Implications of the Electron/Positron Excesses on Astrophysics and Particle Physics

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DOI: http://dx.doi.org/10.3204/DESY-PROC-2009-03/Ibarra

A series of experiments measuring high energy cosmic rays have recently reported strong indications for the existence of an exotic source of high energy electrons and positrons. We review the implications of this result for astrophysics and particle physics with special emphasis on decaying dark matter as the origin of the PAMELA and Fermi anomalies.

1 Introduction

Different experiments measuring high energy cosmic rays have reported over the last months a wealth of new results pointing to the existence of an exotic source of electrons and positrons. The PAMELA collaboration reported evidence for a sharp rise of the positron fraction at energies $7-100$ GeV [1], possibly extending towards higher energies, compared to the expectations from spallation of primary cosmic-rays on the interstellar medium [2]. This result confirmed previous hints on the existence of a positron excess from HEAT [3], CAPRICE [4] and AMS-01 [5]. Almost at the same time, the balloon-borne experiments ATIC [6] and PPB-BETS [7] reported the discovery of a peak in the total electron plus positron flux at energies 600-700 GeV, while the H.E.S.S. collaboration [8] reported a substantial steepening in the high energy electron plus positron spectrum above 600 GeV compared to low energies. More recently, the Fermi LAT collaboration has published measurements of the electron plus positron flux from 20 GeV to 1 TeV with unprecedented accuracy [9], revealing an energy spectrum that roughly follows a power law $E^{-3.0}$ without prominent spectral features. Simultaneously, the H.E.S.S. collaboration reported a measurement of the cosmic ray electron plus positron spectrum at energies larger than 340 GeV, confirming the Fermi result of a power-law spectrum with spectral index of $3.0 \pm 0.1(\text{stat.}) \pm 0.3(\text{syst.})$, which furthermore steepens at about 1 TeV [10]. The measured energy spectrum is much harder than the expectations of conventional diffusive models, suggesting the existence of additional sources of high energy electrons and positrons in the Galaxy.

One of the most popular astrophysical interpretations of the electron/positron excesses are the electron-positron pairs produced by the interactions of high energy photons in the strong magnetic field of nearby pulsars, such as Geminga or Monogem [11, 12, 13]. This interpretation requires, though, a rather large percentage of the total spin-down power injected in the form of electron-positron pairs, about 40%, and a large cut-off of the electron/positron energy spectrum, about 1 TeV. Alternatively, the electron/positron excesses could be explained by the combined emission of both nearby and distant pulsars, this solution requiring a percentage of spin-down power ranging between 10-30% and again a large cut-off in the energy spectrum, 800-1400 GeV [14].

A more exciting explanation of the cosmic ray electron/positron excesses is the possibility that the electrons and positrons are produced in the annihilation or the decay of dark matter particles. Would this interpretation be confirmed by future experiments, the electron/positron excesses would constitute the first non-gravitational evidence for the existence of dark matter in our Galaxy. The interpretation of the PAMELA and Fermi results in terms of dark matter is subject to constraints from the flux measurements of other cosmic ray species. A very important constraint arises from the measurements of the antiproton flux by PAMELA [15], BESS95 [16], BESS95/97 [17], CAPRICE94 [18], CAPRICE98 [19] and IMAX [20], which are hitherto consistent with the expectations from conventional propagation models, thus excluding the possibility of a large antiproton flux from dark matter annihilation or decay [21].

The steep rise in the positron fraction observed by PAMELA and the Fermi results on the total electron plus positron flux can be explained by dark matter annihilations in the center of the Milky Way, provided the dark matter particle has a mass in the TeV range and annihilates preferentially into $\tau^+\tau^-$ or 4μ [22]. This interpretation of the positron excess, however, typically requires the *ad hoc* introduction of large boost factors. Furthermore, it has been argued that if dark matter annihilations are the origin of the PAMELA anomaly, the predicted gamma-ray emission from the center of the Galaxy is in conflict with the H.E.S.S. observations for typical cuspy halo profiles [23].

In the remainder, we will discuss the possibility that dark matter decay could be the origin of the PAMELA and Fermi excesses. We will show that there exist a number of decay channels which can accommodate simultaneously the PAMELA data on the positron fraction and the Fermi data on the total electron plus positron flux, while being at the same time consistent with present measurements of the antiproton flux and the diffuse extragalactic gamma-ray flux [24, 25]. This explanation to the cosmic ray anomalies requires that the dark matter particle should have a mass of a few TeV and a lifetime around 10^{26} s. In this framework, no boost factors are required and the gamma-ray emission from the center of the Galaxy is consistent with present measurements [26].

In Section 2 we will present some motivations to consider the scenario of decaying dark matter, in Section 3 we will show our results for the high-energy cosmic rays from dark matter decay and lastly, in Section 4, we will present our conclusions.

2 Decaying Dark Matter

One of the necessary requirements for the viability of a dark matter candidate is to have a lifetime longer than the age of the Universe. However, present observations do not require absolute stability of the dark matter particles, as is implicitly assumed in most studies of the indirect detection of dark matter. Most of these analyses focus on the possibility that the dark matter is constituted by weakly interacting massive particles (WIMPs) which annihilate in the center of the Milky Way, producing an exotic contribution to the positron flux observed at Earth. It is interesting to note that, being weakly interacting, these particles are typically very short-lived. To be more precise, a WIMP with a mass of $\mathcal{O}(100$ GeV) will generically decay into Standard Model particles with a lifetime of $\mathcal{O}(10^{-25}$ s), which is obviously too short to constitute a viable dark matter candidate. In particular, this is the case for the lightest neutralino in the Minimal Supersymmetric Standard Model (MSSM), which in general decays too fast into Standard Model particles, for instance via $\chi_1^0 \to \gamma\nu$. Then, in order to obtain a lifetime longer than the age of the Universe, the dangerous WIMP couplings to Standard Model particles have to be suppressed by at least 22 orders of magnitude, which may be justified in some particular frameworks but which is nonetheless dubious. Therefore, in the absence of a compelling explanation for this extreme suppression of the coupling, the simplest possibility to guarantee the longevity of a WIMP is to *impose* a symmetry which prevents the fast decays into Standard Model particles. In the case of the MSSM this symmetry is R-parity, which guarantees that the neutralino is absolutely stable.

However, WIMPs only correspond to a subclass of all dark matter candidates; the dark matter particle could also have interactions with ordinary matter much weaker than the weak interactions. If the dark matter particle is superweakly interacting, the decay rate into Standard Model particles is naturally suppressed, thus yielding lifetimes which can be larger than the age of the Universe or perhaps a few orders of magnitude smaller. In the latter case, to obtain a sufficiently long lifetime, a suppression of the coupling by just a few orders of magnitude suffices, which can be justified in simple models. These dark matter candidates eventually decay into Standard Model particles, producing an exotic contribution to the cosmic-ray fluxes which may be detected at Earth. In the next section, the possible signatures of decaying dark matter in the cosmic-ray fluxes will be discussed in detail.

In fact, many superweakly interacting dark matter candidates have been recently proposed which decay into Standard Model particles with lifetimes longer than the age of the Universe. A very interesting candidate is the gravitino in R-parity breaking vacua [27, 28, 29], which is motivated by the requirement of a consistent thermal history of the Universe with supersymmetric dark matter, baryogenesis through leptogenesis and successful primordial nucleosynthesis. Other candidates for decaying dark matter recently proposed are hidden sector gauge bosons or gauginos [30, 31], where the decay rate is suppressed by a small kinetic mixing between a hidden $U(1)$ gauge group and the $U(1)$ of hypercharge, right-handed sneutrinos in scenarios with Dirac neutrino masses [32], where the decay rate is suppressed by the tiny neutrino Yukawa couplings, or hidden sector fermions [33] and bound states of strongly interacting particles [34, 26], where the decay rate is suppressed by the scale of grand unification.

Instead of analyzing the cosmic-ray signatures for each of these scenarios, we will present here the results of a model-independent approach which encompasses the main features of all the scenarios listed above [24, 25].

3 High-energy cosmic rays from dark matter decay

We will assume that the Milky way halo is populated with dark matter particles with mass $M_{\rm DM}$ and lifetime $\tau_{\rm DM}$ which are distributed following a Navarro-Frenk-White density profile [35]. In order to keep the analysis as model-independent as possible, we have considered the predictions for the positron fraction and the total electron plus positron flux for various decay channels and different dark matter masses and lifetimes [24, 25]. Namely, in the case of a fermionic dark matter particle $\psi_{\rm DM}$, we have considered that the dark matter particle decays exclusively via the two-body decay channels $\psi_{\rm DM} \to Z^0\nu$, $\psi_{\rm DM} \to W^{\pm}\ell^{\mp}$, as well as the three-body decay channel mediated by a heavy scalar $\psi_{\rm DM} \to \ell^+\ell^-\nu$, with $\ell = e,\ \mu,\ \tau$ being the charged leptons. On the other hand, for a scalar dark matter particle $\phi_{\rm DM}$, we have considered the two-body decay channels $\phi_{\rm DM} \to Z^0Z^0$, $\phi_{\rm DM} \to W^+W^-$, $\phi_{\rm DM} \to \ell^+\ell^-$. The fragmentation of the weak gauge bosons produces a continuous spectrum of positrons (mainly from π^+ decay) that we have obtained using the event generator PYTHIA 6.4 [36]. Then, with the energy spectrum of positrons being calculable, the only free parameters from the particle physics point of view are the dark matter mass and lifetime.

Antimatter particles propagate through the halo in a complicated way that we describe by means of a stationary two zone diffusion model with cylindrical boundary conditions [37]. For the positron propagation we will adopt the MED propagation model defined in [38], although our conclusions for the electron/positron fluxes are rather insensitive to the choice of propagation parameters or to the choice of dark matter halo profile.

We show in Fig. 1, top-left plot, the predicted positron fraction for a dark matter particle which decays as $\psi_{\rm DM} \to Z^0\nu$, compared to the PAMELA, HEAT, CAPRICE and AMS-01 data for dark matter masses $M_{\rm DM} = 5$ and 100 TeV. We also show, in the top-right plot, the corresponding total electron plus positron flux compared to the Fermi, HESS, PPB-BETS, ATIC, AMS-01, BETS and HEAT data. For each mass, the dark matter lifetime and the normalization of the background flux of electrons have been left as free parameters which have been determined to provide a qualitatively good fit to the PAMELA and Fermi measurements. In this decay channel, the only source of electrons and positrons is the fragmentation of the Z^0 boson, which produces relatively soft particles. As a result, even though this decay mode can produce a visible excess in the positron fraction, the energy spectrum is in general too flat to explain the high rise observed by PAMELA. An exception occurs if the dark matter mass is very large, $M_{\rm DM} \gtrsim 50$TeV. In this case, the electrons and positrons from dark matter decay are boosted to high enough energies to produce the steep rise in the positron fraction. However, these high dark matter masses seem to be in conflict with the H.E.S.S. observations, which require a fall-off in the total electron plus positron spectrum at ~ 1TeV.

More promising is the case when the dark matter particle decays as $\psi_{\rm DM} \to W^\pm\ell^\mp$. In this case, the positrons created in the fragmentation of the $W^\pm$ gauge bosons again produces a rather flat contribution to the positron fraction. However, the hard electrons and positrons resulting from the decay of the $\mu^\pm$ and $\tau^\pm$ leptons or directly from the dark matter decay into $e^\pm$ produce a rise in the total energy spectrum and in the positron fraction. The decay mode $\psi_{\rm DM} \to W^\pm e^\mp$ which can produce a steep rise in the positron fraction and is thus consistent with the PAMELA observations, produces also a steep rise and a sharp fall-off in the total electron plus positron flux, which is not observed by Fermi. Thus, the possibility that the dark matter particle decays preferentially in this decay mode, which was favored by the PAMELA observations, is now excluded in the light of the Fermi results on the total electron plus positron flux. On the other hand, the positrons produced in the decay mode $\psi_{\rm DM} \to W^\pm\tau^\mp$ induce a contribution to the positron fraction and the electron plus positron flux which is too flat to explain the anomalies observed by PAMELA and Fermi. Lastly, as shown in Fig. 1, second panel from the top, the decay mode $\psi_{\rm DM} \to W^\pm\mu^\mp$ can nicely accommodate the PAMELA and Fermi observations when the dark matter mass is $M_{\rm DM} \simeq 3\,$TeV and the lifetime is $\tau_{\rm DM} \simeq 2.1\times10^{26}\,$s.

Similar conclusions hold when the dark matter particle decays into a lepton-antilepton pair and a neutrino. In this case many possibilities can arise depending on the specific particle physics scenario. We will just concentrate on the case where the lepton and the antilepton carry the same flavor and the decay is mediated by a heavy scalar. In this case, the spectrum produced is flatter than in the two body decay $\psi_{\rm DM} \to W^\pm\ell^\mp$ discussed above, but the same conclusions hold: the decay mode $\psi_{\rm DM} \to e^-e^+\nu$ predicts a peak in the total electron plus positron spectrum which is not observed by Fermi, and the decay mode $\psi_{\rm DM} \to \tau^-\tau^+\nu$ produces an electron plus positron spectrum with an energy dependence much steeper than $E^{-3.0}$ at high energies, in conflict with the Fermi measurements. However, the decay channel $\psi_{\rm DM} \to \mu^-\mu^+\nu$

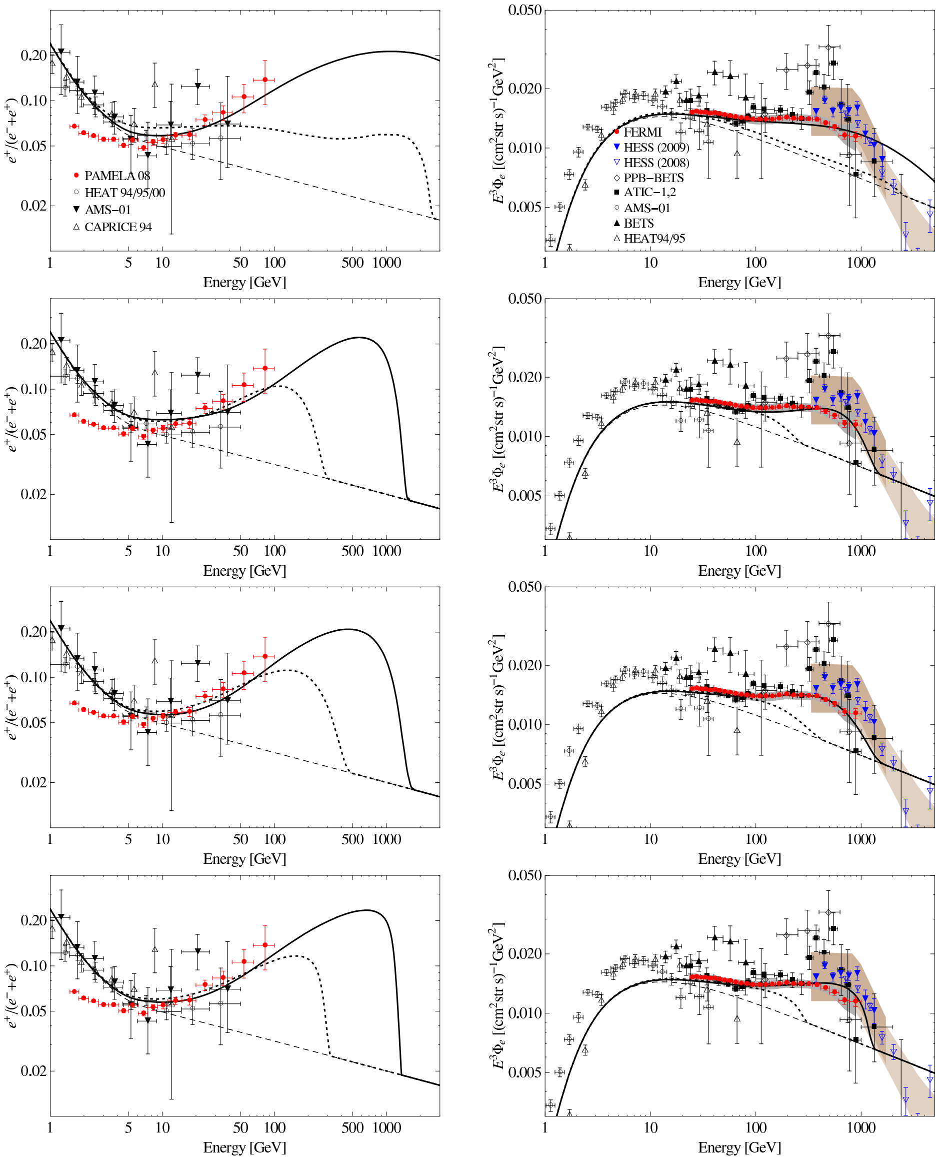

Figure 1: Positron fraction (left panel) and total electron plus positron flux (right panel) for various dark matter decay channels and masses. The dashed line shows the background fluxes as discussed in Ref. [25]. Solar modulation is taken into account using the force field approximation with $\phi = 550\,\text{MV}$. From top to bottom, we show $\psi_{\text{DM}} \to Z^0\nu$ with $M_{\text{DM}} = 100\,\text{TeV}$ (solid) and $5\,\text{TeV}$ (dotted); $\psi_{\text{DM}} \to W^\pm\mu^\mp$ with $M_{\text{DM}} = 3000\,\text{GeV}$ (solid) and $600\,\text{GeV}$ (dotted); $\psi_{\text{DM}} \to \mu^-\mu^+\nu$ with $M_{\text{DM}} = 3500\,\text{GeV}$ (solid) and $1000\,\text{GeV}$ (dotted); $\psi_{\text{DM}} \to \ell^\pm\ell^\mp\nu$ with equal branching ratio into the three charged lepton flavors, with $M_{\text{DM}} = 600\,\text{GeV}$ (dotted) and $2500\,\text{GeV}$ (solid). The last three cases can accommodate reasonably well the energy spectra of the positron fraction and the total flux.

can reproduce quite nicely the Fermi electron plus positron spectrum and the steep rise in the positron fraction observed by PAMELA when the dark matter mass is $M_{\rm DM} \simeq 3500$GeV and the lifetime is $\tau_{\rm DM} \simeq 1.1 \times 10^{26}$ s, as shown in Fig. 1, third panel from the top.

In some decaying dark matter scenarios, the dark matter particle decays into charged leptons of different flavors and not exclusively in just one channel. As an illustration of the predictions of this class of scenarios, we show in Fig. 1, bottom panel, the positron fraction and the total electron plus positron flux for a dark matter particle which decays $\psi_{\rm DM} \to \ell^+\ell^-\nu$ with identical branching ratio into the three flavors, for dark matter masses $M_{\rm DM} = 600$ GeV (dotted) and 2500 GeV (solid), inspired in the particularly interesting case where dark matter neutralinos decay into light hidden gauginos via kinetic mixing, or vice-versa [31]. It is interesting that this possibility is also in agreement with the PAMELA and Fermi data, as is apparent from the plot.

The most promising decay channels for a fermionic or a scalar dark matter particle are listed in Tab. 1, where we also show the approximate mass and lifetime which provide the best fit to the data. It should be borne in mind that the astrophysical uncertainties in the propagation of cosmic rays and in the determination of the background fluxes of electrons and positrons are still large. Besides, the existence of a possibly large primary component of electrons/positrons from astrophysical sources, such as pulsars, cannot be precluded. Therefore, the precise values of the dark matter parameters can vary. These results can nevertheless be used as a guidance for building models with decaying dark matter as an explanation of the PAMELA and Fermi anomalies.

Decay Channel	$M_{\rm DM}$ [GeV]	$\tau_{\rm DM}$ [10^{26}s]
$\psi_{\rm DM} \to \mu^+\mu^-\nu$	3500	1.1
$\psi_{\rm DM} \to \ell^+\ell^-\nu$	2500	1.5
$\psi_{\rm DM} \to W^\pm\mu^\mp$	3000	2.1
$\phi_{\rm DM} \to \mu^+\mu^-$	2500	1.8
$\phi_{\rm DM} \to \tau^+\tau^-$	5000	0.9

Table 1: Decay channels for fermionic and scalar dark matter, $\psi_{\rm DM}$ and $\phi_{\rm DM}$ respectively, that best fit the Fermi and PAMELA data.

Decay modes into weak gauge bosons produce an associated antiproton flux, which is severely constrained by present experiments [15, 16, 17, 18, 19, 20]. Indeed, the measurements of the antiproton flux do not show any deviation with respect to the theoretical expectations from spallation of cosmic rays on the interstellar medium, thus constraining the size of any exotic contribution. Therefore, purely leptonic dark matter decays are favored over the decays into weak gauge bosons. Nevertheless, as discussed in [39, 25], the antiproton flux produced by the dark matter decay into weak gauge bosons can be consistent with present measurements for certain choices of propagation parameters, especially when the dark matter mass is large. It is interesting to note that an antiproton flux from dark matter decay is necessarily accompanied by an antideuteron flux which could be observed in future experiments [39].

A very important constraint on the decaying dark matter scenario stems from observations of the diffuse extragalactic gamma-ray flux. The scenario of decaying dark matter predicts a well-defined angular map of gamma rays in the diffuse extragalactic background [40]. Furthermore, decay modes which can successfully reproduce the PAMELA and Fermi results lead to different signatures in the diffuse extragalactic gamma-ray flux. Therefore, future observations by the

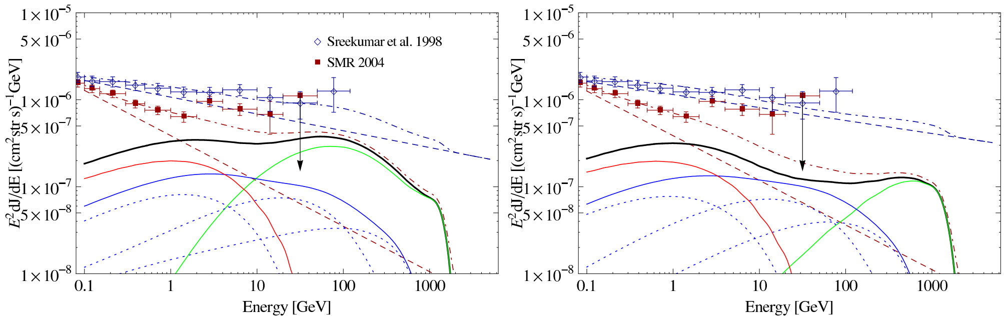

Figure 2: Extragalactic diffuse gamma-ray flux for $\psi_{\rm DM} \to W^{\pm}\mu^{\mp}$ (left panel) and $\psi_{\rm DM} \to \mu^-\mu^+\nu$ (right panel) for the dark matter mass and lifetime that can reproduce the observed positron fraction and total electron plus positron flux. We included gamma-rays produced directly in the final state radiation of the muons and the fragmentation of $W^{\pm}$ (green line), gamma-rays from inverse Compton scattering of dark matter electrons and positrons on the interstellar radiation field (solid blue line; the dotted blue lines show the fluxes that come from scattering on the cosmic microwave background, on the thermal radiation of dust and on star light from left to right) and gamma-rays from inverse Compton scattering outside of our galaxy (red). The black solid line shows the overall flux. The dark red and dark blue lines show the total flux (dash-dotted) adding an isotropic extragalactic background (dashed) with a power-law spectrum. Normalization and power index are chosen to fit one of the two shown data sets [42, 43].

Fermi Large Area Telescope (LAT) may exclude or give support to the paradigm of decaying dark matter and could exclude some decay channels, thus giving invaluable constraints on the properties of the dark matter particles.

The total extragalactic diffuse gamma-ray flux receives several contributions. The first one stems from the photons produced directly in the dark matter decay (mainly via π^0 decay) or final state radiation of the final particles. The second one is produced during the propagation of the electrons and positrons in the Galaxy, through the inverse Compton scattering on the interstellar radiation field, which includes the cosmic microwave background, thermal dust radiation and starlight [41]. Lastly, there exists a background contribution, presumably originating in Active Galactic Nuclei (AGNs), which is perfectly isotropic and which has an energy spectrum which is assumed to follow a simple power law; the normalization and index will be treated as free parameters to be determined by requiring a good fit of the total flux to the data.

We show in Fig.2 the predictions for the total diffuse extragalactic diffuse gamma ray background for the two promising decay modes $\psi_{\rm DM} \to W^{\pm}\mu^{\mp}$ (left panel) and $\psi_{\rm DM} \to \mu^-\mu^+\nu$ (right panel). We show the gamma-ray fluxes from final state radiation and $W^{\pm}$ fragmentation (green) and from galactic (blue) and extragalactic (red) inverse Compton scattering of dark matter electrons and positrons. We also show the total flux compared to the extraction of the extragalactic diffuse gamma-ray flux by Sreekumar et al. [42] and by Strong, Moskalenko and Reimer [43], averaging over the whole sky excluding the region of the galactic plane with latitudes $|b| < 10^\circ$ and assuming a power law for the genuinely extragalactic component. In both cases, they are consistent with the present data and show a deviation from the putative power law of the astrophysical background, which could be observed by the Fermi LAT, depending on the precise spectrum of the genuinely extragalactic contribution to the flux. Furthermore, this deviation is more prominent in the decay mode $\psi_{\rm DM} \to W^{\pm}\mu^{\mp}$, due to the gamma rays produced in the fragmentation of the W boson, thus offering a way of discriminating between these two decay channels.

4 Conclusions

Astrophysical and cosmological observations do not require the dark matter particles to be absolutely stable. If they are indeed unstable, their decay into electrons and positrons might occur at a sufficiently large rate to allow the indirect detection of dark matter through an anomalous contribution to the cosmic electron/positron fluxes. In this work we have investigated whether the anomalies in the positron fraction and the total electron plus positron flux reported by the PAMELA and the Fermi LAT collaborations, respectively, could be interpreted as a signature of the decay of dark matter particles. We have shown that indeed some decaying dark matter scenarios can reproduce reasonably well the energy spectra of the positron fraction and the total flux, while being at the same time consistent with present measurements of the antiproton flux and the radio and gamma-ray fluxes. We have also discussed the expectations from the scenario of dark matter decay for the diffuse extragalactic gamma-ray flux, which will be tested in the near future by the Fermi LAT.

Acknowledgements

The author would like to thank Wilfried Buchmüller, Gianfranco Bertone, Laura Covi, Michael Grefe, Koichi Hamaguchi, Tetsuo Shindou, Fumihiro Takayama, Andreas Ringwald, Christoph Weniger, Tsutomu Yanagida and very especially David Tran for very pleasant collaborations. This work was partially supported by the DFG Cluster of Excellence "Origin and Structure of the Universe."

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