Constraining $U(1)_{L\mu - L\tau}$ charged dark matter model for muon $g - 2$ anomaly with AMS-02 electron and positron data

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Abstract. Very recently, the Fermi-Lab reported the new experimental combined results on the magnetic momentum of muon with a $4.2\sigma$ discrepancy compared with the expectation of the Standard Model [1]. A new light gauge boson $X$ in the $L_{\mu - L\tau}$ model provides a good explanation for the $g - 2$ anomaly. A Dirac fermion dark matter with a large $L_{\mu - L\tau}$ charge can explain both the $g - 2$ anomaly and the dark matter relic density [2]. In this work, we focus on the case that the mass of the dark matter is larger than the mass of muon (i.e. $m_{\Psi} > m_{\mu}$) for which the channel $\Psi\Psi \rightarrow \mu^-\mu^+$ opens. Although the cross section $(\sigma\nu)_{\mu^-\mu^+}$ is smaller by a factor of $1/q_{\Psi}^2$ ($q_{\Psi}$ represents the $L_{\mu - L\tau}$ charge of the dark matter) compared with the channel $\Psi\Psi \rightarrow XX \rightarrow \nu\bar{\nu}\bar{\nu}\bar{\nu}$, the resulting secondary electrons and positrons could imprint on their spectra above GeV energies due to the reacceleration effect of cosmic ray propagation. We use the AMS-02 measurements of electrons and positrons to constrain the annihilation cross section of the channel $\Psi\Psi \rightarrow \mu^-\mu^+$, which rules out part of the parameter space of the large $L_{\mu - L\tau}$ charged dark matter model to account for the muon $g - 2$ anomaly.

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1 Introduction

Over the past decades, the Standard Model (SM) of particle physics achieved a great success. However, it still faces severe challenges when confronting some experimental anomalies, such as the dark matter (DM), the mass of neutrinos, and the muon $g-2$ anomaly [3–5]. Recently, the Fermi-lab reported a combined 4.2σ discrepancy of the muon $g-2$ measurement from the SM prediction [1]. Such a tension raises a big challenge to the SM. Many models containing new interactions with the muon sector were proposed to explain this tension [5–15]. The $U(1)_{L\mu-L\tau}$ model, which assumes a local gauge symmetry, provides naturally a gauge boson $X$ to interact with the muon and can account for the $g-2$ anomaly [16–19]. This well-studied $L\mu-L\tau$ model with an MeV scale boson could also avoid the constraints from other experiments [20–24].

The $L\mu-L\tau$ model has also been widely studied to explain the relic density of DM, the mass of neutrinos, and the Galactic centre gamma ray excess [25–29]. However, usually a heavy mass of $X$ is needed which was inconsistent with other experiments [20, 21, 24]. Recently, ref. [2] proposed an SM singlet Dirac DM ($\Psi$) model with an $L\mu-L\tau$ charge $q_{\Psi}$. Distinct from the large mass of $O(10^3)$ GeV of $X$ and DM required to explain the relic density in [25, 26], this additional $q_{\Psi}$ parameter can explain the DM relic density with much lighter $X$ and DM particles. The cross section for $\Psi\Psi \rightarrow \mu^+\mu^-$ is smaller than $\Psi\Psi \rightarrow XX \rightarrow \nu\bar{\nu}\nu\bar{\nu}$ by a factor $q_{\Psi}^2$ for $m_{\Psi} > m_X$. The free parameter $q_{\Psi}$ opens a new window to explain both the $g-2$ anomaly and the DM relic density, which is also consistent with other experiment limits.

Following [2], we focus on the case $m_{\Psi} > m_\mu > m_X$, in which the channel $\Psi\Psi \rightarrow \mu^+\mu^-$ opens for the non-relativistic DM. Although the mass of DM can be small (e.g., <GeV), we argue that the secondary positrons and electrons from DM annihilation could also have a non-negligible effect on the GeV cosmic electron and positron spectrum due to the reacceleration effect, which can thus be probed by space-based detector like AMS-02. Parts of the parameter space to explain both the DM relic density and $g-2$ anomaly would be ruled out when considering the limits from AMS-02 data.

This work is organized as follows: in section 2, we introduce the $U(1)_{L\mu-L\tau}$ model that we used. In section 3 we briefly describe the propagation and background of electrons and...
positrons. In section 4, we set our constraints using the AMS-02 data. We conclude this work in section 5.

2 $L_\mu - L_\tau$ model

In this work, we have considered an extension of the SM with a simple extra local $U(1)_{L_\mu - L_\tau}$ symmetry to the SM Lagrangian. Therefore, the Lagrangian remains invariant under the $SU(3)_c \times SU(2)_L \times U(1)$ gauge symmetry. The DM considered here contains an additional charge $q_\Psi$. The charge $q_\Psi$ for muon (tau) is +1(-1) [2]. Although this large charge $q_\Psi$ seems unnatural for the theory, it is allowed phenomenologically. The Lagrangian is

$$
\mathcal{L} = \mathcal{L}_{\text{SM}} - g_X X_\lambda (\bar{\mu} \gamma^\lambda \mu - \bar{\tau} \gamma^\lambda \tau + \nu_{\mu L} \gamma^\lambda \nu_{\mu L} - \nu_{\tau L} \gamma^\lambda \nu_{\tau L}) - \frac{1}{4} X_{\mu \nu} X^{\mu \nu} + \frac{1}{2} m_X^2 X_\mu X^\mu \\
+ \bar{\Psi}(i \not\partial - m_\Psi) \Psi - q_\Psi g_X X_\lambda \bar{\Psi} \gamma^\lambda \Psi,
$$

(2.1)

where $X_\mu$ and $\Psi$ denotes the $U(1)_{L_\mu - L_\tau}$ gauge boson and Dirac DM, $X^{\mu \nu}$ is the field strength of $X_\mu$. We have ignored the kinetic mixing and the right-hand neutrino terms since they are irrelevant for our phenomenological discussion below. Therefore we have four free parameters in this model: $m_X, g_X, m_\Psi, q_\Psi$.

The new combined result on the magnetic moment of muon measured by the Fermi-Lab shows a 4.2 $\sigma$ deviation from the SM

$$
\Delta a_\mu = a_\mu^{\text{exp}} - a_\mu^{\text{SM}} = 251 \pm 59 \times 10^{-11}
$$

(2.2)

The new gauge boson $X$ could contribute to an extra magnetic moment of muon $a_\mu$. The one-loop contribution is

$$
\Delta a_\mu^X = \frac{g_X^2}{8 \pi^2} \int_0^1 dx \frac{2 m_\mu^2 x^2 (1 - x)}{x^2 m_\mu^2 + (1 - x) m_X^2}.
$$

(2.3)

As discussed in [2, 5], with $g_X \sim 10^{-4}$ and $m_X \sim O(10)$ MeV, this gauge boson $X$ could explain the $g - 2$ anomaly and avoid the current experimental limits (see figure 1 in [2] and figure 32 in [5]).

In this work, we focus on the case of $m_\Psi > m_\mu > m_X$. Thus DM could annihilate through $\Psi \Psi \rightarrow XX$ process following with $X \rightarrow \nu \bar{\nu}$. The cross section of the process contributes to the most DM abundance is

$$
(\sigma v)_{XX} = \frac{(q_\Psi g_X)^4}{4 \pi m_\Psi} \frac{(m_\Psi^2 - m_X^2)^{3/2}}{(2 m_\Psi^2 - m_X^2)^2}.
$$

(2.4)

This cross section is related to the s-channel process $\Psi \Psi \rightarrow \mu \mu$ (for $m_X \ll m_\Psi$) as

$$
(\sigma v)_{\mu^- \mu^+} = \frac{[1 + m_\mu^2/(2 m_\Psi^2)](1 - m_\mu^2/m_\Psi^2)^{1/2}}{q_\Psi^2} \times (\sigma v)_{XX}.
$$

(2.5)

Roughly $(\sigma v)_{\mu^- \mu^+}$ is $q_\Psi^2$ smaller than $(\sigma v)_{XX}$. The additional parameter $q_\Psi$ is helpful to explain the DM abundance. Annihilation of DM into charged particles and photons is constrained by CMB observation since it increases the ionization fraction and changes the CMB anisotropies. Previous work show the constraints are about $f_{\text{eff}}^{(\sigma v)} <$
4.1 \times 10^{-28} \text{cm}^3/\text{s/GeV} \text{[30, 31]}, \text{where } f_{\text{eff}} \text{ is the weighted efficiency factor. In this work, we choose } f_{\text{eff}} = 0.08 \text{ and } f_{\text{eff}} = 1 \text{ to represent the conservative and progressive limits i.e. } (\sigma v)_{ff}/(2m_{\Psi}) \leq 5.1 \times 10^{-27} \text{ cm}^3 \text{s}^{-1} \text{ GeV}^{-1} \text{ and } (\sigma v)_{ff}/(2m_{\Psi}) \leq 4.1 \times 10^{-28} \text{ cm}^3 \text{s}^{-1} \text{ GeV}^{-1} \text{[30, 31]} \text{. In this work, we employ MICROmegas [32] to calculate the DM relic density. The constraint we used is } 0.1199 - 0.0027 < \Omega_{\chi} < 0.1199 + 0.0027 \text{[33]. Therefore } g_{\Psi} \text{ needs to be large enough that the dominating channel } \Psi \Psi \rightarrow XX \rightarrow \nu \bar{\nu} \text{ could reach the value required to give the correct DM abundance and the } \Psi \Psi \rightarrow ff \text{ channel is consistent with the CMB limits.}

In the case } m_{\Psi} > m_{\mu}, \text{ the non-relativistic } \Psi \text{ would also annihilate into } \mu \bar{\mu} \text{ in the Milky Way and contribute to the spectrum of cosmic ray electrons and positrons. After reacceleration in the propagation, the sub-GeV } e^+ e^- \text{ could be accelerated to higher energies [35], which are detectable for the space-based experiments like AMS-02.}

## 3 Cosmic ray electrons and positrons

### 3.1 Propagation

Cosmic ray electrons and positrons propagate diffusively in the Galaxy. Numerical tools have been developed to calculate the propagation of cosmic rays, such as GALPROP [36] and DRAGON [37]. In this work we adopt the LikeDM code [38] to calculate the propagation process. This package employs a Green’s function method based on numerical tables obtained with GALPROP for given distribution of the source. This method has been verified to be a good approximation to the GALPROP result, and is much more efficient. The propagation framework is assumed to be diffusion plus reacceleration, which was found to be well consistent with the secondary and primary nuclei measured by AMS-02 [39, 40]. The propagation parameters we used include the diffusion coefficient \( D(E) = \beta D_0(E/4 \text{ GeV})^\delta \), the Alfvénic speed \( v_a \) which characterizes the reacceleration effect [41] and the characteristic height of the cosmic ray extended halo \( z_h \). We use six different groups of propagation parameters to show the effects on our result. The propagation parameters we used are shown in table 1. These sets of propagation parameters are widely adopted as the canonical “medium” parameters.

Low-energy cosmic rays are affected by the solar modulation [42–44]. We adopt the simple force-field approximation with the modulation potential to calculate this effect [45]. We vary the modulation potential from 0.6 GV to 0.8 GV to show the effect on our result. For

| \( D_0^a \) \((10^{28} \text{ cm}^2 \text{s}^{-1})\) | \( z_h \) \((\text{kpc})\) | \( v_A \) \((\text{km} \text{s}^{-1})\) | \( \delta \) |
|---|---|---|---|
| 1 | 2.7 | 2 | 35.0 |
| 2 | 5.3 | 4 | 33.5 |
| 3 | 7.1 | 6 | 31.1 |
| 4 | 8.3 | 8 | 29.5 |
| 5 | 9.4 | 10 | 28.6 |
| 6 | 10.0 | 15 | 26.3 |

Diffusion coefficient at } R=4\text{GV.}

Table 1. Propagation parameters.
the DM density profile, we adopt the typical NFW, Einasto and isothermal distribution [46–48] with local density $\rho_0 = 0.3$ GeV cm$^{-3}$ [49]. The injected $e^+e^-$ spectrum from $\Psi\Psi \rightarrow \mu^-\mu^+$ is calculated using the PPPC4 package [50].

Figure 1 shows the $e^- + e^+$ spectrum after the propagation, for $m_\Psi = 0.2$ GeV and $(\sigma v)_{\mu^-\mu^+} = 3 \times 10^{-26}$ cm$^3$ s$^{-1}$. The AMS-02 measurements are also shown for comparison [51]. We can see that the reacceleration effect accelerate electrons and positrons to higher energies than $m_\Psi$.

### 3.2 Background

The actual astrophysical background is quiet complicated, which includes both the primary electrons from e.g., supernova remnants and pulsar, and the secondary electrons and positrons from the inelastic collisions between cosmic ray nuclei and the medium. In this work, we discuss two approaches of the cosmic backgrounds [53].

#### 3.2.1 Phenomenological background

Since we focus on the spectral features which are distinct from the “smooth” background, it is reasonable to fit the majority of the observational spectra by the background [43, 52]. We adopt the background model in [53], which includes three components, the primary $e^-$, secondary $e^-e^+$, and an extra source term of $e^-e^+$, i.e.,

$$\phi_{e^-} = C_{e^-}E^{-\gamma_{e^-}} \left[1 + \left(\frac{E}{E_{br}^{-e^-}}\right)^{\gamma_{e^-}}\right]^{-1} \exp(-E/E_{c}^{-e^-}),$$

$$\phi_{e^+} = C_{e^+}E^{-\gamma_{e^+}} \left[1 + \left(\frac{E}{E_{br}^{e^+}}\right)^{\gamma_{e^+}}\right]^{-1},$$

$$\phi_{s} = C_s E^{-\gamma_{s}} \exp(-E/E_{c}^{s}).$$

The total background energy spectrum of $e^- + e^+$ is

$$\phi_{bkg,e^{\pm}} = \phi_{e^-} + 1.6\phi_{e^+} + 2\phi_{s},$$

where the factor 1.6 is due to the asymmetry of the $e^+$ and $e^-$ production in $pp$ collisions [54]. The best-fit parameters we adopt are shown in 2 as the prior [38]. These best-fit background
parameters are not fixed when we add the DM contribution. Instead, we allow some freedom of the backgrounds to get a global best-fit to the data. We multiply factors $\alpha_i E^\beta_i$, with $i=e^-, e^+, s$, on $\phi^e_-, \phi^e_+$, and $\phi_s$. When we adopt the profile likelihood method to fit the data with the DM model, we scan the adjustment factors $\alpha_i$ and $\beta_i$ with ranges $[0.1, 10]$ and $[-0.5, 0.5]$. These factors mimics the main uncertainties in astrophysical produced by the Fermi mechanism of acceleration, that typically generates power-law spectra [55]. These adjustment factors $\alpha_i$ and $\beta_i$ make sure our background is flexible before we add the DM model. Such fitting method has been adopt in the previous work [38, 53, 55].

3.2.2 Physical background

Another way to calculate a more physical background provides the injection spectrum of different components of sources, and calculate the propagation of them. Here we assume a three-segment broken power-low model with an exponential cutoff for the injection spectrum of primary electrons. The first break at several GeV is to account for the low-energy data, and the second break at several tens GeV is to explain the spectral hardening, and the cutoff is to reproduce the high-energy data which actually affect little for the energy range we consider about [56–58]. The injection spectrum of primary electrons is

$$\Phi_{e^-} = A_{e^-} E^{-\nu_{e^-}} \left[ 1 + \left( E/E_{br1}^{e^-} \right)^3 \right]^{(\nu_{e^-} - \nu_{2}^{-})/3} \times \left[ 1 + \left( E/E_{br2}^{e^-} \right)^3 \right]^{(\nu_{2}^{-} - \nu_{3}^{-})/3} \exp \left( -E/E_{c}^{e^-} \right).$$

(3.5)

The secondary positron spectrum from pp collisions is calculated by the GALPROP code. A constant factor is multiplied to its flux during the fitting, which accounts for possible uncertainties of the theoretical prediction [59].

The contribution of the pulsar is also considered in this model, which is described by an exponential cutoff power law

$$\Phi_{psr} = A_{psr} E^{-\nu_{psr}} \exp \left( -E/E_{c}^{psr} \right).$$

(3.6)

The spatial distribution of pulsars is adopted to be the same as the primary cosmic ray source distribution [36]. Each parameters is also corresponds to an adjustment factor for a global best-fit.

4 Results

We use a maximum likelihood fitting to constrain the DM component. The data used include the AMS-02 positron fraction [60] and the total electron plus positron flux [51]. Assuming the DM annihilates to $\mu^-\mu^+$ in the Milky Way halo, we calculate the $\chi^2$ ($\chi^2$) without (with)
the DM contribution. $\chi^2$ with the DM contribution is a global fit result of the adjustment factors as the variables. While $\chi^2_0$ fits with only the phenomenological/physical background contribution. We set the 2$\sigma$ upper limits on the DM annihilation cross section through setting $\Delta\chi^2 = \chi^2 - \chi^2_0 > 2.71$. The results are shown in figure 2. The limits on the $(\sigma v)_{\mu^-\mu^+}$ change from $10^{-28}$ cm$^3$ s$^{-1}$ to $10^{-27}$ cm$^3$ s$^{-1}$ dependent on the propagation parameters, different background choice, DM density distribution and solar modulation. The fiducial choice used is the second propagation parameters in table I, the NFW profile and 0.6 GV solar modulation when each model is varied. All constraints are more stringent than the conservative CMB limits while as strong as the progressive one. Higher solar modulation potential give a stronger effect in subGeV. Thus the limits are stronger for the lower solar modulation potential. Propagation parameters show little effects on the results and Einasto DM density distribution give the strongest limits. Since the phenomenological background describes the electron/positron spectrum better than the physical background and the pulsar contribution is partly degenerate with the DM contribution, the phenomenological background give a better constraint than the physical background. It needs to note that our results are roughly one order stronger than the results in [35]. This is because we have involved the primary electron background by choosing the phenomenological smooth background or the physical one order stronger than the results in [35]. They only calculated the contribution from secondary components and DM, which derives a weaker constraint.

When we considering the $L_\mu - L_\tau$ model, following [2], we scan the parameters $m_X$ and $g_X$ for any given $m_\Psi$ and $q_\Psi$ to make sure these parameters are consistent with the current limits such as Borexino [23], CHARM [22], BABAR [20] and CCFR [21]. The allowed parameter space is shown as figure 1 in [2]. For a given $m_\Psi$ and $q_\Psi$, We can scan the parameters $m_X$ and $g_X$ in the allowed parameter space and calculate the $(\sigma v)_X$ to test whether the parameters can explain the DM abundance. The results are shown in figure 3. We find that the parameters with $110\text{MeV}<m_\Psi<400\text{MeV}(180\text{MeV})$ that can explain simultaneously the $g-2$ anomaly and the DM abundance are partly excluded by the AMS-02 data with the phenomenological (physical) background. The limits from AMS-02 are more stringent in the low mass range. For the $g-2$ anomaly and DM abundance favored regions (red regions), $q_\Psi$ is smaller for lighter DM, and thus the $q_\Psi^{-2}$ suppression factor of $(\sigma v)_{\mu^-\mu^+}$ to $(\sigma v)_X$ is bigger. For the same value $(\sigma v)_X$ to explain the relic density, $(\sigma v)_{\mu^-\mu^+}$ is larger, and hence the AMS-02 constraint is more stringent. The constraints from CMB are also shown, for both the conservative and progressive limits. Since the progressive constraint is as strong as the AMS-02 constraint (see in Fig 2), their exclusion regions are quite similar as expected. While the conservative constraint is much weaker, thus it can not exclude any $g-2$ anomaly favored regions.

5 Conclusion

The $\text{U}(1)_{L_\mu-L_\tau}$ with an MeV scale gauge boson $X$ could explain the $g-2$ anomaly well and avoid the limits from other experiments. A large charged DM that is heavier than the muon and $X$ particle could explain the DM abundance and also escape the constraints from the CMB. In this work, we use the AMS-02 electron and positron data to constrain this anomaly well.
The 2σ upper limits on the DM annihilation cross section $(σv)_{µ^-µ^+}$ through the process $ΨΨ → µ^-µ^+$ as a function of DM mass (from 110 MeV to 2 GeV). (a) shows the effects of the propagation parameters, in which the propagation parameters are shown in table 1, the DM density distribution is NFW and solar modulation potential is 0.6 GV. The physical background result is also shown in purple. (b) shows the effects of the DM density distribution. Halo 1,2,3 represent NFW, Einasto and isothermal distribution. The propagation parameters is the second in table 1 and solar modulation potential is 0.6 GV. (c) shows the effects of solar modulation. Solar modulation potential is adopt as 0.6 GV, 0.7 GV and 0.8 GV. The propagation parameters is the second one and the DM density distribution is NFW. The conservative and progressive CMB limits are also shown.
Figure 3. The parameter space in the plane of $m_{\Psi}$ and $q_{\Psi}$. The red (light red) region is favored by the $g-2$ at 1$\sigma$ (2$\sigma$) confidence level together with the DM relic abundance. The shaded blue(green) region is ruled out by the AMS-02 electron and positron spectra with the phenomenological(physical) background (We adopt the NFW DM density distribution. The propagation parameters are the second one and the solar modulation potential is 0.6 GV). The conservative(progressive) CMB limits are shown in gray(orange), while the progressive CMB limits are much overlapped with the phenomenological background AMS-02 limits.

model. By means of the reacceleration effect of electrons and positrons in the Milky Way, low-energy electrons and positrons can be accelerated to the AMS-02 energy range, and can thus be strongly constrained. The limits for $(\sigma v)_{\mu^-\mu^+}$ could be down to $\sim 10^{-29}$ cm$^3$ s$^{-1}$ ($\sim 10^{-28}$ cm$^3$ s$^{-1}$) for phenomenological(physical) background, although the DM density distribution and solar modulation affect the result. Part of the parameter region to account for the $g-2$ anomaly can also be excluded.

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