A quantitative study of AMS-02 $e^\pm$ data. What can we learn about dark matter?

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Abstract. We present the results of a combined analysis of the whole set of AMS-02 electrons and positrons data conducted in a self-consistent framework in which a theoretical modeling of all the components that can contribute to the observed fluxes is realized. We study the main features of the electron/positron emission from primary and secondary astrophysical sources, as well as from dark matter annihilation/decay processes, with the purpose of assessing a way to disentangle a possible dark matter signal from a loosely known astrophysical background. Then, we investigate the conditions under which a good agreement between theoretical predictions and experimental measurements can be achieved, with a particular focus on the constraints that can be derived on dark matter properties.

1. Introduction
Among the different strategies used to detect a non-gravitational imprint of Dark Matter (DM), the search for an excess of antimatter in the flux of charged Cosmic Rays (CRs) plays a preeminent role. In particular, in recent years, a great interest has been triggered by the observation of a steep rise in the energy spectrum of the positron fraction. Such an observation, performed firstly by the PAMELA satellite [1] and then confirmed at an unprecedented level of precision by the AMS-02 experiment [2], can be interpreted either as a smoking gun signature of a leptophilic TeV-scale WIMP or as the imprint of some astrophysical mechanisms at work. Examples of such mechanisms can be the emission from Pulsar Wind Nebulae (PWNe) and/or Supernova Remnants (SNRs) or the diffusive shock acceleration of secondary positrons within the shock regions of SNRs.

In this proceeding, based on [3, 4], we present a quantitative study of the whole set of leptonic data that have been recently published by the AMS-02 Collaboration [5, 6, 7]. We analyse these data within a theoretical model that takes into account all astrophysical emissions either from primary sources, namely PWNe and SNRs, or of secondary origin, together with a possible exotic contribution arising from DM annihilation or decay. Our aim is to understand firstly if a DM contribution has to be necessarily included in the model in order to fit the data and then to quantitatively assess to what extent AMS-02 data can be used to constrain DM properties.
2. Our model

As already pointed out, electrons and positrons can be emitted by astrophysical processes or be the outcome of a DM annihilation (or decay) event. Particles of astrophysical origin can come either from primary sources (SNRs or PWNe) or be the result of the collisions that involve primary CRs (proton and Helium nuclei) scattering off particles of the Interstellar Medium (ISM). In this latter case, electrons and positrons are usually labeled as secondaries.

SNRs are capable of accelerating particles of the ISM through diffusive shock acceleration processes and thus they can be seen as sources of electrons. The energy spectrum of the particles accelerated by SNRs can be modeled as a power-law with an exponential cut-off. Therefore, as explained in detail in [3, 4], the flux from each SNR is determined by five parameters: the normalization $Q_{0,\text{SNR}}$, the power-law index $\gamma_{\text{SNR}}$, the cut-off energy $E_c$, the SNR distance $d$, and its age $T$. We fix $E_c = 2$ TeV and we divide the whole population of SNRs in two categories, based on their distance from Earth. The near SNRs are the ones within 3 kpc: all their parameters are fixed to the values reported in the Green catalogue [8] and only a free normalization of the flux generated by the Vela SNR (the dominant contributor) is allowed. On the other hand, far SNRs are treated as an average population of sources distributed according to the distribution described in [9] and with common values for $Q_0$ and $\gamma_{\text{SNR}}$, which will appear as free parameters in our fits.

PWNe are expected to emit both electrons and positrons through a mechanism known as spin-down emission. As for SNRs, also for this class of sources the flux is usually modelled as a power-law with an exponential cut-off. We set $E_c = 2$ TeV and we take the distance and age of each PWN from the ATNF catalogue [10]. We are thus left with two free parameters which will enter our fits: the efficiency $\eta_{\text{PWN}}$ that determines the normalization of the $e^\pm$ flux and $\gamma_{\text{PWN}}$ which is its spectral index. If not otherwise stated, these two parameters will be assumed to be the same for all the PWNe that will be considered in our analysis.

As far as the secondary contribution is concerned, we set the flux of primary CRs by fitting the proton and Helium fluxes measured by the AMS-02 experiment [11], while for the inclusive cross section for the production of $e^\pm$ in spallation reactions we adopt the parameterization described in [12].

Concerning DM contribution, we consider 6 possible annihilation/decay channels: $e^+e^-$, $\mu^+\mu^-$, $\tau^+\tau^-$, $b\bar{b}$, $W^+W^-$, $Z^0Z^0$. For every channel, the $e^\pm$ energy spectrum is taken from [13]. The DM distribution in the Galaxy is assumed to follow a NFW profile, while the local DM density is assumed to be $0.4 \text{ GeV/cm}^3$.

Lastly, once produced by the afore-mentioned sources, electrons and positrons have to propagate across the Galaxy and through the heliosphere before being detected. We model the propagation within the Galaxy by means of the two-zone diffusion model [14] and the solar modulation with the force field approximation [15]. The parameters that rule the galactic propagation are the ones of the so-called MED model [16], while the Fisk potential $\phi$ associated to solar modulation will be a free parameter of the fit.

| $\eta_{\text{PWN}}$ | $\gamma_{\text{PWN}}$ | $Q_{0,\text{SNRs}}[10^{23} \text{ erg/s}]$ | $\gamma_{\text{SNRs}}$ | $\bar{\bar{N}}_{\text{Vela}}$ |
|---------------------|---------------------|-----------------------------------|---------------------|------------------|
| 0.0368$^{+0.0011}_{-0.0014}$ | 1.948$^{+0.022}_{-0.022}$ | 1.231$^{+0.014}_{-0.028}$ | 2.238$^{+0.015}_{-0.013}$ | 0.978$^{+0.031}_{-0.130}$ |
| $\chi^2_{\text{tot}}/184$ d.o.f | $\chi^2_{e^+}$ (49 data pts) | $\chi^2_{e^-}$ (48 data pts) | $\chi^2_{\text{sum}}$ (50 data pts) | $\chi^2_{\text{pf}}$ (43 data pts) |
| 1.03 | 39.7 | 33.6 | 36.0 | 81.7 |

Table 1. The top row reports the best-fit parameters for the purely astrophysical fit, while in the bottom row the chi-square associated to the different datasets are listed.
3. Results

3.1. Interpreting AMS-02 data

Our aim is to perform a fit of the four observables measured by the AMS-02 experiment within different theoretical models. In order to sample the parameter space of each model, we employ a Markov Chain Monte Carlo (MCMC) scan, implemented through the CosmoMC package [19]. We decide to consider in our analysis only data above 10 GeV. This choice is justified since the sector which is most relevant for the study of $e^\pm$ primary sources is the high energy region, while the low energy part of the spectra is heavily influenced by the modeling of the solar modulation and this could potentially bias our results.

Firstly we perform a purely astrophysical fit of AMS-02 data. Within this model, which we label astro model, electrons and positrons are either of secondary origin, or they are accelerated by SNRs and PWNe. Therefore, the free parameters that appear in the fit are six: $Q_{0,\text{SNR}}, \gamma_{\text{SNR}}, N_{\text{Vela}}, \eta_{\text{PWN}}, \gamma_{\text{PWN}}$ and $\phi$. Their best-fit values are reported in Table 1, together with the global $\chi^2$ and the chi-square associated to each dataset (we have 4 datasets, one for every observable measured by AMS-02). As it can be seen, while the global chi-square denotes a remarkably good agreement between the astro model and the whole set of AMS-02 data, the fit appears to be not that good in reproducing the positron fraction, for which the chi-square per data-point is found to be around 2. We consider this to be a solid motivation to investigate the possibility to have additional $e^\pm$ sources.

On the one hand, this additional contribution can come from DM annihilation or decay. To investigate this scenario, we fit AMS-02 data within a model, labeled as astro+DM model, in which, together with the six parameters associated to the astrophysical emission that were listed in the previous paragraph, we also have the two parameters that determine the $e^\pm$ yield generated by DM: the DM mass $m_{DM}$ and its annihilation cross section $\langle \sigma v \rangle$ (or lifetime $\tau$ for the decaying DM case). Among the different annihilation channels that we consider, the highest agreement with AMS-02 data is achieved by a WIMP annihilating into $\mu^+\mu^-$ and $\tau^+\tau^-$. In particular, for the $\mu^+\mu^-$ case, the best-fit configuration is the one in which $m_{DM} = 89^{+22}_{-10}$ GeV.
and $\langle \sigma v \rangle = 8.4^{+3.7}_{-1.6} \times 10^{-26} \text{ cm}^3 \text{s}^{-1}$, while for the $\tau^+\tau^-$ channel the highest likelihood is achieved when $m_{DM} = 619^{+760}_{-210} \text{ GeV}$ and $\langle \sigma v \rangle = 6.8^{+1.4}_{-1.3} \times 10^{-24} \text{ cm}^3 \text{s}^{-1}$. The agreement with AMS-02 data improves with respect to the purely astrophysical case: the global chi-square per degree of freedom is 0.78 ($\mu^+\mu^-$) and 1.14 ($\tau^+\tau^-$) while the chi-square per data point of the positron fraction is 1.16 ($\mu^+\mu^-$) and 1.23 ($\tau^+\tau^-$). As it is shown in the left panel of Fig. 1, these best-fit configurations are also fully compatible with the upper limits derived in [17, 18] as a result of an investigation of the IGRB measured by the Fermi-LAT experiment.

On the other hand, a comparably good agreement with AMS-02 data can be achieved by refining the astro model. One way to do this is to relax the assumption that all the PWNe share the same efficiency $\eta_{psr}$ by allowing the efficiencies of the five most powerful PWNe to vary independently. As shown in [4], under these assumptions, the global $\chi^2$ per degree of freedom drops to 0.8 and the $\chi^2$ per data point of the positron fraction is 1.16. It has to be remarked, however, that even within this refined scenario, the addition of a DM annihilating into $\mu^+\mu^-$ and $\tau^+\tau^-$ provides a sizeable improvement in the agreement with data. In fact, once that DM is added, the global $\chi^2$ becomes 0.67 ($\mu^+\mu^-$) and 0.75 ($\tau^+\tau^-$), while the $\chi^2$ per data point of the positron fraction is reduced to 1.00 ($\mu^+\mu^-$) and 0.94 ($\tau^+\tau^-$).

Another possible refinement of the astro model is realized by considering a single additional PWN, whose contribution to the $e^\pm$ fluxes lies on top of the emission from the other astrophysical primary sources. This model is characterised by 9 free parameters: the six ones that characterize the astro model plus the distance $d_{psr}$, the age $T_{psr}$ and the efficiency $\eta_{psr}$ of the additional pulsar. In the best-fit configuration, $d_{psr} = 0.59^{+0.11}_{-0.15}$ kpc, $T_{psr} = 980^{+820}_{-210}$ kyr and $\eta_{psr} = 0.45^{+0.07}_{-0.13}$, the global chi-square per degree of freedom is 0.7 and the chi-square per data point of the positron fraction is 0.89. In the right panel of Fig. 1, the 1$\sigma$ and 2$\sigma$ contours of this additional PWN in the ($d_{psr}, T_{psr}$) plane are shown together with the pulsars of the ATNF catalogue.

3.2. Constraining the DM contribution

Our aim in this Section is to use AMS-02 data to constrain the DM parameters space. In other words, we use AMS-02 data to determine the maximal contribution that DM can give to the leptonic observables once that the astrophysical background is realistically modeled and primary
astrophysical sources are taken into account.

We set these upper limits within the astro+DM model that was described above. For fixed values of the DM mass we perform a MCMC sample of the parameters of the model and we marginalize over the PWNe and SNRs parameters in order to build the posterior distribution function (pdf) of the DM annihilation cross section (or lifetime, in the decaying DM case). If we denote with $P$ the pdf for $\langle \sigma v \rangle$, we can set an upper limit $\langle \sigma v \rangle_{UL}$ with a confidence level $\alpha$ by simply requiring that $P(\langle \sigma v \rangle \leq \langle \sigma v \rangle_{UL}) = \alpha$. Results for a 2$\sigma$ confidence level are shown in Fig. 2.

4. Conclusions
We have presented here a summary of the quantitative study of AMS-02 data that has been carried out in [3, 4]. We have described the different contributions to the electron and positron fluxes and we have investigated which are the ranges of parameters preferred by experimental data.

As it has been showed, a purely astrophysical model in which all the PWNe share the same efficiency and spectral index can fit the whole set of data quite well but fails in reproducing the measured positron fraction. Therefore, AMS-02 data seem to demand either for a more refined model in which these assumptions are relaxed or for an additional $e^\pm$ source. As we have discussed here, this additional contribution can come either from DM annihilation/decay or from the emission of an additional PWN, with properties (distance and age) different from the sources of the ATNF catalogue. Because of the large freedom in the parameters under scrutiny, it is not possible, at present, to disentangle between these different interpretations. In our opinion, the investigation of independent and multi-wavelength channels could help in achieving a deeper understanding of this issue.

Lastly, we have investigated how AMS-02 data can be used to set robust constraints on the DM parameters space. By means of a Bayesian approach we have derived upper limits on DM annihilation or lifetime which are competitive with the bounds that can be derived in other indirect channels. This demonstrates that despite our poor knowledge of the astrophysical background leptonic data can provide an invaluable help in probing DM properties.

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