Implications of an astrophysical interpretation of PAMELA and Fermi-LAT data for future searches of a positron signal from dark matter annihilations

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The recent data from PAMELA and Fermi-LAT can be interpreted as evidence of new astrophysical sources of high energy positrons. In that case, such astrophysical positrons constitute an additional background against the positrons from dark matter annihilation. In this paper, we study the effect of that background on the prospects for the detection of a positron dark matter signal in future experiments. In particular, we determine the new regions in the (mass, $\langle \sigma v \rangle$) plane that are detectable by the AMS-02 experiment for several dark matter scenarios and different propagation models. We find that, due to the increased background, these regions feature annihilation rates that are up to a factor or three larger than those obtained for the conventional background. That is, an astrophysical interpretation of the present data by PAMELA and Fermi-LAT implies that the detection of positrons from dark matter annihilation is slightly more challenging than previously believed.

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I. INTRODUCTION

If dark matter consists of WIMPs – weakly interacting massive particles – they can annihilate with each other and be indirectly detected by searching for their annihilation products, mainly gamma rays, neutrinos, and antimatter. This indirect detection technique is in fact one of the promising avenues toward the determination of the dark matter nature. Such a complex task will certainly require input from accelerator searches, direct detection experiments, as well as the indirect detection of dark matter in multiple channels. Several experiments, including PAMELA \cite{1} and Fermi \cite{2}, are already looking for such signals in cosmic rays, and planned experiments, such as AMS-02 \cite{3}, will measure the cosmic ray spectrum with even higher precision, possibly revealing a dark matter signature. Thanks to these experimental efforts the detection of dark matter and its identification may soon become a reality.

Recently, the PAMELA collaboration reported \cite{4} an excess (with respect to the conventional background model) in the positron fraction for the energy range 1.5 – 100 GeV. Later on, the Fermi-LAT collaboration reported \cite{5} the measurement of the flux of electrons plus positrons up to 1 TeV. These two measurements strongly indicate the existence of additional sources of high energy cosmic ray positrons \cite{6}. Among the possible sources, dark matter annihilations \cite{7} (or decays) as well as astrophysical sources such as pulsars \cite{8,9,10,11,12,13} or supernova remnants \cite{14,15,16} have been considered in the literature.

Though viable, an interpretation of PAMELA and Fermi-LAT data in terms of dark matter annihilations is rather disfavoured \cite{8}. In fact, the annihilation rate for a thermal relic is about three orders of magnitude smaller than the one needed to explain the data. Hence, one has to resort to non-thermal candidates or to low-velocity enhancement mechanisms, both tightly constrained by experimental data \cite{17,18,19,20,21}. Moreover, because both leptons and hadrons are typically generated in dark matter annihilations, they tend to overproduce gamma rays and antiprotons. As a result, significant regions of the parameter space that is compatible with the positron excess are already excluded by present constraints \cite{22,23}. It was also suggested \cite{7,24} that dark matter decays, rather than annihilations, may explain the positron signal. Several models of this kind have been recently studied –see e.g. \cite{25}– and they are typically less constrained than annihilation models. In any case, we are interested in alternative interpretations of the data so we will not consider the dark matter possibility any further.

The additional source of positrons required to explain the PAMELA and Fermi-LAT data may also be of an astrophysical nature, such as pulsars \cite{8,9,10,11,12,13} or supernova remnants \cite{14,15,16}. Indeed, it has been shown that, under reasonable assumptions, they can account for the spectral features observed by Fermi-LAT and for the rising positron fraction measured by PAMELA. In this paper we suppose that the cosmic ray data from PAMELA and Fermi-LAT is explained by new astrophysical sources of high energy positrons.

Such astrophysical positrons constitute, therefore, a new background against the positrons from dark matter annihilation. This new background must be taken into account in determining the sensitivity of future experiments to a positron dark matter signal. That is precisely what we do in this paper. We reassess the sensitivity of the AMS-02 experiment to a positron signal from dark
matter annihilations in light of the new positron background implied by an astrophysical explanation of the PAMELA and Fermi-LAT data. In the next section we introduce the four dark matter scenarios used as benchmark throughout this paper, and the assumptions that enter into the computation of the positron signal from dark matter annihilations are explained. Then, in section III, we derive the positron background implied by an astrophysical interpretation of PAMELA and Fermi-LAT data. Finally, in section IV we obtain our main results. By combining the previously found signal and background, we study the sensitivity of the positron signal from dark matter annihilations are explained. Then, in section III, we derive the positron background implied by an astrophysical explanation of the positron back-

|  | $L$ (kpc) | $K_0$ (kpc$^2$/Myr) | $\alpha$ |
|---|---|---|---|
| MIN | 1 | 0.00595 | 0.55 |
| MED | 4 | 0.0112 | 0.70 |
| MAX | 15 | 0.0765 | 0.46 |

TABLE I: Values of propagation parameters widely used in the literature and roughly providing minimal and maximal positron fluxes, or constitute the best fit to the $B/C$ data.

To obtain the positron spectrum for each of these possibilities we relied on PYTHIA as implemented in the DarkSUSY package.

The positrons produced from dark matter annihilation in the Galactic halo lose their energy via inverse Compton and synchrotron processes as they propagate in interstellar space. Such effects can be taken into account by solving the diffusion-loss equation:

$$\frac{\partial}{\partial t} \frac{dn}{dE} = \nabla \cdot [K(E, \vec{x}) \nabla \frac{dn}{dE}] + \frac{\partial}{\partial E} [b(E, \vec{x}) \frac{dn}{dE}] + Q(E, \vec{x})$$

where $K$ is the diffusion constant, $b$ is the energy loss rate, and $Q$ is the source term. It is assumed that, within the diffusion zone, $K$ is constant in space and varies only with energy. This energy dependence can be modeled as

$$K(E) = K_0 \left( \frac{E}{\text{GeV}} \right) ^\alpha \text{cm}^2\text{s}^{-1},$$

where $K_0$ and $\alpha$ are propagation parameters. The energy loss rate is given by

$$b(E) = 10^{-16} \left( \frac{E}{\text{GeV}} \right) ^2 \text{s}^{-1}.$$

The source term, $Q$, takes into account the properties of the dark matter particle: its mass, annihilation cross section, dominant annihilation modes, and distribution in the Galaxy. In relation to this last issue, we assume a NFW profile with a local dark matter density of 0.3 GeVcm$^{-3}$. Regarding the boundary conditions, we take the diffusion zone to be a slab of thickness $2L$, and assume that the positron density is zero at $z = \pm L$ – free escape boundary conditions. The values of $L$, $K_0$, and $\alpha$ will depend on the propagation model. In the following we will consider the well-known MIN, MED, and MAX models, which assign values to these parameters according to Table I. With these elements we can proceed to compute the positron flux from dark matter annihilations.

Figure I displays the positron flux as a function of the energy for the different dark matter scenarios we consider and for the MED propagation model. In that figure...
the model with direct annihilation into \( \bar{b}b \), \( W^+ W^- \) or \( e^+ e^- \) and a typical Kaluza-Klein model. In all cases we set \( m_{DM} = 300 \text{ GeV} \) and \( \langle \sigma v \rangle = 3.0 \times 10^{-26} \text{ cm}^3\text{s}^{-1} \).

![Diagram of the positron spectrum from dark matter annihilations after including propagation effects (MED model). Each line corresponds to a different model: annihilation into \( \bar{b}b \), \( W^+ W^- \) or \( e^+ e^- \) and a typical Kaluza-Klein model. In all cases we set \( m_{DM} = 300 \text{ GeV} \) and \( \langle \sigma v \rangle = 3.0 \times 10^{-26} \text{ cm}^3\text{s}^{-1} \).](https://example.com/diagram1)

The recent data from PAMELA and Fermi-LAT go a long way toward the determination of the background positron flux. The PAMELA collaboration reported \( \Phi^{PAMELA} \) the measurement of the positron fraction, \( \frac{\Phi^+}{\Phi^- + \Phi^+} \), in the energy range between 1.5 GeV and 100 GeV. The Fermi-LAT collaboration, later on, reported \( \Phi^{Fermi-LAT} \) the measurement of the total flux of electrons plus positrons, \( \Phi^+ + \Phi^- \), in the 20 GeV to 1 TeV energy range. By combining these two measurements, the absolute flux of positrons can be determined as

\[
\Phi_{e^+} = \left( \frac{\Phi_{e^+}^{PAMELA}}{\Phi_{e^-}^{PAMELA} + \Phi_{e^+}^{PAMELA}} \right) \times \left( \Phi_{e^-} + \Phi_{e^+} \right)_{Fermi-LAT}^{Fermi-LAT}
\]

for energies below 100 GeV. Let us emphasize that this procedure became possible only recently, after the release of the electron plus positron spectrum by the Fermi-LAT collaboration. The positron flux up to 100 GeV can, therefore, be directly extracted from the available data.

Beyond 100 GeV we cannot rely on experimental data.
to obtain the positron flux, so we will instead resort to a specific astrophysical model: the pulsar interpretation of PAMELA and Fermi-LAT [3]. Such interpretation assumes that in the energy range between 100 GeV and 1 TeV the electron and positron flux reaching the Earth is the result of two different contributions. The first one is an almost homogeneous and isotropic Galactic cosmic ray component produced by supernova remnants. The second one is the local contribution of a few pulsars. This pulsar contribution is expected to be more significant at higher energies.

It was found in [3] that among the candidate sources from the ATNF radio pulsar catalogue, only the Monogem (PSR B0656+14) and the Geminga (PSR J0633+1746) pulsars give a significant contribution to the high energy electron and positron flux. Moreover, a good fit to both the PAMELA and Fermi-LAT data could be obtained with $E_{\text{cut}} = 1100$ GeV, $\eta_{e^{-}} = 40\%$, and $\Delta t = 6 \times 10^{3}$ yr. We will consider those parameters as defining the default pulsar model and use them to obtain, from figures 4 and 5 in [3], the positron flux up to 300 GeV. In figure 2 this positron flux (blue solid line) is compared with the conventional positron background (green dotted line) and also with the absolute positron flux derived from Pamela and Fermi-LAT data in [35] (black squares). As seen in the figure, the uncertainty in present data allows the positron flux to be somewhat larger than the prediction of the default pulsar model.

To take that possibility into account we consider an additional astrophysical background, denoted in the figure as upper (red dashed line). That background has the same shape as the pulsar one but a slightly larger normalization—by a factor 1.4. In the following, we refer to these two backgrounds as the astrophysical backgrounds and assume that the true background is somewhere between them. Notice that besides being compatible with the absolute positron flux, the astrophysical backgrounds are both clearly distinguishable from the conventional one.

It is important to stress that our results do not strongly depend on the specific pulsar model adopted and that similar conclusions are obtained even if alternative astrophysical explanations are considered. In fact, up to 100 GeV the absolute positron flux is essentially known from data, so all models should give roughly the same background in that region. And it is precisely in this low energy region where the positron flux is larger for the dark matter models and masses we consider. Besides, between 100 GeV and 300 GeV, the positron flux, even if not known, is not expected to have any particular features, for the $e^{-} + e^{+}$ spectrum measured by Fermi-LAT is rather flat. So, in this high energy the positron flux is not expected to deviate much from the two backgrounds we study. Moreover, we have explicitly checked that alternative astrophysical interpretations such as that put forward in [4] indeed give rise to a very similar positron flux in that energy range. At even higher energies ($E \gtrsim 300$ GeV), the predicted flux could well be very different, but that would not affect the detection of a dark matter positron signal in AMS-02.

The difference between the conventional background and the astrophysical ones depends on the energy and, as seen in figure 2, amounts to more than one order of magnitude at 300 GeV. This energy dependence is crucial for our analysis. Had the difference between the conventional and the astrophysical backgrounds been an energy independent factor $f$, most of our analysis would have been unnecessary. In that case, the positron dark matter signal required for detection would simply have been $\sqrt{f}$ larger than for the conventional background, independently of the dark matter model. Alas, that is clearly not the case; the astrophysical backgrounds are not only larger than the conventional one, they also have a different energy dependence. Thus, it is not possible to predict how much larger the signal will have to be in order to ensure detectability, and such a number is expected to depend also on the dark matter model. In the next section we will quantitatively study these issues.

IV. SENSITIVITY OF AMS-02

For definiteness, we will focus our sensitivity analysis on the AMS-02 experiment [5]. AMS-02 will take data for about 3 years and is expected to measure the positron spectrum up to about 300 GeV. Its larger geometric acceptance—420 cm$^2$ sr compared to PAMELA’s 20.5 cm$^2$ sr—make it an ideal instrument to search for and detect the positron signal from dark matter annihilations.

To claim the observation of a positron signature from dark matter annihilation in a given experiment, the spectral data must be statistically distinguishable from the predicted background spectrum. A $\chi^2$ test is one statistical tool that allows us to assess that hypothesis. The $\chi^2$ of a set of data over the expected background is defined

![Region detectable by AMS-02](image)

**FIG. 3:** Regions in the plane $(mass, \langle \sigma v \rangle)$ that will be detectable by AMS-02 with three years of data for different dark matter scenarios and the MED propagation model. The area above the band is detectable for both astrophysical backgrounds.
as

\[ \chi^2 = \sum_i \frac{(N_{i}^{obs} - N_{i}^{BG})^2}{N_{i}^{obs}}, \]

where the sum is over energy bins, \( N_{i}^{obs} \) is the number of events observed in the \( i \) energy bin and \( N_{i}^{BG} \) is the number of events in the \( i \) energy bin predicted from the background contribution. In writing equation (6), Gaussian errors have been assumed. For our analysis we use 20 energy bins equally spaced in logarithmic scale between 10 GeV and 300 GeV. To assess the sensitivity of AMS-02 we calculate the annihilation rate needed to distinguish, with three years of data, the signal from the background at 95% confidence level – that is, we require that \( \chi^2 \gtrsim 31 \). Let us emphasize that sensitivity analysis of this kind have been presented in the literature for several models, see for instance [34, 37]. They were done, however, before the release of PAMELA and Fermi-LAT data and relied on the conventional positron background. The novelty in our analysis is the use of the new positron background implied by an astrophysical explanation of PAMELA and Fermi-LAT.

Figure 4 shows, in the plane \( (mass, \langle \sigma v \rangle) \), the regions that are detectable by the AMS-02 experiment for the four different dark matter scenarios we consider and for the MED propagation model. For each dark matter model, we compute, at a given mass, the \( \langle \sigma v \rangle \) required to observe positrons for each of the two astrophysical backgrounds. A narrow band in the plane \( (mass, \langle \sigma v \rangle) \) is thus obtained for each model. The lower limit of such band corresponds to the results for the astrophysical background from the default pulsar model whereas the upper limit corresponds to the results for the upper astrophysical background. The area above the band can be considered, henceforth, as detectable for both astrophysical backgrounds. From the figure we see that the model with direct annihilation into \( e^+ e^- \) offers the best perspectives, with required annihilation rates well below the typical one \( (\langle \sigma v \rangle \sim 3 \times 10^{-26}\text{cm}^{-3}\text{s}^{-1}) \) for low masses, \( m \lesssim 300 \text{ GeV} \). The models with annihilation into \( W^+ W^- \) and \( b \bar{b} \) also look promising. For masses below about 300 GeV, they are detectable even for annihilation rates smaller than \( 10^{-25}\text{cm}^3\text{s}^{-1} \). So, for typical rates only moderate boost factors, which may be compatible with the standard \( \Lambda \text{CDM} \) scenario of structure formation, are needed to enhance the signal to a detectable level. A similar conclusion applies to the KK model in the low mass range, \( m \lesssim 350 \text{ GeV} \). Thus, even if not guaranteed, AMS-02 has good chances of observing a positron signal from a not-so heavy dark matter particle.

Figures 4 and 5 show the detectable regions for the other two propagation models: MIN and MAX. They display the same pattern observed in figure 3 but with slightly larger values of \( \langle \sigma v \rangle \) for MIN and slightly smaller ones for MAX. These three figures constitute the main result of this paper. They present new detectable regions in AMS-02 for several scenarios of dark matter and different propagation models.

If a positron excess over the astrophysical backgrounds were indeed observed at AMS-02, it would certainly be difficult to attribute it to dark matter rather than to a more complicated background. To do so, one would likely have to observe a dark matter specific feature such as the sharp spectral edge expected for the model with annihilation into \( e^+ e^- \), or one would have to combine inputs from collider searches, direct detection experiments, and other indirect detection channels. What we have found in figures 4 and 5 are the regions in which the positron channel can contribute to the identification of dark matter through indirect searches.
It is important to notice the differences between the models that are detectable in AMS-02, see previous figures, and those that can explain the Pamela and Fermi-LAT data in terms of dark matter annihilations. These models require $\langle \sigma v \rangle \gtrsim 10^{-23}\text{cm}^{-2}\text{s}^{-1}$, multi-TeV masses, and leptonic final states, and are highly constrained by present data. The detectable models, in contrast, may feature masses in the 100 GeV range, can annihilate into leptons, quarks, or gauge bosons, and have typical annihilation rates of order $10^{-25} - 10^{-26}\text{cm}^3\text{s}^{-1}$, small enough to avoid present constraints from antiprotons and gamma rays. Besides, the detectable models include candidates from well-motivated scenarios for physics beyond the standard model, such as universal extra-dimensions and low-energy supersymmetry.

One may wonder how much different are the new detectable regions in figures 3, 4 and 5 from the old ones, those obtained for the conventional background model. Since the astrophysical positron background is larger than the conventional one, we certainly expect that for a given dark matter mass the new regions lie at a higher value of $\langle \sigma v \rangle$. How much higher? Let us define a funcion $r$, that tells us exactly that, as

$$r \equiv \frac{\langle \sigma v \rangle_{\text{astr}}}{\langle \sigma v \rangle_{\text{conv}}}.$$  

Here $\langle \sigma v \rangle_{\text{astr}}$ is the annihilation rate required for detection at AMS-02 given the astrophysical background (the quantity shown in the three previous figures) while $\langle \sigma v \rangle_{\text{conv}}$ is the corresponding quantity for the conventional background. We know for sure that $r > 1$. Figure 6 shows $r$ as a function of the dark matter mass for the four dark matter scenarios we consider and the MIN propagation model. As before, the bands correspond to the results for the two astrophysical backgrounds. Notice that the largest value of $r$ we find in the figure is about 3, for the model with annihilation into $e^+e^-$. Hence, the annihilation rate required to observe a signal is up to a factor of three larger than the one obtained for the conventional background model. For the KK model $r$ is between 1.6 and 2.0, whereas for models with annihilation into $b\bar{b}$ and $W^+W^-$ is smaller –up to 1.4. The behaviour of $r$ displayed in the figure can be qualitatively understood from the spectrum (figure 1) and the backgrounds (figure 2). Models with a larger positron flux at higher energies are more sensitive to the difference between the conventional and the astrophysical backgrounds (which is more prominent at higher energies), yielding a larger value of $r$. In other words, a larger $r$ is correlated with a larger positron flux at high energies.

In figure 7 we show $r$ as a function of the dark matter mass for the MAX propagation model. The pattern is the same observed in the previous figure but with smaller values of $r$ for the four models of dark matter. The maximum values of $r$ are approximately given by 1.8, 1.5, 1.3, and 1.3 respectively for the $e^+e^-$, $KK$, $W^+W^-$, and $b\bar{b}$ models. As expected, the results for the MED propagation model (not shown) are in between the MIN and MAX results.

These two figures demonstrate the relevant effect of the new astrophysical background on the prospects of detection of a dark matter positron signal in future experiments. Given the larger background, the signal required to claim an observation is also larger, by up to a factor 3 for the models we analized. The precise number depends on the dark matter scenario, the propagation model, and the astrophysical background, as illustrated in figures 6 and 7.
V. CONCLUSION

We have studied the implications of an astrophysical explanation of the PAMELA and Fermi-LAT data for future searches of positrons from dark matter annihilations. If astrophysical positrons account for such data, they constitute a new background against the positrons from dark matter annihilations. After deriving the new positron background implied by PAMELA and Fermi-LAT, we reassessed the sensitivity of AMS-02 to a positron dark matter signal for several dark matter scenarios and different propagation models. We found the new detectable regions for AMS-02 and showed that they feature annihilation rates of order $10^{-25} - 10^{-26} \text{cm}^3\text{s}^{-1}$. Hence, despite the larger positron background revealed by PAMELA and Fermi-LAT, the detection of a positron signal from dark matter annihilations is still within the reach of future experiments such as AMS-02.

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