Phenomenology of $U(1)_{L_\mu-L_\tau}$ charged dark matter at PAMELA/FERMI and colliders

Seungwon Baek

Institute of Basic Science and Department of Physics, Korea University,
Seoul, 136–701, Korea
E-mail: sbaek@korea.ac.kr

Pyungwon Ko

School of Physics, KIAS,
Seoul, 130–722, Korea
E-mail: pko@kias.re.kr

Abstract: Recent data on $e^+/e^-$ and $\bar{p}$ cosmic rays suggest that dark matter annihilate into the standard model (SM) particles through new leptophilic interaction. In this paper, we consider a standard model extension with the gauged $U(1)_{L_\mu-L_\tau}$ group, with a new Dirac fermion charged under this $U(1)$ as a dark matter. We study the muon $(g-2)_\mu$, thermal relic density of the cold dark matter, and the collider signatures of this model. $Z'$ productions at the Tevatron or the LHC could be easily order of $O(1)-O(10^3)$ fb.

Keywords: dark matter, collider.
1. Introduction

The Standard Model (SM) should be extended in order to accommodate the nonbaryonic cold dark matter (CDM) of the universe. There are many options for cold dark matter candidates in particle physics models: axion, neutralino or gravitino lightest supersymmetric particle (LSP) [1, 2], lightest Kaluza-Klein particle (LKP) [2], and lightest particle in a hidden sector [3], to name a few. However, we do not have enough information on the detailed nature of CDM, except that $\Omega_{CDM}h^2 = 0.106 \pm 0.008$ [4]. More information from direct and indirect dark matter searches and colliders are indispensable for us to diagnose the particle identity of the CDM, namely its mass and spin and other internal quantum number(s).

Recently, PAMELA reported a sharp increase of positron fraction $e^+/(e^+ + e^-)$ in the cosmic radiation for the energy range 10 GeV to 100 GeV [5], and no excess in $\bar{p}/p$ [6] from the theoretical calculations. And also very recently, Fermi-LAT [7] and HESS [8] data showed clear excess of the $e^+ + e^-$ spectra in the multi-hundred GeV range above the conventional model [4], although they do not confirm the previous ATIC [10] peak.

These data (at least a part of them) could be due to some astrophysical origins such as pulsars [11, 12]. A more exciting possibility from particle physics point of view would be interpreting them as indirect signatures of cold dark matters through their pair annihilations or decays. In this paper we take the second avenue, namely particle physics explanations of positron excess. Model independent study [13] show that multi-TeV scale
DMs dominantly annihilating into SM leptons, especially into $\tau^+\tau^-$ or $4 \mu$'s, are most favored. If one assumes the standard cosmology, large boost factor (BF) of $O(10^3)$ is also required to enhance the event rates.

From the viewpoint of model building and grand unification, it is non-trivial to construct this kind of leptophilic model. However it is still phenomenologically viable, and we have to verify or falsify this class of models by comparing the predictions with the data. In this paper we explicitly construct a leptophilic model and work out the physical consequences in detail. There are already many papers available studying the implications of the PAMELA/FERMI data in different models and/or context [14].

The simplest model for the leptophilic (or hadrophobic) gauge interaction is to gauge the global $U(1)_{L_\mu - L_\tau}$ symmetry of the standard model (SM), which is anomaly free [15, 16, 17, 18]. Within the SM, there are four global $U(1)$ symmetries which are anomaly free:

$$L_e - L_\mu, \quad L_\mu - L_\tau, \quad L_\tau - L_e, \quad B - L$$

One of these can be implemented to a local symmetry without anomaly. The most popular is the $U(1)_{B-L}$, which can be easily implemented to grand unified theory. Two other symmetry involving $L_e$ are tightly constrained by low energy and collider data. On the other hand, the $L_\mu - L_\tau$ symmetry is not so tightly constrained, and detailed phenomenological study has not been available yet. Only the muon $(g - 2)_\mu$ and the phenomenology at muon colliders have been discussed [18, 13]. This model can be extended by introducing three right-handed neutrinos and generate the neutrino masses and mixings via seesaw mechanism [16]. Also $U(1)_{L_\mu - L_\tau}$ can be embedded into a horizontal $SU(2)_H$ [16] acting on three lepton generations, which may be related with some grand unification.

In this paper, we extend the existing $U(1)_{L_\mu - L_\tau}$ model by including a complex scalar $\phi$ and a spin-1/2 Dirac fermion $\psi_D$, with $U(1)_{L_\mu - L_\tau}$ charge 1. There is no anomaly regenerated in this case, since we introduced a vectorlike fermion. The complex scalar $\phi$ gives a mass to the extra $Z'$ by ordinary Higgs mechanism. And the Dirac fermion $\psi_D$ plays a role of the cold dark matter, whose pair annihilation into $\mu$ or $\tau$ explains the excess of $e^+$ and no $\bar{p}$ excess as reported by PAMELA [5, 6]. Then we study CDM cosmology (thermal relic density and (in)direct signatures) and collider phenomenology of the $U(1)_{L_\mu - L_\tau}$ model with Dirac fermion dark matter in detail.

In Sec. 2, we define the model and discuss the muon $(g - 2)_\mu$ in our model. In Sec. 3, we calculate the thermal relic density of the CDM $\psi_D$, and identify the parameter region that is consistent with the data from cosmological observations. We also present the signatures for indirect search experiments: $e^+e^-$, neutrinos, and gamma rays from the DM annihilations, including the Sommerfeld enhancement. In Sec. 4, we study the collider signatures of the model at various colliders encompassing Tevatron, B factories, LEP(2), the $Z^0$ pole and LHC, including productions and decays of $Z'$, the SM Higgs boson and the newly introduced $U(1)_{L_\mu - L_\tau}$ charged scalar boson. Our results are summarized in Sec. 5. We note that this model was discussed briefly by Cirelli, et.al in Ref. [13] in the context of the muon $(g - 2)_\mu$ and the relic density. In this paper, we present the quantitative analysis on these subjects in detail, as well as study various signatures at various colliders including the Tevatron and the LHC.
2. Model and the muon $(g - 2)_\mu$

The new gauge symmetry $U(1)_{L_\mu - L_\tau}$ affects only the 2nd and the 3rd generations of leptons. We assume $l_L^{i=2(3)}$, $l_R^{i=2(3)}$ ($i$: the generation index) carry $Y' = 1(-1)$. We further introduce a complex scalar $\phi$ with $(1,1,0)(1)$ and a Dirac fermion $\psi_D$ with $(1,1,0)(1)$, where the first and the second parentheses represent the SM and the $U(1)_{L_\mu - L_\tau}$ quantum numbers of $\phi$ and $\psi_D$, respectively. The covariant derivative is defined as

$$D_\mu = \partial_\mu + ieQA_\mu + i \frac{e}{sWcW} (I_3 - s^2WQ)Z_\mu + ig'Y'Z'_\mu \quad (2.1)$$

The model lagrangian is given by

$$L_{\text{Model}} = L_{\text{SM}} + L_{\text{New}} \quad (2.2)$$

$$L_{\text{New}} = -\frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} + \overline{\psi}_D (iD \cdot \gamma - M_{D}) \psi_D$$

$$+ D_\mu \phi^\dagger D^\mu \phi - \mu^2 \phi^\dagger \phi - \lambda \phi^\dagger \phi^2 - \lambda_H \phi^\dagger \phi H^\dagger H. \quad (2.3)$$

In general, we have to include renormalizable kinetic mixing term for $U(1)_Y$ and $U(1)_{L_\mu - L_\tau}$ gauge fields, $B_{\mu\nu} Z'^{\mu\nu}$, which will lead to the mixing between $Z$ and $Z'$. Then the dark matter pair can annihilate into quarks through $Z-Z'$ mixing in our case, and the $\overline{p}$ flux will be somewhat enhanced, depending on the size the $Z-Z'$ mixing. However, electroweak precision data and collider experiments give a strong constraint on the possible mixing parameter, since the mixing induces the $Z'$ coupling to the quark sector. Furthermore, if one assumes that the new $U(1)_{L_\mu - L_\tau}$ is embedded into a nonabelian gauge group such as $SU(2)_H$ or $SU(3)_H$, then the kinetic mixing term is forbidden by this nonabelian gauge symmetry [16]. In this paper, we will assume that the kinetic mixing is zero to simplify the discussion and to maximize the contrast between the positron and the antiproton fluxes from the dark matter annihilations.

In this model, there are two phases for the extra $U(1)_{L_\mu - L_\tau}$ gauge symmetry depending on the sign of $\mu^2_\phi$:

- **Unbroken phase**: exact with $\langle \phi \rangle = 0$, $\mu^2_\phi > 0$ and $M_{Z'} = 0$,

- **Spontaneously broken phase**: by $\mu^2_\phi < 0$, nonzero $\langle \phi \rangle \equiv v_\phi \neq 0$, and $M_{Z'} \neq 0$

In the unbroken phase, the massless $Z'$ contribute to the muon $(g - 2)_\mu$ as in QED up to the overall coupling:

$$\Delta a_\mu = \frac{\alpha'}{2\pi}. \quad (2.4)$$

Currently there is about $3.4\sigma$ difference between the BNL data [22] and the SM predictions [23] in $(g - 2)_\mu$:

$$\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = (302 \pm 88) \times 10^{-11}. \quad (2.5)$$

1Similar idea for the DM was considered in [20, 21] in the context of Stueckelberg $U(1)_X$ extension of the SM model.

2Because of this simplification, the direct detection rate from the CDM (in)elastic scattering off nuclei vanishes identically. However this is no longer true if the kinetic mixing is included. This case is discussed in brief in Sec. 3.2.
The $\Delta a_{\mu}$ in (2.4) can explain this discrepancy, if $\alpha' \approx 2 \times 10^{-8}$. However, this coupling is too small for the thermal relic density to satisfy the WMAP data. The resulting relic density is too high by a several orders of magnitude. Also the collider signatures will be highly suppressed. Therefore we do not consider this possibility any further, and consider the massive $Z'$ case (broken phase) in the following.

In the broken phase, it is straightforward to calculate the $Z'$ contribution to $\Delta a_{\mu}$. We use the result obtained in Ref. [18]:

$$\Delta a_{\mu} = \frac{\alpha'}{2\pi} \int_0^1 dx \frac{2m_{\mu}^2x^2(1-x)}{x^2m_{\mu}^2 + (1-x)M_{Z'}^2} \approx \frac{\alpha'}{2\pi} \frac{2m_{\mu}^2}{3M_{Z'}^2}$$

(2.6)

The second approximate formula holds for $m_{\mu} \ll M_{Z'}$. In Fig. 1, shown in the blue band is the allowed region of $M_{Z'}$ and $\alpha'$ which is consistent with the BNL data on the muon $(g-2)_\mu$ within $3\sigma$ range. There is an ample parameter space where the discrepancy between the BNL data and the SM prediction can be explained within the model.

3. Dark matter: Relic density and (In)direct signatures

3.1 Thermal relic density

In our model, the Dirac fermion $\psi_D$ and its antiparticle $\bar{\psi}_D$ are CDM candidates. The thermal relic density of $\psi_D$ and $\bar{\psi}_D$ is achieved through the DM annihilations into muon, tau leptons or their neutrinos through s-channel $Z'$-exchange. They can also annihilate into the real $Z'$ pairs when kinematically allowed.

$$\psi_D \bar{\psi}_D \to Z'^* \to l^+l^-, \nu_l \bar{\nu}_l \ (l = \mu, \tau),$$
$$\psi_D \bar{\psi}_D \to Z'Z'.$$

(3.1)

We modified the micrOMEGAs [24] in order to calculate the relic density of the $U(1)_{L_{\mu}-L_{\tau}}$ charged $\psi_D$ CDM. It is easy to fulfill the WMAP data on $\Omega_{CDM}$ for a wide range of the DM mass, as shown in Fig. 1. The black curves represent constant contours of $\Omega h^2 = 0.106$ in the $(M_{Z'}, \alpha)$-plane for $M_{\psi_D} = 10, 100, 1000$ GeV (from below). We can clearly see the $s$-channel resonance effect of $Z' \to \psi_D \bar{\psi}_D$ near $M_{Z'} \approx 2M_{\psi_D}$. The blue band is the allowed region by the $(g-2)_\mu$ at the $3\sigma$ level. We also show the contours for the $Z'$ production cross sections at various colliders: B factories (1fb, red dotted), Tevatron (10fb, green dot-dashed), LEP(10fb, pink dotted), LEP2(10fb, orange dotted) and LHC (1 fb, 10 fb and 100 fb in blue dashed curves). The cross sections in the parentheses except the LHC case roughly correspond to the upper bounds that each machine gives. Therefore the left-hand sides of each curve is ruled out by the current collider data. Note that a larger parameter space can be accessed by the LHC. These issues and other collider signatures are covered in the next section.

The current experimental mass bound of SM-like $Z'$ is 923 GeV from the search for a narrow resonance in electron-positron events [25]. We emphasize, however, that in our model the $Z'$ boson as light as $\sim 10$ GeV is still allowed by present data from various
colliders. It is mainly because the production cross section at the Tevatron is suppressed since \(Z'\) should be produced from the couplings to the 2nd and 3rd family leptons.

In the range \(100 \text{ GeV} \lesssim M_{\Psi_D} \lesssim 10 \text{ TeV}, \alpha \gtrsim 10^{-3}\) and \(100 \text{ GeV} \lesssim M_{Z'} \lesssim 1 \text{ TeV}\), the relic density and \(\Delta a_\mu\) constraints can be easily satisfied simultaneously while escaping the current collider searches. We note that if the \((g-2)_\mu\) constraint is not considered seriously or if we assume there are other sector which saturate the \((g-2)_\mu\) upper bound, then all the region in the right-hand side of the blue band is also allowed.

![Figure 1](image.png)

**Figure 1:** The relic density of CDM (black), the muon \((g-2)_\mu\) (blue band), the production cross section at \(B\) factories (1 fb, red dotted), Tevatron (10 fb, green dotdashed), LEP (10 fb, pink dotted), LEP2 (10 fb, orange dotted), LHC (1 fb, 10 fb, 100 fb, blue dashed) and the \(Z^0\) decay width \(2.5 \times 10^{-6} \text{ GeV}\), brown dotted) in the \((\log_{10} \alpha', \log_{10} M_{Z'})\) plane. For the relic density, we show three contours with \(\Omega h^2 = 0.106\) for \(M_{\Psi_D} = 10 \text{ GeV}, 100 \text{ GeV}\) and \(1000 \text{ GeV}\). The blue band is allowed by \(\Delta a_\mu = (302 \pm 88) \times 10^{-11}\) within \(3 \sigma\).

### 3.2 Direct detection rates

Since we ignored the kinetic mixing between the new \(U(1)\) gauge boson and the SM \(U(1)_Y\) gauge boson \(B_\mu\), there would be no signal in direct DM detection experiments in this model. The messenger \(Z'\) does not interact with electron, quarks or gluons inside nucleus. Also there would be no excess in the antiproton flux in cosmic rays in this case, while one could have an excess in the positron signal in a manner consistent with the PAMELA/Fermi data. However there would be a small kinetic mixing between two \(U(1)\) gauge field strength tensor. If we assume a small kinetic mixing \(\theta(\sim 10^{-3} = 10^{-2})\) between the \(Z'_\mu\) and photon,
then spin-independent cross section for direct detection rate will be given by

\[
\sigma_{\text{SI}} = \frac{4}{\pi} \left( \frac{M_{\psi_D} M_A}{M_{\psi_D} + M_A} \right)^2 [\lambda_p Z + \lambda_n (A - Z)]^2,
\]

(3.2)

where \( Z \) and \( A \) are the atomic number and the mass number of a nucleus. The couplings \( \lambda_{p(n)} \)'s of the CDM to proton and neutron are given by

\[
\lambda_p = \pm \frac{e g'}{2 M^2_{Z'}} \left[ \theta_{Z'\gamma} + \frac{\theta_{Z'Z}}{4 \sin \theta_w \cos \theta_w} (1 - 4 \sin^2 \theta_w) \right] \quad (3.3)
\]

\[
\lambda_n = \mp \frac{e g' \theta_{Z'Z}}{8 M^2_{Z'} \sin \theta_w \cos \theta_w} \quad (3.4)
\]

where the upper (lower) sign corresponds to \( \psi_D(\overline{\psi}_D) \) DM scattering. Note that \( \lambda_p \) and \( \lambda_n \) are dominated by the \( Z' - \gamma \) and \( Z' - Z \) mixing, respectively. This is because photon couples to the nucleon charge, whereas the \( Z^0 \) couples to the neutral current weak charge of a nucleon. The \( Z^0 \) coupling to a proton is proportional to \( (1 - 4 \sin^2 \theta_w) \), and thus highly suppressed compared to the \( Z^0 \) coupling to a neutron. Also let us note that the cross section on a nucleus could be small, if there is a cancellation between \( \lambda_p \) and \( \lambda_n \) terms depending on the sign of \( \theta_{Z'\gamma} \) and \( \theta_{Z'Z} \) in Eqs (3.3)-(3.5).

If we consider a dark matter scattering on single proton target, one has

\[
\sigma_{\psi_Dp} \approx 16 \pi \alpha \alpha' \frac{\theta_{Z'\gamma}^2}{\theta_{Z'Z}^2} \frac{M^4_{\psi_D}}{M^4_{Z'}} \approx 1.3 \times 10^{-42} \text{cm}^2 \left( \frac{100 \text{ (GeV)}}{M_{Z'}} \right)^4 \left( \frac{\alpha'}{10^{-2}} \right) \left( \frac{\theta_{Z'\gamma}}{10^{-2}} \right)^2 \quad (3.5)
\]

which is dominated by \( Z' - \gamma \) mixing. The resulting cross section is close to the current upper bounds from XENON10 [26] and CDMS [27] experiments. We have assumed that the DM \( \psi_D \) is much heavier than proton. Similarly, the SI cross section on a neutron target is given by

\[
\sigma_{\psi_Dn} \approx \frac{\pi \alpha \alpha' \theta_{Z'Z}^2}{\sin^2 \theta_w \cos^2 \theta_w} \frac{M^2_{\psi_D}}{M^4_{Z'}} \approx 4.6 \times 10^{-43} \text{cm}^2 \left( \frac{100 \text{ (GeV)}}{M_{Z'}} \right)^4 \left( \frac{\alpha'}{10^{-2}} \right) \left( \frac{\theta_{Z'\gamma}}{10^{-2}} \right)^2 \quad (3.6)
\]

The scattering cross section on the proton by \( Z - Z' \) mixing is suppressed by \( (1 - 4 \sin^2 \theta_w)^2 \) relative to the scattering cross section on the neutron target, and thus negligible. In either case, one can evade the bounds from XENON10 and CDMSII by taking a heavier \( Z' \) mass, smaller coupling \( \alpha' \) or smaller mixing angle \( \theta \). If \( Z' \) is light, one may have too large SI cross section, in conflict with XENON10 and CDMSII.

### 3.3 Sommerfeld enhancement and boost factor (BF)

The DM annihilation cross section at the freeze-out temperature is typically \( \langle \sigma v \rangle \sim 3 \times 10^{-26} \text{ cm}^3/\text{sec} \). To explain the PAMELA or Fermi data, \( \langle \sigma v \rangle \sim 3 \times 10^{-23} \text{ cm}^3/\text{sec} \) is required. Therefore we need a boost factor (BF) of order of \( 10^3 \). A large BF can come from
the so-called Sommerfeld enhancement in the $S$–wave DM annihilation. The Sommerfeld factor, given by the ratio of the radial wavefunction at infinity to that at the origin,

$$S_k = \left| \frac{\chi_k(\infty)}{\chi_k(0)} \right|^2$$  \hspace{1cm} (3.7)

can be calculated by solving the radial $S$–wave Schrödinger equation \cite{28} with the attractive Yukawa potential in our model:

$$-\frac{1}{2M_{\psi_D}} \frac{d^2}{dr^2} \chi_k(r) - \frac{\alpha'}{2r} e^{-M_{Z'} r} \chi_k(r) = \frac{k^2}{2M_{\psi_D}} \chi_k(r).$$  \hspace{1cm} (3.8)

Here $k = M_{\psi_D} v$ and $v$ is the relative velocity of two annihilating DM particles. The boundary condition for the above Schrödinger equation is

$$\chi_k'(r) \rightarrow ik\chi_k(r) \text{ as } r \rightarrow \infty, \quad \chi_k(0) = 1.$$  \hspace{1cm} (3.9)

Fig. 2 shows the prediction for the Sommerfeld enhancement factor in our model for various values of DM: $M_{\psi_D} = 10, 100, 1000, 2000$ GeV. For a given values of the DM mass and the $M_{Z'}$, the $\alpha'$ are chosen in such a way that they satisfy the relic density, i.e. each lines are predictions of the Sommerfeld enhancement factor along the constant relic density contours in Fig. 2. We can see that it is easy to get the enhancement factor $\sim 10^3$.

**Figure 2:** The predictions of Sommerfeld enhancement factor in our model along the constant contours in Fig. 2.
3.4 Indirect signatures: positron, neutrino and photon fluxes

Now we show the prediction of $e^+/e^+e^-$ spectra in our model in Fig. 3. The positron flux at the Earth can be calculated from the solution of the diffusion equation as

$$\Phi_{e^+}(\odot, \epsilon) = \frac{\beta_{e^+}}{4\pi} \frac{\kappa \tau_E}{\epsilon^2} \int_\epsilon^\infty d\epsilon_S f(\epsilon_S) \tilde{I}(\lambda_D),$$

(3.10)

where $\odot$ represent the position of the sun, $\epsilon = E_{e^+}/E_0$ ($E_0 = 1$ GeV). The function $f(\epsilon_S)$ is the positron energy spectrum from the dark matter annihilation at the source. The “diffusive halo function” $\tilde{I}(\lambda_D)$ with $\lambda_D^2 = 4K_0\tau_E(\epsilon^{\delta-1} - \epsilon_S^{\delta-1})/(1 - \delta)$ encodes the information on the propagation of positron from the source to the Earth. The parameter $\kappa = \eta/\langle \sigma v \rangle (\rho_\odot/M_{\psi_D})^2$ is a factor relevant to the particle physics [$\eta = 1/2$ (1/4) for Majorana (Dirac) DM]. The other parameters are: the speed of the positron $\beta_{e^+}$ and and $\tau_E = 10^{16}$ sec. We used the NFW DM density profile [31]:

$$\rho(r) = \rho_\odot \left( \frac{r_\odot}{r} \right)^\gamma \left( 1 + \frac{r_\odot/r_s}{1 + (r/r_s)^\alpha} \right)^{\beta - \gamma}/\alpha.$$

(3.11)

where $(\alpha, \beta, \gamma, r_s) = (1, 2, 1, 20$ kpc) and $\rho_\odot = 0.3$ GeV/cm$^3$ is the DM density near the Sun. To obtained the halo funtion $\tilde{I}(\lambda_D)$, we used the method suggested in [31]. We also used the cosmic ray propagation parameters which correspond to the medium primary antiproton fluxes [32]: $\delta = 0.70$, $K_0 = 0.0112$ kpc$^2$/Myr, and $L = 4$ kpc. For the plot, Fig. 3, we fixed the DM mass $M_{\psi_D} = 2$ TeV. The required BF is about 5200, which is a little bit larger than the maximal Sommerfeld enhancement in Fig. 2 can give. However, an additional enhancement factor of about 2–3 can be easily obtained from the clumpy structure of dark matter density. We also have checked with other DM masses ranging from 1 TeV to 3 TeV, which can also fit the PAMELA data very well.

Although the PAMELA data alone can be fitted with a wide range of the DM mass [13], the simultaneous fit including the Fermi and HESS data is non-trivial and gives more strong constraint on the DM mass. Fig. 3 shows a fit to the PAMELA, Fermi and HESS data in our model. First, we obtained the absolute positron flux from the PAMELA data and the known background positron and electron spectrum [9]. The resulting spectra agree with the Fermi data when we rescale the background by a factor $r \sim 0.7$. This rescaling also makes all the Fermi data lie above the background. The HESS data has also been allowed a rescale factor $r_H$. Now we fitted the three parameters $r, r_H$ and the BF to the data, assuming the data are independent with each other. For the DM mass $M_{\psi_D} = 2$ TeV, we obtained an excellent fit $\chi^2_{min}/d.o.f = 53/50$, $r = 0.7$, $r_H = 0.84$ and BF = 5200. For the lighter and heavier DM masses, the fit quality becomes worse. We have also checked that the isothermal DM profile also gives similar results. The reason can be traced back to the fact that the positrons we observe comes mainly from the sources not that far from the Sun where the DM density does not differ much for different DM profiles, although the NFW profile is far more cuspy than the isothermal profile when approaching the Galactic center.

Since the DM pair annihilates into the 2nd and 3rd generation leptons including neutrinos in our model, we expect large neutrino flux. The neutrino flux can be detected
Figure 3: The fit to the PAMELA data in our model.

Figure 4: The fit to the PAMELA, Fermi and HESS data in our model.

through the upward-going muons in the Super-Kamiokande (SK). Also the neutral pion from the tau decay can produce sizable photon flux, which can also be compared with the
existing gamma-ray searches such as HESS\textsuperscript{3}. The main contribution to the neutrino and
the gamma-ray flux comes from the Galactic center where the DM density is the highest.
For this reason we consider only neutrinos and gamma-rays from the Galactic center. The
differential fluxes of neutrinos and photons from the Galactic center can be easily calculated
from the formula \textsuperscript{[2]} for the case of Dirac DM:
\begin{equation}
\frac{dF_i}{dE_i}(\psi, E) = \langle \sigma v \rangle \frac{dN_i}{dE} \frac{1}{16\pi M_D^2} \int_{\text{line of sight}} ds \rho^2(r(s, \psi)),
\end{equation}
where \(i = \nu, \gamma\) and \(s\) is the distance from the Earth in the angular direction \(\psi\) from the
line connecting the Earth and the Galactic center (GC).

The neutrinos from the GC can be detected at the superkamiokande (SK) as the muon
neutrios transform into the muons through the weak interactions in the rocks below the
SK. The neutrino-induced muon flux is written as
\begin{equation}
F_{\mu^+\mu^-} = \int dE_{\nu\mu} \frac{dF_{\nu\mu}}{dE_{\nu\mu}} f(E_{\nu\mu}).
\end{equation}
The function \(f(E_{\nu\mu})\) is the probability of a muon neutrino with energy \(E_{\nu\mu}\) transforming
into muon with energy larger than \(E_{\text{th}}\), and is given by \textsuperscript{[34]}
\begin{equation}
f(E_{\nu\mu}) = \int_{E_{\text{th}}}^{E_{\nu\mu}} dE_{\mu} \left( \frac{d\sigma_{\nu\mu}(p\rightarrow\mu(\bar{\tau}))X}{dE_{\mu}} n_{p}^{(\text{rock})} + \frac{d\sigma_{\nu\mu}(n\rightarrow\mu(\bar{\tau}))X}{dE_{\mu}} n_{n}^{(\text{rock})} \right) R(E_{\mu}, E_{\text{th}}),
\end{equation}
where \(d\sigma_{\nu\mu}(p(n)\rightarrow\mu(\bar{\tau}))X/dE_{\mu}\) is the scattering cross section of a neutrino with proton
(neutron) to create a muon with energy \(E_{\mu}\) \textsuperscript{[35]}:
\begin{align}
\frac{d\sigma_{\nu\mu}(p\rightarrow\mu(\bar{\tau}))X}{dE_{\mu}} &= \frac{2m_p G_F^2}{\pi} \left( 0.21 + 0.29 \frac{E_{\mu}^2}{E_{\nu\mu}^2} \right), \\
\frac{d\sigma_{\nu\mu}(n\rightarrow\mu(\bar{\tau}))X}{dE_{\mu}} &= \frac{2m_n G_F^2}{\pi} \left( 0.29 + 0.21 \frac{E_{\mu}^2}{E_{\nu\mu}^2} \right).
\end{align}
For the number density of proton (neutron) in the rock, we use \(n_{p(n)}^{(\text{rock})} = 2.65 \times 10^{23}\) \((N_A = 6.022 \times 10^{23})\).
\(R(E_{\mu}, E_{\text{th}})\) is the distance a muon with \(E_{\mu}\) can travel inside the rock before losing energy below \(E_{\text{th}}\), and is fitted to be \textsuperscript{[34]}
\begin{equation}
R(E_{\mu}, E_{\text{th}} = 10\text{GeV}) = 10^{a+by+cy^2}(\text{km}),
\end{equation}
where \(y = \log_{10}(E_{\mu}/1\text{GeV})\), \(a = -3.29186\), \(b = 1.52594\), and \(c = -0.147224\).

Fig. \textsuperscript{3} shows the predictions for the neutrino-induced muon flux for the DM masses
\(M_{\psi_D} = 3, 2, 1.5, 1\) TeV (from above). We obtained the annihilation cross section in such
a way that each DM mass fits the PAMELA, Fermi and HESS data as described above.
We used the NFW (solid red curves) and the isothermal (dashed blue curves) profiles for
the plot. We can see that the 3 TeV DM is already ruled out by the SK bound because it
needs too large BF. The 2 TeV DM which fits the CR data best is only marginally allowed.

\textsuperscript{3}See also \textsuperscript{[1]} for the gamma-ray constraint.
0
5
10
15
20
25
30

Cone half angle from GC [deg]

Muon flux $[10^{-15}$ cm$^{-2}$ s$^{-1}$]

Figure 5: Thick solid red curves (thick dashed blue curves) are predictions of the neutrino-induced up-going muon flux from the annihilation of dark matter with masses 3, 2, 1.5, 1 TeV from above, for the NFW (isothermal) dark matter profile. The thin solid line is the superkamiokande bound.

The lower DMs are allowed with the NFW profile. However, if the isothermal profile is used, all the DM are allowed because this profile is flat near the Galactic center and the neutrinos are not much produced.

Fig. 6 shows the predictions for the gamma-ray flux from the Galactic center ($0.1^\circ$ region from the GC) $^{36}$ and the Galactic Center ridge ($|b| < 0.3^\circ, |l| < 0.8^\circ$) $^{37}$. We can see that the constraints on the DM annihilation for the NFW profile become more severe than in the neutrino case. That is the NFW predicts too much gamma-ray, exceeding even the current data for the massive DM. However, if more flat profile like the isothermal profile is used, the predictions are below the current data.

4. Collider Signatures

New particles in this model are $Z'$, $s$ (the modulus of $\phi$) and $\psi_D$. $Z'$ couples only to muon, tau or their neutrinos, or the $U(1)_{L_\mu-L_\tau}$ charged dark matter. The new scalar $s$ can mix with the SM Higgs boson $h_{SM}$, affecting the standard Higgs phenomenology.

Let us discuss first the decay of $Z'$ gauge boson and its productions at various colliders. In the broken phase with $M_{Z'} \neq 0$, $Z'$ can decay through the following channels:

$$Z' \rightarrow \mu^+\mu^-, \tau^+\tau^-, \nu_\alpha\bar{\nu}_\alpha \text{ (with } \alpha = \mu \text{ or } \tau), \psi_D \bar{\psi}_D,$$

if they are kinematically allowed. Since these decays occur through $U(1)_{L_\mu-L_\tau}$ gauge interaction, the branching ratios are completely fixed once particle masses are specified. In
Figure 6: The gamma ray flux from the GC (left panel) and GC ridge (right panel). Thick solid red curves (thick dashed blue curves) are predictions of the gamma ray flux from the annihilation of dark matter with masses 3, 2, 1.5, 1 TeV from above, for the NFW (isothermal) dark matter profile.

particular,

$$\Gamma(Z' \rightarrow \mu^+ \mu^-) = \Gamma(Z' \rightarrow \tau^+ \tau^-) = 2\Gamma(Z' \rightarrow \nu_\mu \bar{\nu}_\mu) = 2\Gamma(Z' \rightarrow \nu_\tau \bar{\nu}_\tau) = \Gamma(Z' \rightarrow \psi_D \bar{\psi}_D)$$

if $M_{Z'} \gg m_\mu, m_\tau, M_{DM}$. The total decay rate of $Z'$ is approximately given by

$$\Gamma_{tot}(Z') = \frac{\alpha'}{3} M_{Z'} \times 4(3) \approx \frac{4}{3} \frac{(\alpha')}{10^{-2}} \frac{M_{Z'}}{100 \text{GeV}}$$

if the channel $Z' \rightarrow \psi_D \bar{\psi}_D$ is open (or closed). Therefore $Z'$ will decay immediately inside the detector for a reasonable range of $\alpha'$ and $M_{Z'}$.

$Z'$ can be produced at a muon collider as resonances in the $\mu\mu$ or $\tau\tau$ channel via

$$\mu^+ \mu^- \rightarrow Z^* \rightarrow \mu^+ \mu^- (\tau^+ \tau^-).$$

The LHC can also observe the $Z'$ which gives the right amount of the relic density as can be seen in Fig. 1. Its signal is the excess of multi-muon (tau) events without the excess of multi-e events.

The dominant mechanisms of $Z'$ productions at available colliders are

$$q\bar{q} \text{ (or } e^+e^-) \rightarrow \gamma^*, Z^* \rightarrow \mu^+ \mu^- Z', \tau^+ \tau^- Z' \rightarrow Z^* \rightarrow \nu_\mu \bar{\nu}_\mu Z', \nu_\tau \bar{\nu}_\tau Z'$$

There are also vector boson fusion processes such as

$$W^+W^- \rightarrow \nu_\mu \bar{\nu}_\mu Z' \text{ (or } \mu^+ \mu^- Z'), \text{ etc.}$$

$$Z^0 Z^0 \rightarrow \nu_\mu \bar{\nu}_\mu Z' \text{ (or } \mu^+ \mu^- Z'), \text{ etc.}$$

$$W^+ Z^0 \rightarrow \nu_\mu \bar{\nu}_\mu Z' \text{ (or } \mu^+ \mu^- Z'), \text{ etc.}$$

and the channels with $\mu \rightarrow \tau$. We will ignore the vector boson fusion channels in this paper, since their contributions are expected to be subdominant to the $q\bar{q}$ or $e^+e^-$ annihilations.
In Fig. 1, we present the \( Z' \) production cross sections at B factories, \( Z^0 \) pole, LEP(2), Tevatron and LHC. We find that the light \( M_{Z'} \) region that can accommodate the muon \( (g - 2)_\mu \) is almost excluded by the current collider data. The remaining region can be covered at the LHC with high integrated luminosity \( \gtrsim 50 \) fb\(^{-1}\).

The signatures of \( Z' \) will be an \( s \)-channel resonance in the dimuon invariant mass spectrum, or its deviation from the SM predictions as in Drell-Yan production of the muon pair. Therefore one could expect that the number of multi-muon events at colliders is enhanced compared with the SM predictions. The \( e^+e^- \) channel will be diluted compared with the \( \mu^+\mu^- \) channel, since the \( e^+e^- \) final state in the \( Z' \) decay can appear only through the \( Z' \) decay into a tau pair and \( \tau \rightarrow e\nu\bar{\nu} \) in this model.

Now let us discuss the Higgs phenomenology in our model. In general, there can be a mixing between the SM Higgs boson \( h_{SM} \) and a new scalar \( s \) (the modulus of \( \phi \)) due to the \( \lambda_{H\phi} \) coupling in \((2.3)\). As a consequence, the Higgs searches at colliders can be quite different from those of the SM. For example, one can imagine

\[
\text{gg} \rightarrow h_{SM}^* \rightarrow s^* \rightarrow Z' Z',
\]

followed by \( Z' \rightarrow \mu^+\mu^-, \tau^+\tau^-, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau, \psi_D\bar{\psi}_D \). This makes an additional contribution to the \( Z' \) production at the LHC. However, we did not include this \( Z' \) pair production through gluon fusion in Fig. 1 for simplicity, since it depends on the unknown free parameter \( \lambda_{H\phi} \), and thus is more model dependent. In any case, the generic collider signatures of the new \( Z' \) are the excess of multi-muon or tau events, compared with the SM. It is strongly desirable to search for \( \mu\mu\mu\mu, \tau\tau\tau\tau, \) or \( \mu\mu\tau\tau \) or large missing \( E_T \) from \( \mu\mu\nu\nu \) events at LEP, LEP2, Tevatron and at the LHC.

We can introduce an angle \( \beta \) so that the ratio of two scalar VEV’s is given by \( \tan \beta = v_\phi/v_{h_{SM}} \), and an angle \( \alpha \) that parametrizes the mixing of \( h_{SM} \) and \( s \):

\[
h_{SM} = H_1 \cos \alpha - H_2 \sin \alpha, \quad s = H_1 \sin \alpha + H_2 \cos \alpha, \tag{4.1}
\]

where \( H_{1(2)} \) denotes the lighter (heavier) mass eigenstate of two scalars.

In Fig. 7, we show the branching ratios (BRs) of the two-body decay modes of \( H_{1,2} \) for \( M_{Z'} = 300 \) GeV. We have fixed \( M_{H_2} = 700 \) GeV \( (M_{H_1} = 150 \) GeV\) for the plots of the \( H_1 \) \( (H_2) \) decay \( [ \) the left (right) column \( ] \). Note that the modes \( H_{1,2} \rightarrow Z'Z' \) (solid blue) and \( H_2 \rightarrow H_1 H_1 \) (solid green), which are absent in the SM Higgs decay, can dominate for large \( \alpha \) and small \( \tan \beta \). If \( H_i \)'s and \( Z' \) are heavy enough compared with the CDM in our model, a decay \( H_i \rightarrow Z'Z' \) followed by one or both of the \( Z' \) decaying into a pair of CDM or a pair of neutrinos could occur. Therefore the Higgs could have somewhat large invisible branching ratio, compared with the SM Higgs boson. Therefore Higgs signatures at the Tevatron or the LHC could be quite exotic.

5. Conclusions

Recent possible anomalies in the cosmic ray data reported by PAMELA, Fermi-LAT and HESS Collaborations may be due to astrophysical origins such as pulsars. However, it is
Figure 7: In the left (right) column are shown the branching ratios of the lighter (heavier) Higgs $H_1(2)$ into two particles in the final states: $tt$ (solid in red), $bb$ (dashed red), $c\bar{c}$ (dotted red), $s\bar{s}$ (dot-dashed red), $\tau\bar{\tau}$ (solid orange), $\mu\bar{\mu}$ (dashed orange), $WW$ (dashed blue), $ZZ$ (dotted blue) and $Z'Z'$ (solid blue) for difference values of the mixing angle $\alpha$ and $\tan\beta$. We fixed $M_{Z'} = 300$ GeV. We also fixed $M_{H_2} = 700$ GeV ($M_{H_1} = 150$ GeV) for the plots of the left (right) column.

also tantalizing to consider them as the first hint for the existence of weakly interacting cold dark matter. In this paper, we considered a leptophilic CDM model with extra $U(1)_{L_{\mu} - L_{\tau}}$ gauge symmetry which is one of the anomaly free global symmetry in the SM. We have introduced a new complex scalar $\phi$ and Dirac fermion $\psi_D$ which are charged under the new $U(1)_{L_{\mu} - L_{\tau}}$. The $U(1)_{L_{\mu} - L_{\tau}}$ charged Dirac fermion $\psi_D$ can be a good CDM that might explain the positron excess reported by HEAT, PAMELA and FERMI, without producing excess in antiproton flux as observed by PAMELA. This model is constrained by the muon
(g − 2)µ and collider searches for a vector boson decaying into µ⁺µ⁻ at the Tevatron, LEP(2) and B factories. The collider constraints favors ψ_{DM} heavier than ∼ 100 GeV. We calculated the relic density of the CDM with these constraints, and still find that the thermal relic density could be easily within the WMAP range. We also considered the production cross section of the new gauge boson Z' at the LHC, which could be 1 fb –1000 fb. The new gauge boson Z' will decay into µ̅µ, τ̅τ, their neutrino partners or even to a pair of CDM’s. Therefore the final states will be rich in muons or taus, or missing E_T. Most parameter space of this model is within the discovery range at the LHC with enough integrated luminosity ≳ 50 fb⁻¹. It is remained to be seen whether there are excess in the multimuon or multitaus events at the Tevatron or at the LHC.

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