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Interpretation of the AMS-02 leptons and nuclei measurements: Implications and perspectives for dark matter search

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Summary. — AMS-02 is running since four years: a powerful apparatus for dark matter searches has been set up, in order to study the important antiparticle-to-particle ratios and cosmic leptons and nuclei spectra, up to the TeV scale. Official papers dedicated to hadronic physics are incoming. The unprecedented precision of AMS-02 data permits to greatly reduce the astrophysical uncertainties which affect cosmic rays (CR) propagation, allowing to study CR anomalies and highlight new phenomena, to corroborate or falsify present dark matter (DM) theories and to explore the TeV-ish dark matter scenario opportunities.

1. – Theoretical uncertainties: removing the background for DM indirect search in the antiproton channel

Before dealing with dark matter particle candidates for space search, a close examination of the uncertainties that afflict the CR spectra, in particular the antiproton one, is mandatory to understand the limit of current knowledge. Mainly these uncertainties come from four sectors: the overall CR propagation scheme in our Galaxy, the modelization of the DM halo, the nuclear cross sections for antiprotons production in the interstellar medium (ISM), and the annihilation branching ratios of the DM particle [1]. The astrophysical function for the antiproton spectrum in fig. 1 right shows the importance of the propagation model over the DM profile. The so-called in the literature MIN, MED MAX parameters configurations produce low, medium or high CR fluxes, respectively. Past experiments were not able to fix the CR propagation physics: the parameters were lying in very wide ranges. This translated into two orders of magnitude of fluxes uncertainty, one above and one below the MED set. The choice of the DM profile (fig. 1 left) is less significant, but, in addition, it must be taken into account that overdense regions

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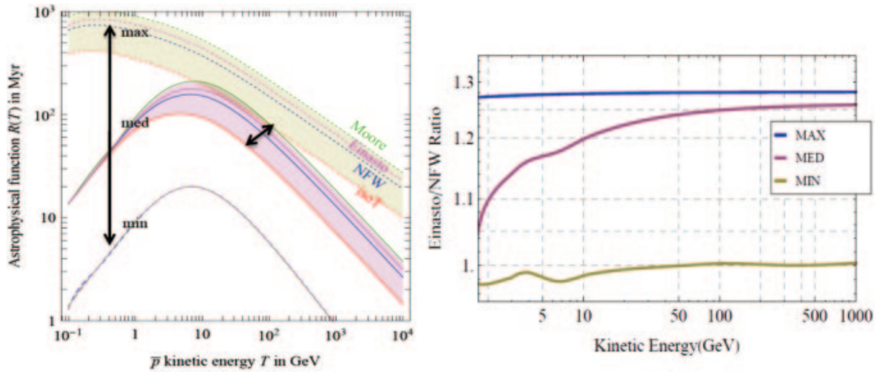

Fig. 1. – Left: propagation uncertainties from the so-called in the literature MIN-MED-MAX sets, as a function of the dark matter profile [2]. Right: Einasto *vs.* NFW profile ratio for the three propagation sets, I computed with the *PPPC4DMID* package [3].

(spikes) in the Galactic Centre could produce an annihilation enhancement, increasing particle fluxes [1].

The third fundamental source of uncertainties lies in nuclear physics: the cross sections for *pp* and *p*He collisions in the ISM which produce antiprotons are poorly known, with an accuracy that is very far from what required in the CR physics inaugurated by AMS-02 [1]: 20%–40% uncertainties have to be considered when putting constraints to dark matter properties from the antiproton channel (fig. 2 left). Uncertainties linked to the DM sector itself, such as the preferred annihilation channels (fig. 2 right) and the important Next-to-Leading-Order (NLO) corrections to the tree level DM primary flux [4], are hard to be removed, but they are still lower than the fundamental uncertainty which afflicts the cosmic rays propagation physics and the nuclear one.

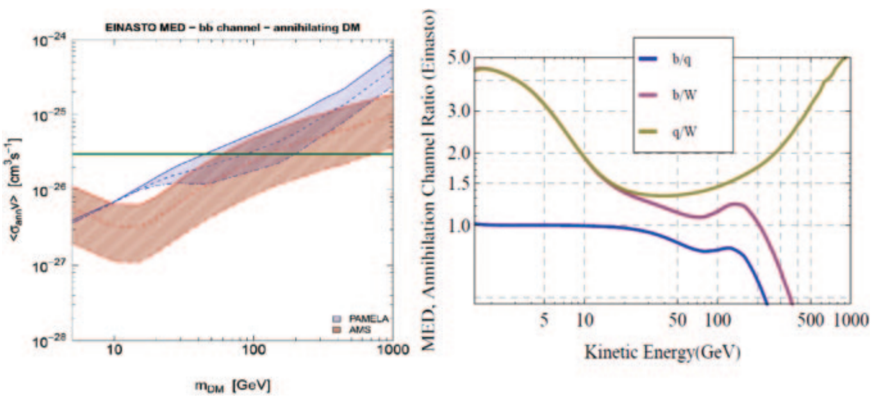

Fig. 2. – Left: DM annihilation cross section constraints from PAMELA antiprotons (blue) and AMS-02 projected data [5], with three different nuclear uncertainties assumed (5%, 20%, 40%). Right: antiproton annihilation channels ratios for bottom (b) *vs.* up/down (q) *vs.* vector boson (W), I obtained using a MED set and an Einasto profile.

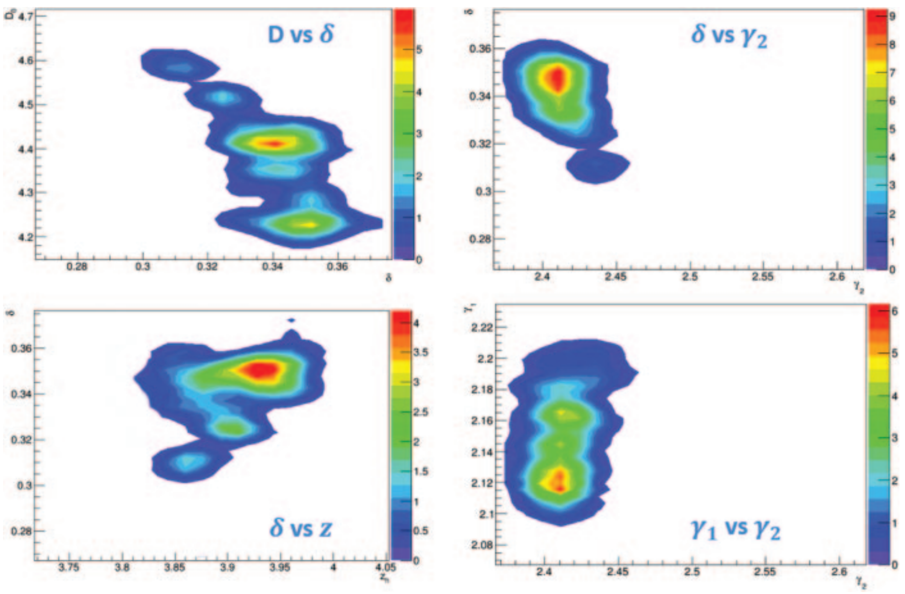

Fig. 3. – MCMC CR propagation parameters correlations: for the diffusion coefficient (D), the diffusion index (δ), the diffusive halo thickness (z) and injection indeces ($\gamma_{1,2}$). I obtained these maps using projections for B/C and boron, carbon, oxygen spectra from AMS-02, as constraints for the parameters scan.

2. – Multiple constraints to fix CR propagation physics: an MCMC approach

After a century of CR physics, finally AMS-02 offers the chance to *disentangle* the galactic properties, narrowing the parameters ranges: this is fundamental not only for DM indirect search but also for astroparticle physics and astrophysics in general. AMS-02 measures CR nuclei spectra with % accuracy up to to 2 TeV and up to iron, allowing to perform a full realistic parameters scan with multiple precise constraints. The main approach is to study and simulate CR spectra with GALPROP [6], applying a Monte Carlo Markov-Chain (MCMC) method [7] to achive multi-dimensional parameters constraints from the experimental data (fig. 3).

With boron over carbon ratio (B/C), boron, carbon and oxygen projected spectra from AMS-02 we can easily constrain, for the first time, the fundamental parameters that drive CRs, defining an almost univocal propagation scheme. Hence, after AMS-02 data it will be possible to achive a consistent best fit that points towards a MED set: the errors associated to the fundamental propagation parameters are greatly reduced (fig. 4), with a a factor 10 of improvement for each of them. Identifying a single well-posed propagation configuration, we can break down the astrophysical uncertainties that afflict the predicted DM primary antiproton flux, with an overall improvement factor of 20–50 in the 10–500 GeV range (fig. 5): this makes the DM discovery easier, faster and more reliable [8]. Once removed the background, one can move to the characterization of the DM candidate features and understand if a DM signal could emerge from this *astrophysical noise* [1].

	Units	Range	% error before	New range	% error after	Improvement $\varepsilon_{beore}/\varepsilon_{after}$
z	kpc	3 – 10	54%	3.8 – 4.3	6%	9
r_{max}	kpc	10 – 30	50%	20 – 24	9%	6
D_{0xx}/10^28	$cm^2 s^{-1}$	0.2 – 9.7	96%	3.9 – 4.4	6%	16
$\delta_{1,2}$		0.23 – 0.85	57%	0.32 – 0.36	6%	10
V_{Alfven}	km s^{-1}	7 – 117	89%	19 – 33	27%	3
V_{0conv}	km s^{-1}	0 – 22	100%	11 – 13.5	10%	10
dV_C/dz	km $s^{-1} kpc^{-1}$	0 – 12	100%	8.5 – 10.5	11%	10

Fig. 4. – CR propagation uncertainties before (left) and after (right) AMS-02, for each of the main propagation parameters; the columns show the ranges used in the literature till now, along with the per cent error w.r.t. the mean value, and the projections for the effective ranges and errors after AMS-02 nuclear measurements, according to the MCMC simulations I performed. In green the single improvement factors are reported.

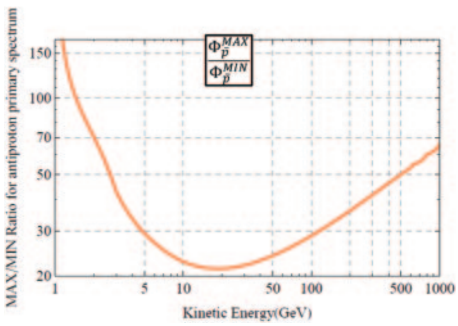

Fig. 5. – Reduction of astrophysical uncertainties after AMS-02: the MAX/MIN Dark Matter antiproton flux ratio I estimated with the *PPPC4DMID* package represents the background for the indirect search.

3. – DM candidates for AMS-02 in the post-Higgs era

It is well known that AMS-02 and PAMELA results in antiproton and positron channels are difficult to be explained within the same standard or dark matter model: the positron fraction rises with increasing energy, opposite to the expected behavior of secondaries produced in the ISM [1] [9]. On the other hand, for antiprotons, PAMELA's experimental data show a perfect secondary spectrum with nonexotic astrophysical origins. In order to reproduce this tension between leptonic and hadronic CR results, the particle dark matter candidate must satisfy several properties: the cross section has to be large and the mass must be greater than 1–2 TeV, that is also suggested by LHC lack of discoveries and many astrophysical observations [1]. This grants a DM which is able to annihilate into positrons and also antiprotons but at very high kinetic energies (> 200 GeV). For what concerns the spin statistics, the criterion to discern one theory from another is that only few particles (spin 0, 1 bosons and Majorana fermions) are their own antiparticle and so capable to self-annihilate and avoid the specious fine tuning of DM decaying models [1]. The heaviest candidates which could match the prescriptions obtained from astroparticle physics are the *AMSB* SUSY Wino, the Universal Extra Dimension (UED) Lighest Kaluza-Klein Particle (LKP), and the Scalar Multiplet

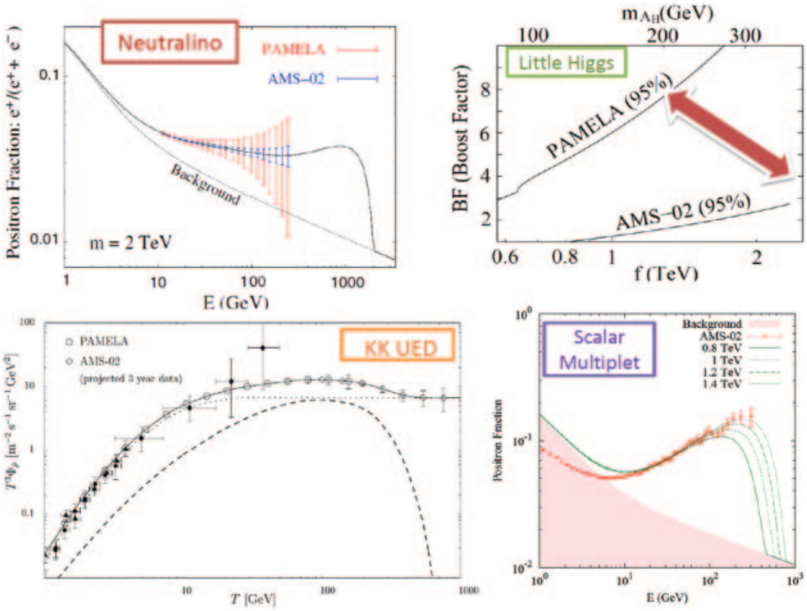

Fig. 6. – Main heavy DM candidates for space search, with simulations for AMS-02 discovery potential in positrons and antiprotons channels: Wino neutralino and Little Higgs *massive photons* (upper row), Kaluza-Klein particle and scalar multiplet particle (lower row).

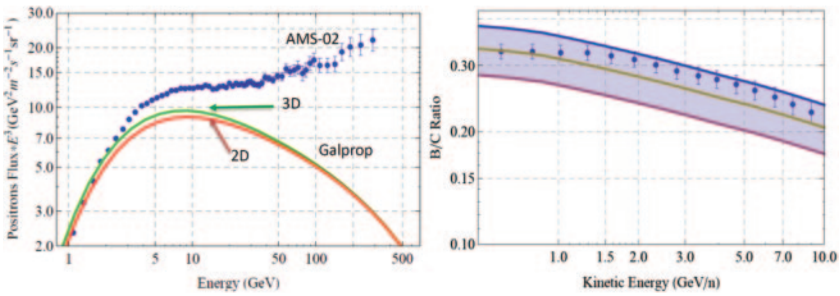

Fig. 7. – Left: secondary positrons flux simulated with GALPROP, in 2 and 3 dimensions. Right: 15% uncertainty band from nuclear physics, solar modulation and at source nuclei abundances estimation only, without the associated propagation uncertainty (this work).

(fig. 6) [8] [10]. Also the so-called Dynamical DM theories, which provide intriguing flattening of the positron fraction up to the TeV scale [11], should be taken into account.

4. – Recent results: how can we read them?

From 2014 leptons results by AMS-02 [9] [12] [13], some fundamental remarks may be derived. First of all, the positron fraction can be described by the sum of a diffusive spectrum and a single power law, with no clear sign of substructures nor anisotropy; above 250 GeV it no longer exhibits a remarkable increase with energy. Then, for what concerns the single e^+ spectrum, standard simulations with pure secondaries are not capable of reproducing positrons data (and they are not completely satisfactory also for electrons), without introducing primary DM or/and astrophysical components (fig. 7 left). An additional peculiar observation is that e^- and e^+ spectra show neat hardenings above 30 GeV, which are not reproducible within the standard paradigms: the change of slope is very similar for electrons and positrons, with an approximately conserved $\Delta\gamma$ between them [13]. Pulsars could be viable sources to describe this scenario: anyone of the well-known nearby pulsars, such as Geminga and Monogem [14] [15], can satisfactorily provide enough e^+ to reproduce AMS-02 observations and the predicted anisotropy level is, at present, consistent with limits from Fermi-LAT and AMS-02. Both the pulsar (nearby ones or altogether, from the ATNF catalogue, with $d < 3\,\text{kpc}$) and the DM scenarios can fit the observations: it is a fundamental problem to distinguish these two scenarios. If the positron excess is from pulsars, it may have a characteristic spectrum with many structures or steps, because the parameters of pulsars might differ from one to another. If such fine structures are not discovered, it would be a strong support to the DM interpretation. Other fundamental hints come from the secondaries/primaries ratios, *i.e.* the ratio between a nuclear species produced in the supernova (SNR) and one due to spallation process during propagation, such as the B/C: as anticipated at ICRC 2013 [16] (and also at CERN AMS-02 days 2015), it does not rise at high energies, up to about 700 GeV/n. The fact that SNRs hadronic reacceleration models at high energies are ill-favored is very important for CR antipron physics, beacuse it excludes the possibility of an antiprotons rise which could represent a fake signal for dark matter search: hence the $\bar{p}$ channel will be the most significant signal of new particle physics, even much clearer than the leptonic one. Finally the quite slow decreasing of the B/C ratio above 50 GeV/n seems to allow us to exclude anisotropic CR propagation models and alternative long galactic permanence models, such as Cowsik's [17]. Concluding, it must be stressed that theoretical uncertainties are significantly greater than AMS-02 experimental errors (fig. 1 left, fig. 7 right): tens of % *vs.* 1%). A joint effort of the nuclear and particle community is mandatory to fully exploit the information contained in AMS-02 data.

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