UNCERTAINTIES IN THE ANTIPROTON FLUX PRODUCED FROM COSMIC-RAY INTERACTIONS

AND ITS IMPORTANCE FOR INDIRECT SEARCHES OF DM

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Outline

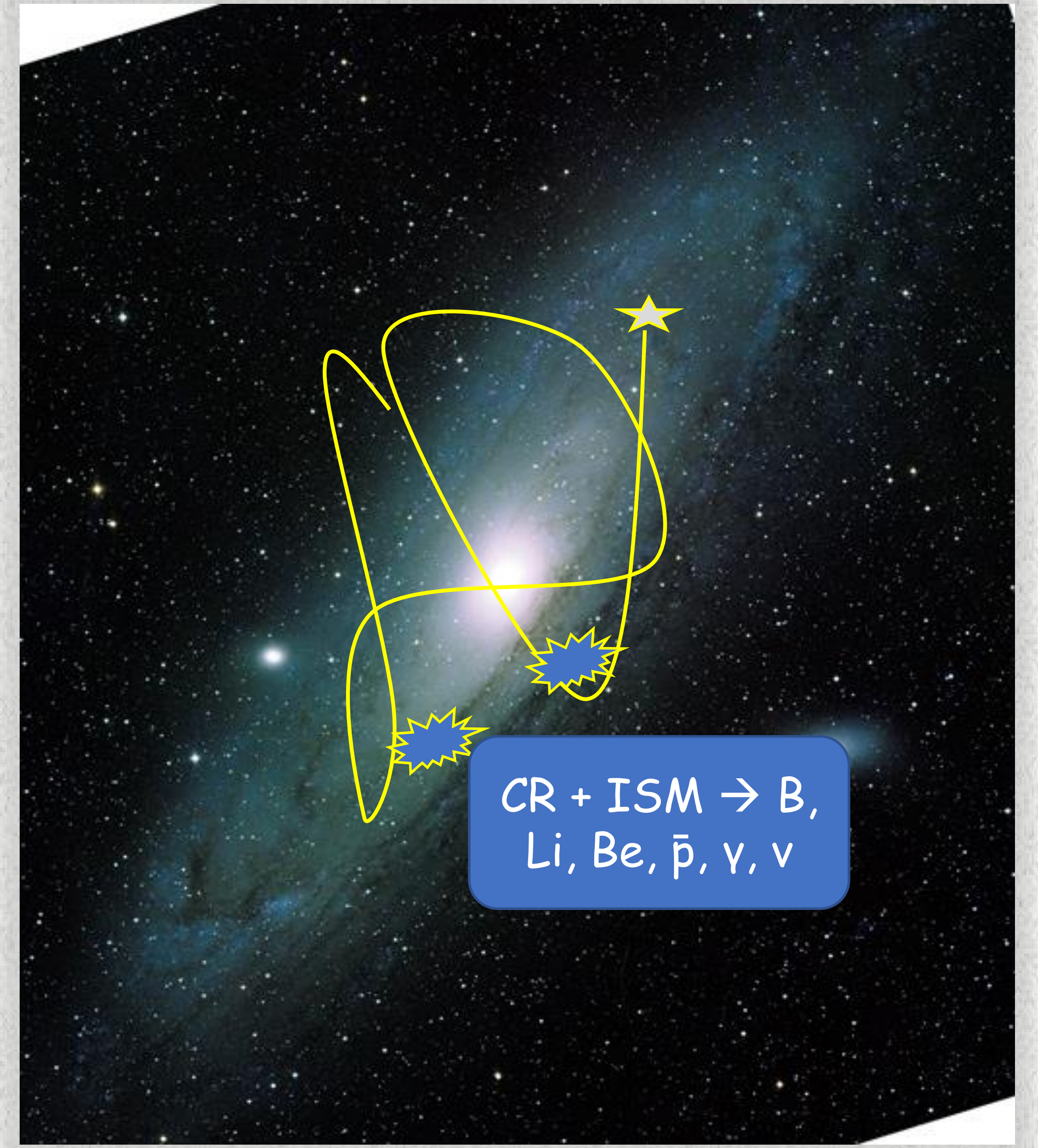
➢ **Propagation and generation of secondary particles**

➢ **Antiproton production**

- **Background of cosmic p̄**
- **Primary production hints?**

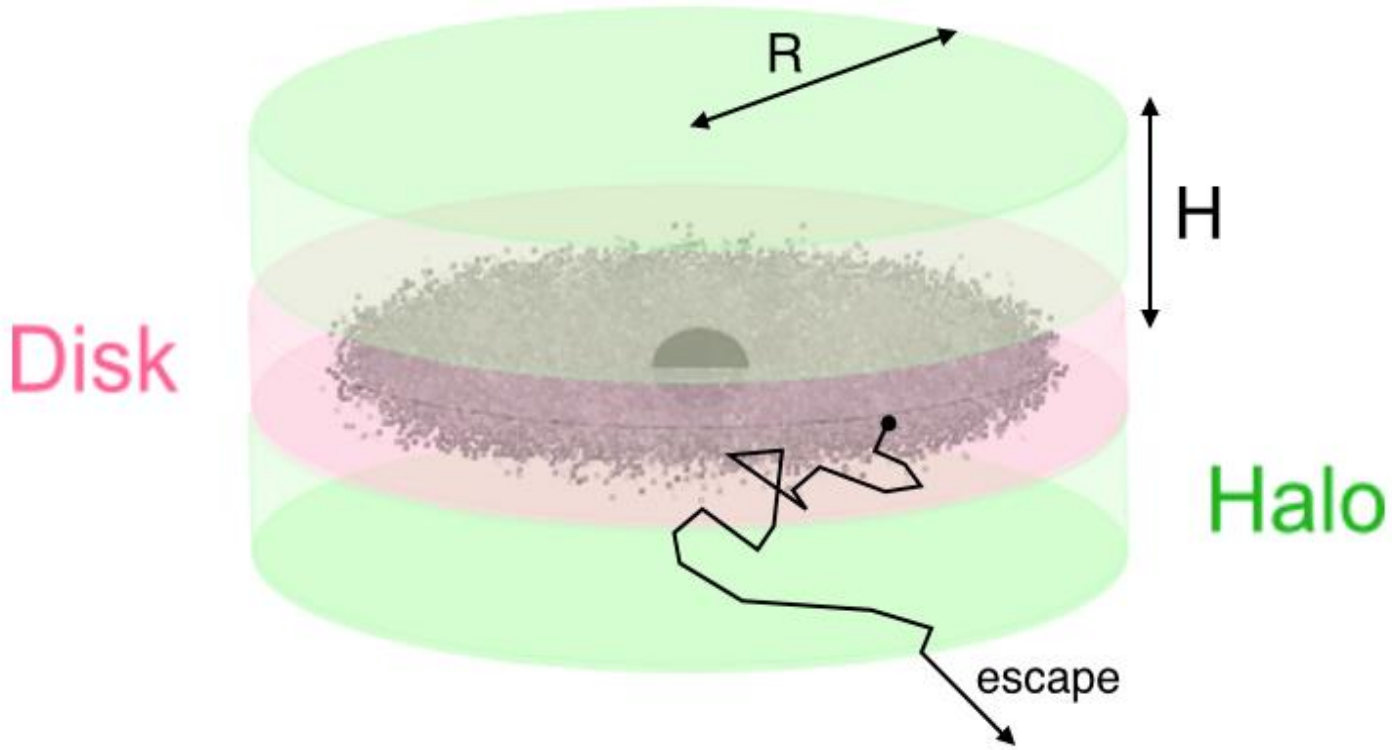
Full uncertainties associated to CR production of antiprotons

Is there any hint of exotic sources of antiproton production?



Diffusive transport of Galactic cosmic rays

❖ The basic idea is that primary particles are accelerated in astrophysical sources (namely SNRs) and propagate throughout the Galaxy, occasionally interacting with gas, mainly in the disc of the Galaxy, and there they produce secondary nuclei through spallation.



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

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

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

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

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

Markov-chain Monte Carlo analysis

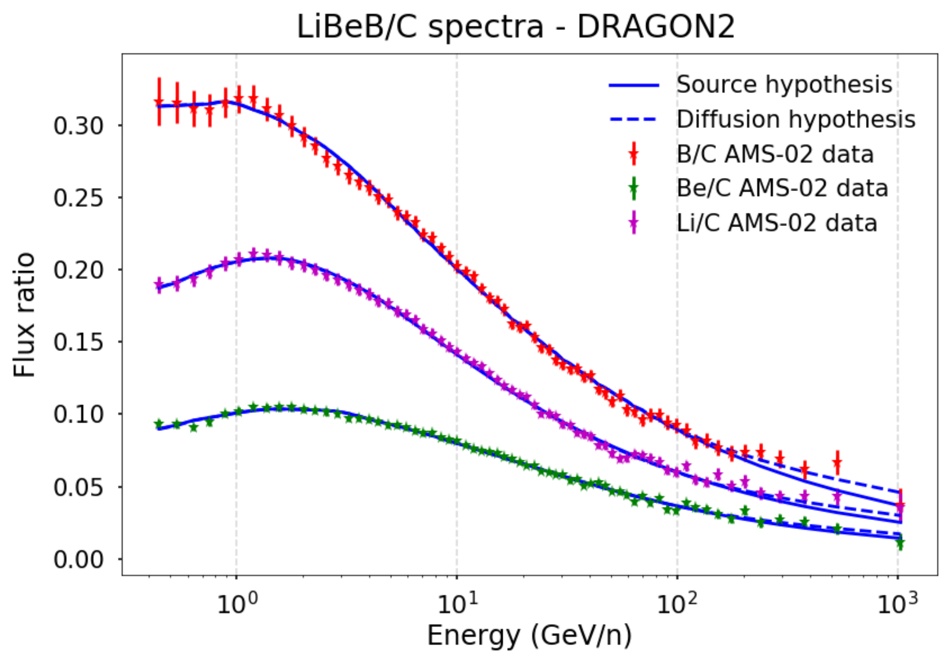
Solved with the *DRAGON* code with cross sections option *DRAGON2* and *Winkler*
https://github.com/cosmicrays/DRAGON2-Beta_version

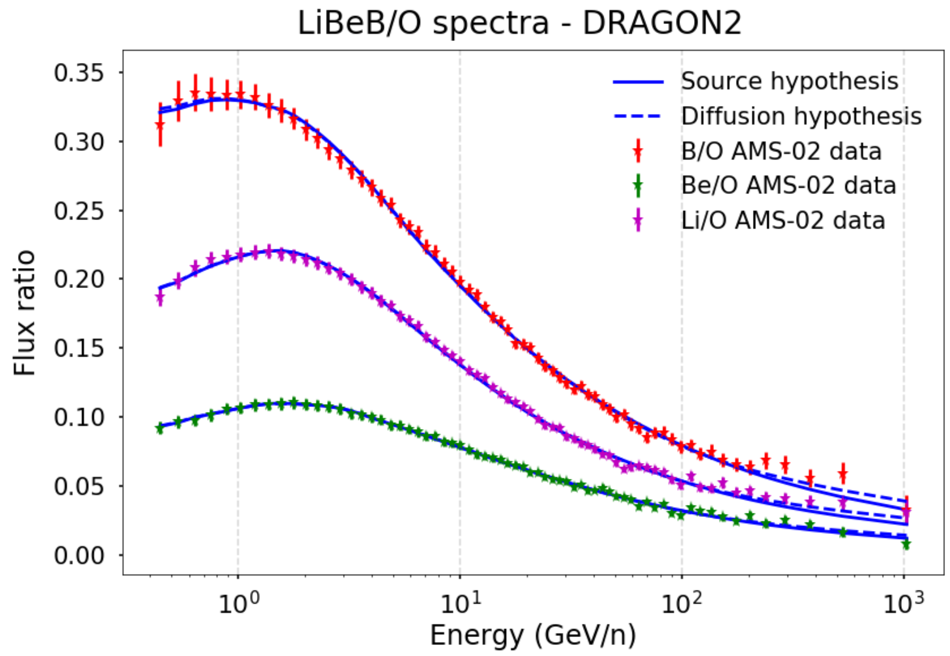
- Two different diffusion coefficients tested:

$$D = D_0 \beta^\eta \left(\frac{R}{R_0}\right)^\delta \qquad \textbf{Source hypothesis}$$

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

- Systematic uncertainties in the parametrization of D are small in the region from 1 to 200 GeV





Markov-chain Monte Carlo analysis

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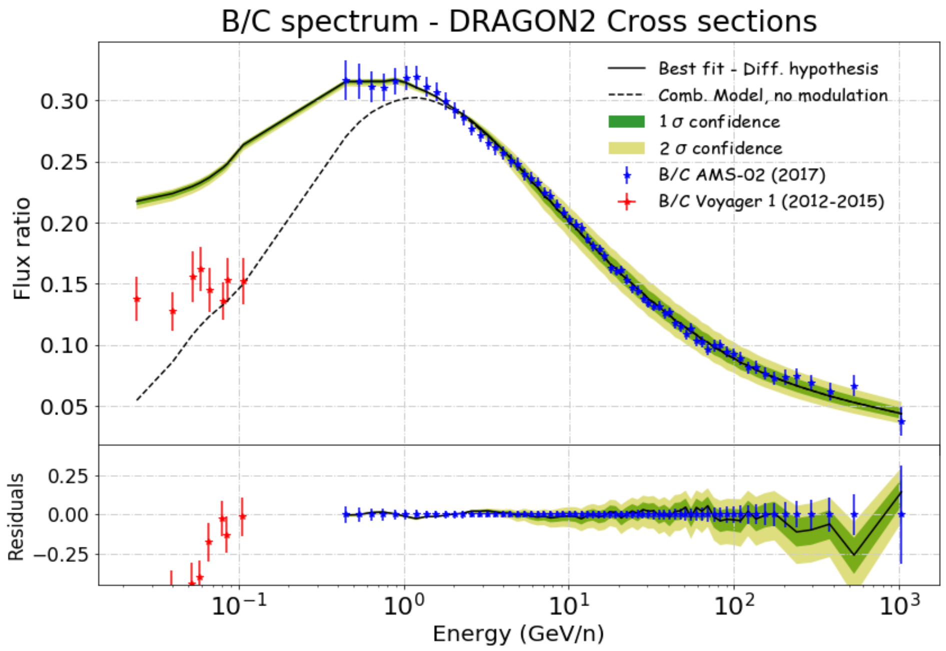
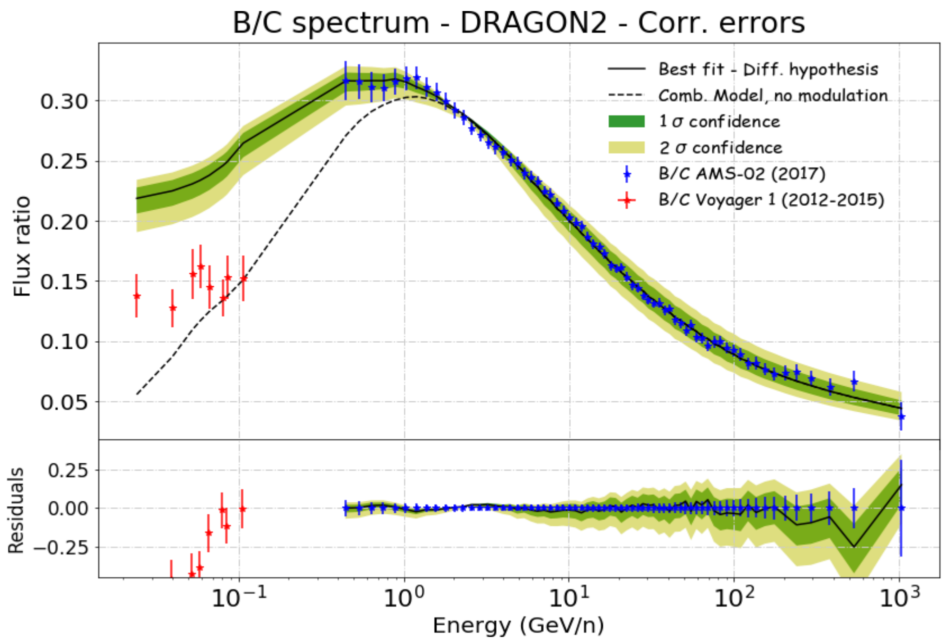
https://github.com/cosmicrays/DRAGON2-Beta_version

- Precision of AMS-02 data ~2-5%
- No public release of errors correlation
- Estimate of the covariance matrix from **Heisig, korsmeier, Winkler (2020)**. arXiv:2005.04237v2
- Systematic uncertainties from the experiment become progressively more important at very low and very high energies

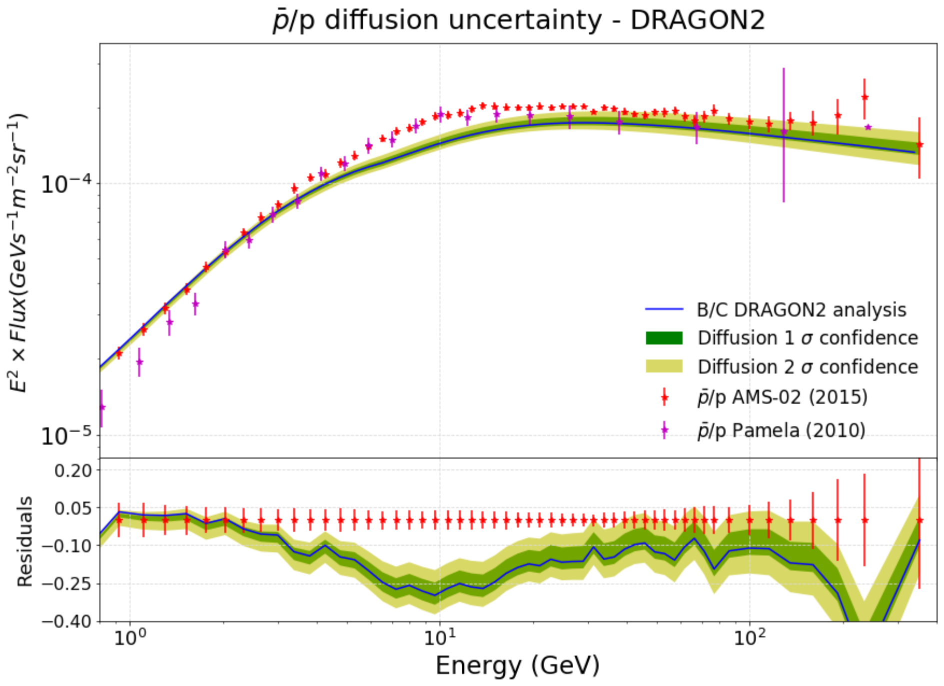


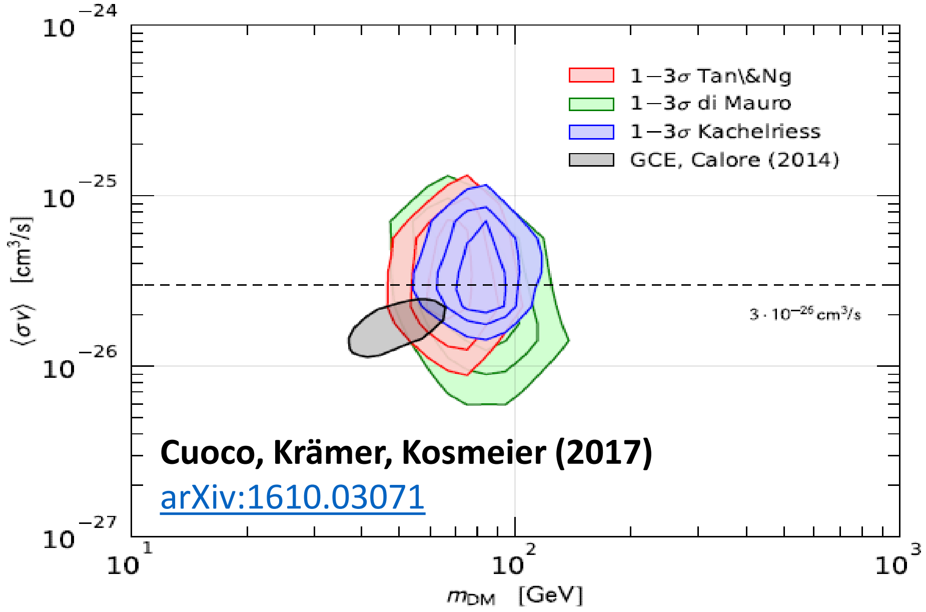


ANTIPROTON PREDICTIONS

Secondary production from CR interactions

$$q_{\mathrm{CR+ISM}\to\bar{p}}(T_{\bar{p}}) = \int_0^\infty dT 4\pi n_{\mathrm{ISM}} \Phi_{\mathrm{CR}}(T) \frac{d\sigma_{\mathrm{CR+ISM}\to\bar{p}}}{dT_{\bar{p}}}(T, T_{\bar{p}})$$





Cuoco, Krämer, Kosmeier (2017)
arXiv:1610.03071

Primary production from Dark matter?

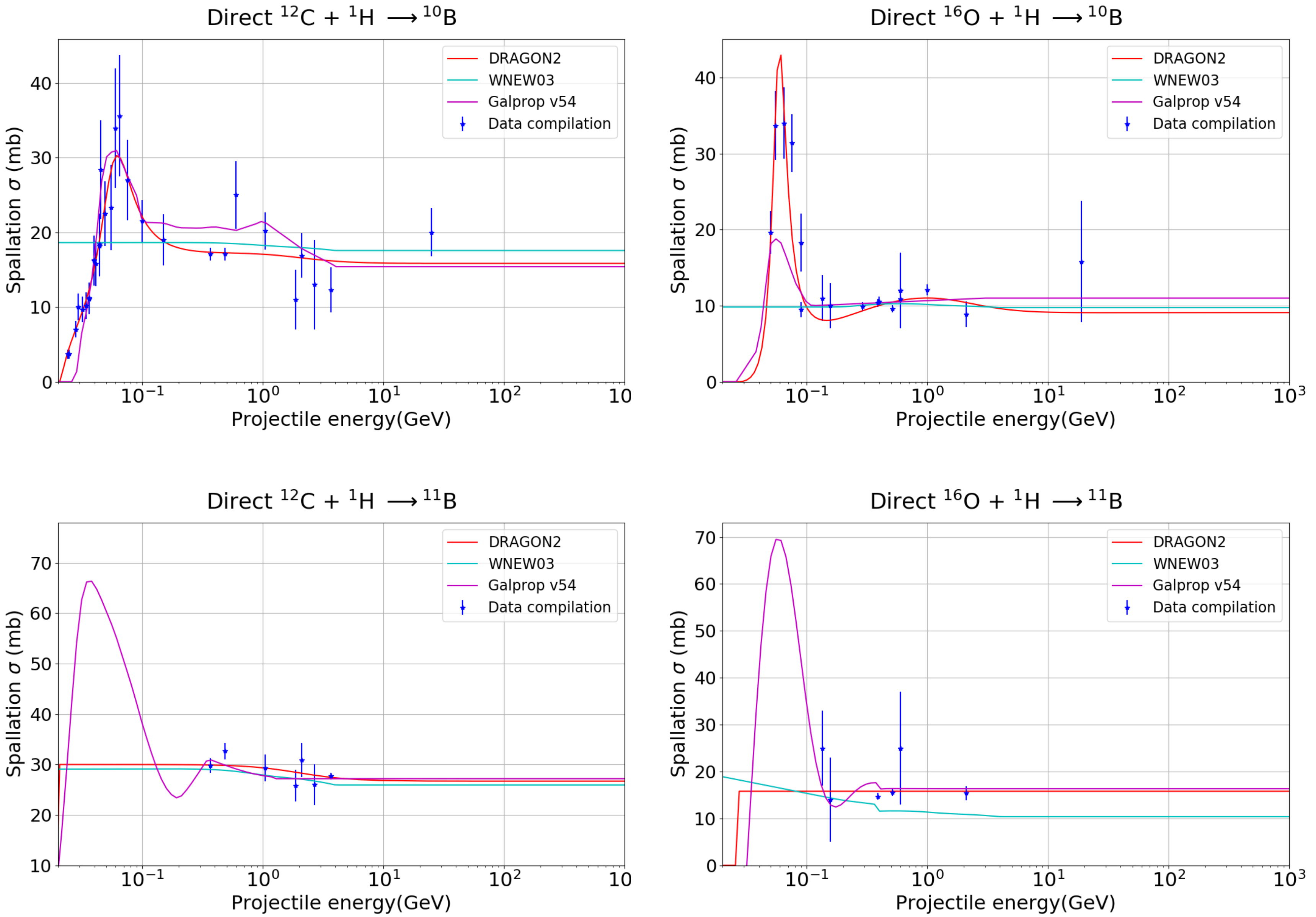
$$q_{\bar{p}}^{(\mathrm{DM})}(\boldsymbol{x}, T) = \frac{1}{2}\left(\frac{\rho(\boldsymbol{x})}{m_{\mathrm{DM}}}\right)^2 \sum_f \langle \sigma v \rangle_f \frac{\mathrm{d}N_{\bar{p}}^f}{\mathrm{d}T}$$

B production cross sections

Important lack of data

Average uncertainties of data ~ 22%

Parametrizations based on these data and are extrapolated for channels with no existent data



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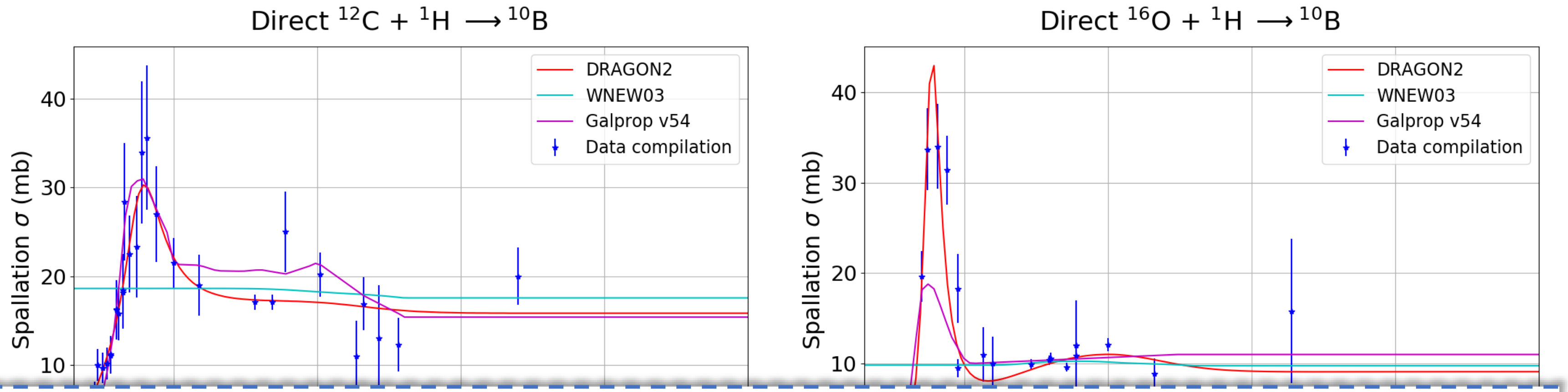


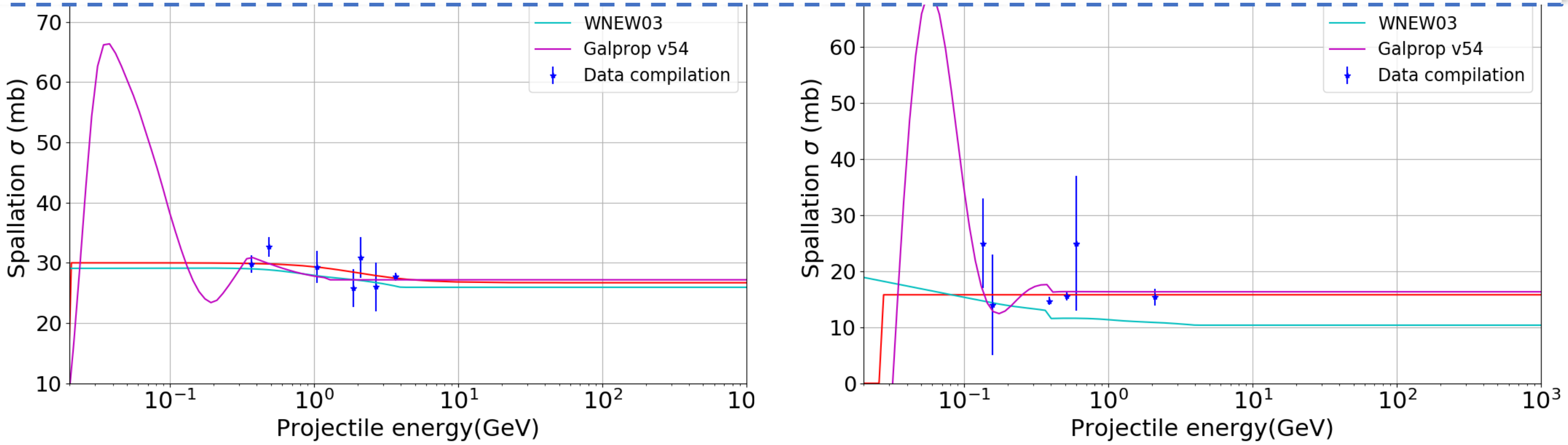
Important la

Average unc
of data ~ 22%

High uncertainties in XSecs → High uncertainties in the secondary CRs

$$Q_{sec}(E) \propto \sum^{pr} J_{pr}(E)\, \sigma_{pr \rightarrow sec}(E)$$

Parametrizations based on these data and are extrapolated for channels with no existent data

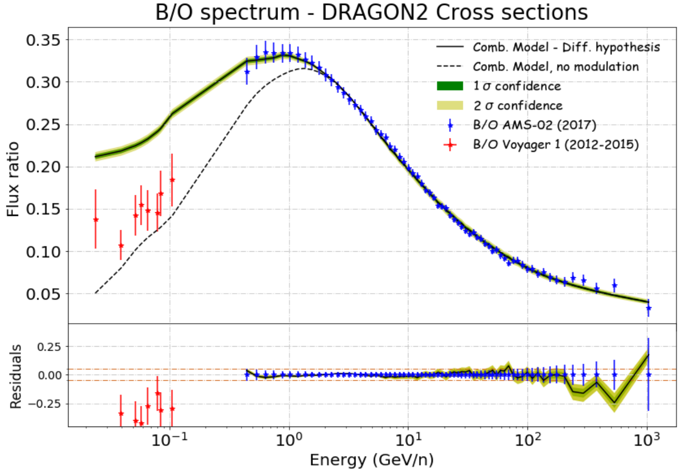


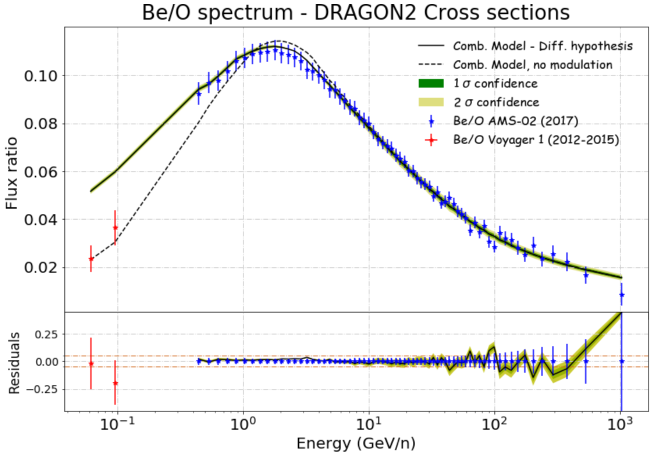
COMBINED ANALYSIS

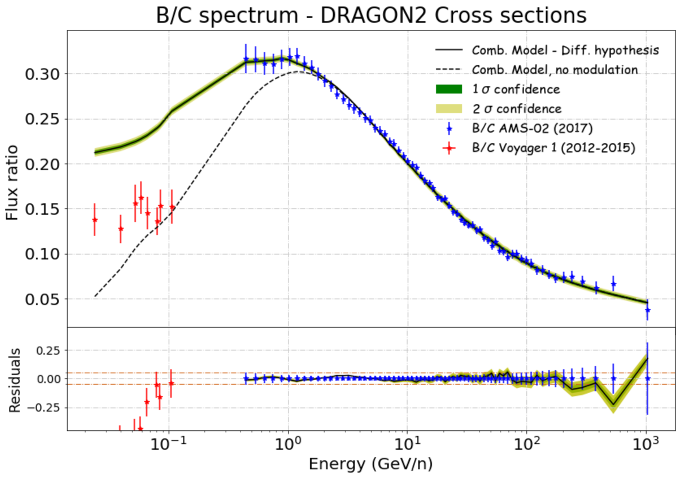
B/O, B/C, Be/C, Be/O, p̄/p
+ **scaling factors** for the XS parametrization

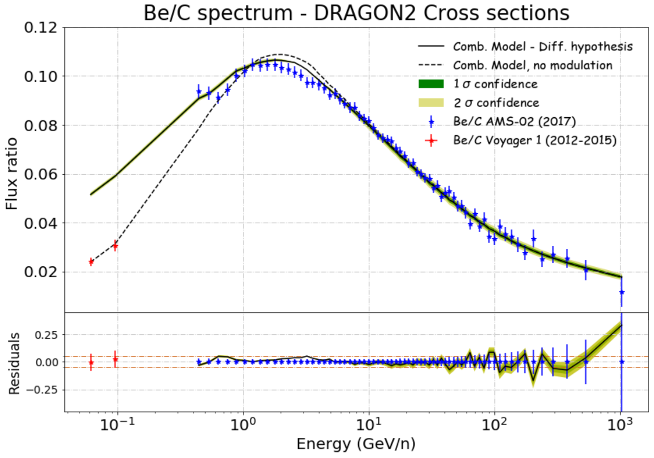
$$\frac{J_k}{J_j}(E) \propto \frac{\sum^{\alpha\to k} J_\alpha(E)\sigma_{\alpha\to k}(E)}{\sum^{\alpha\to j} J_\alpha(E)\sigma_{\alpha\to j}(E)} \xrightarrow{\text{high energies}} \sim \frac{\sum^{\alpha\to k} C_\alpha E^{-\gamma_\alpha}\sigma_{\alpha\to k}(E)}{\sum^{\alpha\to j} C_\alpha E^{-\gamma_\alpha}\sigma_{\alpha\to j}(E)}$$

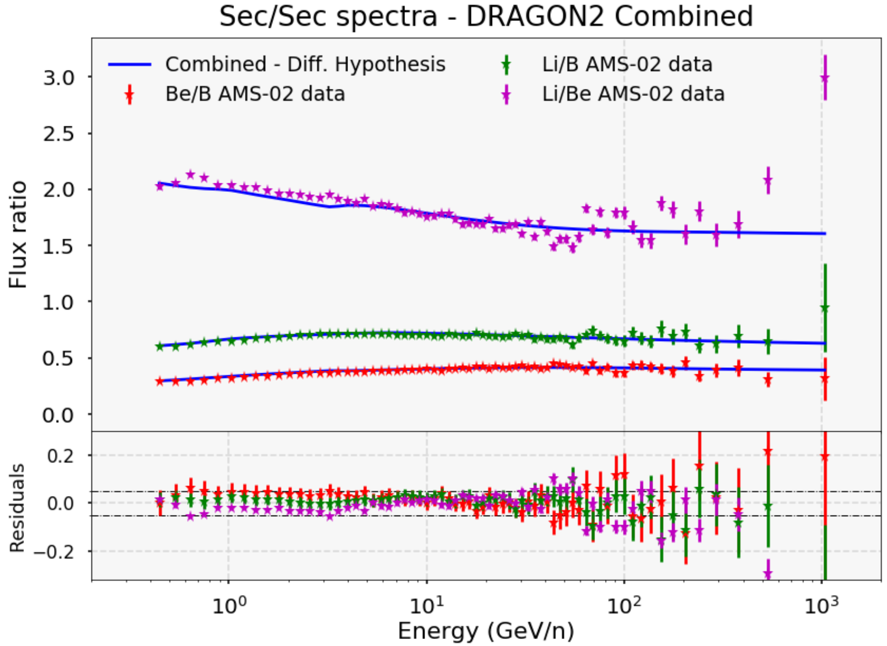
PRELIMINARY











Scaling factors are mainly dependent on the **secondary-over-secondary ratios**

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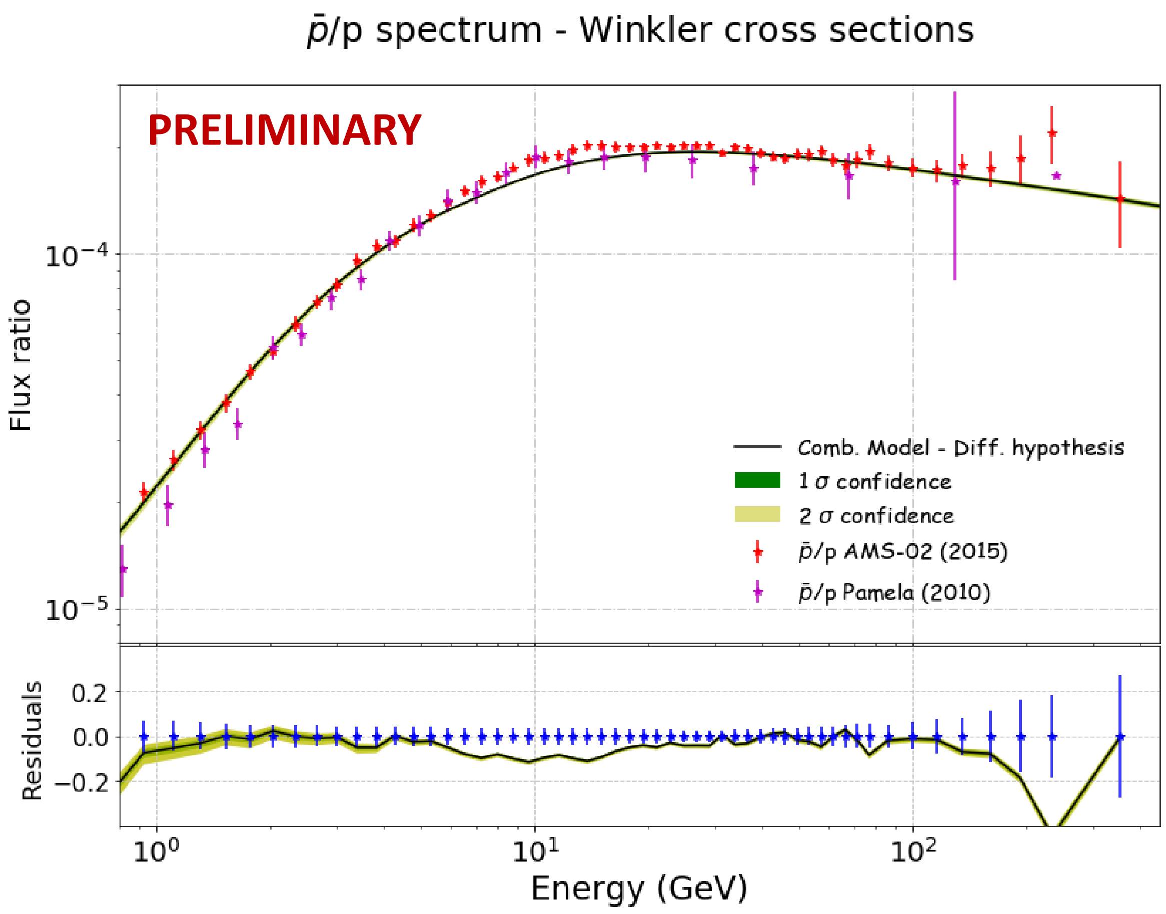
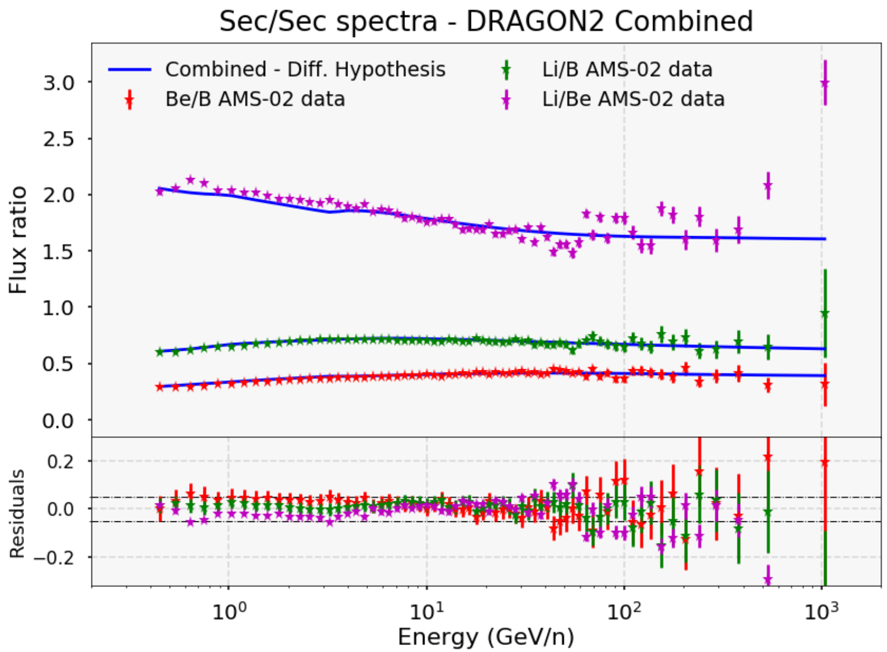




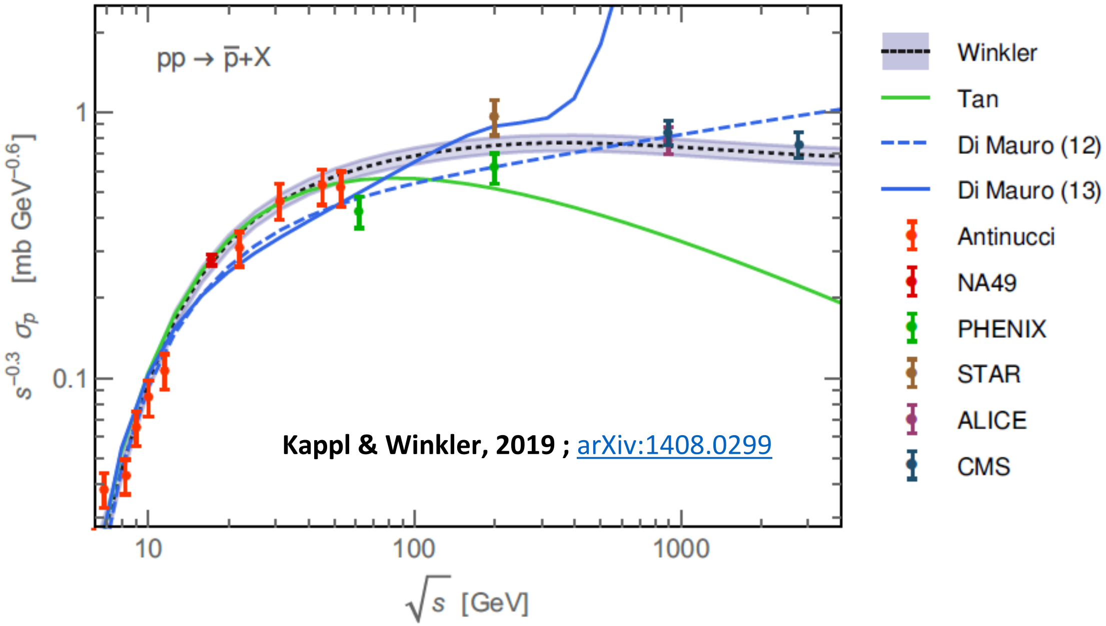
Scaling factors are mainly dependent on the **secondary-over-secondary ratios**

ANTIPROTON XSECS

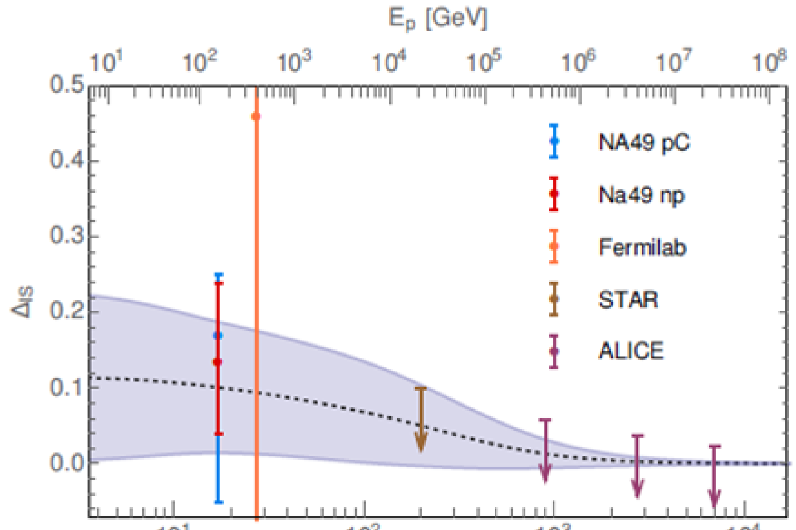
$$p + p \longrightarrow \{\bar{n} \longrightarrow \bar{p}\} + X$$

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

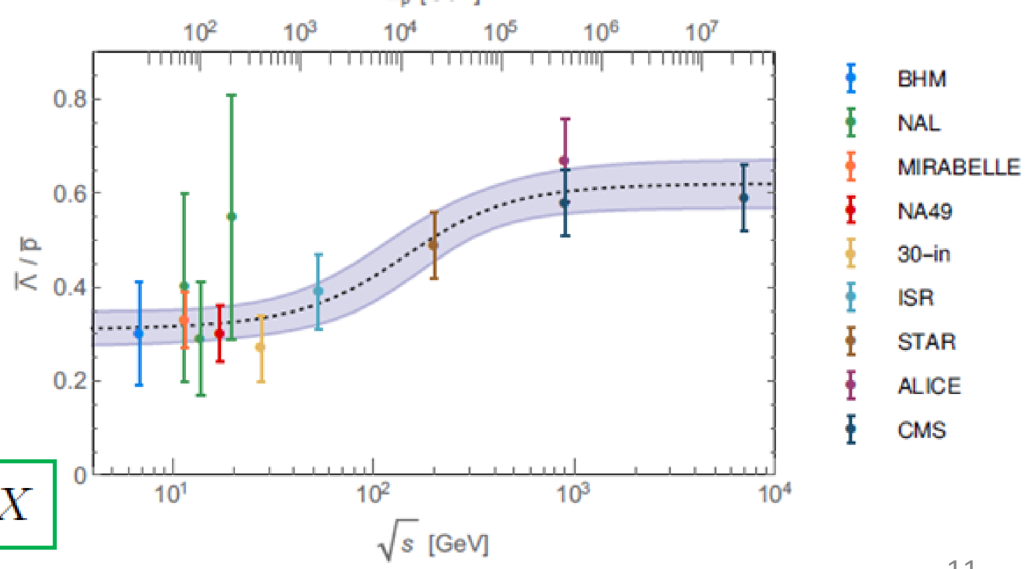
$$\left(E\frac{d^3\sigma}{dp^3}\right)_{pp\to\bar{p}} = \left(E\frac{d^3\sigma}{dp^3}\right)^{\text{prompt}}_{pp\to\bar{p}} \cdot \left(2 + \boxed{\Delta_{IS}} + 2\,\Delta_{\Lambda}\right)$$



Kappl & Winkler, 2019 ; arXiv:1408.0299



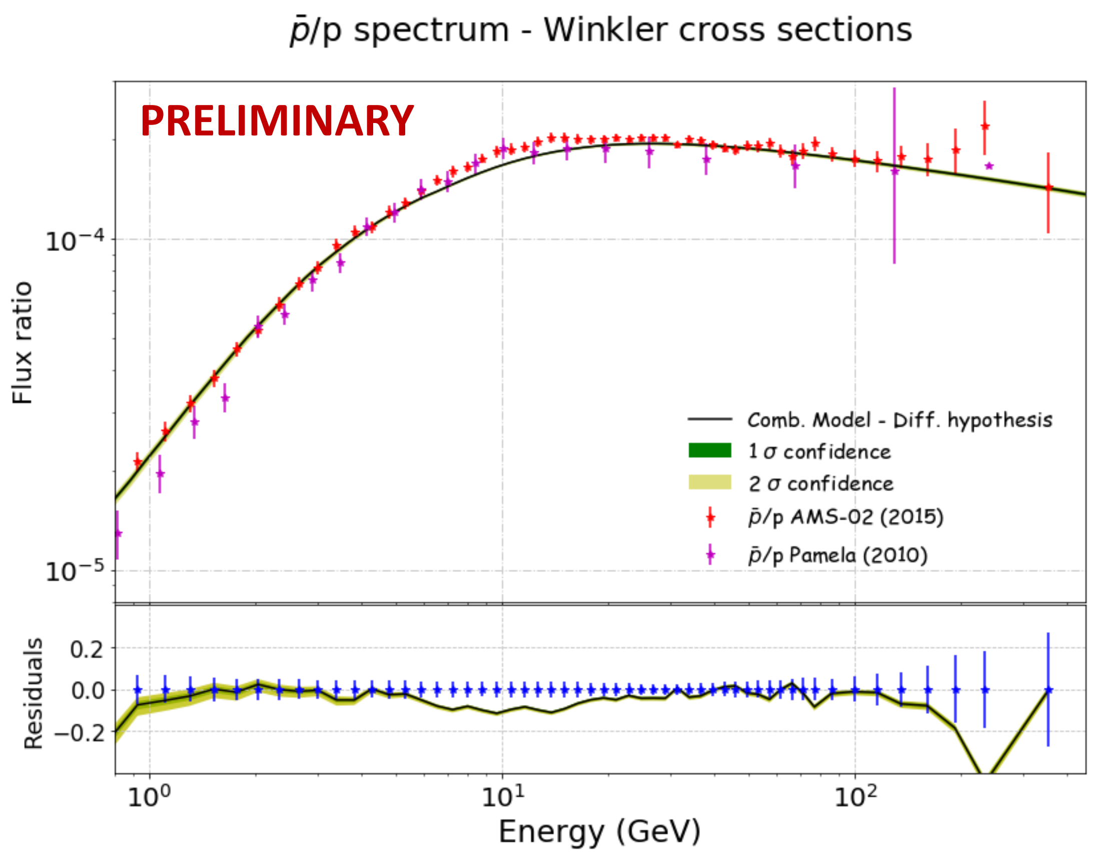
Reinert, Winkler 2017 ; arXiv:1712.00002

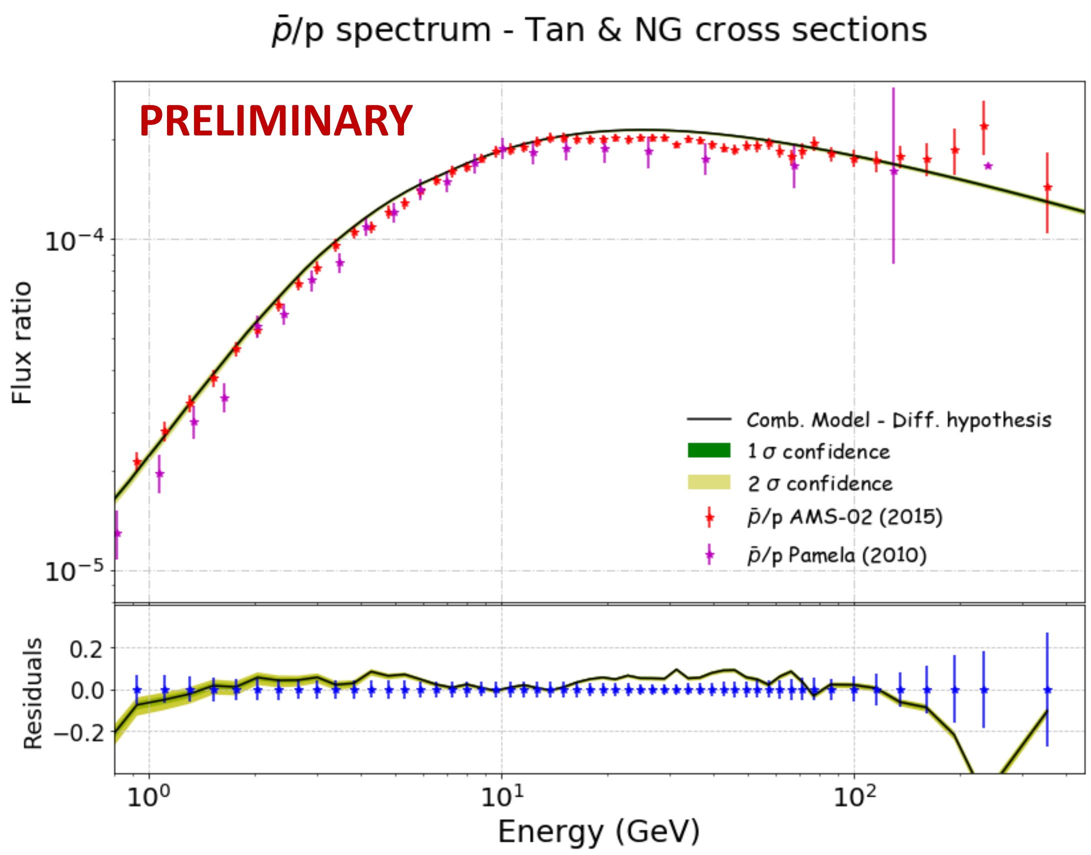


$$p + p \longrightarrow \{\bar{\Lambda}, \bar{\Sigma} \longrightarrow \bar{p}\} + X$$

ANTIPROTON XSECS

Uncertainties in the cross sections parametrizations of antiproton production estimated to be from 12% to 20% in **Korsmeier, Donato, di Mauro 2018** arXiv:1802.03030





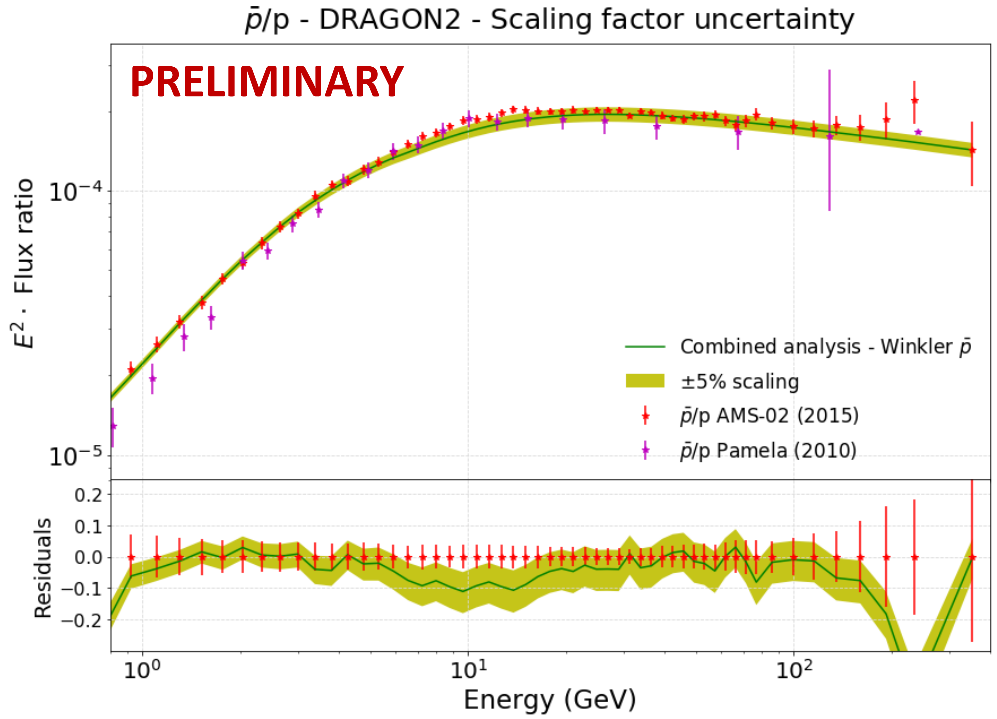
Winkler, 2017 arXiv:1701.04866v1

Tan and N.G., 1982 https://journals.aps.org/prd/abstract/10.1103/PhysRevD.26.1179

OTHER SYSTEMATIC UNCERTAINTIES

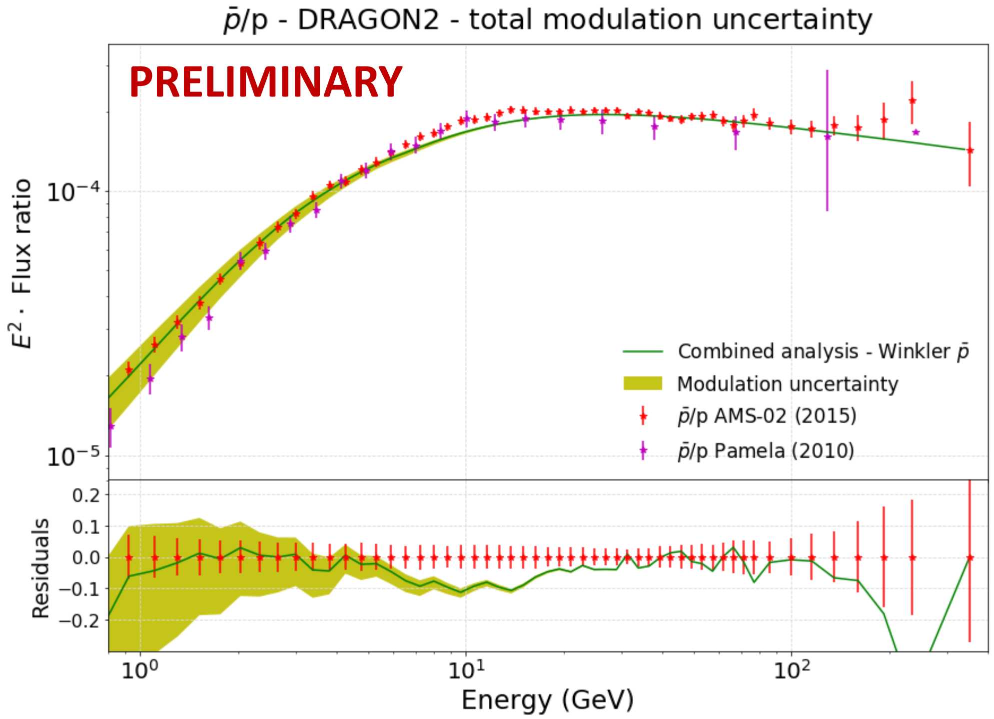
Scaling factors uncertainties

- Also related to the inelastic cross sections and the "shape" of the parametrizations
- Estimated to be around ± 5%



Modulation uncertainties

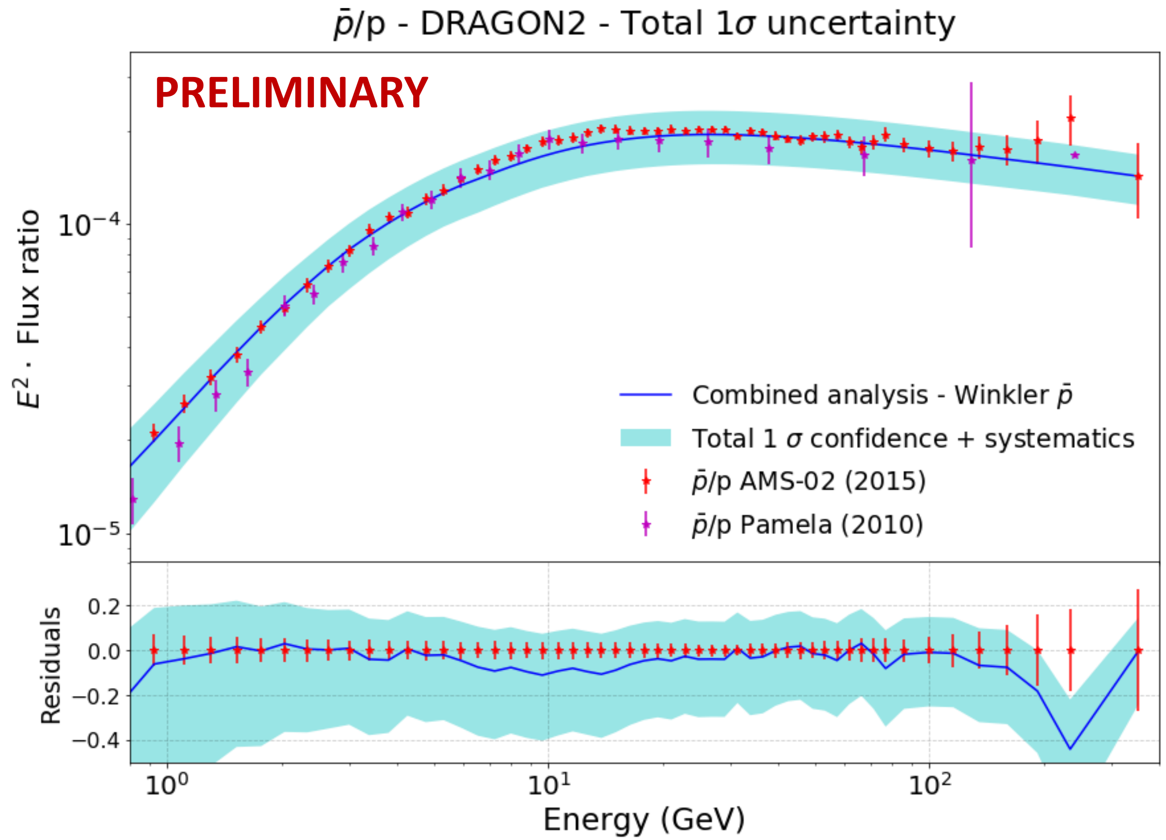
- Force-Field approximation with the Cholis-Hooper-Linden (arXiv:1511.01507) correction
- Neutron monitor (NEWK experiment) + Voyager-01 data

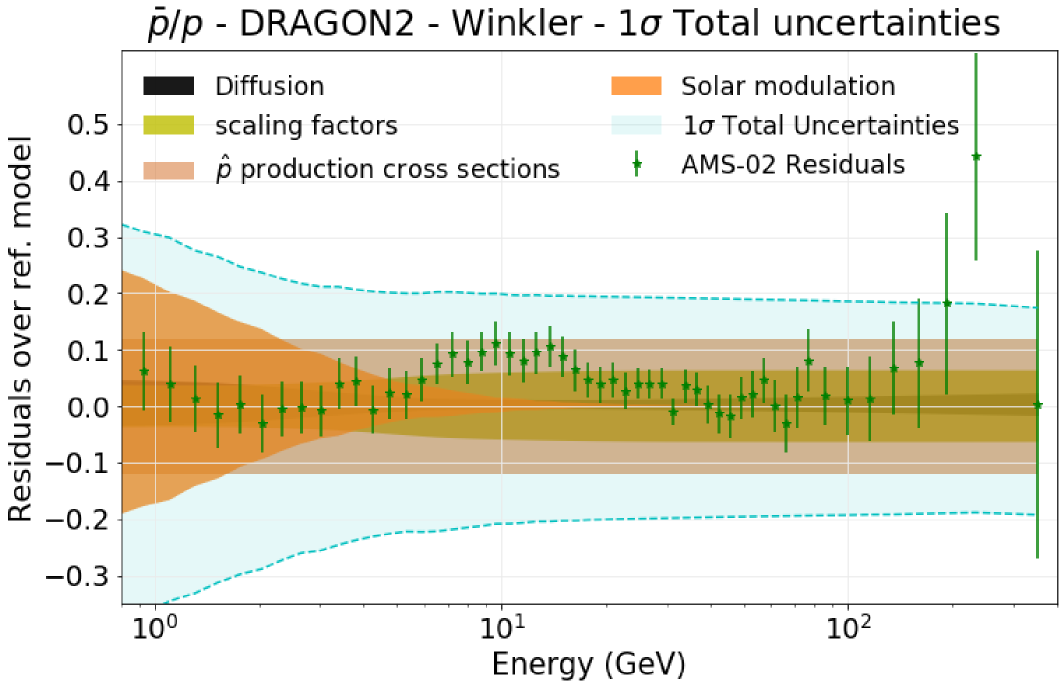


TOTAL UNCERTAINTIES

These results do not have into account:

- ✗ Heavy elements (~2%)
- ✗ Primary uncertainties
- ✗ Correlations in AMS-02 data





The excess found around 10 GeV is not significant even under conservative assumptions

In conclusion…

- We have seen that using the most recent cross sections of antiproton production, an **evident excess of data** appears over the models, peaking around 10 GeV

- In turn, we have demonstrated that with a careful analysis of the quantities that play an important role in the derivation of the propagation modelling, the **residuals** with respect to the model are **of 10%** in that energy region

- The most important source of uncertainties is related to the **cross sections of antiproton production**

- Finally, an estimation of the total, statistical and systematic, uncertainties makes this **excess of data over model not significant at all**, even with conservative assumptions

THANK YOU FOR YOUR ATTENTION!

BACK UP →

Diffusive transport of Galactic cosmic rays

- The basic idea is that primary particles are accelerated in astrophysical sources (namely supernovae) and propagate throughout the Galaxy, occasionally interacting with gas, mainly in the disc of the Galaxy, and there they produce secondary nuclei through spallation.

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

DRAGON2 cross sections
arXiv:1711.09616v2

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

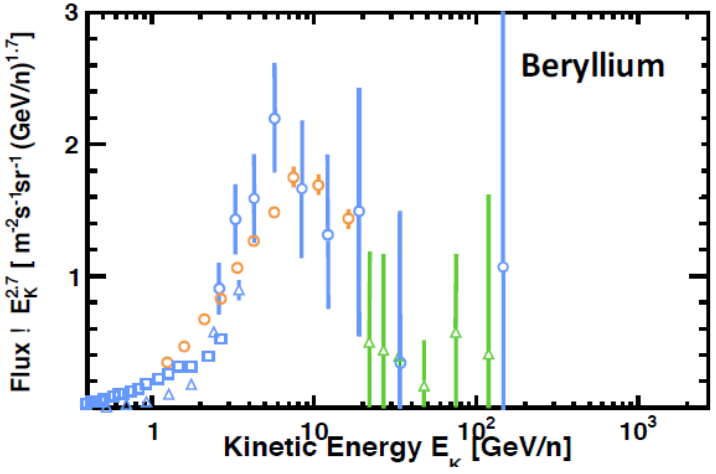
$$\boxed{\frac{J_{\mathrm{sec}}}{J_{\mathrm{pr}}} \sim D(E)\,\sigma(E)}$$

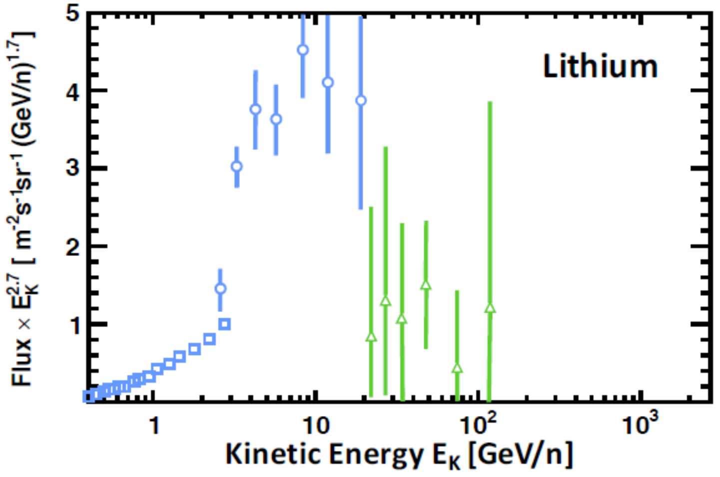
$$\Gamma^s_{j\to i} = \beta_j c n_t \sigma_{j\to i} N_j$$

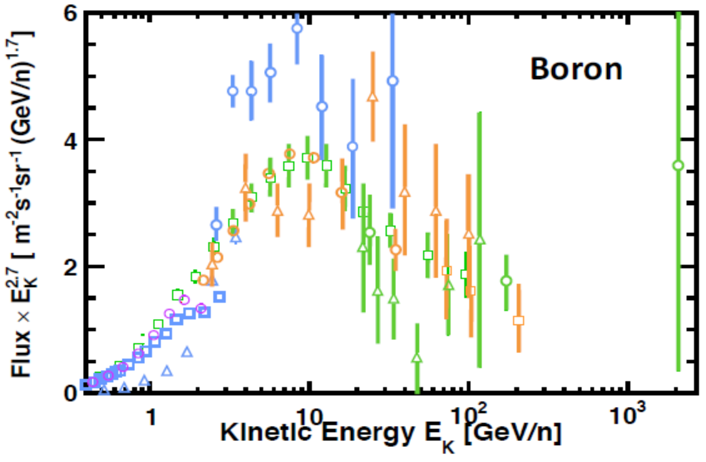
Solved with the DRAGON code https://github.com/cosmicrays/DRAGON2-Beta_version

CURRENT SITUATION

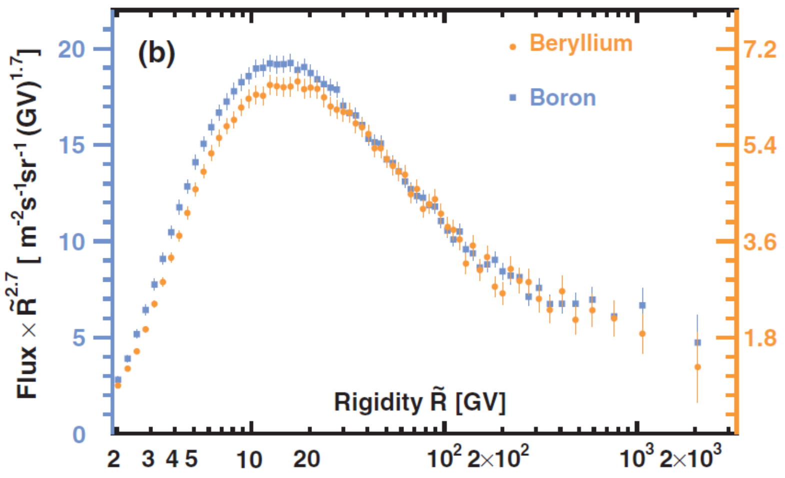
Li and Be at the level of B







AMS-02



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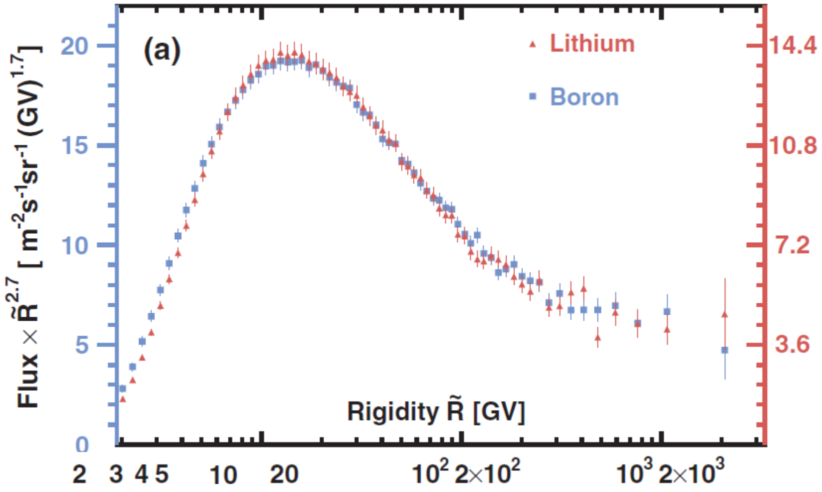
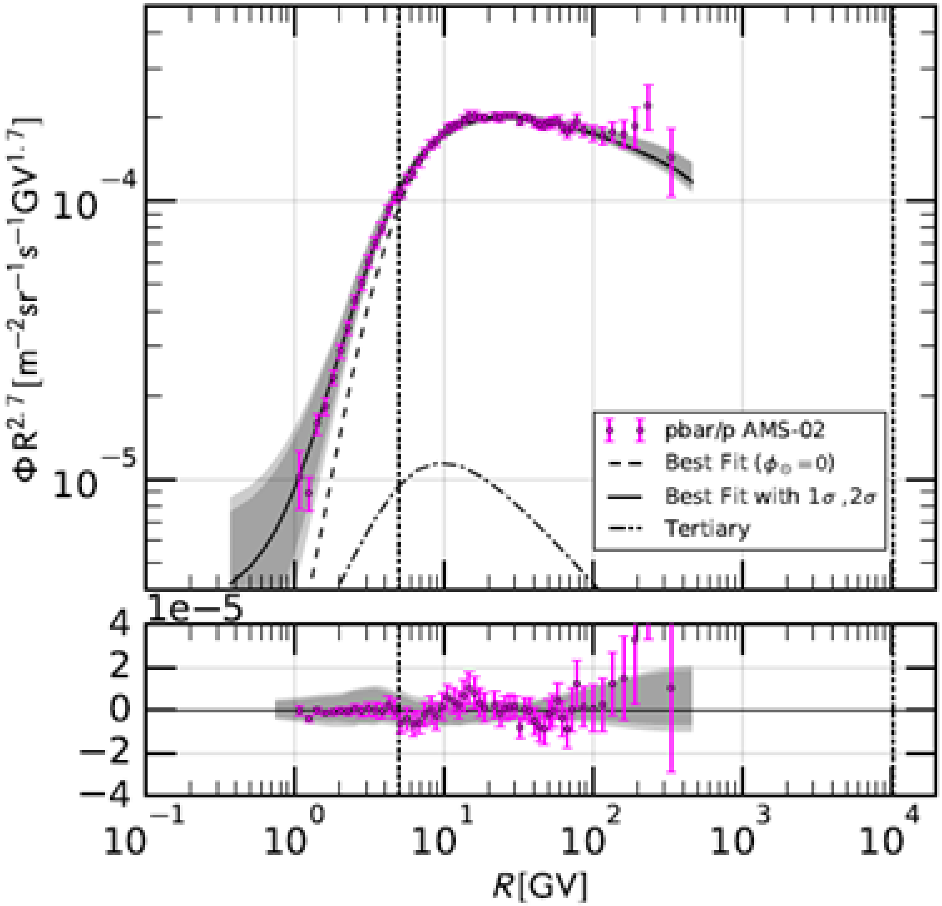
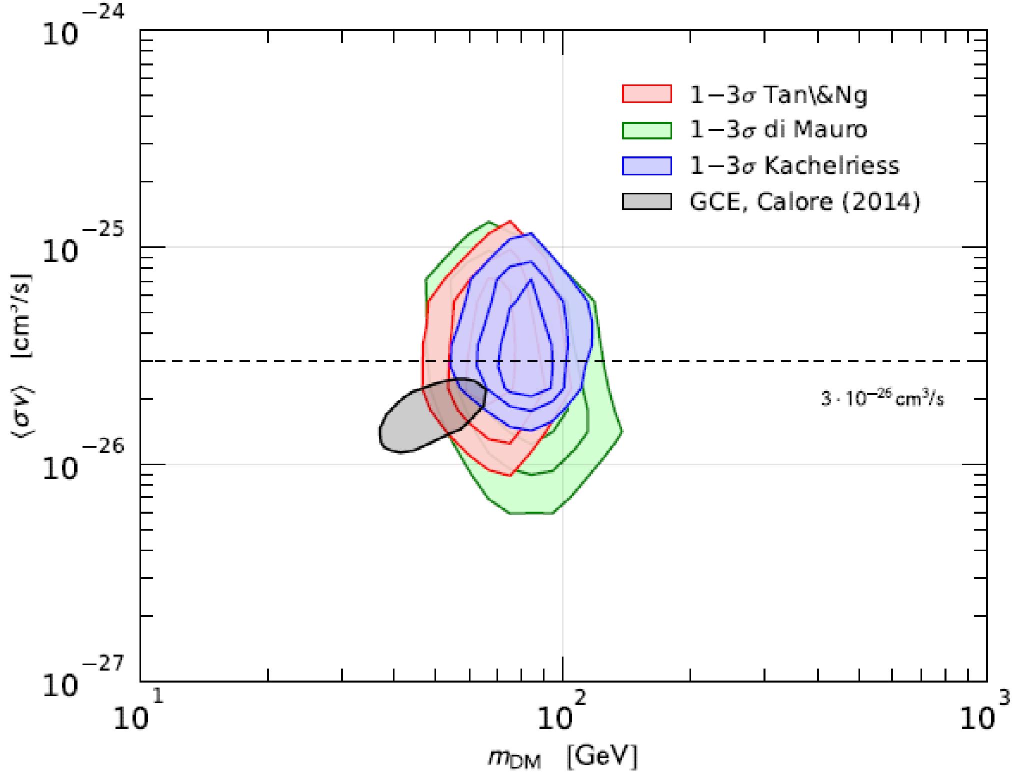


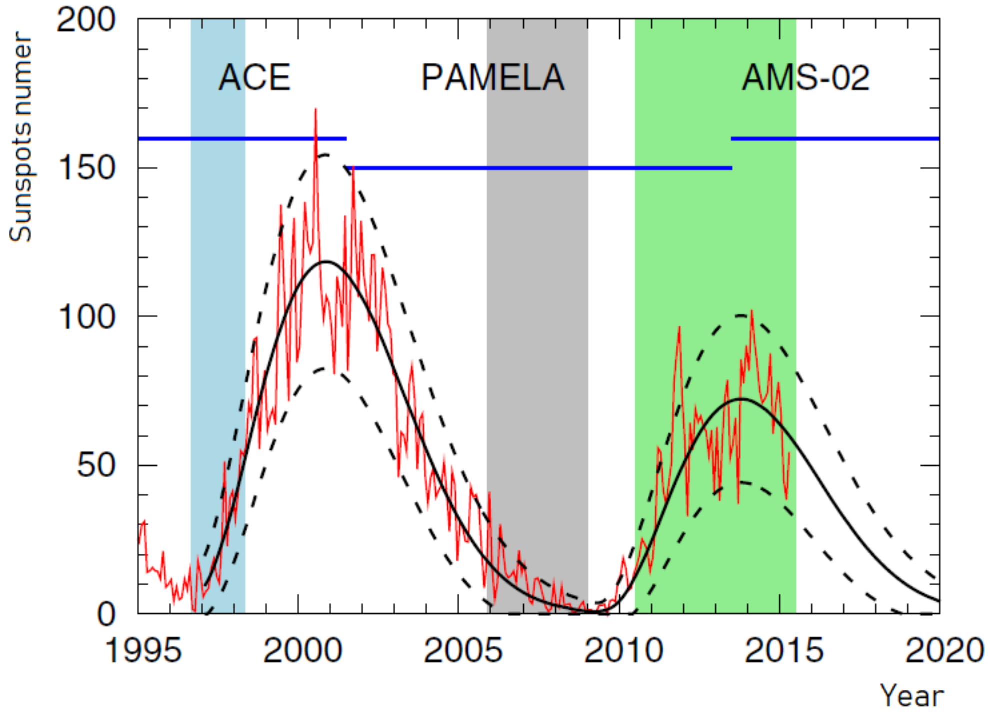
Discrepancy around 10-11 GeV points to a 80 GeV dark matter particle

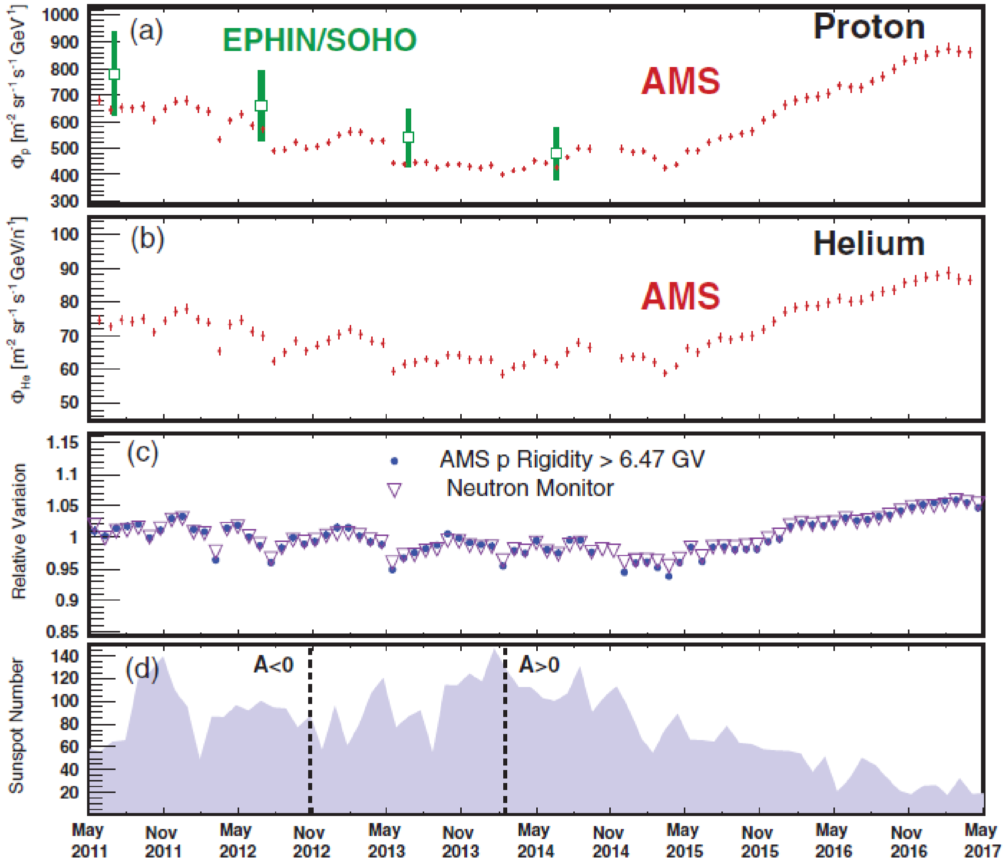




Cuoco, Krämer, Kosmeier, 2017 ; arXiv:1610.03071

SOLAR MODULATION





- Force-Field approximation
- Neutron monitor (NEWK experiment) + Voyager-01 data
- $\bar{p}$ with the Cholis-Hooper-Linden (arXiv:1511.01507) correction

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

$$\phi^{\pm}(t, \mathcal{R}) = \phi_0(t) + \phi_1^{\pm}(t)\,\mathcal{F}\left(\frac{\mathcal{R}}{\mathcal{R}_0}\right)$$