Pedro de la Torre Luque
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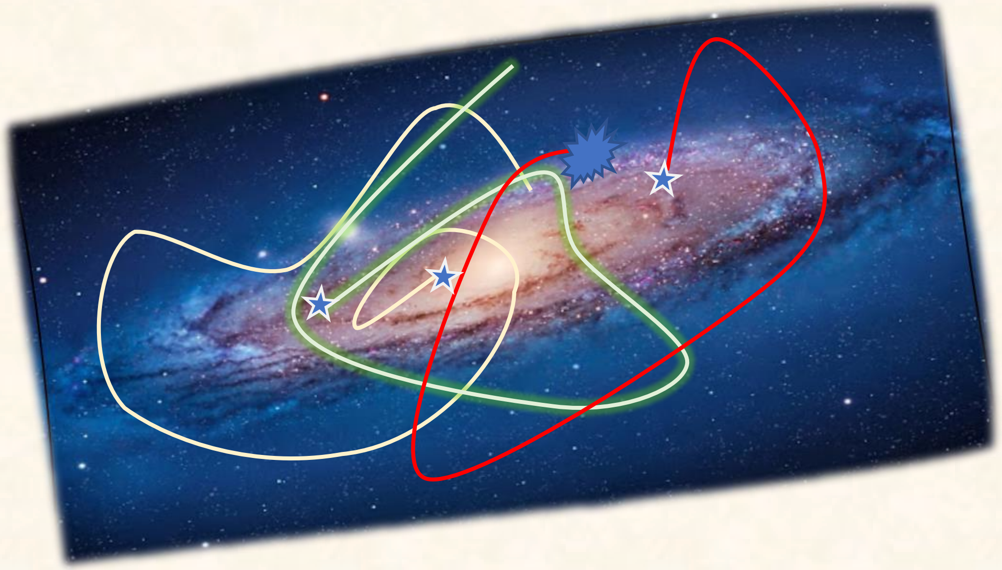
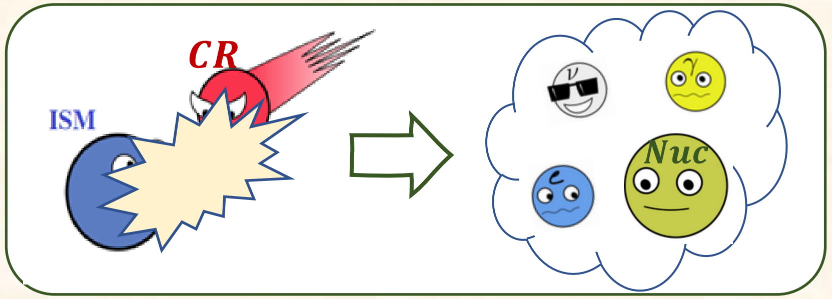
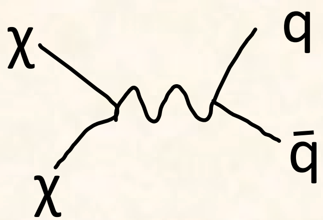
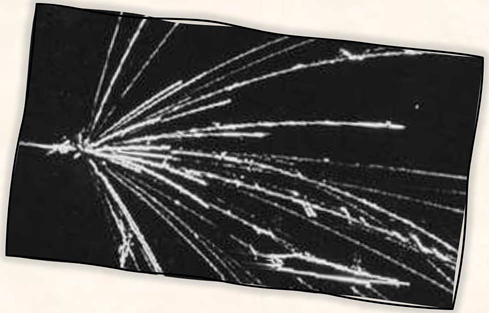
ECRS – 24/07/2022

Indirect dark matter searches with anti-nuclei

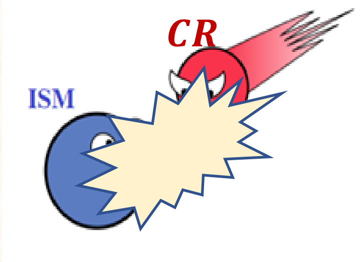








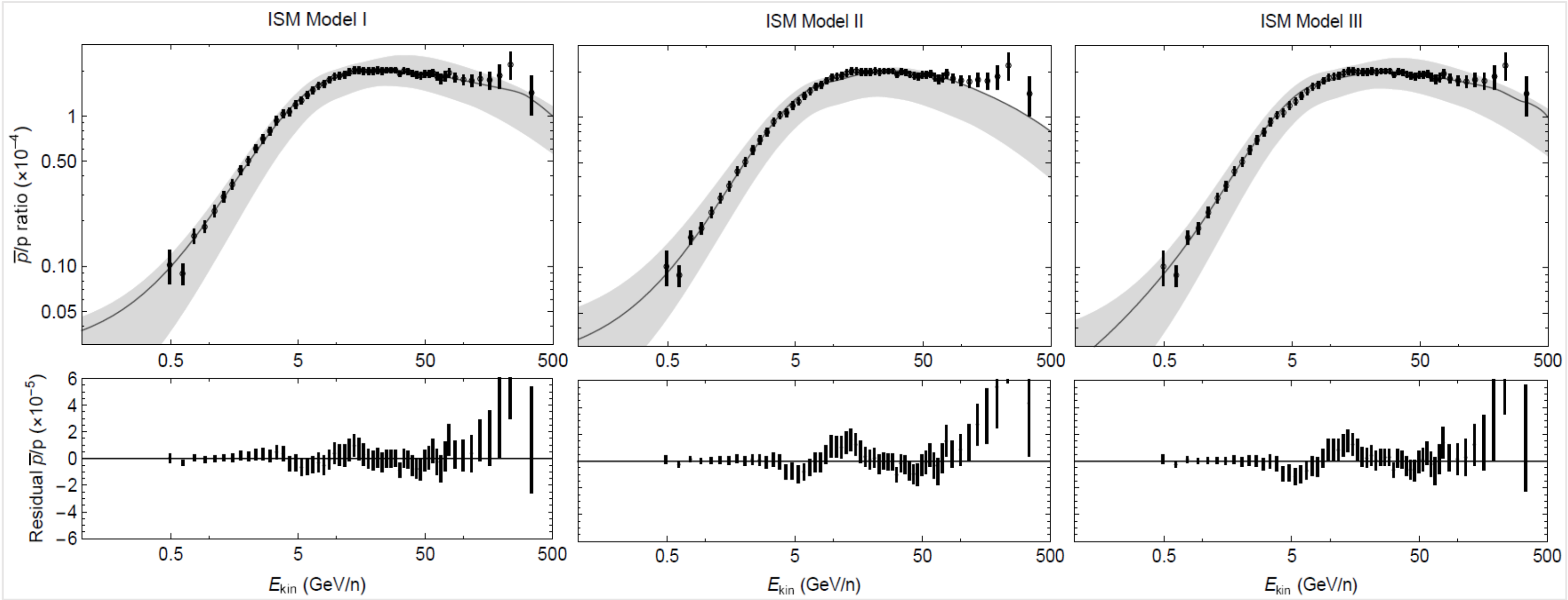
Antiproton *excesses* – *The spectral excess*



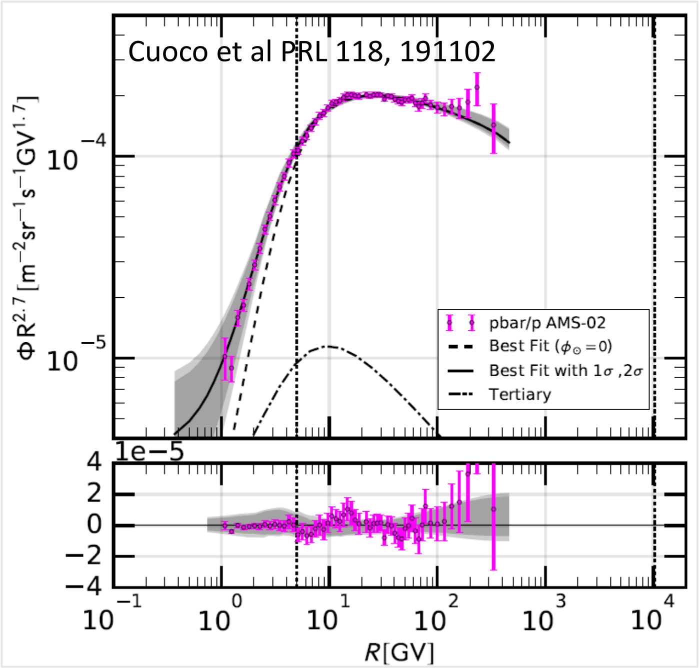
Recent studies have claimed the possibility of an **excess** of data over the predicted flux **at around 10-20 GeV**, which can be the **signature of dark matter** annihilating or decaying into antiprotons

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

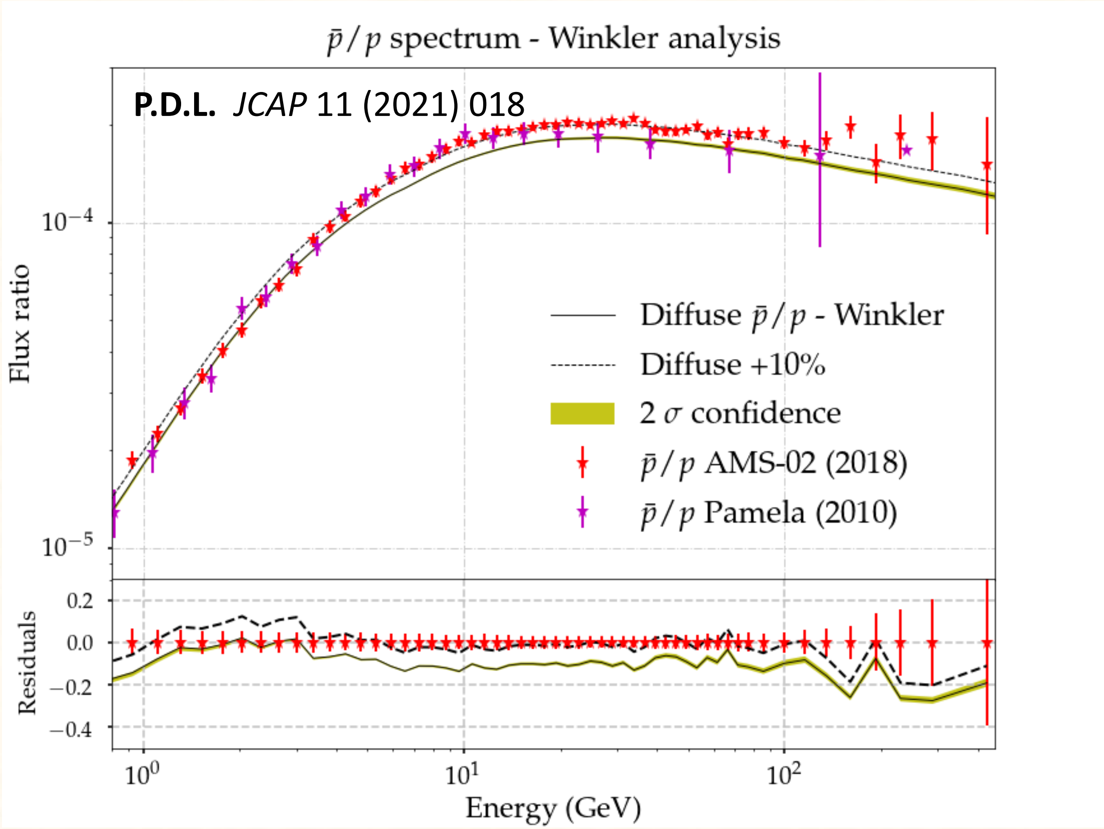
$\chi + \chi \rightarrow \bar{p}$



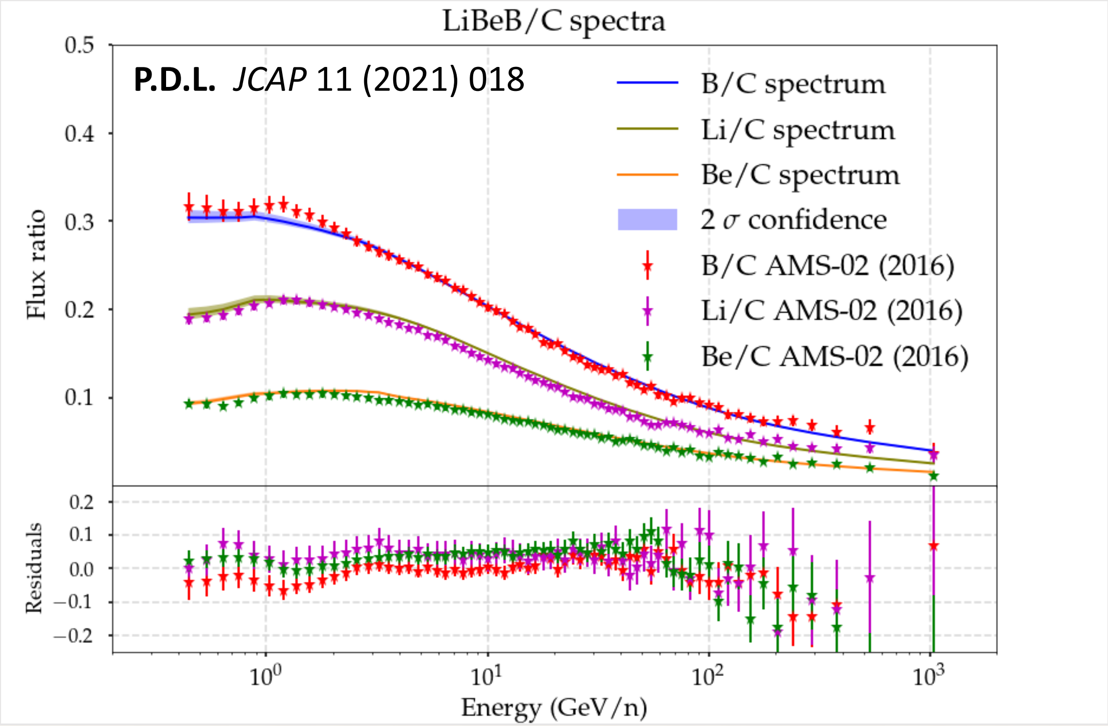
Cholis, Linden, Hooper PRD 99, 103026



Antiproton excesses – *The grammage excess*



Diff. coeff. predicted by the flux-ratios of B, Be and Li underpredicts the antiproton flux by a 10-20%→ **Grammage tension**



$$\frac{J_{sec}}{J_{pr}} \sim \sigma(E)/D(E)$$

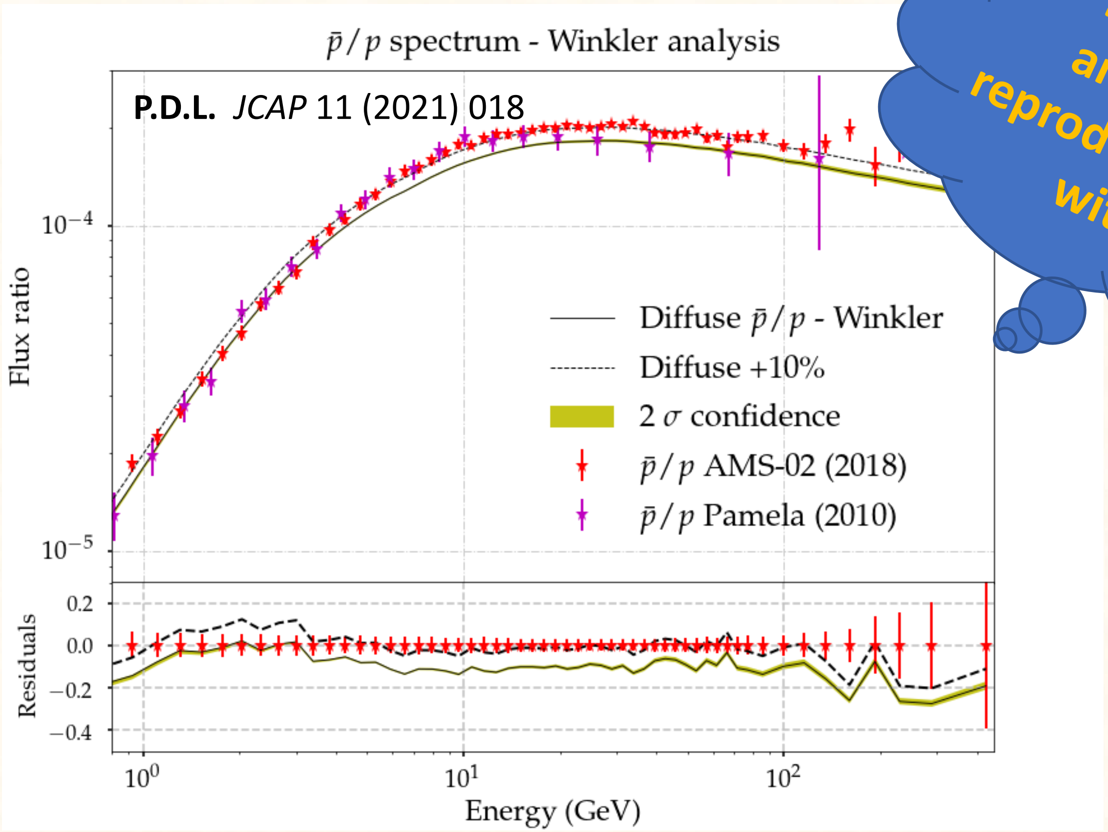
Diffusion coefficient

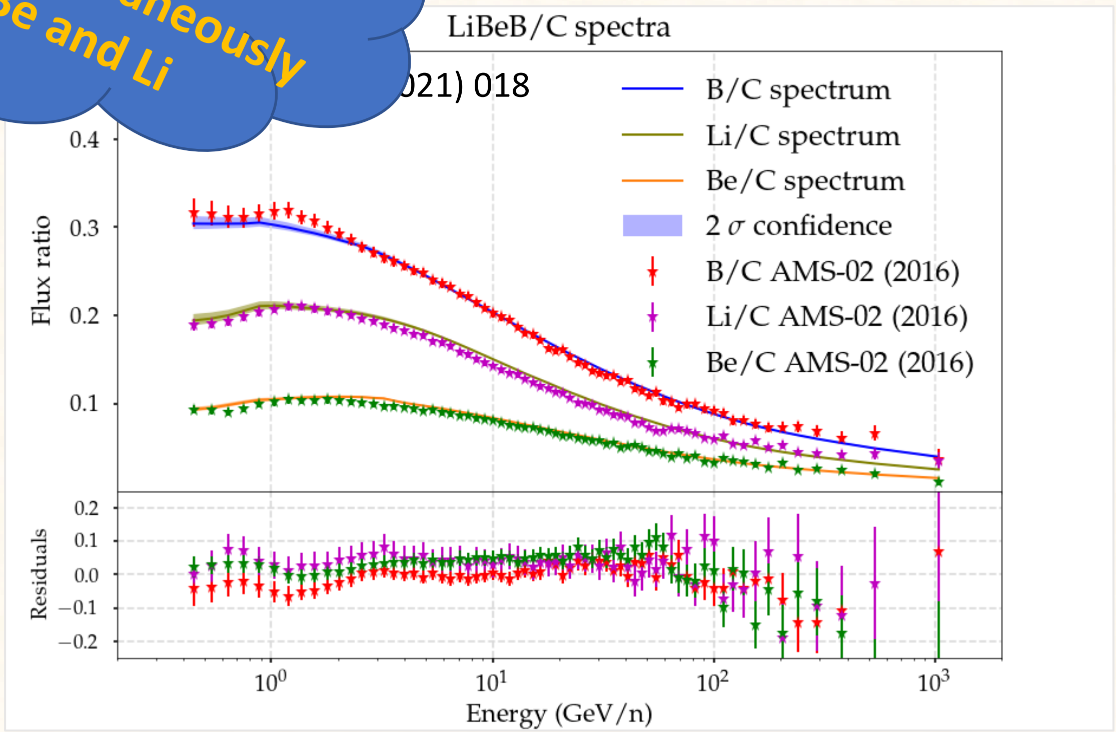
Production cross sections

Antiproton *excesses* – *The grammage excess*

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

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





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Antiproton ***excesses*** *– The grammage excess*

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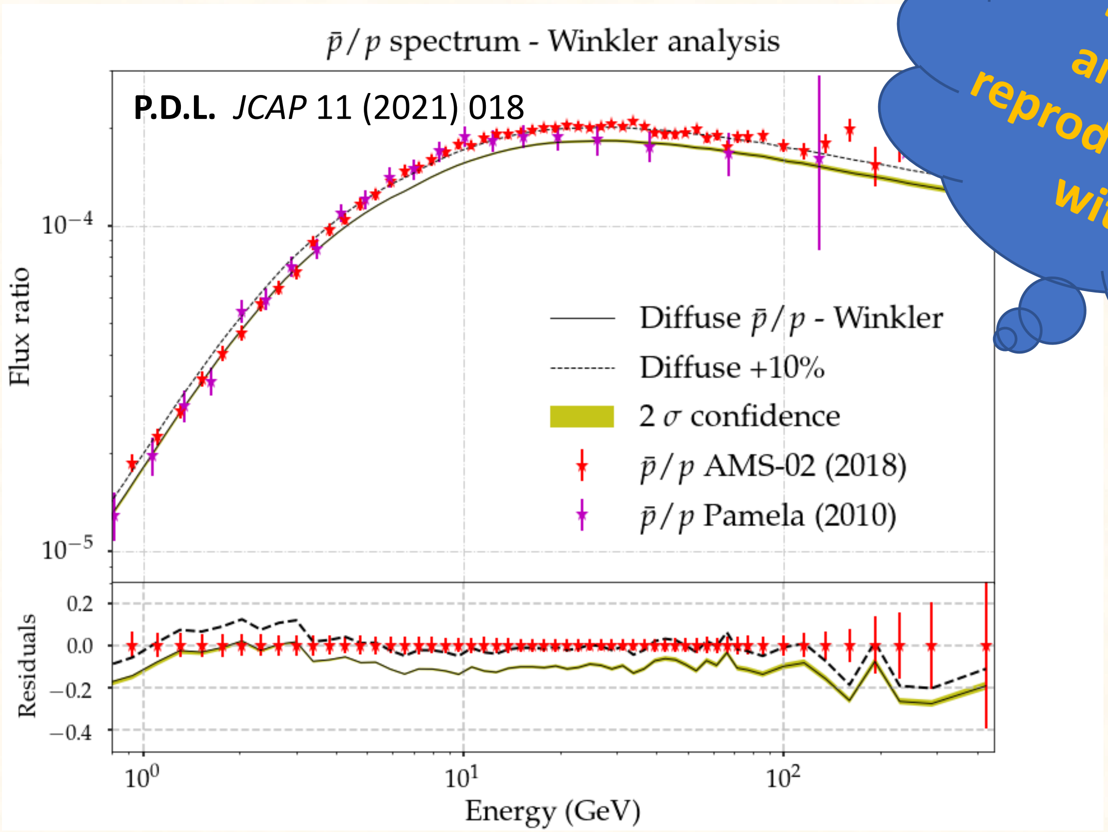
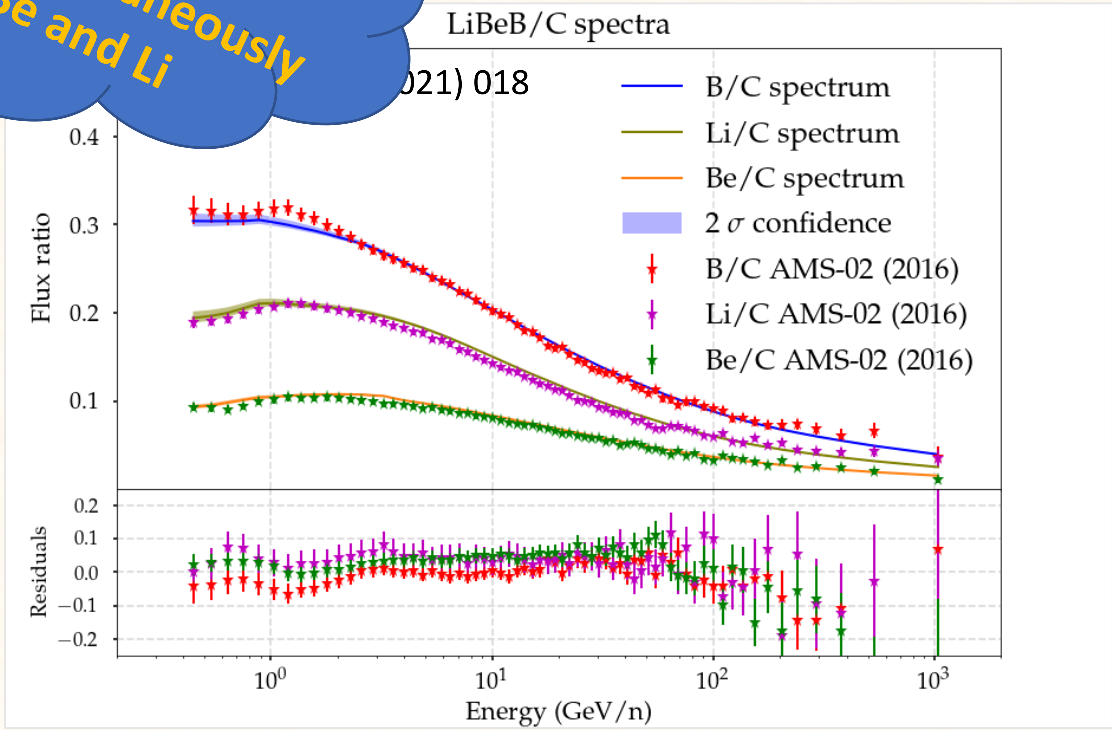


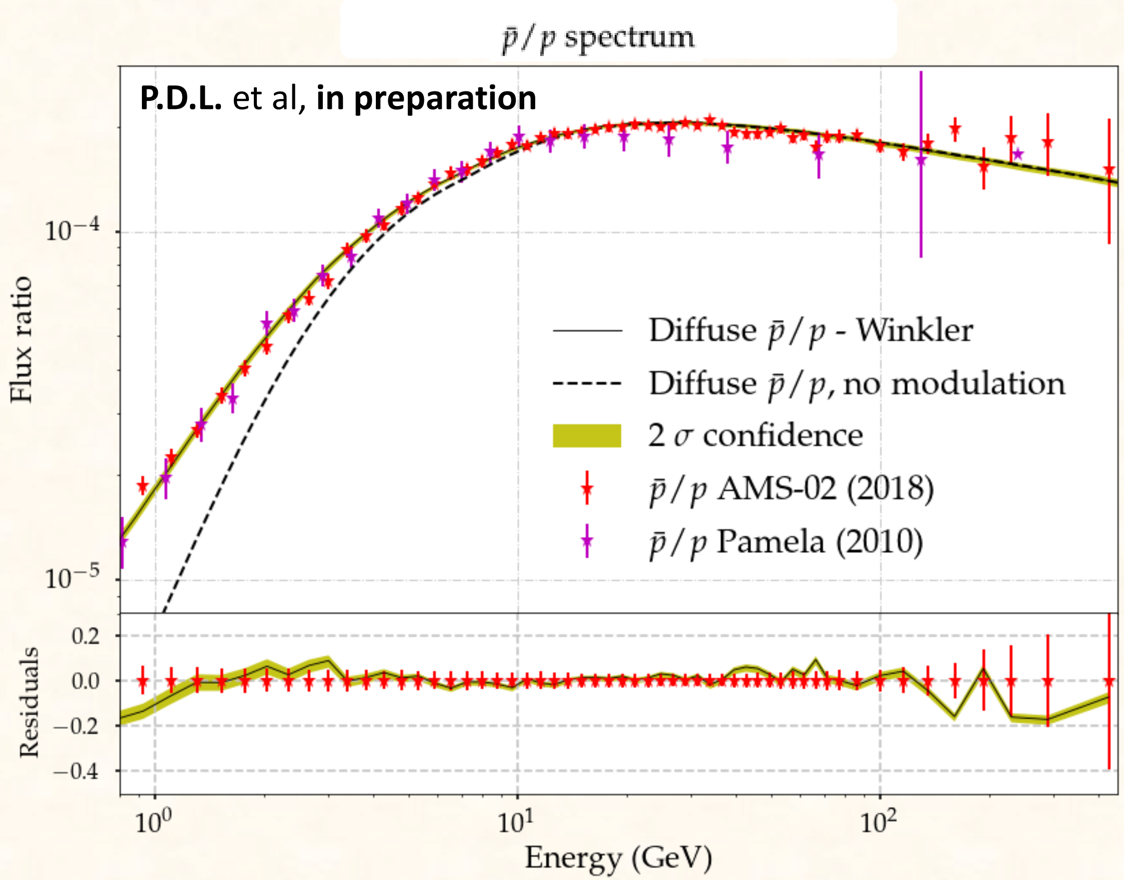


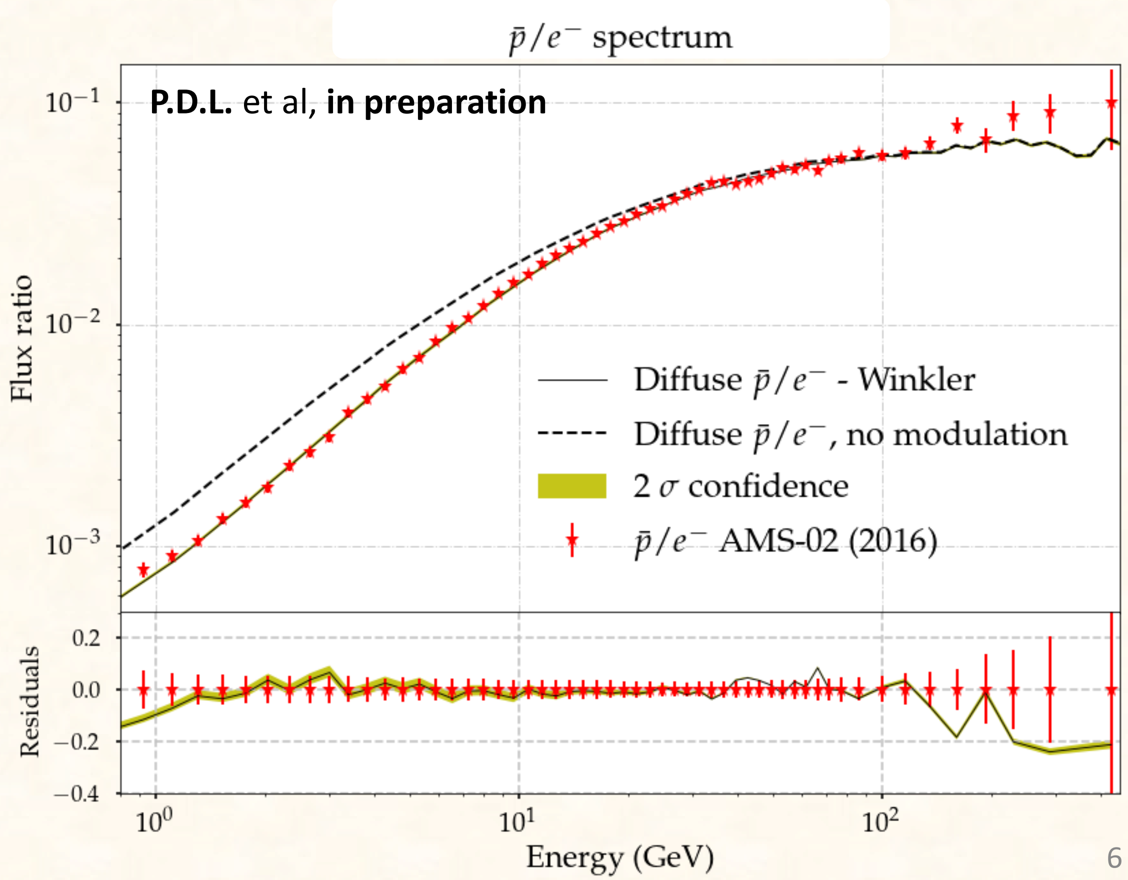
Conclusion: Cross sections uncertainties and can explain the excess alone, but more uncertainties are present!

Antiproton *excesses* – *The grammage excess*

Cross sections uncertainties are crucial in the assessment of these possible signals, but dark matter component is still statistically preferred

B/C, B/O, Be/C, Be/O, Ap/p (Prop. parameters)
^{10}Be/^{9}Be, ^{10}Be/Be (H), **Be/B, Li/B, Li/Be** (S_X)
Ap/e$^+$, Ap/e$^-$ → S_{Ap}, propagation params.



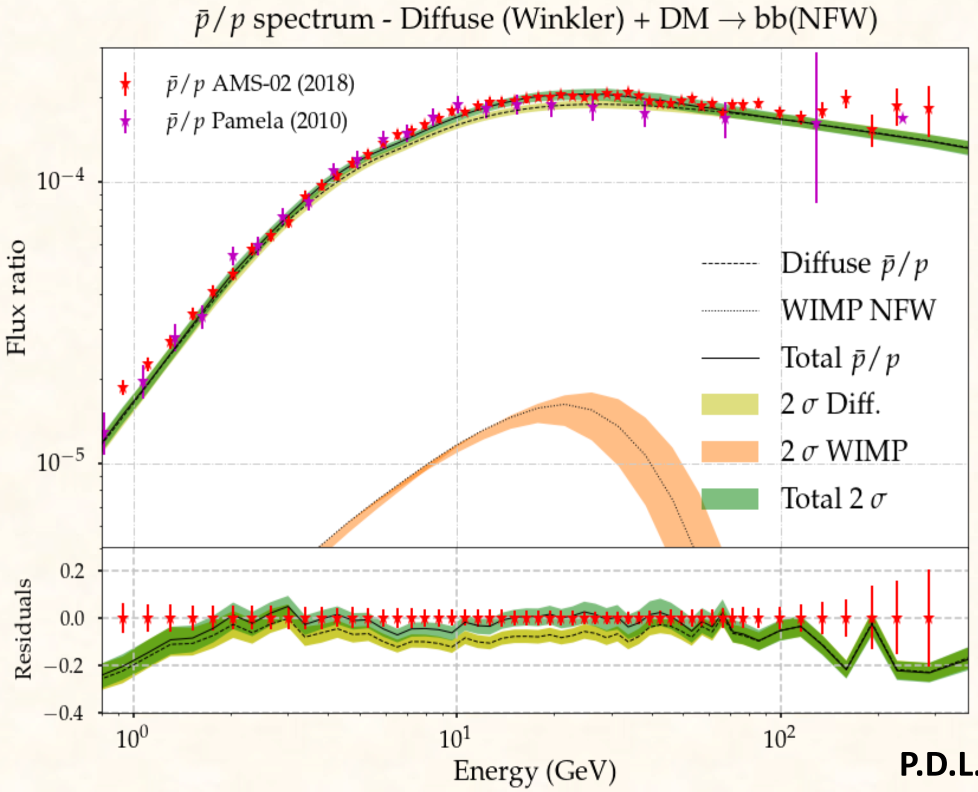


Antiproton *excesses* – ***The grammage excess***

DM globally favoured. The way to asses the antiproton uncertainties affect the properties of the DM candidate reproducing the signal. Significance below 1σ

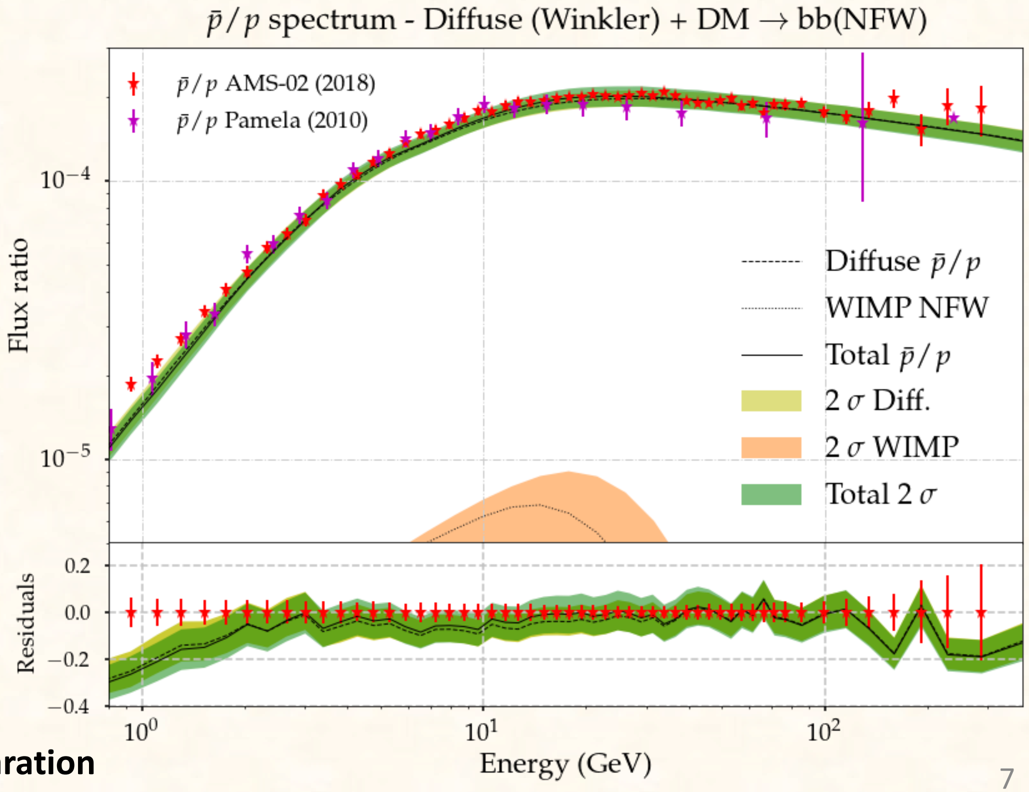
Full XS prior constrains

$M\chi \sim 160$ GeV
$<\sigma v> \sim 7{\cdot}10^{26}\ \mathrm{cm^3/s}$



No XS prior constrains

$M\chi \sim 100$ GeV
$<\sigma v> \sim 2{\cdot}10^{26}\ \mathrm{cm^3/s}$

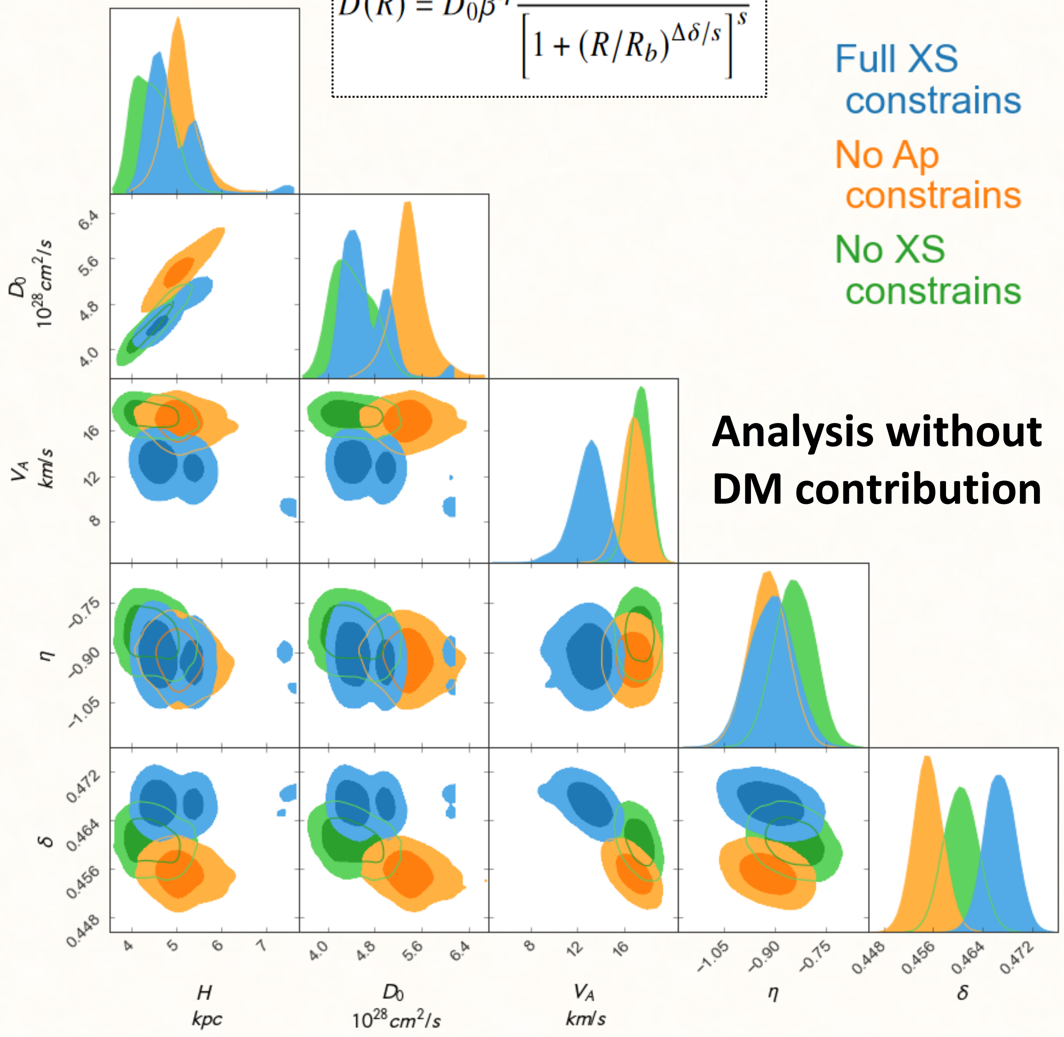


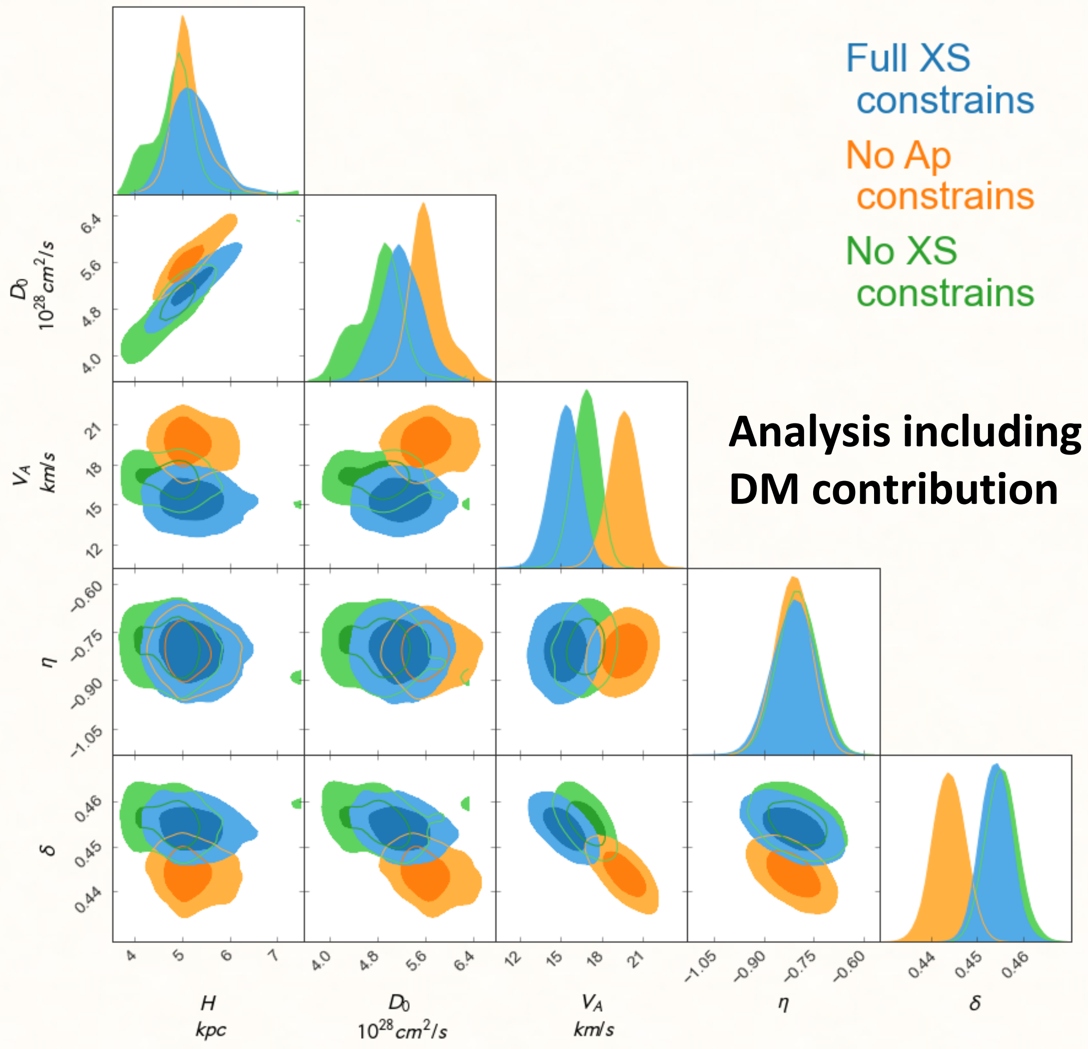
P.D.L. et al, **in preparation**

- ➢ **The predicted parameters are compatible within 1σ uncertainty**
- ➢ **Both hypotheses lead to roughly same propagation parameters!**

Prop. Params are robustly inferred?

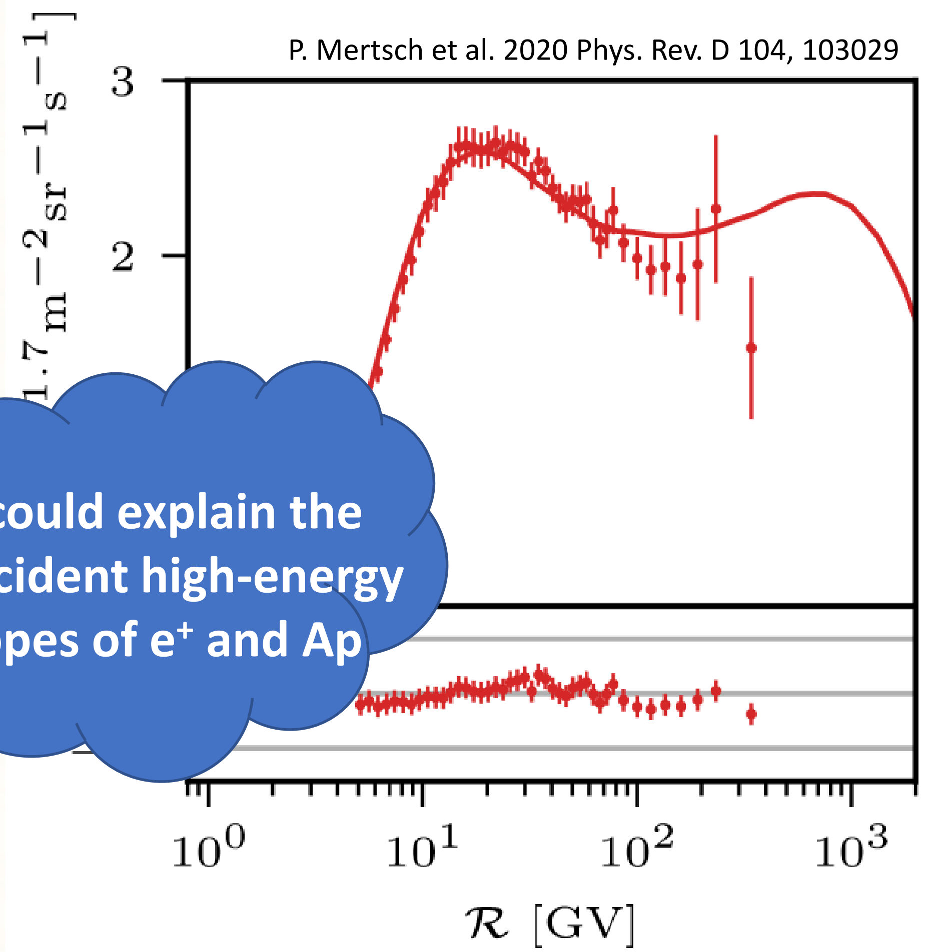
$$D(R) = D_0 \beta^{\eta} \frac{(R/R_0)^{\delta}}{\left[1 + (R/R_b)^{\Delta\delta/s}\right]^{s}}$$





Antiproton *excesses* – *More possibilities*

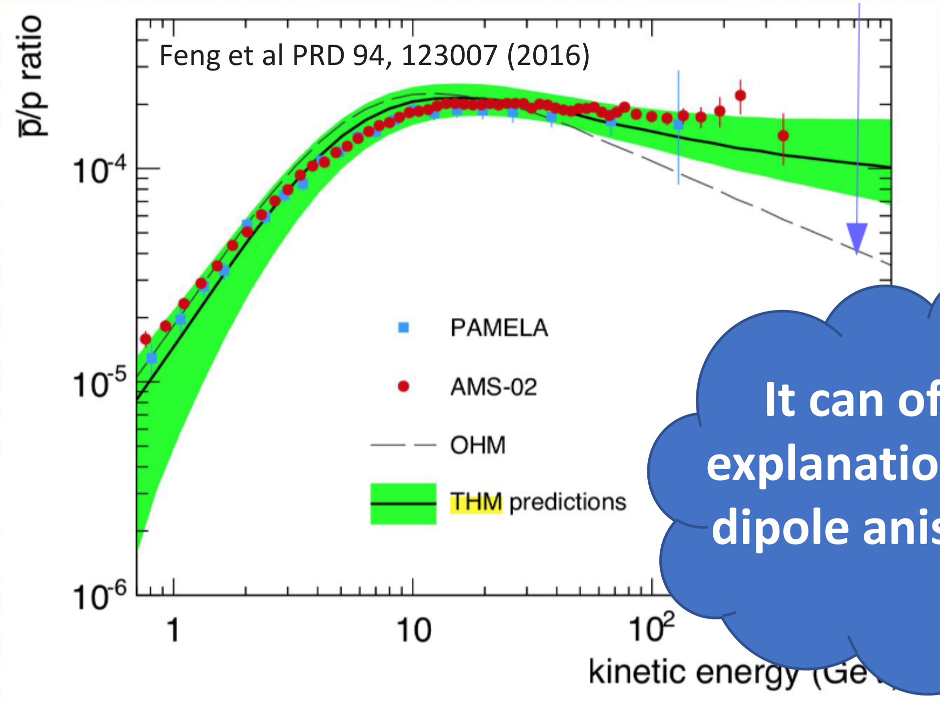
SNRs accelerating antiprotons



It could explain the coincident high-energy slopes of e⁺ and Ap

Inhomogeneous diffusion coefficient

(See also: Zhao et al 2021 arXiv:2109.04112)

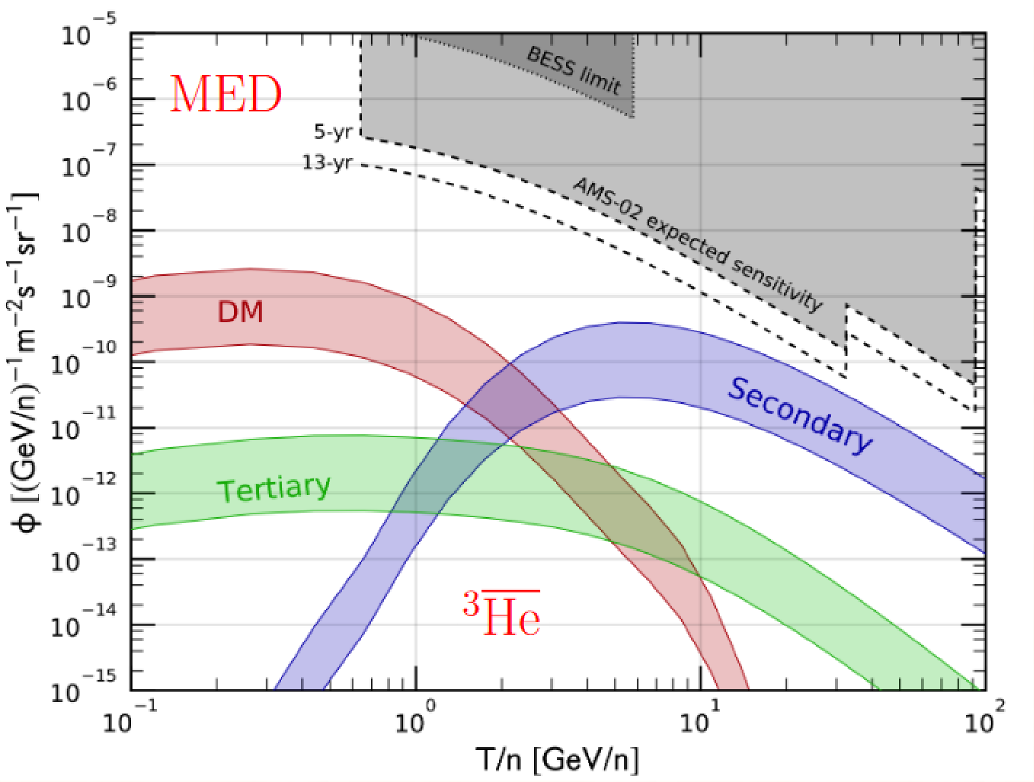


It can offer an explanation for the dipole anisotropy?

Gas Inhomogeneities and the non-uniformity of the CR transport are not explored in depth

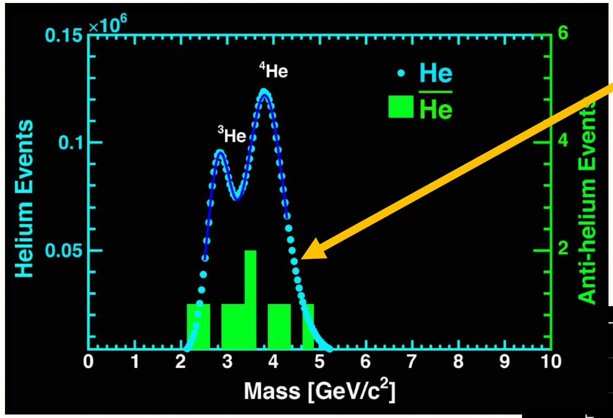
Anti-nuclei as the dark matter smoking gun

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



M. Korsmeir et al. (2018) Phys. Rev. D97, 103011

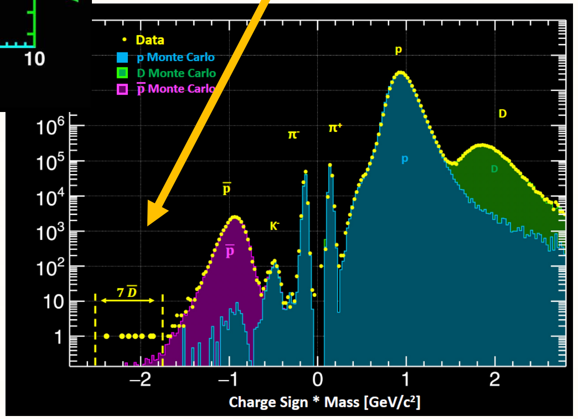
AMS-02 has already some anti-nuclei candidates!



Up to 9 Anti-He events

Paolo Zuccon MIAPP 2021

Up to 7 Anti-D events



Anti-nuclei as the dark matter smoking gun

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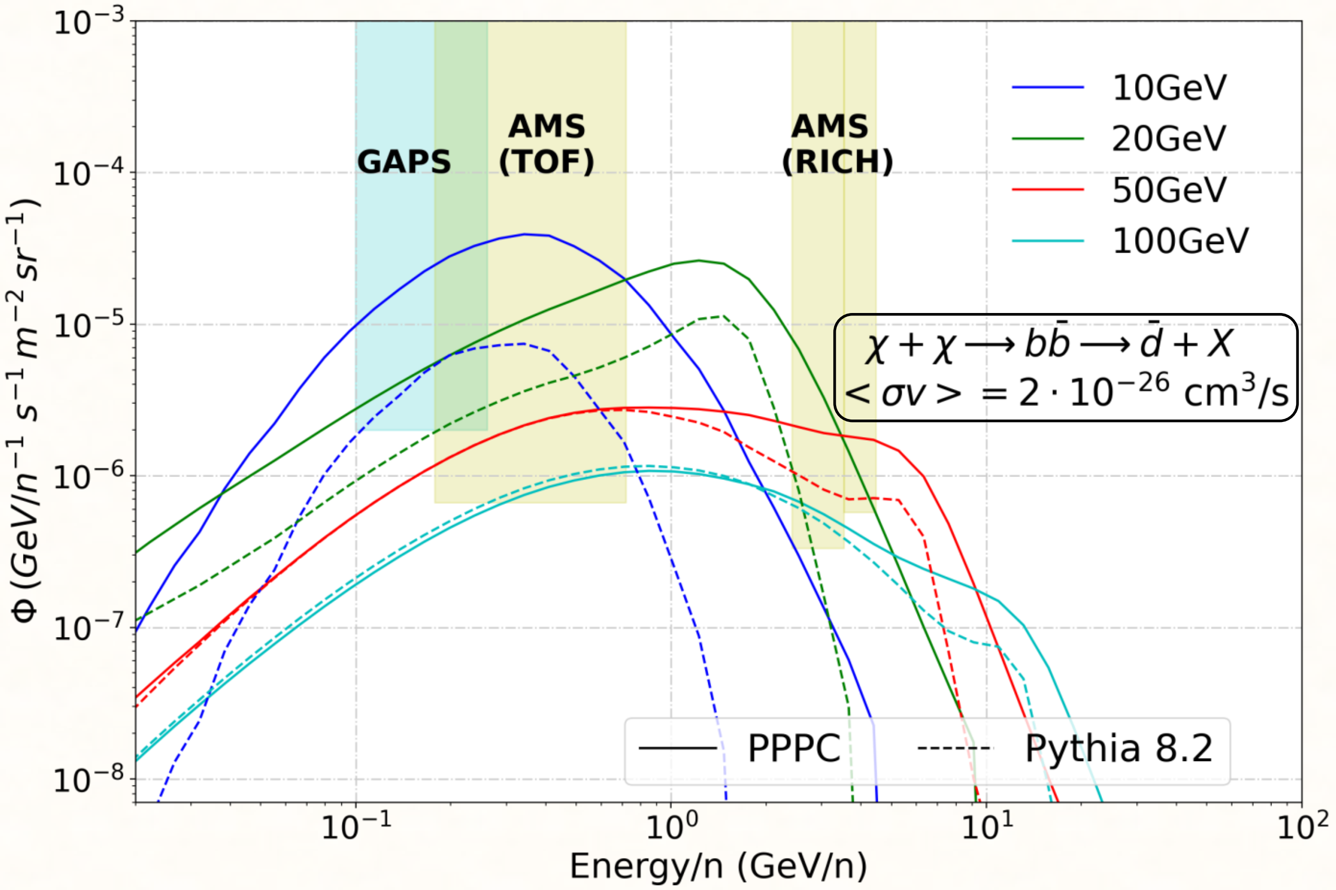


Astrophysical DM excesses and hints

<u>GC GeV excess</u> 30-80 GeV

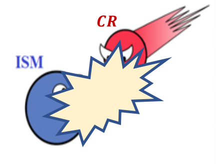
<u>Anti-p excess</u> 60-160 GeV

<u>γ-ray lines</u> ~133 GeV

<u>DAMA excess</u> 10-70 GeV

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

Anti-nuclei propagation in *DRAGON2*



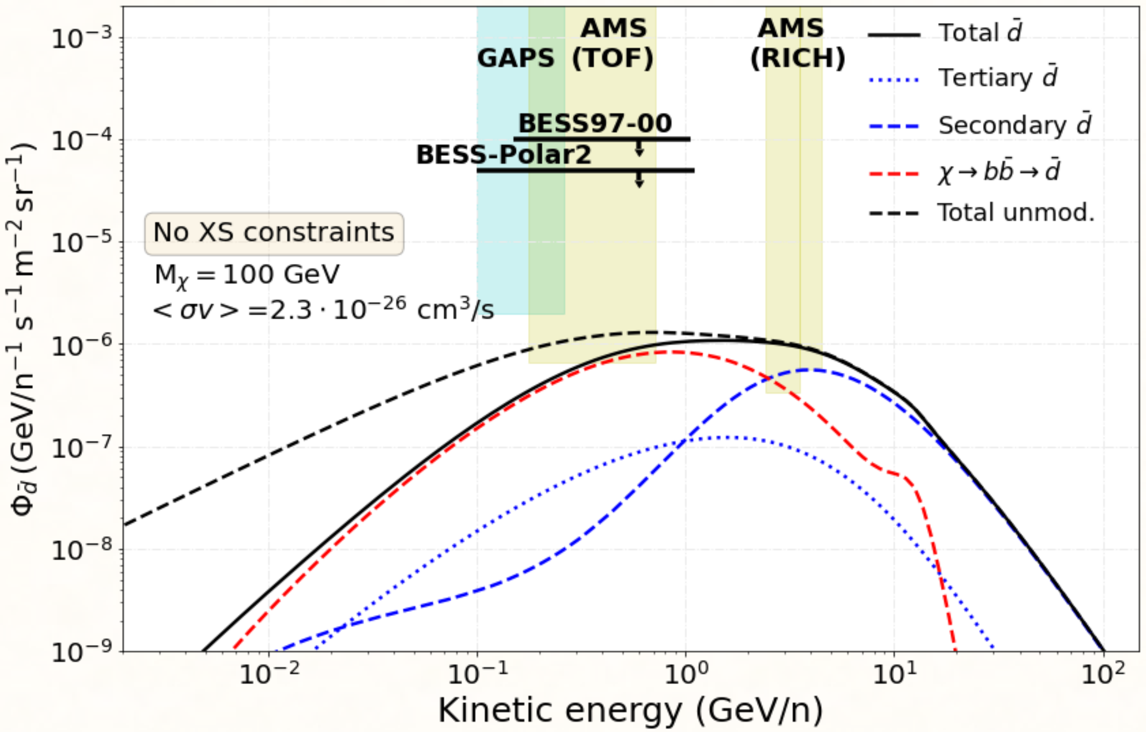
$p_{CR} + p_{ISM} \rightarrow \bar{D}$

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

https://github.com/cosmicrays/DRAGON2-Beta_version
https://github.com/tospines/Customised-DRAGON2_beta

Anti-nuclei from CR collisions can be detected soon!

P.D.L., M. Winkler, T. Linden et al, **in preparation**



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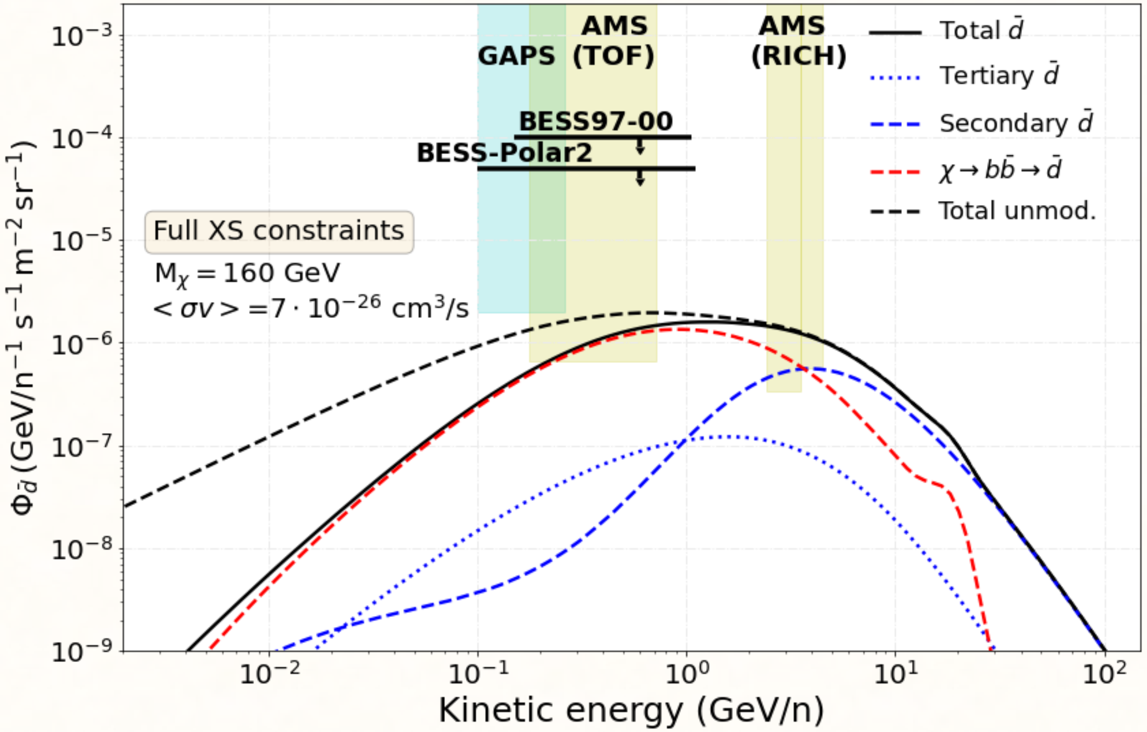
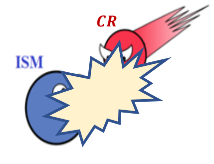


Limits are drawn for: 15 yr of AMS-02 operation and 35 days x 3 flights (LDB) for GAPS

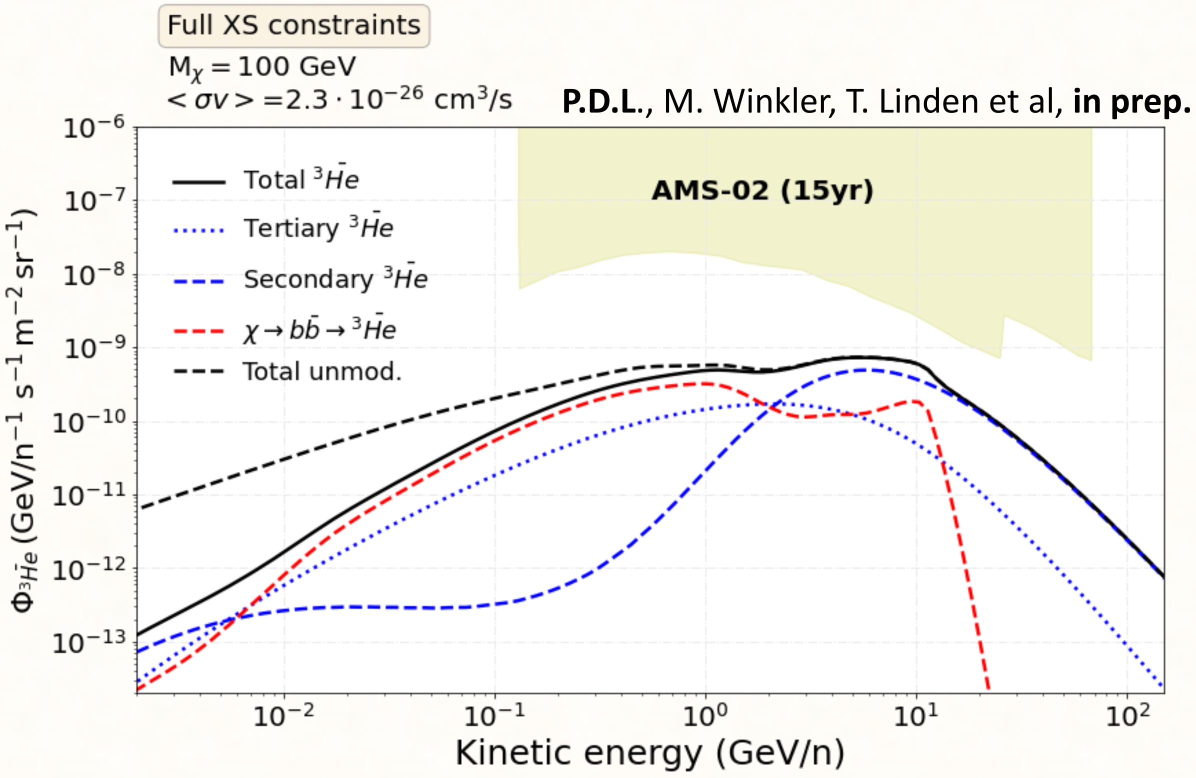
Anti-nuclei propagation in *DRAGON2*

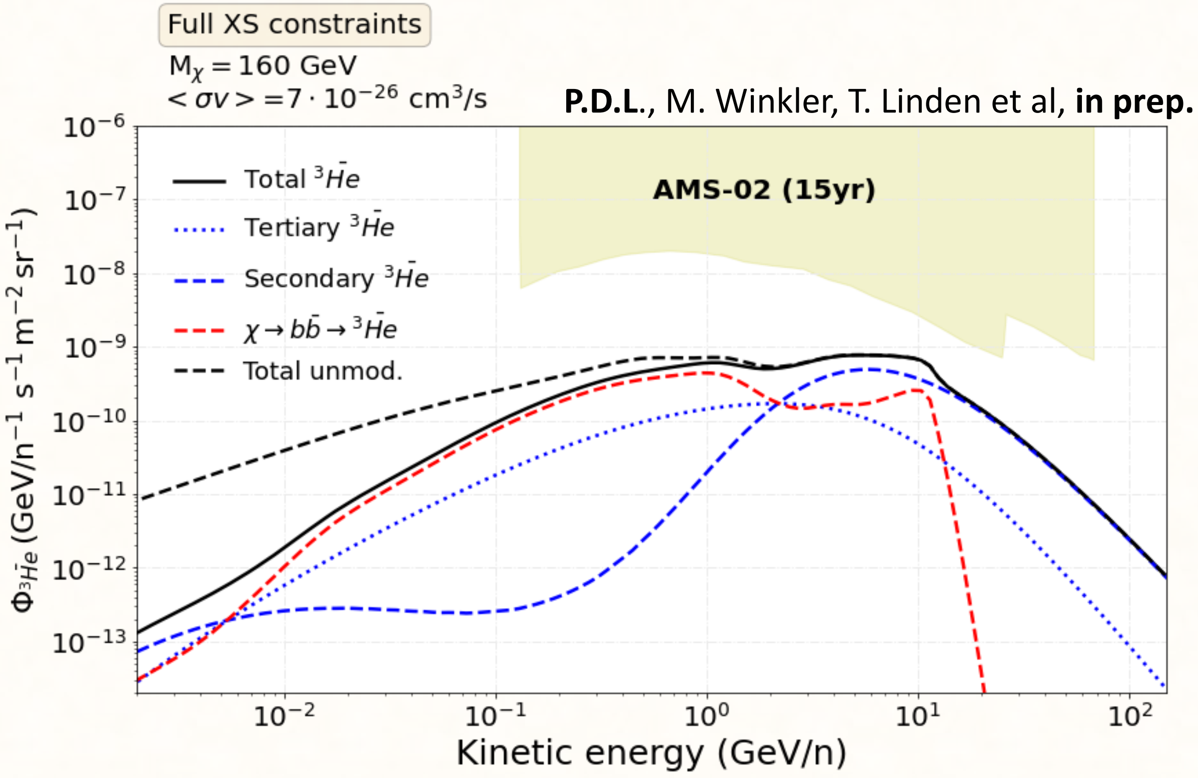


$p_{CR} + p_{ISM} \rightarrow {}^3\overline{He}$

$\chi + \chi \rightarrow {}^3\overline{He}$

✓ **Λ_b production** is a very important source of anti-helium, even able to explain some of the events reported by AMS-02… See Winkler, Linden (2021) PRL 136, 101101





Conclusions

- **Every antimatter particle**, for which we have data, **have unveiled our limited ability of predictions** so far
- Exciting period when experimental data is allowing us to go **beyond standard paradigm of Galactic CR propagation** – Complexity of the physics involving the production and transport of particles in astrophysical media
- ***No significant discrepancy* is found in the *antiproton* data**
- A careful analysis of the **background** (propagation) **uncertainties** can prove (disprove) any current anomaly – Possible (WIMP) **dark matter** signals are going to be tested in the next few years, thanks to AMS-02 and GAPS

Pedro de la Torre Luque – ECRS 2022
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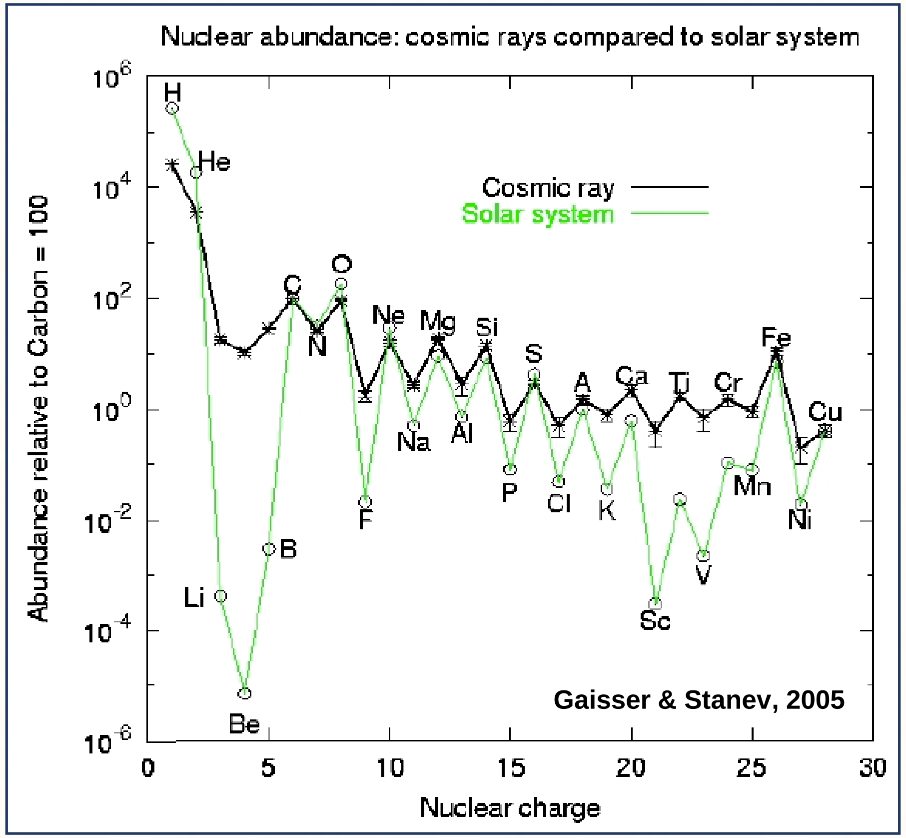
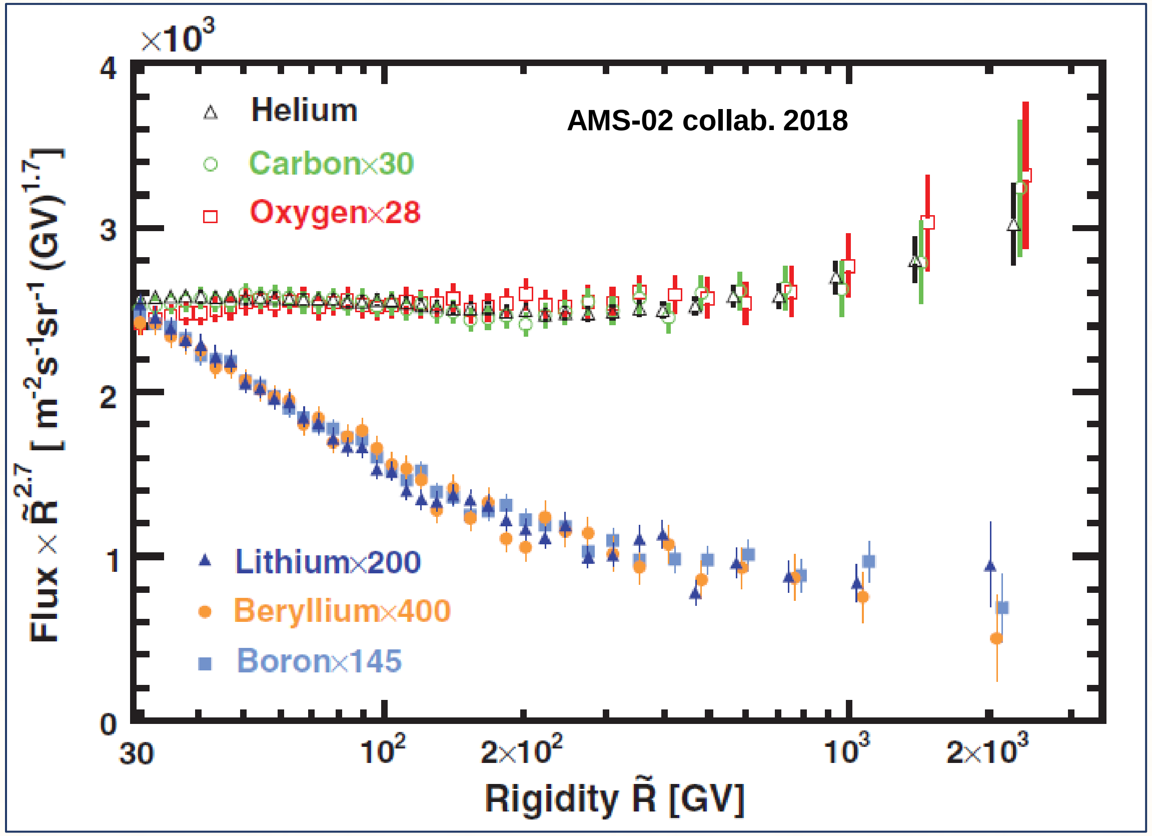
BACK UP

Primary CRs are accelerated in astrophysical sources (presumably SNRs) and propagate throughout the Galaxy, occasionally interacting with gas in the disc of the Galaxy, and there they produce secondary nuclei through spallation.

Abundance of secondary nuclei explained if CRs propagate for hundred millions of years



Secondary CRs offer a sensitive tool to infer the grammage traversed by these particles



Diffusive transport of Galactic cosmic rays

Propagation equation is solved with the DRAGON2 code
https://github.com/cosmicrays/DRAGON2-Beta_version

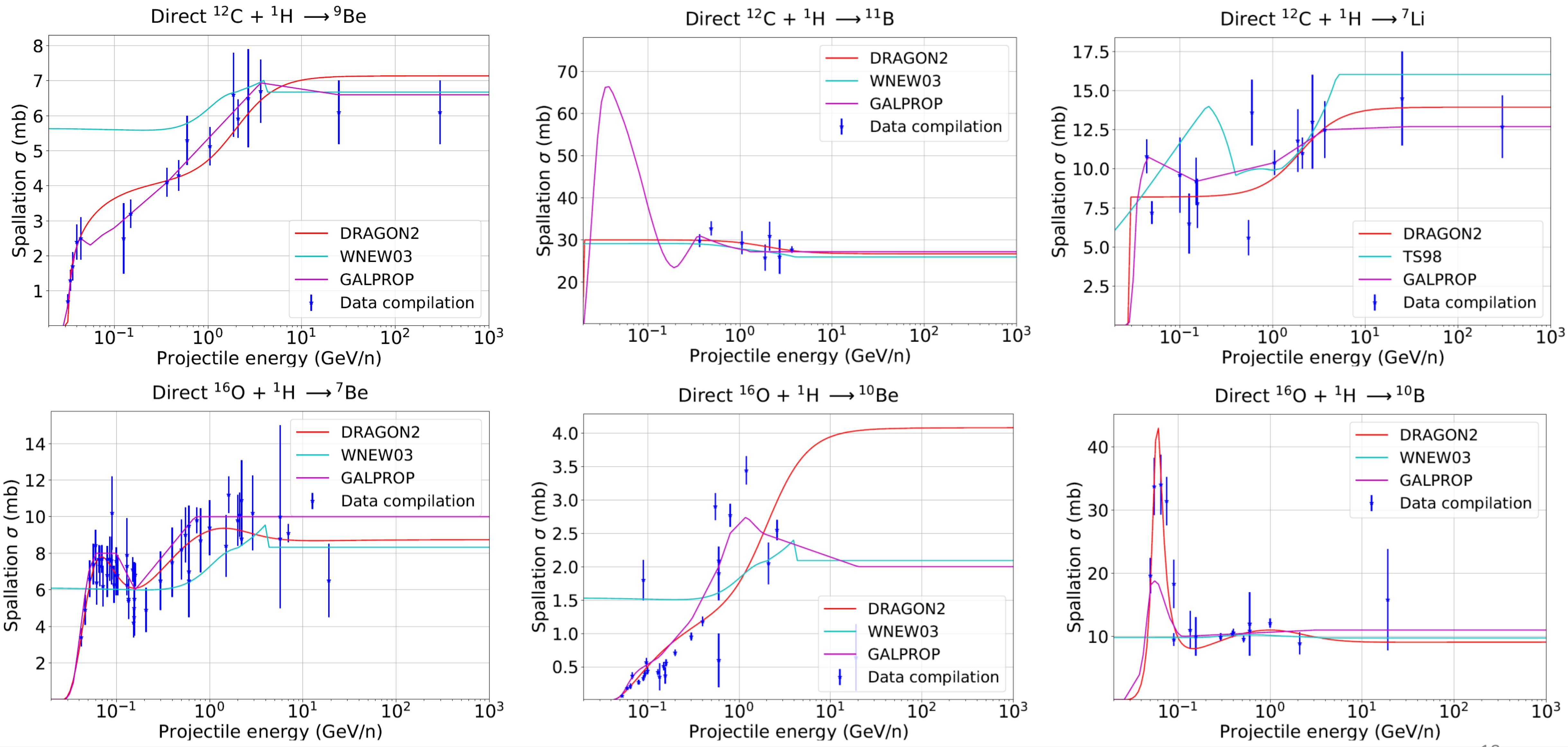
$$\vec{\nabla} \cdot (-D\nabla N_i - \vec{v}_\omega N_i) + \frac{\partial}{\partial p}\left[p^2 D_{pp} \frac{\partial}{\partial p}\left(\frac{N_i}{p^2}\right)\right] = Q_i + \frac{\partial}{\partial p}\left[\dot{p}N_i - \frac{p}{3}\left(\vec{\nabla}\cdot\vec{v}_\omega N_i\right)\right]$$
$$-\frac{N_i}{\tau_i^f}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

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

$$\frac{J_{sec}}{J_{pr}} \sim \sigma(E)/\,D(E)$$

$$\Gamma^s_{j\to i} = \beta_j c n_t \sigma_{j\to i} N_j$$

Cross sections parametrizations

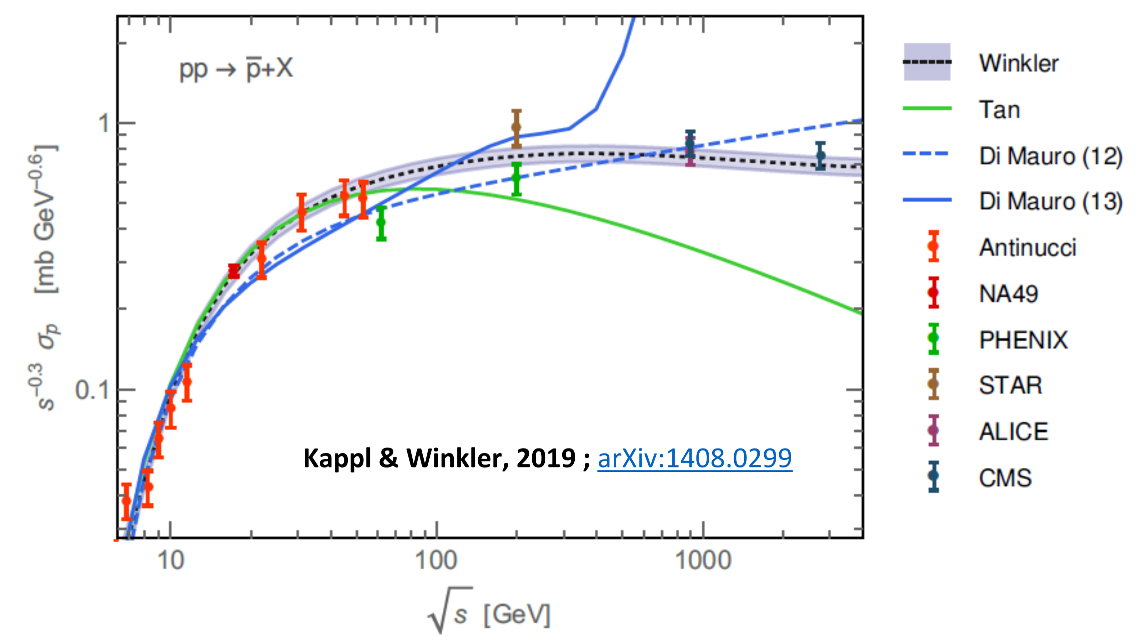


Antiproton cross sections

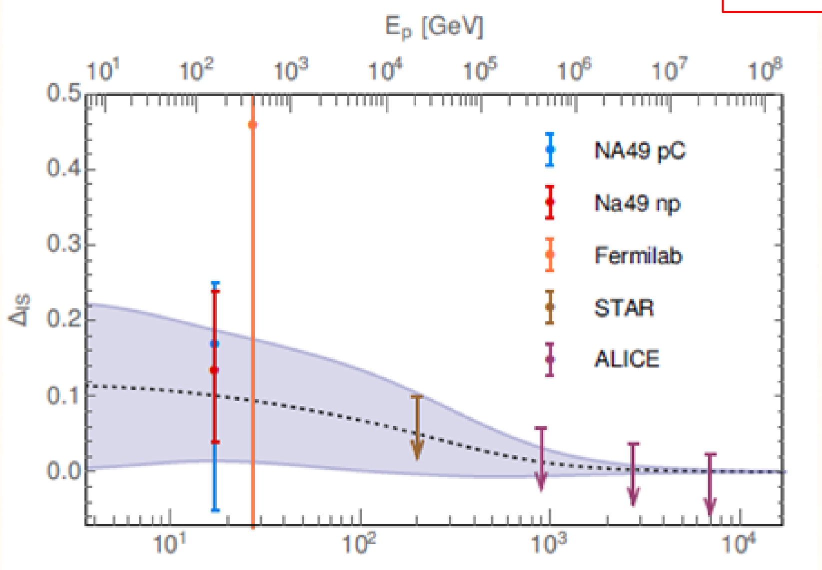
$$\left(E\frac{d^3\sigma}{dp^3}\right)_{pp\to\bar{p}} = \left(E\frac{d^3\sigma}{dp^3}\right)^{\text{prompt}}_{pp\to\bar{p}} \cdot (2 + \Delta_{IS} + 2\,\Delta_{\Lambda})$$

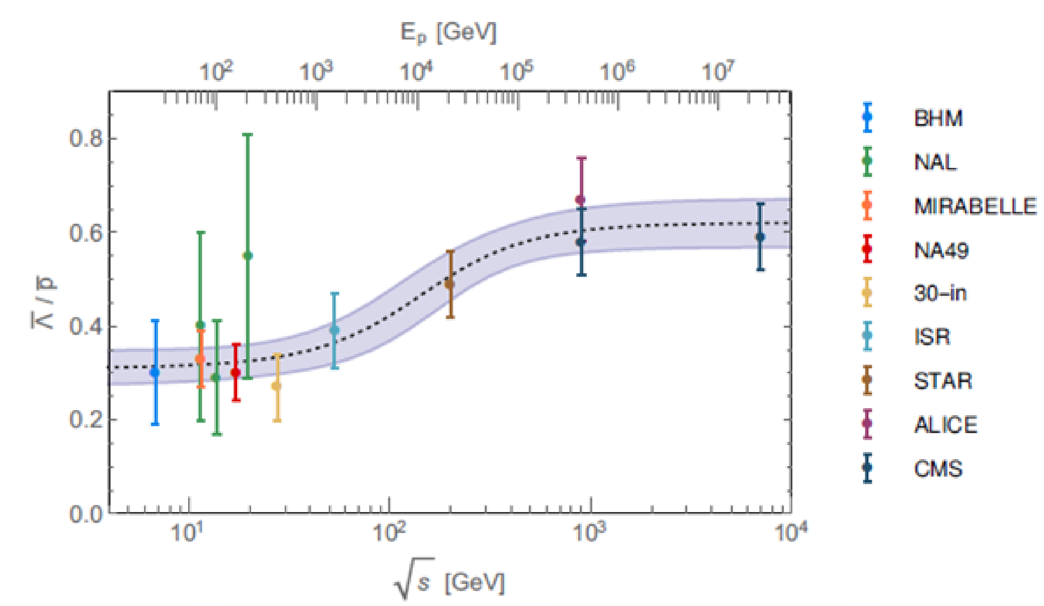
$$p + p \longrightarrow \{\bar{n} \longrightarrow \bar{p}\} + X$$

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



Kappl & Winkler, 2019 ; arXiv:1408.0299

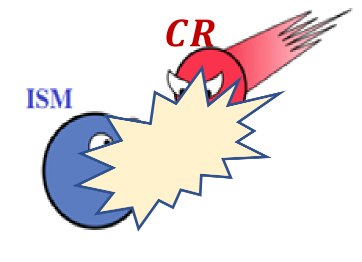




$$p + p \longrightarrow \{\bar{\Lambda}, \bar{\Sigma} \longrightarrow \bar{p}\} + X$$

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

Antiproton ***excesses*** – *The spectral excess*



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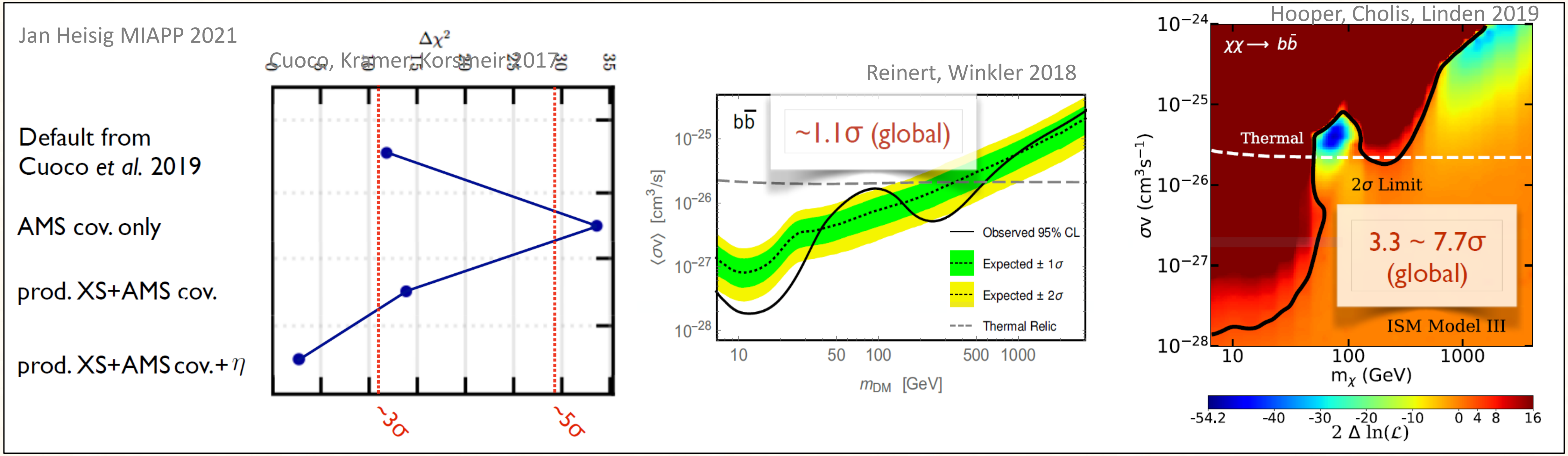
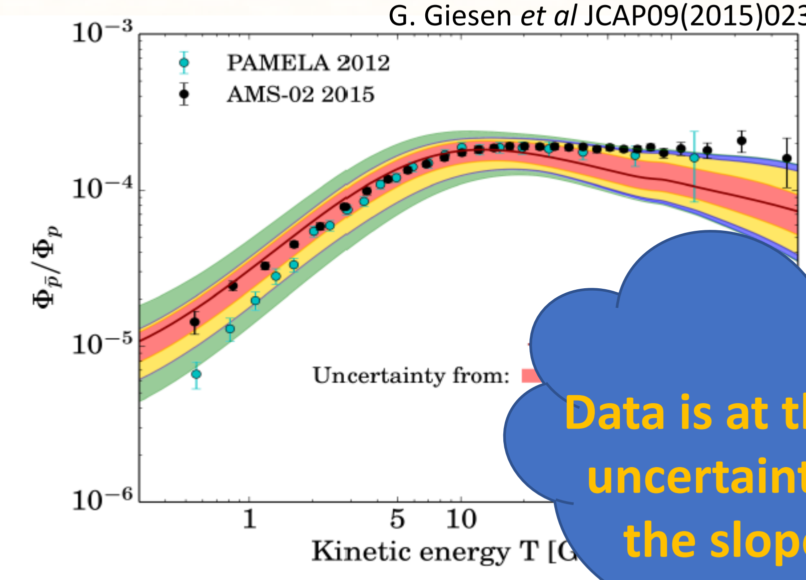
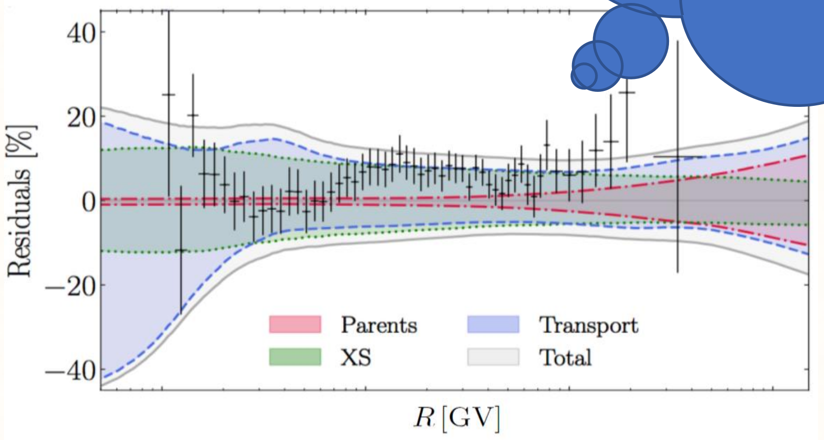


Antiproton excess

G. Giesen *et al* JCAP09(2015)023



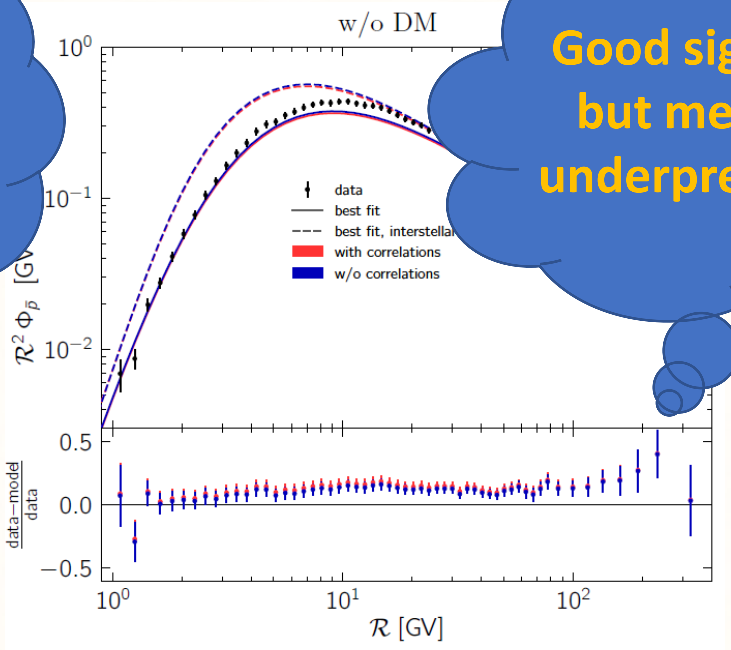
Data is at the edge of the uncertainty bands, and the slope is too soft



Boudaud et al Phys. Rev. Research 2, 023022

Tension in the **amount of grammage** predicted from the secondary CRs B, Be and Li and that predicted from antiprotons

No one has shown a set of propagation parameters that allow us to reproduce at the same time B, Be, Li and antiprotons

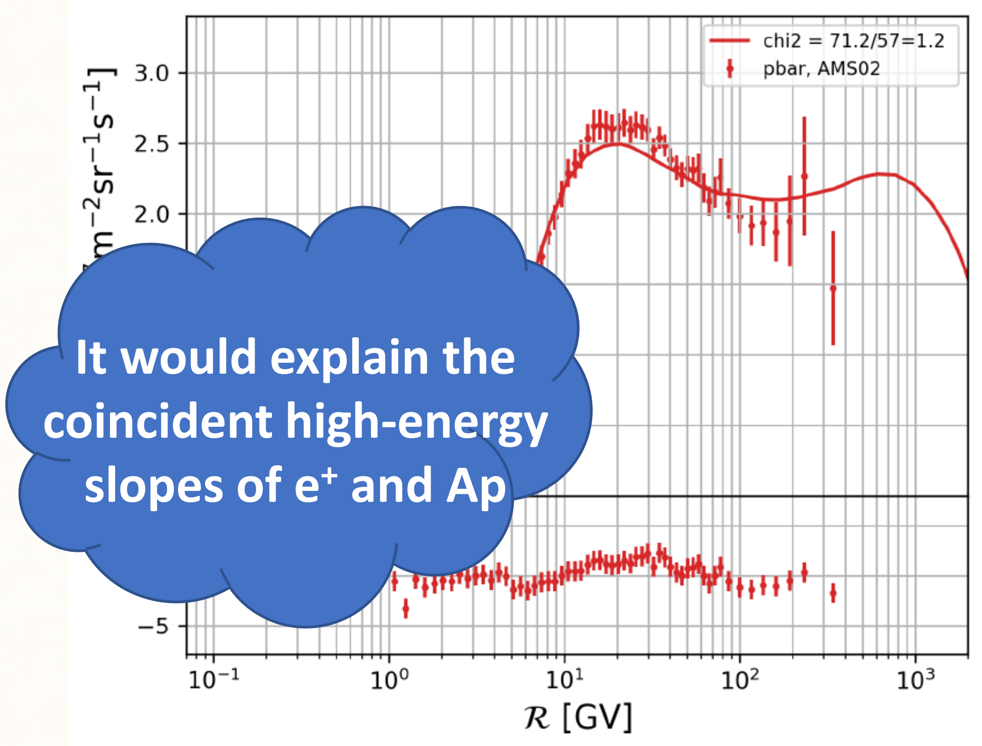


Good significance ($\chi^2 \sim 1$), but median parameters underpredict the spectrum

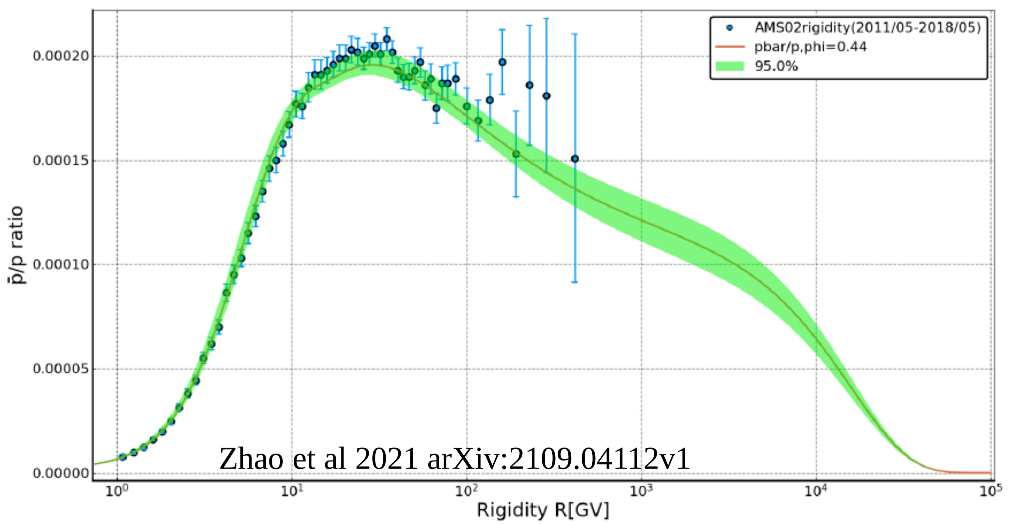
Heisig, Korsmeier, Winkler Phys. Rev. Research 2, 043017

Antiproton excess

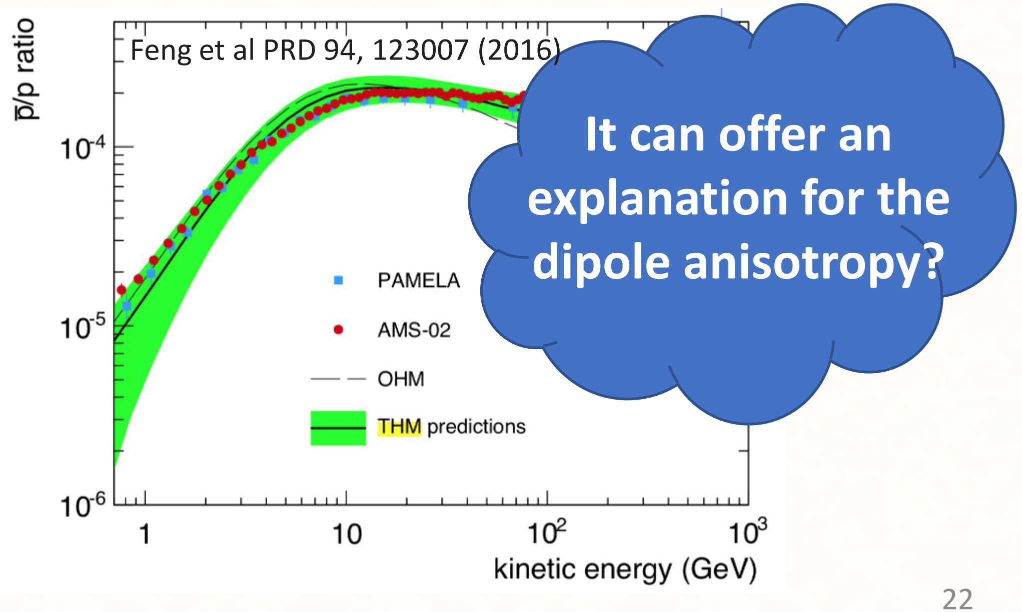
P. Mertsch et al. 2020 arXiv: 2021.12853



Nearby source accelerating antiprotons
Caveat: Antiproton spectrum not well reproduced



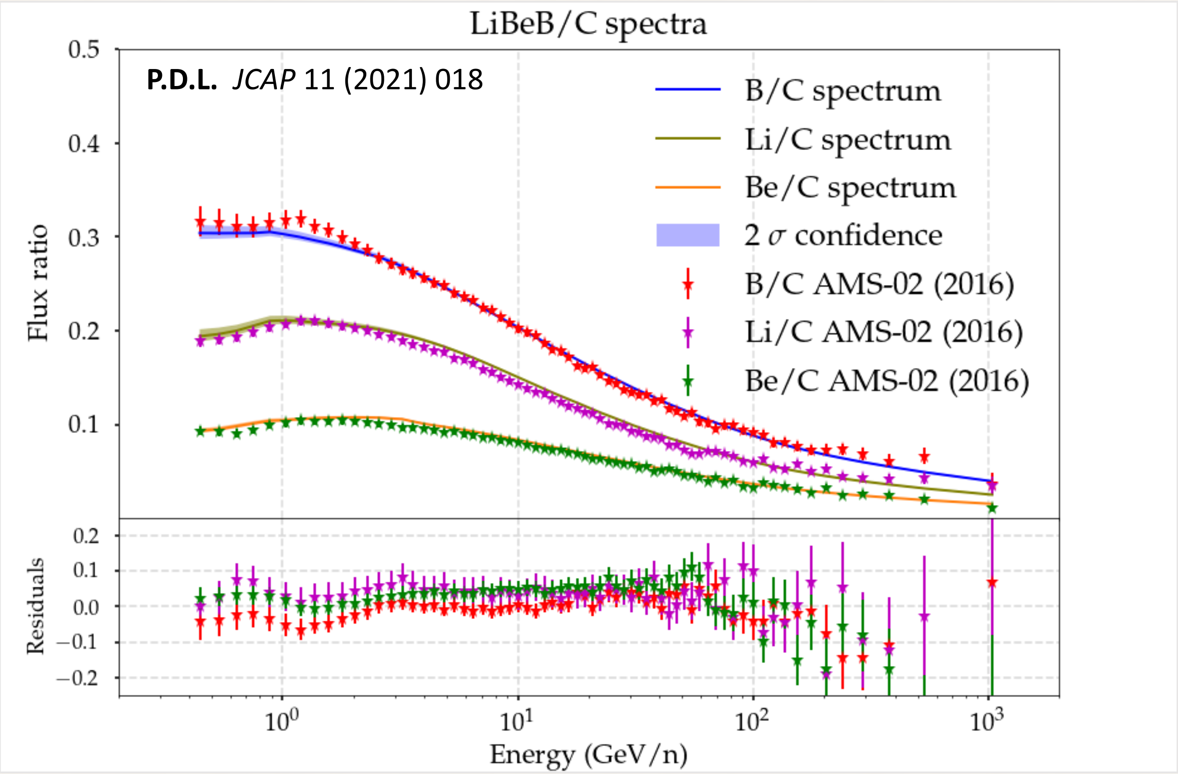
Inhomogeneous diffusion coefficient
Caveat: predicted δ not compatible with MHD theory

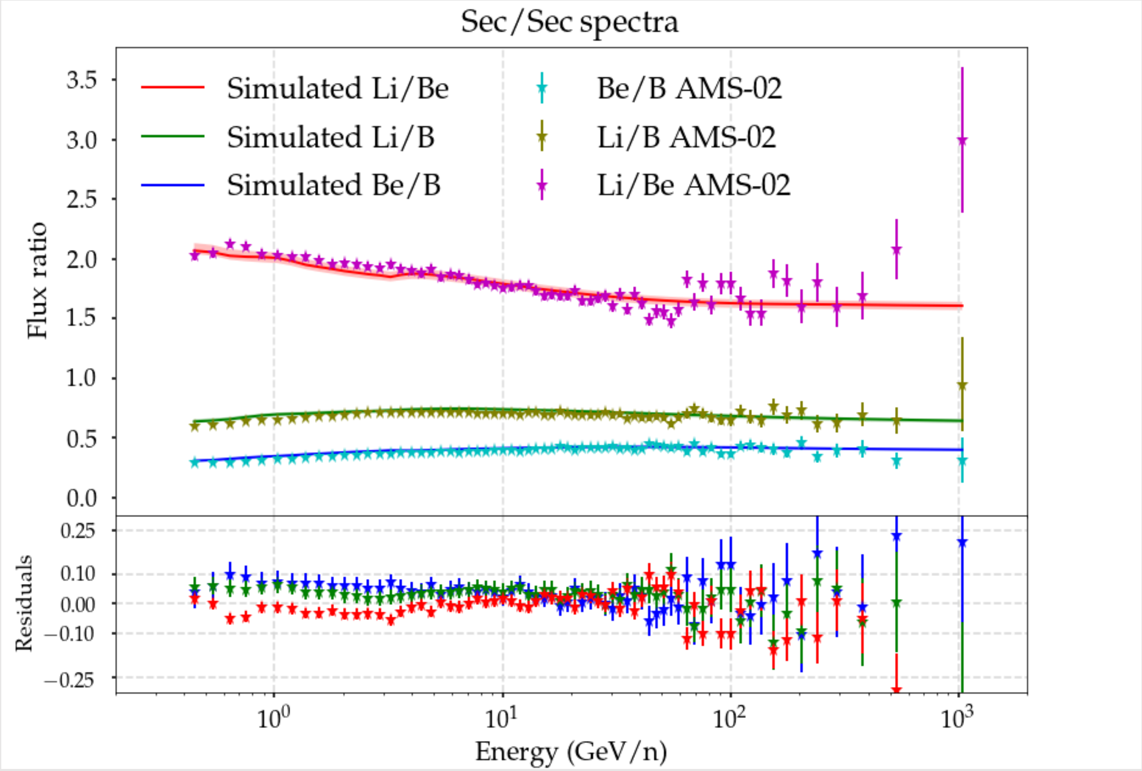


Precise studies of secondary CRs: *The antiproton excesses*

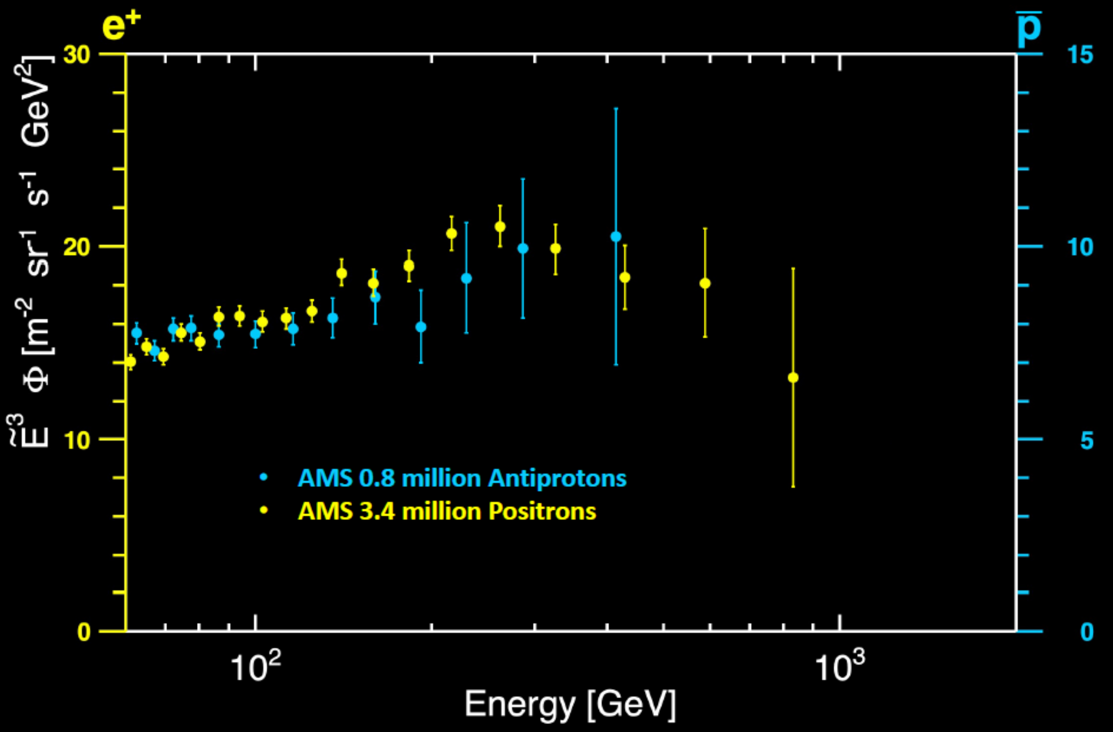
- *DRAGON2* cross sections for heavy secondary CRs
- *Winkler* (2017) cross sections for antiprotons

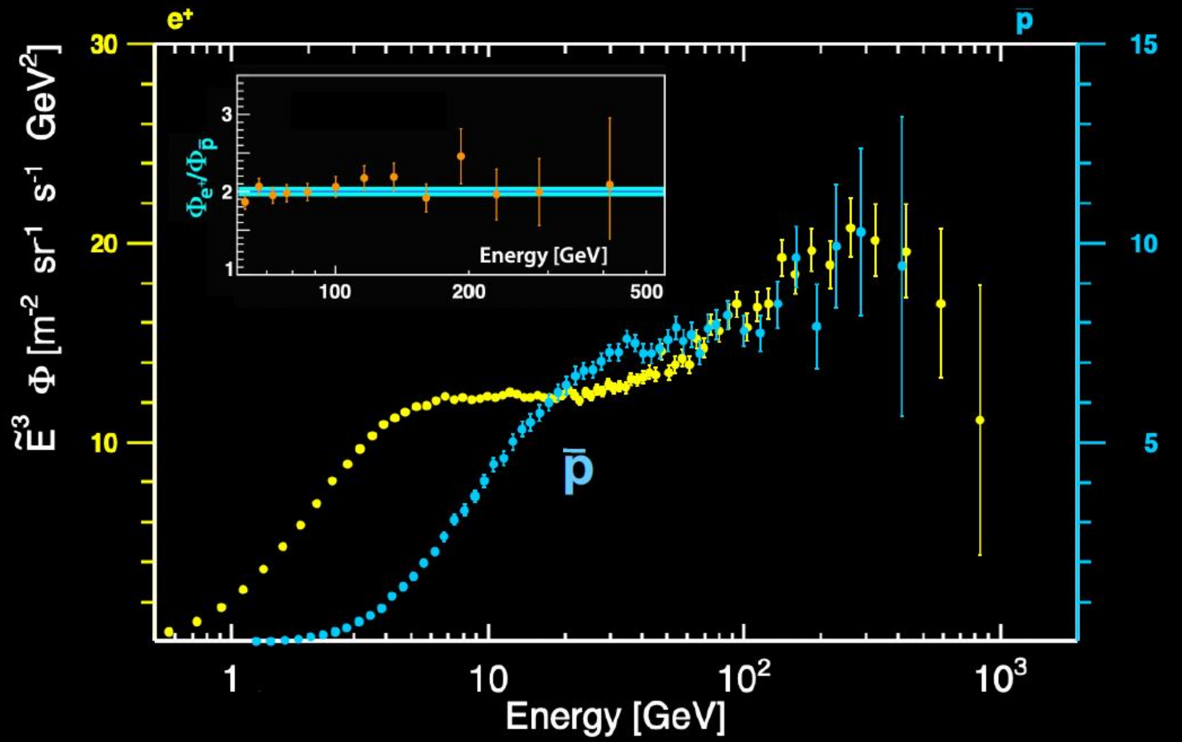
B/C, B/O, Be/C, Be/O, Ap/p (Prop. parameters)
^{10}Be/^{9}Be, ^{10}Be/Be (H), **Be/B, Li/B, Li/Be** (S_X)
Ap/e$^+$, Ap/e$^-$ → S_{Ap}, propagation params





AMS-02 Positrons and antiprotons

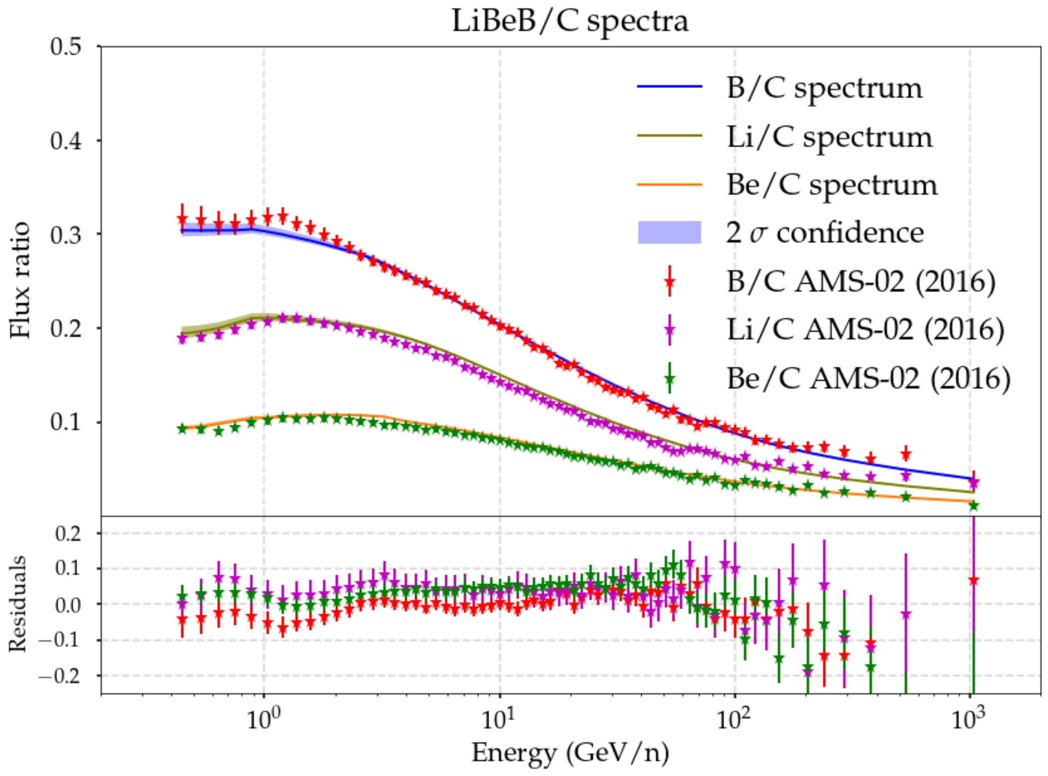




Paolo Zuccon MIAPP 2021

There is a set of propagation parameters that reproduce the energy dependence of the antiproton and the other secondary CRs (B, Be and Li)

Crucial role played by the cross sections scale factors → $S_B \sim$ **0.97** S_{Be}, $S_{Li} \sim$ **0.90**



- DRAGON2 cross sections for heavy secondary CRs
- Winkler (2017) cross sections for antiprotons

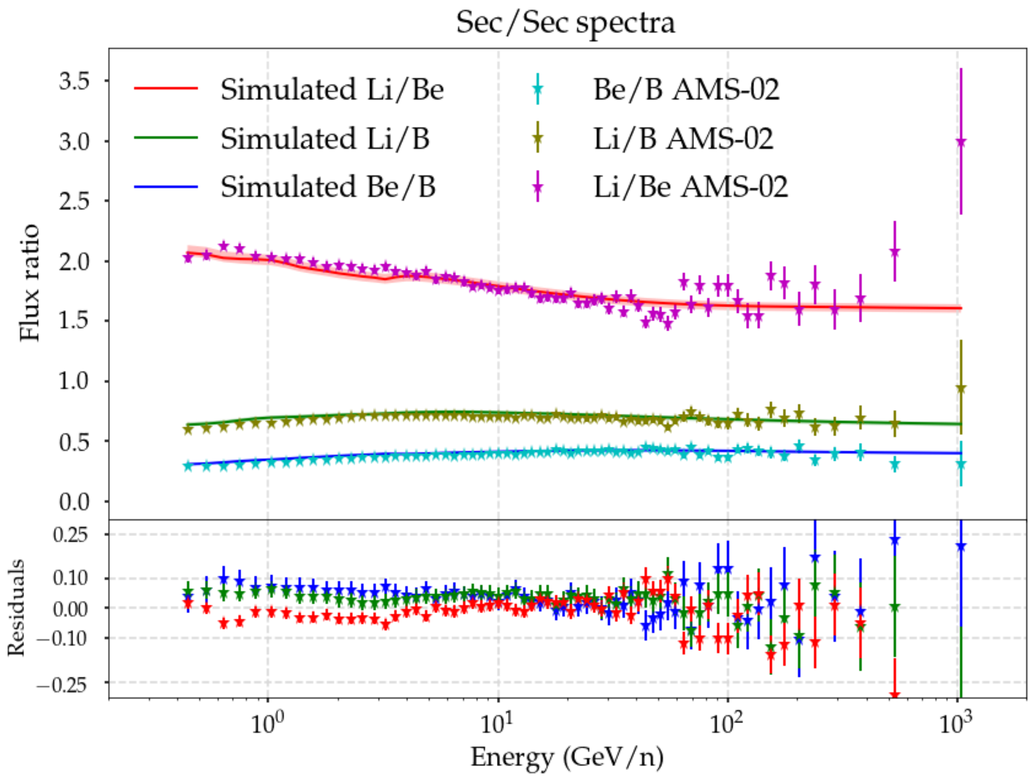
- Diffusion Coefficient $$D(R) = D_0 \beta^\eta \frac{(R/R_0)^\delta}{\left[1 + (R/R_b)^{\Delta\delta/s}\right]^s}$$

B/C, B/O, Be/C, Be/O, Ap/p (Propagation parameters)
^{10}Be/^{9}Be, ^{10}Be/Be (H), **Be/B, Li/B, Li/Be** (Scale factors, S_X)

Ap/p spectrum included at E > 4 GeV to avoid the impact of systematic uncertainties associated to solar modulation

There is a set of propagation parameters that reproduce the energy dependence of the antiproton and the other secondary CRs (B, Be and Li)

Crucial role played by the cross sections scale factors → $S_B \sim$ **0.97** S_{Be}, $S_{Li} \sim$ **0.90**



- DRAGON2 cross sections for heavy secondary CRs
- Winkler (2017) cross sections for antiprotons

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

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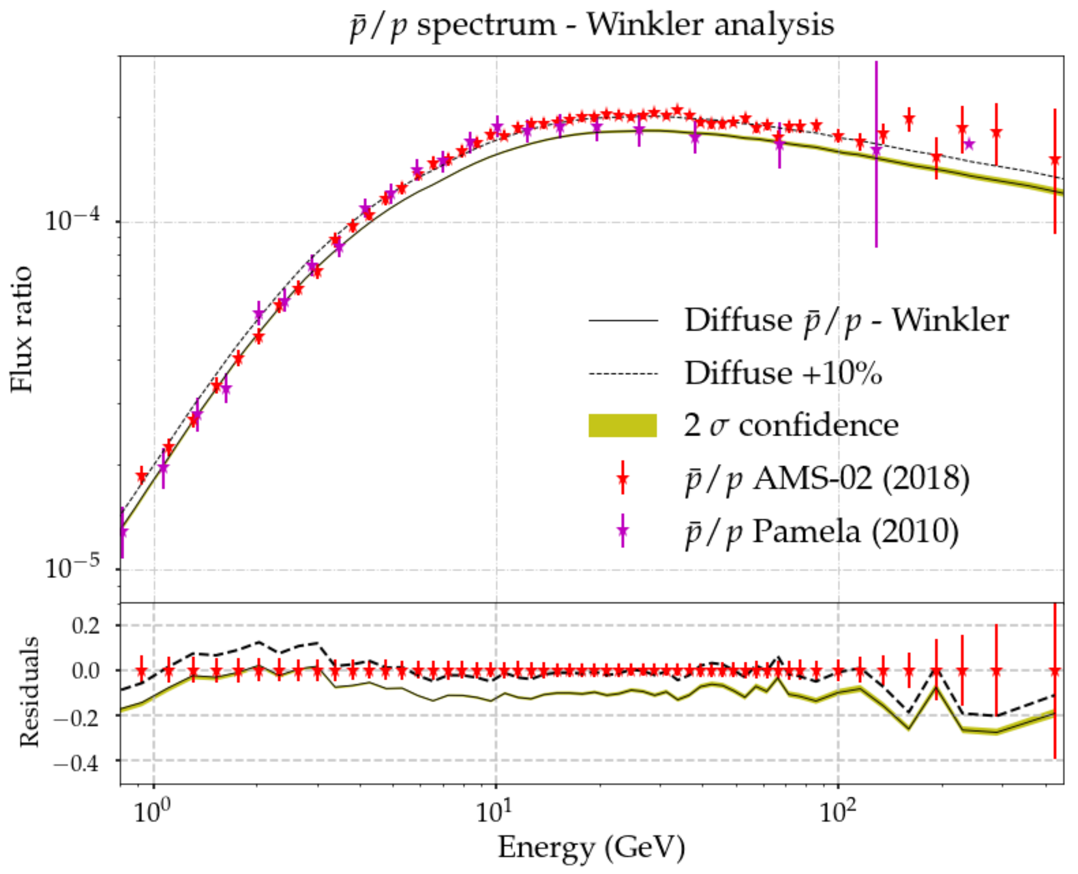

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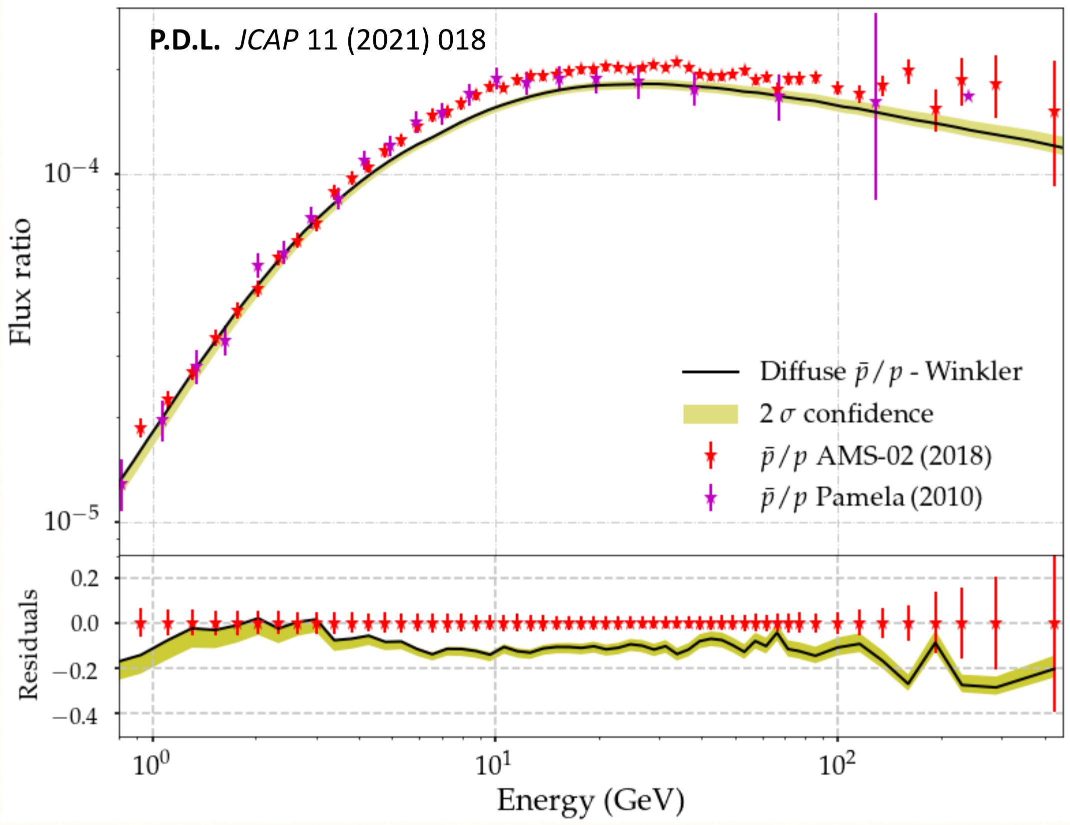
B/C, B/O, Be/C, Be/O, Ap/p (Propagation parameters)
^{10}Be/^{9}Be, ^{10}Be/Be (H), **Be/B, Li/B, Li/Be** (Scale factors, S_X)

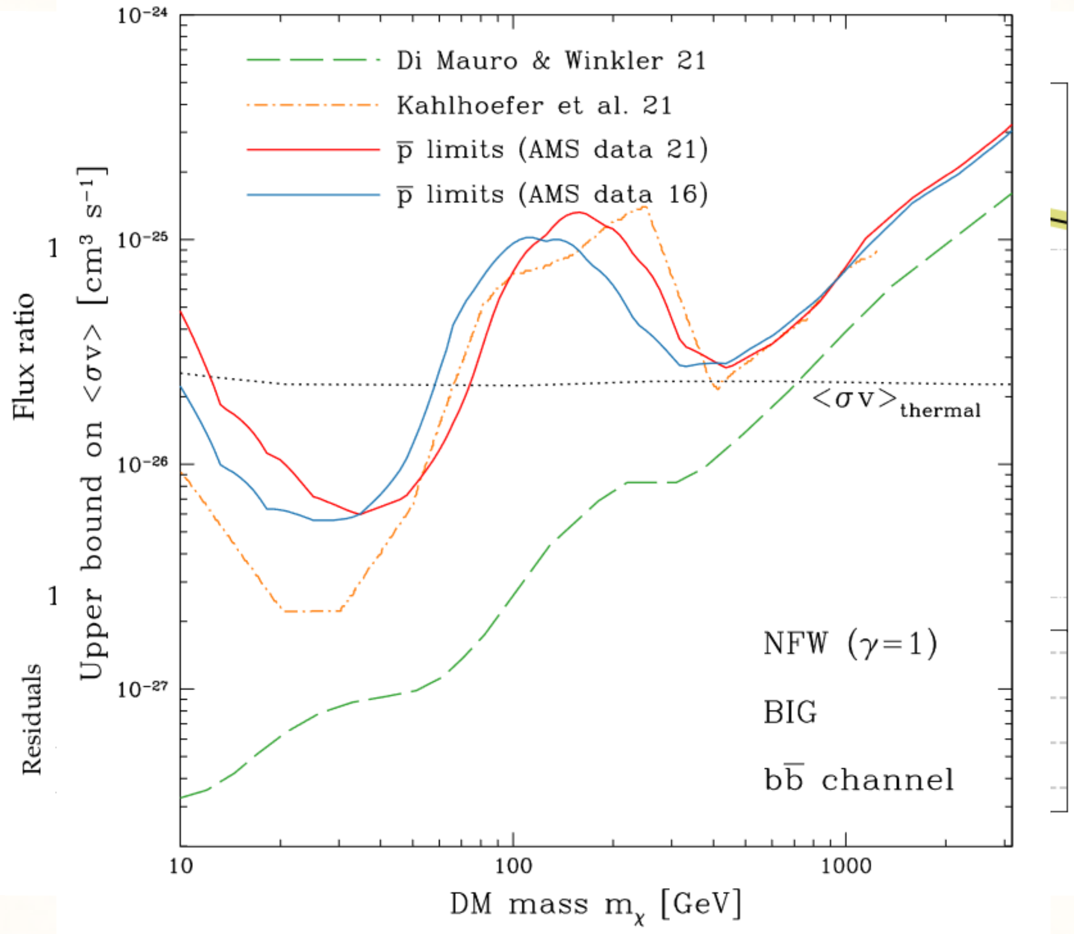
Ap/p spectrum included at E > 4 GeV to avoid the impact of systematic uncertainties associated to solar modulation

Precise studies of secondary CRs: The antiproton excesses

Flatter residuals lead to mass and annihilation rate larger with the new set of data from AMS-02



Calore et al arXiv:2202.03076v1



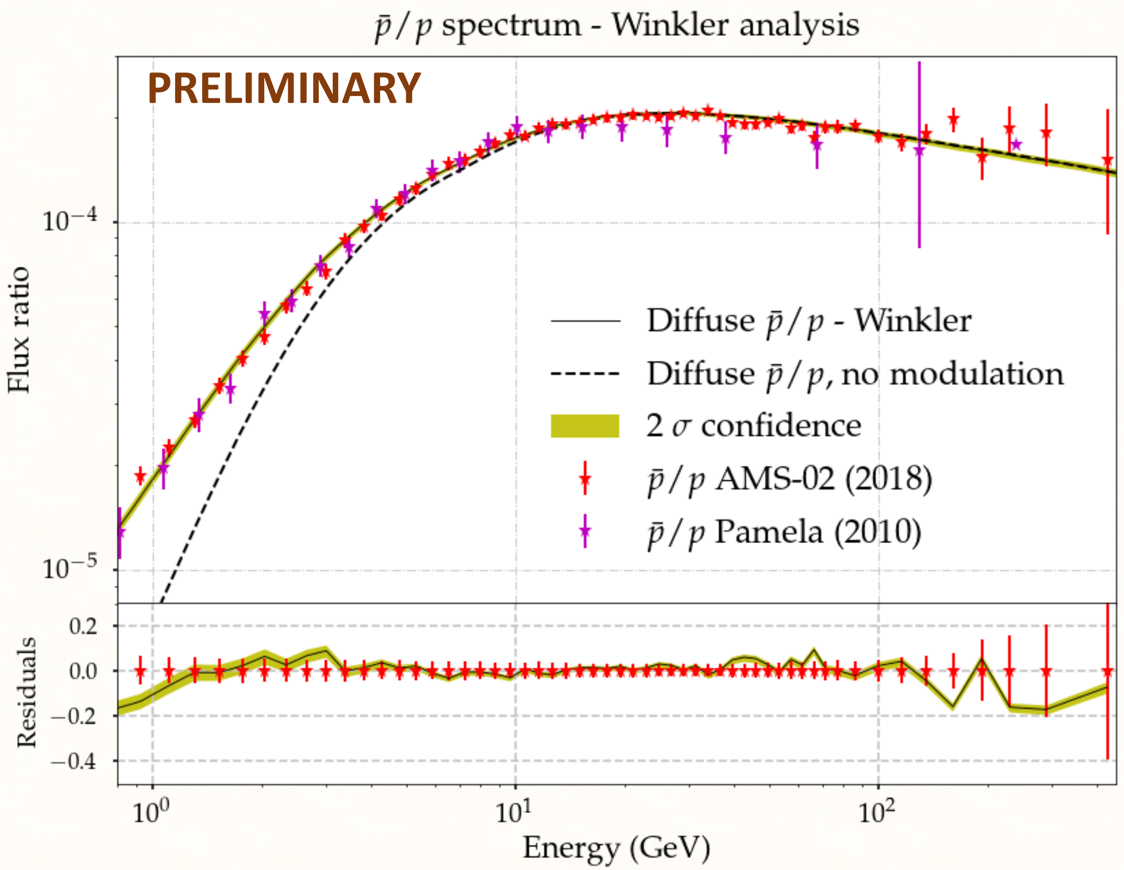
Combined antiproton analysis

- Included Ap/e$^+$ and Ap/e$^-$ as well as a scale factor (**S_{Ap}**) to renormalize cross sections of Ap production

B/C, B/O, Be/C, Be/O, Ap/p (propagation params)
^{10}Be/^{9}Be, ^{10}Be/Be (H), **Be/B, Li/B, Li/Be** (S_X)
Ap/e$^+$, Ap/e$^-$ → S_{Ap}, propagation params

- Prior constrains on the Ap cross sections impact on the predicted grammage:

Different tests are performed for different prior constrains

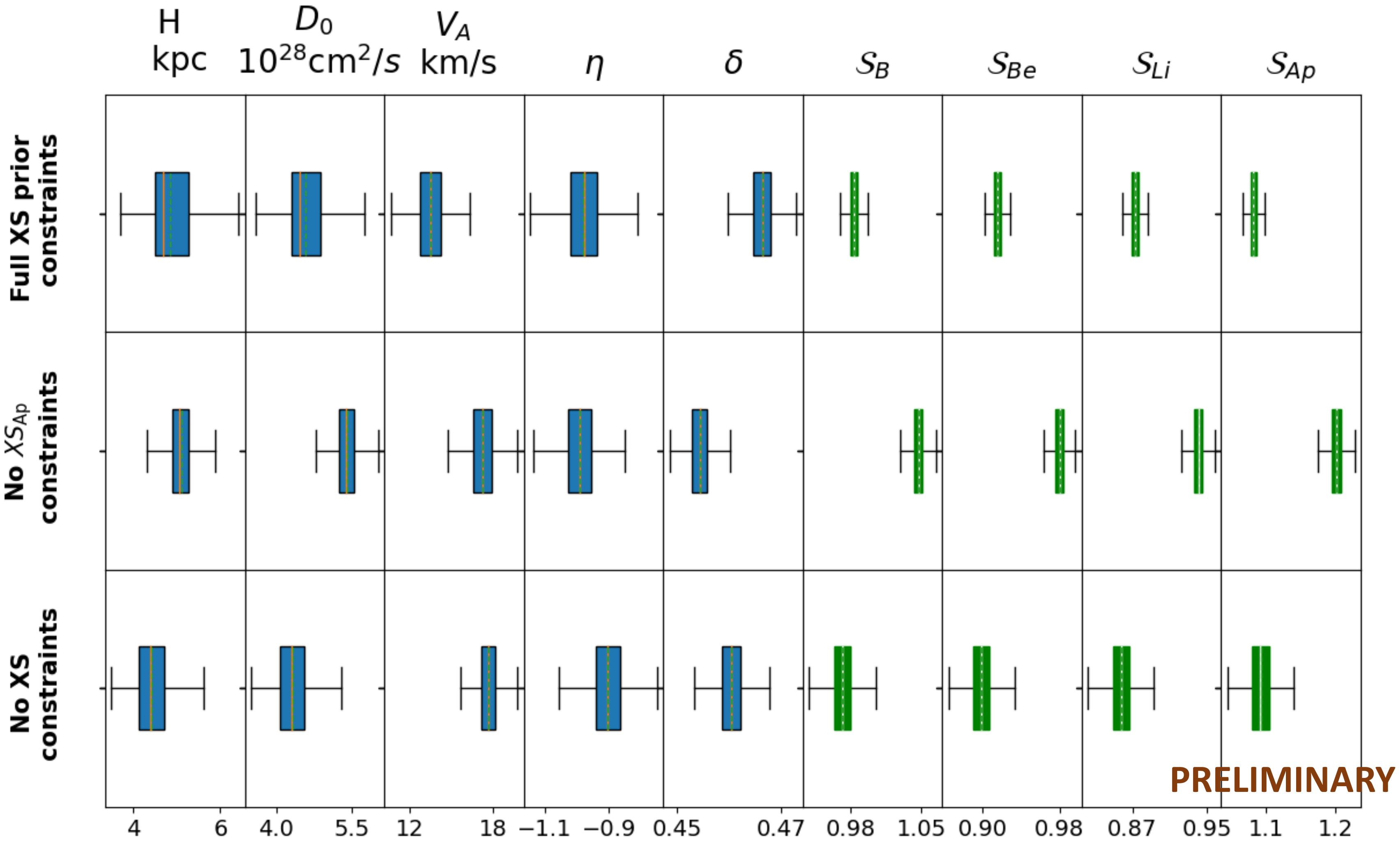


I. Propagation parameters that best describe the spectra of all these secondary CRs

II. Scaling needed to reconcile the antiproton data with B, Be and Li data

III. Is there room for any WIMP contribution on the antiproton spectrum?

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

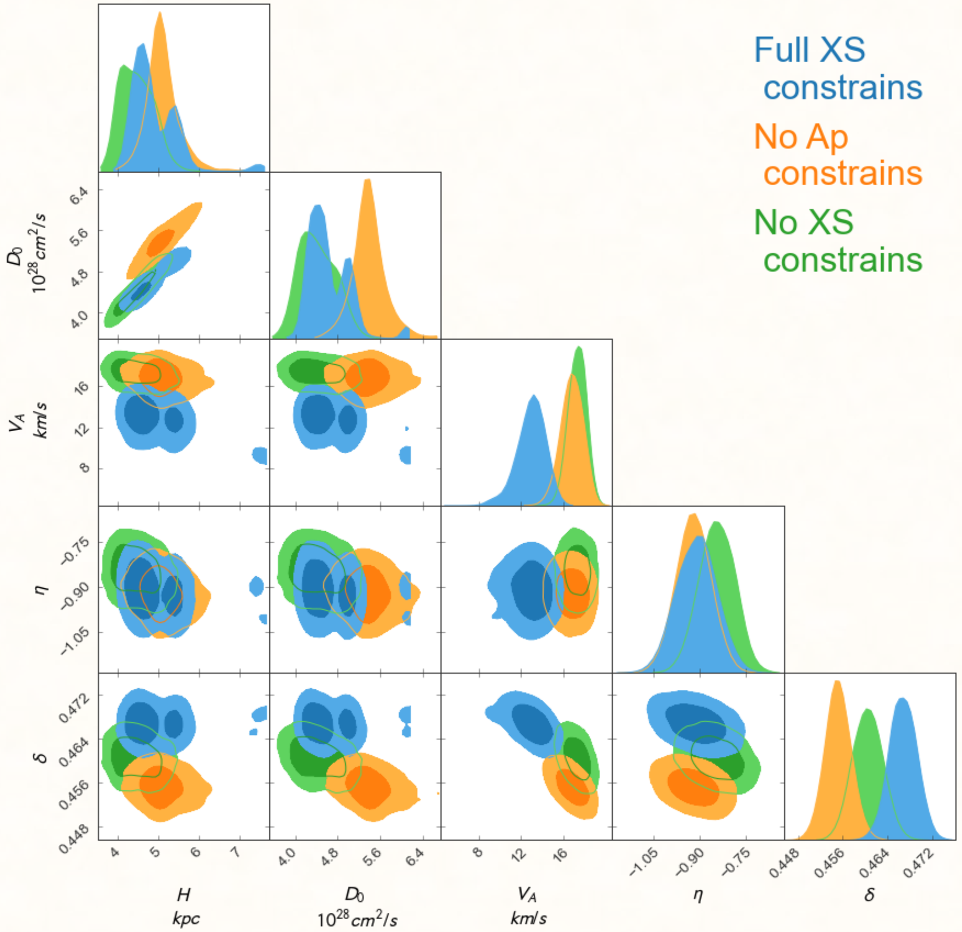


The predicted parameters associated to the energy dependence of the diffusion coefficient are compatible even within 1σ uncertainty

Main change is found in the normalization of the diffusion coefficient and H parameters → Prior constrains in cross sections only affect the normalization of the predicted grammage

NO DM

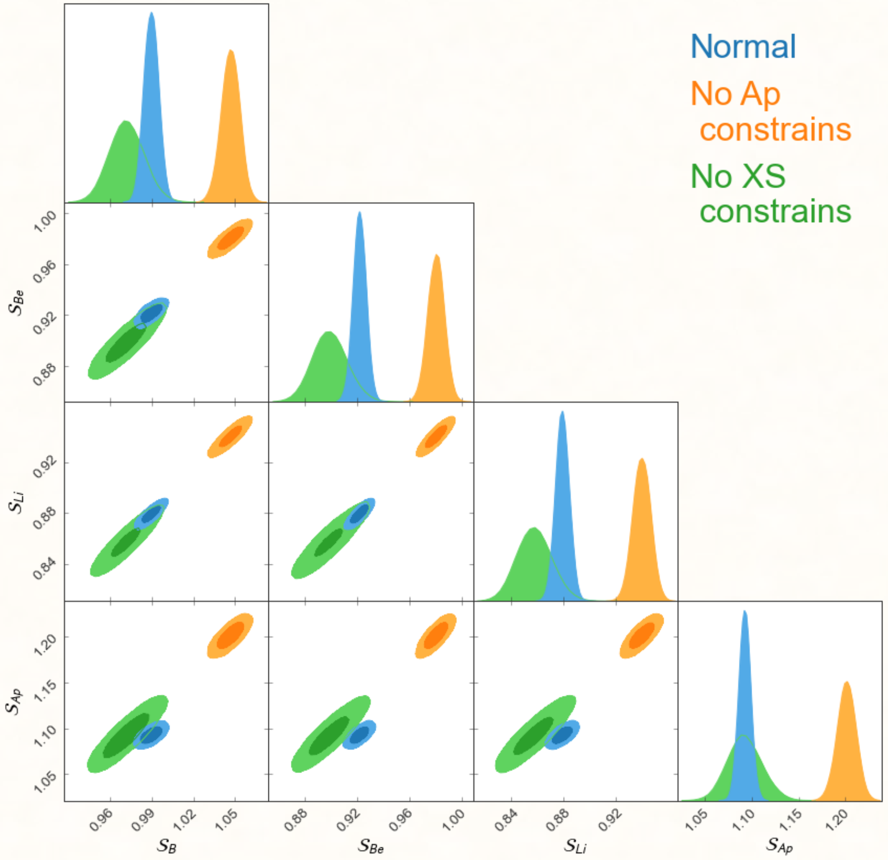
$$D(R) = D_0 \beta^{\eta} \frac{(R/R_0)^{\delta}}{\left[1 + (R/R_b)^{\Delta\delta/s}\right]^{s}}$$



Full XS constrains

No Ap constrains

No XS constrains

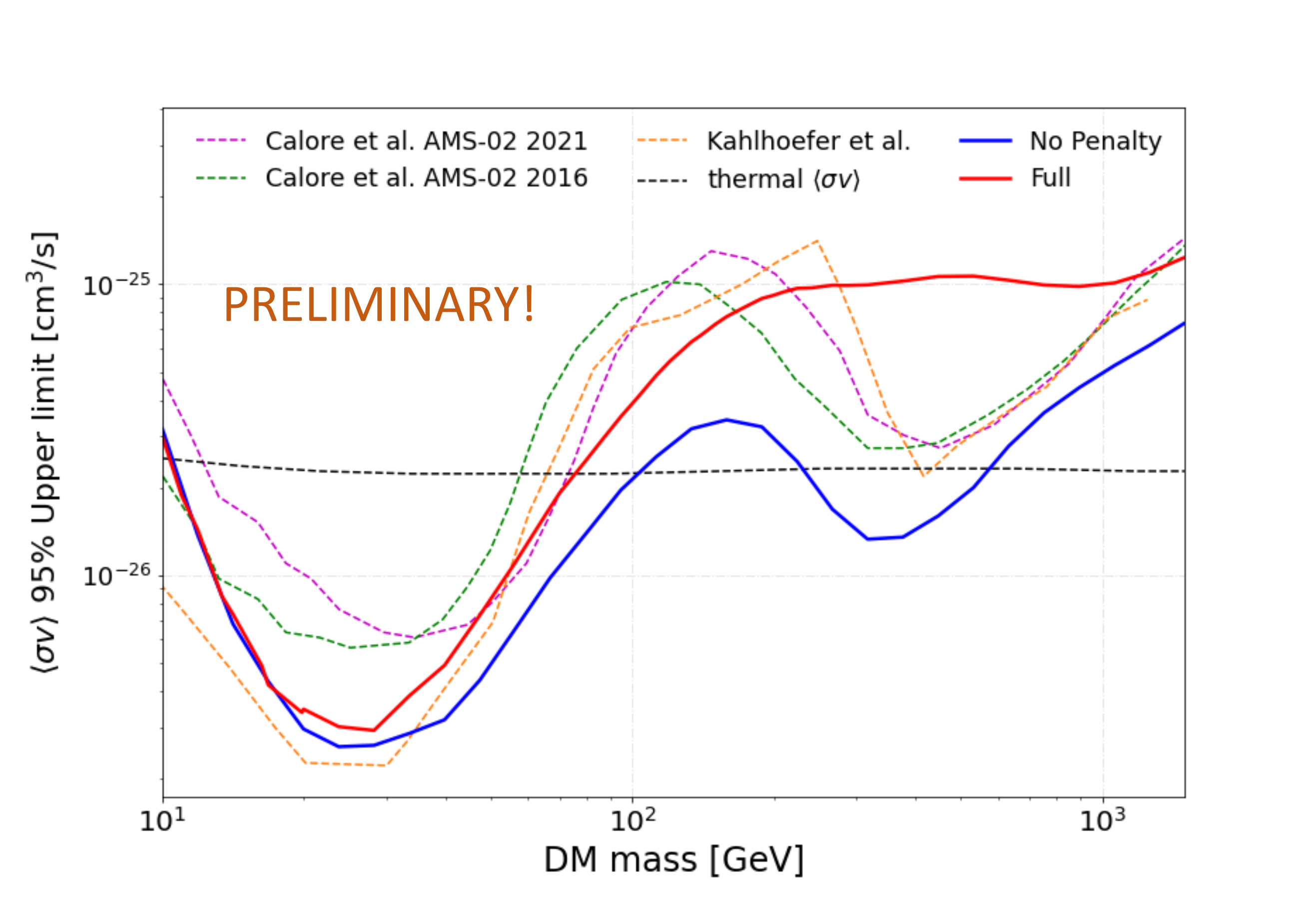


Normal

No Ap constrains

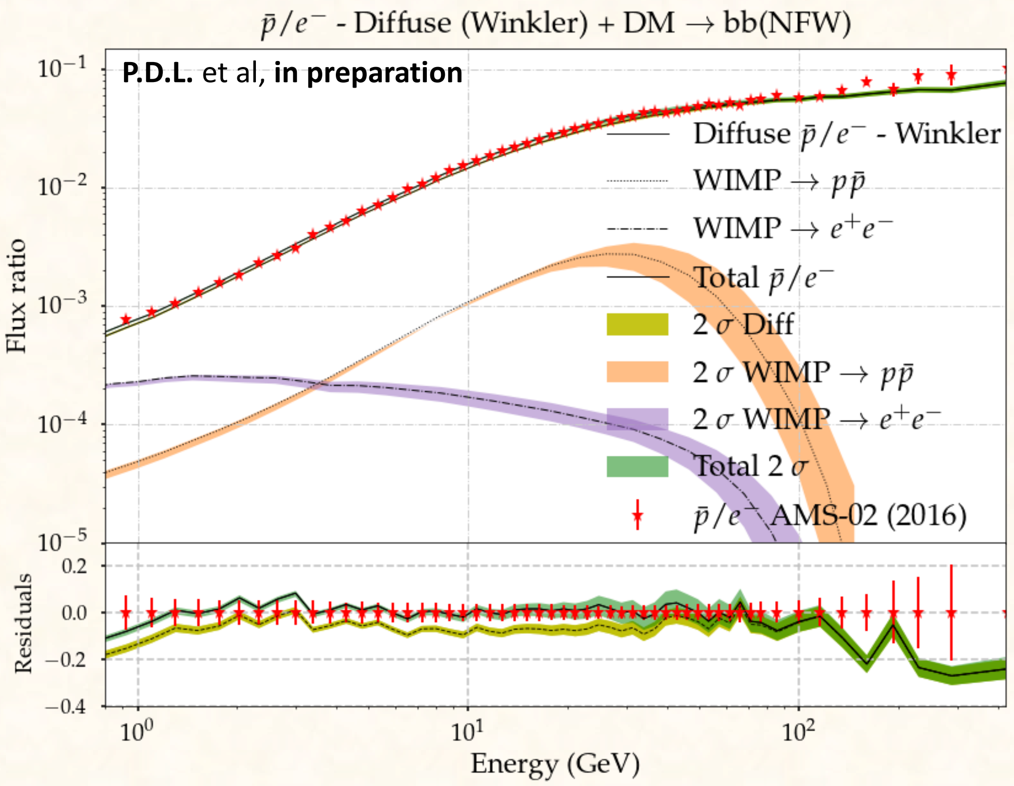
No XS constrains

DM limits from different analyses

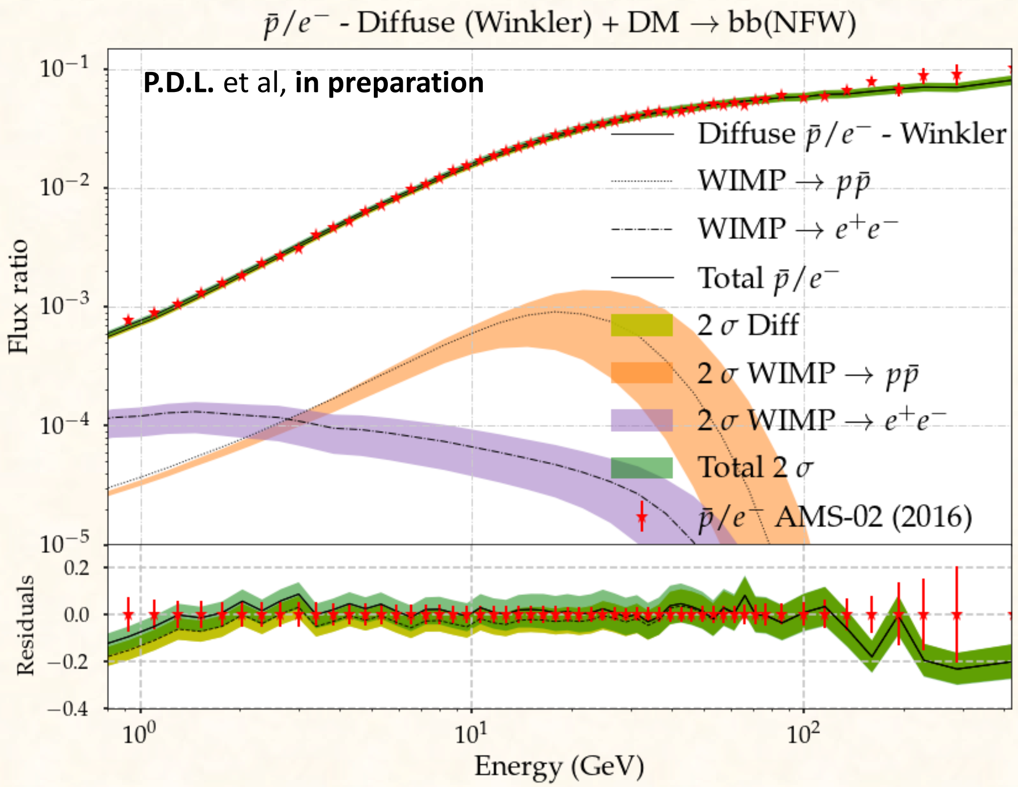


Antiproton *excesses* – *The grammage excess*

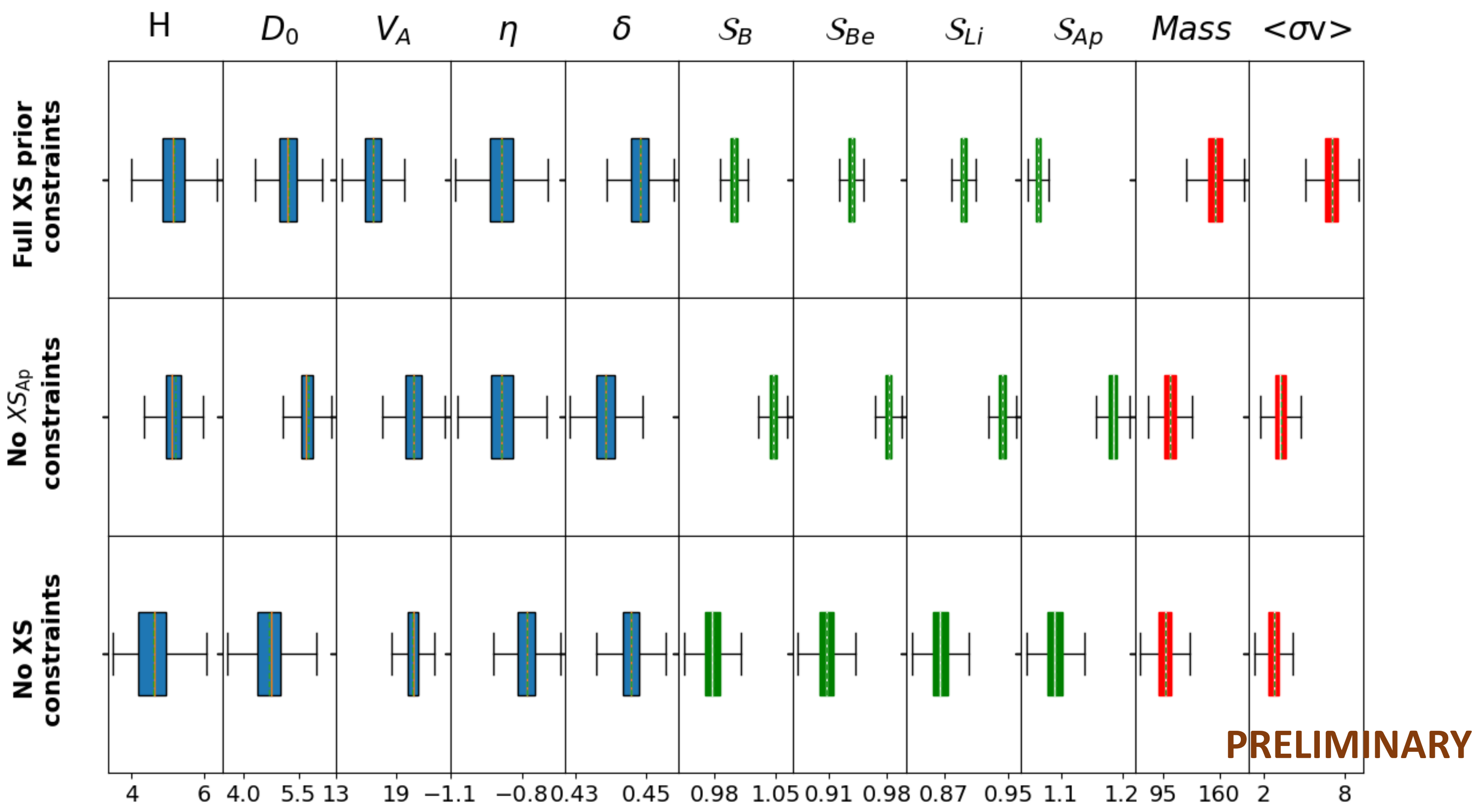
Full XS prior constrains Mχ ~ 160 GeV, <σv> ~ 7·10^{26} cm^3/s



No XS prior constrains Mχ ~ 100 GeV, <σv> ~ 2·10^{26} cm^3/s



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



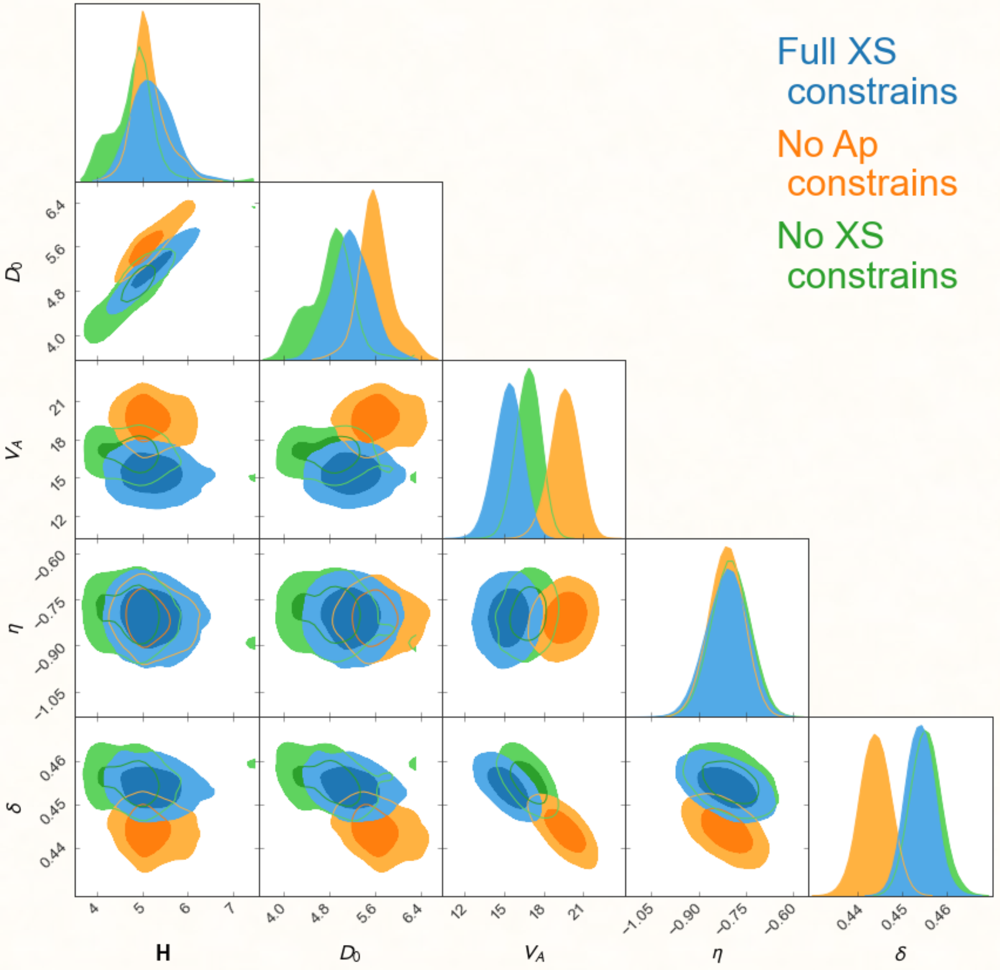
Propagation parameters are again very similar in every analysis and similar to the parameters found in the analyses without including dark matter component.

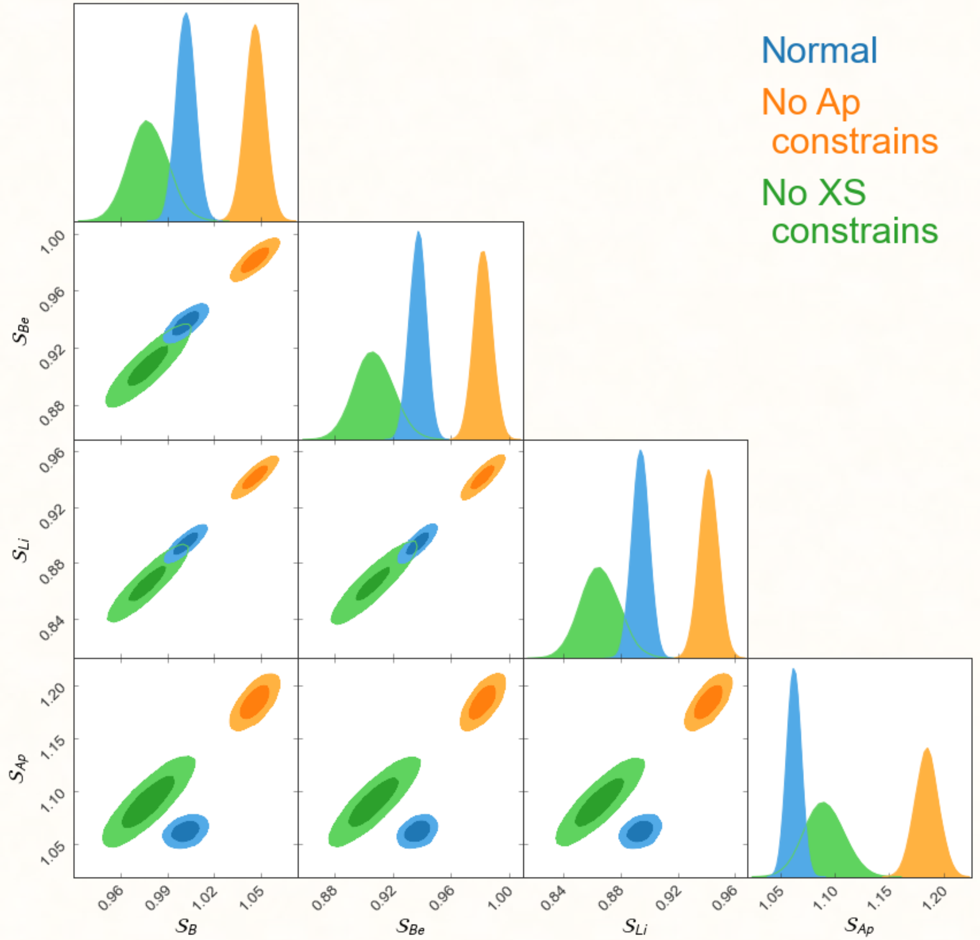
DM masses are slightly bigger than usually reported, due to the use of 2018 data-set

Scale factors are statistically needed. The case with no cross sections prior constrains finds (unsurprisingly) similar results as earlier analyses taking into account the full uncertainty bands

DM model

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

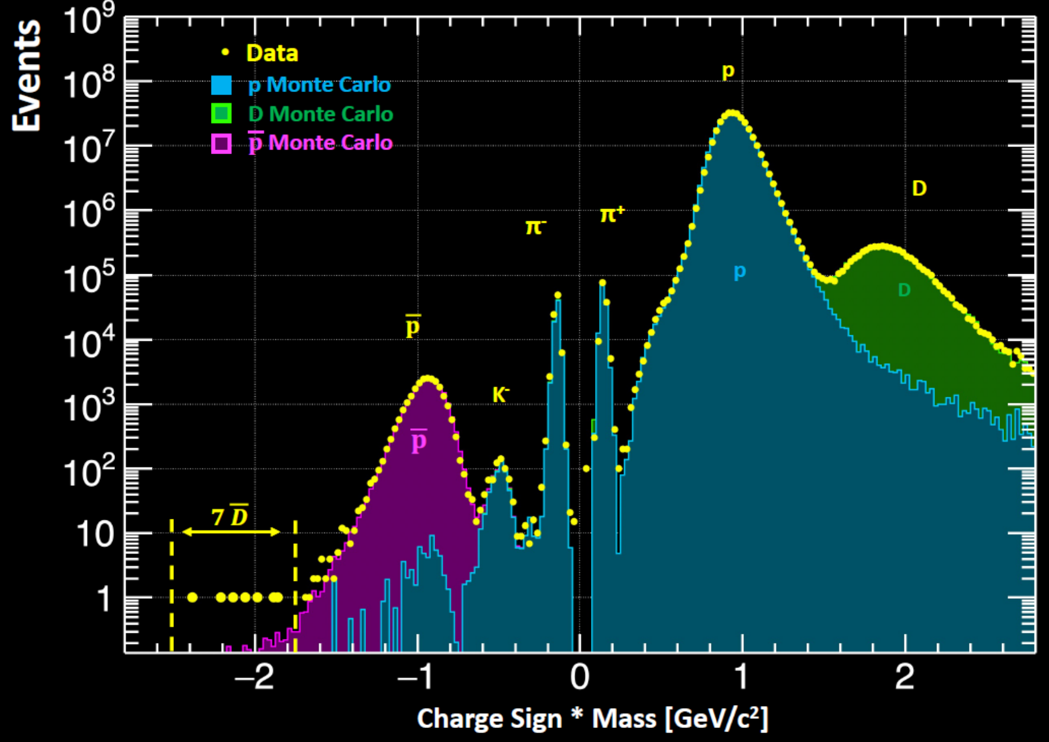


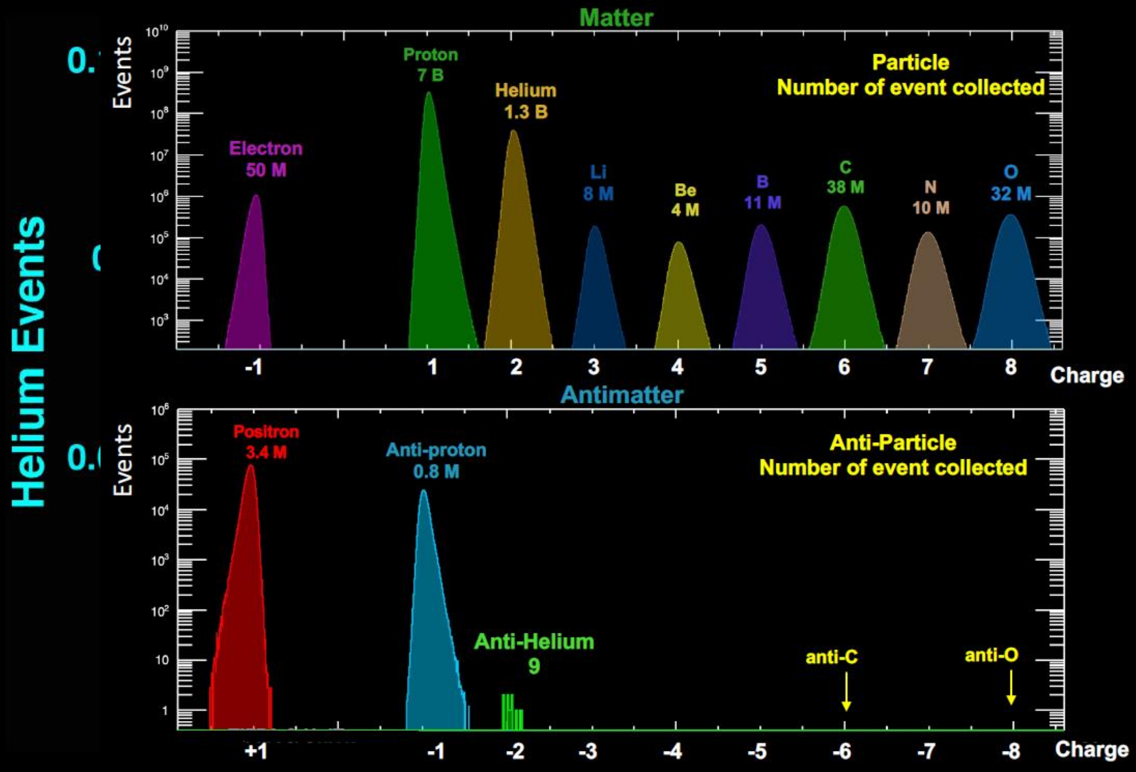


Dark matter constraints

- Analysis incorporate a dark matter component, still allowing the cross sections to be rescaled.
- A WIMP annihilating into bb pairs and then subsequent decay of these into leptons and antiprotons is simulated with WimpSim.
- A larger <σv> implies less scaling of the antiprotons, which increases the total value of the likelihood.
- The hypothesis of a dark matter component is disfavoured against the hypothesis of Ap cross sections scale ($\Delta\chi^2 \sim 160$ – over around 600 points). However, the hypothesis with dark matter + cross sections scaling is favoured against the other ones ($\Delta\chi^2 \sim 38$).

ANTI-NUCLEI: AMS-02 mass-charge spectra

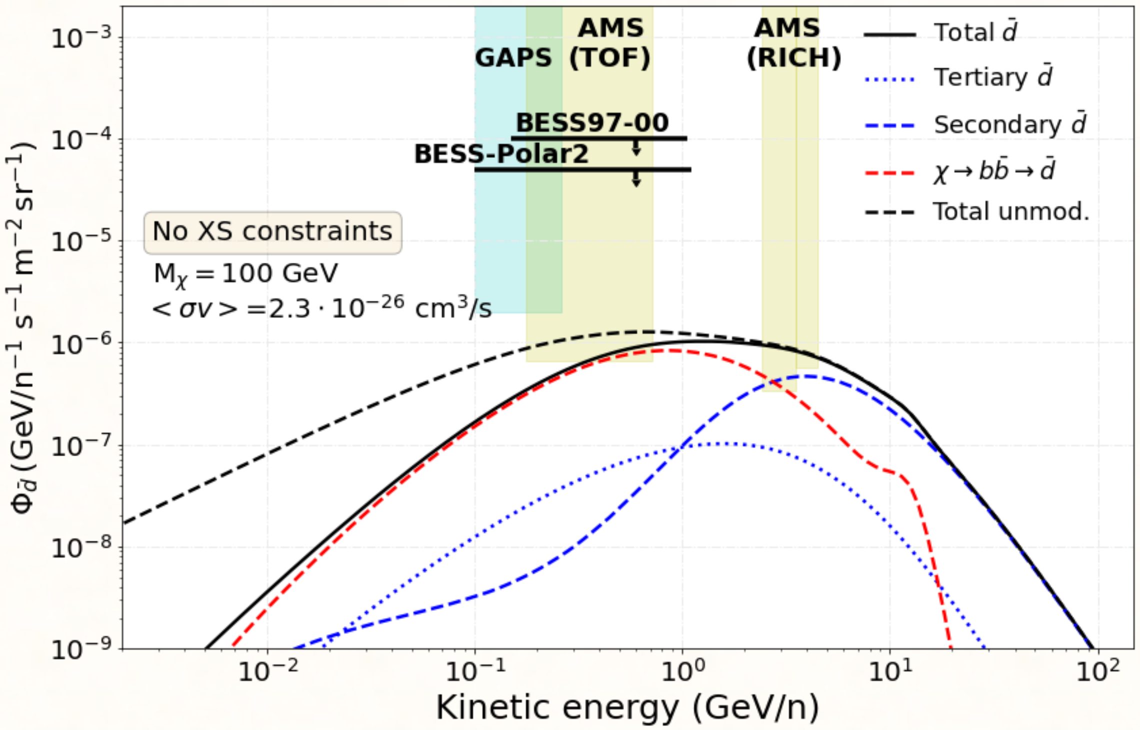




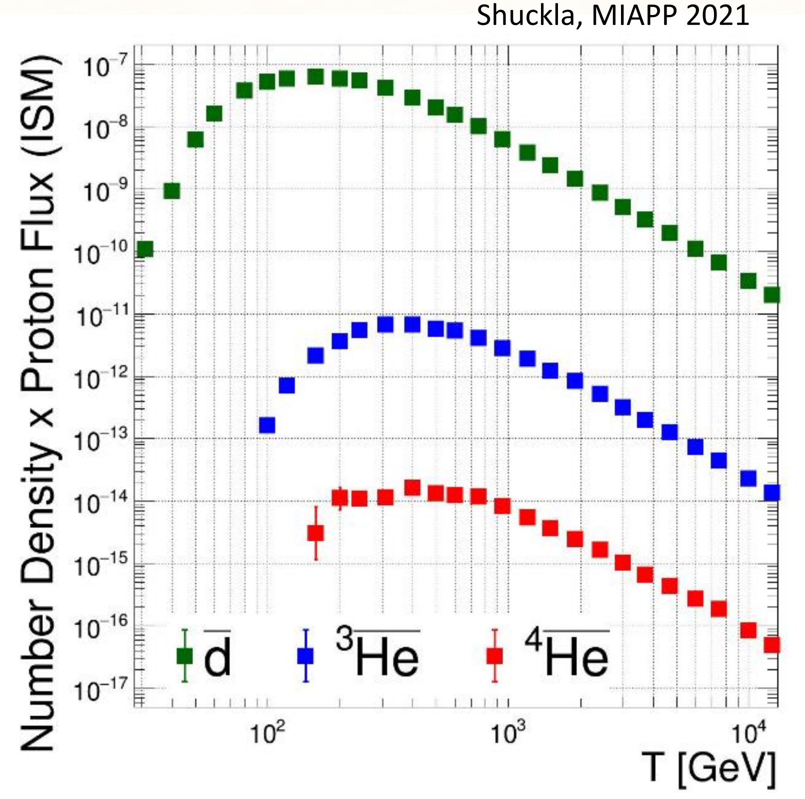
Paolo Zuccon MIAPP 2021

Anti-nuclei as the dark matter smoking gun

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



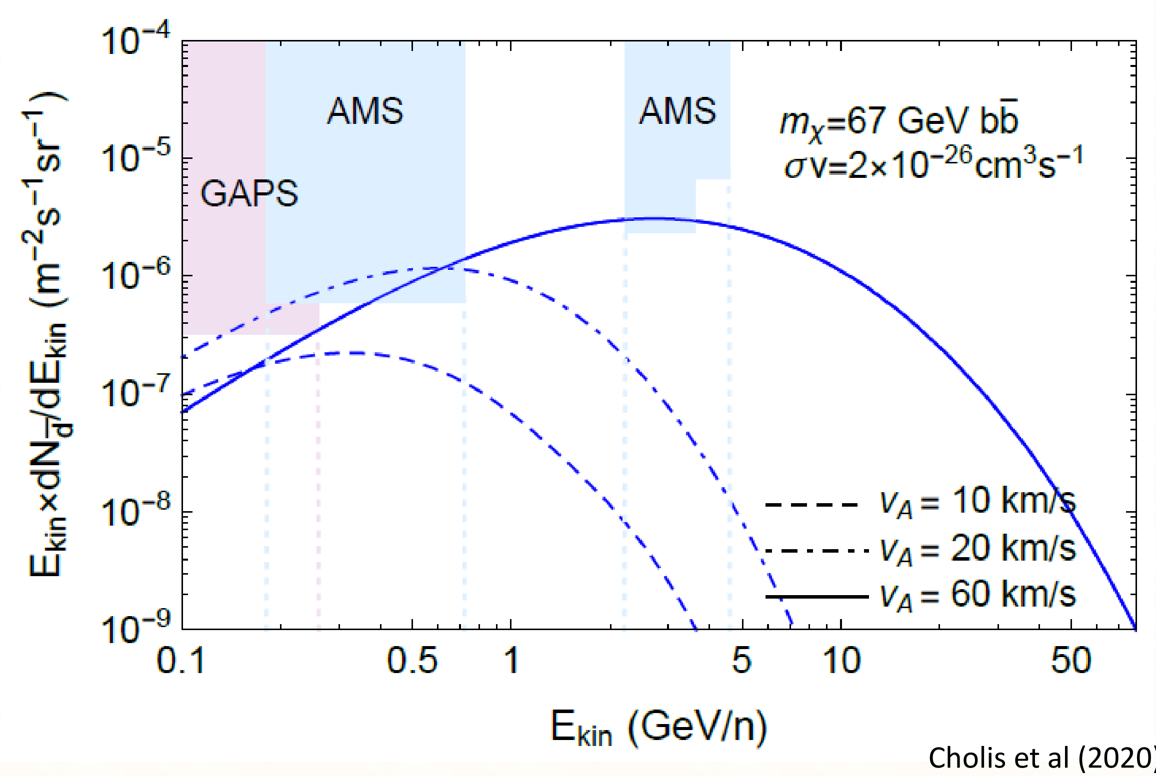
Shuckla, MIAPP 2021

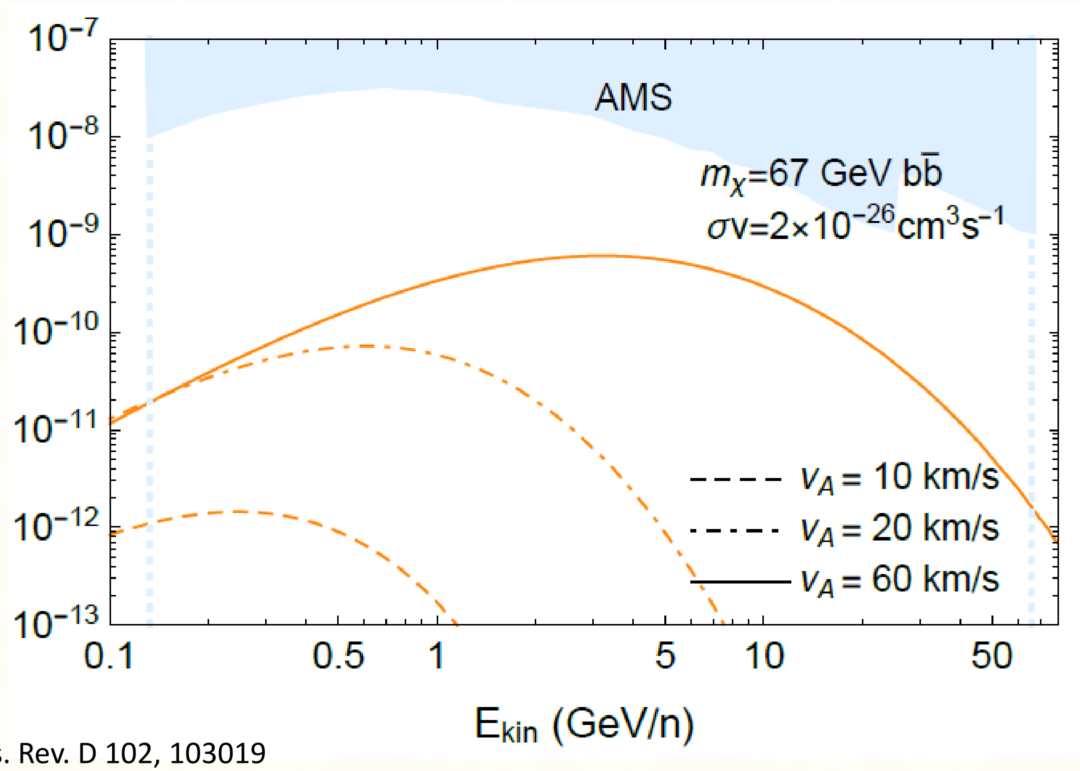


Detected anti-D events possibly explained, but impossible to explain more anti-He events!

Boosting the dark matter signal

Reacceleration is able to enhance the DM signal and make it more important at larger energies, however, large reacceleration is in contradiction with other observables

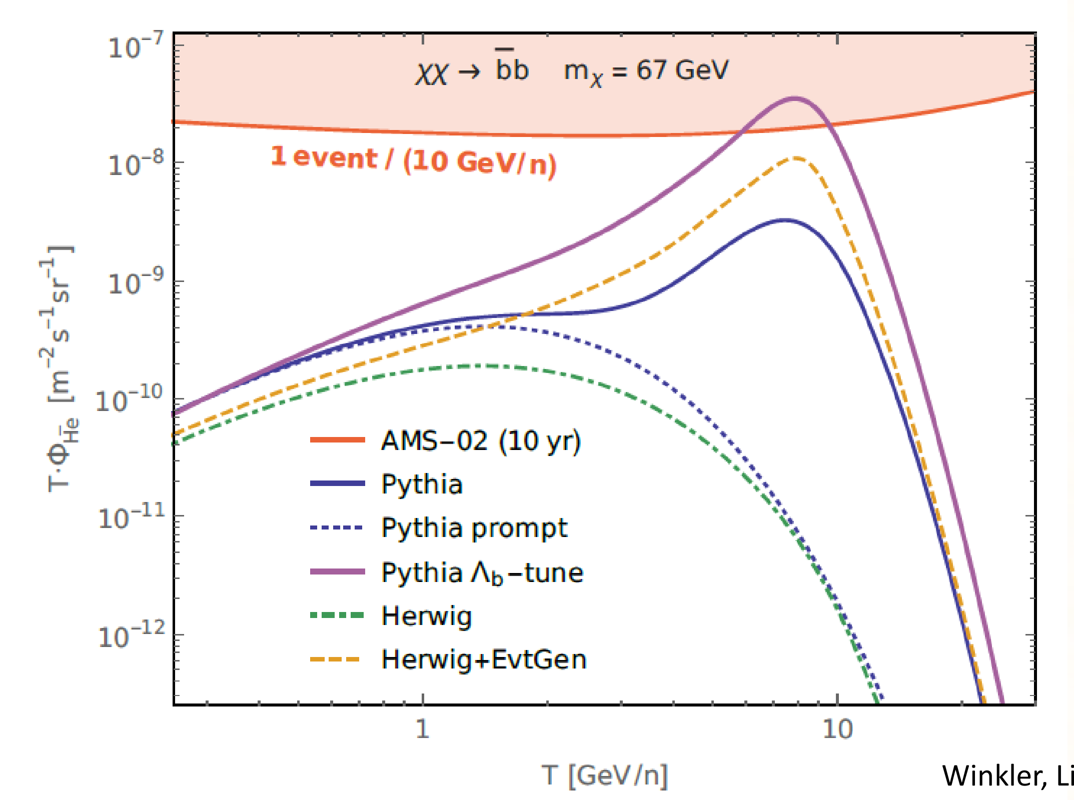


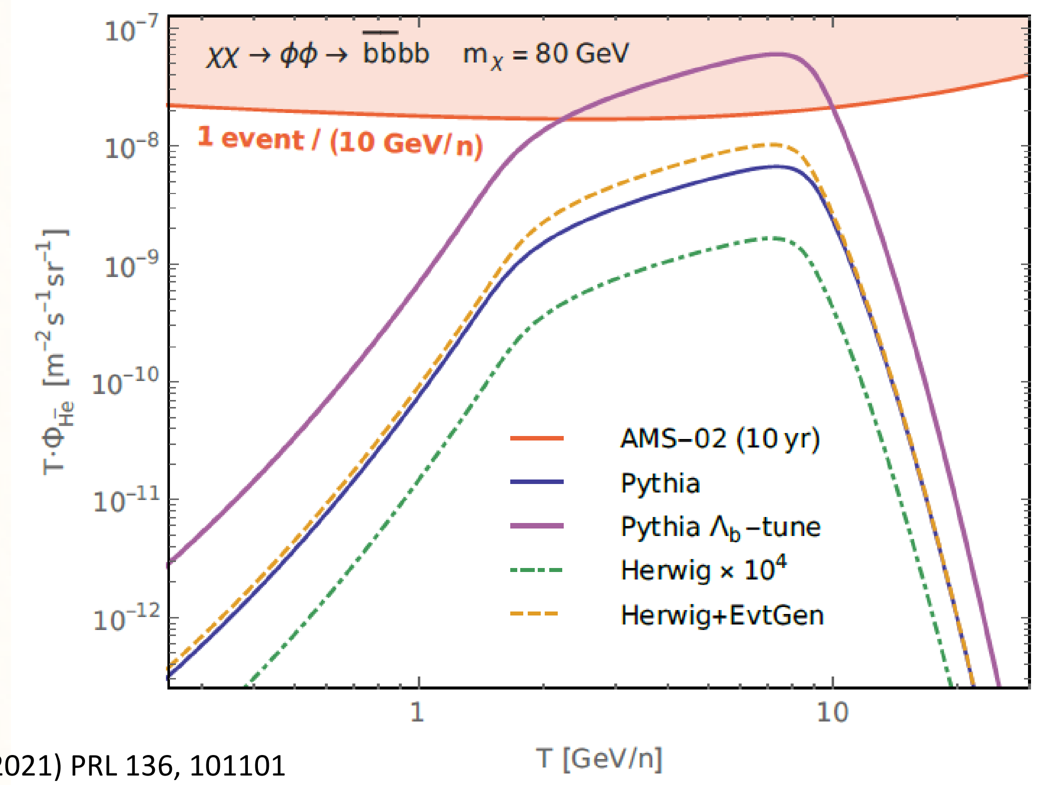


Cholis et al (2020) Phys. Rev. D 102, 103019

Boosting the dark matter signal

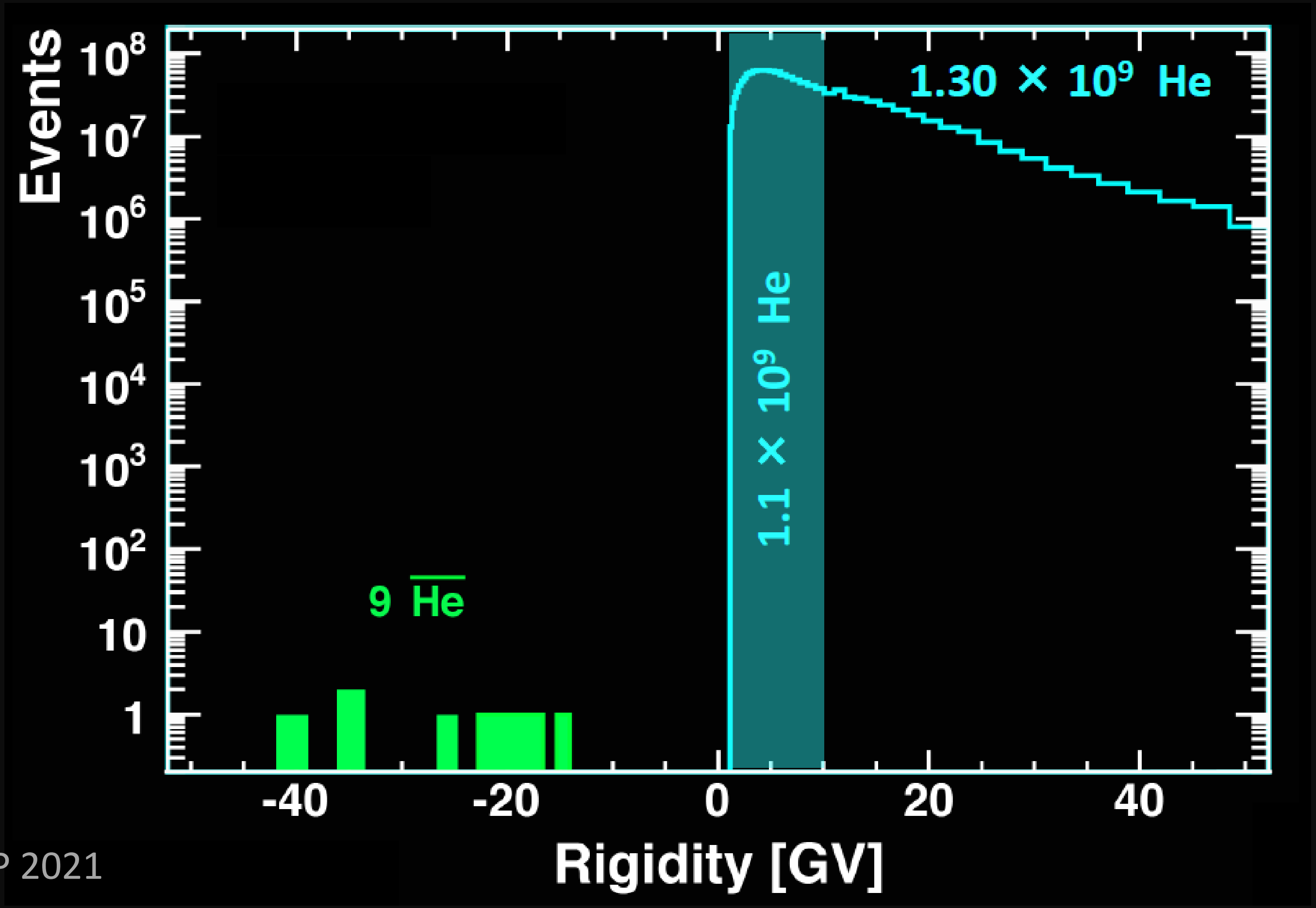
✓ **Λ_b production** is a very important source of anti-helium, even able to explain the events reported by AMS-02, although not yet well constrained





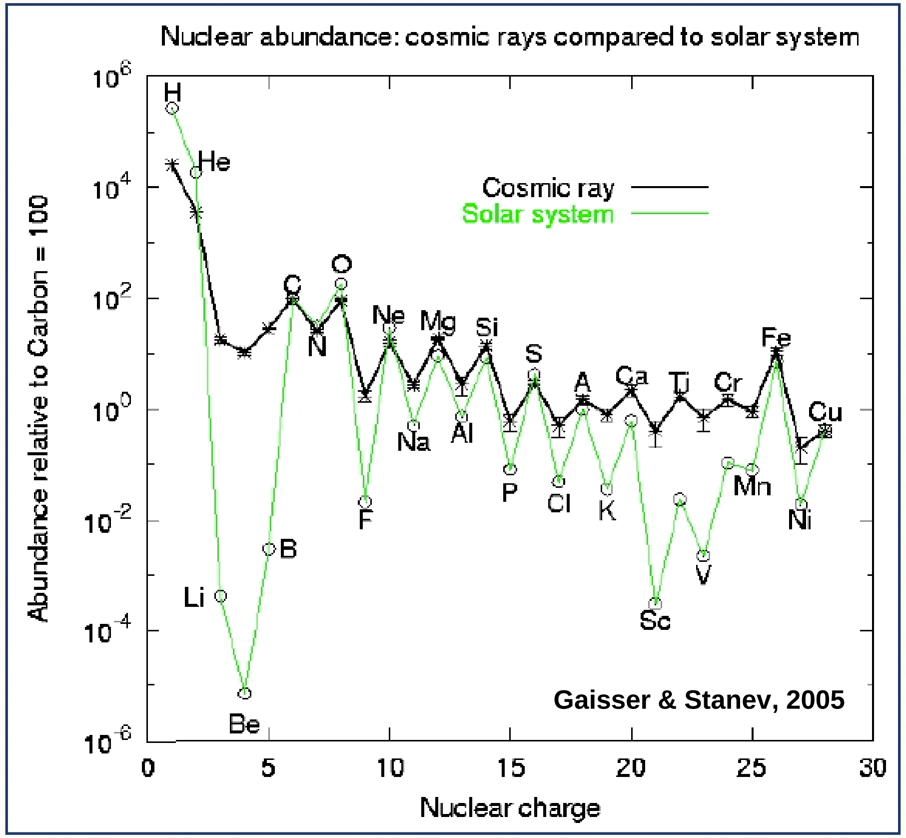
Winkler, Linden (2021) PRL 136, 101101

AMS-02 energy spectrum points to an <u>important problem</u>…

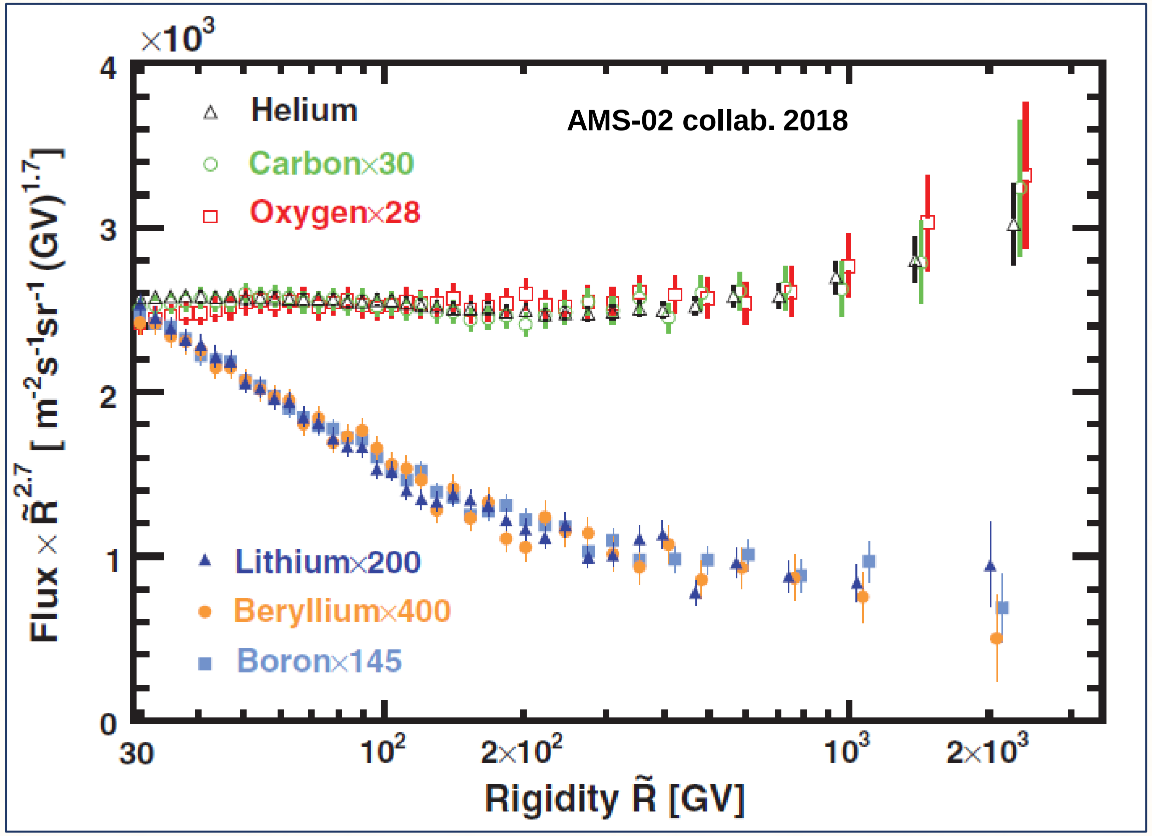


Primary CRs are accelerated in astrophysical sources (presumably SNRs) and propagate throughout the Galaxy, occasionally interacting with gas in the disc of the Galaxy, and there they produce secondary nuclei through spallation.

Abundance of secondary nuclei explained if CRs propagate for hundred millions of years



Secondary CRs offer a sensitive tool to infer the grammage traversed by these particles



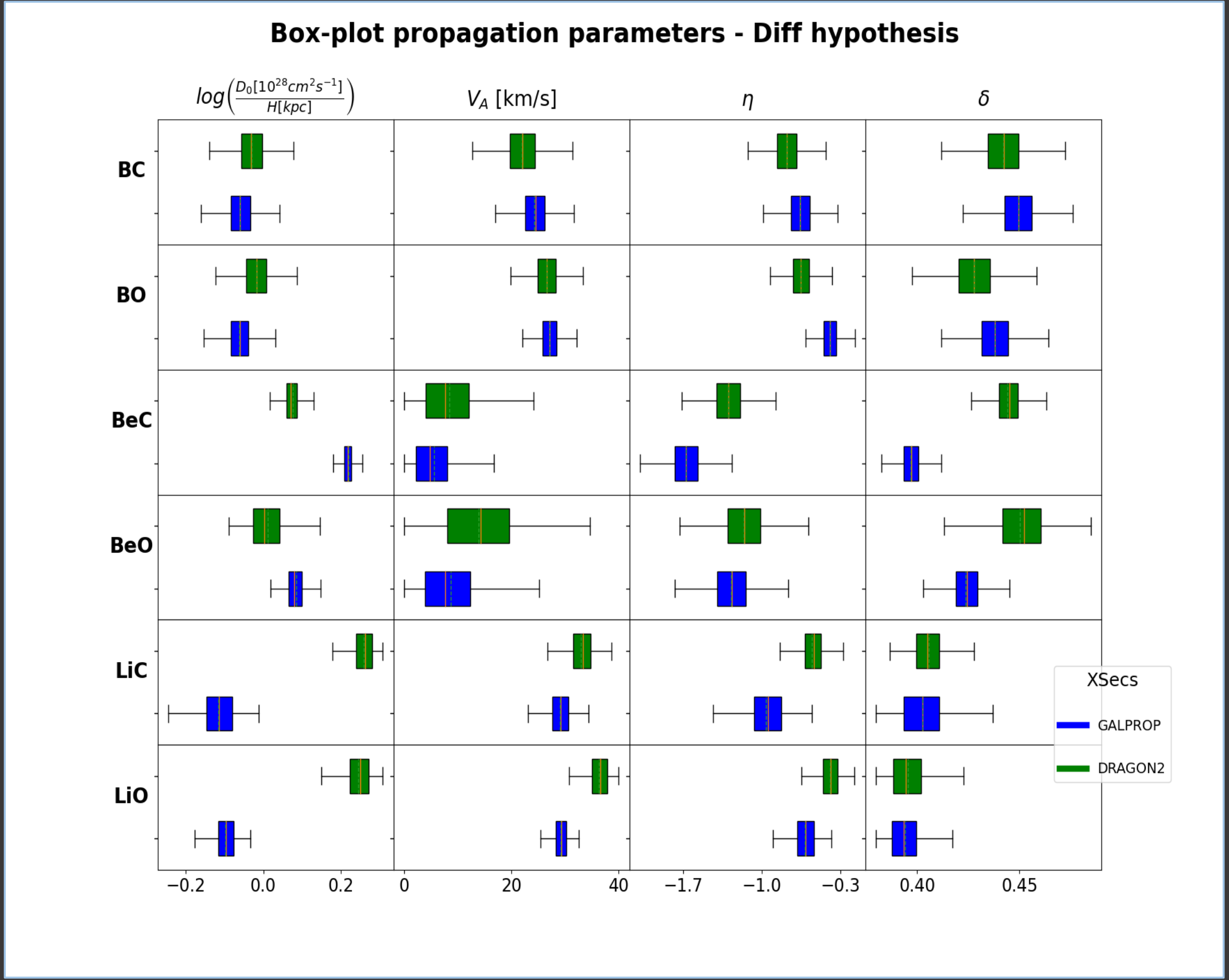
Determination of propagation parameters

Combined analyses are needed!

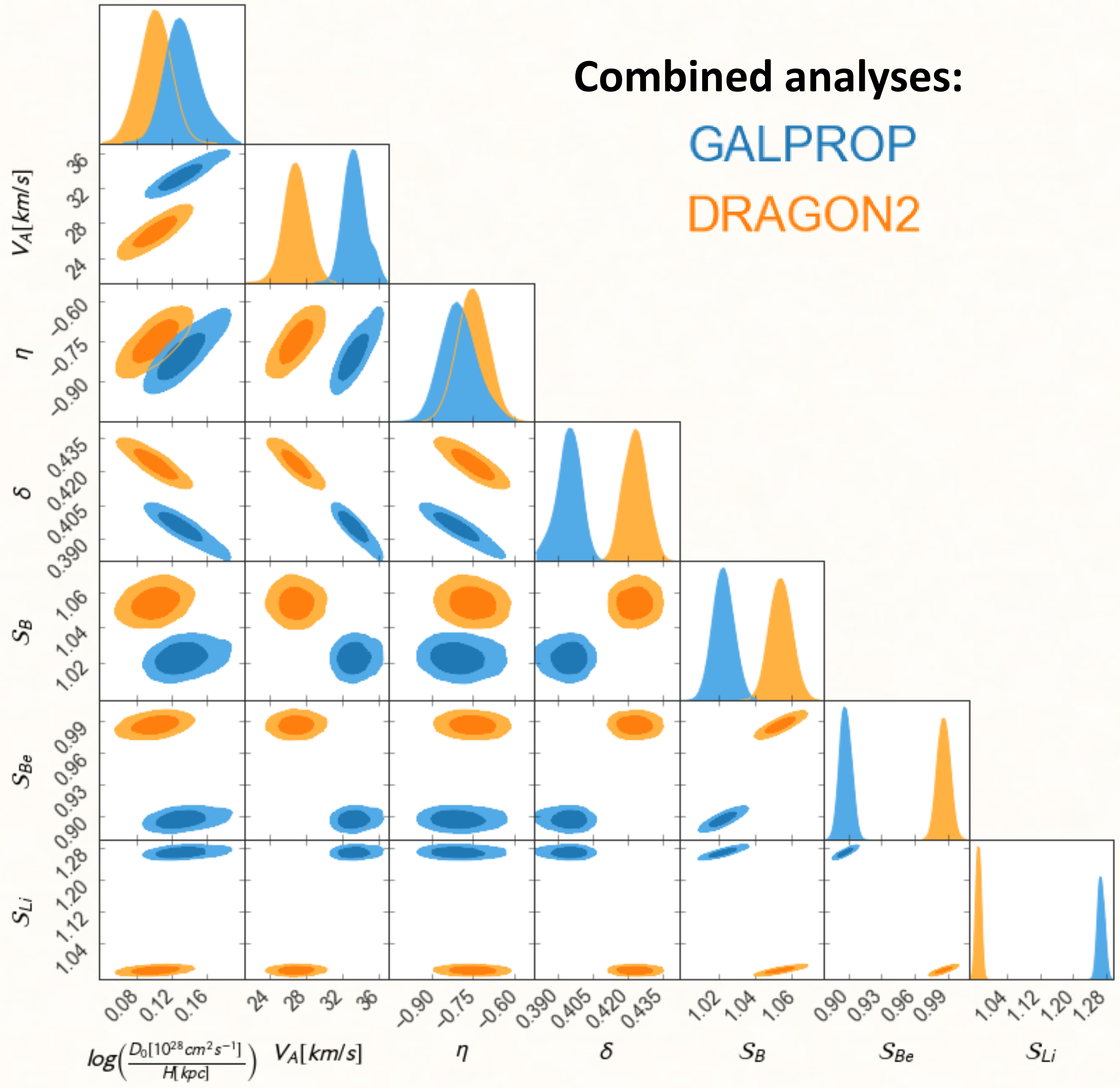
- Negative η values → Wave dissipation
- V_A compatible with ~ 20-30 km/s
- Large dispersion of δ: 0.39 – 0.46,
  (specially hard for Li ratios)

Δδ=0.14, R_b=312 GV, R_0=4GV

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



P. De La Torre Luque *et al* JCAP07(2021)010

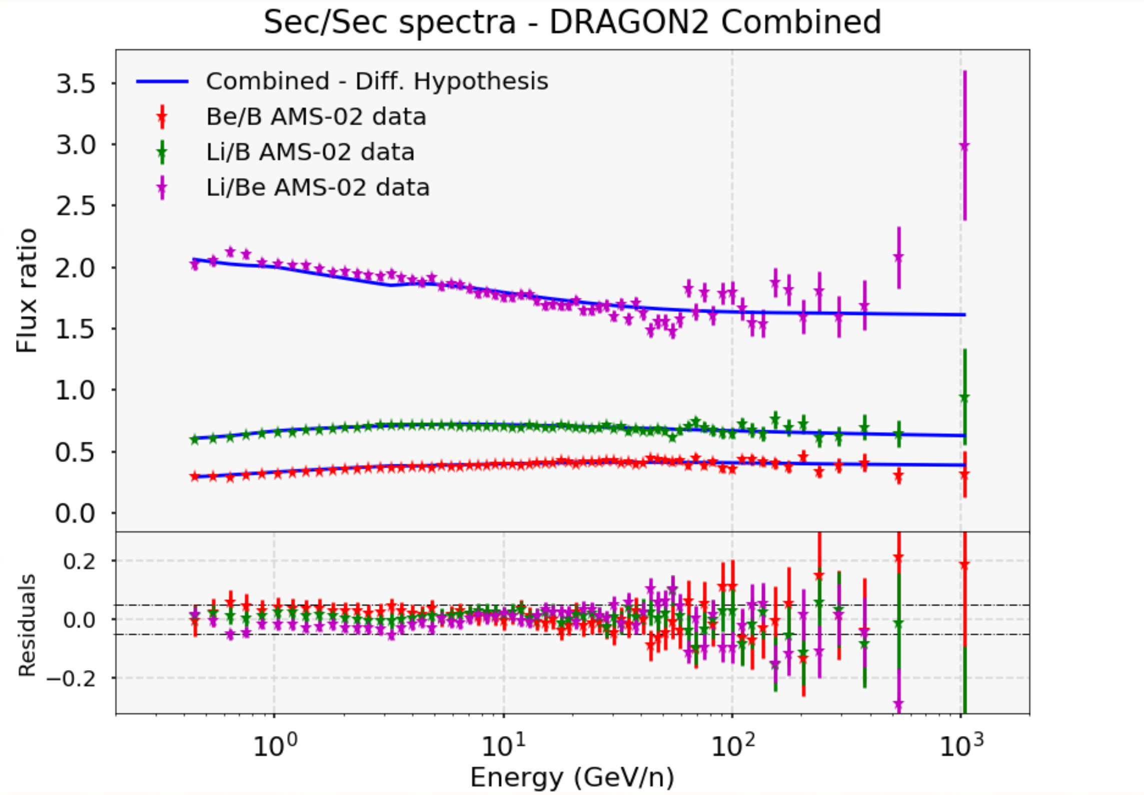


Combined analyses:

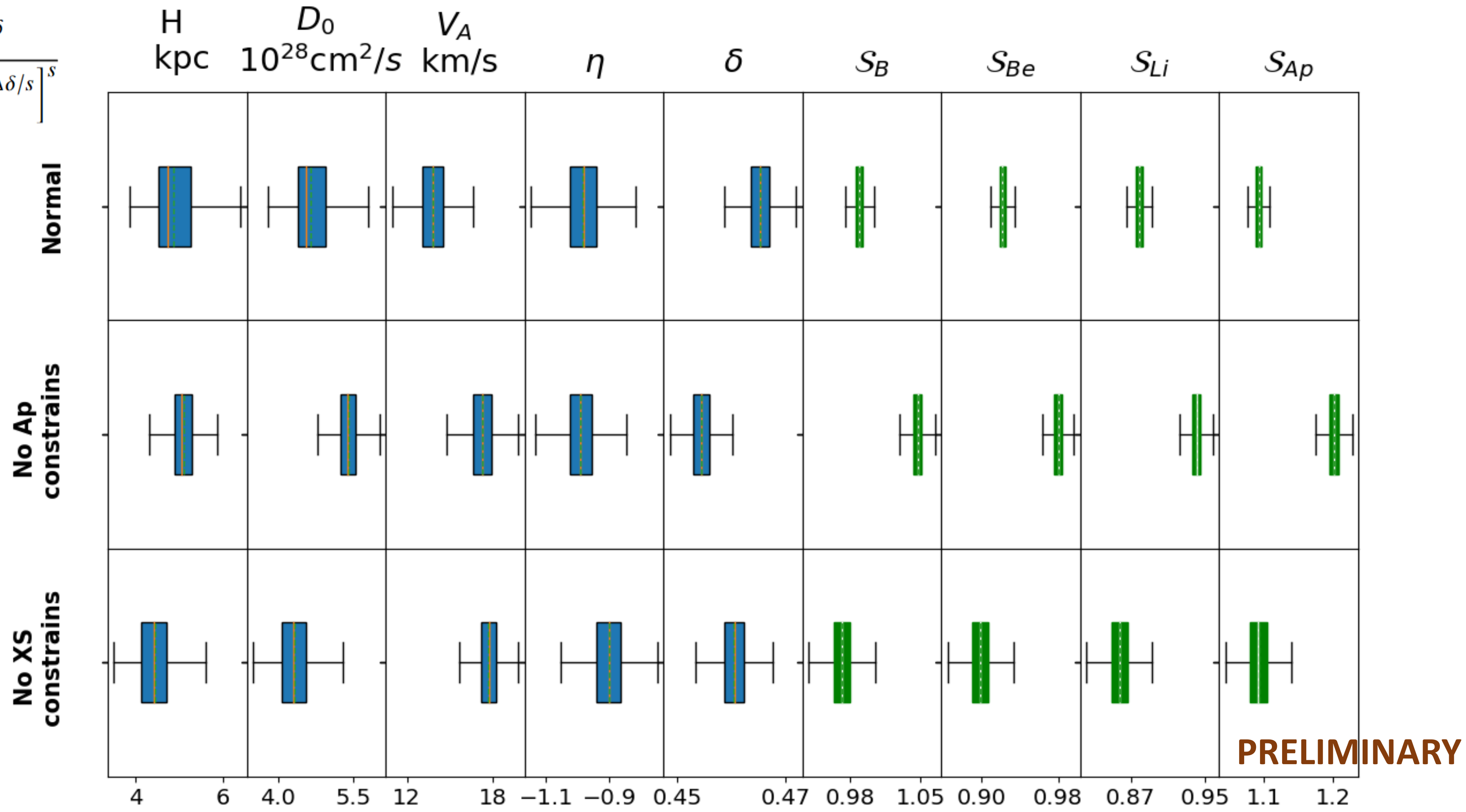
GALPROP

DRAGON2

- **Propagation parameters seem to be compatible for different cross sections parametrizations**
- **The spectra of all these ratios become compatible (within 1 σ uncertainties) with experimental data for scale factors S_X < 1.06 (< 6% scale)**



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



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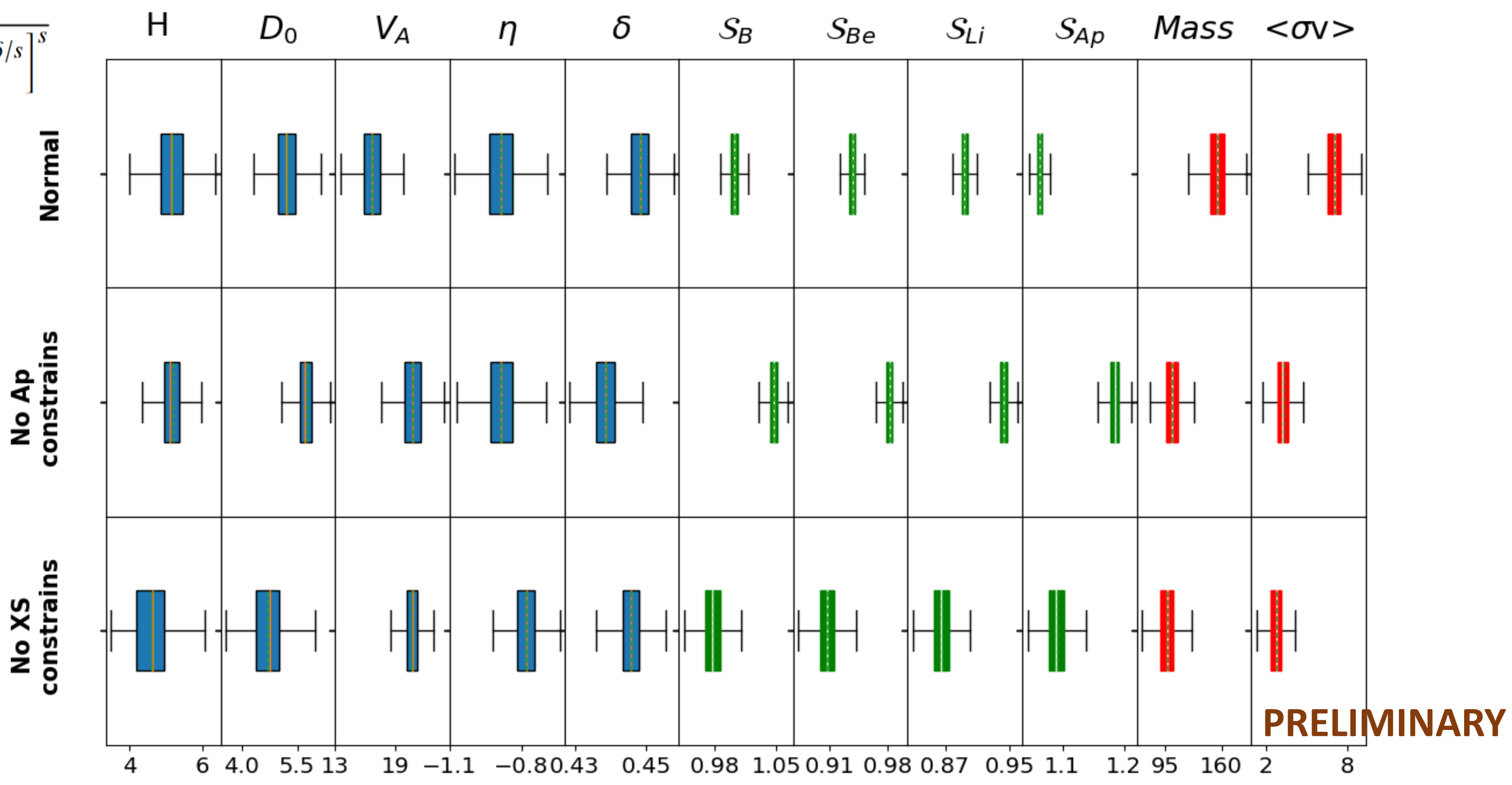

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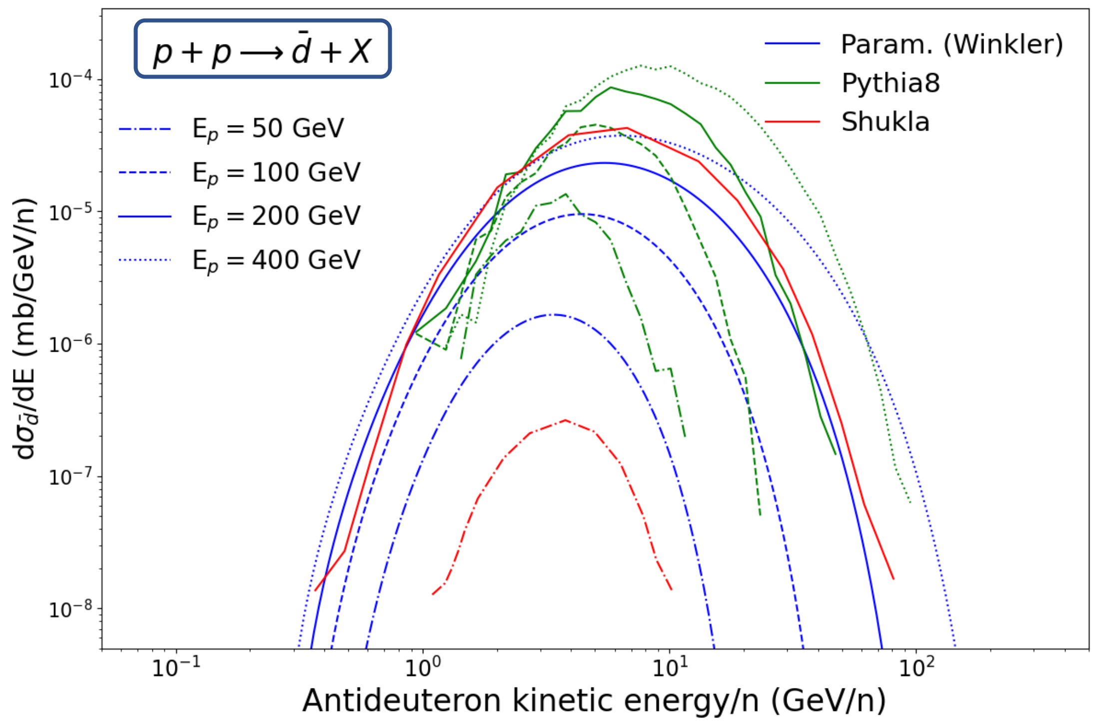
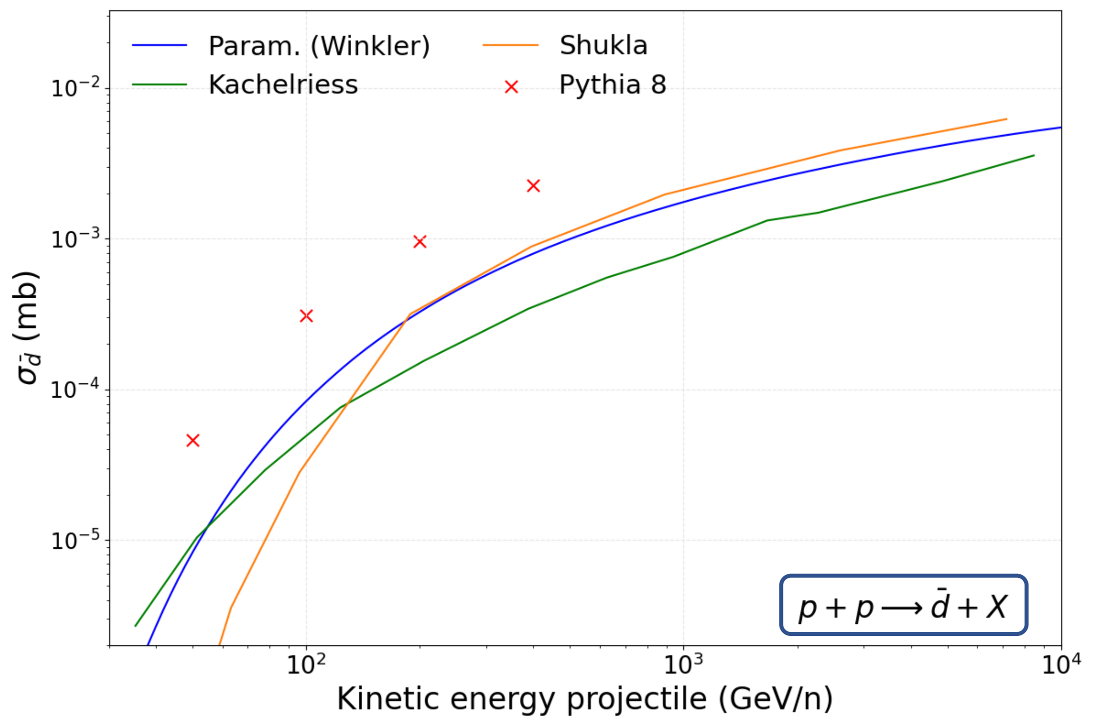
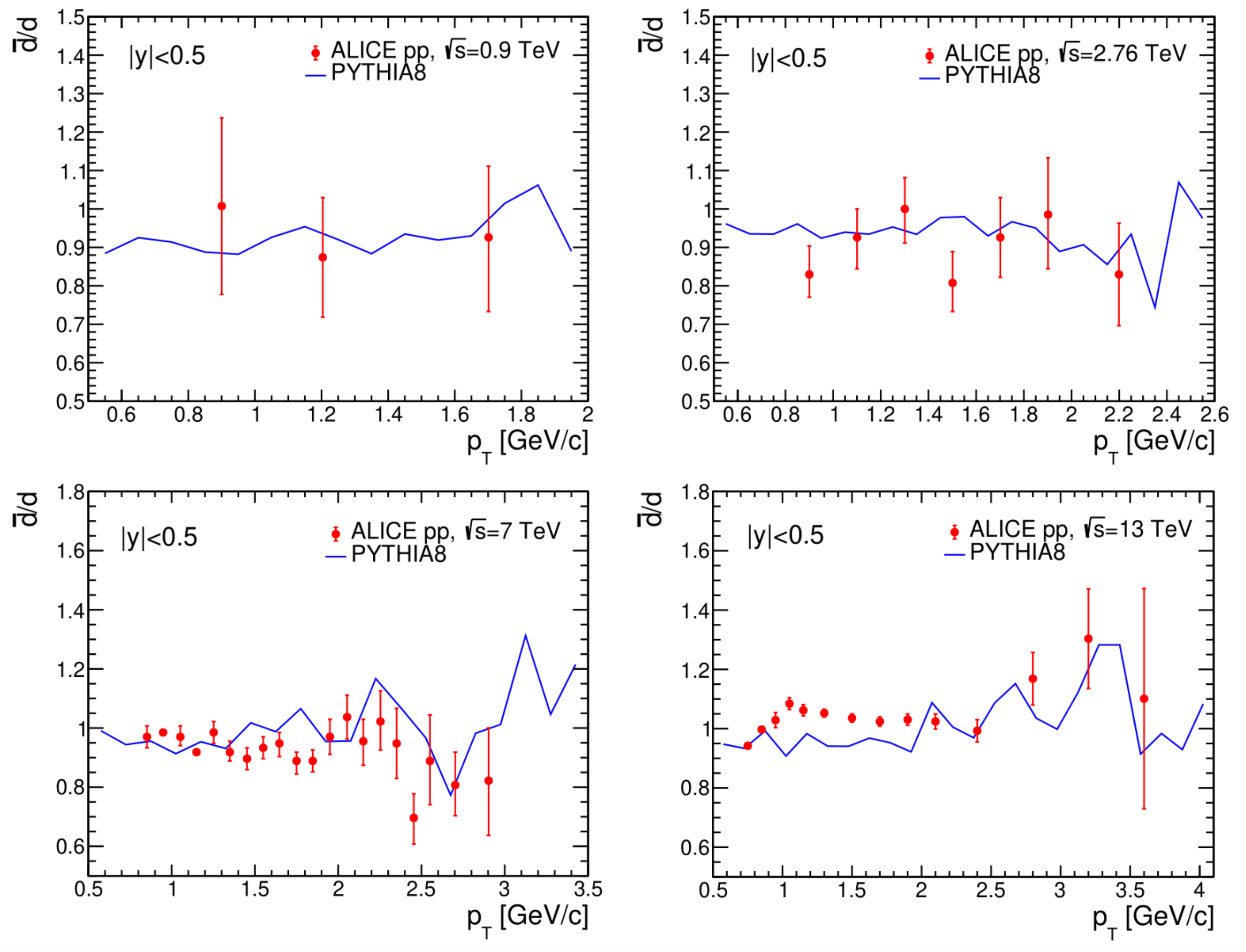
Implementation of anti-nuclei propagation in *DRAGON2*

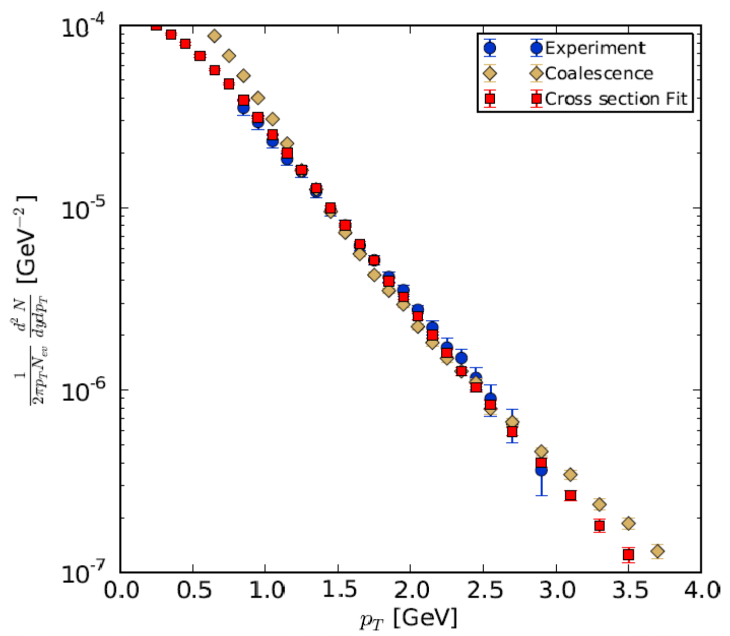
Cross sections of antinuclei production are being computed with Pythia8… in progress



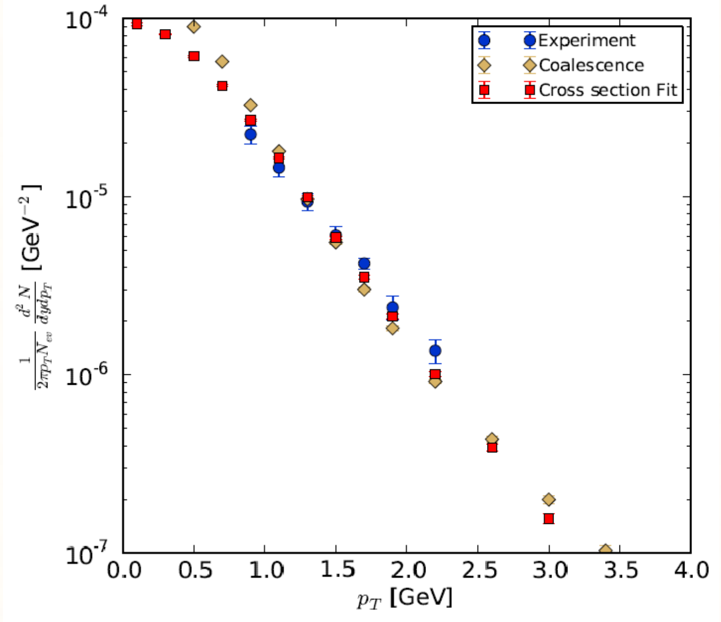


PYTHIA8 cross sections



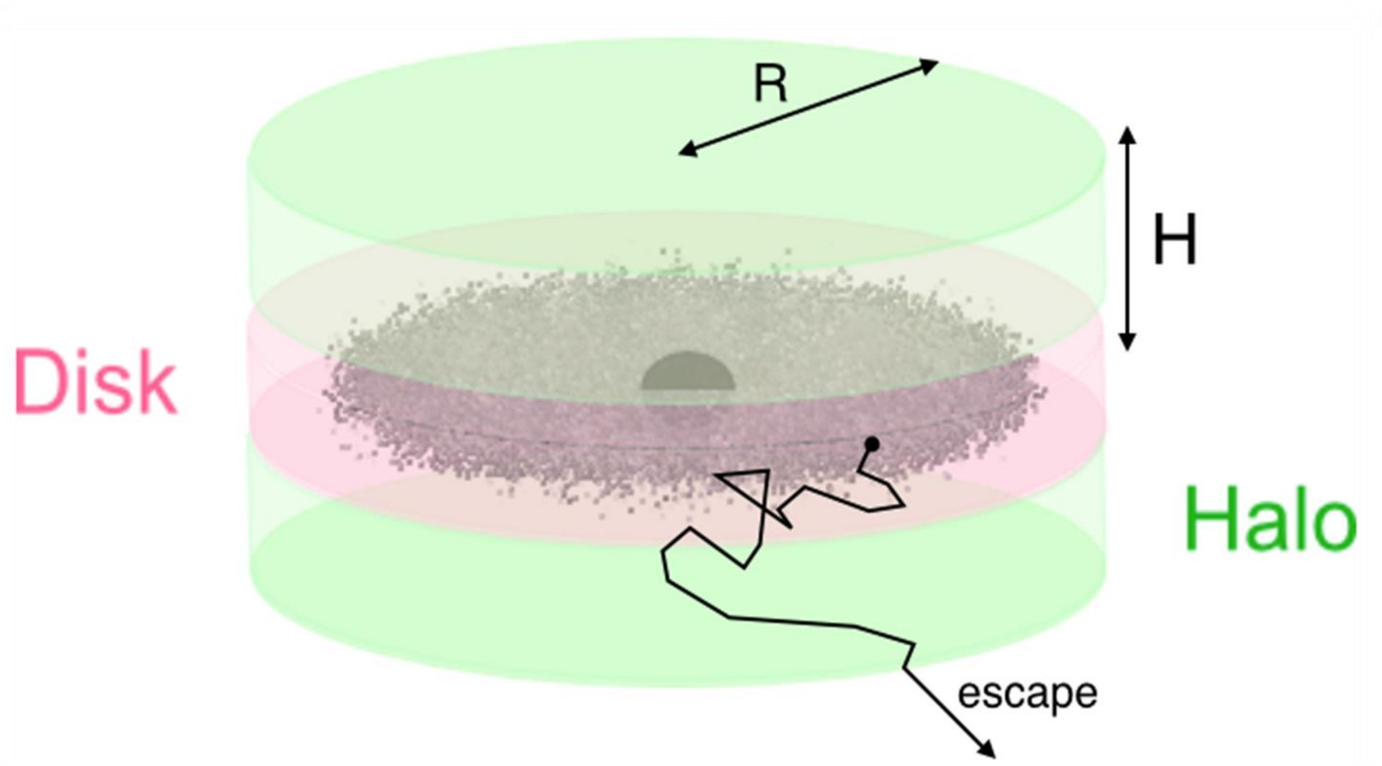


Dal and Raklev PRD 91, 123536



Diffusive transport of Galactic cosmic rays

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



Secondary-to-primary ratios are key to evaluate the diffusion coefficient

Diffusion coefficient ($D \propto 1/\tau^{diff}$)

$N_{pr} \propto Q_{pr}(E)/D(E)$

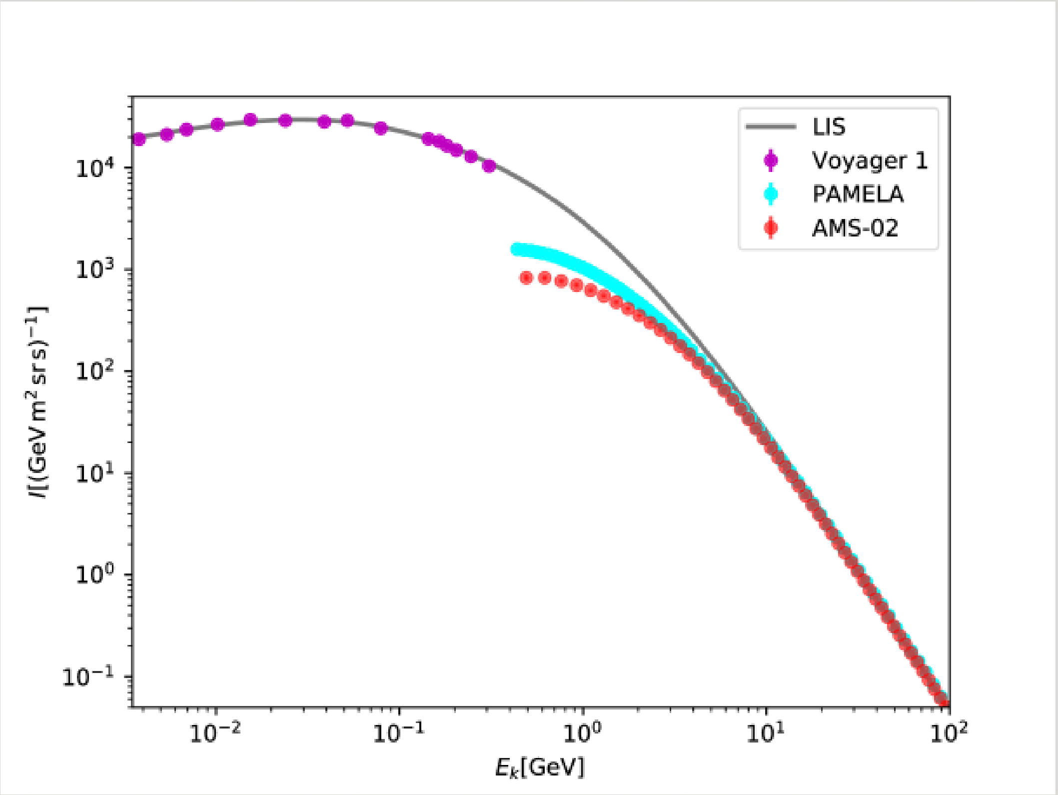
$N_{sec} \propto Q_{sec}(E)/D(E)$

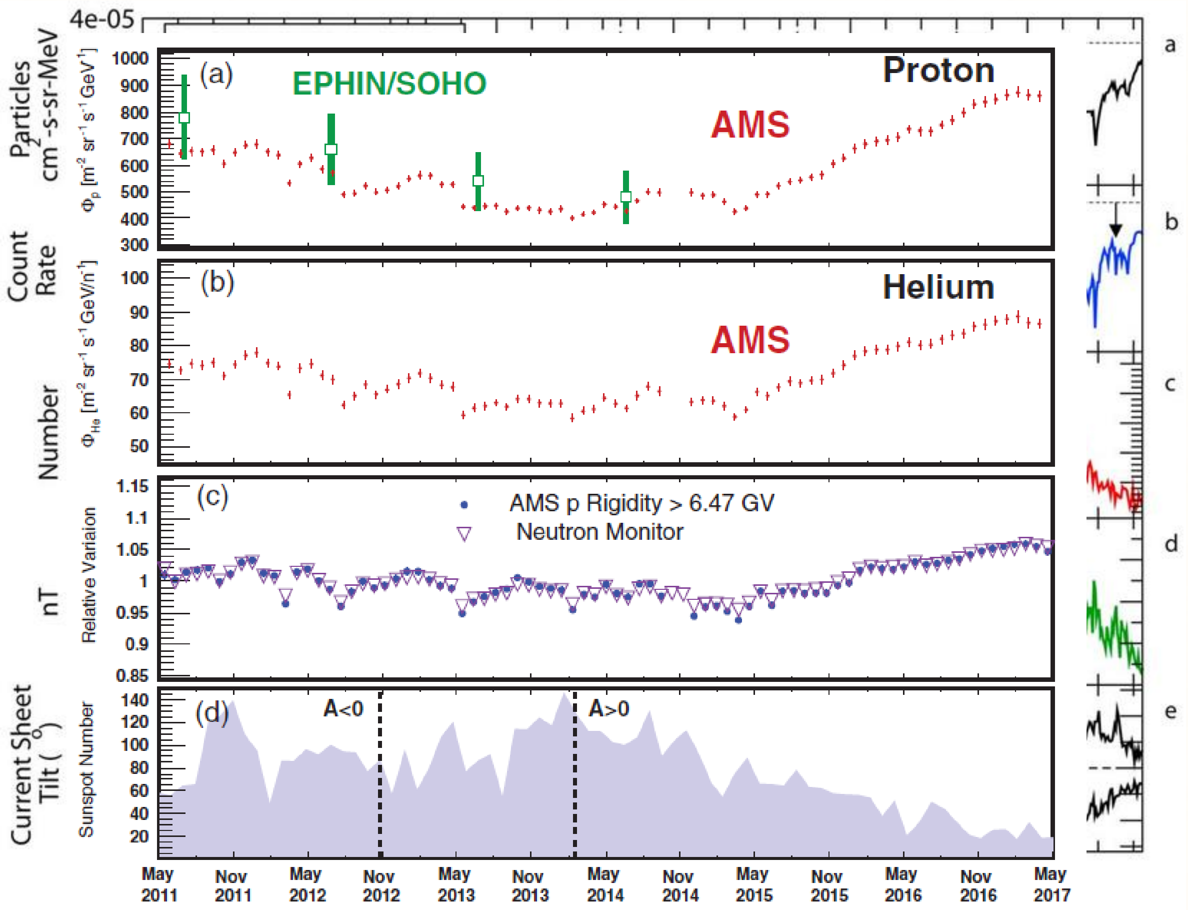
$Q_{sec} \propto N_{pr}(E)\,\sigma(E)$

$$\frac{N_{sec}}{N_{pr}} = \frac{Q_{sec}}{Q_{pr}} \sim \sigma(E)/D(E)$$

Complexity of cross sections measurements and the amount of interaction channels involved in the CR network obey us to employ parametrizations

Solar modulation

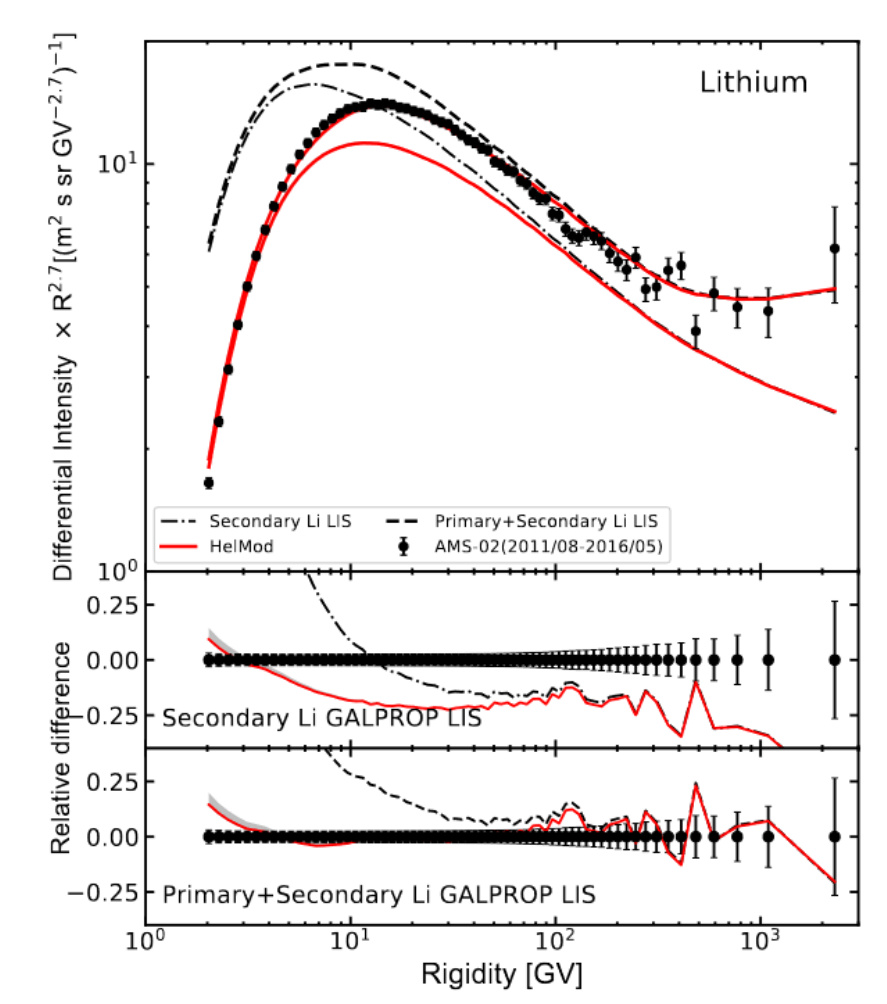




- Detailed heliospheric simulations or Force-Field approximation
- Neutron monitor experiments + Voyager-01 data

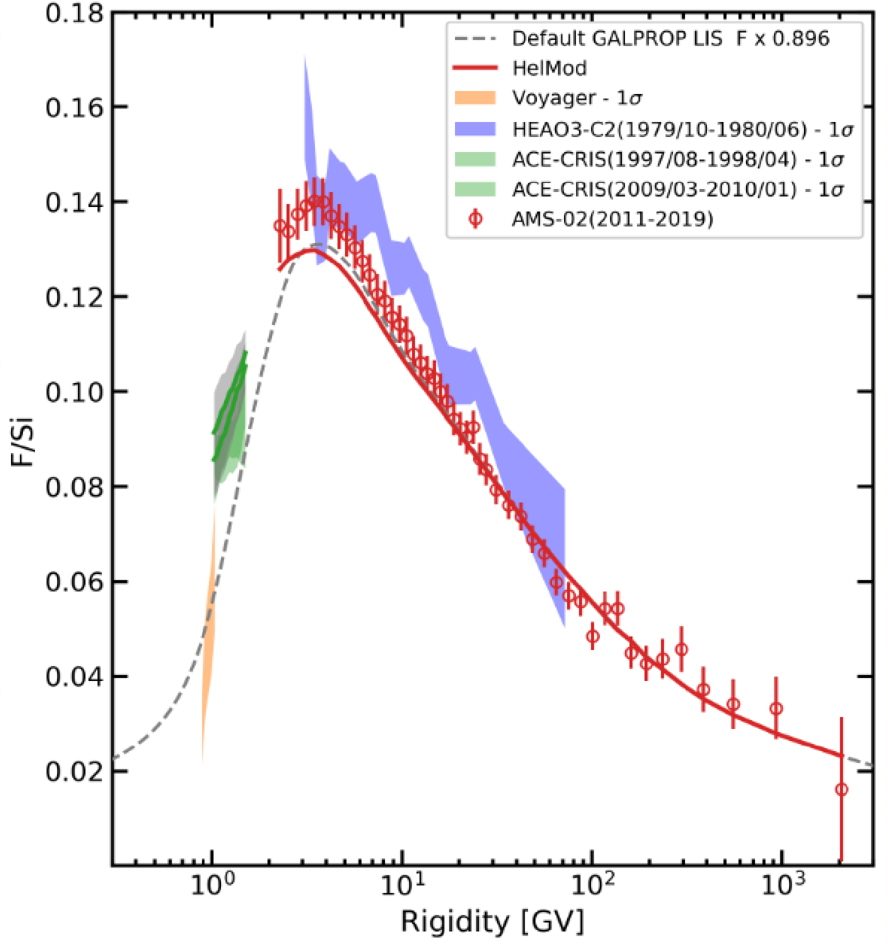
$$\Phi^{\mathrm{TOA}}(T) = \frac{2mT + T^2}{2m\,(T + \frac{Z}{A}\phi) + (T + \frac{Z}{A}\phi)^2}\,\Phi^{\mathrm{IS}}(T + \frac{Z}{A}\phi)$$

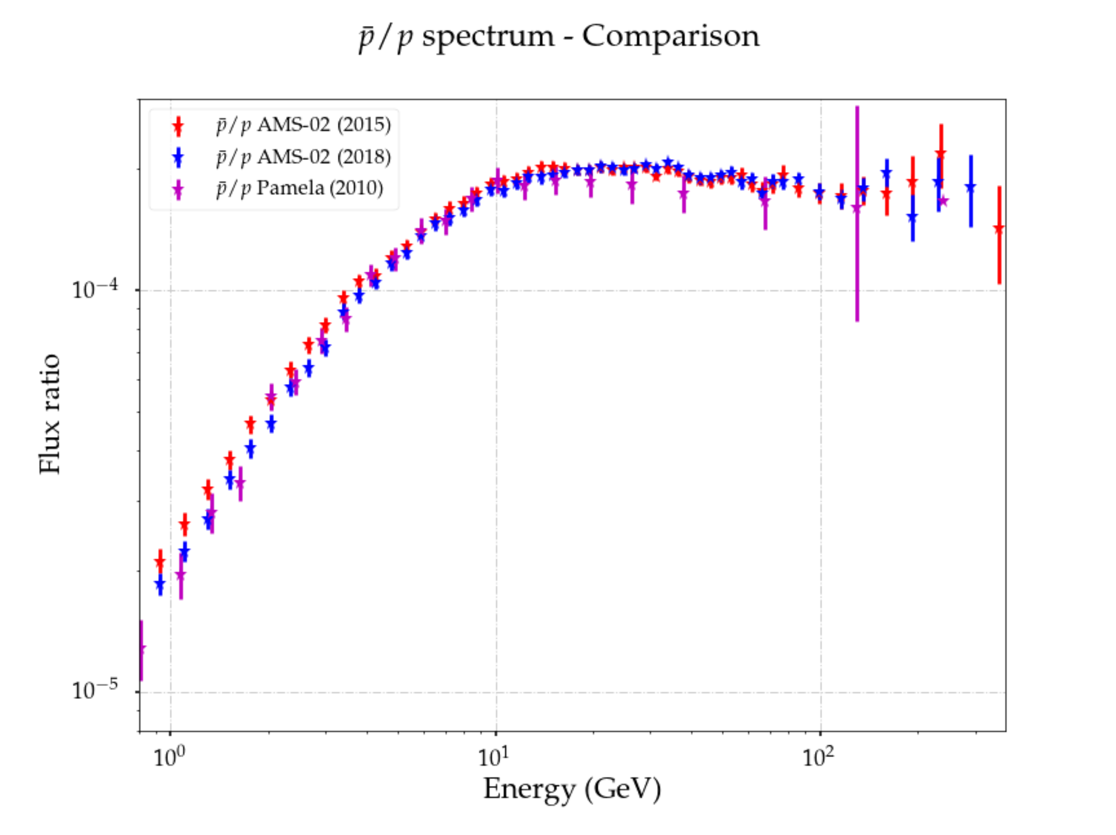
Extra contributions of secondary CRs?

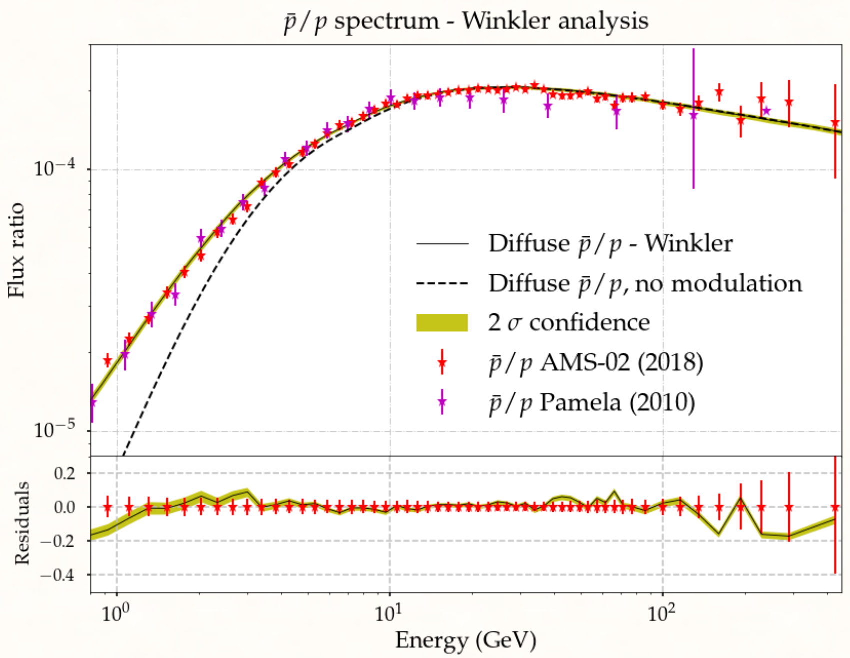


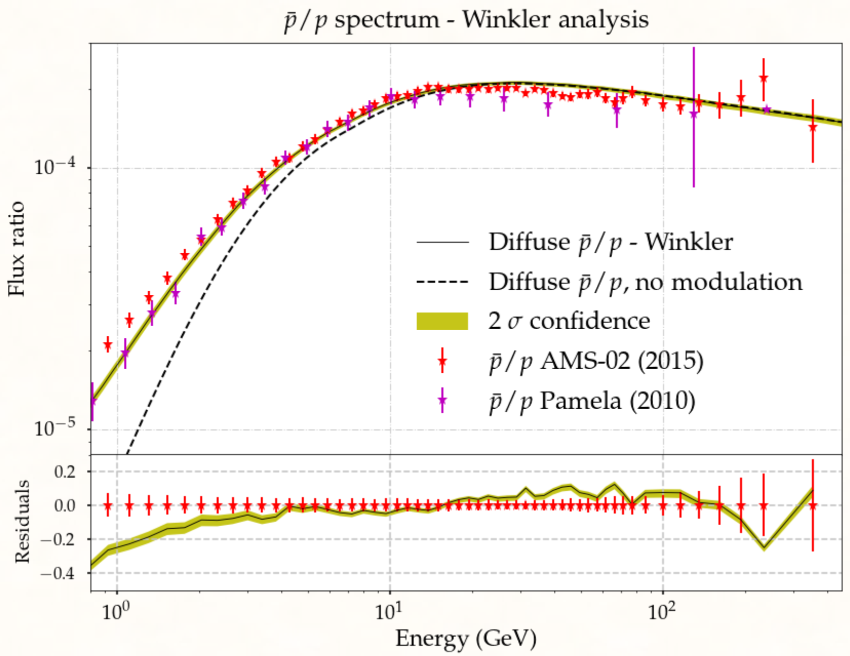
M. J. Boschini *et al* 2020 *ApJ* **889** 167

M. J. Boschini *et al* 2021 arXiv:2106.01626




$\bar{p}/p$ spectrum - Comparison
$\bar{p}/p$ AMS-02 (2015)
$\bar{p}/p$ AMS-02 (2018)
$\bar{p}/p$ Pamela (2010)
Flux ratio
10^{-4}
10^{-5}
10^0
10^1
10^2
Energy (GeV)


$\bar{p}/p$ spectrum - Winkler analysis
Diffuse $\bar{p}/p$ - Winkler
Diffuse $\bar{p}/p$, no modulation
2 σ confidence
$\bar{p}/p$ AMS-02 (2018)
$\bar{p}/p$ Pamela (2010)
Flux ratio
10^{-4}
10^{-5}
Residuals
0.2
0.0
−0.2
−0.4
10^0
10^1
10^2
Energy (GeV)


$\bar{p}/p$ spectrum - Winkler analysis
Diffuse $\bar{p}/p$ - Winkler
Diffuse $\bar{p}/p$, no modulation
2 σ confidence
$\bar{p}/p$ AMS-02 (2015)
$\bar{p}/p$ Pamela (2010)
Flux ratio
10^{-4}
10^{-5}
Residuals
0.2
0.0
−0.2
−0.4
10^0
10^1
10^2
Energy (GeV)