

Probing the axion-photon-dark photon interaction at future e^+e^- colliders

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We study the interaction between photons, dark photons, and axions at future lepton colliders, focusing on single-photon events with missing energy as the experimental signature. We find that future facilities such as the International Linear Collider, Circular Electron-Positron Collider, and Future Circular Collider will be sensitive to the axion-photon-dark photon coupling down to the order of 10^{-4} GeV^{-1} for dark photon masses around $\mathcal{O}(10 \text{ GeV})$, assuming that the axion is extremely light and escapes detection. We further show that longitudinal beam polarization at the International Linear Collider can enhance the signal significance by a factor of 4, providing the strongest projected reach in the model parameter space. Existing constraints from Large Electron-Positron II are analyzed for comparison. Furthermore, the mass of dark photon can be determined by measuring the sharp dropoff in the distribution of the recoil mass.

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I. INTRODUCTION

The exploration of light and weakly coupled particles beyond the Standard Model (SM) is interesting on its own in the search for new physics. Among the most theoretically motivated candidates are axions, originally proposed to solve the strong CP problem (see, e.g., [1] for a review), and dark photons, which arise as gauge bosons of hidden $U(1)$ symmetries appearing in many extensions of the SM, including string-theoretic and grand unification models (see, e.g., [2] for a review).

Both axions and dark photons are typically light and feebly interacting with the visible sector through higher-dimensional operators or a kinetic mixing term. Of particular interest is the possibility of an interaction vertex involving an axion, a photon, and a dark photon, which can arise naturally in UV completions involving heavy fermions charged under both SM and dark gauge groups [3,4]. This interaction gives rise to a rich phenomenology not only in astrophysical and cosmological contexts [5–17], but also in collider and reactor experiments, where it leads to

distinctive signatures beyond those induced by kinetic mixing alone [18–21]. Moreover, the axion-photon-dark photon interaction has also been studied in various other contexts [22,23].

In this work, we explore the phenomenology of the axion-photon-dark photon interaction at Large Electron-Positron (LEP) II and future lepton colliders. In particular, we study processes $e^+e^- \rightarrow \gamma'$ and $e^+e^- \rightarrow \gamma'a$ followed by decay $\gamma' \rightarrow \gamma a$, where γ' and a represent dark photon and axion, respectively. These processes yield the same collider signature consisting of a single photon plus missing energy, as the axion escapes detection. The single-photon signature is especially clean at lepton colliders because of the relatively low and well-understood backgrounds. We analyze existing data from LEP II to place constraints on the axion-dark photon-photon coupling and then project the sensitivity of future machines such as the International Linear Collider (ILC) [24,25], the Future Circular Collider (FCC-ee) [26], and the Circular Electron-Positron Collider (CEPC) [27]. In addition, we demonstrate that the recoil-mass spectrum in these events contains a distinctive maximum feature that can be used to reconstruct the mass of dark photon. We also demonstrate the enhancement of the signal significance using the longitudinal polarized beams at the ILC.

This paper is organized as follows. In Sec. II, we present the theoretical framework; in Sec. III, we analyze the signal at LEP and future colliders; in Sec. IV, we analyze the signal at ILC with polarized beams; finally, we conclude our findings in Sec. V.

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II. THE MODEL

We consider a dark sector involving a light pseudoscalar a and a dark photon γ' that originate from a broken $U(1)_D$ global symmetry and a broken $U(1)_X$ gauge symmetry [3,4], respectively. The relevant interactions can be described by an effective Lagrangian that includes both kinetic mixing and a dimension-five operator involving the axion, dark photon, and SM photon:

$$\mathcal{L} \supset -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\epsilon}{2c_W}F_{\mu\nu}F'^{\mu\nu} + \frac{g_{a\gamma'\gamma}}{2c_W}aF_{\mu\nu}\tilde{F}'^{\mu\nu}, \quad (1)$$

where c_W stands for cosine of the weak mixing angle, $F_{\mu\nu}$ and $F'_{\mu\nu}$ are the field strength tensors of the hypercharge and the dark photon, respectively, and $\tilde{F}'^{\mu\nu} \equiv \frac{1}{2}\epsilon^{\mu\nu\rho\sigma}F'_{\rho\sigma}$ is the dual field strength. The coupling $g_{a\gamma'\gamma}$ has a dimension of 1/mass, and its magnitude depends on the UV completion, such as heavy fermion loops or anomaly-induced interactions.

Because of kinetic mixing, the dark photon can decay into SM particles. The partial decay width of the dark photon into a pair of charged leptons is given by

$$\Gamma(\gamma' \rightarrow \ell^+\ell^-) = \frac{\epsilon^2 e^2}{12\pi} m_{\gamma'} \left(1 + \frac{2m_\ell^2}{m_{\gamma'}^2}\right) \sqrt{1 - \frac{4m_\ell^2}{m_{\gamma'}^2}}, \quad (2)$$

where e is the electromagnetic coupling and $m_{\gamma'}$ and m_ℓ are masses of the dark photon and lepton ℓ , respectively.

For hadrons, partial decay widths can be related to the muon channel via

$$\Gamma(\gamma' \rightarrow \text{hadrons}) = \Gamma(\gamma' \rightarrow \mu^+\mu^-) \times R(m_{\gamma'}^2), \quad (3)$$

where the function

$$R(m_{\gamma'}^2) \equiv \frac{\sigma(e^+e^- \rightarrow \text{hadrons})}{\sigma(e^+e^- \rightarrow \mu^+\mu^-)}$$

encodes the effects of hadronic resonances and the mixing of the dark photon with QCD vector mesons. The values of $R(m_{\gamma'}^2)$ can be taken from measurements [28].

As γ' is heavy enough, it could decay into a SM W -boson pair. The partial decay width is

$$\Gamma(\gamma' \rightarrow W^+W^-) = \frac{\epsilon^2 e^2}{192\pi} m_{\gamma'} \left(\frac{m_{\gamma'}}{m_W}\right)^4 \left(1 - 4\frac{m_W^2}{m_{\gamma'}^2}\right)^{3/2} \lambda(x), \quad (4)$$

where $\lambda(x) = 1 + 20x^2 + 12x^4$ with $x = m_W/m_{\gamma'}$.

In addition, the dimension-five operator allows the decay $\gamma' \rightarrow \gamma a$ and $\gamma' \rightarrow Z a$ when kinematically allowed, with partial widths given by

$$\Gamma(\gamma' \rightarrow a\gamma) = \frac{g_{a\gamma'\gamma}^2}{96\pi} m_{\gamma'}^3 \left(1 - \frac{m_a^2}{m_{\gamma'}^2}\right)^3, \quad (5)$$

$$\Gamma(\gamma' \rightarrow aZ) = \frac{t_W^2 g_{a\gamma'\gamma}^2}{96\pi} m_{\gamma'}^3 \left\{ \left[1 - \left(\frac{m_Z - m_a}{m_{\gamma'}}\right)^2\right] \times \left[1 - \left(\frac{m_Z + m_a}{m_{\gamma'}}\right)^2\right]^{3/2} \right\}, \quad (6)$$

where t_W is the tangent of the weak mixing angle and m_a is the mass of the axion. In the kinematically allowed region and for a light axion, the decay $\gamma' \rightarrow a\gamma$ dominates over $\gamma' \rightarrow aZ$ because the latter is suppressed by t_W^2 and the phase space factor. Furthermore, when $m_{\gamma'} g_{a\gamma'\gamma} \gtrsim \epsilon$, the partial width $\Gamma(\gamma' \rightarrow a\gamma)$ exceeds the decay widths into SM leptons and hadrons, making the axion-photon channel the leading decay mode of the dark photon. This is the parameter space on which we focus in this paper.

A heavy dark photon, without the existence of axion, has been searched at the CERN Large Hadron Collider (LHC) using $pp \rightarrow \gamma'$ with $\gamma' \rightarrow \mu^+\mu^-$ for a dark photon up to 70 GeV by the LHCb Collaboration [29] and up to 200 GeV by the CMS Collaboration [30]. The kinematic mixing parameter $\epsilon^2 \gtrsim 10^{-6}$ (10^{-5}) is excluded for $m_{\gamma'} \simeq 10$ GeV (70 GeV) [29], and $\epsilon^2 \gtrsim 5 \times 10^{-5}$ as $m_{\gamma'} = 200$ GeV [30]. Searches for the heavy dark photon at future lepton colliders have also been studied in Refs. [31,32].

III. PHOTONS AND MISSING ENERGY AT LEPTON COLLIDERS

The presence of axion-photon-dark photon interaction leads to photon signatures at e^+e^- colliders, particularly single-photon events with missing energy. These arise from processes such as $e^+e^- \rightarrow \gamma' \rightarrow \gamma a$ and $e^+e^- \rightarrow \gamma^*/Z \rightarrow a\gamma'$, followed by $\gamma' \rightarrow \gamma a$ as depicted in Fig. 1. If the axion is sufficiently light and weakly coupled to the SM particles, it escapes detection and causes missing energy. In this study, we first constrain the parameter space using LEP II data [33,34]. Then we further consider future colliders, such as ILC, FCC-ee, and CEPC.

A. LEP II

Single-photon events with missing energy have been studied at the LEP to search for supersymmetry and extra dimensions [33,34].¹ The results can be applied to the search for dark photons shown in Fig. 1. Two production channels contribute to signal events: (i) $e^+e^- \rightarrow \gamma' \rightarrow \gamma a$ and (ii) $e^+e^- \rightarrow \gamma^*/Z \rightarrow a\gamma'$ with $\gamma' \rightarrow \gamma a$. It should be noted that channel (i) is proportional to ϵ^2 , while channel

¹Multiple-photon plus missing-energy events at LEP can also constrain the interactions in Eq. (1), although these constraints are weaker than those from single-photon events (see Appendix A).

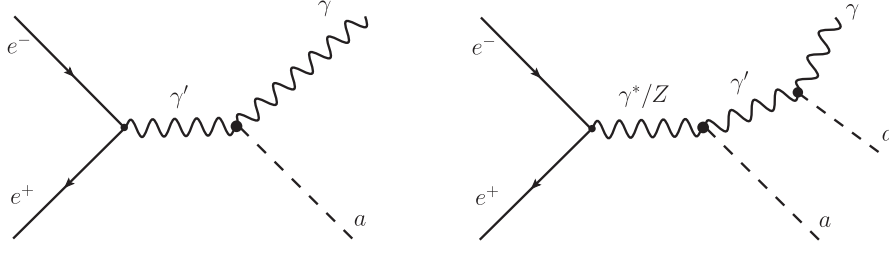


FIG. 1. Feynman diagrams for the single-photon plus missing-energy signal.

(ii) is proportional to $g_{a\gamma'\gamma}^2$. Figure 2 shows the production cross section of $a\gamma'$ at LEP. The contribution from the Z-boson exchange diagram is significantly smaller than that from the off-shell photon exchange. This suppression arises from the weak mixing angle in the $Za\gamma'$ coupling, as well as the additional propagator suppression from the Z-boson mass.

We used the observed number of single-photon events at total energy $\sqrt{s} = 189$ GeV with selection of transverse momentum of photon $p_T(\gamma) > 0.02\sqrt{s}$ from Table 2 in Ref. [34]. Assuming a detector efficiency of 80% and a theoretical uncertainty of 1% and applying the CL_s method, we obtain a bound on the cross section for the single-photon plus the missing-energy process of ~ 0.32 pb at the 95% confidence level. Applying this bound, we obtain constraints on ϵ and $g_{a\gamma'\gamma}$ for various $m_{\gamma'}$ assuming extremely light m_a . In our study, we take $m_a = 1$ MeV for simplicity. The left panel in Fig. 3 shows the constraints of two couplings, $g_{a\gamma'\gamma}$ and ϵ for $m_{\gamma'} = 20$ GeV. The region above the red curve is excluded, since more single-photon events are generated than expected. We see that the cross section is insensitive to ϵ as $g_{a\gamma'\gamma} \gtrsim 10^{-3}$ GeV⁻¹, which means that the process (ii) dominates. A slightly weaker bound is observed at large ϵ where the decay branching ratio $\text{Br}(\gamma' \rightarrow \gamma a)$ decreases.

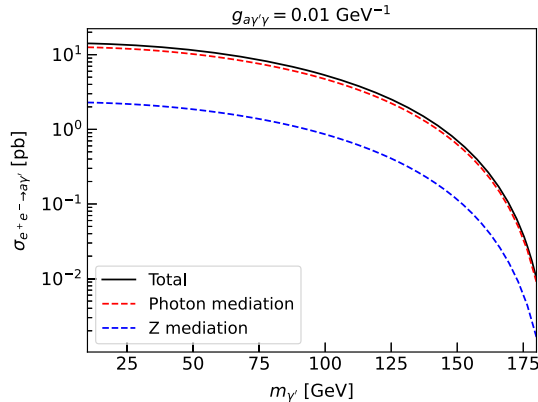


FIG. 2. The production cross section of $a\gamma'$ at LEP. The solid black line represents the total cross section, while the dashed red and blue lines indicate the individual contributions from photon and Z-boson exchange diagrams, respectively. We fix $g_{a\gamma'\gamma} = 0.01$ GeV⁻¹.

Because of the presence of the kinetic mixing term, characterized by the parameter ϵ in Eq. (1), the Z-boson mass and its couplings are modified. These deviations are tightly constrained by precision Z-pole measurements at LEP [35,36]. In addition, searches for narrow resonances decay into dileptons at the LHC impose bounds on dark photon production and its branching ratio into leptons. We recast the constraints from the CMS dimuon search [30] accordingly (see Appendix B). The resulting exclusions projected in $(\epsilon, g_{a\gamma'\gamma})$ plane are shown as the gray regions in the left panel in Fig. 3 for a representative dark photon mass $m_{\gamma'} = 20$ GeV. Combining CMS dilepton searches, Z-pole, and LEP data, we find the viable parameter space is $g_{a\gamma'\gamma} \lesssim 1.5 \times 10^{-3}$ GeV⁻¹ and $\epsilon \lesssim 2.0 \times 10^{-3}$.

The right panel in Fig. 3 shows the projection of the LEP constraints on the $(m_{\gamma'}, g_{a\gamma'\gamma})$ plane, assuming that $\epsilon \ll m_{\gamma'} g_{a\gamma'\gamma}$ satisfied the Z-pole and CMS dimuon searches constraints. Also, the red curve shows the upper limit of the single-photon plus missing-energy production cross section.²

B. Future e^+e^- colliders

We analyze the single-photon signal with missing energy at future e^+e^- colliders. Simulations of signal and SM background processes are performed using MadGraph5 [37]. The dominant background is $e^+e^- \rightarrow \nu\bar{\nu}\gamma$, with a leading-order cross section of ~ 1.56 pb at $\sqrt{s} = 250$ GeV.

The distributions of recoil mass and photon polar angle are shown in Fig. 4. A characteristic dropoff is seen in the histogram of recoil mass, which is related to the mass of the dark photon. For heavier dark photons, the photon from dark photon decay is more energetic. Therefore, the upper bound of the recoil mass is smaller, according to the definition $M_{\text{recoil}}^2 = s - 2\sqrt{s}E_\gamma$, where E_γ is the energy of the observed photon. We also notice that the recoil-mass distribution exhibits sharp edges at $M_{\text{recoil}}^{\text{max}}$, allowing the dark photon mass to be reconstructed via

$$m_{\gamma'} = \sqrt{s - (M_{\text{recoil}}^{\text{max}})^2}. \quad (7)$$

²We note that this constraint from LEP excludes the region that explains the muon $g - 2$ anomaly studied in [22].

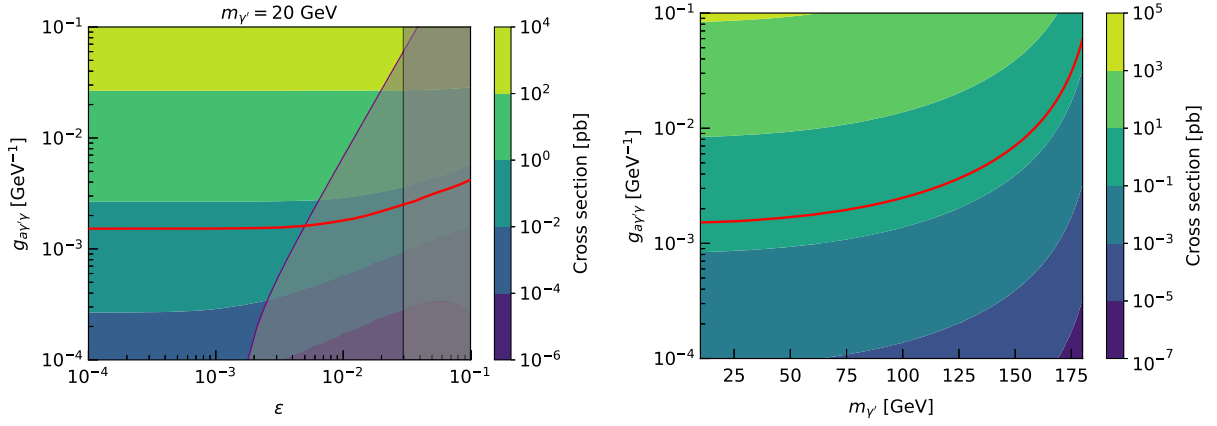


FIG. 3. Constraints from LEP single-photon data (red line) projected on the $(\epsilon, g_{A\gamma\gamma})$ plane (left) and the $(m_{\gamma'}, g_{A\gamma\gamma})$ plane (right). In the left panel, we fix $m_{\gamma'} = 20$ GeV, while in the right panel, we set $\epsilon \ll m_{\gamma'} * g_{A\gamma\gamma}$. The color gradient indicates the total cross section of the signal processes. The upper bound of cross section is shown with the red curve. The gray regions to the right of the solid purple and solid black curves are excluded by CMS dimuon searches [30] and by precision measurements at the Z pole [35,36], respectively.

Two peaks are shown in the SM background: The peak at the Z-boson mass comes from $e^+e^- \rightarrow \gamma Z(\rightarrow \nu\bar{\nu})$, while another one close to the total energy is contributed by a three-body final state of $e^+e^- \rightarrow \gamma\nu_e\bar{\nu}_e$ through a W boson mediated in the t channel and with initial-state radiations. Heavier dark photons also lead to broader angular distributions of the emitted photon. In contrast, SM background photons are concentrated near the beam line.

To optimize the signal-to-background ratio, we apply the following cuts:

$$M_{\text{recoil}} \notin [m_Z - 2\Gamma_Z, m_Z + 2\Gamma_Z], \quad (8)$$

$$|\cos\theta_\gamma| < 0.75, \quad (9)$$

where m_Z and Γ_Z are the Z-boson mass and the total decay width, respectively. After applying these cuts, the

background is reduced by $\sim 65\%$, while the pass efficiency of the dark photon signal ranges from 65% to 80% depending on $m_{\gamma'}$. The resulting cross sections after selections for $m_{\gamma'} \geq 20$ GeV are shown in Fig. 5. For $m_{\gamma'} \lesssim 100$ GeV, the signal cross sections remain almost unchanged, since the total energy $\sqrt{s}$ is much higher than $m_{\gamma'}$. We compute event yields as $N_{s,b} = \sigma_{s,b} \times \mathcal{L}$ is the number of events after the selections with the lower scripts s and b representing the dark-photon signals and the SM background, respectively, and $\mathcal{L}$ is the integrated luminosity. Taking the projected luminosity shown in Table I for different colliders in the future, we then evaluate the significance $\mathcal{Z} = N_s/\sqrt{N_b}$. Requiring $\mathcal{Z} = 5$, we obtain projected sensitivities for ILC, FCC-ee, and CEPC shown in Fig. 6. These machines are sensitive to the coupling $g_{A\gamma\gamma}$ down to $\sim 10^{-4}$ GeV $^{-1}$ for $m_{\gamma'} \sim \mathcal{O}(10\text{--}100)$ GeV. For heavier dark photons with

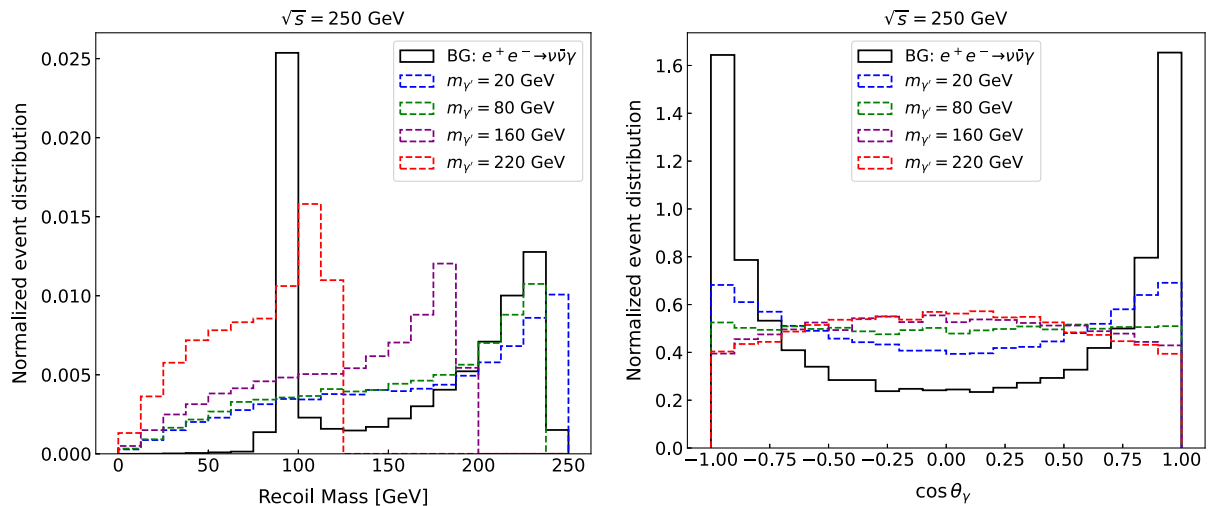


FIG. 4. Recoil-mass distribution (left) and photon polar angle distribution (right). The solid black histogram represents the SM background; dashed curves correspond to signal with $m_{\gamma'} = 20, 80, 160, 200$ GeV (blue, green, purple, and red, respectively).

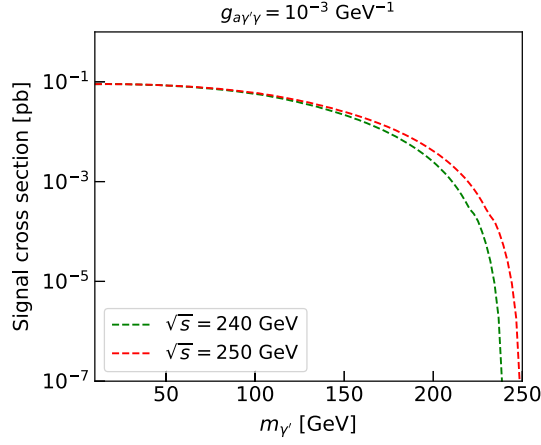


FIG. 5. Signal cross section after selection cuts for $\sqrt{s} = 240$ (green dashed line) and 250 GeV (red dashed line). We fix $g_{a\gamma\gamma} = 10^{-3} \text{ GeV}^{-1}$, $m_a = 1 \text{ MeV}$, and $\epsilon \ll g_{a\gamma\gamma} m_{\gamma'}$.

$m_{\gamma'} \gtrsim 200 \text{ GeV}$, these e^+e^- colliders quickly fail to probe $g_{a\gamma\gamma}$ with single-photon events due to the limited total energy.

IV. POLARIZATION SEARCH AT THE ILC

Beam polarization is one of the key advantages of the ILC which can enhance the sensitivity to the $e^+e^- \rightarrow a\gamma'$ signal. Let P_{e^-} and P_{e^+} denote the longitudinal polarizations of the electron and positron beams, respectively. The polarized cross section is given by [38]

$$\begin{aligned} \sigma(P_{e^-}, P_{e^+}) = & \frac{1}{4} [(1 + P_{e^-})(1 + P_{e^+})\sigma_{RR} \\ & + (1 - P_{e^-})(1 - P_{e^+})\sigma_{LL} \\ & + (1 + P_{e^-})(1 - P_{e^+})\sigma_{RL} \\ & + (1 - P_{e^-})(1 + P_{e^+})\sigma_{LR}], \end{aligned} \quad (10)$$

where σ_{ij} denotes the cross section for initial helicities i (electron) and j (positron).

For an s -channel process mediated by a spin-1 gauge boson, the total angular momentum along the beam axis must satisfy $J_z = \pm 1$. This implies that only opposite-helicity configurations contribute, while the same-helicity (LL and RR) states vanish in the ultrarelativistic limit [38].

For the SM background $e^+e^- \rightarrow \nu\bar{\nu}\gamma$, the dominant contribution arises from t -channel W exchange, which

TABLE I. Projected luminosities at future e^+e^- colliders.

Collider	$\sqrt{s}$ (GeV)	Luminosity (ab $^{-1}$)	Notes
ILC [25]	250	2.0	10-year Higgs factory phase
FCC-ee [26]	240	5.0	3-year Higgs factory phase
CEPC [27]	240	13.0	10-year operation with 30 MW synchrotron radiation power

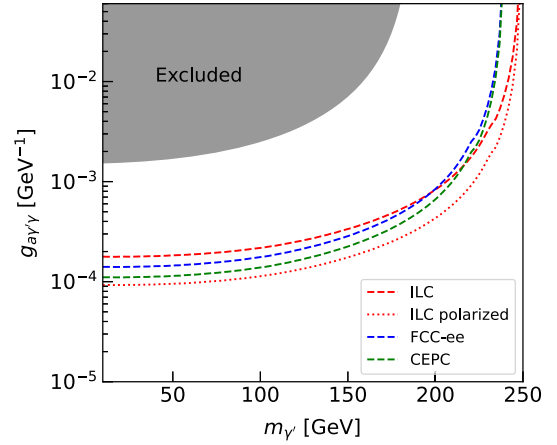


FIG. 6. Sensitivity projections at ILC (red dashed line), FCC-ee (blue dashed line), and CEPC (green dashed line) on the $(m_{\gamma'}, g_{a\gamma\gamma})$ plane. The red dotted line denotes the projected sensitivity at the ILC with longitudinally polarized beams (see Sec. IV for details). The gray region is excluded by LEP II data.

couples only to left-handed electrons and right-handed positrons, whereas the s -channel Z exchange contributes almost equally to both the LR and RL channels. Thus, the LR configuration provides the largest contribution. The same-helicity cross sections vanish in both SM background channels. At leading order and $\sqrt{s} = 250 \text{ GeV}$, we find $\sigma_{LR}^{\text{BG}} \simeq 8.17 \text{ pb}$ and $\sigma_{RL}^{\text{BG}} \simeq 2.70 \text{ pb}$.

In contrast, the signal exhibits the opposite helicity preference. As shown in Fig. 7, we find $\sigma_{RL}^{\text{sig}} \simeq 5 \times \sigma_{LR}^{\text{sig}}$ for the dominant signal process $e^+e^- \rightarrow a\gamma'$ (with $\gamma' \rightarrow a\gamma$) at $\sqrt{s} = 250 \text{ GeV}$. The difference between the LR and RL signal cross sections originates from the interference between the photon- and Z -exchange amplitudes. For $\sqrt{s} > m_Z$, this interference is constructive in the RL channel and

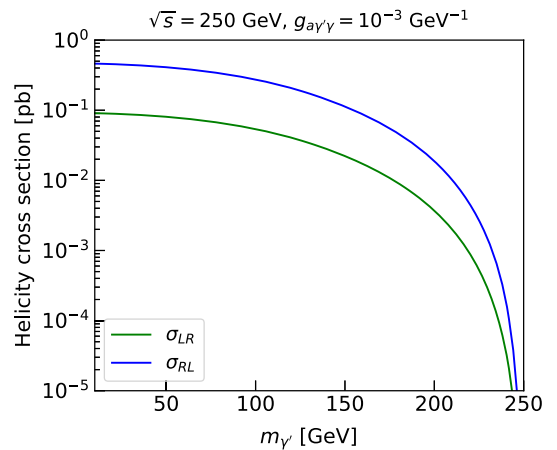


FIG. 7. Helicity cross sections for the signal processes at $\sqrt{s} = 250 \text{ GeV}$. The green line represents the cross section for initial left-handed electron and right-handed positron (σ_{LR}), and the blue line indicates the cross section for initial right-handed electron and left-handed positron (σ_{RL}).

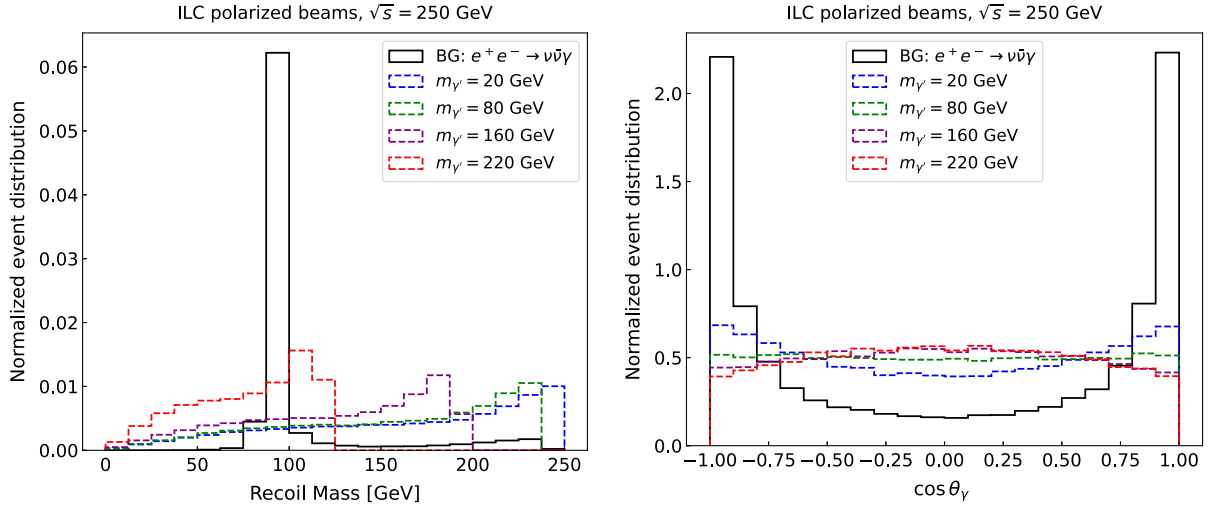


FIG. 8. The same as Fig. 4, but with longitudinal polarized beams $P_{e^-} = +0.8$ and $P_{e^+} = -0.3$ at the ILC.

destructive in the LR channel, leading to an enhancement of σ_{RL}^{sig} and a suppression of σ_{LR}^{sig} .

Since the background is dominated by the LR channel, while the signal is largest in the RL channel, the optimal strategy is to enhance the RL contribution and suppress the LR one. Within the standard ILC baseline capabilities [24], a representative choice is $P_{e^-} \simeq +0.8$ and $P_{e^+} \simeq -0.3$, which increases the weight of σ_{RL} and simultaneously reduces that of σ_{LR} .

In Fig. 8, we show the normalized recoil-mass and photon polar angle distributions for the ILC beam-polarized setup. Compared to the unpolarized case in Fig. 4, the high recoil-mass background events originating from t -channel W exchange are significantly suppressed, while the signal distribution remains largely unchanged. The photon polar angle distribution is also very similar to the unpolarized case.

Using the same kinematic cuts in Eqs. (8) and (9), we evaluate the improvement in sensitivity from beam polarization. We find that the signal significance increases by a factor of about 4 compared to the unpolarized search. Figure 9 shows the significance $\mathcal{Z}$ as a function of the integrated luminosity at the ILC for a benchmark point $m_{\gamma'} = 20$ GeV and $g_{a\gamma'\gamma} = 2 \times 10^{-4}$ GeV $^{-1}$. For this parameter space choice, achieving $\mathcal{Z} = 5$ requires only $\mathcal{L} \simeq 0.1$ ab $^{-1}$ with polarized beams, whereas more than an order of magnitude larger luminosity is needed for the unpolarized case.

The resulting sensitivity is shown as the dotted red curve in Fig. 6 on the $(m_{\gamma'}, g_{a\gamma'\gamma})$ plane, providing the strongest reach into the parameter space.

V. CONCLUSION

We have explored the potential of future lepton colliders to probe the interaction between axions, dark photons, and Standard Model photons through dimension-five operators. Such interactions can naturally arise in models with light pseudoscalar particles and dark photons, and may be

generated at the loop level via heavy fermions charged under both $U(1)_Y$ and $U(1)_D$.

Focusing on single-photon events with missing energy, we analyzed the signal processes $e^+e^- \rightarrow \gamma' \rightarrow \gamma a$ and $e^+e^- \rightarrow \gamma^*/Z \rightarrow a\gamma' \rightarrow aa\gamma$, under the assumption of a light axion that escapes detection. The axion-photon-dark photon coupling $g_{a\gamma'\gamma}$ larger than about 10^{-3} GeV $^{-1}$ is excluded by LEP II data for $m_{\gamma'} \lesssim 100$ GeV. We studied the relevant kinematic distributions and developed selection strategies to optimize the signal-to-background ratio. In particular, the recoil mass and the angular distribution of the emitted photon were found to be especially effective in discriminating signals from background.

Using these strategies, we projected the sensitivity reach of ILC, CEPC, and FCC-ee. We found that these future facilities can probe the coupling $g_{a\gamma'\gamma}$ in the range of $\sim 10^{-4}$ to 10^{-3} GeV $^{-1}$ for dark photon masses between 10 and 230 GeV. Furthermore, we demonstrated that the photon energy spectrum offers a viable method to reconstruct the dark photon mass through recoil kinematics, providing an additional handle on signal characterization.

We also analyzed the signal using beam polarization at the ILC. We found that the signal and background exhibit markedly different helicity structures: The SM background is dominated by the LR (left-handed electron and right-handed positron) initial state due to the dominant contributions of t -channel W exchange, while the signal is enhanced in the RL (right-handed electron and left-handed positron) initial state due to constructive photon- Z interference. Exploiting the standard ILC polarization configuration, we found that the signal significance improves by approximately a factor of 4 relative to the unpolarized case, with the discovery reach achievable using only $\mathcal{O}(0.1)$ ab $^{-1}$ of data for a benchmark point $m_{\gamma'} = 20$ GeV and $g_{a\gamma'\gamma} = 2 \times 10^{-4}$ GeV $^{-1}$. The resulting polarized sensitivity provides the best projected reach in the $(m_{\gamma'}, g_{a\gamma'\gamma})$ parameter space among all e^+e^- collider options considered.

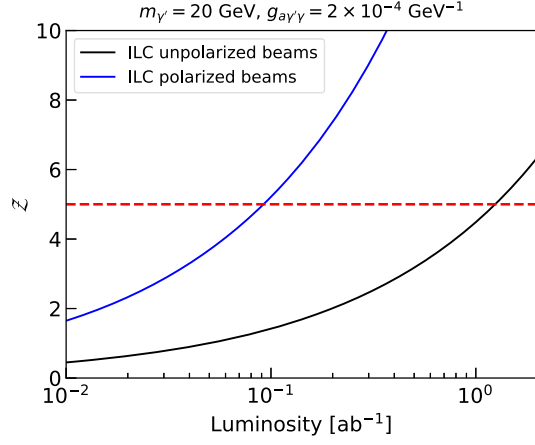


FIG. 9. Significance $\mathcal{Z}$ as a function of the integrated luminosity at the ILC with fixing $m_{\gamma'} = 20$ GeV and $g_{a\gamma'\gamma} = 2 \times 10^{-4}$ GeV $^{-1}$. The solid black and blue curves correspond to the single-photon plus missing-energy search with unpolarized and polarized beams, respectively. The dashed red line indicates the $\mathcal{Z} = 5$ threshold.

Our results highlight the importance of high-luminosity lepton colliders in exploring light and weakly coupled new physics, offering complementary coverage to fixed-target, astrophysical, and hadronic collider searches. This work paves the way for probing rich dynamics within the dark sector at next-generation facilities.

Finally, we note that the existing LHC monophoton searches can provide a complementary constraint on the axion–dark photon interaction, particularly for heavier dark photon regions. A dedicated detector-level analysis, as well as projections for the HL-LHC and HE-LHC, could significantly extend the sensitivity into the higher-mass region of the dark photon parameter space and is left for future work.

ACKNOWLEDGMENTS

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

APPENDIX A: LEP CONSTRAINTS FROM TWO-PHOTON PLUS MISSING ENERGY

Searches for multiphoton final states with missing energy at LEP can also be used to constrain the interaction in Eq. (1). In our model, the relevant signal topologies are shown in Fig. 10. We assume that the axion is sufficiently light and couples only weakly to the SM sector, so that it escapes the detector and contributes to the missing-energy signature.

In the parameter space considered in this analysis, the contribution from the signal process shown in the left panel in Fig. 10 is subdominant. This is because dark photon production in this channel is proportional to ϵ^2 . Enhancing this contribution would require a large kinetic mixing parameter ϵ , which simultaneously suppresses the branching ratio of the dark photon decay into the $a\gamma$ final state. Moreover, such large values of ϵ are already excluded by CMS dilepton searches and precision Z-pole measurements.

In contrast, the production of dark photons in the topology shown in the right panel in Fig. 10 is proportional to $g_{a\gamma'\gamma}^2$. A larger value of this coupling not only enhances the production rate, but also increases the branching fraction of the dark photon decay into the photon-axion final state, making this channel more relevant for LEP searches.

To recast the LEP bounds, we use the L3 data collected at a center-of-mass energy $\sqrt{s} = 189$ GeV, with the event selection requiring at least two photons with energy above 1 GeV and a global transverse momentum of photons $P_T > 0.02\sqrt{s}$ [34]. We assume a detector efficiency of

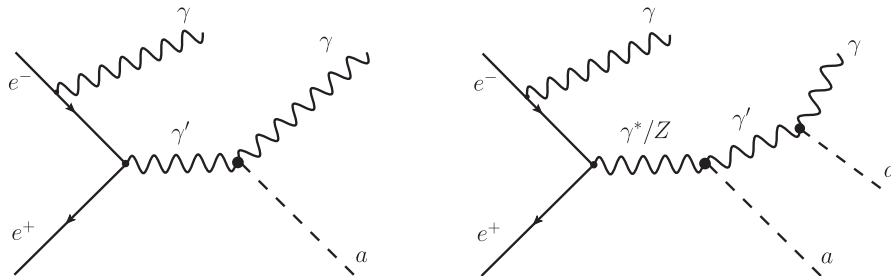


FIG. 10. Feynman diagrams for the two-photon plus missing-energy signal.

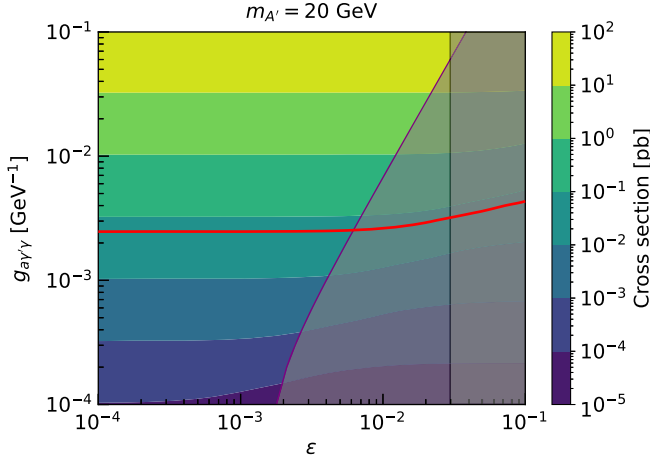


FIG. 11. Constraints from LEP data of two-photon plus missing energy (red line) projected on the $(\epsilon, g_{A'\gamma\gamma})$ plane. We fix $m_{\gamma'} = 20$ GeV. The color gradient indicates the total cross section of the two-photon signal processes. The gray regions to the right of the solid purple and solid black curves are excluded by CMS dimuon searches [30] and by precision measurements at the Z pole [35,36], respectively.

80% and a theoretical uncertainty of 1%. Using the CL_s method, we obtain an upper limit on the total cross section for the two-photon plus missing-energy process of 0.057 pb at 95% confidence level.

This bound is translated into a constraint on $(\epsilon, g_{A'\gamma\gamma})$ for $m_{\gamma'} = 20$ GeV, as shown in Fig. 11. We find that the resulting constraint from the two-photon channel is weaker

by roughly a factor of 2 compared to the single-photon limit.

APPENDIX B: RECASTING THE LHC DILEPTON LIMIT

In our model, the branching fractions of the dark photon differ from those in the conventional dark photon scenario due to the presence of new decay channels such as $\gamma' \rightarrow a\gamma$ and $\gamma' \rightarrow aZ$, whenever kinematically allowed. Therefore, when recasting the LHC constraints from narrow-resonance dilepton searches, these modified branching ratios must be taken into account [22]. In particular, the bound on the kinetic mixing parameter must be rescaled to account for the reduced branching ratio of γ' decays into leptons. The modified bound on the kinetic mixing ϵ_{bound} can be obtained by

$$\epsilon_{\text{bound}}^2 \text{BR}(\gamma' \rightarrow \ell^+ \ell^-) = \epsilon_0^2 \text{BR}_0(\gamma' \rightarrow \ell^+ \ell^-), \quad (\text{B1})$$

where ϵ_0 is the LHC bound on the kinetic mixing in the conventional dark photon model [30] and $\text{BR}_0(\gamma' \rightarrow \ell^+ \ell^-)$ is the corresponding branching ratio without additional decay channels.

Applying this procedure, we obtain the constraint on ϵ shown by the solid purple curves in Figs. 3 and 11 for $m_{\gamma'} = 20$ GeV using the dimuon searches data at CMS [30]. As the coupling $g_{A'\gamma\gamma}$ increases, the dimuon branching fraction of the dark photon is progressively suppressed, leading to a correspondingly weaker bound on the kinetic mixing parameter.

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