Cross sections for cosmic rays

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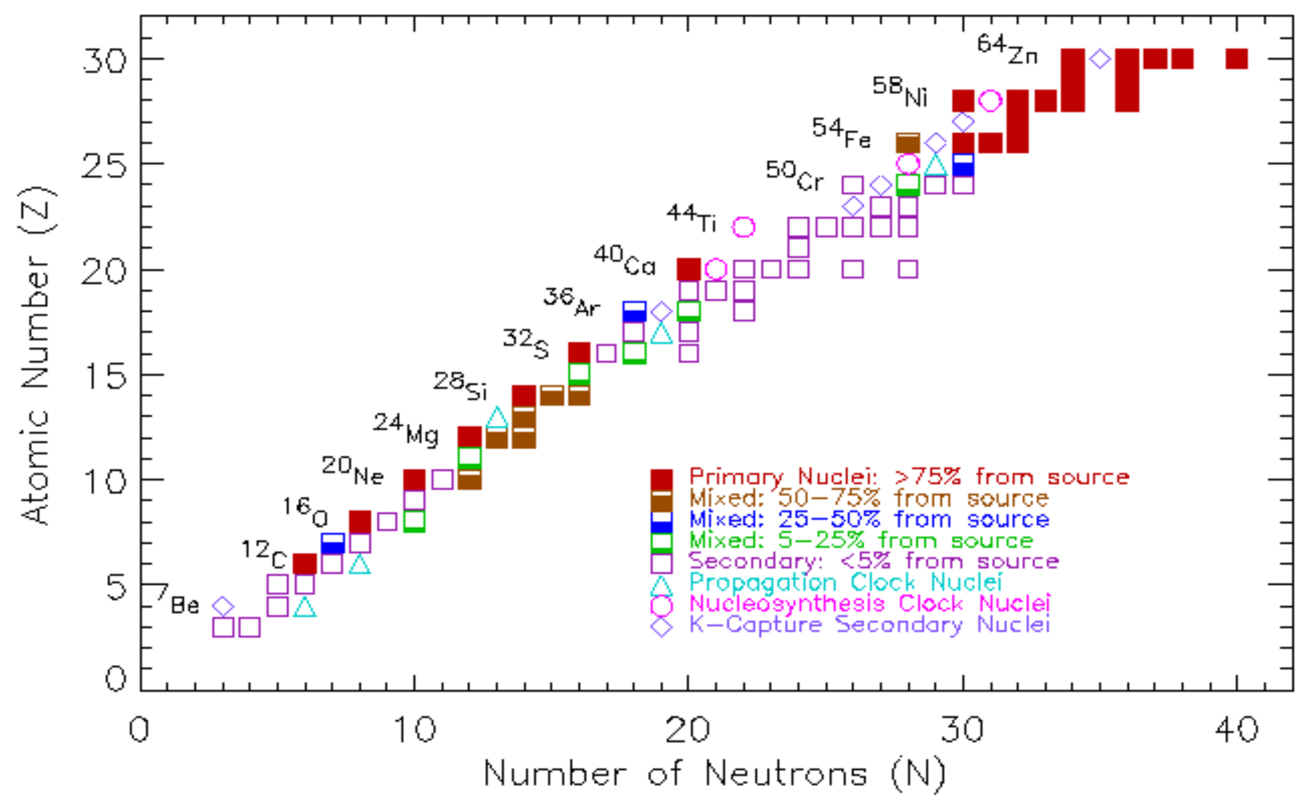
"PAW'24 -Physics at Amber Int. Workshop "

CRs in the Galaxy

Primaries: produced in the sources (SNR and Pulsars)
H, He, CNO, Fe; e-, e+; possibly e^+, p^-, d^- from Dark Matter annihilation

Secondaries: produced by spallation of primary CRs (p, He,C, O, Fe) on the interstellar medium (ISM): Li, Be, B, sub-Fe, [...], (radioactive) isotopes ; e^+, p^-, d^-

Primaries = present in sources:
Nuclei: H, He, CNO, Fe; e-, (e+) in SNR (& pulsars)
e^+, p^+, d^+ from Dark Matter annihilation
Secondaries = NOT present in sources, thus produced by **spallation** of primary CRs (p, He, C, O, Fe) on ISM
Nuclei: LiBeB, sub-Fe, ... ;
e^+, p^+, d^+; ... from inelastic scatterings



Propagation equation

$$\frac{\partial \psi}{\partial t} - \nabla \cdot \{D(E)\nabla\psi\} + \frac{\partial}{\partial E}\left\{\frac{dE}{dt}\psi\right\} = Q(E, \mathbf{x}, t)$$

diffusion — en. losses — source spectrum

Diffusion: $D(x,R)$ a priori
usually assumed isotropic in the Galaxy: $D \sim D_0 R^\delta$
D_0 and δ usually fixed by B/C

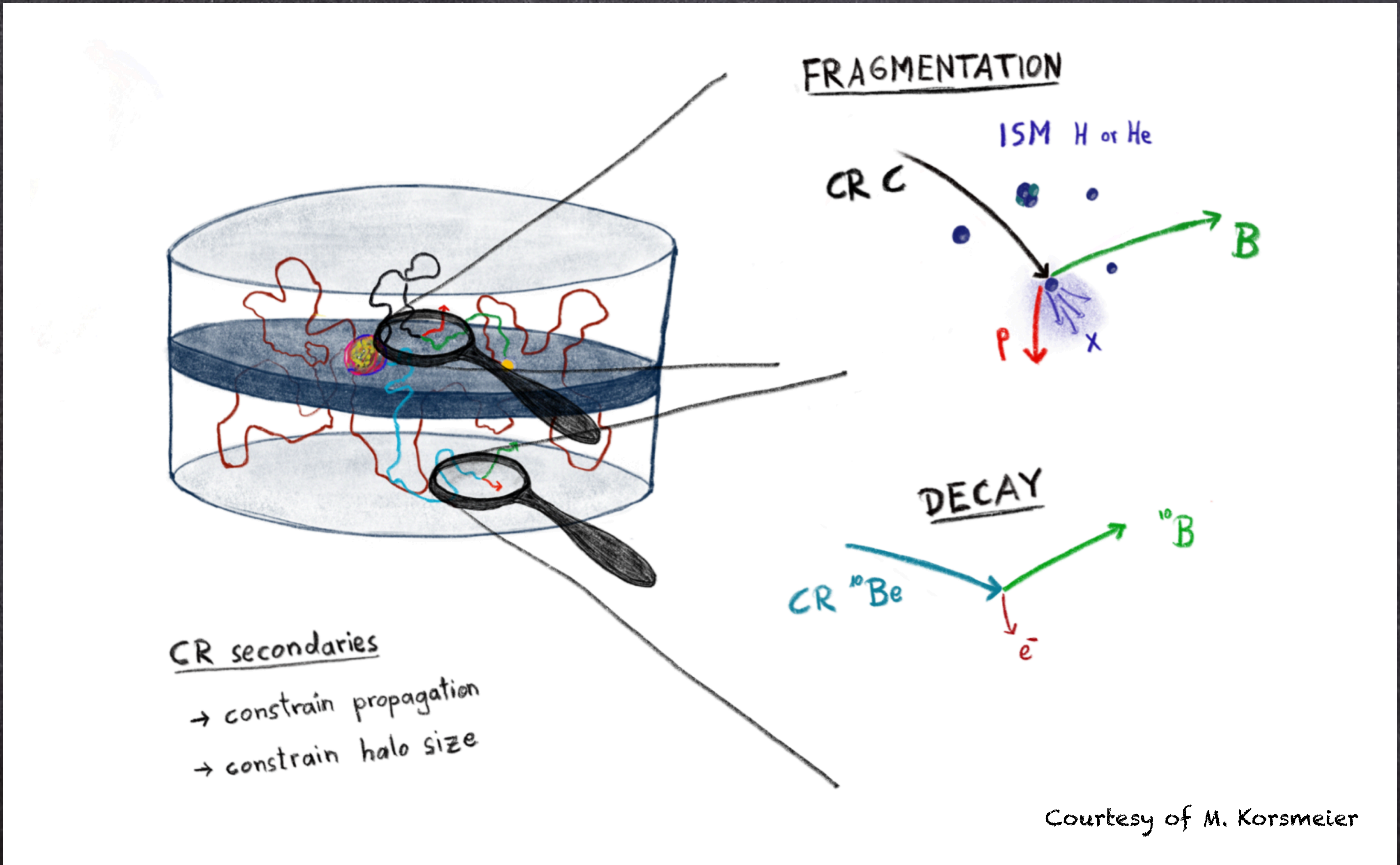
Energy losses: Nuclei: ionisation, Coulomb
Leptons: Synchrotron on the galactic $B \sim 3.6\ \mu G$
Inverse Compton on photon fields (stellar, CMB, UV, IR)

Sources: Supernova Remnants, $Q(E) \propto E^{-\gamma}$

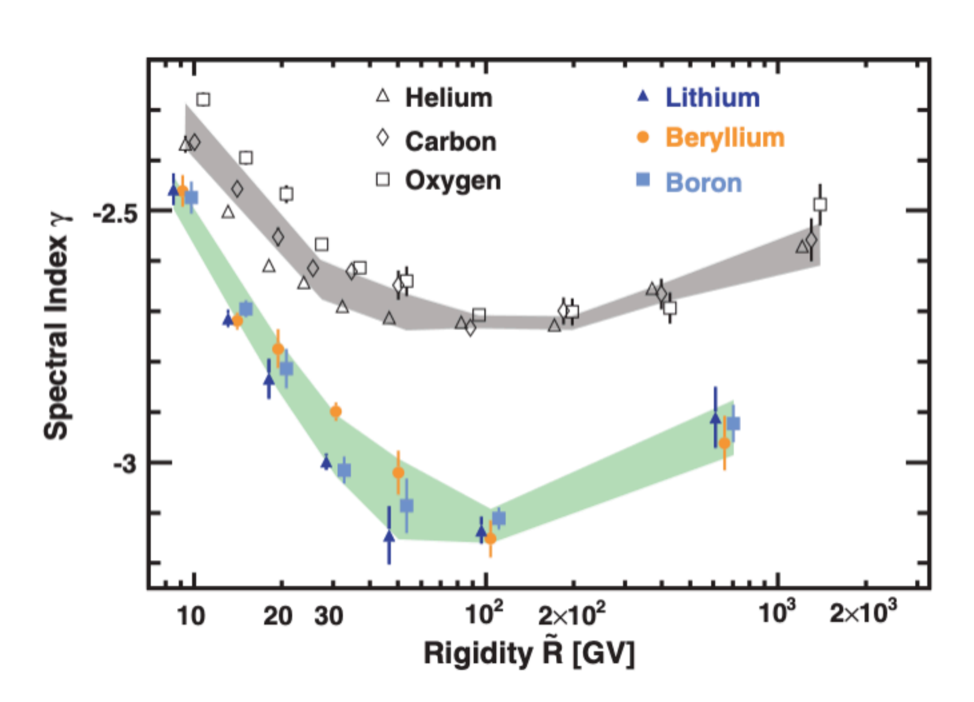
Nuclear fragmentation, $Q_j(E) \propto n_{ISM}\, \sigma_{ij}\, \psi_i$

Dark Matter annihilation, see below

Interactions and decays in the Galaxy

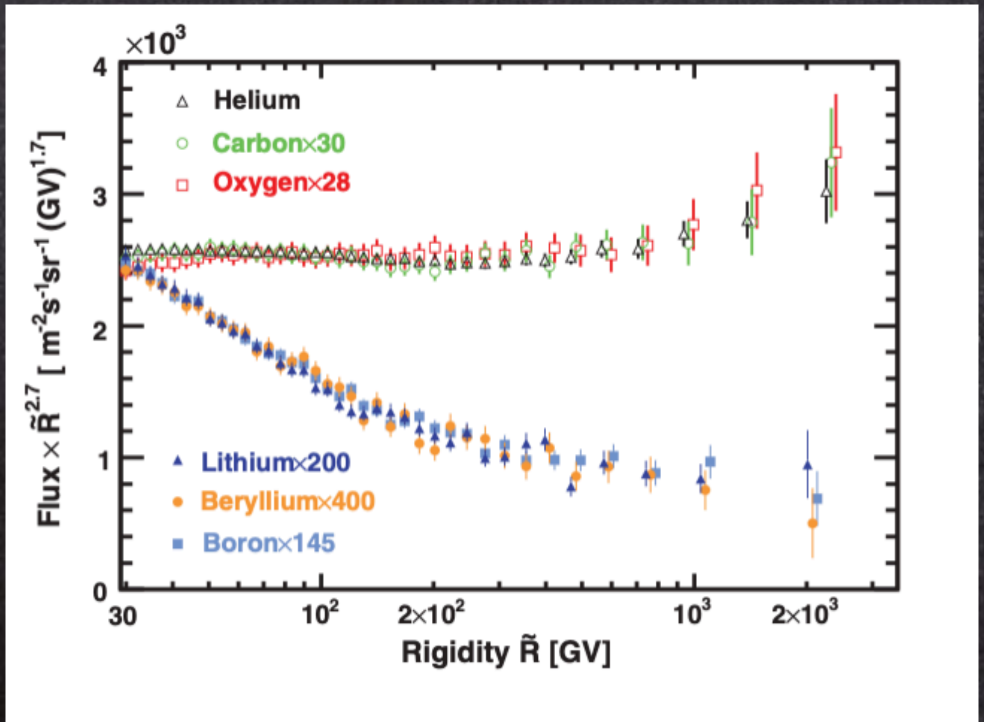


The spectrum of secondary fluxes



See talk by A. Kounine

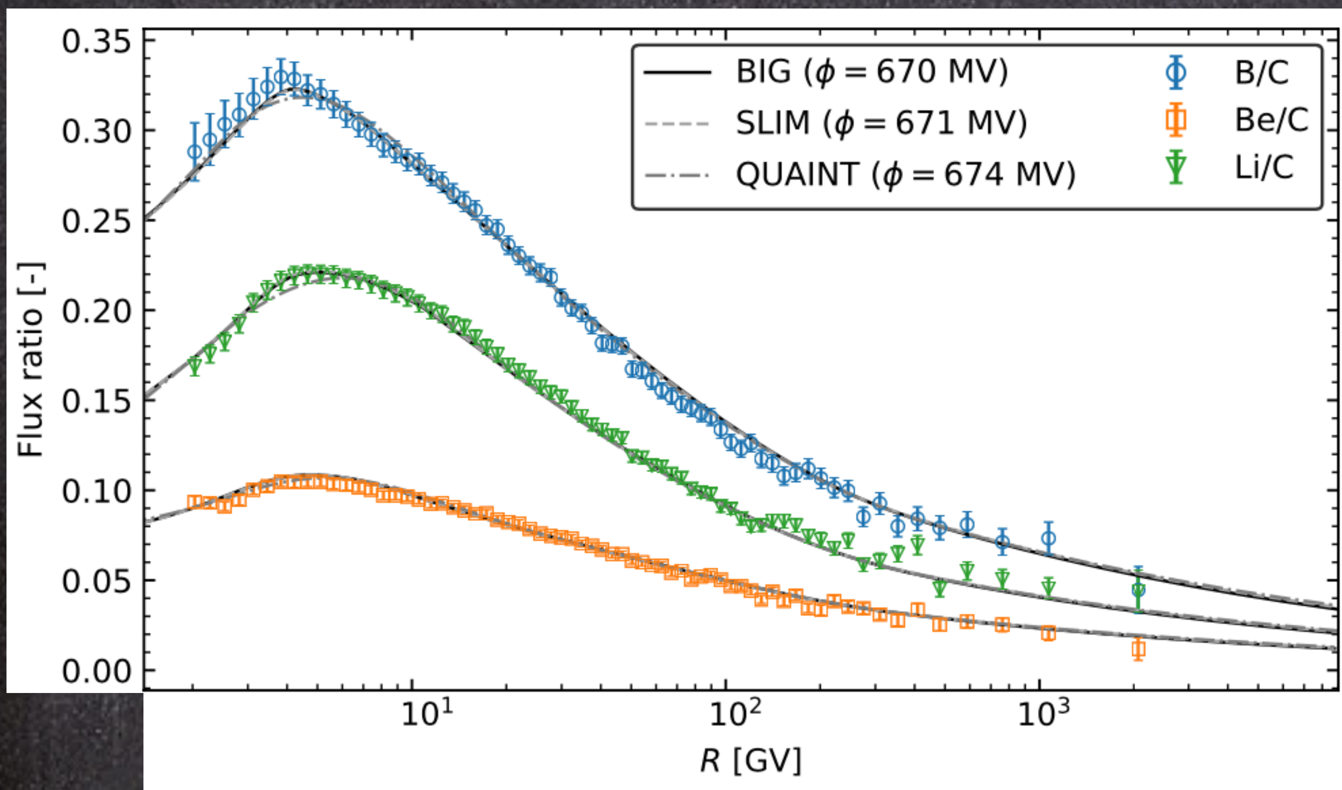
The rigidity dependence of Li, Be and B are nearly identical, but different from the primary He, C and O (and also p).

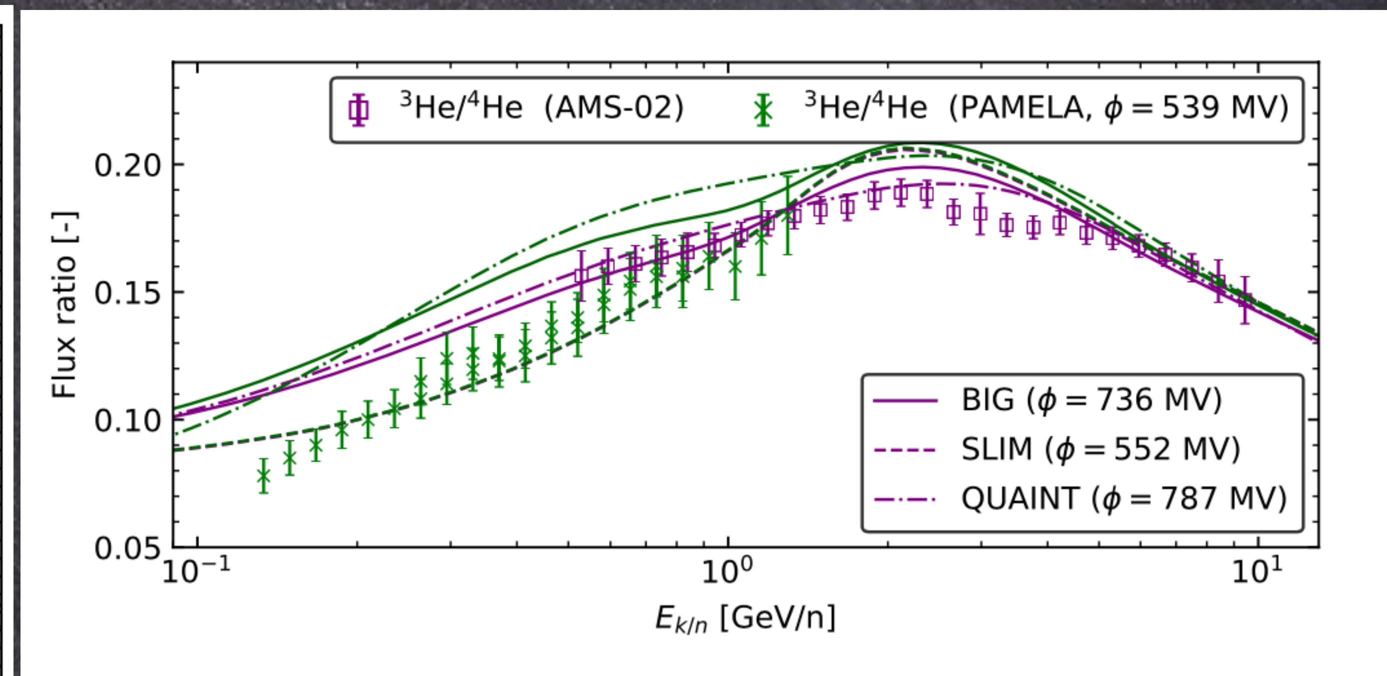


Li, Be, B fluxes measured by Pamela and AMS show an identical hardening w.r.t. energy above 200 GV. The spectral index of secondaries hardens 0.13 +- 0.03 more than for primaries

Propagation models vs data

Weinrich+ A&A 2020





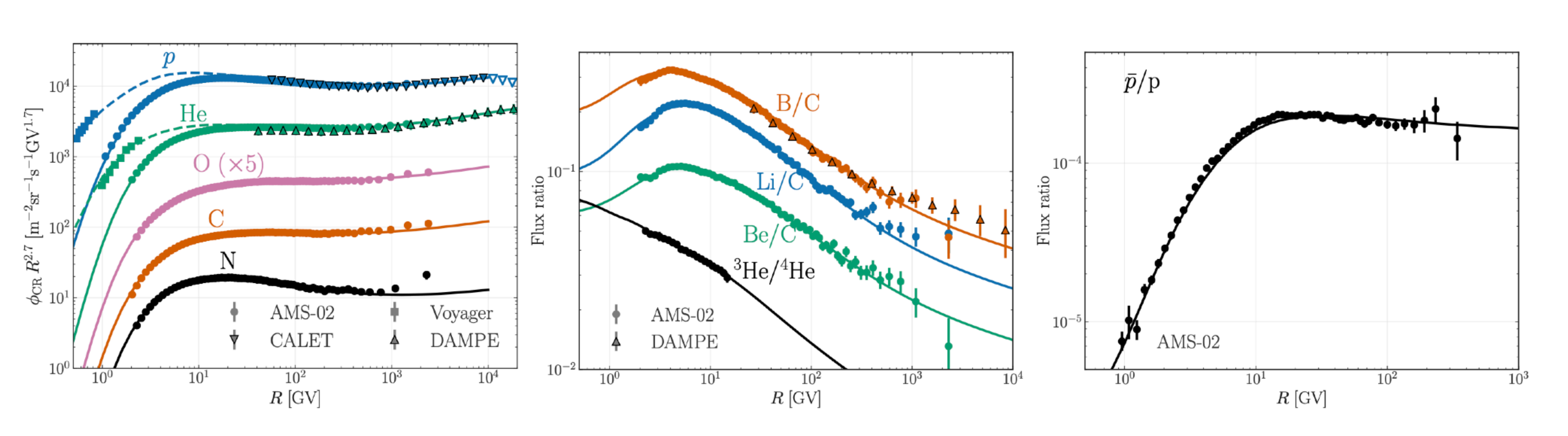
Data on secondary/primary species are well described by propagation model with diffusione coefficient power index δ = 0.50 ± 0.03.

Convection + reaccelerating, or pure diffusion both work.

Propagation models vs data

Several propagation models are tested

Di Mauro, Korsmeier, Cuoco 2311.17150



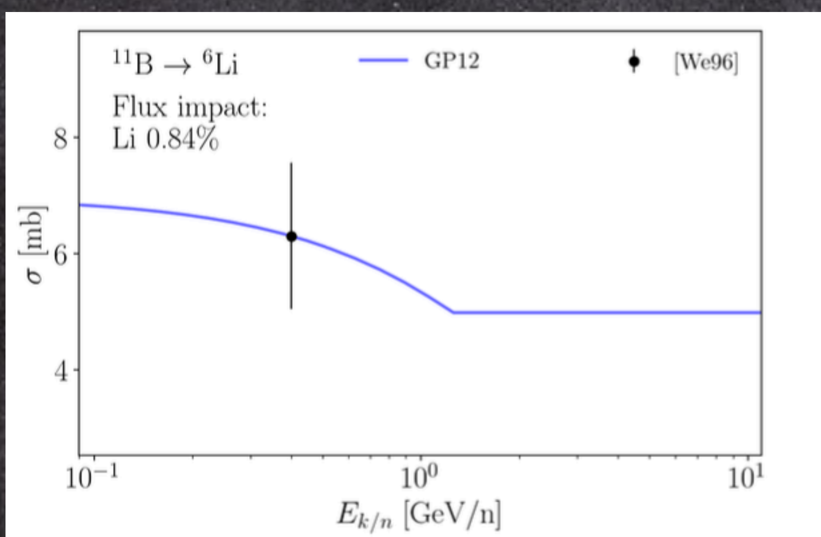
Fragmentation cross section uncertainties currently prevent a better understanding of CR propagation

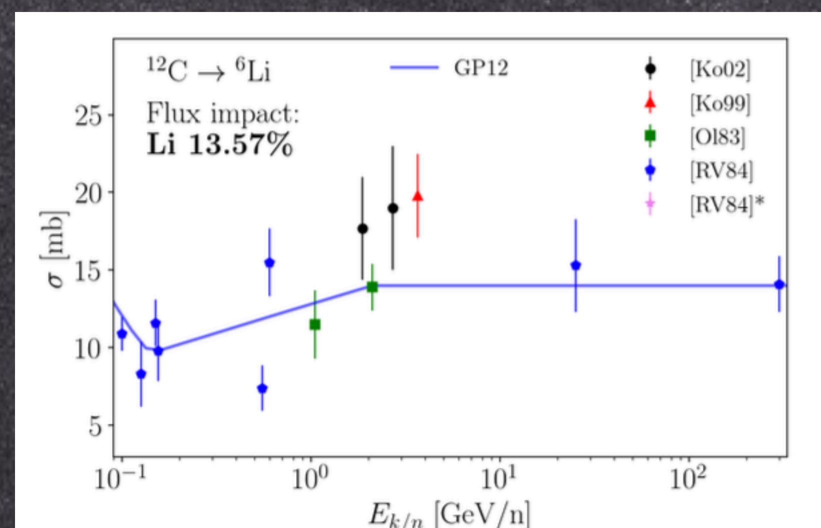
Korsmeier & Cuoco, PRD 2021

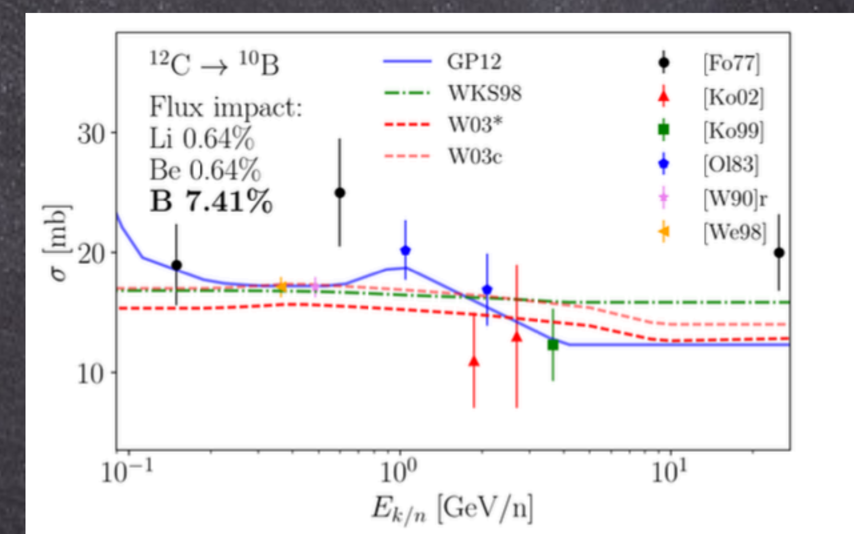
Cross sections for Galactic cosmic rays

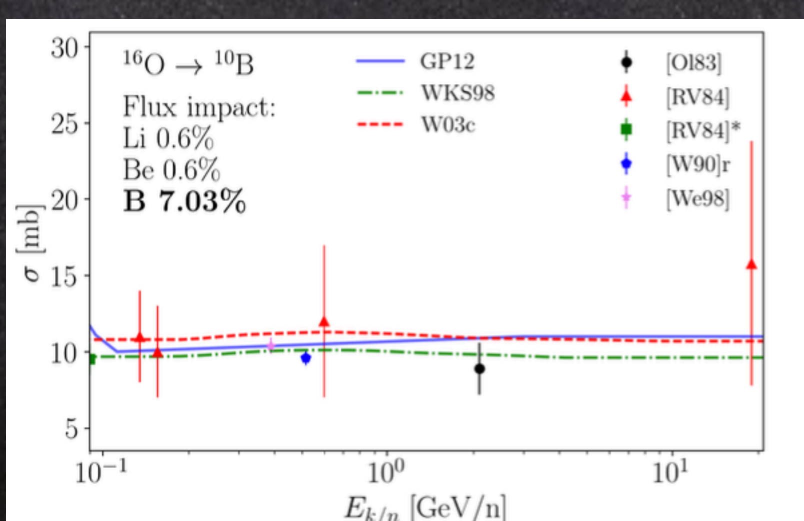
Data driven parameterizations (Silberberg&Tsao), semi-empirical formulae (Webber+), parametric formulae/direct fit to the data (Galprop), MonteCarlo codes (Fluka, Geant, ...)

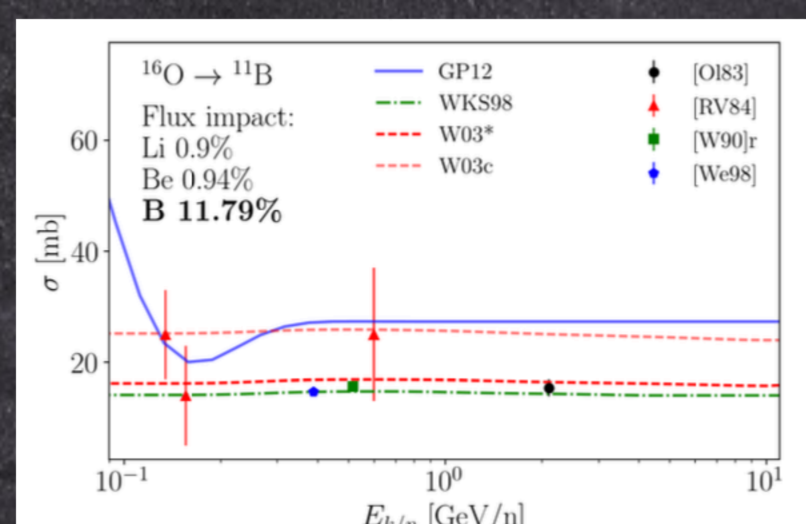
Genolini, Moskalenko, Maurin, Unger PRC 2018

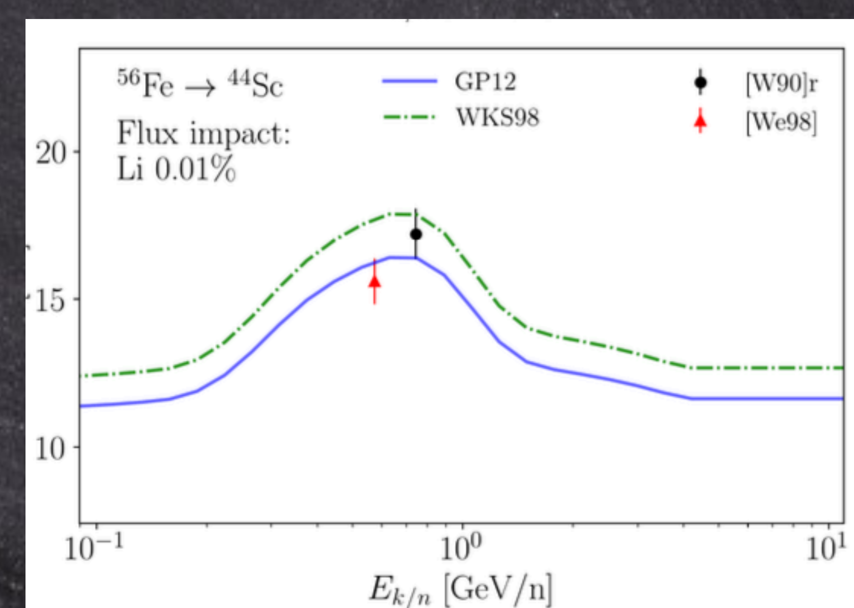








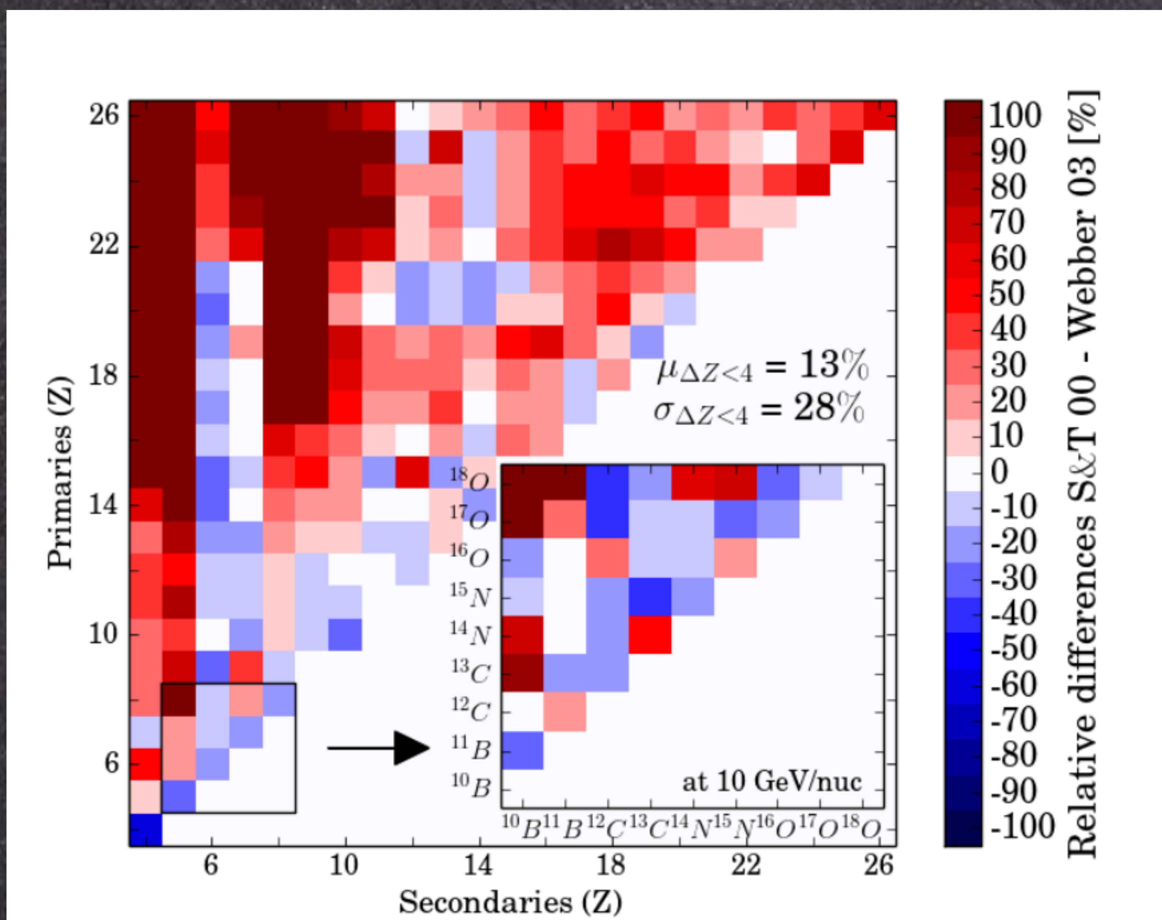


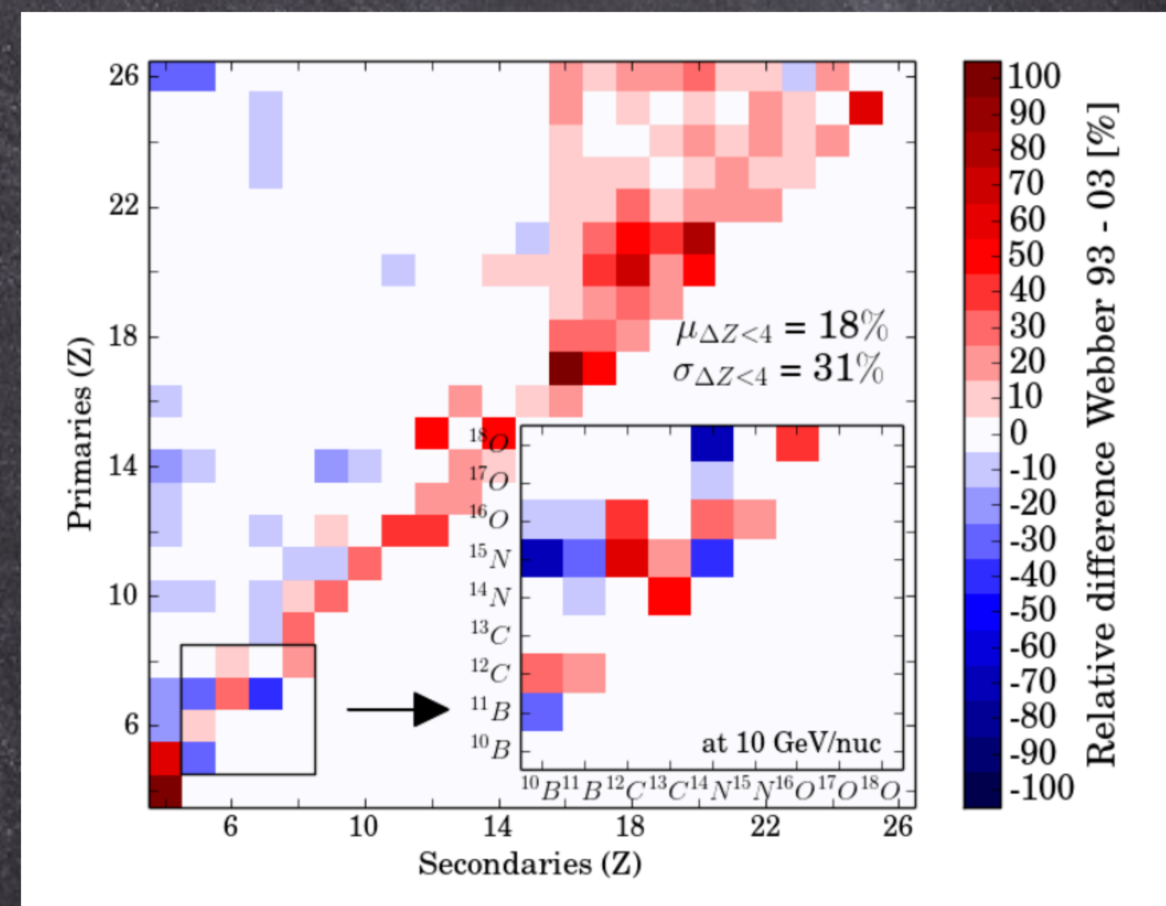


Differences in the XS parameterizations

Genolini, Putze, Salati, Serpico A&A 2015

Differences in one parameterization wrt a benchmark model



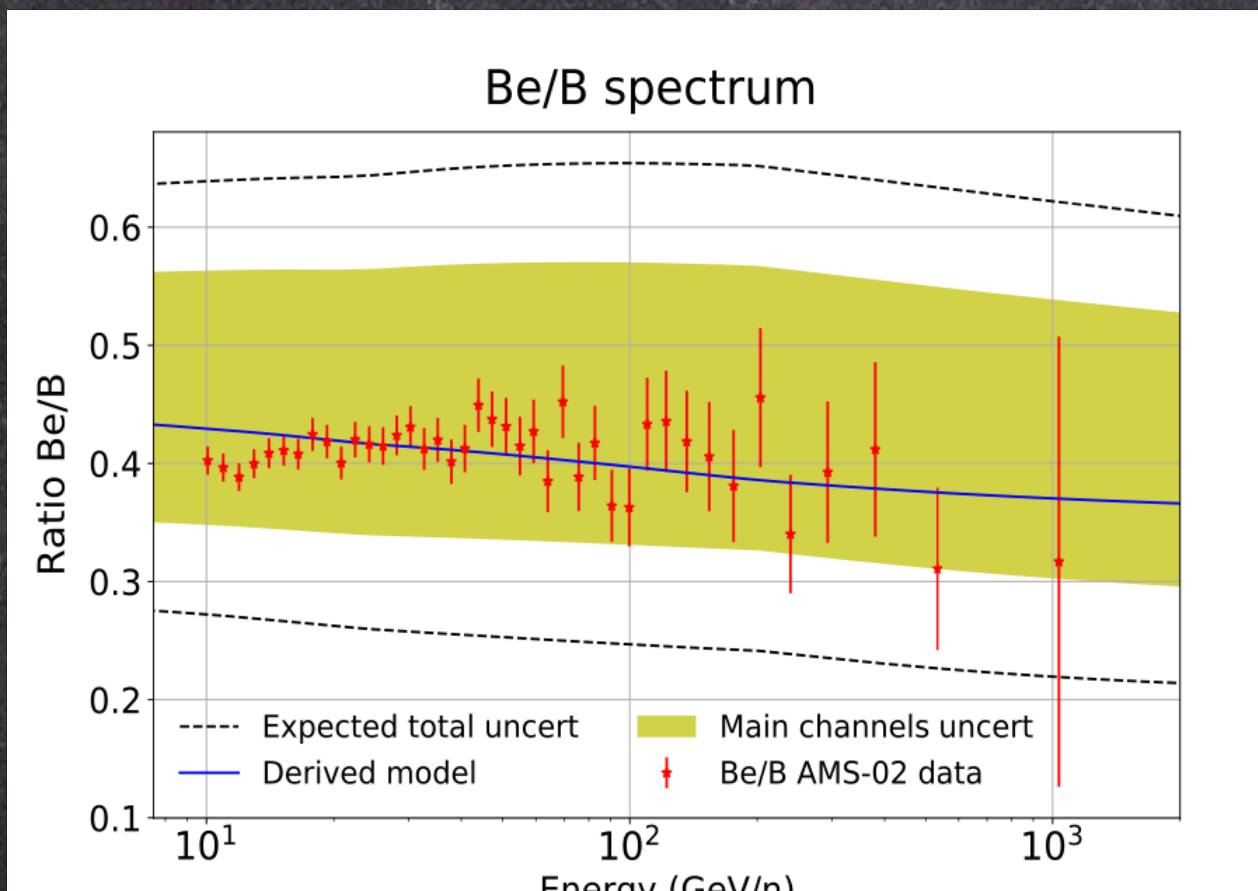


Even with the same, although scarce data,
interpretation may be different

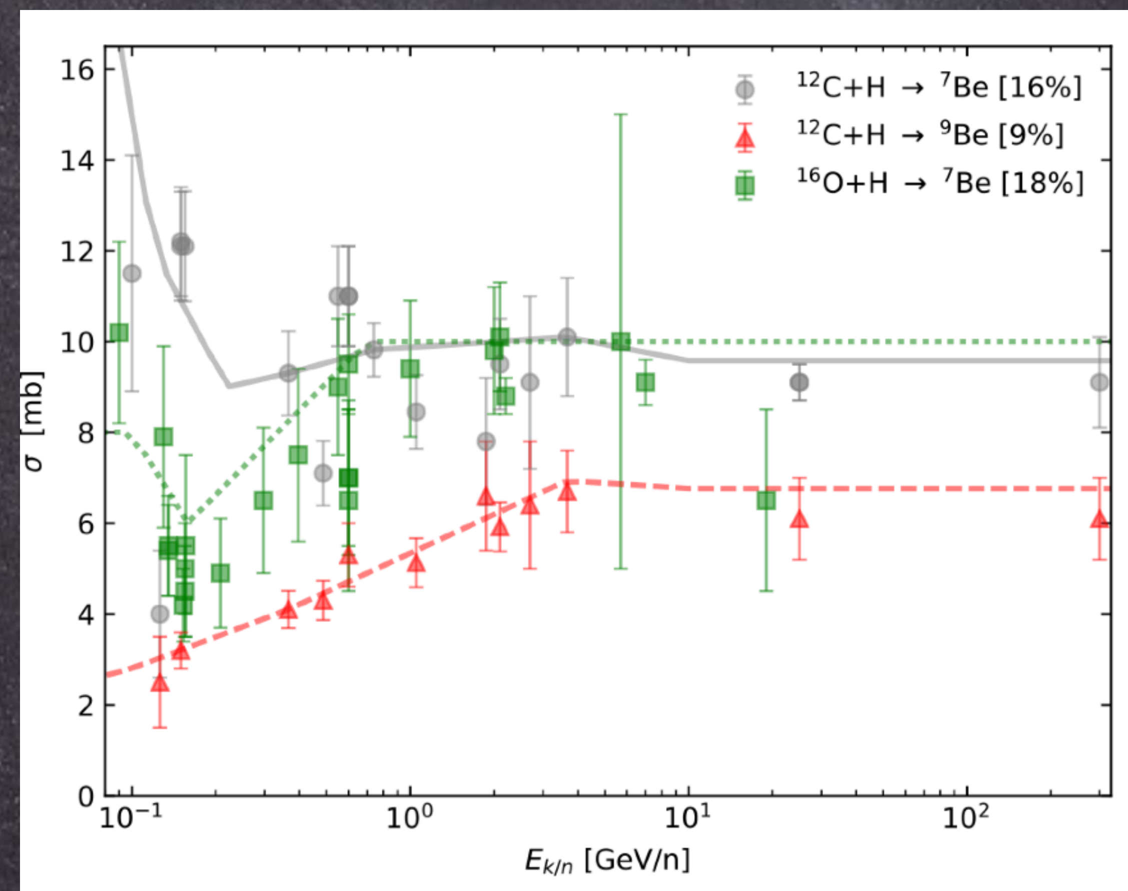
Fragmentation cross sections

They matter in both directions: as a loss term for progenitors, as a source term for daughters

De La Torre Luque+ JCAP 2021



Weinrich+ A&A 2021



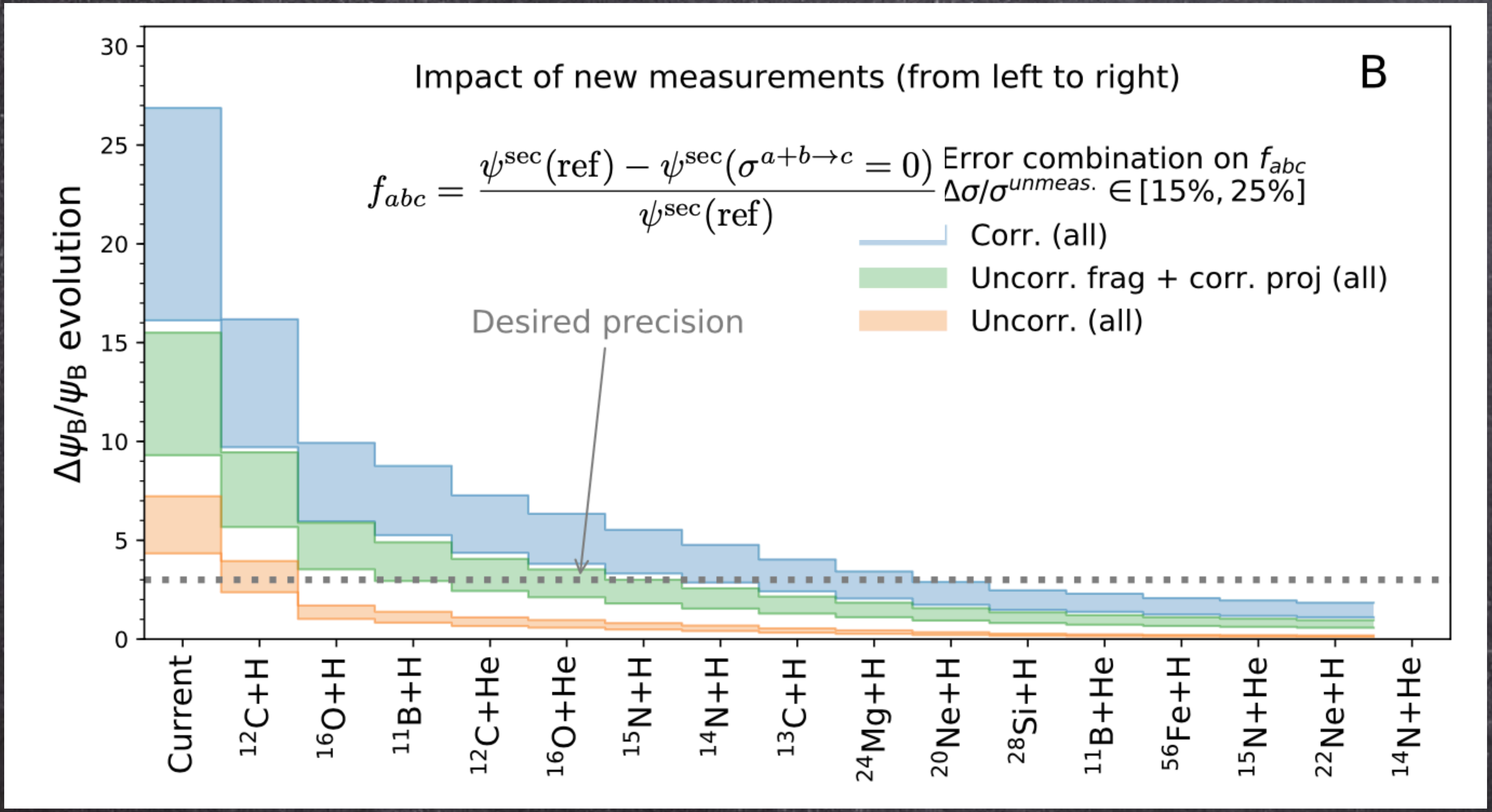
Probably the most limiting aspect now

Dedicated campaigns are needed (LHC, NA61, Amber, ...)

Most relevant physics cases

Improve Boron production cross sections

Genolini, Moskalenko, Maurin, Unger PRC 2018

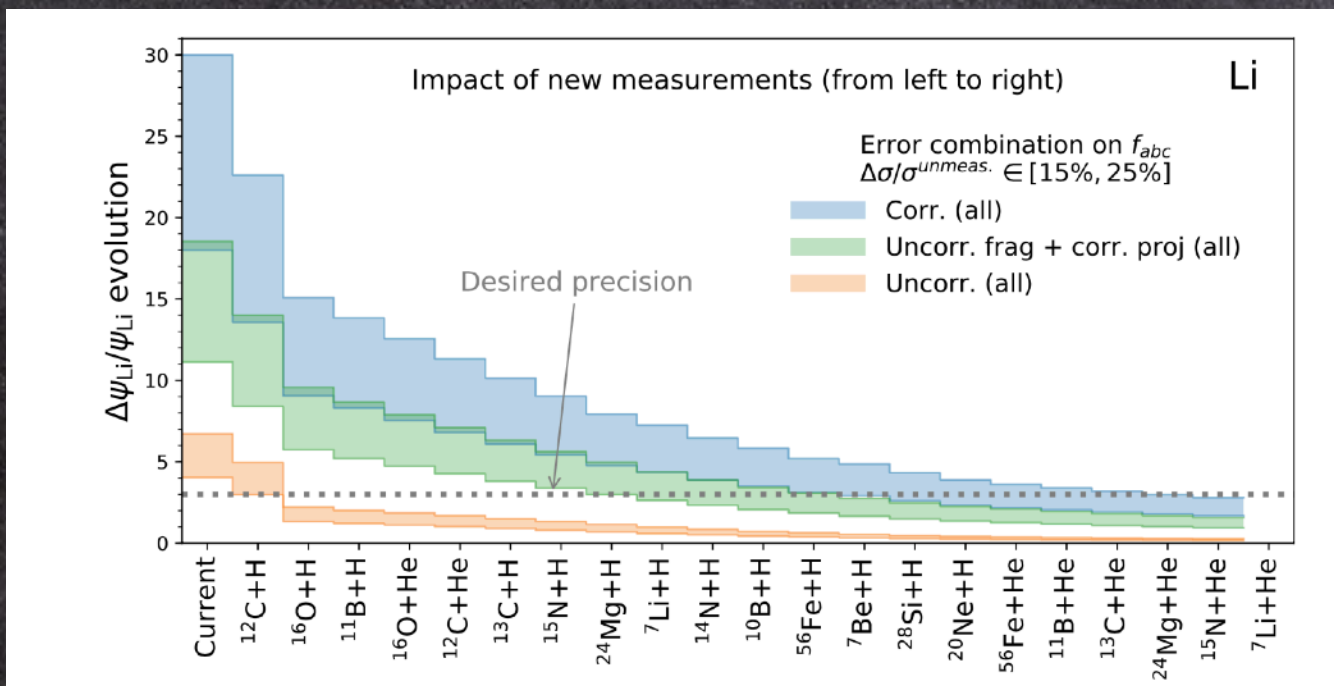


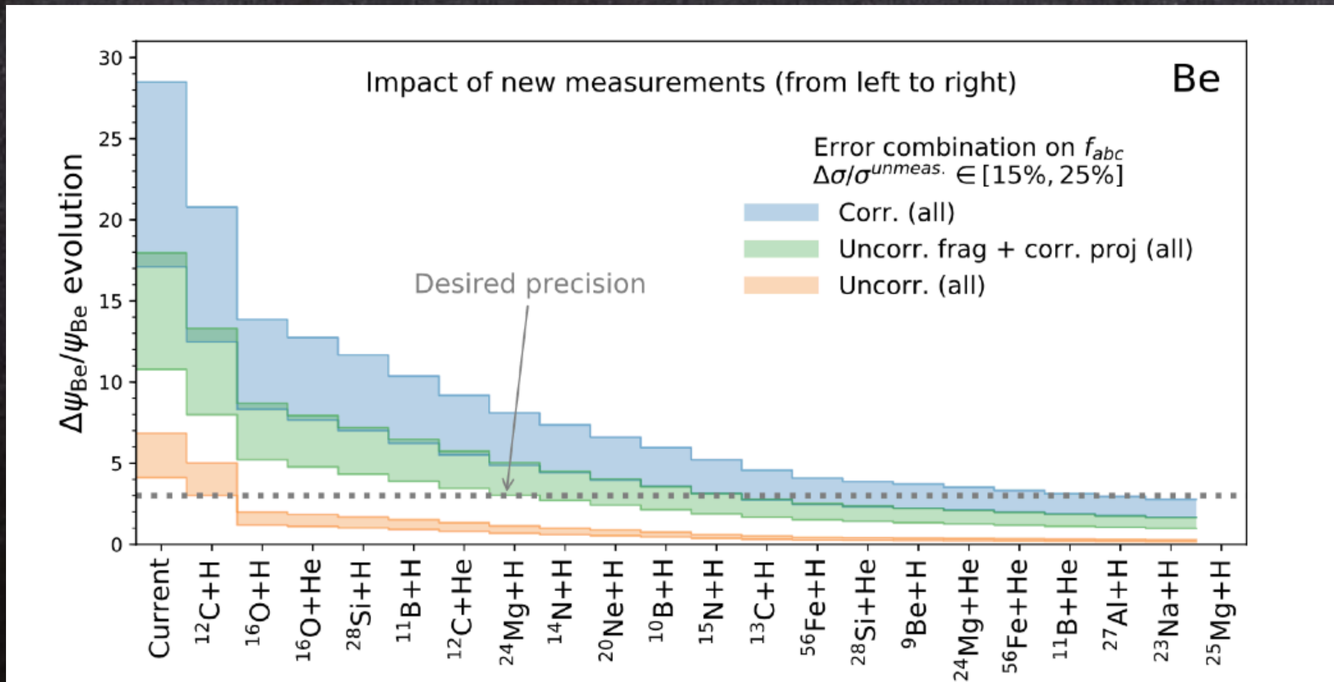
The evolution of error on the calculated B flux as if new reactions were measured with perfect accuracy (^{12}C+H is the most critical one)

Most relevant physics cases

Improve Lithium and Berillium production cross sections

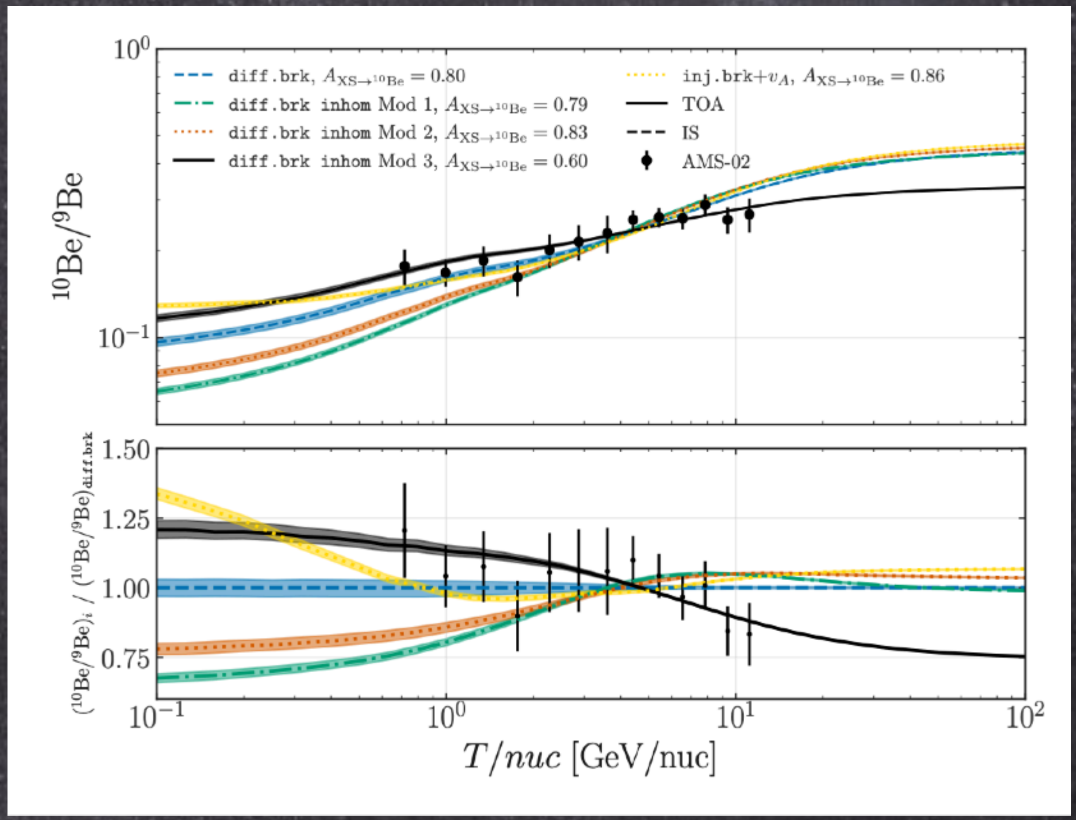
Genolini, Moskalenko, Maurin, Unger PRC 2018





Evoli, Morlino, Blasi, Aloisio PRD 2020

Di Mauro, Korsmeier, Cuoco 2311.17150

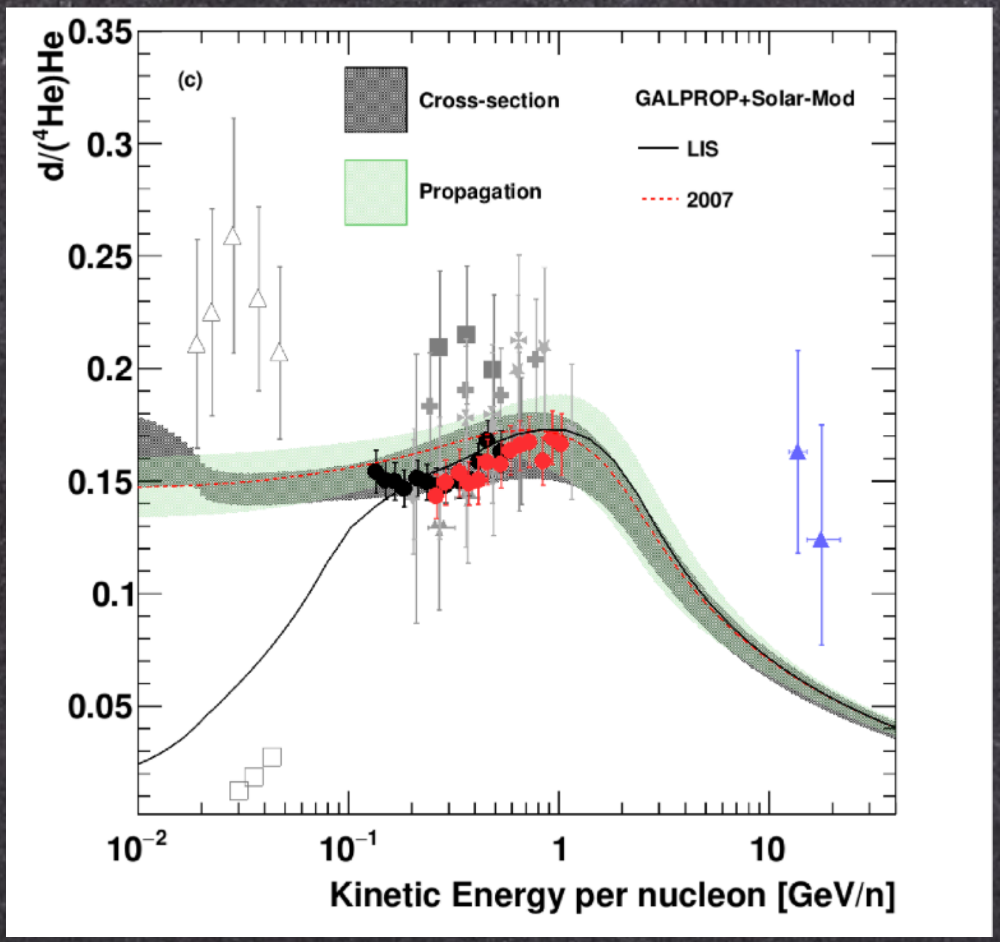


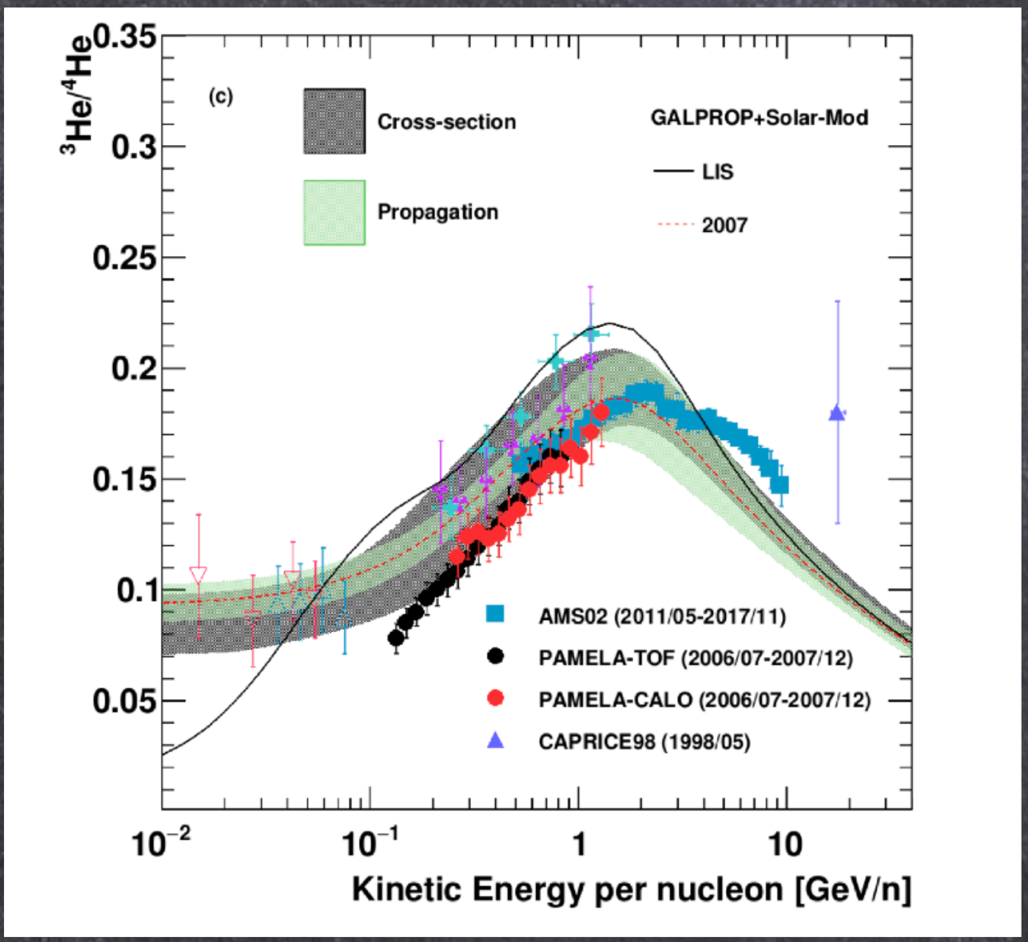
Beriullium case very relevant

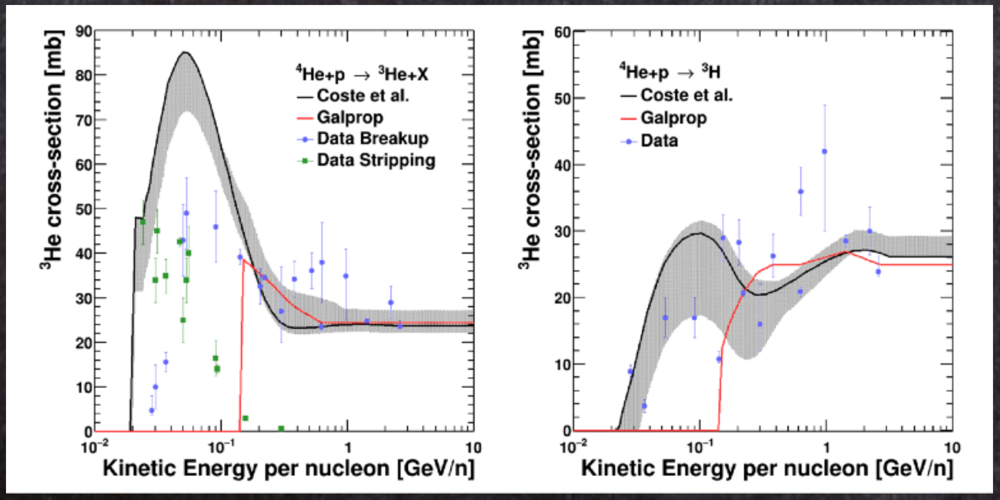
H and He isotopes

Coste+ A&A 2012

Gomez-Coral+ PRD 2024







Modelization of cross sections relies on poor data

Antimatter

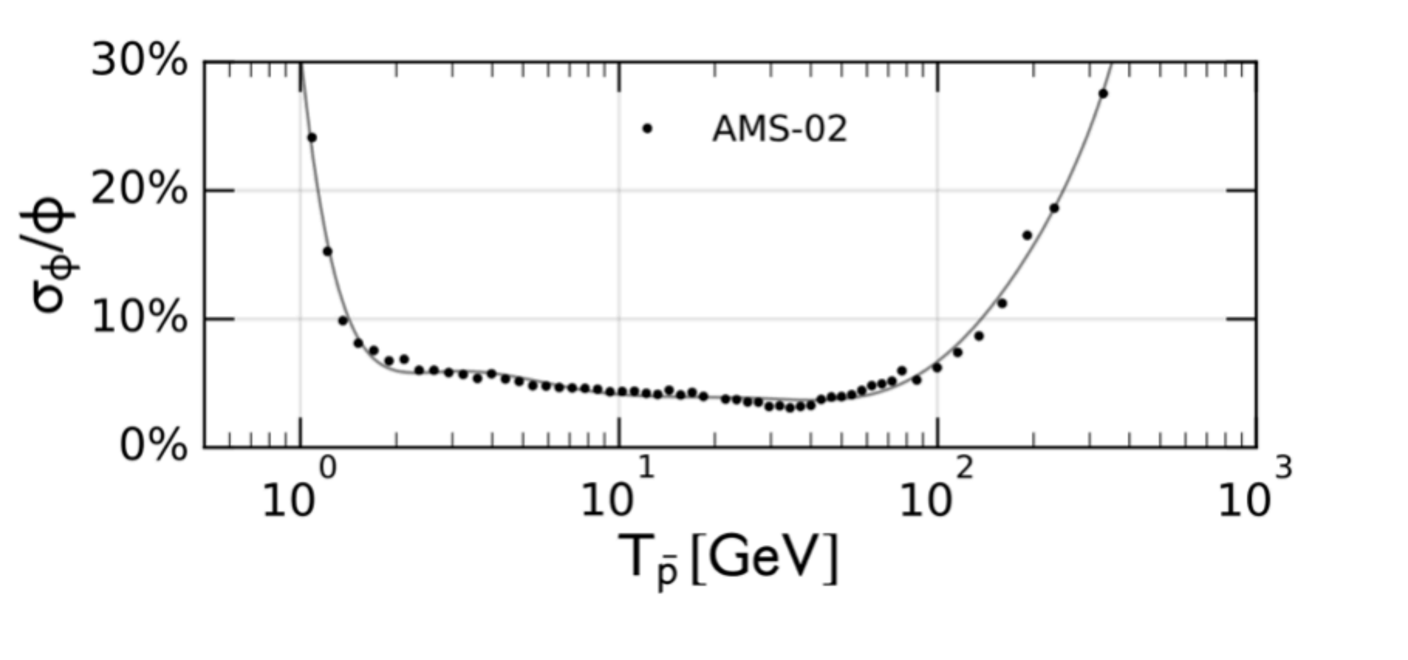
in the Galaxy

Antiproton production by inelastic scatterings

Korsmeier, FD, Di Mauro PRD 2018

$$q_{ij}(T_{\bar{p}}) = \int_{T_{\rm th}}^{\infty} dT_i \; 4\pi \, n_{{\rm ISM},j} \, \phi_i(T_i) \, \frac{d\sigma_{ij}}{dT_{\bar{p}}}(T_i, T_{\bar{p}}). \qquad \frac{d\sigma_{ij}}{dT_{\bar{p}}}(T, T_{\bar{p}}) = p_{\bar{p}} \int d\Omega \; \sigma_{\rm inv}^{(ij)}(T_i, T_{\bar{p}}, \theta).$$

Data from space are very precise



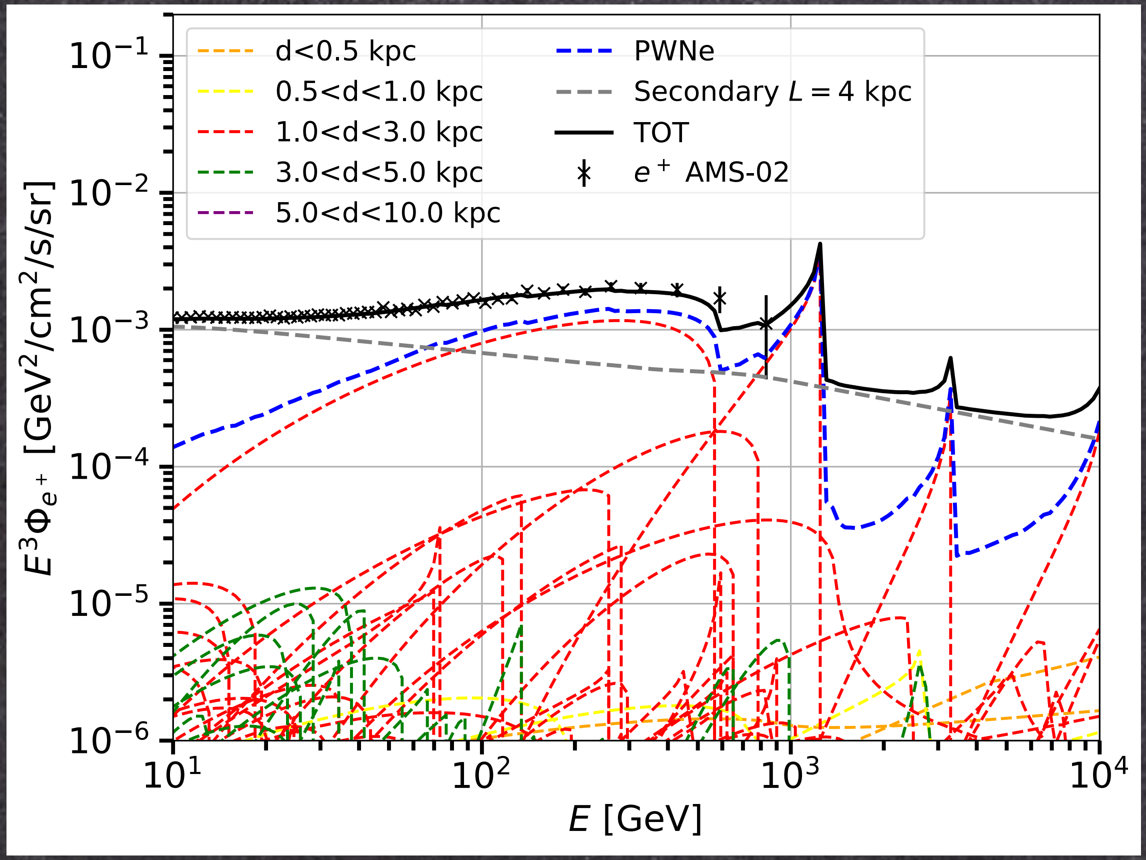
See talk by

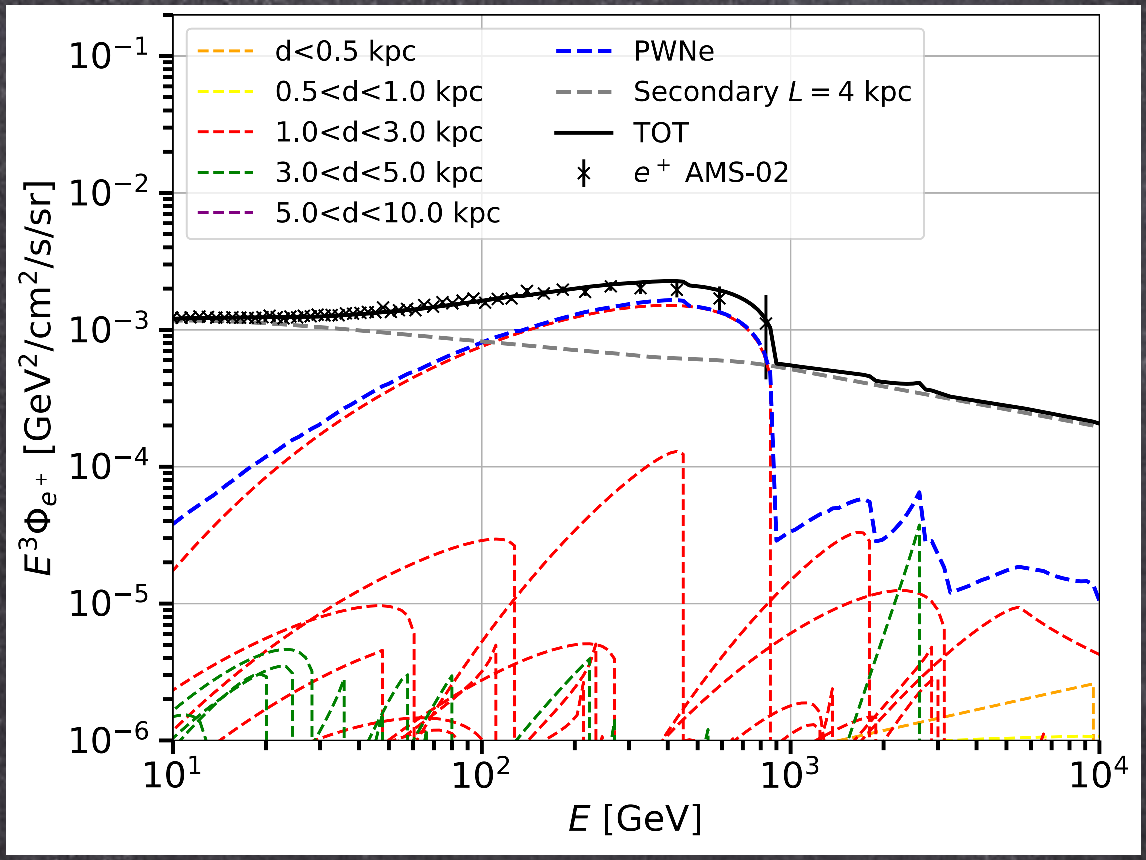
M. Di Mauro

We need cross sections at <3%

Fit of Galactic pulsar populations to AMS-02 e+ data

Orusa, Di Mauro, FD, Manconi JCAP 2021





The contribution of pulsars to e+ is dominant above 100 GeV and may have different features.

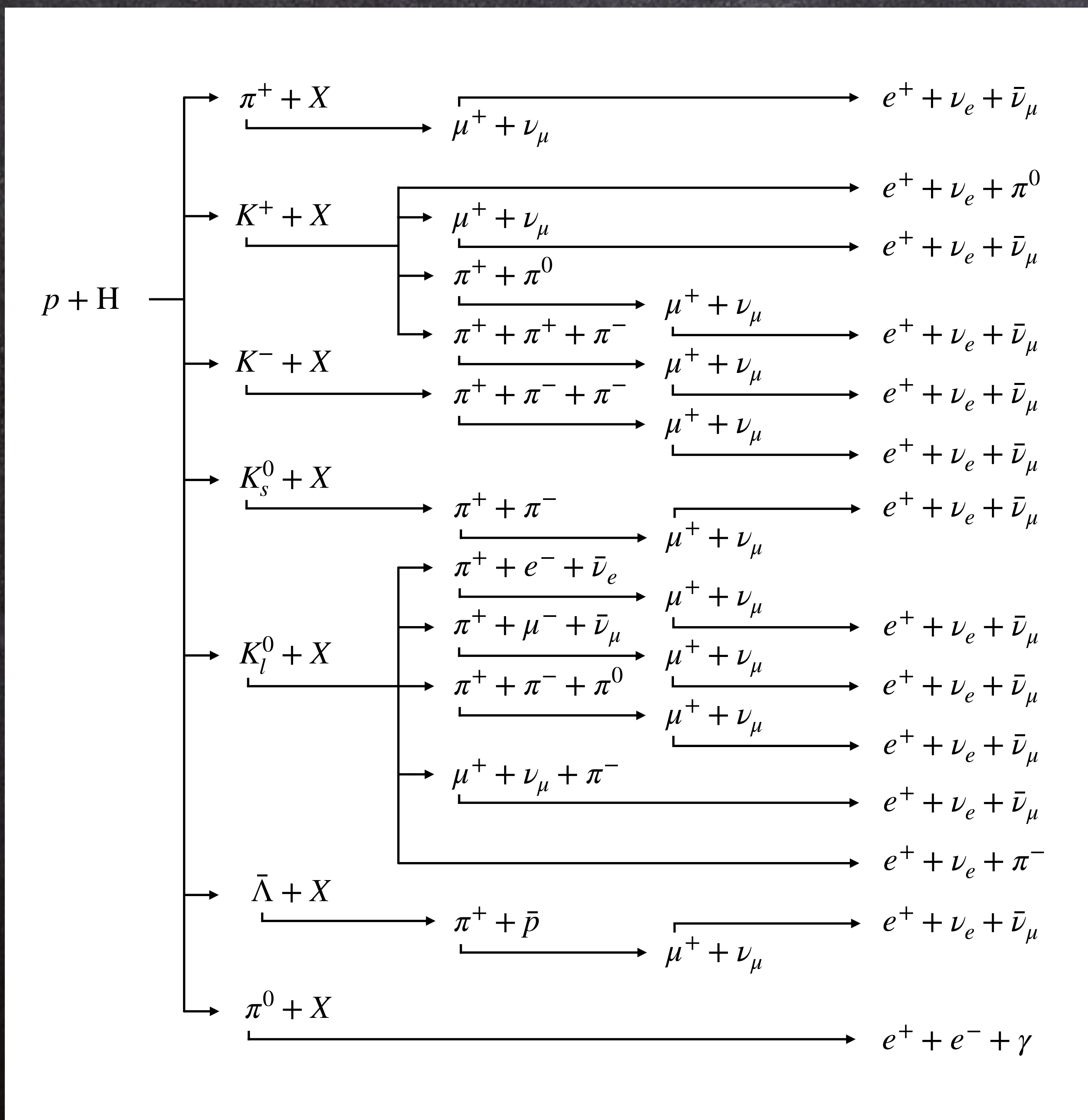
E>1 TeV: unconstrained by data.

Secondaries forbid evidence of sharp cut-off.

No need for Dark Matter, indeed

e+ production channels

$$q_{ij}(T_{e^+}) = 4\pi\, n_{\mathrm{ISM},j} \int dT_i\, \phi_i(T_i) \frac{d\sigma_{ij}}{dT_{e^+}}(T_i, T_{e^+})$$



L. Orusa, M. Di Mauro, FD, M. Korsmeier PRD 2022

We include all these contributions.

Similarly for collisions with nuclei.

We repeat ALL the analysis for e- under charge conjugation

The e± production chain from π± production

$$\frac{d\sigma_{ij}}{dT_{e^+}}(T_i, T_{e^+}) = \int dT_{\pi^+} \frac{d\sigma_{ij}}{dT_{\pi^+}}(T_i, T_{\pi^+})\, P(T_{\pi^+}, T_{e^+})$$

Integral over the pion production cross section convolved with the probability density function P

$$\frac{d\sigma_{ij}}{dT_{\pi^+}}(T_i, T_{\pi^+}) = p_{\pi^+} \int d\Omega\, \sigma_{\rm inv}^{(ij)}(T_i, T_{\pi^+}, \theta)$$

The pion production cross section is the integral of the lorentz Invariant cross section over scattering angle (or p_T)

$$\sigma_{\rm inv}^{(ij)} = E_{\pi^+} \frac{d^3\sigma_{ij}}{dp^3_{\pi^+}}$$

← data

A fit is performed on the σ_{inv} data

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Experiment	$\sqrt{s}$ [GeV]	$\sigma_{\rm inv}$	n	Ref.
NA49	17.3	×	×	[22]
ALICE	900	×	-	[23]
CMS	900, 2760, 7000, 13000	×	-	[24, 25]
Antinucci	π^+ (3.0, 3.5, 4.9, 5.0, 6.1, 6.8)	-	×	[26]
	π^-(3.0, 3.5, 4.9, 5.0, 6.1, 6.8)	-	×	[26]
	K^+ (2.8, 3.0,3.2, 5.0, 6.1, 6.8)	-	×	[26]
	K^- (4.9, 5.0, 6.1, 6.8)	-	×	[26]
NA61	6.3, 7.7, 8.8, 12.3, 17.3	-	×	[21]

We use data on σ_{inv}, the multiplicity n or both.

Results on the σ_{inv} for π^+ production

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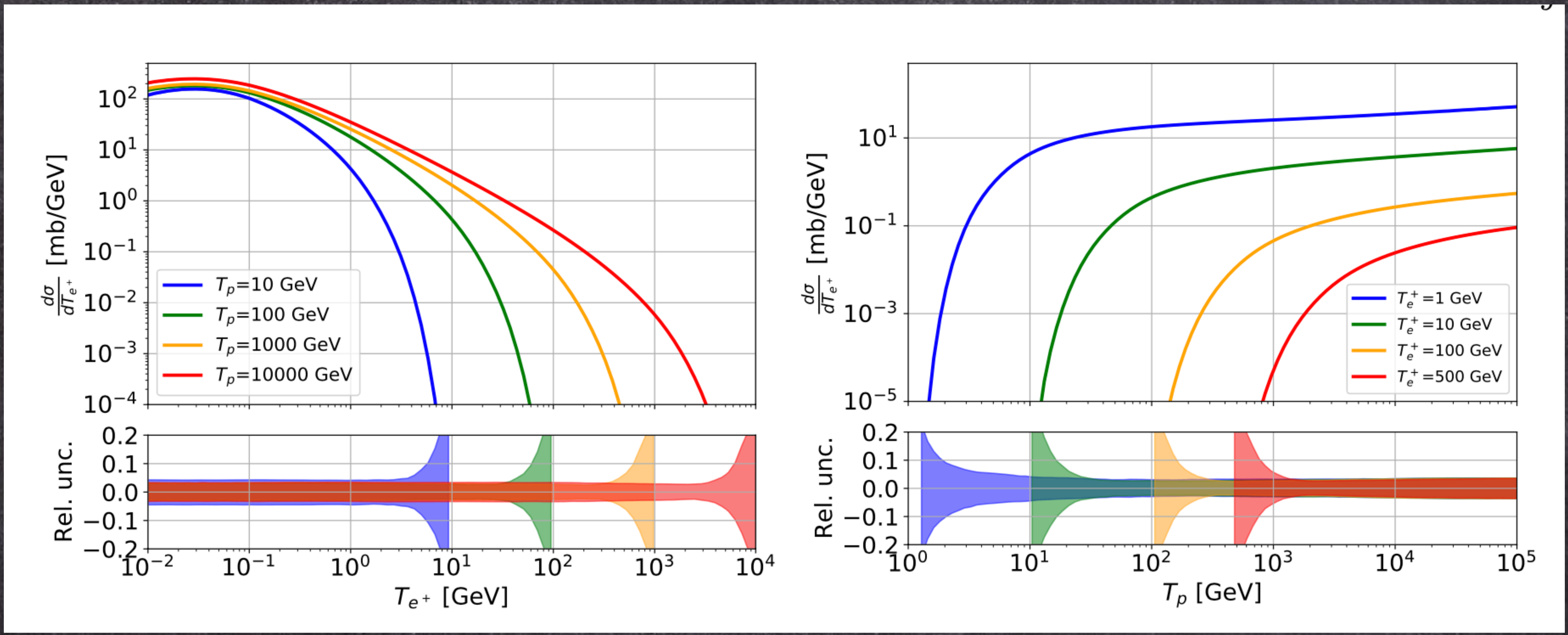

Data are fitted with very small uncertainties

Our parameterizations result appropriate, data are very precise

Total cross section from pp—> e+ + X

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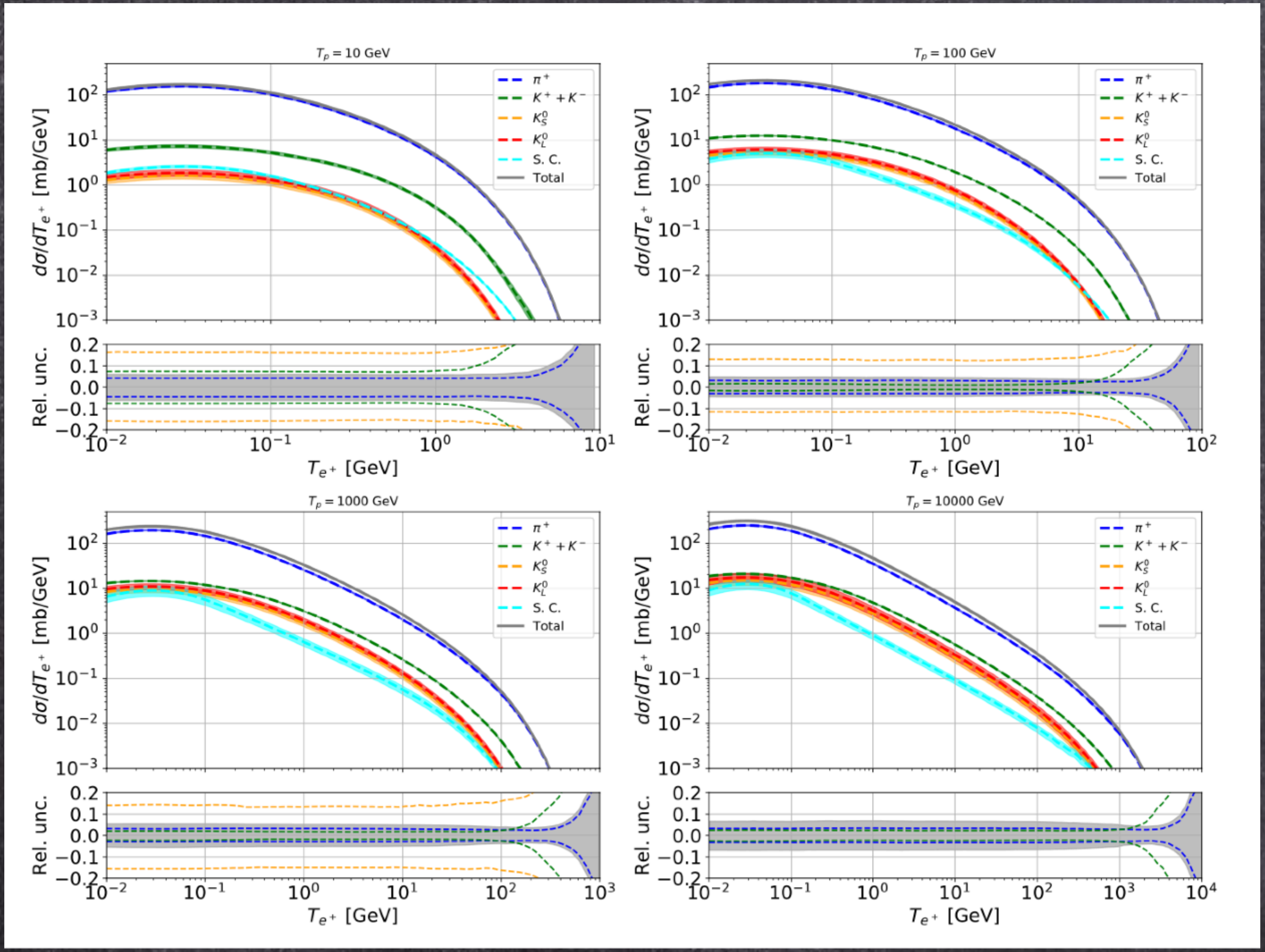

All channels contributing >0.5% are included.

Uncertainty globally contained to <10%

Effect of scattering off nuclei

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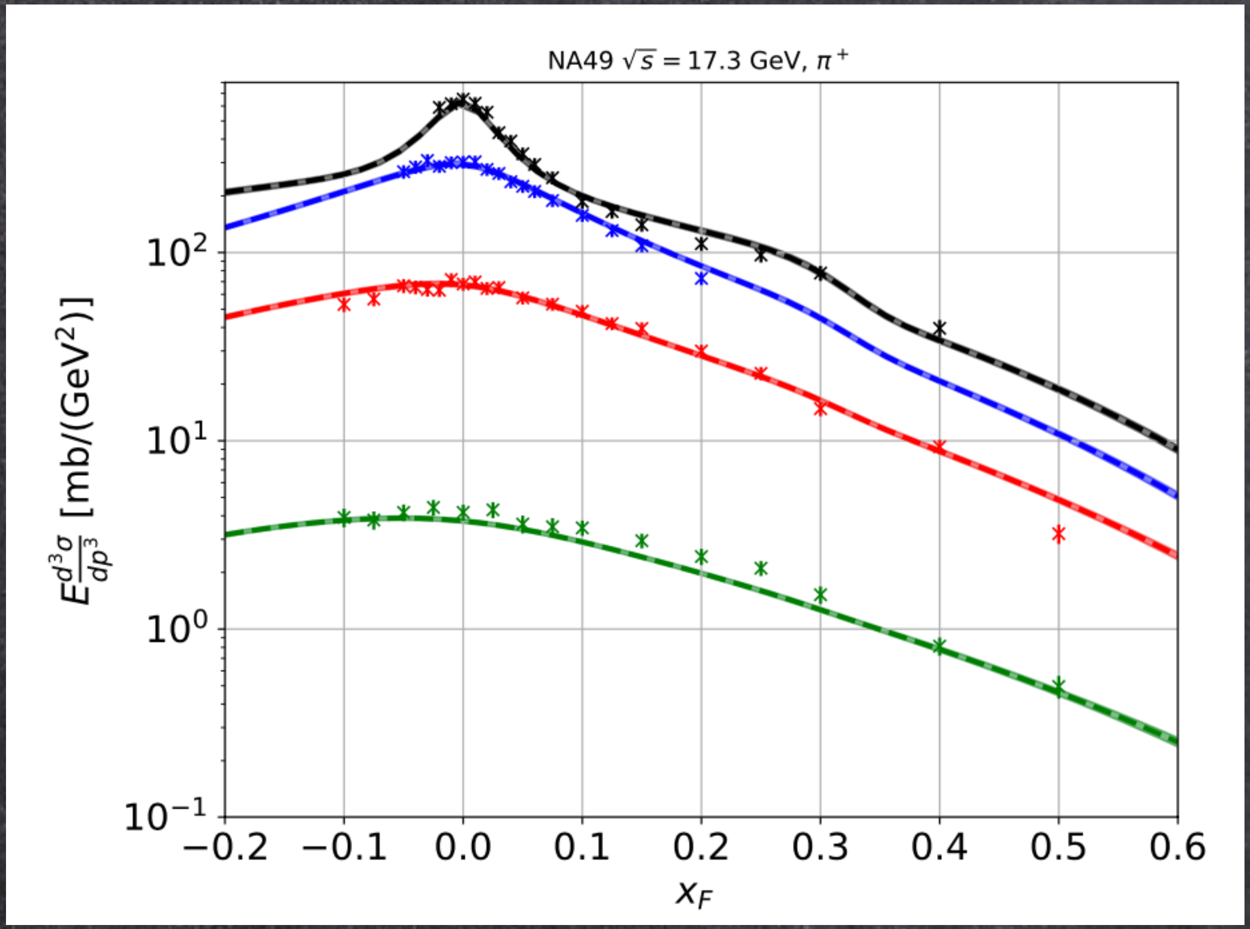
We need a model for the scattering involving He.
No data are there. We rely on NA49 p+C—>e⁺+X data



Uncertainty is small, but very likely is not the true one

Data on He are necessary

Final results on e+ cross section

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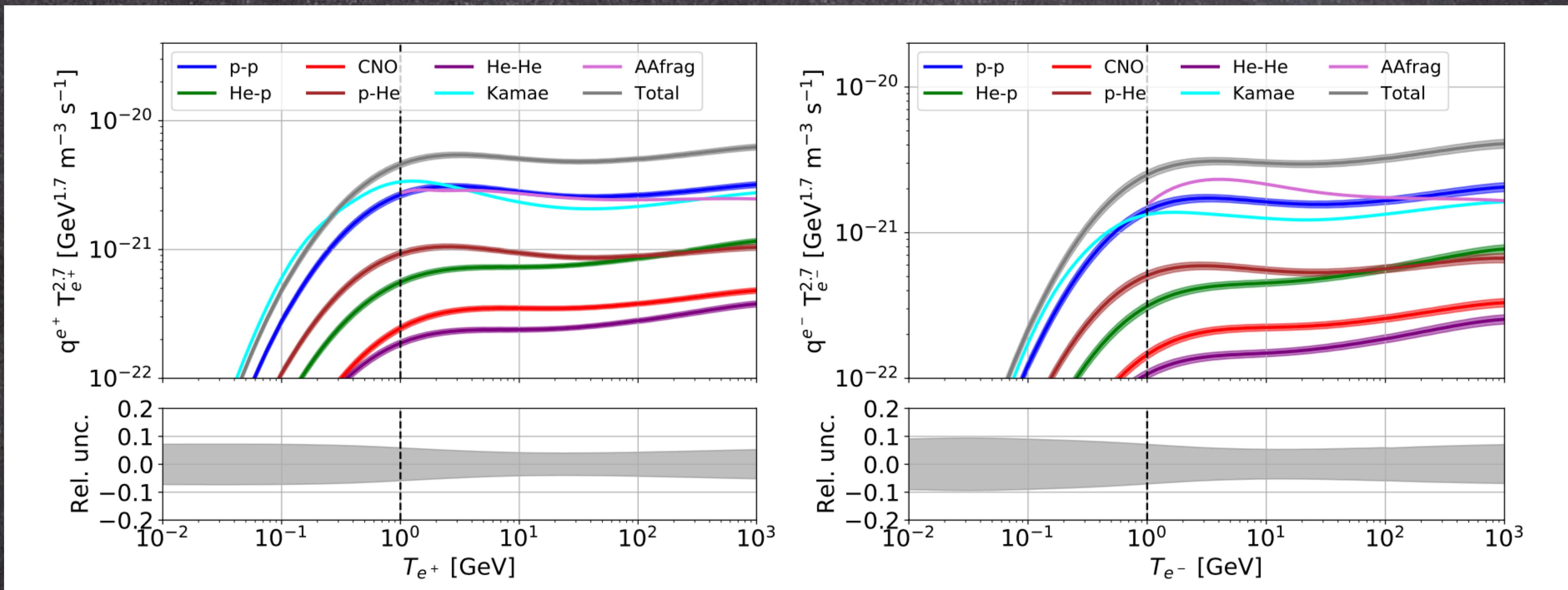
Positrons | Electrons



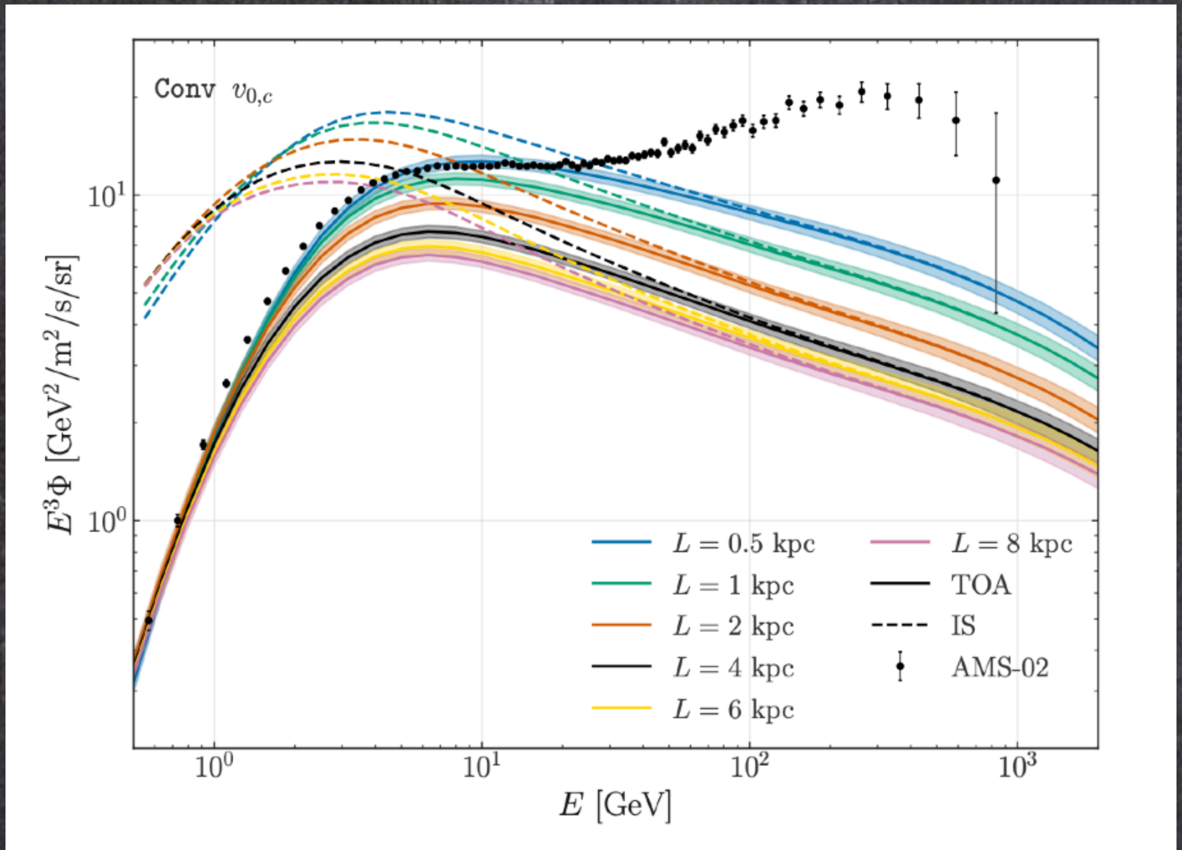
Production cross section is now known why 7-8% uncertainty above 1 GeV. Below we extrapolate.

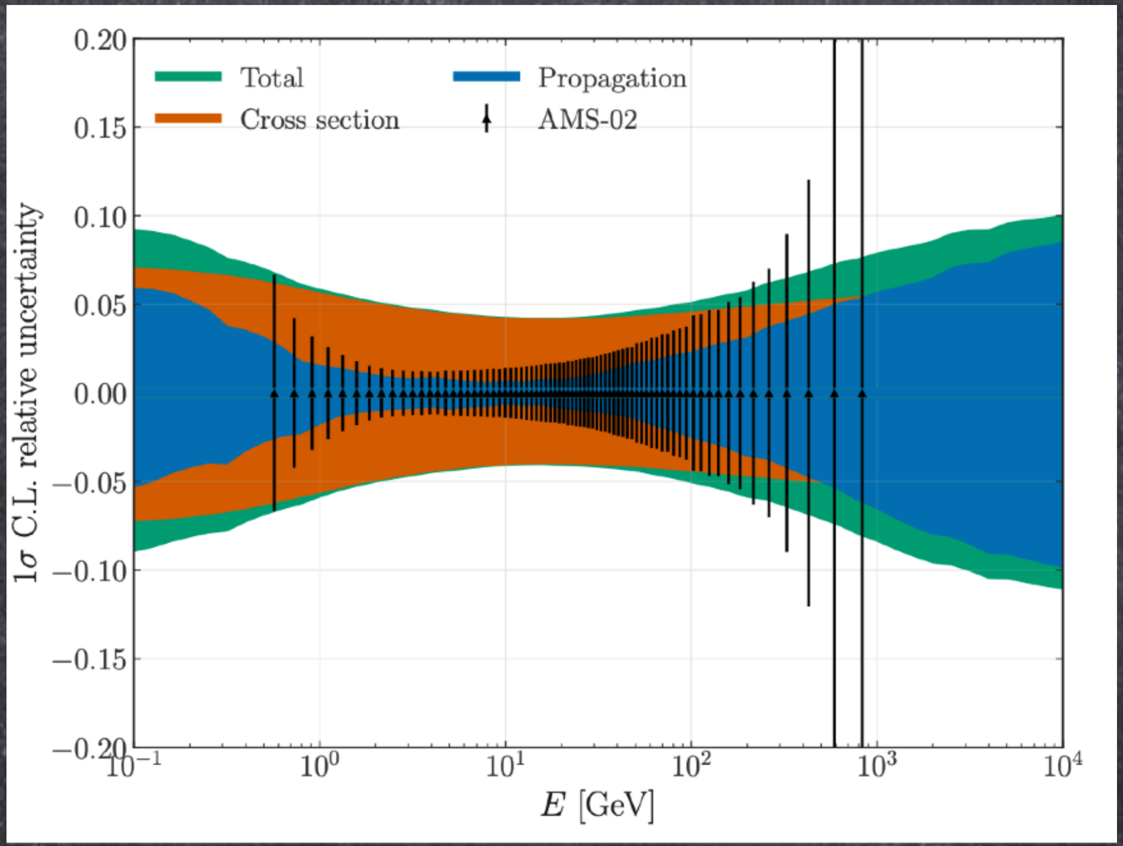
Comparison with MonteCarlo computations is done for p-p.

Similar results for e-.

The role of e± secondaries

Di Mauro, FD, Korsmeier, manconi, Orusa, PRD 2023



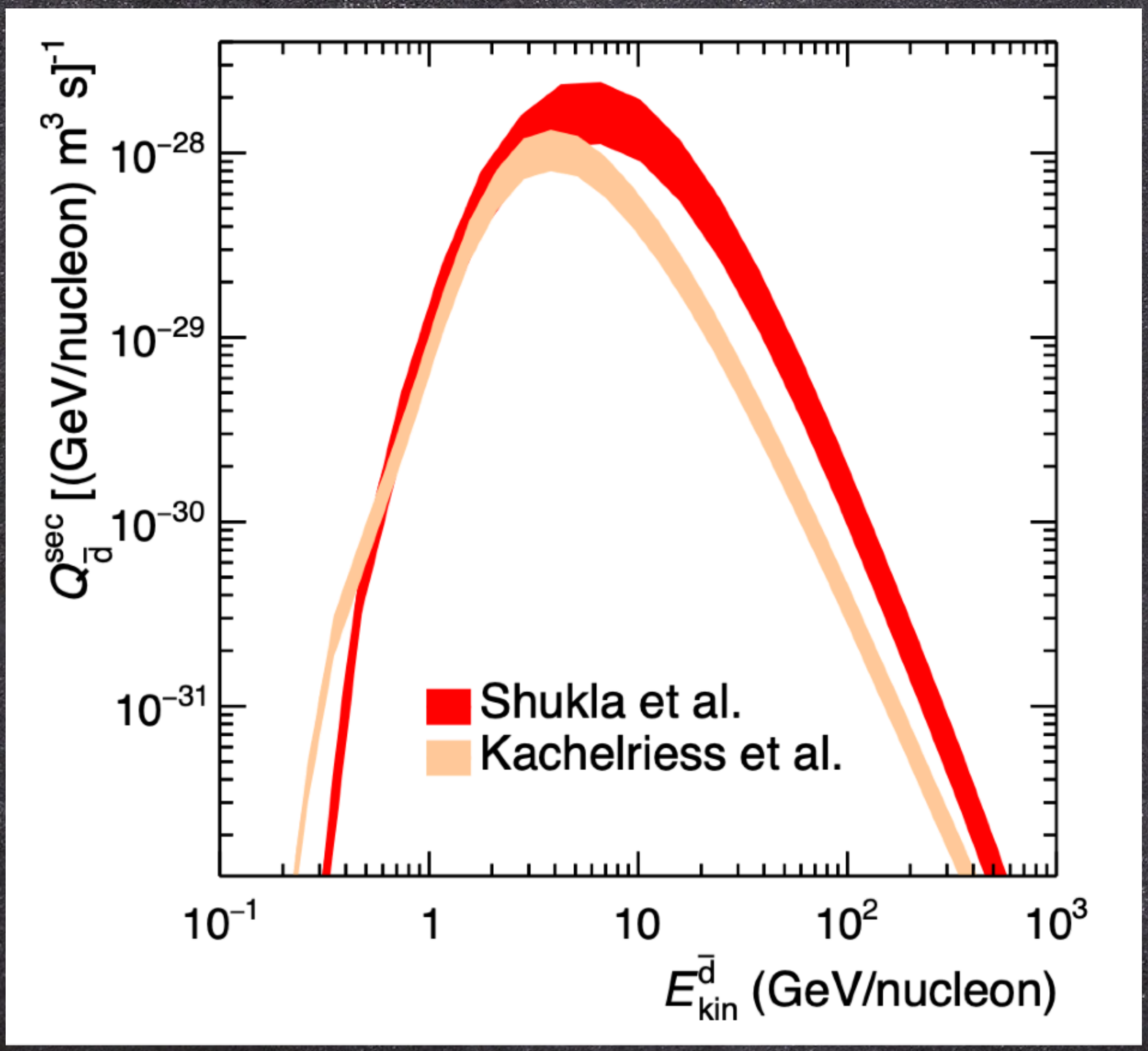


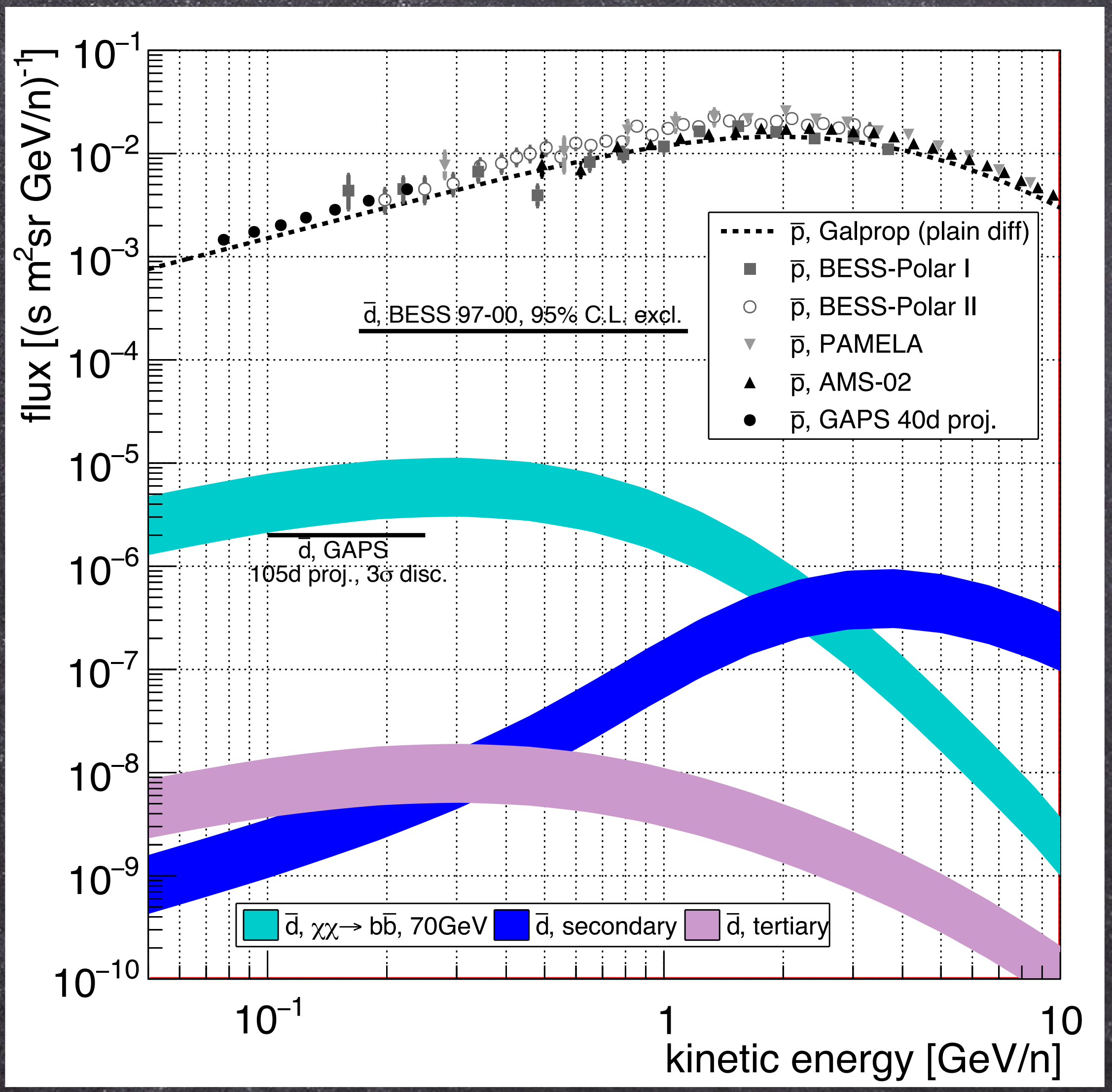
e+ secondaries contribute significantly to shape the spectrum at Earth below few GeV

Cross section uncertainties at the same level or greater than propagation ones (L= 4 kpc)

Antideuterons persepctives

Serksnyte et al,PRD 2022





Low energy window is a discovery field

Uncertainty in cross sections (left)

Uncertainties on P_c is ± 70%, P_c^3 in the flux (right)

Conclusions

Great efforts to better understand nuclei and antinuclei in CRS: theory models, data from space, data from colliders.

Data from space are actually hampered by lack of precise (<10%) ross section: nuclei, isotopes, antimatter, γs

Data from colliders are highly desirable.
A specific receipt can be provided by the astroparticle community

A dedicated workshop at CERN 16-18/10/2024
https://indico.cern.ch/event/1377509/

Wishes' list

Partial, and personal

1. Low energy ($0.1 < T_{pbar} < 10$ GeV) antiprotons from p-p
2. Antideuteron fusion at low energies (p beam ~ $10-10^2$ GeV)
3. p+He--> e^++X (p+He--> π^++X)
4. ^{12}C+p --> LiBeB fragments with isotopes

+ many more!

Analytical formulae for e± production XS

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The procedure is fully data driven

$$\sigma_{\rm inv} = \sigma_0(s)\, c_1 \left[F_p(s, p_T, x_R) + F_r(p_T, x_R)\right] A(s),$$

$$F_p(s, p_T, x_R) = (1 - x_R)^{c_2} \exp(-c_3\, x_R)\, p_T^{c_4} \times \exp\left[-c_5 \sqrt{s/s_0}^{\,c_6} \left(\sqrt{p_T^2 + m_\pi^2} - m_\pi\right)^{c_7 \sqrt{s/s_0}^{\,c_6}}\right], \tag{8}$$

$$F_r(p_T, x_R) = (1 - x_R)^{c_8} \times \exp\left[-c_9\, p_T - \left(\frac{|p_T - c_{10}|}{c_{11}}\right)^{c_{12}}\right] \times \left[c_{13} \exp(-c_{14}\, p_T^{c_{15}} x_R) + c_{16} \exp\left(-\left(\frac{|x_R - c_{17}|}{c_{18}}\right)^{c_{19}}\right)\right]$$

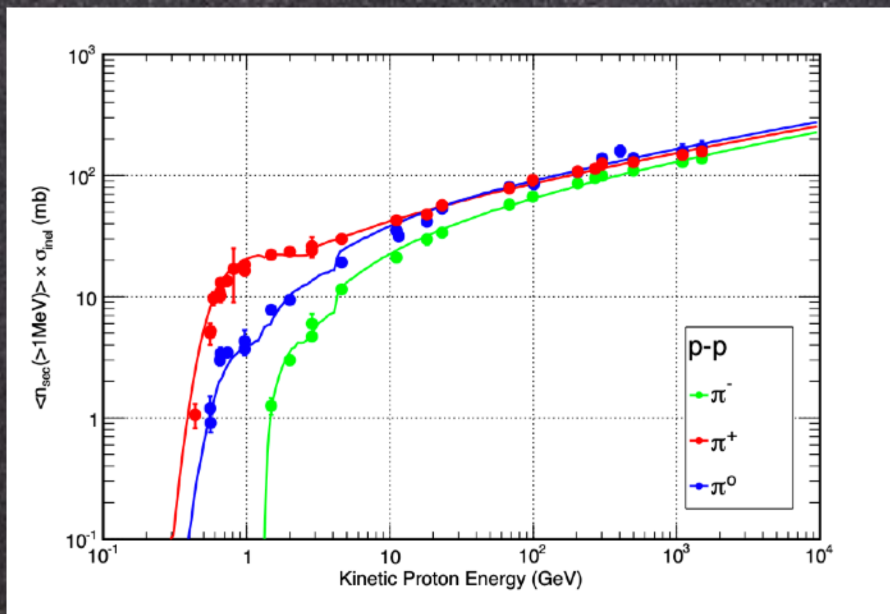
$$A(s) = \frac{1 + \left(\sqrt{s/c_{20}}\right)^{c_{21} - c_{22}}}{1 + \left(\sqrt{s_0/c_{20}}\right)^{c_{21} - c_{22}}} \left(\sqrt{\frac{s}{s_0}}\right)^{c_{22}}$$

F_s and F_r mainly driven by NA49 data

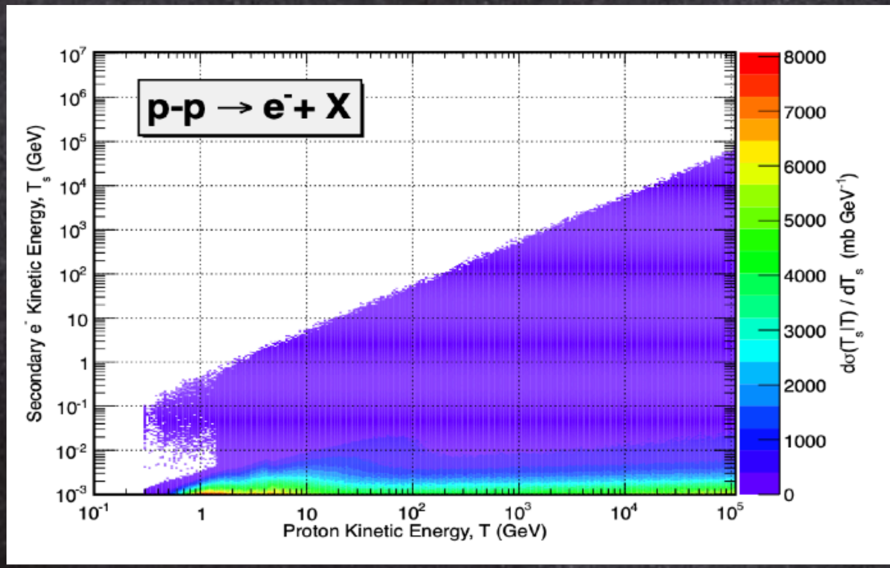
High energy behavior A(s) tested on CMS and ALICE data

Fluka MC generator

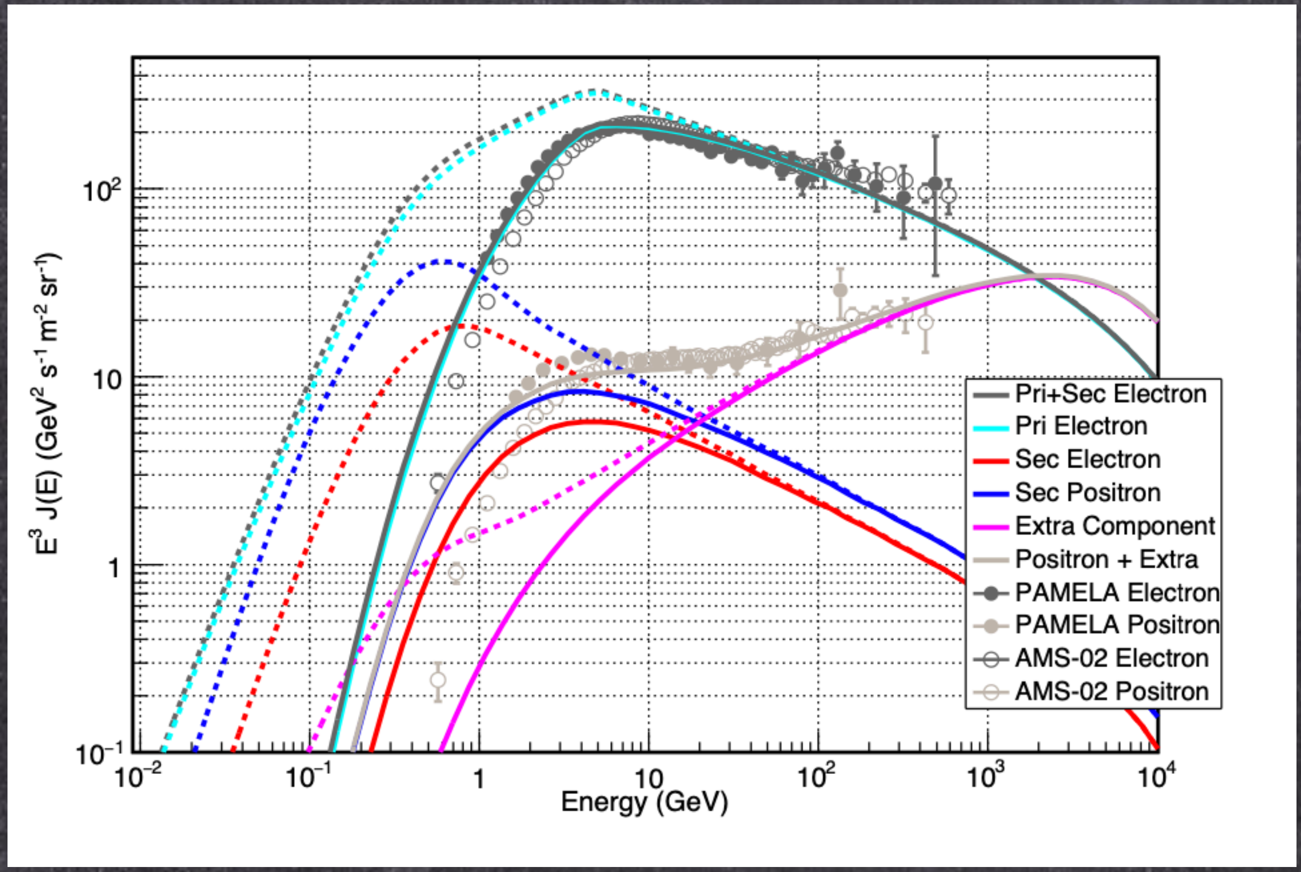
N. Mazziotta+, AP 2017



Points are from Dermer 1986



T_e is severely degraded from Projectile energy

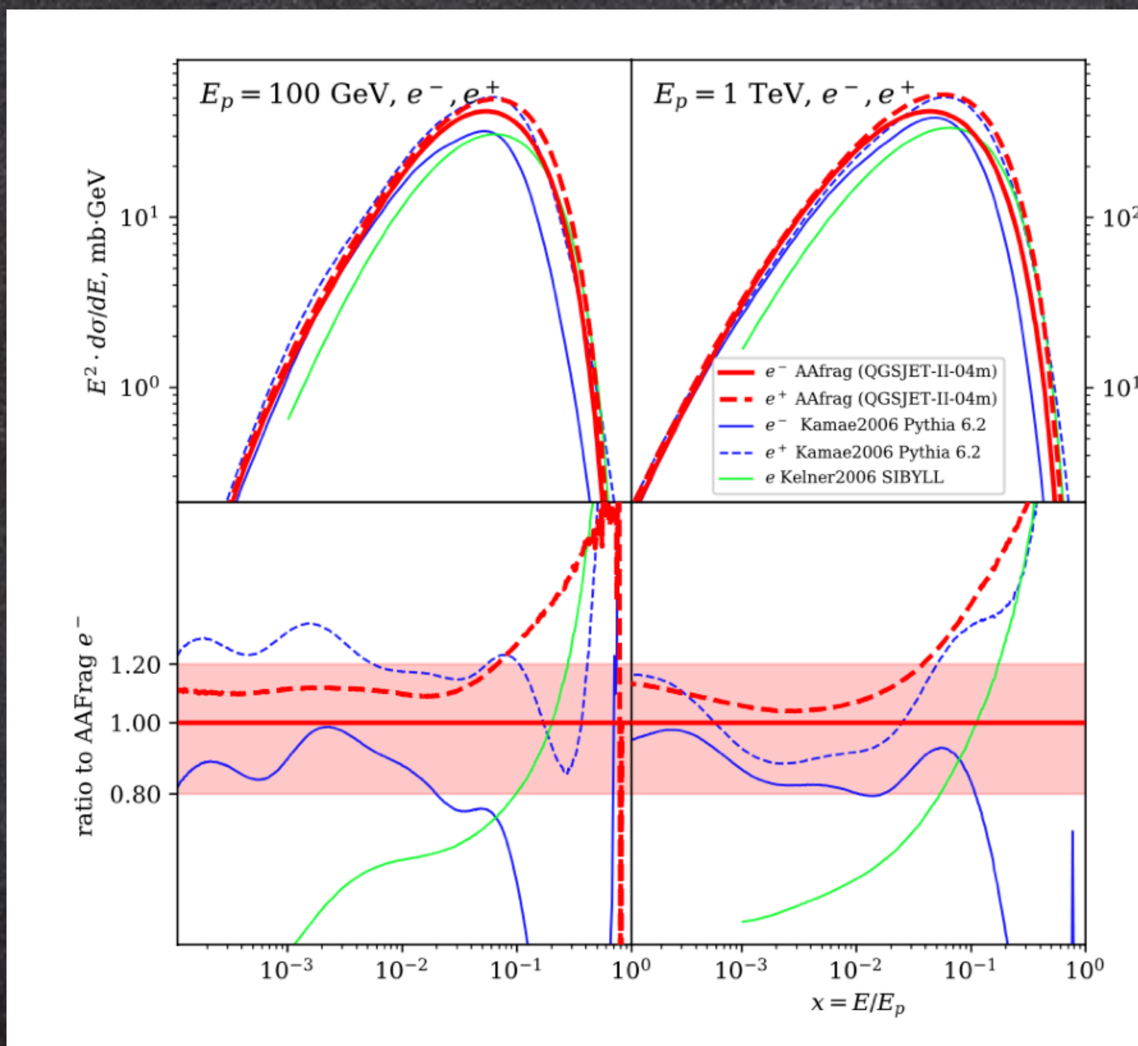


Propagated e+ and e- w.r.t. data

Comparison with Monte Carlo generators

Koldobskiy et al., PRD 2021, 2110.00496

Results with Aafrag



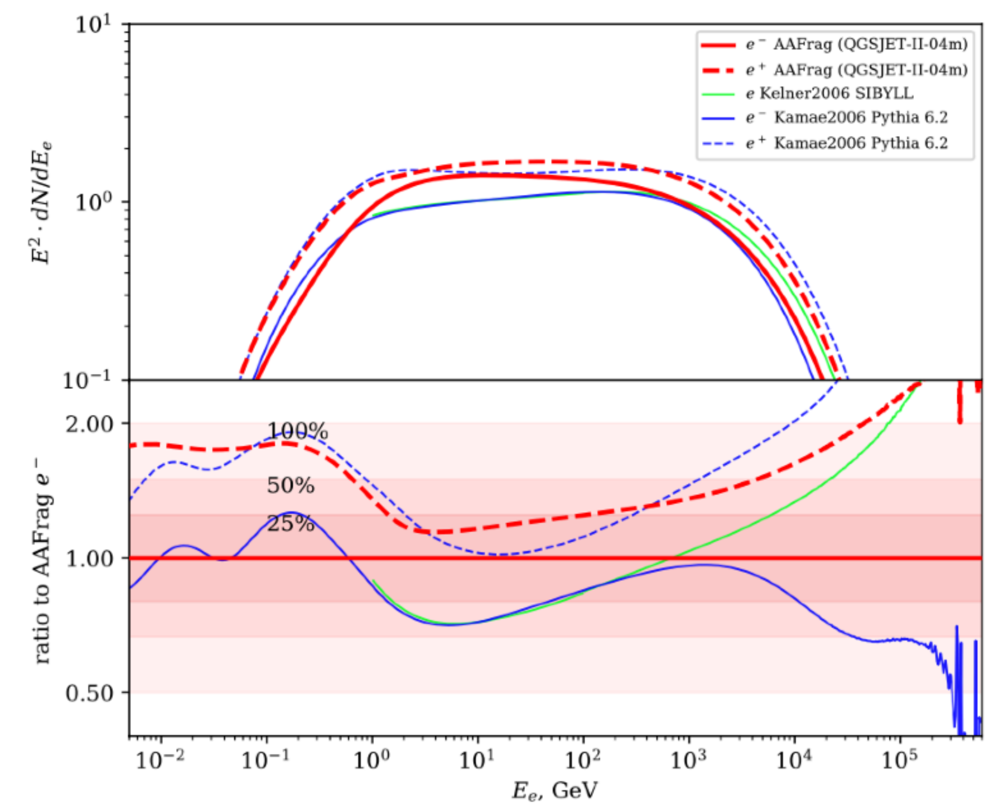


FIG. 9: Electron and positron fluxes for a power-law cosmic ray spectrum ($\propto 1/p^2 \exp(-p/p_0)$) .

Different MC modelings lead to considerable differences in the Production cross section, and consequently on the source spectrum

Results at large sqrt(s)

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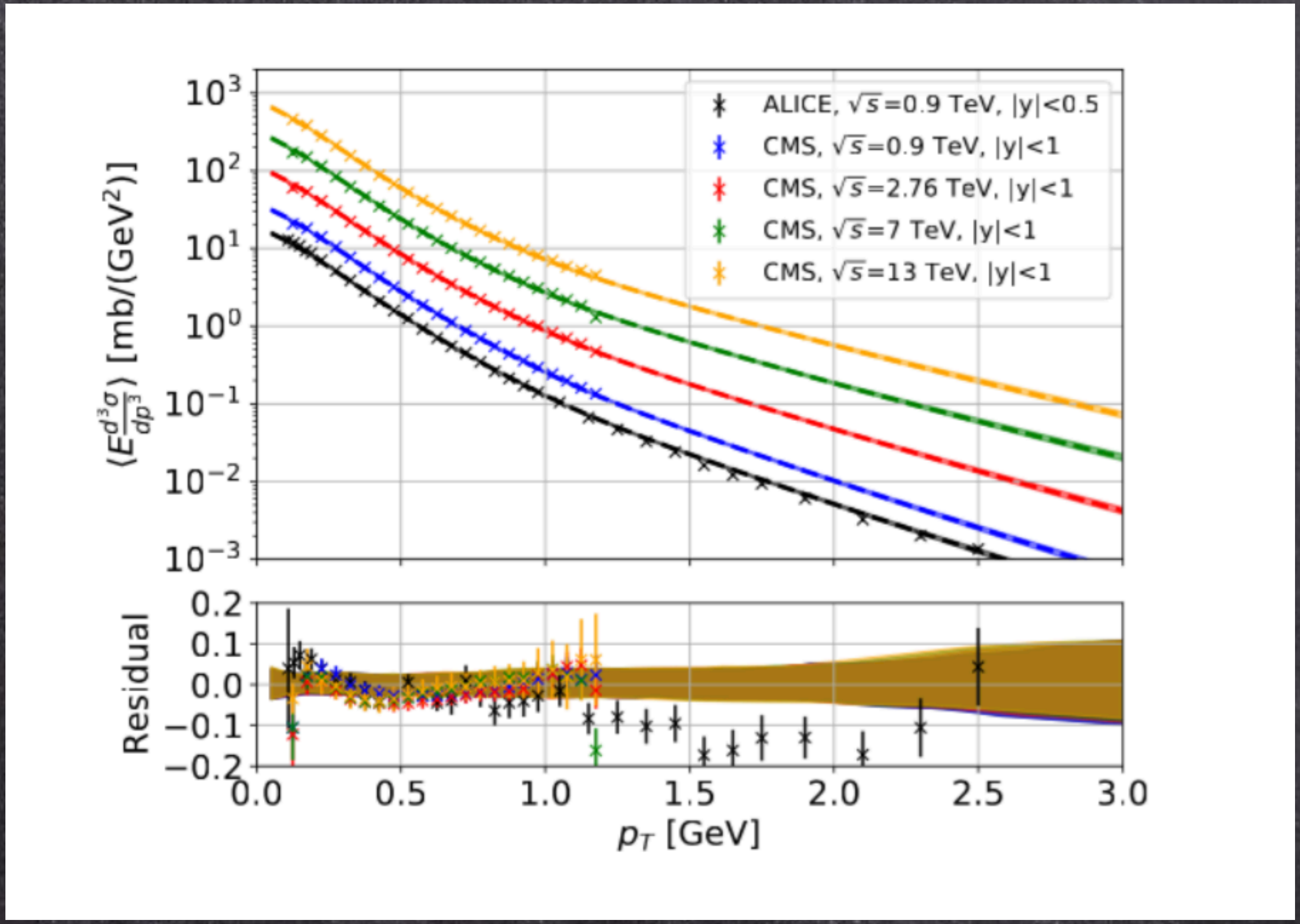
We use σ_{inv} or multiplicity



Uncertainties between 5% and 10% - most relevant is 5% at low p_T

Antimatter or γ-rays sources from DARK MATTER

Annihilation

$$Q_{\rm ann}(\vec{x},E) = \epsilon \left(\frac{\rho(\vec{x})}{m_{DM}}\right)^2 \sum_f \langle\sigma v\rangle_f \frac{dN^f_{e^\pm}}{dE}$$

Decay

$$Q_{\rm dec}(\vec{x},E) = \left(\frac{\rho(\vec{x})}{m_{DM}}\right) \sum_f \Gamma_f \frac{dN^f_{e^\pm}}{dE}$$

- ρ DM density in the halo of the MW
- m_{DM} DM mass
- $\langle\sigma v\rangle$ thermally averaged annihilation cross section in SM channel f
- Γ DM decay time
- e+, e- energy spectrum generated in a single annihilation or decay event

Annihilations take place in the whole diffusive halo