Dark matter annihilations and decays after the AMS-02 positron measurements

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Abstract

The AMS-02 collaboration has recently presented measurements of excellent quality of the cosmic electron and positron fluxes as well as the positron fraction. We use the measurements of the positron flux to derive, for the first time, limits on the dark matter annihilation cross section and lifetime for various final states. Working under the well-motivated assumption that a background positron flux exists from spallations of cosmic rays with the interstellar medium and from astrophysical sources, we find strong limits on the dark matter properties which are competitive, although slightly weaker, than those derived from the positron fraction. Specifically, for dark matter particles annihilating only into e^+e^- or into $\mu^+\mu^-$, our limits on the annihilation cross section are stronger than the thermal value when the dark matter mass is smaller than 100 GeV or 60 GeV, respectively.

1 Introduction

In a large class of dark matter scenarios, the annihilations or decays of the dark matter particles produce a positron flux, accompanied by an electron flux, thus opening the possibility of the indirect detection of dark matter in our Galaxy through the observation of an excess in the cosmic positron flux or positron fraction relative to the expected astrophysical backgrounds. In the last few years, data of extraordinary quality on the positron flux or fraction have been collected by several experiments, notably CAPRICE [1], HEAT [2], AMS-01 [3], PAMELA [4,5] and AMS-02 [6,7]. The most striking result is the observation of a rise in the positron fraction starting at $\sim 10\,\text{GeV}$ and extending at least to 350 GeV, as recently confirmed by the AMS-02 collaboration [6]. While dark matter annihilations

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or decays provide an explanation for this observation, the cosmic positron backgrounds are still poorly understood and it is not possible at the moment to make a definite statement about the origin of this excess.

From a conservative point of view, the measurements of the positron flux or fraction allow one to set limits on the dark matter annihilation cross section and decay width in a given dark matter scenario. Many studies have derived limits on the dark matter parameters employing measurements of the positron fraction under the assumption that the positron background vanishes or that the only source of background is secondary production due to spallations of cosmic rays in the interstellar medium (see *e.g.* [8–15]). This approach was recently improved in [16], where a search was undertaken in the positron fraction for the spectral features which are predicted to arise in certain final states of dark matter annihilations. We will consider in this paper the limits that can be obtained from the positron flux and which, in contrast to the positron fraction, do not require knowledge of the electron flux and are therefore cleaner from the theoretical point of view. These limits are complementary (and as we will show, competitive) to those derived from the positron fraction. We will also include in our calculation a plausible background model to take into account a possible primary component of astrophysical origin in the positron flux, which is likely to exist and which presumably provides the additional source of positrons when the dark matter annihilations or decays cannot totally explain the rise in the positron fraction (for example, when the dark matter mass is smaller than 300 GeV or when the annihilation cross section or decay rate is too small). Besides, most analyses neglect the positron data at low energies (see however recent analyses [16,17] where the low energy data of the positron fraction was used). Nevertheless, the exquisite measurements provided by experiments, together with the excellent agreement of the observations with the expectations from non-exotic physics which leave little room for an exotic component in the positron fraction, allow us to set very stringent bounds on the dark matter properties.

The paper is organized as follows: in section 2 we review the methods to calculate the positron fluxes at the Earth from dark matter annihilations or decays and we present an ansatz for the background electron and positron fluxes. In section 3 we present our calculation of the limits on the annihilation cross section and lifetime and we apply it to various possible final states. Lastly, in section 4 we present our conclusions.

2   Primary and secondary positron fluxes at the Earth

The annihilations or decays of dark matter particles in the Milky Way dark matter halo at the position $\vec{r}$ with respect to the galactic center produce a primary positron flux with a rate per unit energy and unit volume which is given by (for reviews, see [18, 19]):

$$
Q_{e^+}(E, \vec{r}) = \begin{cases} \dfrac{1}{2} \dfrac{\rho_{\mathrm{DM}}^2(\vec{r})}{m_{\mathrm{DM}}^2} \sum_f \langle \sigma v \rangle_f \dfrac{dN_{e^+}^f}{dE} & \text{(annihilations)} , \\[3ex] \dfrac{\rho_{\mathrm{DM}}(\vec{r})}{m_{\mathrm{DM}}} \sum_f \Gamma_f \dfrac{dN_{e^+}^f}{dE} & \text{(decays)} , \end{cases}
\tag{1}
$$

where $\langle \sigma v \rangle_f$ denotes the velocity weighted annihilation cross-section, Γ_f the decay rate and $dN_{e^+}^f/dE$ the energy spectrum of positrons produced in the annihilation or decay channel

f, which we simulate using the event generator PYTHIA 8.1 [20]. Besides, $\rho_{\text{DM}}(\vec{r})$ denotes the density of dark matter particles in the Milky Way halo, which we assume spherically symmetric and with a radial distribution described by the Einasto profile [21–23]:

$$\rho_{\text{DM}}(r) = \rho_0 \exp\left[-\frac{2}{\alpha}\left(\frac{r}{r_s}\right)^{\alpha}\right] , \tag{2}$$

with $\alpha = 0.17$ and $r_s = 28$ kpc. The overall normalization factor ρ_0 will be chosen to reproduce the local dark matter density $\rho_\odot = 0.39$ GeV/cm^3 [24–28] with $r_\odot = 8.5$ kpc.

The propagation of positrons in the Milky Way is commonly described by a stationary two-zone diffusion model with cylindrical boundary conditions [29]. Under this approximation, the number density of particles per unit energy, $f_{e^+}(E, \vec{r}, t)$, satisfies the following transport equation:

$$0 = \frac{\partial f_{e^+}}{\partial t} = \nabla \cdot [K(E, \vec{r})\nabla f_{e^+}] + \frac{\partial}{\partial E}[b(E, \vec{r})f_{e^+}] + Q(E, \vec{r}) , \tag{3}$$

with boundary conditions such that the solution $f_{e^+}(E, \vec{r}, t)$ vanishes at the boundary of the diffusion zone, which is approximated by a cylinder with half-height $L = 1 - 15$ kpc and radius $R = 20$ kpc. In this equation, $K(E, \vec{r})$ is the diffusion coefficient which we assume constant throughout the diffusion zone and is parametrized as $K(E) = K_0(E/\text{GeV})^\delta$, while $b(E, \vec{r})$ is the rate of energy loss, which is dominated by the inverse Compton scattering of the positrons on the interstellar radiation field and by the synchrotron losses on the Galactic magnetic field. Information on the parameters K_0, δ and L can be inferred from the flux measurements of other cosmic ray species, mainly from the Boron to Carbon ratio [30]. There exist, however, degeneracies among them which cannot be broken with present experiments, therefore there is a continuous family of parameters leading to the same B/C ratio. We will choose for our analysis the MED propagation model proposed in Ref. [31] from an analysis of the primary antiproton flux from dark matter annihilations, and which is characterized by $K_0 = 0.0112\,\text{kpc}^2/\text{Myr}$, $\delta = 0.70$ and $L = 4\,\text{kpc}$. Useful parametrizations to calculate the number density of positrons using this formalism were given in [32]. Finally, the interstellar (IS) positron flux at the position of the Sun is given by:

$$\Phi_{e^+}^{\text{DM,IS}}(E) = \frac{c}{4\pi} f_{e^+}(E) , \tag{4}$$

The observation of the positron flux produced in dark matter annihilations or decays is hindered by the existence of still poorly known astrophysical backgrounds. The positron background contains a secondary component produced in collisions of cosmic rays in the interstellar medium. Different calculations [33, 34] suggest that the spectrum of secondary positrons at energies larger than 2 GeV follows a simple power law

$$\Phi_{e^+}^{\text{sec,IS}}(E) = C_{e^+} E^{-\gamma_{e^+}} , \tag{5}$$

where γ_{e^+} is in the range $3.3 - 3.7$. In addition, there may be a primary positron component produced *e.g.* by the interactions of high-energy photons in the strong magnetic fields of pulsars [35–39] (other possible sources of cosmic positrons are a nearby gamma-ray burst [40] or hadronic interactions inside the same sources that accelerate galactic cosmic rays [41]).

We will assume that this potential contribution to the positron flux can be parametrized as a simple power law multiplied by an exponential cut-off:

$$\Phi_{e^+}^{\text{source,IS}}(E) = C_s E^{-\gamma_s} \exp(-E/E_s) \,. \tag{6}$$

The total interstellar positron flux can then be expressed as:

$$\Phi_{e^+}^{\text{IS}}(E) = \Phi_{e^+}^{\text{sec,IS}}(E) + \Phi_{e^+}^{\text{source,IS}}(E) + \Phi_{e^+}^{\text{DM,IS}}(E) \,. \tag{7}$$

The positron flux at low energies is significantly altered by solar modulation effects. Under the force field approximation [42, 43], the flux at the top of the atmosphere (TOA) is related to the flux at the heliospheric boundary by the following relation [44]:

$$\Phi_{e^+}^{\text{TOA}}(E) = \frac{E^2}{(E + \phi_{e^+})^2} \Phi_{e^+}^{\text{IS}}(E + \phi_{e^+}) \,, \tag{8}$$

where ϕ_{e^+} is a parameter that varies between $\sim 500\,\text{MV} - 1.3\,\text{GV}$ over the eleven-year solar cycle.

Measurements of the positron flux are complemented by measurements of the positron fraction, defined as the positron flux over the total electron plus positron flux. From the theoretical perspective, the derivation of limits on the dark matter properties from the positron fraction requires the knowledge of the electron flux, which is difficult to model. Therefore, for our analysis of the AMS-02 data on the positron fraction, we will simply fix the electron flux at the top of the atmosphere to the data measured by the AMS-02 collaboration itself [7], and which were collected in the same period as the positron data.[1] For electron energies between 2 and 350 GeV, which is the range of interest for calculating the positron fraction, we find that the electron flux is well described by the sum of two power laws which are distorted due to solar modulation effects:

$$\Phi_{e^-}^{\text{TOA}}(E) = \frac{E^2}{(E + \phi_{e^-})^2} \left[C_1 (E + \phi_{e^-})^{-\gamma_1} + C_2 (E + \phi_{e^-})^{-\gamma_2} \right] \,, \tag{9}$$

where $C_1 = 2.6 \times 10^3 \,\text{s}^{-1}\,\text{sr}^{-1}\,\text{m}^{-2}\,\text{GeV}^{-1}$, $\gamma_1 = 3.83$, $C_2 = 35 \,\text{s}^{-1}\,\text{sr}^{-1}\,\text{m}^{-2}\,\text{GeV}^{-1}$, $\gamma_2 = 2.83$ and $\phi_{e^-} = 1.3\,\text{GV}$ (see Fig. 1, left plot).

3   Limits on the dark matter annihilation cross section and lifetime

To set limits on the dark matter annihilation cross section and lifetime, we first use the measurements of the positron flux from the AMS-02 [7] collaboration. We will make the well-motivated assumption that the background receives a contribution from secondary positrons produced in cosmic ray spallations with a spectrum given by Eq. (5) and possibly a contribution from astrophysical sources with a spectrum given by Eq. (6). The form of these

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[1]Note that the primary electron flux produced in the dark matter annihilations and decays is, in most models, identical to the primary positron flux, given by Eq. (4), while the measured electron flux is about one order of magnitude larger than the positron flux. Therefore, at a given energy, we do not expect a significant contribution to the total electron flux from dark matter annihilations or decays for the parameters that saturate the observational limits on an exotic component in the positron flux.
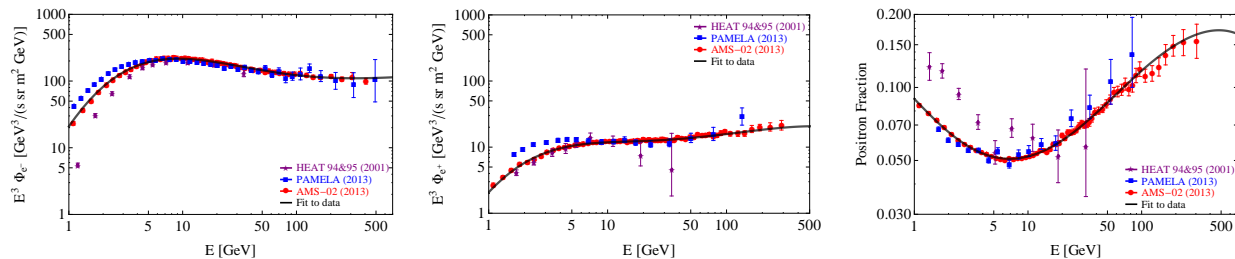
Figure 1: Measurements by the HEAT, PAMELA and AMS-02 experiments of the electron flux (left plot), positron flux (middle plot) and positron fraction (right plot) together with the fit to the data of the "background models" described in the text.

spectra is well justified when $E \gtrsim 2\,\mathrm{GeV}$, hence we will use only data satisfying this condition in our analysis. We then select an energy window in the positron data and perform a χ^2 test with the six parameters appearing in the flux at the top of the atmosphere, C_{e^+}, γ_{e^+}, C_s, γ_s, E_s and ϕ_{e^+} with the restrictions C_{e^+}, $C_s \geq 0$, $3.7 > \gamma_{e^+} > 3.3$, $\gamma_{e^+} > \gamma_s$, $E_s > 0$, $1.3\,\mathrm{GV} > \phi_{e^+} > 0.5\,\mathrm{GV}$. For windows reaching energies larger than $\sim 10\,\mathrm{GeV}$ the secondary contribution does not provide by itself a good fit to the data, hence it is necessary to include a source contribution, Eq. (6), with a harder spectrum than the secondary contribution. Concretely, for the AMS-02 measurements of the positron flux [7] we obtain the best fit for $E = 2 - 350\,\mathrm{GeV}$ when $C_{e^+} = 72\,\mathrm{s^{-1}\,sr^{-1}\,m^{-2}\,GeV^{-1}}$, $\gamma_{e^+} = 3.70$, $C_s = 1.6\,\mathrm{s^{-1}\,sr^{-1}\,m^{-2}\,GeV^{-1}}$, $\gamma_s = 2.51$, $E_s = 1.0\,\mathrm{TeV}$ and $\phi_{e^+} = 0.93\,\mathrm{GV}$ (see Fig. 1, middle plot).[2] We then introduce a contribution to the positron flux from the annihilations or decays of dark matter particles with mass m_{DM} and annihilation cross section $\langle \sigma v \rangle$ or lifetime τ and recalculate the χ^2 of the best fit model. The 2σ exclusion line for this concrete energy window is obtained by determining, for a given final state and dark matter mass, the cross section and lifetime which gives a χ^2 which exceeds the χ^2 of the "pure background" model by more than 4. Lastly, we select, for a given dark matter mass, the most stringent limit among those obtained from sampling various energy windows. Our procedure is illustrated in Fig. 2 for the case of annihilations and decays into a $\mu^+ \mu^-$ pair from our analysis of the AMS-02 measurements of the positron flux. The plot shows the limits on the annihilation cross section (left plot) and lifetime (right plot) obtained from sampling fifty-three energy windows (shown in purple), together with the curve that gives the most stringent limit for each mass (shown in red).

Following this procedure, we have calculated the limits on the annihilation cross section and lifetime for the final states $e^+ e^-$, $\mu^+ \mu^-$, $\tau^+ \tau^-$, $b\bar{b}$ and $W^+ W^-$; the results are presented in Fig. 3. The limits shown with solid lines correspond to the best limits sampling over all windows, while those shown with dashed lines were derived selecting windows containing only energies larger than 10 GeV. The latter limits are mildly affected by the modeling of the solar modulation and are therefore more robust. The limits are very strong for the $e^+ e^-$ final state and, in fact, present measurements of the positron flux probe cross sections smaller than the "thermal cross section", $\langle \sigma v \rangle = 3 \times 10^{-26}\,\mathrm{cm^3/s}$, for dark matter masses

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[2]Note that the best fit for the solar modulation parameter of our background models is different for electrons and for positrons. Charge-sign dependent solar modulation effects were also noted from the PAMELA data [45, 46].
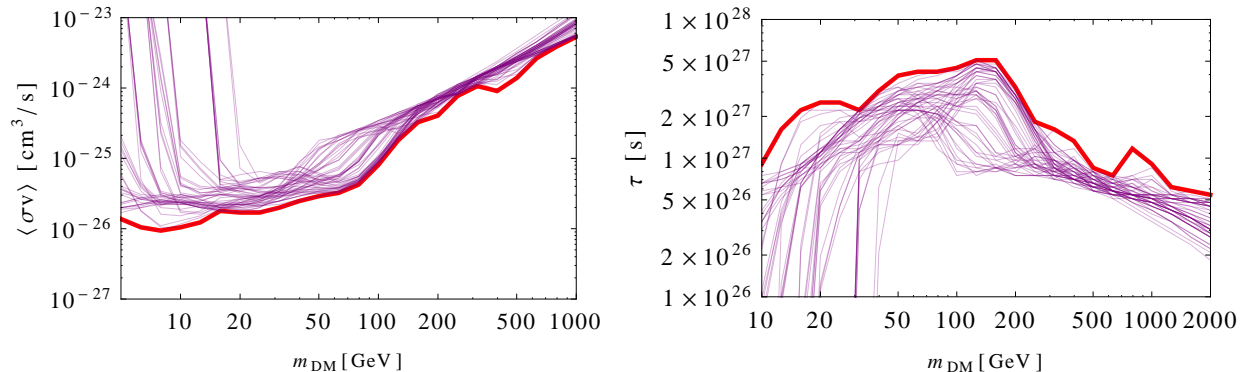
Figure 2: 2σ limits on the dark matter annihilation cross section (left plot) and lifetime (right plot) derived from the AMS-02 data on the positron flux, assuming the final state $\mu^+\mu^-$. The thin purple lines show the limits for each of the fifty-three energy windows used in our analysis, while the thick red line shows the best limit for each dark matter mass.

below 100 GeV; in the case of the $\mu^+\mu^-$ final state the limits are below the thermal cross section for $m_{\rm DM} \lesssim 60\,{\rm GeV}$. We have calculated the limits also for the Navarro-Frenk-White profile and the isothermal profile, as well as for the MIN and MAX propagation models presented in Ref. [31] and we have found that the conclusions are mildly affected by the choice of the halo profile or by the choice of propagation parameters.

Following the same procedure we have derived for comparison limits on the annihilation cross section and the lifetime using data on the positron fraction published by AMS-02. To calculate the positron fraction, we fix the electron flux to the parametrization given in Eq. (9) derived from the AMS-02 measurements [7]. We now postulate a background positron flux consisting in a power law plus a second power law with a cut-off, modified using the force field approximation to take into account the solar modulation effects. This model reproduces very well the AMS-02 data in the range $E = 2\,{\rm GeV} - 350\,{\rm GeV}$ when $C_{e+} = 61\,{\rm s}^{-1}\,{\rm sr}^{-1}\,{\rm m}^{-2}\,{\rm GeV}^{-1}$, $\gamma_{e+} = 3.70$, $C_s = 2.4\,{\rm s}^{-1}\,{\rm sr}^{-1}\,{\rm m}^{-2}\,{\rm GeV}^{-1}$, $\gamma_s = 2.60$, $E_s = 1.4\,{\rm TeV}$ and $\phi_{e+} = 0.83$, giving a $\chi^2/d.o.f = 27.78/52$, leaving little room for an exotic component in the positron fraction.[3] As before, we now introduce an additional component in the positron flux and recalculate the minimum χ^2 of the new model in various energy windows. Finally, we determine the 2σ exclusion lines for each energy window and select, for each dark matter mass, the best limit. The resulting limits for the final states e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, $b\bar{b}$ and W^+W^- are shown in Fig. 4 for dark matter annihilations (left plot) and dark matter decays (right plot).

Lastly, we compare in Fig. 5 the limits on the annihilation cross section or lifetime derived from the positron flux measured by HEAT [2], PAMELA [5] and AMS-02 [7], as well as from the positron fraction measured by AMS-02 [6], assuming the final states $\mu^+\mu^-$ (upper plots) and $b\bar{b}$ (lower plots). We also show for comparison the limits reported by the Fermi-LAT collaboration in Ref. [47] from measurements of the gamma-ray flux. For annihilations into $\mu^+\mu^-$, the limits on the cross section derived from the AMS-02 measurements of the positron flux are, at $m_{\rm DM} = 10\,{\rm GeV}$, two orders of magnitude stronger than those reported by the Fermi-LAT collaboration, while, at $m_{\rm DM} = 1\,{\rm TeV}$, about a factor of three stronger. On the

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[3]Note that the parameters of the "only background model" for the positron flux inferred from the AMS-02 measurements of the positron fraction are compatible with those inferred from the positron flux itself.
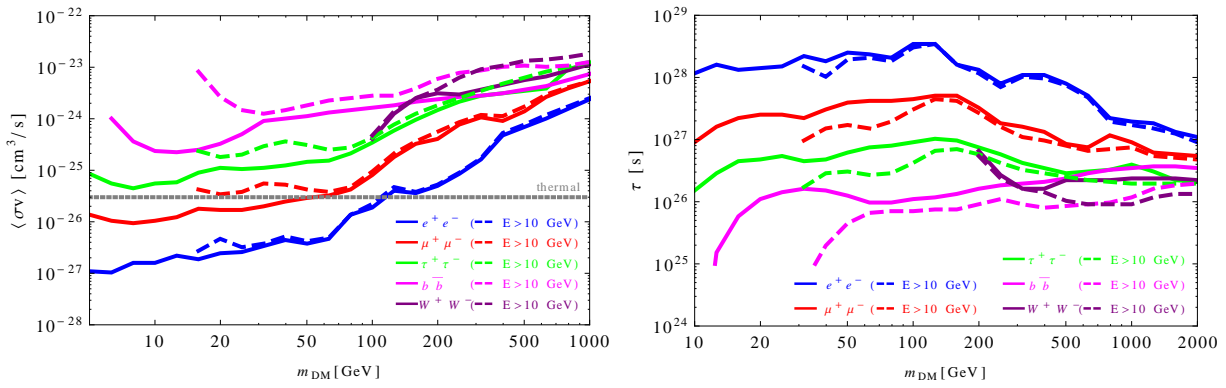
Figure 3: Limits on the annihilation cross section (left plot) and the lifetime (right plot) derived from the AMS-02 data on the positron flux, assuming the final states e^+e^-, $\mu^+\mu^-$, $\tau^+\tau^-$, $b\bar{b}$ and W^+W^-. The limits shown as solid lines were derived from sampling over various energy windows while the dashed lines, from considering those windows including only data with energies above 10 GeV.
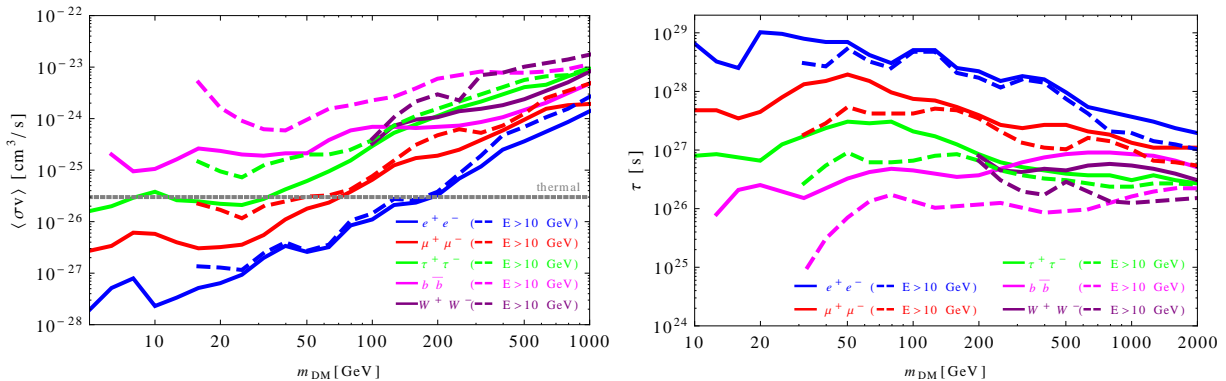

Figure 4: Same as Fig. 3 but using the AMS-02 data on the positron fraction.

other hand, the limits derived from the measurements of the positron fraction are stronger than the limits from the positron flux by a factor ranging between 1 and 4, depending on the mass. The same conclusions apply to the limits on the dark matter lifetime. It is remarkable that the HEAT measurements already provide better limits in this annihilation channel that the Fermi-LAT data. Annihilations and decays into $b\bar{b}$ generate softer positrons and harder gamma-rays than $\mu^+\mu^-$, therefore we expect weaker limits on the annihilation cross section and lifetime from positron measurements and stronger limits from gamma-ray measurements. Indeed, and as shown in the figure, for this channel the Fermi-LAT limits are comparable to those derived from the AMS-02 measurements of the positron flux, and slightly worse than those derived from the positron fraction.
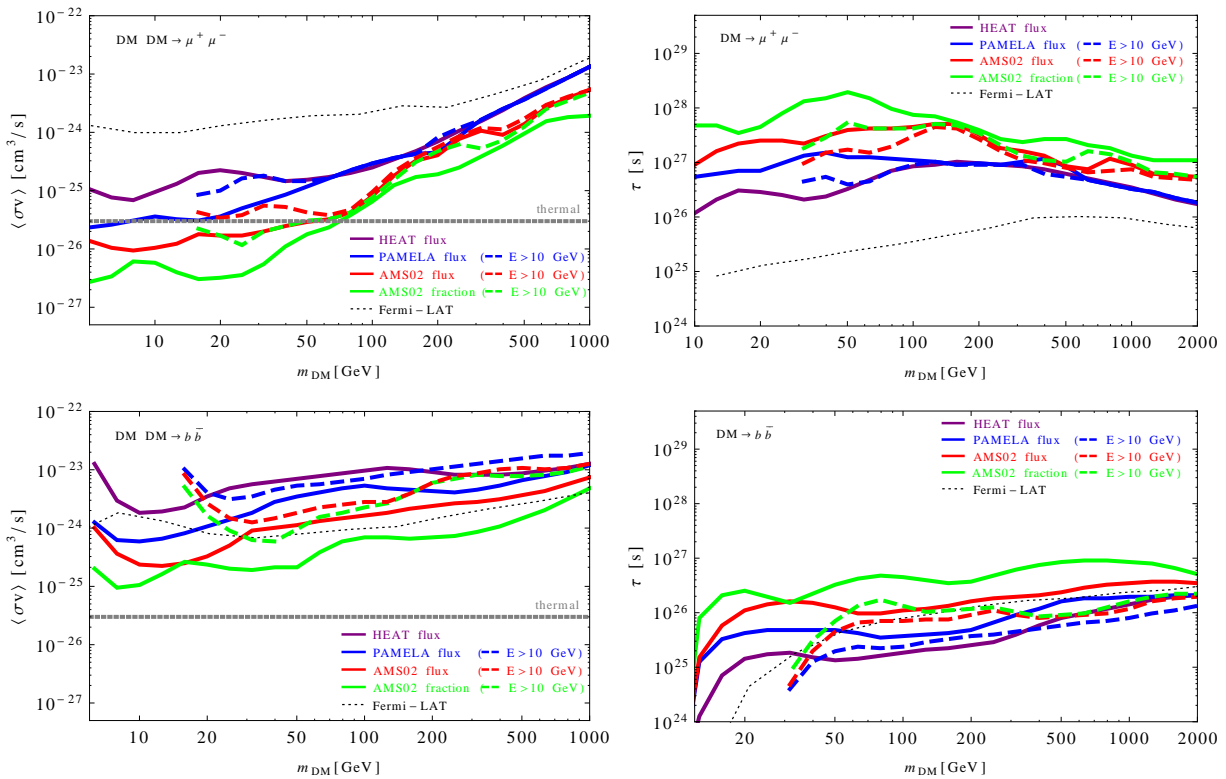
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Figure 5: Limits on the annihilation cross section (left plot) and the lifetime (right plot) derived in this paper from the HEAT, PAMELA and AMS-02 measurements of the positron flux and the AMS-02 measurements of the positron fraction, assuming the final state $\mu^+\mu^-$ (upper plots) and $b\bar{b}$ (lower plots), together with the limits reported by the Fermi-LAT collaboration in Ref. [47].

4   Conclusions

We have derived limits on the dark matter annihilation cross section and lifetime using, for the first time, measurements of the positron flux, as well as using measurements of the positron fraction. In deriving the limits, we have made the well-motivated assumption that a background positron flux exists. We have parametrized the interstellar background flux above 2 GeV as a sum of two components: a first one with an energy spectrum following a simple power law, as suggested by theoretical calculations of the secondary positron flux, and a second one following a simple power law times an exponential cut-off, as generically expected from astrophysical positron sources. Finally, the cosmic positron flux at the top of the atmosphere was calculated employing the force field approximation. The parameters entering in the background positron flux have then been fitted to the data together with the primary flux from dark matter annihilations or decays. We have further optimized the search by applying this procedure to fifty-three energy windows of different sizes and then choosing for each dark matter mass the best among all fifty-three limits. The resulting limits are very strong and are competitive to those derived from the positron fraction and also competitive (and for some channels stronger) than the limits reported by the Fermi-LAT collaboration on those same final states from gamma-ray flux measurements. Specifically, we

find that the measurements of the positron flux by AMS-02 probe the thermal cross section when the dark matter particles annihilate only into e^+e^- or into into $\mu^+\mu^-$, provided the dark matter mass is smaller than 100 GeV or 60 GeV, respectively.

Acknowledgements

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