PROCEEDINGS OF SCIENCE

Antinuclei predictions from antiproton-motivated models

Pedro De la Torre Luque,[a,*] **Martin Winkler**[a] **and Tim Linden**[a]

[a] *Stockholm University and The Oskar Klein Centre for Cosmoparticle Physics, Alba Nova, 10691 Stockholm, Sweden*
E-mail: pedro.delatorreluque@fysik.su.se, martin.winkler@fysik.su.se, linden@fysik.su.se

The measurement of antiparticles in cosmic rays (CRs) has revealed our limited knowledge on their production and propagation throughout the Galaxy. Even the first tentative antinuclei events detected by AMS-02 are generating a remarkable debate in the community. In particular, early analyses of the AMS-02 antiproton spectrum revealed the possibility of an anomaly that fit very well with the expected production from a weakly interacting massive particle (WIMP). We present here an antiproton analysis in combination with different ratios of B, Be and Li and use these models to update expectations on the flux of antinuclei with newly derived cross sections and WIMP annihilation spectra.
We find that the expected antideuteron flux is compatible with the hint of a few events detected by AMS-02 while the derived flux of antihelium is still around one order of magnitude below the current sensitivity of AMS-02. This, if the preliminary signal of antihelium events detected is confirmed, opens a window for new astrophysical production mechanisms and physics beyond the standard model.

27th European Cosmic Ray Symposium (ECRS 2022)
25-29 July 2022
Nijmegen, the Netherlands

*Speaker

https://pos.sissa.it/

PoS(ECRS)119

1. Dark matter indirect searches with CR antiparticles

The detection of CR antiparticles has long been used as a window for indirect searches of dark matter, in particular for WIMPs. However, no clear signature from decay or annihilation of a dark matter particle has been detected so far [1]. What is more, the measurements of antiparticles spectra have revealed our lack of knowledge on their astrophysical production (either produced by sources, like pulsars [2] or primordial black holes [3], or produced from the interactions of CRs with gas [4]) and their transport throughout the Galaxy. It turns out, in fact, that the indirect WIMP searches carried out are also allowing us to improve substantially our models on the propagation and production of CRs.

After the Alpha Magnetic Spectrometer (AMS-02) released the antiproton spectra in 2016 [5], a few works claimed the existence of a possible excess [6–8] at 10-20 GeV that could be well explained with the production of antiprotons from a WIMP with an annihilation rate close to the thermal relic one and a mass compatible with the Galactic Centre GeV excess observed in gamma-rays [9]. Subsequently, most efforts were dedicated to understand the different sources of systematic uncertainties involved in the prediction of the antiproton spectrum measured at Earth. While the most significant uncertainties come from the cross sections of antiproton production [10], together with those from the description of CR propagation and solar modulation [11], correlations of the systematic errors in AMS-02 data were found to be also important to evaluate the significance of the signal [12]. Although different analyses report a different significance for this anomaly, most of the recent works suggest that the excess is well explained combining all these sources of systematic uncertainties [11, 13].

Interestingly, the AMS-02 collaboration has recently reported the tentative detection of tens of antideuteron ($\overline{d}$) events and up to a dozen of events that have charges and masses that seem consistent with antihelium nuclei ($\overline{He}$), opening up again the game to analyse the compatibility of these signals with exotic and standard mechanisms of astrophysical production. Indeed, the production of $\overline{He}$ from interactions of CRs with interstellar gas is expected to be well below the AMS-02 sensitivity and completely unable to explain the detection of similar number of events of $\overline{He}$ and $\overline{d}$ nuclei. On top of this, the production of these antiparticles from a generic WIMP annihilating or decaying into Standard Model (SM) particles predict a $\overline{He}$ flux at Earth that is still far to explain the number of observed events [14]. Therefore, different exotic sources of antihelium and mechanisms to boost its production have been explored, although yet none of these models seem to be consistent with the recent observation from AMS-02 reporting that the antihelium events detected are evenly distributed in $^3\overline{He}$ and $^4\overline{He}$ (i.e. similar amounts of both isotopes of antihelium are detected).

In this work, we analyse the spectra of the light secondary CR species B, Be, Li in combination with $\overline{p}$ in a scenario where antiprotons can also be produced by annihilation of a generic WIMP into $b\bar{b}$ final states. We carry out different analyses that mainly differ on how we treat uncertainties in antiproton cross sections, finding that the propagation parameters and WIMP mass inferred roughly agree in every case (within the 1σ uncertainties in their determination). Then, we revisit the and update the existent predictions of the light antinuclei spectra ($^3\overline{He}$ and $\overline{d}$), for which we have computed new cross sections for both, their secondary and dark matter production. These cross sections account for the decays of antihyperons (essentially the $\overline{\Lambda_b}$ particle) and trition ($\overline{T}$).

2. Antiproton combined analyses

The full system of coupled propagation equations, assuming cylindrical symmetry of the galactic magnetic field and gas distribution, for all the isotopes involved in the CR network from $Z = 14$ (Silicon) to $^3\overline{He}$ is solved numerically with a customised version of the DRAGON2 code [15, 16] [1], that will be publicly available at https://github.com/tospines/Customised-DRAGON2_Antinuclei. Here, we use a diffusion-reacceleration setup, where the spatial diffusion coefficient is parameterised as:

$$D(R) = D_0 \beta^{\eta} \frac{(R/R_0)^{\delta}}{\left[1 + (R/R_b)^{\Delta\delta/s}\right]^{s}}, \quad (1)$$

with $R_0 = 4$ GV. Here the parameters δ, η and D_0 are determined by a fit of data, as explained below, while the rest of parameters are set to $\Delta\delta = 0.14 \pm 0.03$, $R_b = 312 \pm 31$ GV and $s = 0.040 \pm 0.0015$ [17]. The halo height, H, and the Alfvèn speed, V_A, are also determined from fit to the data. For the rest of ingredients involved in the computation of the fluxes of CRs, we employ identical setup as in Ref. [18], where we refer the reader for details.

In order to determine the propagation parameters δ, η, D_0, H and V_A we employ a Markov chain Monte Carlo (MCMC) analysis that has been presented in our past works [13, 18, 19], which, in this case, consists of a combined fit to AMS-02 data of the spectra of the main secondary CR nuclei (B, Be and Li) along with the $\bar{p}$ spectra. The fitting procedure includes the injection parameters of the primary CRs included in our simulation set-up (e$^-$, ^{1}H, ^{4}He, ^{12}C, ^{14}N, ^{16}O, ^{20}Ne, ^{24}Mg and ^{28}Si). Concretely, we include in the fit the B/C, B/O, Be/C, Be/O, $\bar{p}$/p, $\bar{p}/e^+$ and $\bar{p}/e^-$ flux ratios together with the ^{10}Be/Be and ^{10}Be/^{9}Be ratios, as well as the secondary-to-secondary flux ratios among B, Be and Li. The model for the positron flux is obtained taking the parameterisation given by the AMS-02 collaboration in Ref. [20], since the positron flux is subject to many uncertainties that are beyond the scope of this study.

This procedure incorporates a nuisance parameter for each of the secondary CR particles involved ($\mathcal{S}_B$, $\mathcal{S}_{Be}$, $\mathcal{S}_{Li}$ and $\mathcal{S}_{Ap}$) that allow us to modify the normalization of the original cross sections. We define the prior distributions of all propagation parameters as a uniform distribution, while those from the nuisance parameters are defined to follow a Gaussian whose variance is that of the cross sections experimental data, and which, essentially, acts as a penalty factor preventing from having large variations of the original cross sections normalization. Then, we also include the contribution of a WIMP annihilating into $b\bar{b}$ final states producing $\bar{p}$, e^+ and e^-, as explained in Ref. [18]. This allows us to infer the WIMP mass and the annihilation rate ($\langle\sigma v\rangle$) along with the rest of transport parameters and nuisance factors.

The results for this "Standard" or "Canonical" analysis described above can be seen in Fig. 1, where we show the $\bar{p}/p$ and $\bar{p}/e^+$ spectra evaluated with best-fit [2] parameters inferred. We obtain a WIMP mass of $M_{WIMP} = 130.3^{+18.}_{-16.43}$ GeV and annihilation rate of $\langle\sigma v\rangle = 2.03 \pm 0.64 \cdot 10^{-26}$ cm^3/s and a (local) significance of $\sim 1.1\sigma$ with respect to the hypothesis with not dark matter production of antiprotons, similar to what was found in other recent analyses [12, 21, 22]. As no significant excess is found, we derived bounds for the WIMP masses in the GeV range, which are shown in

[1] The original code is available at https://github.com/cosmicrays/DRAGON2-Beta_version

[2] Here, we refer to the best-fit parameters as the median obtained in the probability distribution function obtained in the MCMC procedure for each parameter

PoS(ECRS)119

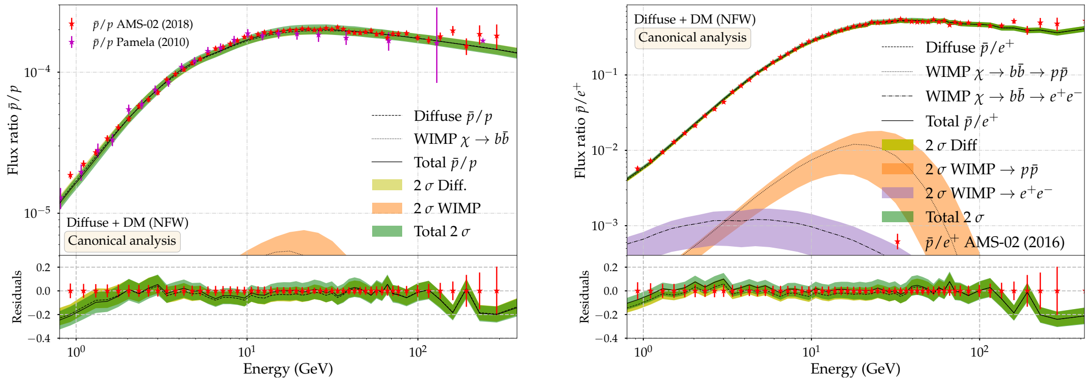

Figure 1: $\bar{p}$ spectra evaluated in the scenario where the contribution from WIMP annihilation into $b\bar{b}$ final states is included, with the transport parameters obtained in our Canonical analysis. Left: $\bar{p}/p$ spectrum. Right: $\bar{p}/e^+$ spectrum. The statistical uncertainty in the determination of the propagation parameters (not including modulation uncertainties) is shown as a yellow band and the uncertainty related to the determination of the WIMP properties (mass and annihilation rate) is shown as an orange band. In the right panel, the production of $\bar{p}_{DM}/e^+$ from a WIMP and the fraction of positrons produced from the WIMP particle (e^+_{DM}/e^+) are shown.

Fig. 2. As it can be seen from the figure, these results allow us to rule out the thermal relic cross sections for WIMP masses below $\sim$ 60 GeV.

We also carried out other two similar analyses finding similar conclusions: The analysis with "No cross sections constraints" where the priors for the scale factors follow a uniform distribution (in this scenario, the scale factors can vary freely) and the analysis where we make the variance of the Gaussian prior for the antiproton cross sections be similar to the one associated to the B cross sections, what causes that same variations of the antiproton cross sections are penalised in the same way as the other secondary CRs. This would represent the case in which our antiproton cross sections are constrained more tightly and, thus, we call this the analysis with "Full cross sections constraints". The probability distribution functions (PDFs) of the inferred parameters in these analyses are shown in Figure 3, where we overlap the PDFs obtained in each analysis.

3. Predicted antinuclei fluxes

In this section, we report the updated expectations for the fluxes of $\overline{d}$ and $^3\overline{He}$ at Earth. The computation of the spectra of these particles has been implemented in a new customised version of the `DRAGON2` code, that is intended to be publicly released at `https://github.com/tospines/Customised-DRAGON-versions/tree/main/Custom_DRAGON2_v2-Antinuclei`. In these calculations we are considering the production of these antinuclei from p-p, p-He, He-p and He-He collisions, their tertiary contribution and the contribution from a generic WIMP annihilating into $b\bar{b}$ final states. The cross sections of these particles are computed using the analytic coalescence model (see e.g. Ref. [24]), which approximates the multi-antinucleon spectra as the product of single-antinucleon spectra (ignoring correlations in the antinucleon production). The coalescence factor, which accounts for the phase space volume in which antinucleons coalesce, is defined as a function of the coalescence momentum, p_c, that we fix to 215 MeV for $\overline{d}$ and 239 MeV for $^3\overline{He}$ [25].

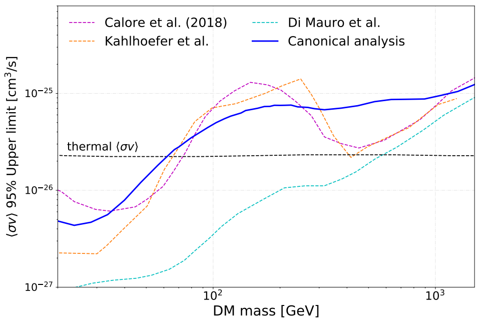

Figure 2: Upper limits at 95% confidence level on $\langle \sigma v \rangle$ derived from our Canonical analysis, compared with those obtained by Refs. [21–23] for the analysis using the same $\bar{p}$ data-set (2018).

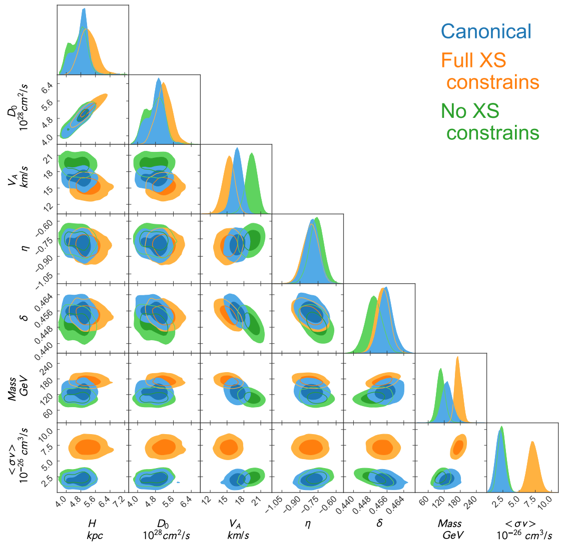

Figure 3: Probability distributions of the considered propagation parameters obtained for the analyses reported in this work.

For this, we use the cross sections of antiproton production described in Ref. [26] and take into account the isospin asymmetry for the production of antineutrons and antiprotons. The propagation parameters used to make these calculations are those obtained in our combined analyses of the $\bar{p}$, B, Be and Li spectra, as well as for the WIMP mass and annihilation rate.

The left panel of Figure 4 shows the predicted $\overline{d}$ spectrum produced from CR collisions on the interstellar gas (secondary $\overline{d}$), the spectrum produced from annihilation from a generic WIMP and the tertiary component. As we observe in the figure, the peak at above 20 GeV/n, produced from $\bar{\Lambda}_b$ particles formed from the annihilation of the WIMP particle could be hardly visible in the total spectrum. These spectra are compared to the upper-limits from the Balloon-borne Experiment with a Superconducting Spectrometer (BESS) [27], the sensitivity regions of GAPS [28] (for the expected three flights of 35 days) and AMS-02 (15 years of operation) and the ALADInO [29] forecasted sensitivity. As we see, the expected WIMP flux would be possibly detected in the next years, although we have to remind the reader that these predictions can be uncertain by even one order of magnitude, mainly because of our limited knowledge on the coalescence process. We also remark that even the detection of antideuterons produced from CR interactions seems to be achievable in a mid-to-short term. In addition, we notice that the detection of these antinuclei by the TOF detector would be a very strong indication of new physics, given that the standard mechanism of secondary production of $\overline{d}$ is unable to produce enough events at the energies covered by this detector.

In the right panel of Figure 4 we show the predicted $^3\overline{He}$ spectrum compared to AMS-02 (15 years of operation) and the forecasted sensitivity for the ALADInO experiment. In this case, the peak produced by $\bar{\Lambda}_b$ particles would manifest much more clearly. However, the expected flux much below the estimated sensitivity of AMS-02, which challenges the "Standard" scenario that we are testing here if these few tentative events detected are confirmed. One of the most promising

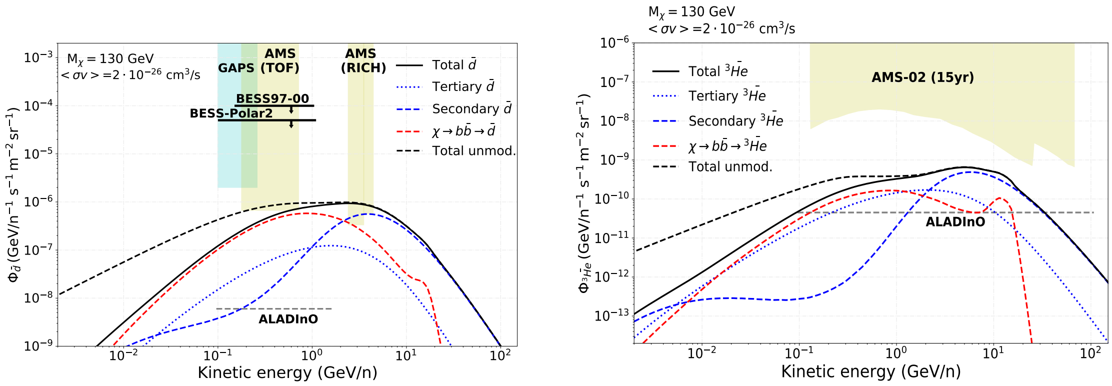

Figure 4: Left panel: Predicted $\overline{d}$ spectrum produced from CR collisions on the interstellar gas (secondary $\overline{d}$), from annihilation from a generic WIMP and the tertiary component compared to the upper-limits obtained by the BESS experiment, the sensitivity region of GAPS (three flights of 35 days) and AMS-02 (15 years) and the ALADInO forecasted sensitivity. **Right panel:** Similar to what is shown in the left panel but for the $^3\bar{He}$ spectrum compared to AMS-02 (15 years) and the future the ALADInO experiment.

explanations for this detection is a significantly larger production of $\bar{\Lambda}_b$ particles [25], that could be tested in the detectors at LHC.

4. Conclusions

While the excitation about the possible antiproton excess still remains, most of the new analyses are revealing that the discrepancy is not significant enough and that the astrophysical uncertainties are still high to reveal clear signatures of dark matter. In the analyses presented here, we find that antiprotons are compatible with the rest of secondary CRs and obtain a maximum significance of $\sim 1\sigma$ for a WIMP of mass between 110 and 170 GeV and annihilation rate around the thermal relic one. We notice that these WIMP parameters are in tension with those from the Galactic Center Excess. In addition, we derived dark matter bounds that seem compatible with other recent analyses of the 2018 antiproton data-set. However, we it should be noticed that neglecting the spatial dependence of the diffusion coefficient could significantly change these bounds because it would affect both, the spectra of particles produced by CR interactions and the dark matter signal at Earth.

Then, we have explored the predicted spectra of the antinuclei species $\overline{d}$ and $\overline{He}$ as an exciting option to look for new physics from CR measurements. Excitingly, other astrophysical excesses that have been correlated with dark matter (e.g., GCE, DAMA, etc.), predict an antinuclei flux that is within the sensitivity range reached by detectors such as AMS-02 and GAPS in the coming years. From our evaluations, we find that the expected antideuteron flux produced from annihilation of the WIMP found in our analysis could be detectable by AMS-02 and even GAPS in the region from $\sim 0.2 - 10$ GeV. Remarkably, even the production of secondary antideuterons would be detectable at GeV energies. Therefore, we consider that both sources of production of antideuterons are compatible with the hint of a few events detected by AMS-02. In contrast, the derived flux of antihelium is still around one order of magnitude below the current sensitivity of AMS-02. We remark here that the unique feature produced in the antihelium spectrum by the decay of the $\bar{\Lambda}_b$

particle could be fundamental for future dark matter searches. If the preliminary signal of a few antihelium events detected is confirmed and the analysis techniques of AMS-02 shows to be robust enough we could really be witnessing the first signal of physics beyond the standard model, although new astrophysical production mechanisms could also be at play.

References

[1] R. K. Leane *et al.*, "Snowmass2021 cosmic frontier white paper: Puzzling excesses in dark matter searches and how to resolve them," (2022).

[2] D. Hooper, P. Blasi, and P. D. Serpico, Journal of Cosmology and Astroparticle Physics **2009**, 025 (2009).

[3] A. Barrau, G. Boudoul, F. Donato, D. Maurin, P. Salati, and R. Taillet, Astronomy and Astrophysics **388** (2001), 10.1051/0004-6361:20020313.

[4] P. d. l. T. Luque, "Cosmic-ray propagation and production of secondary particles in the galaxy," (2022).

[5] M. Aguilar *et al.* (AMS Collaboration), Phys. Rev. Lett. **117**, 091103 (2016).

[6] A. Cuoco, M. Krämer, and M. Korsmeier, Phys. Rev. Lett. **118**, 191102 (2017).

[7] A. Reinert and M. W. Winkler, JCAP **01**, 055 (2018), arXiv:1712.00002 [astro-ph.HE] .

[8] M.-Y. Cui, Q. Yuan, Y.-L. S. Tsai, and Y.-Z. Fan, Phys. Rev. Lett. **118**, 191101 (2017).

[9] M. Ackermann *et al.*, The Astrophysical Journal **840**, 43 (2017).

[10] M. Korsmeier, F. Donato, and M. Di Mauro, Phys. Rev. D **97**, 103019 (2018).

[11] M. Boudaud, Y. Génolini, L. Derome, J. Lavalle, D. Maurin, P. Salati, and P. D. Serpico, Phys. Rev. Research **2**, 023022 (2020).

[12] J. Heisig, M. Korsmeier, and M. W. Winkler, Phys. Rev. Research **2**, 043017 (2020).

[13] P. De la Torre Luque, F. Gargano, F. Loparco, M. N. Mazziotta, and D. Serini, J. Phys. Conf. Ser. **1690**, 012010 (2020).

[14] E. Carlson, A. Coogan, T. Linden, S. Profumo, A. Ibarra, and S. Wild, Phys. Rev. D **89**, 076005 (2014), arXiv:1401.2461 [hep-ph] .

[15] C. Evoli, D. Gaggero, A. Vittino, G. Di Bernardo, M. Di Mauro, A. Ligorini, P. Ullio, and D. Grasso, JCAP **02**, 015 (2017), arXiv:1607.07886 [astro-ph.HE] .

[16] C. Evoli, D. Gaggero, A. Vittino, M. Di Mauro, D. Grasso, and M. N. Mazziotta, JCAP **07**, 006 (2018), arXiv:1711.09616 [astro-ph.HE] .

[17] Y. Génolini *et al.*, Phys. Rev. Lett. **119**, 241101 (2017), arXiv:1706.09812 [astro-ph.HE] .

[18] P. D. L. T. Luque, JCAP **11**, 018 (2021), arXiv:2107.06863 [astro-ph.HE] .

[19] P. D. L. T. Luque, M. N. Mazziotta, F. Loparco, F. Gargano, and D. Serini, JCAP **07**, 010 (2021), arXiv:2102.13238 [astro-ph.HE] .

[20] M. Aguilar *et al.* (AMS Collaboration), Phys. Rev. Lett. **122**, 041102 (2019).

[21] M. Di Mauro and M. W. Winkler, Phys. Rev. D **103**, 123005 (2021).

[22] F. Calore, M. Cirelli, L. Derome, Y. Genolini, D. Maurin, P. Salati, and P. D. Serpico, SciPost Phys. **12**, 163 (2022).

[23] F. Kahlhoefer, M. Korsmeier, M. Krämer, S. Manconi, and K. Nippel, JCAP **2021**, 037 (2021), arXiv:2107.12395 [astro-ph.HE] .

[24] P. Chardonnet, J. Orloff, and P. Salati, Phys.Lett.B. **409**, 313 (1997), arXiv:astro-ph/9705110 .

[25] M. Winkler and T. Linden, Phys. Rev. Lett. **126**, 101101 (2021), arXiv:2006.16251 [hep-ph] .

[26] M. W. Winkler, JCAP **02**, 048 (2017), arXiv:1701.04866 [hep-ph] .

[27] K. Abe *et al.*, Phys. Rev. Lett. **108**, 131301 (2012).

[28] T. Aramaki, C. Hailey, S. Boggs, P. von Doetinchem, H. Fuke, S. Mognet, R. Ong, K. Perez, and J. Zweerink, Astroparticle Physics **74**, 6 (2016).

[29] R. Battiston, in *43rd COSPAR Scientific Assembly. Held 28 January - 4 February*, Vol. 43 (2021) p. 1369.

PoS(ECRS)119