Possible Dark Matter Annihilation Signal in the AMS-02 Antiproton Data

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Using the latest AMS-02 cosmic-ray antiproton flux data, we search for a potential dark matter annihilation signal. The background parameters about the propagation, source injection, and solar modulation are not assumed *a priori* but based on the results inferred from the recent B/C ratio and proton data measurements instead. The possible dark matter signal is incorporated into the model self-consistently under a Bayesian framework. Compared with the astrophysical background-only hypothesis, we find that a dark matter signal is favored. The rest mass of the dark matter particles is ∼20–80 GeV, and the velocity-averaged hadronic annihilation cross section is about $(0.2–5) \times 10^{-26}$ cm^3 s^{-1}, in agreement with that needed to account for the Galactic center GeV excess and/or the weak GeV emission from dwarf spheroidal galaxies Reticulum 2 and Tucana III. Tight constraints on the dark matter annihilation models are also set in a wide mass region.

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Introduction.—The precise measurements of cosmic-ray (CR) antiparticle spectra by space-borne instruments, such as PAMELA and AMS-02, provide very good sensitivity to probe the particle dark matter (DM) annihilation or decay in the Milky Way. The CR antiprotons, which primarily come from the inelastic collisions between the CR protons (and helium) and the interstellar medium (ISM), are effective to constrain the DM models [1–3]. Recent observations of the antiproton fluxes [4–6] are largely consistent with the expectation from the CR propagation model, leaving very limited room for the annihilation or decay of DM [2,7–10].

There are several sources of uncertainties in using antiprotons to constrain DM models. The largest uncertainty may come from the propagation parameters. Usually, the secondary-to-primary ratio of CR nuclei, such as the boron-to-carbon ratio (B/C), and the radioactive-to-stable isotope ratio of secondary nuclei, such as the beryllium isotope ratio ^{10}Be/^{9}Be, are used to determine the propagation parameters [11,12]. Limited by the data quality, the constraints on the propagation parameters are loose [13,14]. Even though the effect on the background antiproton flux due to uncertainties of propagation parameters is moderate, the flux from the DM component depends sensitively on the propagation parameters [15]. Additional uncertainties include the injection spectrum of the CR nuclei, solar modulation, and hadronic interaction models [8]. Those uncertainties make the DM searches with antiprotons inconclusive [16,17].

Given the new measurements of the proton, helium, and B/C data by PAMELA and AMS-02 [18–21], improved constraints on the propagation and source injection parameters can be obtained through global Bayesian approaches [22–25]. With these data, we conduct a global study to determine the propagation, injection, and solar modulation parameters simultaneously using the Markov chain Monte Carlo (MCMC) method [26]. These "background" parameters and their likelihoods can be incorporated in the study of the DM model parameters by means of the Bayesian theorem, giving self-consistent and unbiased judgment of the DM models (see earlier attempts [17,23]). In this work, we apply this method to the most recently reported antiproton fluxes measured by AMS-02 [6]. Furthermore, we improve the constraints on the solar modulation parameters with the time-dependent proton fluxes measured by PAMELA [27]. Note, however, that we adopt a relatively simple one-zone diffusion model in this work. It is possible that in reality the ISM and CR propagation are more complicated, e.g., vary everywhere [25].

Background.—Here we simply introduce the fitting procedure to determine the propagation, injection, and solar modulation parameters [26,28]. Hereafter they are referred to as background parameters. We work in the diffusion reacceleration [29] framework of the CR propagation, which was found to reproduce the peak of the B/C data around 1 GeV/n well [30]. The injection spectrum of nuclei is assumed to be a broken power law with respect to rigidity. Although the spectrum of helium (and heavier nuclei) is found to be harder than that of protons, we assume a unified set of injection parameters of all nuclei. Such an assumption is expected to not sensitively affect the calculation of the B/C ratio. The solar modulation model is adopted to be the force-field approximation [31]. As for the modulation potential, we employ a time-variation form $\Phi = \Phi_0 + \Phi_1 \times \tilde{N}(t)$ to connect the modulation with solar activities which are characterized by the sunspot number [32] $\tilde{N}(t)$ (normalized to 1 at the solar maximum of cycle 24). The data used in the fitting include the B/C data by ACE [33] and AMS-02 [21], the proton spectrum by AMS-02 [19], and the time-dependent proton fluxes by PAMELA [27]. The ^{10}Be/^{9}Be ratio is not well measured yet. We use some old data in the fitting (see Ref. [26]).

The numerical tool GALPROP [34,35] is adopted to calculate the propagation of CRs. We have developed a global fitting tool, COSRAYMC, which incorporates GALPROP into the MCMC sampler [36], enabling an efficient survey of the high-dimensional parameter space of the CR propagation [37,38]. Once the background parameters are obtained, the secondary production of antiprotons can be obtained, as shown in Fig. 1. Note that there are uncertainties from the antiproton production cross section [39–43]. Especially, it has been found that an asymmetry exists between the antineutron and antiproton production for pp collisions, which tends to give more antineutrons [45]. An energy-independent rescaling factor of $\kappa \simeq 1.3 \pm 0.2$ has been suggested to approximate the ratio of antineutron-to-antiproton production cross sections [41]. The energy dependence of κ is unclear at present [41,42]. We expect that a constant factor is a simple and reasonable assumption. For the results shown in Fig. 1, we adopt $\kappa = 1.2$.

DM annihilation.—Antiprotons can also be produced via the DM annihilation or decay. In this work, we focus on the discussion of DM annihilation. The density profile of DM is adopted to be Navarro-Frenk-White profile [46], $\rho(r) = \rho_s[(r/r_s)(1 + r/r_s)^2]^{-1}$, where $r_s = 20$ kpc and $\rho_s = 0.26$ GeV cm^{-3}. The production spectrum of antiprotons is calculated using the tables given in Ref. [47].

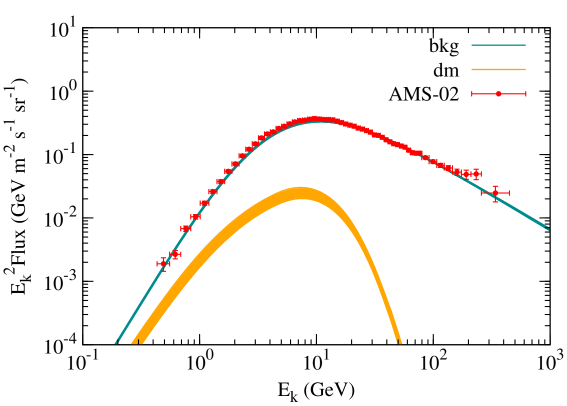

FIG. 1. Secondary and DM annihilation antiproton fluxes calculated for 2σ ranges of the background parameters determined in the fitting to the B/C, ^{10}Be/^{9}Be, and proton data. As an illustration, the mass of the DM particle is 47 GeV, the cross section is 10^{-26} cm^3 s^{-1}, and the annihilation channel is $b\bar{b}$.

Figure 1 shows the results of DM-induced antiproton fluxes, for $m_\chi = 47$ GeV and $\langle\sigma v\rangle = 10^{-26}$ cm^3 s^{-1} (for illustration), and various background parameters which lie in the 2σ ranges derived in the background fitting. Because of the improved constraints on the propagation parameters (e.g., the half height of the propagation halo $z_h = 5.9 \pm 1.1$ kpc [28]), the DM annihilation-induced antiproton fluxes are constrained in a range of a factor of $\sim$2, which improve much compared with previous studies (e.g., [15,23]).

Results of DM constraints.—From the Bayesian theorem, one can always update the prior from independent measurements. The posterior probability density of the parameter $\langle\sigma v\rangle$ for a given mass of the DM particle m_χ can be written as

$$\mathcal{P}(\langle\sigma v\rangle)|_{m_\chi} \propto \int \mathcal{L}(m_\chi, \langle\sigma v\rangle, \boldsymbol{\theta}_{\rm bkg}, \kappa) p(\boldsymbol{\theta}_{\rm bkg}) p(\kappa) d\boldsymbol{\theta}_{\rm bkg} d\kappa, \tag{1}$$

where $\mathcal{L}$ is the likelihood function of model parameters $(m_\chi, \langle\sigma v\rangle, \boldsymbol{\theta}_{\rm bkg}, \kappa)$ calculated from the AMS-02 antiproton data, $p(\boldsymbol{\theta}_{\rm bkg})$ is the prior of background parameters $\boldsymbol{\theta}_{\rm bkg}$ which is obtained via the MCMC fitting to the B/C, ^{10}Be/^{9}Be, and proton data, and $p(\kappa)$ is the prior of the antineutron-to-antiproton production ratio, which is assumed to be Gaussian distribution $N(1.3, 0.2^2)$ [41,45].

We find that the AMS-02 data favor a DM component with a mass of a few tens GeV and an annihilation cross section of the thermal production level for the quark final state. This conclusion holds for different antiproton production cross sections given in Refs. [39–41] as well as different source distributions of CRs [48]. The logarithmic Bayes factor value ($2\ln K$) of the DM component is found to be about 11–54 for the three cross section parameterizations used. The best-fit DM mass is about 40–60 GeV, and the annihilation cross section is about $(1–3) \times 10^{-26}$ cm^3 s^{-1} for the $b\bar{b}$ channel. Figure 2 shows the favored parameter regions on the $m_\chi - \langle\sigma v\rangle$ plane. For DM annihilation into W^+W^-, similar results can be found with slightly heavier masses (due to the mass threshold to produce W bosons). Using the PAMELA data, Ref. [17] obtained similar results, although in a suggestive way with significantly larger uncertainties.

It is interesting to note that such a favored parameter region is consistent with that to fit the GeV γ-ray excess in the Galactic center region [56,57] as well as the tentative γ-ray excesses in the directions of two dwarf galaxies [58,59]. Also, we find that the favored DM mass is consistent with that inferred from a tentative γ-ray linelike signal with energies $\sim$43 GeV from a population of clusters of galaxies [60]. Such a consistency, if not solely due to coincidence, strongly supports the common DM origin of the antiproton "anomaly" and GeV γ-ray excesses.

We also derive the upper limits of the DM annihilation cross section for DM masses of 10–10^4 GeV, as shown in

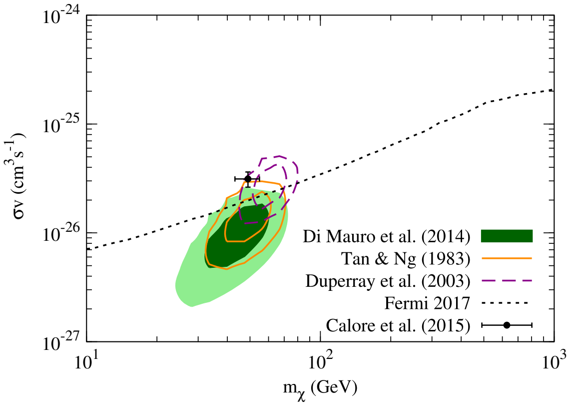

FIG. 2. Shaded regions and contours are the 68% and 95% credible regions, respectively, of parameters $m_\chi - \langle\sigma v\rangle$ to fit the antiproton data, for three parameterizations of the antiproton production cross sections [39–41]. The annihilation channel is assumed to be $b\bar{b}$. Also shown are the Fermi-LAT exclusion limits from observations of dwarf spheroidal galaxies [54] and the best-fit parameters (with a rescaling of the local density) through a fitting to the Galactic center GeV excess [55].

Fig. 3. Here the 95% credible limit of $\langle\sigma v\rangle$ is obtained by setting $[\int_0^{\langle\sigma v\rangle}\mathcal{P}(x)dx]/[\int_0^{\infty}\mathcal{P}(x)dx]=0.95$. Compared with that derived from the combined analysis of the Fermi-LAT γ-ray emission from a population of dwarf spheroidal galaxies [54], our limits are in general stronger, except for the mass range of 30–150 GeV, where we find a signal favored by the antiproton data. The DM density profiles may affect our constraints by a factor of $\lesssim 2$, for the Einasto or isothermal profile [23]. On the other hand, the local density adopted in this work, 0.3 GeV cm^{-3}, may be lower than that from recent kinematics measurements [61], which makes our constraints more conservative.

Conclusion.—Compelling evidence indicates that DM particles consist of a substantial fraction of the energy density of the Universe. It is also widely anticipated that these exotic particles can annihilate with each other and produce stable high-energy particle pairs, including, for example, electrons and positrons, protons and antiprotons, neutrinos and antineutrinos, and γ rays. However, so far no solid evidence for DM annihilation has been reported, yet.

In this work, we use the precise measurement of the antiproton flux by AMS-02 to probe the DM annihilation signal. The CR propagation parameters, proton injection parameters, and the solar modulation parameters, which are derived through independent fitting to the B/C and ^{10}Be/^{9}Be ratios, and the time-dependent proton fluxes, are taken into account in the posterior probability calculation of the DM parameters self-consistently within the Bayesian framework. Such an approach does not assume background parameters in advance and thus tends to give less biased results of the DM searches.

We find that the antiproton data suggest the existence of a DM signal. The favored mass of DM particles ranges from 20 to 80 GeV, and the annihilation cross section is about $(0.2–5)\times 10^{-26}$ cm^3 s^{-1}, for the $b\bar{b}$ channel. Though further studies are still needed to firmly establish the DM origin of the antiproton "anomaly," we notice that the inferred DM parameters are well consistent with that found in the modeling of the Galactic center GeV excess and/or the weak GeV emission in the directions of Reticulum 2 and Tucana III. Such a remarkable consistency, if not due to coincidence, points towards a common DM annihilation origin of these signals. The indication of a similar signal from various targets and different messengers will be very important for the search for particle DM. For other possibilities to explain the current puzzle, please see [62]. We keep in mind that the current framework of the CR propagation is relatively simple. A more detailed model may be necessary for future improvement of the understanding of this problem.

We have obtained the upper limits on the DM annihilation cross section from the antiproton data, which are stronger than that set by the Fermi-LAT observations of a population of dwarf spheroidal galaxies in a wide mass range. The improvement of constraints is expected to be beneficial from more precise measurements of the data by AMS-02, which reduce the uncertainties of both the background and the expectation of the signal. Our improved method also helps because the background parameters are taken into account with a proper likelihood instead of a choice by hand.

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Note added.—Recently, Ref. [66] appeared on arXiv. We have different approaches but consistent results.

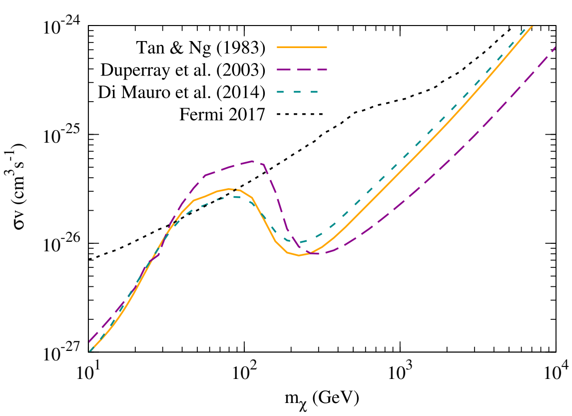

FIG. 3. The 95% credible upper limits of the DM annihilation cross section versus the mass derived through a fitting to the AMS-02 data, compared with that from Fermi-LAT observations of dwarf spheroidal galaxies [54].

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