Eur. Phys. J. C (2022) 82:592
https://doi.org/10.1140/epjc/s10052-022-10552-1

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Theoretical Physics

Search for invisible dark photon in γe scattering at future lepton colliders

S. C. İnan[1,a], **A. V. Kisselev**[2,b]

[1] Department of Physics, Sivas Cumhuriyet University, 58140 Sivas, Turkey
[2] Division of Theoretical Physics, A.A. Logunov Institute for High Energy Physics, NRC "Kurchatov Institute", Protvino 142281, Russia

Received: 12 April 2022 / Accepted: 26 June 2022 / Published online: 6 July 2022

Abstract For the first time, the production of a massive dark photon (DP) in the γe^- scattering at the future lepton colliders ILC, CLIC, and CEPC is examined. The invisible decay mode of the DP is addressed. We have studied both the unpolarized scattering and the collision of the Compton backscattered photons with the polarized electron. The missing energy distributions are shown. We have considered the wide range 1–1000 GeV of the DP mass $m_{A'}$. The excluded regions at the 95% CL in the plane $(\varepsilon, m_{A'})$, where ε is the kinetic mixing parameter, are obtained. In particular, in the low mass region, 1–10 GeV our bounds for the 90 GeV CEPC are several times stronger than experimental limits obtained by the BaBar collaboration. For the polarized scattering, the excluded bounds for all three colliders are approximately 20% stronger as compared with the unpolarized case.

1 Introduction

One of the main goals of the present and proposed collider experiments is to search for dark matter (DM) particles. The DM makes up approximately 85% of the total mass in the Universe. Its existence is firmly confirmed by gravitational experiments [1,2], but composition and nature are still an open question. We consider a DM scenario in which no DM fields are charged under the SM gauge group, and the lightest stable DM particles, χ, can only interact with SM through the exchange of a vector mediator, dark photon (DP) (also known as hidden or heavy photon) [3–12]. It is usually denoted as A'. In its turn, the DP kinetically mixes with the SM $U(1)_Y$ hypercharge gauge field at the renormalizable level (*kinematic-mixing portal*) [7]. Such mixing can be generated by loops of massive particles charged under both $U(1)_Y$ and secluded $U(1)'$ symmetries. That kinetic-mixing portal model may be extended to 5D by adding one flat ED [13]. The existence of a new light dark sector can be also connected to a generation of neutrino masses [14]. An electroweak gauge extension of the SM by adding an extra $U(1)'$, with mixing with the standard $U(1)_Y$ can also result in a new boson [15–17]. For recent reviews on the DP, see, for instance, [18–25]. In particular, astrophysical constraints on the DP parameters can be found in [26–34], while bounds from $(g-2)_{\mu,e}$ are presented in [35,36].

The main mechanisms of the DP production are meson decays ($\pi^0, \eta \to A'\gamma$) [37], bremsstrahlung ($eZ \to eZA'$ and $pZ \to pZA'$) [38,39], Drell-Yan ($q\bar{q} \to A'$), and annihilation ($e^+e^- \to A'\gamma$). The process of pair annihilation into a dark and an ordinary photon provided a striking benchmark (mono-photon plus missing energy) for the DP search at the LEP [40–43]. A probing new physics in final states containing a photon and missing transverse momentum in proton-proton collisions was presented by the ATLAS and CMS Collaborations [44–47]. For the most recent results on the DPs from the LHC, see [48–51]. The ATLAS and CMS search sensitivities for DPs at the high luminosity LHC can be found in [52,53]. A DP phenomenology at the LHC and HL-LHC was studied in [54–57], and searches of the DPs at the LHeC and FCC-he colliders were discussed in [58].

A probing new light gauge boson similar to the photon in e^+e^- collisions is of particular interest [59–72]. The searches for the DP at e^+e^- colliders [73–78] (see also review papers [18–25]) have looked for its decays to the e^+e^-, $\mu^+\mu^-$ and $\pi^+\pi^-$ final states, as well as for invisible decays of A'. The DP production in the Compton-like $\gamma e \to A'e$ process is studied in [79,80]. The inverse process, $A'e \to \gamma e$, is recently considered in [81]. The gamma factory's discovery potential through the low energy dark Compton scattering is analyzed in [82]. In [83] the $\gamma\gamma \to \gamma A'$ process for MeV scale collider is considered.

In the present paper we examine a novel DP production based on a high energy γe^- scattering at the lepton

[a] e-mail: sceminan@cumhuriyet.edu.tr
[b] e-mail: alexandre.kisselev@ihep.ru (corresponding author)

colliders ILC [84,85], CLIC [86,87], and CEPC [88,89], the $\gamma e^- \to A'e^-$ process. Both unpolarized and polarized collisions are considered in the wide DP mass region 1–1000 GeV. We expect the DP to decay predominantly into *invisible* dark-sector particles. Let us underline that up to now the DP production at high energy lepton colliders was studied only for the e^+e^- mode of these colliders [68–71].

2 Massive dark photon

As it was already mentioned above, the DP does not directly couple to SM fields. But there could be a small coupling to the electromagnetic current J_μ due to *kinetic mixing* between the SM hypercharge and the field strength tensor of the DP field. Consider the case when the dark sector is represented by just a single extra $U(1)'$ gauge group. Let B_μ, $\bar{A}'_\mu$ be the mediator fields of the SM $U(1)_Y$ symmetry and dark $U(1)'$ gauge group. The gauge Lagrangian can be taken in the following form

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} \bar{F}'_{\mu\nu} \bar{F}'^{\mu\nu} - \frac{\varepsilon}{2c_W} \bar{F}'_{\mu\nu} B^{\mu\nu} , \quad (1)$$

where $B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$ and $\bar{F}'_{\mu\nu} = \partial_\mu \bar{A}'_\nu - \partial_\nu \bar{A}'_\mu$ are the field strength tensors of $U(1)_Y$ and $U(1)'$, respectively, c_W is the cosine of the Weinberg angle θ_W, and $\varepsilon \ll 1$ is the kinetic mixing parameter. The kinetic mixing can be generated at the one-loop level by massive particles charged under both $U(1)_Y$ and $U(1)'$ symmetries. After diagonalization of the gauge fields W^3_μ, B_μ, and DP field $\bar{A}'_\mu$ [23],

$$\begin{pmatrix} W^3_\mu \\ B_\mu \\ \bar{A}'_\mu \end{pmatrix} = \begin{pmatrix} c_W & s_W & -s_W\varepsilon \\ -s_W & c_W & -c_W\varepsilon \\ t_W\varepsilon & 0 & 1 \end{pmatrix} \begin{pmatrix} Z_\mu \\ A_\mu \\ A'_\mu \end{pmatrix} , \quad (2)$$

where s_W and t_W are the sine and tangent of θ_W, we obtain the interaction Lagrangian up to $O(\varepsilon^2)$

$$\mathcal{L}_{\text{int}} = eJ_\mu A^\mu - \varepsilon e J_\mu A'^\mu + \varepsilon e' t_W J'_\mu Z_\mu + e' J'_\mu A'^\mu + \mathcal{L}_{A'\chi} . \quad (3)$$

Here A_μ, Z_μ are the physical gauge fields, and A'^μ is the physical field of the DP. J'_μ and e' are the DM matter current and DP coupling to the dark-sector matter, respectively. In (3) we have added the last term which describes a $A'\chi\chi$ interaction, where χ is a dark matter particle. The form of this interaction is left unspecified. As one can see in (3), the coupling of the massive DP the SM fermions is $-\varepsilon e$. The Z gauge boson acquires the coupling strength $\varepsilon e' t_W$ to the dark sector current.

Thus, there are three unknown parameters: the DP mass, $m_{A'}$, the mixing parameter, ε, and the $A' \to \chi\bar{\chi}$ branching. The latter is taken to be unity, if we assume that $m_{A'} > 2m_\chi$. The dimensionless mixing parameter ε is a priori unknown and presumably lies in the 10^{-12}–10^{-2} region, depending on the DP mass [33,39,90–95] (see also Fig. 8.16 in [96], where sensitivities for the DP in the plane mixing parameter ε versus $m_{A'}$ are collected). The DP mass $m_{A'}$ can also vary in a wide range, but most of experimental searches for the invisible DP were aimed at the $m_{A'}$ in the region 1 MeV – 10 GeV [18–25], see Fig. 1. We will examine the wider DP mass region 1–1000 GeV.

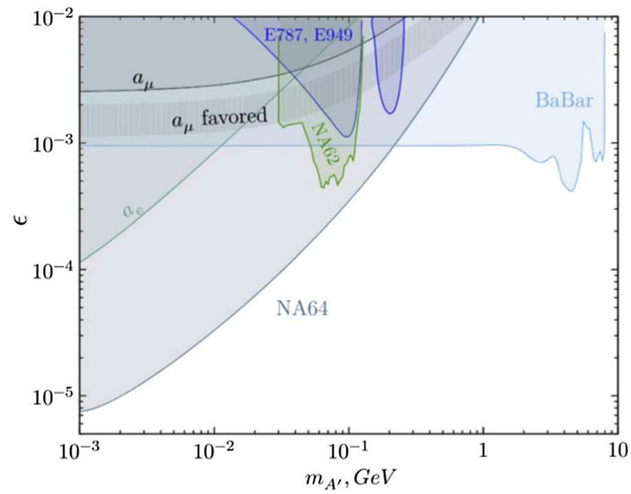

Fig. 1 The existing limits for the massive dark photon going to invisible final states. The constraints from $a_e = (g-2)_e$ and $a_\mu = (g-2)_\mu$ are also shown. The figure is taken from [24]

3 Invisible dark photon production in Compton-like scattering

The production of the DP in the center-of-mass system of the γe^- scattering,

$$\gamma + e^- \to A' + e^- , \quad (4)$$

is depicted in Fig. 2. As is known, linear e^+e^- colliders can operate in γe and $\gamma\gamma$ modes [97–99]. The $\gamma\gamma$ facilities at the future circular colliders are examined in [100–104]. In particular, a number of processes in γe and $\gamma\gamma$ collisions at the CEPC have been studied in [105]. At the lepton collider hard real photons may be generated by the laser Compton backscattering, when soft laser photons collide with electron beams. As a result, a large flux of photons is produced which carry a great amount of the parent electron energy. A γe ($\gamma\gamma$) collider has a number of advantages over e^+e^- collider. Among they are (i) Higgs can be s-channel produced; (ii) higher cross sections for charged particles; (iii) higher mass reach in some channels; (iv) pure QED interaction (in e^+e^- a Z boson exchange is present); (v) higher polarization of initial states. The γe and $\gamma\gamma$ modes were considered for a number of processes at the future lepton colliders [106–117],

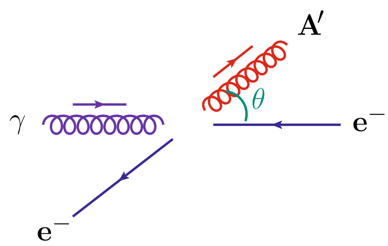

Fig. 2 The production of the dark photon A' in the γe^- collision

but the DP production in γe or $\gamma\gamma$ collisions have not yet been studied at the ILC, CLIC, or CEPC.

Let E_0 be the energy of the initial laser photon beam, E_e be the energy of the initial electron beam, while E_γ be the energy of the Compton backscattered (CB) photon. The differential cross section for the unpolarized DP production accompanied by electron at the lepton collider operating in the γe mode is defined as

$$\frac{d\sigma}{d\cos\theta} = \int_{x_{\min}}^{x_{\max}} dx f_{\gamma/e}(x)\, \frac{d\hat{\sigma}}{d\cos\theta} \ . \tag{5}$$

Here $f_{\gamma/e}(x)$ is the distribution of the CB photon in the variable $x = E_\gamma/E_e$,

$$x_{\min} = \frac{p_\perp^2}{E_e^2} \ , \quad x_{\max} = \frac{\zeta}{1+\zeta} \ , \quad \zeta = \frac{4E_0E_e}{m^2} \ , \tag{6}$$

$p_\perp$ is the transverse momentum of the outgoing particles, m is the electron mass, and θ represents the scattering angle of the outgoing DP (see Fig. 2). The laser beam energy E_0 is chosen to maximize E_γ. It is achieved, if $\zeta = 4.8$, and we get $x_{\max} = 0.83$, see Eq. (6).

The spectrum of the CB photons in formula (5) is defined as follows [97]

$$f_{\gamma/e}(x) = \frac{1}{g(\zeta)}\left[1 - x + \frac{1}{1-x} - \frac{4x}{\zeta(1-x)} + \frac{4x^2}{\zeta^2(1-x)^2}\right], \tag{7}$$

where

$$g(\zeta) = \left(1 - \frac{4}{\zeta} - \frac{8}{\zeta^2}\right)\ln(\zeta+1) + \frac{1}{2} + \frac{8}{\zeta} - \frac{1}{2(\zeta+1)^2} \ . \tag{8}$$

The differential cross section for the process $\gamma e^- \to A'e^-$ in the center-of-mass system of the colliding particles is defined as

$$\frac{d\hat{\sigma}}{d\cos\theta} = \frac{1}{32\pi\hat{s}}\frac{\sqrt{(\hat{s}+m_{A'}^2-m^2)^2 - 4\hat{s}m_{A'}^2}}{\hat{s}-m^2} \times |F(\hat{s},\cos\theta)|^2 \ , \tag{9}$$

where $\sqrt{\hat{s}} = \sqrt{sx}$ is the center-of-mass energy of the backscattered photon and electron, $\hat{s} \geqslant (m_{A'}+m)^2$. A matrix element of the process (4) is a sum of two diagrams in Fig. 3, in which the $A'e^-e^+$ coupling constant is equal to $-\varepsilon e$. An explicit expression for the square matrix element $|F|^2$ is given in Appendix A.

The main background comes from the SM process

$$\gamma e^- \to e^-\nu\bar{\nu} \ , \tag{10}$$

see the diagrams in Figs. 4 and 5. In detector it looks like an event with an isolated electron and missing transverse energy. We apply the cut on the transverse momenta of the final electron, $p_\perp > 10$ GeV, and its rapidity, $|\eta| < 2.5$. In order to reduce the SM background, we also impose the cut on an invisible invariant mass, $|m_{A'} - m_{\text{invis}}| < 5$ GeV.

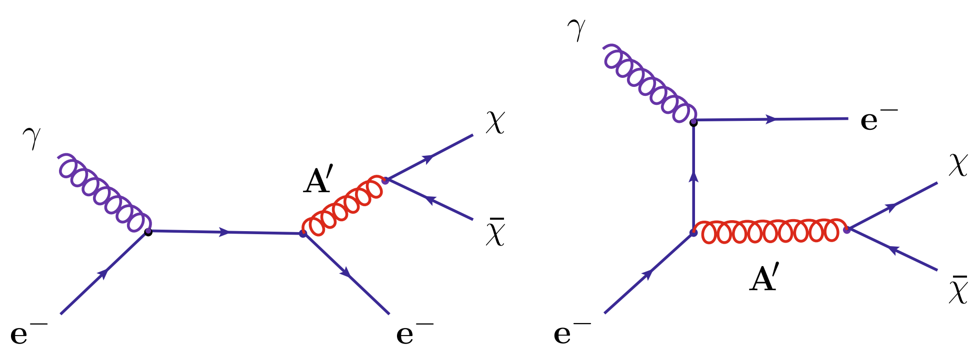

Fig. 3 The diagrams for the production of the dark photon in the γe^- collision, with its subsequent invisible decay into dark matter particles

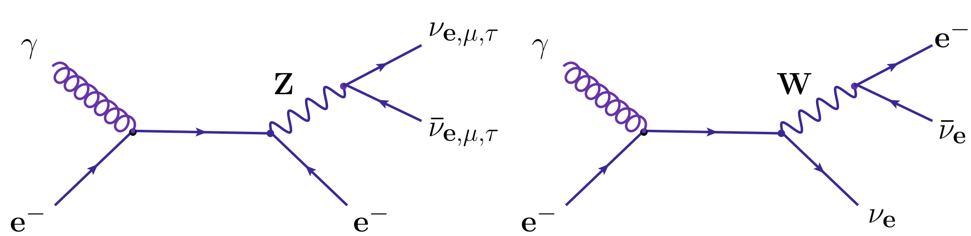

Fig. 4 The s-channel diagrams for the SM process $\gamma e^- \to e^- + \not{E}$

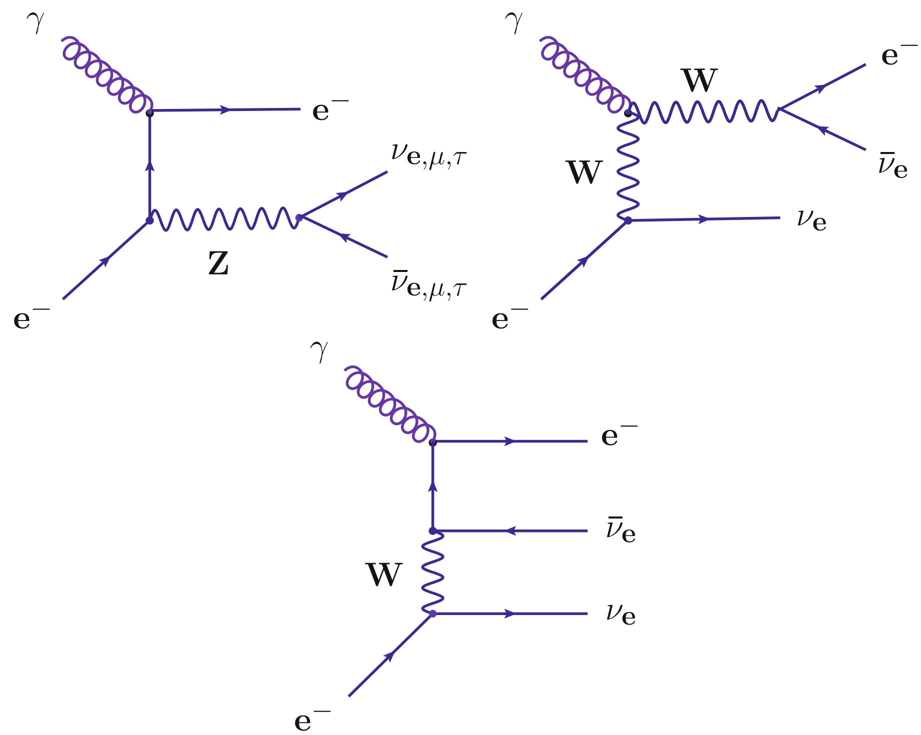

Fig. 5 The u-channel diagrams for the SM process $\gamma e^- \to e^- + \not{E}$

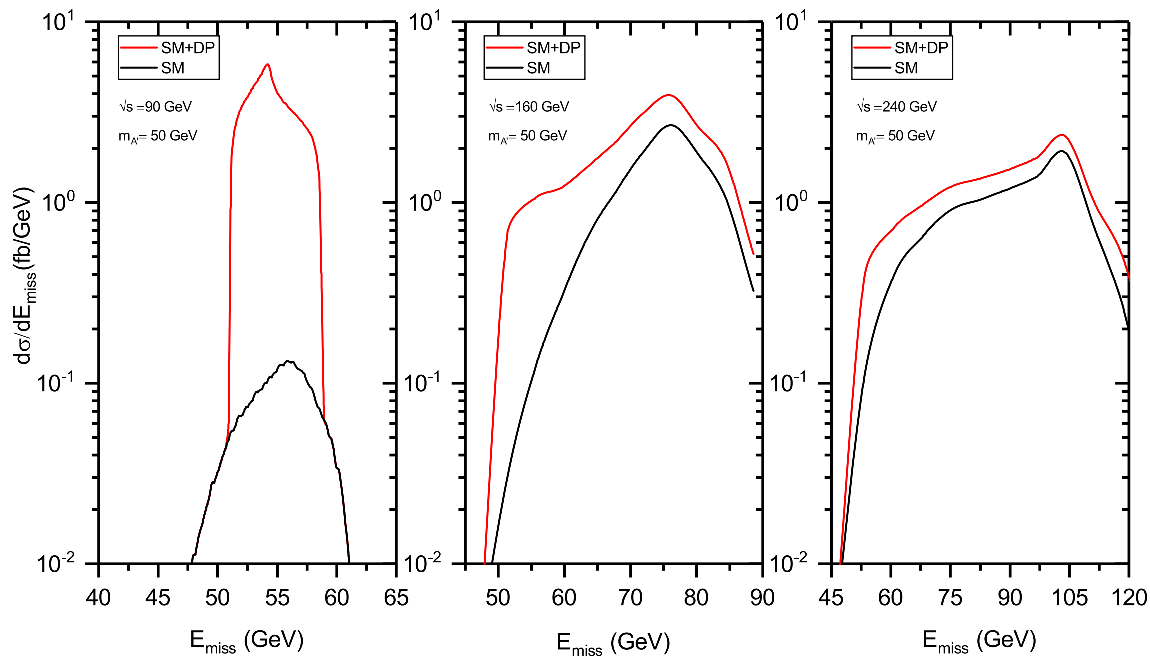

Fig. 6 The differential cross sections for the unpolarized $\gamma e^- \to e^- + \not{E}$ scattering at the collider CEPC. The mixing parameter is fixed to be $\varepsilon = 0.1$

In numerical calculations, especially in background calculations, CalcHEP program was also used [118]. We have used the following statistical significance (SS) formula [119],

$$SS = \sqrt{2[(S+B)\,\ln(1+S/B) - S]}, \tag{11}$$

where S and B are the numbers of the signal and background events, respectively. Note that $SS \simeq S/\sqrt{B}$ for $S \ll B$.

In Figs. 6, 7 and 8 we present differential cross sections of the $\gamma e^- \to e^- + \not{E}$ scattering as functions of the missing energy for a fixed value of the mixing parameter ε. The results for the colliders CEPC, ILC, and CLIC are given, for the DP masses $m_{A'} = 50$ GeV, 100 GeV, and 200 GeV, respectively. In all figures, red (black) curves correspond to the cross sections with (without) account of the dark photon

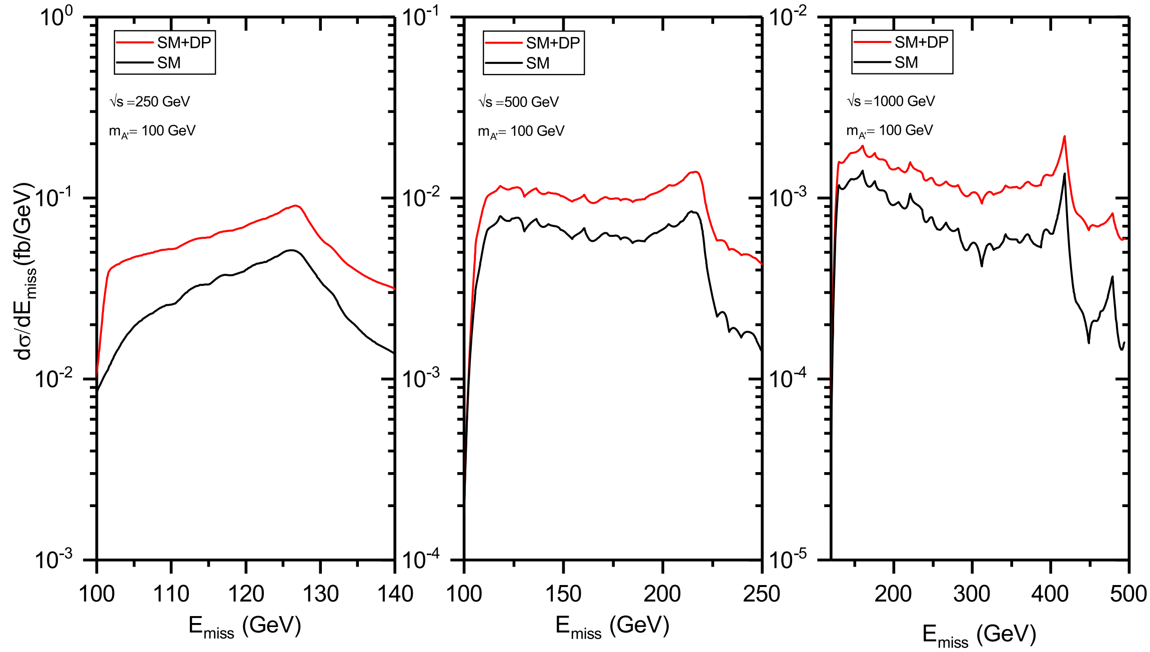

Fig. 7 The same as in Fig. 6, but for the collider ILC

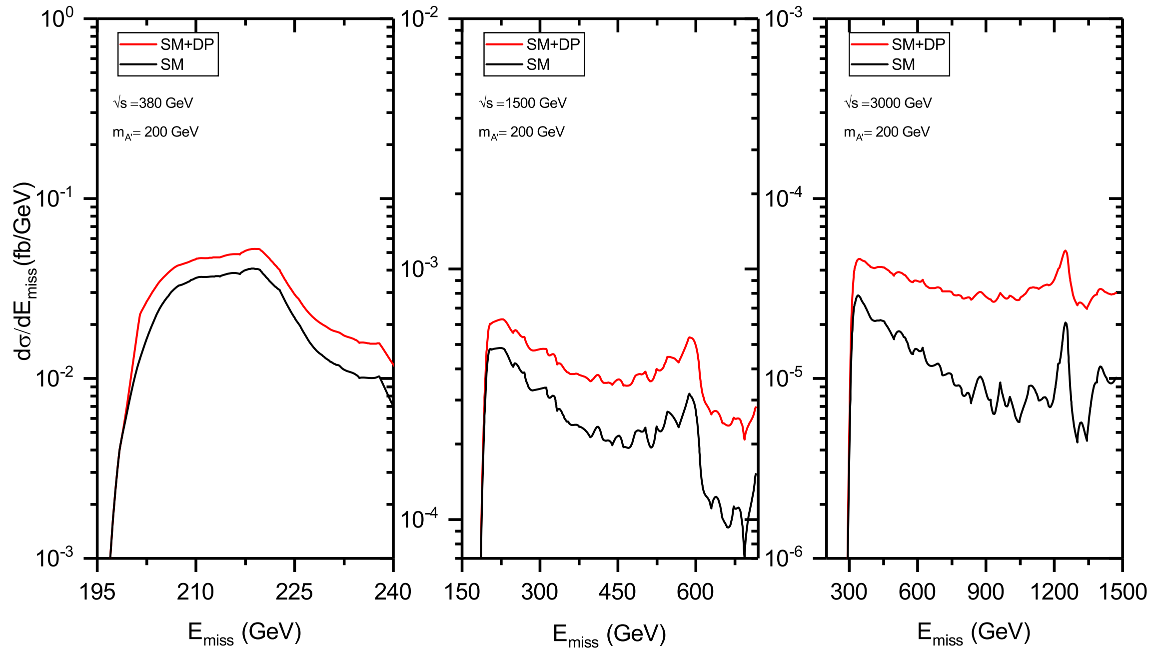

Fig. 8 The same as in Fig. 6, but for the collider CLIC

contributions. It turns out that DP is the dominant effect for high missing energy values. We have also made calculations for different values of $m_{A'}$. Our calculations show that deviations of the cross sections from the SM predictions become smaller as the DP mass $m_{A'}$ grows.

The excluded bounds for the massive DP going to invisible final states are presented in Figs. 9 and 10 in the plane the kinetic mixing parameter ε versus DP mass $m_{A'}$. In Fig. 9 the results for the unpolarized $\gamma e^- \to A' e^-$ collision are given for the CEPC (left panel), ILC (middle panel), and CLIC (right panel). The strongest bound on ε is achieved for the 90 GeV CEPC. In the region $m_{A'} = 1$–10 GeV it is 2–4 orders of magnitude stronger than the experimental bounds obtained by the BaBar collaboration shown in Fig. 1.

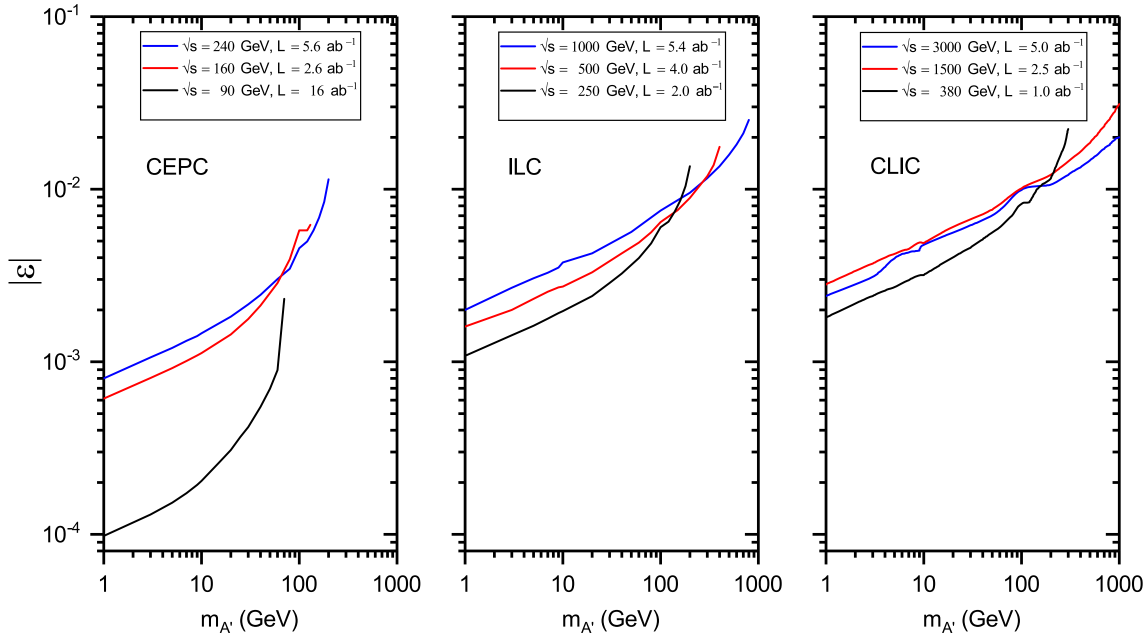

Fig. 9 The excluded bounds at the 95% CL on the dark photon mass $m_{A'}$ and kinetic mixing parameter ε for the invisible dark photon production in the *unpolarized* $\gamma e^- \to A'e^-$ collision

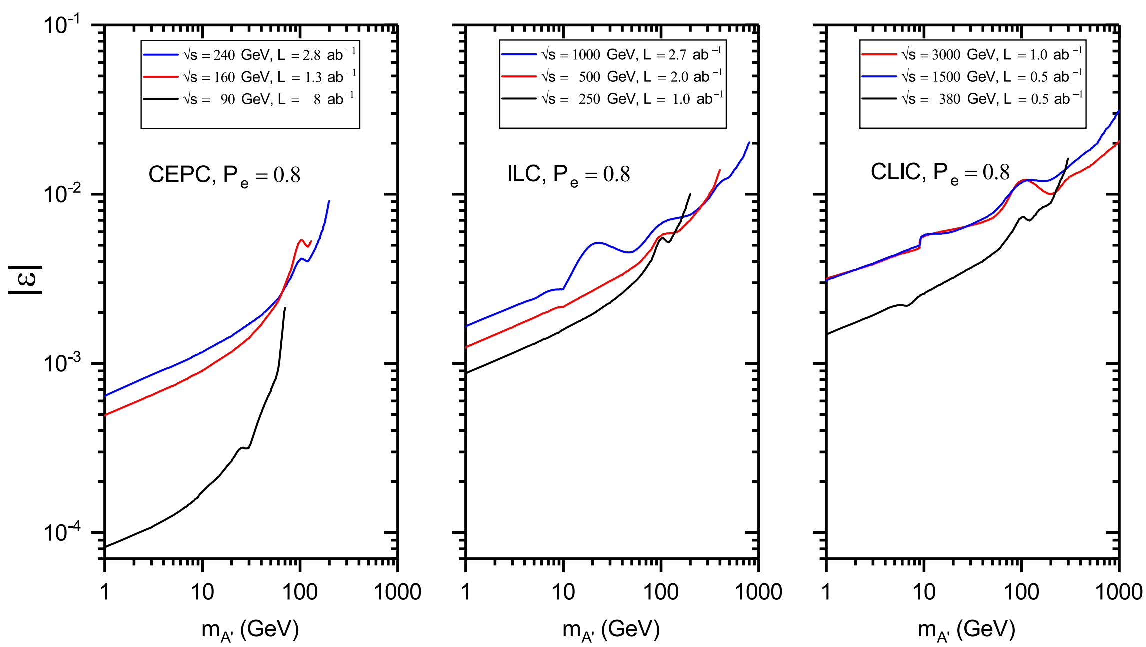

Fig. 10 The excluded bounds at the 95% CL on the dark photon mass $m_{A'}$ and kinetic mixing parameter ε for the invisible dark photon production in the collision of the *unpolarized* real photon with the electron whose polarization is equal to 80%

The constraints for the ILC collider with the energy of 160 GeV and 240 GeV are comparable with the BaBar constraints in this mass region. The sensitivity decreases as $m_{A'}$ grows.

The results for the polarized case are shown in Fig. 10. The polarized electron sources of the future linear colliders have been discussed in the current ILC [85], CLIC [86], and CEPC [88] designs. We consider the *unpolarized CB photons* and $P(e^-) = 80\%$ polarization of the initial electron beam for all three colliders. By analogy with the ILC project, we assume that for the polarized γe^- collision, the CEPC integrated luminosity is 50% less than the integrated luminosity for the unpolarized γe^- scattering. One can see that the obtained excluded bounds are on average 20% better compared to the unpolarized bounds (Fig. 9). For the CLIC, a 10% improvement takes place only for the energy $\sqrt{s} = 380$ GeV. As for the electron beam polarization of P(e^-) = −80%, our calculations show that it does not offer any advantage over the unpolarized case. The reason is that the SM background gets larger for P(e^-) = −80% with respect to the unpolarized collision, while the signal remains almost the same.

4 Conclusions

In the present paper, we have studied the production of the massive dark photon (DP) in the γe^- scattering at the future lepton colliders ILC, CLIC, and CEPC, when the DP decays predominantly into invisible dark matter particles. The real photons are generated by the laser Compton backscattering when the soft laser photons collide with the electron beams. Both the unpolarized and polarized collisions are studied. For the polarized $\gamma e^- \to A' e^-$ process we have assumed that the incoming CB photon is unpolarized, while the polarization of the electron beam is taken to be 80% for all three colliders. The wide region 1–1000 GeV of the DP mass $m_{A'}$ is considered. The missing energy distributions for signal and background are presented. We have derived the excluded regions at the 95% CL in the plane $(\varepsilon, m_{A'})$, where ε is the kinetic mixing parameter. Our excluded bounds for the polarized collisions at the ILC and CEPC are approximately 20% stronger compared to the unpolarized excluded bounds. In particular, in the low mass region 1–10 GeV our excluded bounds for the 90 GeV CEPC are in average 2–4 orders of magnitude stronger that the experimental bounds obtained by the BaBar collaboration. The CEPC constraints with energies of 160 GeV and 240 GeV are comparable with the BaBar bounds in this mass range, and the ILC excluded bounds are close to them.

Note that up to now the production of the DP at future lepton colliders (both for the visible and invisible DP decays) was studied only for the e^+e^- mode of these colliders.

As was already mentioned in Introduction, the DP production in the Compton-like $\gamma e \to A' e$ process was studied in the fixed target experiments [79,80,82]. However, these low energy experiments were dealing with low mass DPs ($m_{A'} < 100$ MeV), while we examine heavy DPs ($m_{A'} > 1$ GeV).

Our method can be also applied to dark axionlike pseudoscalars (scalars). Consider the coupling of a pseudoscalar ALP a to a electron field ψ. It is given by the Lagrangian (see, for instance, [120])

$$\mathcal{L} = g_{a\bar{\psi}\psi} \partial_\mu a \bar{\psi} \gamma^\mu \gamma^5 \psi \, . \tag{12}$$

Then the amplitude of the process $\gamma e^- \to a e^-$ will be proportional to the electron mass m_e. So, we expect that the pseudoscalar cross section will be suppressed with respect to the dark photon cross section. Nevertheless, we consider studying axionlike (pseudo)scalars as a future direction.

Data Availability Statement This manuscript has no associated data or the data will not be deposited. [Authors' comment: We give predictions for future colliders.]

Funded by SCOAP^3. SCOAP^3 supports the goals of the International Year of Basic Sciences for Sustainable Development.

Appendix A

The matrix element of the process (4) is given by the sum of s- and u-channel diagrams presented in Fig. 3. Correspondingly, we get

$$|F(s, \cos\theta)|^2 = (\varepsilon e^2)^2 \left[|F_s|^2 + |F_u|^2 + (F_s F_u^* + F_s^* F_u) \right] , \tag{A.1}$$

where

$$\begin{aligned} |F_s|^2 &= \frac{2}{(s-m^2)^2} \left[-su + m^2(3s + u + 2m_{A'}^2) + m^4 \right] , \\ |F_u|^2 &= \frac{2}{(u-m^2)^2} \left[-su + m^2(3u + s + 2m_{A'}^2) + m^4 \right] , \\ F_s F_u^* &= F_s^* F_u = \frac{2}{(s-m^2)(u-m^2)} \\ &\quad \times \left[m_{A'}^2 (s+u) - m_{A'}^4 + m^2(s + u - 2m_{A'}^2) + 2m^4 \right] . \end{aligned} \tag{A.2}$$

The Mandelstam variable u is equal to

$$u = m_{A'}^2 + m^2 - \frac{1}{2s} \Big[(s+m^2)(s + m_{A'}^2 - m^2) + (s-m^2)\sqrt{(s + m_{A'}^2 - m^2)^2 - 4s\, m_{A'}^2} \cos\theta \Big], \tag{A.3}$$

where θ is a scattering angle of the DP in the center-of-mass frame of the colliding particles (see Fig. 2). For $m_{A'} = 0, \varepsilon = 1$, the above formulas coincide with well-known formulas for the Compton scattering [121].

References

1. V. Trimble, Existence and nature of dark matter in the Universe. Annu. Rev. Astron. Astrophys. **25**, 425 (1987)
2. G. Bertone, D. Hooper, History of dark matter. Rev. Mod. Phys. **90**, 045002 (2018). arXiv:1605.04909
3. P. Fayet, Effects of the spin 1 partner of the goldstino (gravitino) on neutral current phenomenology. Phys. Lett. B **95**, 285 (1980)
4. P. Fayet, On the search for a new spin 1 boson. Nucl. Phys. B **187**, 184 (1981)
5. L.B. Okun, Limits of electrodynamics: paraphotons? Sov. Phys. JETP **56**, 502 (1982) (**Zh. Eksp. Teor. Fiz. 83, 892 (1982)**)
6. P. Galison, A. Manohar, Two Z's or not two Z's? Phys. Lett. B **136**, 279 (1984)
7. B. Holdom, Two $U(1)$'s and ε charge shifts. Phys. Lett. B **166**, 196 (1986)
8. B. Holdom, Searching for ε charges and a new $U(1)$. Phys. Lett. B **178**, 6 (1986)
9. K.R. Dienes, C.F. Kolda, J. March-Russell, Kinetic mixing and the supersymmetric gauge hierarchy. Nucl. Phys. B **492**, 104 (1997). arXiv:hep-ph/9610479
10. N. Arkani-Hamed, D.P. Finkbeiner, T.R. Slatyer, N. Weiner, A theory of dark matter. Phys. Rev. D **79**, 015014 (2009). arXiv:0810.0713
11. M. Pospelov, A. Ritz, M.B. Voloshin, Secluded WIMP dark matter. Phys. Lett. B **662**, 53 (2008). arXiv:0711.4866
12. D. Hooper, N. Weiner, W. Xue, Dark forces and light dark matter. Phys. Rev. D **86**, 056009 (2012). arXiv:1206.2929
13. T.G. Rizzo, Kinetic mixing, dark photons and an extra dimension. Part I, JHEP **07**, 118 (2018). arXiv:1801.08525
14. E. Bertuzzo, S. Jana, P.A. Machado, R.Z. Funchal, Neutrino masses and mixings dynamically generated by a light dark sector. Phys. Lett. B **791**, 210 (2019). arXiv:1808.02500
15. F. Del Aguila, The physics of Z' bosons. Acta Phys. Pol. B **25**, 1317 (1994). arXiv:hep-ph/9404323
16. K.S. Babu, C.F. Kolda, J. March-Russell, Leptophobic $U(1)'$s and the R_b-R_c crisis. Phys. Rev. D **54**, 4635 (1996). arXiv:hep-ph/9603212
17. T.G. Rizzo, Gauge kinetic mixing and leptophobic Z' in E_6 and $SO(10)$. Phys. Rev. D **59**, 015020 (1998)
18. M. Raggi, V. Kozhuharov, Results and perspectives in dark photon physics. Riv. Nuovo Cim. **38**, 449 (2015)
19. F. Curciarello, Review on dark photon. EPJ Web Conf. **118**, 01008 (2016)
20. M. Battaglieri et al., US cosmic visions: new ideas in dark matter 2017: Community report. arXiv:1707.04591
21. P. Ilten, Y. Soreq, M. Williams, W. Xue, Serendipity in dark photon searches. JHEP **06**, 004 (2018). arXiv:1801.04847
22. J. Beacham et al., Physics beyond colliders at CERN: beyond the Standard Model working group report. J. Phys. G Nucl. Part. Phys. **47**, 010501 (2020). arXiv:1901.09966
23. M. Fabbrichesi, E. Gabrielli, G. Lanfranchi, The physics of the dark photon: a primer, SpringerBriefs in Physics (2020). arXiv:2005.01515
24. A. Filippi, M. De Napoli, Searching in the dark: the hunt for the dark photon. Rev. Phys. **5**, 100042 (2020). arXiv:2006.04640
25. M. Graham, C. Hearty, M. Williams, Searches for dark photons at accelerators. Annu. Rev. Nucl. Part. Sci. **71**, 37 (2021)
26. E.D. Carlson, Limits on a new $U(1)$ coupling. Nucl. Phys. B **286**, 378 (1987)
27. D.A. Dobrescu, Massless gauge bosons other than the photon. Phys. Rev. Lett. **94**, 151802 (2005). arXiv:hep-ph/0411004
28. M. Pospelov, A. Ritz, Astrophysical signatures of secluded dark matter. Phys. Lett. B **671**, 391 (2009). arXiv:0810.1502
29. H.K. Dreiner, J.-F. Fortin, C. Hanhart, L. Ubaldi, Supernova constraints on MeV dark sectors from e^+e^- annihilations. Phys. Rev. D **89**, 105015 (2014). arXiv:1310.3826
30. K.-Y. Choia, K. Kadota, I. Park, Constraining dark photon model with dark matter from CMB spectral distortions. Phys. Lett. B **771**, 162 (2017). arXiv:1701.01221
31. M. Dutra et al., MeV dark matter complementarity and the dark photon portal. JCAP **03**, 037 (2018). arXiv:1801.05447
32. J.H. Chang, R. Essig, S.D. McDermott, Revisiting Supernova 1987A constraints on dark photons. JHEP **01**, 107 (2017). arXiv:1611.03864
33. J.H. Chang, R. Essiga, S.D. McDermott, Supernova 1987A constraints on sub-GeV dark sectors, millicharged particles, the QCD axion, and an axion-like particle. JHEP **09**, 051 (2018). arXiv:1803.00993
34. X. Bi et al., Axion and dark photon limits from Crab Nebula high-energy gamma rays. Phys. Rev. D **103**, 043018 (2021). arXiv:2002.01796
35. G.W. Bennett et al., (Muon g-2 Collaboration), Final report of the muon E821 anomalous magnetic moment measurement at BNL. Phys. Rev. D **73**, 072003 (2006). arXiv:hep-ex/0602035
36. M. Pospelov, Secluded $U(1)$ below the weak scale. Phys. Rev. D **80**, 095002 (2009). arXiv:0811.1030
37. P. Ilten, J. Thaler, M. Williams, W. Xue, Dark photons from charm mesons at LHCb. Phys. Rev. D **92**, 115017 (2015). arXiv:1509.06765
38. S. Gninenko, D. Kirpichnikov, M. Kirsanov, N. Krasnikov, The exact tree-level calculation of the dark photon production in high-energy electron scattering at the CERN SPS. Phys. Lett. B **782**, 406 (2018). arXiv:1712.05706
39. J.D. Bjorken, R. Essig, P. Schuster, N. Toro, New fixed-target experiments to search for dark gauge forces. Phys. Rev. D **80**, 075018 (2009). arXiv:0906.0580
40. G. Abbiendi et al., (OPAL Collaboration), Search for anomalous photonic events with missing energy in e^+e^- collisions at $\sqrt{s}=$ 130 GeV, 136 GeV and 183 GeV. Eur. Phys. J. C **8**, 23 (1999). arXiv:hep-ex/9810021
41. M. Acciarri et al., (L3 Collaboration), Single and multiphoton events with missing energy in e^+e^- collisions at $\sqrt{s}=189$ GeV. Phys. Lett. B **470**, 268 (1999). arXiv:hep-ex/9910009
42. A. Heister et al., (ALEPH Collaboration), Single photon and multiphoton production in e^+e^- collisions at $\sqrt{s}$ up to 209 GeV. Eur. Phys. J. C **28**, 1 (2003)
43. J. Abdallah et al., (DELPHI Collaboration), Photon events with missing energy in e^+e^- collisions at $\sqrt{s}=130$ to 209 GeV. Eur. Phys. J. C **38**, 395 (2005). arXiv:hep-ex/0406019
44. G. Aaad et al., (ATLAS Collaboration), Search for long-lived neutral particles decaying into lepton jets in proton-proton collisions at $\sqrt{s}=8$ TeV with the ATLAS detector. JHEP **11**, 088 (2014). arXiv:1409.0746
45. M. Aaboud et al., (ATLAS Collaboration), Search for new phenomena in events with a photon and missing transverse momentum in pp collisions at $\sqrt{s}=13$ TeV with the ATLAS detector. JHEP **06**, 059 (2016). arXiv:1604.01306
46. V. Khachatryan et al., (CMS Collaboration), A search for pair production of new light bosons decaying into muons. Phys. Lett. B **752**, 146 (2016). arXiv:1506.00424
47. A.M. Sirunyan et al., (CMS Collaboration), Search for new physics in final states with a single photon and missing transverse momentum in proton-proton collisions at $\sqrt{s}=13$ TeV. JHEP **02**, 074 (2019). arXiv:1810.00196
48. G. Aad et al., (ATLAS Collaboration), Search for new phenomena in events with an energetic jet and missing transverse momentum in pp collisions at $\sqrt{s}=13$ TeV with the ATLAS detector. Phys. Rev. D **103**, 112006 (2021). arXiv:2102.10874

49. G. Aad et al. (ATLAS Collaboration), Observation of electroweak production of two jets in association with an isolated photon and missing transverse momentum, and search for a Higgs boson decaying into invisible particles at 13 TeV with the ATLAS detector. arXiv:2109.00925
50. A.M. Sirunyan et al., (CMS Collaboration), Search for dark matter produced in association with a leptonically decaying Z boson in proton–proton collisions at $\sqrt{s} = 13$ TeV. Eur. Phys. J. C **81**, 13 (2021). arXiv:2008.04735
51. A.M. Sirunyan et al., (CMS Collaboration), Search for dark photons in Higgs boson production via vector boson fusion in proton–proton collisions at $\sqrt{s} = 13$ TeV. JHEP **03**, 011 (2021). arXiv:2009.14009
52. ATLAS Collaboration, Search prospects for dark-photons decaying to displaced collimated jets of muons at HL-LHC, ATL-PHYS-PUB-2019-002 (2019)
53. CMS Collaboration, Search sensitivity for dark photons decaying to displaced muons with CMS at the high-luminosity LHC, CMS-PAS-FTR-18-002 (2018)
54. D. Curtin, R. Essig, S. Goric, J. Shelton, Illuminating dark photons with high-energy colliders. JHEP **02**, 157 (2015). arXiv:1412.0018
55. E. Gabrielli, M. Heikinheimo, B. Mele, M. Raidal, Dark photons and resonant monophoton signatures in Higgs boson decays at the LHC. Phys. Rev. D **90**, 055032 (2014). arXiv:1405.5196
56. A. Berlin, F. Kling, Inelastic dark matter at the LHC lifetime frontier: ATLAS, CMS, LHCb, CODEX-b, FASER, and MATHUSLA. Phys. Rev. D **99**, 015021 (2019). arXiv:1810.01879
57. M. Cobal et al., Z-boson decays into an invisible dark photon at the LHC, HL-LHC, and future lepton colliders. Phys. Rev. D **102**, 035027 (2020). arXiv:2006.15945
58. M. D'Onofrio, O. Fischer, Z.S. Wang, Searching for dark photons at the LHeC and FCC-he. Phys. Rev. D **101**, 015020 (2020). arXiv:1909.02312
59. P. Fayet, U-boson production in e^+e^- annihilations, Ψ and Υ decays, and light dark matter. Phys. Rev. D **75**, 115017 (2007). arXiv:hep-ph/0702176
60. R. Essig, P. Schuster, N. Toro, B. Wojtsekhowski, An electron fixed target experiment to search for a new vector boson A' decaying to e^+e^-. JHEP **02**, 009 (2011). arXiv:1001.2557
61. L. Barze et al., Radiative events as a probe of dark forces at GeV-scale e^+e^- colliders. Eur. Phys. J. C **71**, 1680 (2011). arXiv:1007.4984
62. M. Karliner, M. Low, J.L. Rosner, L.-T. Wang, Radiative return capabilities of a high-energy, high-luminosity e^+e^- collider. Phys. Rev. D **92**, 035010 (2015). arXiv:1503.07209
63. M. He, X.-G. He, C.-K. Huang, Dark photon search at a circular e^+e^- collider. Int. J. Mod. Phys. A **32**, 1750138 (2017). arXiv:1701.08614
64. S. Biswas, E. Gabrielli, M. Heikinheimo, B. Mele, Dark-photon searches via ZH production at e^+e^- colliders. Phys. Rev. D **96**, 055012 (2017). arXiv:1703.00402
65. M. He, X.-G. He, C.-K. Huang, G. Li, Search for a heavy dark photon at future e^+e^- colliders. JHEP **03**, 139 (2018). arXiv:1712.09095
66. L. Marsicano et al., Dark photon production through positron annihilation in beam-dump experiments. Phys. Rev. D **98**, 015031 (2018). arXiv:1802.03794
67. J. Jiang et al., Production and constraints for a massive dark photon at electron-positron colliders. Chin. Phys. C **44**, 023105 (2020). arXiv:1910.07161
68. J.-J. Blaising, P. Roloff, A. Sailer, U. Schnoor, Physics performance for dark matter searches at $\sqrt{s} = 3$ TeV at CLIC using mono-photons and polarised beams. arXiv:2103.06006
69. J. Kalinowski, W. Kotlarski, P. Sopicki, A.F. Zarnecki, Simulating hard photon production with WHIZARD. Eur. Phys. J. C **80**, 634 (2020). arXiv:2004.14486
70. J. Kalinowski, W. Kotlarski, K. Mekala, P. Sopicki, A.F. Zarnecki, Sensitivity of future e^+e^- colliders to processes of dark matter production with light mediator exchange. Eur. Phys. J. C **81**, 955 (2021). arXiv:2107.11194
71. J. Kalinowski, W. Kotlarski, K. Mekala, P. Sopicki, A.F. Zarnecki, Dark matter searches with mono-photon signature at future e^+e^- colliders, *Proceedings of the XXVIII International Workshop on Deep-Inelastic Scattering and Related Subjects* (DIS 2021), Stony Brook University, New York, USA, 12-16 April 2021. arXiv:2107.12730
72. X. Chen, Z. Hu, Y. Wu, K. Yi, Search for dark photon and dark matter signatures around electron–positron colliders. Phys. Lett. B **814**, 136076 (2021). arXiv:2001.04382
73. J.P. Lees et al., (BaBar Collabolaration), Search for a dark photon in e^+e^- collisions at BaBar. Phys. Rev. Lett. **113**, 201801 (2014). arXiv:1406.2980
74. J.P. Lees et al., (BaBar Collabolaration), Search for invisible decays of a dark photon produced in collisions at BaBar. Phys. Rev. Lett. **119**, 131804 (2017). arXiv:1702.03327
75. B. Ablikim et al. (BESIII Collabolaration), Dark photon search in the mass range between 1.5 and 3.4 GeV/c^2. Phys. Lett. B **774**, 252 (2017). arXiv:1705.04265
76. A. Anastasi et al., (KLOE Collaboration), Limit on the production of a low-mass vector boson in $e^+e^- \to U\gamma$, $U \to e^+e^-$, with the KLOE experiment. Phys. Lett. B **750**, 663 (2015). arXiv:1509.00740
77. A. Anastasi et al., (KLOE-2 Collaboration), Combined limit on the production of a light gauge boson decaying into $\mu^+\mu^-$ and $\pi^+\pi^-$. Phys. Lett. B **784**, 336 (2018). arXiv:1807.02691
78. E. Kou et al. (Belle II collaboration), The Belle II Physics Book, Prog. Theor. Exp. Phys. **2019**, 123C01 (2019). arXiv:1808.10567 (**Erratum, Prog. Theor. Exp. Phys. 2020, 029201 (2020)**)
79. S.S. Chakrabarty, I. Jaeglé, Search for dark photon, axion-like particles, dark scalar, or light dark matter in Compton-like processes. arXiv:1903.06225
80. M. Smirnov et al., Light dark bosons in the JUNO-TAO neutrino detector. arXiv:2109.04276
81. Y. Hochberg, B. von Krosigk, E. Kuflig, T.C. Yu, The impact of dark Compton scattering on direct dark matter absorption searches. arXiv:2109.08168
82. S. Chakraborti et al., Gamma factory searches for extremely weakly-interacting particles. Phys. Rev. D **104**, 055023 (2021). arXiv:2105.10289
83. X. Wong, Y. Huang, Dark photon production via $\gamma\gamma \to \gamma A'$. Eur. Phys. J. C **81**, 442 (2021). arXiv:2103.15079
84. T. Behnke et al., The International Linear Collider technical design report—volume 1: executive summary. arXiv:1306.6327
85. P. Bambade et al., The International Linear Collider: a global project. arXiv:1903.01629
86. H. Braun et al. (CLIC Study Team), CLIC 2008 parameters, CERN-OPEN-2008-021, CLIC-NOTE-764
87. M.J. Boland et al. (CLIC and CLICdp Collaborations), Updated baseline for a staged Compact Linear Collider, CERN-2016-004. arXiv:1608.07537
88. The CEPC Study Group, CEPC Conceptual Design Report: Volume 1—accelerator. arXiv:1809.00285
89. The CEPC Study Group, CEPC Conceptual Design Report: Volume 2—physics & detector. arXiv:1811.10545
90. N. Arkani-Hammed, N. Weiner, LHC signals for a superunified theory of dark matter. JHEP **12**, 104 (2008). arXiv:0810.0714

91. M. Baumgart et al., Non-abelian dark sectors and their collider signatures. JHEP **04**, 014 (2009). arXiv:0901.0283
92. M. Goodsell, J. Jaeckel, J. Redondo, A. Ringwald, Naturally light hidden photons in large volume string compactifications. JHEP **11**, 027 (2009). arXiv:0909.0515
93. M. Goodsell, A. Ringwald, Light hidden-sector $U(1)s$ in string compactifications. Fortschr. Phys. **58**, 7126 (2010). arXiv:1002.1840
94. R. Essig, J. Kaplan, P. Schuster, N. Toro, On the origin of light dark matter species. arXiv:1004.0691
95. M. Cicoli, M. Goodsell, J. Jaeckel, A. Ringwald, Testing string vacua in the lab: from a hidden CMB to dark forces in ux compactifications. JHEP **07**, 114 (2011). arXiv:1103.3705
96. Briefing Book, European Strategy for particle physics preparatory group. arXiv:1910.11775
97. I.F. Ginzburg, G.L. Kotkin, V.G. Serbo, V.I. Telnov, Colliding γe and $\gamma\gamma$ beams based on the single-pass e^+e^- colliders (of VLEPP type). Nucl. Instrum. Methods **205**, 47 (1983)
98. I.F. Ginzburg, G.L. Kotkin, S.L. Panfil, V.G. Serbo, V.I. Telnov, Colliding γe and $\gamma\gamma$ beams based on single-pass e^+e^- accelerators II. Polarization effects, monochromatization improvement. Nucl. Instrum. Methods **219**, 5 (1984)
99. V.I. Telnov, The photon collider at ILC: status, parameters and technical problems. Acta Phys. Pol. **37**, 1049 (2006). arXiv:physics/0604108
100. R. Aleksan, A. Apyan, Y. Papaphilippou, F. Zimmermann, Scenarios for circular gamma-gamma Higgs factories, in *Proceedings of the 6th International Particle Accelerator Conference* (PAC2015), 3-8 May, (Richmond, 2015), p. 2156–2159
101. W. Chou, Circular accelerator-based & recirculating linac-based $\gamma\gamma$ collider. Talk at the ICFA Mini-Workshop on future gamma-gamma Collider, 23–26, Tsinghua University (Beijing, China, April 2017)
102. C. Zhang, W. Chou (for the BggC Study Group), A proposed $\gamma\gamma$ collider in China. Talk at the Photon Beam Workshop, 27–28 November 2017 (Padova, Italy, 2017)
103. R. Belusevic, Versatile $e^+e^-/\gamma\gamma/ep$ facilities at a future circular collider. J. Mod. Phys. **8**, 1 (2017). arXiv:1805.06360
104. R. Belusevic, An $e^+e^-/\gamma\gamma/ep$ accelerator complex at a future circular collider. JHEP **5**, 425 (2019)
105. P.S. Bhupal Dev, R.N. Mohapatra, Y. Zhang, Probing TeV scale origin of neutrino mass at future lepton colliders via neutral and doubly-charged scalars. Phys. Rev. D **98**, 075028 (2018). arXiv:1803.11167
106. Y.-C. Guo, C.-X. Yue, Z.-C. Liu, The signatures of doubly charged leptons in future linear colliders. J. Phys. G Nucl. Part. Phys. **44**, 085004 (2017). arXiv:1611.08843
107. L. Rahili, A. Arhrib, R. Benbrik, Associated production of SM Higgs with a photon in type-II seesaw models at the ILC. Eur. Phys. J. C **79**, 940 (2019). arXiv:1909.07793
108. M. Demirci, A.I. Ahmadov, Neutralino pair production via photon–photon collisions at the ILC. Phys. Rev. D **94**, 075025 (2016). arXiv:1610.09398
109. G.-Li Liu, F. Wang, K. Xie, X.-F. Guo, Probing lepton flavor violation signal via $\gamma\gamma \to l_i \bar{l}_j$ in the left-right twin Higgs model at the ILC. Phys. Rev. D **96**, 035005 (2017). arXiv:1701.00947
110. H. Yang, Z.-Q. Chen, C.-F. Qiao, NLO QCD corrections to exclusive quarkonium-pair production in photon-photon collision. Eur. Phys. J. C **80**, 806 (2020). arXiv:2006.05351
111. M. Köksal, Model-independent study on the anomalous $\tau\bar{\tau}\gamma$ couplings at the ILC. Nucl. Phys. B **971**, 115520 (2021). arXiv:2104.01003
112. T.G. Rizzo, New physics beyond the Standard Model at $\gamma\gamma$ colliders. Nucl. Instrum. Methods A **472**, 37 (2001). arXiv:hep-ph/0008037
113. F. Bechtel et al., Studies for a photon collider at the ILC. Nucl. Instrum. Methods A **564**, 243 (2006). arXiv:physics/0601204
114. S.C. İnan, A.V. Kisselev, A search for axion-like particles in light-by-light scattering at the CLIC. JHEP **06**, 183 (2020). arXiv:2003.01978
115. S.C. İnan, A.V. Kisselev, Polarized light-by-light scattering at the CLIC induced by axion-like particles. Chin. Phys. C **45**, 043109 (2021). arXiv:2007.01693
116. S.C. İnan, A.V. Kisselev, Probing anomalous quartic $\gamma\gamma\gamma\gamma$ couplings in light-by-light collisions at the CLIC. Eur. Phys. J. C **81**, 664 (2021). arXiv:2009.09712
117. S.C. İnan, A.V. Kisselev, Probing anomalous $\gamma\gamma\gamma Z$ couplings through γZ production in $\gamma\gamma$ collisions at the CLIC. JHEP **10**, 121 (2021). arXiv:2108.04478
118. A. Belyaev, N. D. Christensen, A. Pukhov, CalcHEP 3.4 for collider physics within and beyond the Standard Model. Comput. Phys. Commun. **184**, 1729 (2013). arXiv:1207.6082
119. G. Cowan, K. Cranmer, E. Gross, O. Vitells, Asymptotic formulae for likelihood-based tests of new physics. Eur. Phys. J. C **71**, 1554 (2011). arXiv:1007.1727
120. L. Di Luzio, M. Giannotti, E. Nardi, L. Visinelli, The landscape of QCD axion models. Phys. Rep. **870**, 1 (2020). arXiv:2003.01100
121. V. Berestetskii, E. Lifshitz, V. Pitaevskii, *Quantum Electrodynamics: Volume 4 (Course of Theoretical Physics)*, Second edition (Butterworth-Heinemann, 1982), p. 354–359