Gamma-ray Constraints on Hadronic and Leptonic Activities of Decaying Dark Matter

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Abstract

While the excess in cosmic-ray electrons and positrons reported by PAMELA and Fermi may be explained by dark matter decaying primarily into charged leptons, this does not necessarily mean that dark matter should not have any hadronic decay modes. In order to quantify the allowed hadronic activities, we derive constraints on the decay rates of dark matter into $WW$, $ZZ$, $hh$, $q\bar{q}$ and $gg$ using the Fermi and HESS gamma-ray data. We also derive gamma-ray constraints on the leptonic $e^+e^-$, $\mu^+\mu^-$ and $\tau^+\tau^-$ final states. We find that dark matter must decay primarily into $\mu^+\mu^-$ or $\tau^+\tau^-$ in order to simultaneously explain the reported excess and meet all gamma-ray constraints.
1 Introduction

The existence of dark matter (DM) has been firmly established by numerous observations, though the nature of DM mostly remains unknown. In particular, it is not known whether DM is absolutely stable or not. If DM is unstable, it will eventually decay into lighter particles which may be observed as an excess in the cosmic-ray spectrum.

If DM is related to new physics which appears at the weak scale, it is natural to expect that the DM mass is in the range $\mathcal{O}(100)$ GeV–$\mathcal{O}(10)$ TeV. However, the longevity of DM whose mass is of the weak scale is a puzzle and calls for some explanation. The (quasi)stability may be the result of a discrete symmetry or extremely weak interactions. For instance, in a supersymmetric (SUSY) theory, the lightest SUSY particle (LSP) is stable and therefore a candidate for DM if R-parity is an exact symmetry. However, R-parity violation may be a common phenomenon in the string landscape [1], in which case the LSP DM is unstable and eventually decays into Standard Model (SM) particles. On the other hand, if DM is in a hidden sector which has extremely suppressed interactions with the SM sector, the only way to probe DM may be to look in the cosmic rays for signatures of its decay products.

Recently, much attention has been given to the electron/positron excess reported by PAMELA [2], ATIC [3], PPB-BETS [4] and Fermi [5]. The excess clearly suggests that we need to modify our current understanding of the production/acceleration/propagation of cosmic-ray electrons and positrons. Of the many explanations proposed so far for this excess, DM decay or annihilation remains an exciting possibility. In order to account for the excess by DM decay/annihilation, DM should mainly produce leptons with suppressed hadronic branching ratios, otherwise the anti-protons produced would likely exceed the observed flux [6]. Further model-independent analysis also revealed that, if one requires that the PAMELA/Fermi excess be explained by DM annihilation, the gamma-rays accompanying the lepton production exceeds the observed flux unless a significantly less steep DM profile is assumed [7, 8]. Thus, the leptophilic decaying DM scenario has recently gained momentum [9, 10, 11, 12, 13, 14, 15].

Leptophilic decaying DM models can be broadly divided into two categories. One is such that DM first decays into additional light particles, which subsequently decay into
muons or electrons, while the decays into hadrons are forbidden by kinematics [16]. The other is such that the DM particle couples mainly to leptons due to symmetry [10] or geometric setup [17]. While the hadronic activities are absent in the former case, it is model-dependent to what extent the DM is leptophilic in the latter case. One example is the hidden gauge boson decaying into the SM particles through a mixing with a $U(1)_{B-L}$ gauge boson [9]; the DM is certainly leptophilic in the sense that it mainly decays into leptons, but a certain amount of quarks are also produced.

The purpose of this paper is to study the current constraints on the hadronic and leptonic decay of DM. The anti-proton flux is known to provide a tight constraint on the hadronic activities, but there are large uncertainties in the propagation [18]. The other constraint comes from gamma-ray observation. In contrast to charged cosmic-ray particles, gamma-rays travel undeflected and there is no uncertainty in the propagation; the main uncertainty is the dark matter profile. Furthermore, the Fermi satellite has been measuring gamma-rays with both unprecedented precision and statistics, and we can expect a significant improvement over EGRET data [19, 20]. In this paper we will derive constraints on the partial decay rates of DM into $WW$, $ZZ$, $hh$, $q\bar{q}$ and $gg$ as well as $e^+e^-$, $\mu^+\mu^-$ and $\tau^+\tau^-$ using the Fermi [21, 22] and HESS [23] data. The bounds obtained in this paper are not only generic but also can be used to know what branching ratios are allowed in decaying DM models which account for the PAMELA/Fermi cosmic-ray electron/positron excess.

2 Analysis

There are several contributions to the gamma-ray spectrum when DM decays into SM particles. Photons from fragmentation are generated by the decay of mesons, especially $\pi^0$, and final-state radiation (FSR) is always produced when the DM decays into charged particles. The electrons and positrons produced by the DM decay will lose energy by emitting synchrotron radiation in the galactic magnetic field and through inverse Compton (IC) scattering off ambient photons (star light, dust re--emission, and CMB). In this section we summarize the calculation of these contributions and how we derive constraints.
2.1 Local contributions

First, we use PYTHIA 6.4.21 [26] to simulate the fragmentation of the various final states at a range of DM masses, and for charged final states we use the expression in Ref. [27] for the photon multiplicity from final-state radiation. Since these contributions are local to the site of DM decay, and because gamma-rays travel undeflected, the differential flux from our galactic DM halo is given by flux conservation:

\[
\left( \frac{d\Phi_\gamma}{dE d\Omega} \right)_{\text{local}}^{\text{(gal.)}} = \frac{1}{4\pi} \frac{r_\odot \rho_\odot}{m_{\text{DM}} \tau} \left( \frac{dN_{\gamma}^{\text{(frag.)}}}{dE} + \frac{dN_{\gamma}^{\text{(FSR)}}}{dE} \right) J(\Delta \Omega)
\]  

(1)

where \( r_\odot = 8.5 \text{kpc} \) is the solar distance from the galactic center [28], \( \rho_\odot = 0.3 \text{GeV cm}^{-3} \) is the density of the DM halo at this distance, \( \tau \) is the DM lifetime, and

\[
J(\Delta \Omega) = \frac{1}{\Delta \Omega} \int_{\Delta \Omega} d\Omega \int_{\text{l.o.s.}} ds \left( \frac{\rho_{\text{DM}}(\vec{x})}{\rho_\odot} \right)
\]

(2)

is the line-of-sight integral, in which \( \Delta \Omega \) is the region of sky observed by a given experiment and \( \rho_{\text{DM}}(\vec{x}) \) is the halo profile. In this analysis we use the NFW halo profile [29].

There is also an isotropic, diffuse extragalactic contribution on cosmological scales from DM residing in our past light cone. We find that this contribution to the differential flux is given by

\[
\left( \frac{d\Phi_\gamma}{dE d\Omega} \right)_{\text{local}}^{\text{(ex.)}} = c \frac{\Omega_{\text{DM}} \rho_c}{4\pi H_0 \Omega_{\text{M}}^{1/2} m_{\text{DM}} \tau} \int_1^{\infty} dy \frac{y^{-3/2}}{\sqrt{1 + \Omega_\Lambda / \Omega_{\text{M}} y^{-3}}} \left( \frac{dN_{\gamma}^{\text{(frag.)}}}{d(Ey)} + \frac{dN_{\gamma}^{\text{(FSR)}}}{d(Ey)} \right)
\]

(3)

where \( y \equiv 1 + z \) and the cosmological parameters are given by Ref. [30]; the density of radiation is taken to be negligible. This expression duplicates the result of Ref. [31].

2.2 Contributions from propagating electrons and positrons

Electrons and positrons as final states of DM decay, as well as those from the fragmentation of other final states, will lose energy via synchrotron radiation and IC scattering off ambient photons. Here we describe the calculation of these effects and the resulting contribution to the gamma-ray flux; our analysis parallels that of Ref. [32].

First, let us consider the galactic contribution. The diffusion of \( e^\pm \) is governed by the equation

\[
K(E) \nabla^2 f_e(E, \vec{x}) + \frac{\partial}{\partial E} \left[ b(E, \vec{x}) f_e(E, \vec{x}) \right] + Q(E, \vec{x}) = 0
\]

(4)
where $K(E)$ is the diffusion coefficient, $f_e(E, \vec{x})$ is the $e^\pm$ phase space distribution, $b(E, \vec{x}) = b_{\text{syn}}(E, \vec{x}) + b_{\text{IC}}(E, \vec{x})$ is the energy loss rate, and $Q(E, \vec{x})$ is the $e^\pm$ source term. For this analysis we adopt the MED propagation model \[33\] to set $K(E)$ and the geometric boundary of diffusion. Under this model the propagation length for $e^\pm$ with $E \gtrsim 100$ GeV is $\mathcal{O}(0.1)$ kpc before losing its most of the energy. In the limit that this length is small compared to the distance traveled, $f_e(E, \vec{x})$ is well-approximated by

$$f_e(E, \vec{x}) = \frac{1}{b(E, \vec{x})} \frac{\rho_{\text{DM}}(\vec{x})}{m_{\text{DM}}} \int_0^\infty dE' \frac{dN_e}{dE'}.$$  \hspace{1cm} (5)

The energy loss rate due to synchrotron radiation is given by

$$b_{\text{syn}}(E) = \frac{4}{3} \sigma_T \left( \frac{E}{m_e} \right)^2 \left( \frac{B^2}{2} \right)$$  \hspace{1cm} (6)

where $\sigma_T$ is the Thomson cross-section and $B \approx 3\mu$G is taken as the strength of the galactic magnetic field. The energy loss rate due to IC scattering is given by

$$b_{\text{IC}}(E, \vec{x}) = \int dE_\gamma dE_{\gamma\text{BG}} (E_\gamma - E_{\gamma\text{BG}}) \frac{d\sigma_{\text{IC}}}{dE_\gamma} f_{\gamma\text{BG}}(E_{\gamma\text{BG}}, \vec{x})$$  \hspace{1cm} (7)

where $d\sigma_{\text{IC}}/dE_\gamma$ is the IC differential cross-section as given in Ref. \[34\], and $f_{\gamma\text{BG}}(E_{\gamma\text{BG}}, \vec{x})$ is the sum of the CMB radiation field and the galactic radiation field (star light and dust re-emission). In our calculation we use the interstellar radiation field (ISRF) furnished by the GALPROP collaboration \[35\].

Because the magnetic field is so weak, synchrotron emissions would only be in the radio and is thus only relevant in this calculation as an energy-loss mechanism. On the other hand, IC processes for $e^\pm$ of $E \sim \mathcal{O}(100)$ GeV would produce gamma-rays of $E \sim \mathcal{O}(1)$ GeV which is in the range of the Fermi observations. Therefore, the differential gamma-ray flux is given by

$$\left( \frac{d\Phi_\gamma}{dE d\Omega} \right)_{\text{prop.}}^{(\text{gal.})} = \frac{1}{4\pi} \frac{1}{\Delta \Omega} \int d\Omega \int_{1.0.s} ds \int dE_e dE_{\gamma\text{BG}} \frac{d\sigma_{\text{IC}}}{dE} f_{\gamma\text{BG}}(E_{\gamma\text{BG}}, \vec{x}) f_e(E, \vec{x}).$$  \hspace{1cm} (8)

Now let us turn to the extragalactic contribution. On cosmological distances, there is no interstellar radiation field, only the CMB, and negligibly small magnetic fields. Thus, the only energy-loss mechanism is IC scattering of CMB photons. Moreover, assuming

\footnote{The value of the magnetic field strength may be different close to the galactic center.}
the universe is indeed isotropic and homogeneous, the distributions of CMB photons and DM are spatially invariant. Then the diffusion equation becomes
\[
\frac{\partial}{\partial E} [b(t,E)f_e(t,E)] + Q(t,E) + H E \frac{\partial f_e(t,E)}{\partial E} = \frac{\partial f_e(t,E)}{\partial t}
\]  
(9)
where \(H\) is the Hubble parameter. Since the CMB photon energy is so low the \(e^\pm\) are non-relativistic in the center-of-momentum frame, the energy loss rate due to IC scattering is given by the Thomson limit
\[
b_{\text{cosm}}(y,E) = \frac{4}{3} \left( \frac{E}{m_e} \right)^2 \sigma_T \left( \rho_{\text{CMB}} y^4 \right)
\]  
(10)
where \(\rho_{\text{CMB}} \simeq 0.26\, \text{eV cm}^{-3}\) is the present-day CMB energy density and \(y \equiv 1 + z\) as before. The timescale of energy-loss \(E/b_{\text{cosm}} \lesssim \mathcal{O}(10^{14})\, \text{sec}\) is much less than the Hubble time, so the term \(\mathcal{O}(H)\) in the diffusion equation can be ignored. This gives for the \(e^\pm\) spectrum
\[
f_e(y,E) = \frac{1}{b_{\text{cosm}}(y,E)} \frac{1}{m_{\text{DM}}} \left( \rho_{\text{DM}} y^3 \right) \int_E^\infty dE' \frac{dN_e}{dE'} .
\]  
(11)
Finally, we find for the differential flux
\[
\left( \frac{d\Phi_\gamma}{dEd\Omega} \right)_{\text{prop.}} = \frac{c}{4\pi H_0 \Omega_M^{1/2}} \int_1^\infty dy \frac{y^{-9/2}}{\sqrt{1 + \Omega_\Lambda/\Omega_M y^{-3}}} A(y,E)
\]  
(12)
where
\[
A(y,E) \equiv \int dE_e dE_{\gamma_{\text{BG}}} \frac{d\sigma_{\text{IC}}}{d(Ey)} f_{\gamma_{\text{BG}}}(y,E_{\gamma_{\text{BG}}}) f_e(y,E_e)
\]  
(13)
and \(f_{\gamma_{\text{BG}}}(y,E_{\gamma_{\text{BG}}})\) is the CMB spectrum at redshift \(z = y - 1\). Comparable expressions for annihilating dark matter may be found in Refs. [36, 37].

2.3 Derivation of constraints from data sets

We derive constraints using three data sets: observation of gamma-rays from the galactic center (within 0.1°) by the HESS telescope [23], observation of the galactic mid-latitude (10° ≤ |b| ≤ 20°) diffuse gamma-ray flux by the Fermi LAT [21], and preliminary data for the isotropic diffuse flux (|b| ≥ 10°) also by the Fermi LAT [22].
We do not use the HESS observation of the galactic center ridge \cite{24} because it requires a subtraction of nearby flux levels. The result of this procedure is highly profile dependent: we find that for the NFW profile this procedure weakens the constraint by a factor 5, and for the less-cuspy isothermal profile the constraint would be weakened by a factor 200. Before the procedure our result is comparable to that of Ref. \cite{8}.

For various DM masses and lifetimes, we calculate and sum the various contributions to the gamma-ray flux for each of the energy bins of each data set, with two exceptions due to limited computational power:

- We use only the two highest bins of the Fermi mid-latitude data (energy $\sim \mathcal{O}(10)\text{ GeV}$) when calculating the constraints for weak boson and colored channels. Since the spectra from DM decay are harder than the observed spectra, any excess will be dominated by the highest energy bins anyway.

- We include galactic ICS for comparison to the HESS galactic center data only for the leptonic final states, because they copiously produce hard $e^\pm$. Also, since we cannot know at this time how much galactic contribution (namely, galactic ICS and galactic halo contributions) is present in the isotropic flux reported by Fermi, we give this constraint both with and without galactic contribution added in. For the Fermi mid-latitude data we include galactic ICS for all channels.

Then, we compute how many standard deviations the calculated flux exceeds the data for these bins and take the largest of these, as in Ref. \cite{8}. Again because the spectra from DM decay are harder than the observed spectra, this statistic is little different than reduced-$\chi^2$, but without the aliasing errors due to the number of effective degrees of freedom changing near a contour. The $3\sigma$ contours are shown on Figures \ref{fig:weak} \ref{fig:Higgs} and \ref{fig:colored} for weak and Higgs boson, colored and leptonic channels, respectively. The lower dotted blue line is the constraint from Fermi isotropic diffuse flux without galactic contribution, and the upper dotted-dashed blue line is the the constraint with galactic contribution.

### 2.4 Uncertainties

Finally, let us consider the uncertainties in these calculations:

\footnote{We are grateful to J. F. Beacom \cite{25} for pointing this out.}
Figure 1: $3\sigma$ constraints for WW, ZZ and hh final states. The lower dotted blue line is the constraint from Fermi isotropic diffuse flux without galactic contribution, and the upper dotted-dashed blue line is the the constraint with galactic contribution.

- **DM halo profile:** We use the NFW profile for the galactic dark matter halo. If we were to use instead the isothermal profile, the calculated flux of fragmentation and FSR photons from the galactic center would be reduced by a factor 4, weakening the constraint from the HESS observation. By contrast, because the Fermi observations cover a much larger portion of the sky looking away from the galactic center, switching to the isothermal profile would hardly change these constraints.
Figure 2: $3\sigma$ constraints for colored final states.

- **Local DM density:** We use the conservative, standard value $\rho_\odot = 0.3\text{ GeV cm}^{-3}$ for the DM halo density at the radius of our solar system, though a wide range is accepted [38]. A recent analysis gives the value $\rho_\odot = 0.39\text{ GeV cm}^{-3}$ within 10% [28].

- **ICS calculation:** There are uncertainties associated with parameters such as the galactic magnetic field and interstellar radiation field, as well as the choice of the diffusion model and the approximation of dropping the diffusion effect in calculating the $e^\pm$ phase space distribution. Ref. [39] found that the same calculation with a slightly different setup matched the numerical results of GALPROP, and Ref. [8] estimates that the no-diffusion approximation can change photon flux by a factor of 2.
Consequently, we estimate that the uncertainty in our calculation of ICS is $\mathcal{O}(1)$.

### 3 Discussion

For a whole range of DM masses, it is the Fermi isotropic diffuse flux that places most stringent constraints on the lifetime, followed by the Fermi galactic mid-latitude data and then by the HESS galactic center data. We can also see that for the hadronic channels shown in Figs. 1 and 2 as well as for the $\tau^+\tau^-$ channel shown in Fig. 3 the constraints
derived from the Fermi mid-latitude data becomes weaker at heavier DM masses. This feature can be understood as follows. The gamma-ray energy spectrum from decaying DM is dominated by fragmentation and final-state radiation at energies near the threshold $\sim m_{\text{DM}}/2$, while the up-scattered photons through IC process dominate at low energies. Since the Fermi mid-latitude data is available up to $\mathcal{O}(10)$ GeV, it depends on the DM mass which contribution becomes important. The up-scattered photons tend to be dominant at $E \simeq \mathcal{O}(10)$ GeV for a DM mass above $\mathcal{O}(1)$ TeV. That is why the constraints become flatter above $\mathcal{O}(1)$ TeV. The constraints from the Fermi isotropic data, which also goes up to $\mathcal{O}(10)$ GeV, show a similar flattening for $u\bar{u}$, $b\bar{b}$, $gg$ and $\tau^+\tau^-$ final states, which fragment into hard mesons. It is interesting to note that the IC scattering is important for the hadronic and $\tau^+\tau^-$ modes if the DM mass is heavier than several TeV.

From Fig. 3 one can see that the decay into $e^+e^-$ and $\tau^+\tau^-$ are more tightly constrained than that into $\mu^+\mu^-$. This is because the direct production of energetic electron/positron enhances the gamma-ray flux through final-state radiation and IC scattering, and because the decay of $\tau$ is accompanied by the fragmentation photons. The DM lifetime should be $\mathcal{O}(10^{26})$ sec in order to explain the PAMELA/Fermi excess in cosmic-ray electrons/positrons (shown by the orange ellipses in the figure). Therefore, in order to simultaneously satisfy the gamma-ray constraints and as well as account for the PAMELA and Fermi excess, DM must decay primarily into either muons or taus.

Suppose that the DM mainly decays into $\mu^+\mu^-$ at a lifetime of $\mathcal{O}(10^{26})$ sec. The allowed hadronic branching ratio is about $\mathcal{O}(10)\%$ from the figure. Of course the precise value depends on DM models. In next section we consider a DM model in which a hidden gauge boson decays into quarks and leptons through a mixing with an $U(1)_{B-L}$ gauge boson. The allowed hadronic branching ratio in this DM model is about 30% at a reference point, $m_{\text{DM}} = 2$ TeV and $\tau = 1.5 \times 10^{26}$ sec.

We may, however, compare these generic gamma-ray constraints with the generic constraints from neutrinos. Bounds on leptonic final states from upward-going muons due to neutrinos interacting with the Earth [40] are 10–100 times weaker than those presented here, though the direct neutrino bounds from IceCube+DeepCore will surpass present-day gamma-ray constraints after a few years of running [41].

In the above analysis we required that the the DM contribution should not exceed
the Fermi/HESS data points at more than 3σ. If a fraction $f$ of the observed flux is
due to the astrophysical gamma-ray sources, the constraint on the DM lifetime will be
improved by about $1/f$. For instance, Ref. [42] proposed a model of blazars and estimate
its contribution to the diffuse isotropic gamma-ray flux. Although there is uncertainty
in the blazar model, their estimate agrees well with the preliminary Fermi data. As the
astrophysical understanding of the origin of the observed gamma-rays flux is improved,
the constraint on the DM property gets stronger.

4 Constraints on a dark matter model

Using the constraints derived in the previous section, we should be able to check whether
a specific DM model is allowed by the current gamma-ray observation. As an example,
we take up a model which was proposed in Ref. [43] to account for the PAMELA and
Fermi excess.

First, let us briefly review the model (see the original reference for details). The life-
time needed to account for the excess is of $\mathcal{O}(10^{26})$ seconds, and such a longevity calls for
some explanation. To this end we introduce an extra dimension, which is assumed to be
compactified on $S^1/Z_2$ with two distinct boundaries. Suppose that a hidden $U(1)_H$ gauge
field is confined on one boundary and the SM particles on the other. In such a set-up, di-
rect interactions between the two sectors are suppressed by a factor of $\exp(-M_* L)$, where
$M_*$ is the five-dimensional Planck scale and $L$ denotes the size of the extra dimension. For
e.g. $M_* L \sim 10^2$, the direct couplings are so suppressed that the hidden gauge boson will
be practically stable in a cosmological time scale [43]. Assuming that the hidden $U(1)_H$
gauge symmetry is spontaneously broken, the hidden gauge boson, $A_H$, can be therefore
a candidate for DM.

Let us introduce an $U(1)_{B-L}$ in the bulk. Through a kinematic mixing between the
$U(1)_H$ and $U(1)_{B-L}$, which is generically present, the $A_H$ will then decay into the SM
quarks and leptons at a rate determined by their $B-L$ quantum number. After integrating
out the heavy $U(1)_{B-L}$ gauge boson\(^3\), the effective couplings between the hidden gauge

\(^3\)We expect that the $U(1)_{B-L}$ gauge symmetry is spontaneously broken around the grand uni fication
theory (GUT) scale of about $10^{15} \text{ GeV}$, since the seesaw mechanism [44] for neutrino mass generation
suggests the right-handed neutrinos of a mass about $10^{15} \text{ GeV}$.  

boson $A_H$ and the SM fermion $\psi_i$ can be extracted from the $U(1)_{B-L}$ gauge interactions

$$\mathcal{L}_{\text{int}} = -\lambda q_i \frac{m^2}{M^2} A_H^\mu \bar{\psi}_i \gamma^\mu \psi_i,$$

where $\lambda$ is a coefficient of the kinetic mixing, $q_i$ denotes the $B-L$ charge of the fermion $\psi_i$, and $m$ and $M$ are the masses of the hidden gauge boson $A_H$ and the $U(1)_{B-L}$ gauge boson, respectively. The lifetime of $A_H$ is therefore given as

$$\tau \simeq 1 \times 10^{25} \text{ sec} \left( \sum_i N_i q_i^2 \right)^{-1} \left( \frac{\lambda}{0.01} \right)^{-2} \left( \frac{m}{2 \text{ TeV}} \right)^{-5} \left( \frac{M}{10^{15} \text{ GeV}} \right)^4,$$

where $N_i$ is the color factor (3 for quarks and 1 for leptons), the sum is taken over the SM fermions, and we have neglected the fermion masses. The introduction of the $U(1)_{B-L}$ has two merits. One is that, for a natural choice of the $B-L$ breaking scale, the lifetime of DM falls in a desired range of $\mathcal{O}(10^{26})$ seconds. The other is that the DM decay mode is leptophilic and the branching ratios simply reflect the $B-L$ charge assignment, which makes the model very predictive; the branching ratio into a quark pair is given by $2/39$, while that into a charged lepton pair is $2/13$.

In a similar way as we did in the previous section, we have derived constraints on the lifetime of $A_H$ from the gamma-ray data. See Fig. 4. The Fermi galactic mid-latitude data plays an important role in constraining the model at low side of DM masses, while the HESS galactic center data takes over for the high side. For example, the lifetime of the $A_H$ of mass 500 GeV (2 TeV) should be longer than about $2 \times 10^{25} \ (2.7 \times 10^{25})$ seconds. We take the reference point $m_{\text{DM}} = 2 \text{ TeV}$ and the lifetime $\tau = 1.5 \times 10^{26} \text{ sec}$ shown as a star in Fig. 4 which can explain both the Fermi and PAMELA excess. The antiproton flux was calculated for the reference point and we found that it is consistent with the current PAMELA [6] and other observational data on the cosmic-ray antiproton. On the other hand, as one can see from Fig. 4, the reference point is marginally excluded by the bound obtained from the Fermi isotropic diffuse data. Since the gamma-ray flux calculation is more robust over the antiproton flux, we conclude that the hidden gauge boson DM model, which can account for both the PAMELA and Fermi excess while satisfying the antiproton flux constraint, is now marginally excluded by the Fermi isotropic diffuse gamma-ray data.

The flux of the antiproton produced by DM annihilation/decay is very sensitive to the diffusion...
Figure 4: $3\sigma$ constraints for $U(1)_{B-L}$ model with a star representing the reference point, $m_{DM} = 2 \text{ TeV}$ and $\tau = 1.5 \times 10^{26} \text{ sec}$, which accounts for both PAMELA and Fermi excess.

5 Conclusions

In this paper we have derived constraints on the partial decay rates of DM into $WW$, $ZZ$, $hh$ and $q\bar{q}$ as well as $e^+e^-$, $\mu^+\mu^-$ and $\tau^+\tau^-$ using the gamma-ray data observed by the Fermi LAT and HESS. One of the merits of using gamma-ray is that the predicted flux does not depend on the diffusion model in the Galaxy, in contrast to charged cosmic-rays. The constraints derived in this paper provide implications for DM model-building attempting to account for the PAMELA/Fermi excess. According to our results, the allowed hadronic branching ratio is of $\mathcal{O}(10)$ %. We have applied the result to a DM model based on the hidden gauge boson decaying through a mixing with the $U(1)_{B-L}$, and found that the model is now marginally excluded by the Fermi gamma-ray observation. The allowed hadronic branching ratio is about 30% at the reference point shown as a star in Fig. 4.
Gamma-ray observations have the power to constrain the properties of DM. Thanks especially to the Fermi LAT data, which provides greater accuracy and statistics over the experiments in the past, the gamma-ray constraint has become as tight as or even tighter than current neutrino and antiproton constraints. Further observation by the Fermi satellite will hopefully shed light on the dark sector of our Universe.

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