Cosmic Ray Signatures of Decaying Dark Matter

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Abstract. Astrophysical and cosmological observations do not require the dark matter particles to be absolutely stable. If they are indeed unstable, their decay into Standard Model particles might occur at a sufficiently large rate to allow the indirect detection of dark matter through an anomalous contribution to the high energy cosmic ray fluxes. We analyze the implications of the excess in the total electron plus positron flux and the positron fraction reported by the Fermi and PAMELA collaborations, respectively, for the scenario of decaying dark matter. We also discuss the constraints on this scenario from measurements of other cosmic ray species and the predictions for the diffuse gamma ray flux and the neutrino flux. In particular, we expect a sizable dipole-like anisotropy which may be observed in the near future by the Fermi-LAT.

1. Introduction
A series of astrophysical and cosmological observations have revealed the existence of a new particle which is not contained the Standard Model of Particle Physics: the dark matter particle. Despite the overwhelming evidences for its existence, very little is known about the fundamental properties of the dark matter particle, such as the mass, the spin, the lifetime or the interaction cross section with ordinary matter. There are different methods to constrain, or hopefully determine, these properties: direct detection, indirect detection and collider searches. The possibility of the indirect detection of dark matter has received a lot of attention in the last two years, after the PAMELA collaboration reported the existence of an excess in the positron fraction at energies larger than 7 GeV [1]. Furthermore, the measurements of the total electron plus positron flux by the Fermi collaboration hint towards an excess at high energies [2]. In this talk we will discuss the possibility that the decay of dark matter particles could be the origin of these anomalies.

Many models have been proposed where the dark matter particle is indeed predicted to decay with a cosmologically long lifetime, yielding potentially observable signatures in high-energy cosmic rays. Some examples are gravitinos in general supersymmetric models (namely, models without imposing R-parity conservation) [3, 4, 5], where the decay rate is doubly suppressed by the supersymmetry breaking scale and by the small R-parity violation; hidden sector $U(1)$ gauge bosons or gauginos [6, 7], where the decay rate is suppressed by a small kinetic mixing between a hidden $U(1)$ gauge group and the $U(1)$ of hypercharge; hidden sector $SU(2)$ gauge bosons, where the decay rate is suppressed by a possibly large breaking scale of the hidden $SU(2)$ “custodial symmetry” [8]; right-handed sneutrinos in scenarios with Dirac neutrino masses [9], where the decay rate is suppressed by the tiny neutrino Yukawa couplings; or hidden sector fermions [10]
and bound states of strongly interacting particles [11], where the decay rate is suppressed by the scale of grand unification.

Instead of analyzing the cosmic-ray signatures for each of these scenarios separately, we will present here the results of a model-independent approach which encompasses the main features of all the scenarios listed above [12, 13]. We will first discuss the parameters which can reproduce the PAMELA and Fermi electron/positron excesses and later on we will discuss the predictions for the antiproton flux, the gamma-ray flux and the neutrino flux.

2. Decaying Dark Matter as possible explanation of the electron/positron anomalies

We will assume that the Milky way halo is populated with dark matter particles with mass $m_{DM}$ and lifetime $\tau_{DM}$ which are distributed following a Navarro-Frenk-White density profile [14]. In order to keep the analysis as model-independent as possible, we will consider the following decay channels for a fermionic dark matter particle:

$$\psi \rightarrow Z^0 \nu ,$$
$$\psi \rightarrow W^\pm \ell^\mp ,$$
$$\psi \rightarrow \ell^+ \ell^- \nu ;$$

(1)

the results for a scalar dark matter particle can be found in [12, 13]. The fragmentation of the weak gauge bosons produces a continuous spectrum of electrons and positrons (mainly from $\pi^+$ decay) that we have obtained using the event generator PYTHIA 6.4 [15]. Then, once a particular decay mode has been assumed, the only free parameters from the particle physics point of view in this analysis are the dark matter mass and lifetime.

Charged particles propagate through the halo in a complicated way before reaching the Earth. We will describe the propagation by means of a stationary two zone diffusion model with cylindrical boundary conditions [16]. For the positron propagation we will adopt the MED propagation model defined in [17], although our conclusions are rather insensitive to the choice of propagation parameters or to the choice of dark matter halo profile.

The predicted positron fraction in the case where the dark matter particles decay via $\psi_{DM} \rightarrow Z^0 \nu$ is shown in the left panel of Fig. 1, compared to the PAMELA, HEAT, CAPRICE and AMS-01 data, for the exemplary dark matter masses $m_{DM} = 5$ and 100 TeV. In the right panel we show the corresponding total electron-plus-positron flux compared to the results from Fermi, H.E.S.S., PPB-BETS, BETS, ATIC, HEAT, CAPRICE and AMS-01. The dark matter lifetimes and the normalization of the primary electron flux have been chosen in each case to provide a reasonable fit to the PAMELA and Fermi data points. In this decay channel, the dominant source of electrons and positrons is the fragmentation of the $Z^0$ boson (with a rather small branching ratio of $Z^0$ decays into a pair of charged leptons), 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 steep rise observed by PAMELA. An exception occurs if the dark matter mass is very large, $m_{DM} > 50$ 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 large dark matter masses seem to be in conflict with the H.E.S.S. observations, which require a falloff in the total electron-plus-positron spectrum at $\sim 1$ TeV [18].

On the other hand, we show in Fig. 2 the results in the case that a fermionic dark matter particle decays into three leptons $\psi \rightarrow \ell^+ \ell^- \nu$, via a virtual scalar particle. The decay $\psi \rightarrow e^+ e^- \nu$ can accommodate the PAMELA anomaly when the dark matter mass is larger than $\sim 300$ GeV. However, this decay mode cannot be the origin of the excess observed by Fermi since it predicts a rather prominent bump in the spectrum which is not observed. More promising is the decay
Po sitron fraction (left panel) and total electron-plus-positron flux (right panel) for the decay channel \( \psi_{\text{DM}} \rightarrow Z^0 \nu \) with \( m_{\text{DM}} = 100 \text{ TeV} \) (solid) and 5 TeV (dotted). The dashed line shows the background fluxes as discussed in the text. Solar modulation is taken into account using the force field approximation with \( \phi_F = 550 \text{ MV} \).

The decaying dark matter channels that can qualitatively reproduce the PAMELA and Fermi measurements, assuming the conventional diffusive model for the background electrons and positrons [19], are listed in Table 1. In this table there are two striking facts: i) the dark matter particle must be fairly heavy and ii) it must have a lifetime which is of the order of \( 10^{26} \text{ s} \).

More importantly, for a given decay channel, the requirement that the decay of dark matter particles is the origin of the PAMELA and Fermi excesses fixes the dark matter mass and lifetime, which are the only free parameters from the particle physics point of view. Therefore, it is possible to make predictions for the fluxes of antiprotons, gamma-rays and neutrinos in order to test the decaying dark matter interpretation of the electron/positron excesses.

3. Predictions for the antiproton flux

Decay modes into weak gauge bosons produce an associated antiproton flux, which is severely constrained by present experiments. Indeed, the measurements of the antiproton flux and

\[
\begin{array}{|c|c|c|}
\hline
\text{Decay Channel} & m_{\text{DM}} \text{ [GeV]} & \tau_{\text{DM}} \text{ [10}^{26}\text{s]} \\
\hline
\psi_{\text{DM}} \rightarrow \mu^+ \mu^- \nu & 3500 & 1.1 \\
\psi_{\text{DM}} \rightarrow \ell^+ \ell^- \nu & 2500 & 1.5 \\
\phi_{\text{DM}} \rightarrow \mu^+ \mu^- & 2500 & 1.8 \\
\phi_{\text{DM}} \rightarrow \tau^+ \tau^- & 5000 & 0.9 \\
\psi_{\text{DM}} \rightarrow W^\pm \mu^\mp & 3000 & 2.1 \\
\hline
\end{array}
\]

Table 1. Decay channels for fermionic and scalar dark matter, \( \psi_{\text{DM}} \) and \( \phi_{\text{DM}} \), respectively, that best fit the Fermi and PAMELA data for the MED propagation model and the NFW halo profile.

The decaying dark matter channels that can qualitatively reproduce the PAMELA and Fermi measurements, assuming the conventional diffusive model for the background electrons and positrons [19], are listed in Table 1. In this table there are two striking facts: i) the dark matter particle must be fairly heavy and ii) it must have a lifetime which is of the order of \( 10^{26} \text{ s} \).
the antiproton-to-proton fraction do not show any deviation with respect to the theoretical expectations from spallation of cosmic rays on the interstellar medium [20], thus constraining the size of any exotic contribution. The decay mode $\psi \rightarrow W^{\pm}e^{\mp}\nu$ predicts an antiproton-to-proton fraction which is in tension with the experimental measurements [13]. Therefore, purely leptonic dark matter decays are favored over decays into weak gauge bosons.

4. Predictions for the gamma-ray flux
The gamma ray flux from dark matter decay consists of two components. First, the prompt radiation of gamma-rays produced in the decay of the dark matter particle itself, coming from final state radiation, pion decay, etc. The prompt decay can also include in certain models monoenergetic lines which, if observed, would constitute an unequivocal signature of dark matter [5, 7, 8]. The prompt radiation is in turn constituted by two components: the halo
component and the extragalactic component. The former depends on the dark matter profile, displaying a strong dependence in the direction of the galactic center and being much milder at high galactic latitudes (|b| > 10°). Being the Earth 8.5 kpc away from the Galactic Center, this contribution is anisotropic, even if the halo profile is spherically symmetric, which may be detected in experiments as will be discussed below. On the other hand, the extragalactic contribution is assumed to be perfectly isotropic and is in most regions of the sky numerically smaller than the halo contribution. Moreover, the flux of gamma-rays of cosmological origin is attenuated by the electron-positron pair production on the extragalactic background light emitted by galaxies in the ultraviolet, optical and infrared frequencies [21]. However, the flux of gamma-rays originating from the decay of dark matter particles in the halo is barely attenuated by pair production on the Galactic interstellar radiation field at energies below 10 TeV [22]. Thus, the total flux is dominated by the halo component, yielding a slightly anisotropic gamma-ray flux.

In addition to the prompt radiation, the total gamma ray flux also receives a contribution from the inverse Compton scattering radiation of electrons and positrons produced in the decay on the interstellar radiation field (which includes the cosmic microwave background, thermal radiation of dust and starlight), which generates gamma rays with energies between 100 MeV and 1 TeV [23].

If decaying dark matter is the origin of the electron/positron excesses, the predicted gamma ray flux should not exceed the total measured gamma-ray flux in any direction of the sky. Furthermore, since the flux from dark matter decay is roughly (but not completely) isotropic, the flux from dark matter decay should not be much larger than the diffuse extragalactic gamma ray background determined assuming as only background the diffuse emission from

Figure 3. Left panel: Anisotropy of the gamma-ray flux from dark matter decay $\psi \rightarrow \mu^+ \mu^- \nu$ as a function of energy. The dotted line shows the background anisotropy as expected from the Galactic foreground, while the solid line shows the anisotropy of signal + background. We also show the signal + background anisotropy neglecting gamma rays from inverse Compton scattering (dashed, overlapping with solid line). The boxes show estimates of the statistical errors for one-year and five-year Fermi LAT observations. Right panel: Gamma-ray fluxes averaged over all Galactic longitudes, excluding the region $|b| < 10^\circ$, as a function of energy. The thin solid line shows the gamma rays from dark matter decay. The two dash-dotted lines show the astrophysical extragalactic background and the Galactic foreground separately. The thick solid line shows the sum of all contributions, whereas the dotted line shows the sum without contributions from dark matter. The data points show preliminary Fermi LAT data [24] for the total diffuse flux (upper points, in the $10^\circ : 90^\circ$ region we averaged the presented preliminary results appropriately) and the extragalactic background (lower points).
the galaxy. We show in Fig.3, right panel, the prediction for the averaged diffuse gamma ray flux in the region $10^\circ \leq |b| \leq 90^\circ$, $0 \leq \ell < 360^\circ$, for the decay mode $\psi \rightarrow \mu^+\mu^-\nu$ and for the mass and lifetime which reproduce the PAMELA and Fermi measurements. Indeed, the prediction for the total gamma-ray flux including the contribution from dark matter decay does not exceed the present measurements on the total diffuse gamma ray flux in that region of the sky. Furthermore, the contribution to the gamma-ray flux from dark matter decay (which resembles a diffuse extragalactic gamma-ray flux) is also below the extracted data points by the Fermi collaboration [24], thus allowing this decay mode as a possible explanation of the electron/positron excesses [25]. Notice that this decay channel predicts a rise in the energy spectrum of the diffuse extragalactic gamma ray flux at energies larger than 100 GeV.

The Earth is not located in the center of the Milky Way dark matter halo, therefore the flux from the decay of dark matter particles from the hemisphere in the direction of the galactic center should be larger than the flux from the hemisphere in the direction of the galactic anticenter. We show in Fig.3, left panel, the predicted anisotropy for the channel $\psi \rightarrow \mu^+\mu^-\nu$ calculated as $A = (J_{GC} - J_{GA})/(J_{GC} + J_{GA})$, where $J_{GC}$ is the flux in the region $10^\circ \leq |b| \leq 90^\circ$, $-90^\circ \leq \ell < 90^\circ$ and $J_{GA}$ is the flux in the region $10^\circ \leq |b| \leq 90^\circ$, $90^\circ \leq \ell < 270^\circ$. At high energies the anisotropy predicted by the conventional GALPROP model is at most a few percent (dotted line), whereas the anisotropy predicted by the scenario with dark matter decay can be as large as 20% (solid line). Remarkably, this conclusion holds for all decaying dark matter scenarios which explain the Fermi and PAMELA results, thus providing a very powerful test of the decaying dark matter interpretation of the electron/positron excesses [25].

5. Predictions for the neutrino flux

The decay of dark matter particles also produces neutrinos, which travel in straight lines through the Galaxy, essentially without any interactions. The only modifications to the fluxes during the propagation are due to flavour oscillations, which yield similar neutrino fluxes in all flavors regardless of the initial flavour composition.

The backgrounds for the neutrino signal from dark matter decay is produced by cosmic-ray interactions with the Earth’s atmosphere; In our analysis we will use the atmospheric neutrino fluxes calculated by Honda et al. [26].

We show in Fig.4, left panel, the 90% exclusion region in the lifetime vs. mass plane for different decaying dark matter scenarios from the non-observation of an excess in the Super-Kamiokande data [27]. It is apparent from the figure that the masses and lifetimes required to explain the electron/positron excesses are allowed by present experiments. On the other hand, we show in the right panel the projected 90% exclusion region at IceCube in one year from the non-observation of a significant excess in the total rate of neutrino induced upward through-going muons. It is interesting to note that IceCube will probe part of the region of the parameter space which is of relevance for the decaying dark matter interpretation of the PAMELA and Fermi anomalies.

6. Conclusions

Many well-motivated particle physics scenarios predict that dark matter particles decay with a lifetime much longer than the age of the Universe. We have shown that the decay of dark matter particles could be the explanation of the cosmic ray anomalies reported by the PAMELA and Fermi collaborations, if the dark matter mass is in the TeV range and the lifetime is $\mathcal{O}(10^{26}$ s). We have also discussed the predictions of this interpretation for the antiproton, gamma-ray and neutrino fluxes.
Figure 4. *Left panel:* 90% C.L. exclusion region in the lifetime vs. mass plane for a decaying dark matter candidate from the non-observation of a significant excess in the total rate of neutrinos observed at Super-Kamiokande. *Right panel:* 90% C.L. exclusion prospects after one year at IceCube.

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