Prospects for Dark Matter Search at the Super c-tau Factory

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We present perspectives for searching for light dark matter production mediated by a leptophilic scalar $\phi$ and a dark photon $A'$ in experiments at the Super c-tau Factory. Based on the analysis of the associative production of mediators and $\tau$-leptons at the energies of the future collider, the possibility of searching in the non-excluded 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 SCTF for light dark matter search.

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 kind of phenomena can be explained by assuming that DM is a kind of particles, which should have some certain properties. We follow a simplified models 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 $\phi$ 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 $B^+ \rightarrow K^+ \phi$ and $K^+ \rightarrow \pi^+ \phi$ [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 BSM 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 is occurred. We refer the additional scalar particle as a dark leptophilic scalar $\phi$. A Lagrangian of that interaction is given by

$$\mathcal{L}^\phi_{\text{int}} = -\xi \sum_{\ell=e,\mu,\tau} \frac{m_\ell}{v} \bar{\ell} \phi \ell - g_D \bar{\chi} \phi \chi,$$

where $\xi$ 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 $\phi$ and fermionic DM states $\chi$ with a coupling constant $g_D$.

In the MeV – GeV mass range, if kinematically allowed, dominant decay modes of the dark leptophilic scalar are to lighter DM states and to leptons, with partial widths given by [11]

$$\Gamma_\phi^{\chi \bar{\chi}} = g_D^2 \frac{m_\phi}{8\pi} \beta^3,$$

$$\Gamma_\phi^{e^+ e^-} = \xi^2 \frac{m_\phi^2}{v^2} \frac{m_\phi}{8\pi} \beta^3,$$

where $\beta_f = \sqrt{1 - 4m_f^2/m_\phi^2}$, $m_\phi$ - mass of the mediator, $m_f$ - 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 $U_D(1)$ gauge group, whose interaction between the SM charged fermionic current is similar to the ordinary photon of electromagnetism [4, 12, 13]. We refer 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 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]

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{2} \frac{\varepsilon}{\cos \theta_W} B^\mu B^\nu F^\mu_{\nu} + \mathcal{L}_{\text{Dark}} - e_D A'^\mu j_D^\mu_{\text{DM}},$$

where $F^\mu_{\nu} \equiv \partial_\mu A'^\nu - \partial_\nu A'^\mu$ is the dark photon gauge field $A'^\mu$, strength tensor, $B_{\mu\nu} \equiv \partial_\mu B_\nu - \partial_\nu B_\mu$ is the SM weak hypercharge strength tensor; $e = \sqrt{4\pi \alpha_{\text{EM}}}$ is the $U(1)$ coupling constant, and $e_D = \sqrt{4\pi \alpha_{\text{DM}}}$ is the $U_D(1)$ coupling constant. $j_D^\mu_{\text{DM}} = \bar{\chi} \gamma^\mu \chi$ for fermionic DM states. $\mathcal{L}_{\text{Dark}}$ is a term containing a DM and dark photon states Lagrangians.

After spontaneous symmetry breaking in the MeV – GeV mass range, the main contribution of mixing by the term $B^\mu F^\mu_{\nu}$ 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 $\varepsilon e$ with the electromagnetic current $j_{\text{EM}}^\mu$:

$$\mathcal{L}_{\text{int}} = -\varepsilon e A'^\mu_{\nu} j_{\text{EM}}^\mu - e_D A'^\mu_{\nu} j_D^\mu_{\text{DM}}.$$
We consider light DM states $\chi$ with mass $m_\chi < m_{A'}/2$ and $e_D > e$. Thus, if kinematically allowed, dark photon are 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]

$$\Gamma^{\chi A} = \frac{1}{3} \alpha_D m_{A'} \left(1 + \frac{2 m^2_\chi}{m^2_{A'}}\right) \beta_\chi,$$

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

$$\Gamma^{\text{hadrons}} = \frac{1}{3} \epsilon^2 \alpha m_{A'} \left(1 + \frac{2 m^2_\ell}{m^2_{A'}}\right) \beta_\mu R,$$

where $\beta_f$ has the same definition as in (2) and (3).

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

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, $Br(\phi \to \chi\chi) \approx 1$ and $Br(A' \to \chi\chi) \approx 1$. If such invisible $\phi$ and $A'$ exists, they could be produced by $e^+e^-$ collisions at the 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 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 $\sigma_x = 17.8 \mu m$ and $\sigma_y = 0.178 \mu m$, respectively, with bunch length $\sigma_z = 10 \text{ mm}$ at the interaction point, the number of particles per bunch $N_p = 7.1 \times 10^{10}$. In Fig. 2, we provide the $\phi$ and $A'$ production cross-section dependencies on their masses at the energies of 4.2 and 7 GeV, taking into account the NLO corrections from bremsstrahlung and ISR [17–23].

III. DARK LEPTOPHILIC SCALAR

The main SM background to the $e^+e^- \to \tau^+\tau^- \phi$ and $e^+e^- \to \tau^+\tau^- A'$ signals at the future collider are the processes with a similar signature with missing energy $e^+e^- \to \tau^+\tau^- \nu_\ell\nu_\ell$, 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 $W$-bosons propagators.

For each collider mode, using the statistical approach described in [24], we estimate 90\% C.L. areas in the model parameter space available for research at the SCTF.
FIG. 2. The dependencies of $e^+e^- \rightarrow \tau^+\tau^- + (\phi \rightarrow \text{invisible})$ [left panel] and $e^+e^- \rightarrow \tau^+\tau^- + (A' \rightarrow \text{invisible})$ [right panel] cross sections on the mediators mass at the running energies of the future SCTF.

FIG. 3. The Sensitivity curves on the coupling $\xi$ as a function of the $\phi$ mass at the 90% C.L. are obtained assuming integrated luminosity of $3 \text{ ab}^{-1}$ at the collider energies $\sqrt{s} = 4.2 \text{ GeV}$ (dashed red), $\sqrt{s} = 7 \text{ GeV}$ (dashed green), and assuming integrated luminosity of $30 \text{ ab}^{-1}$ at $\sqrt{s} = 7 \text{ GeV}$ (dashed blue). Existing constraints [25–30] (shaded areas) as well as the favored muon anomalous magnetic moment $(g-2)_\mu$ area [7, 26] (gray dashed) are also shown.

IV. DARK PHOTON

On the next step we estimated the available parameter ranges for models with a vector mediator. In Fig. 4 we present the SCTF sensitivity curves at the 90% C.L. in the $[\varepsilon, m_{A'}]$ plane. The existing experimental constraints are also shown: bounds in channels where $A'$ is allowed to decay invisibly from the NA62 [32], NA64 [31], BABAR [33], the measurement for $Br(K^+ \rightarrow \pi^+\nu\bar{\nu})$ by the E787 [36] and E949 [37] experiments, as well as the favored muon anomalous magnetic moment $(g-2)_\mu$ area [38] (gray dashed) are also shown.

FIG. 4. The Sensitivity curves on the mixing strength $\varepsilon$ as a function of the $A'$ mass at the 90% C.L. are obtained assuming integrated luminosity of $3 \text{ ab}^{-1}$ at the collider energies $\sqrt{s} = 4.2 \text{ GeV}$ (dashed red), $\sqrt{s} = 7 \text{ GeV}$ (dashed green), and assuming integrated luminosity of $30 \text{ ab}^{-1}$ at $\sqrt{s} = 7 \text{ GeV}$ (dashed blue). Existing constraints [31–37] (shaded areas) as well as the favored muon anomalous magnetic moment $(g-2)_\mu$ area [38] (gray dashed) are also shown.

We can see that the SCTF with about $30 \text{ ab}^{-1}$ can provide new data in the non-excluded region $0.01 \text{ GeV} \lesssim m_{A'} \lesssim 3.5 \text{ GeV}$ and $\varepsilon$ 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 $\varepsilon$, it can be possible to de-
In this work we have proposed a search for invisible decays of dark leptophilic scalar and dark photon in the processes $e^+e^- \rightarrow \tau^+\tau^-\phi$ and $e^+e^- \rightarrow \tau^+\tau^-A'$, respectively, at the future SCTF. We present the promising sensitivity on the scalar coupling constant $\xi$ and the dark photon mixing strength $\epsilon$ 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 non-excluded parameter spaces below $4$ GeV. In addition, we have discussed the constraints on the light thermal DM models. In Fig. 5 we plot the expected values at the 90% C.L. for the dimensionless DM annihilation cross section parameter $y = \varepsilon^2\alpha_D(m_\chi/m_{A'})^4$ depending on the DM mass $m_\chi$. The limits on the variable $y$ are calculated under the convention $\alpha_D = 0.5$ and $\alpha_D = 0.1$, and $m_{A'} = 3m_\chi$ [40, 43], larger ratios $m_\chi/m_{A'}$ qualitatively change the physics and larger $\alpha_D$ can run towards the non-perturbative regime [41].

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, shown as the solid black lines [49]. Bounds from other experiments for comparison are also shown [8, 13, 31, 33, 39, 40, 42–48].

We can see that the model for scalar DM can be excluded by the combined possible future data from the SCTF at $\sqrt{s} = 7$ GeV, 3 ab$^{-1}$ and 30 ab$^{-1}$ and BABAR [33]; 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 $\alpha_D = 0.5$, $0.1$ GeV $\lesssim m_\chi \lesssim 1$ GeV and $0.2$ GeV $\lesssim m_\chi \lesssim 1$ GeV by $\alpha_D = 0.1$, respectively; for pseudo-Dirac DM in the mass region $0.7$ GeV $\lesssim m_\chi \lesssim 1$ GeV by $\alpha_D = 0.1$.

In addition to the processes of associative production of a vector mediator with $\tau$ leptons, we evaluated the possibility of detecting mediators in $\tau$ decays $\tau \rightarrow \ell\nu\nu\tau A'$, where $\ell = e, \mu$. To estimate, we used the SCTF running energy of 4.2 GeV with the highest value of the $\tau$ pair production cross section. The Fig. 6 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 $\varepsilon \lesssim 0.001$ in the $\mathrm{MeV} - \mathrm{GeV}$ mass of $A'$ range.

**V. SUMMARY**

In this work we have proposed a search for invisible decays of dark leptophilic scalar and dark photon in the processes $e^+e^- \rightarrow \tau^+\tau^-\phi$ and $e^+e^- \rightarrow \tau^+\tau^-A'$, respectively, at the future SCTF. We present the promising sensitivity on the scalar coupling constant $\xi$ and the dark photon mixing strength $\epsilon$ 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 non-excluded parameter spaces below $4$ GeV. In addition, we have discussed the constraints on
FIG. 7. Normalized \( \cos \theta \) distribution. On the left plot: \( \theta \) is an angle between momentums of initial electron and final mediator. On the right plot: \( \theta \) is an angle between momentums of final tau and final mediator. Red dotted line correspond to dark scalar with mass = 0.5 GeV and \( \xi = 0.1 \) and blue solid line correspond to dark photon with \( \varepsilon = 0.0003 \). \( \sqrt{s} = 7 \) GeV.

light thermal DM. We provide the expected 90\% C.L. sensitivity on the dimensionless DM annihilation cross section parameter \( y \). We find that the future SCTF data can expand the search light DM for the mass region 0.001 GeV \( \lesssim \chi \lesssim 1 \) GeV; for the scalar, pseudo-Dirac and Majorana type of light DM can be excluded by the combined data from the future STCF and BABAR for the mass region 0.1 GeV \( \lesssim \chi \lesssim 1 \) 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. 7, 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.

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