Implications of the first AMS-02 measurement for 
dark matter annihilation and decay

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Abstract

In light of the first measurement on the positron fraction by the AMS-02 experiment, we perform a detailed global analysis on the interpretation of the latest data of PAMELA, Fermi-LAT, and AMS-02 in terms of dark matter (DM) annihilation and decay in various propagation models. The allowed regions for the DM particle mass and annihilation cross section or decay lifetime are obtained for channels with leptonic final states: $2e$, $2\mu$, $2\tau$, $4e$, $4\mu$ and $4\tau$. We show that for the conventional astrophysical background the AMS-02 positron fraction data alone favour a DM particle mass $\sim$ 500(800) GeV if DM particles annihilate dominantly into $2\mu$($4\mu$) final states, which is significantly lower than that favoured by the Fermi-LAT data on the total flux of electrons and positrons. The allowed regions by the two experiments do not overlap at a high confidence level (99.99999\%C.L.). We consider a number of propagation models with different halo height $Z_h$, diffusion parameters $D_0$ and $\delta_{1/2}$, and power indices of primary nucleon sources $\gamma_{p1/p2}$. The normalization and the slope of the electron background are also allowed to vary. We find that the tension between the two experiments can be only slightly reduced in the model with large $Z_h$ and $D_0$. The consistency of fits is improved for annihilation channels with $2\tau$ and $4\tau$ final states which favours TeV scale DM particle with large cross sections above $10^{-23}$\,cm$^3$s$^{-1}$. In all the considered leptonic channels, the current data favour the scenario of DM annihilation over DM decay. In the decay scenario, the charge asymmetric DM decay is slightly favoured.
1 Introduction

Compelling evidence from astronomical observations has indicated that dark matter contributes to nearly 27% of the energy density of the Universe \[\text{1}\]. Popular DM candidates such as the weakly interacting massive particles (WIMPs) are expected to annihilate or decay into standard model (SM) final states in the Galactic halo and beyond, which may leave imprints in the fluxes of cosmic-ray particles, including electrons, positrons, antiprotons, and cosmic gamma-rays. The ongoing satellite-borne experiments, such as PAMELA, Fermi-LAT, and AMS-02 etc. are searching for such potential indirect signatures of DM with high precision.

Significant progresses have been made in the recent years. For instance, the PAMELA collaboration has reported that the ratio of the positron flux to the total flux of electrons and positrons rises with increasing energy in the range 10–100 GeV, which is not expected from conventional astrophysical backgrounds \[\text{2, 3}\]. This result was later confirmed by Fermi-LAT, which further showed that the positron fraction continues to rise in the higher energy range 100–200 GeV \[\text{4}\]. The total flux of electrons and positrons measured by the ballon-borne experiment ATIC and BBP-BETS also showed an excess in 300–700 GeV with a peak located at around 600 GeV \[\text{5, 6}\]. Although the ATIC/BBP-BETS “bump” was not confirmed by Fermi-LAT \[\text{7, 8}\] and HESS \[\text{9, 10}\], the featureless power-law spectrum measured by Fermi-LAT corresponds to a power index 3.08 \[\text{8}\] which is harder than what expected from the conventional astrophysical background, and may also require an exotic source of cosmic-ray electrons/positrons.

Recently, the Alpha Magnetic Spectrometer (AMS-02) collaboration has released the first measurement of the positron fraction based on the collected \(6.8 \times 10^6\) events of electron and positron with unprecedented accuracy \[\text{12}\]. The result shows a steadily increasing of positron fraction from 10 to \(\sim 250\) GeV, which is consistent with the previous measurements by PAMELA and Fermi-LAT. The spectrum measured by AMS-02 is slightly lower than PAMELA for electron energy larger than \(\sim 40\) GeV, and the slope of the positron fraction spectrum decreases by an order of magnitude from 20 to \(\sim 250\) GeV. Furthermore, the current AMS-02 data show no significant fine structure or anisotropy in the positron flux.

The rising spectrum of positron fraction may have astrophysical origins, such as from nearby pulsars \[\text{13, 14}\] and supernovae remnants \[\text{15, 16}\]. These explanations will be constrained by the anisotropy and the high energy behaviour of the positron flux. Halo DM annihilation or decay can provide an alternative explanation. Given the precisely measured shape of the positron fraction spectrum by AMS-02, more insights on the nature of DM can be obtained. Although at this stage it is still impossible to distinguish different type of exotic sources, this precision measurement on the positron fraction spectrum may
shed new light on the origin of high energy cosmic-ray positrons.

In this work, we perform an updated global analysis on the DM interpretation of the current measurement of cosmic-ray electrons and positrons, for both annihilation and decay scenarios. We calculate the propagation of cosmic-ray particles using the numerical package GALPROP. Typical channels of DM annihilation and decay with final states $2\nu$, $2\mu$, $2\tau$, $4e$, $4\mu$ and $4\tau$ are investigated in a number of propagation models with different halo heights $Z_h$, diffusion parameters $D_0$, $\delta_1$, $\delta_2$ and power indices of primary nucleon sources $\gamma_{p1, p2}$, etc.. The normalization and the slope of the electron background are also allowed to vary. The results show that for DM annihilating into $2\mu$ and $4\mu$ final states, the allowed parameter regions determined by AMS-02 positron fraction data is highly inconsistent with that favoured by Fermi-LAT data on the total flux of electrons and positrons. We find that the tension between the two experiments can be slightly reduced in the case of large $Z_h$ and $D_0$. More consistent fits are obtained for $\tau$-lepton final states, which favours TeV scale DM with large cross sections above $10^{-23}$ cm$^3$s$^{-1}$. In all the considered leptonic channels, we find that the current data favour the scenario of DM annihilation over DM decay. For the DM decay scenario, both the charge symmetric and asymmetric cases are investigated. In the decay scenario, the charge asymmetric DM decay is slightly favoured.

This paper is organized as follows. In Sec. 2 we outline the framework for calculating the propagation of the cosmic-ray particles and the primary sources from DM annihilation and decays. In Sec. 3 we describe the data selection and the strategy of the data fitting in a number of propagation models. The numerical results are presented in Sec. 4. We finally conclude in Sec. 5.

2 Sources and propagation of cosmic-ray particles

In the diffusion models of cosmic-ray propagation, the Galactic halo within which the diffusion processes occur is parametrized by a cylinder with radius $R \approx 20$ kpc and half-height $Z_h$. The number densities of cosmic-ray particles are vanishing at the boundary of the halo. The processes of energy losses, reacceleration, annihilation, as well as the secondary sources of cosmic-rays are confined within the Galactic disc. The diffusion equation for the cosmic-ray particles is given by

$$\frac{\partial \psi}{\partial t} = \nabla \left( D_{xx} \nabla \psi - V_c \psi \right) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{1}{\partial p} \frac{1}{p^2} \psi - \frac{\partial}{\partial p} \left[ \dot{p} \psi - \frac{p}{3} \left( \nabla \cdot V_c \right) \psi \right] - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi + q(r, p),$$

where $\psi(r, p, t)$ is the number density per unit of total particle momentum, which is related to the phase space density $f(r, p, t)$ as $\psi(r, p, t) = 4\pi p^2 f(r, p, t)$. For steady-state diffusion,
it is assumed that $\partial \psi / \partial t = 0$. The spatial diffusion coefficient $D_{xx}$ is parametrized as

$$D_{xx} = \beta D_0 \left( \frac{\rho}{\rho_0} \right)^{\delta_{1,2}}, \quad (2)$$

where $\rho = p/(Ze)$ is the rigidity of the cosmic-ray particle, and $\delta_{1,2}$ is the power spectral index when $\rho$ is below (above) a reference rigidity $\rho_0$. The parameter $D_0$ is a normalization constant, and $\beta = v/c$ is the velocity of the cosmic-ray particle with $c$ the speed of light. The values of $D_0$ and $\delta_{1,2}$ are determined by the ratio between secondary and primary cosmic-ray species such as the ratio of Boron to Carbon (B/C) and that of isotopes $^{10}$Be/$^{9}$Be, etc.. The convection term is related to the drift of cosmic-ray particles from the Galactic disc due to the Galactic wind. The direction of the wind is usually assumed to be along the $z$-direction perpendicular to the galactic disc, and is a constant $V_C = [2\theta(z) - 1]V_c$.

The diffusion in momentum space is described by the reacceleration parameter $D_{pp}$ which is related to the Alfvén speed $V_a$ of the disturbances in the hydrodynamical plasma as follows

$$D_{pp} = \frac{4V_a^2 p^2}{3D_{xx}\delta_i (4 - \delta_i^2) (4 - \delta_i)}, \quad (3)$$

where $\delta_i = \delta_1$ or $\delta_2$, depending on the rigidity. The momentum loss rate is denoted by $\dot{p}$, and $\tau_f, \tau_r$ are the time scales for fragmentation and radioactive decay, respectively. High energy electrons/positrons loss energy due to the processes like inverse Compton scattering and synchrotron radiation. The typical propagation length is around a few kpc for electron energy around 100 GeV. In the calculation of energy loss rate, we take the interstellar magnetic field to be

$$B(r, z) = B_0 \exp \left( -\frac{r - r_0}{r_0} \right) \exp \left( -\frac{|z|}{z_0} \right), \quad (4)$$

with $B_0 = 5 \times 10^{-10}$ Tesla, $r_0 = 10$ kpc, and $z_0 = 2$ kpc.

The injection spectrum of a primary cosmic-ray particle $A$ ($A = e^-, p, \ldots$) is assumed to have a broken power law behaviour $dq_A(p)/dp \approx \rho^{-\gamma_A}$, with $\gamma_A = \gamma_{A1}(\gamma_{A2})$ for the rigidity $\rho_A$ below (above) a reference rigidity $\rho_{As}$. Secondary cosmic-ray particles are treated as decay products of charged pions and kaons created in collisions of primary cosmic-ray particles with interstellar gas.

The flux of the cosmic-ray particle is related to its density function as

$$\Phi = \frac{v}{4\pi} \psi(p). \quad (5)$$

For high energy electrons/positrons $v \approx c$. At the top of the atmosphere (TOA) of the Earth, the fluxes of cosmic-rays are affected by solar winds and the heliospheric magnetic
field. This effect is taken into account using the force-field approximation [17]. The electron/positron flux at the top of the atmosphere of the Earth $\Phi_{e^\pm}_{\text{TOA}}$ which is measured by the experiments is related to the interstellar flux as follows

$$\Phi_{e^\pm}_{\text{TOA}}(T_{\text{TOA}}) = \left(\frac{2m_e T_{\text{TOA}} + T^2_{\text{TOA}}}{2m_e T + T^2}\right) \Phi_e(T),$$

where $T_{\text{TOA}} = T - \phi_F$ is the kinetic energy of electrons/positrons at the top of the atmosphere of the Earth. We take $\phi_F = 0.55$ GV in numerical analysis. As we are interested in electrons/positrons fluxes at energies above $\sim 20$ GeV, the effect of solar modulation is less significant.

In this work, we solve the diffusion equation and calculate the energy losses for electrons by ionization, Coulomb interactions, bremsstrahlung, inverse Compton, and synchrotron using the publicly available numerical code GALPROP v54 [18–22] which makes use of realistic astronomical information on the distribution of interstellar gas and other data as input, and consider various kinds of data including primary and secondary nuclei, electrons and positrons, $\gamma$-rays, synchrotron radiation, etc. in a self-consistent way. Other approaches based on simplified assumptions on the Galactic gas distribution which allows for fast analytic solutions can be found in Refs. [?]. In solving the propagation equation, we use a very fine grid in kinetic energy space with a logarithmic scale factor 1.02. The calculations of the electron propagation in this work are cross-checked by comparing the results with that from the GALPROP webrun [28].

The primary source term from the annihilation of Majorana DM particles has the form

$$q_e(r, p) = \frac{\rho(r)^2 \langle \sigma v \rangle}{2m^2} \sum_X \eta_X \frac{dN_e^{(X)}}{dp},$$

where $\langle \sigma v \rangle$ is the velocity-averaged DM annihilation cross section multiplied by relative velocity (referred to as cross section), and $\rho(r)$ is the DM energy spatial distribution function. $dN_e^{(X)}/dp$ is the injection spectrum from DM particles annihilating into $e^\pm$ via all possible intermediate states $X$ with $\eta_X$ the corresponding branching fractions.

In the case of DM decay, if the DM particle is not its own antiparticle, its decay into charged leptons can be charge asymmetric, for instance, $\chi \to e^+ + Y^-$ while $\bar{\chi} \to e^- + Y^+$, where $Y^\pm$ can be the SM gauge boson $W^\pm$ or charged Higgs boson $H^\pm$ or other charged particle in new physics models. In the generic case where the energy density of the relic DM particles is also asymmetric, i.e., $\rho_\chi(r) \neq \rho_{\bar{\chi}}(r)$, the source term can be written as

$$q_{e^\pm}(r, p) = \frac{\rho(r)}{2m_\chi} (1 \pm \epsilon) \sum_X \eta_X \frac{dN_e^{(X)}}{dp},$$

where $\rho(r) \equiv \rho_\chi(r) + \rho_{\bar{\chi}}(r)$, $\epsilon \equiv (\rho_\chi(r) - \rho_{\bar{\chi}}(r))/(\rho_\chi(r) + \rho_{\bar{\chi}}(r))$, and $\tau$ is the life-time of the DM particle. The case where $\epsilon = 1$ ($-1$) corresponds to the DM particle decaying
into $e^+$ ($e^−$) only, and $\epsilon = 0$ corresponds to the DM decay equally into $e^+$ and $e^−$. The charged leptons from the decay of $Y^\pm$ are not considered, which corresponds to the case with maximal charge asymmetry. The phenomenology of charge asymmetric decay has been investigated previously in Refs. [29,30].

The injection spectra $dN_e^{(X)}/dp$ from DM annihilation and decay are calculated using the numerical package PYTHIA v8.175 [31]. For the decay scenario, we assume that $X^\pm$ are much lighter than the DM particle, and neglect its mass effect in the kinematics of DM decay.

The fluxes of cosmic-ray electrons and positrons from DM annihilation depend only weakly on the DM halo profile. In this work, we shall take the Einasto profile [32]

$$\rho(r) = \rho_\odot \exp \left[ -\left( \frac{2}{\alpha_E} \right) \left( \frac{r^\alpha_E - r^\alpha_E\odot}{r^\alpha_E\odot} \right) \right],$$

with $\alpha_E \approx 0.17$ and $r_s \approx 20$ kpc. The local DM energy density is fixed at $\rho_\odot = 0.43$ GeV cm$^{-3}$ [33].

### 3 Data selection and fitting schemes

In order to avoid uncertainties caused by solar modulation, we consider the latest cosmic-ray data from satellite-borne experiments with electron energy above 20 GeV which include 4 data points from PAMELA in 2010 [3], 10 data points from Fermi-LAT data in 2011 [4], and 31 data points from AMS-02 [12] for the positron fraction. For the total flux of electrons and positrons we consider the updated data of Fermi-LAT in 2010 [8] which contain 28 data points. We also include the data of electron flux measured by PAMELA (18 data points) [34] and very recently by AMS-02 (32 data points) [35]. They are important for constraining the primary electron background. Thus in total 123 data points are included in the global fits. We do not include the data of positron flux and the total flux of electrons and positrons recently reported by by AMS-02, as they are less accurate in comparison with the AMS-02 result of positron fraction and the electron flux. Some previous global fits to the earlier data can be found in Refs. [36–38]. Note that the electron spectrum of the Fermi-LAT 2010 data is smoother than the one previously reported in 2009 [7], which results in visible modifications to the best-fit parameters such as the DM particle mass and annihilation cross section or decay lift-time.

In this work, the DM particle annihilating and decay into two-body and four-body charged leptonic final states $e, \mu, \tau$ are investigated. The relevant quantities are determined through $\chi^2$-fits to the data. The expression of $\chi^2$ is given by

$$\chi^2 = \sum_i \frac{(f_{i}^{\text{th}} - f_{i}^{\text{exp}})^2}{\sigma_i^2},$$
where \( f_i^{\text{th}} \) are the theoretical predictions. \( f_i^{\exp} \) and \( \sigma_i \) are the central values and errors of experimental data, respectively. The index \( i \) runs over all the available data points.

The outcome of the global fits depends on the choice of the parameters appearing in the propagation equation Eq. (11). The uncertainties related to these parameters need to be discussed separately. The height of the propagation halo \( Z_h \) and the diffusion parameters such as \( D_0 \) and \( \delta_{1,2} \) affect both the cosmic-ray backgrounds and the DM-induced cosmic-ray fluxes, while the primary injection indices \( \gamma_{e1,e2} \) and \( \gamma_{p1,p2} \) affect the backgrounds of electrons and positrons. We first consider two benchmark propagation models which are extensively studied in the literature

- **Model A**, the so-called conventional diffusive reacceleration model [20,22] which is commonly adopted by the current experimental collaborations such as PAMELA [34,39,40] and Fermi-LAT [8,41] as a benchmark model for the astrophysical backgrounds and the propagation of cosmic antiparticles from DM annihilation/decay. The location of the observed peak in the spectrum of B/C at about 1 GeV is well reproduced in this model. The propagation parameters in this model are determined from fitting the ratio of the secondary to primary nuclei such as B/C, the flux of primary such as Carbon, and the Galactic distribution of cosmic-ray sources are determined from the EGRET gamma-ray data. In this model, the break in the diffusion coefficient is \( \rho_0 = 4 \) GV with \( \delta_1 = \delta_2 = 0.34 \). The break of the primary electron source and proton sources are \( \rho_e = 4 \) GV, and \( \rho_p = 9 \) GV, respectively. The Alfvén velocity is set to \( V_a = 36.0 \) km s\(^{-1}\). The power indices \( \delta_{1,2}, \gamma_{e1,e2}, \gamma_{p1,p2} \) as well as other parameters in this model are listed in Tab. 1.

- **Model B**, the parameter set determined from a comprehensive global Bayesian analysis to the data of B/C, \(^{10}\text{Be}/^{9}\text{Be}, \text{Carbon and Oxegen}, \text{etc.}, \text{using nested sampling Markov Chain Monte Carlo method [42]} \). The gamma-ray data of Fermi-LAT are used to determine the distribution of cosmic-ray sources. In this model, the break in the diffusion coefficient is the same \( \rho_0 = 4 \) GV. The break of the primary electron source and proton sources are \( \rho_e = 4 \) GV, and \( \rho_p = 10 \) GV, respectively. The Alfvén speed is \( V_a = 39.2 \) km s\(^{-1}\). Other parameters in the model are listed in Tab. 1.

In Ref. [42], the uncertainties as well as the correlations of the propagation parameters of Model B were carefully studied, which facilitates the investigation on the uncertainties induced by each propagation parameter separately. The allowed ranges for these parameters at 95\% C.L. are given by [42]

\[
Z_h = (3.2 - 8.6) \text{ kpc}, D_0 = (5.45 - 11.2) \times 10^{28} \text{ cm}^2 \text{s}^{-1}, \delta_2 = 0.26 - 0.35, \\
\gamma_{p1} = 1.84 - 2.00, \gamma_{p2} = 2.29 - 2.47, V_a = (34.2 - 42.7) \text{ km s}^{-1}.
\] (11)
Some of the parameters such as $\delta_1$, $\gamma_{p1}$ and $V_a$ only affect the predicted fluxes at low energies. The parameters which are most relevant to the electron and positron fluxes at high energies above 20 GeV are $Z_h$, $D_0$, $\delta_2$ and $\gamma_{p2}$. To see how the fit results change within the uncertainties of the parameters, we consider several limiting cases in each case one of the parameters is set at its upper or lower limit given in Eq. (11). The differences in the fit results can be regarded as an estimation of the uncertainties from that propagation parameter. Thus besides Model A and B, we further consider the following six propagation models:

- **Model C1 (C2)**, the halo half-height $Z_h$ is taken to its lower (upper) limit $Z_h = 3.2 (8.6)$ kpc. Since it has been shown that $Z_h$ and $D_0$ are positively correlated [42], we must take the value of $D_0$ to be $5.45 (11.2) \times 10^{28}$ cm$^2$s$^{-1}$ accordingly. The rest of parameters in this model are fixed at their best-fit values as that in Model B.

- **Model D1 (D2)**, the power index $\delta_2$ is taken to is lower (upper) limit $\delta_2 = 0.26 (0.35)$, and the relation $\delta_1 = \delta_2$ is still assumed. The rest of parameters are the same as that in Model B.

- **Model E1 (E2)**, the power index of the injection spectrum of proton $\gamma_{p2}$ which is related to the source of secondary positrons is taken to its lower and upper limit $\gamma_{p2} = 2.29 (2.47)$. The rest of parameters are the same as that in Model B.

The corresponding parameters in all the eight propagation models from Model A to Model E2 are summarized in Tab. 1.

### Table 1: Parameters of eight propagation models from Model A to Model E2. The diffusion coefficient $D_0$ is in units of $10^{28}$ cm$^2$s$^{-1}$.

| Model | $z_h$(kpc) | $D_0$   | $\delta_2$ | $\gamma_{e1}/\gamma_{e2}$ | $\gamma_{p1}/\gamma_{p2}$ |
|-------|------------|---------|------------|--------------------------|--------------------------|
| A     | 4.0        | 5.75    | 0.34       | 1.6/2.5                  | 1.82/2.36                |
| B     | 3.9        | 6.59    | 0.30       | 1.6/2.5                  | 1.91/2.42                |
| C1(C2)| 3.2(8.6)   | 5.45(11.2) | 0.30       | 1.6/2.5                  | 1.91/2.42                |
| D1(D2)| 3.9        | 6.59    | 0.26(0.35) | 1.6/2.5                  | 1.91/2.42                |
| E1(E2)| 3.9        | 6.59    | 0.30       | 1.6/2.5                  | 1.91/2.29(2.47)          |

In all the considered models the power indices of primary electron $\gamma_{e1}/\gamma_{e2}$ are fixed at 1.6/2.5 which are determined from fitting the early cosmic-ray electron data. In order to take into account the uncertainties in the primary electrons, we multiply a scaling factor $\kappa$ and an energy-dependent factor $(E/\text{GeV})^\delta$ to the primary electron flux $\Phi_{e^-}^{bg}$ after propagation. The expressions for the positron fraction and the total flux of electron and
positron are modified as follows

\[ \Phi_{\text{tot}} = \left( \kappa \frac{E}{\text{GeV}} \delta \Phi_{e^+}^{\text{bg}} + \Phi_{e^+}^{\text{DM}} \right) + \left( \Phi_{e^-}^{\text{DM}} + \Phi_{e^+}^{\text{DM}} \right), \]

\[ R_{e^+} = \left( \Phi_{e^+}^{\text{DM}} + \Phi_{e^+}^{\text{bg}} \right) / \Phi_{\text{tot}}, \]

(12)

where \( \Phi_{e^\pm}^{\text{DM}} \) and \( \Phi_{e^\pm}^{\text{bg}} \) are the fluxes from DM annihilation/decay and background calculated from the GALPROP code, respectively. Both the values of \( \kappa \) and \( \delta \) are treated as free parameters to be determined from the data. Thus in the case of DM annihilation, we have in total four free parameters: \( m_\chi, \langle \sigma v \rangle, \kappa, \) and \( \delta \) to be determined by the experimental data in eight different propagation models from Model A to Model E2. Note that under the approximation \( \Phi_{e^\pm}^{\text{bg}} \ll \Phi_{e^\pm}^{\text{DM}} \ll \Phi_{e^-}^{\text{bg}} \), which is often valid at high energies, the positron fraction can be rewritten as

\[ R_{e^+} \approx \frac{\Phi_{e^+}^{\text{DM}}}{\kappa \frac{E}{\text{GeV}} \delta \Phi_{e^-}^{\text{bg}}} \]

(13)

Since \( \Phi_{e^+}^{\text{DM}} \) is proportional to \( \langle \sigma v \rangle \), it is expected that in this limit there will be a degeneracy in determining \( \langle \sigma v \rangle \) and \( \kappa \), which means that if we only consider the data of positron fraction \( \langle \sigma v \rangle \) will be sensitive to \( \kappa \). This degeneracy can be removed by including the measurements of electron fluxes by PAMELA \cite{34} and recently by AMS-02 \cite{35}.

In comparing the experimental data with the theoretical predictions, we take into account the effect of finite energy resolution of the detectors, namely, the predicted fluxes are convoluted according to the energy resolution for each experimental detector. The energy resolution of PAMELA is nearly a constant \( \sim 5\% \) above 10 GeV \cite{43}. The energy resolution of Ferm-LAT is \( \sim 6\% \) at 7 GeV and \( \sim 15\% \) at 1 TeV, and we take the numerical values from Ref. \cite{8} in the calculation. For the resolution of AMS-02 detector, we use the parametrization \( \sigma(E)/E = [(0.104/\sqrt{E/\text{GeV}})^2 + (0.014)^2]^{1/2} \) which reaches \( \sim 1.4\% \) at high energies \cite{12}.

4 Results

4.1 Fits with annihilating dark matter

We first consider DM annihilation into charged leptons in Model A and B. The best-fit parameters and the corresponding \( \chi^2/\text{d.o.f} \) value for each annihilation channel are given in Tab. 2. The predicted spectra of the positron fraction and the total flux of electrons and positrons corresponding to the best-fit parameters are shown in Fig. 1 and Fig. 2 respectively. In general, the qualities of the fits are not good for final states with electrons and muons. Among all the channels, only the 2\( \tau \) and 4\( \tau \) channels have \( \chi^2/\text{d.o.f} < 2 \). For 2e
Table 2: Best-fit values of parameters $m_\chi$, $\langle \sigma v \rangle$, $\kappa$ and $\delta$, as well as the $\chi^2$/d.o.f for DM particles annihilating into $2e$, $2\mu$, $2\tau$, $4e$, $4\mu$ and $4\tau$ final states. For each final states, the values in the first (second) row corresponds to the results in Model A (B). The cross section $\langle \sigma v \rangle$ is in units of $10^{-26}$ cm$^3$s$^{-1}$.

| Channel | $m_\chi$(GeV) | $\langle \sigma v \rangle$ | $\kappa$ | $\delta(\times10^{-2})$ | $\chi^2_{\text{tot}}$/d.o.f |
|---------|---------------|----------------------------|---------|-------------------------|----------------------------|
| $2e$    | 407.1         | 67.8                       | 1.064   | -6.43                   | 450.56/119                 |
|         | 404.9         | 55.9                       | 1.079   | -7.72                   | 403.40/119                 |
| $2\mu$  | 570.0         | 244                        | 0.997   | -4.12                   | 343.25/119                 |
|         | 793.8         | 387                        | 1.136   | -8.71                   | 299.60/119                 |
| $2\tau$ | 1534.3        | 1780                       | 1.154   | -7.62                   | 219.67/119                 |
|         | 1860.1        | 2230                       | 1.234   | -10.4                   | 210.78/119                 |
| $4e$    | 423.5         | 59.0                       | 0.924   | -2.25                   | 415.21/119                 |
|         | 664.2         | 115                        | 1.106   | -8.22                   | 355.25/119                 |
| $4\mu$  | 1095.7        | 497                        | 1.049   | -5.32                   | 290.18/119                 |
|         | 1409.7        | 690                        | 1.158   | -9.01                   | 262.22/119                 |
| $4\tau$ | 3068.4        | 3860                       | 1.186   | -8.26                   | 205.72/119                 |
|         | 3794.3        | 4980                       | 1.260   | -10.9                   | 199.29/119                 |

final states, the large $\chi^2$/d.o.f = 3.67 (3.28) in Model A (B) indicates a high inconsistency between the theoretical expectation and the experimental data. The best-fit values are $m_\chi \approx 407$ (405) GeV and $\langle \sigma v \rangle \approx 6.8$ (5.6) $\times 10^{-25}$ cm$^3$s$^{-1}$ in Model A (B). It is known that the spectra of DM annihilation into $2e$ and $4e$ are too sharp to fit the measured relatively smooth fluxes, which can be seen clearly in Fig. 1 and Fig. 2. Thus in the remainder of this section we should focus on DM annihilation/decay into $\mu$ and $\tau$ final states. The contours for the allowed regions from the global fit for parameters ($m_\chi$, $\langle \sigma v \rangle$) and ($\kappa$, $\delta$) at 99% C.L. corresponding to $\Delta \chi^2 = 9.21$ for two variables are shown in Fig. 3 and Fig. 4, respectively. For all the final states, the favoured DM annihilation cross sections are larger than the typical thermal WIMP annihilation cross section $\langle \sigma v \rangle_0 \approx 3 \times 10^{-26}$ cm$^3$s$^{-1}$ by 2–3 orders of magnitude, especially for $2\tau$ and $4\tau$ cases. The figures show that the values of $\langle \sigma v \rangle$ roughly scales with DM particle mass as $m_\chi^2$, which is due to the term $\langle \sigma v \rangle/m_\chi^2$ in the source term in Eq. (7). The the allowed values of $\kappa$ and $\delta$ are mostly determined by the electron data from AMS-02 [35] and PAMELA [34]. As shown in Fig. 4, there exists a negative correlation between $\kappa$ and $\delta$, as they appear as a combination $\kappa(E/E_0)^\delta$. For a given value of $E$, increasing the value of $\kappa$ leads to a decrease of $\delta$. 

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Figure 1: Predicted positron fraction (left) and the total flux of electrons and positrons (right) from DM annihilating to $2e$, $2\mu$ and $2\tau$ final state according to the best-fit parameters shown in Tab. 2 in Model A and B. The data of positron fraction from PAMELA [8], AMS-02 [12] and Fermi-LAT2012 [4] the total flux from Fermi-LAT [8] the electrons flux from PAMELA [34] and AMS-02 [35] are also shown.

In Fig. 3, we also show the regions allowed by each single measurement such as AMS-02, PAMELA and Fermi-LAT. As already discussed in the previous section, the measurement of positron fraction alone can hardly constrain the value of $\kappa$ and $\delta$. We take the values of $\kappa$ and $\delta$ as inputs, with central values and uncertainties determined from each global fit. The correlations between $\kappa$ and $\delta$ are taken into account using the covariance matrix calculated from the global fit using the MINUIT package, which are consistent with Fig. 4. In all the figures, there is a visible difference between the AMS-02 favoured region and that from the global fit, which is due to the stronger $\kappa$-dependence of the positron fraction.
than that of the total flux of electrons and positrons.

For 2μ final states, the favoured DM particle mass and the cross section from the global fit are: $m_\chi \approx 570 \ (794) \text{ GeV}$ and $\langle \sigma v \rangle \approx 2.4 \ (3.9) \times 10^{-24} \text{ cm}^3\text{s}^{-1}$ for model A (B). Previous fits using PAMELA and Fermi-LAT data showed that both the positron fraction and the total flux of electrons and positrons can be well fitted for 2μ and 4μ channels \cite{36,38}. This conclusion is changed after AMS-02. Unlike the PAMELA positron fraction data which can only determine the annihilation cross section as a function of DM particle mass, the high precision AMS-02 data actually constrain both the mass and annihilation cross section in a relatively small region. The first AMS-02 data feature a steady decreasing slope of the positron fraction. From 20 GeV to $\sim 250$ GeV, the slope of the positron fraction decreases by an order of magnitude. Such a trend disfavour a TeV scale DM particle preferred by the Fermi-LAT data as for such a heavy DM particle the predicted slope of the spectrum

Figure 2: The same as Fig. 1 but for DM annihilating into 4e, 4μ and 4τ final states.
Figure 3: Allowed regions in \( (m_\chi, \langle \sigma v \rangle) \) plane at 99% C.L. for DM annihilating into 2\( \mu \), 2\( \tau \), 4\( \mu \) and 4\( \tau \) final states from the Global fits. The regions allowed by data of PAMELA \cite{3}, Fermi-LAT \cite{4,8} and AMS-02 \cite{12} are shown for a comparison. The AMS-02 favoured regions are also displayed in the insets. See text for explanations.

will not drop in the low energy region \( E \lesssim 300 \) GeV. On the other hand, as can be seen in Fig. 1, a low mass DM cannot account for the excesses in Fermi-LAT data.

The inconsistency between AMS-02 and Fermi-LAT data in 2\( \mu \) and 4\( \mu \) channels in Model A can be clearly seen in Fig. 3 in which the allowed regions by AMS-02 and Fermi-LAT at 99% C.L. in \( (m_\chi, \langle \sigma v \rangle) \) plane are plotted separately. In the figure, neither the cross section nor the DM particle mass determined by the AMS-02 data is consistent with Fermi-LAT data for 2\( \mu \) and 4\( \mu \) channels. For instance, for 2\( \mu \) channel, the Fermi-LAT data alone favour \( m_\chi \approx 1.3 \) TeV which is far away from the value \( \sim 476 \) GeV determined by AMS-02. The best fitted cross section from Fermi-LAT is \( \langle \sigma v \rangle \approx 6.8 \times 10^{-24} \) cm\(^3\)s\(^{-1}\) which is also larger roughly by a factor of two. In Fig. 5 detailed comparisons between the AMS-02 and Fermi-LAT favoured regions at higher confidence levels 99.99% (99.99999%) C.L. corresponding to \( \Delta \chi^2 = 23.0 \) (32.2) are shown for model A. One sees that even at 99.99999% C.L. the two experimental results of AMS-02 and Fermi-LAT cannot be reconciled. The situation in model B is similar as shown in Fig. 6. In this model the favoured regions by AMS-02 and Fermi-LAT are also well separated.

It is necessary to check if such an observation is robust against the variations of the
propagation parameters. We first consider the effect of changing the diffusion coefficient $D_0$ and the diffusion halo height $Z_h$. It is known that change in $D_0$ can result in changes in the ratio of secondaries to primaries. In Fig. 6, we show how the allowed regions change in model C1 (C2), which corresponds to a typically lower (upper) value of $D_0 = 5.45 \times 10^{28}$ cm$^2$s$^{-1}$, and $Z_h = 3.2 \times (8.6)$ kpc. The corresponding spectra for positron fraction and the total flux of electrons and positrons for best-fit parameters are also shown in Fig. 6. We find that for larger diffusion constant $D_0 = 11.2 \times 10^{28}$ cm$^2$s$^{-1}$, the disagreement between the results of AMS-02 and Fermi-LAT can be slightly reduced. This is due to the fact that a larger $D_0$ reduces the background of the positron fraction, which leaves greater room for heavier DM particle. In $2\mu$ channel, the best-fit DM particle mass is $m_\chi = 602$ GeV in Model C1. But for Model C2, the best-fit value is $m_\chi = 1.3$ TeV with the $\chi^2$/d.o.f value decreasing from 332.1/119 (Model C1) to 189.6/119 (Model C2), indicating a more consistent fit. Note that in this case the value of $Z_h = 8.6$ kpc is also quite large.

We then consider the variation of the power index $\delta_2$ in the diffusion term. In Model D1 (D2) the value of $\delta_2$ is set to be 0.26 (0.35). The results are shown in Fig. 7. Since the value of $\delta_2$ is well constrained, the changes in the allowed regions are less significant in comparison with Model B. Finally consider the variation of the power index $\gamma_p$ is considered. In model E1 (E2), the value of $\gamma_p$ is set to 2.29 (2.47). The fit results are also shown in Fig. 7. The change in $\gamma_p$ has greater effect in positron fraction than that in the total flux of electrons and positrons. This can be understood as the secondary positrons mainly arise from the interactions between the primary proton and the interstellar medium. We find again that the variation of $\gamma_p$ cannot relax the tension between the two experiments.

In a brief summary, we have found that in these models from A to E2, only the one with large diffusion coefficient $D_0$ and $Z_h$ can slightly reduce the tension between AMS-02
and Fermi-LAT. Since the uncertainties in $\kappa$ and $\delta$ have been considered in the fits, the results indicate that such a discrepancy between AMS-02 and Fermi-LAT are unlikely to be removed by varying the normalization and slope of the astrophysical background.

In the case of $2\tau$ channel, the predicted fluxes are much smoother compared with that in the $2e$ and $2\mu$ channels. The agreement with the data is improved. In Model A (B), the goodness of fit is $\chi^2$/d.o.f = 1.8 (1.7), the favoured DM particle mass is around 1.5 (1.9) TeV with cross section $\langle \sigma v \rangle \approx 1.8 (2.2) \times 10^{-23} \text{ cm}^3\text{s}^{-1}$. As shown in Fig. 5, the region of parameters favoured by the AMS-02 data is marginally consistent with that favoured by Fermi-LAT at 99% C.L.. At higher confidence level such as 99.99999%, there is a visible overlap between the two experiments. In both Model A and B, the best-fit annihilation cross sections are very large, which calls for a large boost factor of $\mathcal{O}(600 - 700)$, and can be severely constrained by the nonobservation of gamma-rays from various sources in the sky. For instance, the constraint from the Galactic diffuse gamma-ray can reach...
Figure 6: (Left column) Comparison of allowed regions in \((m_\chi, \langle \sigma v \rangle)\) plane at 99% C.L. by the data of AMS-02 on positron fraction [12] and Fermi-LAT on the total flux of electrons and positrons [8] for DM annihilating into \(2\mu\) and \(4\mu\) final states in Model B, C1 and C2, corresponding to the variation of \(Z_h\) and \(D_0\). (Middle column) predictions for the positron fraction with the best-fit parameters shown in Tab. 2 in the three models. (Right column) predictions for the total flux of electrons and positrons with the best-fit parameters in the three models. See text for explanation.
Figure 7: Allowed regions in $(m_\chi, \langle \sigma v \rangle)$ plane at 99% C.L. by the data of AMS-02 on positron fraction \[12\] and Fermi-LAT on the total flux of electrons and positrons \[8\] for DM annihilating into $2\mu$ and $4\mu$ final states in D1 and D2, corresponding to the variation of $\delta_2$ (upper row) and in Model E1 and E2, corresponding to the variation of $\gamma_{p2}$ (lower row). The allowed regions in Model B are shown for a comparison.
\[ \sim 1 \times 10^{-23} \text{cm}^3\text{s}^{-1} \] at \( m_\chi \approx 1.5 \text{ TeV} \) for \( 2\tau \) channel with isothermal DM profile. Similar discussions only considering the AMS-02 data can be found in Refs. [15, 16].

The fit results for DM particle annihilating into four-lepton channels are shown in Tab. [2]. The injection spectra from the four-lepton channels are in general smoother than the corresponding two-lepton channels, which results in better fits. Among all the channels, the \( 4\tau \) channel has the lowest \( \chi^2/\text{d.o.f} \approx 1.7 \) (1.6) in both Model A (B). The four-lepton channels in general prefer larger DM particle masses. For instance, the best-fitted DM mass is \( \sim 1 - 1.5 \text{ TeV} \) for \( 4\mu \) and \( \sim 3 - 4 \text{ TeV} \) for \( 4\tau \) final states. The required cross sections are also large, as it is shown in the right column of Fig. [3].

### 4.2 Fits with decaying dark matter

We proceed to perform global fits for the DM decay scenario. Although the injection spectrum from a decaying DM particle with mass \( m_\chi \) should be the same for the annihilating DM particle with mass \( m_\chi/2 \), the final electron/positron flux after propagation is slightly different due to the different DM density distribution dependences, namely, the source term is proportional to \( \rho(r) \) in the case of DM decay, but it is proportional to \( \rho^2(r) \) in the case of DM annihilation. For Einasto profile, the final electron/positron flux after propagation tends to be slightly steeper in the case of DM decay. Such a small spectral difference between decay and annihilation is unlikely to be distinguished by PAMELA and Fermi-LAT data, but can lead to significantly different results when fit includes precision AMS-02 data.

We first consider the case with charge symmetric decays, namely, \( \epsilon = 0 \). The results of best-fit parameters are listed in Tab. [3] for Model A and Model B. We find that in general the fits in the case of DM decay have larger \( \chi^2 \) than that in DM annihilation. For instance, for the channels with electron final states, the \( \chi^2/\text{d.o.f} \) can reach \( \sim 7.3 \) (6.9) in Model A (B), indicating rather poor fits with electron final states. Thus we shall focus on \( \mu \) and \( \tau \) final states instead.

In Fig. [10] we show the allowed regions in the \((m_\chi, \tau)\) plane at 99\% C.L. for DM particle decaying into \( 2\mu, 2\tau, 4\mu \) and \( 4\tau \) final states in Model A. The corresponding allowed regions in \((\kappa, \delta)\) plane at the same confidence level are shown in the right panel of Fig. [4]. We follow the same fitting strategy in obtaining the allowed region in \((m_\chi, \tau)\) plane by each single experiment as in the case of DM annihilation, namely, the values of \( \kappa \) and \( \delta \) from the global fit are taken as inputs. From the figure, one sees that there is no overlapping region between Fermi-LAT and AMS-02 favoured region at 99\% C.L. in Model A for all the final states. In the case of Model B, very similar results are obtained. The contours of the allowed regions in \((m_\chi, \langle \sigma v \rangle)\) plane for Model C1 and C2 are shown in Fig. [11]. We find that for the Model C2 with large diffusion coefficient, the tension between AMS-02
and Fermi-LAT is not reduced as that in the case of DM annihilation. In $2\mu$ channel, the best-fit DM particle mass is $m_\chi = 705$ GeV in Model C1. For Model C2, the best-fit value is $m_\chi = 733$ GeV with the $\chi^2$/d.o.f value decreasing from $456.1/119$ (Model C1) to $461.3/119$ (Model C2). Thus there is no improvement in the goodness-of-fit.

| mode | $m_\chi$(GeV) | $\tau$(×$10^{26}$s) | $\kappa$ | $\delta$(×$10^{-2}$) | $\chi^2_{\text{tot}}$/dof |
|------|---------------|----------------------|----------|----------------------|--------------------------|
| $2e$ | 334.0         | 21.1                 | 0.632    | 6.79                 | 892.87/119               |
|      | 332.1         | 24.2                 | 0.673    | 4.25                 | 836.39/119               |
| $2\mu$ | 654.8        | 6.27                 | 0.806    | 1.40                 | 510.77/119               |
|      | 691.1         | 6.39                 | 0.856    | -1.24                | 493.92/119               |
| $2\tau$ | 1762.4       | 2.15                 | 1.019    | -4.41                | 291.92/119               |
|      | 1860.1        | 2.19                 | 1.072    | -6.79                | 291.56/119               |
| $4e$ | 506.2         | 19.3                 | 0.737    | 3.54                 | 622.69/119               |
|      | 523.7         | 19.9                 | 0.787    | 0.81                 | 594.44/119               |
| $4\mu$ | 1258.6        | 5.76                 | 0.882    | -0.78                | 414.90/119               |
|      | 1328.4        | 5.85                 | 0.933    | -3.32                | 406.53/119               |
| $4\tau$ | 3455.5        | 1.97                 | 1.058    | -5.34                | 265.93/119               |
|      | 3647.0        | 2.01                 | 1.112    | -7.69                | 266.56/119               |

Table 3: Best-fit values of $m_\chi$, $\tau$, $\kappa$ and $\delta$, as well as the $\chi^2$/d.o.f for DM particles decaying into $2e$, $2\mu$, $2\tau$, $4e$, $4\mu$ and $4\tau$ final states, assuming no charge asymmetry. For each final states, the values in the first (second) row corresponds to the results in Model A (B).

In the case of charge asymmetric decay, i.e. $\epsilon \neq 0$, the predicted positron fraction can vary without changing the total flux of electrons and positrons. For $\epsilon = 1$, the positron fraction is increased by a factor of two compared with the case where $\epsilon = 0$. On the other hand, $\epsilon < 0$ will suppress the positron fraction. Introducing $\epsilon$ leads to more freedom to fit the data. However, from Eq. (8) and Eq. (13), change in the factor $(1 + \epsilon)$ can be compensated by the changes in the values of $\kappa$ and $\delta$. Thus a precise determination of $\epsilon$ requires that the values of $\kappa$ and $\delta$ should be precisely determined independently.

In the first step, we consider a simplified case where $\kappa$ and $\delta$ are fixed at some typical values $\kappa = 0.85$ and $\delta = 0$. For fixed $\kappa$ and $\delta$, the values of $\epsilon$ can be well determined from the global fit. In the left panel of Fig. 12 the values of $\chi^2$ as a function of $\epsilon$ are shown. At 99% C.L., only the $2\mu$ channel slightly prefers a nonzero $\epsilon$ in the range $0.02 - 0.41$. The allowed values of $\epsilon$ for $2\tau$, $4\mu$ and $4\tau$ channels are all compatible with zero.

When $\kappa$ and $\delta$ are treated as free parameters in the global fit, the $\chi^2$ values decrease significantly. For instance, in $2\tau$ channel, the minimal value of $\chi^2$ is reduced from 294.5 to
Figure 8: The same as Fig. 1 but for the case of DM decay.
Figure 9: The same as Fig. 2 but for the case of DM decay.
Figure 10: The same as Fig. 3 but for the allowed regions in \((m_\chi, \tau)\) plane at 99\% C.L. for DM decaying into 2\(\mu\), 2\(\tau\), 4\(\mu\) and 4\(\tau\) final states from the Global fits.

254.1. In all the four channels the best-fit values are \(\epsilon \approx 1\). However, as shown in the right panel of Fig. 12, the corresponding \(\chi^2\) curves are rather flat for \(\epsilon > 0\), which indicates less accurate determinations of \(\epsilon\), especially for 2\(\tau\) and 4\(\tau\) channels. At 99\% C.L., the allowed ranges for \(\epsilon\) are \(\sim 0.66 - 1.0\) and \(\sim 0.64 - 1.0\) for 2\(\mu\) and 4\(\mu\) channels, respectively. For 2\(\tau\) and 4\(\tau\) channels, the allowed ranges are \(\sim 0.41 - 1.0\) and \(\sim 0.20 - 1.0\) respectively. We thus conclude that the current data slightly favour the scenario of asymmetric DM decay. But the statistical significance is not very high. For obtaining a robust conclusion, more experimental data are needed.

5 Conclusions

The AMS-02 collaboration has released the first measurement of the positron fraction with unprecedented accuracy. Using the publicly available GALPROP code, we have performed a global analysis on the latest data of PAMELA, Fermi-LAT, and AMS-02, in terms of DM annihilation and decay into 2\(e\), 2\(\mu\), 2\(\tau\), 4\(e\), 4\(\mu\) and 4\(\tau\) final states. A number of propagation models with different halo heights \(Z_h\), diffusion parameters \(D_0, \delta_{1,2}\) and
power indices of primary nucleon sources $\gamma_{p1, p2}$, etc. are considered. The normalization and slope of the background electron fluxes are also allowed to vary. We have found that for $2\mu$ and $4\mu$ final states, the parameter regions determined by AMS-02 is significantly different from that favoured by Fermi-LAT data on the total flux of electrons and positrons. For the conventional background model (Model A), the two allowed regions do not overlap even at 99.99999% C.L. For other models, we find that the tension between the two experiments can only be slightly reduced in the case of large $Z_h$ and $D_0$ in Model C2. The consistency of fits are improved for $2\tau$ and $4\tau$ final states, which favours TeV scale DM with large cross sections corresponding to the boost factor of $O(1000)$. However, such large annihilations can be in tension with the current measurements of cosmic gamma-rays. In all the considered leptonic channels, we find that the current data favour the scenario of DM annihilation over DM decay. In the decay scenario, we have considered both charge symmetric and asymmetric decays. The results are sensitive to the value of $\kappa$ and $\delta$. For fixed typical values of $\kappa$ and $\delta$, the charge asymmetric factor $\epsilon$ is well determined and compatible with zero at 99% C.L.. When both $\kappa$ and $\delta$ are taken as free parameters, the global fits favour $\epsilon = 1$, but the uncertainties in $\epsilon$ become significantly larger. Thus, currently the charge asymmetric DM decay is only slightly favoured.

Note added: As we were finalizing the first version of the manuscript, a preprint with similar global fitting analysis but different treatment of backgrounds and different focus came out [47]. The conclusions in this work are in agreement with theirs.
Figure 12: Values of $\chi^2$ as a function of charge asymmetric parameter $\epsilon$ from the global fits for the decay final states $2\mu$, $4\mu$, $2\tau$ and $4\tau$ for the case with fixed $\kappa = 0.85$ and $\delta = 0$ (left) and with $\kappa$ and $\delta$ as free parameters determined by the global fit (right).

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