Pedro de la Torre Luque
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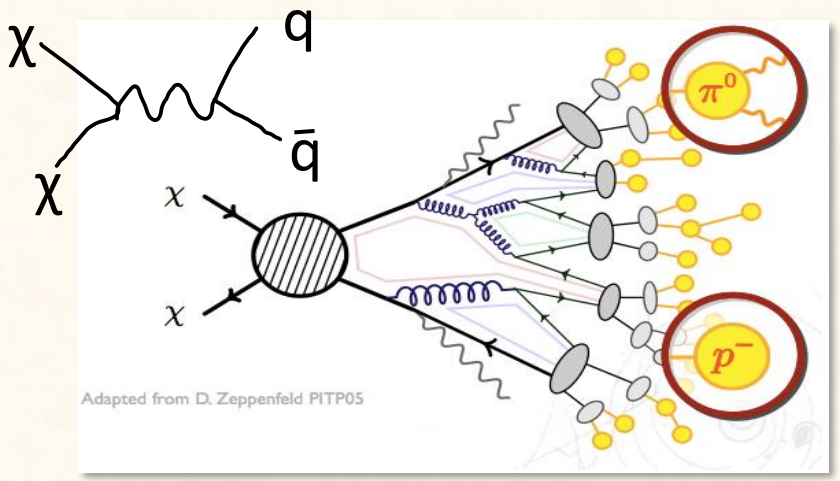
CR anti-nuclei predictions and their detectability in the next years



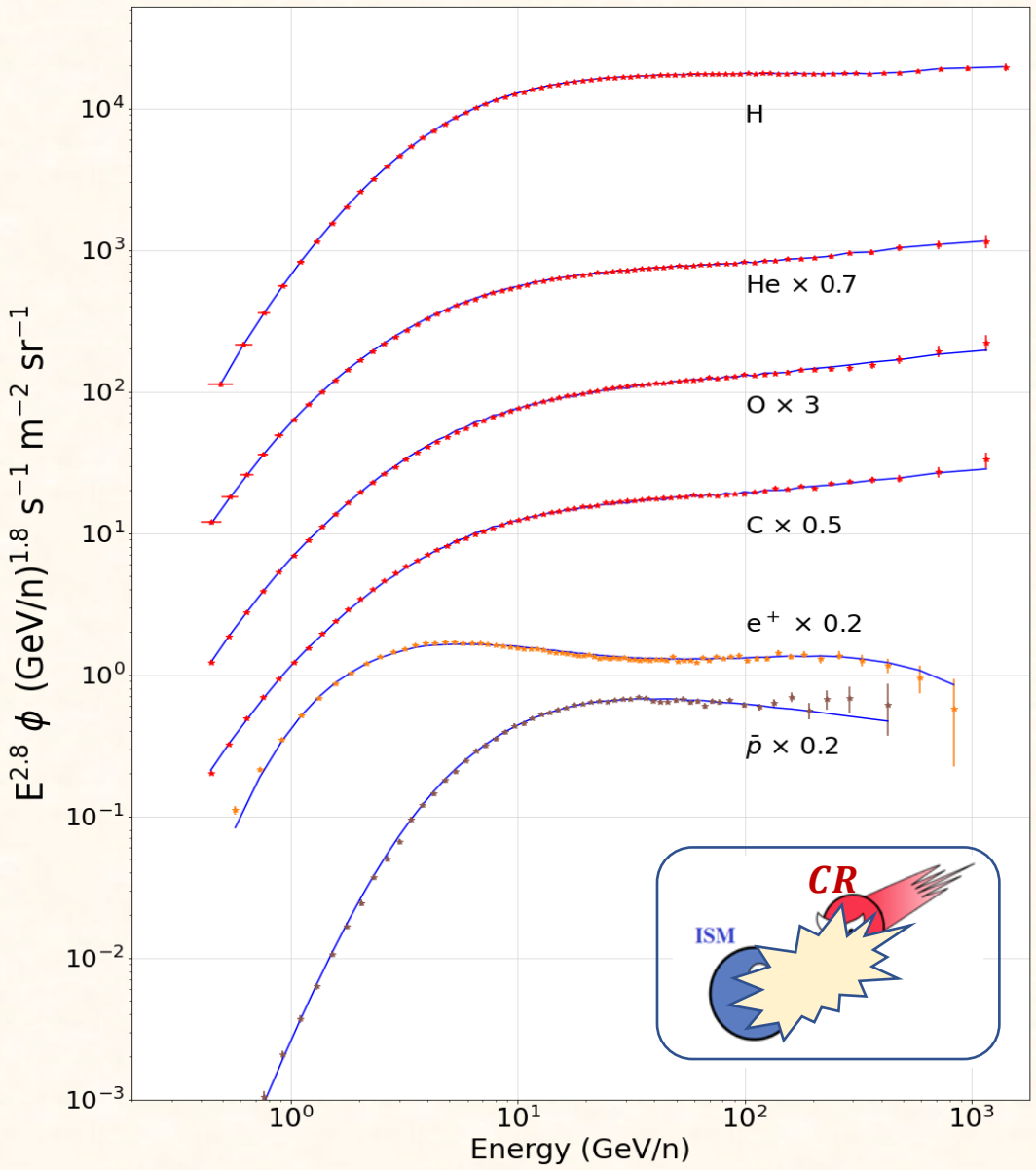
Potential of antiparticles to reveal the existence of BSM physics

High precision data for the fluxes of CR nuclei allow us to accurately model the production of CR antiparticles and uncertainties related.

The antiproton spectrum allows us to strongly constrain the existence of BSM physics due to the expected low production and uncertainty in their modelling.

Specially, well motivated **WIMPs** ($M_\chi \sim O(100\ GeV)$) are expected to leave imprints in the GeV energy region.

Flux of CR nuclei and antiparticles (data from AMS-02)



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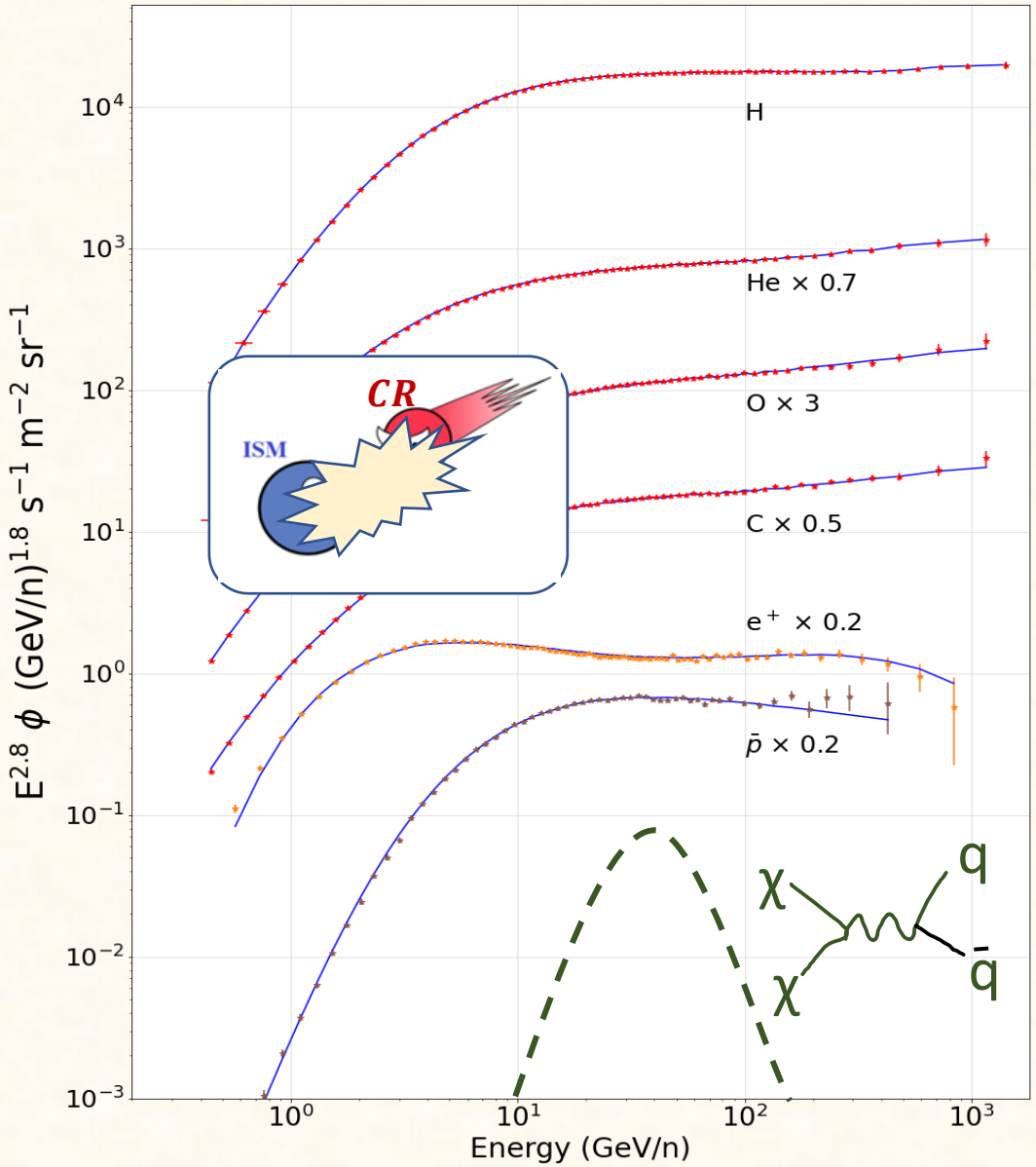
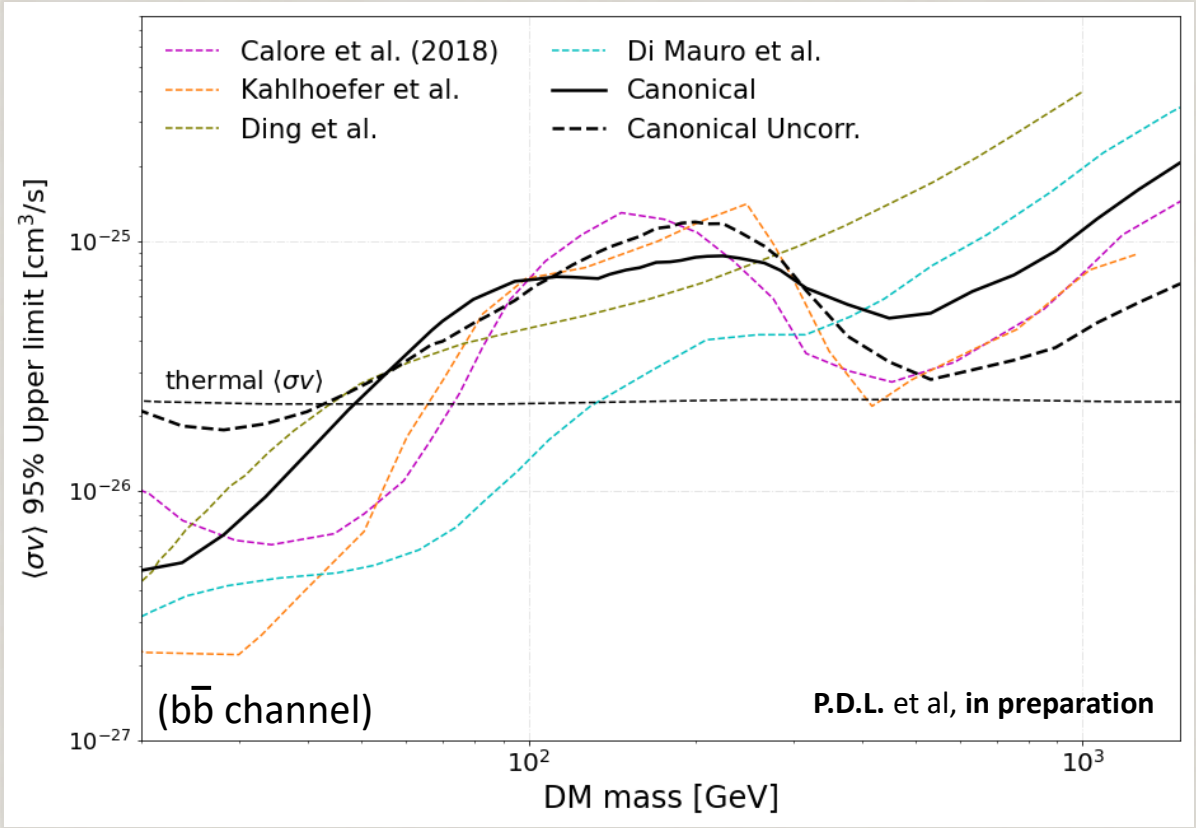
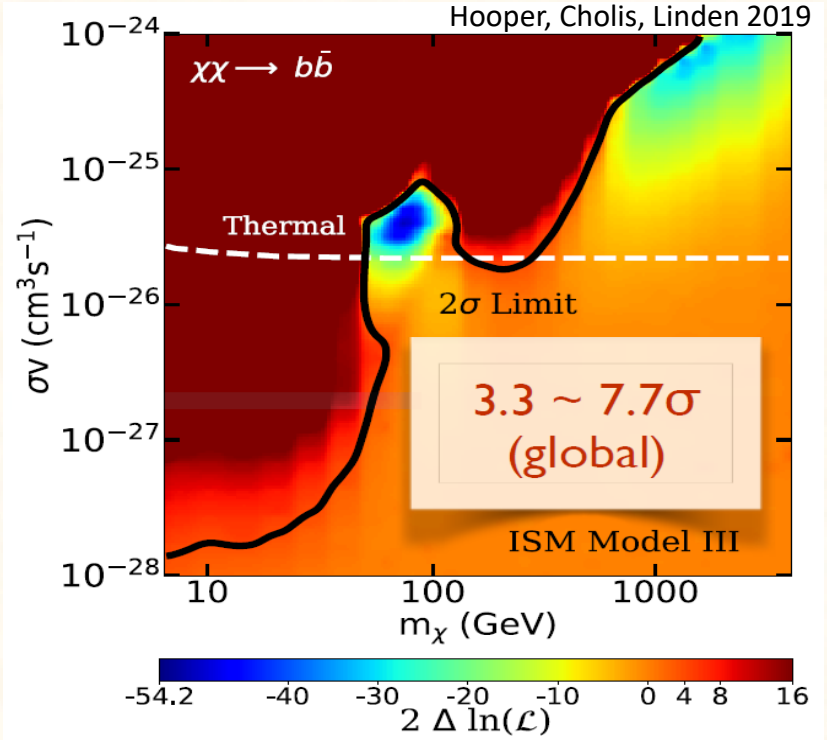


Dark matter bounds from antiproton analyses



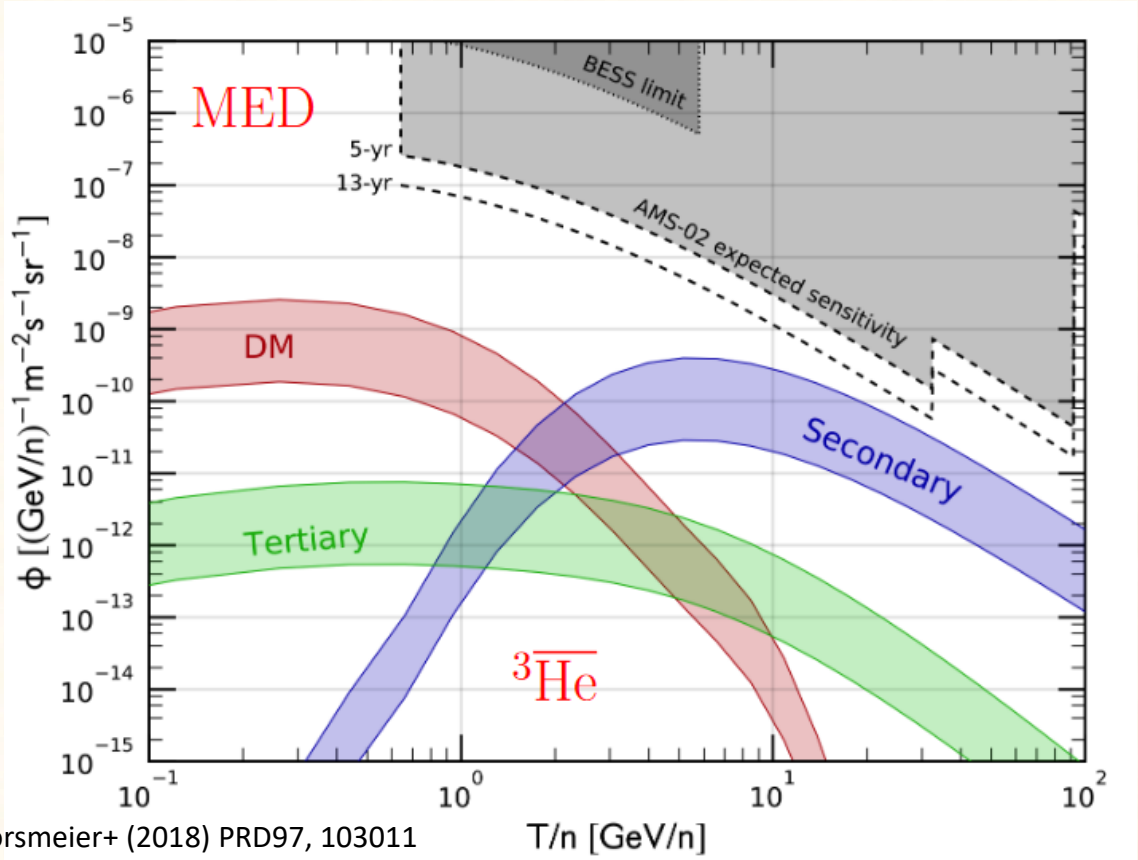


No excess found in the latest $\overline{p}$ analyses

Detailed DM searches found different sources of uncertainties difficult to avoid in our current studies: Cross sections, AMS-02 correlated errors, diffusion process …

Anti-nuclei as the dark matter smoking gun

The window to prove (or disprove) many possible astrophysical excesses

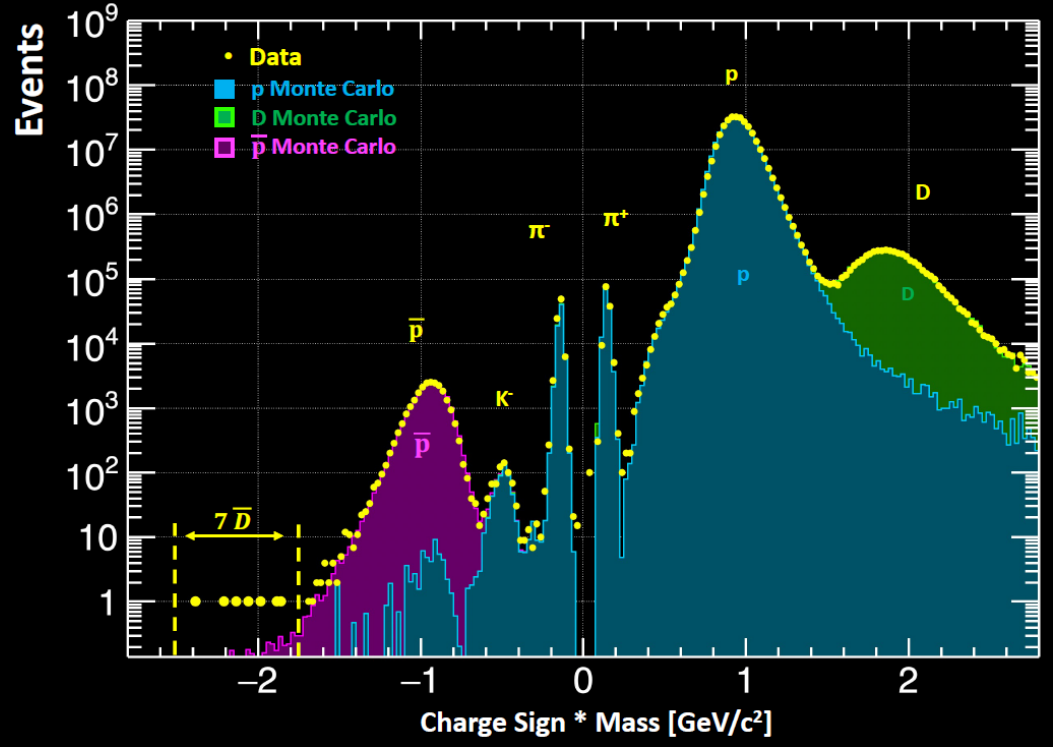


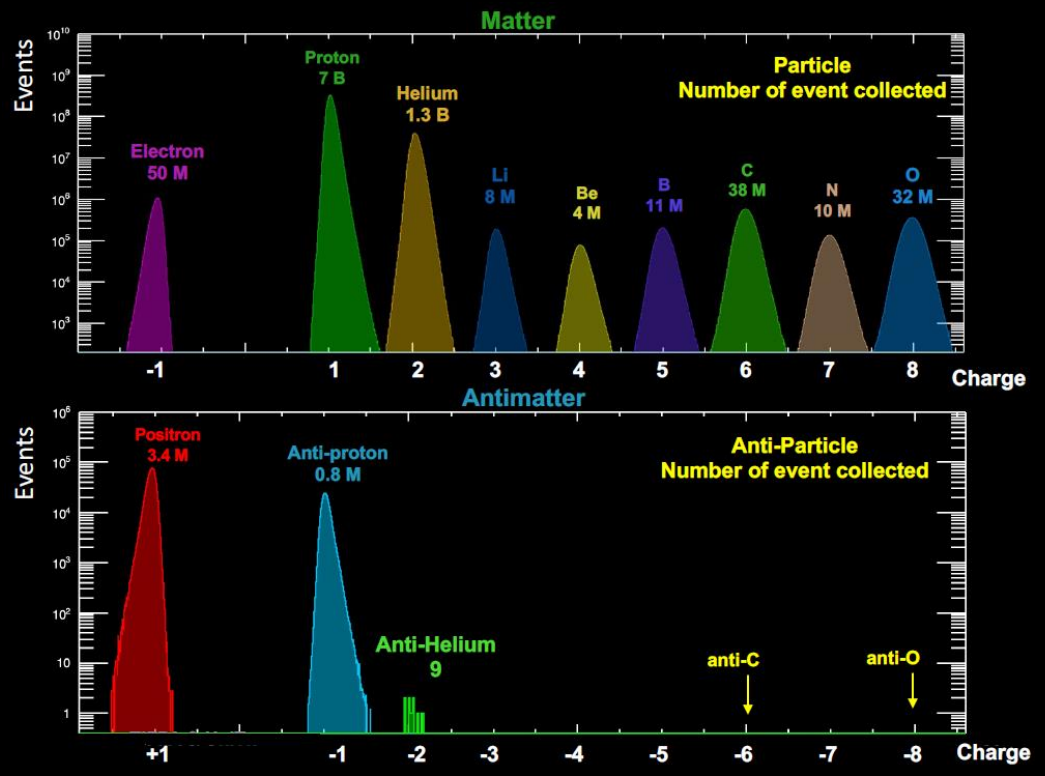
M. Korsmeier+ (2018) PRD97, 103011

For kinematical reasons, the production of anti-nuclei from CR interactions is not important at energies below the GeV, offering a **clear way to spot the production of anti-nuclei from dark matter** (at least for masses below ~hundreds of GeV)

Secondary anti-nuclei produced from homologous interactions as for $\overline{p}$, but highly suppressed (due to coalescence)!

ANTI-NUCLEI: AMS-02 mass-charge spectra





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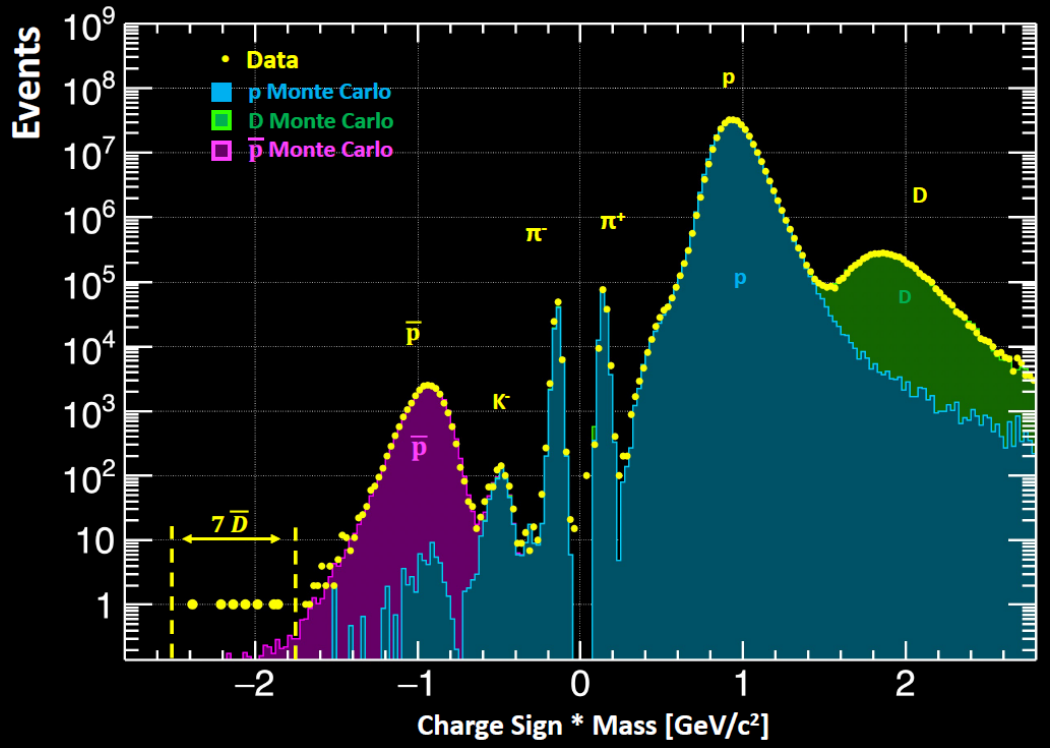
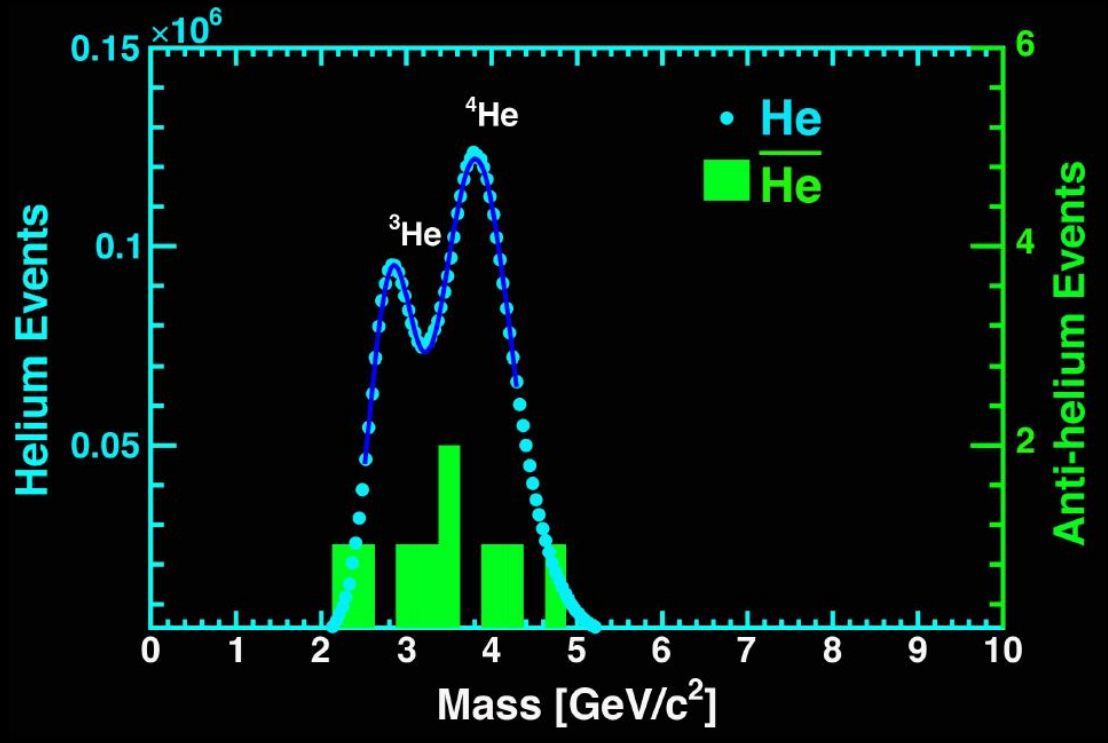
ANTI-NUCLEI: AMS-02 mass-charge spectra





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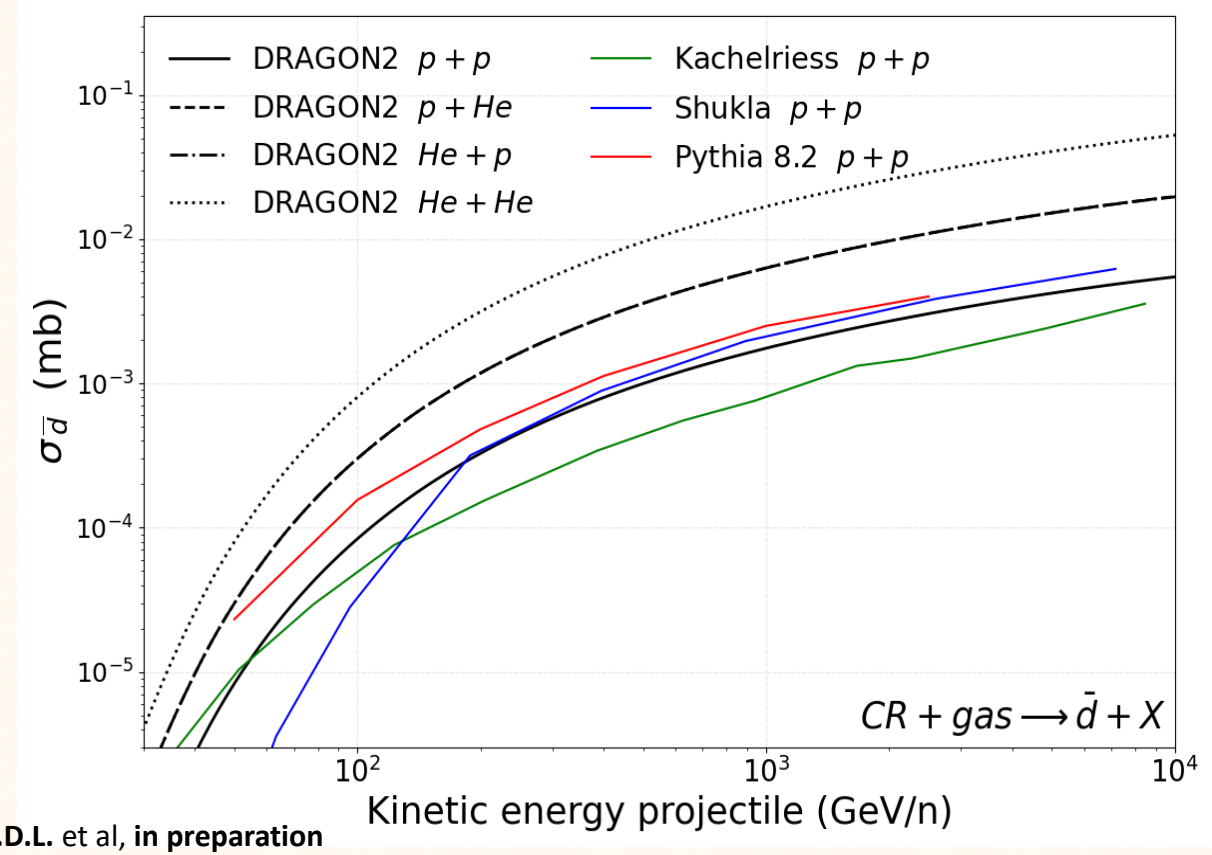
Propagation setup

Propagation code: github.com/tospines/Customised-DRAGON-versions/Custom_DRAGON2_v2-Antinuclei/

❖ Implementation of anti-nuclei dark matter and secondary production in DRAGON2

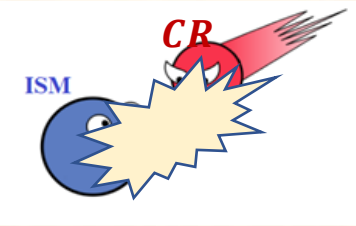
- Cross sections derived from analytical coalescence model. Using fits of antiproton (antineutron) production from Winkler, JCAP 02, 048 (2017)
- DM spectrum at production derived from Pythia 8.2 simulating a neutral colorless resonance.
  Space and momentum (p_c) conditions for coalescence. Also including production from anti-hyperons
- Inelastic cross sections and tertiary production computed extrapolating antiproton parametrizations



P.D.L. et al, **in preparation**

Astrophysical production

$CR + ISM \rightarrow \bar{He}, \bar{d}$

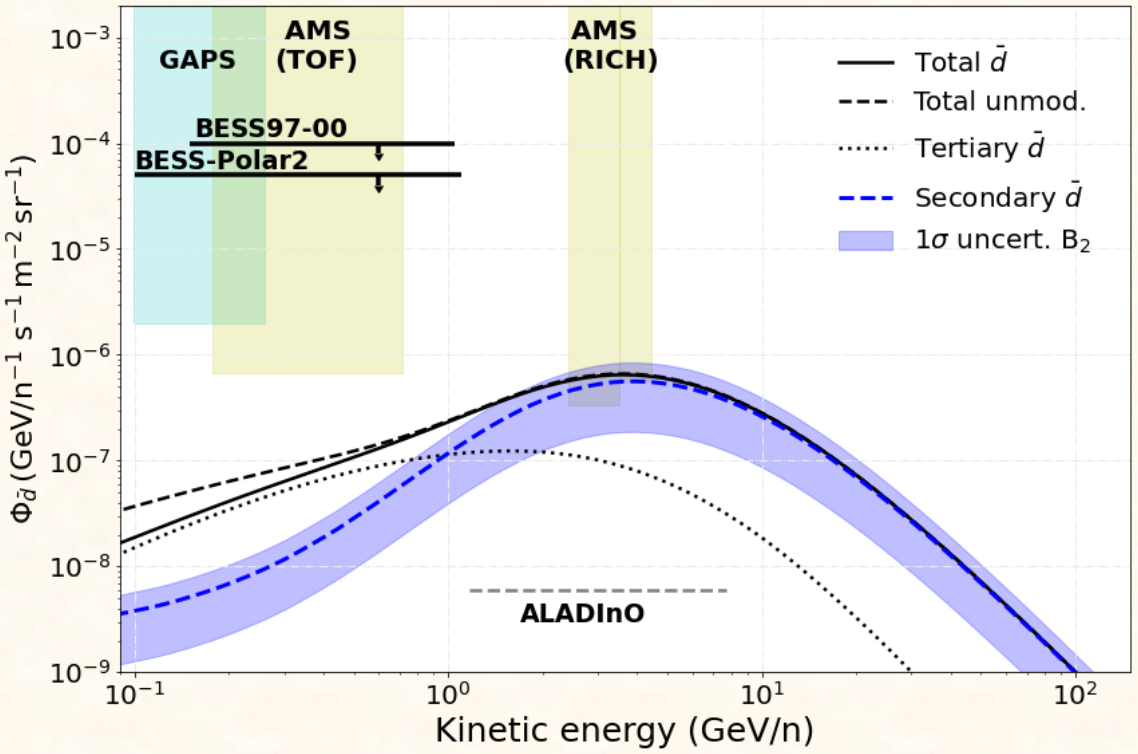


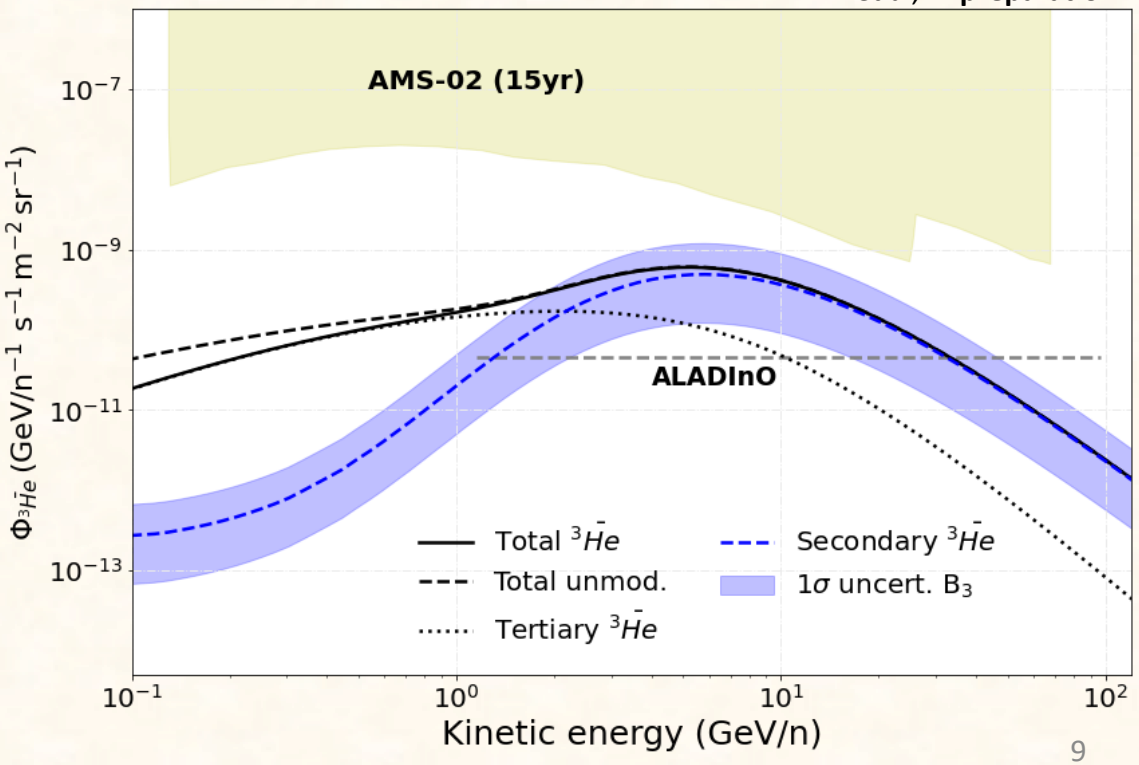
Can we explain the AMS-02 measurements without invoking any exotic source?

Main uncertainty is the coalescence parameter, the rest of uncertainties are under ~10%

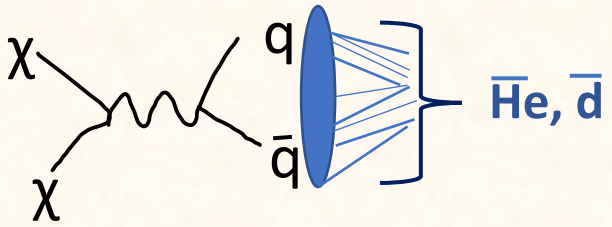
We expect to have measurements of the $\bar{d}$ flux in the next years!! But nothing about $\bar{He}$ till ALADInO or AMS-100 (foreseen to 2039)

P.D.L. et al, **in preparation**



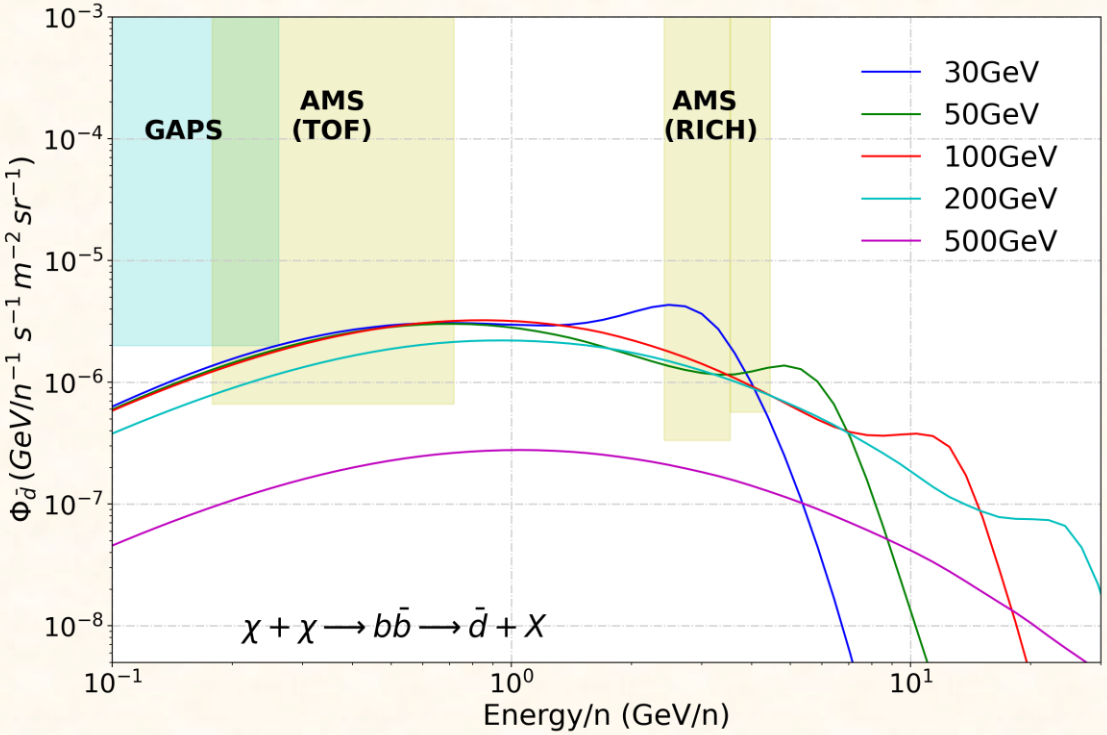


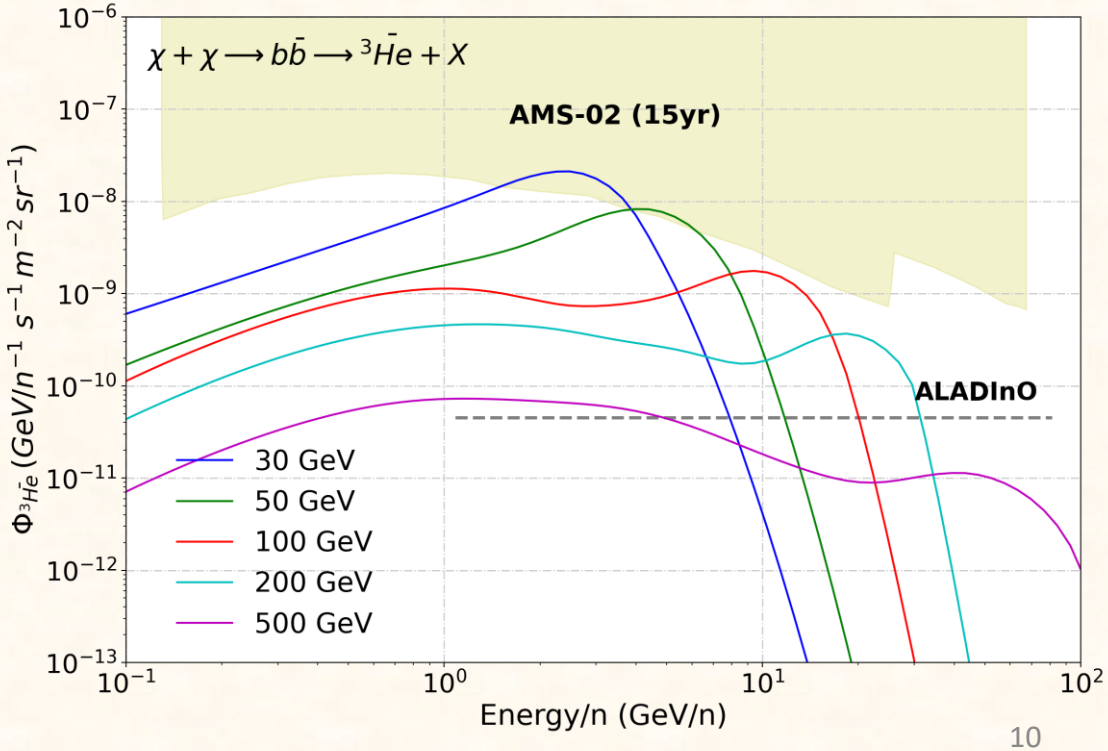
DM production: Upper Limits



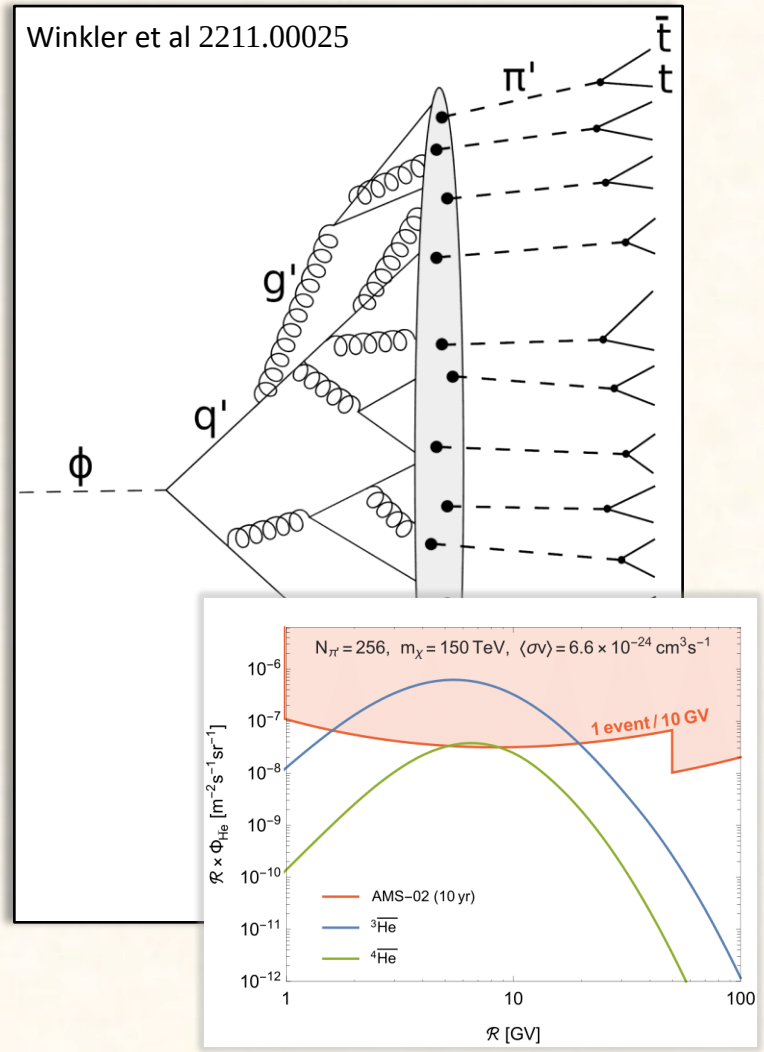
Maximal antinuclei flux allowed from our antiproton bounds. Uncertainties in the coalescence momentum can hardly explain the detection of $O(1)$ antihelium-3 event by AMS-02, but are **unable to explain any detection of antihelium-4 by AMS-02**…

P.D.L. et al, **in preparation**





How to explain the AMS-02 $\overline{\text{He}}$ detection?



Our standard predictions do not explain total He events and foreseen a ratio $\overline{\text{He}}$-4/$\overline{\text{He}}$-3 of ~ 1/1000

Two main models proposed so far:

Galactic anti-clouds (Poulin et al. 1808.08961) (see also 2304.04623)

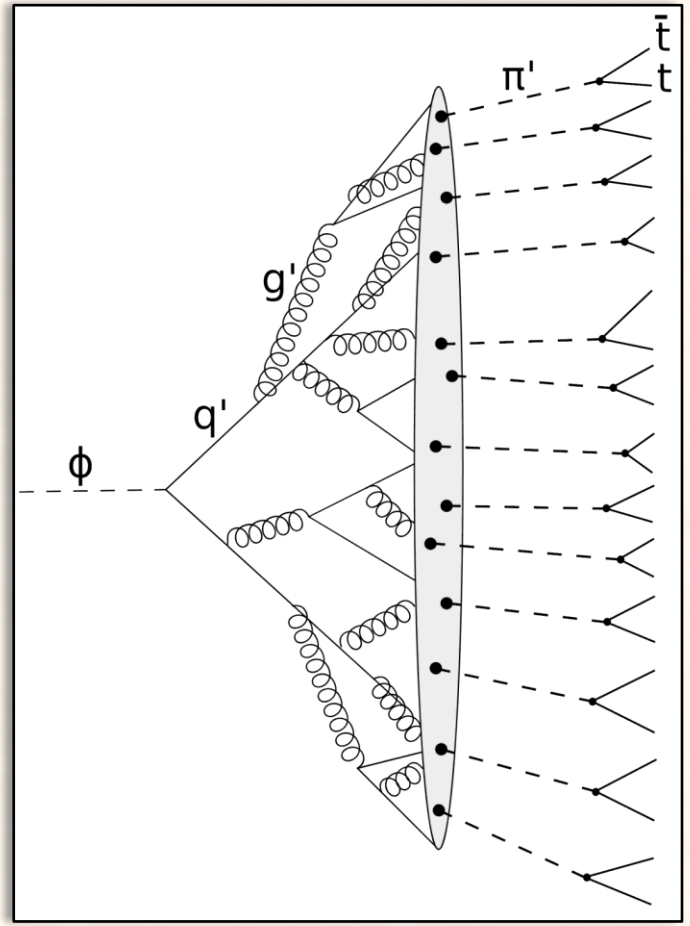
Would produce much more $\overline{\text{He}}$-4 than $\overline{\text{He}}$-3

QCD-Like Dark sector (Winkler, **PDL**, Linden 2211.00025)

Can explain AMS-02 detections, but needs to be explored further

A solution: QCD-Like Dark sector

Winkler, **PDL**, Linden
ArXiv:2211.00025



The observation of antihelium-4 is much harder to explain because standard models predict a production ratio ~ 1/1000

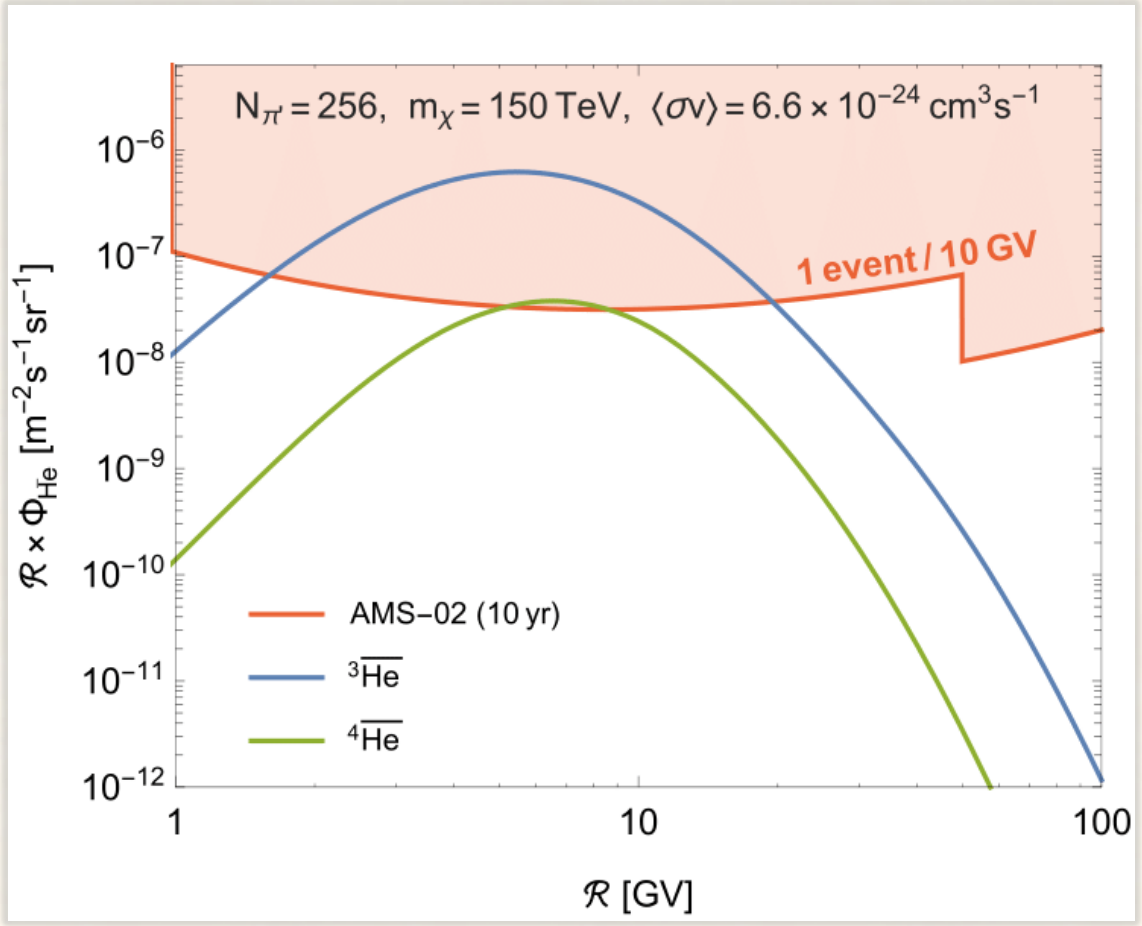
A **strongly coupled dark sector** can produce a "dark parton shower", generating high multiplicity of "dark pions". These would subsequently decay into SM quarks through, e.g., the Higgs or top portals, **triggering a hadronic shower.**

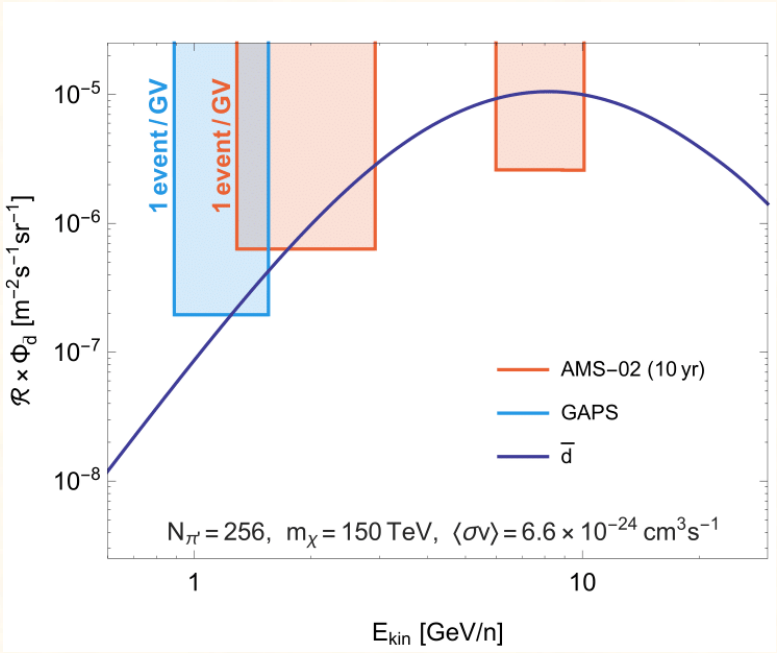
Simulated with Pythia as $\chi\chi \to \phi\phi \to 2\bar{q}'q' \to N_{\pi'}\,\pi' \to N_{\pi'}\,\bar{t}t$

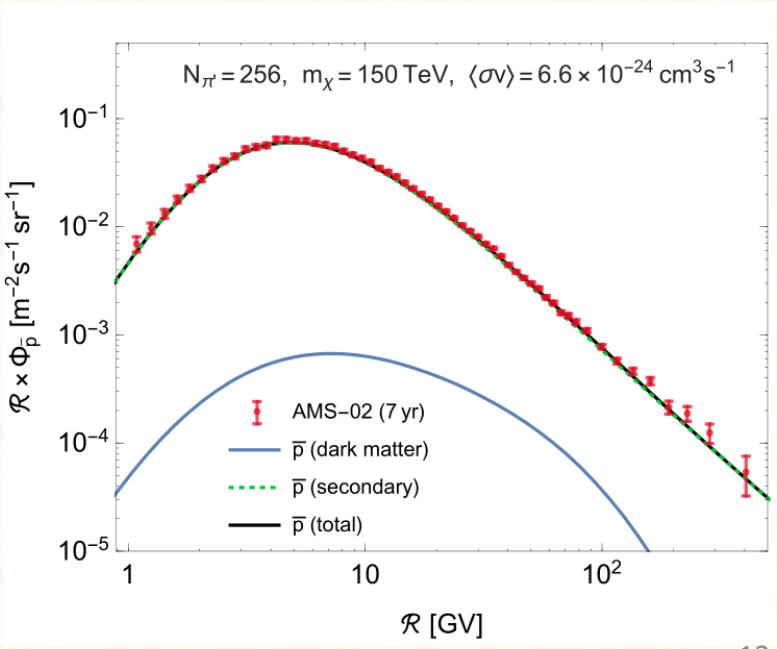
This could have escaped detection at LHC and it offers a pathway to look for excesses in the ditop channel

QCD-Like Dark sector

From factorized formula: $N_A \propto (N_p)^A$







Conclusions

CR anti-nuclei predictions and their detectability in the next years

- **Anti-nuclei** are a very promising channel to study **signals from dark matter** and constrain our current **WIMP** models – **At reach in the next decade!**
- **The secondary production of anti-deuteron is already detectable by AMS-02** (need to refine experimental analysis of the events detected)
- Exciting preliminary detection of anti-helium seems to challenge our models… WIMP production seems insufficient… **need of invoking exotic scenarios**
- QCD-like dark sector can be a viable solution and testable in accelerators!

Pedro de la Torre Luque – 12/09/2023
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BACK UP

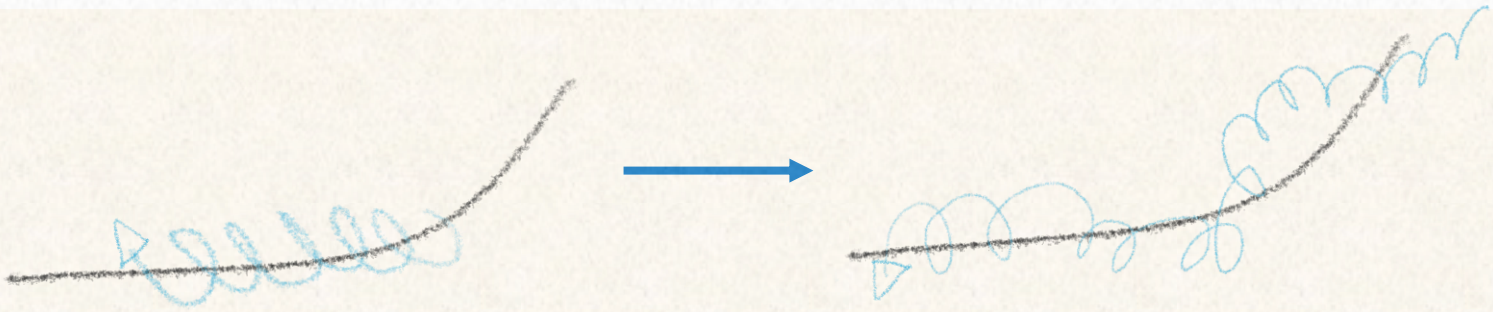
The propagation of CRs – Diffusion equation

- The basic idea is that primary particles are accelerated in astrophysical sources (namely SNRs) and propagate throughout the Galaxy during millions of years, due to scattering with plasma waves. Occasionally, they interact with gas and produce secondary nuclei through spallation.

$$\vec{\nabla}\cdot(-D\nabla N_i - \vec{v}_\omega N_i) + \frac{\partial}{\partial p}\left[p^2 D_{pp}\frac{\partial}{\partial p}\left(\frac{N_i}{p^2}\right)\right] = Q_i + \frac{\partial}{\partial p}\left[\dot{p}N_i - \frac{p}{3}\left(\vec{\nabla}\cdot\vec{v}_\omega N_i\right)\right]$$
$$-\frac{N_i}{\tau_i^f} + \sum\Gamma^s_{j\to i}(N_j) - \frac{N_i}{\tau_i^r} + \sum\frac{N_j}{\tau^r_{j\to i}}$$

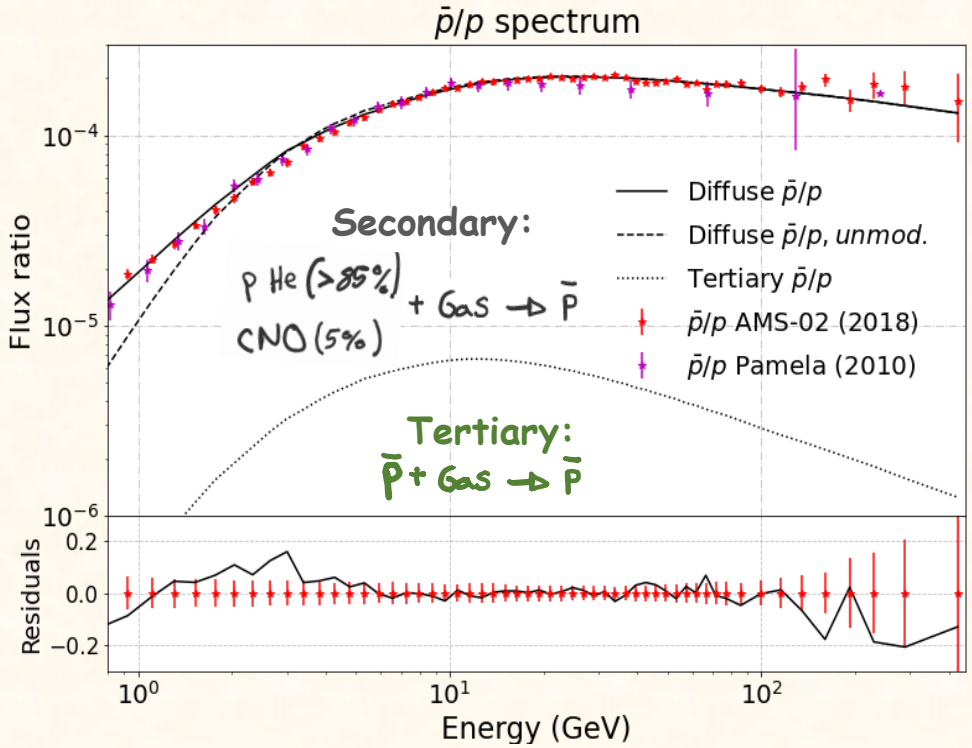
$$D_{pp} \propto \frac{p^2 V A^2}{D}$$

$$D = D_0\beta^\eta\left(\frac{R}{R_0}\right)^\delta F(\vec{r},z)$$

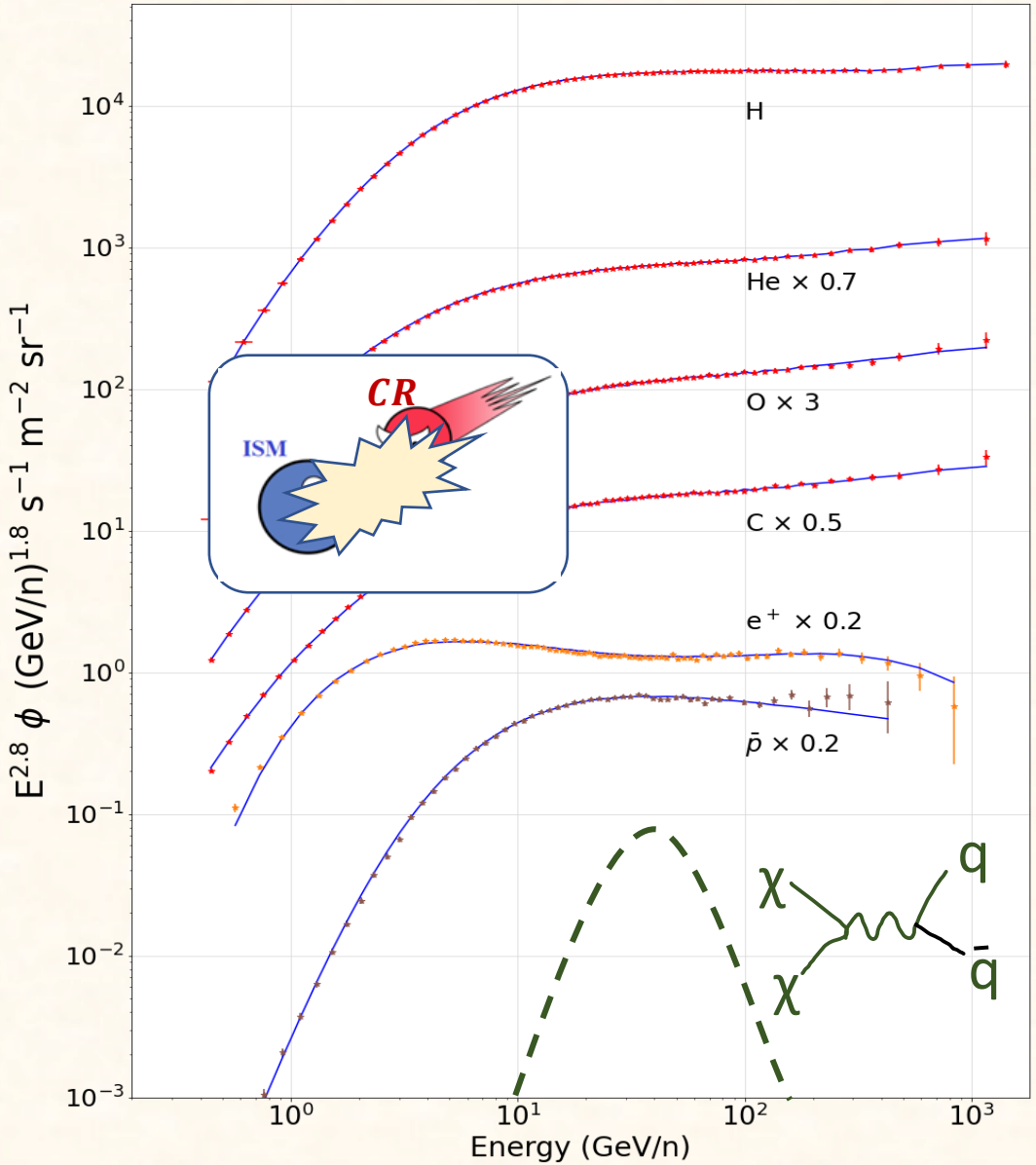


Potential of antiparticles to reveal the existence of BSM physics

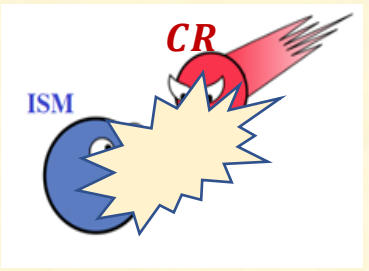
p + p → p + p + p + $\bar{p}$ (High energy protons produce lower energy antiprotons)



Flux of CR nuclei and antiparticles (data from AMS-02)



Antiproton *excess* – A DM signal?

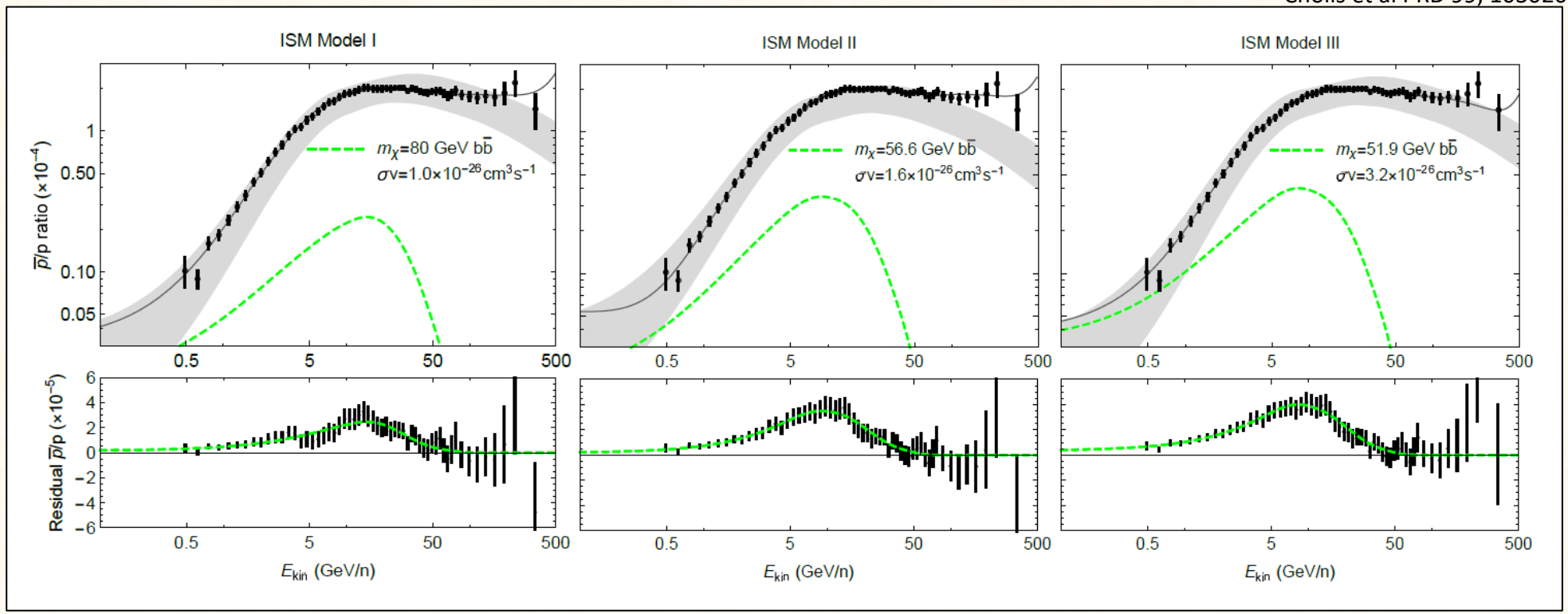


Several studies claimed the possibility of an **excess** of data over the predicted flux **at around 10-20 GeV**, which can be the **signature of dark matter** annihilating or decaying into antiprotons

$p_{CR} + p_{ISM} \rightarrow \bar{p}$

$\chi + \chi \rightarrow \bar{p}$

Cholis et al PRD 99, 103026



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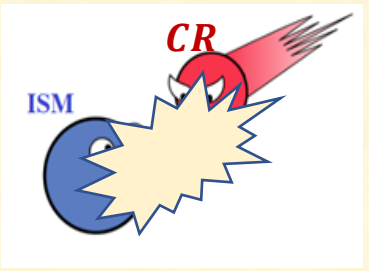
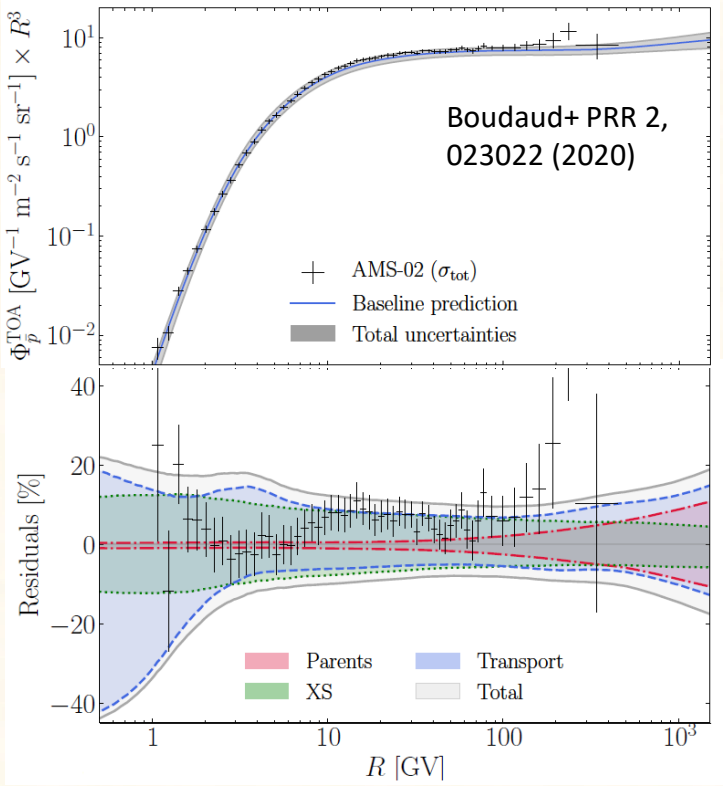
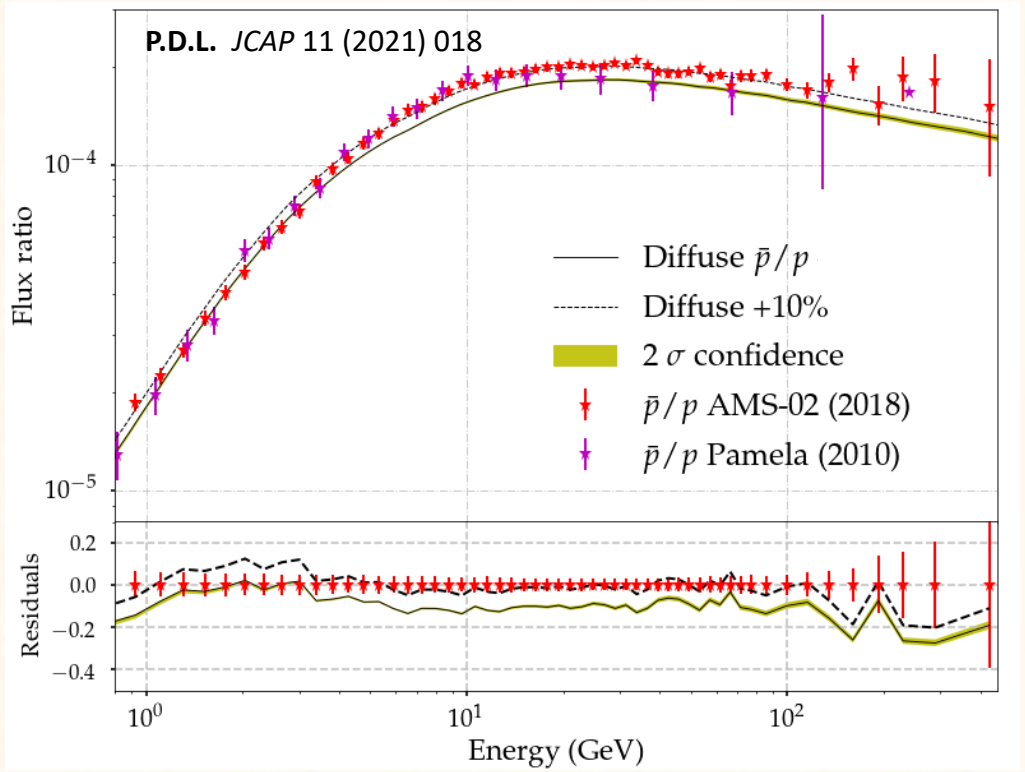


Further investigations revealed that the $\bar{p}$ spectrum is **totally compatible with the rest of CRs**, without any need of dark matter.
Cross sections uncertainties and AMS-02 correlated errors are crucial

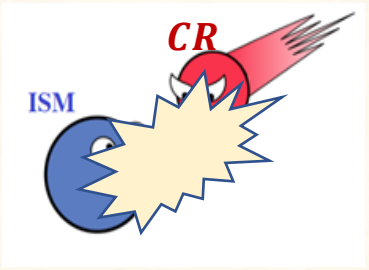
$p_{CR} + p_{ISM} \rightarrow \bar{p}$

$\chi + \chi \rightarrow \bar{p}$





Antiproton excesses – *The spectral excess*



$p_{CR} + p_{ISM} \rightarrow \bar{p}$

$\chi + \chi \rightarrow \bar{p}$

All analysis coincided in the position of the excess, but not in its significance… again, **the astrophysical uncertainties were not completely understood** (and they aren't yet!)

Jan Heisig MIAPP 2021

Default from Cuoco *et al.* 2019

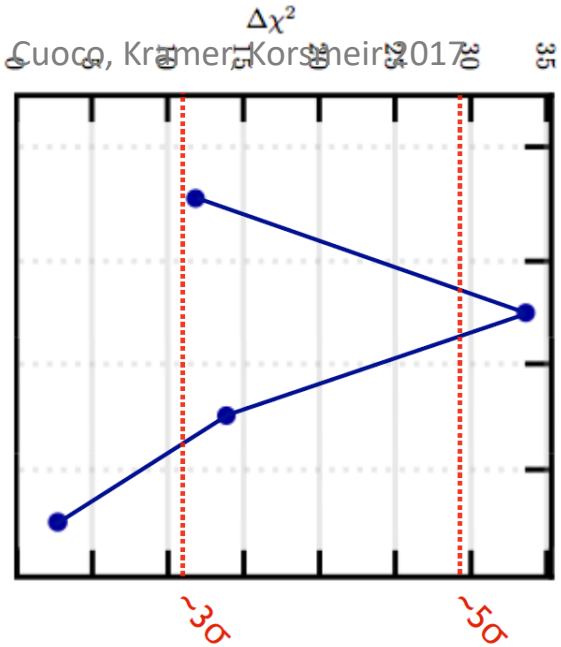
AMS cov. only

prod. XS+AMS cov.

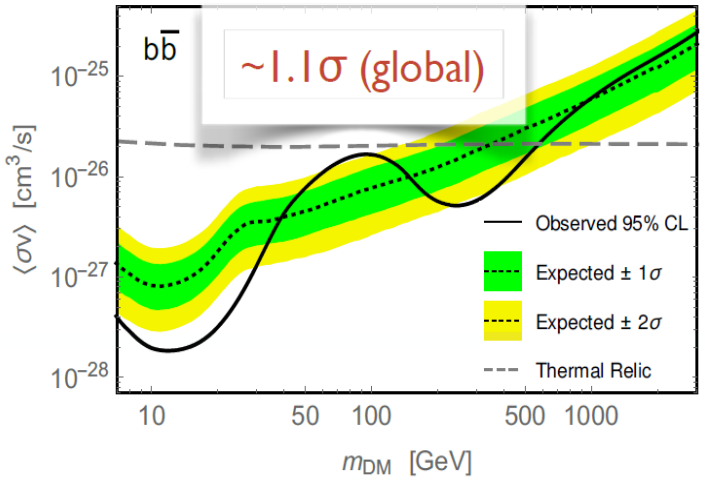
prod. XS+AMS cov.+ η

$D(E) \sim D_0 \beta^\eta E^\delta$

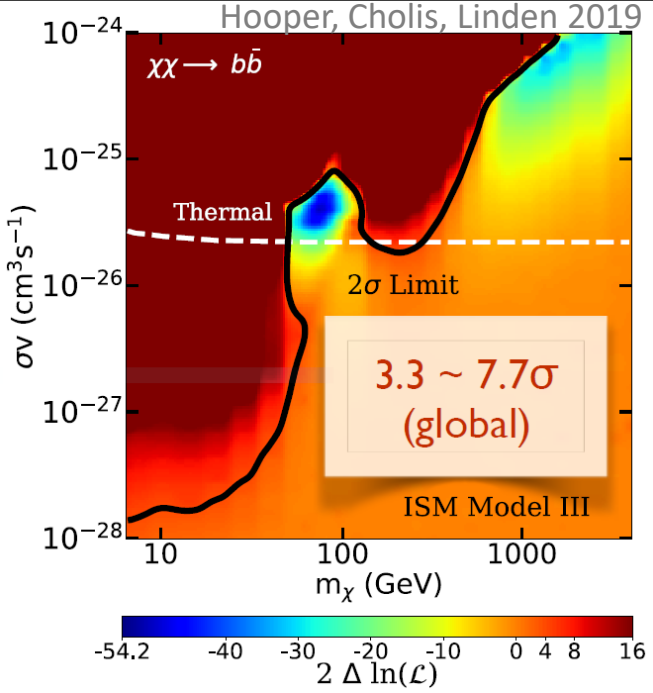
Cuoco, Krämer, Korsmeier 2017



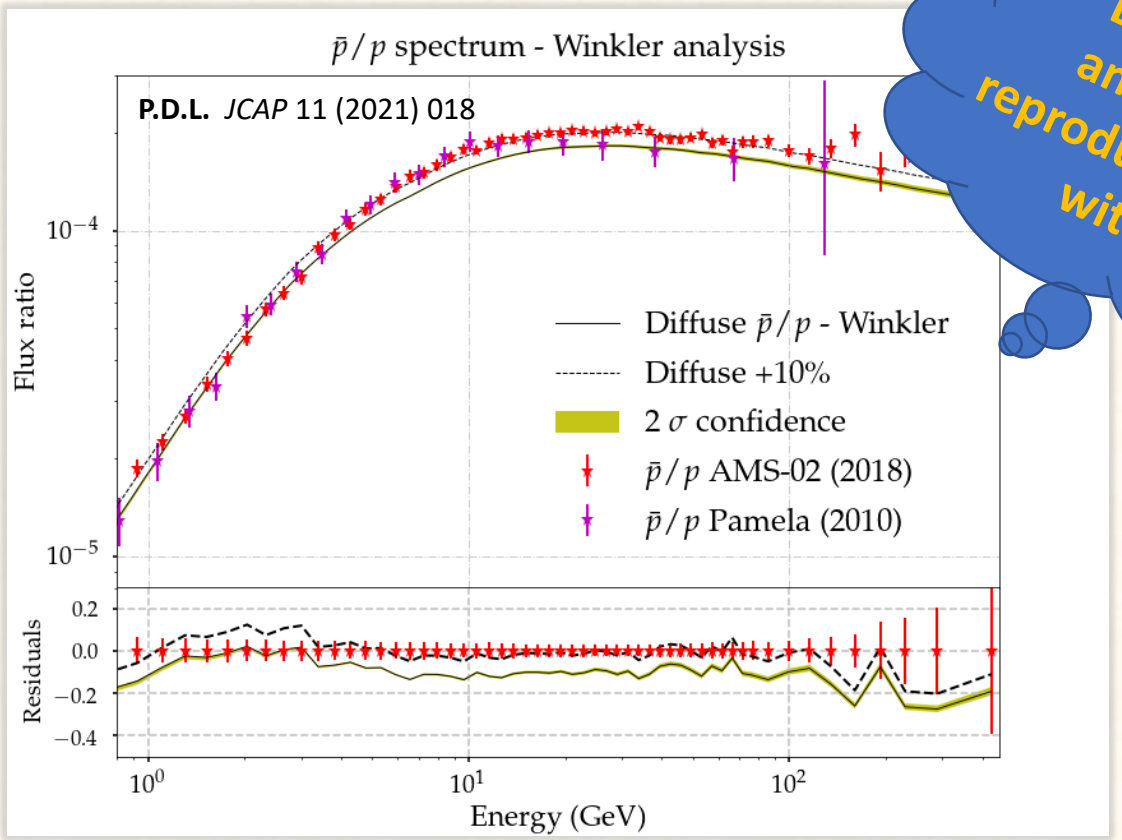
Reinert, Winkler 2018



Hooper, Cholis, Linden 2019

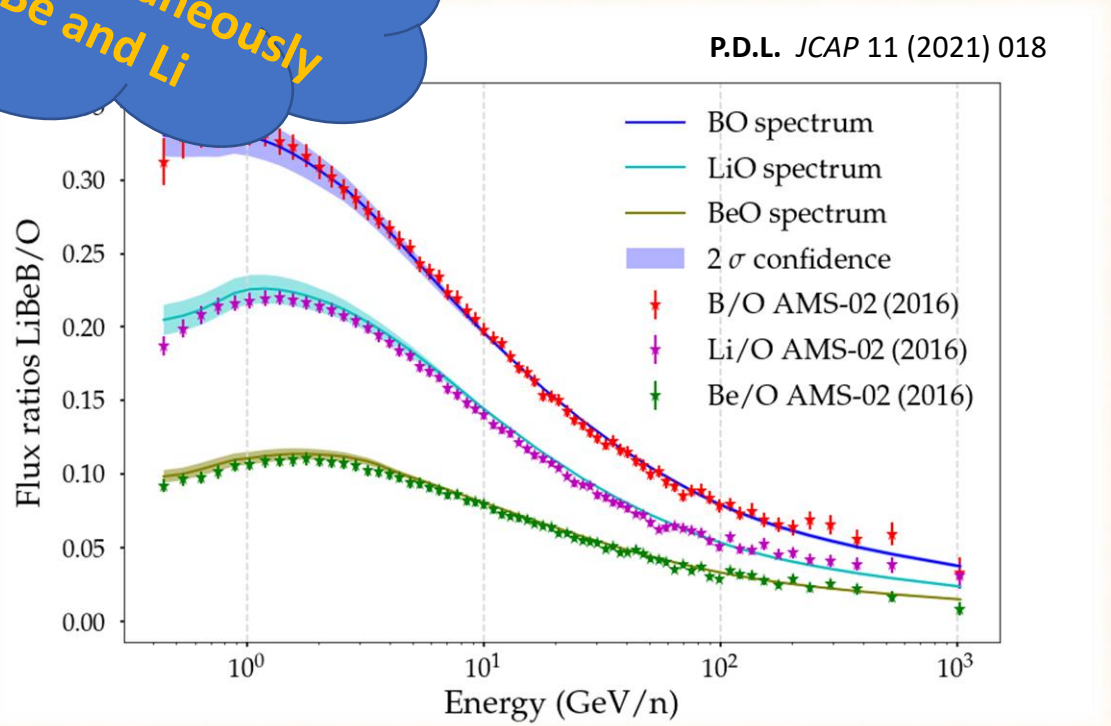


Antiproton *excesses* – *The grammage excess*



Energy spectrum of antiprotons is easily reproduced simultaneously with B, Be and Li

…coeff. predicted by the flux-ratios of …Li underpredicts the antiproton …0%→ **Grammage tension**



<u>Conclusion</u>: Cross sections uncertainties affect very significantly our predictions and can explain the excess

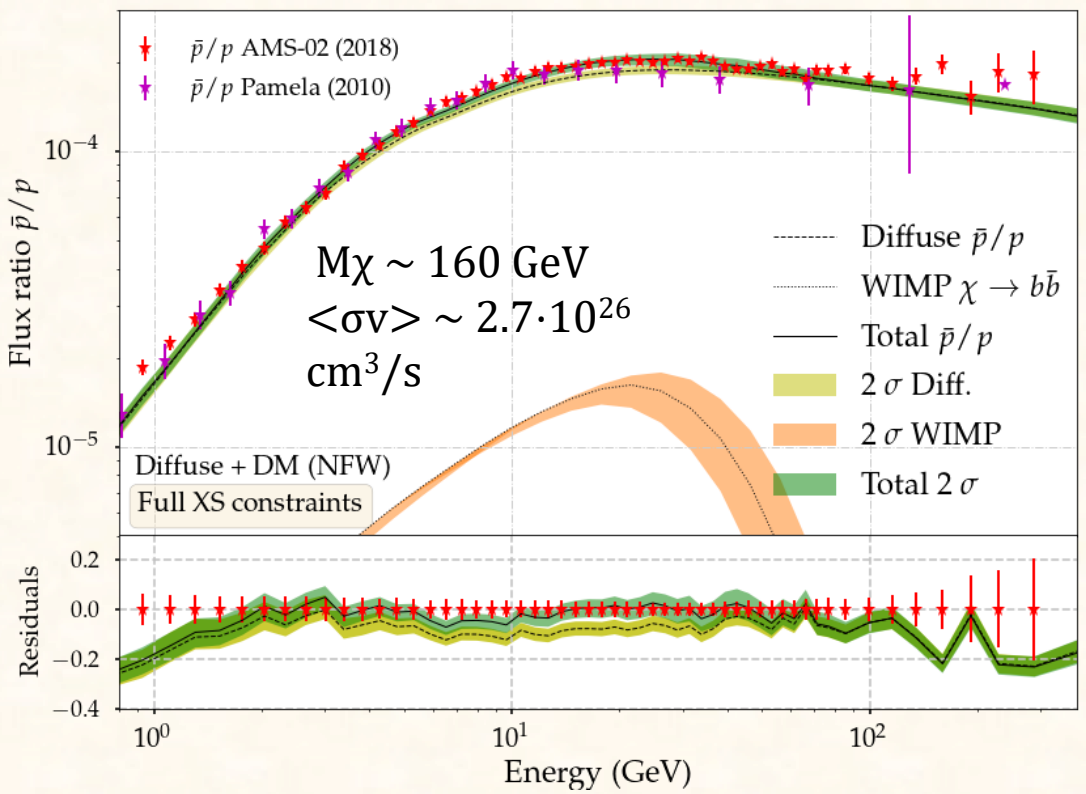
Search for DM features in the antiproton spectrum

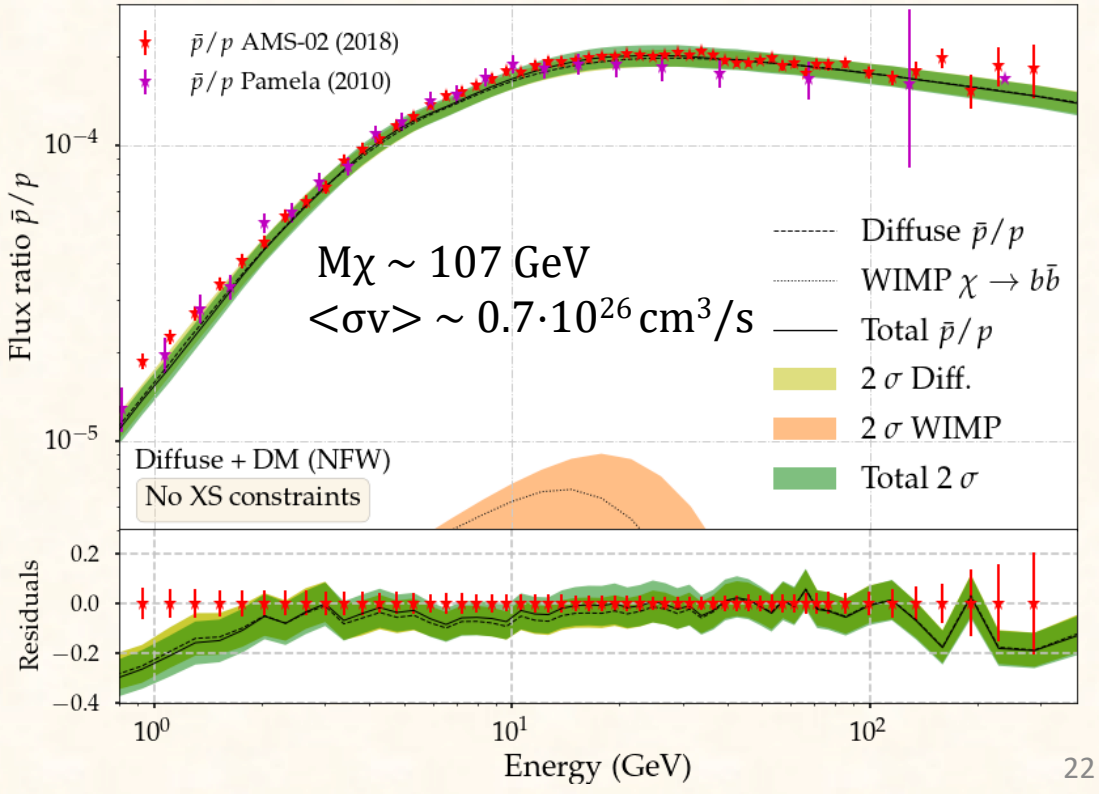
- Combination of B, Be and Li to determine prop. Params
- Cross-section (XS) normalizations as nuisance parameters
- Two modifications of XS prior constraints:
  - No constraints - Penalty factor same as for B (Full cons.)

B/C, B/O, Be/C, Be/O, Ap/p (Prop. parameters)
^{10}Be/^{9}Be, ^{10}Be/Be (H), Li/B

No statistical evidence in any analysis (0.6 < σ < 1.1)

P.D.L. et al, **in preparation**

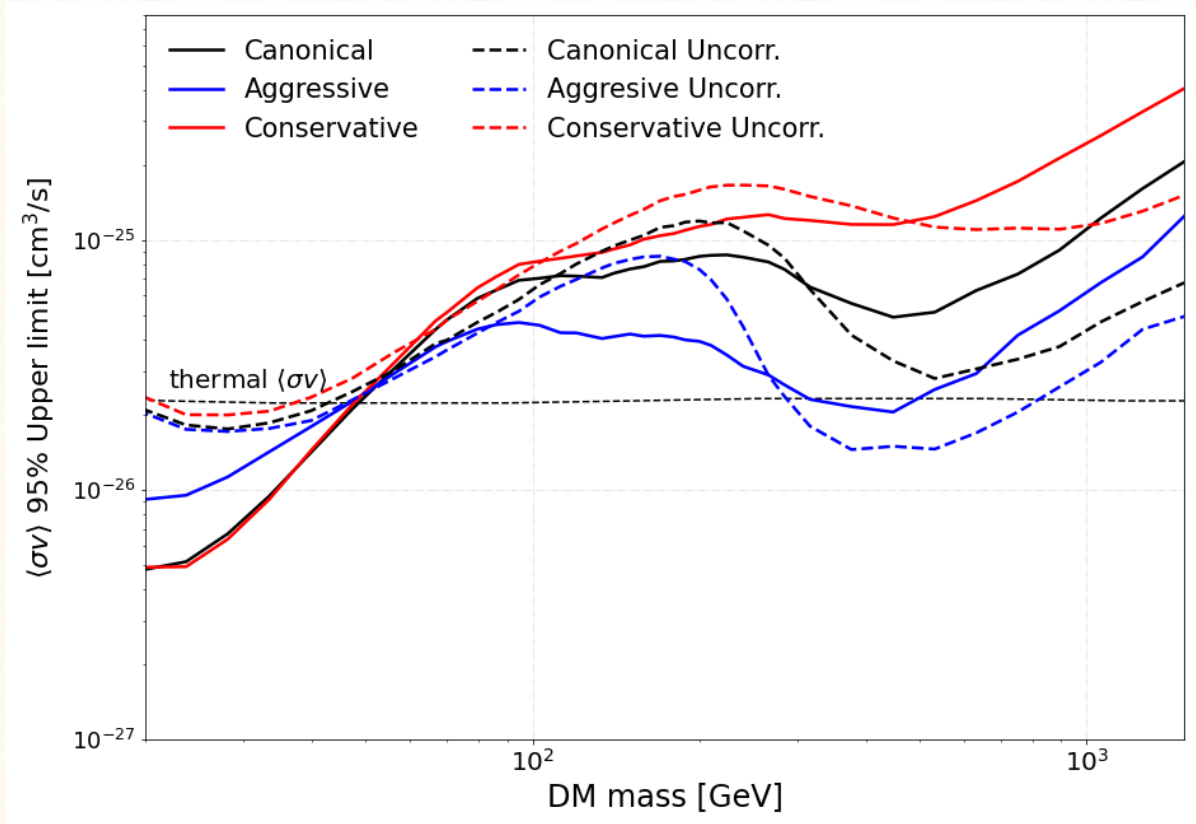


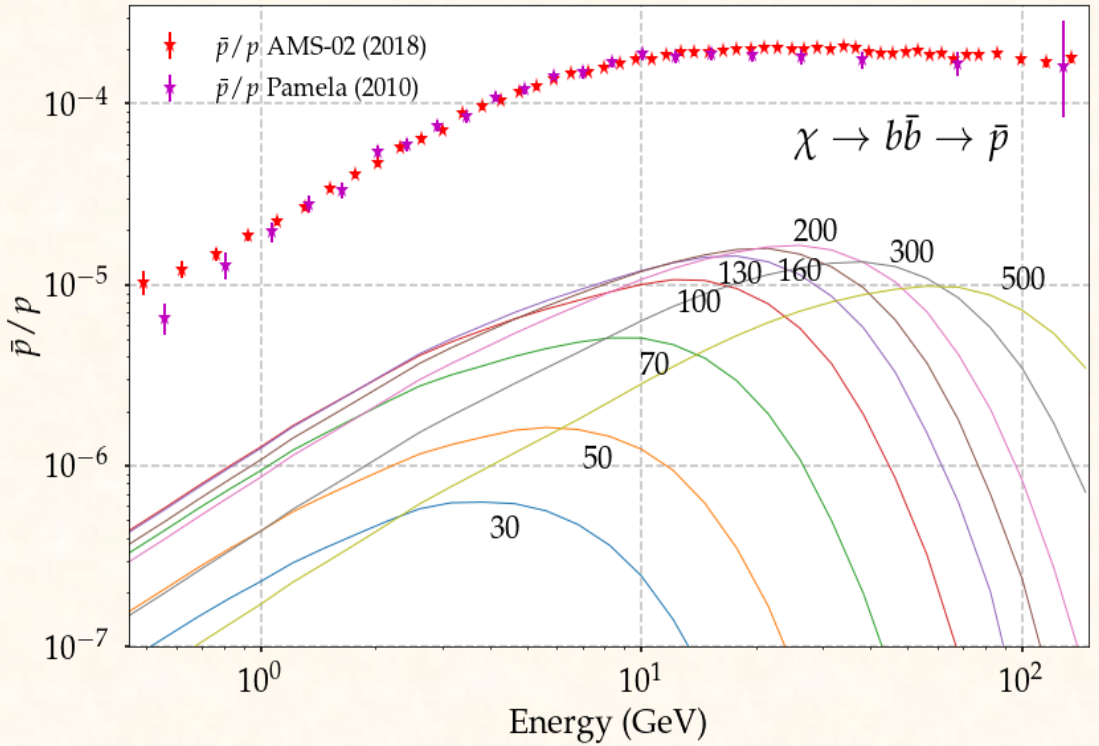


Dark matter bounds from antiproton combined analyses

No hints for WIMP signals in recent analyses…

P.D.L. et al, **in preparation**





These analyses can rule out the thermal relic cross-section for WIMP masses below ~50 GeV
Tension with the GCE!!

However, we are constrained to the classical model of production of antiprotons

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No hints for WIMP signals in recent analyses…

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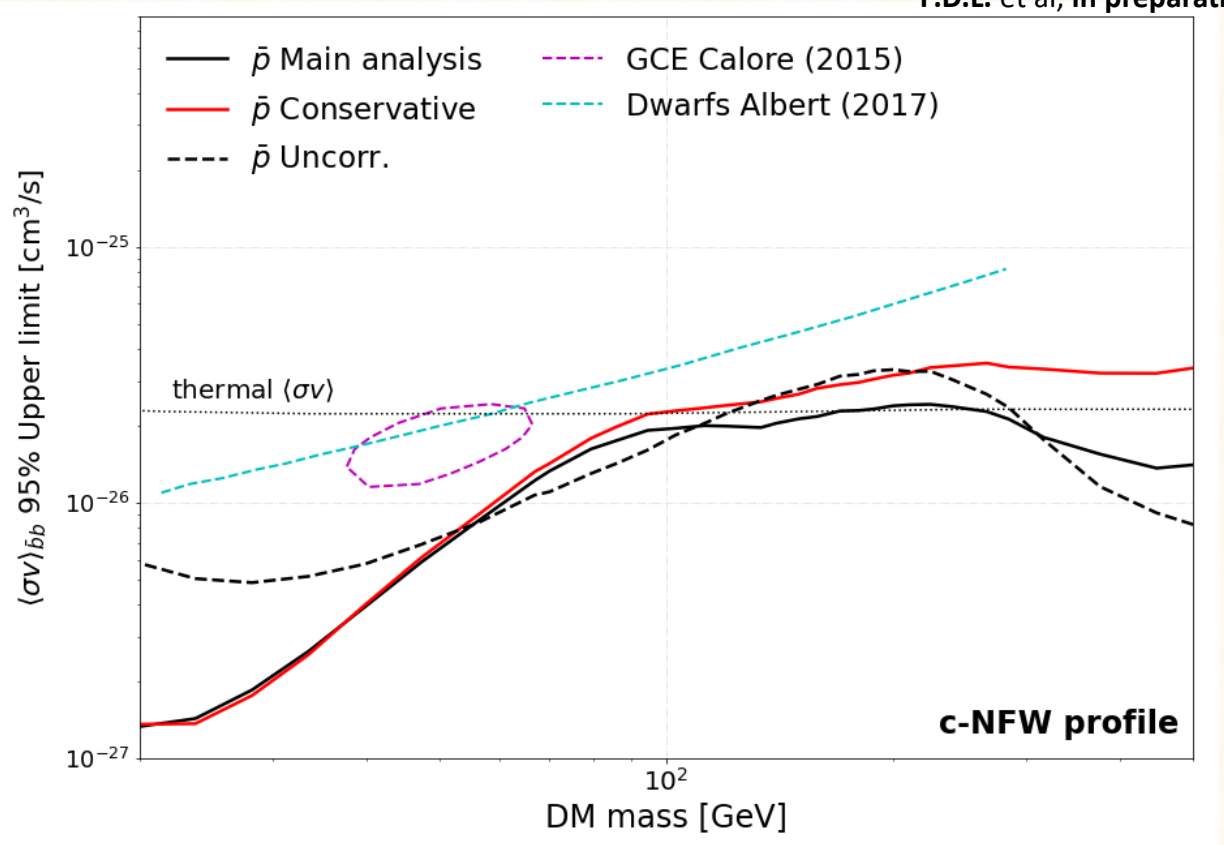

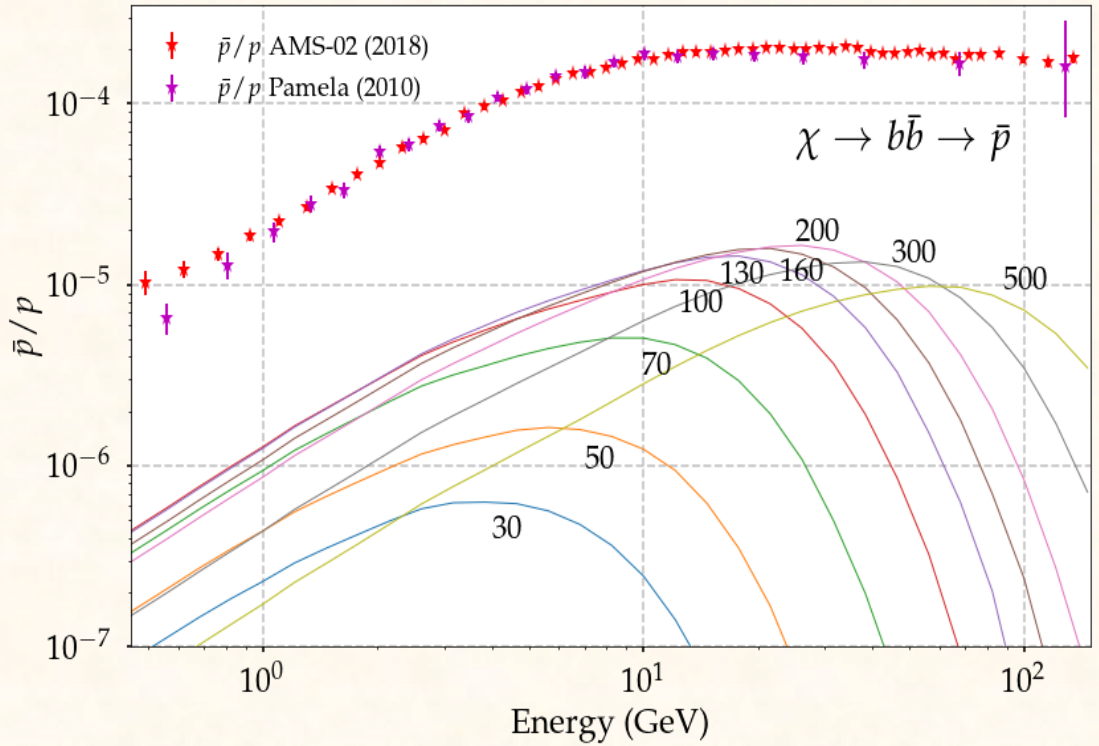

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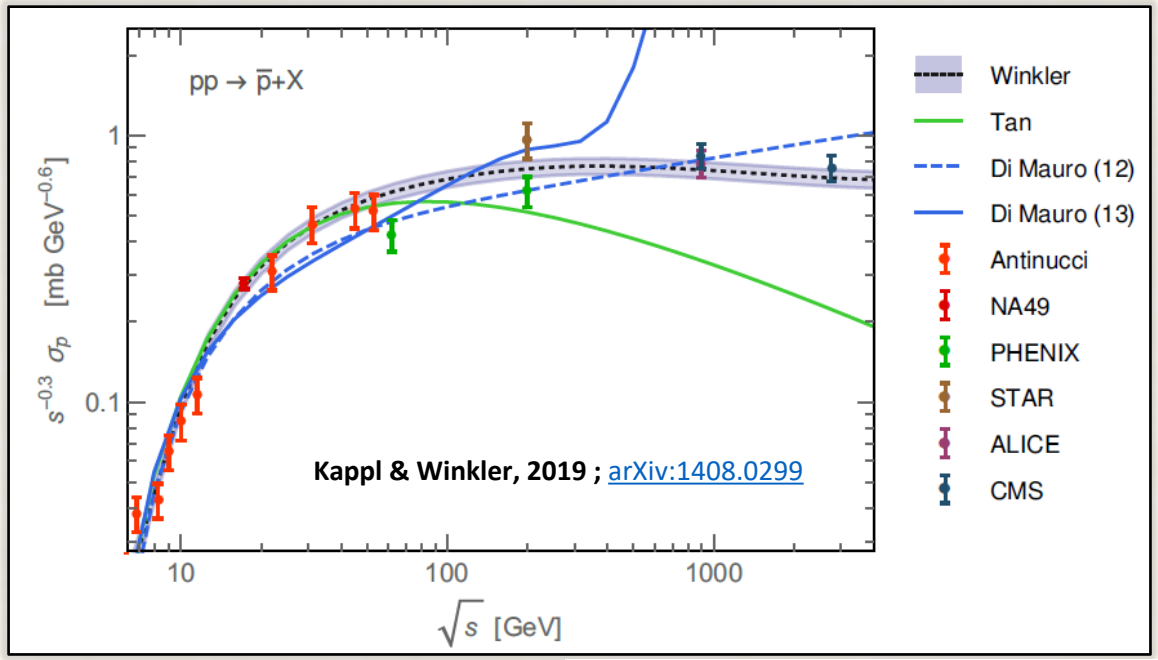
However, we are constrained to the classical model of production of antiprotons

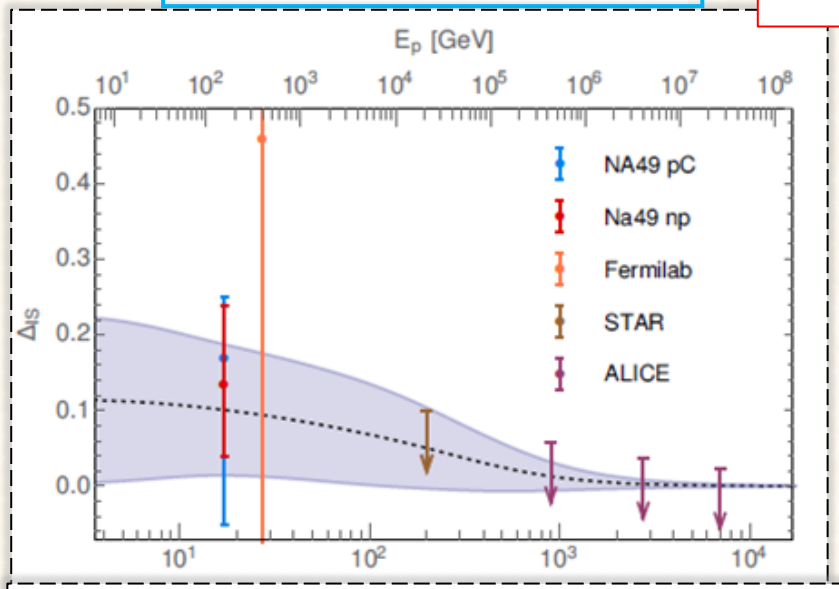
Antiproton cross sections

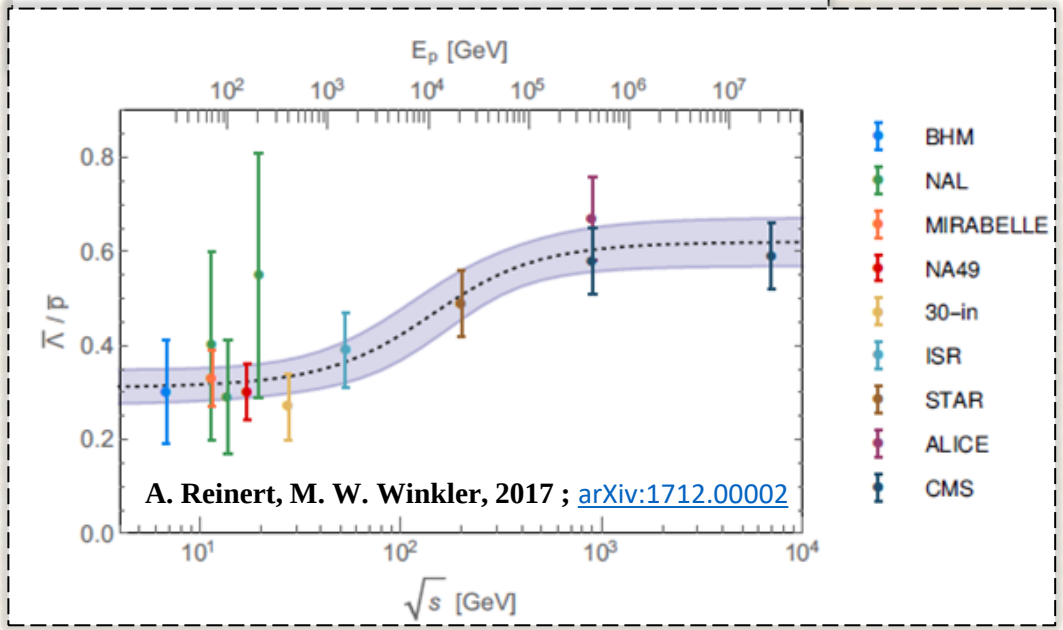
$$\left(E\frac{d^3\sigma}{dp^3}\right)_{pp\to\bar{p}} = \left(E\frac{d^3\sigma}{dp^3}\right)^{\text{prompt}}_{pp\to\bar{p}} \cdot (2 + \Delta_{IS} + 2\,\Delta_{\Lambda})$$



$$p + p \longrightarrow \{\bar{n} \longrightarrow \bar{p}\} + X$$

$$\Delta_{\text{IS}} = \frac{\sigma_{pp\to\bar{n}}}{\sigma_{pp\to\bar{p}}} - 1$$





$$p + p \longrightarrow \{\bar{\Lambda}, \bar{\Sigma} \longrightarrow \bar{p}\} + X$$

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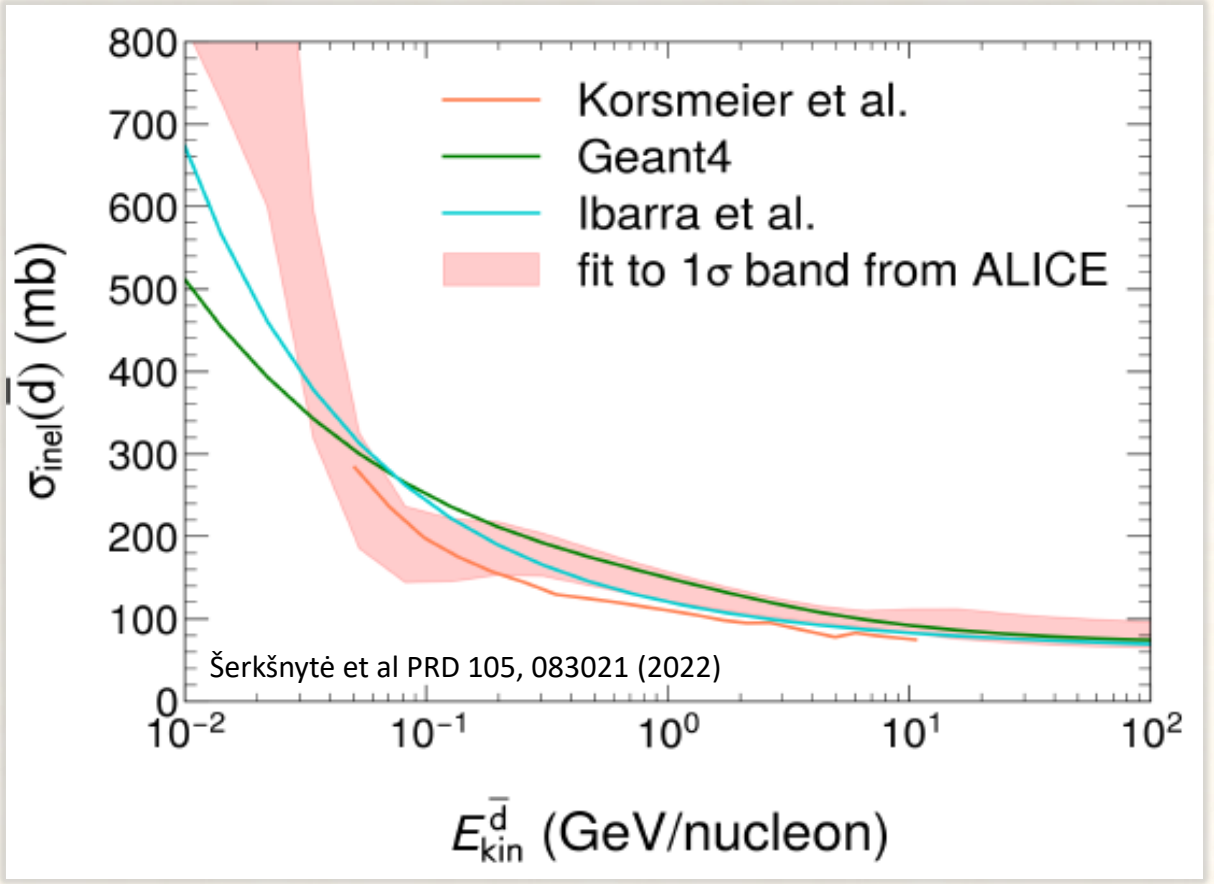
Propagation setup

Propagation code: github.com/tospines/Customised-DRAGON-versions/Custom_DRAGON2_v2-Antinuclei/

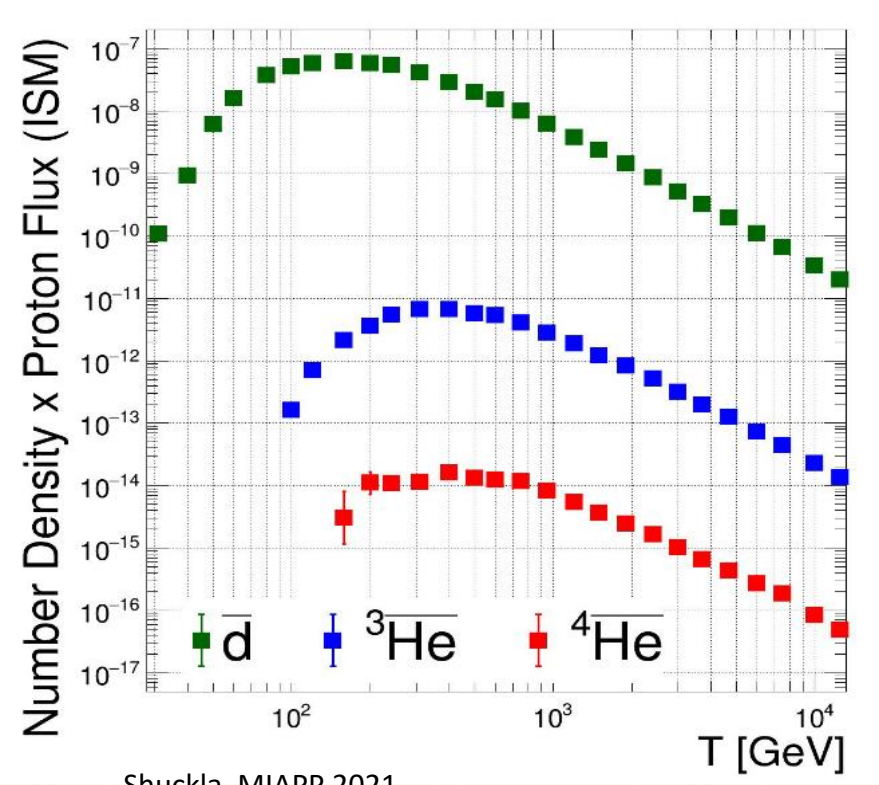
❖ Implementation of anti-nuclei dark matter and secondary production in DRAGON2

- Cross sections derived from analytical coalescence model. Using fits of antiproton (antineutron) production from Winkler, JCAP 02, 048 (2017)
- DM spectrum at production derived from Pythia 8.2 simulating a neutral colorless resonance.
  Space and momentum (p_c) conditions for coalescence. Also including production from anti-hyperons
- Inelastic cross sections and tertiary production computed extrapolating antiproton parametrizations



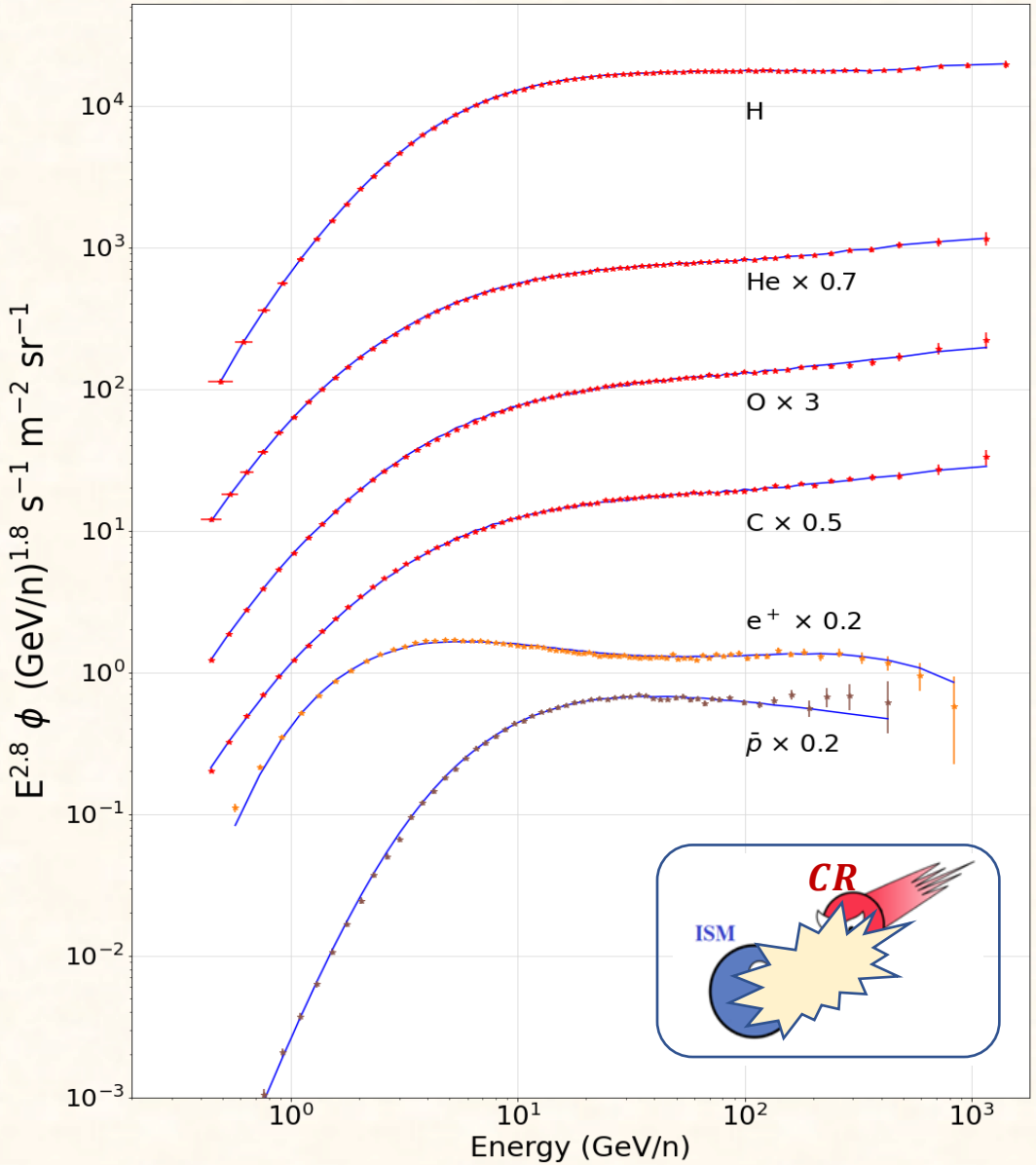
Potential of anti-nuclei to reveal the existence of BSM physics

P + p → p + p + p + ap + ap + an

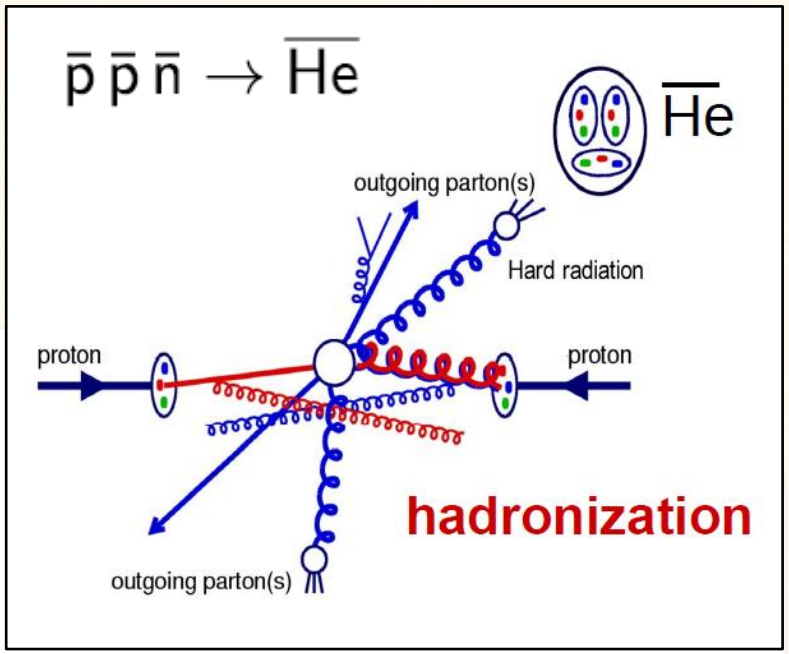


Shuckla, MIAPP 2021

Flux of CR nuclei and anti-nuclei (data from AMS-02)



Formation of anti-nuclei



➢ Simplest coalescence model: *Factorised coalescence*

$$E_{\bar{d}}\frac{d^3N_{\bar{d}}}{dp_{\bar{d}}^3} \simeq B_2\left(E_{\bar{n}}\frac{d^3N_{\bar{n}}}{dp_{\bar{n}}^3}\right) \times \left(E_{\bar{p}}\frac{d^3N_{\bar{p}}}{dp_{\bar{p}}^3}\right) \simeq B_2\left(E_{\bar{p}}\frac{d^3N_{\bar{p}}}{dp_{\bar{p}}^3}\right)^2$$

Antineutrons and antiprotons are produced uncorrelated

$$E_{\bar{A}}\frac{d^3N_{\bar{A}}}{dp_{\bar{A}}^3} \simeq B_A\left(E_{\bar{p}}\frac{d^3N_{\bar{p}}}{dp_{\bar{p}}^3}\right)^A$$

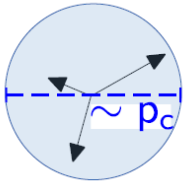
Coalescence parameter can be approximated from the coalescence momentum, p_0

(anti)nucleons with low relative momentum merge to form (anti)nuclei

$$B_2 = \frac{1}{8}\frac{4\pi p_0^3}{3}\frac{m_{\bar{d}}}{m_{\bar{p}}^2}$$

Anti-D $|\Delta p| < p_0$

Anti-He

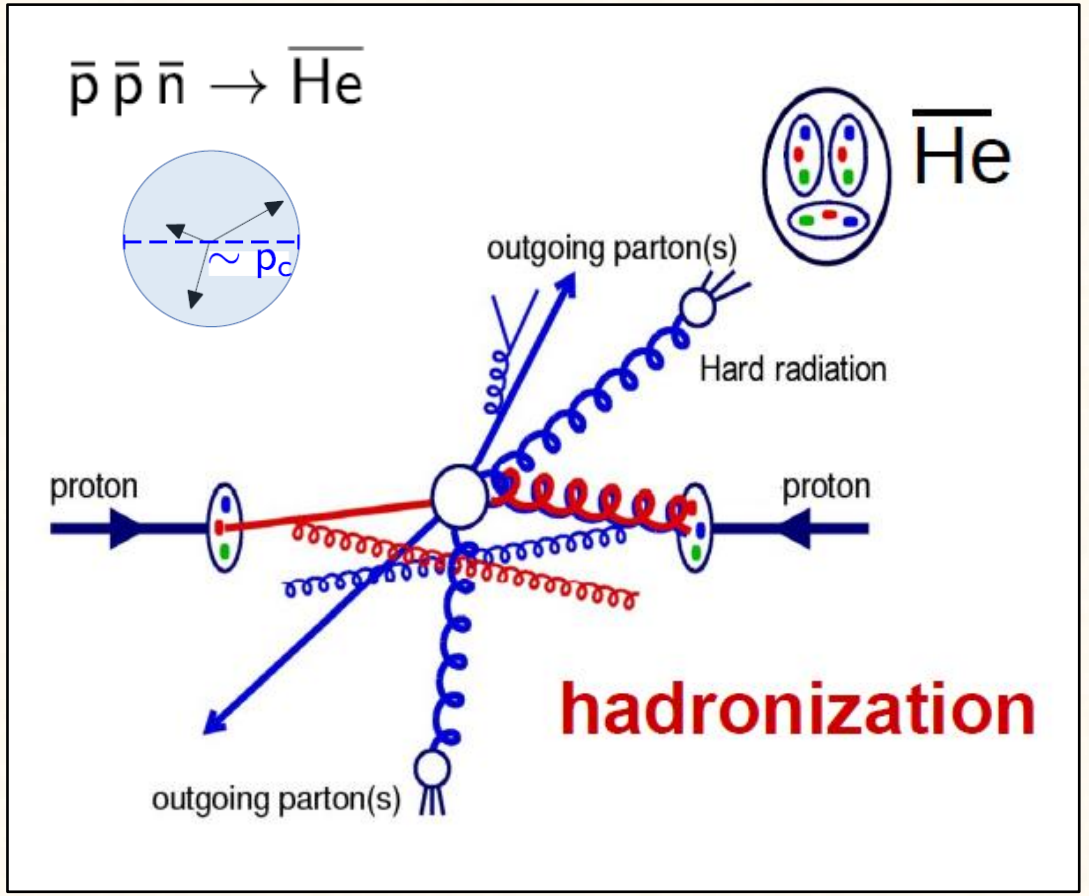


Formation of anti-nuclei: Coalescence

- Secondary anti-nucleons are produced from homologous interactions as for $\bar{p}$. These must coalesce in order to form an anti-nucleus, which hugely suppressed their production!

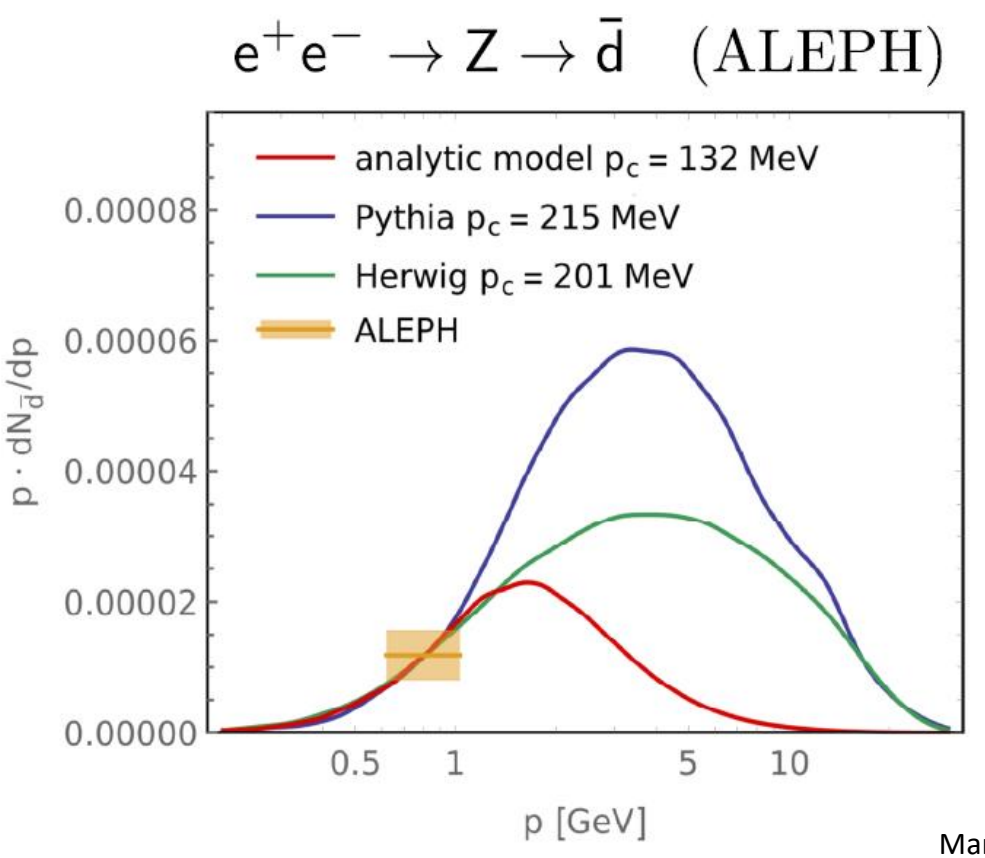
- Simplest coalescence model: *Factorised coalescence*

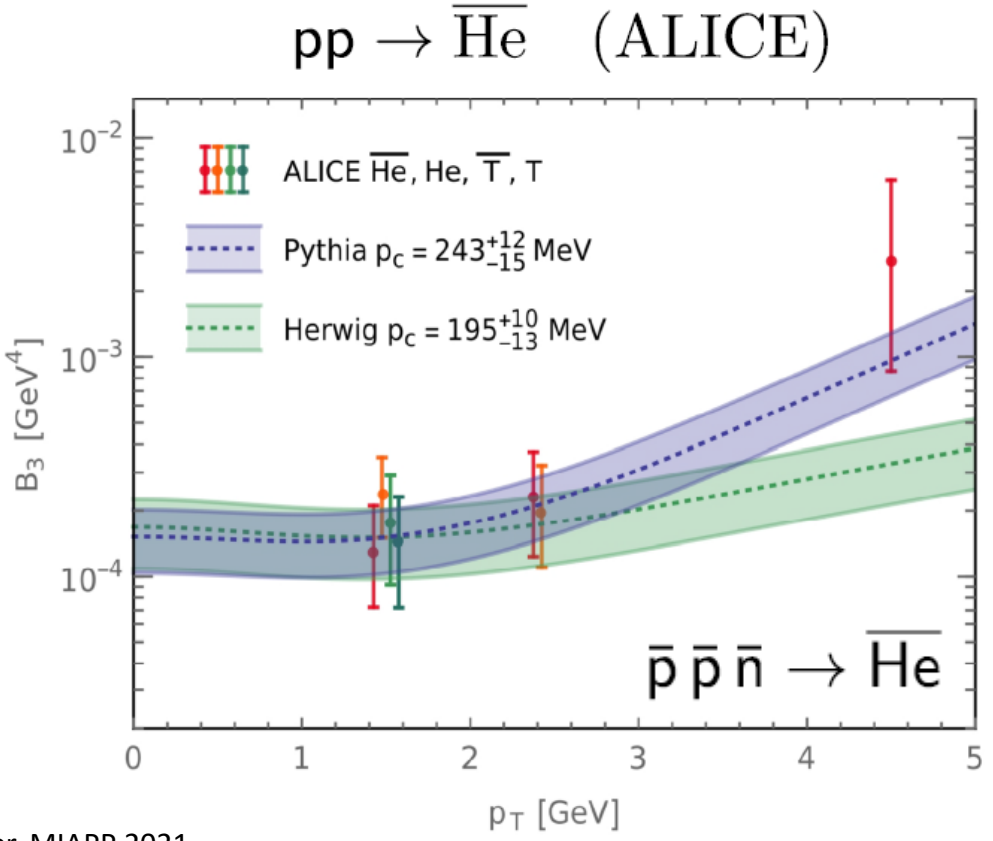
$$E_{\bar{A}}\frac{d^3N_{\bar{A}}}{dp^3_{\bar{A}}} \simeq B_A\left(E_{\bar{p}}\frac{d^3N_{\bar{p}}}{dp^3_{\bar{p}}}\right)^A$$



Formation of anti-nuclei

Coalescence parameter may depend on many kinematical parameters, including the size of the projectile and target

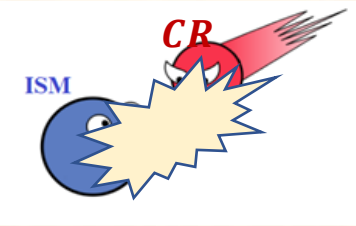




Martin Winkler, MIAPP 2021

Astrophysical production

CR + ISM → $\bar{He}$, $\bar{d}$

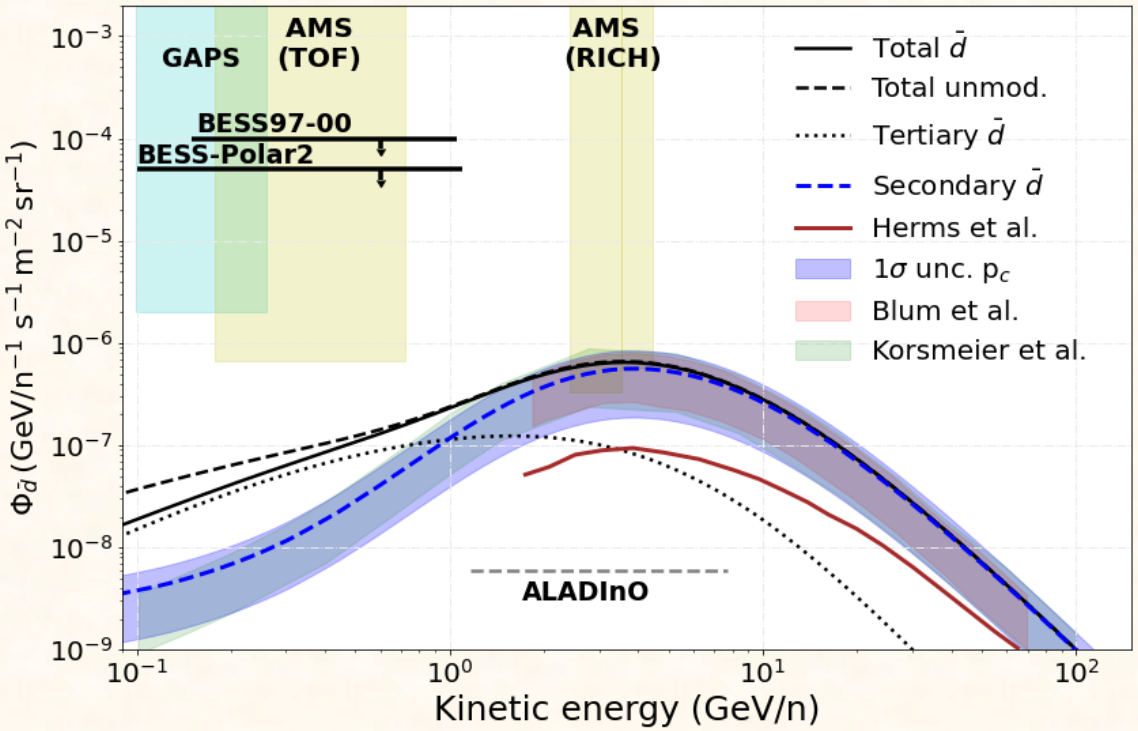


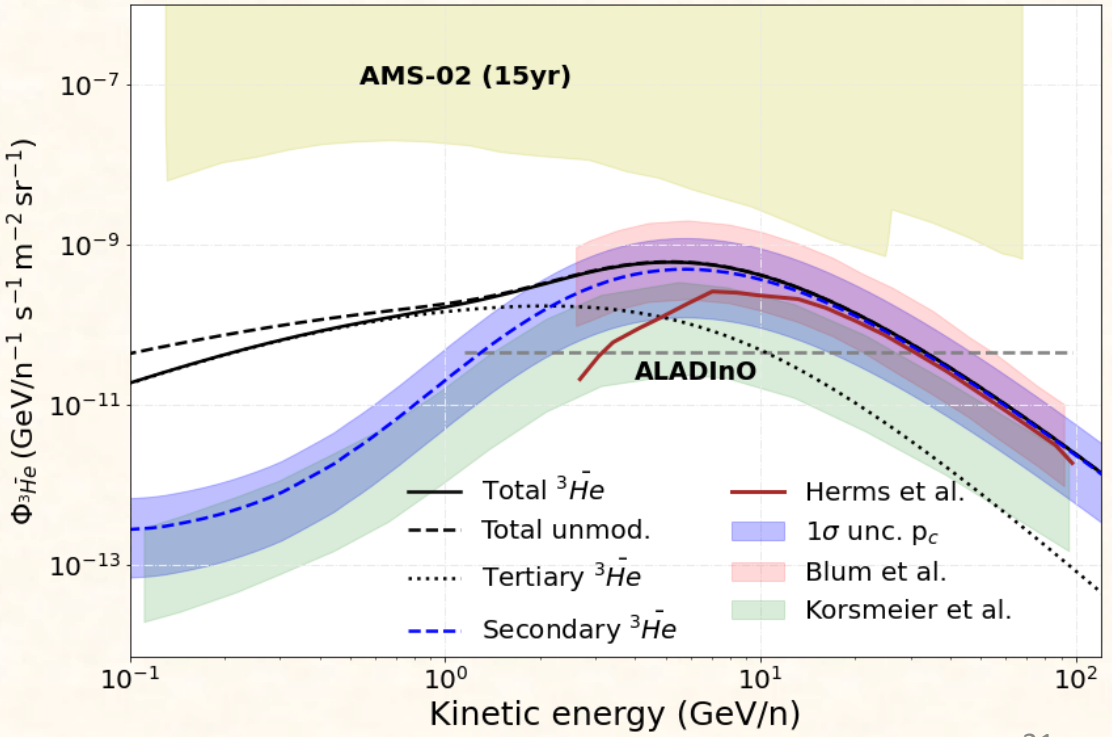
Can we explain the AMS-02 measurements without invoking any exotic source?

Main uncertainty is the coalescence parameter, the rest of uncertainties are under ~10%

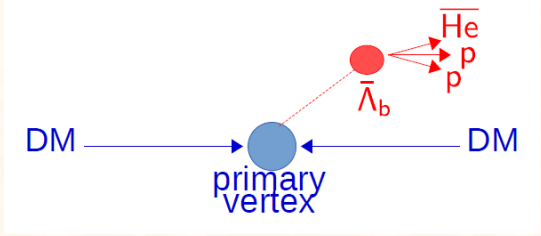
We expect to have measurements of the $\bar{d}$ flux in the next years!! But nothing about $\bar{He}$ till ALADInO or AMS-100 (foreseen to 2039)

P.D.L. et al, **in preparation**

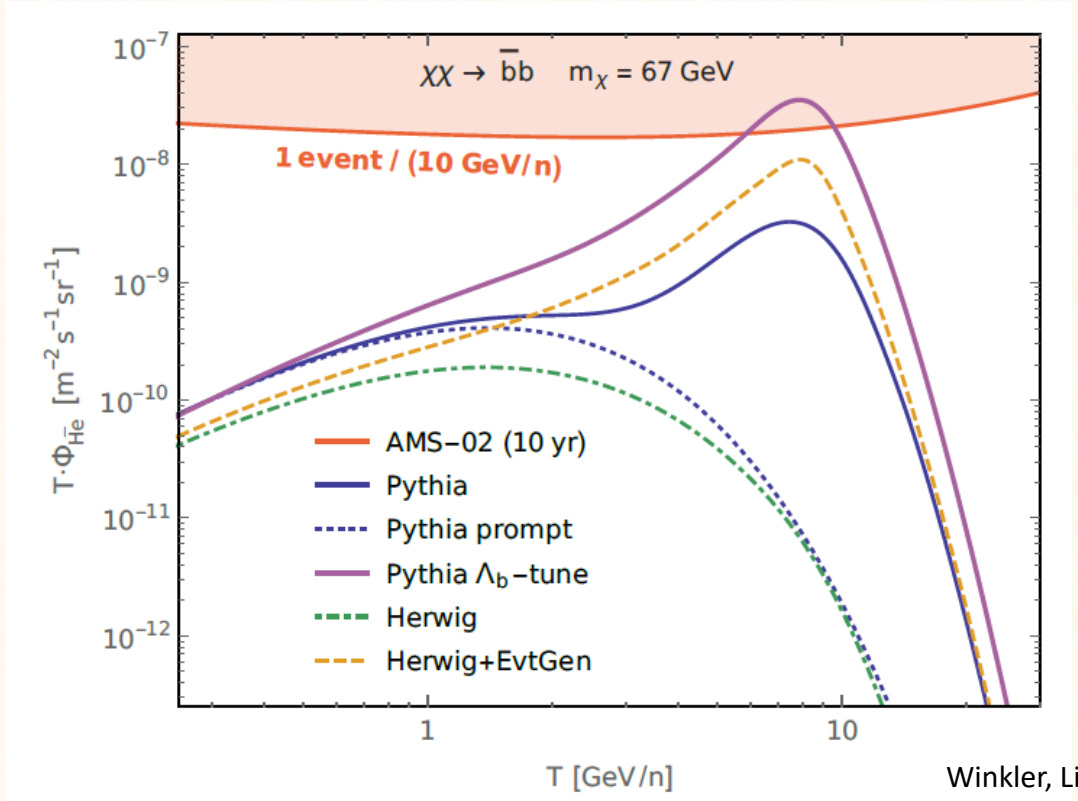


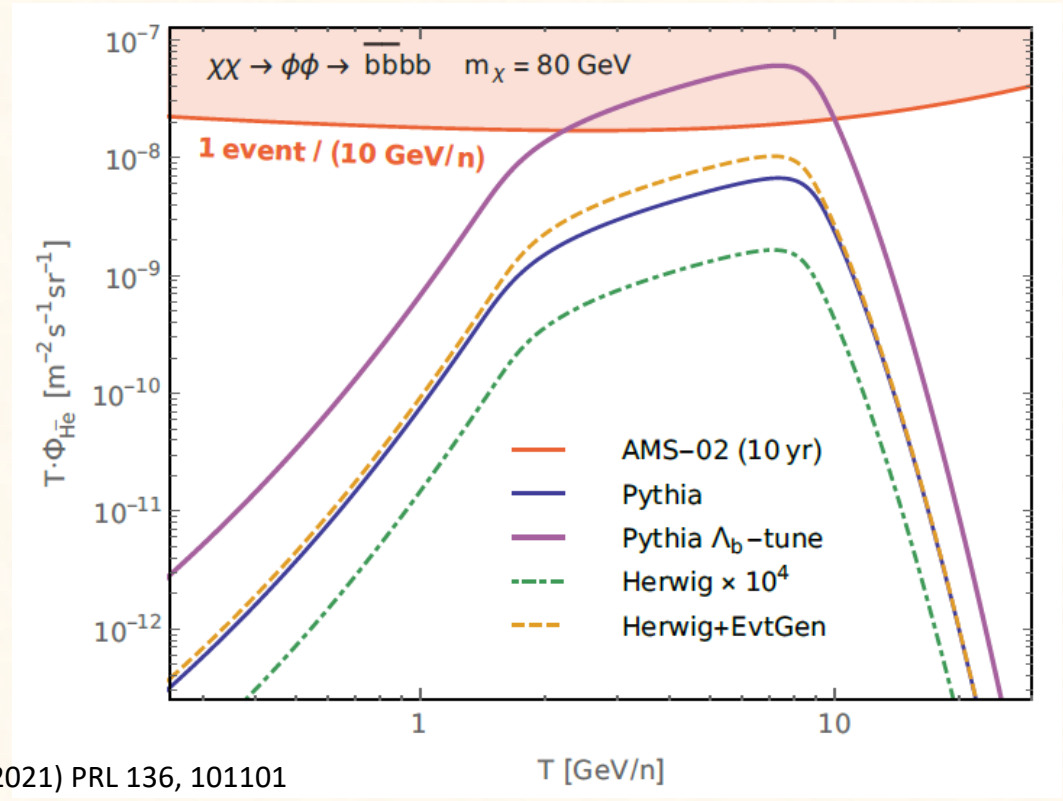


Boosting the dark matter signal



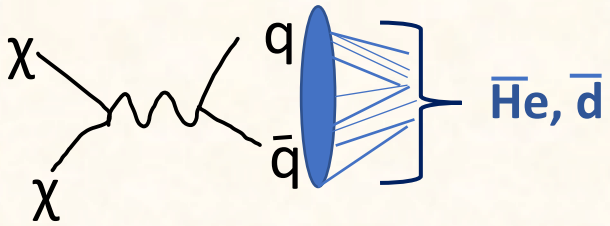
- ✓ **Λ_b production** is a very important source of anti-helium, even able to explain the events reported by AMS-02, although not yet well constrained



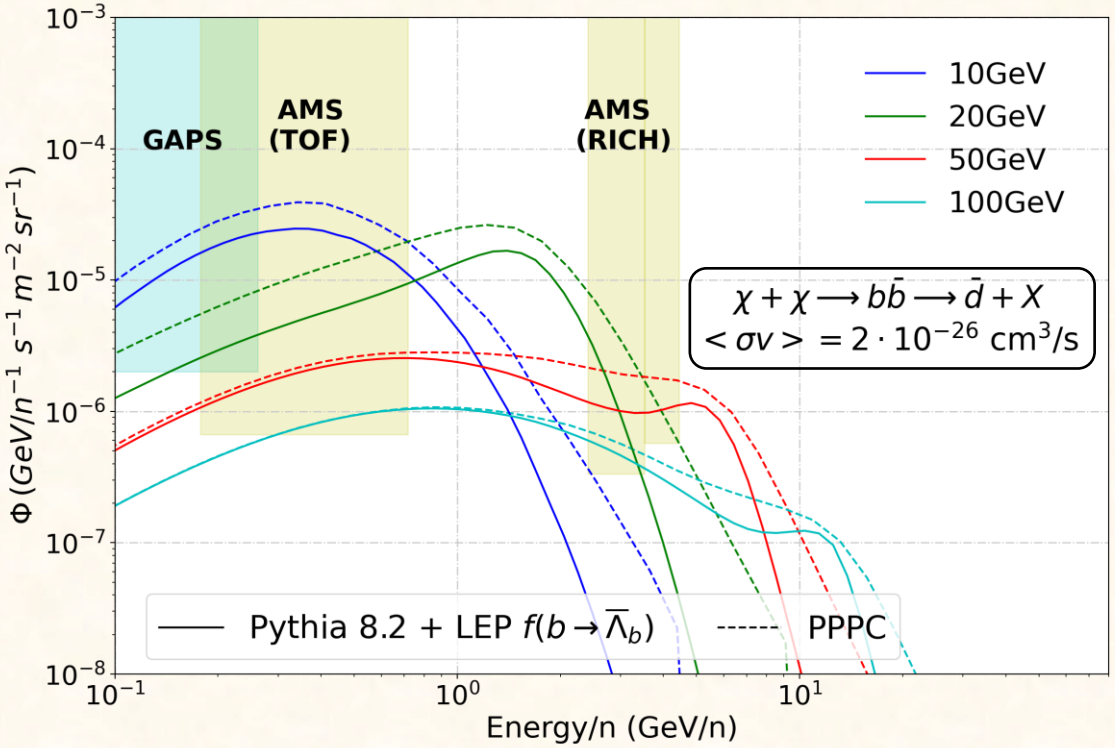


Winkler, Linden (2021) PRL 136, 101101

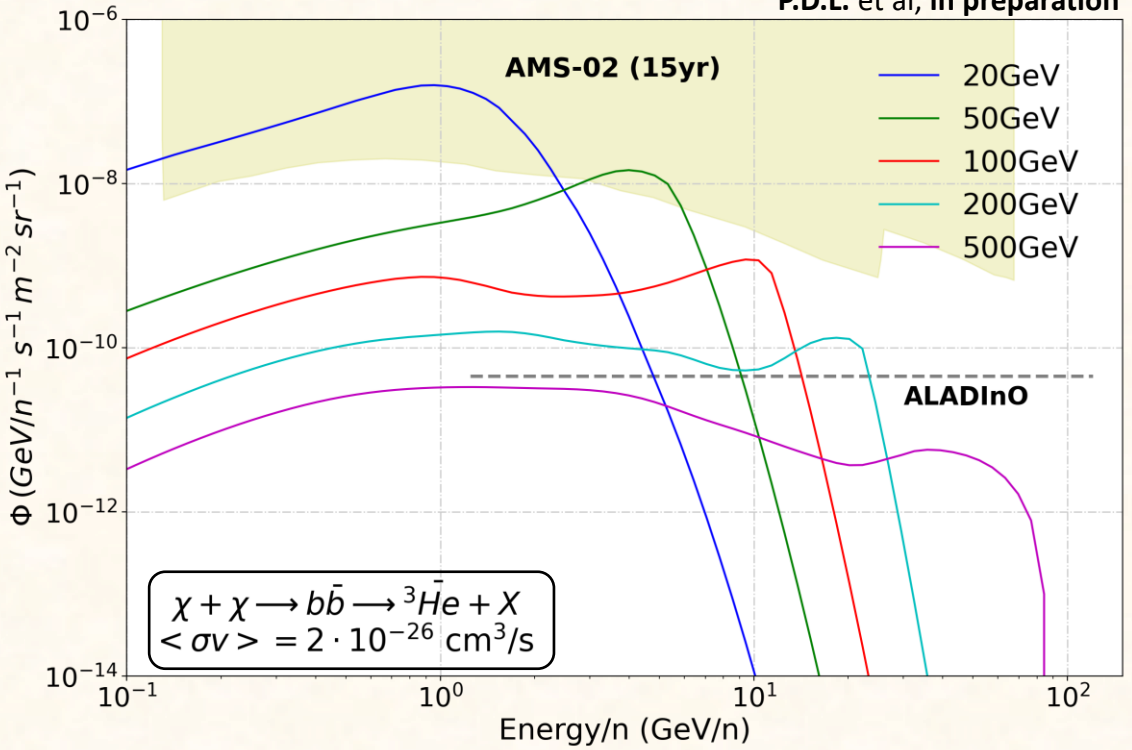
Dark matter production



The window to prove (or disprove) the WIMP paradigm

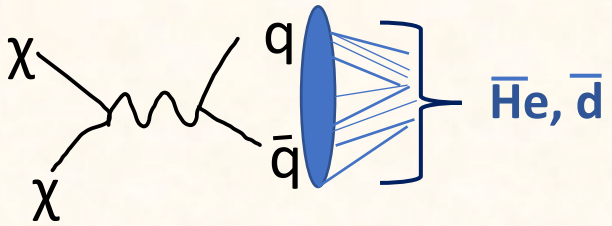


P.D.L. et al, **in preparation**



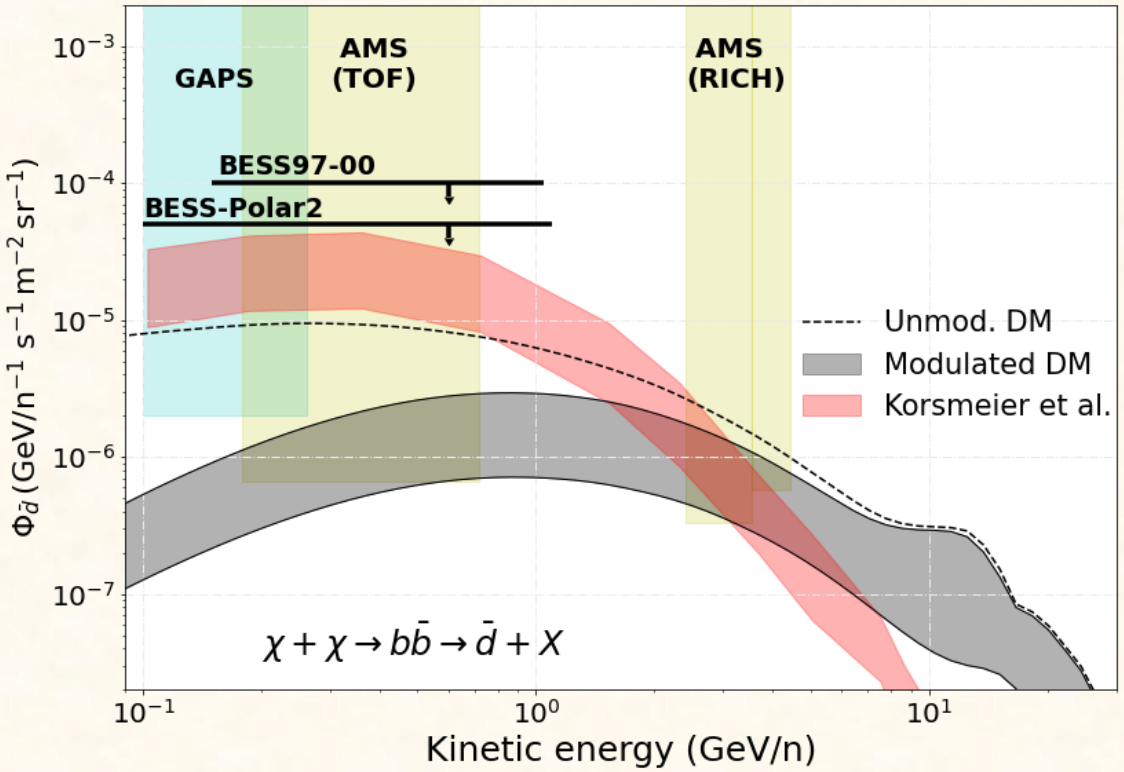
PPPC – M. Cirelli tables:
http://www.marcocirelli.net/PPPC4DMID.html

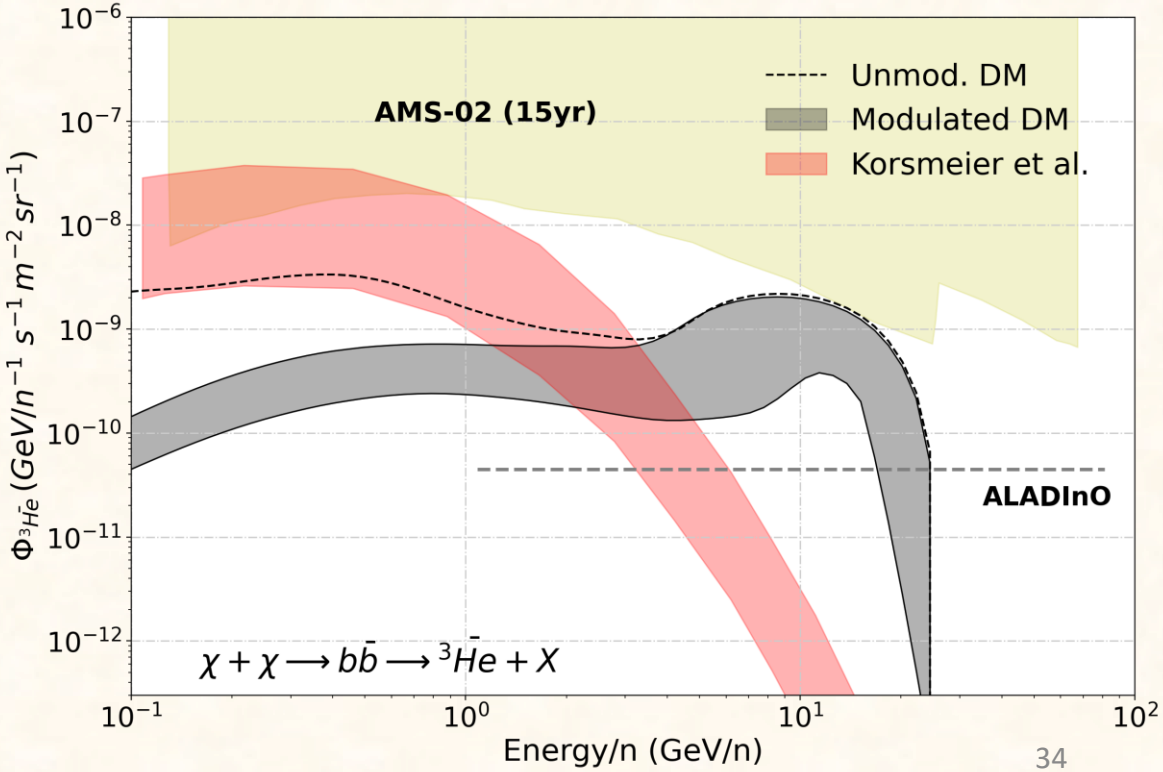
Dark matter production



Estimations of the expected flux from DM hints have changed significantly over the last years. **The measurement of anti-deuteron events by GAPS or the TOF (AMS-02) will certainly evidence exotic mechanisms of production of these particles**

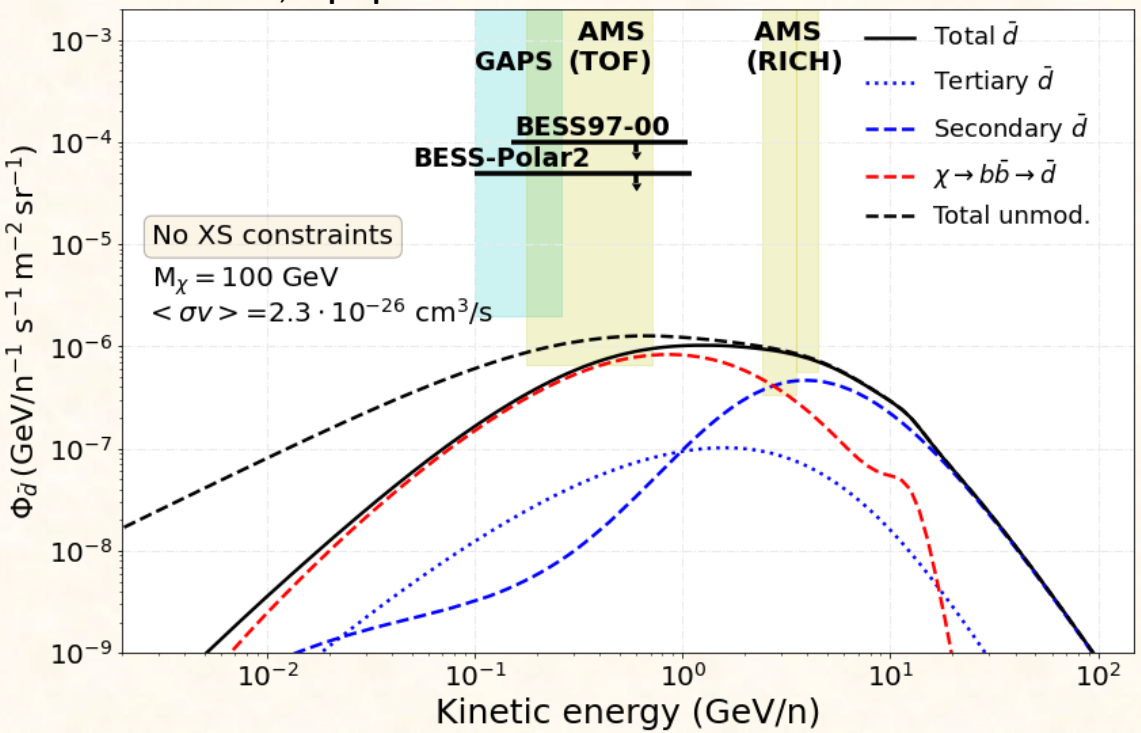
P.D.L. et al, **in preparation**



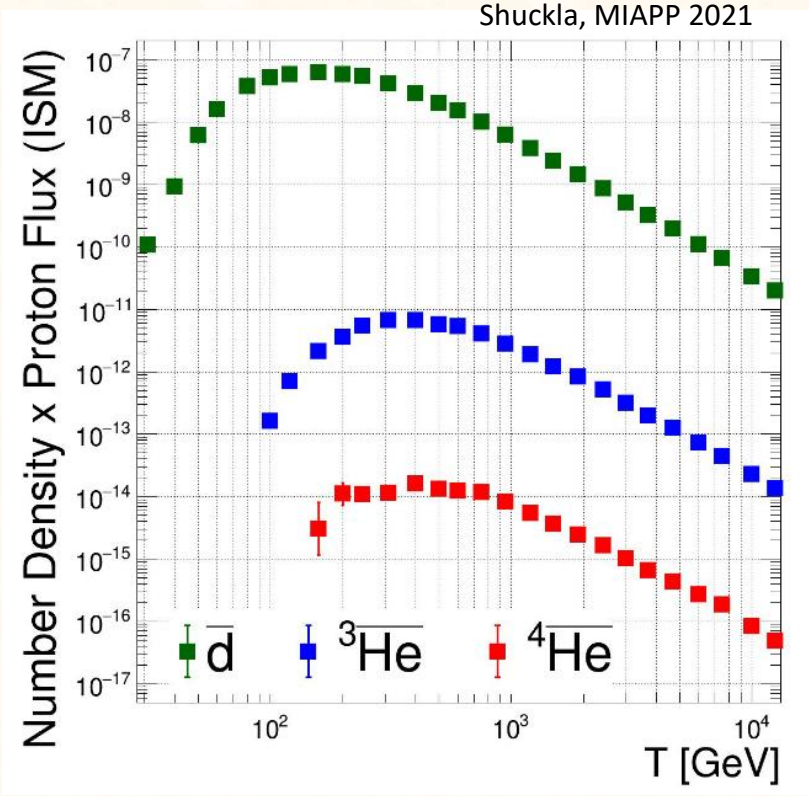


Anti-nuclei as the dark matter smoking gun

P.D.L. et al, **in preparation**



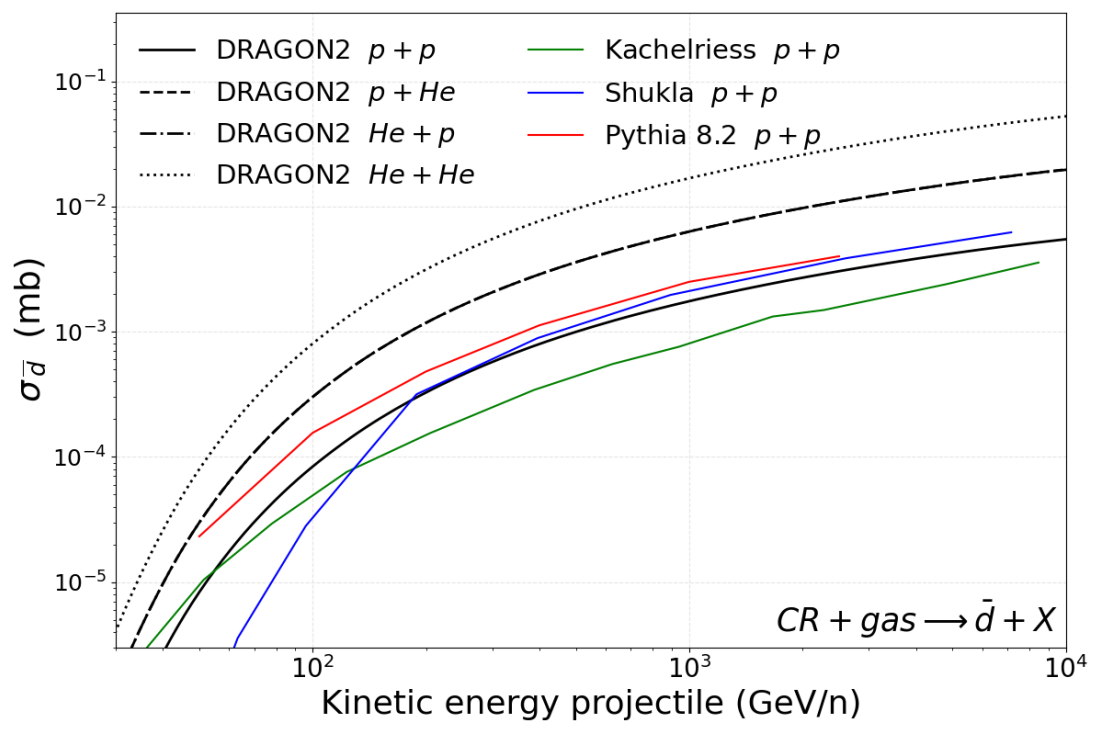
Shuckla, MIAPP 2021

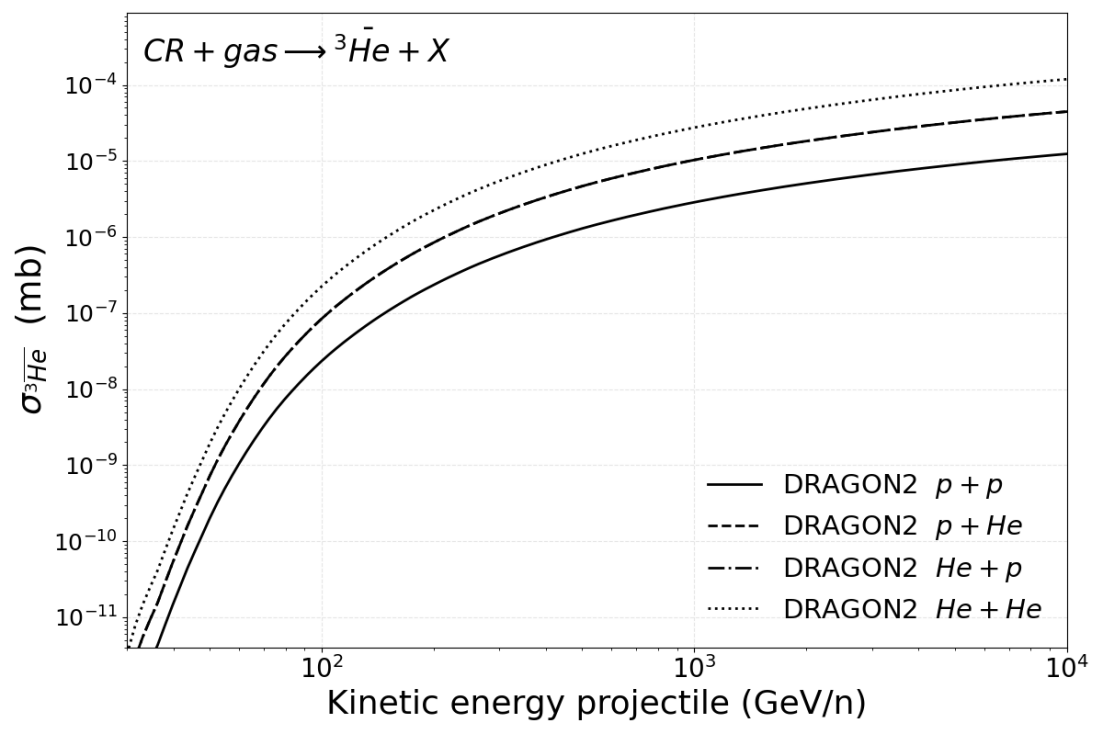


Detected anti-D events possibly explained, but impossible to explain more anti-He events!

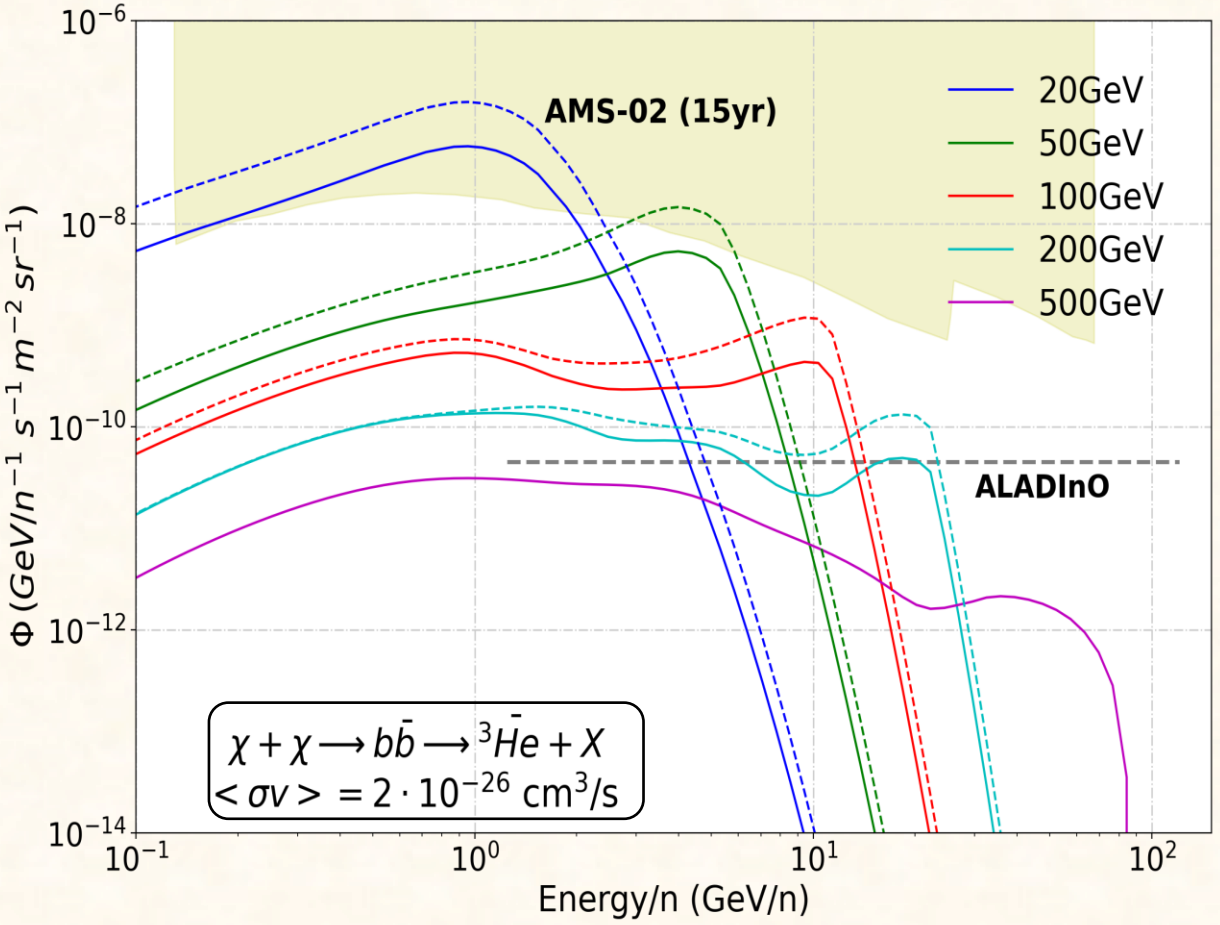
New antinuclei cross sections!

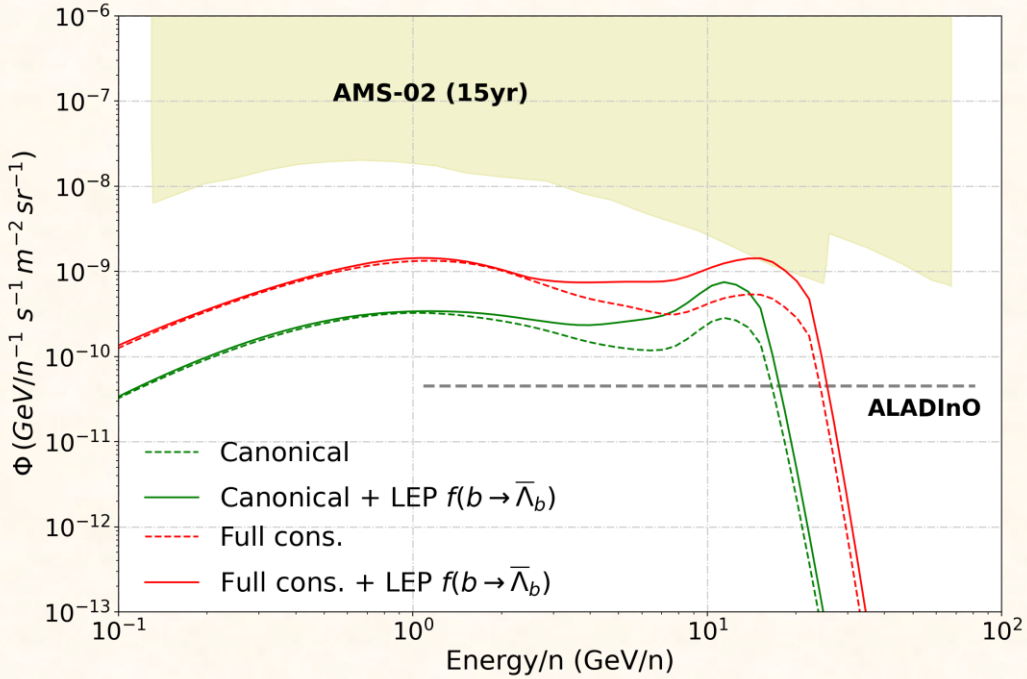
Derived analytically using the factorized coalescence model model from the Winkler (2017) cross sections for antiprotons. Coalescence momentum adjusted to reproduce ALICE p+p data!





LEP correction vs plain Pythia





How to avoid current uncertainties and improve our models!?

- Better description of the **distribution of gas density**
- Refined and more complete description of **solar modulation**
- More **measurements** of **cross sections of production of secondary CRs (B, Be, Li)** at energies above a few GeV/n
- **Cross sections measurements for the production of antiprotons** from He (and heavier nuclei) collisions and broader energy range for p-p collisions
- Improvement on the description of **coalescence** by nuclear codes such as Pythia, motivated by the latest measurements by ALICE and other experiments
- Publication of **AMS-02** upper limits and covariance matrices (correlated errorbars)
- Description of the **propagation** of CRs beyond the spatially-constant scenario