Dark Matter Search in Space: Combined Analysis of Cosmic-Ray Antiproton-to-proton Flux Ratio and Positron Flux Measured by AMS-02

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Abstract

Dark matter searches in space have been carried out for many years. Measurements of cosmic-ray (CR) photons, charged antiparticles, and neutrinos are useful tools for dark matter indirect searches. The antiparticle energy spectra of CRs have several exciting features, such as the unexpected positron excess at \(E \sim 10–500\) GeV and the remarkably flattening antiproton/proton at \(E \sim 60–450\) GeV precisely measured by the AMS-02 experiment, which cannot be explained simultaneously by secondary production in the interstellar medium. In this work, we report a combined analysis of CR antiproton and positron spectra arising from dark matter on the top of a secondary production in a spatial-dependent propagation model. We discuss the systematic uncertainties from the antiproton production cross section using the two latest Monte Carlo generators, i.e., EPOS LHC and QGSJET-II-04m. We compare their results. In the case of EPOS LHC, we find that the dark matter pair annihilating into \(\tau\) leptons channel with a 100% branching ratio and the \(p\)-wave annihilation cross section assumption is the only possible one-channel scenario to explain the data. On the other hand, there is not a single possible channel in the case of QGSJET-II-04m. We also propose possible two-channel scenarios based on these two Monte Carlo generators.

Key words: cosmic rays – dark matter

1. Introduction

After nearly one century of physics investigation, the search for dark matter is still ongoing. This search is carried out in three complementary ways: dark matter production in colliders, direct detection with underground instruments, and indirect detection in cosmic rays (CRs). Dark matter annihilation or decay may produce elementary particles, including neutral particles (photons \([\gamma]\) and neutrinos) and charged ones (positrons \([e^+]\) and antiprotons \([\bar{p}]\)). An impressive amount of dark matter information is being achieved by \(\gamma\)-ray data coming from space-based or ground-based telescopes such as Fermi’s Large Area Telescope \((\text{Fermi-LAT};\) Ackermann et al. 2012, 2015) or the High Energy Stereoscopic System \((\text{H.E.S.S.});\) Abdallah et al. 2016). Besides, valuable pieces of dark matter information from neutrinos are being collected by IceCube \((\text{Aartsen et al.} 2016).\) At the same time, an increase in the accuracy of charged elementary CR particle spectra is driving us to a deeper understanding of the fundamental physics processes in our Galaxy. Thanks to the new generation of detection experiments, such as the Payload for Antimatter Matter Exploration and Light-nuclei Astrophysics \((\text{PAMELA});\) or the Alpha Magnetic Spectrometer \((\text{AMS-02});\) in space, we are able to retrieve dark matter information in charged particle channels. The AMS-02 collaboration has now published the precise \(p/\bar{p}\) ratio measurement between \(0.5\) and \(450\) GeV of kinetic energy, showing that the ratio above \(\sim 60\) GeV experiences a remarkably flat behavior \((\text{Aguilar et al.} 2016a).\) PAMELA has also published similar results, but with less statistical significance \((\text{Adriani et al.} 2013).\) Together with the recent \(e^+\) flux data \((\text{Adriani et al.} 2009;\) Aguilar et al. 2014), which show a surprising excess above \(\sim 10\) GeV, those results give us a hint of extra sources.

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Unlike neutral particles that travel almost along straight lines, charged particles are difficult to trace back to their sources owing to the complex magnetic turbulence in the Galaxy. To constrain a secondary production contribution, one also needs to study the CR \(B/C\) elemental ratio, which has been measured by PAMELA and AMS-02 in space, or by the Advanced Thin Ionization Calorimeter \((\text{ATIC-2});\) and the Cosmic Ray Energetics and Mass \((\text{CREAM});\) on balloons. Besides, systematics from solar modulation and antiparticle production cross section should also be studied \((\text{Feng et al.} 2016).\) Recent studies \((\text{Feng et al.} 2016;\) Boschini et al. 2017b) showed that the excess of antiprotons was not significant but that of positrons was solid given by the current understanding of systematics. Some studies were carried out to interpret the positron excess that were consistent with a smooth \(B/C\) spectrum. According to diffusive shock acceleration \((\text{DSA});\) the sources accelerating \(C–N–O\) are the same as those accelerating helium or protons, which are the main progenitors of antiprotons and positrons \((\text{Blasi} 2009;\) Mertsch & Sarkar 2014; Tomassetti & Donato 2015). However, a recent deuteron-to-helium ratio \((d/He);\) measurement at \(0.5–2\) TeV/n by the satellite mission \(\text{SOKOL}\) \((\text{Turundaeyskiy & Podorozhny}\ 2017)\) showed a rather high value, which is not expected from the predictions tuned against \(B/C\). It stimulates a challenge to DSA \((\text{Tomassetti & Feng} 2017).\) If this deuteron-to-helium ratio measurement is correct, one should expect that the sources accelerating \(C–N–O\) are not the same as those accelerating helium or protons. The positron excess can be explained by nearby sources, which should be compatible with \(d/He\) instead of \(B/C.\) Otherwise, it seems unavoidable to introduce extra source components such as dark matter particle annihilation \((\text{Cirelli & Strumia} 2008;\) Cirelli et al. 2009; Boudaud et al. 2015; Lin et al. 2015b; Yuan et al. 2015), or \(e^+\) pair production mechanisms inside nearby pulsars \((\text{Hooper et al.} 2009;\) Delahaye et al. 2010, 2014; profumo 2011; Linden
Numerous analyses have been performed to interpret the precise $\bar{p}/p$ spectrum measured by AMS-02 independent of $e^+$ with dark matter scenarios (Giesen et al. 2015; Lin et al. 2015a, 2017; Huang et al. 2016; Cui et al. 2017; Cuoco et al. 2017). There are also some combined analyses of PAMELA $\bar{p}$, which has larger uncertainties, and AMS-02 $e^+$ (Cheng et al. 2016). In this paper, we perform a combined analysis of $\bar{p}/p$ and $e^+$ in dark matter scenarios. We reduce some uncertainty from normalizing by analyzing $\bar{p}/p$ instead of $\bar{p}$ spectrum because $p$ are $\bar{p}$ progenitors. For this reason, we avoid injection uncertainties of $e^-$ by analyzing $e^+$ instead of $e^-/(e^++e^-)$. Our basic idea is that the cross section and the mass of dark matter annihilation estimated from $e^+$ data should be consistent with those from $p$ data. Besides, we notice that the antiproton production cross section introduces major systematic uncertainties in the $\bar{p}/p$ spectrum (Di Mauro et al. 2014; Feng et al. 2016; Winkler 2017). Following the implementation of the cross section from MC generators in Feng et al. (2016), we present our study with EPOS LHC and QGSJET-II-04m, which were tuned against the latest LHC experimental data and reproduce the $\bar{p}$ production well (Feng et al. 2016; Lin et al. 2017). In each case, we perform a global fit to the data with all the free parameters in the propagation and dark matter models. We quantify the agreement between model prediction and data with the "p-value" method. We find that $\chi \rightarrow \tau^+\tau^-$ is the only possible channel, with a 100% branching ratio and the $p$-wave cross section assumption, based on the antiproton background calculated by EPOS LHC, while no channel is possible for QGSJET-II-04m. We also study the scenarios that dark matter decays into two channels, which gives a larger $p$-value compared to the one from channel scenarios. Comparisons with the analyses of $\gamma$-ray and cosmic microwave background (CMB) observations are also shown.

This paper is organized as follows. In Section 2, we present our calculations. In Section 2.1, we review briefly the $\bar{p}$ and $e^+$ from astrophysical sources as the background of our analysis. In Section 2.2, we introduce $p$ and $e^+$ flux produced at dark matter annihilation. In Section 2.3, we present our definition of a good fit. In Section 2.4, our consideration of solar modulation uncertainties is shown. In Section 3, we show our results and discussion, including for one annihilation channel in Section 3.1 and for two annihilation channels in Section 3.2. Finally, conclusions are drawn in Section 4.

## 2. Calculations

### 2.1. Astrophysical Background

In convectional CR propagation models, antiparticles are only produced in collisions of high-energy nuclei with the interstellar medium (ISM). The fluxes of their progenitor nuclei and CR propagation process together determine the spectra of antiparticles. The Galactic disk is surrounded by a halo with half-thickness $L$. For each CR species, its propagation can be described by a two-dimensional transport equation:

$$\frac{\partial \psi}{\partial t} = Q + \nabla \cdot (D \nabla \psi) - \psi \Gamma + \frac{\partial}{\partial E}(E \psi),$$

where $\psi = \psi(E, r, z)$ is the number density as a function of energy and space coordinates, and $\Gamma = \beta c n \sigma$ is the destruction rate in the ISM, with density $n$, at velocity $\beta c$ and cross section $\sigma$. The source term $Q$ includes a primary term, $Q_{\text{pri}}$, and a secondary production term $Q_{\text{sec}} = \sum_j \Gamma_j^\gamma \psi_j$, from the interaction of heavier $j$-type nuclei with rate $\Gamma_j^\gamma$. The term $\dot{E} = -dE/dt$ describes ionization and Coulomb losses, as well as radiative cooling of CR leptons. The diffusion coefficient is taken as $D(p, z) = \beta D_0 (R/R_0)^{\delta(z)}$, where $D_0$ shows its normalization, $R = pc/Ze$ is defined as the magnetic rigidity, and $R_0$ is its normalization rigidity. $\delta(z)$ expresses the scaling index.

Recent studies were done to get a set of injection and propagation parameters that could simultaneously reproduce a large set of nuclear data including proton, helium, and carbon fluxes; the $\text{B}/\text{C}$ elemental ratio; and the $^{10}\text{Be}/^9\text{Be}$ isotopic ratio (Evoli et al. 2015; Lin et al. 2015b; Feng et al. 2016; Johannesson et al. 2016). To assess the astrophysical background of antiparticles, we adopt a spatial-dependent model of CR diffusion (Tomassetti 2012, 2015). This model explains the high-energy departures from the standard universal power-law expectations in $p$ and He spectra observed by PAMELA (Adriani et al. 2011) and confirmed by AMS-02 (Aguilar et al. 2015a, 2015b), predicts a harder secondary-to-primary flux ratio later observed by AMS-02, and solves the problems on nuclei anisotropy and diffuse $\gamma$-rays (Feng et al. 2016; Guo & Yuan 2018), while the convectional models failed to do so (Evoli & Yan 2014). In this scenario, the scaling index $\delta(z) = \delta_0(z)$ in the region of $|z| < \xi L$ (inner halo) and $\delta(z) = \delta_0 + \Delta(z)$ when $|z| \geq \xi L$ (outer halo). The normalization is $D_0$ for the inner halo and $\chi D_0$ for the outer one. There is a connecting function of the type $F(z) = (z/\xi L)^\nu$ to ensure a smooth transition of the parameters $\chi$ and $\Delta$ across the two zones (Guo et al. 2015). The injection spectral indices of all the nuclei whose $z > 1$ all equal to $\nu$, while that of protons is $\nu + \Delta \nu$. Based on the method presented in Feng et al. (2016), we redo the Bayesian analysis on those parameters with the latest AMS-02 $\text{B}/\text{C}$ ratio (Aguilar et al. 2016b). In Figure 1, the $\text{B}/\text{C}$ ratio calculations are shown in comparison with the data. We use the DRAGON package (Gaggero et al. 2013),

![Figure 1. Best-fit model calculation and uncertainty band for the B/C ratio in comparison with AMS-02 data (Aguilar et al. 2016b).](image-url)
which is based on the GALPROP package (Strong et al. 2007),
to solve the transport equation. In Table 1, we compare the fit
parameters in the spatial-dependent propagation model (this
work) with those in the standard GALPROP model (SG)
reported in Boschini et al. (2017b). At low rigidity, the
diffusion coefficient has a velocity-dependent factor $\beta^\eta$, where
$\beta = v/c$. We fix $\eta = -4$ in order to reproduce proton
and helium fluxes below 20 GV in this work, while it is a free
parameter in Boschini et al. (2017b). This setting can avoid the
complicated parameters associated with convection, reaceleration,
and the injection break around 7 GV. In the standard GALPROP model, the injection spectral index of protons or helium is no longer a constant and contains two
breaks (i.e., $R_1$ and $R_2$) with different indices (i.e., $\nu_{1p}$, $\nu_{2p}$,
and $\nu_3$) before and after the breaks. We define $\nu_{1He} = \nu$ and $\nu_{1p} = \nu + \Delta \nu$ in order to compare them with those in Boschini et al. (2017b). $V_{\text{diff}}$, $V_{\text{conv}}$, and $dV_{\text{conv}}/dz$, in Table 1, are the Alfvén velocity, the convection wind velocity, and its gradient, respectively.

The antiproton production cross section systematic is one of
the main uncertainties of the astrophysical background. As has
been studied in Feng et al. (2016) and Kachelriess et al. (2015),
two of the most advanced Monte Carlo (MC) generators, EPOS
LHC (Pierog et al. 2015) and QGSJET-II-04m (Kachelriess et al.
2015), can reproduce the recent ground experiments well.
However, due to the scarcity of the antineutron production data, we have no way to test antineutron production cross sections. EPOS LHC predicts that the antineutron/antiproton ratio varies between 1.2 and 2.0, while QGSJET-II-04m shows that it is close to 1 except near the production threshold. As is shown in Figure 2, both model predictions with the latest AMS-02 B/C data (Aguilar et al. 2016b) on the antiproton-to-proton ratio are below the experimental data measured by the same instrument (Aguilar et al. 2016a).

The first measurement of the antiproton production cross
section in the $p + \text{He} \rightarrow \bar{p} + X$ channel was recently made
by the LHCb experiment located at the Large Hadron Collider
(LHC) at CERN (Graziani 2017). Collisions of 6.5 TeV proton beams on He nuclei at rest have been studied. Preliminary results showed that the data were between the predictions of EPOS LHC and QGSJET-II-04m. One should also note that those measurements are focused on a high transverse momentum ($p_T$) range, which is the tail of the production. More data at low $p_T$, where most of the antiprotons are produced, will be appreciated. We believe that the truth should be somewhere between these two models, so we test the dark matter scenarios with the backgrounds predicted by them individually. The positron production cross section is taken from a recent parameterization (Kamae et al. 2006). As shown later in Section 3, the positron production cross section is not a dominating component of the total uncertainties, since the excess of $e^+$ from the background is significant. So we do not discuss other $e^+$ cross sections in this paper.

### Table 1

| Parameter | Unit   | This Work | SG       |
|-----------|--------|-----------|----------|
| $L$       | kpc    | 6.70      | 4.0      |
| $D_0$     | $10^{28}$ cm$^{-1}$ s$^{-1}$ | 2.18 | 4.3 |
| $\delta$  |        | 0.19      | 0.395    |
| $\Delta$  |        | 0.56      | ...      |
| $\xi$     |        | 0.22      | ...      |
| $\chi$    |        | 0.30      | ...      |
| $V_{\text{diff}}$ | km s$^{-1}$ | ... | 28.6 |
| $V_{\text{conv}}$ | km s$^{-1}$ | ... | 12.4 |
| $dV_{\text{conv}}/dz$ | km s$^{-1}$ kpc$^{-1}$ | ... | 10.2 |
| $R_{1p}$  | GV     | ...       | 360      |
| $R_{2p}$  | GV     | 2.39      | 1.69     |
| $\nu_{1p}$ |        | ...       | ...      |
| $\nu_{2p}$ |        | ...       | 2.44     |
| $\nu_3$   |        | ...       | 2.28     |
| $R_{1He}$ | GV     | ...       | 7        |
| $R_{2He}$ | GV     | ...       | 360      |
| $\nu_{1He}$ |      | 2.29      | 1.71     |
| $\nu_{2He}$ |      | ...       | 2.38     |
| $\nu_{3He}$ |      | ...       | 2.21     |

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Figure 2. Model prediction using the best-fit parameters and uncertainty band for the antiproton/proton ratio. Top: EPOS LHC hadronic model prediction. Bottom: QGSJET-II-04m hadronic model prediction. AMS-02 data (Aguilar et al. 2016a) are also shown for comparison.
Pulsars are also important sources that produce secondary positrons. Previous studies showed that it is better to explain the positron spectrum with pulsar models rather than with dark matter models (Boudaud et al. 2015). This is ascribed to the fact that the profile of a pulsar model usually has more degrees of freedom than that of a dark matter model. For example, one must introduce at least three parameters in the pulsar fit, i.e., the cutoff energy, the injection spectral index, and the normalization (Feng & Zhang 2016). In dark matter scenarios, however, there are only two free parameters: the mass of the dark matter $m_\chi$ and the normalization (i.e., thermally averaged annihilation cross section $\langle \sigma v \rangle$) in the case of annihilation, where $\sigma$ is the annihilation cross section and $v$ is the velocity, or $\tau$, which is the lifetime in the case of decay; Giesen et al. (2015). The $\gamma$-ray spectrum of a single pulsar is preferably explained by a leptonic model rather than a hadronic one (Abdo et al. 2011). The spectral index of $\gamma$-rays produced from pion-decay emission (Ellison & Vladimirov 2008) of hadronic interactions should be harder than that through the inverse Compton scattering by leptons in a pulsar. Observation of RX J1713.7–3946 supports the latter. One might easily explain the CR antiproton spectrum by dark matter and the positron by pulsars. In this way, there will be five free parameters, so everything can be explained. However, this is not what we are going to do in this paper. Since the parameters of pulsars are not easy to constrain, we do not consider contributions of them into the astrophysical background.

2.2. The Fluxes of Antimatter from Dark Matter Annihilation

The CR antiparticle fluxes produced by dark matter have been studied and collected in A Poor Particle Physicist Cookbook for Dark Matter Indirect Detection (PPPC; Cirelli et al. 2011). The authors calculated the results with PYTHIA and HERWIG Monte Carlos, so they had a feeling of the uncertainties. Historically, leptons and vector bosons were treated as unpolarized, and parton showers were assumed not to emit W’s and Z’s. Under these assumptions, $\vec{p}$ will not be produced in leptonic channels. However, as is pointed out by Ciafaloni et al. (2011), polarizations and electroweak corrections should be considered, which will modify $e^\pm$ spectra at low energies $E \ll m_\chi$, and produce $\vec{p}$ in leptonic channels owing to W/Z radiation.

We consider dark matter annihilation into the following primary channels: $e^+ e^-$, muons ($\mu^+\mu^-$), taus ($\tau^+\tau^-$), light quarks ($q\bar{q}$), bottom quarks ($b\bar{b}$), and W bosons ($W\bar{W}$) in order to compare this study with the $\gamma$-ray observations (Ackermann et al. 2015). As can be seen later in this paper, $q\bar{q}$, $b\bar{b}$, and $W\bar{W}$ predict too many $\vec{p}$ but not enough $e^\pm$. In order to improve the model, we also study the $VV \rightarrow 4e$, $VV \rightarrow 4\mu$, and $VV \rightarrow 4\tau$, where the annihilation first goes into a new light boson $V$ that will later decay into a pair of leptons proposed by Arkani-Hamed et al. (2009) and Pospelov & Ritz (2009). Previous study by Cholis & Hooper (2014) showed that those channels can also reproduce $e^\pm$. These so-called “four-body” channels will not produce $\vec{p}$. A recent study proposed a “three-body” channel where dark matter decays into a stable neutral particle and a pair of supersymmetry fermions (Cheng et al. 2016), which is also interesting but more complex. Another recent work proposed a new “four-body” channel that dark matter annihilates into light mediators, which later decay into 2$q\bar{q}$ (Huang et al. 2016). We do not discuss this case since it produces mostly $\vec{p}$ in its final state, while we prefer more $e^\pm$ in this study.

We adopt the Navarro, Frenk, and White (NFW; Navarro et al. 1996) profile to describe the galactic distribution of dark matter in the Milky Way, which reads as

$$\rho_{\text{NFW}}(r) = \rho_s \left(\frac{r_s}{r}\right)^{-2},$$

(2)

where $\rho_s = 0.184$ GeV cm$^{-3}$ and $r_s = 24.42$ kpc are the typical scale density and radius, respectively (Cirelli et al. 2011). These values are obtained by setting the density to be $\rho_0 = 0.3$ GeV cm$^{-3}$ at the Sun position $r_0 = 8.33$ kpc. As is shown in Figure 3, the dark matter density profile does not affect the observed positron spectrum near Earth, which is dominated by the local contribution. It is also worth pointing out that the isothermal (Bergstrom et al. 1998), Einasto (2009) and Moore et al. (1999), and Diemand et al. (2004) profile will change the dark matter antiproton contribution normalization by a factor of $\sim$0.5, $\sim$2, and $\sim$4, respectively, in the...
spatial-dependent propagation model. These differences are smaller than those reported in traditional propagation models (Jin et al. 2015).

After getting the fluxes of antiparticles produced by dark matter with the NFW distribution, we take it as the source term in the transport equation (Equation (1)). The differential fluxes of antiparticles at production are \( \mathcal{Q}_{\text{DM}}(E) \propto (\rho/m_{\chi})^2 \) in the case of annihilation and \( \mathcal{Q}_{\text{DM}}(E) \propto (\rho/m_{\chi})^3 \) in the case of decay (Cirelli et al. 2011). Since the fluxes have the same energy dependence for the two cases and the energy spectra at the position of Earth would be similar, we discuss dark matter annihilation here as an example.

2.3. Formalism of the Statistical Test Method

We adopt a frequentist statistical test in this work. Generally speaking, for discovering dark matter, we define the null hypothesis, \( H_0 \), as the astrophysical background, which is to be tested against the alternative \( H_1 \) that includes both the astrophysical background and dark matter signal. For setting dark matter limits, we define \( H_0 \) as the astrophysical background plus dark matter signal to be tested against the background-only hypothesis, \( H_1 \). This work is in the former case. To quantify the agreement between data and the predictions of \( H \), we compute the probability, the widely used “p-value” (Cowan et al. 2011),

\[
p_0 = \int_{t_{0,\text{obs}}}^\infty f (t_0 | \theta) dt_0,
\]

where \( t_0 \) is the \( \chi^2 \) for a given signal strength \( \theta \). \( t_{0,\text{obs}} \) is the observed one. \( f (t_0 | \theta) = \frac{(r/2)^{r/2}}{\sqrt{2\pi}} e^{-t_0^2/(2r)} \) is the distribution of \( t_0 \) for the number of degrees of freedom \( r \), where \( \Gamma(\chi) \) is a gamma function.

2.4. Solar Modulation Uncertainties

Force-field approximation is used to describe solar modulation. However, this approximation fails to describe charge-sign-dependent solar modulation (Maccione 2013; Kappel 2016), which has recently been observed by PAMELA (Adriani et al. 2016) and can be quantitatively studied with high-statistic AMS data. In order to take solar modulation uncertainties into account, the \( \chi^2 \) can be written as a function of \( \langle \sigma v \rangle \) and the dark matter mass \( m_{\chi} \),

\[
\chi^2(m_{\chi}, \langle \sigma v \rangle, \theta_{\text{bkg}}, \phi) = \sum_{i=1}^{N_0} \left( \frac{\chi^\text{exp} - \chi^\text{th}(m_{\chi}, \langle \sigma v \rangle, \theta_{\text{bkg}}, \phi)}{\sigma_k} \right)^2,
\]

where \( \sigma_k = \sqrt{\sigma_{k,0}^2 + \sigma_{k,\phi}^2} \) is the total uncertainty of the data point \( k \) with the model uncertainty (\( \sigma_{k,\phi} \)) introduced by varying the solar modulation potential \( \phi \) from -300 to +700 MV. The prior of background parameters \( \theta_{\text{bkg}} \) is obtained via the fitting to the B/C (Aguilar et al. 2016b), \(^{10}\text{Be}/^{13}\text{Be} \) (Garcia-Munoz et al. 1977, 1981; Hagen et al. 1977; Buffettong et al. 1978; Webber & Kish 1979; Wiedenbeck & Greiner 1980), proton (Aguilar et al. 2015a), helium (Yoon et al. 2011; Aguilar et al. 2015b), and carbon data (Ahn et al. 2009; Adriani et al. 2014). This quantity describes the consistency of model parameters \( (m_{\chi}, \langle \sigma v \rangle, \theta_{\text{bkg}}, \phi) \) and experimental data \( \langle \gamma^\text{exp} \rangle \) with corresponding uncertainties \( (\sigma_{\gamma,0}) \).

In this way, the model is more sensitive to high-energy CR data than low-energy data. This method allows us to make use of the low-energy data without introducing bias from solar modulation models.

3. Results and Discussion

3.1. Dark Matter Annihilation into One Channel

We investigate the possibility of explaining \( \bar{p} \) and \( e^+ \) by one annihilation channel with a 100% branching ratio. We study the \( \bar{p}/p \) spectrum instead of \( \bar{p} \) flux, since the uncertainties of \( \bar{p} \) and those of \( p \) are canceled. To avoid the uncertainties of the \( e^- \) injection spectra, we study \( e^+ \) flux. To avoid solar modulation uncertainties, we use positron flux data above 30 GeV, antiproton-to-proton flux ratio above 10 GeV, and primary proton and nucleus fluxes above 10 GeV. We found that only the \( \chi \text{H} \rightarrow \tau^+ \tau^- \) channel gives us a \( p \)-value greater than \( 10^{-5} \), with a normalized chi square \( \chi^2/n.d.f. = 161.82/207 \) and \( \rho_{nm} = 0.9918 \). We get the best-fit values: \( m_{\chi} = 783 \pm 56 \text{ GeV} \) and \( \langle \sigma v \rangle = (261.20 \pm 23.93) \times 10^{-26} \text{ cm}^2 \text{s}^{-1} \). Other channels are impossible. To give a feeling of the goodness of the fit, we plot the calculated \( \bar{p}/p \) and \( e^+ \) spectra together with the AMS-02 data in Figure 4. On the other hand, however, there is no channel that gives us a large \( p \)-value with QGSJET-II-04m.

In Figure 5, it is shown that this scenario survives from the constraints of Fermi-LAT diffuse measurements (Ackermann et al. 2012), has an overlap with Planck CMB constraints (Ade et al. 2016; Slatyer 2016), but has been excluded by \( \gamma \)-ray observations from Milky Way dwarf spheroidal galaxies under the s-wave-dominated dark matter assumption (Ackermann et al. 2015). The latest study by Masi & Ballardini (2016) also pointed out that dark matter scenarios obtained from CRs positrons are not completely excluded by CMB observations considering the current systematic uncertainties. One should notice that there is still a possibility to accept this scenario if \( p \)-wave annihilation is not negligible, according to a recent study (Zhao et al. 2016).

From this exercise, it is shown that most of the single-channel scenarios cannot simultaneously explain \( \bar{p} \) and \( e^+ \). With respect to the astrophysical background, the excess of \( e^+ \) is solid evidence of an extra \( e^+ \) source, while that of \( p \) is marginal. This requires a large \( \langle \sigma v \rangle \) to explain \( e^+ \) data, while requiring a small \( \langle \sigma v \rangle \) to produce \( \bar{p} \). For quark (e.g., \( q \bar{q} \)) and \( b \bar{b} \) or boson channels (e.g., \( W \bar{W} \)), it predicts not enough \( e^+ \) and too much \( \bar{p} \). For leptonic channels (i.e., \( e^+ e^- \), \( \mu^+ \mu^- \), and \( \tau^+ \tau^- \)), it predicts enough \( e^+ \), but the \( e^+ \) profile of the dark matter signal does not match the data quite well. Thus, we introduce one more channel to get more \( e^+ \) in Section 3.2 to improve the fit.

3.2. Dark Matter Annihilation into Two Channels

Now we come to the possibility that dark matter annihilates into two channels. In Section 3.1, it is shown that more \( e^+ \) in the annihilation will improve the fit. Setting one of the six channels in Section 3.1 as the first channel, we have studied “four-body” lepton channels as the second channels, which are
Seven scenarios with a best-fit $p$-value greater than $10^{-7}$ for EPOS LHC as the antiproton production model are listed in Table 2. The number of degrees of freedom is 208. CH stands for the channel. $BR_i$ is short for the branching ratio of the $i$th channel. Compared with the one-channel scenarios, these two-channel scenarios can improve the quality of the fit a lot. In Table 2, it is shown that $\chi \chi \rightarrow VV \rightarrow 2\tau^+\tau^-$ is the dominating channel in three scenarios with the largest $p$-values. For QGSJET-II-04m, no scenario gives a $p$-value greater than $10^{-7}$. The best scenario gives a $\chi^2/n.d.f = 349.11/208$ and a $p$-value $= 3.1 \times 10^{-9}$ with the parameters: $m_\chi = 545$ GeV, $(\sigma V) \times BR_1 = 3.45 \times 10^{-26}$ cm$^3$ s$^{-1}$ for $\chi \chi \rightarrow q\bar{q}$, and $(\sigma V) \times BR_2 = 74.47 \times 10^{-26}$ cm$^3$ s$^{-1}$ for $\chi \chi \rightarrow VV \rightarrow 2\mu^+\mu^-$. We draw the $\tilde{p}/p$ and $e^+$ plots of dark matter annihilation into $W W$ and $VV \rightarrow 2\tau^+\tau^-$ channels as the "best-fit" example for EPOS LHC in Figure 6. This scenario shows that the mass of dark matter is $1689 \pm 23$ GeV and its $(\sigma V) = (600.02 \pm 21.32) \times 10^{-26}$ cm$^3$ s$^{-1}$ with a branching ratio of $0.890\% \pm 0.017\%$ for $\chi \chi \rightarrow W\bar{W}$ and $99.11\% \pm 0.03\%$ for $\chi \chi \rightarrow VV \rightarrow 2\tau^+\tau^-$. In Figure 7, we show the $\tilde{p}/p$ and $e^+$ plots of dark matter annihilation into $q\bar{q}$ and $VV \rightarrow 2\mu^+\mu^-$ channels for QGSJET-II-04m. This fit gives a low $p$-value, which is $3.1 \times 10^{-9}$. We obtain that the mass of dark matter is $545 \pm 20$ GeV and its $(\sigma V) = (77.92 \pm 4.08) \times 10^{-26}$ cm$^3$ s$^{-1}$, with a branching ratio of $4.42\% \pm 0.17\%$ for $\chi \chi \rightarrow q\bar{q}$ and $95.57\% \pm 0.16\%$ for $\chi \chi \rightarrow VV \rightarrow 2\mu^+\mu^-$. These two plots show that the two antiproton production models do not give consistent results for all the scenarios. As is discussed in Section 2.1, the difference of antineutrino production in these two MC generators is the source of the systematics of the antiproton astrophysical background. Some recent works parameterized the antiproton production cross sections with the latest ground experimental data (Di Mauro et al. 2014; Kappl & Winkler 2014; Winkler 2017), which is also a good way to obtain this cross section. For antineutrino production, however, they assumed an energy-independent scale factor $\kappa \equiv$ antineutrino/antiproton to be a constant according to isospin symmetry, based on a preliminary experimental result published in a conference proceeding (Fischer 2003). One should notice that this energy-independent assumption of $\kappa$ is not precise enough to describe antineutrino production. When the antiproton energy is close to the production threshold, $\kappa$ should be maximum in any model. $\kappa$ goes down when the antiproton energy moves away from the threshold (Feng et al. 2016). An energy-dependent $\kappa$, however, changes the shape of the $\tilde{p}$ flux. More cross section measurement data from accelerators will help to reduce this kind of systematic uncertainty.

As is shown in the top panels of Figures 6 and 7, both MC generators predict a $\tilde{p}/p$ astrophysical background going down with energy above 60 GeV, while AMS-02 data are flat. The dark matter signal makes the $\tilde{p}/p$ spectrum harder and closer to observed data. One should notice that these model predictions are based on the spatial-dependent propagation model. The standard GALPROP model shows that its antiproton astrophysical background calculated with QGSJET-II-04m is compatible with AMS-02 data (Boschini et al. 2017b) at high rigidity. On the other hand, $e^+$ flux measured by AMS-02 is significantly higher than the astrophysical background. If the extra source produces the same among the $e^+$ and $e^-$, one should expect an excess in the $e^-$ spectrum and $e^+ + e^-$

pure lepton channels and do not produce any $\tilde{p}$. In this kind of scenario, we will have more $e^+$ while keeping almost the same amount of $\tilde{p}$.
spectrum. Compared to the astrophysical background, the excess in those spectra (Boschini et al. 2018) is not as significant as that in the pure $\bar{e}^+$ spectrum. The dark matter profile can produce a “cutoff”-like spectrum as is measured by AMS-02. The “best”-fit results can match measurement up to a few hundred GeV.

4. Conclusions

An increase in the accuracy of the CR antiparticle spectra measurements is driving us closer to the answer of dark matter. Together with CR $\gamma$-ray (Ackermann et al. 2012, 2015; Abdallah et al. 2016) and neutrino (Aartsen et al. 2016) spectra, $\bar{p}$ and $e^+$ spectra help us study astrophysical properties of the potential dark matter with $m_\chi \sim 10^9–10^5$ GeV.

### Table 2

$m_\chi$, $s_\chi$, $\chi^2$s, and $p$-values Given by the “Good” Fits in Two-channel Scenarios with EPOS LHC

| CH1 | CH2 | $m_\chi$ (GeV) | $\langle \sigma v \rangle \times \mathcal{R}_1$ ($10^{-26}$ cm$^3$ s$^{-1}$) | $\langle \sigma v \rangle \times \mathcal{R}_2$ ($10^{-26}$ cm$^3$ s$^{-1}$) | $\chi^2$ | $p$-value |
|-----|-----|----------------|------------------------------------------|------------------------------------------|--------|----------|
| $\tau^- \tau^-$ | $VV \rightarrow 2\tau^-\tau^-$ | 1320 ± 14 | 225.29 ± 7.39 | 244.48 ± 9.38 | 164.42 | 0.9885 |
| $q \bar{q}$ | $VV \rightarrow 2\mu^-\mu^+$ | 654 ± 12 | 0.96 ± 0.14 | 89.85 ± 5.7 | 174.85 | 0.9593 |
| $q \bar{q}$ | $VV \rightarrow 2\tau^-\tau^-$ | 1800 ± 23 | 3.97 ± 0.08 | 588.71 ± 12.53 | 162.43 | 0.9916 |
| $b \bar{b}$ | $VV \rightarrow 2\mu^-\mu^+$ | 601 ± 12 | 1.00 ± 0.16 | 81.89 ± 5.46 | 185.60 | 0.8659 |
| $b \bar{b}$ | $VV \rightarrow 2\tau^-\tau^-$ | 1679 ± 34 | 4.38 ± 0.16 | 598.98 ± 15.94 | 149.29 | 0.9992 |
| $W W$ | $VV \rightarrow 2\mu^-\mu^+$ | 624 ± 11 | 1.45 ± 0.16 | 87.59 ± 6.59 | 180.12 | 0.9192 |
| $W W$ | $VV \rightarrow 2\tau^-\tau^-$ | 1689 ± 23 | 5.34 ± 0.10 | 594.68 ± 17.96 | 143.65 | 0.9998 |

Note. The number of degrees of freedom is 208.
We summarize everything here. We present our study on dark matter searches from CR $\bar{p}$ and $e^+$ data above 30 GeV. For the first time, we simultaneously interpret $\bar{p}$ and $e^+$ spectra in the framework of AMS-02 with dark matter scenarios. We find that the $\chi \chi \rightarrow \tau^+\tau^-$ channel with a 100% branching ratio is the best one-channel scenario to reproduce CR $\bar{p}/p$ and $e^+$ flux measurement, with $m_{\chi} = 783 \pm 56$ GeV and $\langle v \rangle = (261.20 \pm 23.93) \times 10^{-26}$ cm$^3$ s$^{-1}$, in the case of EPOS LHC. This scenario is not yet rejected by $\gamma$-ray observation under the $p$-wave cross section assumption. For the antiproton background using the same MC generator, we also propose a two-channel scenario: $m_{\chi} = 1689 \pm 23$ GeV and $\langle v \rangle = (600.02 \pm 21.32) \times 10^{-26}$ cm$^3$ s$^{-1}$. The dominating channel is $\chi \chi \rightarrow VV \rightarrow 2\tau^+\tau^-$, with a branching ratio of 99.11% $\pm$ 0.03%, while the second channel is $\chi \chi \rightarrow WW$, with a branching ratio of 0.890% $\pm$ 0.017%. In the case of QGSJET-II-04m, no scenario gives a good fit. These scenarios predict $\bar{p}/p$ spectra harder than those in the background-only scenario. They also predict an $e^+$ spectrum with a cutoff between 100 and 2000 GeV, which is also observed by AMS-02, even though the shape does not completely match data. Since the direct observation of dark matter annihilation has not yet been reported, our results (i.e., masses, cross sections, and channels) can provide useful information for the collider experiments (ATLAS and CMS) to search for weakly interacting massive particles beyond the standard model.

Comparing to the pulsar scenarios (Feng & Zhang 2016), we find that the $\chi^2/n.d.f.s$ in dark matter fits are higher. This is due to the fact that pulsar models usually have more degrees of freedom. For example, the injection spectral index of a pulsar is a free parameter, which will adjust the pulsar propagation. For example, the injection spectral index of a pulsar is due to the fact that pulsar models usually have more degrees of freedom. For example, the injection spectral index of a pulsar is a free parameter, which will adjust the pulsar propagation.

Recent time-dependent $e^+/e^-$ measurements by PAMELA (Adriani et al. 2016) confirmed charge-sign-dependent solar modulation models (Maccione 2013; Kappl 2016). The convectional force-field approximation (Gleeson & Axford 1968) is not precise enough for us. Recent developments of the solar modulation model (Bobik et al. 2012, 2015; Boschin et al. 2017a) considered more realistic physical processes. This model, namely HelMod, has successfully reproduced proton spectra during solar cycles 23 and 24. Another interesting study discovered that solar modulation parameters are related to the number of solar sunspots and the tilt angle of the heliospheric current sheet 8.1 months in advance (Tomassetti et al. 2017). AMS-02 will publish its much more precise time-dependent $e^+, e^-, \bar{p}$, and $p$ fluxes in the near future, which will allow us to further test HelMod and to reconstruct the fluxes out of the heliosphere.

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References

Aartse, M. G., Abraham, K., Ackermann, M., et al. 2016, EPJC, 76, 531
Abdallah, H., Abramowski, A., Aharonian, F., et al. 2016, PhRvL, 117, 111301
Abdo, A. A., Abramowski, A., Aharonian, F., et al. 2011, ApJ, 734, 28
Ackermann, M., Ajello, M., Atwood, W. B., et al. 2012, ApJ, 761, 91
Ackermann, M., Albert, A., Anderson, B., et al. 2015, PhRvL, 115, 231301
Ade, P. A. R., Aghanim, N., Arnaud, M., et al. 2016, A&A, 594, A13
Adriani, O., Barbarino, G. C., Bazzilevskaya, G. A., et al. 2009, Natur, 458, 607
Adriani, O., Barbarino, G. C., Bazzilevskaya, G. A., et al. 2011, Sci, 332, 69
Adriani, O., Barbarino, G. C., Bazzilevskaya, G. A., et al. 2016, PhRvL, 116, 241105
Adriani, O., Barbarino, G. C., Bazzilevskaya, G. A., et al. 2014, PhRv, 79, 913
Adriani, O., Bazzilevskaya, G. A., Barbarino, G. C., et al. 2013, JETPL, 96, 621, [PZETF 96, 693 (2013)]
Aguiar, M., Aisa, D., Alpat, B., et al. 2015a, PhRvL, 114, 171103
Aguiar, M., Aisa, D., Alpat, B., et al. 2015b, PhRvL, 115, 211101
Aguiar, M., Aisa, D., Alpat, B., et al. 2016a, PhRvL, 117, 091103
Aguiar, M., Aisa, D., Alvino, A., et al. 2014, PhRvL, 113, 121102
Aguiar, M., Ali Cavasonza, L., Ambrosi, G., et al. 2016b, PhRvL, 117, 231102
Ahn, H. S., Allison, P., Bagliesi, M. G., et al. 2009, ApJ, 707, 593
Aarki-Hamed, N., Finkbeiner, D. P., Slatyer, T. R., & Weiner, N. 2009, PhRvD, 79, 015014
Bergstrom, L., Ullio, P., & Buckley, J. H. 1998, APh, 9, 137
Blasi, P. 2009, PhRvL, 103, 051104
Bobik, P., Boella, G., Boschini, M. J., et al. 2012, ApJ, 745, 132
Bobik, P., Boschini, M. J., Torre, S. D., et al. 2015, A&AR, 121, 3920
Boschini, M. J., Della Torre, S., Gervasi, M., et al. 2017b, PhRv, 840, 115
Boschini, M. J., Della Torre, S., Gervasi, M., et al. 2018, ApJ, 854, 94
Boschini, M. J., Della Torre, S., Gervasi, M., La Vacca, G., & Roncaito, P. G. 2017a, arXiv:1704.03573
Boudaud, M., Aupetit, S., Danielewski, H., et al. 2014, A&A, 575, A67
Boultong, A., Orth, C. D., & Mast, T. S. 1978, ApJ, 226, 355
Cheng, H.-C., Huang, W.-C., Huang, X., et al. 2016, arXiv:1608.06382
Cholis, I., & Hooper, D. 2014, PhRvD, 89, 043013
Ciafaloni, P., Comelli, D., Riotto, A., et al. 2011, JCAP, 1103, 051, [Erratum: JCAP, 1210, E01 (2012)]
Cirelli, M., Kalastik, M., Raadal, M., & Strumia, A. 2009, NuPhB, 813, 1
Cirelli, M., & Strumia, A. 2008, arXiv:0808.3867
Cowan, G., Cline, W., & Felder, O. 2011, PhRvL, 115, 211102
Cui, X.-Y., Yuan, Q., Tsai, Y.-L., & Fan, Y.-Z. 2017, PhRvL, 118, 191101
Cuoco, A., Kramer, M., & Korsmeier, M. 2017, PhRvL, 118, 191102
Delahaye, T., Tomassetti, G., et al. 2017, arXiv:1704.03573
Di Mauro, M., Donato, F., Forciacono, N., Lineros, R., & Vittino, A. 2014, JCAP, 1404, 006
Di Mauro, M., Donato, F., Forciacono, N., & Vittino, A. 2016, JCAP, 1605, 031
Einasto, J. 2009, arXiv:0901.0632
Ellison, D. C., & Vladimirov, A. 2008, ApJL, 673, L47
