Constraints on Leptophilic Dark Matter from the AMS-02 Experiment

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Abstract

The annihilation of dark matter particles in the Galactic halo of the Milky Way may lead to cosmic ray signatures that can be probed by the AMS-02 experiment, which has measured the composition and fluxes of charged cosmic rays with unprecedented precision. Given the absence of characteristic spectral features in the electron and positron fluxes measured by AMS-02, we derive upper limits on the dark matter annihilation cross section for leptophilic dark matter models. Our limits are based on a new background model that describes all recent measurements of the energy spectra of cosmic-ray positrons and electrons. For thermal dark matter relics, we can exclude dark matter masses below about 100 GeV. We include the radiation of electroweak gauge bosons in the dark matter annihilation process and compute the antiproton signal that can be expected within leptophilic dark matter models.

Key words: cosmic rays – dark matter

1. Introduction

The AMS-02 Collaboration has published the most precise, separate measurements of the fluxes $\Phi_e$ of cosmic-ray electrons and positrons to date (Aguilar et al. 2014b). The data cover particle energies $E$ up to 500 GeV for positrons and 700 GeV for electrons, respectively. These measurements are inconsistent with pure secondary production. This observation is among the most intriguing in cosmic ray physics, and various models have been proposed in the literature to explain the AMS-02 data. Most models invoke either exotic new physics like annihilations of dark matter particles (e.g., Cholis & Hooper 2013; Feng et al. 2014; Di Mauro et al. 2016), or new astrophysical sources like pulsars and their wind nebulae (e.g., Cholis & Hooper 2013; Linden & Profumo 2013; Kohri et al. 2016), to explain the apparent excess of positrons.

Advocating a pure dark matter origin for the large number of positrons observed in cosmic rays at high energies would require a rather contrived scenario (Bergström et al. 2009; Bertone et al. 2009; Cirelli et al. 2009; Donato et al. 2009; Finkbeiner et al. 2011; Cholis & Hooper 2013; Jin et al. 2013; Boudaud et al. 2015; Yuan et al. 2015), as very large cross sections are necessary to accommodate the measured fluxes. For this reason, hybrid models are introduced in which an unspecified astrophysical background creates a smooth spectrum of positrons (and electrons), while dark matter could be responsible for small additional spectral features on top of the smooth background curve (e.g., Bergström et al. 2013; Ibarra et al. 2014). Previous studies, e.g., Bergström et al. (2013) have employed the positron fraction $(e^+/(e^+ + e^-))$ data from AMS and the simplified phenomenological model introduced by the AMS Collaboration (Aguilar et al. 2013). The overall normalization of the electron flux, needed to compare model predictions to data, was then often derived from the measurement of the $e^+ + e^-$ flux by the Fermi-LAT detector. This approach, however, is problematic for several reasons: first, in the meantime the AMS $e^+ + e^-$ data have been published. While the AMS data sets are self-consistent, i.e., one can derive both the positron fraction and the $e^+ + e^-$ flux from the individual fluxes and conversely, the AMS $e^+ + e^-$ flux is not consistent with the Fermi-LAT $e^+ + e^-$ flux within the quoted experimental uncertainties. Therefore, these two data sets cannot be combined in a fit in a trivial way. Second, the uncertainties on the energy scales have to be taken into account when combining data sets from different experiments. Third, the data from AMS and from Fermi-LAT were taken at different times. The model introduced in (Aguilar et al. 2013) to describe the positron fraction does not contain any time dependent parameters. The data from previous experiments and the data from AMS (Schael 2016) clearly show a time variation of the positron fraction at energies below $\sim$20 GeV. To avoid these issues we use only the published data from AMS and we introduce a new phenomenological model that properly describes the energy and time dependence of both cosmic-ray positrons and electrons. We determine the best-fit values of the model parameters, and discuss how the model can be applied for searches of spectral signatures of exotic processes using the AMS data. We consider a generic leptophilic dark matter model and derive upper limits on the dark matter annihilation cross section from the absence of characteristic spectral features in the electron and positron fluxes measured by AMS-02. We also assess the impact of the uncertainty from cosmic ray propagation and the dark matter halo model on the cross section limits. Electroweak gauge boson radiation in the dark matter annihilation process will lead to a flux of Standard Model particles from the decay and hadronization of the electroweak gauge bosons, including in particular antiprotons. We show that the antiproton flux provides a sensitive and complementary probe of dark matter models, even within the leptophilic scenario we consider.

The article is structured as follows. In Section 2 we discuss the class of dark matter models we consider and describe how we obtain the electron and positron fluxes due to dark matter annihilation in the Galactic halo. The new background model is introduced in Section 3, where we also determine the best-fit values of the model parameters. The calculation of the limits on the dark matter annihilation cross section from AMS-02 data is presented in Section 4. Antiproton fluxes are
generated from the radiation of electroweak gauge bosons and may lead to complementary constraints on the dark matter model, as discussed in Section 5. We summarize and conclude in Section 6.

2. Dark Matter Searches

A large number of possible extensions of the Standard Model providing viable dark matter candidates have been proposed. In our analysis we consider leptophilic dark matter, and may lead to complementary constraints on the dark matter model, as discussed in Section 5. We summarize and conclude in Section 6.

To calculate the electroweak radiation we thus consider a simple model with a $t/u$-channel fermionic mediator and a vector dark matter candidate, as predicted in theories with Majorana dark matter and may lead to complementary constraints on the dark matter model, as discussed in Section 5. We summarize and conclude in Section 6.

3. Background Model

An accurate modeling of the fluxes of astrophysical origin is crucial for dark matter searches. A successful description from first principles of the available measurements of electrons, positrons, protons, antiprotons and nuclei, has not been proposed yet. On the other hand, considering only the electron and positron data, a description in terms of secondary production and astrophysical sources is possible, as done for instance in (di Mauro et al. 2014). In the following, we search for sharp spectral features due to leading-order dark matter annihilation into electron–positron pairs on top of such an astrophysical background that is assumed to be smooth. For this reason, a simple phenomenological description of the background fluxes is suitable for our study.

For the description of their data on the positron fraction, the AMS Collaboration introduced the so-called minimal phenomenological model (Aguilar et al. 2013):

$$
\Phi_e(E) = C_1 E^{-\gamma_1} + C_2 E^{-\gamma_2} \exp(-E/E_3),
$$

$$
\Phi_\nu(E) = C_3 E^{-\gamma_3} + C_4 E^{-\gamma_4} \exp(-E/E_3),
$$

and found that it describes their data extremely well over the full energy range. In fact, the minimal model also works for the description of the positron flux measured by AMS, provided that the effects of solar modulation are described in terms of the so-called force-field approximation (Gleeson & Axford 1968). However, trying to fit the electron flux with the same approach leads to a very poor fit with a $\chi^2$/n.d.f. $\sim$ 340/65. Therefore, we introduce a generalized, phenomenological model that contains a smoothly broken power law for the electrons to

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4 For the study of positrons and antiprotons fluxes, the channel DM + DM → $\nu + \bar{\nu}$ + is irrelevant; nonetheless it is necessary to preserve gauge invariance when including electroweak corrections.
describe the two components expected in the electron flux, namely secondary production and primary electrons from astrophysical sources:

\[
\Phi_+ (E) = (E^2 / \dot{E}^2) \left( C_+ (\dot{E}/E_0)^{-\gamma_+} + C_5 (\dot{E}/E_1)^{-\gamma_5} \exp(-\lambda_5 \dot{E}) \right),
\]

\[
\Phi_- (E) = (E^2 / \dot{E}^2) \left( C_- (\dot{E}/E_0)^{-\gamma_-} \left(1 + (\dot{E}/E_B)^{2} \right)^{b} \right) + C_5 (\dot{E}/E_1)^{-\gamma_5} \exp(-\lambda_5 \dot{E}) \right) \].

This model contains the minimum number of parameters necessary to obtain an accurate description of both electron and positron fluxes. Here, \( \dot{E} = E + \varphi_\pm \) is the energy of particles in interstellar space, before interacting with the heliosphere, and the effective potentials \( \varphi_\pm \) account for the charge-sign dependent impact of the solar magnetic field. In this picture, the solar modulation potentials are the only parameters that are expected to exhibit a time dependence.

The spectral indices for the diffuse terms of positrons and electrons and the common source term are denoted by \( \gamma_+ \), \( \gamma_- \), and \( \gamma_5 \), respectively. \( E_B \) is the location of the spectral break and \( \Delta \gamma_- \) is the difference of the electrons’ spectral indices before and after the break. The smoothness of the break is described by the parameter \( b \). The inverse cutoff energy is given by \( \lambda_5 \), and the \( C_+ \) and \( C_5 \) denote flux amplitudes. With this phenomenological model, we are able to describe electron and positron fluxes above 1 GeV.

We have explicitly included the pivot energies \( E_0 \) and \( E_1 \) in the model. They are fixed numbers that can, in principle, be chosen at will. However, a proper choice will substantially reduce the correlations between the model parameters in the fit used to extract the parameters of the model and increase the stability of the fit. We will use \( E_0 = 5 \) GeV and \( E_1 = 60 \) GeV throughout. We will refer to the first term in the fluxes as the diffuse term and to the second term as the source term, but this need not be related to the actual physics behind the fluxes. In this model the source term is assumed to be charge symmetric, since no evidence for a deficit of electrons has been observed so far. This hypothesis can be tested with the current AMS measurements of lepton fluxes.

To determine the parameters of the model, we perform a \( \chi^2 \) minimization using the AMS data on the separate measurements of cosmic ray electron and positron fluxes (Aguilar et al. 2014b). We also include the last data point of the AMS measurement of the total \( e^+ + e^- \) flux (Aguilar et al. 2014a), covering the energy range from 700 to 1000 GeV, since it is statistically independent from the other data and contains additional information for the modeling at the highest energies. The \( \chi^2 \) is obtained by adding the contributions from these three different data sets.

The systematic uncertainties quoted by the AMS Collaboration vary as a function of energy in the range between 3%–17%. Using these systematic uncertainties, the \( \chi^2 / \text{n.d.f.} \) of the fit is significantly smaller than one, showing that the systematic uncertainties are correlated between energy bins, as expected from the description of the sources of the systematic uncertainties in the corresponding publications. A correct treatment of these correlations would require knowledge of the correlation matrix, which is not published. In this case, the simplest assumption is that the systematic uncertainties consist of an uncorrelated component and a 100% correlated component. Therefore, for each data point, we take the published statistical uncertainty into account, and we add an uncorrelated systematic uncertainty of only 1% in quadrature. We treat the remaining uncertainty with respect to the published one as an overall scale uncertainty on the acceptance, which effectively translates into an uncertainty on the normalization of the fluxes. A similar procedure was used by the AMS Collaboration in (Aguilar et al. 2015). With this prescription we find a \( \chi^2 / \text{n.d.f.} \sim 1 \) and an unbiased pull-distribution. The fit of the positron flux alone would not allow us to constrain the model parameters of the source term with sufficient accuracy to derive limits on a possible dark matter contribution.

The best-fit parameters and their uncertainties \( \sigma_{\text{fit}} \) are listed in Table 1. The \( \chi^2 / \text{n.d.f.} \) is 131/128. The corresponding model curves are illustrated in Figure 2 for both electrons and positrons. The same set of parameters gives good descriptions of the positron fraction and of the \( e^+ + e^- \) flux measured by AMS.

To evaluate the scale uncertainty \( \sigma_{\text{acc}} \) introduced by the correlated systematic uncertainties on the fit parameters, we use the shift method (Heinrich & Lyons 2007): we subtract the 1% error from the quoted systematic uncertainties in quadrature, shift the data points upward by the remaining amount, and repeat the fit. The same procedure is repeated for shifting the data points downward. The value of \( \sigma_{\text{acc}} \) is then taken as the average observed shift in the parameters from the two fits. The resulting uncertainties (see Table 1) are small compared to

| Parameter | Value | \( \sigma_{\text{fit}} \) | \( \sigma_{\text{acc}} \) | \( \sigma_{\text{scale}} \) |
|-----------|-------|----------------|----------------|----------------|
| \( C_- \) | 6.673 ± 0.183 | 0.013 ± 0.105 | 1.052 GeV \(^{-1} \) m \(^{-2} \) sr \(^{-1} \) s \(^{-1} \) |
| \( \gamma_- \) | 3.851 ± 0.051 | 0.007 ± 0.087 | 0.120 GeV \(^{-1} \) |
| \( \Delta \gamma_- \) | 5.650 ± 0.561 | 0.105 ± 0.881 | 10 \(^{-1} \) |
| \( b \) | 4.171 ± 0.675 | 0.078 ± 0.466 | 10 \(^{-1} \) |
| \( 1/E_B \) | 3.043 ± 0.189 | 0.045 ± 0.250 | 10 \(^{-2} \) GeV \(^{-1} \) |
| \( C_+ \) | 2.161 ± 0.065 | 0.014 ± 0.305 | 10 \(^{-1} \) GeV \(^{-1} \) m \(^{-2} \) sr \(^{-1} \) s \(^{-1} \) |
| \( \gamma_+ \) | 3.834 ± 0.107 | 0.007 ± 0.106 | 10 \(^{-1} \) |
| \( C_5 \) | 6.189 ± 0.322 | 0.058 ± 0.494 | 10 \(^{-1} \) |
| \( \gamma_5 \) | 2.525 ± 0.120 | 0.006 ± 0.045 | 10 \(^{-1} \) |
| \( \lambda_5 \) | 1.019 ± 0.727 | 0.251 ± 0.141 | 10 \(^{-3} \) GeV \(^{-1} \) |
| \( \varphi_- \) | 1.406 ± 0.023 | 0.027 ± 0.096 | 10 \(^{-1} \) |
| \( \varphi_+ \) | 1.021 ± 0.048 | 0.022 ± 0.082 | 10 \(^{-1} \) |
the respective values of $\sigma_{\text{fit}}$, except for those of the solar modulation parameters $\varphi_+$ and $\varphi_-$, for which they are of equal magnitude. We also investigate the effect of the overall uncertainty of the energy scale of the AMS detector on the fit results. The AMS Collaboration quotes uncertainties of 5% at 0.5 GeV, 2% in the range from 10 to 290 GeV, and 4% at 700 GeV (Aguilar et al. 2014b), and we connect these values by straight lines in log($E$). The impact of the energy scale uncertainty on the fit parameters can then be studied by changing the energy bin boundaries of the data by the appropriate amount and correcting the integral flux values accordingly. The procedure is done for the two most extreme cases, shifting all energies upward and downward, respectively. The corresponding uncertainty $\sigma_{\text{scale}}$ is calculated as the average of the observed shifts in the parameters. It turns out that this uncertainty is sizable or even dominant for almost all of the fit parameters.

Finally, we tested if our model can also be used to describe the measurements of the positron flux by Pamela (Adriani et al. 2013) and of the electron flux by Pamela (Adriani et al. 2011) and Fermi-LAT (Ackermann et al. 2012). We fix all parameters except $C_+$ and $C_-$. This accounts for a possible difference in the energy scale between the experiments, which would in the simplest case translate to a difference in the normalizations of the fluxes. In addition, since the data sets were recorded at different times, we allow the modulation parameters $\varphi_{\pm}$ to vary. We find in each case a $\chi^2/n.d.f. < 1$ and the best-fit values $C_+ = (1.76 \pm 0.12) \times 10^{-1}$ GeV$^{-1}$ m$^{-2}$ sr$^{-1}$ s$^{-1}$ and $\varphi_+ = (0.67 \pm 0.04)$ GV for the Pamela positron flux, $C_- = (5.45 \pm 0.08)$ GeV$^{-1}$ m$^{-2}$ sr$^{-1}$ s$^{-1}$ and $\varphi_- = (1.11 \pm 0.01)$ GV for the Pamela electron flux, and $C_+ = (6.13 \pm 0.21)$ GeV$^{-1}$ m$^{-2}$ sr$^{-1}$ s$^{-1}$ for the Fermi-LAT electron flux. Though the data points published by these experiments are clearly inconsistent with the AMS data, the obtained fit parameters are within the uncertainties consistent with those given in Table 1, even without taking the uncertainty on the energy scales of PAMELA and Fermi-LAT into account.

Similar studies could be performed using the positron fraction and the combined $e^+ + e^-$ flux. However, a precise analysis is not possible from the published AMS results since these data sets are not statistically independent due to an overlap in the event samples.

4. Model-independent Constraints on the Annihilation Cross Section

For this analysis, we assume that the cosmic ray fluxes consist of a smooth background component that originates at high energies from some unspecified astrophysical source and of a sub-dominant exotic contribution that originates from dark matter annihilation in the Galactic halo. The latter could account for additional structure on top of the background predictions. For the description of the shape of the astrophysical background, i.e., the null hypothesis, we use Equations (2). We do not observe significant deviation from the assumed background in the measured fluxes. We then set constraints on leptophilic dark matter models using the Wilks theorem (Wilks 1938); namely the upper limit value on the signal normalization is obtained, increasing its value until the $\chi^2$ value differs by 2.71 from the null hypothesis. The

![Figure 2. Top panel: electron (blue circles) and positron (red circles) fluxes measured by AMS and multiplied by $E^3$, as described in the text. The best fit model curve (blue solid line for positrons and red solid line for electrons) according to Equations (2) are shown for energies above $E \geq 1$ GeV. The separate contributions from the diffuse (dotted red and dashed blue for positrons and electrons, respectively) and source term (dotted green and dashed green for positrons and electrons, respectively) are also shown. Bottom panel: spectral index $d \log N/d \log E$ obtained from sliding-window fits to data. The solid line represents the spectral index obtained from the fit. The red and blue dashed lines represent the diffuse component for positrons and electrons, respectively, and clearly show the different behavior of electrons and positrons.](image-url)
background model parameters are treated as nuisance parameters. We first compute 95% CL upper limits on the leading order 2 → 2 annihilation cross section. We set upper limits on the normalization of a possible signal due to dark matter annihilation and we subsequently translate them into limits on the velocity averaged annihilation cross section. These limits and the median expected upper limits obtained from 1000 pseudo-data sets are shown in Figure 3. The pseudo-data sets are generated according to the background model, namely assuming that no exotic dark matter contribution is present. For each of these data sets we repeat the calculation of the upper limits. The median upper limits are obtained, taking the median value of the resulting distribution for each mass. Compared to Bergström et al. (2013), we find limits that are about a factor of two weaker. Several aspects that contribute to this difference have already been discussed in the introduction. In addition, the different procedure to calculate the upper limits used in (Bergström et al. 2013) leads, in most cases, to stronger limits. We have investigated the impact of the energy scale uncertainty from the fit, of the choice of different cosmic ray propagation models, and of the uncertainties on the antiproton production cross section. We find that including the uncertainties on the energy scale does not significantly affect the results for the upper limits. More relevant are the uncertainties due to the choice of the cosmic ray propagation scenario and dark matter halo model. To study the impact of the propagation models, we have computed the upper limit using the MIN, MED, and MAX cosmic ray propagation parameters (Cirelli et al. 2011) for the NFW dark matter profile. We also re-computed the upper limits for a fixed propagation scenario (MED) and different dark matter profiles—Einasto (Graham et al. 2006; Navarro et al. 2008), Isothermal (Bahcall & Soneira 1980; Begeman et al. 1991), Burkert (Burkert 1996; Salucci & Burkert 2000; Gentile et al. 2004; Salucci et al. 2007), and Moore (Diemand et al. 2004)—and different dark matter normalizations at the location of the solar system (ρ ∈ [0.25, 0.7] GeV cm⁻³ (Bovy & Tremaine 2012)). The latter has the effect of trivially rescaling the upper limits curve and is the most relevant source of uncertainties. All astrophysical parameters have been taken from (Cirelli et al. 2011).

We have recomputed the upper limits including electroweak correction, but no distinguishable features are noticeable. Indeed, multi-TeV dark matter masses can give rise to 10% corrections, which are sizable for collider studies but are negligible with respect to astrophysical uncertainties when computing dark matter upper limits.

5. Antiproton Flux

A flux of antiprotons is generated by the radiation of electroweak gauge bosons, W⁺ and Z, off the primary standard model particles produced in the dark matter annihilation process. Thus, even for leptophilic dark matter models, antiprotons are produced and the antiproton flux can be compared to measurements to further test and constrain this model. For dark matter particles heavier than the electroweak gauge bosons, M_{DM} > M_{W,Z}, the contributions due to electroweak radiation can be calculated in a model-independent way by using generalized fragmentation functions (Ciafaloni et al. 2011; Ali Cavasonza et al. 2015). The fragmentation function approach works for models where the leading-order annihilation cross section is not helicity suppressed, and it provides reliable results for masses M_{DM} > 5 M_{W,Z} ≈ 500 GeV (Ciafaloni et al. 2011; Ali Cavasonza et al. 2015). However, as we are interested also in smaller dark matter masses, we consider the leptophilic dark matter model presented earlier as a representative model.

In the previous section we have derived model-independent upper limits on the 2 → 2 cross section. The impact on the upper limits of including electroweak radiation is found to be negligible. However, the inclusion of electroweak radiation in our analysis is crucial as an antiproton flux is induced. Assuming that the dark matter annihilation cross section is at its upper limit value, i.e., the values represented by the black line.
in Figure 3, we obtain predictions for the maximum antiproton-to-proton ratio due to dark matter annihilation. These predictions can be compared to the measurements done by the Pamela (Adriani et al. 2010) and AMS-02 Collaboration (Aguilar et al. 2016a), as shown in Figure 4 for representative masses. One of the most relevant sources of uncertainty is the knowledge of the cross section for antiproton production. This has been extensively studied for instance in Donato et al. (2001) and di Mauro et al. (2014), according to whom the uncertainties can be roughly 50% outside the range where the antiproton productions cross section is measured.5

The choice of the cosmic ray propagation model is a second relevant source of uncertainty, dominant at low energies (di Mauro et al. 2014). In Figure 4 the background curve is the “fiducial” antiproton-to-proton astrophysical ratio presented in (Giesen et al. 2015). The uncertainties on the background are those derived in (Giesen et al. 2015). The predictions for the antiproton-to-proton ratio including a dark matter contribution shown in Figure 4 are affected by the same uncertainties. For the sake of simplicity, we do not show them in the figure.

A more reliable estimate of the constraints on the dark matter model from the \( \rho/p \) ratio would require a systematic study of the background uncertainties and the correlation with the dark matter signal as presented in, e.g., Cui et al. (2016), Cuoco et al. (2016), and Korsmeier & Cuoco (2016). We defer such a comprehensive analysis to a forthcoming publication.

Our analysis suggests that for dark matter masses near or above \( \mathcal{O}(1 \text{ TeV}) \) the antiproton flux receives a sizable contribution due to dark matter annihilation in the Galaxy, even for leptophilic models. It is therefore possible to further constrain also leptophilic dark matter models using the complementary information contained in the antiproton flux measurements, in particular for very high dark matter masses \( M_{DM} \gtrsim 1 \text{ TeV} \), as shown in Figure 4. The antiproton flux thus becomes relevant only for large dark matter masses. This regime is where electroweak corrections become model-independent due to the appearance of universal logarithms (as shown in Ciafaloni et al. 2011; Ali Cavasonza et al. 2015). However, to be able to obtain robust and quantitative conclusions, a better understanding of the astrophysical phenomena relevant to charged cosmic ray propagation models is necessary, as well as improved measurements of the inclusive antiproton production cross section at colliders. Additional AMS measurements of cosmic rays fluxes and ratios, like the recent boron-to-carbon ratio (Aguilar et al. 2016b), are expected to provide new input for the modeling of the propagation of charged cosmic rays in the Galaxy. Dedicated studies of antiproton production in proton to helium collisions performed by the LHCb collaboration (Massacrier 2016),6 could help to reduce the uncertainties on the antiproton production cross section.

6 SMOG as a Fixed target in the LHC, https://lbtwiki.cern.ch/bin/view/Smo/SmogasFixedTarget.

6. Conclusions

We have proposed a simple phenomenological model which provides an excellent description of the electron and positron fluxes in cosmic rays as measured by AMS. Several important conclusions can be drawn from our results: (i) the minimal model from (Aguilar et al. 2013) cannot be used to derive values for the cutoff energy of its source term from a fit to the positron fraction alone because it is too simple and does not describe the individual fluxes. (ii) Neither the positron nor the electron flux shows any sharp spectral structures. At high energies, the positron flux is dominated by the source term while the electron flux is dominated by the diffuse term. (iii) The electron flux is consistent with a charge-symmetric source term. However, it can be shown that the electron flux alone can be equally well described by Equations (2) without a source

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5 For more details, refer to (Donato et al. 2001; di Mauro et al. 2014) and references therein.
term. To prove that the source term is indeed charge-symmetric as expected from dark matter models or astrophysical sources used to explain the observed positron excess, a solid description of the physical processes relevant for the diffuse term is needed. (iv) There is evidence for a spectral break in the electron flux at an energy of $\sim$30 GeV. This might be a useful reference point for the cross-calibration with future experiments. (v) The solar modulation parameters for positrons and electrons $\varphi_+$ and $\varphi_-$ are significantly different. This shows that either the force-field approximation breaks down in the case of cosmic ray positrons and/or electrons or even more additional terms are needed in the model.

We would like to point out that the data points below 15 GeV are especially important to constrain the solar modulation parameters as well as the diffuse terms. Therefore, reliable statements about source parameters require a proper treatment of the time dependence of the cosmic ray electron and positron fluxes. At energies below 20 GeV, a time dependence of the fluxes can be expected, possibly exceeding the systematic uncertainties quoted on the average fluxes.

(ii) Even with our assumptions on the degree of correlation between the systematic uncertainties of the AMS data points, we find very good agreement of the data with a smooth model. On the other hand, it has been argued that a certain number of spectral features (“bumpiness”) are expected in the fluxes of positrons and electrons if the standard paradigm for cosmic ray acceleration and propagation holds, namely from the contributions of individual sources, and that the absence of such features would constitute an anomaly in our understanding of cosmic rays (Serpico 2015).

We have used our improved phenomenological description of electron and positron fluxes to place limits on the dark matter annihilation cross section in leptohilic dark matter models. We find that (vii) an appropriate description of the background is crucial, especially for the low energy region, as most of the electrons and positrons produced via dark matter annihilation are soft, since they lose energy while propagating through the Galaxy. (viii) Within this class of models we exclude the region of the parameter space with $M_{\chi} \lesssim 100$ GeV for a thermal relic, even though this bound is somewhat diluted by the uncertainty in the normalization of the dark matter density. (ix) The inclusion of electroweak radiation has a very small impact on the upper limits on the dark matter annihilation cross section. However, contributions due to the radiation of electroweak gauge bosons are of crucial importance as they induce correlation among fluxes of different particles species and, in particular, predict an antiproton flux even within leptohilic dark matter models. This may further allow to constrain this class of models using measurements of the antiproton-to-proton ratio or antiproton flux. The comparison with Pamela and the recent AMS-02 data (Aguilar et al. 2016a) suggests that we might be able to constrain the higher mass region ($M_{\chi} \gtrsim 3$ TeV) of the parameter space, even though a careful analysis of the uncertainties is needed in order to draw robust conclusions.

We acknowledge support by the German Research Foundation DFG through the research training group “Particle and Astroparticle Physics in the Light of the LHC,” the Helmholtz Alliance for Astroparticle Physics (HAP) and the German Federal Ministry of Education and Research (BMBF).

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