as

$$l_{\text{decay}} \approx 0.1\ \text{cm} \left(\frac{p_a}{0.4\ \text{GeV}} \right) \left(\frac{0.2\ \text{GeV}}{m_a} \right)^4 \left(\frac{0.1\ \text{TeV}^{-1}}{g_{a\gamma\gamma}} \right)^2 \quad (4)$$

which indicates that l_{decay} increases for larger values of p_a and smaller values of m_a and $g_{a\gamma\gamma}$. On the other hand, the primary vertex luminous region is dependent on the characteristic of each detector. In our analysis, we will consider the LHCb and ALICE detectors. The LHCb experiment is a single-arm forward spectrometer covering the pseudorapidity range $2 < \eta < 5$ [29]. Due to material interaction, 25% of the photons convert into an electron–positron pair that are reconstructed as tracks [30]. In contrast, at the ALICE experiment, the same phenomena can take place with a probability of 8.5% [31] for photons with $|\eta| < 0.9$. Note that the conversion probabilities account for the reconstruction efficiency of these photons, which are reconstructed as two-track candidates with invariant masses consistent with zero. Additionally, their flight direction can be determined with high precision based on the conversion position.

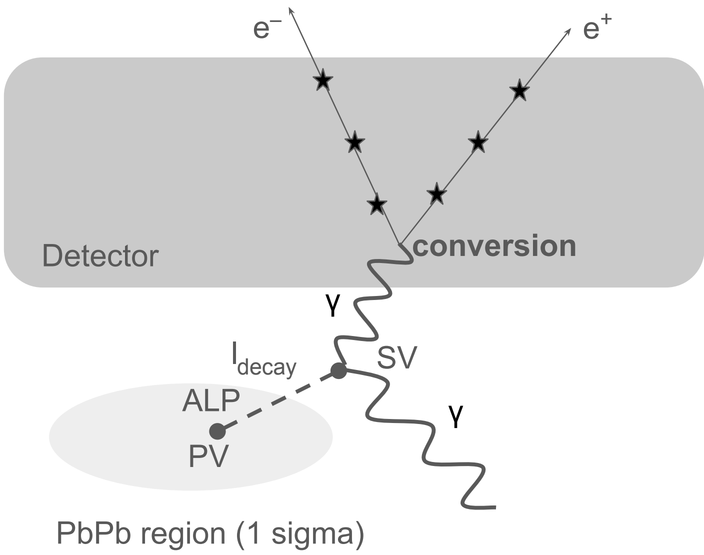

Figure 2. Diagram showing the transverse plane of an ALP decaying into photons outside the luminous region of the PbPb collision. Since the ALP length decay l_{decay} is greater than expected PbPb collision primary vertex (PV), the secondary vertex (SV) of the ALP decay can be identified using photons converted in electron–positron pairs inside the detector. The stars represent the interaction of the electron/positron with the detector.

3. Results

In order to estimate the ALP production in UPCs with the experimental requirements described in the previous section, we will use the SuperChic v4.03 event generator [32]. The ALP candidates will be generated in lead–lead collisions assuming a center of mass energy of 5.5 TeV and that they have masses in the range of 0.2–1 GeV. Following Ref. [32], we will assume that the photon spectrum can be expressed in terms of the electric form factor and that the absorptive corrections $S^2_{abs}(\mathbf{b})$ for $\gamma\gamma$ interactions can be estimated taking into account the multiple scatterings between the nucleons of the incident nuclei, which allows us to calculate the probability for no additional ion–ion rescattering at different impact parameters. The pseudorapidity and transverse momentum of an ALP candidate with $m_a = 0.5$ GeV is shown in Figure 3. One has that the pseudorapidity distribution is larger for central rapidities and the transverse momentum distribution peaks at small $p_{T,a}$, which is expected since the incoming photons, emitted by the lead ions, are characterized by very small transverse momenta [24]. Taking into account the ALP decay into a two-photon system, the resulting photons will also be mainly produced at central rapidities and transverse momentum of the order of 0.22 GeV, as shown in the left and central panels of Figure 4. In addition, the result presented in the right panel, indicate that the photons will be back-to-back in the transverse plane.

Moreover, we impose that the corresponding values must be larger than the sizes of PbPb luminous region in the transverse plane associated with the LHCb and ALICE experiments, which are assumed in this study to be 0.013 cm [29] for the LHCb experiment and 0.5 cm [31] for the ALICE experiment. It is important to emphasize that the background associated with the decay of light mesons is strongly reduced by this assumption, since these mesons decay inside the luminosity region. The candidates selected with the experimental acceptance requirements are used to define fiducial cross-section σ_f as follows:

$$\sigma_f = \sigma \frac{N_{\text{sel}}}{N_{\text{gen}}}, \tag{5}$$

where σ is the ALP cross-section calculated by the event generator SuperChic v4.03 [32], N_{gen} is the generated number of candidates and N_{sel} is the number of ALP candidates after the requirements are applied. The corresponding results for the ALICE and LHCb experiments are presented in Figure 5 considering different values for the ALP–photon coupling and ALP mass. The cross-section is larger for smaller values of m_a, with the maximum value occurring for $g_{a\gamma\gamma}$ of the order of 10^{-5} (10^{-4}) GeV^{-1} at the ALICE (LHCb) detector. Moreover, the values predicted for the LHCb detector are on average one order of magnitude larger than for ALICE, and a larger range of the parameter space is covered by the LHCb detector. Such results are directly associated with the smaller value for the luminous region in LHCb. Given the values for the cross-sections after the implementation of the proposed strategy, we can estimate the corresponding number of events for both experiments. In 2018, the ALICE experiment collected 1 nb^{-1} of integrated luminosity for heavy-ion collisions [33]. As a consequence, the expected number of ALPs decaying into two photons is on the order of 10^{-3} events. In contrast, The LHCb experiment collected 0.25 nb^{-1} of integrated luminosity in 2018 [34], which also suggests that the sensitivity for this search strategy can only be achieved with approximately 10^3 more data. Such results indicate that, although the proposed search strategy eliminates the background associated with the decay of light mesons, the current PbPb luminosities at the ALICE and LHCb detector still are too small to allow us to use it to probe the axion-like particles.

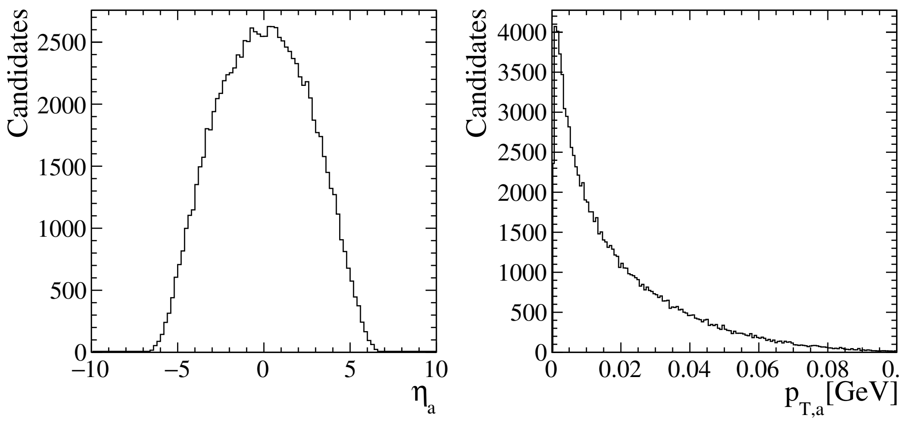

Figure 3. Distributions of (**left**) pseudorapidity and (**right**) transverse momentum of ALP candidates with $m_a = 0.5$ GeV.

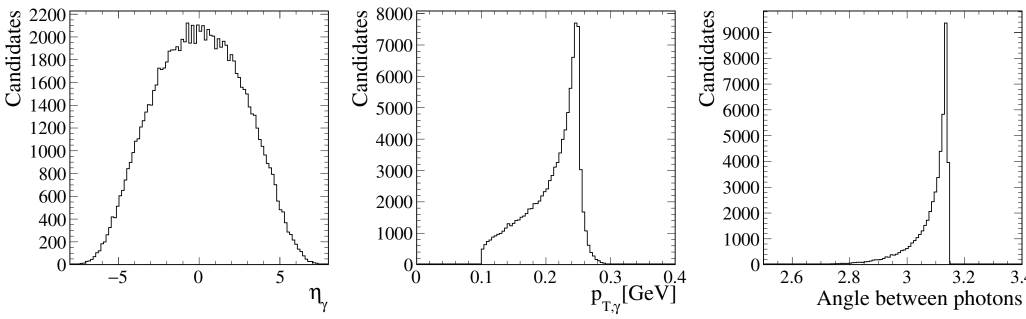

Figure 4. Distributions of (**left**) pseudorapidity and (**center**) transverse momentum of the photons from ALP decays with $m_a = 0.5$ GeV. The azimuthal angle between the two photons from the ALP decay is also shown (**right**).

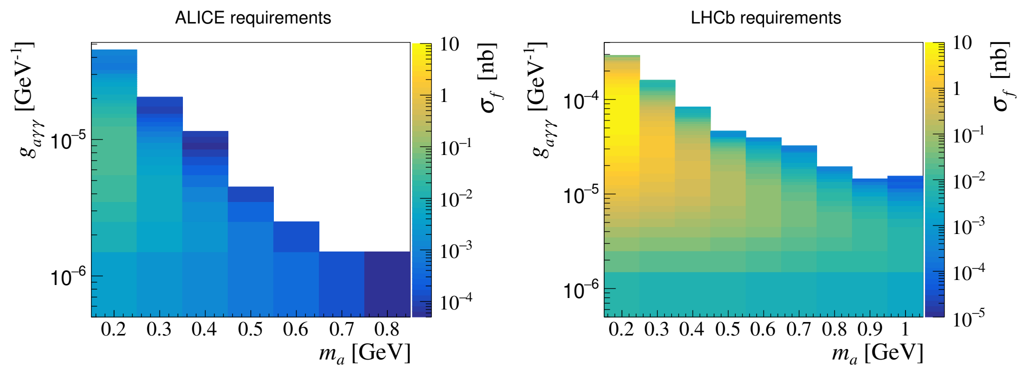

Figure 5. Fiducial cross-sections for ALP production in UPCs for different photon-ALP couplings and ALP masses. The predictions include the acceptance requirements for the photon pseudorapidity, the secondary vertex selection and probability of photon conversion considering the characteristics of the ALICE (left panel) and LHCb (right panel) experiments.

4. Summary

Probing low-mass axion-like particles decaying into two photons remains an experimental challenge due to the large background associated with the decay of light SM mesons. Such a challenge motivates the investigation of new searching strategies. In this paper, we have considered the possibility of eliminating the background by selecting events where the ALP decays outside the luminous region and the photons are converted into electron–positron pairs inside the tracking detector. We have estimated the cross-section for ultraperipheral PbPb collisions at 5.5 TeV and have taken into account the current characteristics of the ALICE and LHCb detectors in the implementation of the proposed searching strategy. Our results indicate that the LHCb detector covers a larger range of values for the ALP mass and ALP–photon coupling when compared to ALICE. However, the current experiment's data sizes imply a very small number of events, making this strategy unfeasible at present. Nevertheless, it is important to emphasize that both experiments collected PbPb collisions in 2023, and more data is expected in the coming years [35,36]. While the predictions of this paper have a limited impact on current or near-future experiments, they present the first results for this novel ALP search strategy using secondary vertex selection in UPC.

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