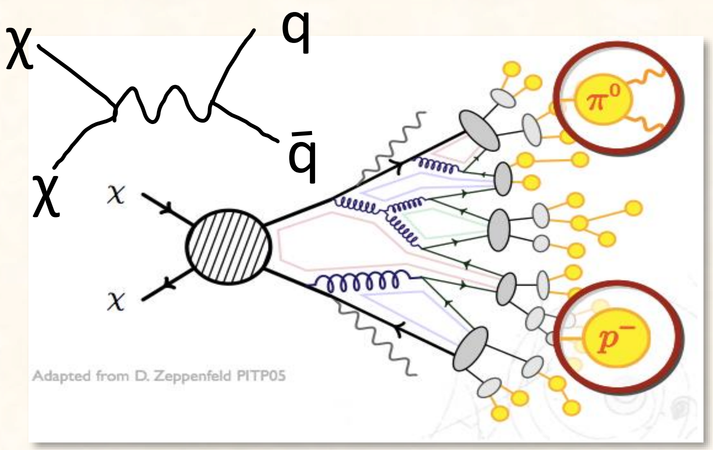
CR antiprotons elucidate prospects for antinuclei detection

ArXiv: 2404.13114
ArXiv: 2401.10329



Pedro de la Torre Luque --- pedro.delatorre@uam.es
Juan de la Cierva fellowship (IFT/UAM - Madrid)

IDM 2024, L'Aquila – 11/07/2024

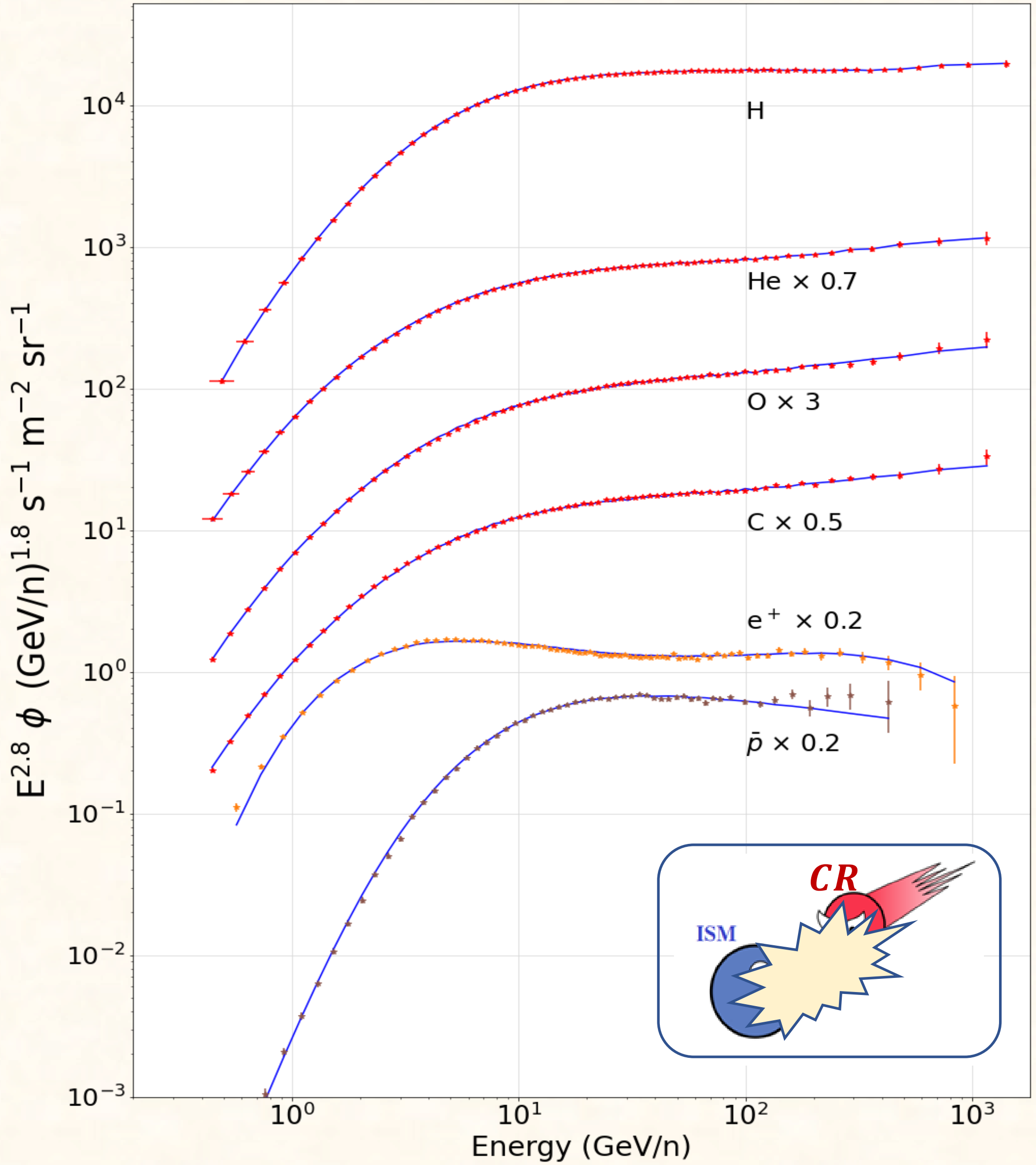
Potential of antiparticles to reveal the existence of BSM physics

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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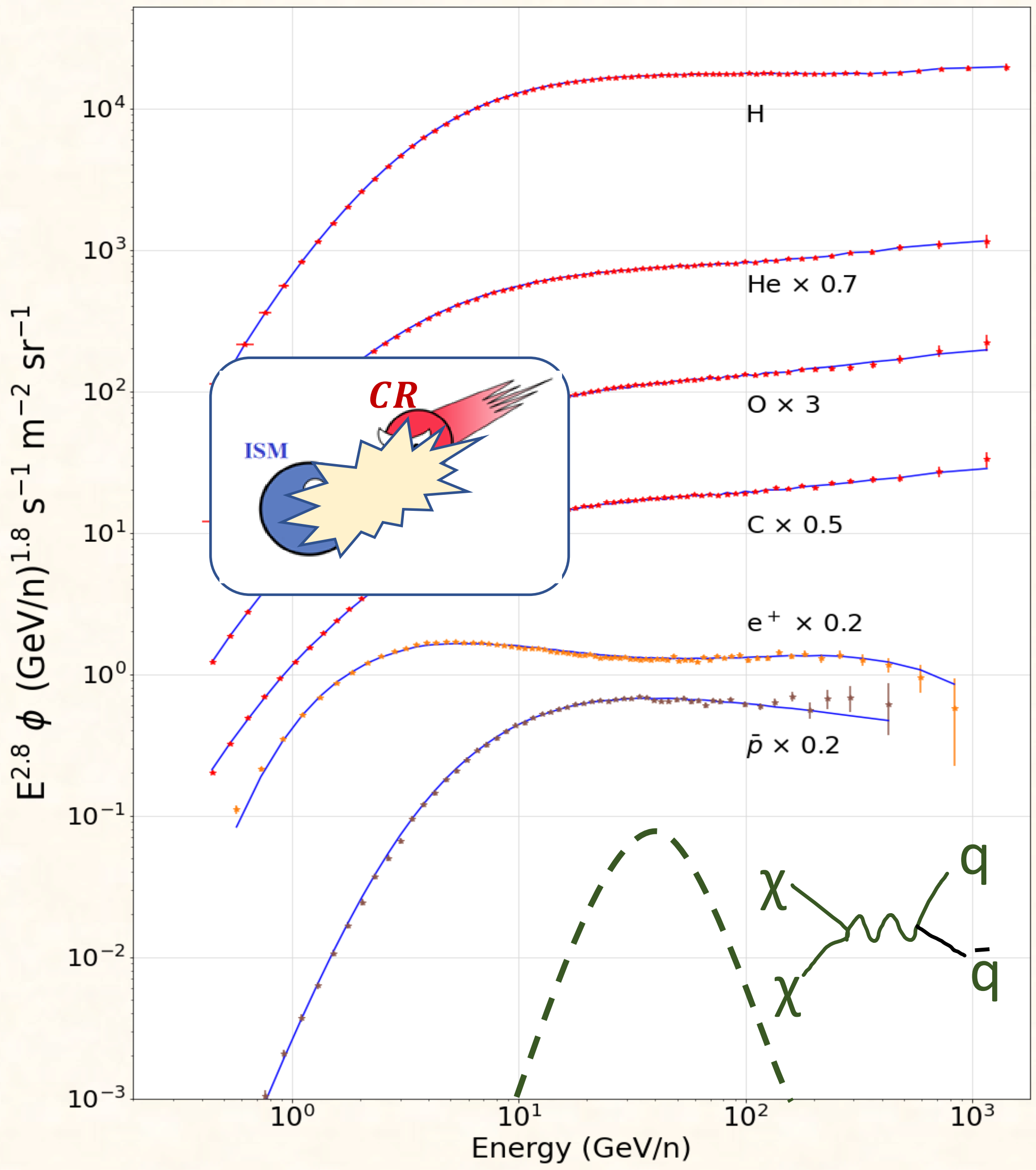
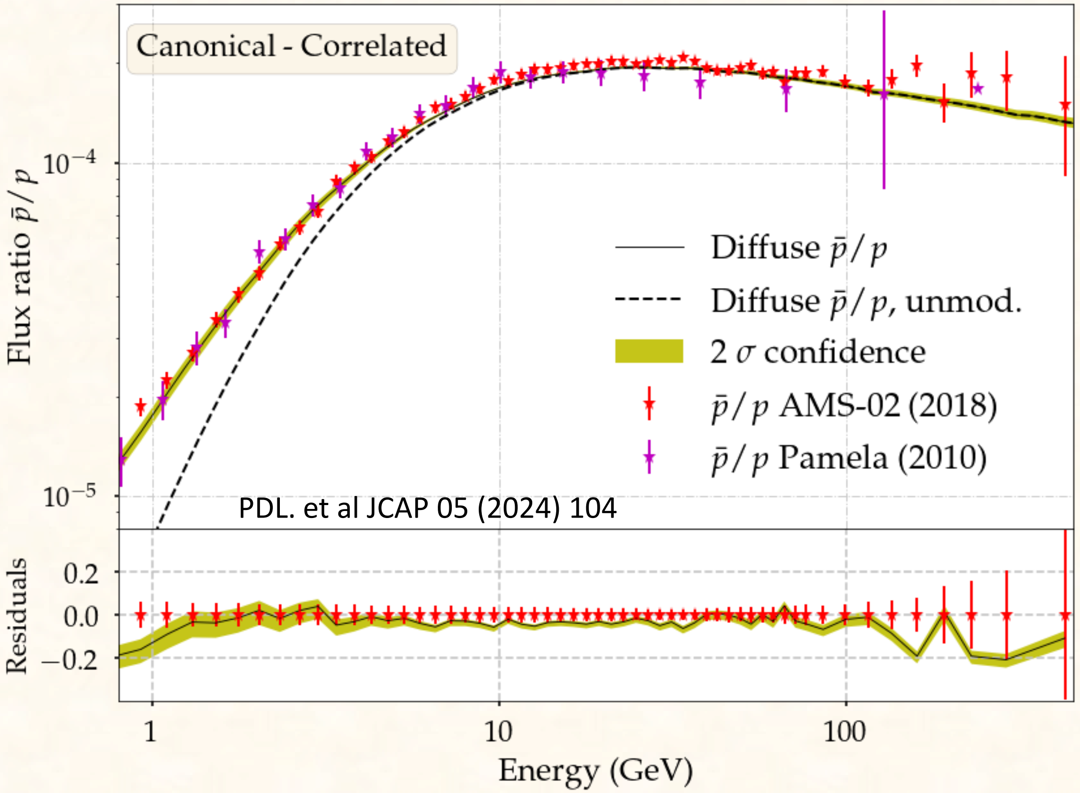


AMS-02 reveals the origin of antiprotons

Recent analyses demonstrate that **antiproton observations are fully compatible with a secondary origin** and all secondary CRs can be well explained considering cross sections uncertainties – However, including also DM production is still preferred in the fit for a WIMP with mass around 70 GeV with annihilation rate close to the thermal relic one…



PDL. et al JCAP 05 (2024) 104

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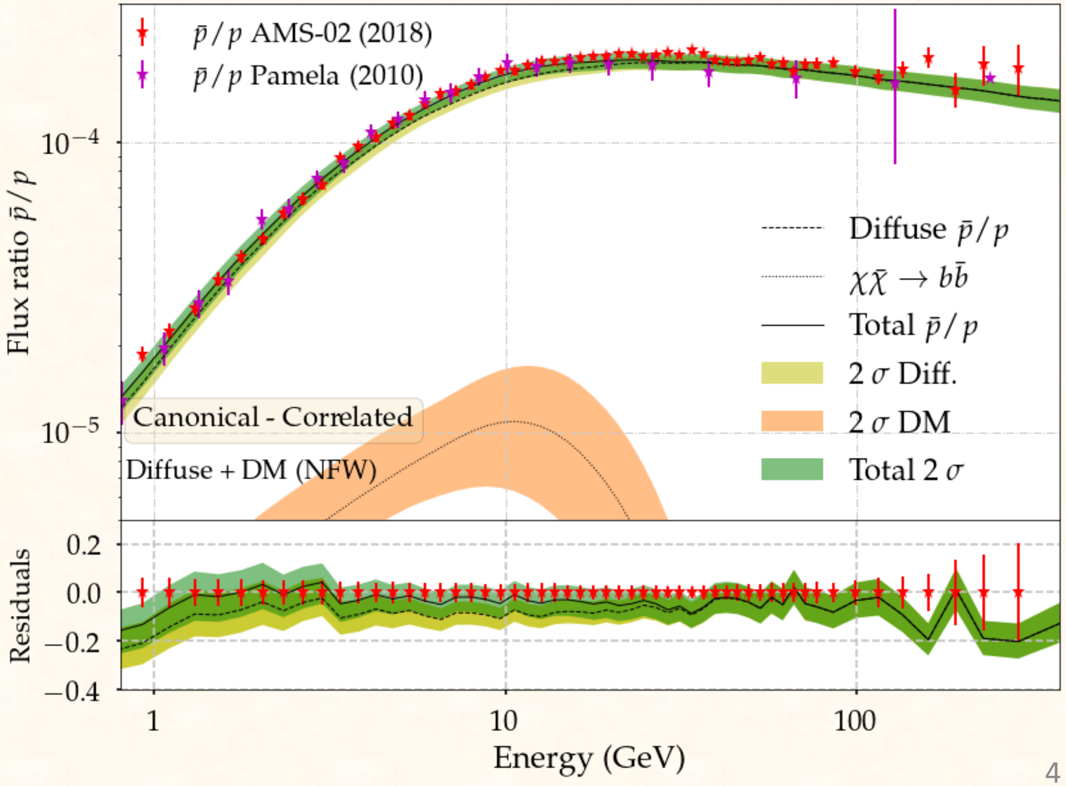
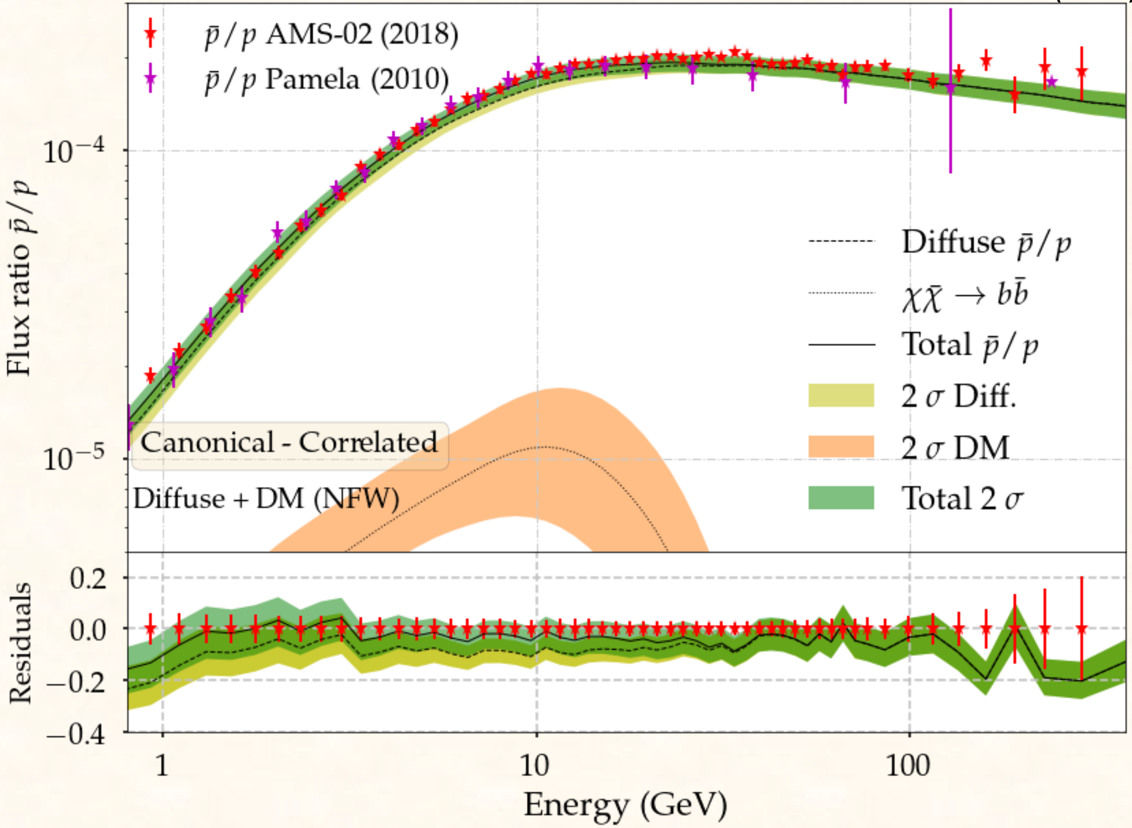


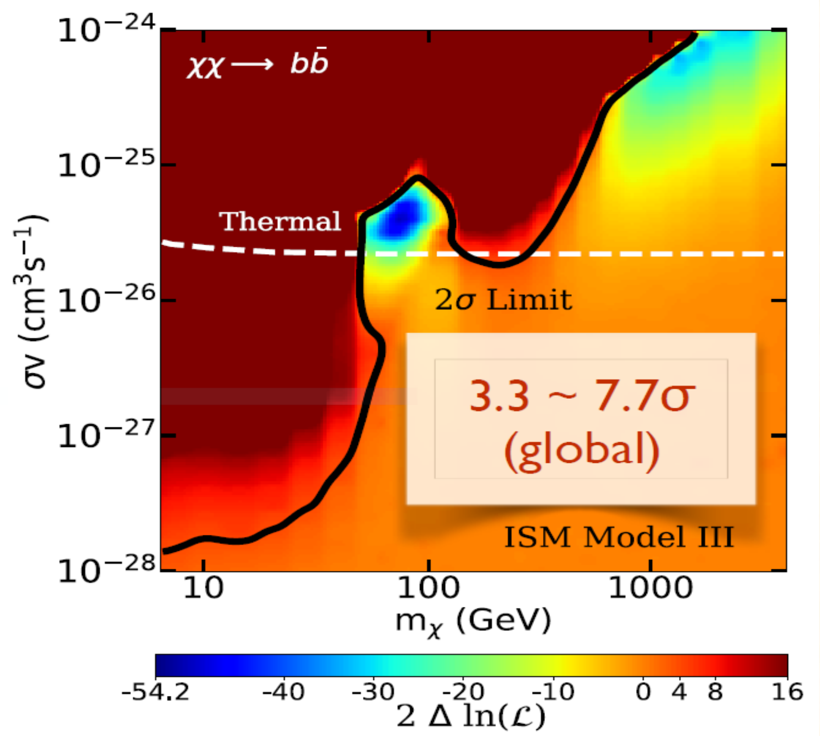
AMS-02 reveals the origin of antiprotons

Detailed DM searches found different sources of uncertainties difficult to avoid in current studies: Cross sections, correlated errors, diffusion model … A statistical evaluation of the signal shows that **there is no significant excess in the data (maximum of 1.8 sigma)**

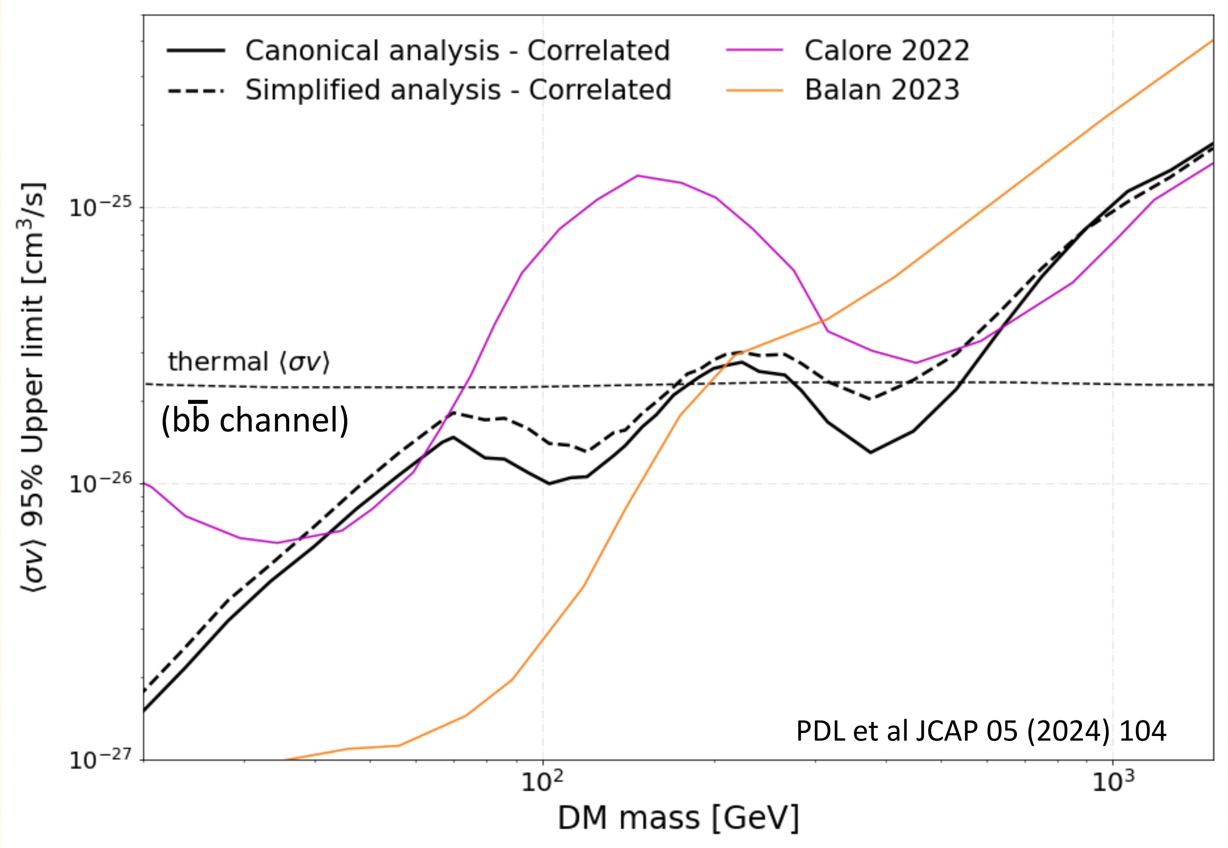
PDL et al JCAP 05 (2024) 104



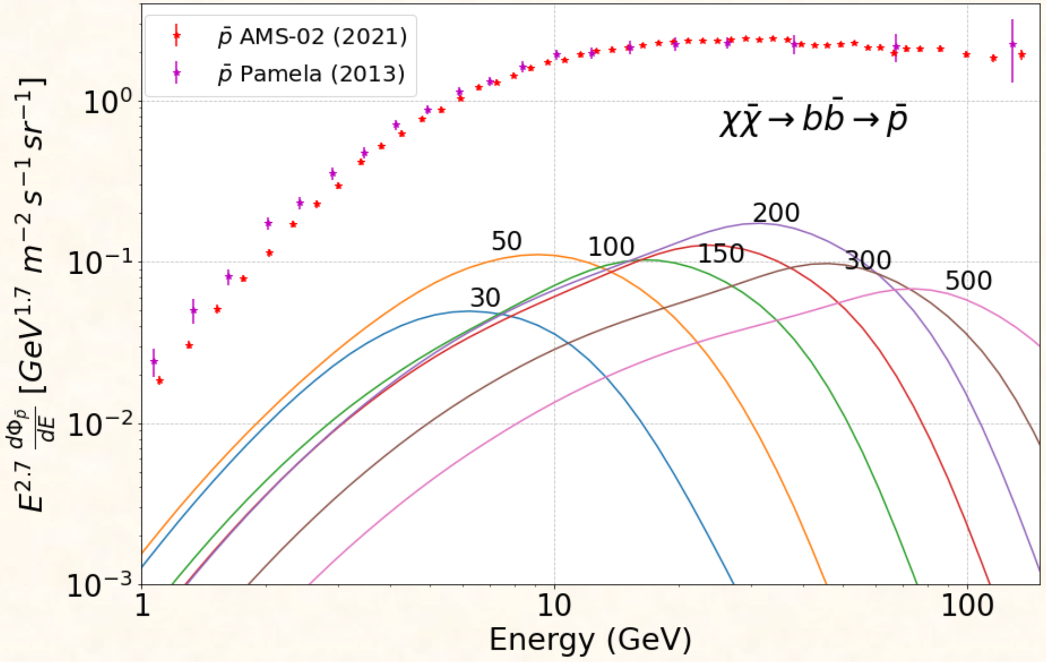
Hooper et al PRD 99, 103026 (2019)



Dark matter bounds from antiproton analyses



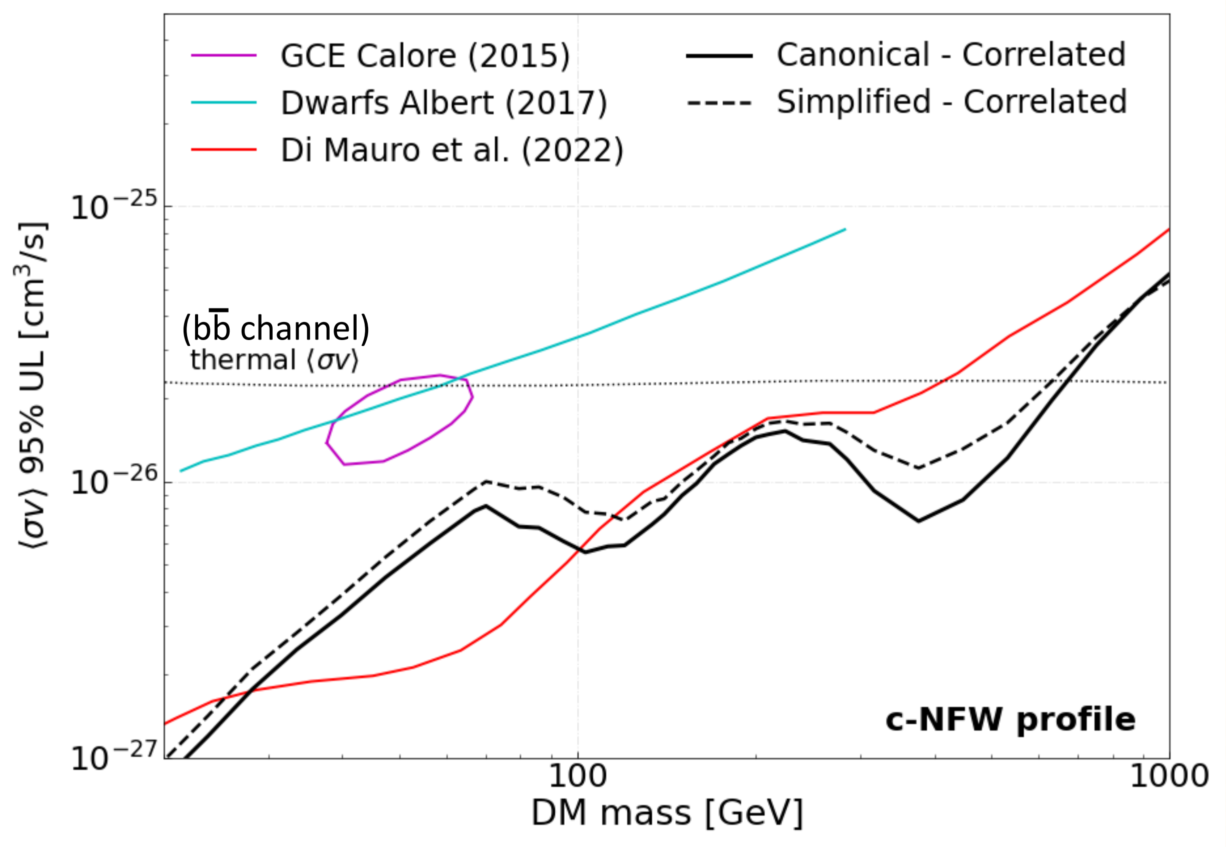
Maximal DM-induced signal (at 2 σ)



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

Leading constraints for WIMPs annihilating into hadronic final states, and ruling out the thermal relic cross sections for masses below ~200 GeV

Dark matter bounds from antiproton analyses



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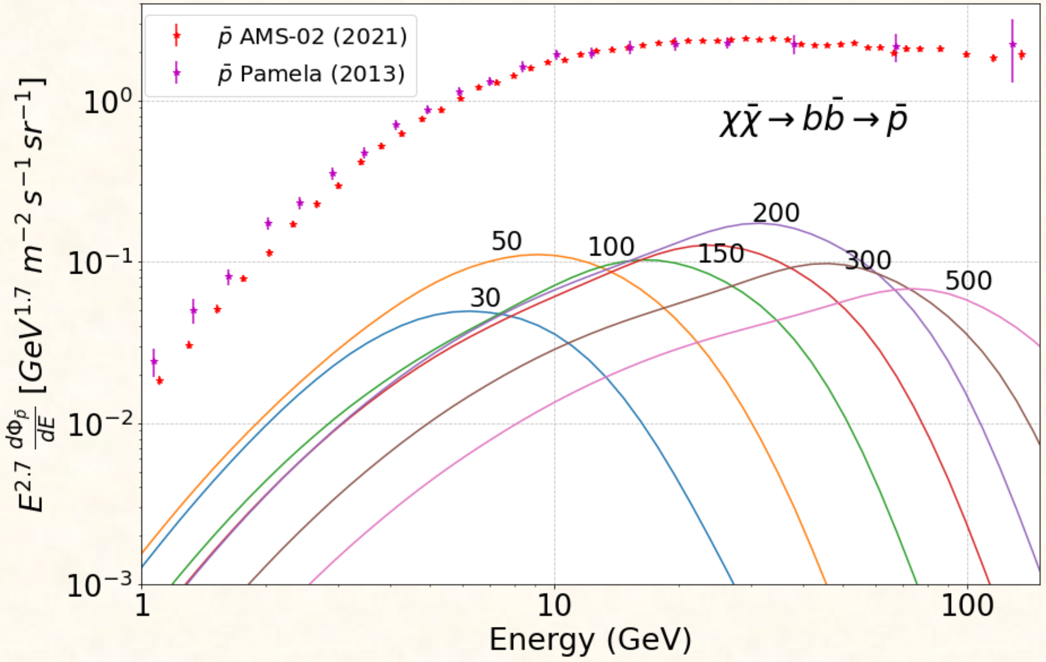

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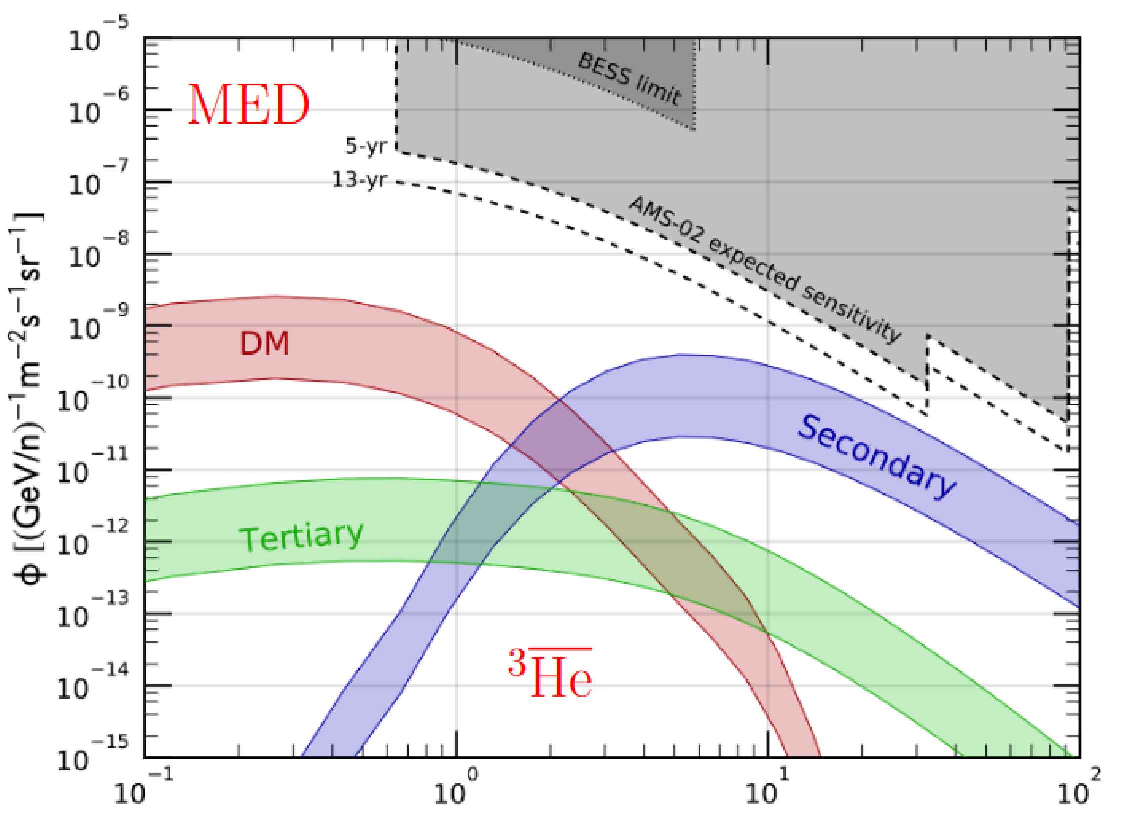
Anti-nuclei as the dark matter smoking gun

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

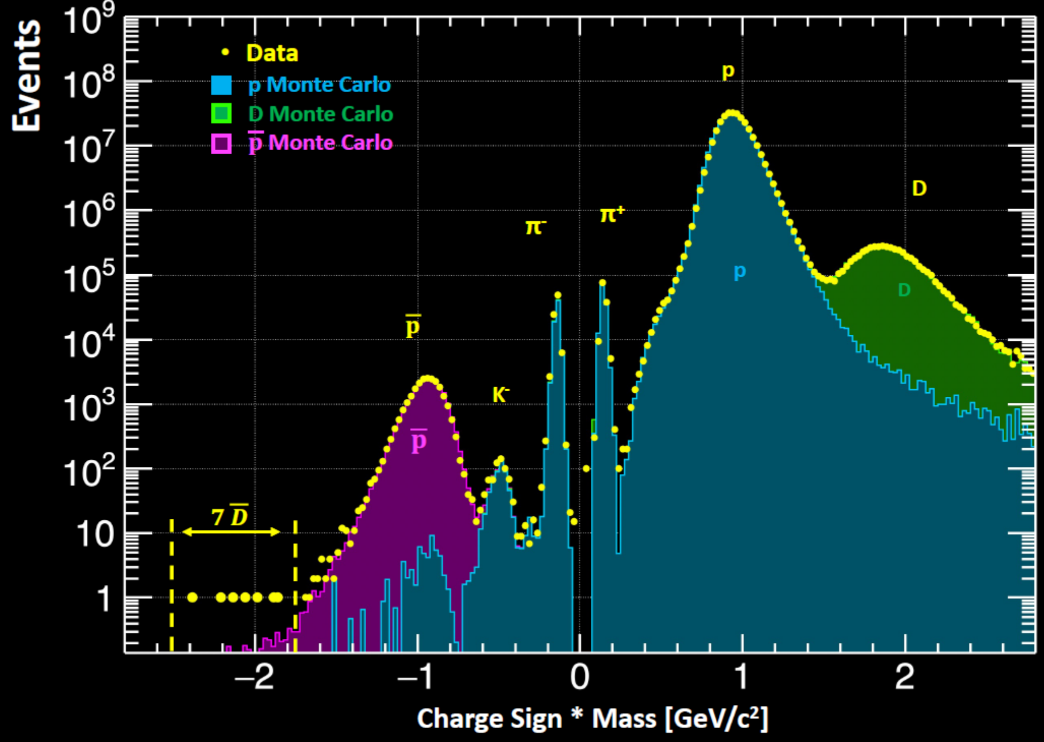


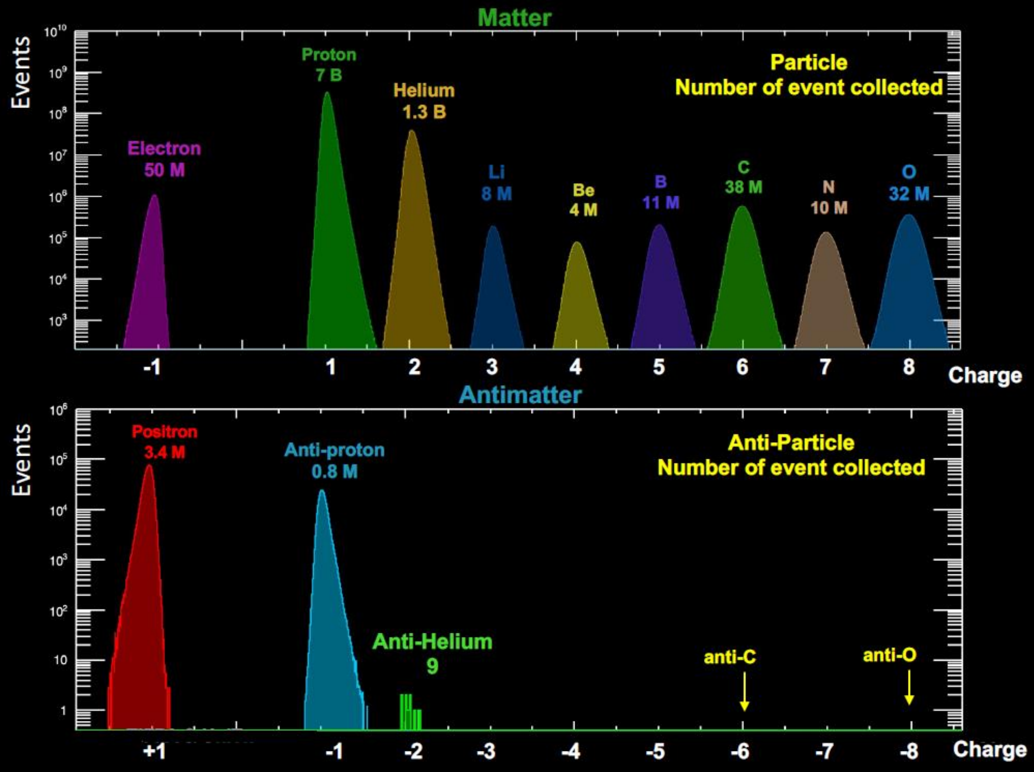
Korsmeier et al (2018) PRD97, 103011

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





Paolo Zuccon MIAPP 2021

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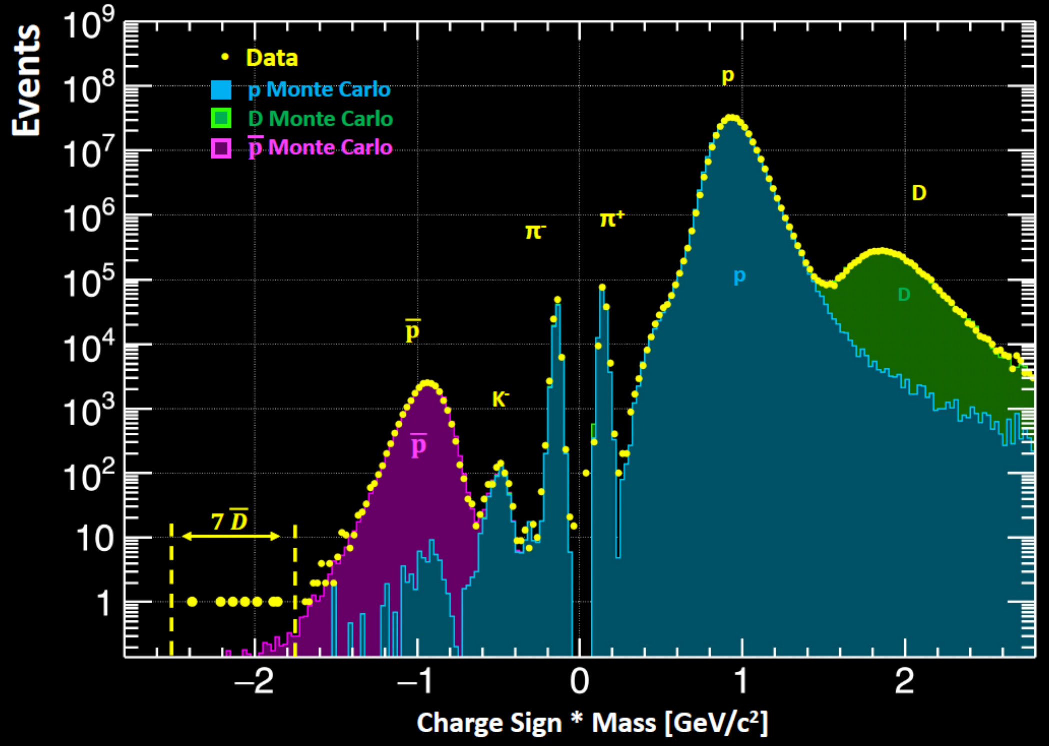

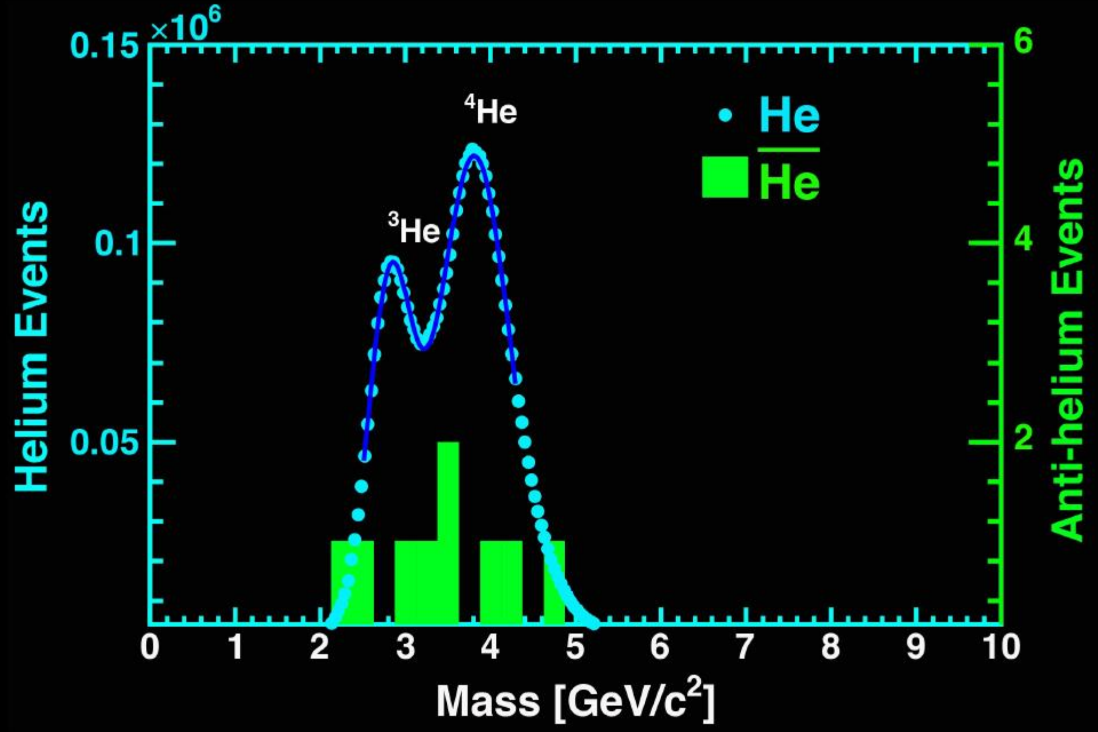

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Propagation setup

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

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

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- DM spectrum at production derived from *Pythia 8.2* simulating a neutral colourless resonance.
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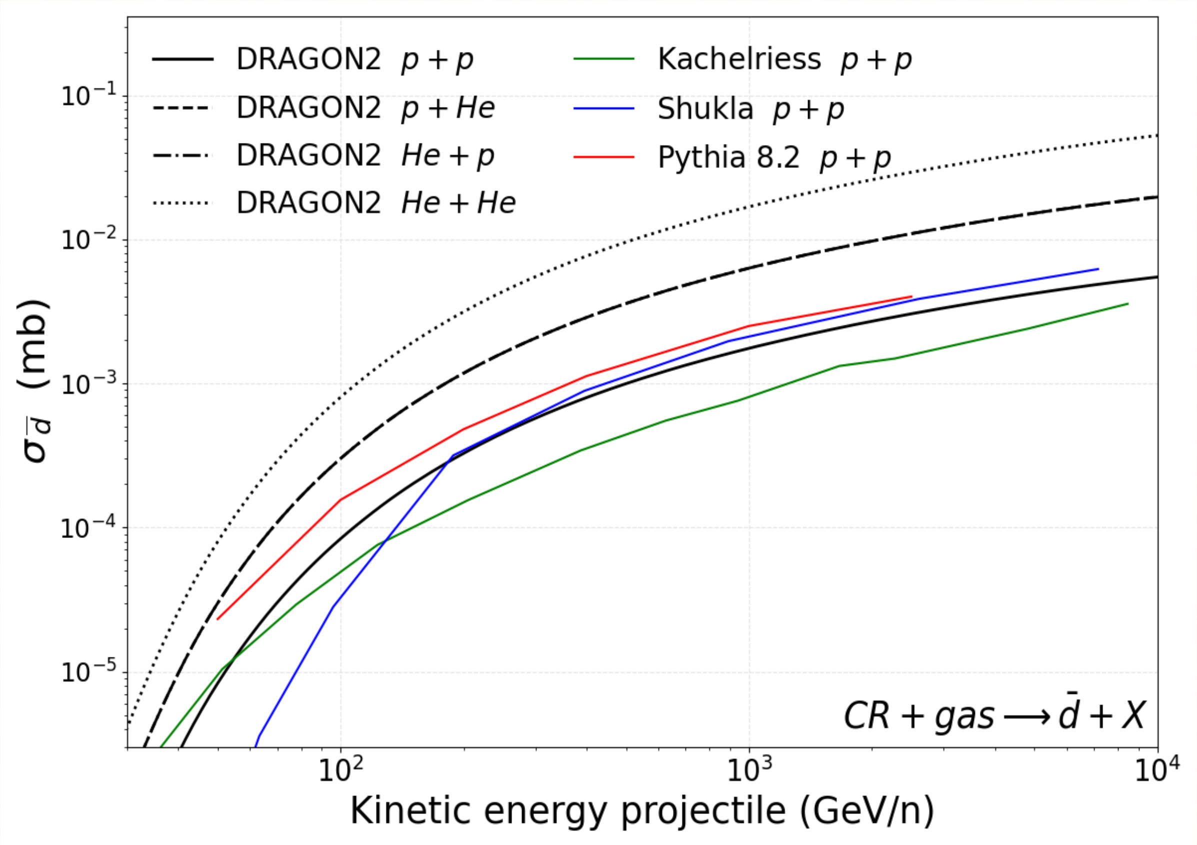
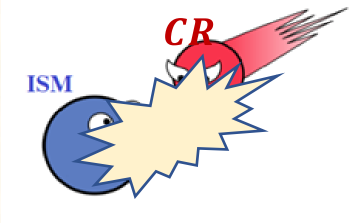


PDL et al, ArXiv: 2404.13114

Astrophysical production

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

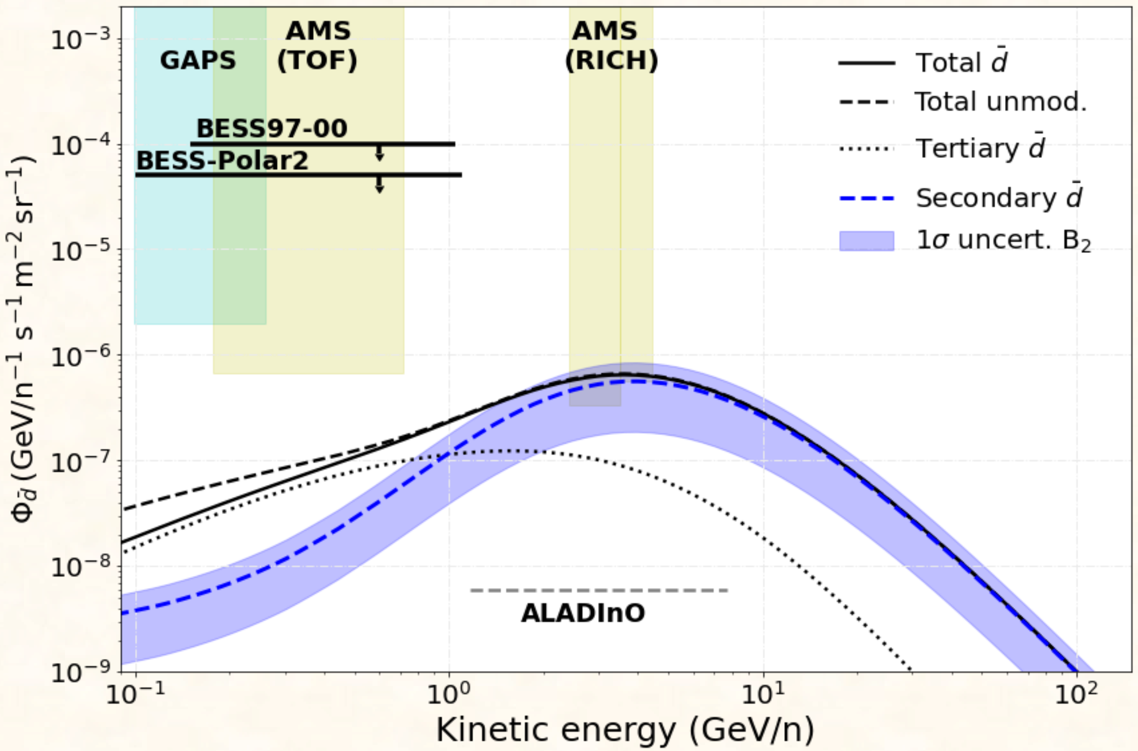


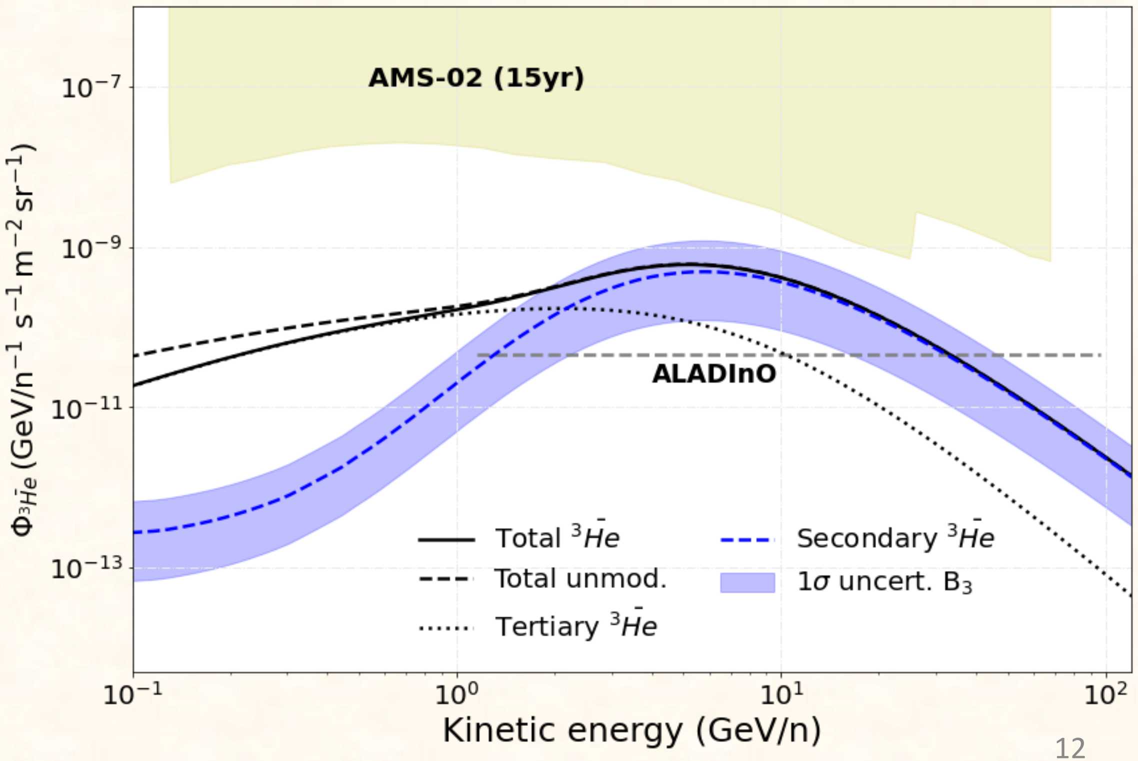
Can we explain the AMS-02 measurements without invoking any exotic source?

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

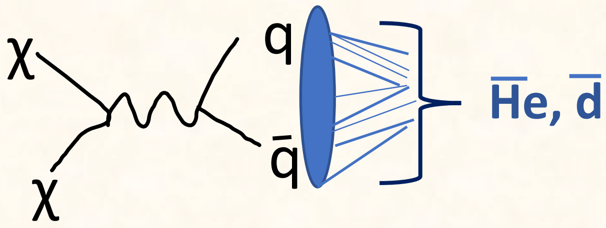
We expect to have measurements of the $\bar{d}$ flux in the next years!! But nothing about $\overline{He}$ till ALADInO or AMS-100 (foreseen to 2039)

PDL et al, ArXiv: 2404.13114



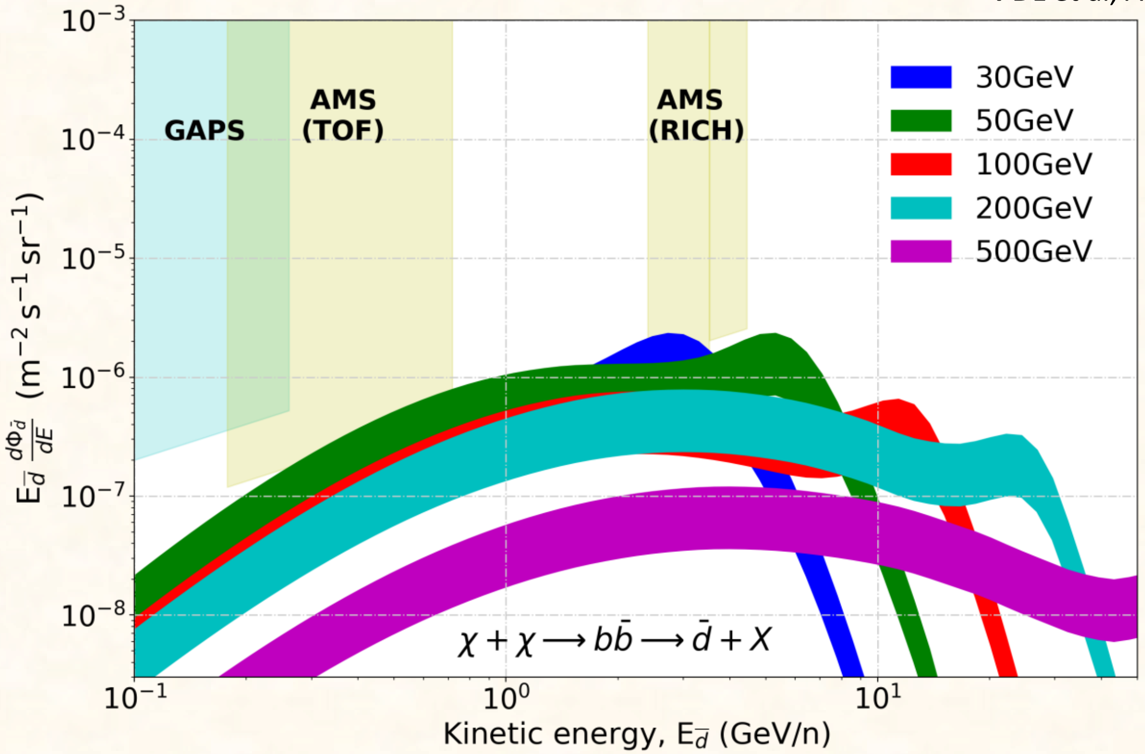


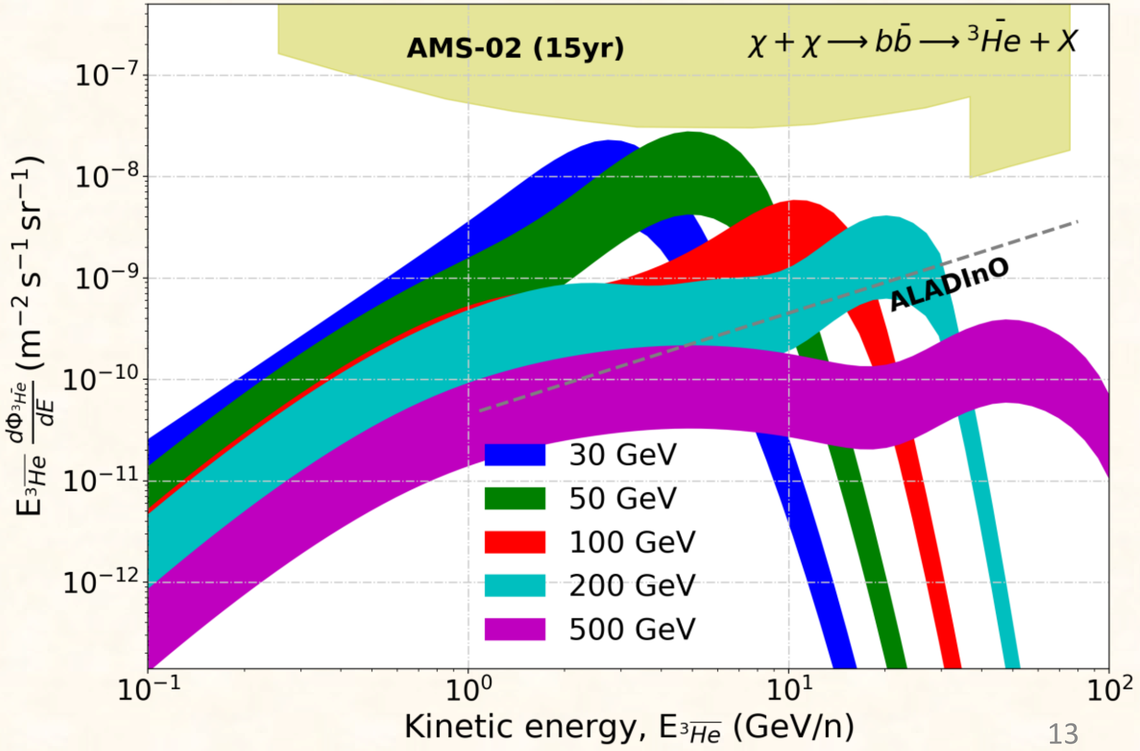
DM production: Upper Limits



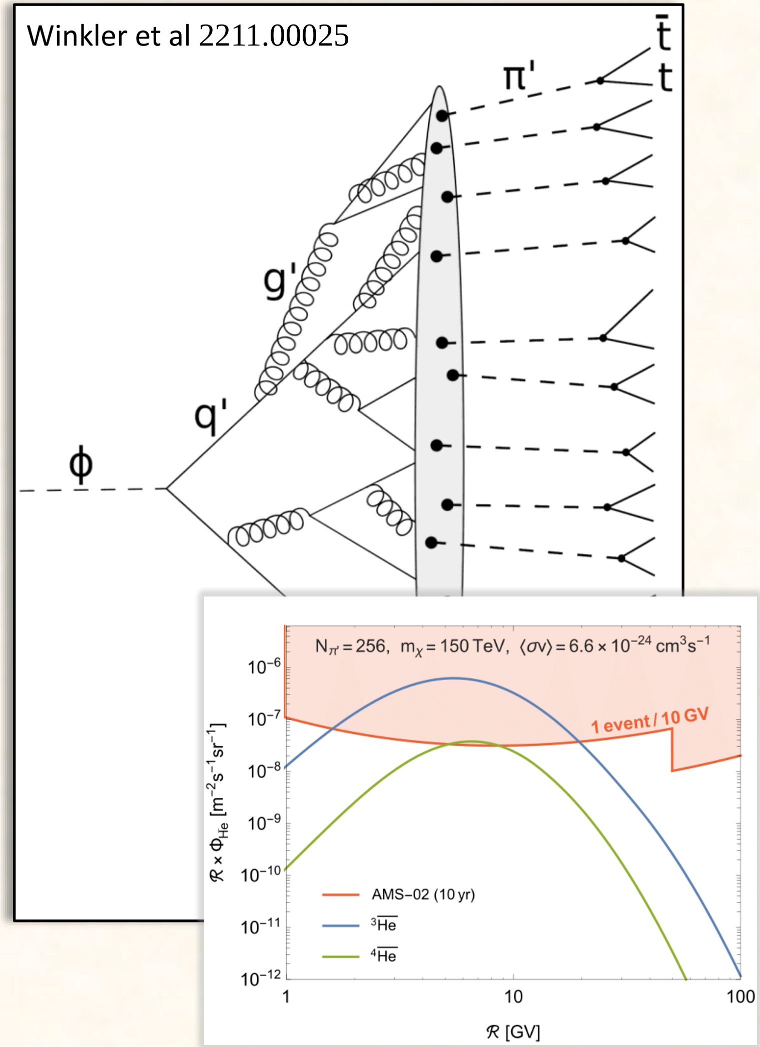
Maximal antinuclei flux allowed from our antiproton bounds. Uncertainties in the coalescence momentum can hardly explain the detection of $O(1)$ antihelium-3 event by AMS-02, but are **unable to explain any detection of antihelium-4 by AMS-02**…

PDL et al, ArXiv: 2404.13114





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

Only a few ideas proposed so far:

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

Stability and cosmological implications must be revised

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

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

Fireball anti-nucleosynthesis (Fedderke et al. 2402.15581)

Fireballs must be very stable for long times and carry negative net antibaryon number

Conclusions

CR antiprotons elucidate prospects for antinuclei detection

- **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**
- A few possible (although speculative) explanations can be viable solutions and testable in accelerators – Although both the measurements and the models employed are yet not totally reliable/exact

Pedro de la Torre Luque – 11/07/2024
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BACK UP

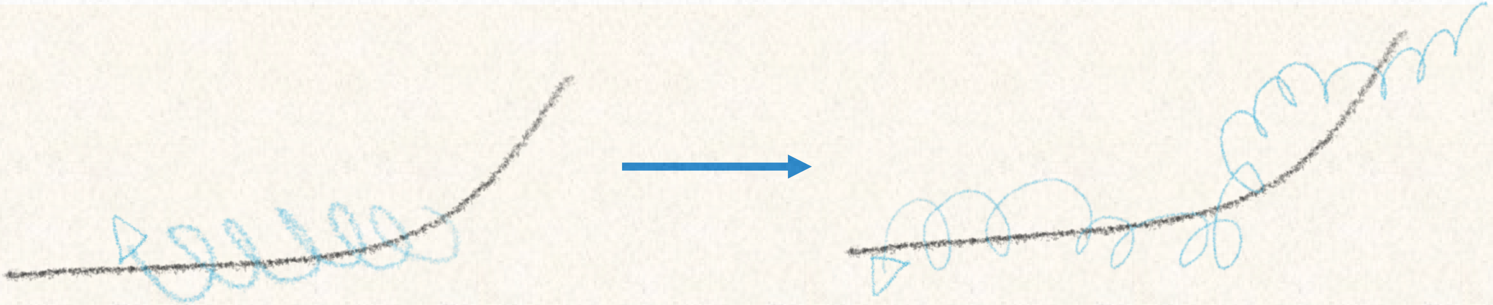
The propagation of CRs – Diffusion equation

- 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.

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

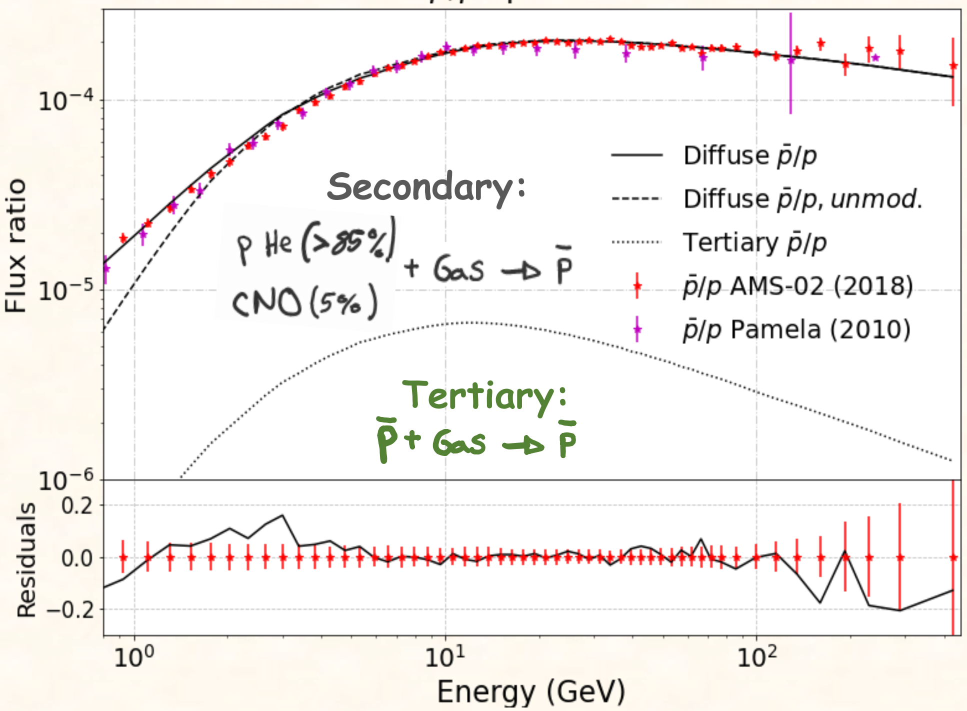
$$\boxed{D_{pp} \propto \frac{p^2\, VA^2}{D}}$$

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

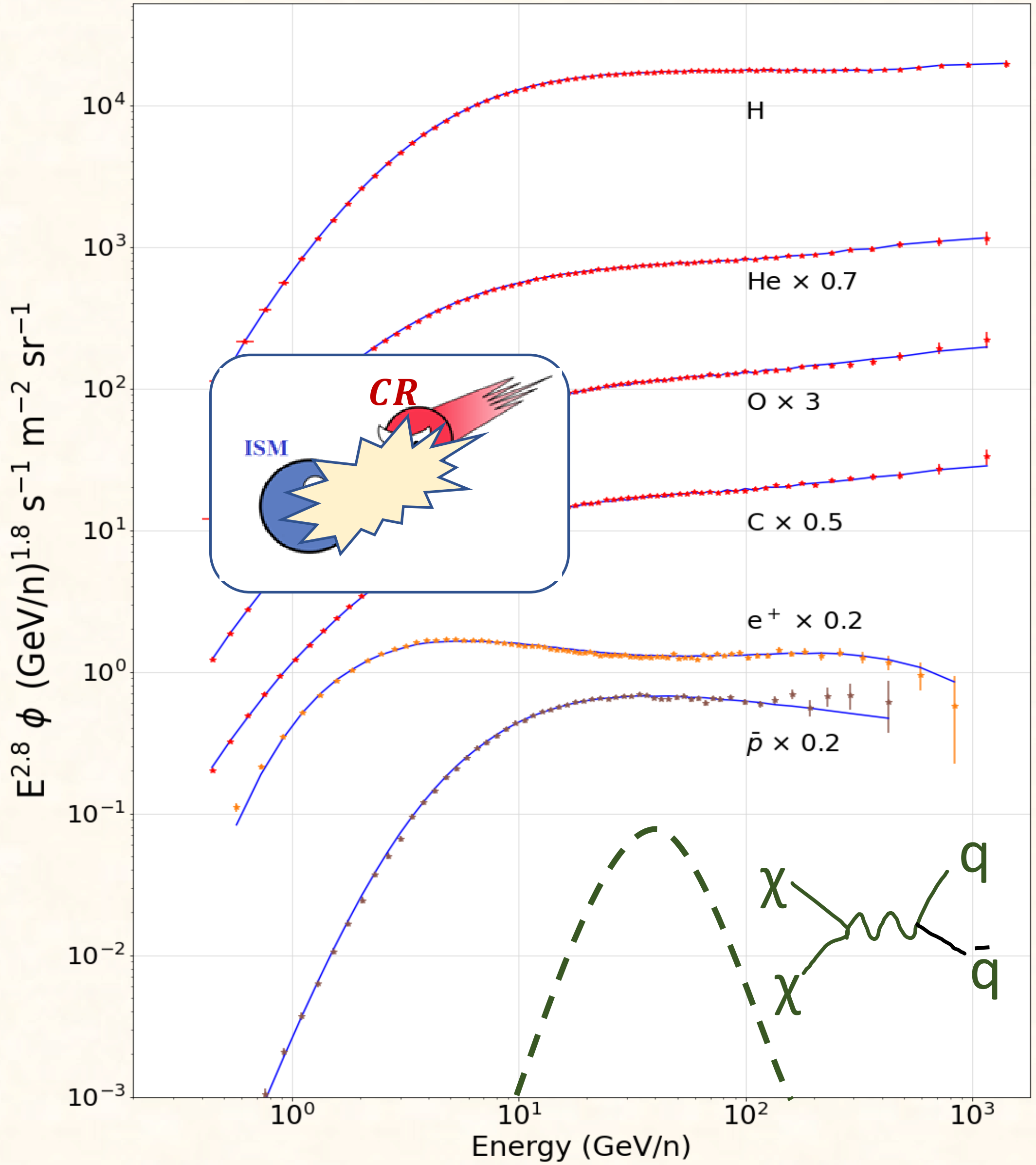


Potential of antiparticles to reveal the existence of BSM physics

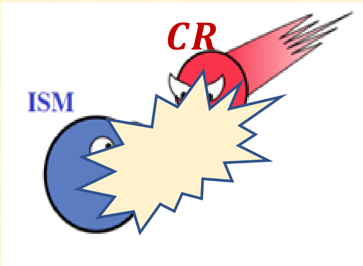
$p + p \rightarrow p + p + p + \bar{p}$ (High energy protons produce lower energy antiprotons)



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



Antiproton *excess* – A DM signal?

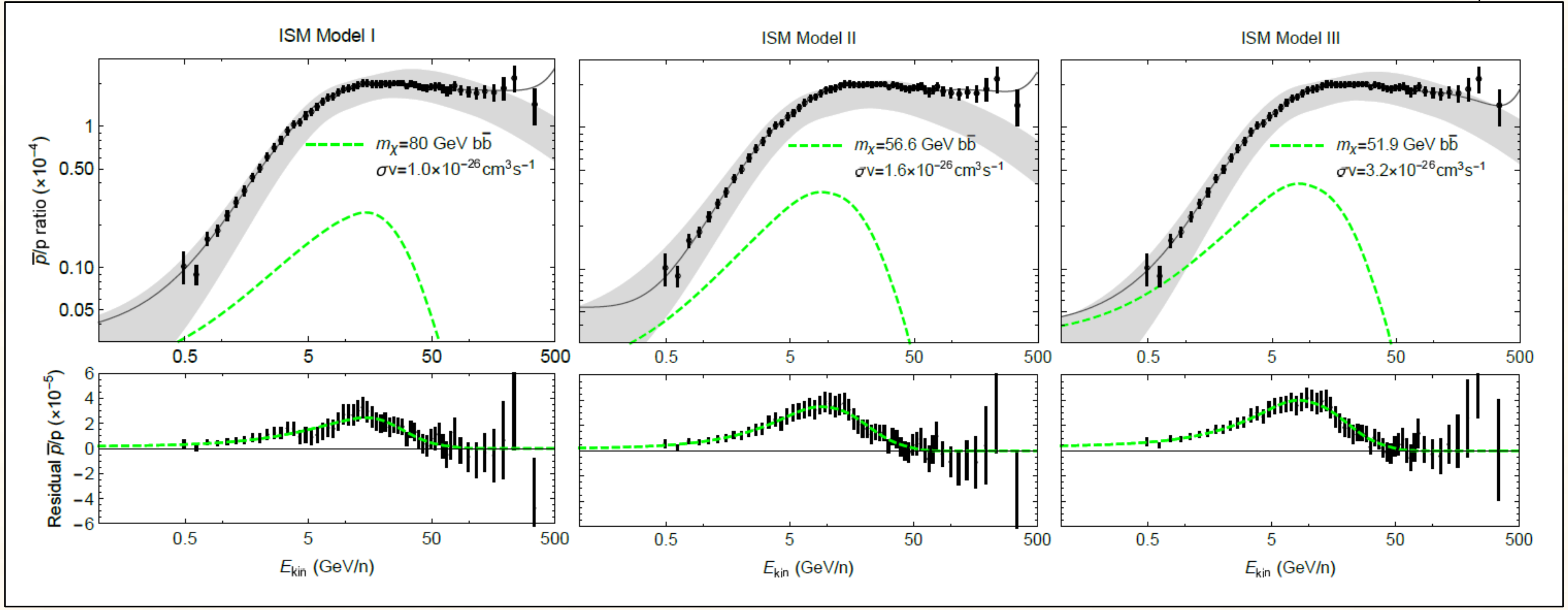


Several studies claimed the possibility of an **excess** of data over the predicted flux **at around 10-20 GeV**, which can be the **signature of dark matter** annihilating or decaying into antiprotons

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

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

Cholis et al PRD 99, 103026



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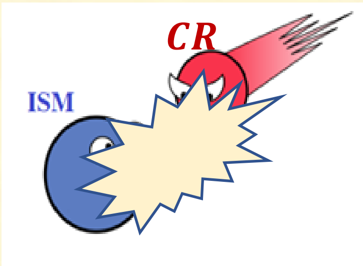
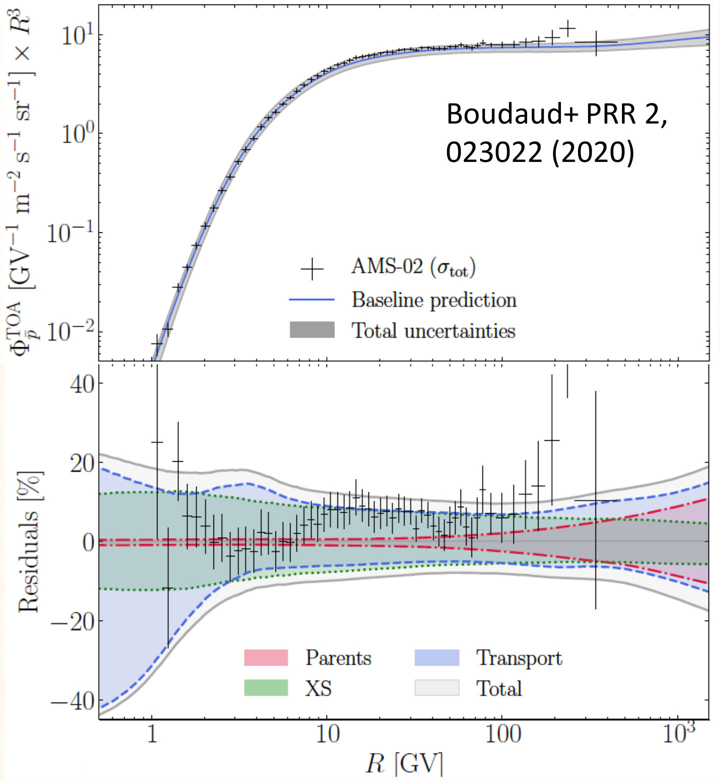
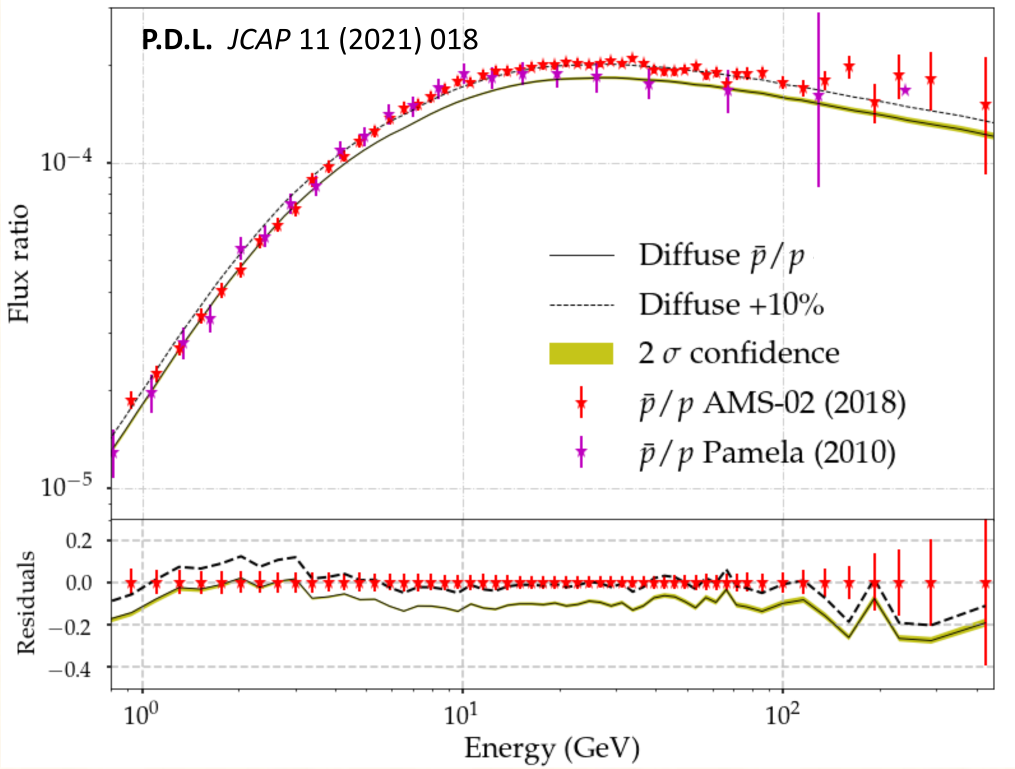


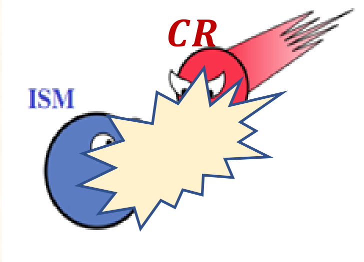
Further investigations revealed that the p̄ spectrum is **totally compatible with the rest of CRs**, without any need of dark matter.
Cross sections uncertainties and AMS-02 correlated errors are crucial

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





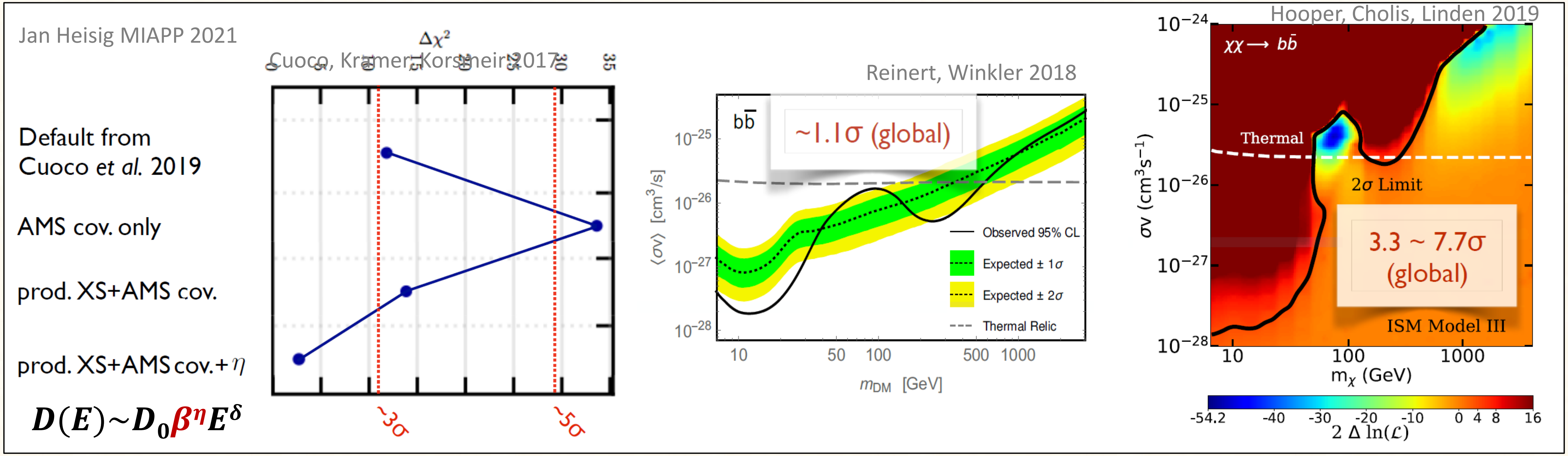
Antiproton *excesses* – *The spectral excess*



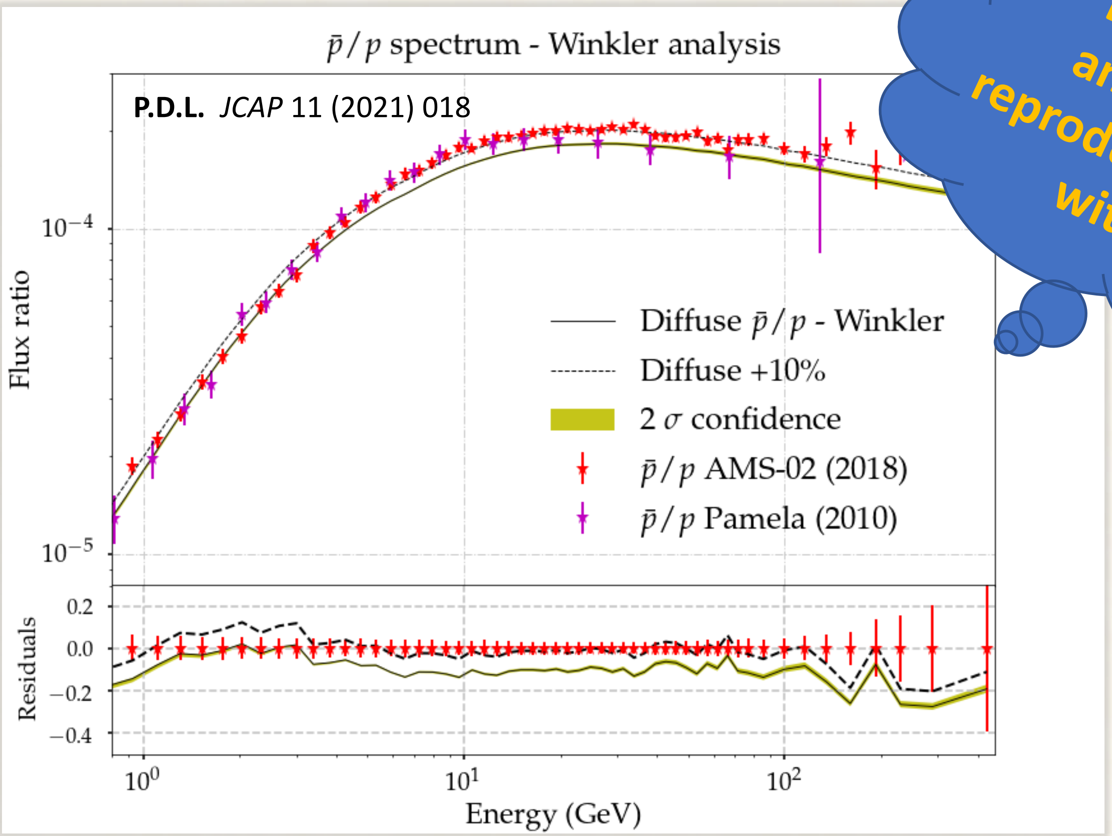
All analysis coincided in the position of the excess, but not in its significance… again, **the astrophysical uncertainties were not completely understood** (and they aren't yet!)

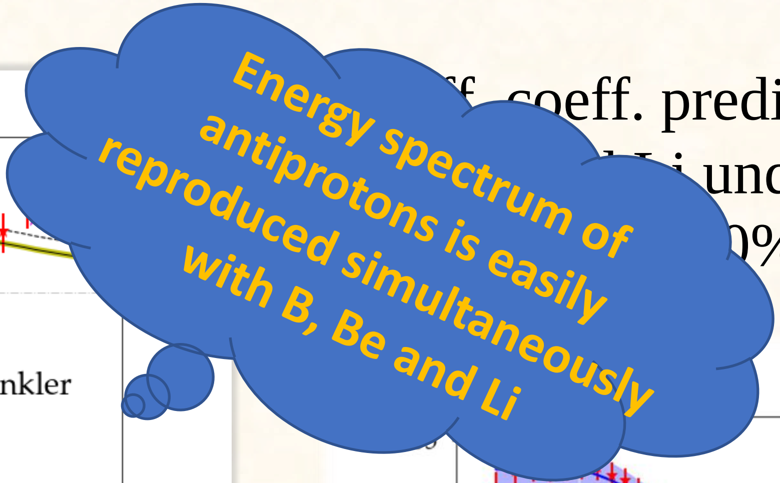
$p_{CR} + p_{ISM} \to \bar{p}$

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

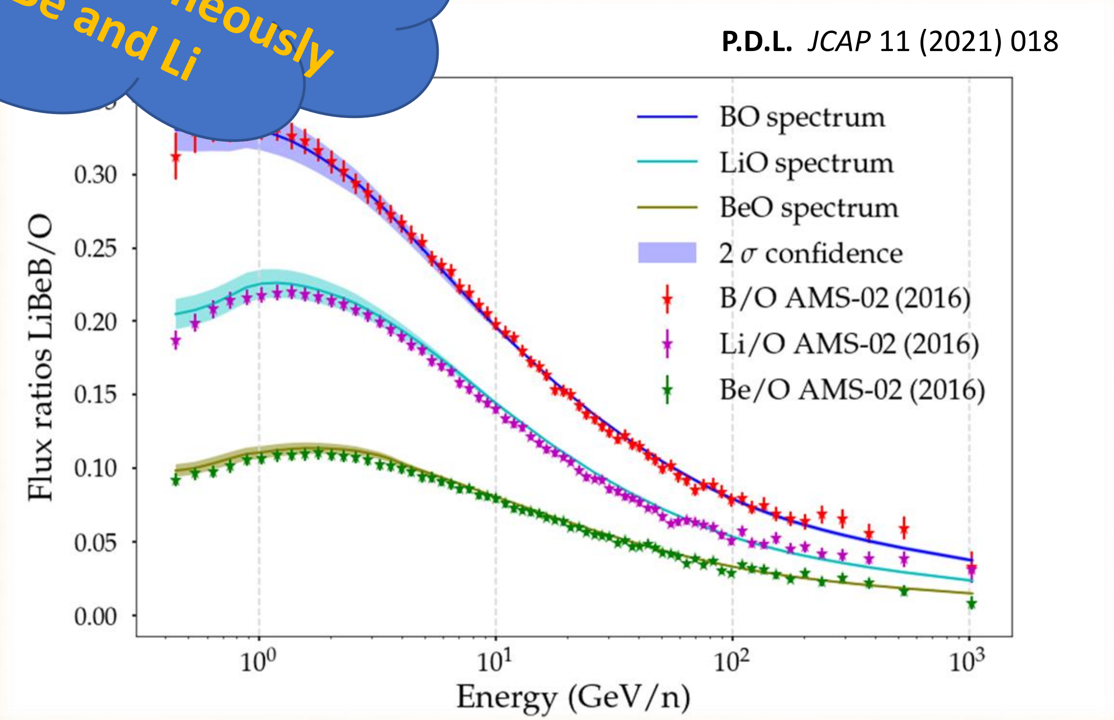


Antiproton excesses – *The grammage excess*





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



Conclusion: Cross sections uncertainties affect very significantly our predictions and can explain the excess

Astrophysical production

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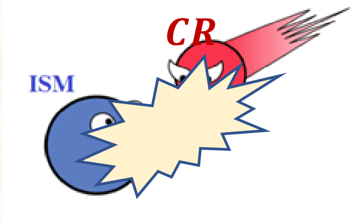

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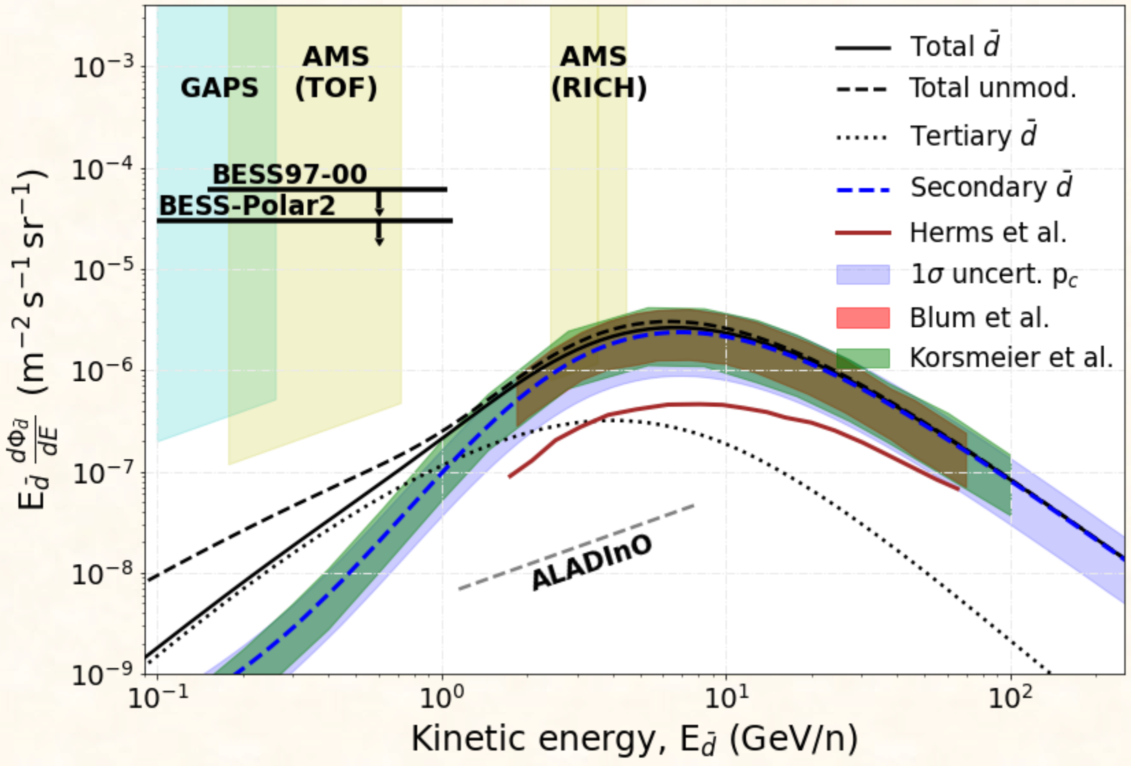
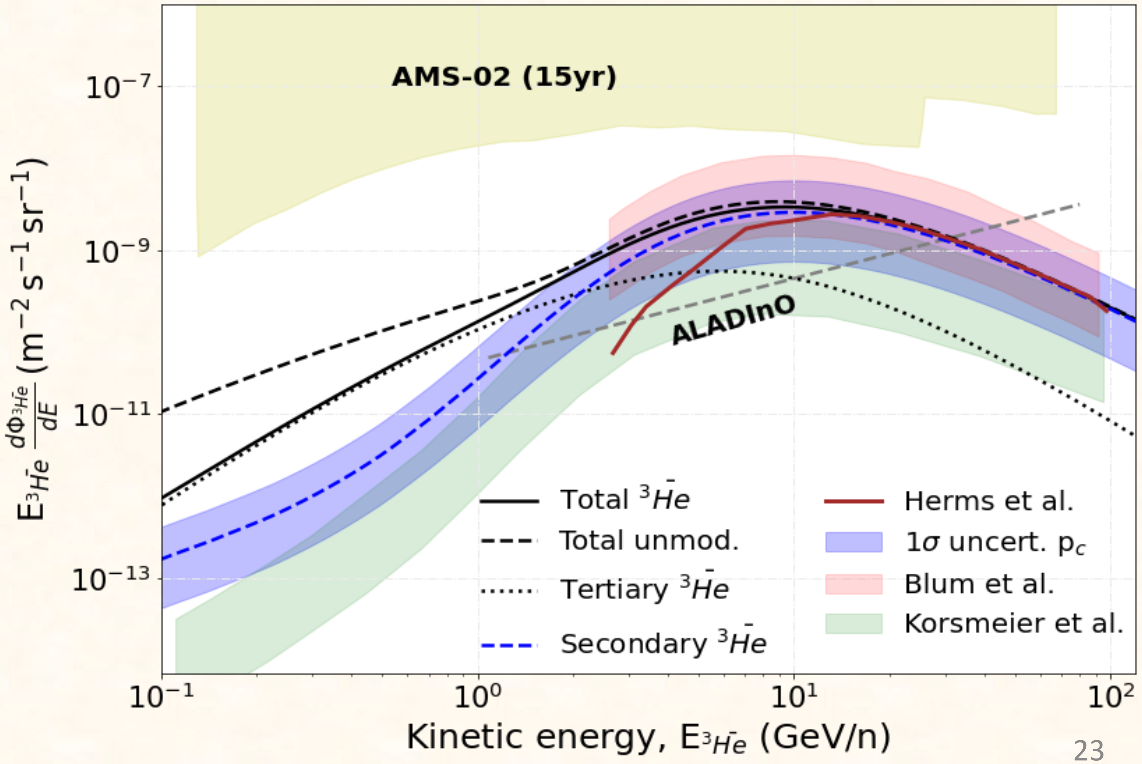
P.D.L. et al, ArXiv: 2404.13114



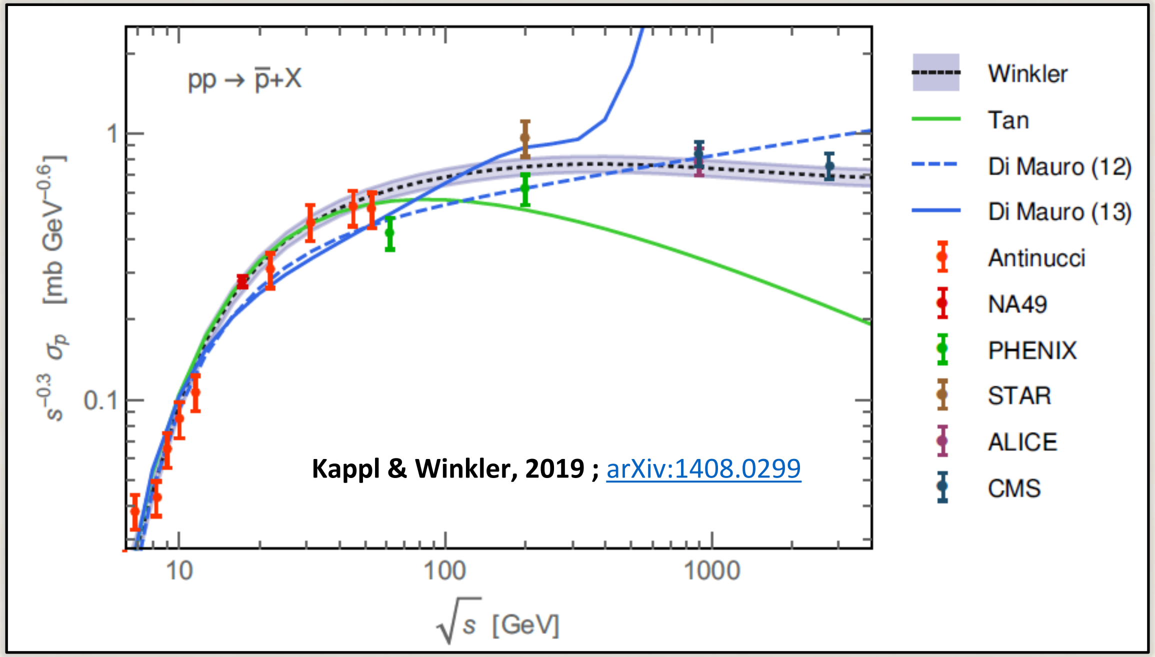


Antiproton cross sections

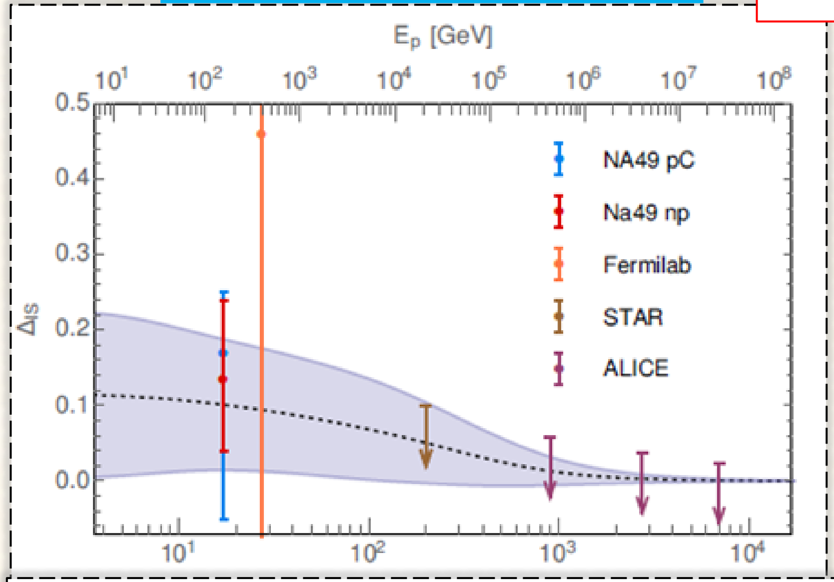
$$\left(E\frac{d^3\sigma}{dp^3}\right)_{pp\to\bar{p}} = \left(E\frac{d^3\sigma}{dp^3}\right)^{\text{prompt}}_{pp\to\bar{p}} \cdot \left(2 + \boxed{\Delta_{IS}} + 2\,\Delta_\Lambda\right)$$

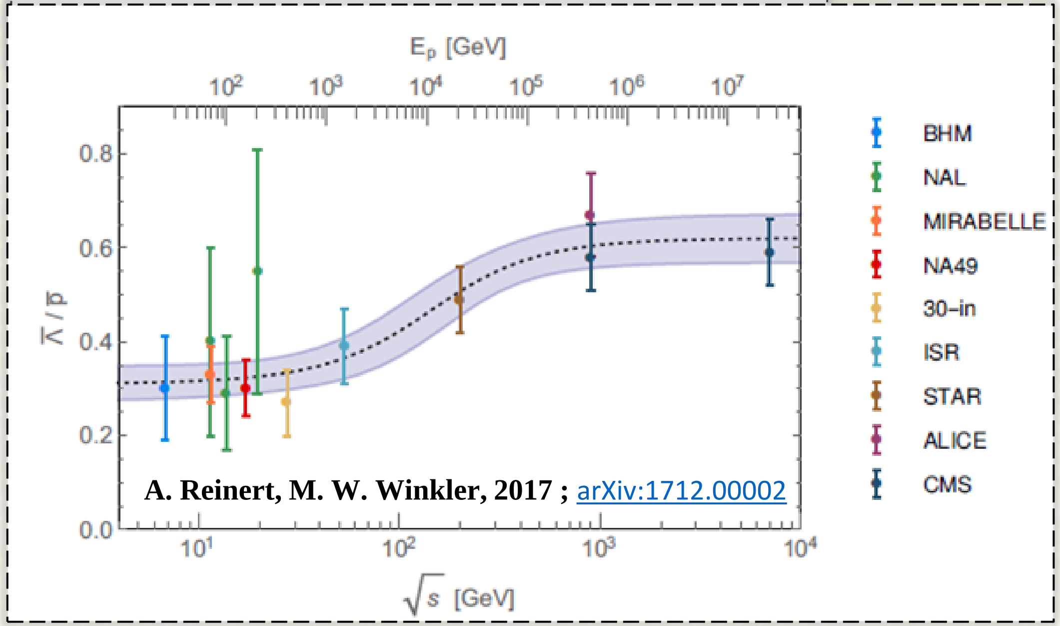
$$p + p \longrightarrow \{\bar{n} \longrightarrow \bar{p}\} + X$$

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



Kappl & Winkler, 2019 ; arXiv:1408.0299





A. Reinert, M. W. Winkler, 2017 ; arXiv:1712.00002

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

24

Propagation setup

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

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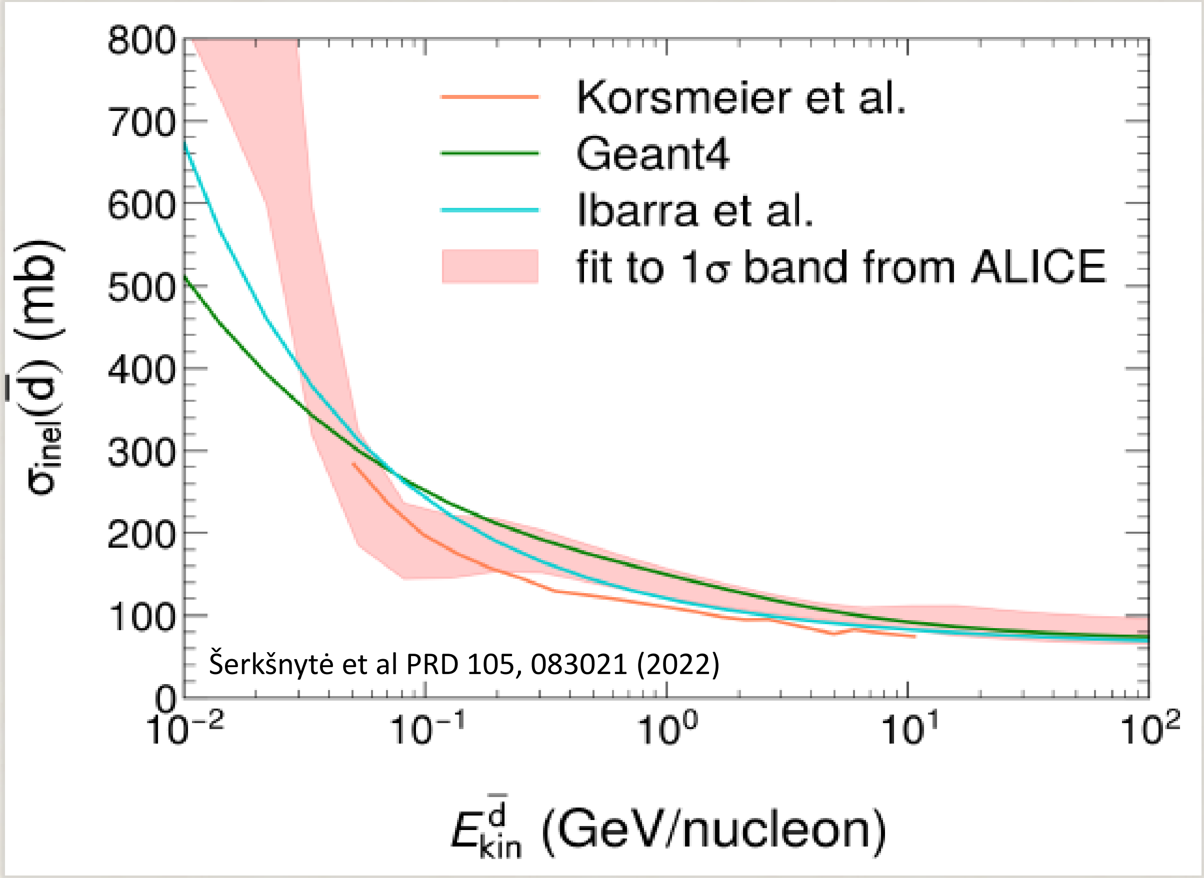

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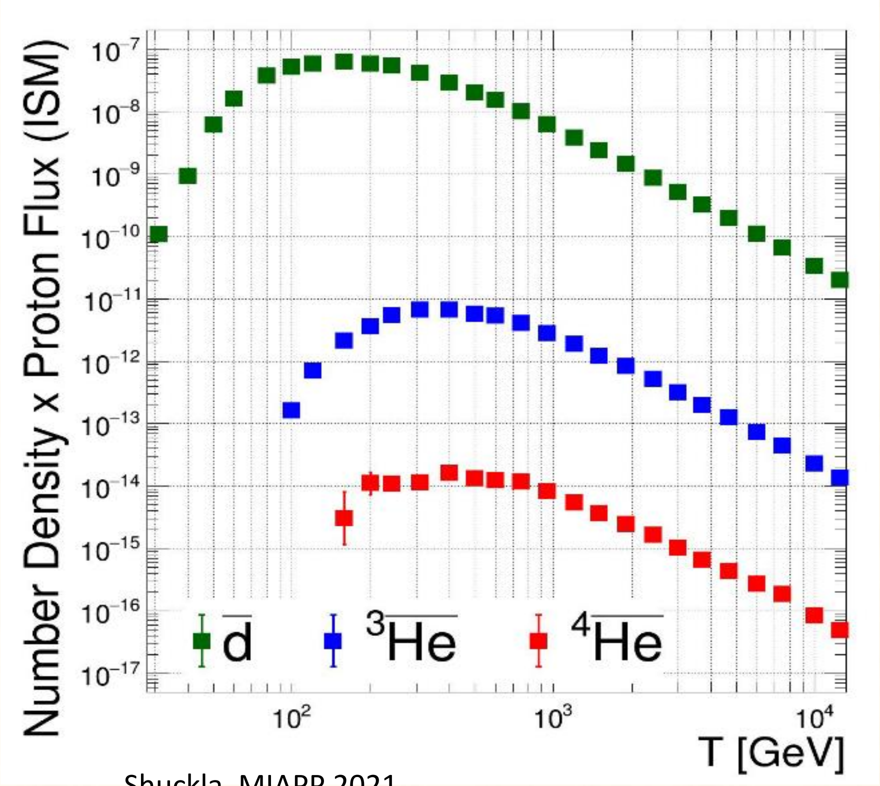
P + p → p + p + p + ap + ap + an



Shuckla, MIAPP 2021

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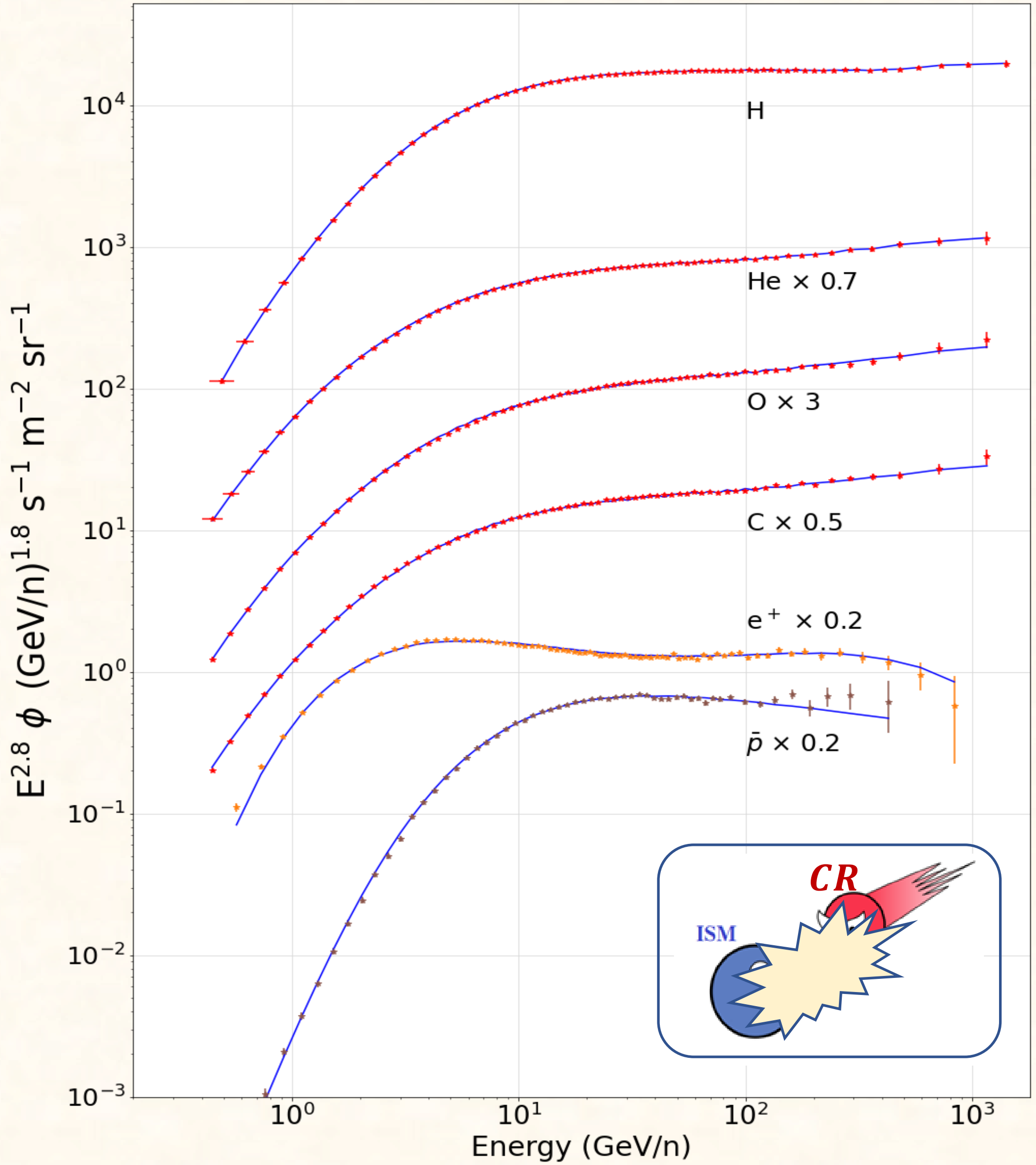
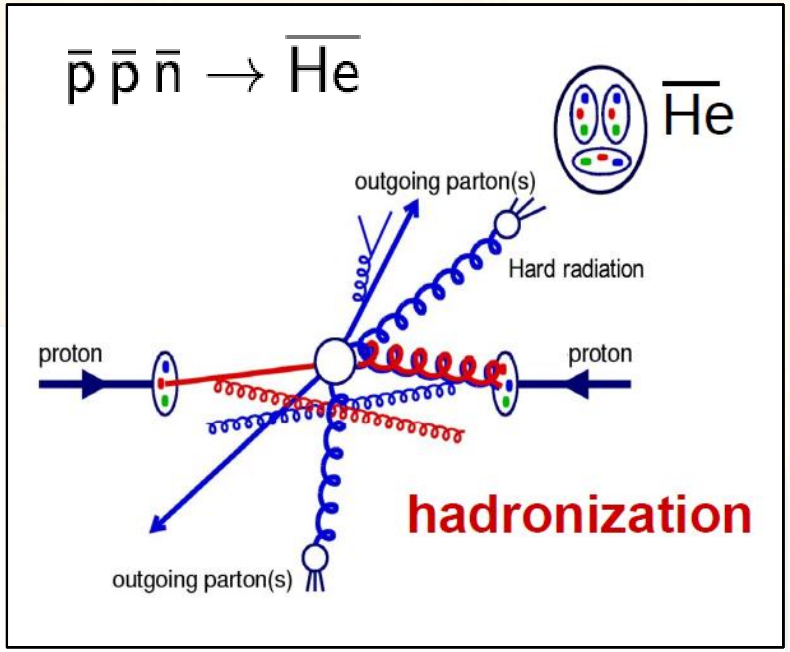


Formation of anti-nuclei



- Simplest coalescence model: *Factorised coalescence*

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

Antineutrons and antiprotons are produced uncorrelated

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

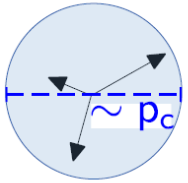
Coalescence parameter can be approximated from the coalescence momentum, p_0

(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

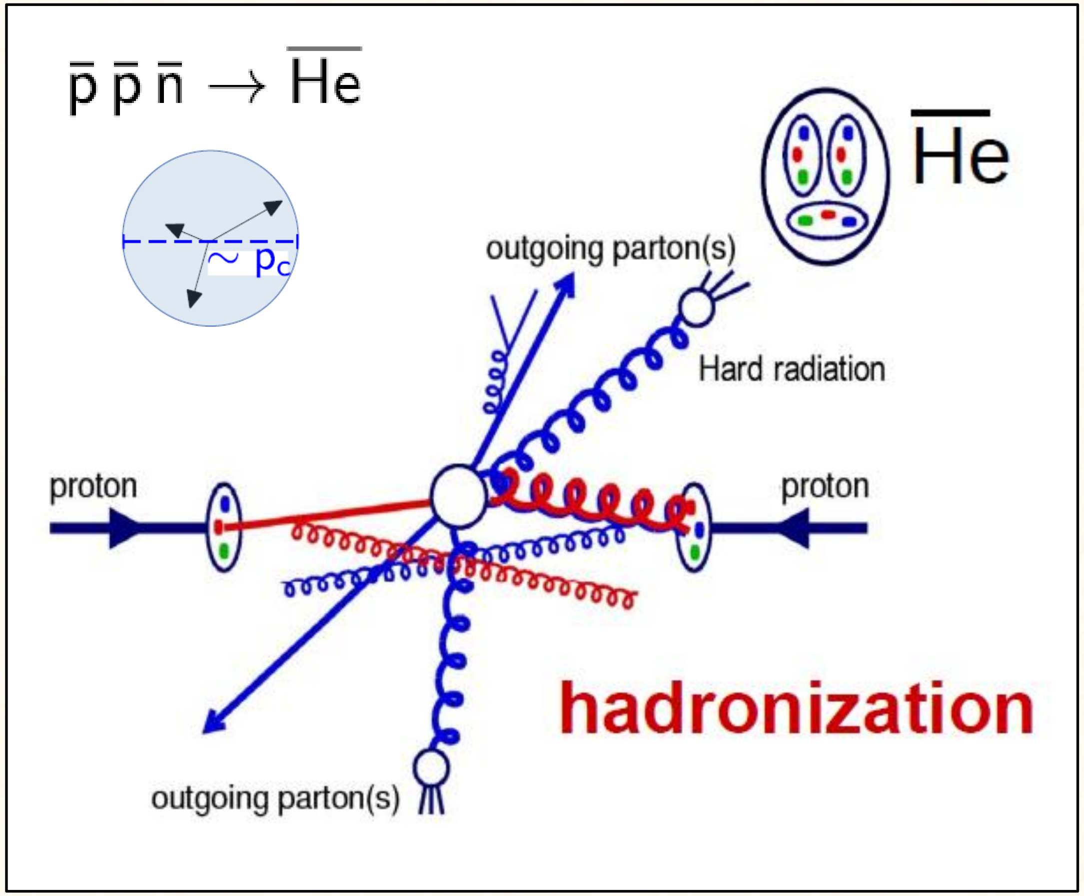


Formation of anti-nuclei: Coalescence

- 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!

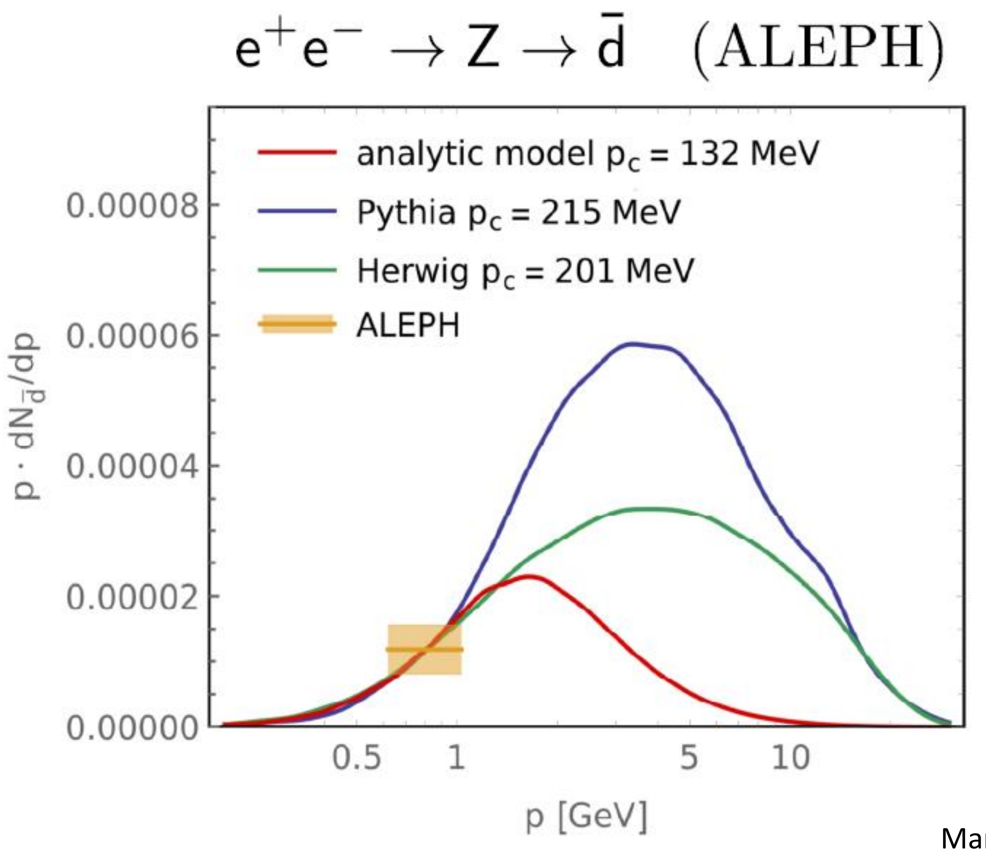
- Simplest coalescence model: *Factorised coalescence*

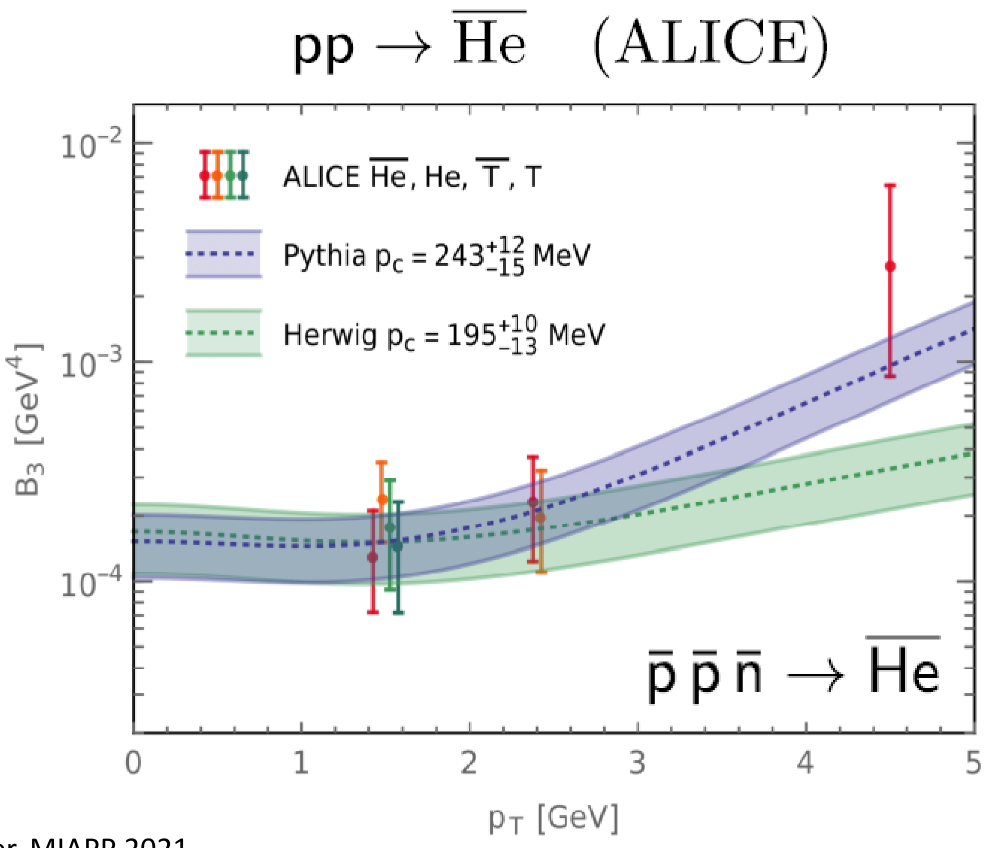
$$E_{\bar{A}} \frac{d^3 N_{\bar{A}}}{dp^3_{\bar{A}}} \simeq B_A \left(E_{\bar{p}} \frac{d^3 N_{\bar{p}}}{dp^3_{\bar{p}}} \right)^A$$



Formation of anti-nuclei

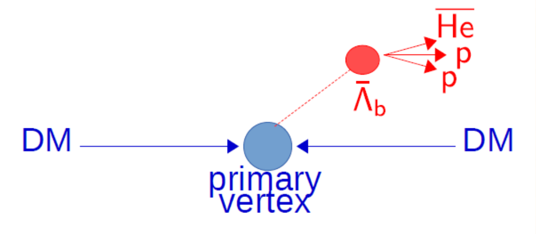
Coalescence parameter may depend on many kinematical parameters, including the size of the projectile and target



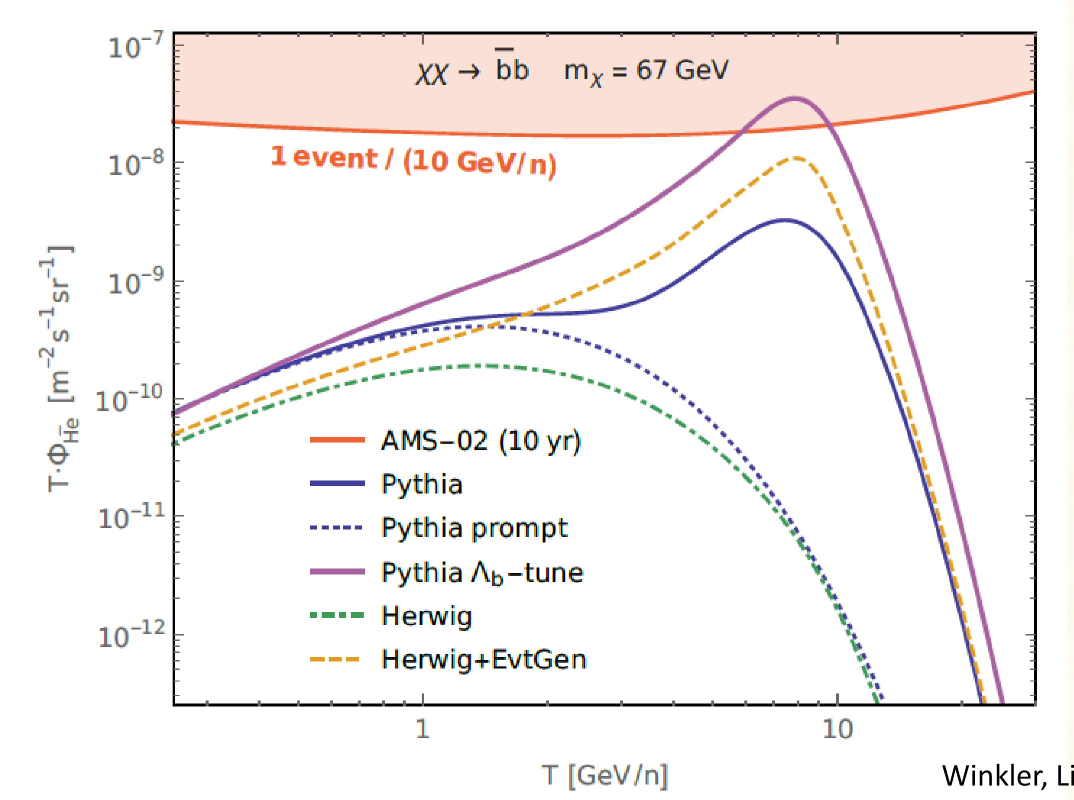


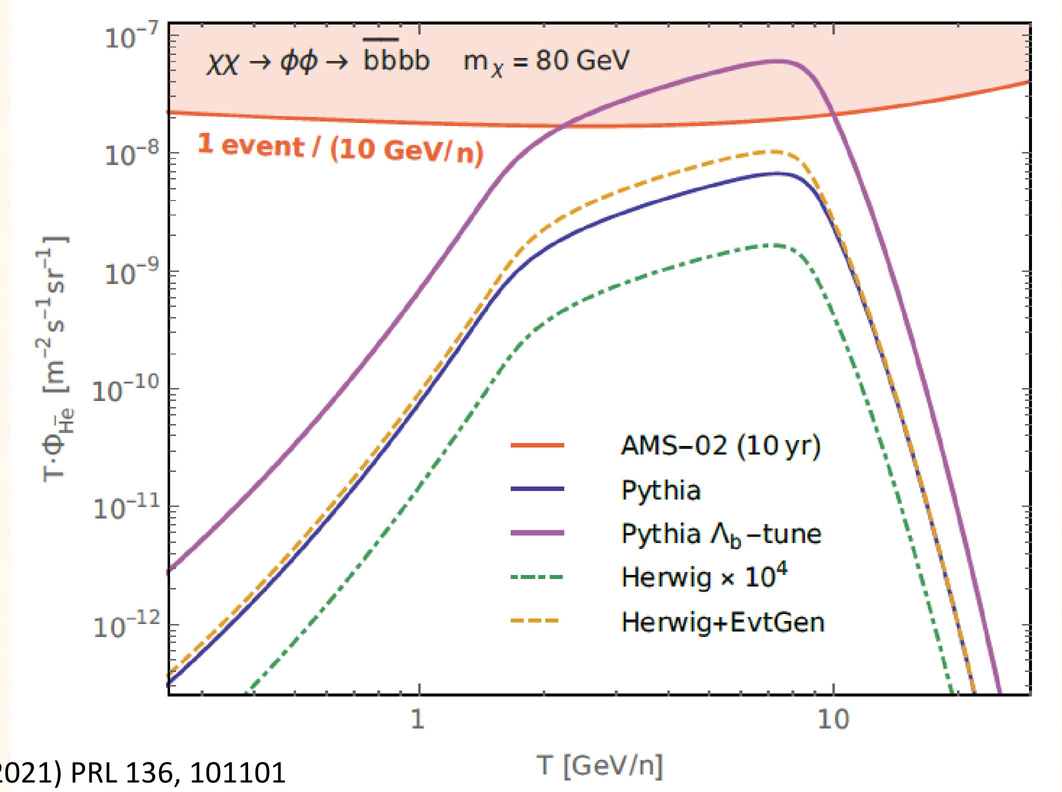
Martin Winkler, MIAPP 2021

Boosting the dark matter signal



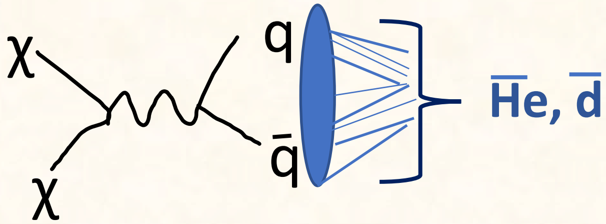
✓ **Λ_b production** is a very important source of anti-helium, even able to explain the events reported by AMS-02, although not yet well constrained



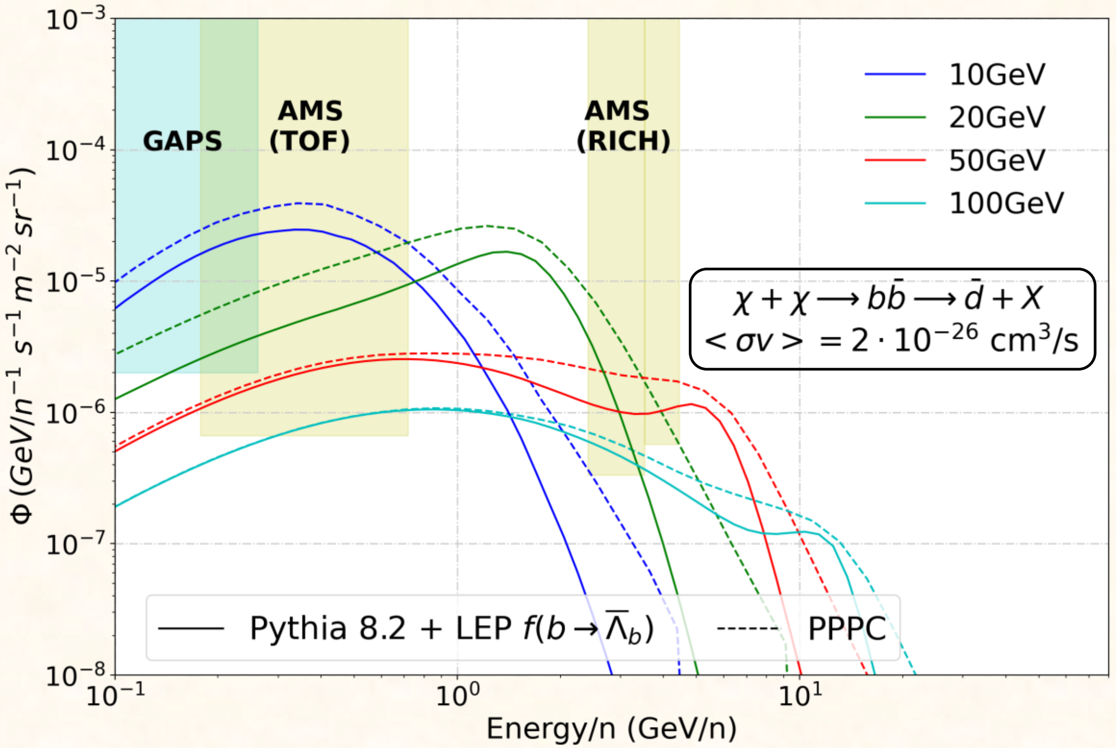


Winkler, Linden (2021) PRL 136, 101101

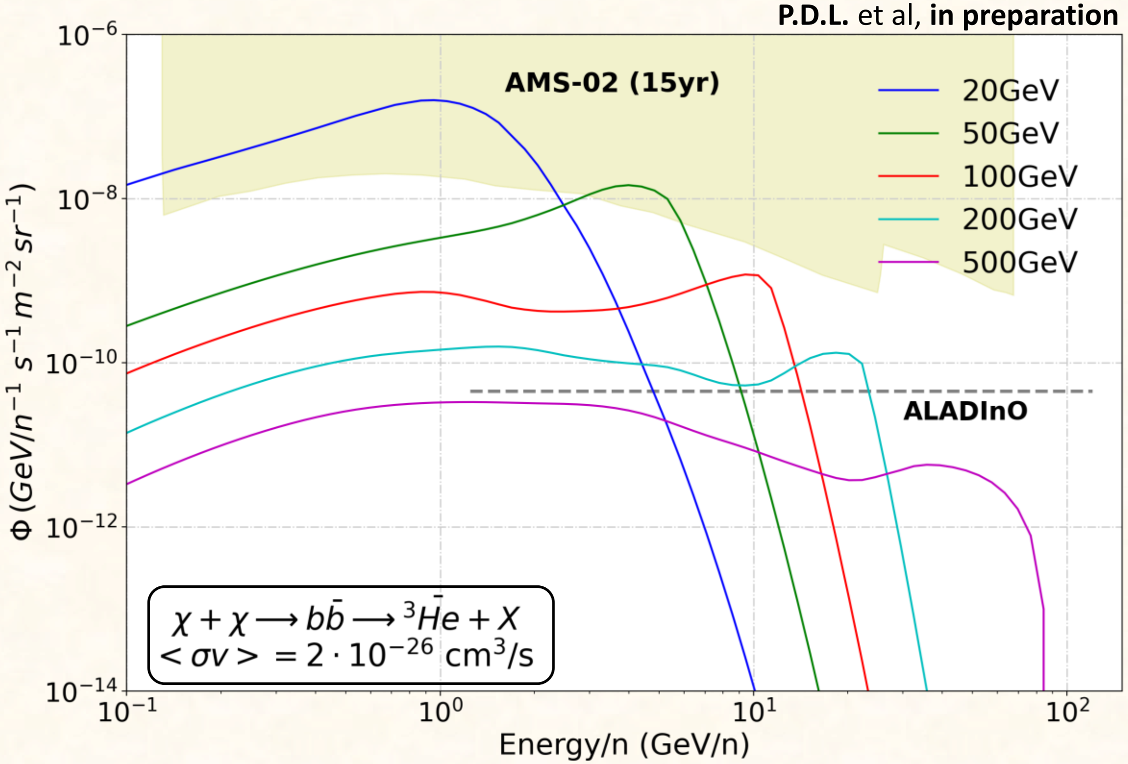
Dark matter production



The window to prove (or disprove) the WIMP paradigm

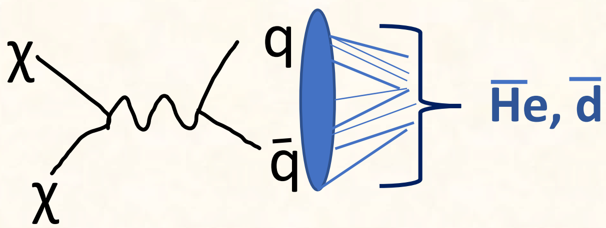


P.D.L. et al, **in preparation**



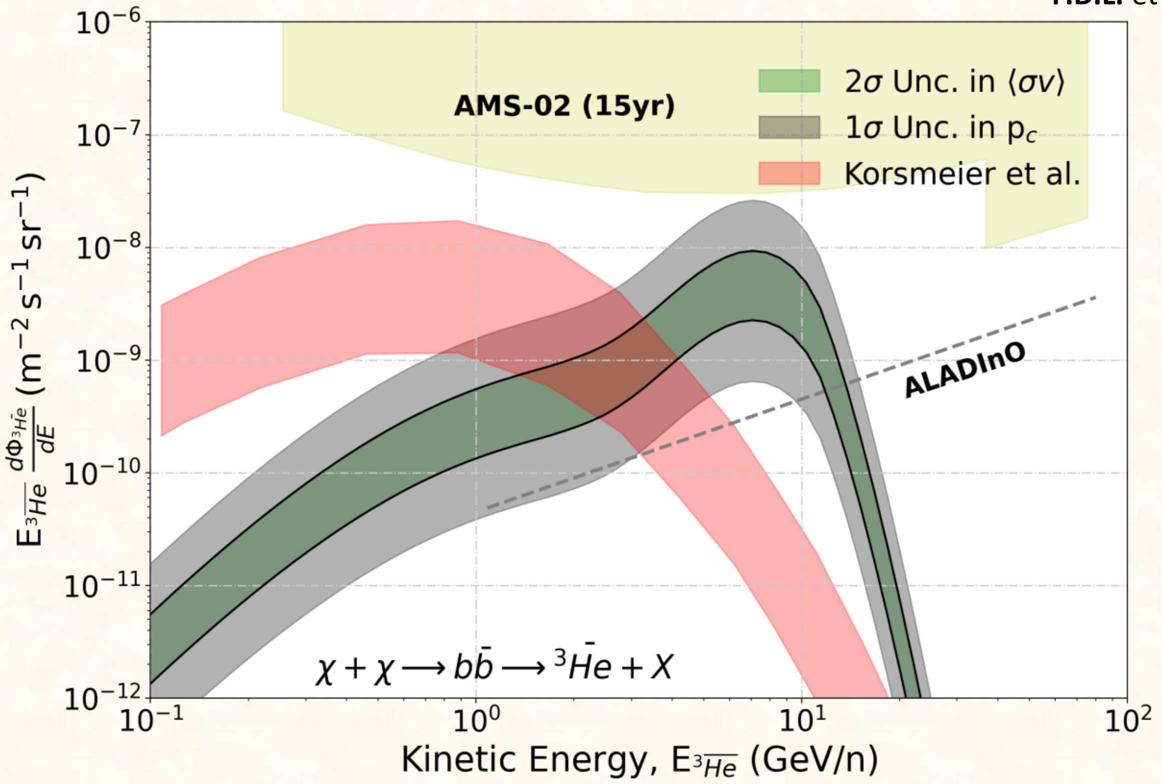
PPPC – M. Cirelli tables:
http://www.marcocirelli.net/PPPC4DMID.html

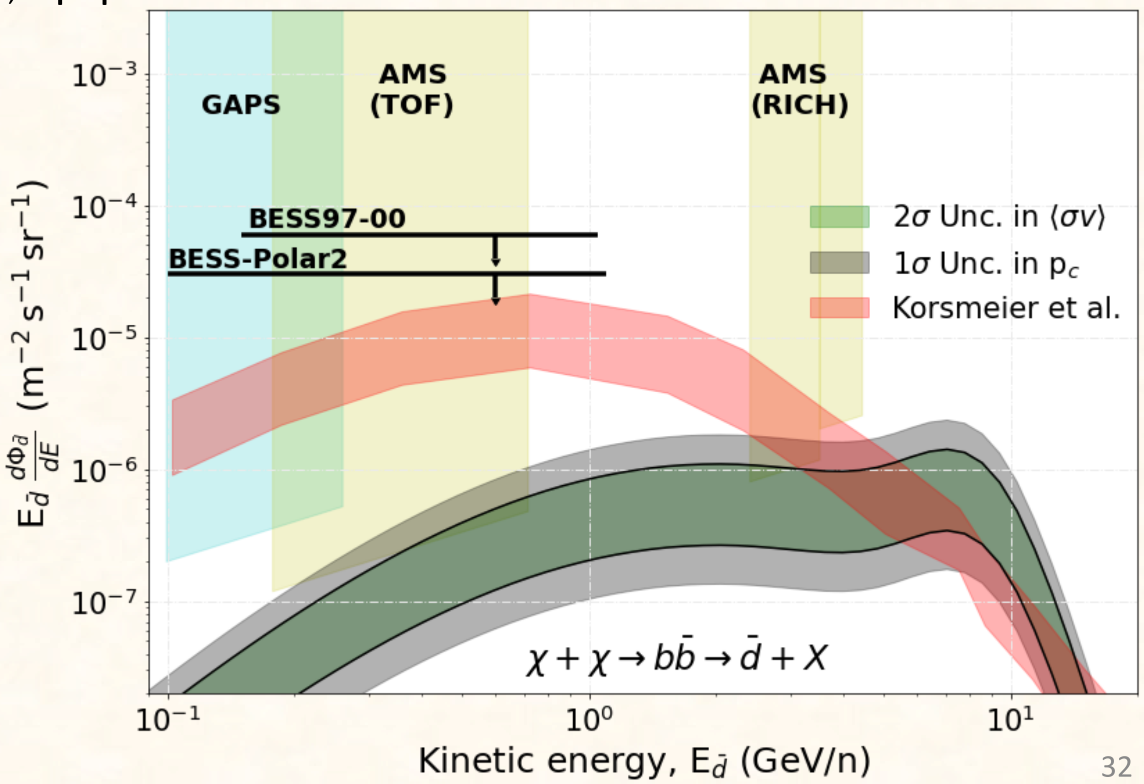
Dark matter production



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**

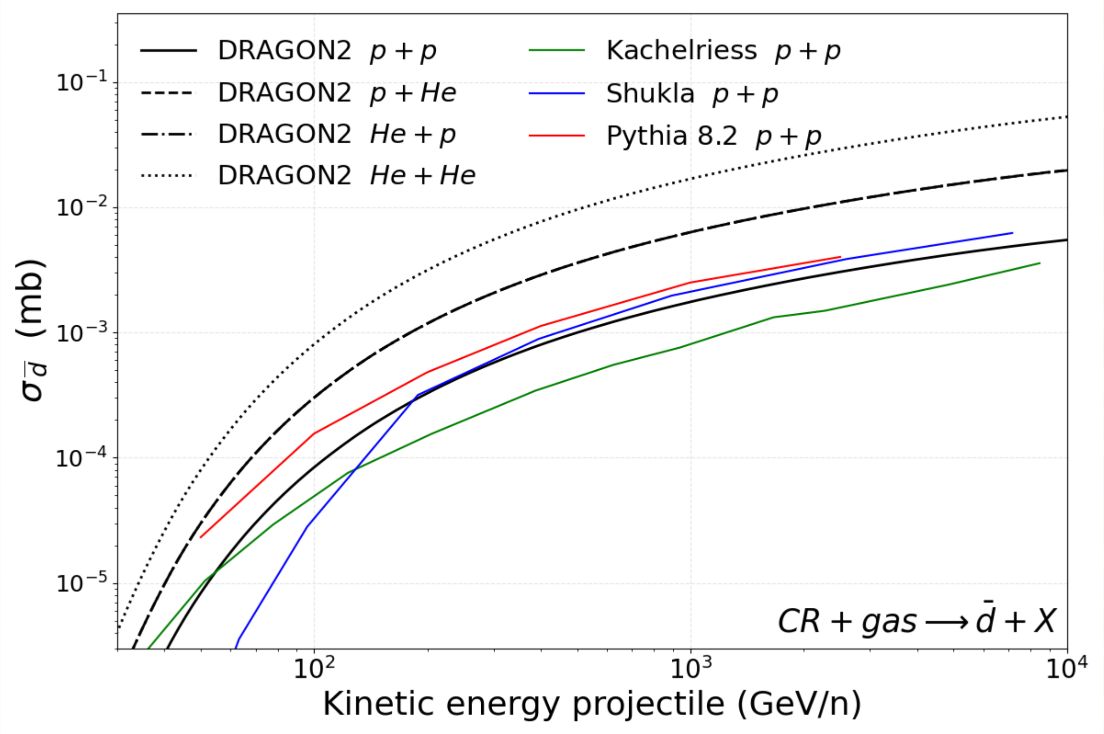
P.D.L. et al, **in preparation**

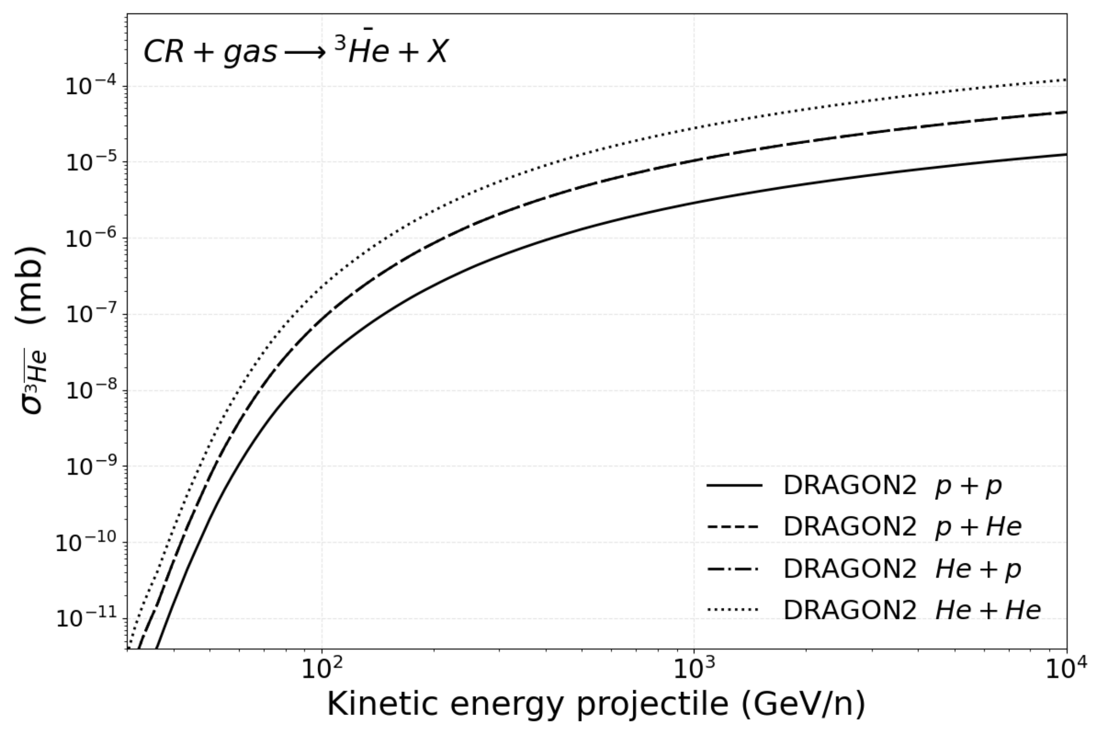




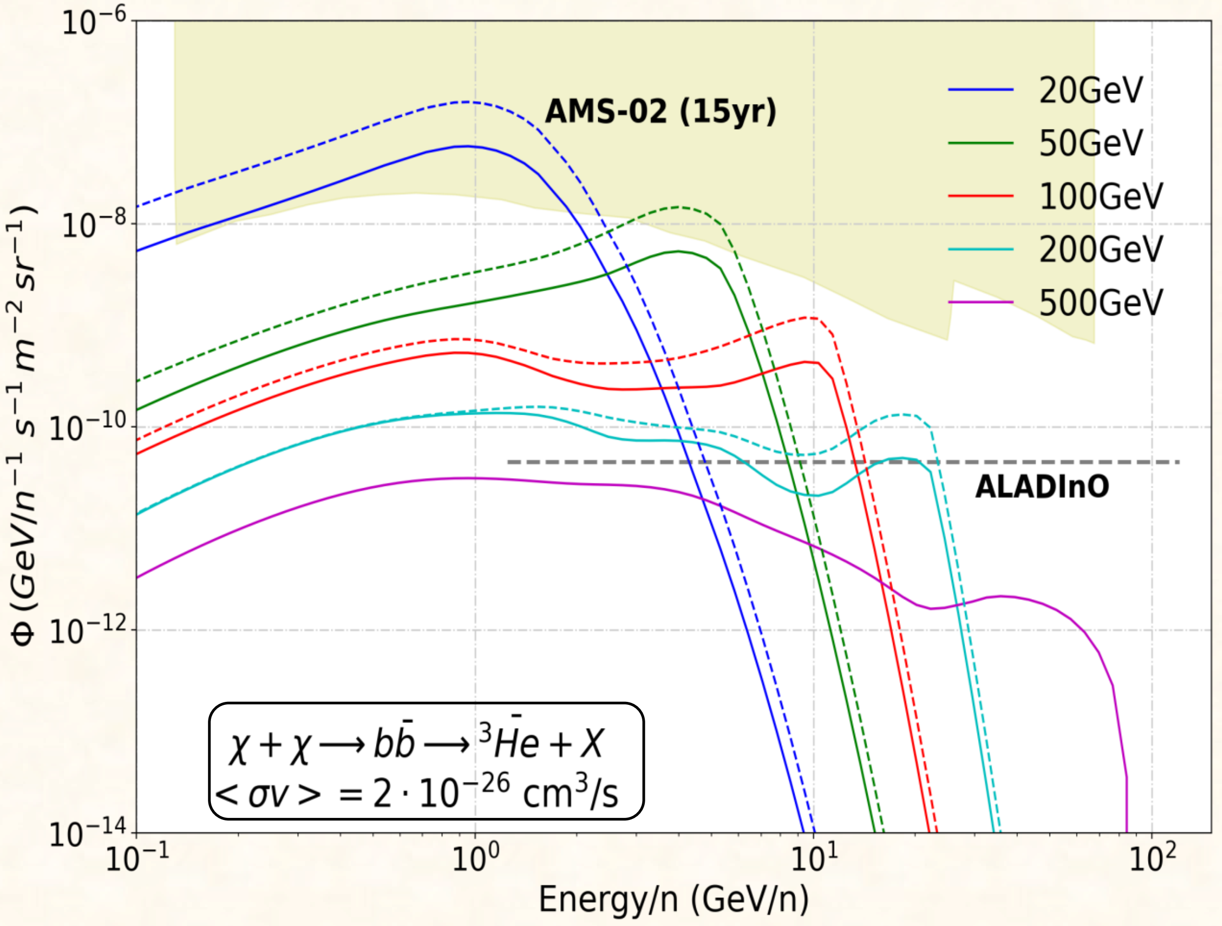
New antinuclei cross sections!

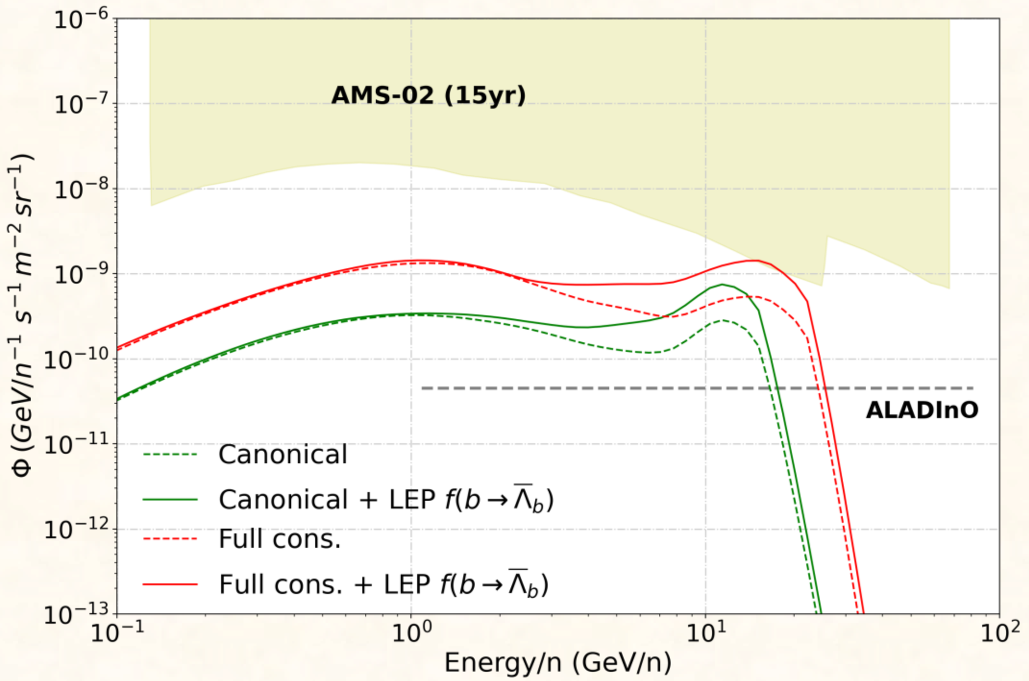
Derived analytically using the factorized coalescence model model from the Winkler (2017) cross sections for antiprotons. Coalescence momentum adjusted to reproduce ALICE p+p data!



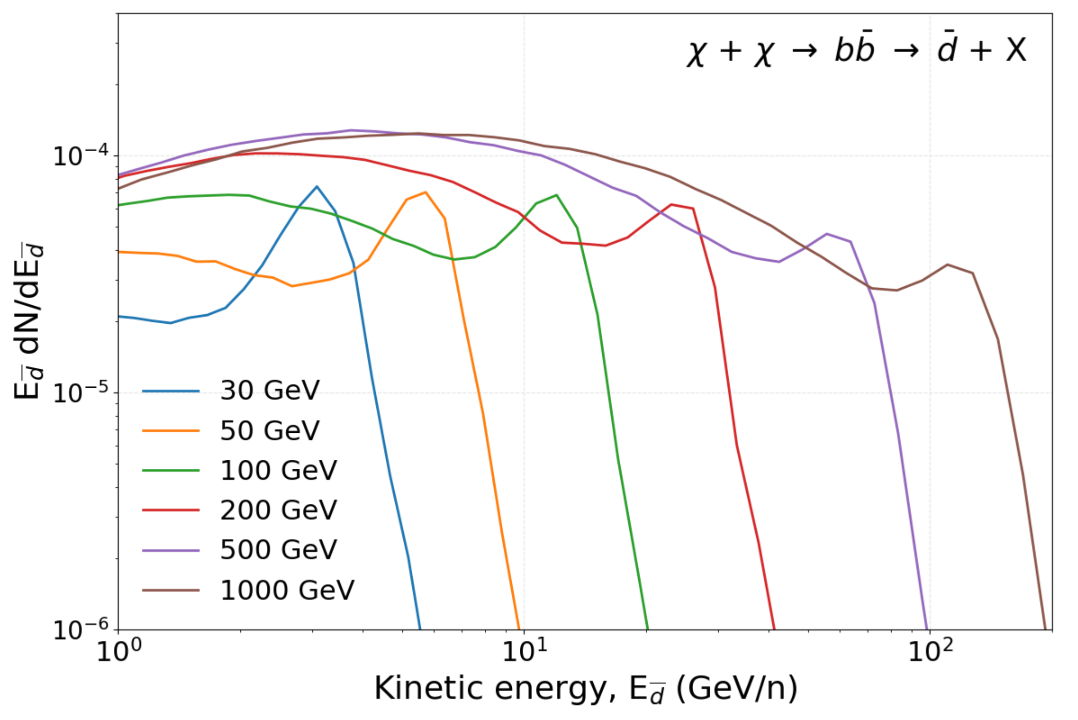


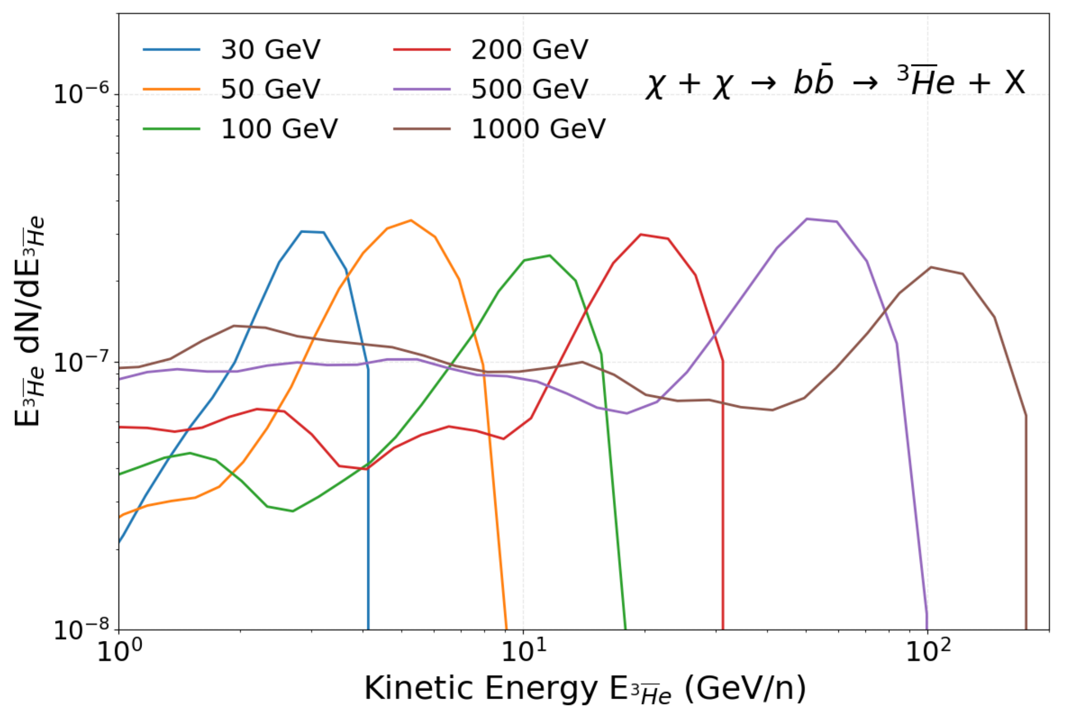
LEP correction vs plain Pythia



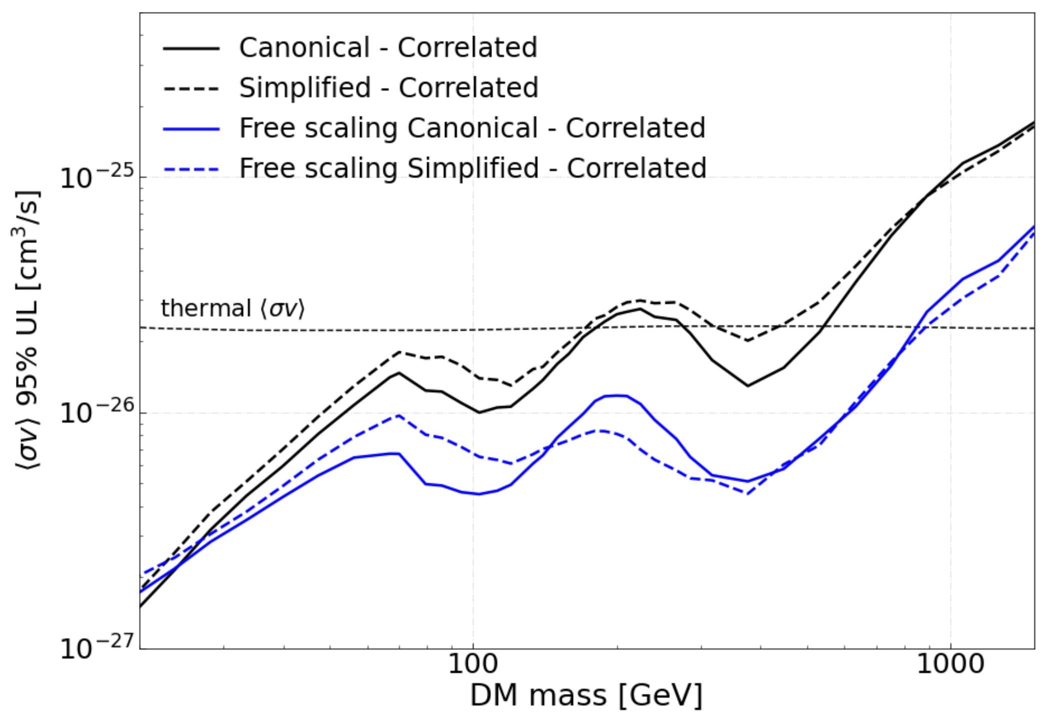


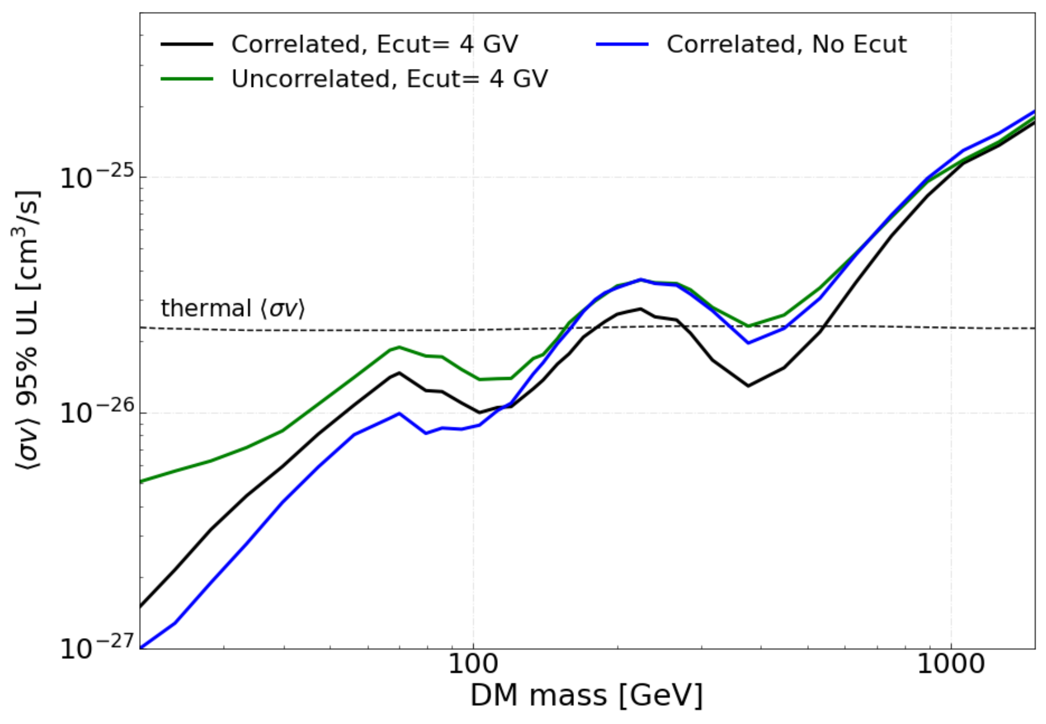
DM injection of antinuclei





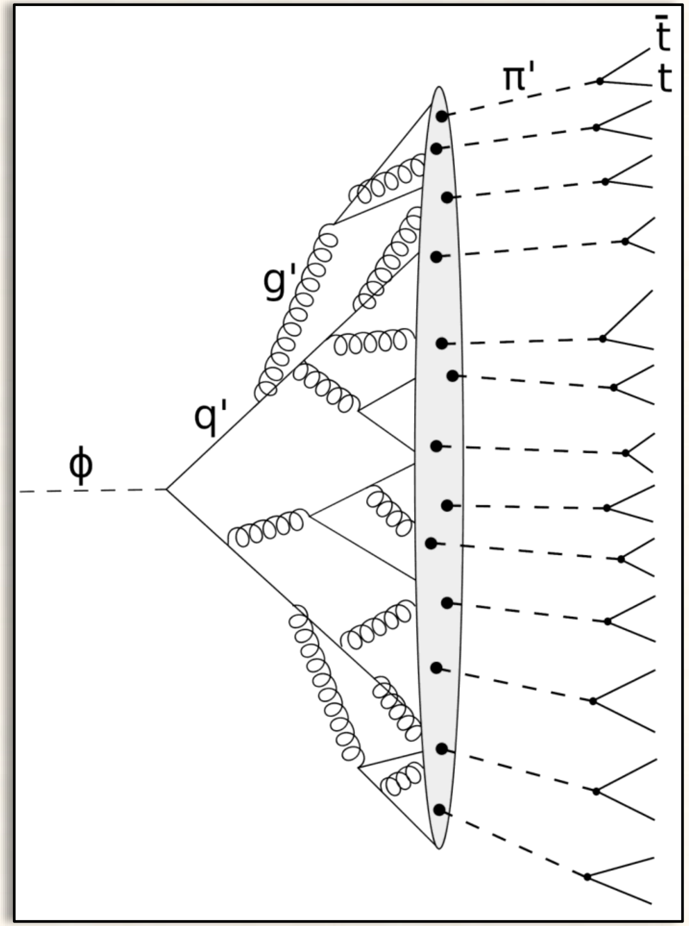
Stronger constraints if some assumptions are relaxed





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: $N_A \propto (N_p)^A$