Prospects for dark matter search at a super c-tau factory

E. E. Boos,* V. E. Bunichev,† and S. S. Trykov‡

D. V. Skobeltsyn Institute of Nuclear Physics, M. V. Lomonosov Moscow State University, Moscow 119991, Russia

(Received 18 August 2022; accepted 26 March 2023; published 19 April 2023)

We present perspectives for searching for light dark matter production mediated by a leptophilic scalar ϕ and a dark photon A' in experiments at a super c-tau factory. Based on the analysis of the associative production of mediators and τ-leptons at the energies of a future collider, the possibility of searching in the nonexcluded region of the parameter space was found. The obtained sensitivity curves at the 90% C.L. for the mediators' mass range below 4 GeV demonstrate the power of the super c-tau factory for light dark matter search.

DOI: 10.1103/PhysRevD.107.075021

I. INTRODUCTION

Many gravitational, astrophysical, and cosmological unexplained phenomena indicate the existence of a special kind of matter, which we call dark matter (DM) [1–3]. Such kinds of phenomena can be explained by assuming that DM is a kind of particle, which should have some certain properties. We follow a simplified model approach, in which it is assumed that there are DM particles of any spin and there are particles, usually scalar or vector, mediating interactions between Standard Model (SM) particles and DM [4].

Many models beyond the SM predict the existence of additional scalars ϕ that can mediate interactions between SM particles and DM [5–7]. Possible couplings of an interaction between additional scalars with SM fermions are constrained by the SM gauge invariance. Now, the minimal extension of the scalar sector by mixing an additional scalar with the SM Higgs boson is strongly constrained by experiments of searching for rare flavor-changing neutral current decays of mesons, such as $B^+ \to K^+\phi$ and $K^+ \to \pi^+\phi$ [8,9], and by searching for heavy DM [4,8–10]. Thus, the MeV—GeV range search area comes to the fore.

In a sub-GeV scale, some beyond the SM theories make it possible to assume that in the SM sector after spontaneous electroweak symmetry breaking, an extra scalar couples exclusively to SM leptons [5–7]. Possible couplings with quarks turn out to be strongly suppressed. Thus, a scalar portal for interaction between heavy-flavored SM leptons and DM occurs. We refer to the additional scalar particle as a dark leptophilic scalar ϕ. A Lagrangian of that interaction is given by

$$\mathcal{L}^{\phi}_{\rm int} = -\xi \sum_{\ell=e,\mu,\tau} \frac{m_\ell}{v} \bar{\ell}\phi\ell - g_{\rm D}\bar{\chi}\phi\chi, \tag{1}$$

where ξ is the flavor-independent coupling constant, $v = 246$ GeV is the SM Higgs vacuum expectation value, and the second term is a Lagrangian of the interaction between the dark scalar ϕ and fermionic DM states χ with a coupling constant $g_{\rm D}$.

In the mass range from several MeV to several GeV, if allowed kinematically, the dominant modes of decay of the dark leptophilic scalar are lighter DM states and massive SM leptons. The corresponding partial decay widths have the form [11]

$$\Gamma_\phi^{\chi\bar{\chi}} = g_{\rm D}^2 \frac{m_\phi}{8\pi}\beta_\chi^3, \tag{2}$$

$$\Gamma_\phi^{\ell^+\ell^-} = \xi^2 \frac{m_\ell^2}{v^2}\frac{m_\phi}{8\pi}\beta_\ell^3, \tag{3}$$

here $\beta_f = \sqrt{1 - 4m_f^2/m_\phi^2}$, m_ϕ is mass of the mediator, and m_f is mass of the mediator decay product.

Another intriguing possibility for providing a portal between the SM and DM sectors is an addition of an extra massive vector boson associated with the spontaneously broken $U_{\rm D}(1)$ gauge group, whose interaction between the SM charged fermionic current is similar to the ordinary photon of electromagnetism [4,12,13]. We refer to such a vector mediator as a dark photon A'. The A' can have a mass in the sub-GeV mass range and couple to the SM via kinetic

*boos@theory.sinp.msu.ru
†bunichev@theory.sinp.msu.ru
‡trykow.sergei@gmail.com

mixing with the ordinary photon. A coupling constant of the interaction between A' and the SM states is suppressed by a kinetic mixing parameter $\varepsilon \ll 1$. A Lagrangian can be written as [12,14,15]

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}\frac{\varepsilon}{\cos\theta_{\rm W}} B^{\mu\nu} F'_{\mu\nu} + \mathcal{L}_{\rm Dark} - e_{\rm D} A'_{\mu} j^{\mu}_{\rm DM}, \quad (4)$$

where $F'_{\mu\nu} \equiv \partial_\mu A'_\nu - \partial_\nu A'_\mu$ is the dark photon gauge field A'_μ strength tensor, $B_{\mu\nu} \equiv \partial_\mu B_\nu - \partial_\nu B_\mu$ is the SM weak hypercharge strength tensor; $e = \sqrt{4\pi\alpha_{\rm EM}}$ is the $U(1)$ coupling constant, and $e_{\rm D} = \sqrt{4\pi\alpha_{\rm D}}$ is the $U_{\rm D}(1)$ coupling constant of the interaction between A', and the DM current $j^{\mu}_{\rm DM} = \bar{\chi}\gamma^\mu\chi$ for fermionic DM states. $\mathcal{L}_{\rm Dark}$ is a term containing DM and dark photon state Lagrangians.

After spontaneous symmetry breaking in the MeV—GeV mass range, the main contribution of mixing by the term $B^{\mu\nu}F'_{\mu\nu}$ in the Lagrangian (4) is given by $(\varepsilon/2)F^{\mu\nu}F'_{\mu\nu}$. Mixing with a heavy Z boson is suppressed by a factor $1/m_Z^2$. After diagonalization of the kinetic terms, the result of mixing leads to the fact that the dark photon A' acquires a coupling εe with the electromagnetic current $j^{\mu}_{\rm EM}$ is

$$\mathcal{L}^{A'}_{\rm int} = -\varepsilon e A'_\mu j^\mu_{\rm EM} - e_{\rm D} A'_\mu j^\mu_{\rm DM}. \quad (5)$$

We consider light DM states χ with mass $m_\chi < m_{A'}/2$ and $e_{\rm D} > e$. Thus, if kinematically allowed, the dark photon is expected to decay predominantly into invisible dark sector final states. If no such decays are allowed, the dark photon will decay into visible SM final states, with decay partial widths given by [11,16]

$$\Gamma^{\chi\bar{\chi}}_{A'} = \frac{1}{3}\alpha_{\rm D} m_{A'}\left(1 + 2\frac{m_\chi^2}{m_{A'}^2}\right)\beta_\chi, \quad (6)$$

$$\Gamma^{\ell^+\ell^-}_{A'} = \frac{1}{3}\varepsilon^2 \alpha m_{A'}\left(1 + 2\frac{m_\ell^2}{m_{A'}^2}\right)\beta_\ell, \quad (7)$$

$$\Gamma^{\rm hadrons}_{A'} = \frac{1}{3}\varepsilon^2 \alpha m_{A'}\left(1 + 2\frac{m_\mu^2}{m_{A'}^2}\right)\beta_\mu R, \quad (8)$$

$$R \equiv \frac{\sigma(e^+e^- \to {\rm hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}, \quad (9)$$

where β_f has the same definition as in (2) and (3).

In this work we focus on searching for invisible decays of the leptophilic scalar ϕ and the dark photon A' in the processes $e^+e^- \to \tau^+\tau^- + (\phi \to {\rm invisible})$ and $e^+e^- \to \tau^+\tau^- + (A' \to {\rm invisible})$, which are shown in the Fig. 1, at the running energies of a future super c-tau factory (SCTF). A SCTF is a promising project of a future electron-positron collider for the energy range from 3 to 7 GeV in the center of mass system that will provide a uniquely high peak luminosity of 10^{35} cm^{-2} s^{-1}. A SCTF physical program is aimed at a detailed study of the processes involving the c-quark and τ-lepton in the final state. For ten years of SCTF operation, the integral luminosity of the collider will exceed 10 ab^{-1}.

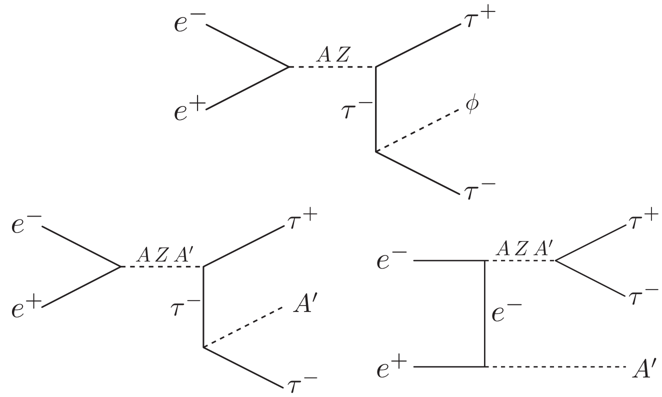

FIG. 1. The Feynman diagrams for the ϕ and A' on-shell production in e^+e^- collisions. We assume that the mediators subsequently decay to lighter DM.

II. CROSS SECTIONS

All calculations and Monte Carlo simulation for signal and background processes were performed using the CompHEP package [17]. In the following, we assume that the mediators' invisible decay mode is predominant, ${\rm Br}(\phi \to \chi\bar{\chi}) \simeq 1$ and ${\rm Br}(A' \to \chi\bar{\chi}) \simeq 1$. If such invisible ϕ and A' exist, they could be produced by e^+e^- collisions at a SCTF and generate a flux of DM particles, which can be detected through the missing energy and momentum. We found that, within the framework of the considered models, the optimal collider regimes for searching for dark matter are sessions at energies of 4.2 GeV and 7 GeV. To accurately take into account radiation effects, we used the following planned beam parameters: the radii of the bunches in the horizontal and vertical dimensions are $\sigma_x = 17.8$ μm and $\sigma_y = 0.178$ μm, respectively, with bunch length $\sigma_z = 10$ mm at the interaction point, and the number of particles per bunch $N_b = 7.1 \times 10^{10}$. In Fig. 2, we provide the ϕ and A' production cross section dependencies on their masses at the energies of 4.2 and 7 GeV, taking into account the Next-to-Leading Order (NLO) corrections from bremsstrahlung and Initial State Radiation (ISR) [17–23].

The main SM background to the $e^+e^- \to \tau^+\tau^-\phi$ and $e^+e^- \to \tau^+\tau^- A'$ signals at a future collider are the processes with a similar signature with missing energy $e^+e^- \to \tau^+\tau^-\bar{\nu}_\ell\nu_\ell$, where $\nu_\ell = \nu_e, \nu_\mu, \nu_\tau$ are the SM neutrinos. For the electron-positron collider running with GeV beam energy such processes are suppressed by Z- and W-boson propagators.

For each collider mode, using the statistical approach described in [24,25], we estimate 90% C.L. areas in the model parameter space available for research at a SCTF. As shown in [25], the significance is well described by the formula $2(\sqrt{S+B} - \sqrt{B})$, (where S and B are signal and

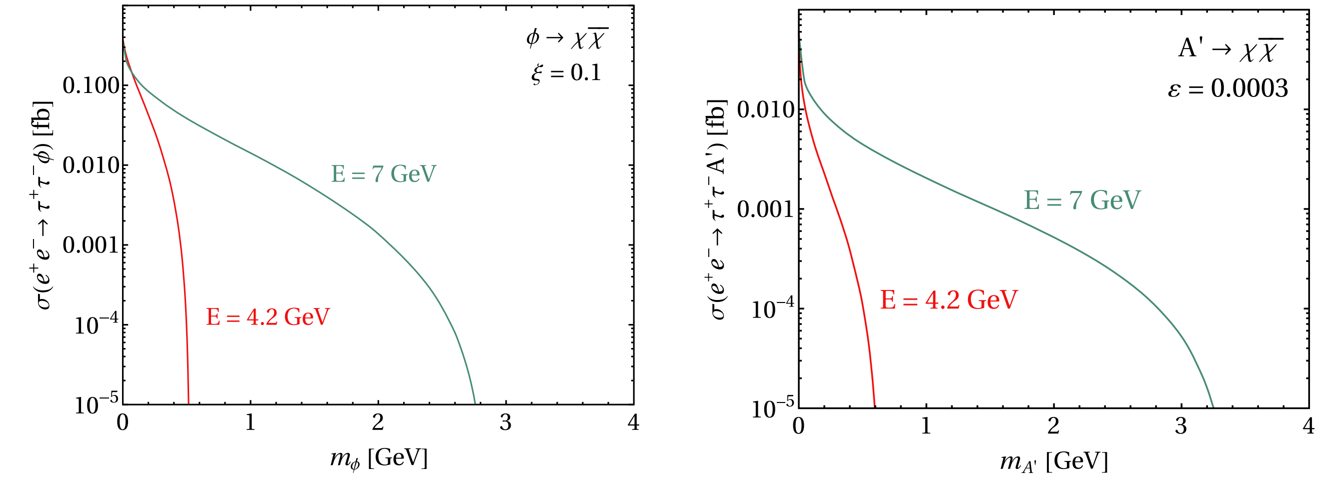

FIG. 2. The dependencies of $e^+e^- \to \tau^+\tau^- + (\phi \to \text{invisible})$ [left panel] and $e^+e^- \to \tau^+\tau^- + (A' \to \text{invisible})$ [right panel] cross sections on the mediator's mass at the running energies of a future SCTF.

background events) for the case of a large number of signal events.

III. DARK LEPTOPHILIC SCALAR

First, we estimated the available parameter ranges for models with a scalar mediator. We report new results for sensitivity to the dark leptophilic scalar production with its subsequent decay to light DM in experiments at a SCTF. In order to estimate the upper limit of the potential capabilities of a SCTF, we first performed simulations under the condition of 100% efficiency of tau lepton detection.

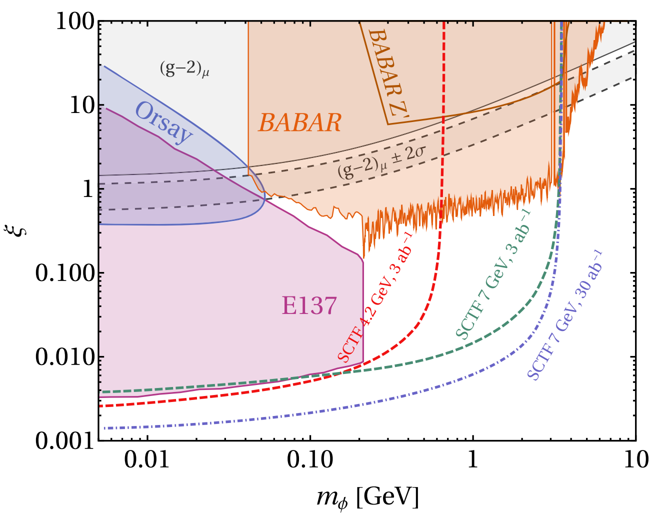

FIG. 3. The sensitivity curves on the coupling ξ as a function of the ϕ mass at the 90% C.L. are obtained assuming integrated luminosity of 3 ab^{-1} at the collider energies $\sqrt{s} = 4.2$ GeV (dashed red), $\sqrt{s} = 7$ GeV (dashed green), and assuming integrated luminosity of 30 ab^{-1} at $\sqrt{s} = 7$ GeV (dashed blue). Existing constraints [26–31] (shaded areas), as well as the favored muon anomalous magnetic moment $(g-2)_\mu$ area [7,27] (gray dashed), are also shown.

Figure 3 shows the sensitivity curves at the 90% C.L. in the $[\xi, m_\phi]$ plane, assuming about 3 ab^{-1} data collected at $\sqrt{s} = 4.2$ GeV (dashed red), $\sqrt{s} = 7$ GeV (dashed green), and 30 ab^{-1} at $\sqrt{s} = 4.2$ GeV (dashed blue) The existing experimental constraints are also shown: bounds in channels where ϕ is allowed to decay visibly from the *BABAR* experiment at the Stanford Linear Accelerator Center (SLAC) [26], the measurement for $\mathrm{Br}(K_L \to \pi^0\phi)$ from the KOTO experiment [27], search for dark bosons Z' with vector couplings only to the second and third generations of

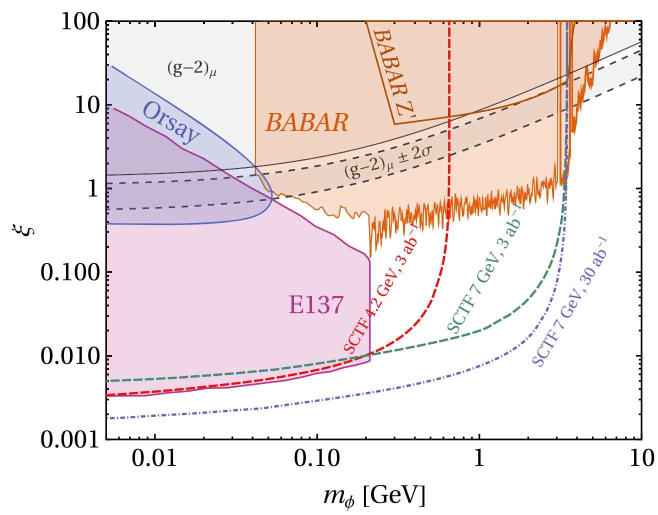

FIG. 4. The sensitivity curves on the coupling ξ as a function of the ϕ mass at the 90% C.L. are obtained assuming integrated luminosity of 3 ab^{-1} at the collider energies $\sqrt{s} = 4.2$ GeV (dashed red), $\sqrt{s} = 7$ GeV (dashed green), and assuming integrated luminosity of 30 ab^{-1} at $\sqrt{s} = 7$ GeV (dashed blue), taking into account the realistic detection efficiency of the tau leptons. Existing constraints [26–31] (shaded areas), as well as the favored muon anomalous magnetic moment $(g-2)_\mu$ area [7,27] (gray dashed), are also shown.

leptons [28], measurement from [29], from the electron beam-dump experiment [30], and search for neutral objects on the SLAC beam dump [31]. Furthermore, taking into account the efficiency of reconstruction and identification of tau leptons at modern colliders [32–34], we construct the sensitivity curves in Fig. 4.

It can be seen that even in the case when the realistic detection efficiency of tau pairs is 50%, the boundaries of the regions available for a SCTF are much wider than those obtained in previous experiments. Due to the high integral luminosity, a SCTF allows one to "feel" mediators with a range of masses below 3.5 GeV and coupling ξ down to 10^{-3}.

IV. DARK PHOTON

On the next step we estimated the available parameter ranges for models with a vector mediator. In Fig. 5 we present SCTF sensitivity curves at the 90% C.L. in the $[\varepsilon, m_{A'}]$ plane, taking into account the 100% efficiency of tau lepton identification. The existing experimental constraints are also shown: bounds in channels where A' is allowed to decay invisibly from NA62 [35], NA64 [36], *BABAR* [37], the measurement for $\mathrm{Br}(K^+ \to \pi^+ \nu\bar{\nu})$ by the E787 [38] and E949 [39] experiments, as well as the anomalous muon magnetic moment $(g-2)_\mu$ favored area [40]. Figure 6 shows the constructed sensitivity curves, taking into account the realistic efficiency of reconstruction and identification of the tau leptons.

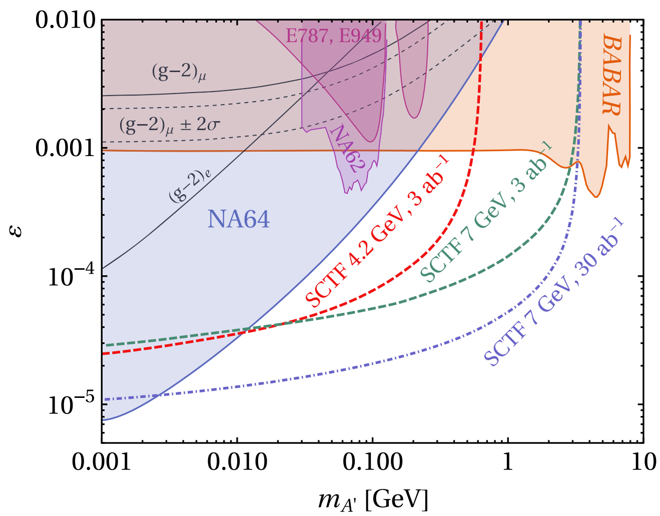

FIG. 5. The sensitivity curves on the mixing strength ε as a function of the A' mass at the 90% C.L. are obtained assuming integrated luminosity of 3 ab^{-1} at the collider energies $\sqrt{s} = 4.2$ GeV (dashed red), $\sqrt{s} = 7$ GeV (dashed green), and assuming integrated luminosity of 30 ab^{-1} at $\sqrt{s} = 7$ GeV (dashed blue). Existing constraints [35–39,41,42] (shaded areas), as well as the favored muon anomalous magnetic moment $(g-2)_\mu$ area [40] (gray dashed), are also shown.

We can see that a SCTF with about 30 ab^{-1} can provide new data in the nonexcluded region 0.003 GeV $\lesssim m_{A'} \lesssim$ 3.5 GeV and ε down to 10^{-5}.

Using constraints on the cross section of the DM annihilation freeze-out and the obtained SCTF sensitivities on the mixing strength ε, it can be possible to derive constraints on the light thermal DM models. In Fig. 7 we plot the expected values at the 90% C.L. for the dimensionless DM annihilation cross section parameter $y = \varepsilon^2 \alpha_{\mathrm{D}} (m_\chi / m_{A'})^4$, depending on the DM mass m_χ. The limits on the variable y are calculated under the convention $\alpha_{\mathrm{D}} = 0.5$ and $\alpha_{\mathrm{D}} = 0.1$, and $m_{A'} = 3 m_\chi$ [8,43,44], larger ratios $m_\chi / m_{A'}$ qualitatively change the physics, and larger α_{D} can run towards the nonperturbative regime [45].

The favored parameters for the scalar, pseudo-Dirac (with a small splitting), and Majorana light thermal DM scenarios, taking into account the observed DM relic density, are shown as the solid black lines [46]. Bounds from other experiments for comparison are also shown [8,13,36,37,43,44,47–53].

We can see that the models for light thermal DM can be excluded by the combined possible future data from a SCTF at $\sqrt{s} = 7$ GeV, 3 ab^{-1} and 30 ab^{-1}, and *BABAR* [37]: for scalar DM in the mass region 0.4 GeV $\lesssim m_\chi \lesssim$ 1 GeV and Majorana DM—0.5 GeV $\lesssim m_\chi \lesssim$ 1 GeV by $\alpha_{\mathrm{D}} = 0.5$; 0.1 GeV $\lesssim m_\chi \lesssim$ 1 GeV and 0.2 GeV $\lesssim m_\chi \lesssim$ 1 GeV by $\alpha_{\mathrm{D}} = 0.1$, respectively; for pseudo-Dirac DM in the mass region 0.7 GeV $\lesssim m_\chi \lesssim$ 1 GeV by $\alpha_{\mathrm{D}} = 0.1$.

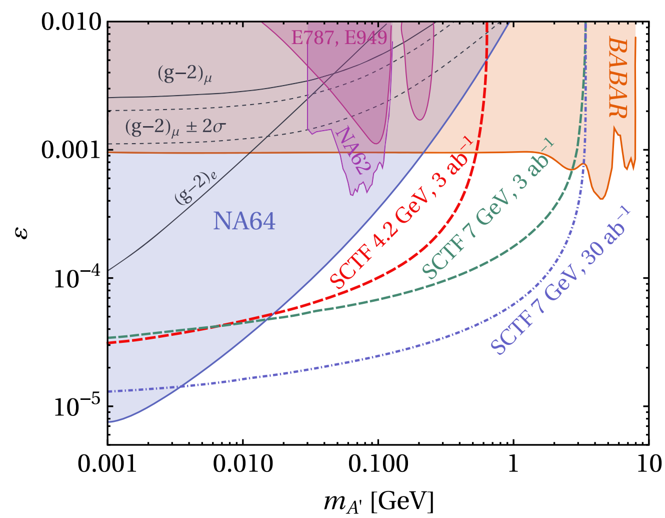

FIG. 6. The sensitivity curves on the mixing strength ε as a function of the A' mass at the 90% C.L. are obtained assuming integrated luminosity of 3 ab^{-1} at the collider energies $\sqrt{s} = 4.2$ GeV (dashed red), $\sqrt{s} = 7$ GeV (dashed green), and assuming integrated luminosity of 30 ab^{-1} at $\sqrt{s} = 7$ GeV (dashed blue), taking into account the realistic detection efficiency of the tau leptons. Existing constraints [35–39,41,42] (shaded areas), as well as the favored muon anomalous magnetic moment $(g-2)_\mu$ area [40] (gray dashed), are also shown.

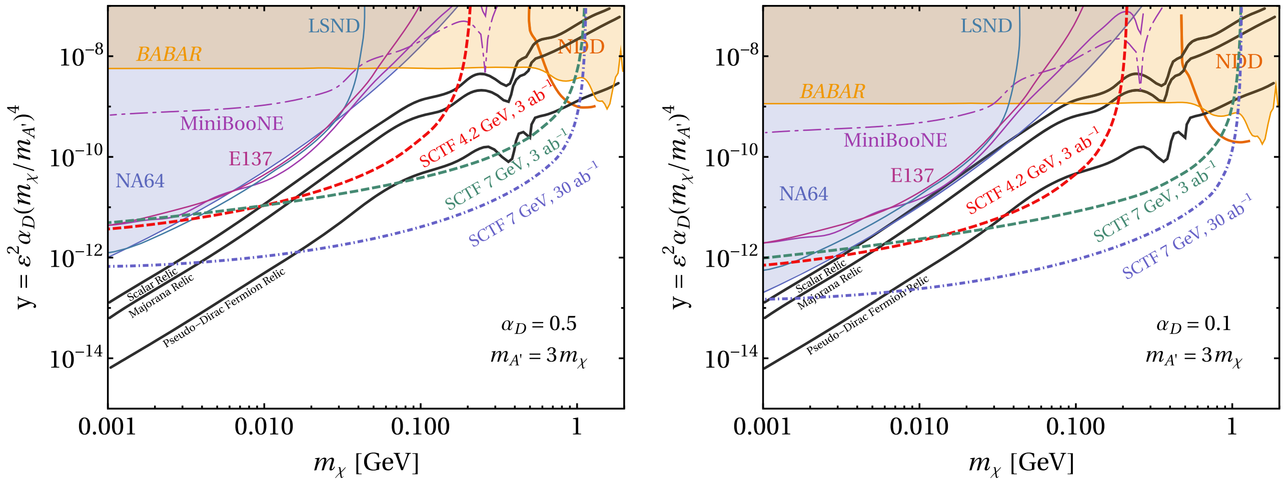

FIG. 7. The sensitivity curves at the 90% C.L. in the $[y, m_\chi]$ plane are obtained for $\alpha_D = 0.5$ (left panel) and $\alpha_D = 0.1$ (right panel), assuming integrated luminosity of 3 ab^{-1} at the collider energies $\sqrt{s} = 4.2$ GeV (dashed red) and $\sqrt{s} = 7$ GeV (dashed green), and assuming integrated luminosity of 30 ab^{-1} at $\sqrt{s} = 7$ GeV (dashed blue). The favored parameter values to account for the observed relic DM density for the scalar, pseudo-Dirac, and Majorana type of light DM [46] are shown as the solid lines. The existing limits are shown in comparison with bounds obtained in Refs. [8,13,36,37,43,44,47–53]. The lines marked as LSND and NDD correspond to the constraints obtained using a Liquid Scintillator Neutrino Detector and Nuclear Direct Detection, respectively.

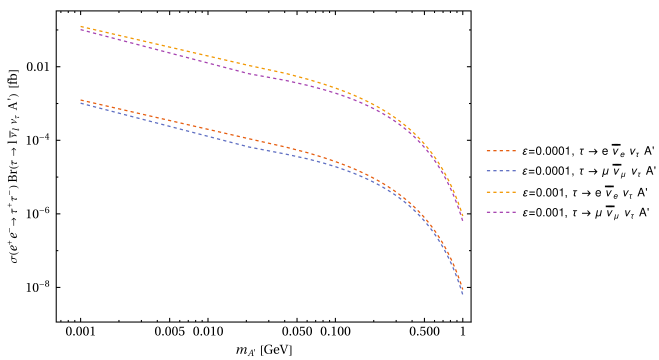

FIG. 8. The cross sections of A' production in e^+e^- collisions at the energy of 4.2 GeV by tau decays in the dominant decay modes $\tau \to \ell\bar{\nu}_\ell\nu_\tau A'$, $\ell = e, \mu$.

In addition to the processes of associative production of a vector mediator with τ leptons, we evaluated the possibility of detecting mediators in τ decays $\tau \to \ell\bar{\nu}_\ell\nu_\tau A'$, where $\ell = e, \mu$. To estimate, we used a SCTF running energy of 4.2 GeV with the highest value of the τ pair production cross section. Figure 8 shows the dependence of these processes' cross sections for $\varepsilon = 0.0001$ and $\varepsilon = 0.001$. It can be seen that taking into account the modes of the collider operation, one should not expect the appearance of such events for $\epsilon \lesssim 0.001$ in the MeV—GeV mass of A' range.

V. SUMMARY

In this work we have proposed a search for invisible decays of the dark leptophilic scalar and dark photon in the

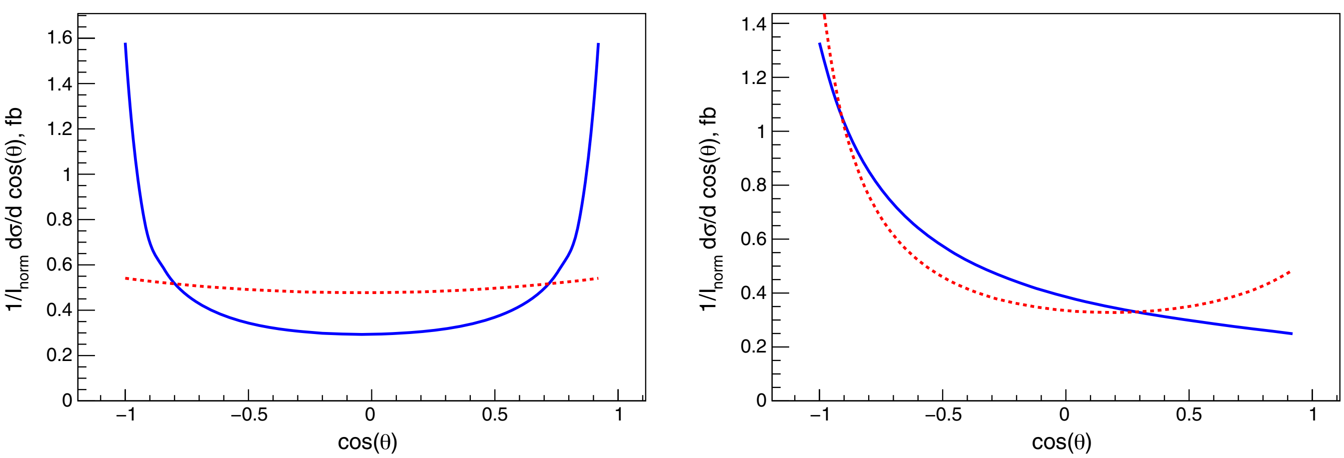

FIG. 9. Normalized cos θ distribution. On the left plot: θ is an angle between momentums of initial electron and final mediator. On the right plot: θ is an angle between momentums of final tau and final mediator. The red doted line corresponds to the dark scalar with mass = 0.5 GeV and $\xi = 0.1$ and the blue solid line corresponds to the dark photon with $\varepsilon = 0.0003$. Note that $\sqrt{s} = 7$ GeV.

processes $e^+e^- \to \tau^+\tau^-\phi$ and $e^+e^- \to \tau^+\tau^-A'$, respectively, at a future SCTF. We present the promising sensitivity on the scalar coupling constant ξ and the dark photon mixing strength ε at $\sqrt{s} = 4.2$, 7 GeV, assuming integrated luminosity of 3 ab^{-1} and 30 ab^{-1} for $\sqrt{s} =$ 7 GeV in the nonexcluded parameter spaces below 3.5 GeV. In addition, we have discussed the constraints on light thermal DM. We provide the expected 90% C.L. sensitivity on the dimensionless DM annihilation cross section parameter y. We find that future SCTF data can expand the search on light DM for the mass region 0.001 GeV $\lesssim m_\chi \lesssim$ 1 GeV; the scalar, pseudo-Dirac, and Majorana types of light DM can be excluded by the combined data from a future SCTF and *BABAR* for the mass region 0.1 GeV $\lesssim m_\chi \lesssim$ 1 GeV.

It should be noted that the search for light dark matter in the processes of associated production with tau leptons is of particular interest since it allows one to simultaneously search for scalar and vector mediators. As shown in Fig. 9, the angular distributions differ significantly for mediators with different spins. By studying the angular correlations in such processes, one can determine the spin nature of mediator particles.

ACKNOWLEDGMENTS

This study was carried out as part of the scientific program of the National Center for Physics and Mathematics, the project “Particle Physics and Cosmology”.

[1] F. Zwicky, Helv. Phys. Acta **6**, 110 (1933).
[2] F. Zwicky, Astrophys. J. **86**, 217 (1937).
[3] V. C. Rubin and W. K. Ford, Jr., Astrophys. J. **159**, 379 (1970).
[4] P. Agrawal *et al.*, Eur. Phys. J. C **81**, 1015 (2021).
[5] G. Marshall and M. Sher, Phys. Rev. D **83**, 015005 (2011).
[6] G. C. Branco, P. M. Ferreira, L. Lavoura, M. N. Rebelo, M. Sher, and J. P. Silva, Phys. Rep. **516**, 1 (2012).
[7] B. Batell, N. Lange, D. McKeen, M. Pospelov, and A. Ritz, Phys. Rev. D **95**, 075003 (2017).
[8] J. Beacham *et al.*, J. Phys. G **47**, 010501 (2020).
[9] G. Lanfranchi, M. Pospelov, and P. Schuster, Annu. Rev. Nucl. Part. Sci. **71**, 279 (2021).
[10] M. Felcini (ATLAS and CMS Collaborations), in *53rd Rencontres de Moriond on Cosmology* (2018), pp. 327–336, arXiv:1809.06341.
[11] D. Abercrombie *et al.*, Phys. Dark Universe **27**, 100371 (2020).
[12] B. Holdom, Phys. Lett. **166B**, 196 (1986).
[13] J. Alexander *et al.*, arXiv:1608.08632.
[14] L. B. Okun, Sov. Phys. JETP **56**, 502 (1982).
[15] P. Galison and A. Manohar, Phys. Lett. **136B**, 279 (1984).
[16] M. Fabbrichesi, E. Gabrielli, and G. Lanfranchi, *The Physics of the Dark Photon*, SpringerBriefs in Physics (Springer, Cham, 2021), 10.1007/978-3-030-62519-1.
[17] E. Boos, V. Bunichev, M. Dubinin, L. Dudko, V. Ilyin, A. Kryukov, V. Edneral, V. Savrin, A. Semenov, and A. Sherstnev (CompHEP Collaboration), Nucl. Instrum. Methods Phys. Res., Sect. A **534**, 250 (2004).
[18] F. A. Berends, R. Kleiss, S. Jadach, and Z. Was, Acta Phys. Pol. B **14**, 413 (1983).
[19] F. A. Berends and A. Böhm, Adv. Ser. Dir. High Energy Phys. **1**, 27 (1988).
[20] F. A. Berends, Nucl. Phys. B, Proc. Suppl. **16**, 185 (1990).
[21] S. Jadach, B. F. L. Ward, and Z. Was, Comput. Phys. Commun. **130**, 260 (2000).
[22] R. J. Akers, Determination of the Tau pair production cross section at the $\Sigma(e^+e^- \to \tau^+\tau^-)$ at the Z^0 Resonance, Ph.D. thesis, Manchester University, 1995.
[23] S. Banerjee, B. Pietrzyk, J. M. Roney, and Z. Was, Phys. Rev. D **77**, 054012 (2008).
[24] S. I. Bityukov and N. V. Krasnikov, Mod. Phys. Lett. A **13**, 3235 (1998).
[25] S. Bityukov, N. Krasnikov, A. Nikitenko, and V. Smirnova, *Proc. Sci.*, ACAT08 (2008) 118.
[26] J. P. Lees *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **125**, 181801 (2020).
[27] J. Liu, N. McGinnis, C. E. M. Wagner, and X.-P. Wang, J. High Energy Phys. 04 (2020) 197.
[28] J. P. Lees *et al.* (*BABAR* Collaboration), Phys. Rev. D **94**, 011102 (2016).
[29] Y.-S. Liu, D. McKeen, and G. A. Miller, Phys. Rev. Lett. **117**, 101801 (2016).
[30] M. Davier and H. Nguyen Ngoc, Phys. Lett. B **229**, 150 (1989).
[31] J. D. Bjorken, S. Ecklund, W. R. Nelson, A. Abashian, C. Church, B. Lu, L. W. Mo, T. A. Nunamaker, and P. Rassmann, Phys. Rev. D **38**, 3375 (1988).
[32] S. Chatrchyan *et al.* (CMS Collaboration), J. Instrum. **7**, P01001 (2012).
[33] V. Khachatryan *et al.* (CMS Collaboration), J. Instrum. **11**, P01019 (2016).
[34] A. M. Sirunyan *et al.* (CMS Collaboration), J. Instrum. **13**, P10005 (2018).
[35] E. Cortina Gil *et al.* (NA62 Collaboration), J. High Energy Phys. 05 (2019) 182.
[36] D. Banerjee *et al.*, Phys. Rev. Lett. **123**, 121801 (2019).

[37] J. P. Lees *et al.* (*BABAR* Collaboration), Phys. Rev. Lett. **119**, 131804 (2017).
[38] S. Adler *et al.* (E787 Collaboration), Phys. Rev. Lett. **88**, 041803 (2002).
[39] A. V. Artamonov *et al.* (BNL-E949 Collaboration), Phys. Rev. D **79**, 092004 (2009).
[40] G. W. Bennett *et al.* (Muon g-2 Collaboration), Phys. Rev. D **73**, 072003 (2006).
[41] H. Davoudiasl, H.-S. Lee, and W. J. Marciano, Phys. Rev. D **89**, 095006 (2014).
[42] R. Essig, J. Mardon, M. Papucci, T. Volansky, and Y.-M. Zhong, J. High Energy Phys. 11 (2013) 167.
[43] M. Battaglieri *et al.*, arXiv:1707.04591.
[44] E. Izaguirre, G. Krnjaic, P. Schuster, and N. Toro, Phys. Rev. Lett. **115**, 251301 (2015).
[45] H. Davoudiasl and W. J. Marciano, Phys. Rev. D **92**, 035008 (2015).
[46] A. Berlin, N. Blinov, G. Krnjaic, P. Schuster, and N. Toro, Phys. Rev. D **99**, 075001 (2019).
[47] A. A. Aguilar-Arevalo *et al.* (MiniBooNE DM Collaboration), Phys. Rev. D **98**, 112004 (2018).
[48] E. Izaguirre, Y. Kahn, G. Krnjaic, and M. Moschella, Phys. Rev. D **96**, 055007 (2017).
[49] E. Izaguirre, G. Krnjaic, P. Schuster, and N. Toro, Phys. Rev. D **91**, 094026 (2015).
[50] B. Batell, R. Essig, and Z. Surujon, Phys. Rev. Lett. **113**, 171802 (2014).
[51] R. Essig, A. Manalaysay, J. Mardon, P. Sorensen, and T. Volansky, Phys. Rev. Lett. **109**, 021301 (2012).
[52] P. deNiverville, M. Pospelov, and A. Ritz, Phys. Rev. D **84**, 075020 (2011).
[53] B. Batell, M. Pospelov, and A. Ritz, Phys. Rev. D **80**, 095024 (2009).