Physics Letters B 782 (2018) 517–522

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Electron flavored dark matter

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ARTICLE INFO

Article history:
Received 19 December 2017
Received in revised form 21 April 2018
Accepted 24 May 2018
Available online 31 May 2018
Editor: G.F. Giudice

Keywords:
Dark matter theory
BSM particle physics

ABSTRACT

In this paper we investigate the phenomenology of the electron flavored Dirac dark matter with two types of portal interactions. We analyze constraints from the electron magnetic moment anomaly, LHC searches of singly charged scalar, dark matter relic abundance as well as direct and indirect detections. Our study shows that the available parameter space is quite constrained, but there are parameter space that is compatible with the current data. We further show that the DAMPE cosmic ray electron excess, which indicates cosmic ray excess at around 1.5 TeV, can be interpreted as the annihilation of dark matter into electron positron pairs in this model.

1. Introduction

About 80% of the matter in our Universe is made of dark matter (DM). Among many different DM scenarios, Weakly Interacting Massive Particle (WIMP) remains to be an interesting candidate since it has a strong connection with physics beyond Standard Model at the TeV scale and can be probed through both direct and indirect detections. There has been several indirect DM searches [1–3] which indicate a possible excess for the electron positron cosmic ray spectrum in the 100 GeV $\sim$ TeV energy region. Most recently the DM Particle Explorer (DAMPE) has reported their first result [4], which observes an excess in the electron positron cosmic ray spectrum up to several TeV. For possible theoretical interpretations, see Refs. [5–39] for detail. This experiment has several good features in terms of probing the electron positron cosmic ray spectrum. 1): it has a good energy resolution in the high energy region ($< 1.2\%$ for $E > 100$ GeV), therefore can be used to detect the line or sharp structure of the particle spectrum in the future. 2): The large detector can have high statistics. 3): It measures both the low and high energy electron positron cosmic ray spectrum. The first feature is interesting since it can be used to probe possible line or sharp structure of the particle spectrum, which give us much more information and has important implications on possible dark matter interpretations.[1]

While there has been various studies of dark matter annihilating or decaying into leptons, here we consider a novel class of dark matter which we call "electron flavored dark matter". In this case, the dark matter carries the electron number and annihilate into electron pairs through the t-channel mediator which could result a possible sharp structure in the electron positron cosmic ray spectrum. We study various constraints such as the electromagnetic properties of the dark matter, fitting the electron magnetic moment, collider phenomenology, dark matter relic abundance and direct detections. More importantly we systematically investigate constraints from indirect DM searches, such as AMS-02 [1], Fermi-LAT [40], IceCube [41] and CMB [42]. Interestingly, combining all constraints together, we show that the electron-flavored DM can address the DAMPE cosmic ray excess without conflicting with any current constraints.

The remaining of the paper is organized as follows: In section 2 we introduce the model in detail. Section 3 is focused on the constraints of electron magnetic moment and colliders. In section 4 and 5 we study their implication on DM relic abundance as well as direct and indirect DM searches. The last part is the concluding remarks.

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[1] The current DAMPE data, however, does not favor significantly on a sharp excess, especially considering that the two bins next to the 1.4 TeV bin actually has a large deficit comparing to the smoothly broken power-law.

https://doi.org/10.1016/j.physletb.2018.05.075

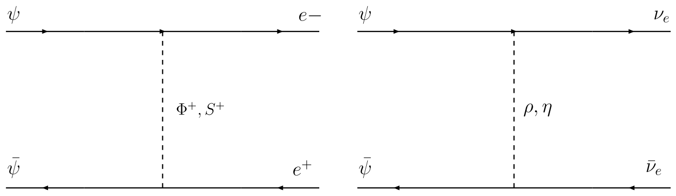

Fig. 1. Annihilation channels of electron flavored Dirac DM.

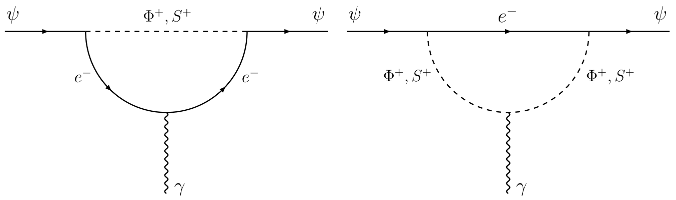

Fig. 2. Feynman diagrams contributing to the DM electromagnetic form factors.

2. Model

We consider a Dirac DM ψ which couples to the electron via portal interactions of two types consistent with the electroweak symmetry. For the first type, ψ couples to the first generation lepton SU(2) doublet l_L^1 with the interaction

$$\text{Model I}: \qquad -\mathcal{L}_{\text{I}} = \kappa_1 \overline{\ell_L^1} \tilde\Phi \psi + \text{h.c.}, \qquad (1)$$

where $\Phi^T \equiv (\Phi^+, (\rho + i\eta)/\sqrt{2})$ is an inert scalar doublet and $\tilde\Phi = i\sigma_2 \Phi^*$. The model has a Z_2 symmetry in which new particles are odd while all SM particles are even. The coupling of ψ with other lepton doublets can be forbidden by another Z_2 symmetry in which ψ and ℓ_L^1 are odd while all other particles are even. Note the mass of ψ needs to be smaller than the neutral and charged scalars so as to be stable DM candidate. For this scenario, the DM can annihilate to e^+e^- and $\bar\nu_e \nu_e$ via t-channel exchanges of charged scalars or neutral scalars shown in Fig. 1.

For the second type model, the DM is coupled to the electroweak singlet e_R via

$$\text{Model II}: \qquad -\mathcal{L}_{\text{II}} = \kappa_2 \overline{\psi} S^+ e_R + \text{h.c.}, \qquad (2)$$

where S^+ is a singly charged scalar singlet. In this case, the DM annihilates only into e^+e^- through exchanges of the charged scalar, corresponding to the left panel of Fig. 1. The discrete flavor symmetry is the same as these in Model I.

We calculate the electromagnetic form factors of the DM, which arise at one loop level from the relevant Feynman diagrams shown in Fig. 2 and contribute to direct detection signals. These diagrams generate the following DM-photon effective interactions [43]:

$$b_\psi \bar\psi \gamma^\mu \psi \partial^\nu F_{\mu\nu} + c_\psi \bar\psi \gamma^\mu \gamma^5 \psi \partial^\nu F_{\mu\nu} + \frac{\mu_\psi}{2} \bar\psi \sigma^{\mu\nu} \psi F_{\mu\nu}, \qquad (3)$$

where b_ψ is the DM charge radius, c_ψ is the axial charge radius or anapole moment and μ_ψ is the magnetic moment. For both models, the results can be summarized by a uniform set of formulae [43]:

$$\mu_\psi = -\frac{e m_\psi \kappa_i^2}{64\pi^2} \int_0^1 dx \frac{x(1-x)}{\Delta_i},$$

$$b_\psi = \frac{e\kappa_i^2}{32\pi^2} \int_0^1 dx \left\{ \frac{x^3 - 2(1-x)^3}{6\Delta_i} + \frac{(x-1)^3(x^2 m_\psi^2 + m_e^2) + 2(1-x)x^4 m_\psi^2}{6\Delta_i^2} \right\},$$

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

where $\Delta_i = x m_i^2 + x(x-1) m_\psi^2 + (1-x) m_e^2$ and the index "i" denotes the charged scalar in each model. Since m_e is much smaller than the momentum transfer $\sqrt{|q^2|} \approx 50$ MeV, the infrared divergence as $m_e \to 0$ is cut-off by the momentum transfer [44]. Therefore we replace m_e by 50 MeV in the numerical calculation.

3. Constraints

Similar to other lepton flavored DM scenarios, the electron DM couplings here face constraints from precision measurement of the electron magnetic dipole moment (MDM) as well as searches at the colliders.

The 2017 PDG tabulates the measured eMDM anomaly as $(1159.65218091 \pm 0.00000026) \times 10^{-6}$ where the uncertainty is only 10^{-10} of the central value [45], constituting one of the most precisely measured physical constants. At one-loop, the modification of eMDM anomaly is [46,47]

$$\delta a_e = \frac{Y_i m_e^2}{4\pi^2 m_i^2} \frac{6x_i^2 \ln(x_i) + 6x_i - 1 - 3x_i^2 - 2x_i^3}{24(1-x_i)^4}, \qquad (5)$$

with $x_i \equiv m_\psi^2/m_i^2$ where the index "i" denotes the charged scalar $\Phi^+ (Y_{\Phi^+} = \kappa_1^2)$ for model I and $S^+ (Y_{S^+} = \kappa_2^2)$ for model II. The x_i dependent factor above increases from $-1/24$ for $x \to 0$ to $-1/48$ for $x \to 1$, leading to a negative δa_e. Compared with muon MDM, the eMDM is not so sensitive to the new physics contribution since δa_e is suppressed by the factor $m_e^2/m_\mu^2 \approx 10^{-5}$. In Fig. 3, the contours of eMDM are shown: the left panel shows in the (m_ψ, m_i) plane by fixing $\kappa = 1$ while the right panel shows in the plane (κ, m_ψ) by fixing $m_i = 2$ TeV. As is clear from these figures, δa_e is much smaller than current experimental un-certainty and eMDM imposes no severe constraint on the couplings κ_1 for model I and κ_2 for model II.

Notice that when both types of portal interactions are included in the model, there will be mixing between the two charged scalars. The δa_e will receive additional contributions that is enhanced by m_i/m_e and it leads to a much more stringent constraint on κ_1 or κ_2. In this case, an $\mathcal{O}(1)$ magnitude of κ_1 or κ_2 can only be obtained for very small or maximal mixing angles [43].

The collider constraints mainly come from the search of a charged scalar. In LHC, the search for the production of a singly charged scalar is always associated with the production of a top quark which is motivated by the two Higgs doublet models. However, in our model the charged scalars only couple to leptons, so the search for production of a singly charged scalar puts no constraint on our model. The other possibility is to search for the production of a pair of charged scalars which decay to two opposite sign electrons and missing transverse energy. This kind of signature is the same as the search for the pair production of the sleptons, which subsequently decay to SM leptons and neutralino. Current constraint [48,49] on the mass of slepton is around 200 GeV, while in our model, we focus on a charged scalar much heavier. So this constraint can be satisfied. As an illustration, we calculate the production cross-section of a pair of charged scalars at 13 TeV at LHC and 100 TeV at pp collider for the mass of charged scalar ranging from 1 TeV to 3 TeV using Madgraph [50]