Dark matter indirect searches: charged cosmic rays

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Abstract. I discuss the status, the recent developments and the prospects of indirect searches for Dark Matter using charged cosmic rays: electrons, positrons, antiprotons and antideuterium.

1. Introduction
Cosmology and astrophysics provide several convincing evidences of the existence of Dark Matter (DM). The observation that some mass is missing to explain the internal dynamics of galaxy clusters and the rotations of galaxies dates back respectively to the ’30s and the ’70s. The observations from weak lensing, for instance in the spectacular case of the so-called ‘bullet cluster’, provide evidence that there is mass where nothing is optically seen. More generally, global fits to a number of cosmological datasets (Cosmic Microwave Background, Large Scale Structure and also Type Ia Supernovae) allow to determine very precisely the amount of DM in the global energy-matter content of the Universe at \( \Omega_{DM} h^2 = 0.1188 \pm 0.0010 \) [1].

All these signals pertain to the gravitational effects of Dark Matter at the cosmological and extragalactical scale. Searches for explicit manifestation of the DM particles that are supposed to constitute the halo of our own galaxy (and the large scale structures beyond it) have instead so far been giving negative results, but this might be on the point of changing, perhaps thanks to ‘indirect searches’. These searches aim at detecting the signatures of the annihilations or decays of DM particles in the fluxes of Cosmic Rays (CRs), intended in a broad sense: charged particles (electrons and positrons, antiprotons, antideuterium), photons (gamma rays, X-rays, synchrotron radiation), neutrinos. In general, a key point of all these searches is to look for channels and ranges of energy where it is possible to beat the ‘background’ from ordinary astrophysical processes (which are, ironically, the usual study matter of CR physicists!). This is for instance the basic reason why searches for charged particles focus on fluxes of antiparticles (positrons, antiprotons, antideuterons), much less abundant in the Universe than the corresponding particles, and searches for photons or neutrinos have to look at areas where the DM-signal to astro-noise ratio can be maximized. Pioneering works have explored indirect detection (ID) as a promising avenue of discovery since the late-70’s. Since then, innumerable papers have explored the predicted signatures of countless particle physics DM models.

1 Here \( \Omega_{DM} = \rho_{DM}/\rho_c \) is defined as usual as the energy density in Dark Matter with respect to the critical energy density of the Universe \( \rho_c = 3H_0^2/8\pi G_N \), where \( H_0 \) is the present Hubble parameter. \( h \) is its reduced value \( h = H_0/100 \text{ km s}^{-1}\text{Mpc}^{-1} \).
Due to the theory prejudices of particles at the weak scale being good candidates (the so-called 'WIMP miracle'), the mass range around TeV-ish DM is being explored right now and will certainly be the focus of even more intense explorations in the near future. Hence, I will focus mostly on it in the following.

2. Electrons and positrons
Since 2008 or so, there has been a flurry of positive results coming from a few indirect detection experiments looking at the fluxes of electrons and positrons, pointing in particular to ‘excesses’ at the TeV and sub-TeV scale. A selection of these results is collected in fig. 1.

Notorious data from the PAMELA satellite [2] showed a steep increase in the energy spectrum of the positron fraction $e^+/e^++e^-$ above 10 GeV up to 100 GeV, compatibly with previous hints from HEAT [3] and AMS-01 [4]. Qualitatively, these findings have been confirmed, and extended to 200 GeV, with an independent measurement by the FERMI satellite [5], although the normalization differs somewhat. More recently, in 2013 and 2014, the AMS-02 experiment on board the ISS has produced high accuracy data [6, 7] that have allowed to confirm the PAMELA $e^+$ rise and also to point out a possible flattening above 300 GeV.

In the measurement of the sum of electrons and positrons ($e^++e^-$), data up to 1 TeV are provided by the FERMI satellite [8] as well as, more recently, by AMS-02 [9]: they both indicate a rather featureless spectrum, although the spectral indexes differ, the one of AMS-02 being steeper. This mild disagreement will probably be settled soon, since the FERMI collaboration has identified a systematic effect which will likely bring its data closer to those of AMS-02 in the upcoming Pass-8 release [10]. Above 1 TeV, data are provided by the Hess [11] and MAGIC [12] telescopes and show some indication for a cutoff or a steepening at energies of a few TeV. The VERITAS telescope has very recently presented new data [13] which also go in the same direction.

![Figure 1](image-url)

**Figure 1.** A compilation of recent and less recent data in charged cosmic rays. Left: positron fraction. Right: sum of electrons and positrons.

The signals presented above are therefore striking because they imply the existence of a source of 'primary' $e^+$ (and $e^-$) other than the ordinary astrophysical ones. This unknown new source can well be itself of astrophysical nature, e.g. one or more pulsar(s) / pulsar wind nebula(æ),
supernova remnants etc. It is however very tempting to try and read in these ‘excesses’ the signature of DM.

Indeed, as already mentioned above, the DM particles that constitute the DM halo of the Milky Way are expected to annihilate (or perhaps decay) into pairs of primary SM particles (such as \textit{b}\overline{b}, \mu^+\mu^−, \tau^+\tau^−, W^+W^− and so on) which, after decaying and through the processes of showering and hadronizing, give origin to fluxes of energetic cosmic rays: \(e^+, e^−, \bar{p}\) (and also \(\gamma\)-rays, \(\nu\)...). Depending on which one has been the primary SM particle, the resulting spectra differ substantially in the details \[14\]. Generically, however, they feature a ‘bump’-like shape, characterized by a high-energy cutoff at the DM particle mass and, for \(e^±\) in particular, a softly decreasing tail at lower energies. It is thus very natural to expect a DM source to ‘kick in’ on top of the secondary background and explain the \(e^±\) excesses. The energy range, in particular, is tantalizingly right: the theoretically preferred TeV-ish DM would naturally give origin to TeV and sub-TeV bumps and rises.

The \(e^−, e^+\) and \(\bar{p}\) produced in any given point of the halo propagate immersed in the turbulent galactic magnetic field. This is exactly analogous to what ordinary charged cosmic rays do (with the only difference that ordinary CRs are mainly produced in the disk). The field consists of random inhomogeneities that act as scattering centers for charged particles, so that their journey can effectively be described as a diffusion process from an extended source (the DM halo) to some final given point (the location of the Earth, in the case of interest). While diffusing, charged CRs experience several other processes, and in particular energy losses due to synchrotron radiation, Inverse Compton Scattering (ICS) on the low energy photons of the CMB and starlight, Coulomb losses, bremsstrahlung, nuclear spallations,... The transport process is solved numerically or semi-analytically using codes such as GALPROP, DRAGON, USINE, PICARD.

The source, DM annihilations or decays, follows \(\rho(\vec{x})\), the DM density distribution in the galactic halo, to the first power (in case of decays) or to the second power (for annihilations). What to adopt for \(\rho(\vec{x})\) is another one of the main open problems in the field. Based on the results of increasingly more refined numerical simulations or on direct observations, profiles that differ even by several orders of magnitude at the GC are routinely adopted: e.g. the classical Navarro-Frenk-White (NFW) or the Einasto one, which exhibit a cusp at the galactic center, or the truncated isothermal or the Burkert one, which feature a central core. All profiles, on the other hand, are roughly normalized at the same value at the location of the Earth, which needs to be determined accurately. These features generally imply that observables which depend mostly on the local DM density (for instance, the flux of high energy positrons, which cannot come from far away due to energy losses) will not be very affected by the choice of profile, while those that are sensitive to the density at the GC will be affected the most (e.g. gamma rays observations of regions close to the GC).

All in all, the DM annihilation (or decay) channel, the DM mass and the annihilation cross section (or decay rate), convoluted with the information on the propagation process and the DM galactic profile allow to determine the expected CR fluxes and compare them with the data. Of course, a proper treatment of the background from astrophysics is crucial to obtain meaningful results (this step often represents the most tricky one in the actual analysis). Under conservative and rather broad assumptions for the background and for propagation, an example of the results of global fits to data, for the case of annihilations, is given in fig. 2. As perhaps well known, the DM needed to fit the data has to: have a mass in the TeV / multi-TeV range, have a very large annihilation cross section (of the order of \(10^{-23}\text{cm}^3/\text{s}\), orders of magnitude larger than the cosmological prejudice) and be leptophilic (to avoid contradicting antiproton bounds for such a large cross section, see the next section). So a global Dark Matter interpretation of the leptonic ‘excesses’ can be attempted. However, even restricting to leptonic data only, some tension is present. First, as apparent in fig. 2, the green and blue regions overlap only marginally, i.e. the positron data tend to prefer a mass smaller than the all lepton ones. This is...
due to the bending of the highest energy AMS-02 data [15]. Secondly, the conclusions reached above may be questioned if one fully exploits the precision of the AMS-02 data and if one relaxes the assumptions (e.g. considering more annihilation channels with different branching ratios). Finally, and perhaps most importantly, a significant tension exists with constraints from gamma rays and from the CMB. We will discuss the former ones in a subsequent section. The CMB ones stem from the fact that DM annihilations in the Early Universe inject energy that modifies the properties of the CMB, mainly via the induction of excessive ionized material at early redshift. Fig. 3 reports two recent determinations of the bounds, that manifestly exclude the DM interpretation of the leptonic ‘excesses’ [1, 16]. These constraints have the advantage of being insensitive to the usual astrophysical uncertainties that affect the gamma and charged CR ray bounds (e.g. the DM profile), but they can be evaded if the cross section is suppressed at low velocities or early times.

So keeping the DM option on the table, the question becomes: how will we be able to
discriminate between a DM versus an astrophysical origin of the excesses? It is repeatedly claimed, e.g. by the press releases of the AMS-02 collaboration [17], that the behavior of the positron fraction spectrum at high energies, which will be precisely measured by the experiment, will allow such discrimination: the assumption is that a DM spectrum would show a sharp cut-off (at the value corresponding to the particle’s mass) while an astrophysical source would present a smoother decline. While it is certainly true that a very important role will be played by precision measurements, unfortunately the above statements are too simplistic. Indeed, for instance, when DM annihilates in a combination of channels, including hadronic ones, its $e^+$ spectrum can be soft. On the other hand, a sufficiently young and nearby pulsar could explain the data and would produce a steep spectral descent. In general, too little is known on the details of CR propagation and on the mechanisms of local astrophysical sources to support the simplistic claims on the shape of the fraction.

A more promising avenue is connected to the arrival direction of the cosmic leptons. Detecting a clear dipole anisotropy would be a clear indication of the existence of a single point source while measuring an isotropic distribution would rather favor a diffuse source such as DM (or a collection of uniformly distributed point sources). The anisotropy measurement is most useful if performed as a function of the energy of the incoming leptons: indeed, low energy cosmic rays are generically predicted to come from farther away (a long propagation degrades the energy) and therefore to have a randomized arrival direction, while high energy ones would better retain the information. FERMI has reported upper bounds as a function of the energy in [18]. AMS-02 has reported a flat upper bound of 3% in [7] and plans to reach a 1% sensitivity in the dipole anisotropy. PAMELA has recently quoted an upper bound of 16% [19].

Very fortunately, the near future has in store more precision data on leptons. The Japanese-led CALET detector [20] and the Chinese-led DAMPE satellite will explore an energy range up to several TeV with unprecedented resolution. CALET has been installed on the ISS in August 2015 while DAMPE is scheduled for launch in December 2015. Remarkably enough, even the future gamma ray imaging telescope CTA plans to be able to measure the positron fraction at high energies, using the Earth-Moon system as a spectrometer [21].

3. Antiprotons
In the antiproton channel, data have been published by PAMELA since 2008 [22] (and then 2010 [23] and 2012 [24]). More recently, AMS-02 has also presented preliminary data on the $\bar{p}/p$ ratio, in a a widely advertised event at CERN [25]. The data-sets from the two experiments, reported in fig. 4, are in very good mutual agreement, although the AMS-02 ones are of course much more accurate and extend to higher energies.

In the AMS presentation strategy [26], the public may be led to believe that the data are at odds with the predictions from astrophysics and therefore that a new component (Dark Matter!) has to be invoked. However, despite the extent to which we would all love AMS to find something extraordinarily new, this is at best clearly premature. Indeed, when one includes, in the computations of the predictions from astrophysics, the latest recent developments, the discrepancy is largely reabsorbed. Such latest developments include: (i) the new measurement of the primary proton and Helium spectra (which, impinging on the interstellar medium, produce the bulk of the astrophysical antiprotons), as delivered by AMS itself [27] \(^2\); (ii) the recent results on the antiproton spallation production cross section [30]; (iii) updated propagation schemes...

A collection of fairer comparisons between the data and the updated predictions from astrophysics is reported in fig. 4 (first 3 panels). The predictions differ slightly because

\(^2\) These measurements are now in very good agreement with the corresponding measurements by PAMELA from 2011 [28], after that AMS has revisited its understanding of the systematic errors with respect to the data presented at ICRC 2013 (see footnote 23 of [29]): now both experiments see a spectral break (a.k.a. a ‘change of slope’) at about 300 GeV.
they employ different inputs and different determinations of the uncertainties. However, the qualitative conclusion is quite apparent: contrarily to the leptonic case, there is no unambiguous excess in antiproton data. On the other hand, it is true that the data seem to prefer a rather flat $\bar{p}/p$, which is somewhat difficult to obtain in current astrophysical models. This may point to propagation schemes characterized by a relatively mild energy dependence of the diffusion coefficient at high energies. Although it is too early to draw strong conclusions, this is an interesting observation and it goes in the same direction as the preference displayed by the preliminary B/C AMS-02 data.

For what concerns Dark Matter, since no excess can undisputedly be claimed, one can derive constraints [31]. This is what is reported in the last panel of fig. 4 for one specific example. Fixing a benchmark DM profile (Einasto) and the MED propagation scheme, the constraints exclude the thermal annihilation cross section $\langle \sigma v \rangle = 3 \cdot 10^{-26} \text{ cm}^3/\text{s}$ for $m_{\text{DM}} \sim 150$ GeV. The modification of the profile or the propagation scheme has the effect of spanning the shaded band, i.e. affecting the bounds by a factor of a few.

Figure 4. Antiproton measurements by PAMELA and AMS-02 compared to the astrophysical prediction and its uncertainties, in three independent analyses, and the constraints on DM annihilation that originate from them. Top-left and bottom-right figures are from [31]; top-right from [32], bottom-left from [33].
4. Antideuterium

Antideuterons (the bound states of an antiproton and an antineutron) are believed to be quite promising as a tool for DM searches. They can be produced by DM via the coalescence of an antiproton and an antineutron originating from an annihilation event, provided that the latter ones are produced with momenta that are spatially aligned and comparable in magnitude [34]. This peculiar kinematics in the production mechanism implies two things. One, that the flux of $\bar{d}$ from DM is (unfortunately) predicted to be much lower than the one of other, more readily produced, charged CRs. Two, that (fortunately) the flux peaks in an energy region, corresponding typically to a fraction of a GeV, where very little astrophysical background $\bar{d}$'s are present, since the latter ones are believed to originate in spallations of high energy cosmic ray protons on the interstellar gas at rest, a completely different kinematical situation. It is therefore sometimes said that the detection of even just one sub-GeV antideuteron in CRs would be a smoking gun evidence for DM.

Figure 5. Spectra of antideuterons as predicted by some benchmark Dark Matter models (solid lines) superimposed to the predicted background from astrophysics, the current Bess limit (green shaded area) and the projected sensitivity of GAPS (pink shaded area) and AMS (blue shaded area). The figure is taken from [35].

Antideuteron searches are mainly discussed within the context of the GAPS and AMS-02 experiments [35]. The former one, in particular, will be a dedicated balloon mission which employs a novel technique: it plans to slow down the $\bar{d}$ nucleus, have it captured inside the detector to form an exotic atom and then annihilate emitting characteristic X-ray and pion radiation. Currently there is only an upper limit from the Bess experiment [36], at the level of about 2 orders of magnitude higher than the most optimistic predictions. The limit and the reach of the future experiments is reported in fig. 5.

5. Generic conclusions

Dark Matter exists and discovering what it is made of is certainly one of the major open problems in particle physics and cosmology nowadays. The key to finding out the answer will probably lie in a tight collaboration among the many different disciplines involved in the quest, including in particular particle physics beyond the Standard Model and CR physics, which is directly relevant for DM ID. The potential problem, in my view, is that progress in both communities might be too slow for the needs (or the wishes) of the other side. In the recent past, there are many examples of cases in which some parts of the DM particle theory community has jumped too quickly on the interpretation of cosmic ray data, without a full understanding of the ‘astrophysics-related’ issues and thus reaching maybe unmotivated conclusions. In the even more recent past, there are other examples of some parts of the CR community crying ‘Dark Matter!’ too quickly, perhaps without a full control of the context. Given the important stakes, it is perhaps more worthwhile to stay focussed and work fruitfully towards the common goal.
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