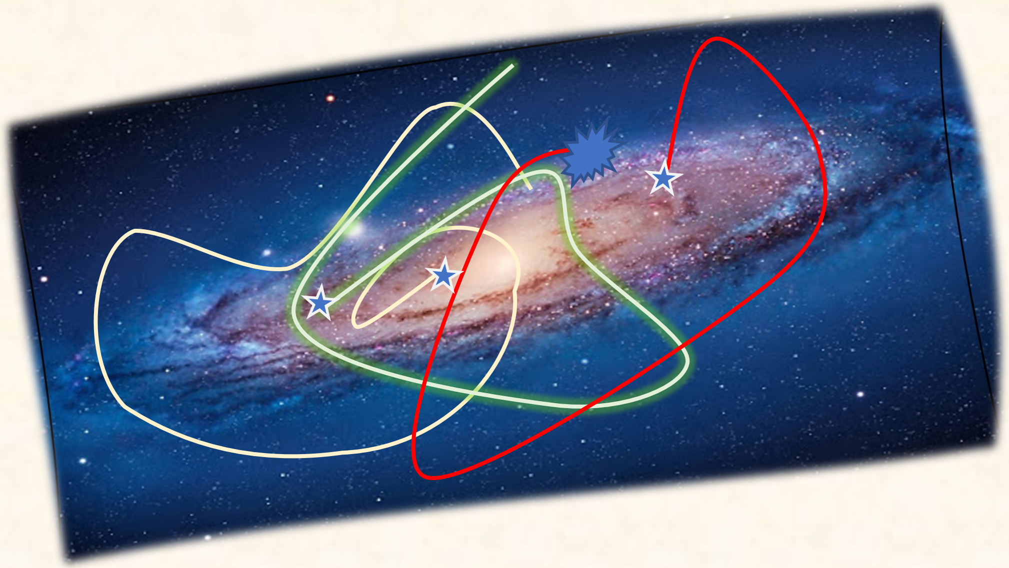
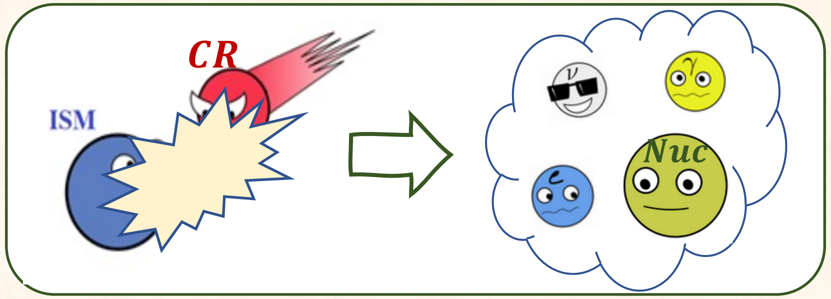
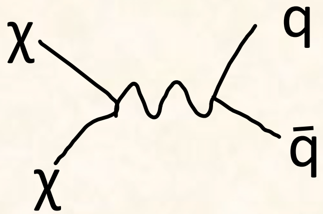
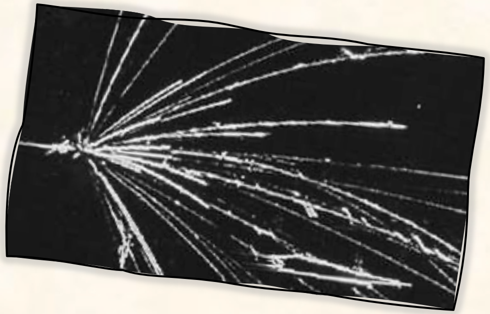
Pedro de la Torre Luque
pedro.delatorreluque@fysik.su.se
Multidark – 24/05/2022

Indirect dark matter searches with anti-nuclei

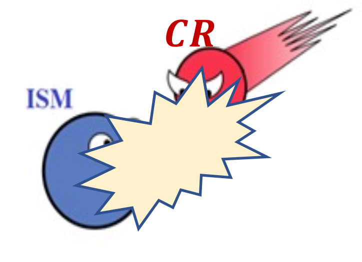








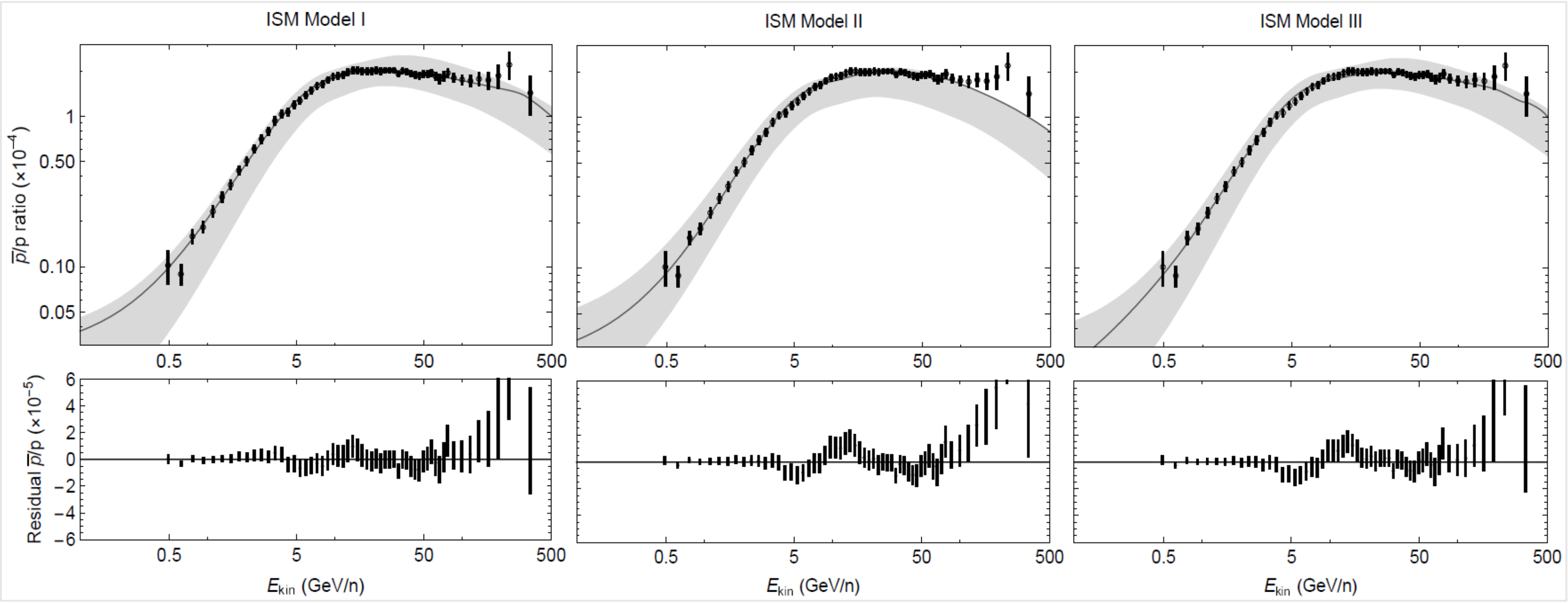
Antiproton *excesses* – *The spectral excess*



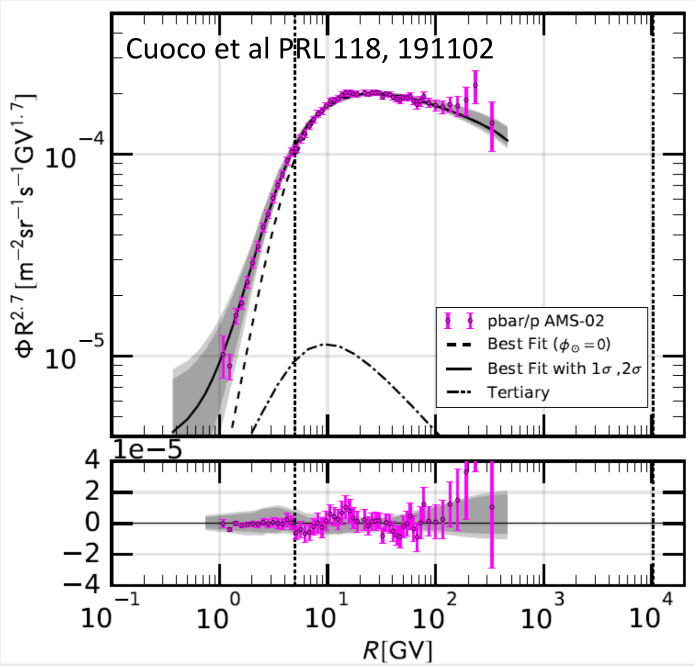
Recent studies have claimed the possibility of an **excess** of data over the predicted flux **at around 10-20 GeV**, which can be the **signature of dark matter** annihilating or decaying into antiprotons

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

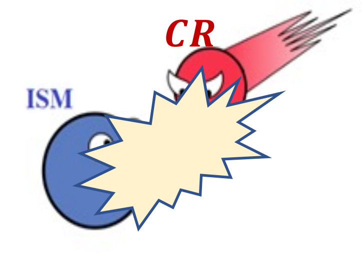
$\chi + \chi \rightarrow \bar{p}$



Cholis, Linden, Hooper PRD 99, 103026



Antiproton *excesses* – *The spectral excess*



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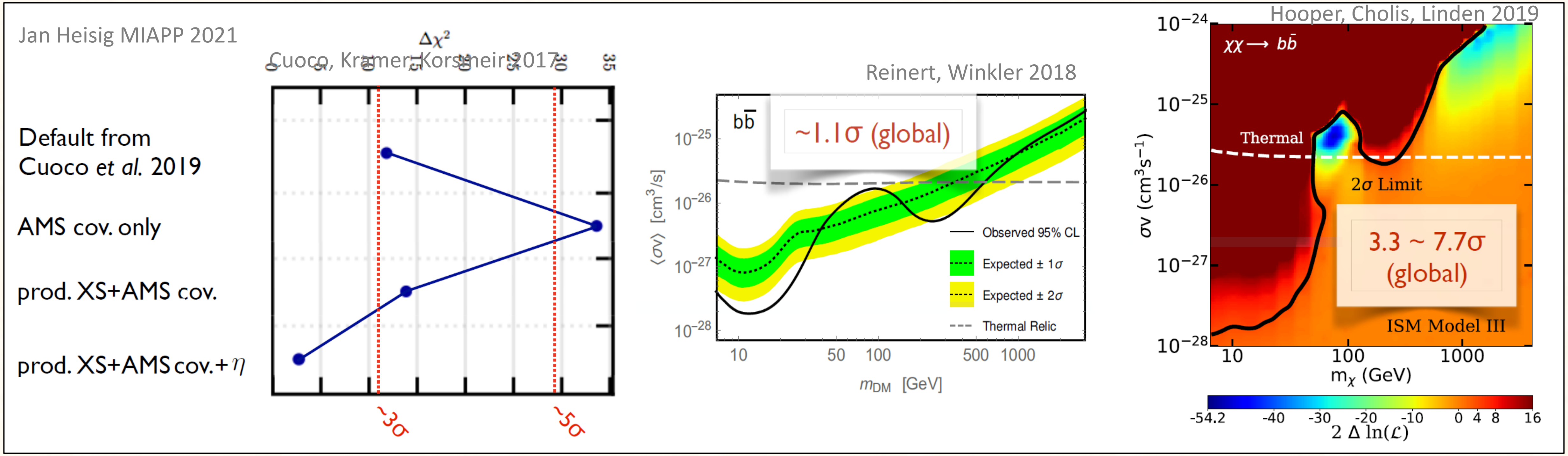
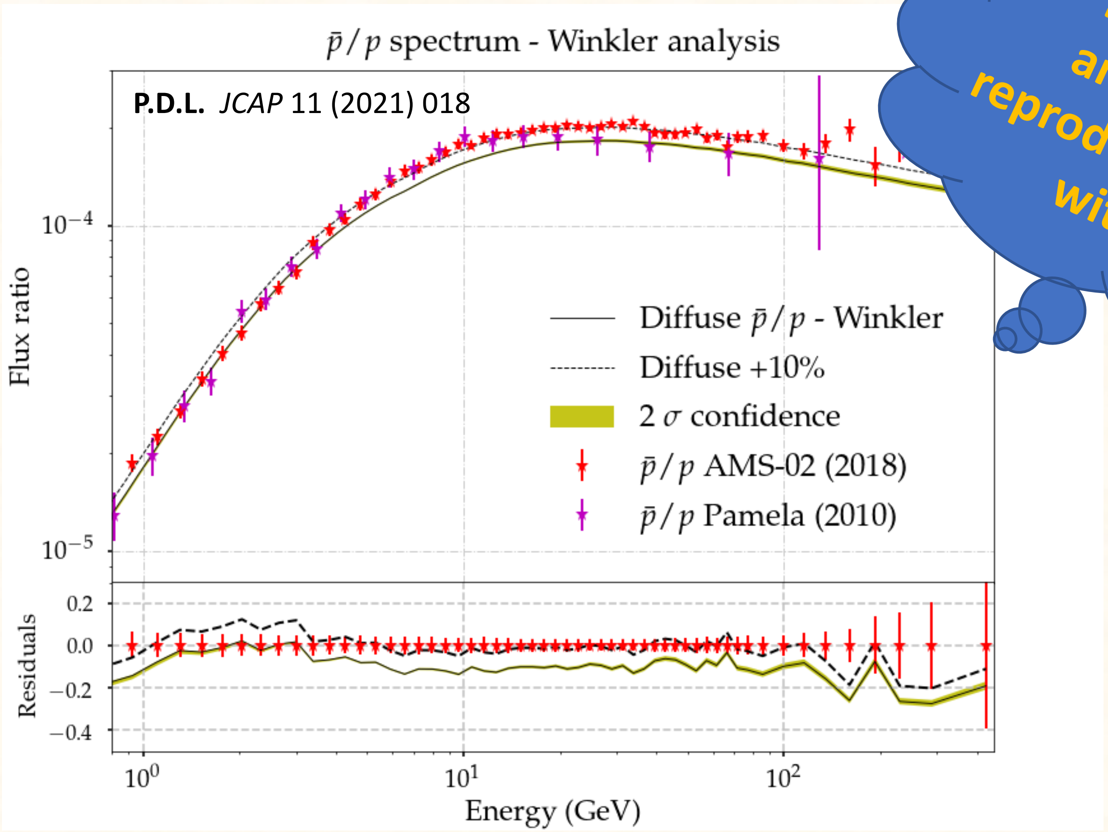
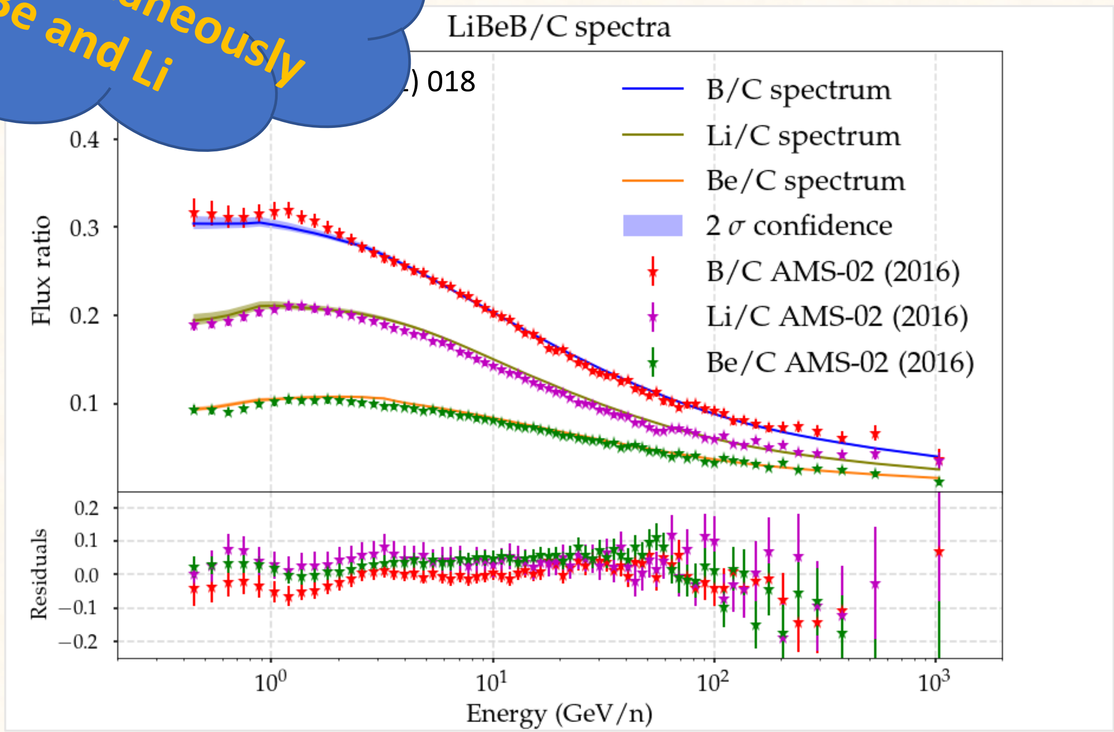


Antiproton excesses – *The grammage excess*

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

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





Diffusion coefficient

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

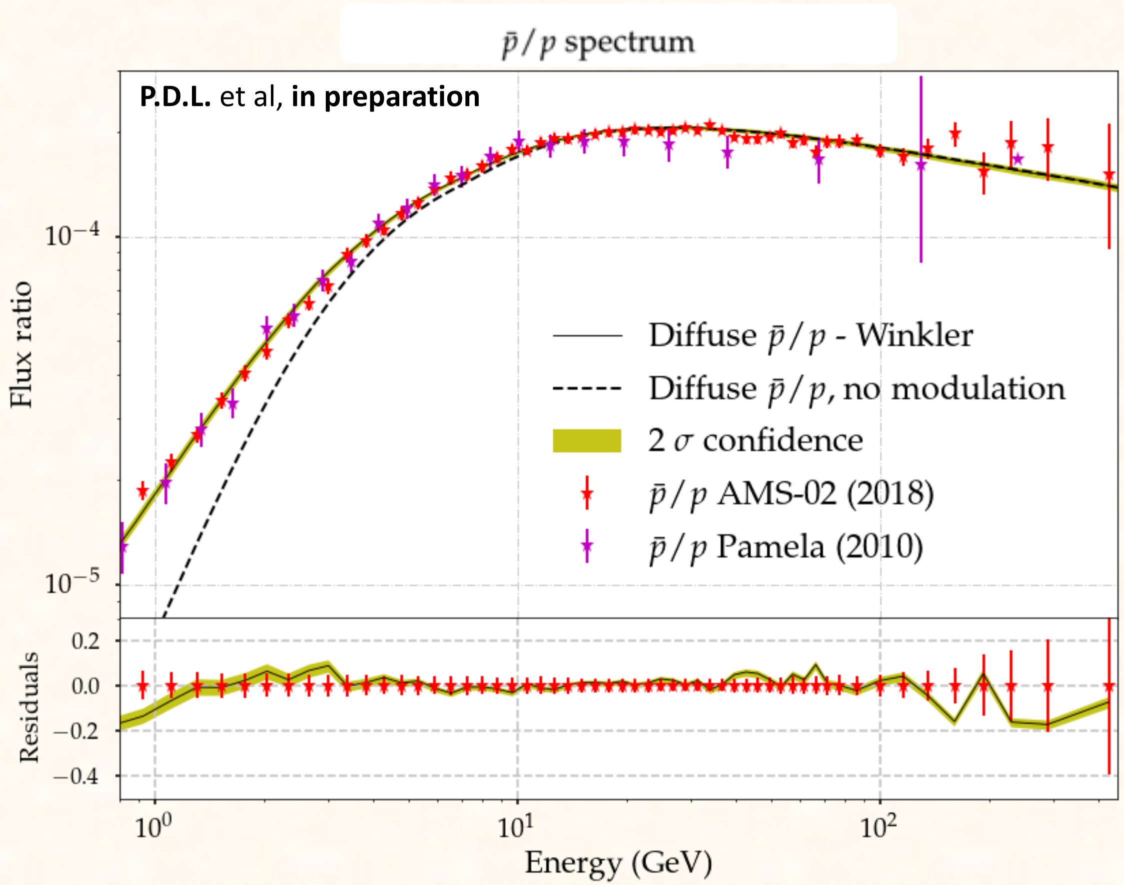
Production cross sections

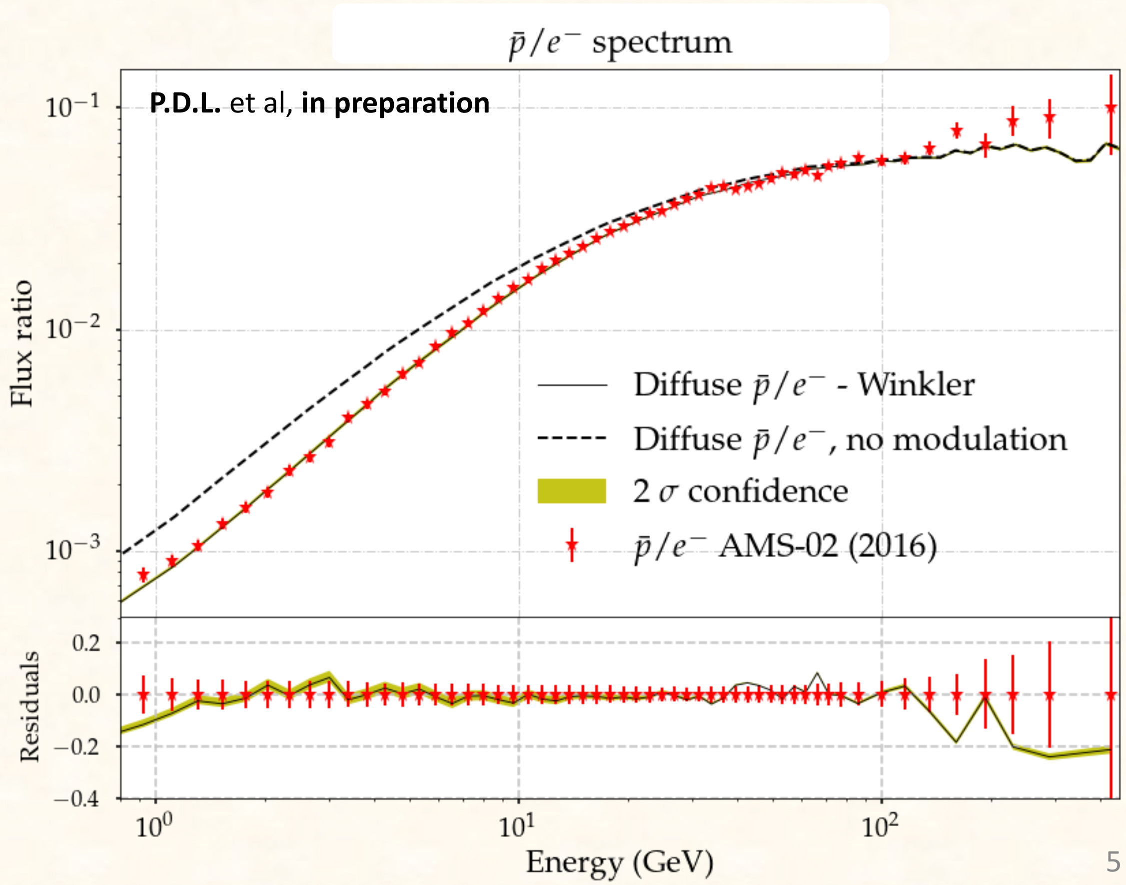
Conclusion: Cross sections uncertainties affect very significantly our predictions and can explain the excess

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.



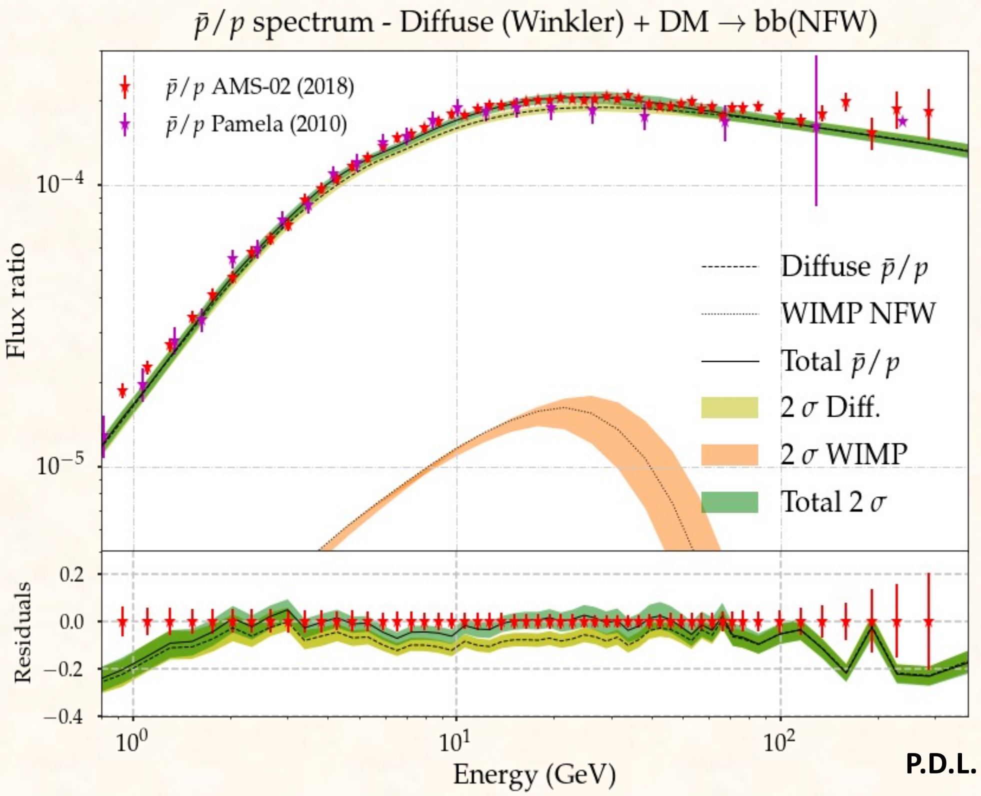


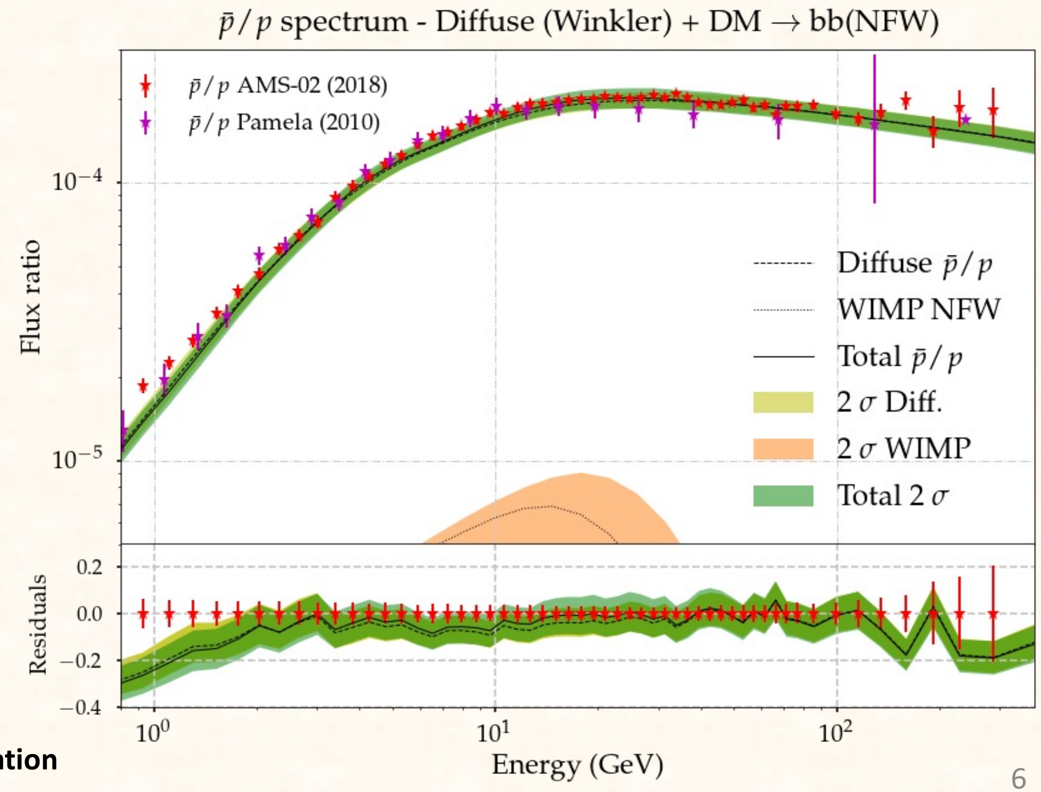
Antiproton *excesses* – *The grammage excess*

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, $<\sigma v> \sim 2{\cdot}10^{26}\ \mathrm{cm^3/s}$

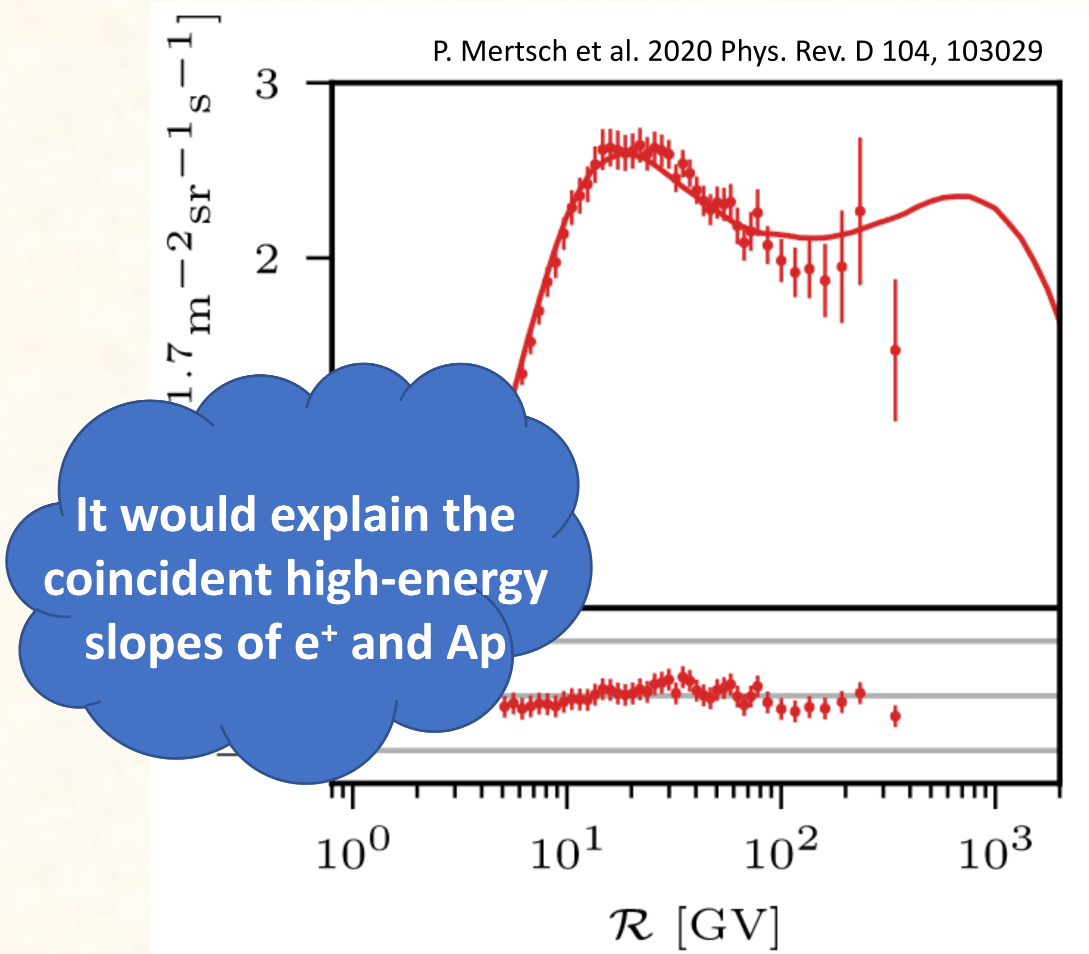




P.D.L. et al, **in preparation**

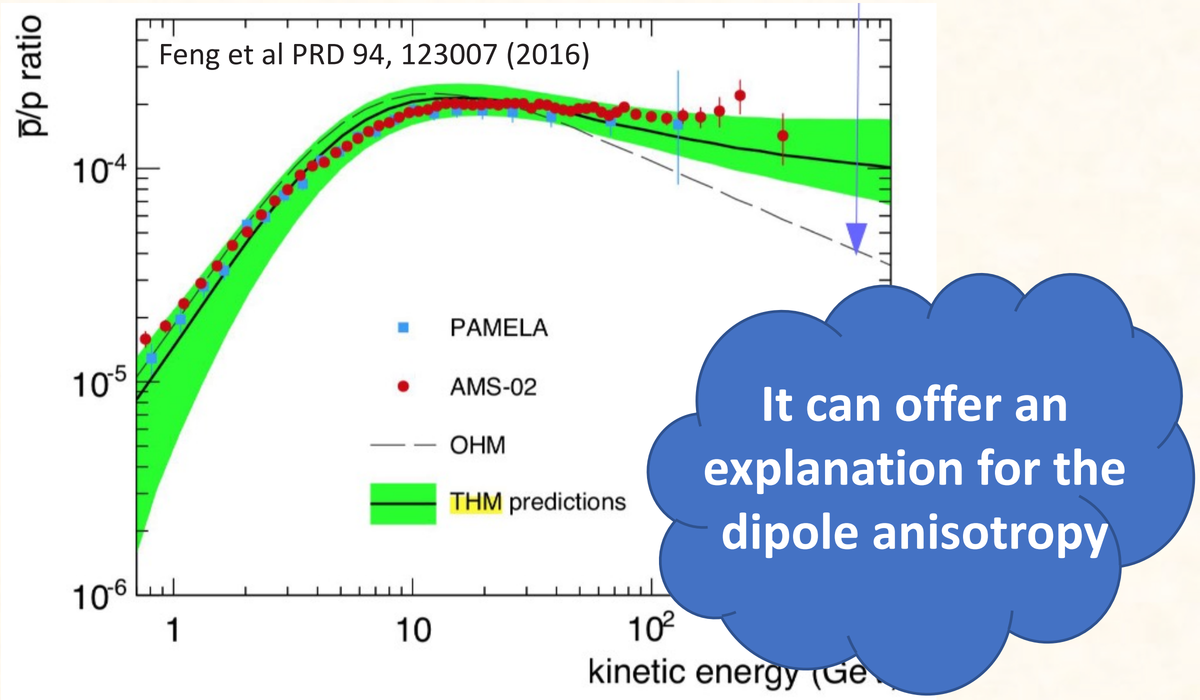
Antiproton *excesses* – *More possibilities*

SNRs accelerating antiprotons



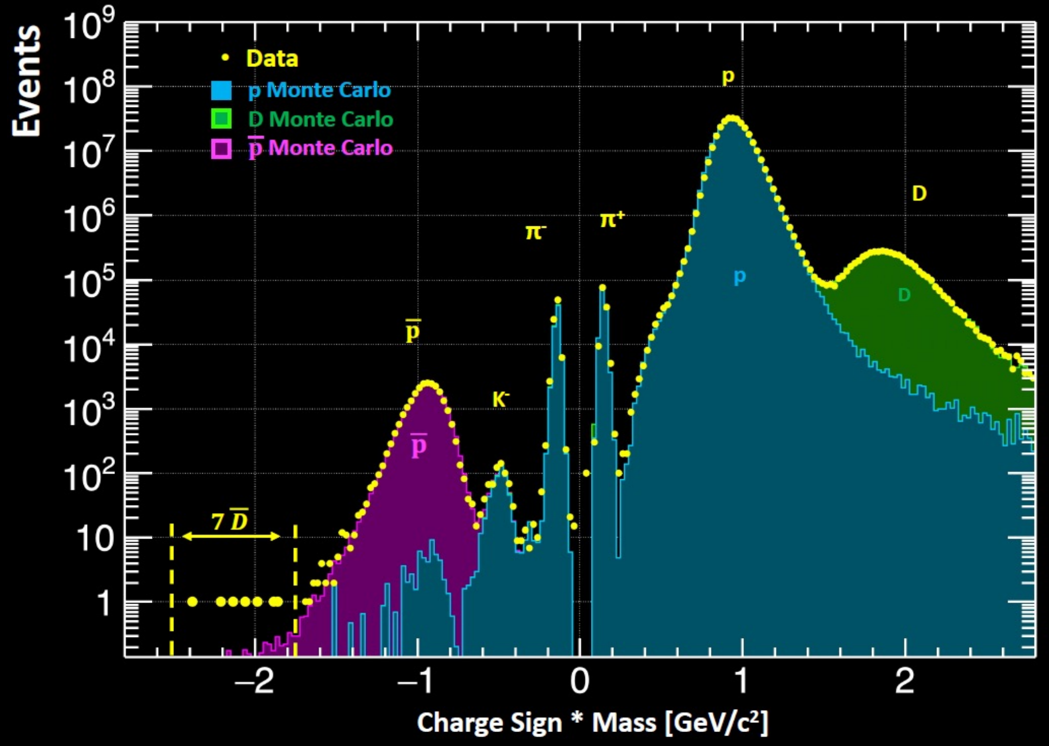
Inhomogeneous diffusion coefficient

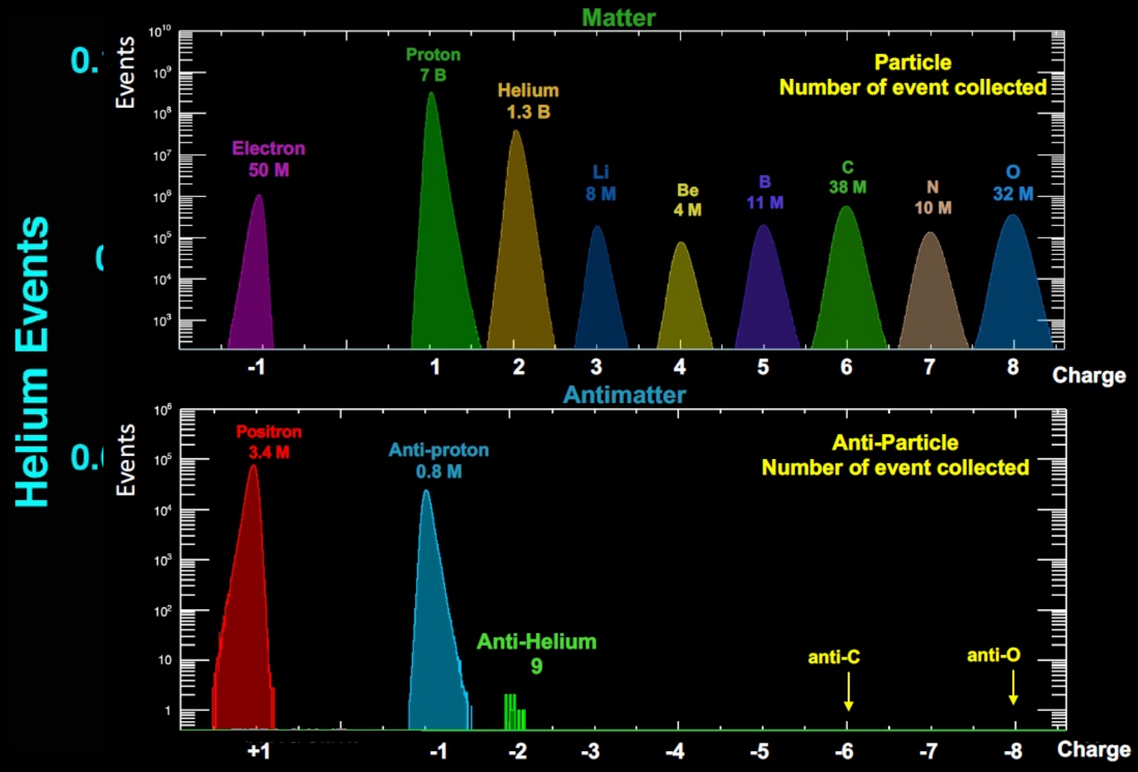
(See also: Zhao et al 2021 arXiv:2109.04112v1)



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

ANTI-NUCLEI: AMS-02 mass-charge spectra

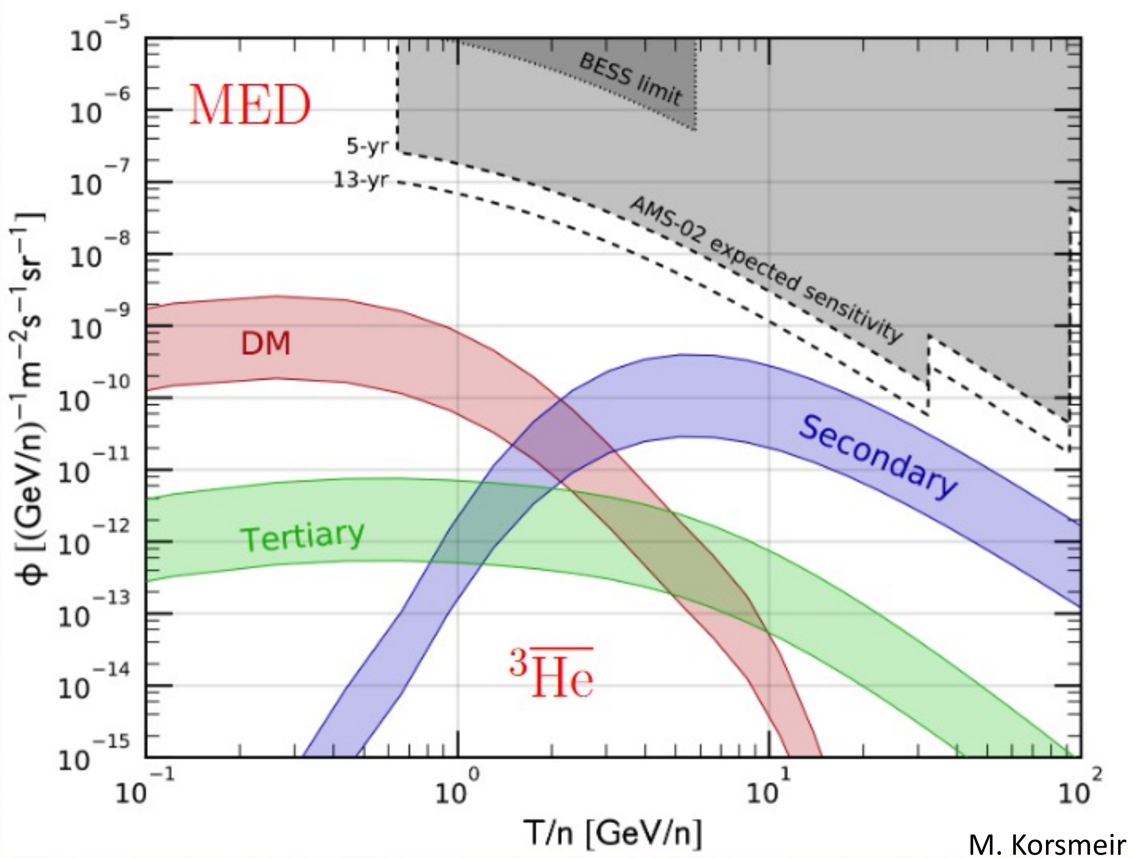




Paolo Zuccon MIAPP 2021

Anti-nuclei as the dark matter smoking gun

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

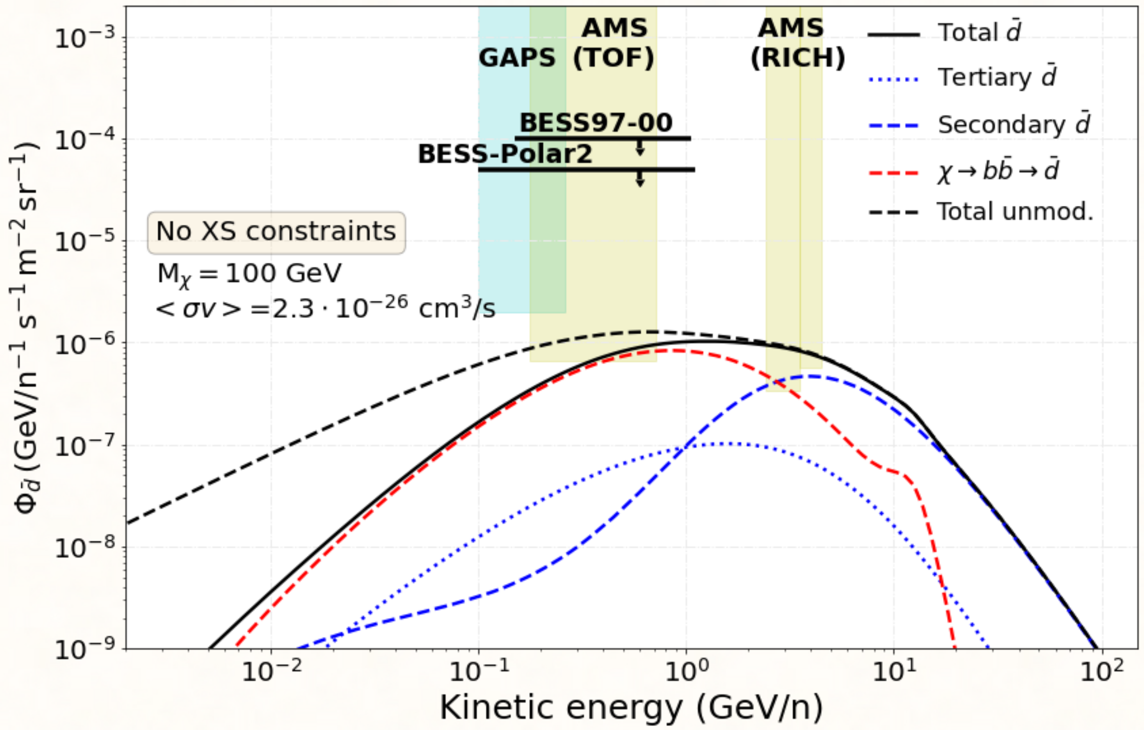


For kinematical reasons, the production of anti-nuclei from CR interactions is not important at energies below the GeV, offering a **clear way to spot the production of anti-nuclei from dark matter** (at least for masses below ~hundreds of GeV)

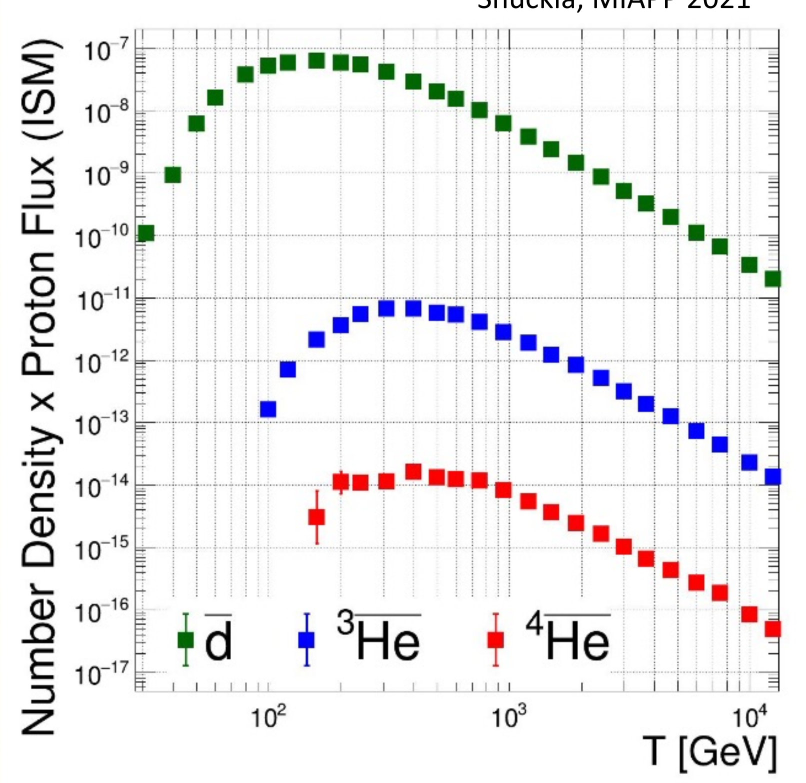
M. Korsmeir et al. (2018) Phys. Rev. D97, 103011

Anti-nuclei as the dark matter smoking gun

P.D.L. et al, in preparation



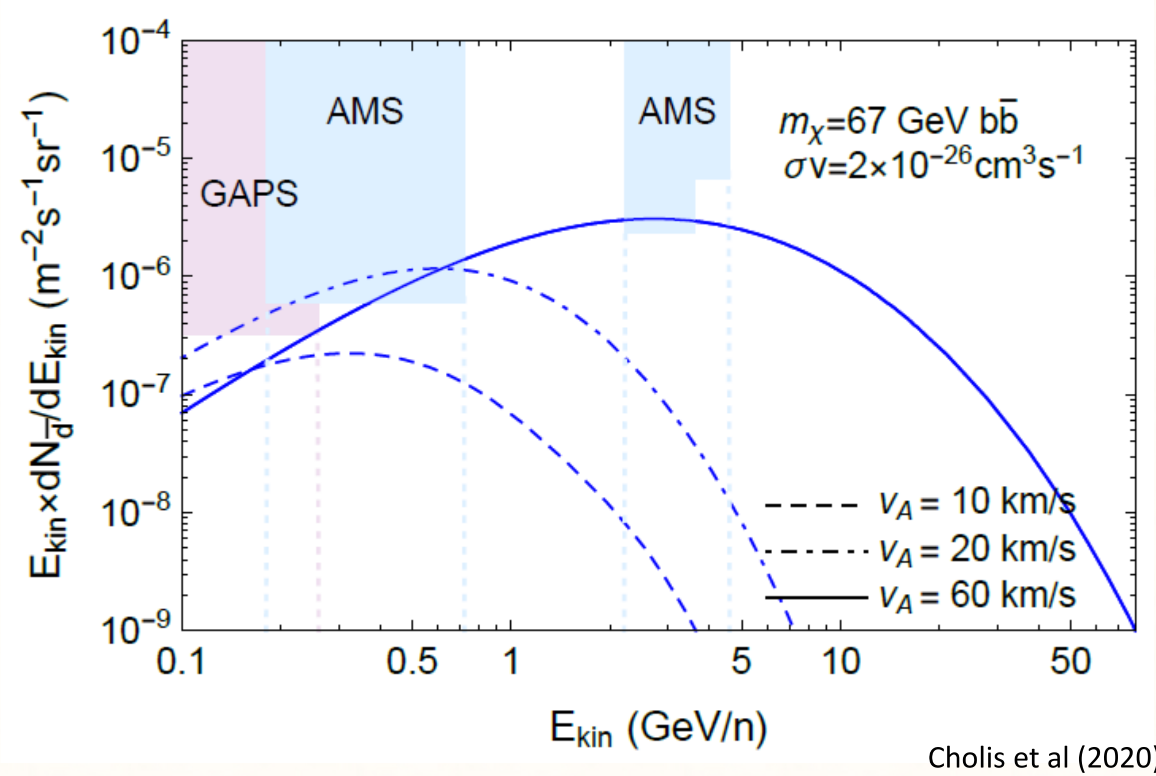
Shuckla, MIAPP 2021

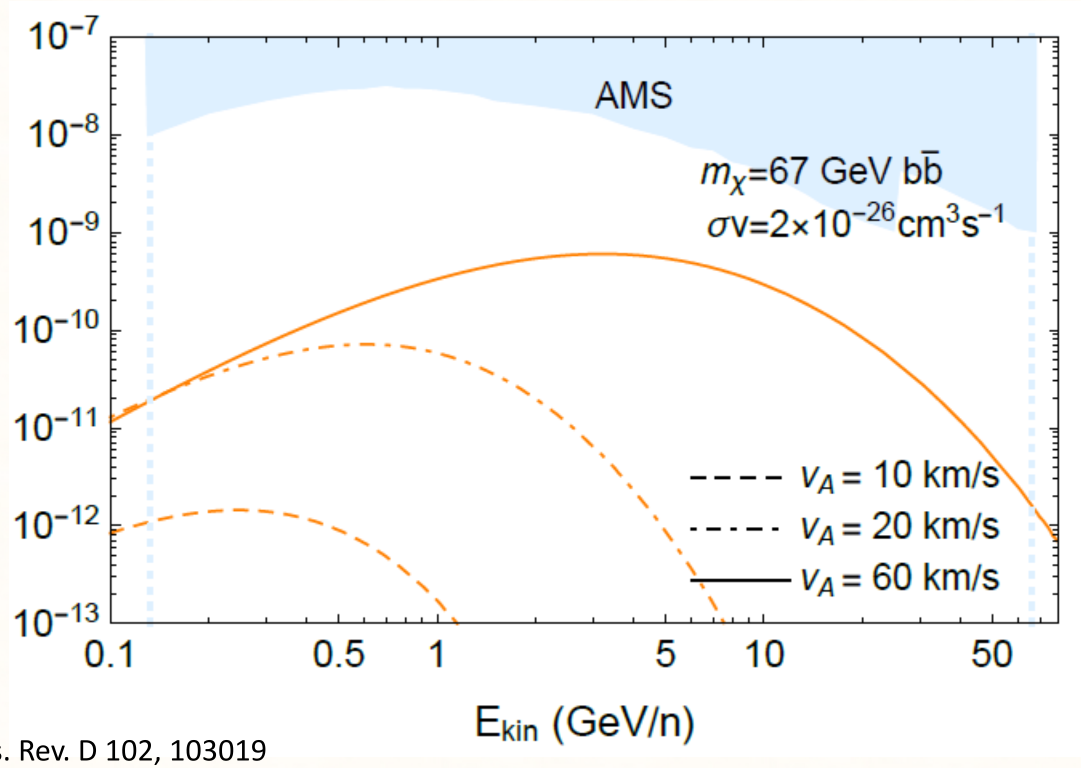


Detected anti-D events possibly explained, but impossible to explain more anti-He events!

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

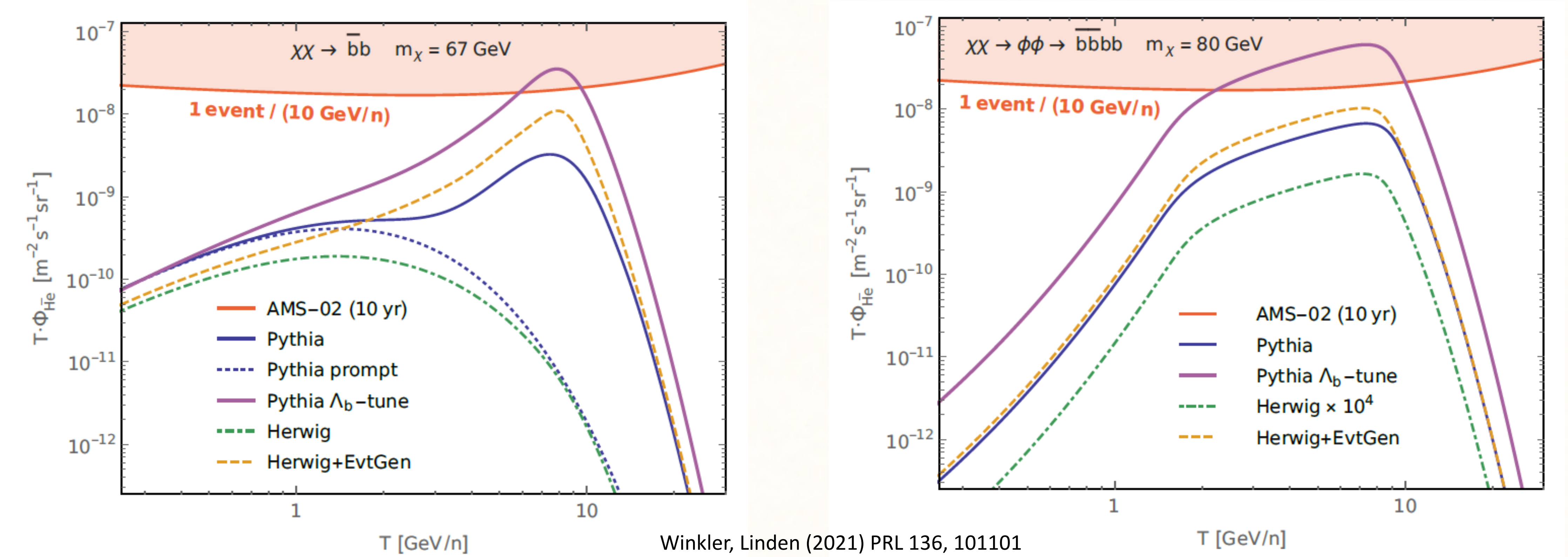




Cholis et al (2020) Phys. Rev. D 102, 103019

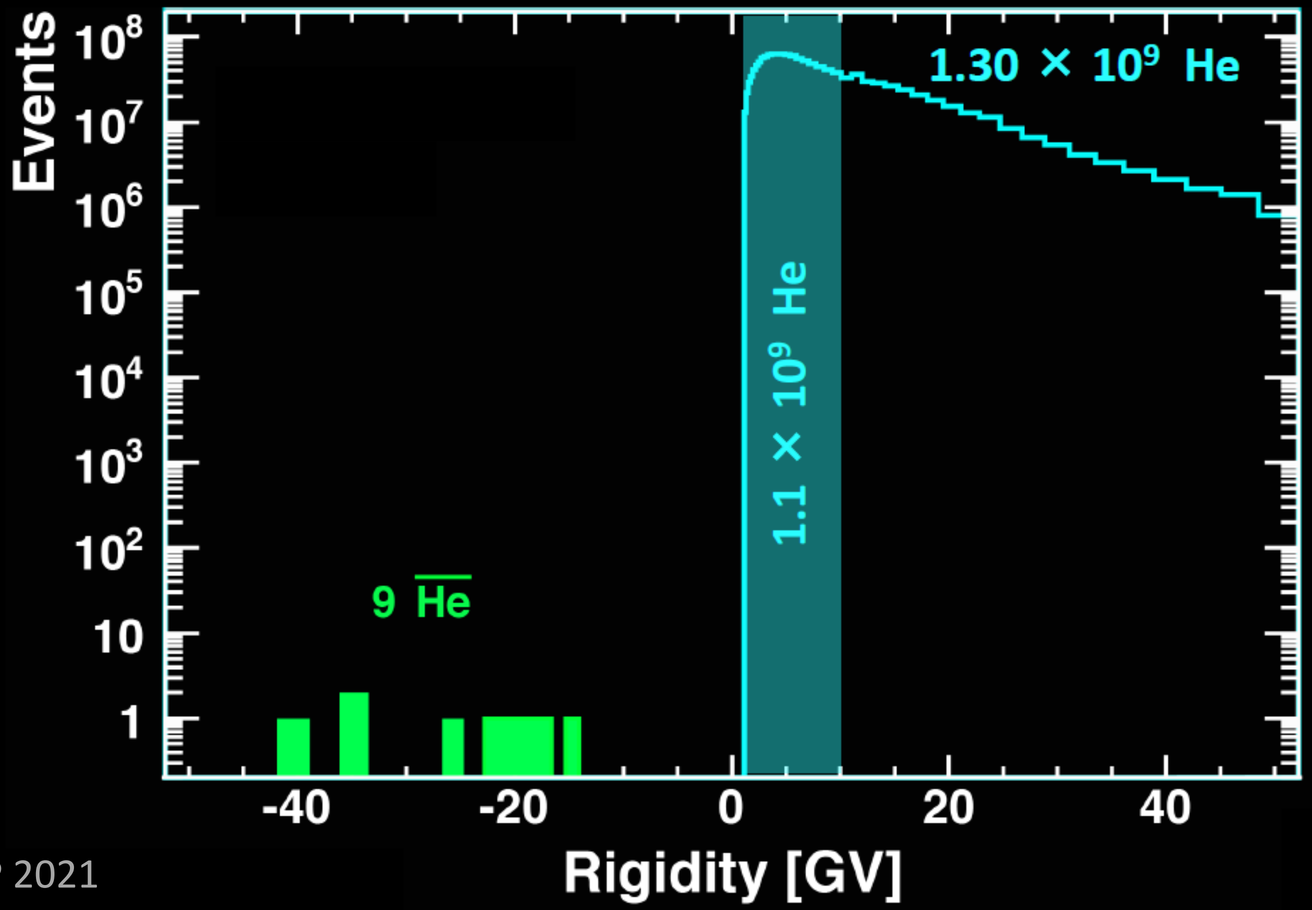
Boosting the dark matter signal

- ✓ **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 important problem…



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Conclusions

- **Every antimatter species, 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 – **Multimessenger studies**
- Crucial role of numerical codes giving the complexity of the expected **anisotropy** and **inhomogeneity** of the transport process
- A careful analysis of the **background** (propagation) **uncertainties** can prove (disprove) any current anomaly – Possible **dark matter** signals are going to be tested in the next few years, thanks to AMS-02 and GAPS

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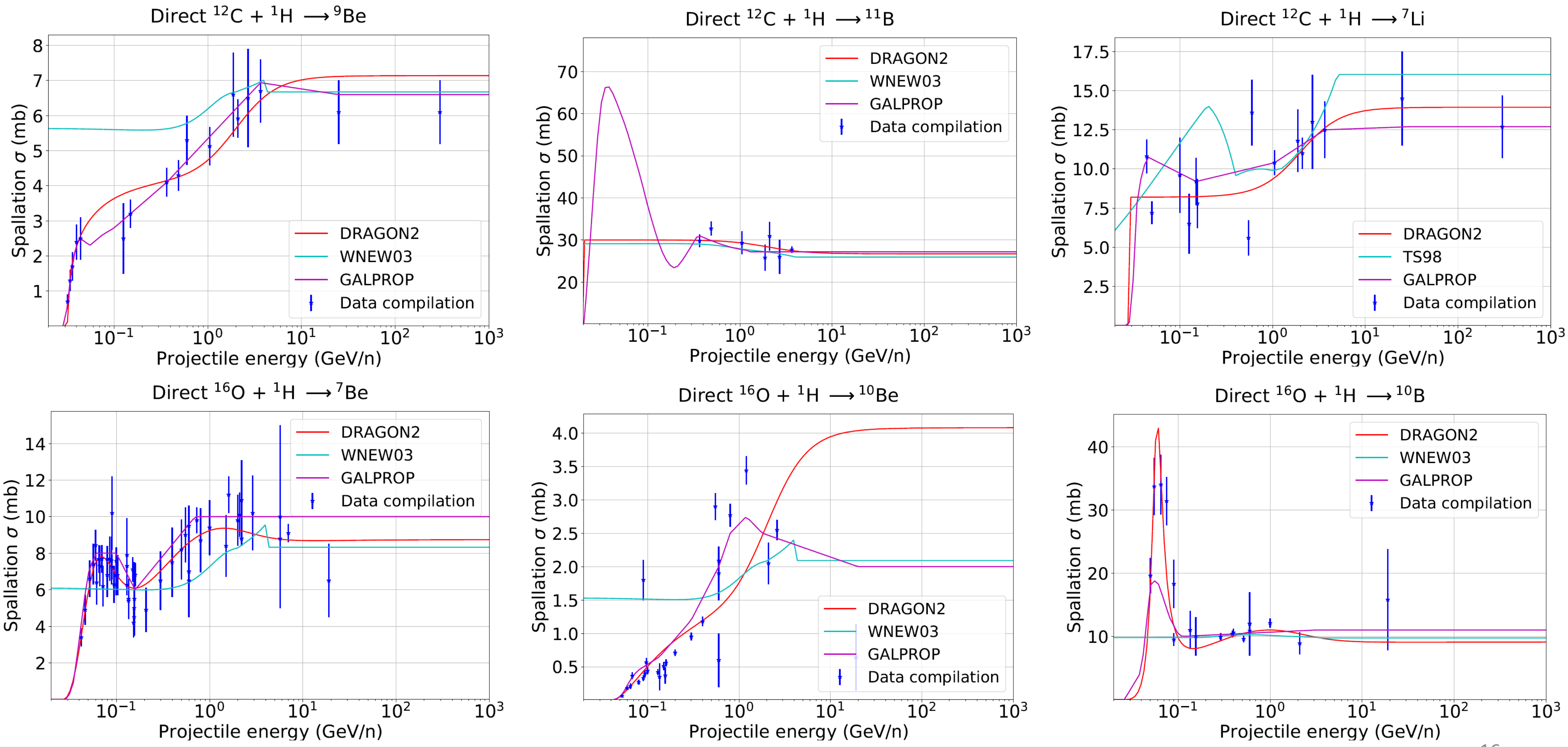
BACK UP

Cross sections parametrizations

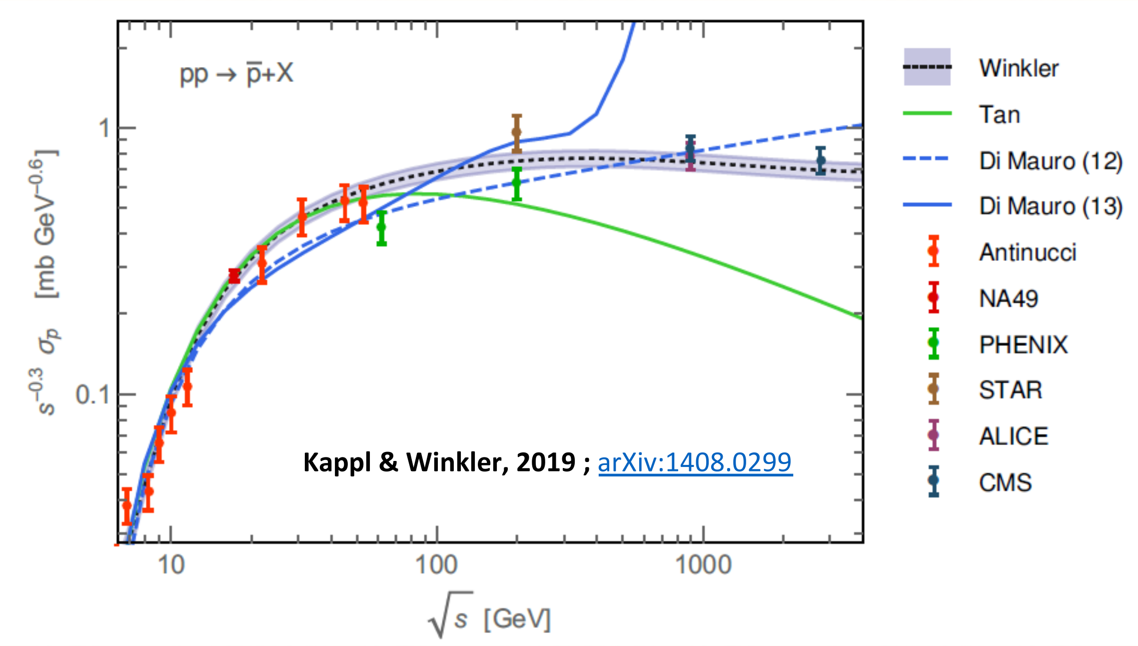


Antiproton cross sections

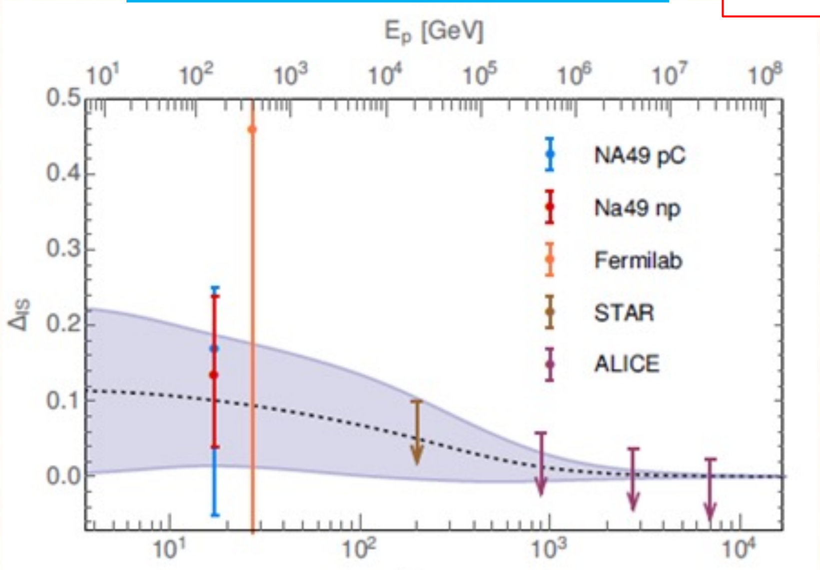
$$\left(E\frac{d^3\sigma}{dp^3}\right)_{pp\to\bar{p}} = \left(E\frac{d^3\sigma}{dp^3}\right)^{\text{prompt}}_{pp\to\bar{p}} \cdot (2 + \boxed{\Delta_{IS}} + 2\,\Delta_{\Lambda})$$

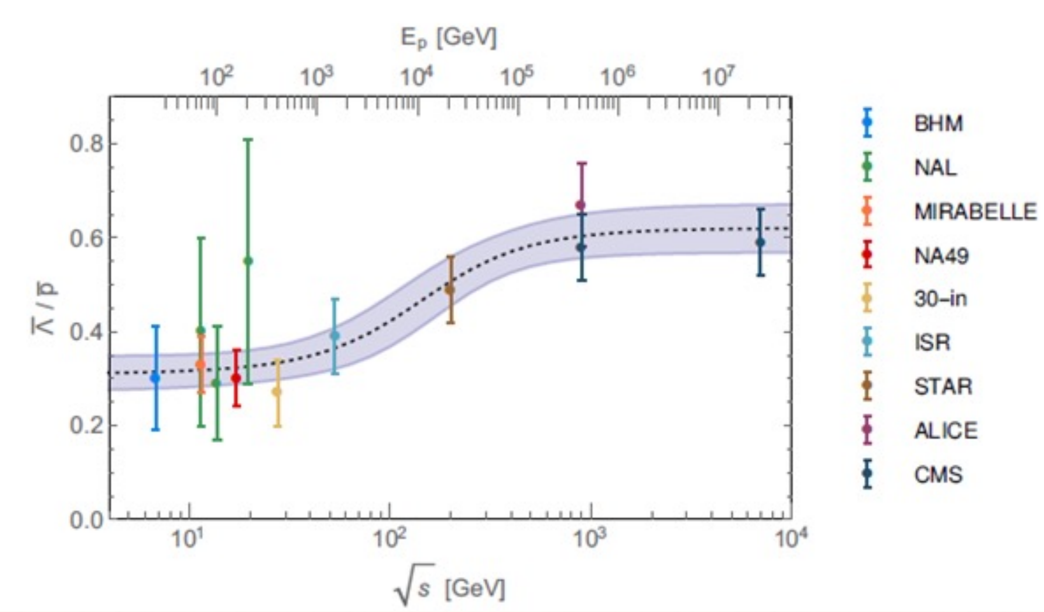
$$p + p \longrightarrow \{\bar{n} \longrightarrow \bar{p}\} + X$$

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



Kappl & Winkler, 2019 ; [arXiv:1408.0299]





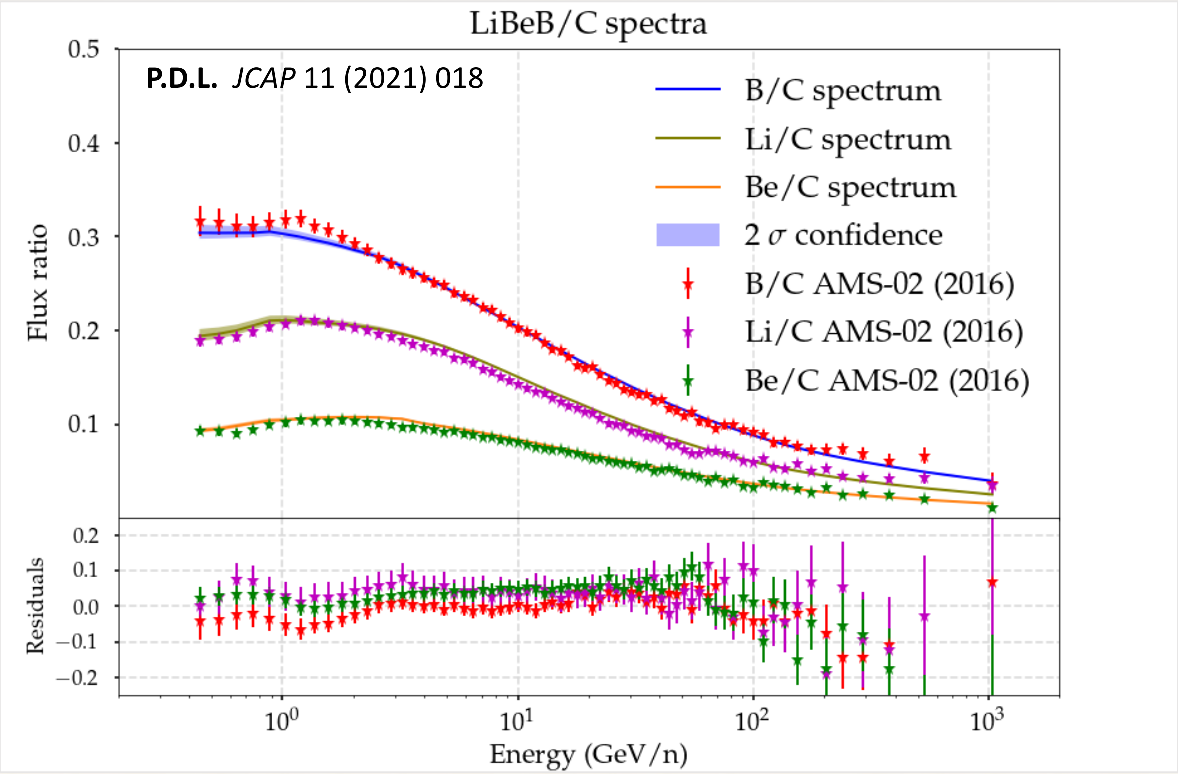
$$p + p \longrightarrow \{\bar{\Lambda}, \bar{\Sigma} \longrightarrow \bar{p}\} + X$$

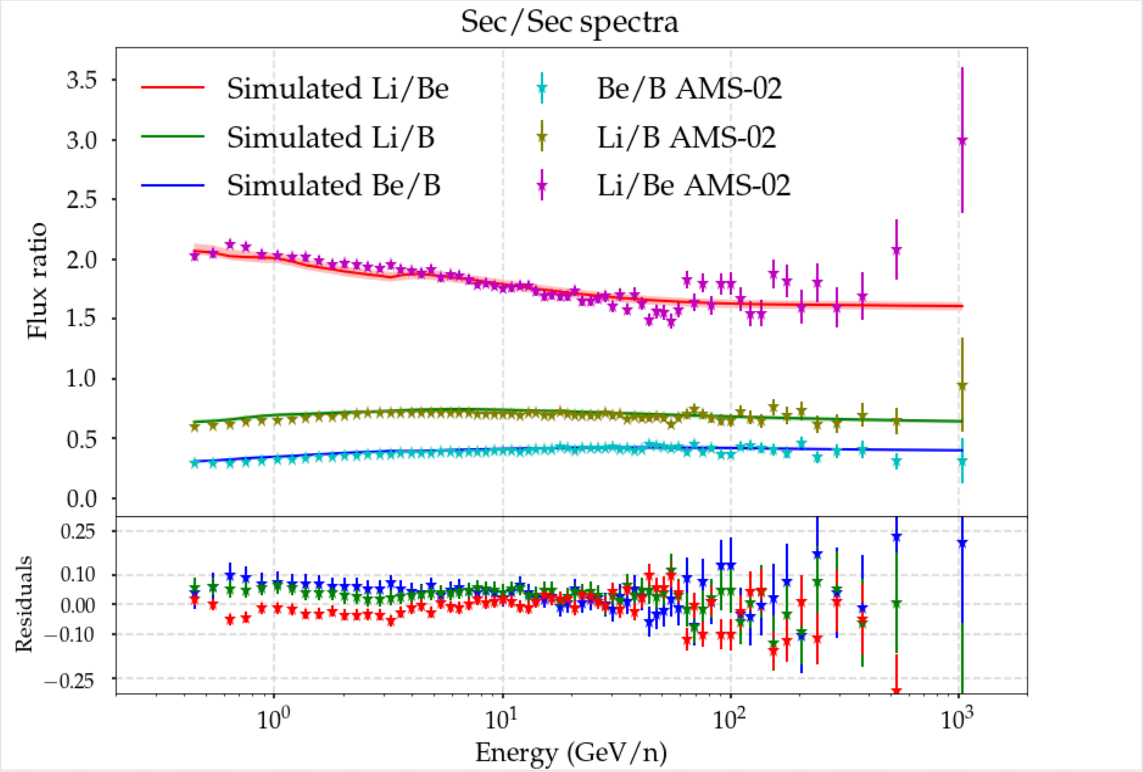
A. Reinert, M. W. Winkler, 2017 ; [arXiv:1712.00002]

Precise studies of secondary CRs: The antiproton excesses

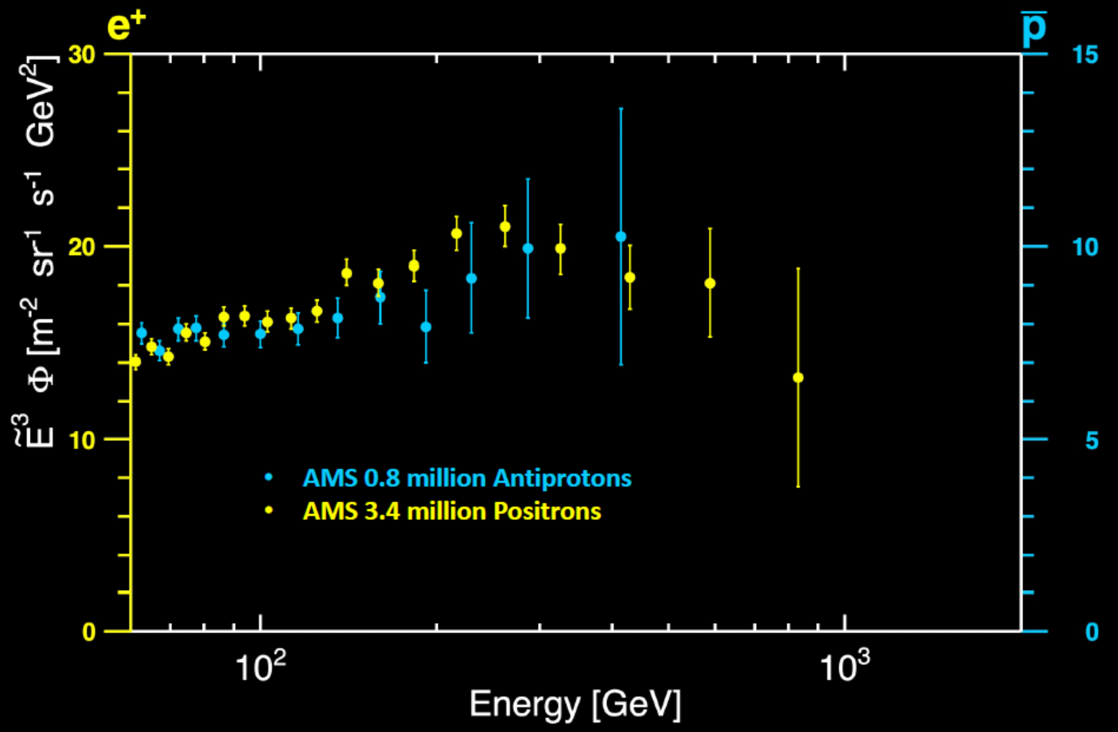
- *DRAGON2* cross sections for heavy secondary CRs
- *Winkler* (2017) cross sections for antiprotons

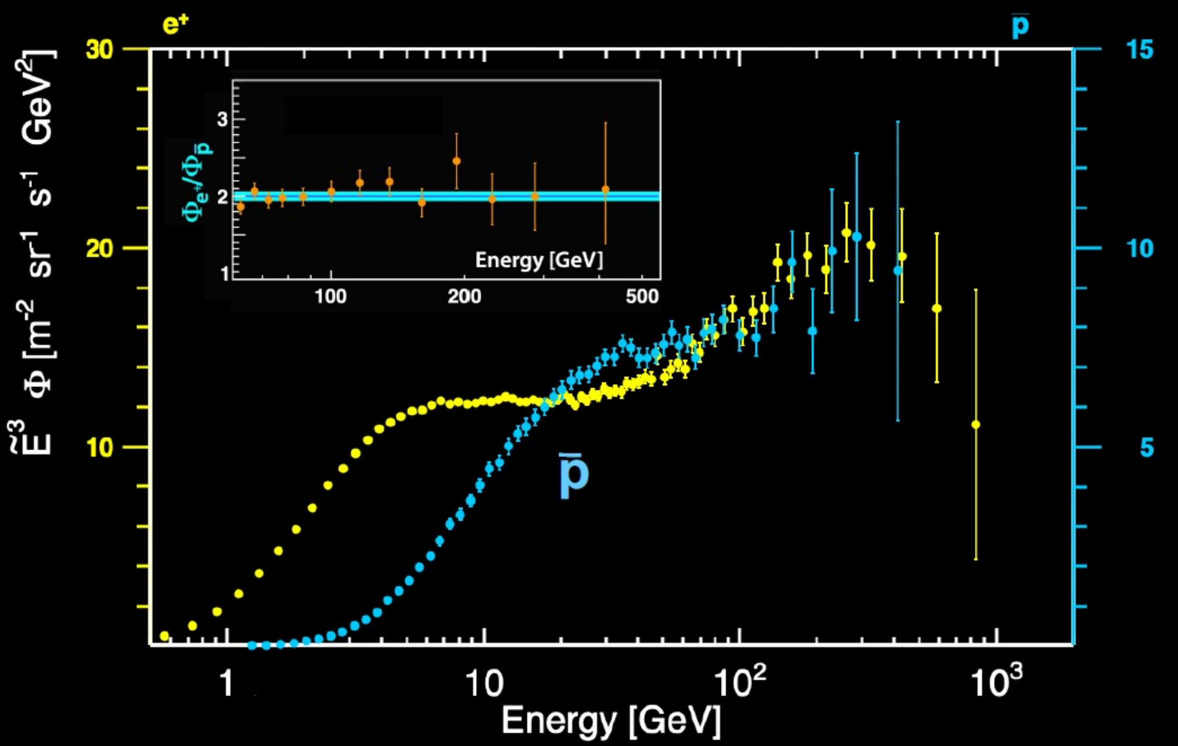
B/C, B/O, Be/C, Be/O, Ap/p (Prop. parameters)
^{10}Be/^{9}Be, ^{10}Be/Be (H), **Be/B, Li/B, Li/Be** (S_X)
Ap/e$^+$, Ap/e$^-$ → S_{Ap}, propagation params





AMS-02 Positrons and antiprotons





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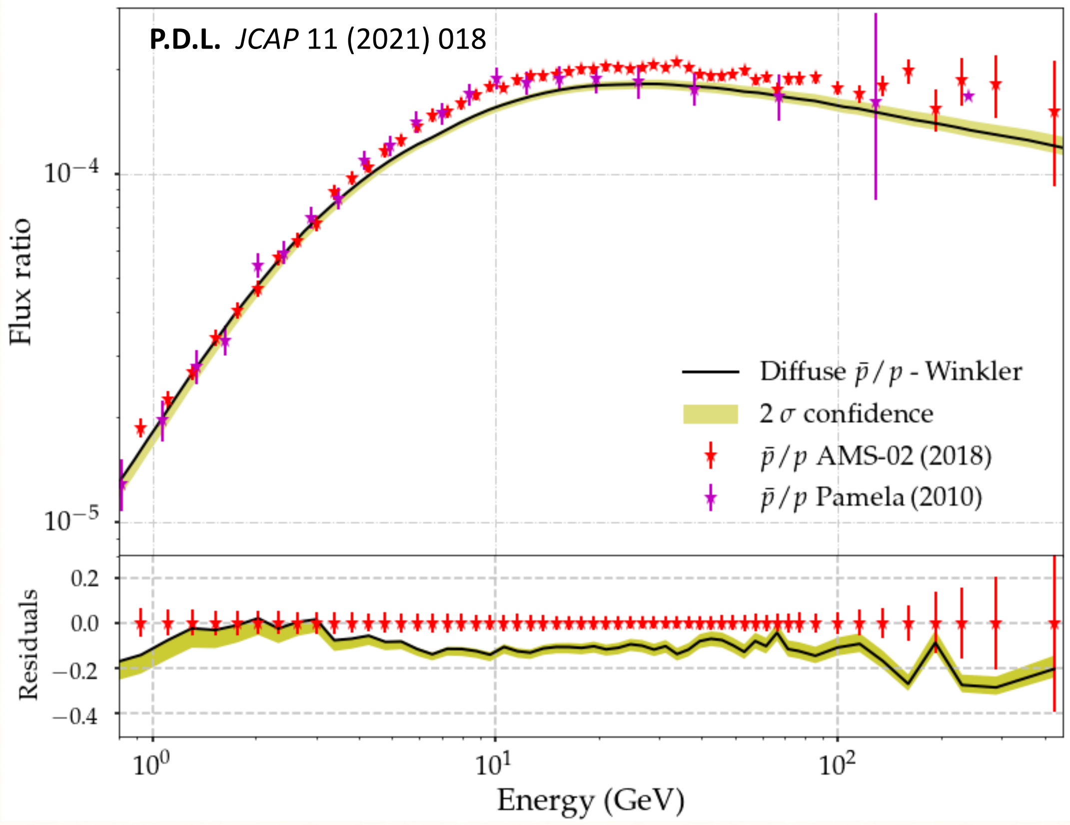
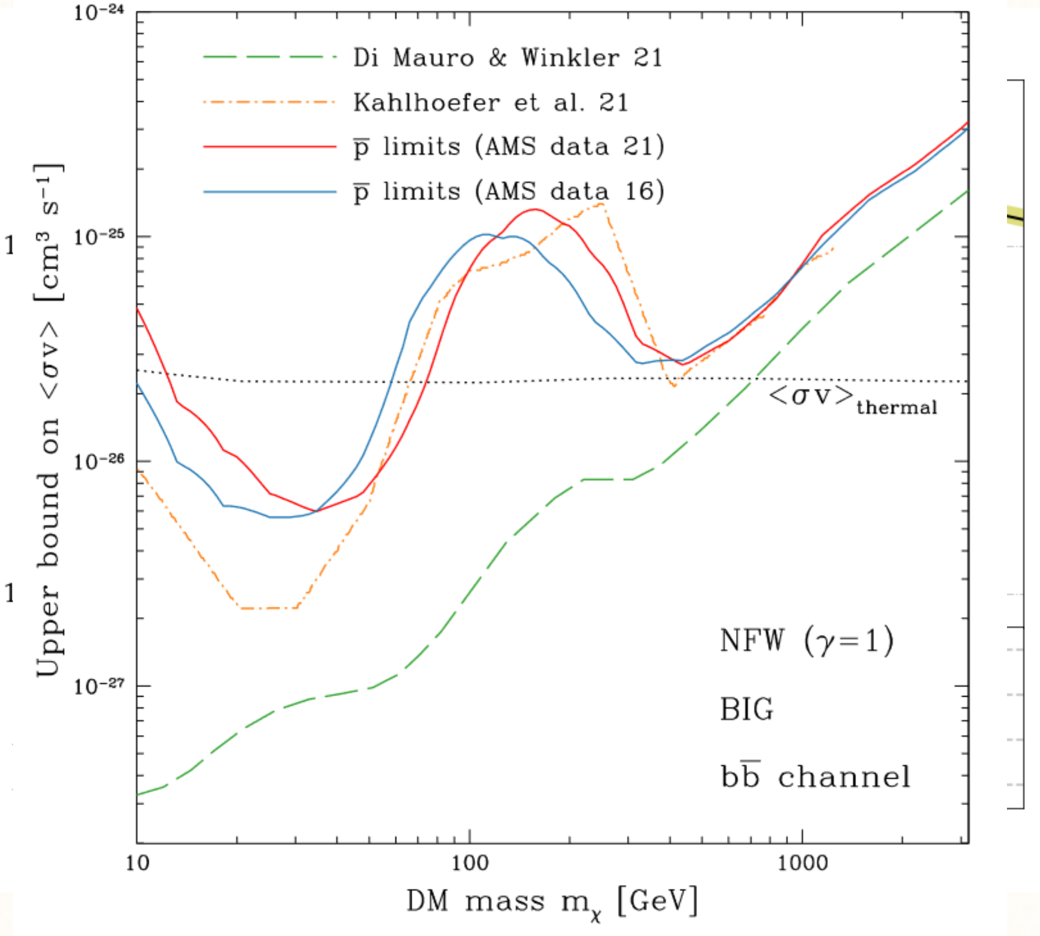
Precise studies of secondary CRs: The antiproton excesses

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



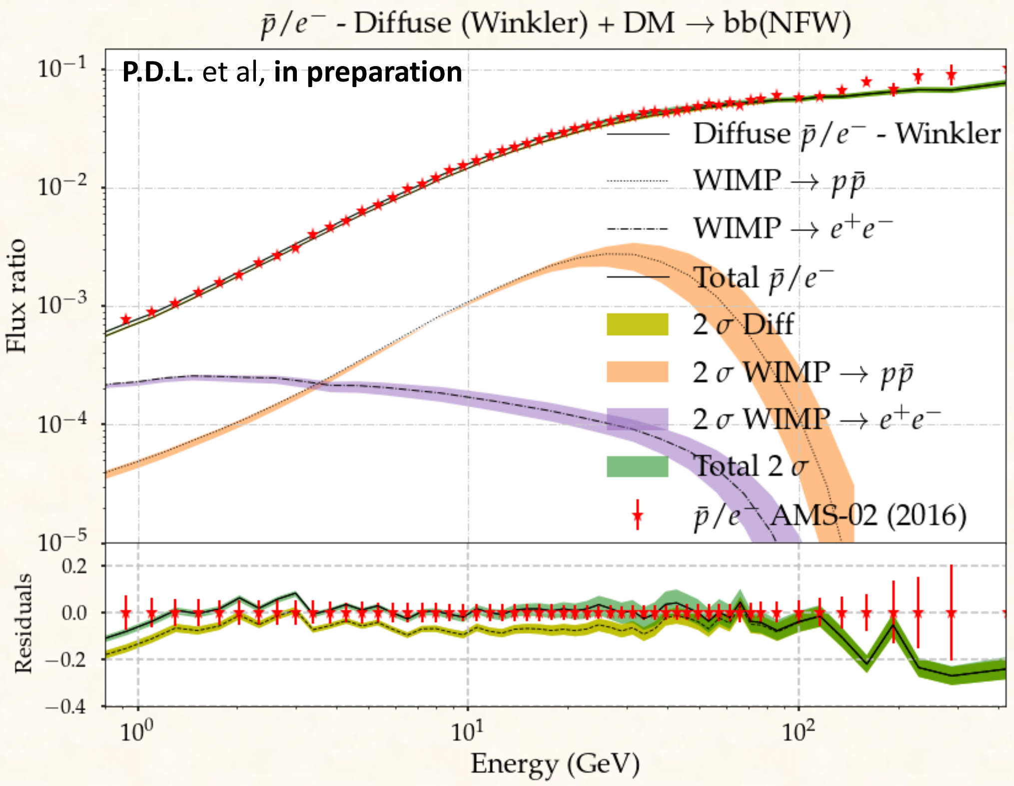
Calore et al arXiv:2202.03076v1

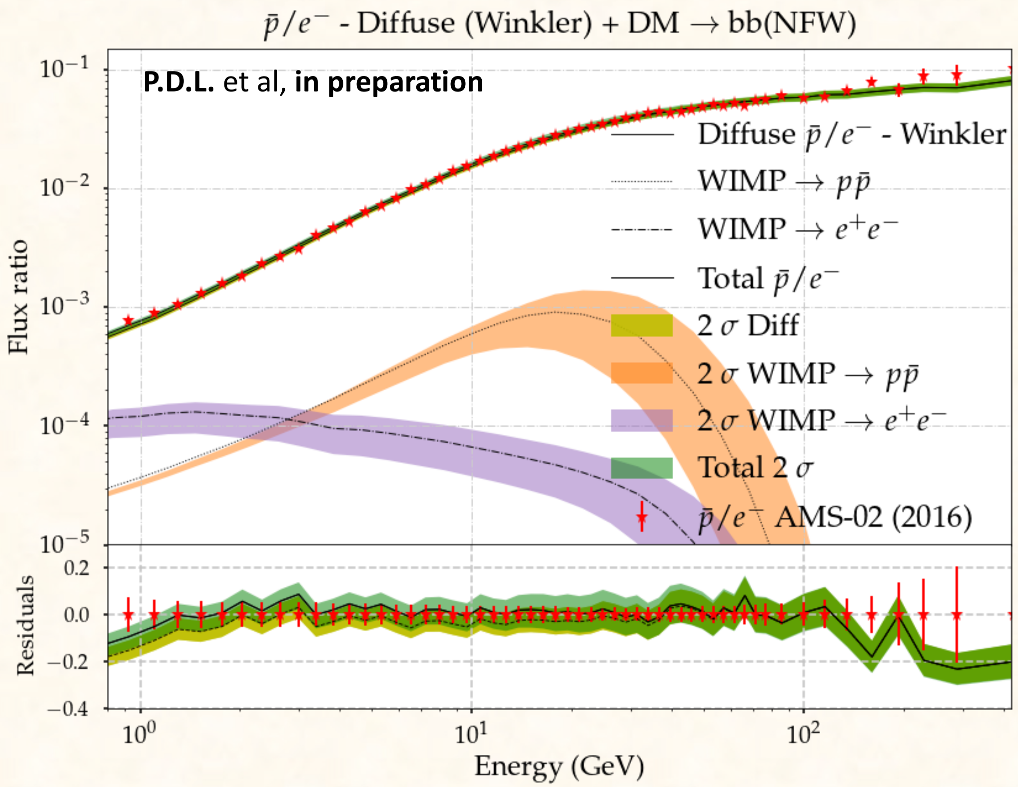


Antiproton *excesses* – *The grammage excess*

Full XS prior constrains $M\chi \sim 160$ GeV, $\langle\sigma v\rangle \sim 7\cdot10^{26}\,cm^3/s$

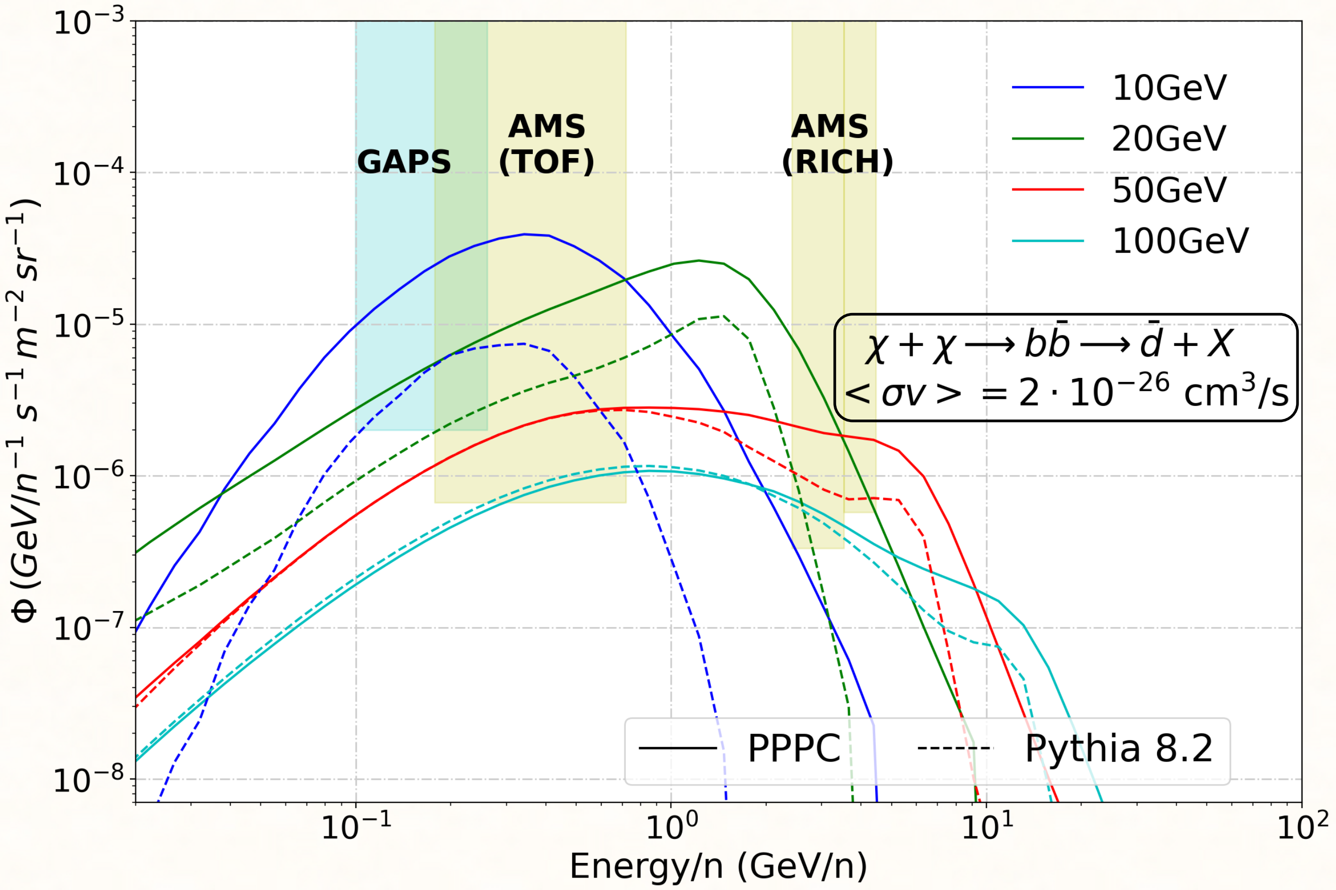
No XS prior constrains $M\chi \sim 100$ GeV, $\langle\sigma v\rangle \sim 2\cdot10^{26}\,cm^3/s$





Anti-nuclei as the dark matter smoking gun

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



Astrophysical DM excesses and hints

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

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

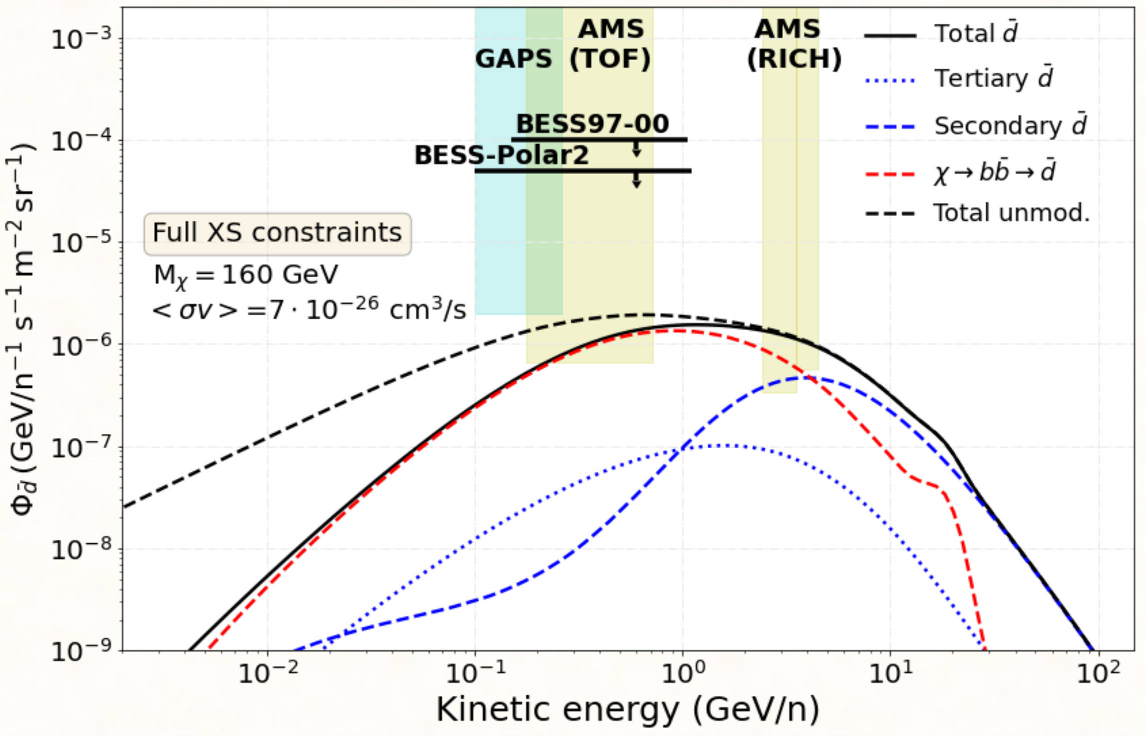
<u>γ-ray lines</u> ~133 GeV

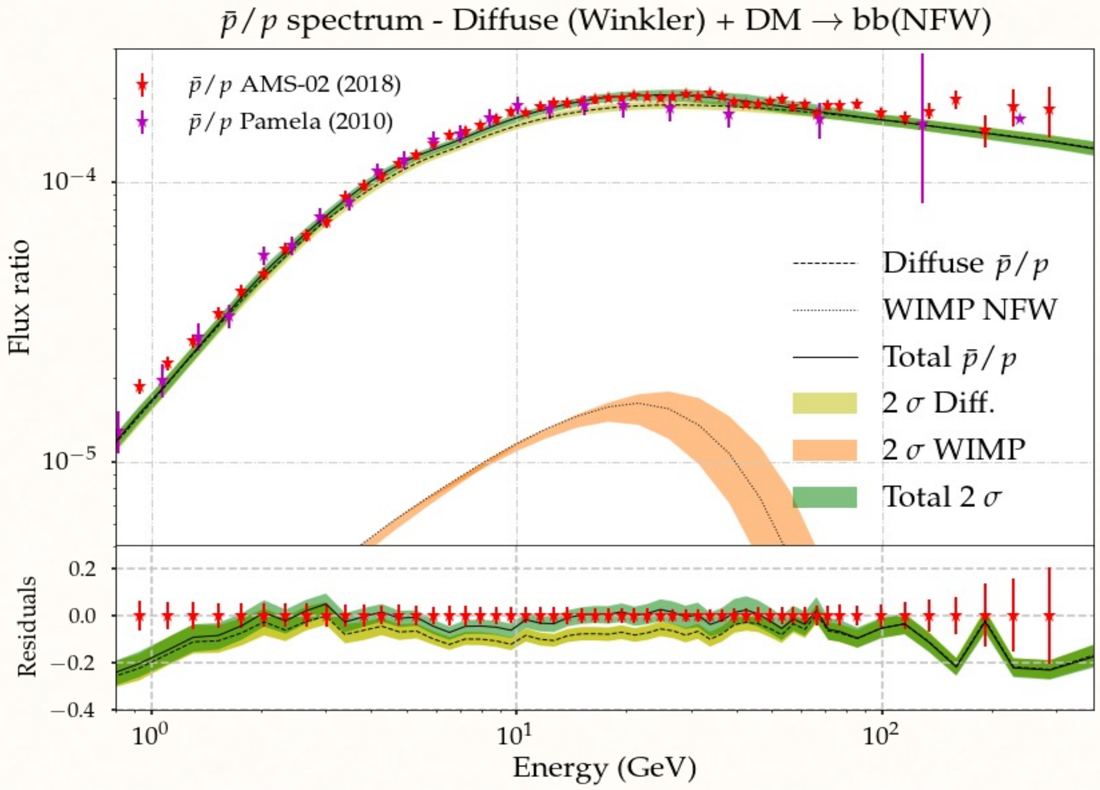
<u>DAMA excess</u> 10-70 GeV

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

Anti-nuclei as the dark matter smoking gun

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

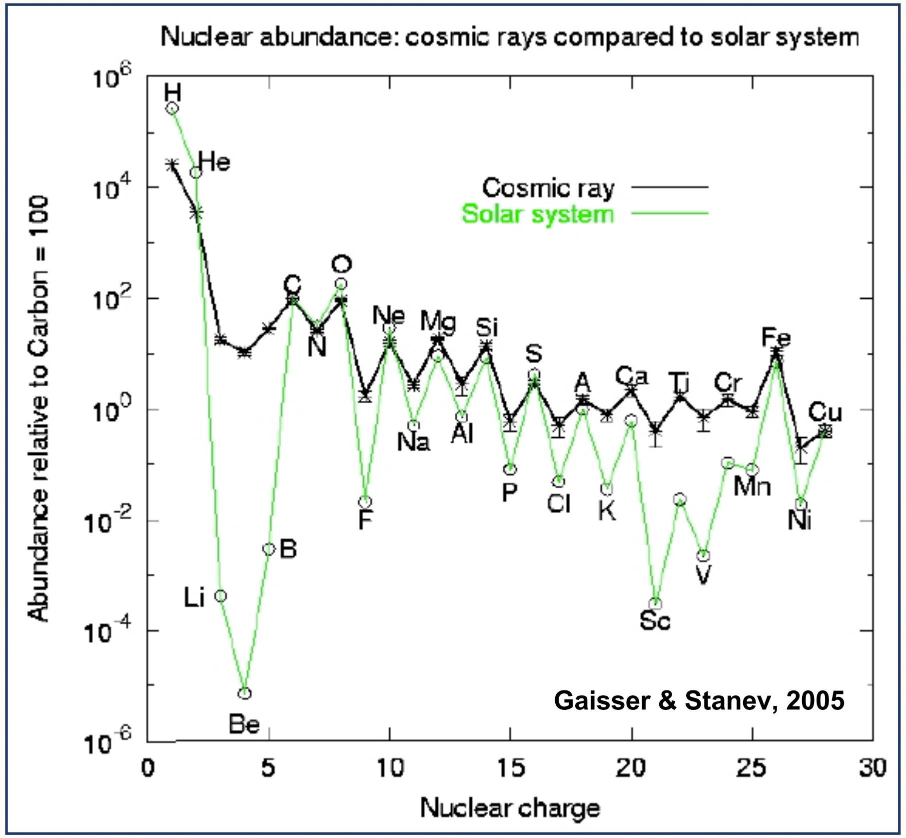




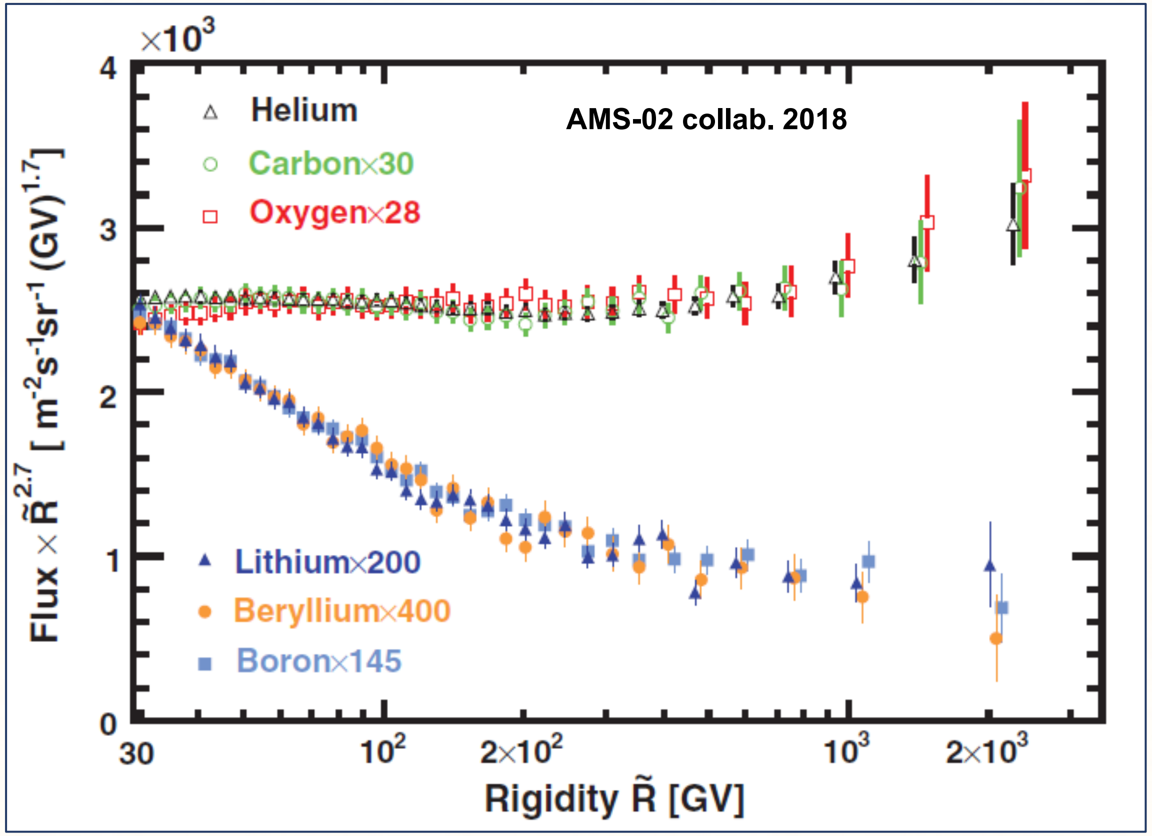
Limits are drawn for: 15 yr of AMS-02 operation and 35 days x 3 flights (LDB) for GAPS

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



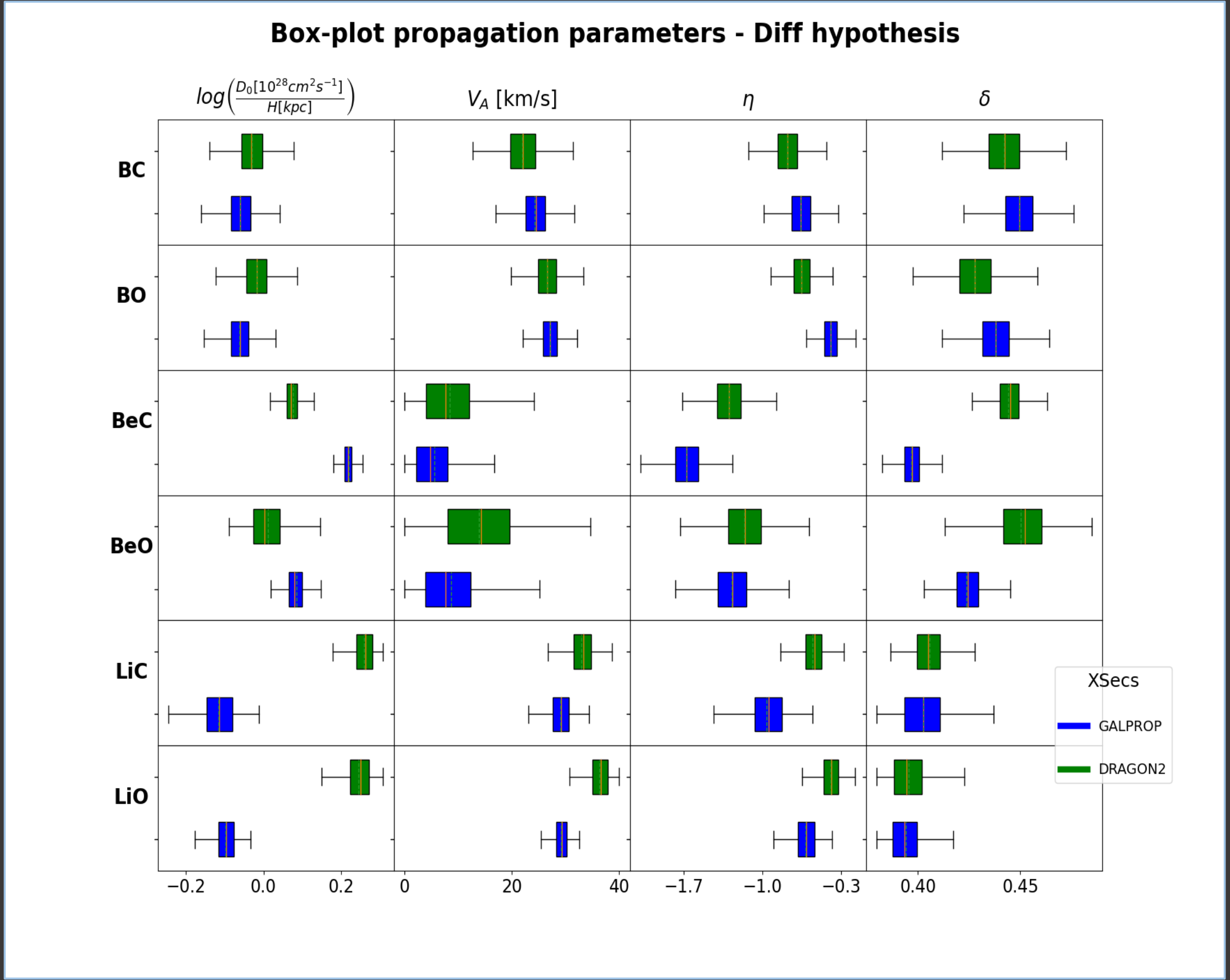
Determination of propagation parameters

Combined analyses are needed!

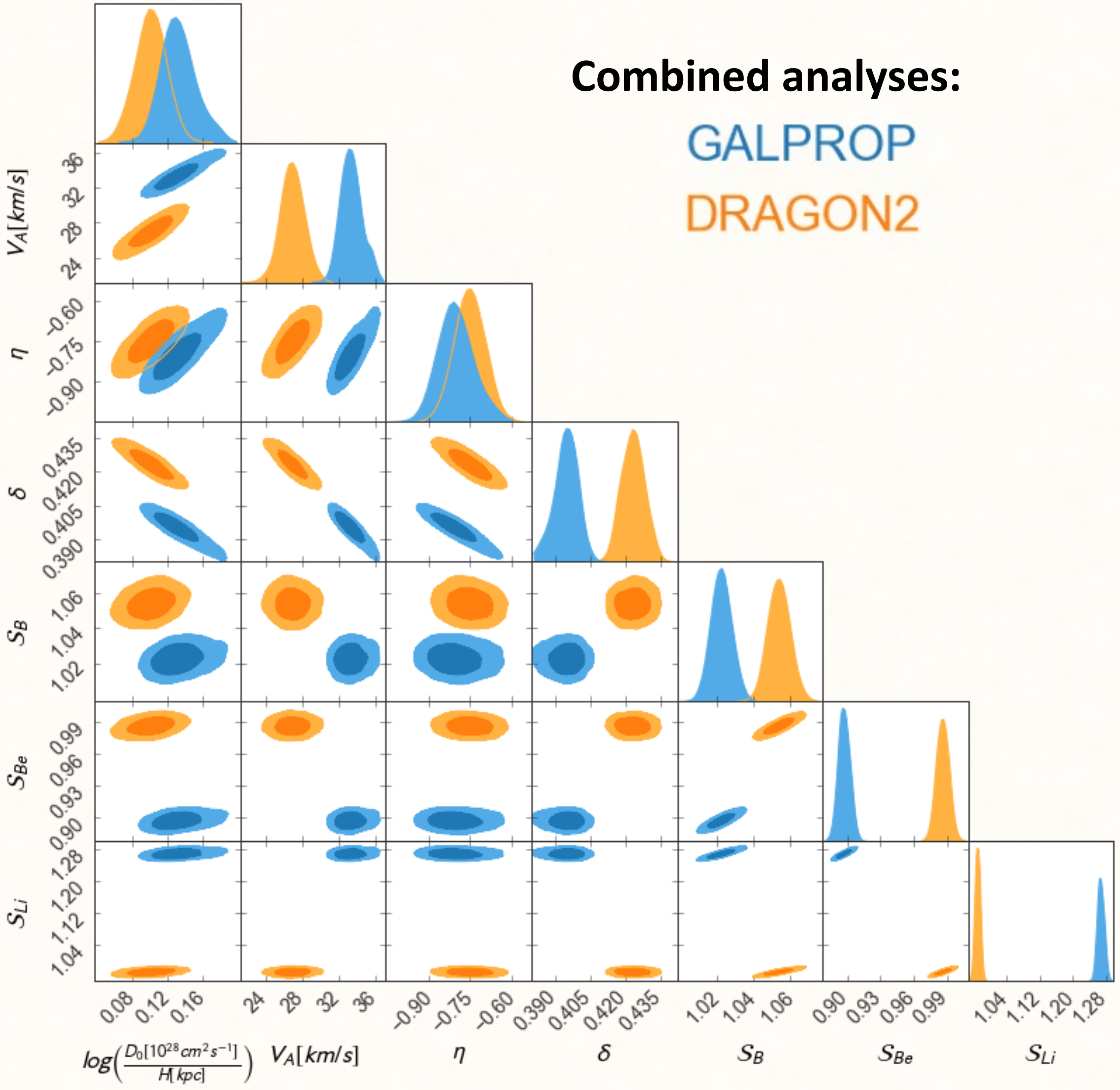
- Negative η values → Wave dissipation
- V_A compatible with ~ 20-30 km/s
- Large dispersion of δ: 0.39 – 0.46, (specially hard for Li ratios)

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

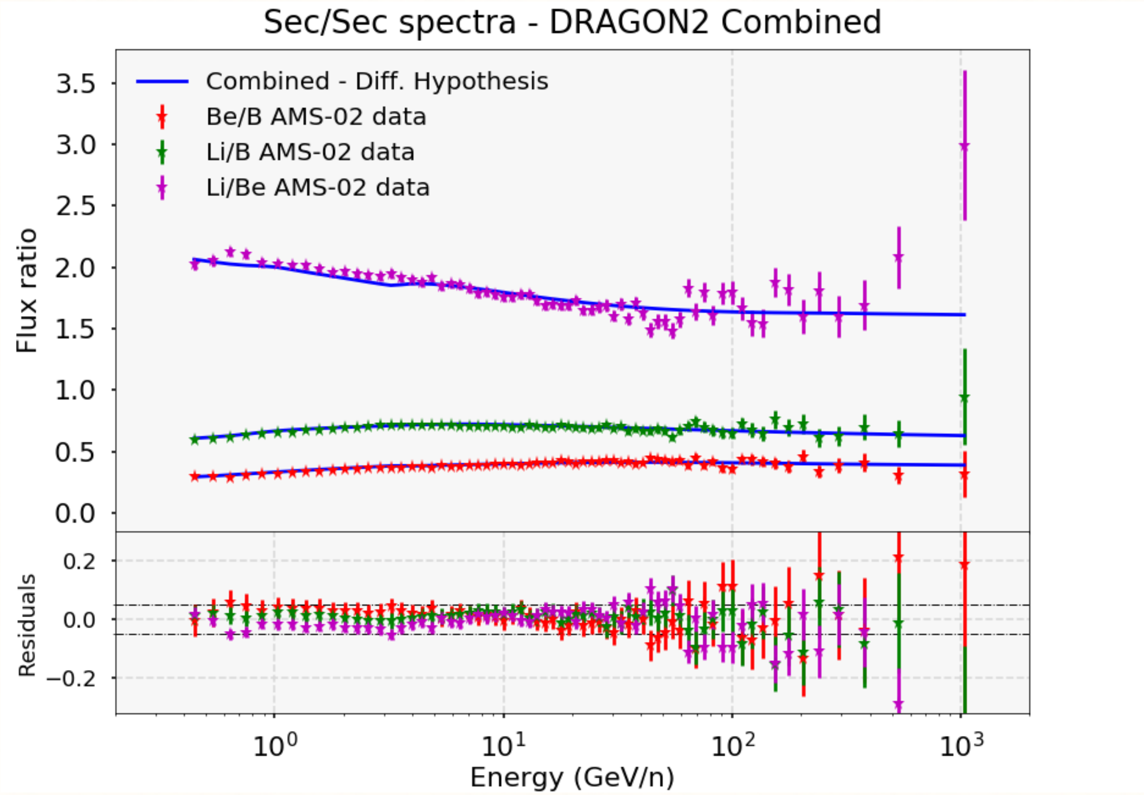


Combined analyses:

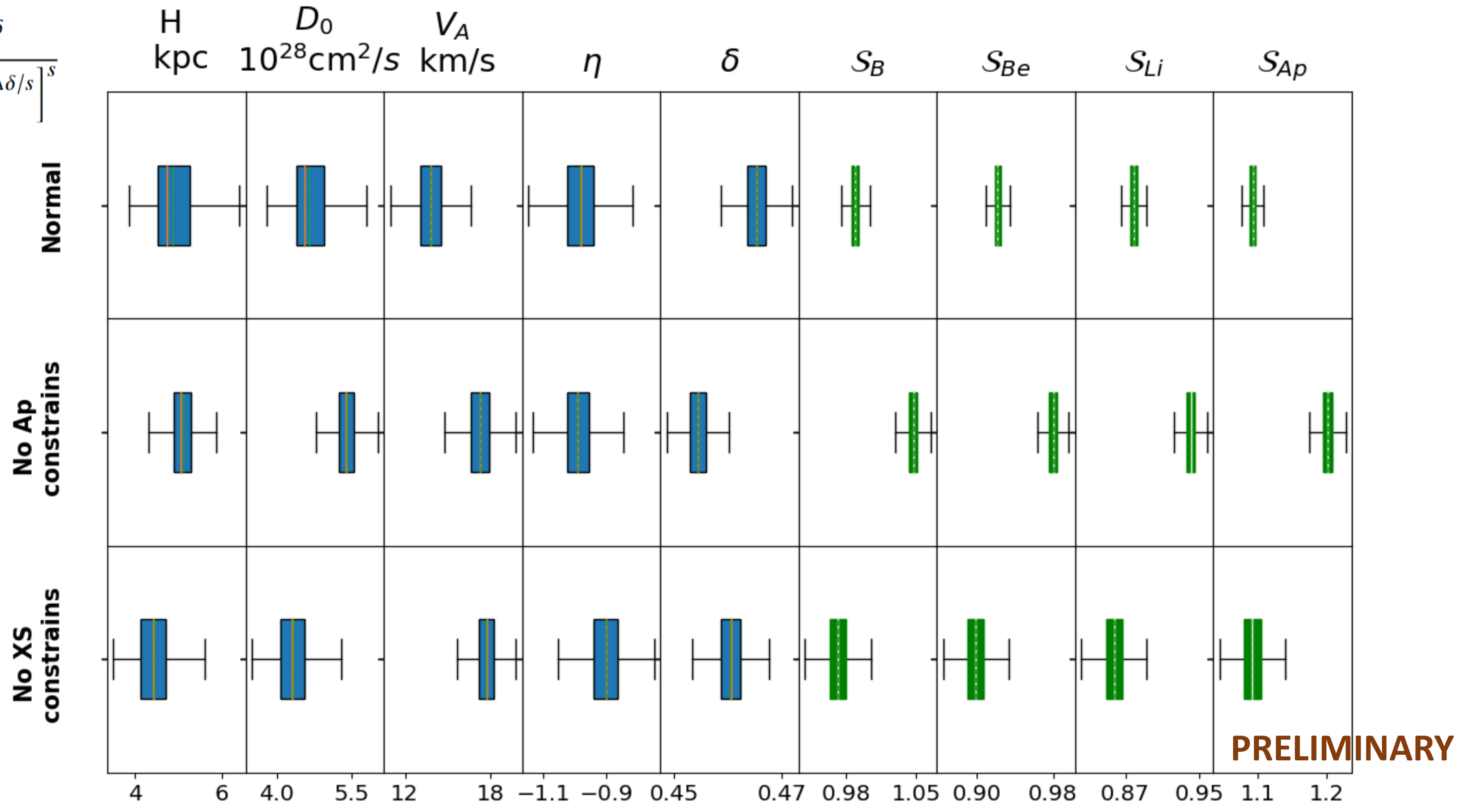
GALPROP

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)**



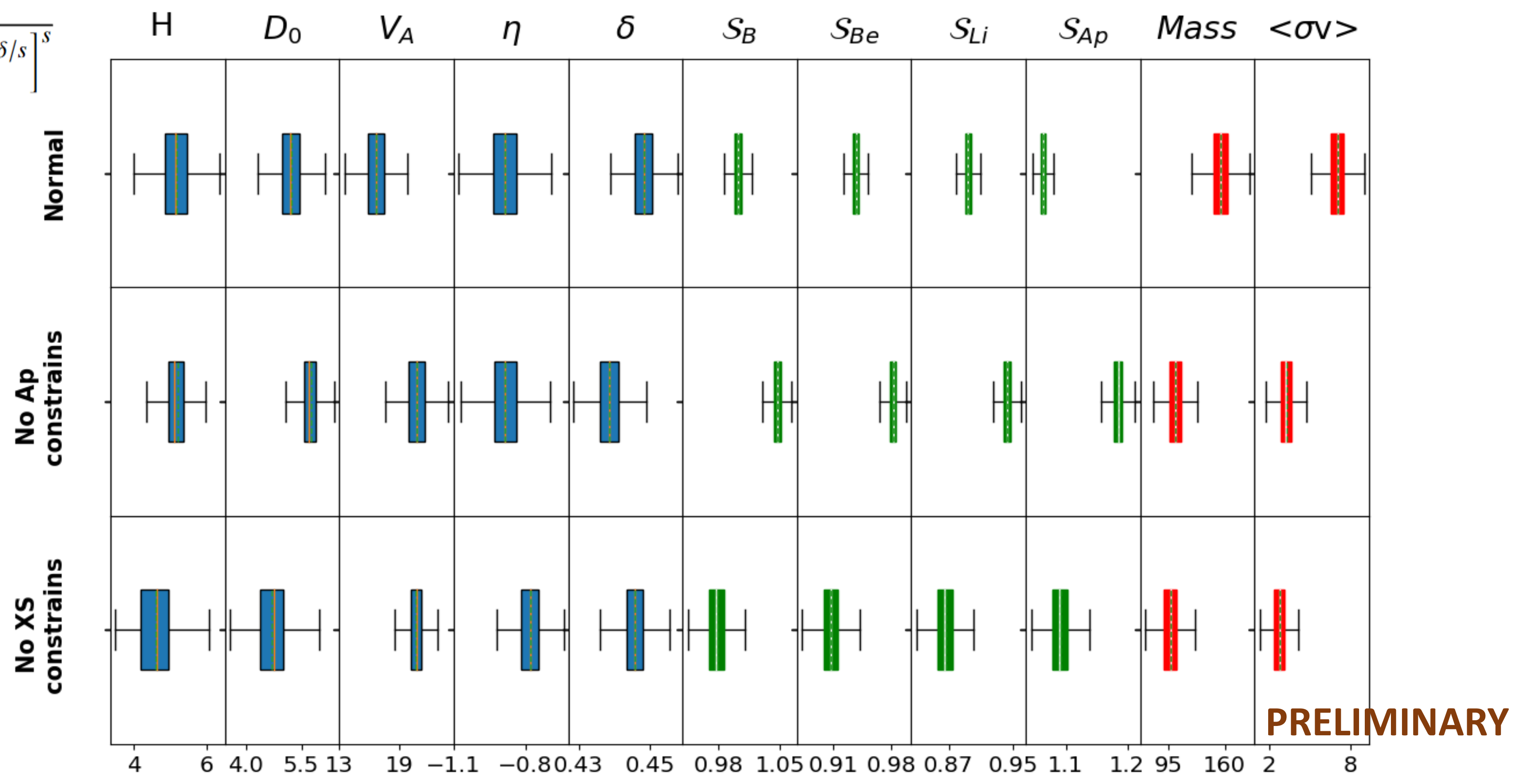
$$D(R) = D_0 \beta^{\eta} \frac{(R/R_0)^{\delta}}{\left[1 + (R/R_b)^{\Delta\delta/s}\right]^{s}}$$



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

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



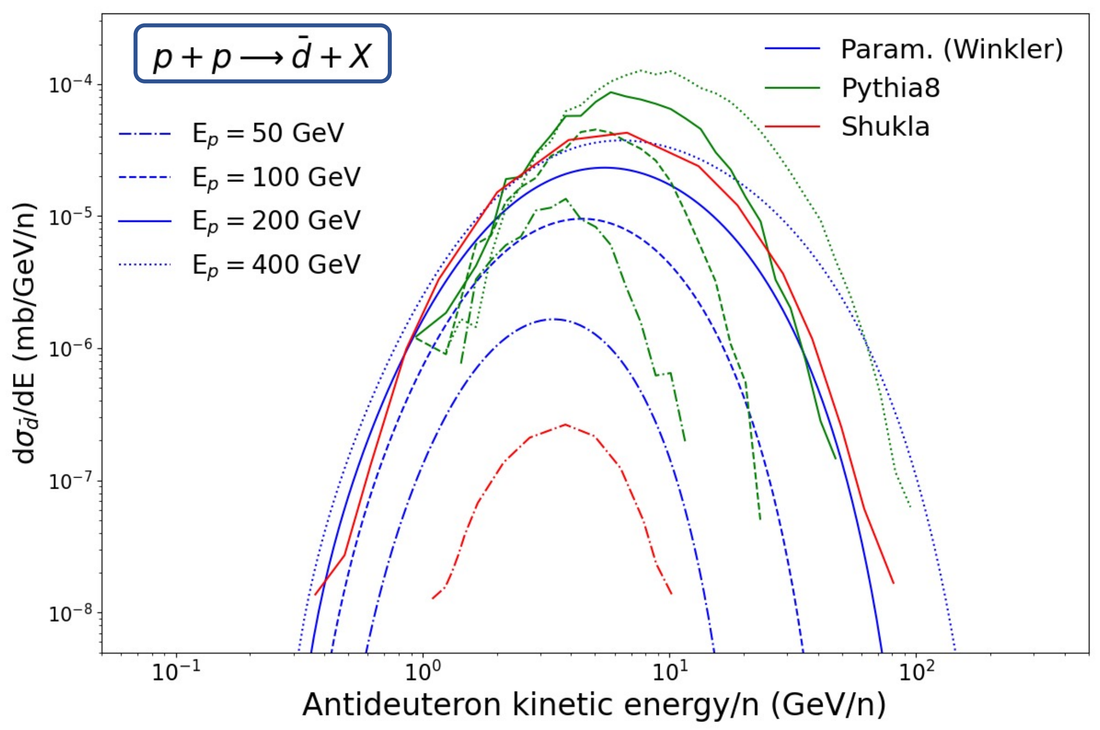
Propagation parameters are again very similar in every analysis and similar to the parameters found in the analyses without including dark matter component.

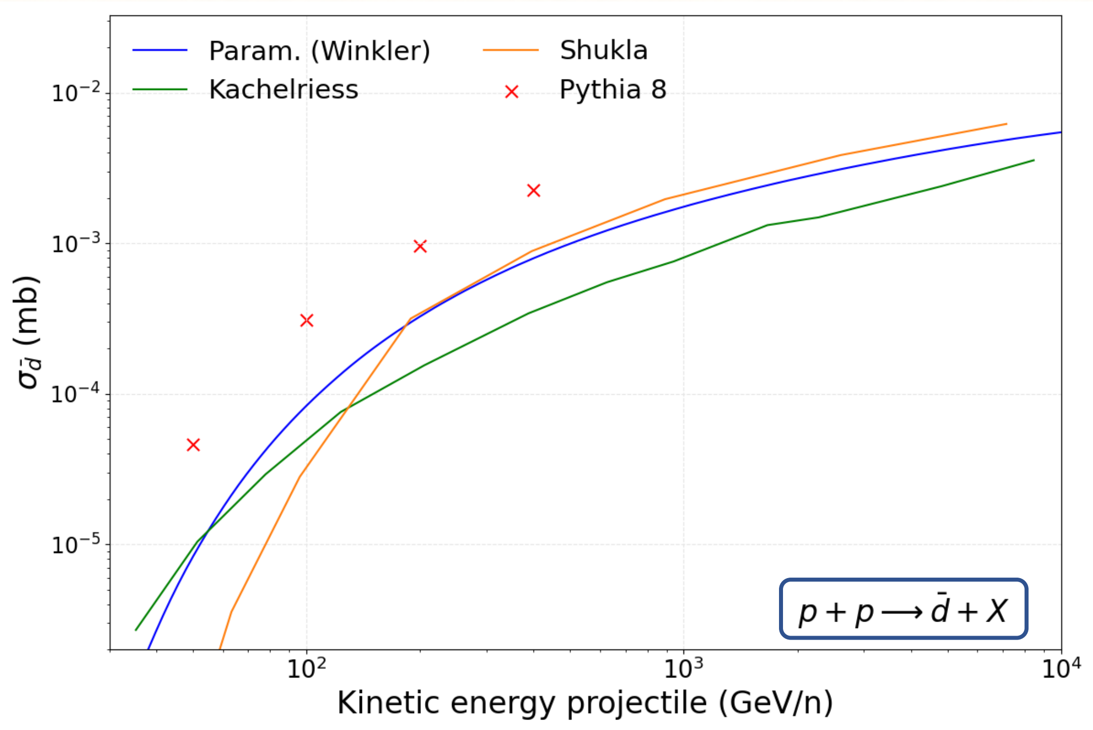
DM masses are slightly bigger than usually reported, due to the use of 2018 data-set

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

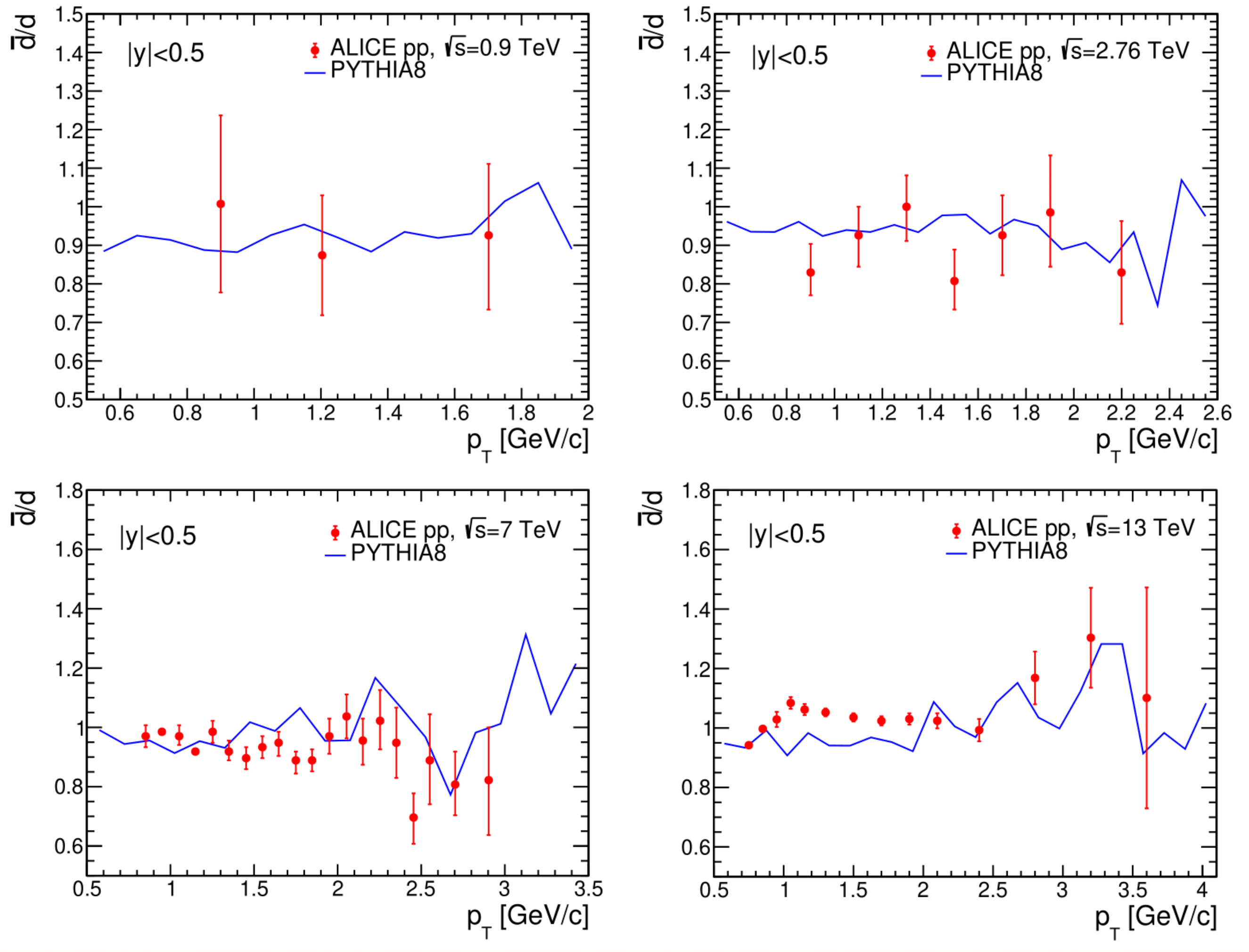
Implementation of anti-nuclei propagation in *DRAGON2*

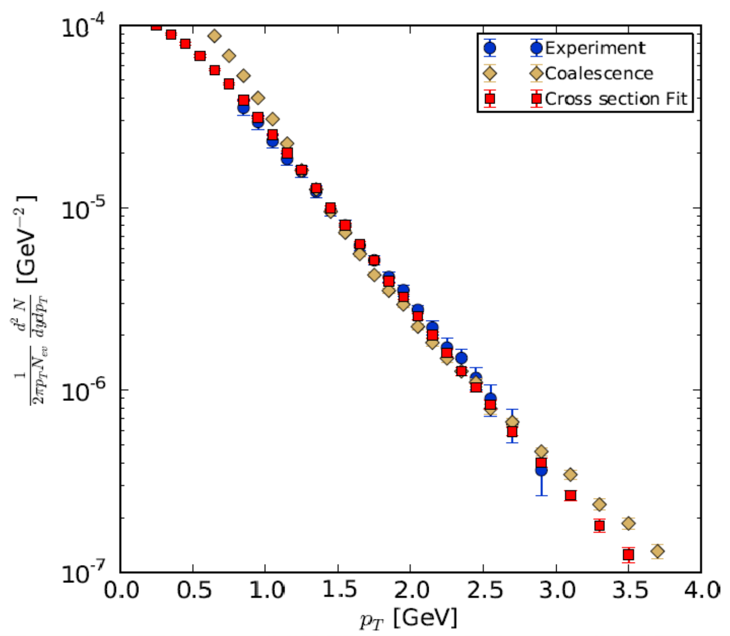
Cross sections of antinuclei production are being computed with Pythia8… in progress



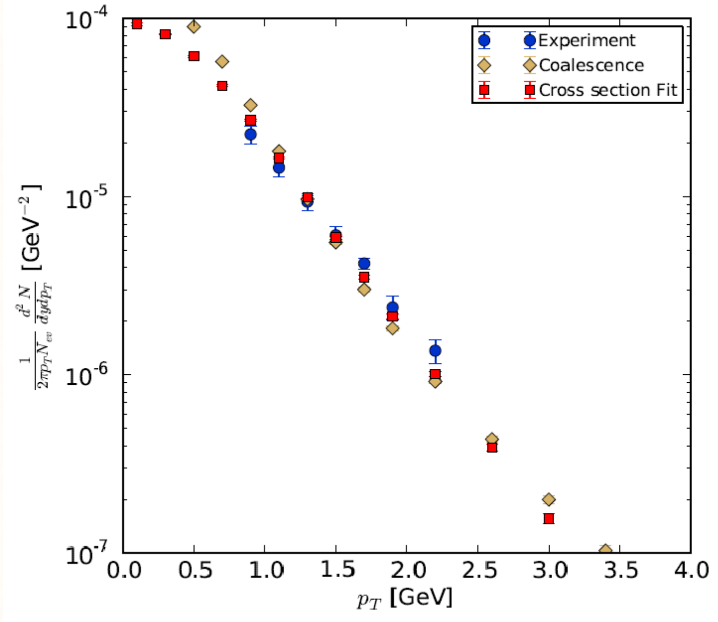


PYTHIA8 cross sections



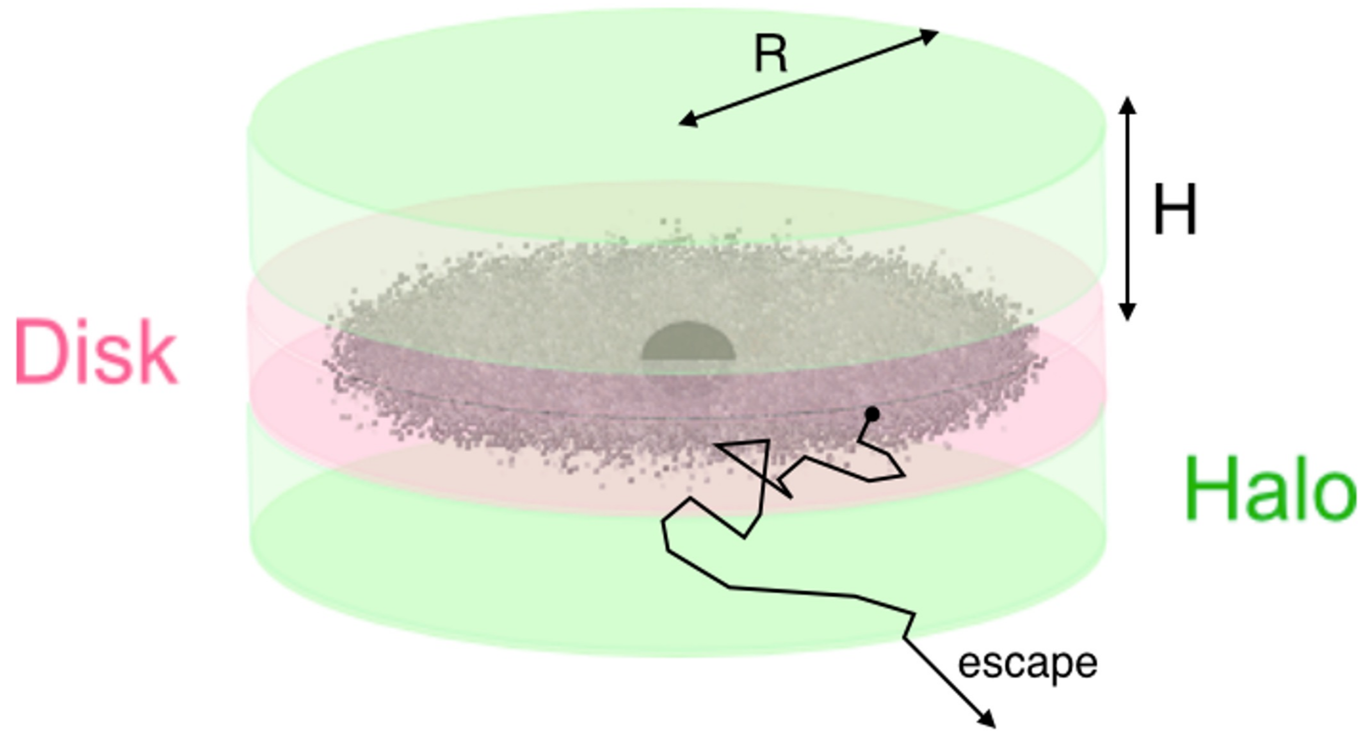


Dal and Raklev PRD 91, 123536



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

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

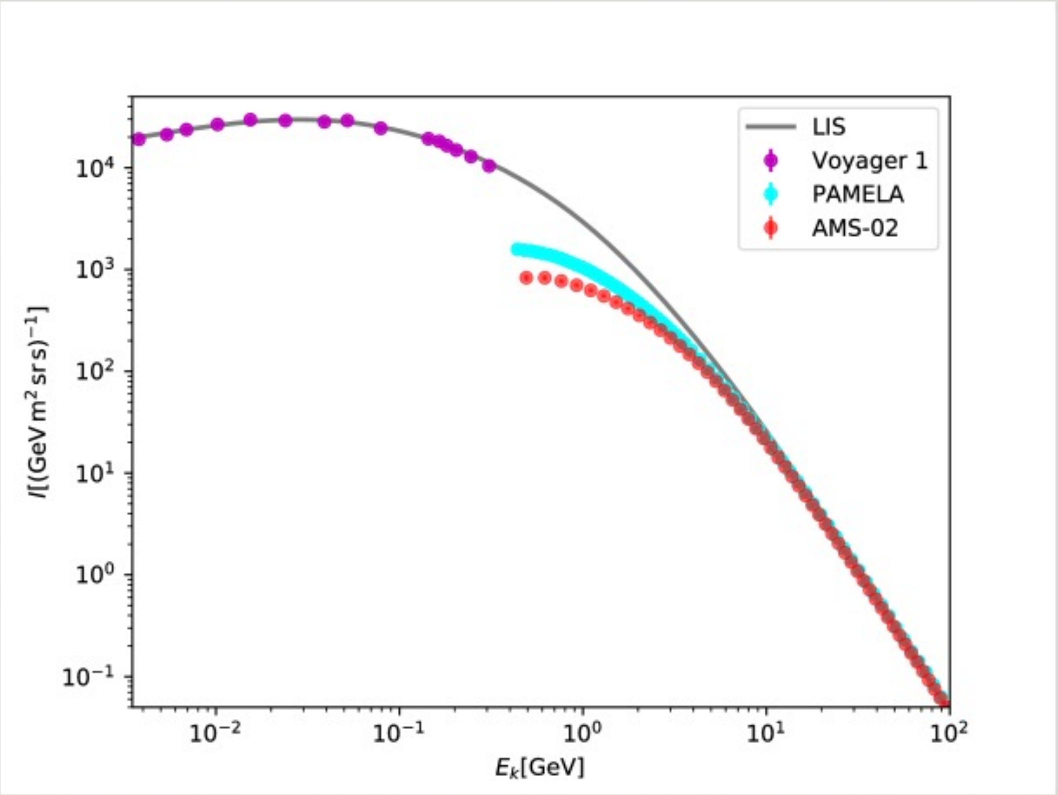
$$N_{sec} \propto Q_{sec}(E)/D(E)$$

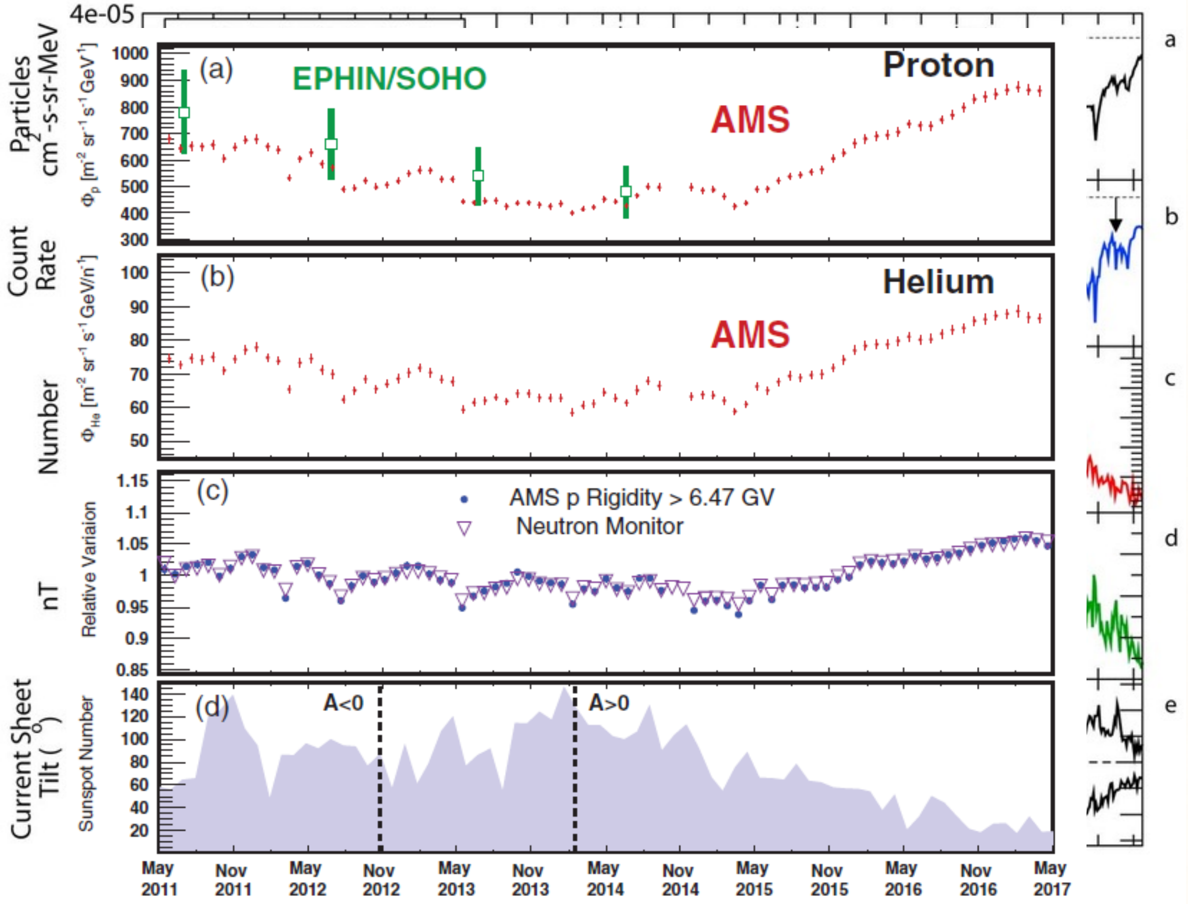
$$Q_{sec} \propto N_{pr}(E)\,\sigma(E)$$

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

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

Solar modulation

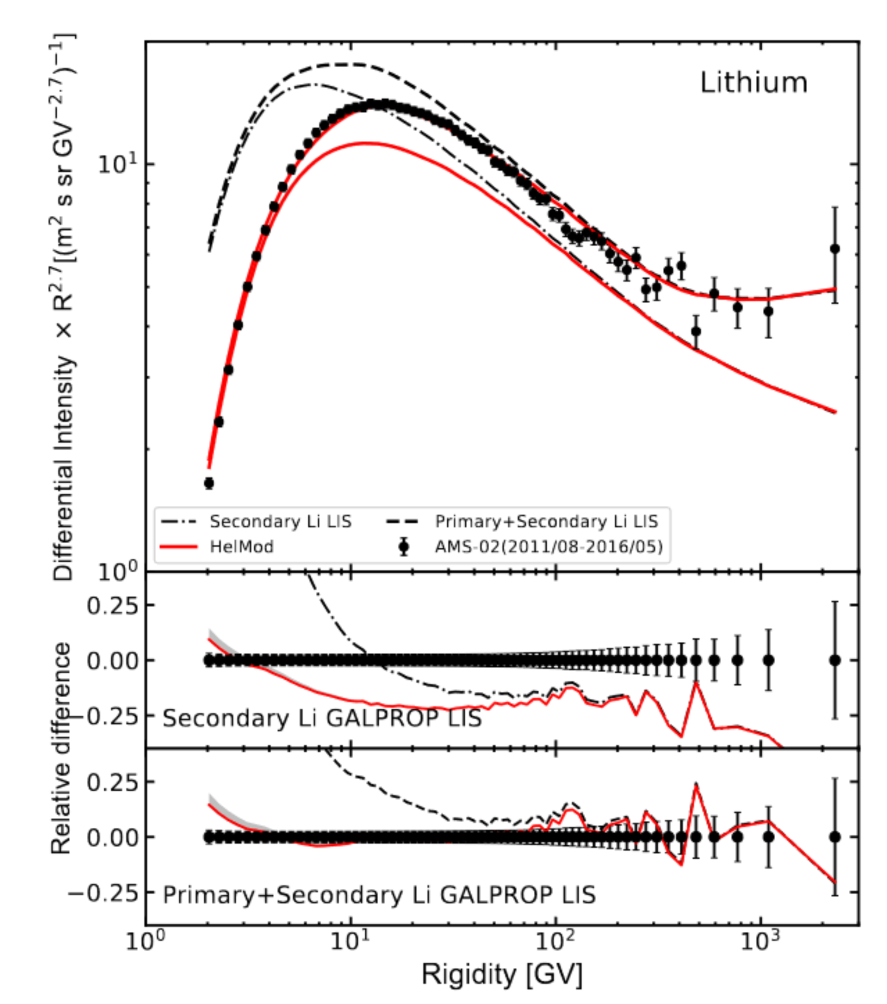




- ❖ Detailed heliospheric simulations or Force-Field approximation
- ❖ Neutron monitor experiments + Voyager-01 data

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

Extra contributions of secondary CRs?



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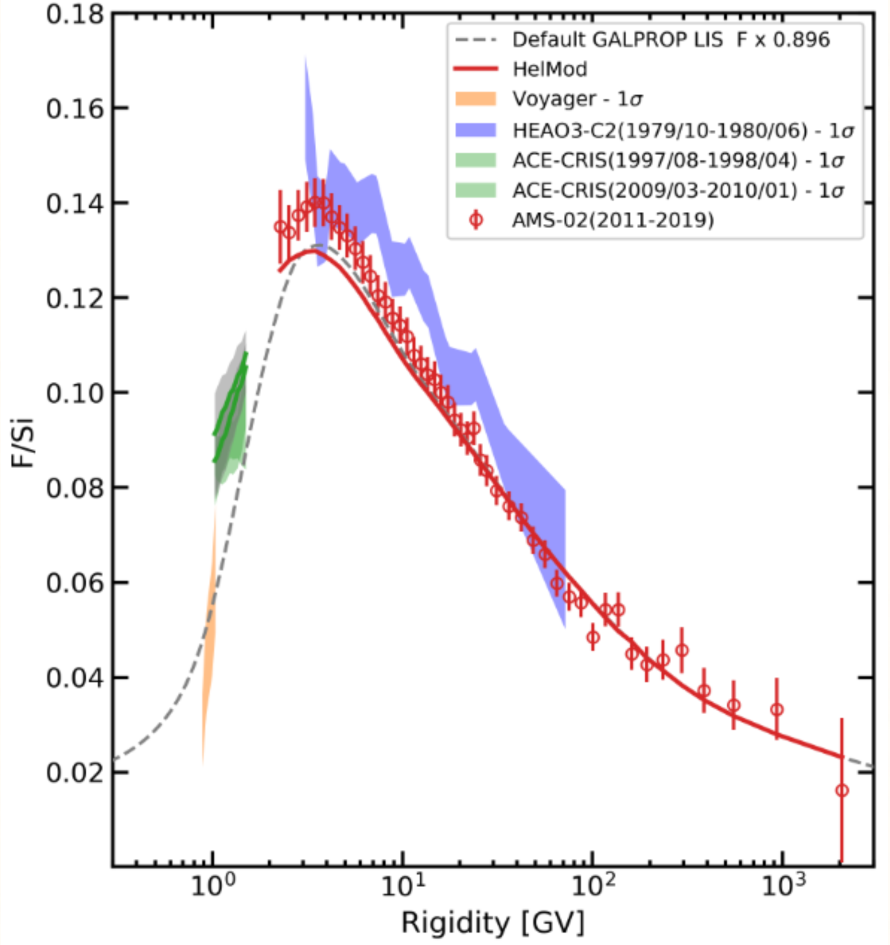
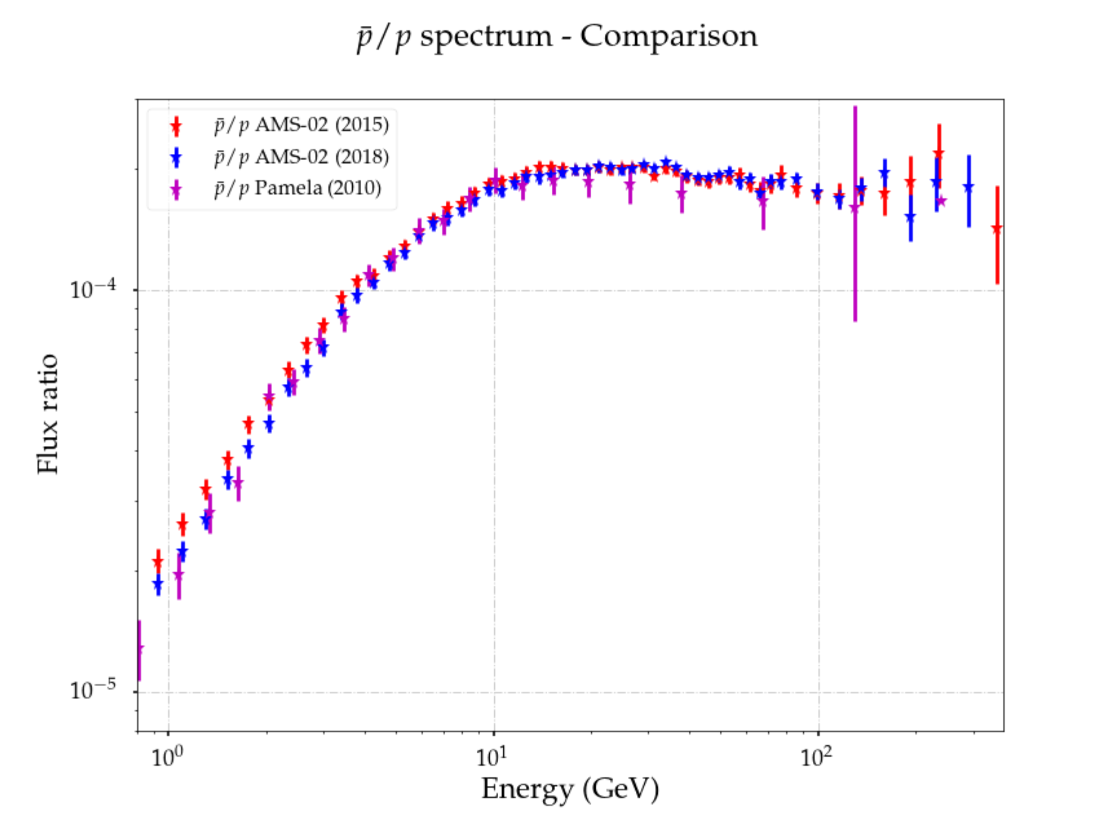
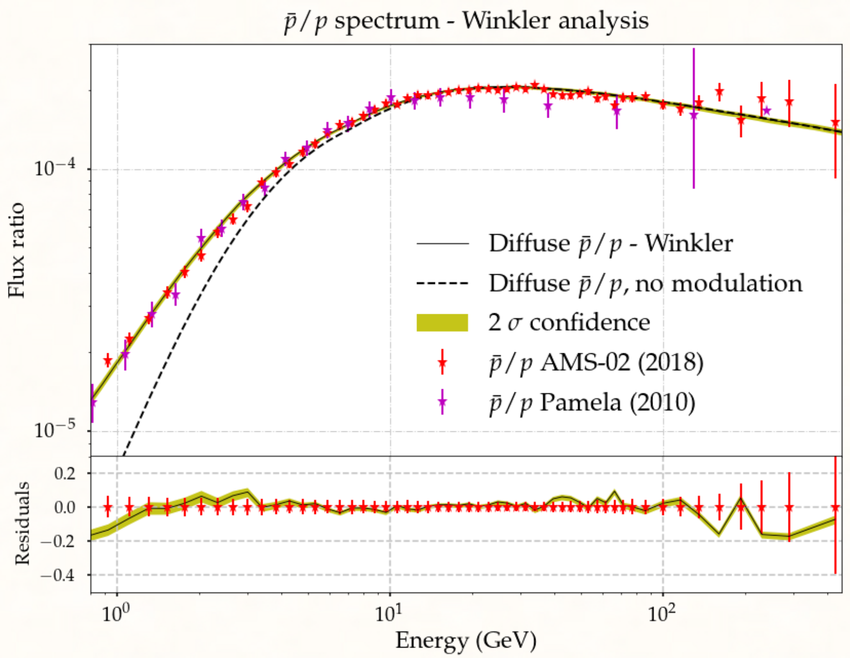
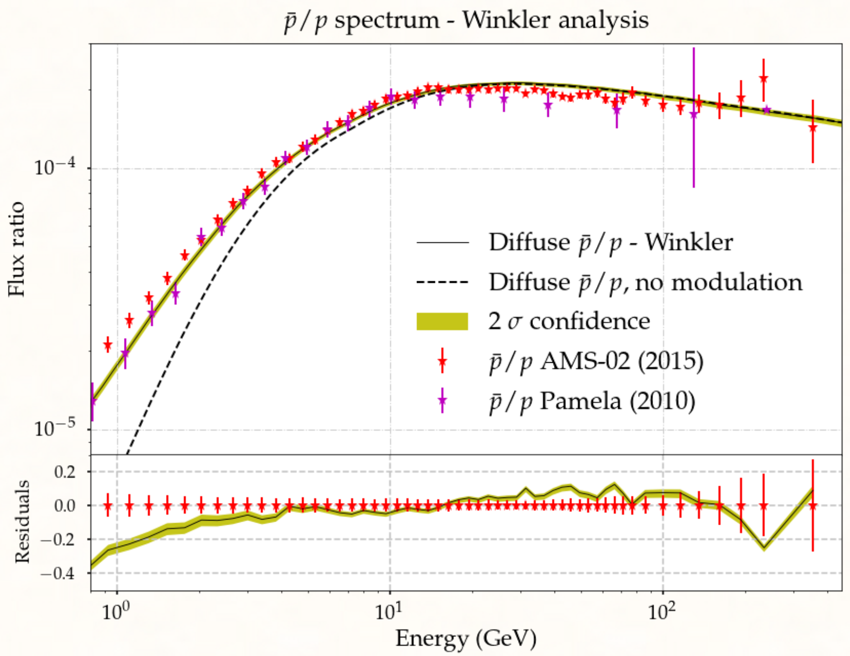




$\bar{p}/p$ spectrum - Comparison
$\bar{p}/p$ AMS-02 (2015)
$\bar{p}/p$ AMS-02 (2018)
$\bar{p}/p$ Pamela (2010)
Flux ratio
Energy (GeV)



$\bar{p}/p$ 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
Residuals
Energy (GeV)



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