

Hidden Sector Dark Matter with Global $U(1)_X$ -symmetry and Fermi-LAT 130 GeV γ -ray Excess

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We suggest a dark matter scenario which could contribute the possible anomaly observed by Fermi-LAT γ -ray space telescope. It is based on the model recently proposed by Weinberg. In our scenario the gamma-ray line signal comes from the fermionic dark matter ($M_{\text{DM}} = 214$ GeV) annihilating into two light scalars with mass around 500 MeV which in turn decay into two neutral pions. Finally the pions can decay into two 130 GeV photons. The strong constraint from the direct detection leaves only the channel of the dark matter annihilation into two light scalars for both the relic density and the Fermi-LAT gamma-ray line signal. The resulting gamma-ray spectrum is rather broad and does not fit to the data perfectly, but the data also show there may be fluctuation in the spectrum. There is no associated Z -boson or Higgs boson production contrary to most other works where the signal comes from the loops of charged particles. The annihilation into the other SM particles are highly suppressed due to the small mixing from the direct detection. Future experiments with more data will give more clues on the possible scenarios.

I. INTRODUCTION

The cosmological and astrophysical observations suggest that 27% of the energy density of the universe is in the form of dark matter (DM) [1, 2]. The most promising candidate for DM is so-called weakly interacting massive particle (WIMP). In that case we may study its nature through creation at accelerators such as LHC, the scattering with ordinary matter, or the pair annihilation into ordinary standard model (SM) particles including photon [4].

The current DM density of the universe is related to the annihilation cross section at the decoupling temperature as

$$\Omega_{\text{DM}} h^2 = \frac{3 \times 10^{-27} \text{cm}^3/\text{s}}{\langle \sigma v \rangle_{\text{th}}}. \quad (\text{I.1})$$

Recently the analysis of FermiLAT gamma-ray data showed that there may be some peak near 130 GeV, which can be interpreted as the annihilation of DM [5, 6]. This interpretation requires the annihilation cross section to be about 4% of freeze-out cross section:

$$\langle \sigma v \rangle_{\gamma\gamma} = 0.042 \langle \sigma v \rangle_{\text{th}} = 0.042 \text{ pb } c. \quad (\text{I.2})$$

Since we expect the annihilation into photons apparently come from loop-induced process whose cross section is estimated to be

$$\frac{\langle \sigma v \rangle_{\gamma\gamma}}{\langle \sigma v \rangle_{\text{th}}} = \left(\frac{\alpha_{\text{em}}}{4\pi} \right)^2 \sim 10^{-7}, \quad (\text{I.3})$$

the observation calls for some non-conventional models. There are many attempts to explain the Fermi-LAT data with DM annihilation or decay by many authors [7–13].

In this paper we introduce a new mechanism that provides a possible explanation for the Fermi-LAT anomaly on the basis of a model recently proposed by Weinberg [14]. This model is originally suggested in order to explain the possible deviation in the effective neutrino number, $\Delta N_{\text{eff}} = 0.36 \pm 0.34$ at the 68 % confidence level from the Planck, WMAP9 polarization and ground-based data [2], although it is not very significant. We will just use the central value of the deviation from now on. The author introduces a complex scalar field charged under a global $U(1)_X$ symmetry in the hidden sector. All the SM particles are neutral under $U(1)_X$ and they interact with the hidden sector via the renormalizable Higgs portal interaction [15]. The Goldstone boson (GB) after spontaneous symmetry breaking can contribute to the relativistic energy density. Moreover he showed that a fermion in the hidden sector can be introduced in such a way that it can carry odd parity after $U(1)_X$ is broken down to Z_2 . So the hidden fermion could be a promising DM candidate. Some authors analyze the Weinberg model in another aspects as well as LHC phenomenology [16, 17].

To give the observed Fermi-LAT gamma-ray line signal, the DM is assumed to have mass around 214 GeV. The correct thermal relic density is achieved by the DM interaction with the light scalar which decays dominantly into the GB. It turns out that the same channel can accommodate the Fermi-LAT data when the light scalar decays subdominantly into neutral pions.

This paper is organized as follows. In Section 2, we define our model based on Weinberg model. In Section 3, we discuss the possibility to explain the Fermi-LAT observation retaining consistency with various other DM phenomenology. We conclude in Section 4.

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II. MODEL

In this section we set up a model, in which two new fields charged under global $U(1)_X$ symmetry χ and Ψ_{\pm} are introduced in addition to the SM fields. Here χ is boson with charge +2 and Ψ_{\pm} is fermion with charge +1 under the $U(1)_X$ symmetry. Notice that the SM fields are neutral under this symmetry. We expect the lighter one of Ψ_{\pm} to be a DM candidate.

Scalar sector: The new Lagrangian for the scalar sector is typically given by

$$\mathcal{L} = \partial_{\mu}\chi^{*}\partial^{\mu}\chi + \mu_{\chi}^2\chi^{*}\chi - \frac{\lambda_{\chi}}{2}(\chi^{*}\chi)^2 - \lambda_{H\chi}(\Phi^{\dagger}\Phi)(\chi^{*}\chi) + \mathcal{L}_{\text{SM}}, \quad (\text{II.1})$$

where μ_{χ}^2 , λ_{χ} , and $\lambda_{\chi\Phi}$ are real. Here we define the scalar fields in the unitary gauge as follows:

$$\Phi(x) = \frac{1}{\sqrt{2}} \begin{bmatrix} 0 \\ v_H + \phi(x) \end{bmatrix}, \quad \chi(x) = \frac{1}{\sqrt{2}} [v_{\chi} + r(x)] e^{2i\alpha(x)}, \quad (\text{II.2})$$

where $v_H^2 = (246 \text{ GeV})^2$ is the vacuum expectation value (vev) of the SM, and v_{χ} is vev of the hidden sector, which can be determined by the analysis of DM data. Then Eq. (II.1) can be rewritten as

$$\begin{aligned} \mathcal{L} = & \frac{1}{2}\partial_{\mu}r\partial^{\mu}r + 2(v_{\chi} + r)^2\partial_{\mu}\alpha\partial^{\mu}\alpha + \frac{1}{2}\mu_{\chi}^2(v_{\chi} + r)^2 \\ & - \frac{\lambda_{\chi}}{8}(v_{\chi} + r)^4 - \frac{1}{2}\lambda_{H\chi}(\Phi^{\dagger}\Phi)(v_{\chi} + r)^2 + \mathcal{L}_{\text{SM}} \end{aligned} \quad (\text{II.3})$$

The CP-even scalar mass-squared matrix in the basis of $(\phi, r)^t$ can be diagonalized by the following mixing matrix

$$\begin{aligned} M_{\text{Higgs}}^2 & \equiv \begin{pmatrix} \lambda_H v_H^2 & \lambda_{H\chi} v_H v_{\chi} \\ \lambda_{H\chi} v_H v_{\chi} & \lambda_{\chi} v_{\chi}^2 \end{pmatrix} \\ & = \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} m_1^2 & 0 \\ 0 & m_2^2 \end{pmatrix} \begin{pmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{pmatrix}, \end{aligned} \quad (\text{II.4})$$

where $\tan 2\theta = 2\lambda_{H\chi}v_H v_{\chi}/(\lambda_{\chi}v_{\chi}^2 - \lambda_H v_H^2)$. The gauge eigenstate $(\phi, r)^t$ can be rewritten in terms of the mass eigenstate $(H_1, H_2)^t$ as

$$\begin{aligned} \phi & = H_1 \cos\theta + H_2 \sin\theta, \\ r & = -H_1 \sin\theta + H_2 \cos\theta. \end{aligned} \quad (\text{II.5})$$

Hereafter we regard H_1 ($m_1=125$ GeV) as the SM Higgs boson, and H_2 as a lighter scalar boson whose mass is expected to be small of the order 500 MeV to accommodate a significant deviation in the effective neutrino number $\Delta N_{\text{eff}} = 0.36$ [14].

Dark sector: The new Lagrangian for the DM sector is given by

$$\begin{aligned} \mathcal{L} = & \frac{i}{2}(\bar{\Psi}_+\gamma^{\mu}\partial_{\mu}\Psi_+ + \bar{\Psi}_-\gamma^{\mu}\partial_{\mu}\Psi_-) \\ & - \frac{i}{4v_{\chi}}\partial_{\mu}\alpha'(\bar{\Psi}_+\gamma^{\mu}\Psi_- - \bar{\Psi}_-\gamma^{\mu}\Psi_+) \\ & - \frac{f}{2}(-H_1 \sin\theta + H_2 \cos\theta)(\bar{\Psi}_+\Psi_+ - \bar{\Psi}_-\Psi_-) \\ & - \frac{1}{2}(m_+\bar{\Psi}_+\Psi_+ + m_-\bar{\Psi}_-\Psi_-), \end{aligned} \quad (\text{II.6})$$

where we redefined $\alpha = \alpha'/(2v_{\chi})$. Here we can take $f > 0$ without loss of generality. Then Ψ_- is a DM candidate with mass $M_{\text{DM}} = m_-$. We also obtain the mass difference, $\Delta m \equiv m_+ - m_- = 2fv_{\chi}$. It turns out that Δm is very large in our scenario as we will see later. To get the large mass difference we need some degree of fine-tuning to get M_{DM} at electroweak scale.

III. DARK MATTER

In our DM analysis, we focus on explaining γ -ray excess at 130 GeV reported by the Fermi-LAT experiment. It is however worth mentioning the constraints from the other experiments before we go to the main part.

Invisible decay of SM Higgs: The current experiment at LHC tells us that the invisible branching ratio of the SM Higgs (B_{inv}) is conservatively estimated to be less than 20% [19]. There are two invisible modes: $H_1 \rightarrow 2\alpha'$ and $H_1 \rightarrow 2\text{DM}$, and their decay rates (Γ_{inv}) are given by [16]

$$\Gamma_{\text{inv}} \equiv \Gamma(H_1 \rightarrow 2\alpha') + \Gamma(H_1 \rightarrow 2\text{DM}), \quad (\text{III.1})$$

$$\Gamma(H_1 \rightarrow 2\alpha') = \frac{m_1^3}{32\pi v_H^2} \sin^2\theta, \quad (\text{III.2})$$

$$\Gamma(H_1 \rightarrow 2\text{DM}) = \frac{f^2 \sin^2\theta}{16\pi m_1^2} (m_1^2 - 4M_{\text{DM}})^{3/2} \quad (\text{III.3})$$

However, we consider $M_{\text{DM}} > m_1/2$ and the latter mode is forbidden kinematically in our scenario. One obtains the following relation [16]

$$\Gamma_{\text{inv}} < \frac{B_{\text{inv}} \cos^2\theta}{1 - B_{\text{inv}}} \Gamma_{\text{Higgs}}^{\text{SM}}, \quad (\text{III.4})$$

where $\Gamma_{\text{Higgs}}^{\text{SM}}$ is the total decay width of the SM Higgs boson and estimated as 4.1×10^{-3} GeV at $m_1=125$ GeV. The upper bound on the invisible decay of Higgs restricts $\theta \lesssim 0.06$. This constraint is much weaker than that from the direct detection of DM.

Another decay mode is $H_1 \rightarrow 2H_2$ whose rate is given by

$$\Gamma(H_1 \rightarrow 2H_2) \simeq \frac{m_1^3 (v_H \cos\theta - v_{\chi} \sin\theta)^2}{128\pi v_H^2 v_{\chi}^2} \sin^2 2\theta. \quad (\text{III.5})$$

We assume this rate is about 10% of that of $H_1 \rightarrow 2\alpha'$ to explain the Fermi-LAT gamma-ray line.

Direct detection: The relevant process contributing to the spin independent scattering cross section is the t -channel diagram mediated by the lighter scalar as shown in Fig. 1. The corresponding elastic cross section is estimated as

$$\sigma_p \approx 0.27^2 \frac{f^2 m_p^2 M_{\text{DM}}^2}{4\pi v_H^2 (M_{\text{DM}} + m_p)^2} \left(\frac{1}{m_1^2} - \frac{1}{m_2^2} \right)^2 \sin^2 2\theta, \quad (\text{III.6})$$

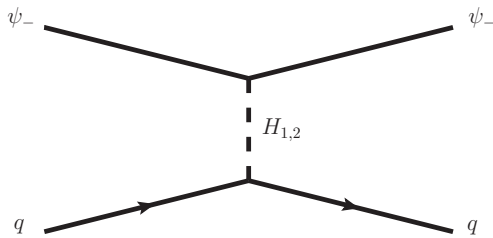


FIG. 1: The Feynman diagram for the elastic scattering of DM off the matter.

where $m_p \approx 1$ GeV is the proton mass. It suggests the following constraint [16], which is derived from the current upper bound reported by XENON100 and LUX [20]:

$$|f \sin 2\theta| \leq \mathcal{O}(10^{-5}). \quad (\text{III.7})$$

Fermi-LAT and Relic density:

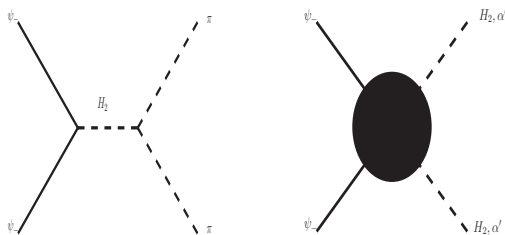


FIG. 2: The dominant Feynman diagrams for the relic density, where the black circle in the right panel represents all the possible channels at tree level.

The possible dominant annihilation channels to obtain the current relic density are shown in Fig. 2. They are i) $2 \text{ DM} \rightarrow 2\pi$, ii) $2 \text{ DM} \rightarrow 2H_2$, iii) $2 \text{ DM} \rightarrow 2\alpha'$ and iv) DM coannihilation channels. But the channel i) is strongly suppressed because its amplitude has the same parametric combination with Eq. (III.7). Therefore the relic density is achieved either by one of ii), iii), iv) or combination of them. The Ref. [16] shows that iv) is dominant when it is allowed, which is not allowed in our case. The annihilation cross sections for the processes ii) and iii) are estimated to be

$$\langle\sigma v\rangle_{2H_2} \approx \frac{3f^4 v_{\text{rel}}^2}{128\pi M_{\text{DM}}^2}, \quad \langle\sigma v\rangle_{2\alpha'} \approx \frac{f^4 v_{\text{rel}}^2}{32\pi m_+^2}. \quad (\text{III.8})$$

In our case it turns out the mode ii) is dominant because $M_{\text{DM}} \ll m_+$.

The photon line observed by Fermi-LAT comes from ii) when $H_2 \rightarrow 2\pi$. Then the pion decays into two photons. It implies that the mass of DM is fixed to be 214 GeV [23]. For either case, the condition Eq. (I.2) can be satisfied if

$$\text{B}(H_2 \rightarrow 2\pi^0) \approx 1.1 \%, \quad (\text{III.9})$$

because $\text{B}(\pi^0 \rightarrow 2\gamma) \simeq 99\%$ [18]. This can be understood as follows: if we set $x_0 = \text{B}(H_2 \rightarrow \pi^0\pi^0)$, $x_+ = \text{B}(H_2 \rightarrow$

$\pi^+\pi^-)$, $x_\alpha = \text{B}(H_2 \rightarrow \alpha'\alpha')$, and considering $\psi_-\psi_- \rightarrow H_2H_2$ dominates, Eq. (I.2) requires

$$4x_0^2 + 2(2x_\alpha x_0) + 2(2x_0 x_+) \approx 4.2 \%. \quad (\text{III.10})$$

Using $x_0 + x_+ + x_\alpha \approx 1$, we get $x_0 \approx 1.1 \%$. We define ratio R as

$$R \equiv \frac{\text{B}(H_2 \rightarrow 2\pi^0)}{\text{B}(H_2 \rightarrow \alpha'\alpha')} \approx 1.1 \%. \quad (\text{III.11})$$

The ratio R is given in the Ref. [17],

$$R = \theta^2 \frac{v_\chi^2}{v_H^2} \left(1 - \frac{4m_\pi^2}{m_2^2}\right)^{1/2} \left(1 + \frac{2m_\pi^2}{m_2^2}\right)^2 \\ \approx 0.011 \left(\frac{\theta}{10^{-5}}\right)^2 \left(\frac{v_\chi}{2.5 \times 10^6 \text{ GeV}}\right)^2. \quad (\text{III.12})$$

We can see $f \approx 0.9$, $\theta \approx 10^{-5}$, and $v_\chi \approx 2.5 \times 10^6$ GeV satisfies both Eq. (III.7) and Eq. (III.9), using micromegas [21]. As a result we can obtain the correct annihilation cross section necessary to explain the Fermi-LAT gamma-ray line. It is worth mentioning that the shape line at 130 GeV is rather wide, if the photons are produced via neutral pions [9, 22], although the fall-off of the peak can be explained and the data still show fluctuation in the spectrum. We also note that in our scenario there is no associated Z -boson or Higgs boson production contrary to most other works where the signal comes from the loops of charged particles. Future experiments with more data will give more clues on the possible scenarios.

IV. CONCLUSIONS

We considered a dark global $U(1)_X$ model with a Goldstone boson and a dark matter [14]. The Goldstone boson can contribute to the effective neutrino number $\Delta N_{\text{eff}} = 0.36$ if the dark scalar mass is about 500 MeV. We showed that this light dark scalar produced by the dark matter annihilation can mix with the SM Higgs boson and about 4% of them can decay into two neutral pions. These pions finally decay into two photons with energy 130 GeV if the dark matter mass is 214 GeV. Our benchmark parameters for the Fermi-LAT gamma-ray line are dark scalar coupling with the dark matter ~ 1 , the mixing angle of the dark scalar with the SM Higgs $\sim 10^{-5}$, and the vev of the dark scalar $\sim 3.5 \times 10^6$ GeV.

The dark matter relic density can possibly be obtained by four channels: i) $2 \text{ DM} \rightarrow 2\pi$, ii) $2 \text{ DM} \rightarrow 2H_2$, iii) $2 \text{ DM} \rightarrow 2\alpha'$ and iv) DM coannihilation. But the strong constraint from the direct detection makes the channel i) always negligible. The parameter space explaining the Fermi-LAT gamma-ray line makes the iii) and iv) suppressed. Therefore only ii) is dominant contribution to the cross section for the relic density.

The obtained gamma-ray spectrum is broad box shape and does not fit to the data perfectly, but the data show

there may be fluctuation in the spectrum. There is no associated $Z\gamma$ or $h\gamma$ production signal contrary to most other works where the signal comes from the loops of charged particles. The annihilation into the other SM particles are highly suppressed due to the small mixing from the direct detection, so we can avoid the constraints from the indirect detection easily. Future experiments with more data will give more clues on the possible scenarios.

The generic signature of the model at the collider is the production of H_1 via $gg \rightarrow H_1$ and its subsequent decay $H_1 \rightarrow H_2 H_2 \rightarrow (\pi\pi)(\alpha'\alpha')$ [17]. However, the branching

ratio $\Gamma(H_1 \rightarrow 2H_2)$ is very small in our scenario as can be seen in Eq. (III.5).

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- [23] If the gamma-ray line were emitted from H_2 , its maximum energy would be just M_{DM} . In our case the peak energy $E_\gamma = 130$ GeV is obtained for $M_{\text{DM}} = 214$ GeV, since it comes from the decay of H_2 into two pions.