Tau flavored dark matter and its impact on tau Yukawa coupling

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Abstract. In this paper we perform a systematic study of the tau flavored dark matter (DM) model by introducing two kinds of mediators (a scalar doublet and a charged scalar singlet). The electromagnetic properties of the DM, as well as their implications in DM direct detections, are analyzed in detail. The model turns out contributing a significant radiative correction to the tau lepton mass, in addition to loosing the tension between the measured DM relic density and constraints of DM direct detections. The loop corrections can be $\mathcal{O}(10\%)$ of the total tau mass. Signal rates of the Higgs measurements from the LHC in the $h \rightarrow \tau\tau$ and $h \rightarrow \gamma\gamma$ channels, relative to the Standard Model expectations, can be explained in this model.

Keywords: dark matter theory, particle physics - cosmology connection

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1 Introduction

Accumulated cosmological and astrophysical observations have confirmed the existence of the cold dark matter (DM): $\Omega h^2 = 0.1199 \pm 0.0022$ [1], which requires an extension to the minimal Standard Model (SM). Since the nature of the DM and the way it interacts with the SM particles remain mysteries, it catalyzes various portals of the DM. Strengths of interactions between ordinary matter and DM are severely constrained by the observed DM relic abundance and exclusion limits from DM direct and indirect detections. Thanks to the advancement of the technology, many well-motivated DM models were tested and excluded by the DM direct and (or) indirect detection experiments! It raises challenge to the DM model building, but shows people hope of discovering DM in the laboratory.

Among various DM models, flavored DM [2–26] is interesting and appealing for the following three reasons: (1) It may naturally explain the galactic center gamma ray excess [19] observed by the Fermi-LAT [27]. (2) It is tightly connected with the flavor physics. (3) It may release the tension between the observed DM relic density and constraints from underground laboratory direct detections. Besides, collider searches of the flavored DMs are accessible and it was pointed out that collider searches are remarkably complementary for the quark(lepton)-portal DM models [2, 9, 11, 23, 24]. Notice that DM could be incorporated into numerous models of flavors. It deserves a systematic study of these models.

In this paper we study phenomenologies of the tau lepton flavored DM by assuming DM is a Dirac fermion and mainly couples to the third generation leptons with an extra scalar doublet and a charged scalar singlet as mediators. We focus on the following aspects of this model: i) the DM electromagnetic form factors, ii) its relic density, iii) signatures in the dark matter direct detection and iv) the impact of the model to the $h\tau\tau$ coupling as well as $h\gamma\gamma$ coupling, where $h$ is the SM-like Higgs. Our findings can be summarized as the followings:

- The tension between the DM relic density and direct detection is highly loosed even for $\mathcal{O}(1)$ Yukawa couplings of the DM with tau lepton. The charge radius of the DM dominates the scattering of the DM with the nuclei for light DM case while the magnetic moment plays more important role in direct detections for the heavy DM case.

- The Yukawa coupling of $h\tau\tau$ can be significantly changed compared to the SM case. Tau lepton mass arises from two parts in this model: the general Yukawa interaction...
and the one-loop radiative correction, whose effect is roughly proportional to the DM mass. It turns out the loop effect can contribute about $\mathcal{O}(10\%)$ of the total tau mass.

- Higgs to diphoton decay rate can be slightly modified in this model. The ratio $\mu_{\gamma\gamma}$ can be in the range $(0.7, 1.25)$, which is still consistent with the current bounds given by the ATLAS and CMS collaborations.

The signatures of the DM at colliders are also briefly discussed in the paper. Compared with previous studies of lepton portal DM models, as was mentioned in the references, our studies are new in the following aspects: (1) We focus on the multi-mediator scenario; (2) The Yukawa couplings of $h\bar{\tau}\tau$ and $h\gamma\gamma$ can be significantly modified in this model.

We further comment on a possible extension of this tau flavored DM model. If one assumes the DM couples both to the muon and tau leptons, then the observed Higgs to $\tau\mu$ decay rate [28, 29] can be generated, but it also gives an overly estimated branching ratio of $\tau \to \mu\gamma$. Thus the lepton flavored DM model can hardly explain the Higgs lepton-flavor-violating (LFV) decays. We refer readers to the ref. [30] for a systematic study of LFV Higgs decay in flavored DM model.

The remaining of this paper is organized as follows: we briefly describe our model in section 2. Section 3 is focused on the phenomenologies of the model, including DM relic density, signatures in direct detections, the $\tau$-lepton mass, $h \to \bar{\tau}\tau$ and $h \to \gamma\gamma$ decay rate. The last part is concluding remarks.

### 2 Model

We extend the SM with an inert scalar doublet $\Phi$, a singly charged scalar singlet $S$ and a Dirac DM $\psi$, which is stabilized by a $Z_2$ discrete flavor symmetry, under which $\psi, \Phi$ and $S$ are odd while all other particles are even. In the following we first describe scalar interactions, then go to the DM interactions. The scalar potential can be written as

$$V = -\mu^2 H^\dagger H + \lambda (H^\dagger H)^2 + m_1^2 \Phi^\dagger \Phi + \lambda_1 (\Phi^\dagger \Phi)^2 + \lambda_2 (\Phi^\dagger \Phi)(H^\dagger H) + \lambda_3 (\Phi^\dagger H)(H^\dagger \Phi) + m_2^2 S^+ S^- + \lambda_4 (S^+ S^-)^2 + \lambda_5 (S^+ S^-)(H^\dagger H) + \lambda_6 (S^+ S^-)(\Phi^\dagger \Phi) + \sqrt{2} \Lambda H^\dagger H \phi S^- + \text{h.c.},$$

(2.1)

where $H^T \equiv (G^+, (h + iG_0 + v)/\sqrt{2})$ is the SM Higgs doublet, $v = 246$ GeV is the vacuum expectation value (VEV), $\Phi^T \equiv (\Phi^+, (\rho + i\eta)/\sqrt{2})$ is the inert scalar doublet, $S^\pm$ is the singly charged scalar singlet and $\Lambda$ has mass dimension $+1$. Assuming that the mass term of $\Phi$ is positive, it develops no VEV. As a result, there is no mixing between $h$ and $\rho$. The masses of neutral scalars can be written as

$$m_h^2 = 2\lambda v^2, \quad m_\rho^2 = m_\eta^2 = m_1^2 + \frac{1}{2}(\lambda_2 + \lambda_3)v^2.$$  

(2.2)

Due to the last term in eq. (2.1), there is mixing between $\Phi^+$ and $S^+$ and the relevant mass matrix is

$$
\begin{pmatrix}
m_1^2 + \frac{1}{2}\lambda_2 v^2 & -\Lambda v \\
-\Lambda v & m_2^2 + \frac{1}{2}\lambda_5 v^2
\end{pmatrix}.
$$

(2.3)
Besides the typical momentum transfer of DM-Nucleon interactions is about 50 MeV, thus relevant for the hγγ couplings as will be seen in the next section.

The Lagrangian can be written as

\[ \lambda \] among these extra scalars and are not so relevant for the study in this paper. \( \lambda_2 \) and \( \lambda_5 \) are relevant for the hγγ and hττ couplings as will be seen in the next section.

We assume that DM only interacts with the new scalars and third generation leptons.

The Lagrangian can be written as

\[ -\mathcal{L}_Y = \kappa_1 \bar{\ell}_L \Phi \psi + \kappa_2 \bar{\psi} S^+ \tau_R + \text{h.c.}, \] (2.6)

where \( \ell_3^L \) is the third generation left-handed lepton doublet, \( \tau_R \) is the right-handed tau lepton, \( \psi \) is the Dirac DM and \( \Phi = i\sigma_2\Phi^* \). As a result, the DM can only annihilate into \( \bar{\tau}\tau \) and \( \tilde{\nu}_e\nu_e \). For the benefit of the direct detection, one needs to calculate the electromagnetic form factors of the DM, which arise at one loop level from the relevant Feynman diagrams shown in figure 1. The induced effective dark matter-photon interactions are

\[ \Delta\mathcal{L}_{\text{EM}}^{\psi} = \lambda_5 \psi \gamma^\mu \bar{\psi} \gamma^\nu F_{\mu\nu} + c_\psi \bar{\psi} \gamma^\mu \gamma^5 \psi \bar{\psi} F_{\mu\nu} + \frac{\mu_\psi}{2} \bar{\psi} F_{\mu\nu} F_{\mu\nu}, \] (2.7)

where \( b_\psi \) is the charge radius, \( c_\psi \) is the axial charge radius or anapole moment and \( \mu_\psi \) is the magnetic moment. Since there is no CP violation in the DM sector, the electric dipole moment term is absent. We assume the following mass hierarchy \( m_\tau \ll m_\psi \ll \tilde{m}_{1,2}, m_{\rho,\eta} \).

Besides the typical momentum transfer of DM-Nucleon interactions is about 50 MeV, thus

\[ \text{Figure 1. Feynman diagrams contributing to the DM electromagnetic form factors.} \]
the momentum transfer, \( \sqrt{-q^2} \), is far smaller than the \( \tau \) mass and constitutes the smallest scale. Collecting all the contributing diagrams and expanding in terms of \( q^2 \), we obtain

\[
\mu_\psi = \sum_{i=1}^{2} \frac{e m_\psi \zeta_i}{64\pi^2} \int_0^1 dx \left( \frac{x (1-x)}{\Delta_i} \right),
\]

\[
b_\psi = \sum_{i=1}^{2} \frac{e \zeta_i}{32\pi^2} \int_0^1 dx \left\{ \frac{x^3 - 2(1-x)^3}{6\Delta_i} + \frac{(x-1)^3(x^2m_\psi^2 + m_i^2) + 2(1-x)x^4m_\psi^2}{6\Delta_i^2} \right\},
\]

\[
c_\psi = \sum_{i=1}^{2} \frac{e \zeta_i}{192\pi^2} \int_0^1 dx \left\{ \frac{-3x^3 + 6x^2 - 6x + 2) x m_i^2 + (-2x^4 + 6x^3 - 9x^2 + 7x - 2) x m_\psi^2}{\Delta_i^2} \right\},
\]

where \( m_\psi \) is the DM mass, \( \zeta_1 = c_1^2 \kappa_1^2 + s_1^2 \kappa_2^2 \), \( \zeta_2 = s_1^2 \kappa_1^2 + c_1^2 \kappa_2^2 \), \( \zeta_1 = c_2^2 \kappa_1^2 - s_2^2 \kappa_2^2 \), \( \zeta_2 = s_2^2 \kappa_1^2 - c_2^2 \kappa_2^2 \), and \( \Delta_i = x m_i^2 + (x-1)m_\psi^2 + (1-x)m_\tau^2 \). We have ignored terms proportional to \( \mathcal{O}(m_\tau^2) \) in eq. (2.8). Note that the limit \( m_\psi, m_\tau \ll \tilde{m}_{1,2} \) allows us to recover the familiar result [2, 31]

\[
b_\psi = \sum_{i} \frac{e \zeta_i^2}{64\pi^2 m_i^2} \left( 1 + \frac{2}{3} \ln \frac{m_i^2}{m_\tau^2} \right), \tag{2.9}
\]

where \( m_\tau \) serves as an infrared regulator.

Similarly there are also form factors for the effective DM-Z boson interactions. The contribution of these interactions to the DM-nuclei scattering cross section is subdominant compared with those arising from electromagnetic form factors. So we neglect these interactions in our calculation.

3 Phenomenology

We will study in this section phenomenologies arising from this model, including the DM relic density, signatures in direct detections, the loop induced \( \tau \) lepton mass, the effective coupling of \( h\tau\tau \) as well as the Higgs to diphoton decay rate. Finally we will discuss signatures of our model at colliders.

3.1 Relic density

We have assumed that the DM is a Dirac fermion and only interacts with the third generation leptons in our model. It annihilates into \( \tau \bar{\nu}_\tau / \bar{\nu}_\tau \) with the relevant Feynman diagrams shown in figure 2. The cold DM was in local thermodynamic equilibrium in the early Universe. When its interaction rate drops below the expansion rate of the Universe, the DM is said to be decoupled. The evolution of the DM number density \( n \), is governed by the Boltzmann equation [32]:

\[
\dot{n} + 3Hn = -\langle \sigma v_{\text{Møller}} \rangle (n^2 - n_{\text{EQ}}^2), \tag{3.1}
\]

where \( H \) is the Hubble constant, \( \sigma v_{\text{Møller}} \) is the total annihilation cross section multiplied by the Møller velocity with \( v_{\text{Møller}} = (|v_1 - v_2|^2 - |v_1 \times v_2|^2)^{1/2} \), brackets denote thermal average and \( n_{\text{EQ}} \) is the number density in thermal equilibrium. It has been shown that \( \langle \sigma v_{\text{Møller}} \rangle = \langle \sigma v_{\text{lab}} \rangle / (1 + K_1(x)/K_2(x)) \langle \sigma v_{\text{cm}} \rangle \) [32], where \( x = m_{DM}/T \) and \( K_i(x) \) is the modified
Bessel functions of the $i$-th order. To derive the relic density of the tau flavored DM, one needs to calculate the thermal average of the total annihilation cross section. Analytically one can approximate the thermal average $\langle \sigma v \rangle$ with the non-relativistic expansion $\langle \sigma v \rangle = a + b \langle v^2 \rangle$ in the lab frame,

$$
\langle \sigma v \rangle = \sum_{i=1}^{4} \zeta_i^2 \left( \frac{m_{\psi_i}^2}{32\pi(m_{\psi_i}^2 + m_{\chi_i}^2)^2} + \langle v^2 \rangle \frac{m_{\psi_i}^2(-7m_{\psi_i}^4 - 18m_{\psi_i}^2\hat{m}_1^2 + \hat{m}_1^4)}{384\pi(m_{\psi_i}^2 + m_{\chi_i}^2)^4} \right)
\left( \frac{1}{16\pi(m_{\chi_i}^2 + m_{\psi_i}^2)(m_{\psi_i}^2 + m_{\chi_i}^2)} + \frac{192\pi(m_{\chi_i}^2 + m_{\psi_i}^2)^3}{192\pi(m_{\chi_i}^2 + m_{\psi_i}^2)^3}ight)
\equiv a + b \langle v^2 \rangle,
$$

where

$$
\Delta = -m_{\psi_i}^2 (7m_{\psi_i}^8 + 16m_{\psi_i}^6(m_{\chi_i}^2 + m_{\psi_i}^2) + m_{\psi_i}^4(5m_{\chi_i}^4 + 32m_{\chi_i}^2\hat{m}_1^2 + 5\hat{m}_1^4))
+ 8m_{\psi_i}^2m_{\chi_i}^4\hat{m}_1^2(m_{\chi_i}^2 + m_{\psi_i}^2) \hat{m}_1^2 - m_{\psi_i}^4\hat{m}_1^4.
$$

(3.3)

Here $\zeta_{1,2}$ were defined below eq. (2.8) and $\zeta_{3,4} = \sqrt{2}\kappa_1^2$. The notation $\hat{m}_i$, where $i = 1, 2, 3, 4$, denotes the mass of $\hat{\phi}^+, \hat{S}^+, \rho$ and $\eta$ respectively.

The present relic density of the DM is simply given by $\rho_{\text{DM}} = m_{\text{DM}}n_{\text{DM}} = m_{\text{DM}}s_0 Y_{\infty}$ [33], where $s_0$ is the present entropy density. The relic abundance can be written in terms of the critical density

$$
\Omega h^2 \approx 2 \times \frac{1.07 \times 10^9}{M_{\text{pl}}} \frac{x_F}{\sqrt{g_* a + 3b/x_F}},
$$

where $a$ and $b$ were defined in eq. (3.2), $M_{\text{pl}}$ is the Planck mass, $x_F = m_{\text{DM}}/T_F$ with $T_F$ being the freezing out temperature of the DM, $g_*$ is the degrees of freedom at the freeze out temperature and the factor 2 on the right-hand side accounts for the fact that DM in our model is a Dirac fermion.

The DM relic density measured by the Planck experiment is $\Omega h^2 = 0.1199 \pm 0.0022$ [1]. To check its constraint on the parameter space, we plot in figure 3a contours of the DM relic density requiring the relic density to be within two standard deviations of the measured central value in the $\kappa_1 - \kappa_2$ plane by setting $\hat{m}_1 = 400$ GeV, $\hat{m}_2 = 600$ GeV and $m_\rho = m_\eta = 700$ GeV. The red, yellow, blue, green and pink contours correspond to $\theta = 0, \pi/8, \pi/4, 3\pi/8$ and $\pi/2$ respectively. One has $\kappa_{1,2} \in [-1.5, 1.5]$ and $\kappa_1, \kappa_2$ can not both take small values.
to give rise to a correct DM relic density. By assuming \( \kappa_1 = \kappa_2 \) and degenerate mediator masses, we show in figure 3b contours of the DM relic density, with the red, yellow, brown, blue, magenta, cyan and orange colored contours corresponding to \( m_\psi = 5 \text{ GeV}, 10 \text{ GeV}, 20 \text{ GeV}, 50 \text{ GeV}, 100 \text{ GeV}, 200 \text{ GeV} \) and \( 500 \text{ GeV} \) respectively. It shows that the heavier the DM is, the larger the annihilation cross section will be, such that larger mediator masses or smaller couplings will be required to get a correct relic density. This can also be seen

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Figure 3. The contours of the relic density within two standard deviations of the measured value: in figure (a), we show contours in \( \kappa_1 - \kappa_2 \) plane with different inputs of mixing angle \( \theta \), by setting \( m_\psi = 100 \text{ GeV}, \tilde{m}_1 = 400 \text{ GeV}, \tilde{m}_2 = 600 \text{ GeV} \) and \( m_\rho = m_\eta = 700 \text{ GeV} \); in figure (b), we show contours in the \( \kappa_1 - m_{\text{all mediators}} \) plane for different DM masses, by assuming all mediators have the same mass and \( \kappa_1 = \kappa_2 \); figure (c) show contours in the \( \tilde{m}_1 - m_\psi \) plane for different values of \( \tilde{m}_2 \), by setting \( \kappa_1 = \kappa_2 = 1 \) and \( m_\rho = m_\eta = 700 \text{ GeV} \); in figure (d), we set \( \kappa_1 = \kappa_2 = 1 \) and plot charged mediator versus neutral mediator masses for several DM masses.
from figure 3c and 3d, where we show the correlation between the DM mass and the charged mediator masses (figure 3c) as well as the correlation between the neutral mediator masses and charged mediator masses (figure 3d). For the input of other parameters of figure 3c and 3d see the caption for details.

3.2 Direct detection

Notice that flavored DM models may help to release the tension between the observed DM relic density and constraints from direct detections, which detect DM scattering from nuclei in underground laboratories. In our model, DM couples to nucleons through loop induced electromagnetic form factors of the DM as well as loop induced dark matter-Higgs interactions. The effective interactions of the DM with nucleon take the following form [2, 31, 34]

\[ f_r^N \bar{\psi} \gamma^\mu \psi N\gamma_\mu N + f_h^N \bar{\psi} \psi \bar{N} N + f_1^N \bar{\psi} i \sigma^{\mu\nu} \psi \frac{q_\mu}{q^2} \bar{N} K^{\mu} N + f_2^N \bar{\psi} i \sigma^{\alpha\mu} \psi \frac{q_\alpha q_\beta}{q^2} \bar{N} i \sigma^{\beta\mu} N \] (3.5)

with \( q^\mu \) being the momentum transfer from nucleon to DM and \( k^\mu \) defined as the summation of momenta of incoming and outgoing nucleon. The Wilson coefficients are given by

\[ f_r^N = e Q_N b_\psi, \quad f_h^N = f_1^N \frac{M_N}{m_h^2} \left( \sum_{q=u,d,s} f_T^N + \frac{2}{9} f_G^N \right), \quad f_1^N = e Q_N \mu_\psi \frac{2}{2m_N}, \quad f_2^N = -e \tilde{\mu}_N h_\psi \frac{2}{2m_N}, \] (3.6)

where \( Q_N \) is the charge of the nucleon, \( \mu_\psi \) and \( b_\psi \) are the magnetic moment and charge radius of the nucleon respectively, \( \tilde{\mu}_N \) is the nucleon magnetic moment, that is, \( \tilde{\mu}_p \approx 2.80 \) and \( \tilde{\mu}_n \approx -1.91 \). Finally \( f_T^N \) is the effective DM-Higgs coupling,

\[ f_T^N = \sum_{i,j=1}^2 \frac{c_{ij} M_\psi}{32 \pi^2} \int_0^1 dx \int_0^{1-x} dy \frac{1-x}{(1-x-y) m_i^2 + (1-y) m_j^2 + (x^2 - x) m_\psi^2}, \] (3.7)

where \( c_{11} \approx \frac{1}{2} \lambda_1 - \frac{1}{2} \lambda_5 \lambda_9 + 2 \Delta s_\theta c_\theta / v \), \( c_{22} \approx \frac{1}{2} \lambda_2 - \frac{1}{2} \lambda_5 \lambda_9 - 2 \Delta s_\theta c_\theta / v \), \( c_{12} = c_{21} = s_\theta c_\theta (\kappa_1 - \kappa_2) |u_s g c_\lambda (\lambda_5 - \lambda_2) + \Delta c_\theta| \) and \( x, y \) are Feynman parameters. We have neglected the \( Z \) mediated interactions in eq. (3.5) since they are subdominant compared with photon mediated processes.

The momentum dependence induced by the magnetic moment term makes it impossible to factorize the differential event rate into the product of the elastic cross section and momentum integration. We therefore need to calculate the differential rate numerically then translate the cross section into event rate in experiment. One more complexity arises since the operators shown above go beyond the traditional spin-independent and spin-dependent characterization of DM nucleus scattering and therefore more nuclear responses are involved [35]. The corresponding classification of the underlying non-relativistic operators responsible for DM nucleon scattering as well as the identification and calculation of nuclear responses for finite-sized nuclei have been performed systematically in an effective field theory framework in refs. [36, 37] following earlier work in ref. [38]. This framework has been implemented in the public code [39] together with statistical analysis for each experiment. We therefore use this code in our analysis and refer the reader to the above literatures for details.

We add constraints of the DM direct detection to the relic density plot in figure 3a, and the new plot is shown in figure 4. For each relic density contour, we plot its corresponding limit from the LUX [40] at the 95% C.L., which is shown as a dashed line with the same
Figure 4. LUX limit as a dashed line for each solid relic density contour in the $\kappa_1, \kappa_2$ plane for different $\theta$. Relic density contours are within two standard deviations of the Planck measured central value and regions outside the dashed lines are excluded at 95% C.L. by the LUX. The other parameters are fixed to be $m_\psi = 100$ GeV, $\tilde{m}_1 = 400$ GeV, $\tilde{m}_2 = 600$ GeV, $m_\rho = m_\eta = 700$ GeV and $\lambda_2 = \lambda_5 = 0$. color as the relic density contour. We can see that the LUX allowed maximum magnitude of $\kappa_{1,2}$ is $1 \sim 2$ while the corresponding relic density allowed magnitudes are smaller, which are thus allowed by the LUX. Notice that all direct detection limit lines intersect at four points when $|\kappa_1| = |\kappa_2|$ just like the case of the relic density contours. This is because $\mu_\psi$ and $b_\psi$ are both independent on the mixing angle $\theta$ in this scenario and the contribution arising from the anapole moment is velocity suppressed and thus negligible.

We also show representative plots in figure 5 on the correlations between the coupling strength $\kappa_1 = \kappa_2$ and the totally degenerate mediator masses, where subfigures 5a, 5b, 5c and 5d correspond to taking the DM mass as 40 GeV, 200 GeV, 1 TeV and 5 TeV, respectively. The other parameters are fixed to be $\lambda_2 = \lambda_5 = 0$, and $\Lambda = 0$ as a result of the assumed degenerate charged scalars. So the effective DM-Higgs coupling is exactly zero in this scenario. Generally the Higgs mediated contribution is suppressed by the Higgs mass squared and thus subdominant compared with contributions of electromagnetic form factors [34]. In each plot, light blue (red) regions are excluded (allowed) by the LUX at the 95% C.L.; the green contours represent regions where the DM relic density is consistent with the measured value within 2$\sigma$ level; the red dot-dashed (blue dashed) line is the LUX limit when considering only the contribution of charge radius (magnetic moment). One can see from these figures the roles played by the magnetic moment and the charge radius in the DM direct detections. For a relatively light DM, the charge radius dominates the contribution to the direct detection; while for the superheavy DM, the magnetic moment plays more important role. This is because the charge radius operator is dimension six while the magnetic moment operator is dimension five. It also shows that the DM should be around 50 GeV or heavier to release the tension between the measured DM relic density and constraints from the LUX.

Finally we comment on constraints from DM indirect detections. The annihilations of the DM in the galaxies are expected to produce flux of cosmic rays, such as gamma rays and neutrinos. A recent combined analysis using data of the MAGIC and Fermi-LAT
Figure 5. LUX excluded and relic density allowed regions for DM with different masses in the couplings versus mediator mass plane. LUX excluded regions at 95% C.L. are shown in light blue while light red regions are allowed. The “$\mu_\psi$ only” dashed line is the LUX limit retaining only the contribution of magnetic dipole moment while “$b_\psi$ only” corresponds to including only charge radius contribution. The green contours are relic density allowed regions within two standard deviations of the Planck central value. The magenta dashed lines are the Fermi-LAT exclusion lines for (a) and (b) as well as H.E.S.S. exclusion lines for (c) and (d), above which the parameter space is excluded. In all plots we assume $\kappa_1 = \kappa_2$, equal mediator masses and $\lambda_2 = \lambda_5 = 0$. 
collaborations finds no signal of DM from γ-ray in the mass range from 10 GeV to 100 TeV and sets upper limit on $\langle \sigma v \rangle$ for DM annihilating into various final states [41]. For the case of DM annihilating into $\tau^+\tau^-$, the exclusion limit is given for $m_{DM} \lesssim 75$ GeV and for $m_{DM} \lesssim 20$ GeV when only segue 1 observations are used. However in our model, we focus on relatively heavy DM and thus these limits from γ-ray searches turn to be almost irrelevant.

For the most recent result of the H.E.S.S., which searches for the annihilations of DM using γ-ray observations towards the inner 300 parsecs of the Milky Way, the observation of no significant γ-ray excess puts exclusion limits on $\langle \sigma v \rangle_{\tau^+\tau^-}$ at 95% C.L. for DM mass from 500 GeV to 2.4 TeV [42]. In our model DM can annihilate into both $\tau^+\tau^-$ and $\bar{\nu}_\tau \nu_\tau$, which may release the tension between the DM relic density and the H.E.S.S. result by tuning sizes of Yukawa couplings and mediator masses, given that the constraint on dark matter relic abundance, the magenta dashed line is the upper bound from DM annihilation to $\tau$ case of DM annihilating into $\bar{\nu}_\tau \nu_\tau$ from the LUX and indirect detection from the IceCube, the pink region is allowed by direct detection. One can see that our model is able to survive from indirect detections. We also overlay the constraint of indirect detection in the four plots of figure 5 represented by the magenta dashed lines above which the indirect detection constraint is not satisfied. We can see for the subfigure 5a with DM mass 40 GeV, the parameter space that is compatible with relic density can not survive under the constraint from both the direct detection and the Fermi-LAT experiment.

For the subfigure 5b with DM mass 200 GeV, the relic density allowed region lies below the Fermi-LAT exclusion limit, where the H.E.S.S. exclusion limit is weaker, and therefore is allowed. The case of a heavier DM with mass 1 TeV as shown in subfigure 5c is marginally allowed. The case of a heavier DM with mass 5 TeV, the parameter space that satisfies constraint of direct detection from the LUX and indirect detection from the H.E.S.S. can give the observed relic density.

### 3.3 Higgs couplings

Precision measurement of the Higgs couplings is one of the most important tasks in the future Higgs factory. The tau lepton Yukawa coupling was measured by the ATLAS and CMS collaborations, whose results are not so consistent with the SM prediction: $\mu_{\tau\tau} = 1.4 \pm 0.4$ by the ATLAS collaboration [44] and $0.78 \pm 0.27$ by the CMS collaboration [45]. In our model, the tau lepton mass arises from two parts: the Yukawa interaction induced term, i.e., $m_{\tau} = y_\tau \sqrt{s}/\sqrt{2}$, as well as loop corrections, $m_{\tau \text{ loop}}$, mediated by the DM and two charged scalars. The mass can be written as

$$m_\tau \approx y_\tau \sqrt{s}/\sqrt{2} + \frac{c_\theta m_{\psi}}{16\pi^2} \left[ \frac{\hat{m}_{\psi}^2}{m_1^2 - m_{\psi}^2} \ln \left( \frac{\hat{m}_1^2}{m_1^2} \right) - \frac{\hat{m}_2^2}{m_2^2 - m_{\psi}^2} \ln \left( \frac{\hat{m}_2^2}{m_2^2} \right) \right],$$

(3.8)

where we have neglected terms proportional to $m_{\tau \psi}^2$ in the calculation of $m_{\tau \text{ loop}}$. We show in the left panel of figure 7 contours of $m_{\tau \text{ loop}} / m_\tau$ in the $m_{\phi} - \hat{m}_2$ plane by setting $\kappa_1 = \kappa_2 = 1$, $c_\theta = 0.6$ and $m_\psi = 100$ GeV which are consistent with DM constraints. It is clear that $m_{\tau \text{ loop}}$ can be $O(10\%)$ of the total tau mass.

The branching ratio for the Higgs decaying into $\tau\bar{\tau}$ can be approximately written as

$$\text{BR}(h \to \tau\bar{\tau}) \approx \frac{m_h}{16\pi^2 \Gamma_{h \to \tau\bar{\tau}}} \left| y_\tau + \sqrt{2} \xi_\tau \right|^2$$

(3.9)
Figure 6. This figure shows the limits from both relic abundance and indirect detection constraint for our model, the green solid line represents the thermal relic density constraint, the magenta dashed line represents the 95% C.L. upper bound from indirect detection for a pair of dark matters annihilate to $\tau^+\tau^-$ [42], the cyan dotted line represents the 90% C.L. upper bound from indirect detection for a pair of dark matter annihilate to $\nu_{\tau}\bar{\nu}_{\tau}$ [43], the region above the red dashed dotted line and blue dashed line are excluded by direct detection using charge radius and magnetic moment of dark matter respectively, the pink region is allowed by direct detection, here we set mass of dark matter is 1 TeV, $\kappa_1 = \kappa_2$, $m_{\hat{\Phi}^+} = m_{\hat{S}^+} = 2m_{\eta,\rho}$. One can see that our model can survive with 1 TeV dark matter mass.

Figure 7. Left panel: contours of $m_{\text{loop}}^{\text{loop}}/m_{\tau}$ in the $\hat{m}_1 - \hat{m}_2$ plane; right panel: contours of $\mu_{\gamma\gamma}$ in the $\hat{m}_1 - \hat{m}_2$ plane, the cyan color marked region satisfy the combined constraint given by the ATLAS and CMS.
Figure 8. Signal rate of Higgs to tau tau relative to the SM expectation as a function of the DM mass. We set $c_\theta = 0.5$, $\lambda_2 = \lambda_5 = 0.1$, $\tilde{m}_1 = 400$ GeV and $\tilde{m}_2 = 600$ GeV as well as $\kappa_1 = -\kappa_2 = 1$ for the red solid curve and $\kappa_1 = \kappa_2 = 1$ for the blue dashed curve. The green band is excluded by the MAGIC and Fermi-LAT results.

where $m_h$ is the SM Higgs mass, $\Gamma_{\text{tot}} = 4.1 \times 10^{-3}$ GeV is the SM Higgs decay width and the loop induced coupling can be written as

$$\xi_\tau = \sum_{i=1}^{2} \frac{y_{ij} m_\psi}{16\pi^2} \int_0^1 dx \int_0^{1-x} dz \frac{1}{x m_\psi^2 + z m_i^2 + (1-x-z) m_j^2 - z(1-x-z) m_h^2},$$

(3.10)

with $y_{11} = \kappa_1 \kappa_2 c_\theta s_\theta [(\lambda_2 c_\theta^2 + \lambda_5 s_\theta^2)v + \Delta s_{2\theta}]$, $y_{22} = -\kappa_1 \kappa_2 c_\theta s_\theta [(\lambda_2 s_\theta^2 + \lambda_5 c_\theta^2)v - \Delta s_{2\theta}]$ and $y_{12} = y_{21} = 1/2 \kappa_1 \kappa_2 c_\theta s_\theta v(\lambda_5 - \lambda_2) + \Delta c_{2\theta}$. We plot in figure 8 the signal rate $\mu_{\tau\tau}$ associated with Higgs measurements, relative to the SM Higgs expectation, as a function of the DM mass by setting $c_\theta = 0.5$, $\lambda_2 = \lambda_5 = 0.1$, $\tilde{m}_1 = 400$ GeV and $\tilde{m}_2 = 600$ GeV as well as $\kappa_1 = -\kappa_2 = 1$ for the red solid curve and $\kappa_1 = \kappa_2 = 1$ for the blue dashed curve. The dashed and dotted horizontal lines represent central values given by the ATLAS and the CMS respectively with light blue and light yellow bands corresponding to uncertainties at the 1$\sigma$ level. Moreover the green region corresponding to DM mass less than 75 GeV is excluded by the MAGIC and Fermi-LAT results as discussed earlier. So for the two parameter choices in this plot, the indirect detection constraint implies a $\mu_{\tau\tau}$ that is relatively away from the corresponding SM value. It should however be mentioned that $\mu_{\tau\tau}$ can be significantly changed for some extreme scenarios and the modification can also be tiny for other cases (small $\kappa_{1,2}$, light DM and heavy degenerate charged scalars).

Due to the existence of charged scalars, the Higgs to diphoton decay width is slightly modified. The decay rate can be written in terms of couplings of the SM Higgs with new charged scalars:

$$\Gamma(h \to \gamma\gamma) = \frac{G_F \alpha^2 m_h^3}{128 \sqrt{2} \pi^3} \left| -6.48 + \sum_{i=1}^{2} \frac{v c_{ii}}{2 s_i^2 m_i^2} A_0 \left( \frac{4 m_i^2}{m_h^2} \right) \right|^2,$$

(3.11)

where $-6.48$ is the contribution of the $W$ and top loops and the second term is the contribution of two new charged scalars with the definition of the loop integral function $A_0(x)$.
following conventions of ref. [46]

\[ A_0(x) = -x^2 \left[ \frac{1}{x} - f(x^{-1}) \right] \quad \text{with} \quad f(x) \equiv \begin{cases} \arcsin^2(\sqrt{x}), & \text{for} \quad x > 1, \\ -\frac{1}{4} \left( \ln \frac{1+\sqrt{1-x^2}}{1-\sqrt{1-x^2}} - i\pi \right)^2, & \text{for} \quad x < 1. \end{cases} \]  

(3.12)

We plot in the right panel of figure 7 contours of \( \mu_{\gamma\gamma} \) in the \( \tilde{m}_1 - \tilde{m}_2 \) plane by setting \( \lambda_2 = \lambda_5 = 0.5 \) and \( c_\theta = 0.8 \). The green dashed lines from the left to the right correspond to \( \mu_{\gamma\gamma} = 0.8, 0.9, 1.0, 1.1, 1.2 \) respectively. The cyan color marked region satisfies the current combined bound given by the ATLAS and CMS collaborations, \( \mu_{\gamma\gamma} = 1.15 \pm 0.18 \), where \( \mu_{\gamma\gamma} = 1.17 \pm 0.27 \) by the ATLAS [47] and \( \mu_{\gamma\gamma} = 1.14^{+0.26}_{-0.23} \) by the CMS [48]. It should be mentioned that the future improved measurements of \( \mu_{\gamma\gamma} \) may put more severe constraint on couplings of the Higgs to new charged scalars.

Finally, let’s comment on the collider searches of this model. The collider signals of lepton portal DM models are events with charged lepton pairs and missing energy. It was showed in ref. [7] that these models have clear signals above the SM background in certain parameter space at the LHC. Searches for signatures of our model at the LHC and lepton colliders such as CEPC or ILC, which are interesting but beyond the reach of this paper, will be shown in a future study.

4 Concluding remarks

Lepton-flavored DM is interesting and appealing for many aspects. In this paper we focused on the phenomenology of the tau-flavored Dirac DM model. The electromagnetic form factors of the DM which are crucial for the DM direct detections, were calculated in the case where there are two types of Yukawa interactions between DM and the third generation leptons. Our study shows that the tension between the observed DM relic density and constraints of DM direct detections are highly loosed. The charge radius dominates the contributions to the dark matter direct detection for the light DM case, while the magnetic moment plays more important role for heavy DM case. In addition the tau Yukawa coupling can be significantly changed in this model, and the one-loop induced tau mass can be \( \mathcal{O}(10\%) \) of the total mass. As a result, the signal rate of \( h \to \bar{\tau}\tau \), relative to the SM expectation, measured by the LHC, can be explained in this model. The Higgs to diphoton ratio is also slightly changed but is still consistent with the current LHC constraint.

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