AMS-02 positron excess and indirect detection of three-body decaying dark matter

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Abstract. We consider indirect detection of meta-stable dark matter particles decaying into a stable neutral particle and a pair of standard model fermions. Due to the softer energy spectra from the three-body decay, such models could potentially explain the AMS-02 positron excess without being constrained by the Fermi-LAT gamma-ray data and the cosmic ray anti-proton measurements. We scrutinize over different final state fermions, paying special attention to handling of the cosmic ray background and including various contributions from cosmic ray propagation with the help of the LIKEDM package. It is found that primary decays into an electron-positron pair and a stable neutral particle could give rise to the AMS-02 positron excess and, at the same time, stay unscathed against the gamma-ray and anti-proton constraints. Decays to a muon pair or a mixed flavor electron-muon pair may also be viable depending on the propagation models. Decays to all other standard model fermions are severely disfavored.

Keywords: cosmic ray theory, dark matter theory, gamma ray theory

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1 Introduction

Although the gravitational evidence of the existence of Dark Matter (DM) is cogent, the direct detection of DM particles is still far from conclusive. Nevertheless, several indirect detection experiments reveal intriguing excesses in the cosmic ray (CR) positron ratio $e^+/e^+ + e^-$ [1–6] and electron (or $e^+ + e^-$) spectra [7–10], which can not be easily accounted for with conventional astrophysical backgrounds. The excess could result from additional astrophysical sources, for example supernova remnants, pulsars or primary cosmic rays interacting with the interstellar medium [11–17]. Alternatively, the DM annihilation or decay may also explain this result (see e.g., the reviews [18–20]).

Models of annihilating DM usually requires large enhancement on the annihilation cross section [21–28], which can be realized via, for example, the Sommerfeld enhancement [29–32] or the Breit-Wigner enhancement [33, 34]. In particular, these models also generate $\gamma$-rays from, for instance, the prompt radiation and the secondary inverse Compton (IC) scattering of $e^\pm$ with the photon background, as well as anti-protons from the final state hadronization. The strong constraints from PAMELA anti-proton and Fermi-LAT $\gamma$-ray have disfavored the DM annihilation as the explanation of the excesses [25, 35–40].

In contrast, decaying DM does not require a large boost factor as long as the decay lifetime is around $10^{26}$ to $10^{27}$ seconds [41–50], depending on the DM mass and decay channels. The $\gamma$-ray bound, nevertheless, still applies in this case and has ruled out many decaying DM models based on two-body decays [51–55]. On the other hand, there exists a class of decaying DM models which features three-body final states and, therefore, has softer decay spectra compared to that of the two-body decay. This class of models can be further categorized, based on final states, into two cases: all final states being standard model (SM) particles (for example, refs. [47, 56–59]) or one of the decay products is an absolutely stable neutral
particle and thus invisible [60–62]. The constraints on the former case have been investigated in refs. [47, 59, 63, 64] and the constraints on the latter case were studied in ref. [65]. In particular, the conclusion of ref. [65] was that, while certain decay modes are strongly disfavored and part of the parameter spaces are ruled out, it is still possible to explain the electron/positron excesses within the constraints.

Given the new measurements of the positron and electron data by AMS-02 [4, 5, 9, 10] and the extragalactic $\gamma$-ray background (EGB) by Fermi-LAT [66], in this work we update the analysis done in ref. [65] and consider decay channels, such as the mixed-flavor final states, that were not considered previously. In particular, we improve the analysis by adopting a more general statistical approach in dealing with the astrophysical background of CRs. For example, parameters in the astrophysical background are treated as nuisance parameters in scanning over the DM parameter space to fit the experimental data. Along the way we also examine whether the decaying DM model can give rise to the recently reported $\gamma$-ray excess at the Galactic center (GC; [67–81]). It turns out that the positron excess and GC $\gamma$-ray excess may not be explained by a single DM component simultaneously due to different energy scales associated with them. Therefore, we treat the $\gamma$-ray data as a constraint, instead of trying to explain it.

The paper is organized as follows. We briefly describe the three-body decaying DM model in section 2. Then we fit the positron CR data to derive the best-fit DM model parameters in section 3. The constraints on the model from the EGB and the $\gamma$-ray emission from the GC are discussed in sections 4 and 5, respectively. Finally we conclude in section 6.

2 Three-body dark matter decays

A meta-stable DM particle decaying to an absolutely stable neutral particle plus a pair of SM particles can occur naturally in supersymmetric theories with conserved $R$-parity. An example is in models with Dirac neutrino masses, a heavier right-handed sneutrino can have a long lifetime of decaying to a lighter right-handed sneutrino with a pair of SM leptons due to the small Yukawa couplings [60, 61]. Another possibility is that if supersymmetry (SUSY) is spontaneously broken in multiple sequestered sectors, then in each SUSY breaking sector there exists a goldstino. Only one linear combination of them is absorbed and becomes the longitudinal component of the gravitino. The other goldstini acquire masses through supergravity effects [82]. If the lightest supersymmetric particle is the gravitino and the next lightest supersymmetric particle is a goldstino, the goldstino decays through dimension-8 operators to three-body final states of one gravitino and a pair of SM particles. It could naturally be long-lived and cosmologically stable [62].

In the following we discuss the primary and secondary energy spectra from models of such three-body decays, where a long-lived DM particle decays into a pair of SM fermions and a stable neutral particle.

2.1 Spectra of three-body dark matter decays

We denote the decaying DM particle by $\chi$, which decays to a stable neutral particle $\chi'$ and a pair of SM fermions $\bar{ff}$. To explain the excesses in the CR electron and positron data, $m_\chi - m_{\chi'}$ needs to be roughly $\mathcal{O}(\text{TeV})$. We therefore expect $m_\chi \sim m_{\chi'} \sim \mathcal{O}(\text{TeV})$ and the masses of the SM fermions are negligible compared with the energy scale of interest. The differential decay widths of the fermion and the anti-fermion are identical. We can define the
Figure 1. Primary spectrum (left), secondary electron (central) and photon (right) spectrum.

The normalized differential decay width as

\[
\frac{dW_f}{dE_f} = \frac{1}{\Gamma} \frac{d\Gamma}{dE_f},
\]  

where \(\Gamma\) is the partial decay width of \(\chi\) to \(\chi'\) and \(E_f\) is the energy of the SM fermion \(f\).

If \(f\) is electron, then its spectrum from the decay is simply \(dW_e/dE_e\). On the other hand, if DM decays 100\% into \(\mu^+\) and \(\chi'\), then the electron spectrum per DM decay is

\[
\frac{dN}{dE_e} (E'_e) = \int_{E'_e}^{E'_\mu} dE'_\mu \frac{dW_{\mu}}{dE_{\mu}} (E'_\mu) \frac{dN_{\mu}}{dE_{\mu}} (E_{\mu}, E'_e),
\]

where \(dN/dE_e (E'_e, E'_\mu)\) is the electron spectrum from the \(\mu\) decay with energy \(E'_\mu\), and

\[
E'^\mu_{\max} = \frac{m^2_{\chi'} - m^2_{\chi}}{2m_{\chi}}.
\]

Ref. [65] considered many different three-body DM decay models, parametrized by different higher-dimensional operators. Here we compare the primary and secondary spectra of three cases: a fermion DM with \(\chi' \gamma^5 \chi f f\), a scalar DM with \(\chi (\chi')^* f f\), and the goldstino decay. We use the tables given in ref. [83] to compute the energy spectrum of electrons/positrons, anti-protons, and photons which come from the decay or hadronization of the fermion pair.

The left panel of figure 1 shows the primary decay spectrum when the decaying DM is the goldstino (black), a scalar (red) and a fermion (blue). The dashed and solid lines correspond to \(m_{\chi} = 1\) and \(2\) TeV, respectively, with \(m_{\chi} - m_{\chi'}\) fixed to be 1 TeV. The goldstino decay featuring derivative couplings has the hardest spectrum, while that of the fermionic DM with axial couplings is the flattest. The center and right panel display the secondary electron and photon spectrum from final state radiation, using the decay \(\chi \rightarrow \chi' \mu^+ \mu^-\) as the example. Although the primary spectra show some variations for the three types of interactions, the resulting electron and photon spectra are quite similar except for the peak region around 300 GeV, where both AMS-02 positron and Fermi-LAT \(\gamma\)-ray data exhibit large uncertainties.

Given the similarities of the spectra from different models, in this work we will use the intermediate energy spectrum, i.e., scalar DM with the scalar-type interaction \(\chi (\chi')^* f f\), as a representative case for data analysis rather than studying all kinds of interactions.
2.2 Scalar DM $\chi(\chi')^* \bar{f}f$

The three-body decay of scalar DM can be parametrized by an effective operator $\frac{1}{\Lambda_\chi}\chi(\chi')^* \bar{f}f$, where $f$ is the SM fermion. The cut-off scale $\Lambda_\chi$ is treated as a free parameter as long as $\Lambda_\chi$ is larger than $m_\chi$ and $m_{\chi'}$. From the effective operator, the differential decay width into the SM fermion pair, $\bar{f}f$, reads
\[
\frac{d\Gamma}{dE_f} = \frac{E_f^2}{32\pi^3 m_f^2 \Lambda_\chi^2} \left( \frac{2m_\chi E_f - m_\chi^2 + m_{\chi'}^2}{(m_\chi - 2E_f)^2} \right)^2.
\] (2.4)

The total decay width is
\[
\Gamma = \frac{m_\chi^3}{768\pi^3 \Lambda_\chi^2} \left[ 1 + 9r^2 - 9r^4 + 12r^2 (1 + r^2) \log(r) \right],
\] (2.5)
where $r \equiv m_{\chi'}/m_\chi$.

The model has three parameters: $m_\chi$, $m_{\chi'}$, and $\Lambda_\chi$. The production rate of SM particles from DM decays mainly depends on $m_\chi \tau$, where $\tau = 1/\Gamma$ is the lifetime of the DM particle $\chi$. The spectral shape of cosmic ray particles, on the other hand, is most sensitive to the DM mass difference $\Delta m_\chi = m_\chi - m_{\chi'}$. The dependence of the final cosmic ray spectra on the other combination of parameters is mild. Therefore we will focus on the two parameters, $m_\chi \tau$ and $\Delta m_\chi$, in our data fitting.

3 Fitting to the charged CR data

To infer the best-fit values of the parameters for the three-body decaying DM, we fit to the positron fraction [5], the total $e^+e^-$ spectra [10], and the anti-proton spectrum [84] measured by AMS-02. For the constraints on the DM parameters using the preliminary AMS-02 anti-proton data, see [85–87]. Note that anti-protons can also be produced via electroweak radiative corrections even the decay products are leptons [88]. This effect has also been included in the fittings.

The density profile of the DM is assumed to be the Navarro-Frenk-White profile [89]
\[
\rho(r) = \frac{\rho_s}{(r/r_s)(1 + r/r_s)^2}
\] (3.1)
with $r_s = 20$ kpc and $\rho_s = 0.35$ GeV cm$^{-3}$ which gives a local density of $\sim 0.4$ GeV cm$^{-3}$. The electron/positron (or anti-proton) source function before propagation is
\[
q(E, x) = \frac{1}{m_\chi \tau} \left( \sum_i B_i \frac{dN}{dE_i} \right) \times \rho(x),
\] (3.2)
where $\tau$ is the lifetime of the DM particle. The parameter $B_i$ is the branching ratio of decay channel $i$, $dN/dE_i$ is the production spectrum of the $e^+e^-$ (or $\bar{p}$) for channel $i$, and the summation is over all decay channels producing $e^+e^-$ (or $\bar{p}$).

The propagation of electrons/positrons and anti-protons in the Milky Way is based on the numerical tool GALPROP [90, 91]. We adopt a fast approach using the so-called “Green’s function” method which has been used in the LiKEDM package [92]. Given the spatial distribution of the CR sources, the Green’s function of “$\delta$-function” kernels for a
The diffusion coefficient is defined as $D(R) = D_0 (R/4\text{GV})^\delta$, with $R$ being the rigidity of particles.

| No. | $D_0^*$ | $\delta^*$ | $z_h$ | $v_A$ |
|-----|----------|------------|-------|-------|
|     | $(10^{28}\text{cm}^2\text{s}^{-1})$ | | (kpc) | (km s$^{-1}$) |
| 1   | 2.7      | 0.33       | 2     | 35.0  |
| 2   | 5.3      | **0.33**   | 4     | **33.5** |
| 6   | 10.0     | 0.33       | 15    | 26.3  |

* The diffusion coefficient is defined as $D(R) = D_0 (R/4\text{GV})^\delta$, with $R$ being the rigidity of particles.

**Table 1.** Propagation parameters.

A series of energies are computed using GALPROP. Then the final propagated spectrum of any injection spectrum can be simply obtained via a weighted summation of the Green’s functions, where the weights are the coefficients of the kernels used to match the injection spectrum. We compute tables of the Green’s functions for various propagation parameters and source distributions (including DM annihilation and decay, as well as background CR source). For more details we refer the readers to ref. [92]. In this work we adopt the diffusive reacceleration propagation model. As a benchmark parameter setting (shown in bold in table 1), we adopt the second group of propagation parameters given in ref. [93]. To get an idea about the possible uncertainties of the propagation parameters, we will also consider the 1st and 6th groups of propagation parameters in ref. [93], which have $z_h = 2$ and 15 kpc and roughly correspond to the minimum (MIN) and maximum (MAX) propagation halos [94, 95]. The detailed propagation parameters are given in table 1.

The backgrounds include primary electrons from CR acceleration sources, and secondary electrons/positrons and anti-protons from interactions between primary CR nuclei and the interstellar medium. The injection spectra of CR nuclei and electrons are assumed to be three-segment broken power-law functions [96, 97]. The injection spectral parameters of primary electrons are determined simultaneously together with the DM parameters in the global fitting. The power-law indices and break rigidities of nuclei are determined by fitting to the measured proton spectra [98, 99], which can be found in ref. [97]. Given the primary nuclei spectra, the secondary $e^+ e^-$ and $\bar{p}$ fluxes can then be obtained. However, they can not be predicted precisely enough due to the following uncertainties: 1) the propagation parameters are determined by the Boron-to-Carbon ratios which have uncertainties, 2) there are uncertainties of the hadronic interaction cross sections to produce positrons and antiprotons, and 3) there could be large fluctuations of the electron/positron intensities in the Milky Way due to their shorter propagation ranges than nuclei. To take into account such uncertainties in predicting the secondary $e^+ e^-$ and $\bar{p}$ fluxes, we assume two free re-scaling constants $\alpha_e$ and $\alpha_{\bar{p}b}$ in the fitting. Note that in principle some of those uncertainties could be energy-dependent, and hence the renormalization factors may not simply be constant. For simplicity, we will not pursue this complication here.

The low energy charged particles are modulated by the solar wind and its associated magnetic field after they enter the heliosphere. This solar modulation effect depends on the solar activities and varies in the solar cycle. In this work we treat the modulation effect by the force-field approximation [100], with two modulation potentials $\Phi_e$ and $\Phi_{\bar{p}b}$ for $e^+ e^-$ and $\bar{p}$, respectively.

The DM contribution depends on three model parameters. However, as we argued in section 2, the total flux mostly depends on $m_\chi \tau$ and the spectra of the electrons and
positrons depend mostly on $\Delta m_\chi$. To reduce the number of free parameters and to extract the most relevant information, we simply fix $m_\chi' = 1\,\text{TeV}$ in our fitting. In total, we have 12 parameters in fitting the spectra: 6 for primary electrons (three power-law indices, two break rigidities, and one normalization), 2 for normalizations of secondary $e^+e^-$ and $\bar{p}$, 2 for solar modulation, and 2 for the DM ($m_\chi\tau$, $\Delta m_\chi$). We use the Markov Chain Monte Carlo (MCMC) method for the fitting [101, 102].

Figure 2 shows the comparisons of the positron fraction (left column), total $e^+e^-$ spectra (middle column), and anti-proton spectra (right column) between the best-fitting model predictions and the measurements, for the benchmark propagation model. Eight decay channels, $\chi \rightarrow \chi' e e$, $\chi \rightarrow \chi' \mu \mu$, $\chi \rightarrow \chi' \tau \tau$, $\chi \rightarrow \chi' b\bar{b}$, $\chi \rightarrow \chi' e\mu$, $\chi \rightarrow \chi' e\tau$, $\chi \rightarrow \chi' \mu\tau$, and $\chi \rightarrow \chi' ll$ ($e : \mu : \tau = 1 : 1 : 1$), are calculated. Except for the quark final state which will over-produce
anti-protons, the goodness-of-fittings of other channels are comparable with each other. The reduced chi-squared values of the fittings, \( \chi^2 \), are all about 1.0–1.1 for 185 degrees of freedom except for \( \chi \rightarrow \chi' b \bar{b} \) whose \( \chi^2 \) is about 3.0. The best-fitting parameters of \( \Delta m_\chi \) and \( m_\chi \tau \) are tabulated in table 2. Note that the best-fitting values of \( \Delta m_\chi \) in general increases as the decay channel varies from \( e, \mu, \tau \), to \( b \), from sub-TeV for the \( e^+ e^- \) channel, multi-TeV for channels involving \( \mu \) or \( \tau \), to 100 TeV for the \( b \bar{b} \) channel.\(^1\) In particular, the best-fit value of \( \Delta m_\chi \) for the universal lepton decay channel \( ll \) is 2.2 TeV, higher than \( \sim 1 \) TeV obtained previously in refs. \[62, 65\], which were based on the Fermi-LAT \( e^+ e^- \) total flux \[8\] and the positron fraction data from PAMELA \[3\]. This is in large part due to the updated electron background, besides fitting to the newer AMS-02 data. As a result it will produce more high energy \( \gamma \)-rays, and as we will see in the next section, the universal lepton decay channel is now disfavored.

The fitting contours on the parameter plane of \( \Delta m_\chi \) and \( m_\chi \tau \), for the eight decay channels, are shown in figure 3. In each panel, the green, red, and blue contours are for propagation parameter setting 1, 2, and 6, respectively, which are shown in table 1. As shown in ref. \[97\], such three parameter settings are typical to represent the systematic uncertainties from the CR propagation, especially for this high energy region. As an illustration, we show the posterior probability distributions of all parameters and their correlations for the case of the \( ee \) channel in the appendix.

### 4 Constraints from EGB

In this section we discuss the compatibility of the DM model to explain the AMS-02 electron/positron data with the EGB as measured by Fermi-LAT \[66\]. The diffuse \( \gamma \)-ray emission from extragalactic DM decay is (e.g., \[103\])

\[
\phi_{\text{EG}}(E) = \frac{c}{4\pi} \frac{\Omega_\chi \rho_c}{m_\chi \tau} \int_0^\infty \frac{dz'}{H(z')} \frac{dN}{dE'} \exp[-\tau(z', E')],
\]

where \( \Omega_\chi \rho_c \) is the current DM density in the Universe, \( H(z) = H_0 \sqrt{\Omega_M(1 + z)^3 + \Omega_\Lambda} \) is the Hubble parameter, \( E' = E(1 + z) \), \( \frac{dN}{dE'} \big|_{\text{prompt}} + \frac{dN}{dE'} \big|_{\text{IC}} \) is the gamma-ray spectrum yielded at redshift \( z' \) for one decay of a DM particle, and \( \tau(z, E) \) is the attenuation optical depth of high energy \( \gamma \)-rays in the cosmic infrared to ultraviolet background. In this work we use the extragalactic background light model of ref. \[104\]. The \( \gamma \)-ray spectrum consists of two parts, the prompt emission associated with the decay of DM particles and the IC emission from the decay products \( e^+ e^- \). We use the same way as that of electrons/positrons to calculate

\(^1\)The channel \( \chi \rightarrow \chi' e\tau \), however, has a larger \( \Delta m_\chi \) than that of \( \chi \rightarrow \chi' \mu\tau \) due to the fact that the likelihood distributions are a bit flat, as indicated by the elongated oval shape in credible regions.
Figure 3. Contours of 68% (inner) and 95% (outer) credible regions on the $\Delta m_{\chi} - m_{\chi}\tau$ plane, from the fittings of the charged CR data. The green, red, and blue contours correspond to the propagation parameter settings 1, 2, and 6, as shown in table 1. The shaded regions are disfavored by the Fermi EGB data at the 95% credible interval (see section 4).
the prompt $\gamma$-ray emission from three-body DM decay (see eq. (2.2)). For the IC emission, we assume instantaneous cooling of $e^+e^-$ after their production in the cosmic microwave background (CMB), which gives the equilibrium $e^+e^-$ spectrum (per decay$^2$) as \[105\]

$$
\frac{dN}{dE_e}(E_e, z) = \frac{1}{b(E_e, z)} \int_{E_e}^{\infty} dE'_e \frac{dN}{dE_e'},
$$

(4.2)

where $b(E_e, z) = 2.67 \times 10^{-17}(1 + z)^4(E_e/\text{GeV})^2 \text{GeV s}^{-1}$ is the IC energy loss rate. The IC photon spectrum can then be calculated using the Klein-Nishina differential scattering cross section \[106\]. The cosmological parameters used are: $H_0 = 67 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.32$, $\Omega_\Lambda = 0.68$, $\Omega_\chi = 0.27$, and $\rho_c = 1.24 \times 10^{11} \text{ M}_\odot \text{ Mpc}^{-3}$ \[107\].

The minimum emission from Galactic DM decay (from the anti-GC direction) will also contribute to the EGB \[51\]. It can be calculated as

$$
\phi_G(E)|_{\text{anti-GC}} = \frac{1}{4\pi m_\chi \tau} \frac{dN}{dE} \times \int_{\text{l.o.s.}} \rho(l) dl,
$$

(4.3)

in which the integration is taken along the line-of-sight toward the anti-GC direction. Again $dN/dE$ consists of the prompt and the IC components. Since most of the DM particles from the anti-GC direction locate outside the propagation halo of Galactic CRs, we neglect the diffusion and consider only the IC cooling in the CMB of $e^+e^-$. So the calculation of the IC emission is identical to the extragalactic case described above. Note that the method to calculate the IC emission from the GC direction as will be discussed in section 5 is different, where the diffusion of $e^+e^-$, as well as the cooling in the Galactic optical/infrared field and magnetic field, needs to be included.

Figure 4 shows the expected diffuse $\gamma$-ray emission from the decay of DM from extragalactic space (blue dashed) and the anti-GC direction (red dash-dotted), for the best-fit models as shown in figure 2. The two bumps of each component correspond to the prompt (higher energy) and IC (lower energy) emissions. We find that the prompt emission of the extragalactic component is suppressed by a factor of a few at the high energies due to the attenuation in the extragalactic background light field. From this plot we can see that if there are $\tau$ leptons or quarks in the decay final state, the DM contribution will exceed the observational data at high energies. Therefore, only the case with $ee$, $\mu\mu$, or $e\mu$ final state particles can potentially survive from the data.

The measured spectrum of the EGB can be well described by an exponential cut-off power-law function, which is expected to come from point source populations such as blazars \[108\]. Fitting to the data with only the background gives a power-law index of $\gamma = 2.32 \pm 0.01$ and a cutoff energy of $E_{\text{cut}} = 288 \pm 41 \text{ GeV}$. Such a spectrum is very distinct from the two-bump structure of the photon spectrum from the DM decay. Therefore we assume an exponential cut-off power-law function as the background and include the DM contribution in the fit to the data. The green dotted line (for $\chi \to \chi'ee$, $\chi \to \chi'\mu\mu$, and $\chi \to \chi'e\mu$ only) shows the curve that best-fits the data when fixing the DM model parameters as those in table 2.

$^2$To obtain the energy spectrum per unit volume, one should multiply it by the decay rate, $\Omega_\chi \rho_c (1 + z)^3/(m_\chi \tau)$. Here we keep this form in order to calculate the IC emission in the same way as that of the prompt emission by eq. (4.1).
Figure 4. Expected γ-ray emission from the best-fit DM models, compared with the EGB data of Fermi-LAT [66].
We can derive constraints on the DM model parameters using the EGB data. The posterior probability density of the parameter $m_\chi \tau$ for any given $\Delta m_\chi$ can be written as

$$P(m_\chi \tau | \Delta m_\chi) \propto \int \exp \left(-\frac{\chi^2}{2}\right) d^3P_{\text{bkg}},$$

(4.4)

where $\chi^2$ is the chi-squared value of the model with background parameters $P_{\text{bkg}}$. The lower limit of $m_\chi \tau$ at the 95% credible interval is then obtained by setting

$$\frac{\int_0^{(m_\chi \tau)^{-1}} P(x^{-1}) \, dx}{\int_0^{\infty} P(x^{-1}) \, dx} = 0.95,$$

(4.5)

in which $x = (m_\chi \tau)^{-1}$. The parameter space excluded by the EGB data is shown by the shaded region in figure 3. One can see that for $\chi \rightarrow \chi' ee$, $\chi \rightarrow \chi' \mu\mu$, and $\chi \rightarrow \chi' e\mu$ channels, there exists regions of parameter space where the AMS-02 positron excess can be explained without being excluded by the EGB constraints. In particular, the $\chi \rightarrow \chi' ee$ channel is the most promising decay, after including the systematic uncertainties from the CR propagation models. For the cases with $\tau$ leptons and quarks, the EGB data strongly constrain the parameter space to explain the $e^+e^-$ excesses. It is worth mentioning that the non-smooth 95% limit is due to the two main peaks from the prompt and IC components and the weak structures of the data.\(^3\)

5 The $\gamma$-ray fluxes from inner Galaxy

In this section we discuss the compatibility of the DM models, that survived the EGB constraints, with the $\gamma$-ray observation from the inner Galaxy. An excess of $\gamma$-rays between 1–10 GeV from the inner Galaxy was identified in the Fermi-LAT data [67–70, 72–81]. The morphology and energy spectrum of this excess has been shown to be consistent with $\mathcal{O}(10)$ GeV DM annihilation with a cross section consistent with thermal production. However, there are also astrophysical alternatives which can explain the data [109–118]. Since the mass scale of the DM particle relevant to the GC excess is different from that to explain the positron excess, which is the focus of this work, we use the GC $\gamma$-ray flux as a consistency check on our model.

The total DM induced $\gamma$-ray fluxes from the inner Galaxy include both the prompt emission and the secondary IC and bremsstrahlung emission. The prompt emission dominates at high energies, while the secondary emission is more important at low energies. For the prompt emission, we use the same method as the case of anti-GC (eq. (4.3)) to calculate its flux. The secondary emission is more complicated. Since the inner Galaxy region contains a large part of the diffusion halo of CRs, the diffusion and cooling of electrons in the Galactic optical/infrared radiation field is important, and the secondary emission can not be simply calculated in the same way as that in the extragalactic space and the anti-GC region in section 4 [119]. We split the calculation of the secondary emission into two parts. The first part is the region inside the propagation cylinder, for which we use GALPROP to calculate the propagation of electrons/positrons and their secondary emission. The second part is the region outside the propagation cylinder, for which we adopt the same method as the calculation of the anti-GC emission.

\(^3\)The inclusion of the DM contribution, e.g., for $\chi' ee$, $\chi' \mu\mu$, and $\chi' e\mu$ channels, can actually give better fit to the data than the background. However, the decrease of the $\chi^2$ value is at most about 7.4, which corresponds to a $\sim 2.2\sigma$ significance when adding two free parameters.
Figure 5. The $\gamma$-ray energy spectra based on the 95% allowed parameters ($\Delta m_\chi$, $\tau \times m_\chi$) as presented in figure 3. The left panel is for $\chi \rightarrow \chi' ee$, and the right panel is for $\chi \rightarrow \chi' \mu\mu$. The two components of IC contributions from outside and inside the propagation halo are presented by orange and light green bands, respectively. The bremsstrahlung is shown in blue, and the direct contribution from the DM decay is shown in grey. The sum of the total contributions are coloured in red. The black boxes are the excess fluxes given in ref. [79].

Figure 5 shows the computed $\gamma$-ray fluxes based on the 95% allowed ranges of parameters ($\Delta m_\chi$, $m_\chi \tau$) (within contours of figure 3) obtained through fitting to the positron data, for $\chi \rightarrow \chi' ee$ (left panel) and $\chi \rightarrow \chi' \mu\mu$ (right panel) channels. Compared with the data [79] of the GC excess, we find that, for the three-body decaying DM capable of explaining the AMS-02 positron excess, the total $\gamma$-ray fluxes are below those necessary to account for the inner galaxy excess except in the two highest energy bins. We should mention that there are still large systematic uncertainties on the fluxes of the GC excess due to different assumptions of the background CR source distribution [81], and there could be a high energy tail of the excess emission [120]. Therefore we conclude that the three-body decaying DM model (with decays to electrons or muons) is marginally consistent with the $\gamma$-ray observations. It is worth mentioning that both the box-shaped total fluxes and the morphology, which could be altered due to the diffusion process [121], from the DM decay are different from the data. Additional sources, such as millisecond pulsars [109–111, 113], together with the decaying DM, might be responsible for the total GC excess.

6 Conclusions

In this work, we considered the possibility of using three-body decaying DM to explain the AMS-02 positron excess and examined the model compatibility with the $\gamma$-ray/anti-proton constraints from Fermi-LAT/AMS-02, assuming the DM decays into a stable neutral particle and a pair of SM fermions. The analysis is carried out using a scalar DM as an illustration, after demonstrating that the secondary electron and photon spectra are insensitive to the assumptions on the specific quantum number of DM as well as the type of interactions responsible for the DM decay.
We first investigated the region of parameter space which can account for the AMS-02 positron excess. To fit the positron data, leptonic channels require the mass splitting between decaying DM and the stable neutral partner to be of $\mathcal{O}(\text{TeV})$. For the hadronic channels, the mass splitting is pushed to be very large, primarily due to the constraints from the anti-proton data. Then we check both the Galactic and extragalactic $\gamma$-ray data from Fermi-LAT observations. We find that channels which hadronize, e.g., $\chi \to \chi' \tau\tau$ and $\chi \to \chi' b\bar{b}$, will overshoot the EGB data observed by Fermi-LAT. Primary decays into the electron and muon channels can survive, at least partly, from the EGB constraints. We finally check the $\gamma$-ray emission of the DM decay into electron and muon channels in the inner Galaxy region, and showed that the predicted $\gamma$-ray fluxes are below the observed excess in the inner Galaxy region considering the systematic uncertainties of the data. In the end, DM models with the decay channel of $\chi \to \chi' ee$ could explain the AMS-02 positron excess, without conflicting with the existing anti-proton and $\gamma$-ray data.

Finally, we would like to point out that apart from continuous $\gamma$-ray spectra, the three-body decaying DM can also radiatively produce monochromatic $\gamma$-rays by connecting two final charged leptons of the same flavor into a loop with a photon insertion as studied in ref. [122]. Assuming no mass suppression due to the chirality flip from closing the fermion loop, the ratio of the partial decay width of $\chi \to \chi' \gamma$ to that of $\chi \to \chi' ff$ can be estimated as $\alpha/4\pi \sim 10^{-3}$ with $\alpha$ being the fine structure constant. The best-fit values of the DM mass splitting responsible for the AMS-02 positron excess are between 0.6 and 1.1 TeV for the $e$ and $\mu$ final states, which correspond to the energies of monochromatic photons of 300 GeV to 1.1 TeV depending on $m_\chi$. The lower bounds on the DM lifetime of $\chi \to \gamma\nu$ final state from the Fermi-LAT observations are about $10^{29}$ sec for DM masses of sub-TeV to TeV [123], which can be translated into $10^{26}$ sec for our case of $\chi \to \chi' ff$, or even weaker if there is additional mass suppression for the radiative photon decay. On the other hand, the best-fit value of the DM lifetime in our model is around $10^{27}$ sec, hence the current monochromatic photon bounds can be satisfied. Future experiments such as the Cherenkov Telescope Array [124] and the High Energy cosmic-Radiation Detection facility [125] are expected to improve the line search sensitivities effectively.

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A Posterior distributions of model parameters from the fitting

Figure 6 shows the marginalized posterior distributions of all the 12 model parameters from fitting to the charged CR data. Here $\chi \to \chi' ee$ channel and propagation model 2 are adopted for illustration. The diagonal panels show the 1-dimensional probability distributions, and
Figure 6. Triangle plot to show the fitting distributions of the model parameters for $\chi \to \chi' ee$ channel and propagation model 2.

other panels show the 2-dimensional 68% (inner) and 95% (outer) credible region. The top (bottom) plot of the first column, for instance, corresponds to the 1-dimensional (2-dimensional) credible distribution for $\log A_e (\Phi_{pb}$ and $\log A_e$), with the rest parameters marginalized. Parameters from left to right are: the logarithm of the normalization of the locally observed electron flux at 25 GeV, the low rigidity spectral index, the logarithm of the first break rigidity, the medium rigidity spectral index, the logarithm of the second break rigidity, the high rigidity spectral index of the injection electron spectrum, the re-adjustment factor of secondary positrons, the re-adjustment factor of secondary anti-protons, the logarithm of $\Delta m_\chi$, the logarithm of $m_\chi \tau$, the solar modulation potential of electrons/positrons, and the solar modulation potential of anti-protons.

B Comparison with the newest positron flux data by AMS-02

We have been aware of the five year data release of AMS-02 on December 8th, 2016, which reported updated measurements of the positron fluxes to higher energies [126]. We compare in figure 7 the newest measurements with our model predictions for $\chi \to \chi' ee$, $\chi \to \chi' \mu \mu$, and $\chi \to \chi' e\mu$ channels, which survive from the EGB constraints. We find that the latter two cases give good fittings to the data, while the extrapolation of the best-fit curve of the decay into an electron-positron pair does not well describe the new data points at higher energies.
\begin{figure}
\centering
\includegraphics[width=0.7\textwidth]{fig7}
\caption{The positron fluxes from our model fittings for $\chi \rightarrow \chi'ee$, $\chi \rightarrow \chi'\mu\mu$, and $\chi \rightarrow \chi'e\mu$ channels, compared with the five year data release of AMS-02 \cite{126}.}
\end{figure}

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