Revisit of cosmic ray antiprotons from dark matter annihilation with updated constraints on the background model from AMS-02 and collider data

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Abstract. We study the cosmic ray antiprotons with updated constraints on the propagation, proton injection, and solar modulation parameters based on the newest AMS-02 data near the Earth and Voyager data in the local interstellar space, and on the cross section of antiproton production due to proton-proton collisions based on new collider data. We use a Bayesian approach to properly consider the uncertainties of the model predictions of both the background and the dark matter (DM) annihilation components of antiprotons. We find that including an extra component of antiprotons from the annihilation of DM particles into a pair of quarks can improve the fit to the AMS-02 antiproton data considerably. The favored mass of DM particles is about $60 \sim 100$ GeV, and the annihilation cross section is just at the level of the thermal production of DM $(\langle \sigma v \rangle \sim O(10^{-26}) \text{ cm}^3 \text{ s}^{-1})$.

Keywords: dark matter, cosmic ray

ArXiv ePrint: 1803.02163

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1 Introduction

Cosmic ray (CR) antiprotons are one of the most important probes to indirectly detect dark matter (DM) particles. Quite a number of balloon and space detectors have been dedicated to precisely measuring the antiproton fluxes and antiproton-to-proton ratios since 1990s [1–14]. Large progresses have been made in recent years thanks to the operation of the Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics (PAMELA; [15]) and the Alpha Magnetic Spectrometer (AMS-02). The antiproton flux has been measured to \( \sim 500 \) GeV by AMS-02 with high precision [14], which improved the constraints on either the CR or the DM models effectively [16–25].

The propagation of CRs is typically one of the largest sources of uncertainties in predicting the background of antiprotons and the signal from DM annihilation [26–28]. The propagation of charged particles in the Milky Way can be described by a diffusion process in the random magnetic field. The collision between primary nuclei and the interstellar gas leads to fragmentation of the parent nuclei and the production of secondary nuclei. Therefore the secondary-to-primary particle ratio, e.g., the Boron-to-Carbon (B/C) ratio, is usually employed to constrain the propagation parameters [29–32]. The precise measurements of CR fluxes and/or flux ratios by AMS-02 [14, 33] shed new light on the understanding of CR propagation [16, 17, 34–36].

Using the improved constraints on the propagation model parameters [16, 34], it was found that there might be an excess of the antiproton flux around a few GeV energies compared with the background contribution from \( pp \) collisions, and a DM model could simply explain this excess without constraints from other observations such as \( \gamma \)-rays [37, 38]. More interestingly, the model parameters to account for the antiproton excess are consistent with that proposed to explain the Galactic center \( \gamma \)-ray excess [39–42], the tentative \( \gamma \)-ray excesses in the directions of two dwarf galaxies [43, 44], and a possible \( \gamma \)-ray line-like feature from a population of clusters of galaxies [45]. Such coincidence makes DM a promising explanation of the possible antiproton excess [46].

Most recently, the AMS-02 collaboration reported new measurements of the primary (He, C, O) and secondary (Li, Be, B) nucleus fluxes [47, 48]. These results are expected to give more consistent constraints on the CR propagation models and parameters since they are closely relevant parent and daughter particles (different from the B/C ratio and proton fluxes used in Ref. [34]). Using the Carbon flux and B/C ratio measured by AMS-02 [33, 47], together with the data at low energies by the Advanced Composition Explorer (ACE) spacecraft near the Earth and the Voyager in the local interstellar space [49, 50], Ref. [51] carried out a study of different propagation model settings and constrained the
propagation parameters in a narrow region. In this work, we revisit the antiproton problem based on the new results of the CR propagation. The updated production cross section of antiprotons via pp collisions with constraints from the most recent collider data will also be employed [52]. In addition, we also develop a more efficient method to calculate the likelihood of the DM component. In Section 2 we present the propagation and proton source parameters which are the basis of the calculation of the background antiproton flux. In Section 3 we investigate the DM contribution to antiprotons. We conclude our work in Section 4.

2 Propagation model parameters and background antiprotons

Charged particles propagate diffusively in a diffusive halo, usually assumed to feature cylindrical symmetry, with a radius of \( R_h \) and a half-height \( z_h \), defined by the extension of the magnetic field. The propagation equation can be written in general as

\[
\frac{\partial \psi}{\partial t} = \nabla \cdot (D_{xx} \nabla \psi - \mathbf{V} \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial \psi}{\partial p} + \frac{\partial}{\partial p} \left[ b \psi + \frac{p}{3} \nabla \cdot \mathbf{V} \right] - \frac{\psi}{\tau} + \mathcal{Q}.
\] (2.1)

The first term in the right-hand-side is the diffusion in the random magnetic field with \( D_{xx} \) being the spatial diffusion coefficient, the second term represents the advection velocity which is assumed to linearly increase along the \( z \)-direction, the third term is the stochastic reacceleration characterized by a diffusion in the momentum space with a diffusion coefficient \( D_{pp} \), the fourth and fifth terms are the interaction and adiabatic energy loss terms, the sixth term represents the fragmentation and/or decay, and the last term is the source function.

The diffusion coefficient is usually assumed to be spatially uniform in the Milky Way, and it can be parameterized as a power-law function of rigidity, \( D(R) = \beta D_0 (R/R_0)^\delta \), where \( \beta \) is the velocity of a particle (in unit of light speed), \( D_0 \) is a normalization constant, \( \delta \) is the rigidity-dependence slope (see below for a modification of the diffusion coefficient). There are proposals of spatially non-uniform (e.g., [32, 53]) or anisotropic diffusion [54] scenarios motivated by recent observations of spectral hardenings of CRs [55, 56] and spatial variation of CR spectral indices inferred from Fermi-LAT \( \gamma \)-ray observations [57, 58]. It has been shown that the \( \bar{p}/p \) ratio also hardens gradually at high energies in the spatially-dependent propagation model [32, 53], and may account for the flat behavior of the \( \bar{p}/p \) ratio as observed by AMS-02 [14]. The effect on the low energy part of the antiproton spectrum (e.g., below 10 GeV) under such complicated propagation models needs further studies. Here we work under the simple uniform diffusion framework, which can actually explain most of the CR and diffuse \( \gamma \)-ray data.

The advection velocity is parameterized as \( \mathbf{V} = d \mathbf{V} / dz \cdot \mathbf{z} \). The reacceleration is characterized by the Alfvénic speed of the plasma, \( v_A \), which bridges the spatial and momentum diffusion coefficients as \( D_{pp} D_{xx} = \frac{4v_A^2}{\delta(4-\delta)^2} \) [59]. The momentum loss rate \( b(p) = -\dot{p} \) includes the ionization and Coulomb scattering losses and radiative cooling (for electrons/positrons). The injection spectrum of nuclei is parameterized as a doubly broken power-law form of rigidity

\[
q(R) \propto \begin{cases} 
(R/R_{br,1})^{-\nu_1}, & R < R_{br,1} \\
(R/R_{br,1})^{-\nu_2}, & R_{br,1} \leq R < R_{br,2} \\
(R/R_{br,1})^{-\nu_3} (R/R_{br,2})^{\nu_3-\nu_2}, & R_{br,2} \leq R 
\end{cases}
\] (2.2)

where \( R_{br,1} \sim \text{GV} \) is to account for the low energy data, and \( R_{br,2} \sim 300 \text{ GV} \) is to account for the high energy spectral hardening [55, 56].
We assume the force-field approximation to describe the solar modulation effect [60]. Since the time periods of data taking of protons and antiprotons by AMS-02 are slightly different, their modulation parameters should also be different. In this work we adopt \( \Phi_{\bar{p}} = \Phi_p + 0.02 \) GV, as suggested by the time-dependent solar modulation potentials [34].

The numerical tool GALPROP [61, 62] is adopted to solve the propagation equation. It was found that the diffusion model with reacceleration of CRs by the random magnetohydrodynamic (MHD) waves fit the data better than the plain diffusion scenario and the model with an advective transportation [51]. In particular, a variant of the velocity-dependence of the diffusion coefficient, \( D(R) = \beta^0 D_0 (R/R_0)^{\delta} \), where \( \eta \) is an empirical modification of the velocity-dependence [63], gives the best fit\(^1\) to the data [51]. Physically such a diffusion behavior may be related to the resonant interactions between CRs and the MHD waves which result in dissipations of such waves corresponding to low energy particles [64]. This model, referred to as DR2 hereafter, is employed to study antiprotons in this work.

We use the CosRayMC tool, which embeds the GALPROP code in the Markov Chain Monte Carlo driver, to fit the model parameters [65]. The proton fluxes measured by Voyager in the local interstellar space [50], AMS-02 [66], and CREAM [67] are used to derive the proton injection spectral parameters. We include the uncertainties of the propagation parameters from independent fit to the B/C ratio and Carbon fluxes as priors. See the Appendix for details of the prior information from the fitting covariance matrix. The fitting results of the source parameters are given in Table 1. Some of the propagation parameters, such as \( D_0 \) and \( z_h \), are consistent with those derived previously in Ref. [34], while the others are slightly different. This is perhaps due to different data sets used in this work (in particular the inclusion of Voyager data). The propagation parameters can not be directly compared with that given in Ref. [38] due to different model settings. However, we find that the parameters \( D_0 \) and \( z_h \) are still similar with each other. The best-fit results of the proton flux and the B/C ratio, together with the observational data, are shown in Figure 1. Note that the injection spectrum of Carbon nuclei is different from that of protons, and we use the results obtained in Ref. [51] to calculate the B/C ratio. The propagation parameters used to plot Figure 1 are the same as that in Table 1.

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\( ^{1}\)The \( \chi^2 \) value of the DR2 model is 105.3 for 160 degrees of freedom. As a comparison, the \( \chi^2 \) values are 578.2 for the PD, 262.5 for the DC, 188.4 for the DC2, 252.2 for the DR, and 248.6 for the DRC models, respectively. See Ref. [34] for the definition of different propagation model settings.

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**Figure 1.** Best-fit proton flux (left) and B/C ratio (right) compared with the Voyager, AMS-02, and CREAM data. In each panel the dashed (solid) line is for the result before (after) the solar modulation.
Table 1. Propagation and proton injection spectral parameters, together with their posterior 68% errors, from fitting to the Voyager, AMS-02, and CREAM data.

| Parameter | Unit             | Value        |
|-----------|------------------|--------------|
| $D_0^\dagger$ | $(10^{28} \text{cm}^2 \text{s}^{-1})$ | $5.98 \pm 1.00$ |
| $\delta$  |                  | $0.411 \pm 0.008$ |
| $z_h$     | (kpc)            | $5.58 \pm 1.39$ |
| $v_A$     | (km s$^{-1}$)    | $27.5 \pm 1.3$ |
| $\eta$    |                  | $-0.27 \pm 0.08$ |
| $A_p^\dagger$ | $(10^{-9} \text{cm}^{-2} \text{s}^{-1} \text{sr}^{-1})$ | $4.43 \pm 0.01$ |
| $\nu_1$   |                  | $2.03 \pm 0.02$ |
| $R_{br,1}$ | (GV)             | $10.3 \pm 0.9$ |
| $\nu_2$   |                  | $2.40 \pm 0.01$ |
| $R_{br,2}$ | (GV)             | $511.8 \pm 86.2$ |
| $\nu_3$   |                  | $2.25 \pm 0.02$ |
| $\Phi_p$  | (GV)             | $0.673 \pm 0.015$ |

$\dagger$ Normalization at $R_0 = 4$ GV. $\dagger$ Normalization of the propagated proton flux at 100 GeV.

The antiproton background produced by inelastic collisions between protons and the interstellar medium can be calculated using the same propagation, proton injection, and solar modulation parameters (referred to as background parameters hereafter) obtained through fitting to the proton flux data. The Markov chains of the background parameters are used, which include the correlations among different parameters. The cross section of antiproton production is an additional source of uncertainties [52, 68–73]. In this work we employ the updated parameterization of the antiproton production cross section based on the most recent collider data [52]. The relative uncertainties of the antiproton fluxes are found to be $\lesssim 10\%$ in the relevant energy range covered by the AMS-02 data. Therefore we multiply a constant factor $\kappa$, which has a Gaussian prior of $N(1.0, 0.1^2)$ on the background antiproton flux when calculating its likelihood.

### 3 DM contribution to antiprotons

The same propagation parameters as obtained in Sec. II are adopted to calculate the antiproton flux from the DM annihilation. The source term of DM annihilation induced antiprotons can be written as

$$q^\text{DM}_p = \frac{\langle \sigma v \rangle}{2m_\chi^2} \frac{dN}{dE} \rho(x),$$  \hspace{1cm} (3.1)

where the DM particle is assumed to be Majorana fermion, $m_\chi$ is the mass of the DM particle, $\langle \sigma v \rangle$ is the velocity-weighted annihilation cross section, $dN/dE$ is the antiproton production spectrum per annihilation, and $\rho(x)$ is the density profile of DM which is assumed to be the Navarro-Frenk-White distribution [74]. The scale radius of the density profile is adopted to be 20 kpc, and the local density is assumed to be 0.3 GeV cm$^{-3}$ [75].

We adopt a simplified way to calculate the likelihood of the DM component taking into account the uncertainties of the background parameters. The antiproton fluxes from the DM annihilation span in a band when the background parameters change [37]. Figure 2 shows the distribution of the ratios of antiproton fluxes at 1 GeV to that calculated with the mean
Figure 2. Distribution of ratios of the DM-induced antiproton fluxes for various background parameters $\theta_{\text{bkg}}$ to that calculated with the mean background parameters $\bar{\theta}_{\text{bkg}}$. The solid line is a fit using Eq. (3.2).

background parameters given in Table 1. This distribution can be fitted with a probability function

$$p(f) \propto \exp \left[ -\left( \frac{f - \mu}{\sigma} \right)^4 \right], \quad (3.2)$$

where $\mu = 0.969$ and $\sigma = 0.491$. The posterior probability of a given set of DM parameters, $(m_\chi, \langle \sigma v \rangle)$, and specified annihilation channel(s), is

$$P_{\text{DM}} \propto \int \mathcal{L}_{\hat{p}}(\theta_{\text{bkg}}, \kappa, f \tilde{\phi}_{\text{DM}}) p(\theta_{\text{bkg}}) p(\kappa) p(f) \, d\theta_{\text{bkg}} \, d\kappa \, df, \quad (3.3)$$

in which $\mathcal{L}_{\hat{p}} \propto \exp(-\chi^2/2)$ is the likelihood of the model given the AMS-02 antiproton data, $\theta_{\text{bkg}}$ is the background parameters as listed in Table 1, $\kappa$ is a constant factor characterizing the uncertainties of the production cross section of antiprotons in $pp$ collisions, $\tilde{\phi}_{\text{DM}}$ is the flux of the DM component calculated with the mean background parameters $\theta_{\text{bkg}}$, $f$ is a constant scale factor describing the variation of the fluxes due to the uncertainties of the background parameters, $p(\theta_{\text{bkg}})$, $p(\kappa)$, and $p(f)$ are the prior probabilities of these parameters, respectively. The prior distribution $p(\theta_{\text{bkg}})$ is obtained through fitting to the proton fluxes (Section 2). To avoid unphysical results with negative coefficients, we limit the prior regions of $f$ in $[0.2, 1.8]$, and $\kappa$ in $[0.5, 1.5]$ in the integration. We have tested that this approximation gives very similar results as the full computation as done in Ref. [37].

We find that a DM component is favored by the AMS-02 data. Assuming $b\bar{b}$ annihilation channel, the favored mass range of the DM particles is about $60 \sim 100$ GeV, and the annihilation cross section is $(0.7 \sim 7) \times 10^{-26}$ cm$^3$ s$^{-1}$, as shown in Figure 3. We estimate the Bayes factor of a DM component with $b\bar{b}$ annihilation channel is about 8.4, which can be regarded as strong evidence supporting the DM model. These results are consistent with
that found previously [37, 38], although the Bayes factor is slightly smaller. The difference of the Bayes factor is due to the update of the propagation model and parameters with a more consistent treatment of the fit to the CR data, in particular the inclusion of the Voyager data. The favored parameter region of DM is also consistent with that inferred from the GeV γ-ray excess from the Galactic center (dashed contours; [41]). A large part of the favored parameter region lies below the constraints obtained with Fermi-LAT observations of a class of dwarf galaxies (dash-dotted line) [76]. A global fit to the data of antiprotons, and γ-rays from the Galactic center and dwarf galaxies give similar results [46], although the propagation model and parameters are different from ours. It can further be noted that such a cross section is also consistent with the value suggested by the relic density for the thermal production scenario of DM.

**Figure 3.** Favored 68% and 95% credible regions (solid contours) on the mass and annihilation cross section of DM for \(b\bar{b}\) channel, compared with that inferred from the Galactic center γ-ray excess with a re-normalization of the local density (dashed contours; [41]). The 95% exclusion limit of Fermi-LAT observations of dwarf galaxies is shown by the dash-dotted line [76].

Figure 4 illustrates the antiproton fluxes of the best-fit models, for the background-only hypothesis (left) and the background + DM hypothesis (right), respectively. Compared with the background prediction, excesses of antiprotons can be seen around a few GeV. It is interesting to note that at high energies the background model is quite consistent with the data, without any significant excess [19, 22–25].

Finally we derive the upper limits on the DM annihilation cross section from the fit to the antiproton data. The 95% upper limit for given \(m_\chi\) is obtained from the following equation

\[
\frac{\int_0^{(\sigma v)_{\nu, 95}} P(x) \, dx}{\int_0^{\infty} P(x) \, dx} = 0.95.
\]  

(3.4)

\(^2\)Different contours are due to different assumptions of the diffuse background emission.
Figure 4. Best-fit model predictions of the antiproton fluxes, compared with the AMS-02 data. The left panel is for the background-only fit, and the right one is for the background + DM fit.

The results are given in Figure 5. The limits are typically stronger than that obtained by $\gamma$-ray observations of dwarf galaxies, except for the “signal region” with $m_\chi \sim 50 - 130$ GeV. These limits may scale down by a constant factor, if the local density of DM is higher (e.g., [77, 78]).

Figure 5. 95% credible level upper limits of the annihilation cross section for $\chi\chi \rightarrow b\bar{b}$ obtained from AMS-02 antiproton data, and that from Fermi-LAT observations of dwarf galaxies [76].

4 Conclusion and discussion

In this work we revisit the indirect detection of DM with CR antiprotons. Several important updates are presented. The propagation parameters of CRs are obtained through fitting to the newest B/C and Carbon flux data by AMS-02, as well as the low energy observations
near the Earth by ACE and in the local interstellar space by Voyager. Using the propagation parameters as priors, we fit the Voyager, AMS-02, and CREAM data of proton fluxes to obtain the source parameters of CR protons and the solar modulation potential. These newly obtained background parameters are then used to calculate the background antiproton fluxes. The production cross section of $pp$ collisions based on the recent collider data is employed. A Bayesian approach taking into account the uncertainties of the background parameters and antiproton production cross section is adopted.

We find that the AMS-02 antiproton data favor a DM component with mass of $60 \sim 100$ GeV and annihilation cross section of $(0.7 \sim 7) \times 10^{-26}$ cm$^3$ s$^{-1}$, for an assumed $b\bar{b}$ channel. The Bayes factor of the DM component is about 8.4. These results are consistent with previous works based on different propagation parameters and antiproton production cross sections [37, 38].

We discuss possible caveats of the current study. One thing that needs to be kept in mind is the uncertainty of the nuclear fragmentation cross section, which would affect the calculation of the B/C ratio and hence the propagation parameters [79, 80]. Better measurements of the fragmentation cross sections for the most relevant species are necessary in future to reduce such uncertainties. The production cross section of antiprotons also needs improvements from future experiments. Second, we assume a relatively simple propagation paradigm with a uniform diffusion coefficient. However, the actual case might be more complicated, as indicated by precise measurements of the CR spectra and diffuse $\gamma$-rays [32, 53, 54]. The impact of these alternative propagation configurations on the antiproton calculation deserves further detailed investigation. Finally, we have assumed that the solar modulation effects of protons and antiprotons are similar, with the only difference of the data-taking time which corresponds to different solar activities. It is, however, possible that the solar modulation is charge-sign-dependent [81–85]. We expect that better understanding of the solar modulation can be achieved via long-term measurements of both the proton and antiproton spectra in a full solar cycle. Our understandings about all these uncertainties are expected to be improved considerably in the near future with the continuous operation of CR experiments and the efforts from colliders, till then the DM contribution to antiprotons can be crucially tested.

**Acknowledgments**

This work is supported by the National Key Research and Development Program of China (No. 2016YFA0400200), the National Natural Science Foundation of China (Nos. 11475085, 11525313, 11535005, 11690030, 11722328), and the 100 Talents program of Chinese Academy of Sciences.
Appendix: Covariance matrix of the propagation parameters from fitting to the AMS-02 B/C ratio and Carbon flux

Here we present the covariance matrix of the propagation parameters, \( \theta = (D_0, \delta, z_h, v_A, \eta) \), derived through fitting to the B/C ratio and Carbon flux data reported by AMS-02. It is

\[
\Sigma = \begin{pmatrix}
0.772 & -2.549 \times 10^{-3} & 0.971 & -0.036 & 0.020 \\
-2.549 \times 10^{-3} & 7.262 \times 10^{-5} & -1.355 \times 10^{-3} & -5.424 \times 10^{-3} & -5.776 \times 10^{-4} \\
0.971 & -1.355 \times 10^{-3} & 1.298 & -0.287 & 0.011 \\
-0.036 & -5.424 \times 10^{-3} & -0.287 & 1.244 & 0.028 \\
0.020 & -5.776 \times 10^{-4} & 0.011 & 0.028 & 9.253 \times 10^{-3}
\end{pmatrix}.
\]

This covariance matrix is used in the fit of the proton injection spectrum as priors. Specifically, we add the following term in the calculation of the \( \chi^2 \) of protons

\[
\chi^2 = (\theta - \bar{\theta}) \Sigma^{-1} (\theta - \bar{\theta})^T,
\]

where \( \bar{\theta} = (6.46, 0.410, 6.11, 29.4, -0.48) \) is the vector of the mean values of the propagation parameter [51]. Note that these values are obtained through fitting to the B/C ratio and Carbon flux data, and are slightly different from that given in Table 1.

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