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AMS-02 measurements interpretation: implications for dark matter indirect search

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Summary. — The unprecedented precision of AMS-02 data inaugurates a new astroparticle era, where astrophysical uncertainties which affect cosmic-ray (CR) propagation can be greatly reduced, allowing to study anomalies and highlight new phenomena, to corroborate or falsify present dark-matter (DM) theories and to explore a TeV-ish dark-matter scenario. AMS-02 published data, *i.e.* positrons, electrons, protons and helium fluxes, already give us important information about CR production and propagation mechanisms, hinting at new fundamental physics. Official papers dedicated to secondaries over primaries ratios and antiprotons physics are incoming and will clarify this puzzling landscape and guide us in the dark-matter search.

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

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. These uncertainties arise mainly from four topics: 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 (left) shows the importance of the propagation model over the DM profile. The so-called MIN, MED, MAX parameter configurations produce low, medium or high CR fluxes, respectively. Past experiments were not able to fix the CR propagation physics: the parameters covered 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

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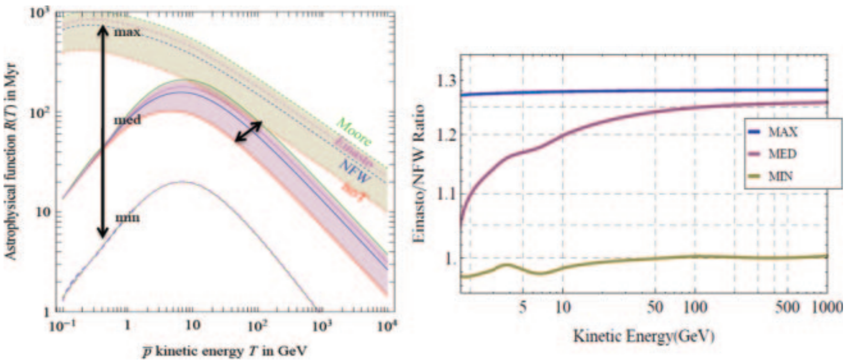

Fig. 1. – Left: Propagation uncertainties from the so-called MIN-MED-MAX sets, as a function of the dark matter profile [2]. Right: Einasto *vs.* NFW profile ratio for the three propagation sets, I computed with the *PPPC4DMID* package [3].

profile (fig. 1 right) has less macroscopic effect; however, in addition, one should consider that overdense regions (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 pHe collisions, which produce antiprotons in the ISM, are poorly known, with an accuracy that is very far from what is required in the CR physics inaugurated by AMS-02 [1]: 20%–40% uncertainties have to be considered when constraining dark-matter properties from the antiproton channel (fig. 2, left). An up-to-date study performed in [5] quantifies the total nuclear uncertainty that must be taken into account for a CR antiprotons simulation (fig. 2, right). Owing to the very partial knowledge of the fundamental cross sections for antiprotons production in the ISM, to claim a discovery, the dark-matter signal should emerge from this huge background.

Uncertainties linked to the DM itself, such as the preferred annihilation channels (fig. 3, right) and the important Next-to-Leading-Order (NLO) corrections to the tree

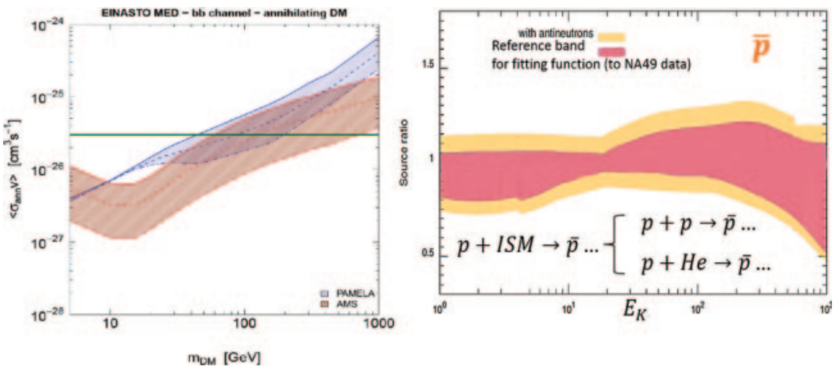

Fig. 2. – Left: DM annihilation cross section constraints from PAMELA antiprotons (blue) and AMS-02 projected data [4], with three different assumptions on nuclear uncertainties (5%, 20%, 40%). Right: Relative uncertainty for antiprotons production in the ISM according to NA49 data (red band), and including antineutrons production [5].

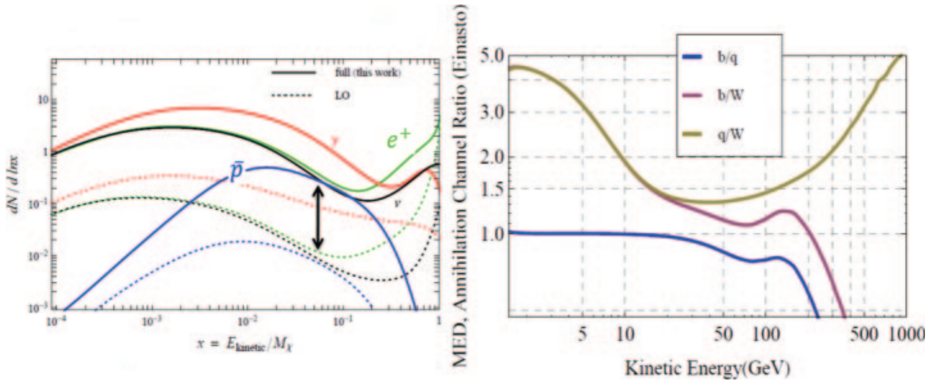

Fig. 3. – Left: CRs primary spectra from DM annihilation into light fermions (positrons, electrons, antiprotons and neutrinos channels), with the corresponding weak boson emission corrections, for a $M = 1\,\mathrm{TeV}$ DM candidate. For comparison, the spectra in the LO approximation (dotted). The difference for antiprotons is almost one order of magnitude. 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.

level DM primary flux [6] (fig. 3, left), are hard to be removed, but they are definitely lower than the fundamental uncertainties characterizing the cosmic-rays–propagation physics and the nuclear one.

2. – Multiple constraints to fix CR-propagation physics: a 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 few % accuracy up to to 2 TeV and up to iron, allowing to perform a full parameters scan with multiple precise constraints. The approach is to study and simulate CR spectra with GALPROP [7], applying a Monte Carlo Markov Chain (MCMC) method [8] to extract multi dimensional parameters constraints from the experimental data (fig. 4).

Using published protons and helium data, Boron over Carbon ratio (B/C from ICRC 2015 [9]), as well as boron, carbon and oxygen projected spectra from AMS-02 we can easily constrain, for the first time, the fundamental parameters that drive CRs propagation, defining an almost univocal scheme. Hence, after AMS-02 data it will be possible to achieve a consistent best fit that points towards a MED set: the errors associated to the fundamental propagation parameters are greatly reduced (fig. 5), with a factor 10 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. 6): this makes the DM discovery easier, faster and more reliable [10]. Once the background is removed, one can move to the characterization of the DM candidate features and understand if a DM signal could emerge from this *astrophysical noise* [1].

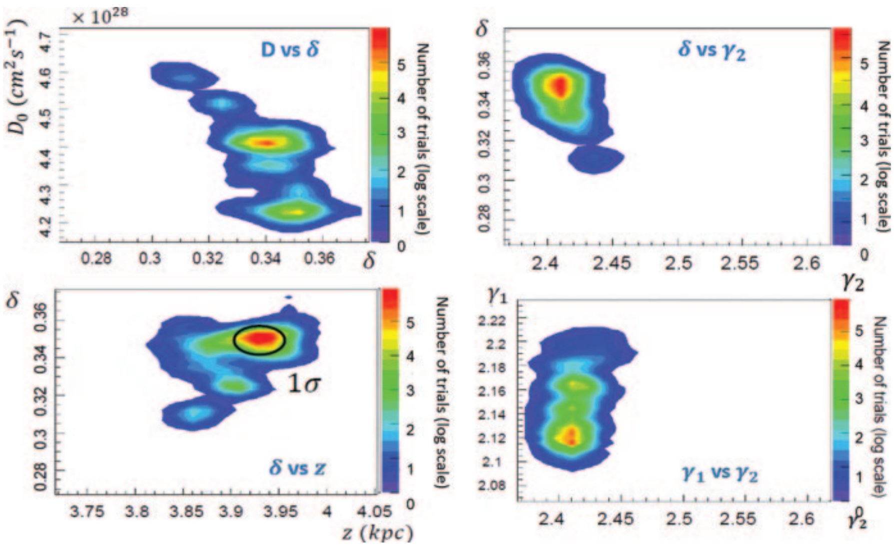

Fig. 4. – MCMC CR-propagation–parameters correlations: for the diffusion coefficient (D), the diffusion index (δ), the diffusive halo thickness (z) and injection indices ($\gamma_{1,2}$). The red regions represent the highest-probability regions for parameters values and the 1 sigma contour defines the border of the parameters degeneracy. I obtained these maps using AMS-02 data as well as projections, as constraints for the parameters scan.

	Unit	Old Range	Error (%)	New Range	Error (%)	Improvement factor $\varepsilon_{before}/\varepsilon_{after}$
z	kpc	3 − 10	54%	3.8 − 4.1	4%	14
D_0/10^28	$cm^2 s^{-1}$	0.2 − 9.7	96%	3.9 − 4.4	6%	16
$\delta_{1.2}$		0.23 − 0.85	57%	0.32 − 0.36	5%	11
V_{Alfven}	km s^{-1}	7 − 117	89%	26 − 33	11%	8
V_{0conv}	km s^{-1}	0 − 22	100%	11 − 13.5	10%	10
dV_C / dz	km s^{-1} kpc^{-1}	0 − 10	100%	8.5 − 10.5	10%	10

Fig. 5. – CR-propagation uncertainties before (left) and after (right) AMS-02, for each of the main propagation parameters; the columns show the ranges used in literature till now, along with the percent 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 improvement factors are reported.

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 explain 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, 11]. On the other hand, for antiprotons, PAMELA's experimental data show a perfect secondary spectrum with nonexotic astrophysical origins. In order to reproduce this difference between leptonic and hadronic CR results, the particle dark-matter candidate must satisfy several properties: the cross section has to

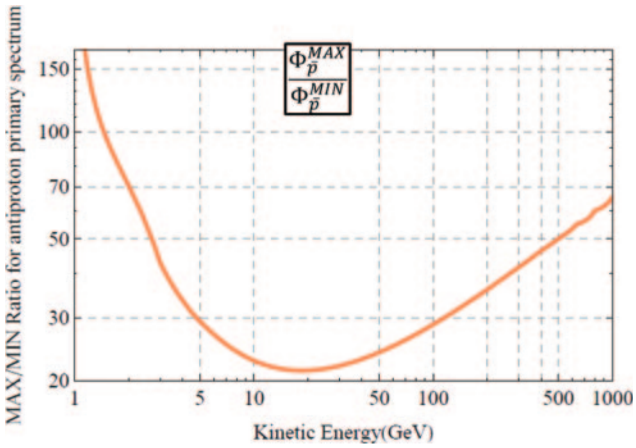

Fig. 6. – Reduction of astrophysical uncertainties after AMS-02: the MAX/MIN Dark-Matter antiproton flux ratio I estimated with the *PPPC4DMID* package represents the background for the indirect search.

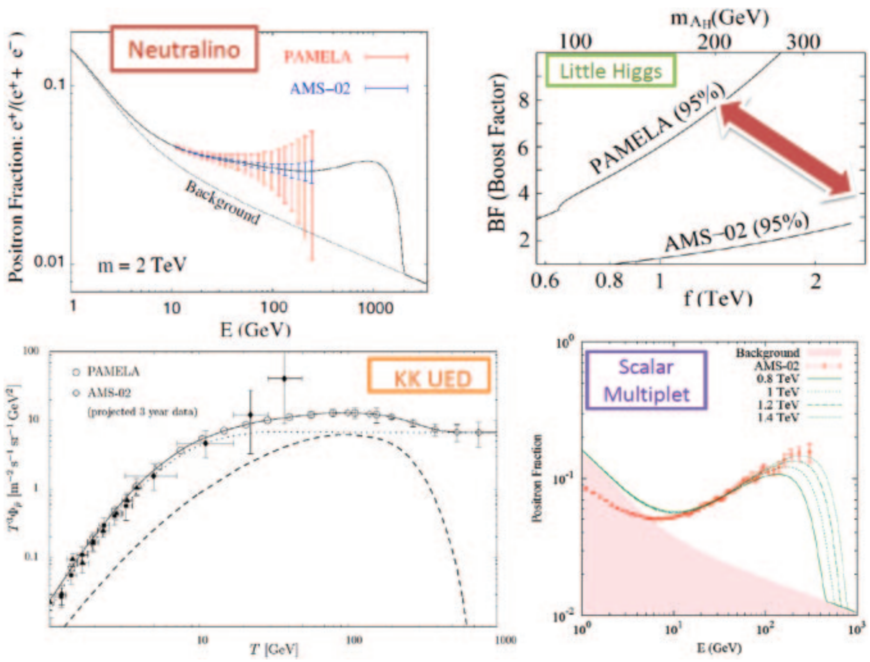

Fig. 7. – Main heavy DM candidates for space search, with simulations for AMS-02 discovery potential in positrons and antiprotons channels: Wino neutralino and Little Higgs *massive photons* (upper row), Kaluza-Klein particle and scalar multiplet particle (lower row).

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 leads to a DM which is able to annihilate into positrons and also antiprotons but at very high kinetic energies (> 200 GeV). The main and more consistent way to develop this CRs enhancement is the following: the Sommerfeld enhancement [12,10], a non-perturbative quantum effect which modifies the annihilation cross section in the regime of small relative velocity of the annihilating particles (typical of the cold DM particles in our galactic halo) and with an effectively long-range force between them. Indeed, this well-known quantum mechanical effect can occur in DM annihilations in the halo if the two annihilating particles exchange an interaction mediated by a force carrier. According to the dark-matter candidate mass, the mass of this Sommerfeld mediator lies between 1 GeV and a few hundred GeV. It is not known if the Sommerfeld boson could give non–tree-level signatures of its existence independent from DM interactions, *i.e.* if it is "dark" or not.

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. 7) [10, 13]. Also the so-called Dynamical DM theories, which provide intriguing flattening of the positron fraction up to the TeV scale [14], should be taken into account.

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

From the AMS-02 2014 leptons results [11, 15, 16], 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. 8, left). An additional peculiar observation is that e^- and e^+ spectra show clear 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 [16]. Pulsars could be viable sources to describe this scenario: nearby pulsars, such as Geminga and Monogem [17, 18], 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 $d < 3\,\mathrm{kpc}$) and the DM scenarios can fit the observations: it is a fundamental problem to distinguish these two scenarios.

Other fundamental hints come from the secondaries/primaries ratios, *i.e.* the ratio between a nuclear species produced in the supernova (SNR) and that due to the spallation process during propagation, such as the B/C: as anticipated at ICRC 2013 [19] (and also at CERN AMS-02 days 2015 and ICRC 2015 [9]), 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, because it reduces the possibility of an antiprotons rise which could represents a fake signal for dark-matter search: hence the $\bar{p}$ channel will be the most significant signal of new particle physics, even cleaner and 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 [20]. Moreover, if the antiproton/proton ratio does not show a decreasing nor an increasing behavior, it will be necessary to study the implications of the flattening in details, to determine

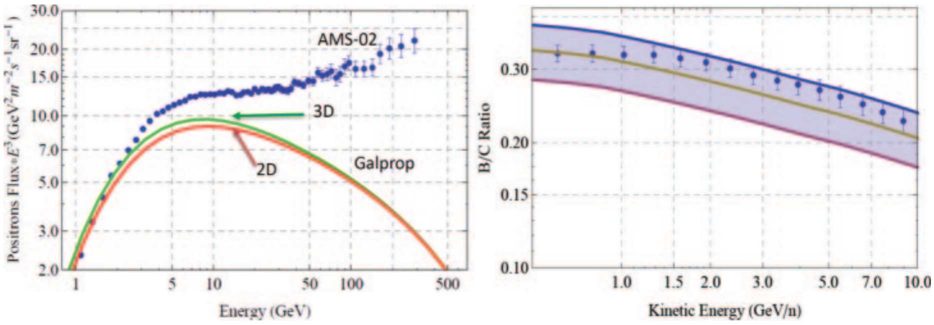

Fig. 8. – Left: Secondary positrons flux simulated with GALPROP, in 2 and 3 dimensions. Right: 15% uncertainty band from nuclear physics, solar modulation and at source nuclei abundances estimation only, without the associated propagation uncertainty (this work).

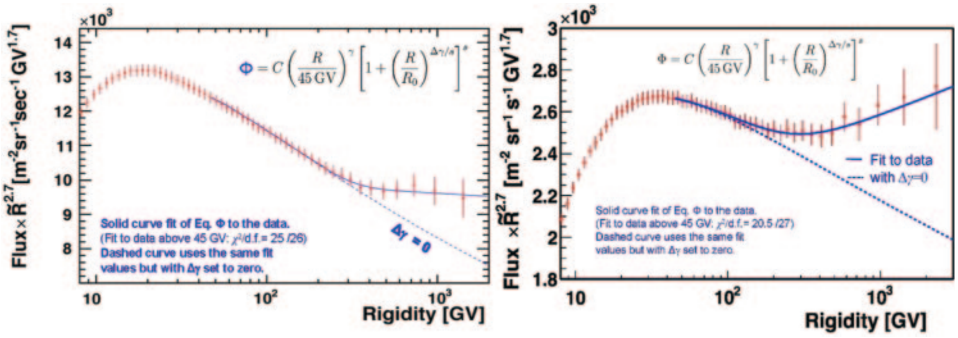

Fig. 9. – Left: AMS-02 protons fitted with a simple parametrization with a break in the power law (solid line) and without (dotted line). Right: AMS-02 Helium spectrum fitted with a simple parametrization with a break in the power law (solid line) and without (dotted line).

the compatibility with a pure secondary spectrum. There are already some hints of an overall compatibility of the observed antiprotons with the secondary expectation within GALPROP framework, which will be discussed by the author in future papers.

For what concerns the hadronic sector, peculiar features have been discovered in protons and helium spectra [21, 22] (fig. 9): a neat change of slope ($\Delta \approx 0.1$) after 300 GeV/n (which could be due to galactic diffusive effects, SNe shock phenomena or nearby high-energy sources), with a conserved difference in gamma indices between p and He of about 0.1, which seems to remain constant at all energies. This fact could suggest a source origin of this change of slope but, in additon, also a pure secondary nucleus, the lithium, preliminarly shows a rise after a few hundred GeV/n: this could change the orthodoxy of the CRs propagation models.

5. – Conclusions

AMS-02 showed an excellent capability and versatility in doing the described dark-matter researches, granting the opportunity to measure CR antiparticle-to-particle ratios with unprecedented precision and guiding the community in the interpretation of CR physics. To say something conclusive about DM indirect detection we have to face first the astrophysical uncertainties: it is possible to determine an almost univocal propagation scheme using multiple constraints from nuclei and fundamental particles spectra. Astrophysical and LHC observations suggest that DM must be very massive, a TeV-ish dark matter: some candidates are more viable than others for space searches. From simulations, the qualitative proportion between the DM mass and the positron fraction maximum is about 3(2) : 1, whereas for antiproton/proton is about 5(4) : 1; positrons and antiprotons rises and falls could be detectable by AMS-02 for $M_{DM} < 3\,\text{TeV}$. To overcome this barrier, new space AMS-like experiments will be mandatory.

The determination of the differing behavior of the leptons spectral indices *versus* energy is a new observation and provides important information on the origins and propagation mechanisms of cosmic-ray electrons and positrons, to shed light on the positron fraction conundrum.

The research for an antiproton signal related to heavy DM particles is going to be published up to 500 GeV: an antiproton anomaly would be very difficult to explain without dark matter, in particular after the incoming AMS-02 B/C ratio results.

Concluding, it must be stressed that theoretical uncertainties are far greater than AMS-02 experimental errors (fig. 1, left, fig. 2, right, fig. 8, 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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