Upper limits on DM annihilation cross sections from the first AMS-02 antiproton data

Hong-Bo Jin\textsuperscript{a,b}, Yue-Liang Wu\textsuperscript{a,c,d}, and Yu-Feng Zhou\textsuperscript{a,c} *

\textsuperscript{a}) State Key Laboratory of Theoretical Physics, \textsuperscript{b}) National Astronomical Observatories, Chinese Academy of Sciences, \textsuperscript{c}) Kavli Institute for Theoretical Physics China, Institute of Theoretical Physics Chinese Academy of Sciences, \textsuperscript{d}) University of Chinese Academy of Sciences, Beijing, 100190, P.R. China

Abstract

The first measurement on the antiproton to proton ratio made by the AMS-02 collaboration agrees with the expectation from conventional cosmic-ray secondaries in the kinetic energy range $\sim 20 - 100$ GeV, which can be turned into stringent upper limits on the dark matter (DM) annihilation cross sections above $\sim 300$ GeV. Using the GALPROP code, we derive the upper limits in various propagation models and DM profiles. We show that in the “conventional” propagation model, for the $q\bar{q}$, $b\bar{b}$, and $W^+W^-$ final states, the constraints could be more stringent than that derived from the recent Fermi-LAT gamma-ray data on the dwarf spheroidal satellite galaxies. Making use of the typical minimal, median and maximal models obtained from a previous global fit to the preliminary AMS-02 data, we show that the variation of the upper limits is about a factor of five. The possibility of DM contribution to the high energy $\bar{p}/p$ data is discussed.

*Emails: hbjin@bao.ac.cn, ylwu@itp.ac.cn, yfzhou@itp.ac.cn
Dark matter (DM) is known to contribute to 26.8% of the total energy density of the Universe [1], however, its particle nature remains largely unknown. If the DM particles can annihilate or decay into the standard model (SM) final states, they will contribute to new primary sources of cosmic-ray particles, and result in significantly changes in the spectra of the cosmic-ray antiparticles such as positrons and antiprotons, as these species are assumed to be secondaries from the conventional cosmic-ray propagation theory. Antiprotons are highly expected from DM annihilation in many DM models, and unlikely to be generated from the nearby astrophysical sources. Compared with cosmic-ray electrons/positrons, the cosmic-ray antiprotons loss much less energy during propagation, and can travel through longer distance in the Galaxy, which makes the antiproton more sensitive to the uncertainties in the propagation parameters and the DM profiles.

Recently, the AMS-02 collaboration has released the first preliminary result of the cosmic-ray antiproton to proton flux ratio $\bar{p}/p$ [2]. The measured kinetic energies of the antiprotons have been extended to $\sim 450$ GeV. Although the spectrum of $\bar{p}/p$ at high energies above 100 GeV tend to be relatively flat, within uncertainties the AMS-02 data are consistent with the background of secondary antiprotons, which can be used to set stringent upper limits on the dark matter (DM) annihilation cross sections, especially for high mass DM particles. The constraints on the DM properties from antiprotons have been investigated previously before AMS-02 (see, eg. [3, 4, 5, 6, 7]). In this work, we explore the significance of the new AMS-02 $\bar{p}/p$ data on constraining the annihilation cross sections of the DM particles in various propagation models and DM profiles. Four representative background models are considered with four different DM profiles. We derive the upper limits using the GALPROP code and show that in the “conventional” propagation model with Einasto DM profile, the constraints could be more stringent than that derived from the Ferm-LAT gamma-ray data on the dwarf spheroidal satellite galaxies. Making use of the typical minimal, median and maximal models obtained from a previous global fit to the preliminary AMS-02 data, we show that the uncertainties on the upper limits is around a factor of five.

We start with a briefly overview on the main features of the cosmic-ray propagation within the Galaxy. The Galactic halo within which the diffusion processes occur is parametrized by a cylinder with radius $R_h = 20$ kpc and half-height $Z_h = 1 - 20$ kpc. The diffusion equation for the cosmic-ray charged particles reads (see e.g. [3])

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

$$- \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi + q(r, p),$$

where $\psi(r, p, t)$ is the number density per unit of total particle momentum. For steady-
state diffusion, it is assumed that $\partial \psi / \partial t = 0$. The number densities of cosmic-ray particles are vanishing at the boundary of the halo, i.e., $\psi(R_h, z, p) = \psi(R, \pm Z_h, p) = 0$. The energy dependent spatial diffusion coefficient $D_{xx}$ is parametrized as $D_{xx} = \beta D_0 (\rho / \rho_0)^\delta$, where $\rho = p / (Ze)$ is the rigidity of the cosmic-ray particle with electric charge $Ze$. The power spectral index $\delta$ can have different values $\delta = \delta_{1(2)}$ when $\rho$ is below (above) a reference rigidity $\rho_0$. The coefficient $D_0$ is a normalization constant, and $\beta = v/c$ is the velocity of the cosmic-ray particle. The convection term in the diffusion equation is related to the drift of cosmic-ray particles from the Galactic disc due to the Galactic wind. The diffusion in momentum space is described by the reacceleration parameter $D_{pp}$ which is related to the velocity of disturbances in the hydrodynamical plasma, parametrized as the Alfvén speed $V_a$ as follows [8]

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

where $w$ characterise the level of turbulence. We take $w = 1$ as only $V_a^2 / w$ is relevant in the calculation. In Eq. (1), the momentum loss rate is denoted by $\dot{p}$ which could be due to ionization in the interstellar medium neutral matter, Coulomb scattering off thermal electrons in ionized plasma, bremsstrahlung, synchrotron radiation, and inverse Compton scattering, etc.. The parameter $\tau_f(\tau_r)$ is the time scale for fragmentation (radioactive decay) of the cosmic-ray nuclei as they interact with interstellar hydrogen and helium.

The spectrum of a primary source term for a cosmic-ray nucleus $A$ is assumed to have a broken power low behaviour $dq_A(p) / dp \propto (\rho / \rho_{As})^{\gamma_A}$ with $\gamma_A = \gamma_{A1}(\gamma_{A2})$ for the nucleus rigidity $\rho$ below (above) a reference rigidity $\rho_{As}$. The spatial distribution of the primary sources is assumed to have the following form [9]

$$q_A(R, z) = q_0 \left( \frac{R}{r_\odot} \right)^\eta \exp \left[ -\xi \frac{R - r_\odot}{r_\odot} - \frac{|z|}{0.2 \text{ kpc}} \right],$$

where $\eta = 0.5$, $\xi = 1.0$. The normalization parameters $q_0$ is determined by the EGRET gamma-ray data.

The secondary antiprotons are created dominantly from inelastic $pp$- and $pA$-collisions with the interstellar gas. The corresponding source term reads

$$q(p) = \beta c n_i \sum_{i=\text{H,He}} \int dp' \frac{d\sigma_i(p, p')}{dp'} n_p(p')$$

where $n_i$ is the number density of interstellar hydrogen (helium), $n_p$ is the number density of primary cosmic-ray proton per total momentum, and $d\sigma_i(p, p')/dp'$ is the differential cross section for $p + \text{H(He)} \rightarrow \bar{p} + X$. In calculating the antiprotons, inelastic scattering to produce “tertiary” antiprotons should be taken into account.
The primary source term from the annihilation of Majorana DM particles has the following form

\[
q(r, p) = \rho(r)^2 \langle \sigma v \rangle \sum_X \eta_X \frac{dN(X)}{dp},
\]

where \( \langle \sigma v \rangle \) is the velocity-averaged DM annihilation cross section multiplied by DM relative velocity (referred to as cross section). \( \rho(r) \) is the DM energy density distribution function, and \( dN(X)/dp \) is the injection energy spectrum of antiprotons from DM annihilating into SM final states through all possible intermediate states \( X \) with \( \eta_X \) the corresponding branching fractions.

The interstellar flux of the cosmic-ray particle is related to its density function as \( \Phi = \frac{v\psi(r, p)}{(4\pi)} \). For high energy nuclei \( v \approx c \). 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 [10]. In this approach, \( \Phi_{\text{TOA}} \) the cosmic-ray nuclei flux at the top of the atmosphere of the Earth which is measured by the experiments is related to the interstellar flux as follows

\[
\Phi_{\text{TOA}}(T_{\text{TOA}}) = \left( \frac{2mT_{\text{TOA}} + T_{\text{TOA}}^2}{2mT + T^2} \right) \Phi(T),
\]

where \( T_{\text{TOA}} = T - \phi \) is the kinetic energy of the cosmic-ray nuclei at the top of the atmosphere of the Earth. We shall take \( \phi = 550 \) MV in numerical analysis.

In our numerical calculations, we shall solve the diffusion equation of Eq. (1) using the publicly available code GALPROP v54 [11, 12, 13, 14, 15] which utilizes realistic astronomical information on the distribution of interstellar gas and other data as input, and considers various kinds of observables in a self-consistent way. Other approaches based on simplified assumptions on the Galactic gas distribution which allow for fast analytic solutions can be found in Refs. [16, 17].

We first consider the so-called “conventional” diffusive re-acceleration model [13, 15] which is commonly adopted by the current experimental collaborations such as PAMELA [21, 22, 23] and Fermi-LAT [24, 25] as a benchmark model for the astrophysical backgrounds. It is useful to consider this model as a reference model to understand how the DM properties could be constrained by the AMS-02 data. Then we consider three representative propagation models selected from a large sample of models obtained from a global Bayesian MCMC fit to the preliminary AMS-02 proton and B/C data using the GALPROP code [26]. They are selected to represent the typically minimal (MIN), median (MED) and maximal (MAX) antiproton fluxes within 95% CL. The parameters in the four models are summarized in Tab. 1 and the predicted proton flux and the B/C flux ratio in these models are shown in Fig. 1 together with the current experimental data. The figures
show an overall agreement with the current data in these models. In the “conventional” model, the predicted B/C ratio is a little higher for the kinetic energy below $\sim 10$ GeV/n, but are consistent with the B/C data in the higher energies. The predictions for the background of the $\bar{p}/p$ flux ratio in these models are shown in Fig. 2. The “MIN”, “MED” and “MAX” models are highly degenerate in the $\bar{p}/p$ ratio. Compared with these models, the “conventional” model predicts more low energy antiprotons but at high energies above 500, the predicted antiprotons are less. In all the four models, below 10 GeV the GALPROP diffusive re-acceleration model underpredicts the $\bar{p}/p$ by $\sim 40\%$, which is a known issue. The agreement with the data can be improved by introducing breaks in diffusion coefficients [27], “fresh” nuclei component [28] or DM contribution [3]. Nevertheless, the background predictions agree with the AMS-02 data well at higher energies in the kinetic energy range $\sim 10 – 100$ GeV. This remarkable agreement can be turned into stringent constraints on the DM annihilation cross section for heavy DM particles.

| model      | $R$(kpc) | $Z_h$(kpc) | $D_0$ | $\rho_0$ | $\delta_1/\delta_2$ | $V_a$(km/s) | $\rho_s$ | $\gamma_{p1}/\gamma_{p2}$ |
|------------|----------|------------|-------|----------|----------------------|-------------|----------|--------------------------|
| Conventional | 20       | 4.0        | 5.75  | 4.0      | 0.34/0.34            | 36.0        | 9.0      | 1.82/2.36                |
| MIN        | 20       | 1.8        | 3.53  | 4.0      | 0.3/0.3              | 42.7        | 10.0     | 1.75/2.44                |
| MED        | 20       | 3.2        | 6.50  | 4.0      | 0.29/0.29            | 44.8        | 10.0     | 1.79/2.45                |
| MAX        | 20       | 6.0        | 10.6  | 4.0      | 0.29/0.29            | 43.4        | 10.0     | 1.81/2.46                |

TAB. 1: Parameters in the propagation models “Conventional” [13 15], “MIN”, “MED” and “MAX” models from Ref. [26]. $D_0$ is in units of $10^{28}$ cm$^2$·s$^{-1}$, the break rigidities $\rho_0$ and $\rho_s$ are in units of GV.
The flux cosmic-ray antiprotons from DM annihilation depend also significantly on the choice of DM halo profile. N-body simulations suggest a universal form of the DM profile

$$\rho(r) = \rho_\odot \left( \frac{r}{r_\odot} \right)^{-\gamma} \left( \frac{1 + (r_\odot/r_s)^\alpha}{1 + (r/r_\odot)^\alpha} \right)^{(\beta-\gamma)/\alpha},$$  

(7)

where $\rho_\odot \approx 0.43 \text{ GeV cm}^{-3}$ is the local DM energy density [31]. The values of the parameters $\alpha$, $\beta$, $\gamma$ and $r_s$ for the Navarro-Frenk-White (NFW) profile [32], the isothermal profile [33] and the Moore profile [34, 35] are summarized in Tab. 2. An other widely adopted DM profile is the Einasto profile [36]

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

(8)

with $\alpha_E \approx 0.17$ and $r_s \approx 20 \text{ kpc}$. 

---

FIG. 2: Predictions for the $\bar{p}/p$ ratio from the four propagation models list in Tab. 1. The data from AMS-02 [2] and PAMELA [29] are shown.
FIG. 3: Upper limits on the cross sections for DM particle annihilation into $b\bar{b}$ final states from the AMS-02 $\bar{p}/p$ data in the “conventional” (upper left), “MED” (upper right), “MIN” (lower left) and “MAX” (lower right) propagation models. Four DM profiles NFW [32], Isothermal [33], Einasto [36] and Moore [34, 35] are considered. The upper limits from the Fermi-LAT 6-year gamma-ray data of the dwarf spheroidal satellite galaxies of the Milky Way are also shown [39]. The horizontal line indicates the typical thermal annihilation cross section $\langle \sigma v \rangle = 3 \times 10^{-26}$cm$^3$s$^{-1}$.

We consider three reference DM annihilation channels $\chi\chi \rightarrow XX$ where $XX = q\bar{q}, b\bar{b}$ and $W^+W^-$. The energy spectra of these channels are similar at high energies. The main difference is in the average number of total antiprotons $N_X$ per DM annihilation of each channel. For a DM particle mass $m_\chi = 500$ GeV, the values of $N_X$ for typical final states are $N_{q\bar{q}} = 2.97$ ($q = u, d$), $N_{b\bar{b}} = 2.66$, and $N_{WW} = 1.42$. The injection spectra $dN^{(X)}/dp$ from DM annihilation are calculated using the numerical package PYTHIA v8.175 [37], in which the long-lived particles such as neutron and $K_L$ are allowed to decay and the final state interaction are taken into account. Since PYTHIA v8.15 the polarization and correlation of final states in $\tau$-decays has been taken into account [38].

In this work, we shall derive the upper limits on the DM annihilation cross section
FIG. 4: The same as Fig. 3 but for DM annihilation into $W^+W^-$ final states.

using the frequentist $\chi^2$-analyses. The expression of $\chi^2$ is defined as

$$\chi^2 = \sum_i \frac{(f_i^{\text{th}} - f_i^{\text{exp}})^2}{\sigma_i^2},$$

where $f_i^{\text{th}}$ are the theoretical predictions. $f_i^{\text{exp}}$ and $\sigma_i$ are the central values and errors of experimental data, respectively. The index $i$ runs over all the available data points. For a given DM particle mass, we first calculate the minimal value $\chi^2_{\text{min}}$ of the $\chi^2$-function, and then derive the 95% CL upper limits on the annihilation cross section, corresponding to $\Delta\chi^2 = 3.84$. All of the 30 data points of the AMS-02 $\bar{p}/p$ data are included in calculating the limits.

In Fig. 3 we show the obtained upper limits on the cross sections for DM particle annihilation into $b\bar{b}$ final states from the AMS-02 $\bar{p}/p$ data in the "conventional", "MED", "MIN" and "MAX" propagation models. Four different DM profiles NFW [32], Isothermal [33], Einasto [36] and Moore [34, 35] are considered. As can be seen, the upper limits as a function of $m_\chi$ show some smooth structure for all the final states and DM profiles. The limits tend to be relatively stronger at $m_\chi \approx 300$ GeV, which is related to the fact that the background predictions agree with the data well at the antiproton energy range $\sim 20-100$ GeV. For a comparison the upper limits from the Fermi-LAT 6-year gamma-ray
data of the dwarf spheroidal satellite galaxies of the Milky Way are also shown [39]. In the “conventional” model, the upper limits from the AMS-02 $\bar{p}/p$ data are found to be compatible with that derived from the Fermi-LAT gamma-ray data for $m_\chi \gtrsim 300$ GeV. This observation holds for most of the DM profiles. In the “MED” model, the constraints are relatively weaker, which is related to the under prediction of low energy $\bar{p}$ in this model and the limits are more conservative. For an estimation of the uncertainties due to the propagation models, from the “MIN” model to the “MAX” model, we find that the variation of the upper limits is within about a factor of five.

For the $W^+W^-$ final states, the results are shown in Fig. 4. The constraints from AMS-02 $\bar{p}/p$ data turn out to be more stringent than that from the Fermi-LAT gamma-ray data for all the four DM profiles in the “convention” model when the DM particle mass is above $\sim 300$ GeV. Again we find that the variation of the upper limits from the “MIN” to the “MAX” model is within a factor of five. The result for the $q\bar{q}$ final states is shown in Fig. 5. Similar to the case of $W^+W^-$ final states, the constraints from $\bar{p}/p$ data are more stringent at about $\sim 300$ GeV. Compared with the case of $W^+W^-$ and $b\bar{b}$, the constraints on the $q\bar{q}$ final states are the most stringent. For all the three final states, we find that the allowed DM annihilation cross section is below the typical thermal cross section for $m_\chi \lesssim 300$ GeV in the conventional propagation model with Einasto profile.
which show that the AMS-02 $\bar{p}/p$ data can impose stringent constraints on DM candidates of weakly interacting massive particles.

![Graph showing $\chi^2_{\text{min}}$ as a function of DM particle mass $m_\chi$](image1)

**FIG. 6:** (Upper left) values of $\chi^2_{\text{min}}$ as a function of DM particle mass $m_\chi$ from a fit to the AMS-02 $\bar{p}/p$ data (with kinetic energy above 20 GeV) in the “conventional” propagation model [13, 15] with the DM profile fixed to Einasto [36]. Three annihilation channels $b\bar{b}$, $q\bar{q}$ and $W^+W^-$ are considered. (Upper right) predicted $\bar{p}/p$ ratio in the case of background (“conventional” model) plus a DM contribution with $m_\chi = 6.5$ TeV, $\langle \sigma v \rangle = 1.9 \times 10^{-24}$ cm$^3$s$^{-1}$, and annihilation final states $W^+W^-$. The flux ratio of antiproton from DM to the proton from the background $\bar{p}_{\text{DM}}/p_{\text{BG}}$ is shown as the dashed line. The data from AMS-02 [2] and PAMELA [29] are also shown. (Lower left) the same as the upper right, but for the $b\bar{b}$ channel with $m_\chi = 10.9$ TeV and $\langle \sigma v \rangle = 3.4 \times 10^{-24}$ cm$^3$s$^{-1}$. (Lower right) the same as the upper right, but for the $q\bar{q}$ channel with $m_\chi = 10.9$ TeV and $\langle \sigma v \rangle = 3.3 \times 10^{-24}$ cm$^3$s$^{-1}$.

As shown in Fig. [2] the spectrum of the AMS-02 $\bar{p}/p$ ratio tends to be flat toward high energies above $\sim 100$ GeV. This trend, if confirmed by the future AMS-02 data, is not expected from the secondary production of antiprotons, and raises the interesting question whether this would leave some room for a heavy DM contribution, similar to the case of the AMS-02 positron fraction [40, 41, 42, 43, 44]. To explore this possibility,
we perform an other fit using the $\bar{p}/p$ ratio data above 20 GeV (15 data points in total) in order to avoid the theoretical uncertainties in the low energy region. The obtained $\chi^2_{\text{min}}$ as a function of $m_\chi$ for the $b\bar{b}$, $q\bar{q}$ and $W^+W^-$ final states in the “conventional” propagation model with Einasto DM profile are shown in Fig. 6. One can see that for the three final states the values of $\chi^2_{\text{min}}$ decrease almost monotonically from $\sim 21$ to $\sim 5$ with an increasing DM particles mass from 100 GeV to 10 TeV, but the $\chi^2$-curves become gradually flat toward high DM masses. Only for the $W^+W^-$ channel, there exists a shallow local minimal at around 6.5 TeV with low statistical significance. From the $\chi^2$-curves, one can see that the DM particles mass is restricted to be above $\sim 2$ TeV at $2\sigma$. For an illustration purpose, we show in Fig. 6 the predictions for the $\bar{p}/p$ ratio in the “conventional” background model with a DM contribution. The DM particles masses and annihilation cross sections chosen to be $m_\chi = 6.5$ TeV, $\langle \sigma v \rangle = 1.9 \times 10^{-24}$ cm$^3$s$^{-1}$ for $W^+W^-$, $m_\chi = 10.9$ TeV, $\langle \sigma v \rangle = 3.4 \times 10^{-24}$ cm$^3$s$^{-1}$ for $b\bar{b}$ channel, and $m_\chi = 10.9$ TeV and $\langle \sigma v \rangle = 3.3 \times 10^{-24}$ cm$^3$s$^{-1}$ for $q\bar{q}$ channel. Note that these values are not from the best-fit values. We conclude that introducing a DM contribution can improve the agreement with the AMS-02 $\bar{p}/p$ data with kinetic energy above 100 GeV, but the statistics is not enough to determine the DM properties such as its mass and interaction strength. If the DM particle mass is indeed at $\mathcal{O}(10)$ TeV scale, next generation precision cosmic-ray detection experiments are needed.

In summary, we have explored the significance of the first AMS-02 $\bar{p}/p$ data on constraining the annihilation cross sections of the DM particles in various propagation models and DM profiles. Four representative background models have been considered with four different DM profiles. We have derived the upper limits using the GALPROP code and shown that in the “conventional” propagation model with Einasto DM profile, the constraints can be more stringent than that derived from the Ferm-LAT gamma-ray data on the dwarf spheroidal satellite galaxies. Making use of the typical minimal, median and maximal models obtained from a previous global fit, we have shown that the uncertainties on the upper limits is around a factor of five. The future more precise AMS-02 data can help to reduce the uncertainties in the derived upper limits.

Note added: As we were completing this study, Ref. [45] appeared on the arXiv, which addresses some of the same problems as discussed here. Although the conclusions are similar, the analysis framework, propagation models parameters are quite different from theirs.

Acknowledgments

Y LW is grateful to S. Ting for warm hospitality and insightful discussions during his visit to the AMS-02 POCC at CERN. We thank P. Zuccon, A. Kounine, A. Oliva and S. Haino
for helpful discussions on the details of the AMS-02 detector. This work is supported in part by the National Basic Research Program of China (973 Program) under Grants No. 2010CB833000; the National Nature Science Foundation of China (NSFC) under Grants No. 10905084, No. 11335012 and No. 11475237; The numerical calculations were done using the HPC Cluster of SKLTP/ITP-CAS.

References

[1] Planck Collaboration, P. Ade et al., Planck 2015 results. XIII. Cosmological parameters, arXiv:1502.01589.

[2] S.Ting, talk at AMS-02 days at CERN, April 15-17, CERN, Geneva, https://indico.cern.ch/event/381134/timetable/#20150415.

[3] D. Hooper, T. Linden, and P. Mertsch, What Does The PAMELA Antiproton Spectrum Tell Us About Dark Matter?, JCAP 1503 (2015), no. 03 021, arXiv:1410.1527.

[4] R. Kappl and M. W. Winkler, The Cosmic Ray Antiproton Background for AMS-02, JCAP 1409 (2014) 051, arXiv:1408.0299.

[5] N. Fornengo, L. Maccione, and A. Vittino, Constraints on particle dark matter from cosmic-ray antiprotons, JCAP 1404 (2014) 003, arXiv:1312.3579.

[6] M. Cirelli and G. Giesen, Antiprotons from Dark Matter: Current constraints and future sensitivities, JCAP 1304 (2013) 015, arXiv:1301.7079.

[7] H.-B. Jin, S. Miao, and Y.-F. Zhou, Implications of the latest XENON100 and cosmic ray antiproton data for isospin violating dark matter, Phys.Rev. D87 (2013), no. 1 016012, arXiv:1207.4408.

[8] V. Ginzburg, V. Dogiel, V. Berezinsky, S. Bulanov, and V. Ptuskin, Astrophysics of cosmic rays, .

[9] A. Strong and I. Moskalenko, Propagation of cosmic-ray nucleons in the galaxy, Astrophys.J. 509 (1998) 212–228, astro-ph/9807150.

[10] L. Gleeson and W. Axford, Solar Modulation of Galactic Cosmic Rays, Astrophys.J. 154 (1968) 1011.

[11] A. Strong and I. Moskalenko, Propagation of cosmic-ray nucleons in the galaxy, Astrophys.J. 509 (1998) 212–228, astro-ph/9807150.
[12] I. V. Moskalenko, A. W. Strong, J. F. Ormes, and M. S. Potgieter, *Secondary anti-protons and propagation of cosmic rays in the galaxy and heliosphere*, Astrophys.J. **565** (2002) 280–296, [astro-ph/0106567](http://arxiv.org/abs/astro-ph/0106567).

[13] A. Strong and I. Moskalenko, *Models for galactic cosmic ray propagation*, Adv.Space Res. **27** (2001) 717–726, [astro-ph/0101068](http://arxiv.org/abs/astro-ph/0101068).

[14] I. V. Moskalenko, A. Strong, S. Mashnik, and J. Ormes, *Challenging cosmic ray propagation with antiprotons. Evidence for a fresh nuclei component?*, Astrophys.J. **586** (2003) 1050–1066, [astro-ph/020480](http://arxiv.org/abs/astro-ph/020480).

[15] V. Ptuskin, I. V. Moskalenko, F. Jones, A. Strong, and V. Zirakashvili, *Dissipation of magnetohydrodynamic waves on energetic particles: impact on interstellar turbulence and cosmic ray transport*, Astrophys.J. **642** (2006) 902–916, [astro-ph/0510335](http://arxiv.org/abs/astro-ph/0510335).

[16] F. Donato, D. Maurin, P. Salati, A. Barrau, G. Boudoul, et al., *Anti-protons from spallations of cosmic rays on interstellar matter*, Astrophys.J. **563** (2001) 172–184, [astro-ph/0103150](http://arxiv.org/abs/astro-ph/0103150).

[17] D. Maurin, R. Taillet, F. Donato, P. Salati, A. Barrau, et al., *Galactic cosmic ray nuclei as a tool for astroparticle physics*, [astro-ph/0212111](http://arxiv.org/abs/astro-ph/0212111).

[18] F. Donato, N. Fornengo, D. Maurin, and P. Salati, *Antiprotons in cosmic rays from neutralino annihilation*, Phys.Rev. **D69** (2004) 063501, [astro-ph/0306207](http://arxiv.org/abs/astro-ph/0306207).

[19] A. Putze, L. Derome, and D. Maurin, *A Markov Chain Monte Carlo technique to sample transport and source parameters of Galactic cosmic rays: II. Results for the diffusion model combining B/C and radioactive nuclei*, Astron.Astrophys. **516** (2010) A66, [arXiv:1001.0551](http://arxiv.org/abs/1001.0551).

[20] M. Cirelli, G. Corcella, A. Hektor, G. Hutsi, M. Kadastik, et al., *PPPC 4 DM ID: A Poor Particle Physicist Cookbook for Dark Matter Indirect Detection*, JCAP **1103** (2011) 051, [arXiv:1012.4515](http://arxiv.org/abs/1012.4515).

[21] O. Adriani, G. Barbarino, G. Bazilevskaya, R. Bellotti, M. Boezio, et al., *A new measurement of the antiproton-to-proton flux ratio up to 100 GeV in the cosmic radiation*, Phys.Rev.Lett. **102** (2009) 051101, [arXiv:0810.4994](http://arxiv.org/abs/0810.4994).

[22] PAMELA Collaboration, O. Adriani et al., *PAMELA results on the cosmic-ray antiproton flux from 60 MeV to 180 GeV in kinetic energy*, Phys.Rev.Lett. **105** (2010) 121101, [arXiv:1007.0821](http://arxiv.org/abs/1007.0821).
[23] **PAMELA** Collaboration, O. Adriani et al., *The cosmic-ray electron flux measured by the PAMELA experiment between 1 and 625 GeV*, *Phys.Rev.Lett.* **106** (2011) 201101, [arXiv:1103.2880](http://arxiv.org/abs/1103.2880).

[24] **Fermi-LAT** Collaboration, M. Ackermann et al., *Fermi LAT observations of cosmic-ray electrons from 7 GeV to 1 TeV*, *Phys.Rev.* **D82** (2010) 092004, [arXiv:1008.3999](http://arxiv.org/abs/1008.3999).

[25] **Fermi-LAT** Collaboration, *Fermi-LAT Observations of the Diffuse Gamma-Ray Emission: Implications for Cosmic Rays and the Interstellar Medium*, *Astrophys.J.* **750** (2012) 3, [arXiv:1202.4039](http://arxiv.org/abs/1202.4039).

[26] H.-B. Jin, Y.-L. Wu, and Y.-F. Zhou, *Cosmic ray propagation and dark matter in light of the latest AMS-02 data*, [arXiv:1410.0171](http://arxiv.org/abs/1410.0171).

[27] I. V. Moskalenko, A. W. Strong, J. F. Ormes, and M. S. Potgieter, *Secondary anti-protons and propagation of cosmic rays in the galaxy and heliosphere*, *Astrophys.J.* **565** (2002) 280–296, [astro-ph/0106567](http://arxiv.org/abs/astro-ph/0106567).

[28] I. V. Moskalenko, A. Strong, S. Mashnik, and J. Ormes, *Challenging cosmic ray propagation with antiprotons. Evidence for a fresh nuclei component?*, *Astrophys.J.* **586** (2003) 1050–1066, [astro-ph/0210480](http://arxiv.org/abs/astro-ph/0210480).

[29] O. Adriani, G. Barbarino, G. Bazilevskaya, R. Bellotti, M. Boezio, et al., *The PAMELA Mission: Heralding a new era in precision cosmic ray physics*, *Phys.Rept.* **544** (2014) 323–370.

[30] O. Adriani, G. Barbarino, G. Bazilevskaya, R. Bellotti, M. Boezio, et al., *Measurement of boron and carbon fluxes in cosmic rays with the PAMELA experiment*, *Astrophys.J.* **791** (2014) 93, [arXiv:1407.1657](http://arxiv.org/abs/1407.1657).

[31] P. Salucci, F. Nesti, G. Gentile, and C. Martins, *The dark matter density at the Sun’s location*, *Astron.Astrophys.* **523** (2010) A83, [arXiv:1003.3101](http://arxiv.org/abs/1003.3101).

[32] J. F. Navarro, C. S. Frenk, and S. D. White, *A Universal density profile from hierarchical clustering*, *Astrophys.J.* **490** (1997) 493–508, [astro-ph/9611107](http://arxiv.org/abs/astro-ph/9611107).

[33] L. Bergstrom, P. Ullio, and J. H. Buckley, *Observability of gamma-rays from dark matter neutralino annihilations in the Milky Way halo*, *Astropart.Phys.* **9** (1998) 137–162, [astro-ph/9712318](http://arxiv.org/abs/astro-ph/9712318).
[34] B. Moore, S. Ghigna, F. Governato, G. Lake, T. R. Quinn, et al., *Dark matter substructure within galactic halos*, Astrophys.J. **524** (1999) L19–L22, astro-ph/9907411.

[35] J. Diemand, B. Moore, and J. Stadel, *Convergence and scatter of cluster density profiles*, Mon.Not.Roy.Astron.Soc. **353** (2004) 624, astro-ph/0402267.

[36] J. Einasto, *Dark Matter*, arXiv:0901.0632.

[37] T. Sjostrand, S. Mrenna, and P. Z. Skands, *A Brief Introduction to PYTHIA 8.1*, Comput.Phys.Commun. **178** (2008) 852–867, arXiv:0710.3820.

[38] P. Ilten, *Tau Decays in Pythia 8*, Nucl.Phys.Proc.Suppl. **253-255** (2014) 77–80, arXiv:1211.6730.

[39] Fermi-LAT Collaboration, M. Ackermann et al., *Searching for Dark Matter Annihilation from Milky Way Dwarf Spheroidal Galaxies with Six Years of Fermi-LAT Data*, arXiv:1503.02641.

[40] AMS Collaboration, L. Accardo et al., *High Statistics Measurement of the Positron Fraction in Primary Cosmic Rays of 0.5C500 GeV with the Alpha Magnetic Spectrometer on the International Space Station*, Phys.Rev.Lett. **113** (2014) 121101.

[41] J. Kopp, *Constraints on dark matter annihilation from AMS-02 results*, Phys.Rev. D**88** (2013) 076013, arXiv:1304.1184.

[42] L. Bergstrom, T. Bringmann, I. Cholis, D. Hooper, and C. Weniger, *New limits on dark matter annihilation from AMS cosmic ray positron data*, Phys.Rev.Lett. **111** (2013) 171101, arXiv:1306.3983.

[43] H.-B. Jin, Y.-L. Wu, and Y.-F. Zhou, *Implications of the first AMS-02 measurement for dark matter annihilation and decay*, JCAP **1311** (2013) 026, arXiv:1304.1997.

[44] Z.-P. Liu, Y.-L. Wu, and Y.-F. Zhou, *Sommerfeld enhancements with vector, scalar and pseudoscalar force-carriers*, Phys.Rev. D**88** (2013) 096008, arXiv:1305.5438.

[45] G. Giesen, M. Boudaud, Y. Genolini, V. Poulin, M. Cirelli, et al., *AMS-02 antiprotons, at last! Secondary astrophysical component and immediate implications for Dark Matter*, arXiv:1504.04276.