Searching for axion-like particle at future $ep$ colliders

Chong-Xing Yue, Ming-Ze Liu and Yu-Chen Guo

Department of Physics, Liaoning Normal University, Dalian 116029, China

Abstract

We explore the possibility of searching for axion-like particle (ALP) by $ep$ collisions via the subprocess $e^-\gamma \rightarrow e^-a \rightarrow e^-\gamma\gamma$. Sensitivities to the effective ALP-photon coupling $g_{a\gamma\gamma}$ for its mass in the range of $10 \text{ GeV} < M_a < 3 \text{ TeV}$ are obtained for the LHeC and its high-energy upgrade, FCC-eh. Comparing to existing bounds on the ALP free parameters, we find that the bounds given by $ep$ colliders are competitive and complementary to other colliders.
I. Introduction

Axion-like particles (ALPs) are often defined as relatively light pseudoscalar particles and appear in many extensions of the standard model (SM). In general, any model with global U(1) symmetry, which is spontaneously broken, predicts the existences of ALPs and their masses and couplings are independent parameters. They couple to the SM fermions via dimension-five operators proportional to the fermion mass, while interactions between ALPs and the SM gauge bosons at leading order could be described by the effective Lagrangian including operators of dimension up to five [1]. At tree-level, there is no dimension-five operator contributing to the couplings of ALP to the Higgs boson, which can be induced at loop level or by the high dimension operators [2]. The experimental constraints on the effective couplings of ALP to ordinary particles have been widely studied using various experimental data from particle physics, astro-particle physics and cosmology. Bounds obtained from the LEP and LHC in di-photon, tri-photon and mono-photon final states have been summarized and partly updated in Refs.[3–7].

In general, the couplings of ALP to photons or $Z$ bosons can be considered independently and might be investigated separately. The present and future collider experiments can be used to search for ALPs with masses in the broad range from eV to TeV [3–12]. At $e^+e^-$ colliders, production of ALP can be studied via photon fusion and ALP-strahlung in association with a photon, $Z$ or Higgs boson [3]. At hadron colliders, exotic Higgs decays and $Z$ boson decays are the most promising search channels, which have been studied in Refs. [7–8]. For GeV-scale ALP produced in photon-fusion, heavy-ion collisions at the LHC can provide strong constraints on ALP-photon couplings [10]. Reference [12] has studied the possibility of detecting ALP at the LHC via the process $pp \rightarrow pp\gamma\gamma$ with the subprocess $\gamma\gamma \rightarrow \gamma\gamma$. A number of these constraints are model-independent and tend to vanish at high masses. It is necessary to further study the possibility of searching for ALPs at upcoming or future collider experiments.

At high energies, in addition to the electromagnetic exchange, the electroweak bosons also play important roles. The $\gamma$ or $Z$ boson exchange induces neutral current deep inelastic scattering, which has been extensively explored via $ep$ collisions. In this article, we will consider the possibility of searching for ALP $a$ at the LHeC and FCC-eh in the model-independent way. We assume that its mass is in the range of 10-3000 GeV and
focus on the subprocess $e^{-}\gamma \rightarrow e^{-}a \rightarrow e^{-}\gamma\gamma$, in which the initial photon comes from the initial proton. The analysis of the relevant SM backgrounds and detection efficiencies of the signals from this process are presented. Our numerical results demonstrates that, compared with other colliders, the bounds given by the LHeC on the ALP free parameters for its mass in the range of 10-100 GeV is competitive and complementary. In addition, the FCC-eh can improve the effective search limit up to 2.5 TeV.

This paper is organized as follows. After reviewing the relevant couplings of ALP to photons and $Z$ bosons, we briefly describe the theory framework in Section II. In section III, we calculate the production cross sections of the process $e^{-}p \rightarrow e^{-}a$ at the LHeC and FCC-eh. Our analysis strategy is also discussed in this section. We finalize the prospective sensitivities of $ep$ collider experiments for the ALP parameter space before concluding in section IV.

II. Effective interactions of ALP

The ALPs we consider are gauge singlets under the SM gauge group and are odd under CP. The effective interactions of the ALP with the SM particles at leading order can be described by the general effective Lagrangian including operators of dimension up to five [1]. In this work, we consider the Lagrangian

\begin{equation}
\mathcal{L} = \frac{1}{2} (\partial_{\mu}a)(\partial^{\mu}a) - \frac{1}{2} M_{a}^{2}a^{2} - \frac{C_{BB}}{4f_{a}}aB_{\mu\nu}\tilde{B}^{\mu\nu} - \frac{C_{WW}}{4f_{a}}aW_{i\mu\nu}\tilde{W}_{i,\mu\nu}.
\end{equation}

Where $B_{\mu\nu}$ and $W_{i\mu\nu}$ are the field strength tensors of the gauge groups $U(1)_{Y}$ and $SU(2)_{L}$, and we have defined the dual field strength tensors by $\tilde{B}_{\mu\nu} = \frac{1}{2} \epsilon_{\mu\nu\rho\sigma}B_{\rho\sigma}$. The ALP mass $M_{a}$ and the decay constant $f_{a}$ are supposed to be free parameters. It should be noted that the effective Lagrangian Eq.(1) does not contain all items in the ALP general effective field theory description. For example, we have not considered the couplings of ALP to gluons or fermions because they cause flavour-changing processes. These processes are strongly constrained by rare decay processes[4, 13]. After electroweak symmetry breaking (EWSB), Eq.(1) can give the couplings of ALP to the SM gauge bosons. The relevant terms, which are related our calculation, are written as

\begin{equation}
\mathcal{L} \supset - \frac{g_{a\gamma\gamma}}{4}aF_{\mu\nu}\tilde{F}^{\mu\nu} - \frac{g_{a\gamma Z}}{4}aF_{\mu\nu}\tilde{Z}^{\mu\nu},
\end{equation}
where $F_{\mu\nu}$ and $Z_{\mu\nu}$ denote the field strength tensors of the electromagnetic field and $Z$ field, respectively, and their duals are defined as above. The couplings $g_{a\gamma\gamma}$ and $g_{a\gamma Z}$ can be written as linear combination of the relevant free parameters

$$g_{a\gamma\gamma} = \frac{C_{BB}c_W^2 + C_{WW}s_W^2}{f_a}, \quad g_{a\gamma Z} = \frac{2c_Ws_W(C_{WW} - C_{BB})}{f_a}.$$

Where $s_W = \sin \theta_W$ and $c_W = \cos \theta_W$ with $\theta_W$ being Weinberg angle. It is obvious that there is $g_{a\gamma\gamma} \gg g_{a\gamma Z}$ for $C_{WW} \simeq C_{BB}$. The loop-induced flavor changing processes like $B \to Ka$ can give strong constraints on the coupling parameter $C_{WW}$ [14]. Thus, it is particularly interesting to consider the case $C_{WW} \ll C_{BB}$. From Eq.(3) we can see that there is $g_{a\gamma Z} \approx -2\tan \theta_W g_{a\gamma\gamma}$ in this case.

### III. Search for ALP at ep colliders

Lepton-hadron scattering has played a crucial role in the exploration of the elementary particles over the past 60 years. After the last ep collider (HERA) with the center-of-mass (c. m.) energy $\sqrt{s} = 318$ GeV, it is natural to consider the possibility of future ep colliders. Two ideas have been discussed: the LHeC [15] that uses the electron beam to collide with the existing LHC beam and the FCC-eh that is an option of Future Circular Collider program. With upgrading of the LHC, the LHeC could upgrade into HE-LHeC by HE-LHC. The electron beam collides with the 7 TeV, 13.5 TeV and 50 TeV $p$-beams, which correspond the LHeC, HE-LHeC and FCC-eh, respectively. A final LHeC run in dedicated operation could bring the total integrated luminosity close to 1 ab$^{-1}$. For the HE-LHeC and FCC-eh, we assume that the total integrated luminosity could reach 2 ab$^{-1}$ and 3 ab$^{-1}$, respectively.

Firstly, we will give the production cross sections for the process $e^-p \to e^-\gamma \to e^-a$ at the LHeC with $\sqrt{s} = 1.3$ TeV and FCC-eh with $\sqrt{s} = 3.5$ TeV. Their expressions can be uniformly written as

$$\sigma(e^-p \to e^-a) = \int dx_1 f_{\gamma/p}(x_1, \mu^2) \cdot \tilde{\sigma}(e^-\gamma \to e^-a),$$

where the photon is emitted from the proton and can be described by the photon distribution function $f_{\gamma/p}(x, \mu^2)$. Considering the mass range possible to be explored, we assume that the ALP mass is in the range of $10$ GeV $< M_a < 1.2$ TeV at the LHeC, and
the mass range is broaden to 3 TeV at the FCC-eh. The numerical results show that the production cross section for $g_{a\gamma Z} \approx 0$ is approximately equal to that for the case of $g_{a\gamma Z} = -2 \tan \theta_W g_{a\gamma\gamma}$. This is because the interference effects between the two kinds of Feynman diagrams induced by $\gamma$ and $Z$ exchanges, are negative which counteract contributions of the $a\gamma Z$ coupling. Thus, we only show the cross sections in final state $e^- a$ for the case of $g_{a\gamma Z} = -2 \tan \theta_W g_{a\gamma\gamma}$ in Fig. 1 as functions of the ALP mass $M_a$ and the coupling constant $g_{a\gamma\gamma}$.

![Cross sections of the process $e^- p \rightarrow e^- a$ at the LHeC and FCC-eh as functions of $M_a$ (left) and $g_{a\gamma\gamma}$ (right).](image)

FIG. 1: Cross sections of the process $e^- p \rightarrow e^- a$ at the LHeC and FCC-eh as functions of $M_a$ (left) and $g_{a\gamma\gamma}$ (right).

Now we consider the possibility of searching for ALP in diphoton decay channel $e^- p \rightarrow e^- a \rightarrow e^- \gamma \gamma$. The signature of the final state is characterized by the presence of a pair of photons with an invariant mass equal to the ALP mass and an isolated electron. The final state could provide relatively high target efficiency. The SM backgrounds for this signal are dominated by the QED subprocess $e^- \gamma \rightarrow e^- \gamma \gamma$ with a real emission photon in the final state. Additional small backgrounds for small ALP mass may arise from the subprocess $e^- \gamma \rightarrow e^- \gamma$ with the third photon candidate coming from beam-induced photon. This kind of backgrounds will be reduced using the very good time resolution $\mathcal{O}(\text{ns})$ of the electromagnetic calorimeter at high photon energies [15]. Thus, we assume that beam backgrounds can be reduced to a negligible level without significantly affecting the signal selection efficiency.

Our event selection requires the photon with energy $E(\gamma) > 10$ GeV and pseudo-
rapidity $|\eta(\gamma)| < 2.5$. The invariant mass of the two photons from decays of ALP will peak close to the ALP mass. For the electron in the final state, transverse momentum $p_T(e) > 10$ GeV and $|\eta(e)| < 2.5$ are required. After the basic cuts, we further employ optimized kinematical cuts according to the kinematical differences between the signal and background. In order to carry out our numerical analysis, we use Madgraph5/aMC@NLO [16] as the parton-level event generator, interface to the CT14QED Parton Distribution Functions (PDFs) [17], then Pythia8 [18] for the parton shower, hadronisation. Finally, we take PGS [19] as a detector emulator by using a LHC parameter card suitably modified for the LHeC.

For the final state of the process $e^- p \rightarrow e^- a \rightarrow e^- \gamma \gamma$, the two photons from ALP decay could be a powerful trigger. We choose to reconstruct the energy and angular distributions of the photons in the lab frame. As a result, the following kinematic variables are exploited to develop additional cuts: the angle $\theta(\gamma e)$ between the photon momentum and electron
momentum, the angle $\theta(\gamma\gamma)$ between two photon momentum, transverse momentum $p_T$ of the photon. We also apply an important global observable, the total transverse energy $E_T$. In Fig. 2 we display the normalized distributions of these observables for some particular choices of the model parameters ($M_a = 200, 400, 600, 800, 1000$ GeV with $g_{a\gamma\gamma} = 10^{-3}$) using MadAnalysis 5 [20]. The signals are well distinguished from the corresponding backgrounds by the angle $\theta(\gamma\gamma)$. The electron momentum in the SM backgrounds is mostly along the photon direction which is different from the signal. Just as expected, the distributions show that the photon $p_T$ spectrum peaks at around half of the ALP mass while the electrons in the SM backgrounds tend to be soft. Considering the kinematics, we impose the following improved cuts:

$$
\begin{align*}
p_T(\gamma) &> 70 \text{ GeV}, \quad \theta(e\gamma) > 2.2, \\
E_T &> 160 \text{ GeV}, \quad \theta(\gamma\gamma) > 2.7.
\end{align*}
$$

These cuts could effectively remove the SM backgrounds. The event selection efficiency has been optimized with respect to the signal, and the statistical significance $S = S/\sqrt{S + B}$, where $S$ and $B$ respectively denote the numbers of signal and background events, are summarized. Here, part of results are shown in Table I.

| Cuts                  | Signal (S) | Background (B) | $S/\sqrt{S + B}$ |
|-----------------------|------------|----------------|------------------|
| initial (no cut)      | 126        | 34910          | 0.674            |
| basic cuts            | 116.12     | 32147.7        | 0.6465           |
| $E_T > 160 \text{ GeV}$ | 112.90     | 2144.3         | 2.3764           |
| $\theta(\gamma e) > 2.2$ | 112.51     | 2068.5         | 2.4091           |
| $p_T(\gamma) > 70 \text{ GeV}$ | 112.40     | 1839.1         | 2.5443           |
| $\theta(\gamma \gamma) > 2.7$ | 107.77     | 443.0          | 4.592            |

Several types of experiments are used to search for ALP, ranging from the searches for direct production of ALP at colliders to those from cosmological and astro-particle
physics experiments. The constraints from these searches can be mapped into the $M_a - g_{a\gamma\gamma}$ plane which are shown in green sectors in Fig. 3. The most competitive bounds for very light ALPs with masses below the MeV scale come from the astrophysics and cosmology, but we consider the ALP mass range here begin with $M_a \sim 10$ GeV, for which collider experiments provide the best limits. Thus, in Fig. 3, we do not show the constraints on the very light ALP. At GeV scale, Ref. 6 provided the excluded parameters region by data from BaBar 23 and LHCb 24, which is adopted here labelled Flavour. For about 10 to 100 GeV, the bounds labelled L3 in Fig. 3 is from the analysis of Ref. 21, in which the L3 collaboration looked for hadronic final states accompanied by a hard photon 22, though it is ultimately superseded by LHC exclusions. For the high ALP mass near the TeV scale, the limits from data of the LHC run 1 25 are extremely strong and should be improved with the addition of run 2 data, especially at higher energies.

![Figure 3: Projected $ep$ colliders sensitivity at 95% CL and existing constraints on the ALP with photon coupling. The green regions are experimentally excluded.](image)

The projected sensitivity contours at 95% CL for the process $e^- p \rightarrow e^- a \rightarrow e^- \gamma\gamma$ at future $ep$ colliders are summarized in Fig. 3. From this figure, one can see that, for the light ALP (i.e. $10$ GeV < $M_a$ < $100$ GeV), di-photon searches for the LHeC and FCC-eh can push significantly beyond current constraints from existing experiments and can
potentially probe the ALP-photon coupling $g_{a\gamma\gamma}$ with the order of $g_{a\gamma\gamma} \sim 10^{-5}$ to $10^{-4}$. Furthermore, the FCC-eh will be sensitive to ALP in a larger range of the parameter space and can significantly improve over existing bounds on ALP from the LHC.

**IV. Conclusions**

The existence of ALPs is a generic feature of many extensions of the SM that extend well beyond axions. Both axions and ALPs may be excellent candidates to explain the nature of dark matter (DM). As pseudo-Goldstone bosons, ALPs can naturally and very weakly couple to the SM particles dominantly by couplings to photons and electroweak gauge bosons. A particular interesting scenario is ALPs decay into a pair of photons.

In this paper, we have investigated the search for ALP diphoton signal at future $ep$ colliders via the process $e^- p \rightarrow e^- a \rightarrow e^- \gamma\gamma$ in a model-independent fashion. Considering the mass range to be possible explored at the LHeC and FCC-eh, we focus on $10 \text{ GeV} < M_a < 3 \text{ TeV}$. A proper treatment of several useful observables is presented according to the kinematical differences between the signals and relevant SM backgrounds based on the simulation performance. We apply an appropriate statistical treatment to obtain the expected bounds on the ALP free parameters. Our central observation is that existing bounds on the ALP-photon coupling for the mass interval 10-100 GeV can be significantly improved via searching for the diphoton signal at the LHeC and FCC-eh. Moreover, the FCC-eh can improve the effective search limit to 2.5 TeV. Thus, we can say that searching for ALP at future $ep$ colliders might become an important handle on new physics scenarios, which are related ALP.

**Acknowledgement**

This work was supported in part by the National Natural Science Foundation of China under Grants No.11875157, 11847303 and 11847019.

[1] H. Georgi, D. B. Kaplan and L. Randall, Phys. Lett. B 169 (1986) 73.
[2] M. Bauer, M. Neubert and A. Thamm, Phys. Rev. Lett. 117 (2016) 181801.

[3] M. J. Dolan, T. Ferber, C. Hearty, F. Kahlhoefer, and K. Schmidt-Hoberg, JHEP 1712 (2017) 094.

[4] K. Choi, S. H. Im, C. B. Park, S. Yun, JHEP 1711 (2017) 070; F. Arias-Aragon and L. Merlo, JHEP 1710 (2017) 168.

[5] N. Craig, A. Hook, S. Kasko, JHEP 1809 (2018) 028; M. Bauer, M. Heiles, M. Neubert, A. Thamm, Eur. Phys. J. C79 (2019) 74.

[6] X. C. Vidal, A. Mariotti, D. Redigolo et al., JHEP 1901 (2019) 113.

[7] M. Bauer, M. Neubert, A. Thamm, JHEP 1712 (2017) 044; I. Brivio, M. B. Gavela, L. Merlo, K. Mimasu, J. M. No, R. del Rey, V. Sanz, Eur. Phys. J. C 77 (2017) 572; M. B. Gavela, R. Houtz, P. Quilez, and R. Del Rey, arXiv:1901.02031 [hep-ph].

[8] K. Mimasu and V. Sanz, JHEP 1506 (2015) 173; J. Jaeckel and M. Spannowsky, Phys. Lett. B 753 (2016) 482.

[9] M. Kleban and R. Rabdan, arXiv:0510183 [hep-ph]; S. Chang, P. J. Fox and N. Weiner, Phys. Rev. Lett. 98 (2007) 111802;

[10] S. Knapen, T. Lin, H. K. Lou and T. Melia, Phys. Rev. Lett. 118 (2017) 171801.

[11] M. Bauer, M. Neubert and A. Thamm, Phys. Rev. Lett. 119 (2017) 031802; J. Heeck, W. Rodejohann, Phys. Lett. B 776 (2018) 385; G. Cacciapaglia, G. Ferretti, T. Flacke, H. Serodio, Eur. Phys. J. C78 (2018) no.9, 724.

[12] C. Baldenegro, S. Fichet, G. Von Gersdorff et al., JHEP 1806 (2018) 131.

[13] M. J. Dolan, F. Kahlhoefer, C. McCabe et al., JHEP 1503 (2015) 171.

[14] E. Izaguirre, T. Lin, B. Shuve, Phys. Rev. Lett. 118 (2017) no.11, 111802; F. Björkeroth, E. J. Chun, S. F. King, JHEP 1808 (2018) 117.

[15] J. Abelleira Fernandez and others, J. Phys. G39 (2012) 075001; F. Zimmermann, O. Bruning and M. Klein, Report No. C13-05-12, p.MOPWO054.

[16] J. Alwall, R. Frederix, S. Frixione et al., JHEP 1407 (2014) 079.

[17] C. Schmidt, J. Pumplin, D. Stump and C. P. Yuan, Phys. Rev. D 93, no. 11, 114015 (2016).

[18] T. Sjöstrand, S. Mrenna and P. Skands, Comput. Phys. Comm. 178 (2008) 852.

[19] J. Conway, R. Culbertson, R. Demina, et al.,
http://conway.physics.ucdavis.edu/research/software/pgs/pgs4-general.htm
[20] E. Conte, B. Fuks, G. Serret, Comput. Phys. Commun. 184, 222 (2013).

[21] G. Alonso-Álvarez, M. B. Gavela, P. Quilez, JHEP 1901 (2019) 113.

[22] O. Adriani et al. (L3 Collaboration), Phys. Lett. B292 (1992) 472.

[23] J. P. Lees et al. (BaBar Collaboration), Phys. Rev. Lett. 107 (2011) 221803, arXiv:1108.3549[hep-ex].

[24] S. Benson and A. Puig Navarro, Report No. LHCb-PUB-2018-006. CERN-LHCb-PUB-2018-006. https://cds.cern.ch/record/2314368.

[25] J. Jaeckel, M. Jankowiak, and M. Spannowsky, Phys. Dark Univ. 2 (2013) 111; A. Mariotti, D. Redigolo, F. Sala, and K. Tobioka, Phys. Lett. B783 (2018) 13.