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Galactic center GeV gamma-ray excess, from dark matter with gauged lepton numbers

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ABSTRACT

The recently observed excess in gamma-ray signal near the Galactic center suggests that dark matter particles may annihilate into charged fermions that produce gamma-ray to be observed. In this paper, we consider a leptonic dark matter, which annihilates into the standard model leptons, $\mu^+\mu^-$ and $\tau^+\tau^-$, by the interaction of the gauged lepton number $\mathrm{U}(1)_{L_\mu - L_\tau}$ and fits the observed excess. Interestingly, the necessary annihilation cross section for the observed gamma-ray flux provides a good fit to the value for the relic abundance of dark matter. We identify the preferred parameter space of the model after taking the existing experimental constraints from the precision measurements including the muon $(g-2)$, tau decay, neutrino trident production, dark matter direct detection, LHC, and LEP experiments.

1. Introduction

The dark matter (DM) problem is one of the pressing issues in particle physics and cosmology. While the existence of DM has been firmly established through various observations of its gravitational effects on multiple scales, its microscopic nature still remains unknown [1]. This situation stimulates a variety of DM searches including the direct detection of dark matter scattering off detector materials, the detection of indirect signals from the dark matter annihilation or decay, and the collider searches of missing energy signatures due to the produced dark matter particles. Of particular, we notice that the new cosmic-ray detection experiments, such as PAMELA [2], AMS-02 [3], and Fermi-LAT [4], based on satellites reach unprecedented sensitivity to the cosmic-ray signals, which leads to better chance to get the indirect information of dark matter properties.

An intriguing observation was made using the public data of the Fermi Large Area Telescope (Fermi-LAT) by Hooper et al. and also other independent groups [5–16]: a gamma-ray excess at $E_\gamma \approx \mathcal{O}$ (GeV) coming from the Galactic center (GC) is found. In the analyses, it is claimed that the gamma-ray excess spectrum is in good agreement with the emission expected from DM annihilation into standard model (SM) charged particles.[1] The GeV excess is well fitted by a DM particle with a mass of $m_{\mathrm{DM}} \approx 30$–$40$ GeV annihilating to $b\bar{b}$ with an annihilation cross section of $\langle\sigma v\rangle \approx 2\times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$ [13,16].[2] Silk et al. pointed out that contributions of the diffuse photon emissions from primary and secondary electrons produced in DM annihilation processes are significant, especially for leptonic final states $(\ell\bar{\ell})$ [14]. It is also noticed that with the inverse Compton scattering (ICS) and bremsstrahlung contributions from electrons, annihilations of DM particles with a mass of $m_{\mathrm{DM}} \approx 10$ GeV into $\ell\bar{\ell}$ provide a good fit with an annihilation cross section of $\langle\sigma v\rangle \approx (1$–$2)\times 10^{-26}\ \mathrm{cm}^3/\mathrm{s}$ [14]. The $b\bar{b}$ final state may be understood by Higgs portal type DM models and studied by several authors [21–24] but a model for the leptonic explanation based on leptophilic DM is relatively less studied for the GeV excess. Here we explore a leptophilic model with the DM mass $m_{\mathrm{DM}} \approx 10$ GeV.

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[1] In Ref. [17], the authors proposed a new mechanism naturally inducing a continuum bump signature in cosmic γ-ray measurements even with a particle directly decaying into two photons, introducing Energy Peak idea together with the postulate of a generic dark sector [18].

[2] We note that recent observation of AMS-02 [19] has started to exclude the $\chi\chi \to b\bar{b}$ dominant DM explanation of relic abundance [20].

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In the heavier mass domain, $M_{\rm DM} \gtrsim 100$ GeV, leptophilic DM models have attracted a lot of attention (see e.g. [25]). due to recent observation of excessive cosmic-ray positron fraction by the PAMELA, Fermi-LAT, and AMS-02 experiments, but lack of excess in the anti-proton fraction [26]. In building the leptophilic DM model, it is attractive to gauge the differences in lepton numbers: $U(1)_{L_e-L_\mu}$, $U(1)_{L_\mu-L_\tau}$, and $U(1)_{L_\tau-L_e}$. These symmetries are anomaly free without extending the SM particle contents [27–29].[3] Leptophilic DM models with a $U(1)_{L_i-L_j}$ gauge symmetry for the positron excess were studied in Refs. [30–32]. In our analysis, we take $U(1)_{L_\mu-L_\tau}$ symmetry for the GeV gamma-ray excess since models with $U(1)_{L_e-L_\mu}$ and $U(1)_{L_\tau-L_e}$ are stringently limited by existing cosmic-ray positron measurements in low energy [33].

It should be also noticed that astrophysical uncertainty in gamma-rays from around the GC including modeling of background emission in the inner galaxy is still big. Moreover, millisecond pulsars [6–8,10,12,34] and pions from the collision of cosmic-rays with gas [6–8,10] can contribute to the GeV scale gamma-ray and have been proposed as alternative explanations of the GeV gamma-ray excess even though the spectral shape from millisecond pulsars looks too soft at the sub-GeV energy range to account for the observed GeV excess spectrum [35]. Also the morphological feature of the observed excess is extended to more than $\sim 10°$ from the GC beyond the boundary of the central stellar cluster which could include numerous millisecond pulsars [13], and observed distributions of gas seem to provide a poor fit to the spatial distribution of the signal [13,36,37].

The contents of the paper is as follows. In Section 2, we explain the leptophilic DM model in detail and present dominant annihilation channels. The model parameter space for the observed DM thermal relic abundance and the GeV gamma-ray excess is clarified. In Section 3, we discuss the existing experimental constrains on the same parameter space, then conclude in Section 4.

2. The model, relic abundance, and Fermi-LAT GeV excess

2.1. The model

We extend the SM:

- by extending the gauge symmetry with $U(1)_{L_\mu-L_\tau}$,
- by introducing a new Dirac fermion ψ, which is identified as dark matter.

The charge assignment for the SM fermions and the new fermion regarding the $L_\mu - L_\tau$ symmetry is given in Table 1. The muon-leptons and anti-tau leptons are (+1), tau-leptons and anti-muon leptons are (−1) and the new fermion has a charge Q'_ψ. We take a universal gauge coupling constant g' for Z' interactions.

For the (spontaneously broken) extended gauge symmetry, we associate a new vector boson Z' with an undetermined mass $m_{Z'}$. The model Lagrangian is written as follows:

$$\mathcal{L} \supset \mathcal{L}_{\rm SM} - \frac{1}{4} Z'_{\alpha\beta} Z'^{\alpha\beta} + \frac{1}{2} m_{Z'}^2 Z'_\alpha Z'^\alpha + i\bar\psi\gamma_\alpha\partial^\alpha\psi - m_\psi\bar\psi\psi + g' Q'_\psi Z'_\alpha \bar\psi\gamma^\alpha\psi + g' Z'_\alpha \sum_{f=\mu,\tau,\nu_\mu,\nu_\tau} Q'_f \bar f\gamma^\alpha f\,, \quad (1)$$

where $Q'_{\psi,f}$ are $U(1)_{L_\mu-L_\tau}$ charges of the DM and a SM fermion f, respectively given in Table 1. In our study, the DM mass m_ψ is taken to be 10 GeV to fit the GeV excess as suggested in Ref. [14] (see also Ref. [38]).

[3] The other anomaly free choice is $U(1)_{B-L}$, but it does not provide lepton specific interactions.

Table 1
Charges under the L_μ–L_τ gauge symmetry.

Particle	ψ	$L_\mu = (\nu_{\mu L}, \mu_L)$, μ_R, $\nu_{\mu R}$	$L_3 = (\nu_{\tau L}, \tau_L)$, τ_R, $\nu_{\tau R}$	Others
Charge	Q'_ψ	+1	−1	0

The ψ particle is neutral under the SM gauge interactions but its presence is seen by L_μ–L_τ interactions. The gauge interaction allows an early time thermal equilibrium with the SM particles and the standard freeze-out took place at $T \sim m_\psi/20$ through the dominant annihilation channels:

$$\psi\bar\psi\ (\to Z'^{(*)}) \to \ell^+\ell^-,\ \nu_\ell\bar\nu_\ell \quad (2)$$

$$\psi\bar\psi \to Z'Z'\,, \quad (3)$$

where $\ell = \mu,\ \tau$. The corresponding Feynman diagrams are depicted in Fig. 1. The DM annihilation into a Z' pair is kinematically allowed only when $m_\psi > m_{Z'}$.

The leading order DM annihilation cross sections are given by

$$\langle\sigma v\rangle_{\psi\bar\psi\to\ell\bar\ell} \simeq \frac{g'^4 Q'^2_\psi}{2\pi} \frac{m_\ell^2 + 2m_\psi^2}{\left(m_{Z'}^2 - 4m_\psi^2\right)^2 + m_{Z'}^2\Gamma_{Z'}^2} \sqrt{1 - \frac{m_\ell^2}{m_\psi^2}} + \mathcal{O}(v^2)\,, \quad (4)$$

$$\langle\sigma v\rangle_{\psi\bar\psi\to Z'Z'} \simeq \frac{g'^4 Q'^2_\psi}{4\pi} \frac{m_\psi^2 - m_{Z'}^2}{\left(m_{Z'}^2 - 4m_\psi^2\right)^2} \sqrt{1 - \frac{m_{Z'}^2}{m_\psi^2}} + \mathcal{O}(v^2)\,, \quad (5)$$

where $\ell = \mu,\ \tau,\ \nu_\mu$, and ν_τ. The decay width of the Z' boson is given by

$$\Gamma_{Z'} \simeq \sum_{\ell=\mu,\tau,\nu_\mu,\nu_\tau} \frac{g'^2}{12\pi m_{Z'}} \left(m_{Z'}^2 + 2m_\ell^2\right) \times \sqrt{1 - \frac{4m_\ell^2}{m_{Z'}^2}}\,\theta\left(m_{Z'} - 2m_\ell\right) + \frac{g'^2 Q'^2_\psi}{12\pi m_{Z'}} \left(m_{Z'}^2 + 2m_\psi^2\right) \sqrt{1 - \frac{4m_\psi^2}{m_{Z'}^2}}\,\theta\left(m_{Z'} - 2m_\psi\right), \quad (6)$$

where θ is the unit step function.

2.2. Relic abundance

Taking the DM relic density $0.11 < \Omega_{\rm DM}h^2 < 0.13$ [39], we found the preferred parameter space for ψ dark matter in $m_{Z'}$–g' plane for $Q'_\psi = 2$ in Fig. 2. The plots for other values of Q'_ψ are also given later. The ballpark range is $1 < m_{Z'}$ [GeV] < 500 and $0.001 < g' < 1.0$ as a reasonable choice within the perturbative regime. Notably, the dip structure appears around $m_{Z'} \simeq 2m_\psi = 20$ GeV due to the resonance in the s-channel annihilation into leptons mediated by the Z' gauge boson. In calculating the thermal average of DM annihilation cross section for the relic abundance, we take the non-negligible effect of DM kinetic energy near the resonance pole, $m_{Z'} \simeq 2m_\psi = 20$ GeV as explained in Ref. [40]. The result is shown in Fig. 2.

2.3. Fermi-LAT GeV excess

We conduct the fit of our model, $\mu^+\mu^- : \tau^+\tau^- = 1:1$, to the observed spectrum of the GC GeV γ-ray excess. Our best fit is obtained for $\langle\sigma v\rangle_{\psi\bar\psi\to\mu^+\mu^-,\tau^+\tau^-} \approx 1.22\times10^{-26}$ cm^3/s with $\chi^2 = 19.22$. Our result can be compared with the results in Ref. [14],