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

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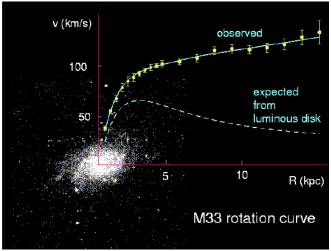
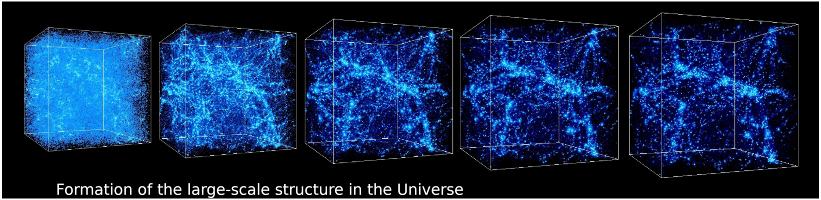
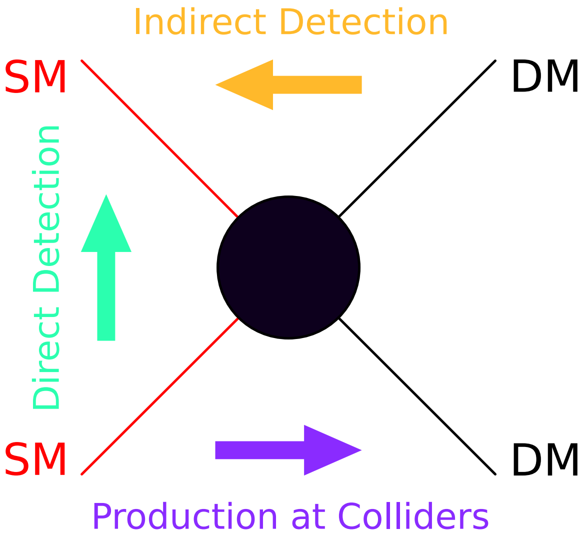


v (km/s)
100
50
observed
expected
from
luminous disk
5
10
R (kpc)
M33 rotation curve

Dark Matter Map in Galaxy Cluster Abell 1689
Hubble Space Telescope ACS/WFC
NASA, ESA, and D. Coe (JPL/Caltech and STScI)
STScI-PRC10-37



Formation of the large-scale structure in the Universe


Indirect Detection
SM
DM
Direct Detection
SM
DM
Production at Colliders

Dark Scalar in the $\mathrm{MeV} - \mathrm{GeV}$ Mass Range

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, 6, 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 ϕ. A Lagrangian of that interaction is given by

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

where ξ is the flavor-independent coupling constant, $v = 246\ \mathrm{GeV}$ 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_{D}.

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 [12, 13, 4, 14, 15]:

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

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 a DM and dark photon states Lagrangians.

After spontaneous symmetry breaking in the $\rm MeV - GeV$ mass range, the main contribution of mixing by the term $B^{\mu\nu}F'_{\mu\nu}$ in the Lagrangian (2) 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 $j^\mu_{\rm EM}$:

$$\mathcal{L}^{A'}_{\rm int} = -\varepsilon e A'_\mu j^\mu_{\rm EM} - e_{\rm D} A'_\mu j^\mu_{\rm DM}. \tag{3}$$

In the $\mathrm{MeV} - \mathrm{GeV}$ 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]

$$\Gamma_\phi^{\chi\bar{\chi}} = g_{\mathrm{D}}^2 \frac{m_\phi}{8\pi} \beta_\chi^3, \qquad \Gamma_\phi^{\ell^+\ell^-} = \xi^2 \frac{m_\ell^2}{v^2} \frac{m_\phi}{8\pi} \beta_\ell^3, \tag{4}$$

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

We consider light DM states χ with mass $2m_\chi < m_{A'}$ and $e_{\mathrm{D}} > e$. 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]

$$\Gamma_{A'}^{\chi\bar{\chi}} = \frac{1}{3} \alpha_{\mathrm{D}} m_{A'} \left(1 + 2\frac{m_\chi^2}{m_{A'}^2}\right) \beta_\chi, \tag{5}$$

$$\Gamma_{A'}^{\ell^+\ell^-} = \frac{1}{3} \varepsilon^2 \alpha m_{A'} \left(1 + 2\frac{m_\ell^2}{m_{A'}^2}\right) \beta_\ell, \tag{6}$$

$$\Gamma_{A'}^{\mathrm{hadrons}} = \frac{1}{3} \varepsilon^2 \alpha m_{A'} \left(1 + 2\frac{m_\mu^2}{m_{A'}^2}\right) \beta_\mu \frac{\sigma(e^+e^- \to \mathrm{hadrons})}{\sigma(e^+e^- \to \mu^+\mu^-)}, \tag{7}$$

where β_f has the same definition as in (4).

All calculations and Monte Carlo simulation for signal and background processes were performed using the CompHEP package [17].

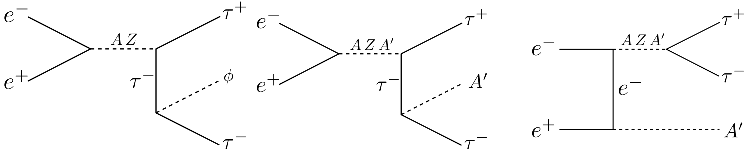


Figure 1: The Feynman diagrams for the ϕ and A' on-shell production in e^+e^- collisions. We assume that the mediators subsequently decays to lighter DM.

We assume that the mediators invisible decay mode is predominant, $Br(\phi \to \chi\bar{\chi}) \simeq 1$ and $Br(A' \to \chi\bar{\chi}) \simeq 1$.

Planned beam parameters at the SCTF:

the radii of the bunches in the horizontal and vertical dimensions are $\sigma_x = 17.8\,\mu\mathrm{m}$ and $\sigma_y = 0.178\,\mu\mathrm{m}$, respectively,

the bunch length $\sigma_z = 10\,\mathrm{mm}$ at the interaction point,

the number of particles per bunch $N_b = 7.1 \times 10^{10}$.

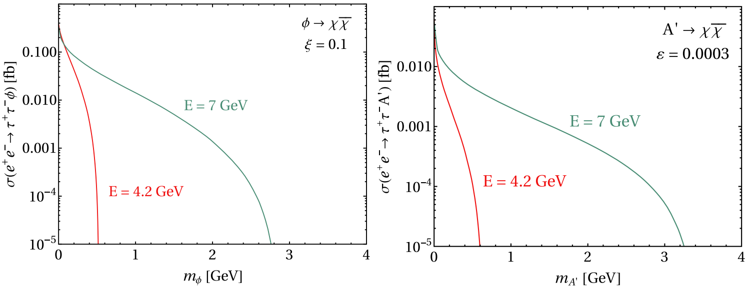


Figure 2: The dependencies of $e^+e^- \to \tau^+\tau^- + (\phi \to \textit{invisible})$ [left panel] and $e^+e^- \to \tau^+\tau^- + (A' \to \textit{invisible})$ [right panel] cross sections on the mediators mass at the running energies of the future SCTF.

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 $e^+e^- \to \tau^+\tau^-\bar{\nu}_\ell\nu_\ell$, where $\nu_\ell = \nu_e, \nu_\mu, \nu_\tau$ are the SM neutrinos.

For each collider mode, using the statistical approach described in *S. Bityukov, N. Krasnikov, A. Nikitenko and V. Smirnova, "Two approaches to combining significances," PoS* ACAT08 *(2008), 118*, we estimate 90% C.L. areas in the model parameter space available for research at the SCTF.

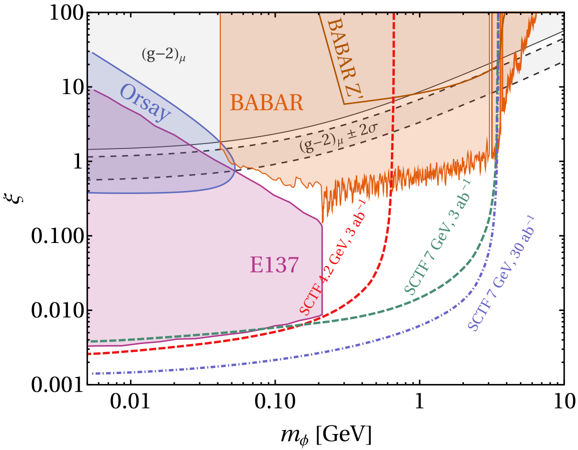


Figure 3: The Sensitivity curves on the coupling ξ as a function of the ϕ mass at the 90% C.L. are obtained assuming integrated luminosity of $3\,\mathrm{ab}^{-1}$ at the collider energies $\sqrt{s} = 4.2$ GeV (dashed red), $\sqrt{s} = 7$ GeV (dashed green), and assuming integrated luminosity of $30\,\mathrm{ab}^{-1}$ at the energy of 7 GeV (dashed blue). Existing constraints [25, 26, 27, 28, 29, 30] (shaded areas) as well as the favored muon anomalous magnetic moment $(g-2)_\mu$ area [7, 26] (gray dashed) are also shown.

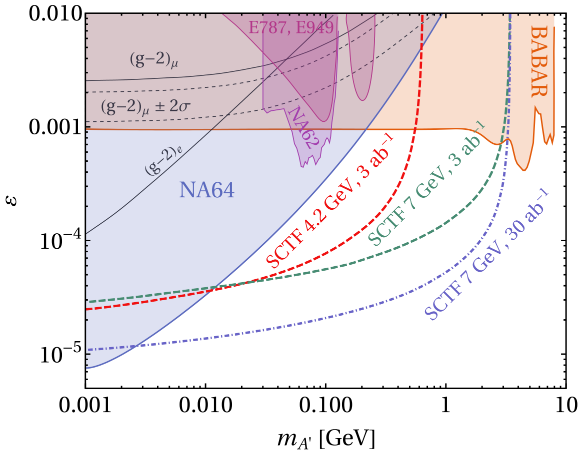


Figure 4: The Sensitivity curves on the mixing strength ε as a function of the A' mass at the 90% C.L. are obtained assuming integrated luminosity of $3\,\mathrm{ab}^{-1}$ at the collider energies $E = 4.2$ GeV (dashed red), $E = 7$ GeV (dashed green), and assuming integrated luminosity of $30\,\mathrm{ab}^{-1}$ at the energy of 7 GeV (dashed blue). Existing constraints [31, 32, 33, 34, 35, 36, 37] (shaded areas) as well as the favored muon anomalous magnetic moment $(g-2)_\mu$ area [38] (gray dashed) are also shown.

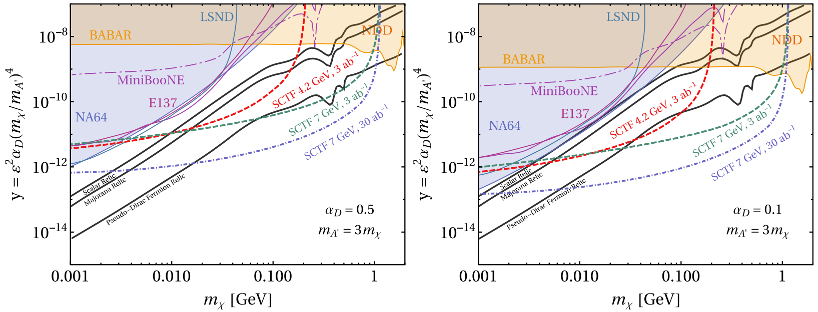


Figure 5: The Sensitivity curves at the 90% C.L. in the $[y, m_\chi]$ plane are obtained for $\alpha_D = 0.5$ (left pannel) and $\alpha_D = 0.1$ (right panel) assuming integrated luminosity of $3\,\mathrm{ab}^{-1}$ at the collider energies $E = 4.2$ GeV (dashed red) and $E = 7$ GeV (dashed green), and assuming integrated luminosity of $30\,\mathrm{ab}^{-1}$ at the energy of 7 GeV (dashed blue). The favored parameters values to account for the observed relic DM density for the scalar, pseudo-Dirac and Majorana type of light DM [49] are shown as the solid lines. The existing limits are shown in comparison with bounds obtained in Refs. [31, 8, 39, 40, 33, 42, 13, 43, 44, 45, 46, 47, 48].

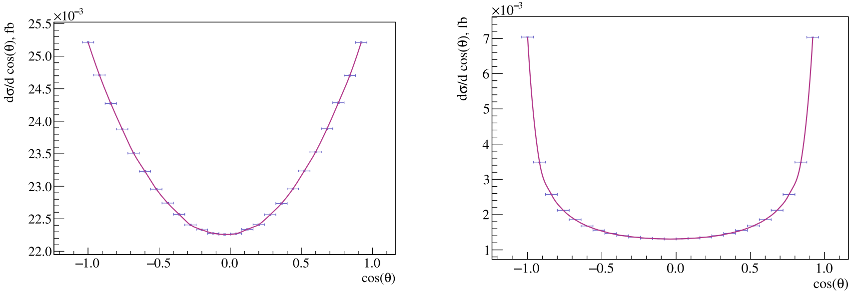
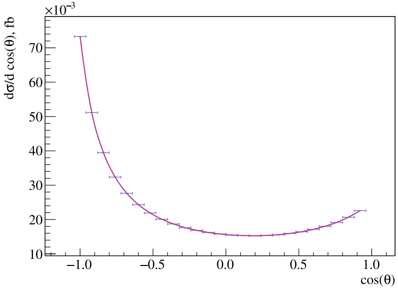


Figure 6: The distributions of the $\cos\theta$, θ is an angle between momentums of initial electron p_1 and final mediator p_5 with mass of $0.5\,\mathrm{GeV}$ at $\sqrt{s} = 7\,\mathrm{GeV}$ for dark scalar by $\xi = 0.1$ (left panel) and dark photon by $\varepsilon = 0.0003$ (right panel).



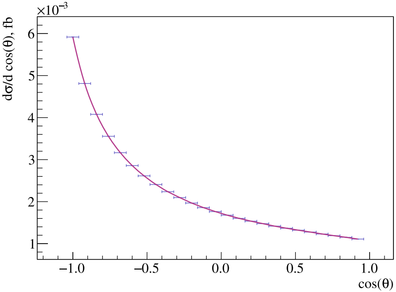


Figure 7: The distributions of the $\cos\theta$, θ is an angle between momentums of final tau-lepton p_3 and final mediator p_5 with mass of $0.5\,\mathrm{GeV}$ at $\sqrt{s} = 7\,\mathrm{GeV}$ for dark scalar by $\xi = 0.1$ (left panel) and dark photon by $\varepsilon = 0.0003$ (right panel).

Summary

- In this work we have proposed a search for invisible decays of dark leptophilic scalar and dark photon in the processes $e^+e^- \to \tau^+\tau^-\phi$ and $e^+e^- \to \tau^+\tau^-A'$, respectively, at the future SCTF. We present the promising sensitivity on the scalar coupling constant ξ and the dark photon mixing strength ε at $E = 4.2, 7\ \mathrm{GeV}$ assuming integrated luminosity of $3\,\mathrm{ab}^{-1}$, and $30\,\mathrm{ab}^{-1}$ for $E = 7\ \mathrm{GeV}$ in the non-excluded parameter spaces below $4\ \mathrm{GeV}$.
- 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 the future SCTF data can expand the search light DM for the mass region $0.001\ \mathrm{GeV} \lesssim m_\chi \lesssim 1\ \mathrm{GeV}$; 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 $0.1\ \mathrm{GeV} \lesssim m_\chi \lesssim 1\ \mathrm{GeV}$.
- 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. 6 and 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.

Thank you for your attention

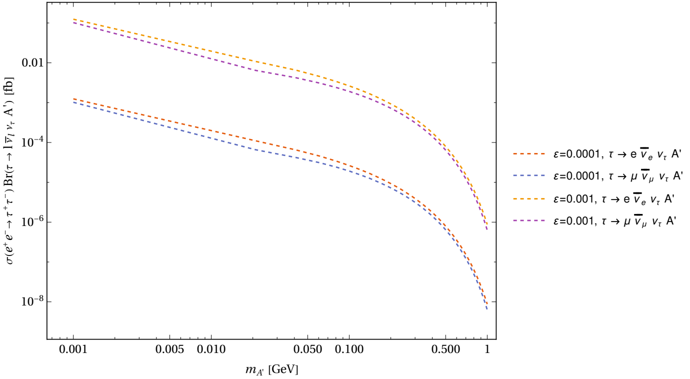


Figure 8: The cross sections of A' production in e^+e^- collisions at the energy of $4.2\,\mathrm{GeV}$ by tau-decays in the dominant decay modes $\tau \to \ell\bar{\nu}_\ell\nu_\tau A'$, $\ell = e, \mu$.

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 the SCTF running energy of 4.2 GeV with the highest value of the τ pair production cross section. 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 $\mathrm{MeV} - \mathrm{GeV}$ mass of A' range.

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