Secondary particles in the Galaxy: the role of cross sections

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Paris 05.12.2022 - "Cosmic Ray in the Multi-Messenger Era"

CRs in the Galaxy

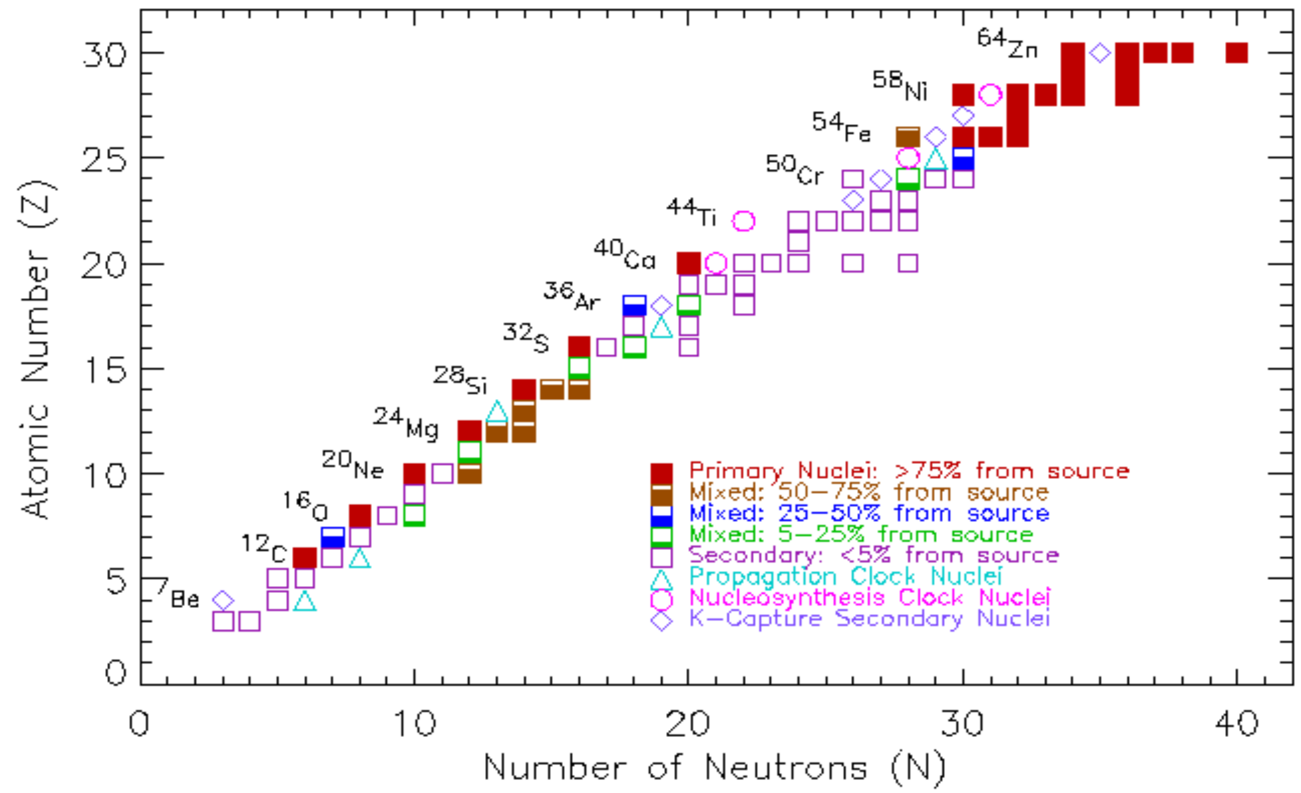
Primaries: produced in the sources (SNR and Pulsars)

H, He, CNO, Fe; e-, e+; possibly e^+, p^-, d^- from Dark Matter annihilation

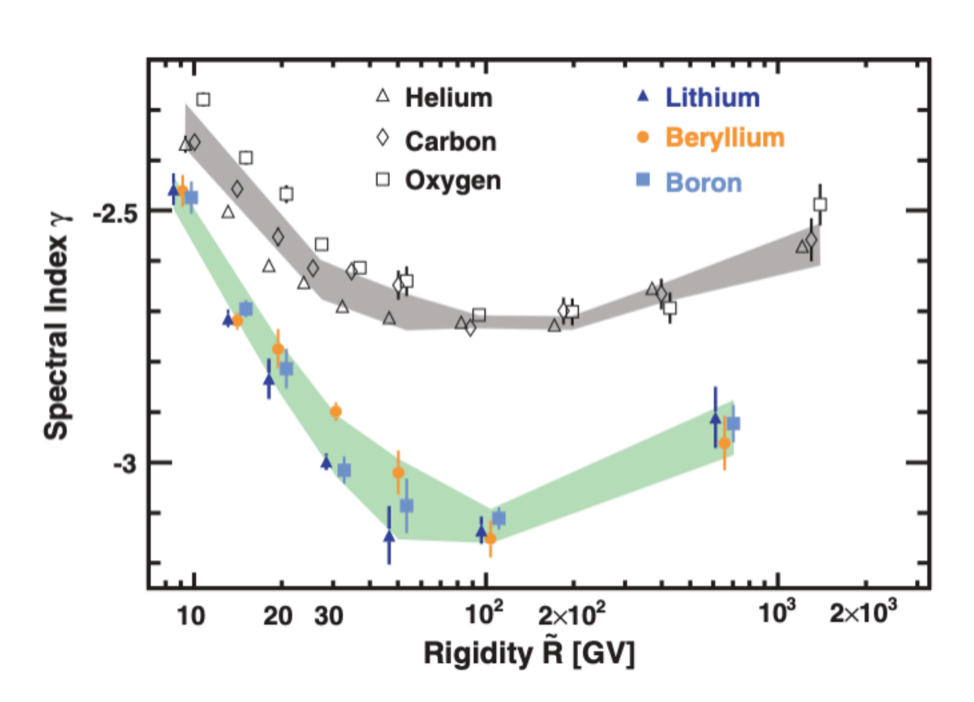
Secondaries: produced by spallation of primary CRs (p, He,C, O, Fe) on the interstellar medium (ISM): Li, Be, B, sub-Fe, [...], (radioactive) isotopes ; e^+, p^-, d^-

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

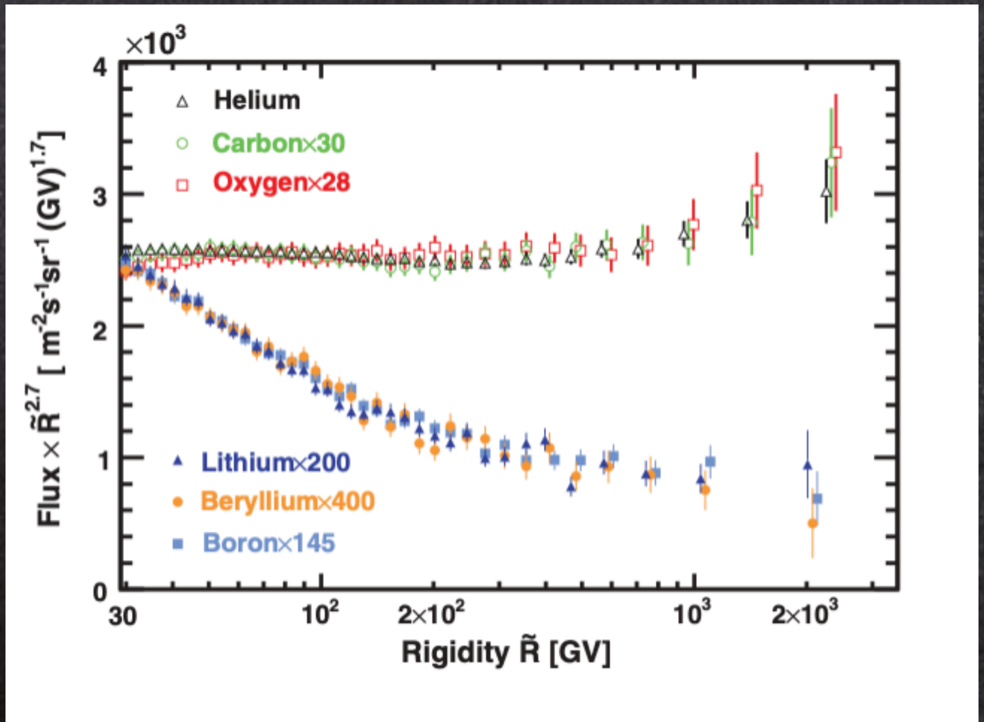


The spectrum of secondary fluxes



See talk by Paolo Zuccon

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

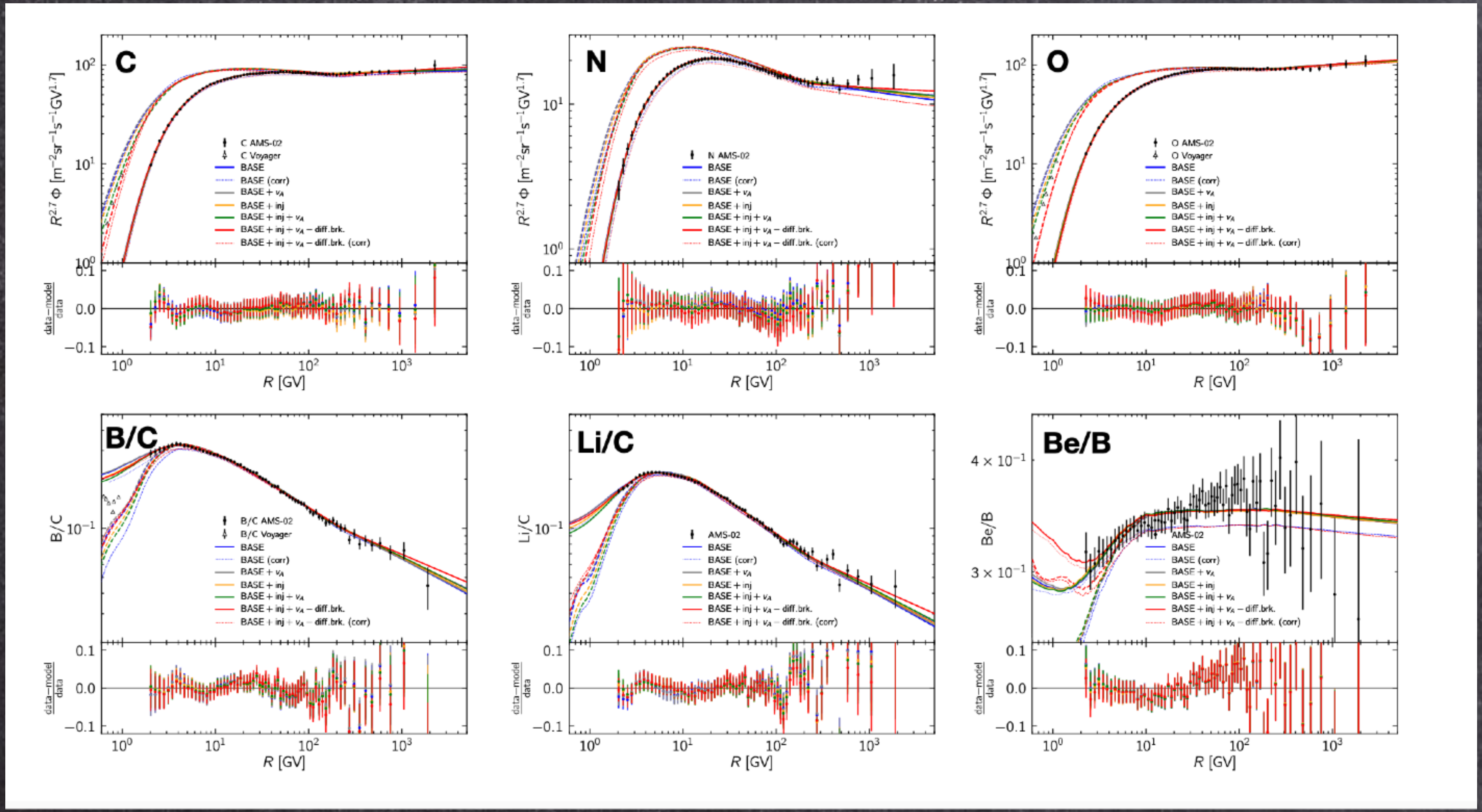


Li, Be, B fluxes measured by Pamela and AMS show an identical hardening w.r.t. energy above 200 GV.
The spectral index of secondaries hardens 0.13 +- 0.03 more than for primaries

Propagation models vs data

Korsmeier & Cuoco, PRD 2021

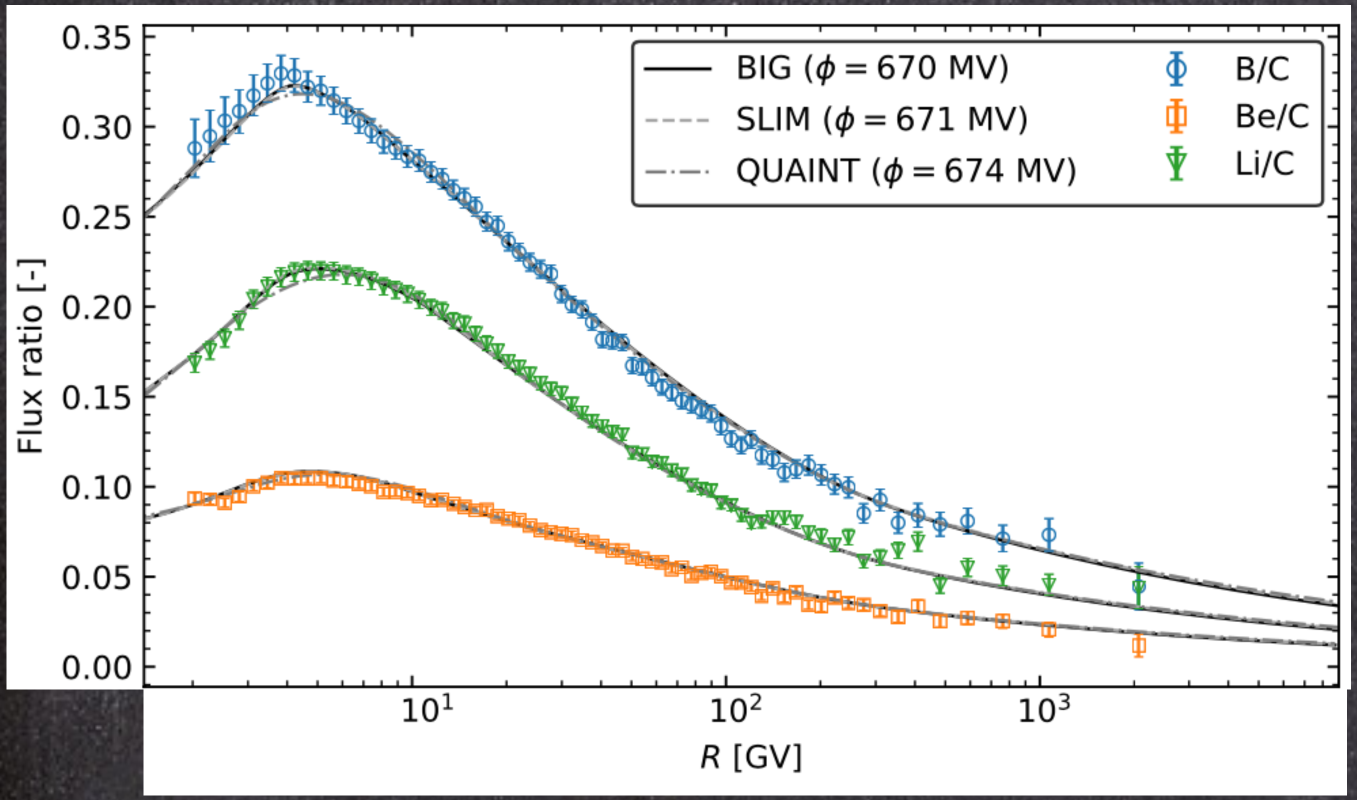
Several propagation models are tested

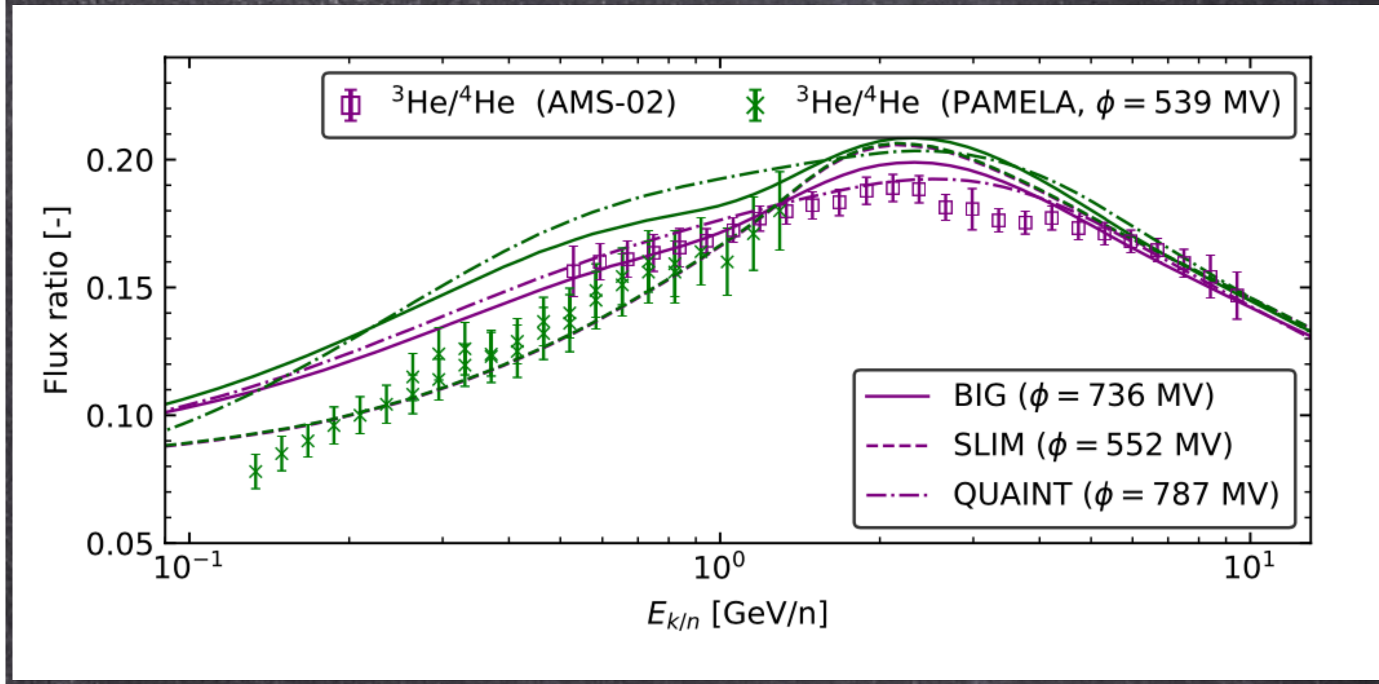


Fragmentation cross section uncertainties currently prevent a better understanding of CR propagation

Propagation models vs data

Weinrich+ A&A 2020





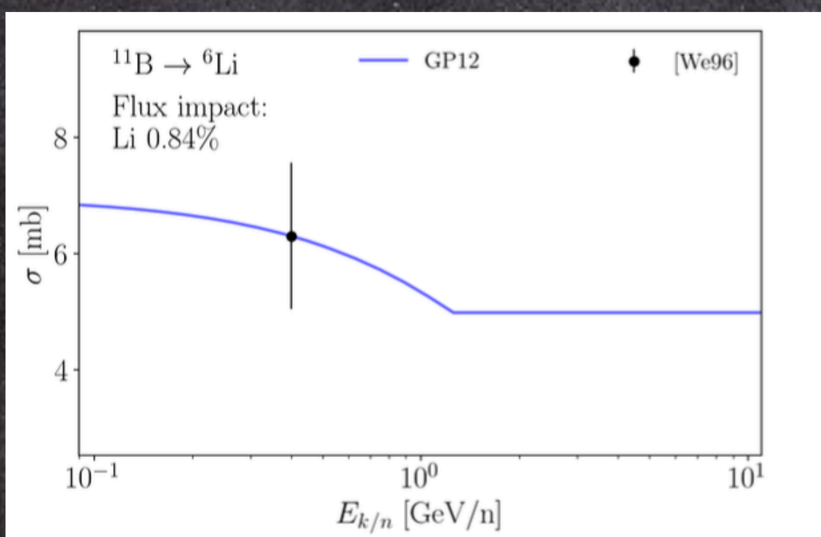
Data on secondary/primary species are well described by propagation model with diffusione coefficient power index $\delta = 0.50 \pm 0.03$.

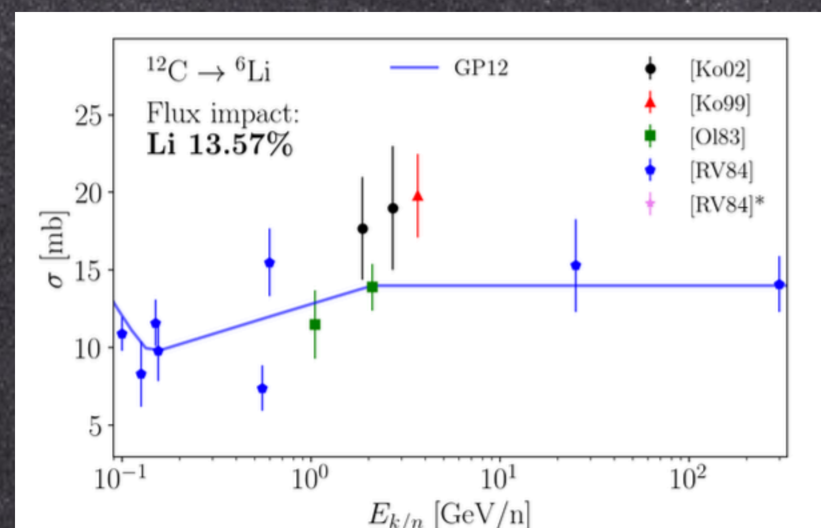
Convection + reaccelerating, or pure diffusion both work.

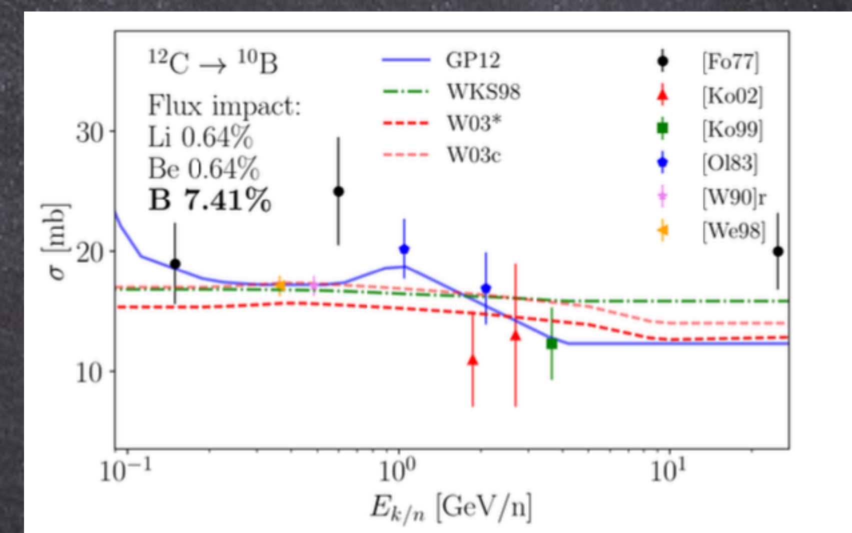
Cross sections for Galactic cosmic rays

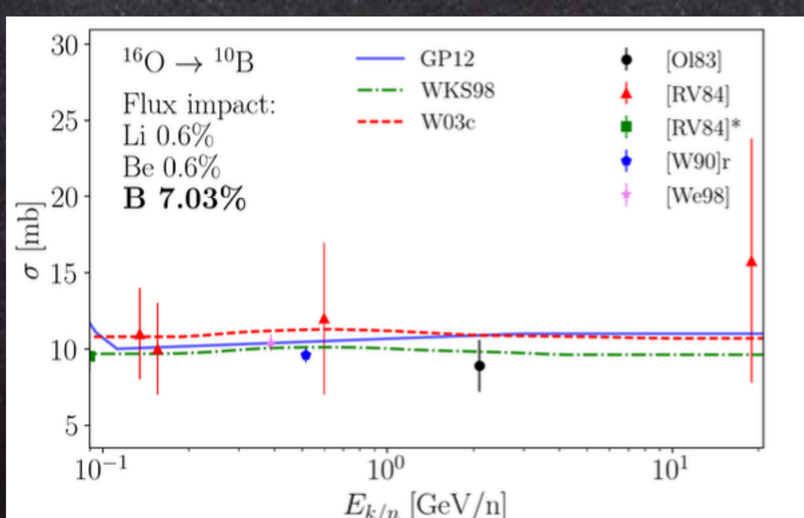
Data driven parameterizations (Silberberg&Tsao), semi-empirical formulae (Webber+), parametric formulae/direct fit to the data (Galprop), MonteCarlo codes (Fluka, Geant, ...)

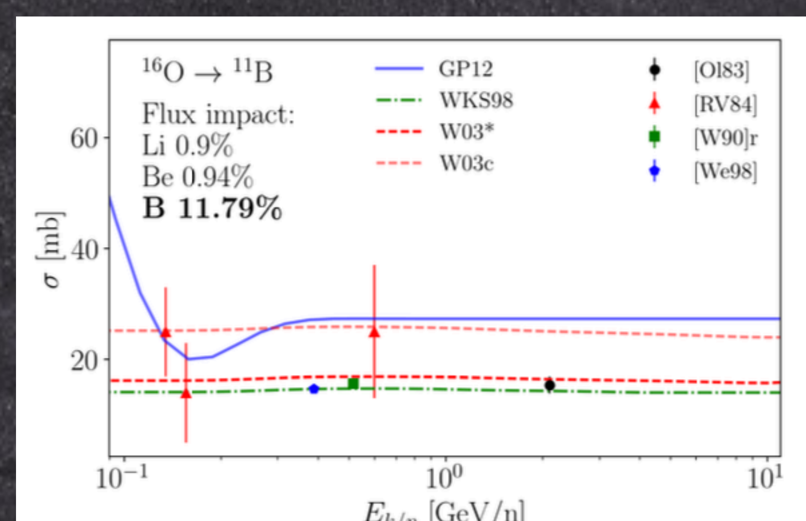
Genolini, Moskalenko, Maurin, Unger PRC 2018

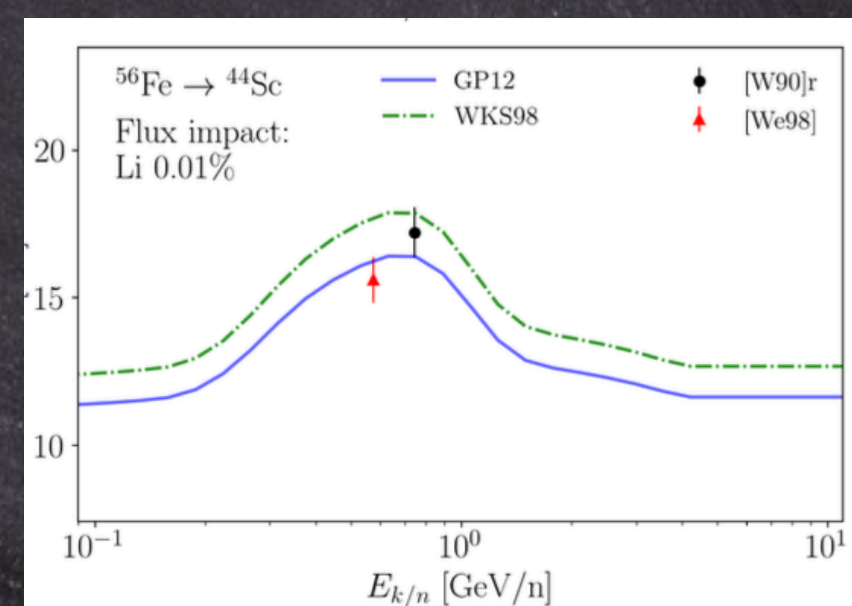








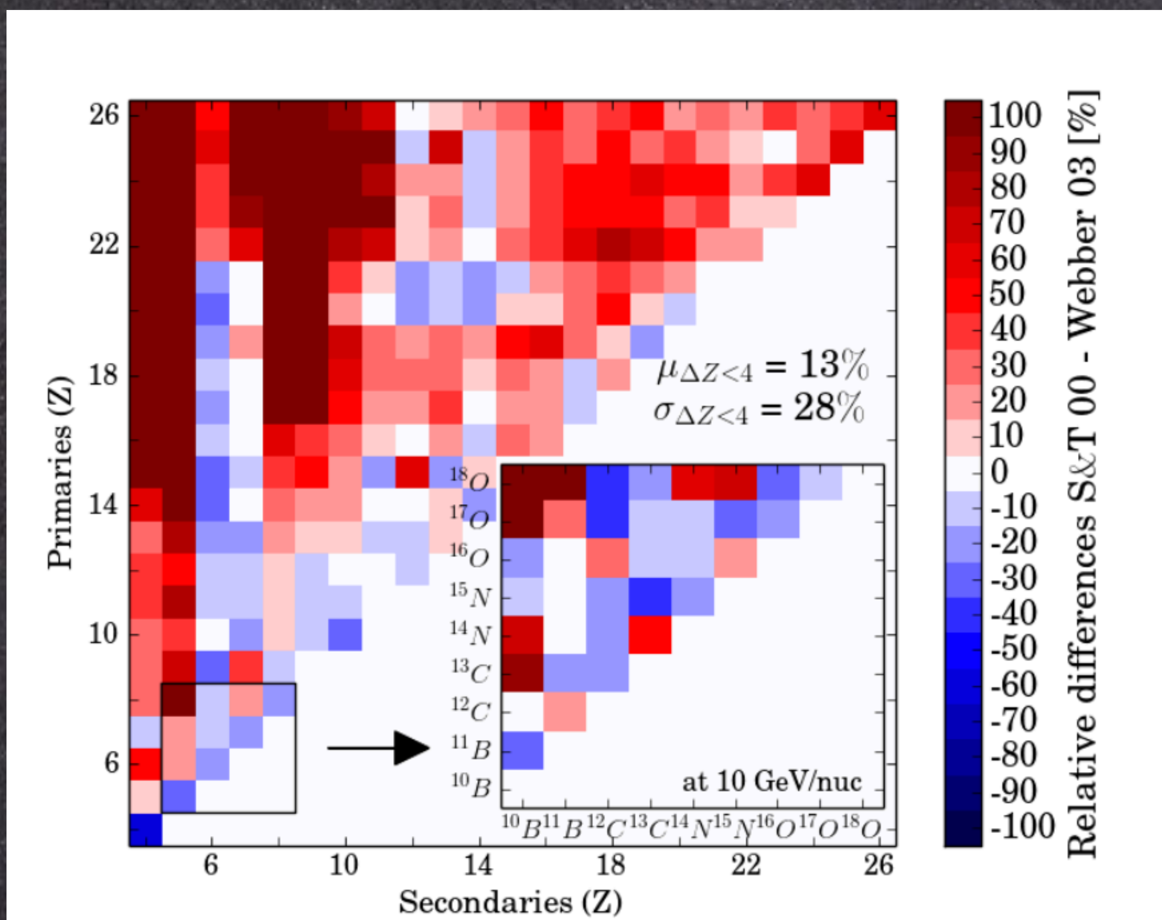


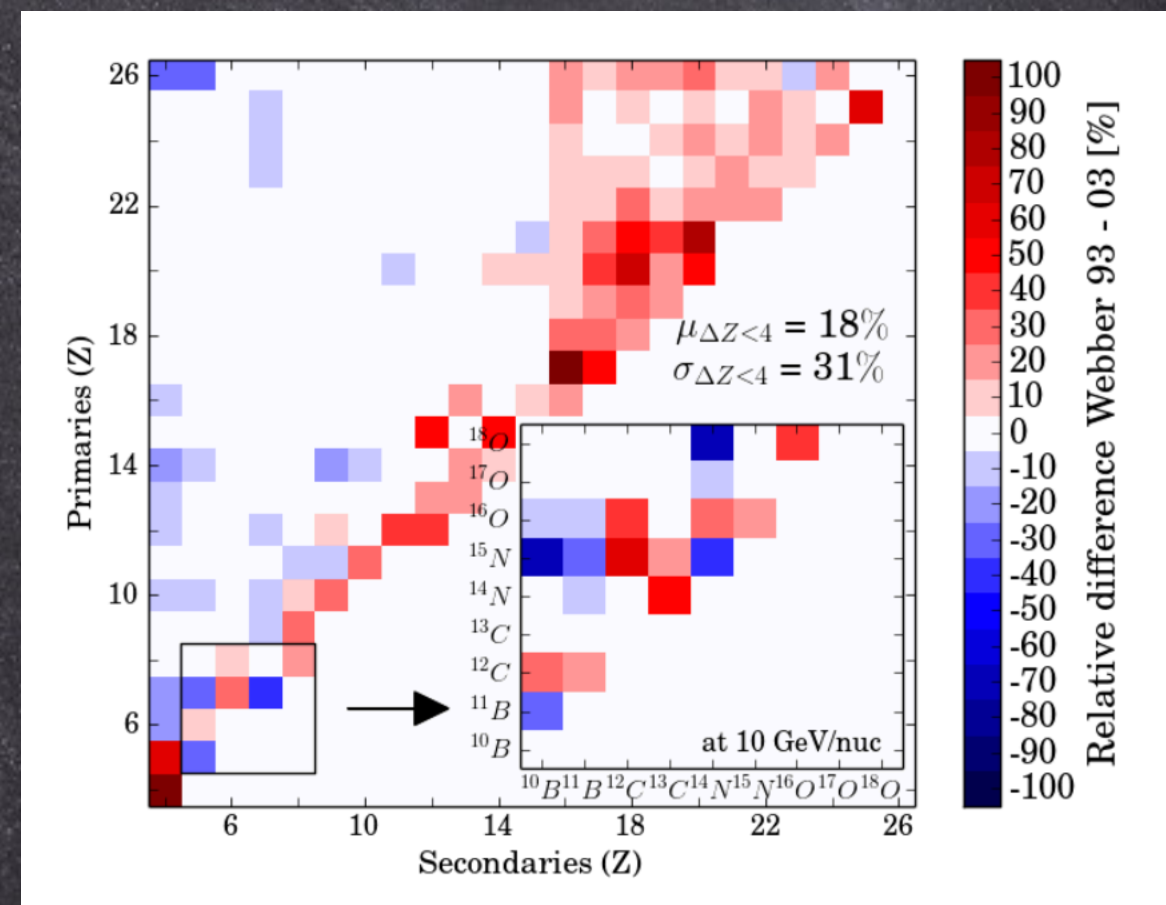


Differences in the XS parameterizations

Genolini, Putze, Salati, Serpico A&A 2015

Differences in one parameterization wrt a benchmark model



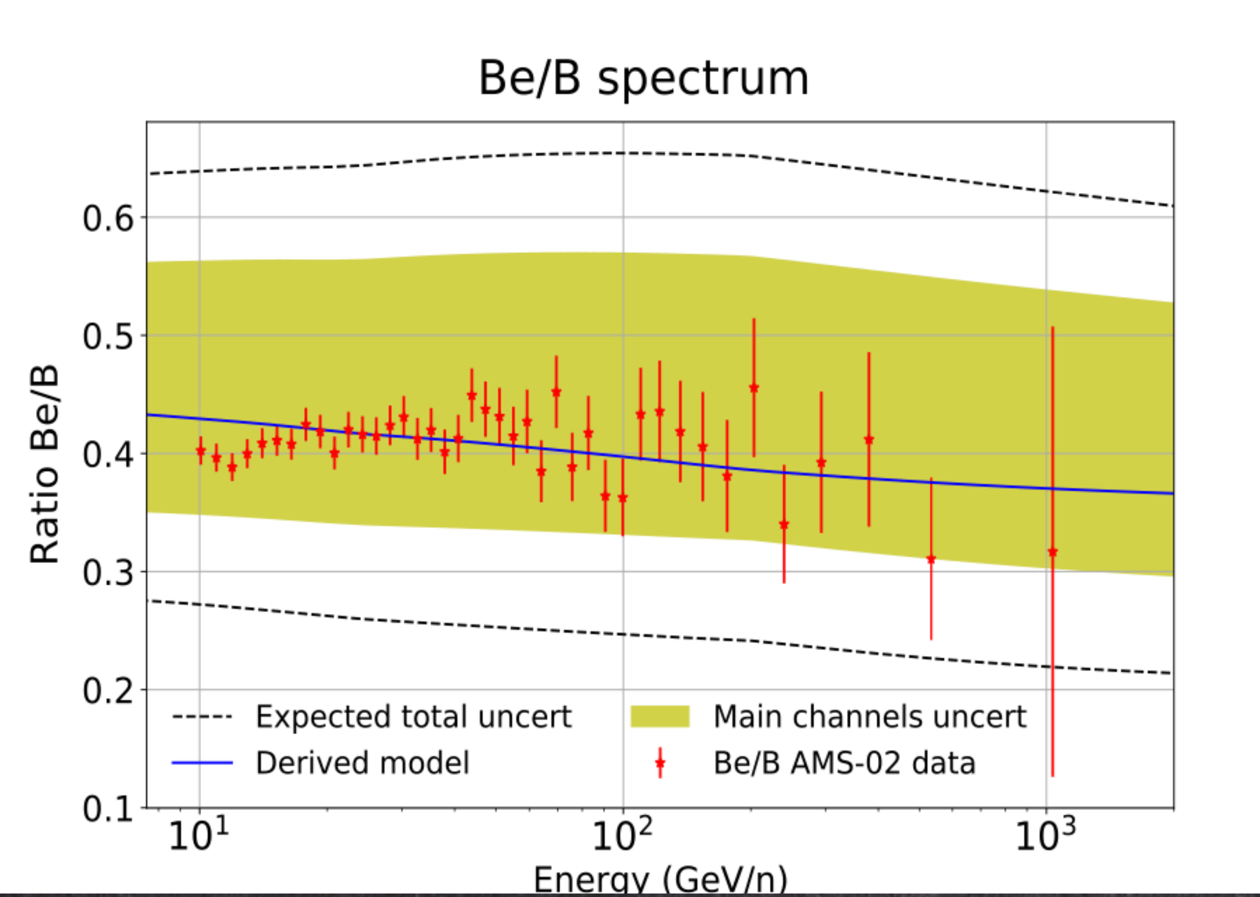


Even with the same, although scarce data,
interpretation may be different

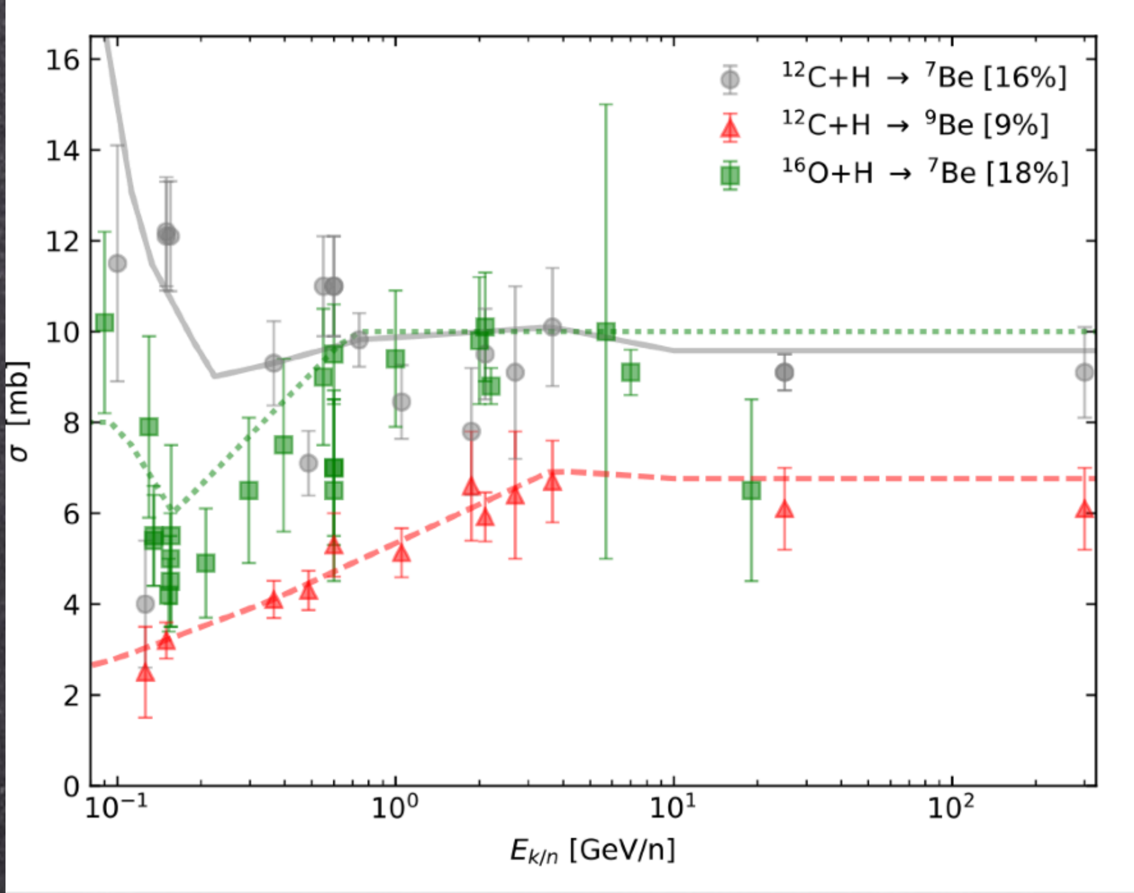
Fragmentation cross sections

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

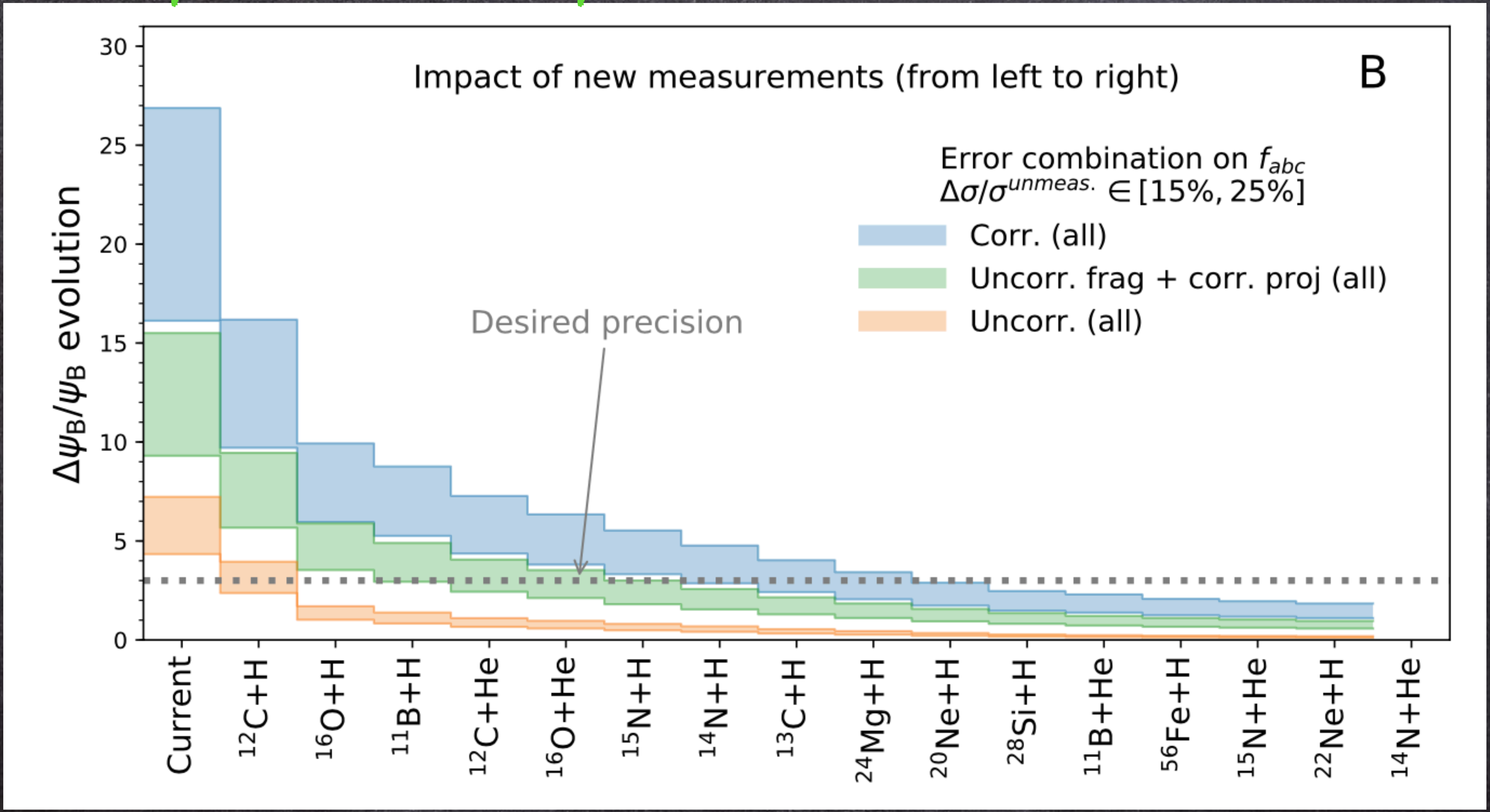


Probably the most limiting aspect now

Dedicated campaigns are needed (LHCb, NA61, Amber/Compass, ...)

Most relevant physics cases

Improve Boron production cross sections



Genolini, Moskalenko, Maurin, Unger PRC 2018

Antimatter

in the Galaxy

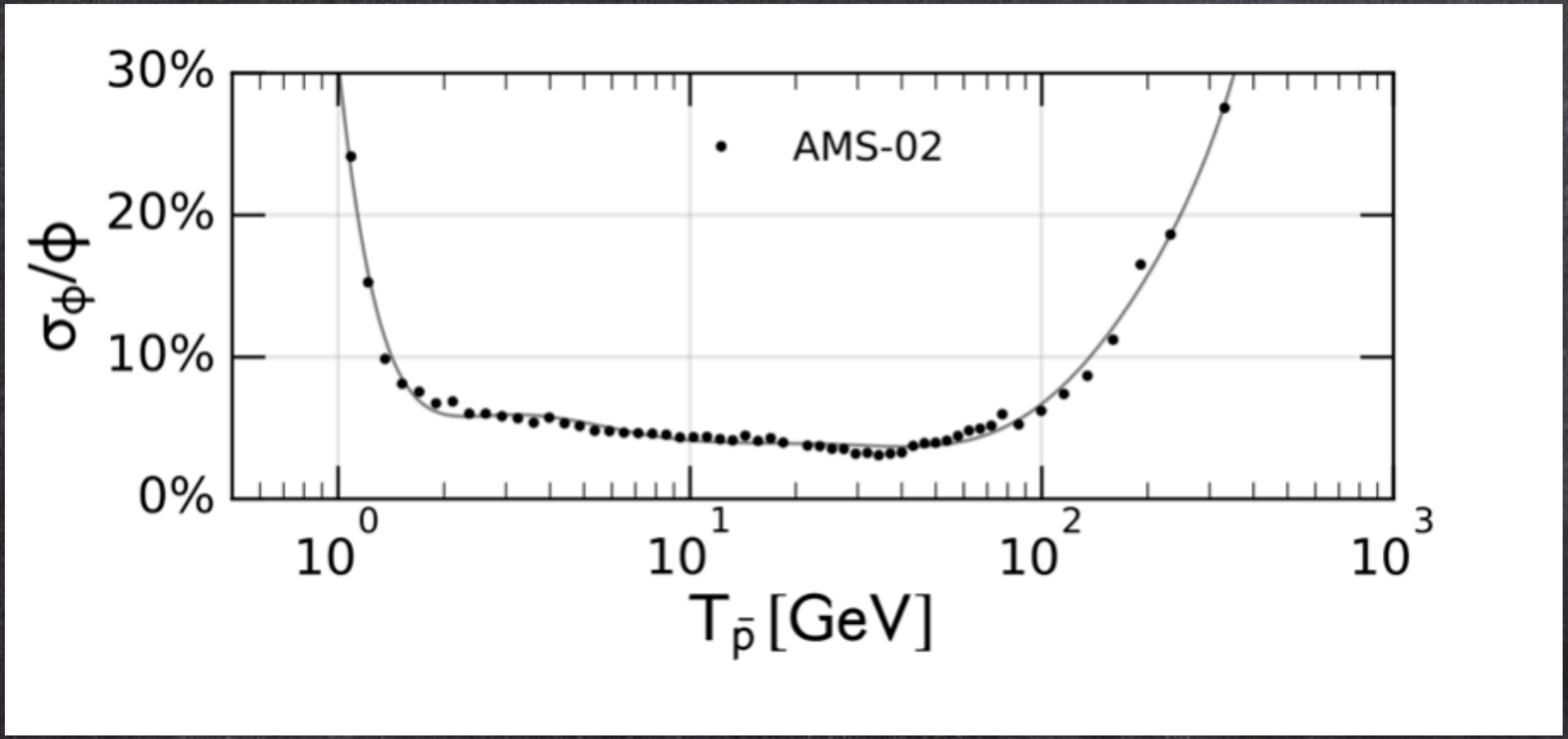
Antiproton production by inelastic scatterings

Korsmeier, FD, Di Mauro PRD 2018

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

$$\frac{d\sigma_{ij}}{dT_{\bar{p}}}(T, T_{\bar{p}}) = p_{\bar{p}} \int d\Omega \; \sigma_{\rm inv}^{(ij)}(T_i, T_{\bar{p}}, \theta).$$

Data from space are very precise



We need cross sections at <3%

Recent data at collider

pp —> pbar+X

NA61 (Aduszkiewicz Eur. Phys. J. C77 (2017))

$\sqrt{s}$=7.7, 8.8, 12.3 and 17.3 GeV

T_p = 31, 40, 80, 158 GeV

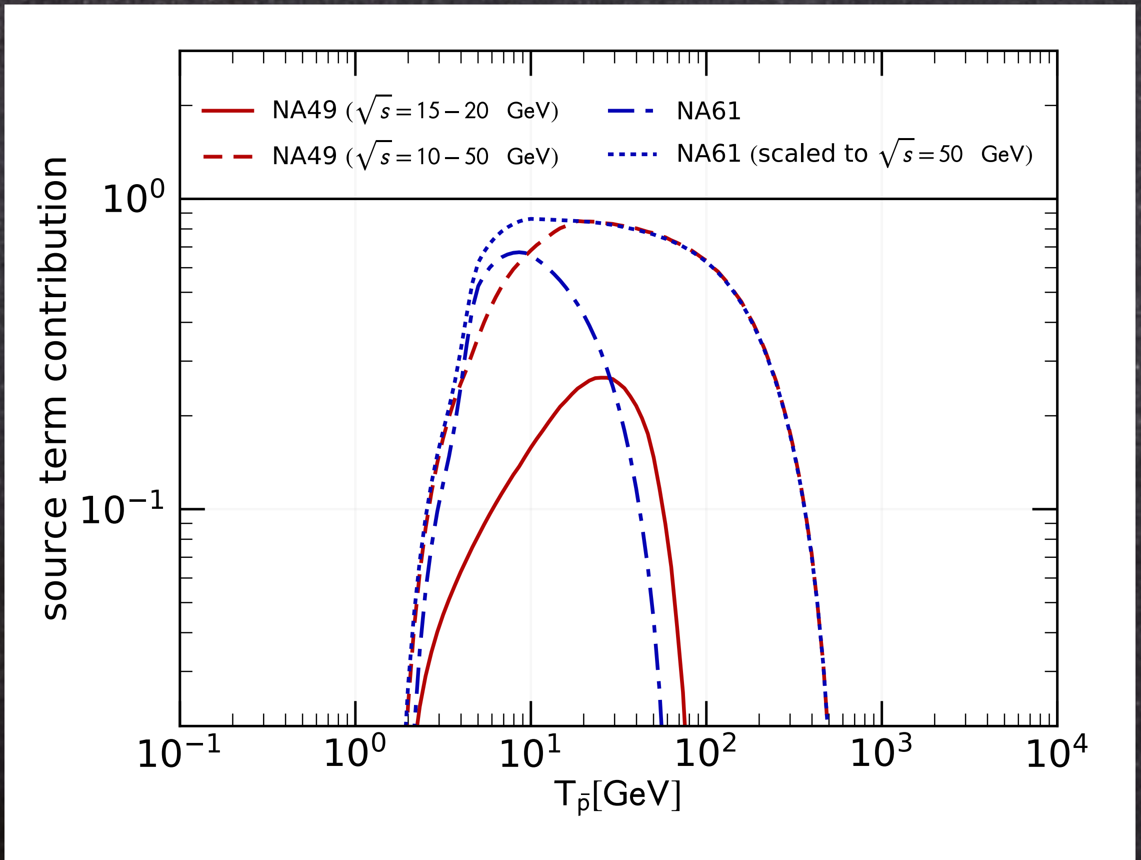
pHe —> pbar + X

LHCb (Graziani et al. Moriond 2017)

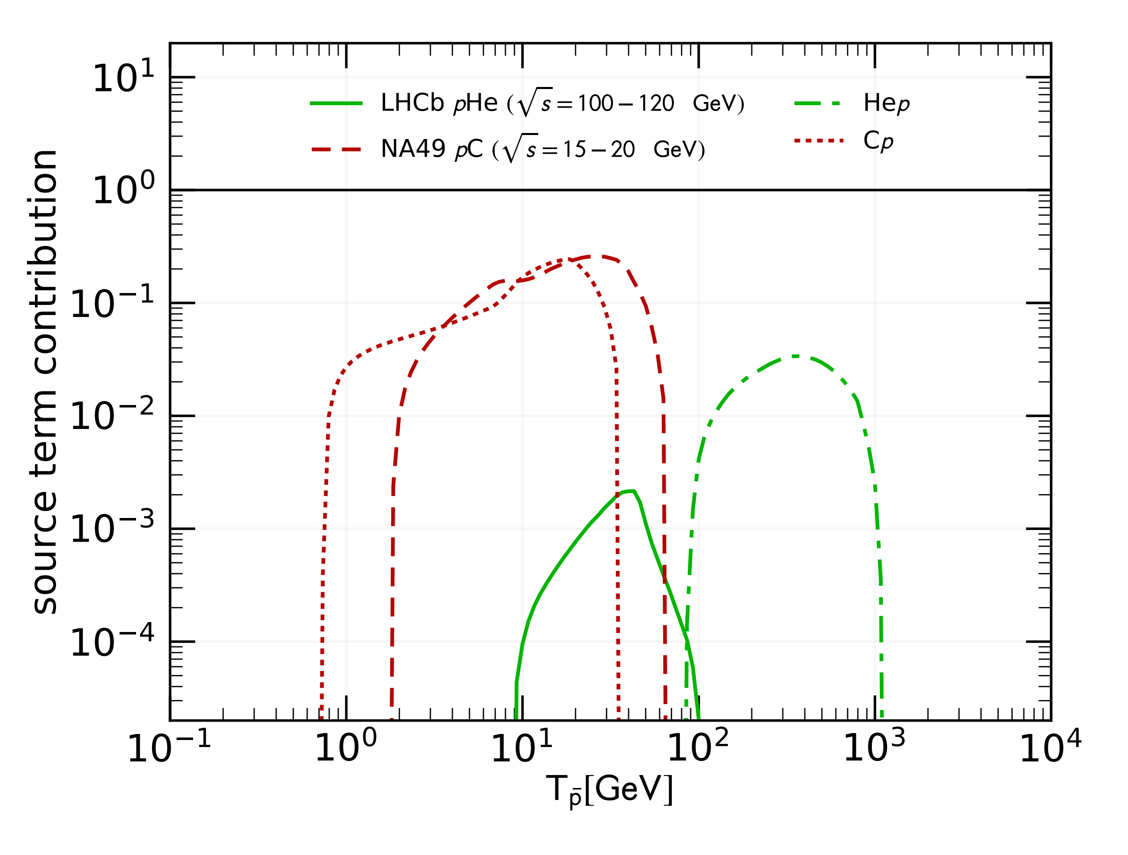
$\sqrt{s}$ = 110 GeV

T_p = 6.5 TeV

Fraction of the pp source term covered by the kinematical parameters space



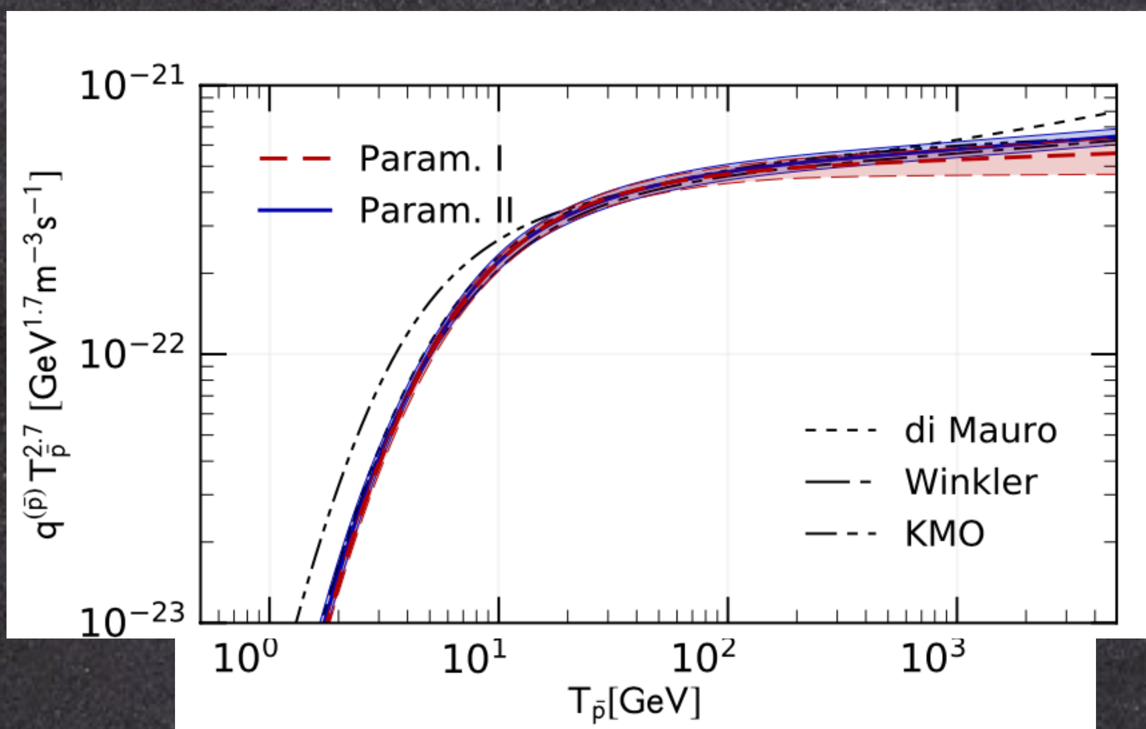
Fraction of the p-nucelus source term covered by the kinematical parameters space



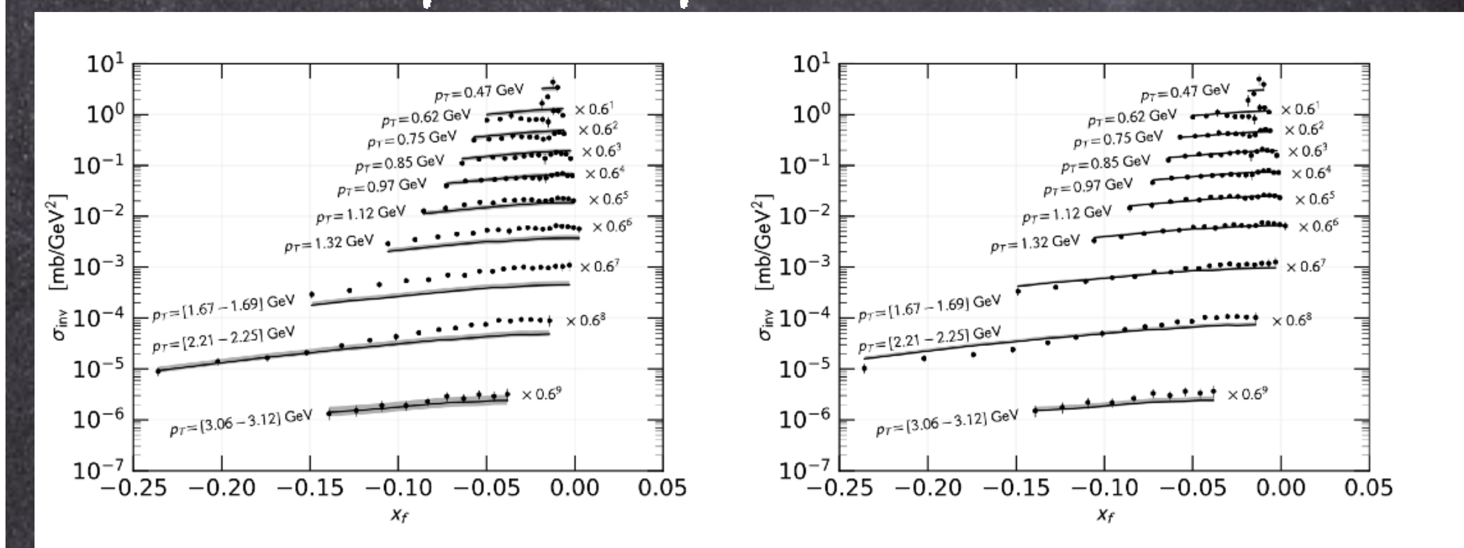
The antiproton source spectrum

Korsmeier, FD, Di Mauro, PRD 2018

pp -> p- X source term



LHCb pHe -> p- X data & our fit

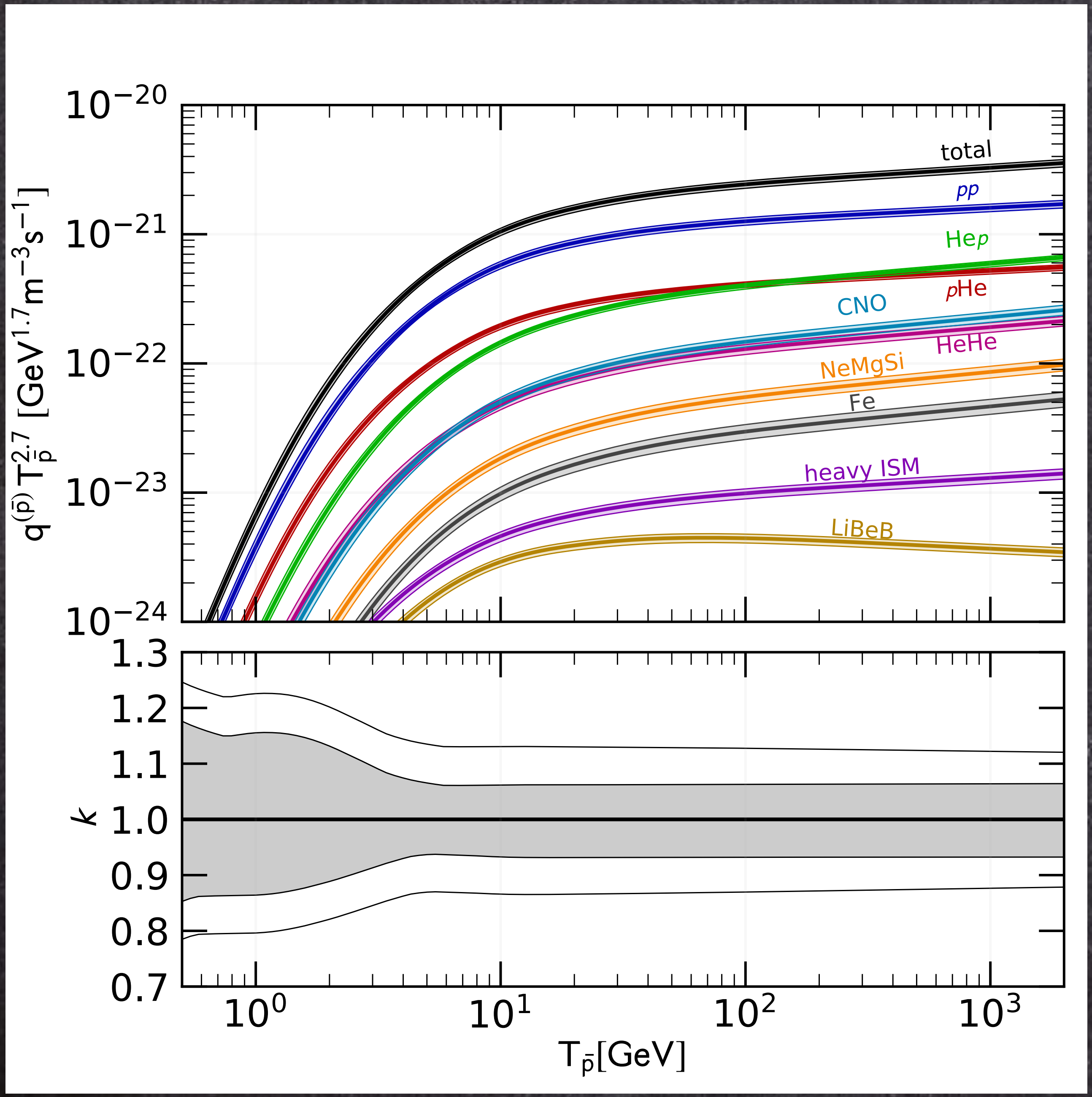


The effect of LHCb data is to select a high energy trend of the pbar source.

A harder trend is preferred.

Effects on the total pbar production

Korsmeier, FD, Di Mauro, 1802.03030, PRD 2018



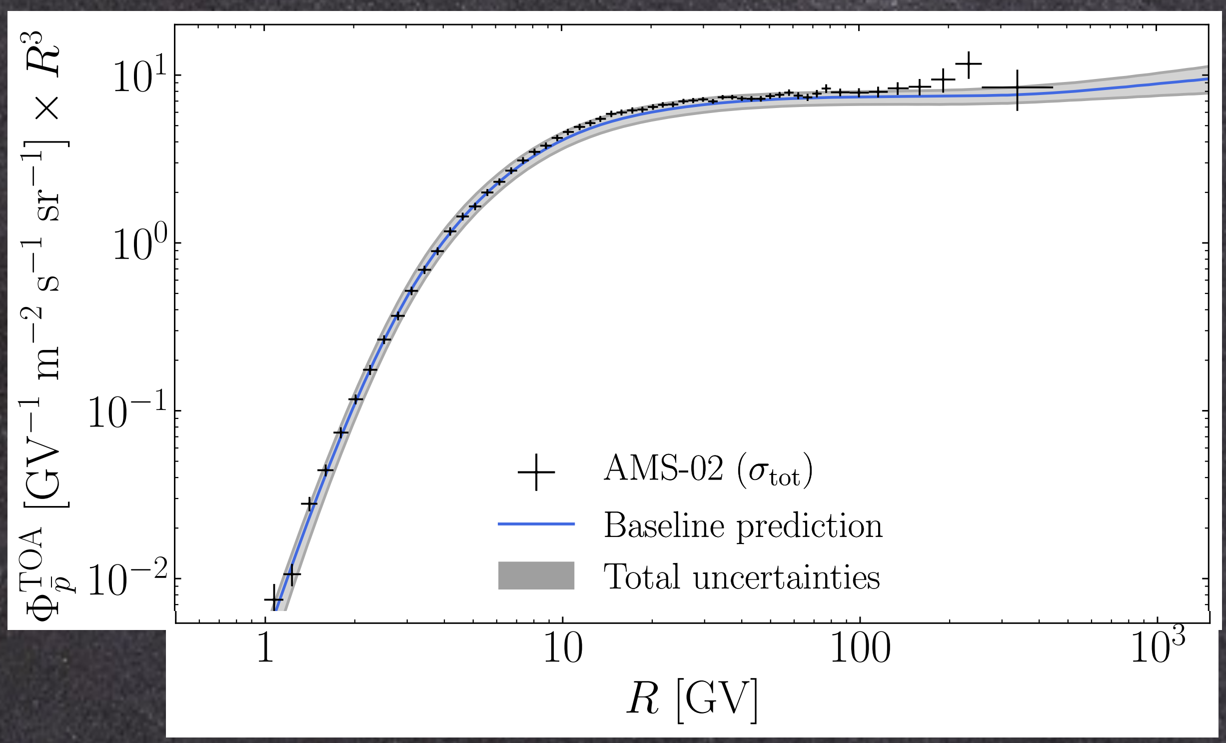
Result with uncertainties in the hyperon correction and isospin violation

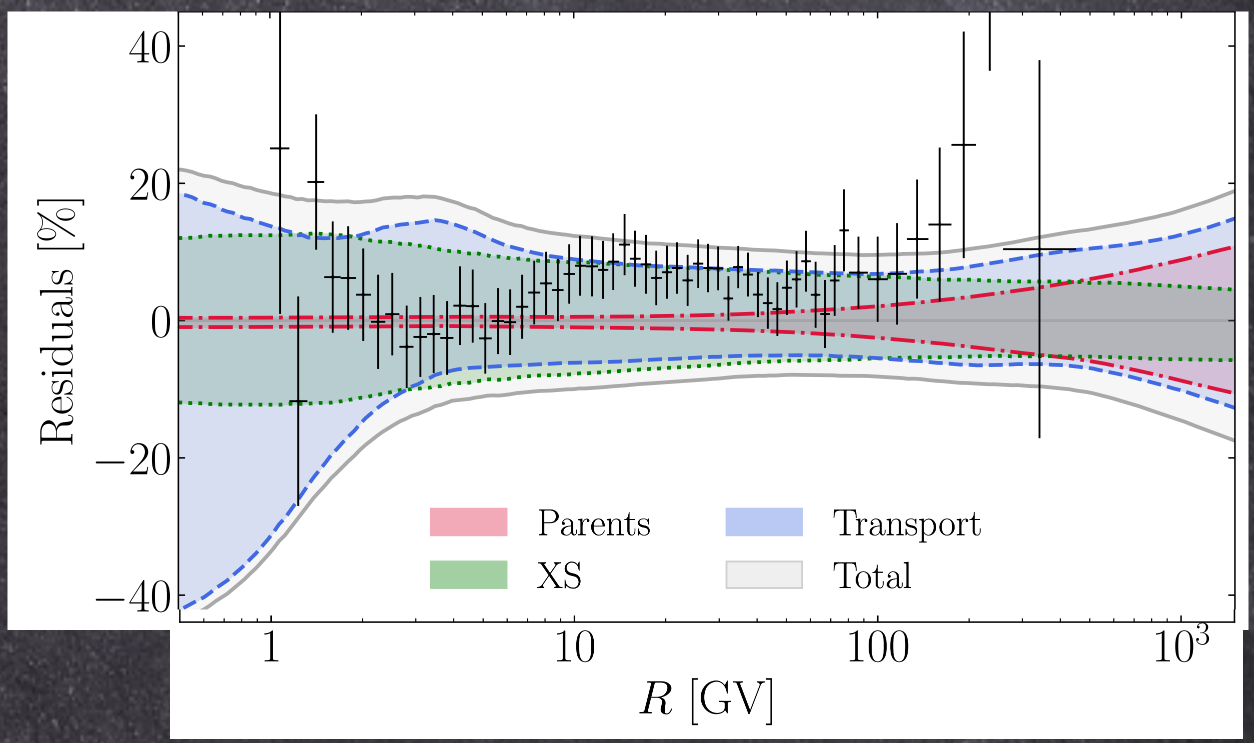
The antiproton source term is affected by uncertainties of ± 10% from cross sections.

Higher uncertainties at very low energies

AMS-02 antiprotons are consistent with a secondary astrophysical origin

M. Boudaud, Y. Genolini, L. Derome, J.Lavalle, D.Maurin, P. Salati, P.D. Serpico PRD 2020



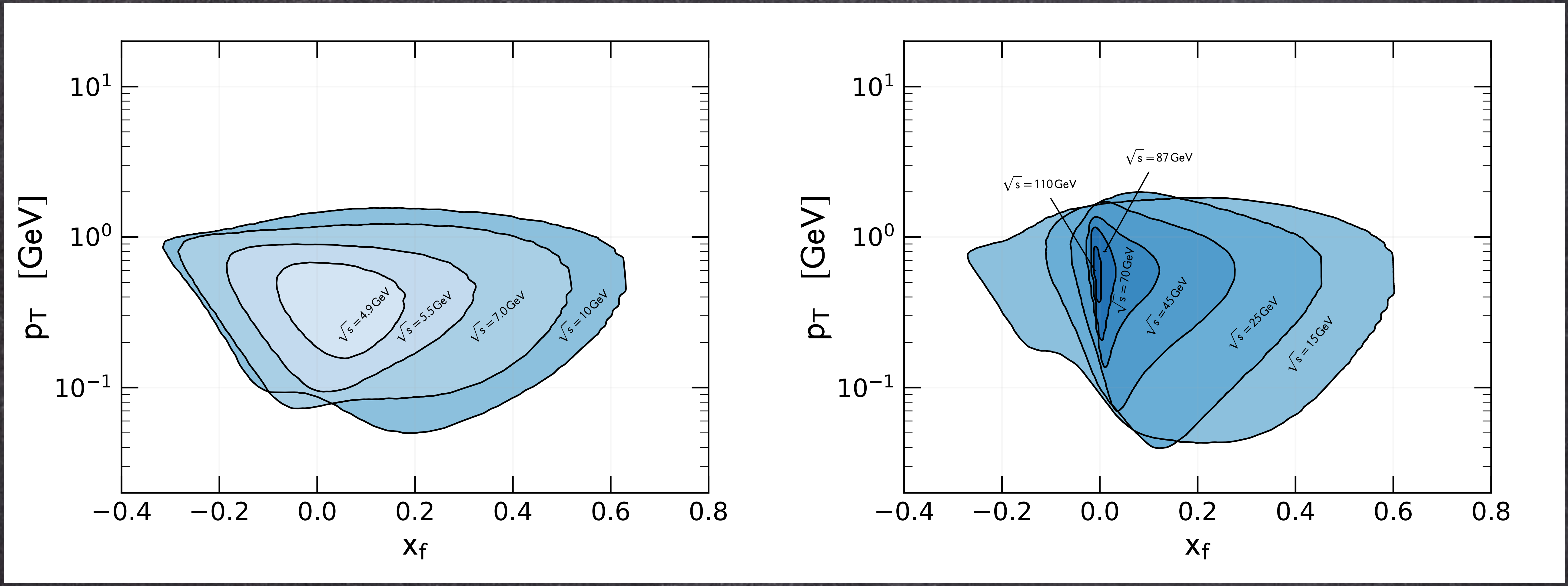


Secondary pbar flux is predicted consistent with AMS-02 data
A dark matter contribution would come as a tiny effect

Transport and cross section uncertainties are comparable

For next generation experiments

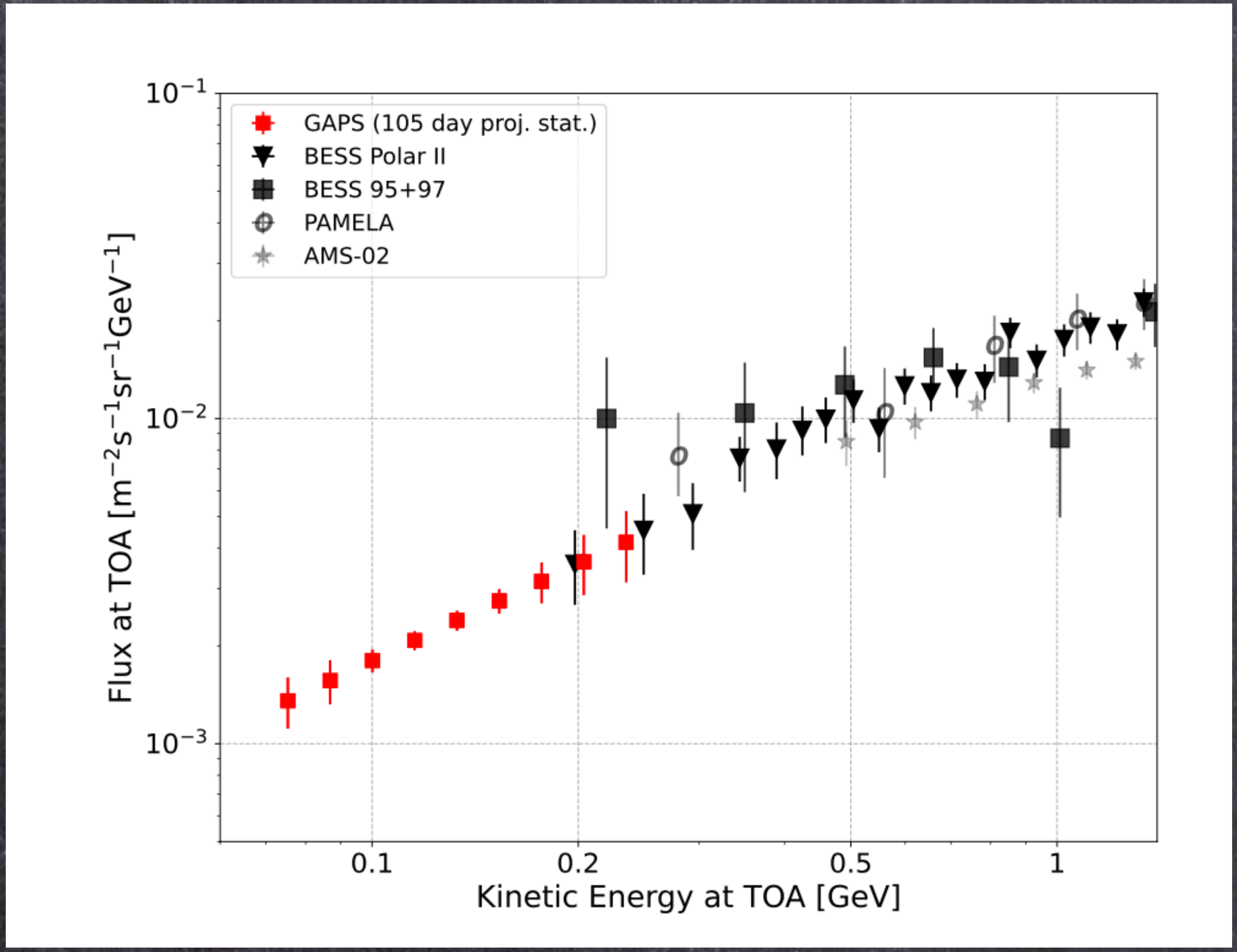
Korsmeier, FD, Di Mauro, 1802.03030, PRD 2018



AMS-02 accuracy is reached if pp -> pbar cross section is measured with 3% accuracy inside the regions, 30% outside.

The new frontier of cosmic antiprotons: low energies by GAPS

Rogers et al. (GAPS Coll.) Astrop. Phys. 2023, 2206.12991

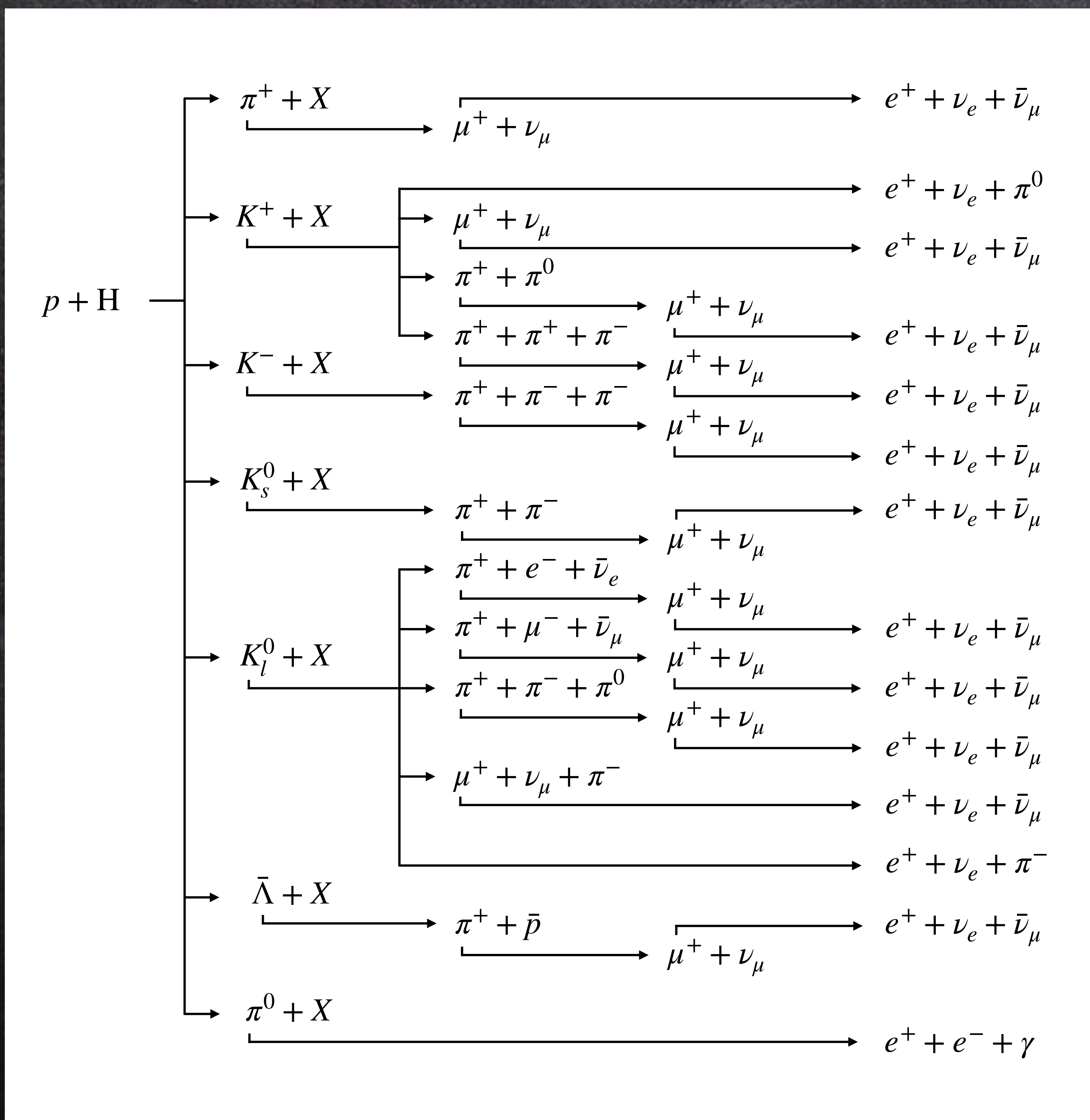


Sub-GeV antiprotons will be measured in 2023 (and 2025, 2027) by GAPS. Robust predictions are needed: cross sections, propagation, solar modulation

The case for Positrons ($e^{\pm}$)

e+ production channels

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



We include all these contributions.

Similarly for collisions with nuclei.

We repeat ALL the analysis for e- under charge conjugation

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

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

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

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.

Analytical formulae for e± production XS

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The procedure is fully data driven

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

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

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

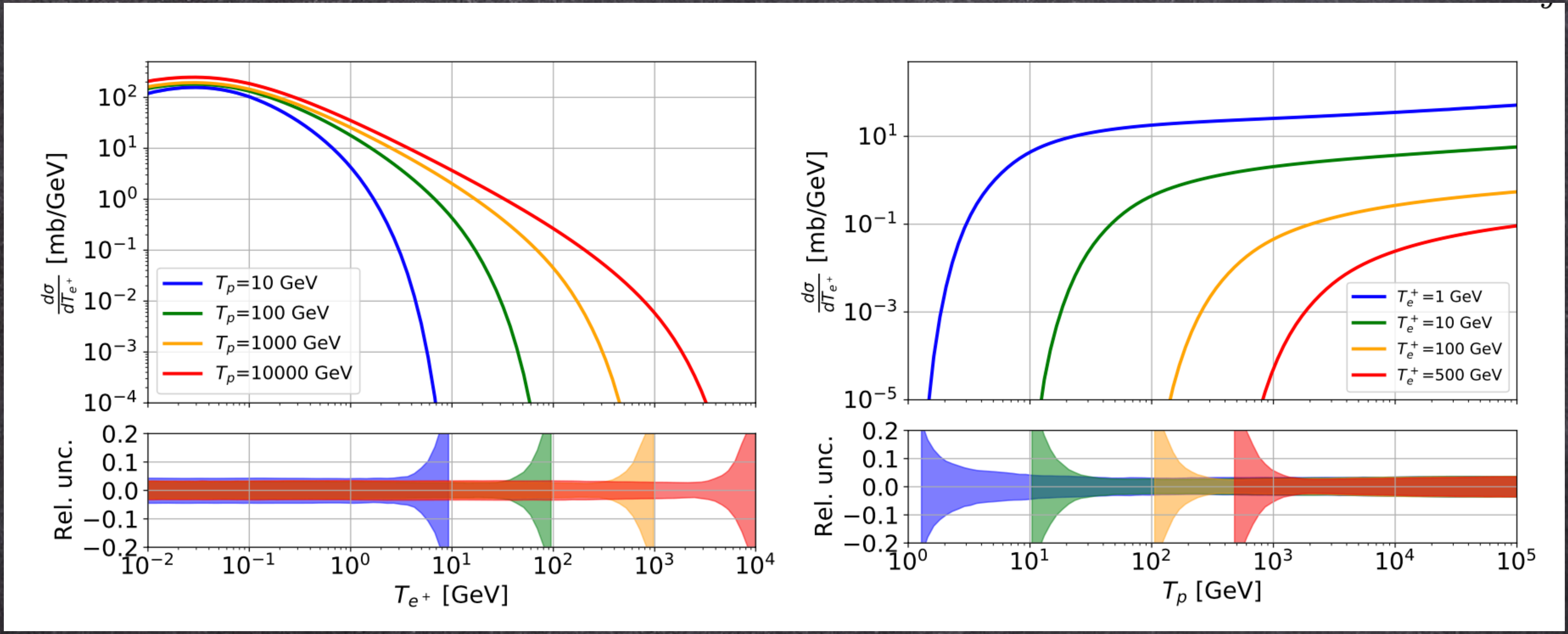
$$A(s) = \frac{1 + \left(\sqrt{s/c_{20}}\right)^{c_{21} - c_{22}}}{1 + \left(\sqrt{s_0/c_{20}}\right)^{c_{21} - c_{22}}} \left(\sqrt{\frac{s}{s_0}}\right)^{c_{22}}$$

F_s and F_r mainly driven by NA49 data

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

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

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

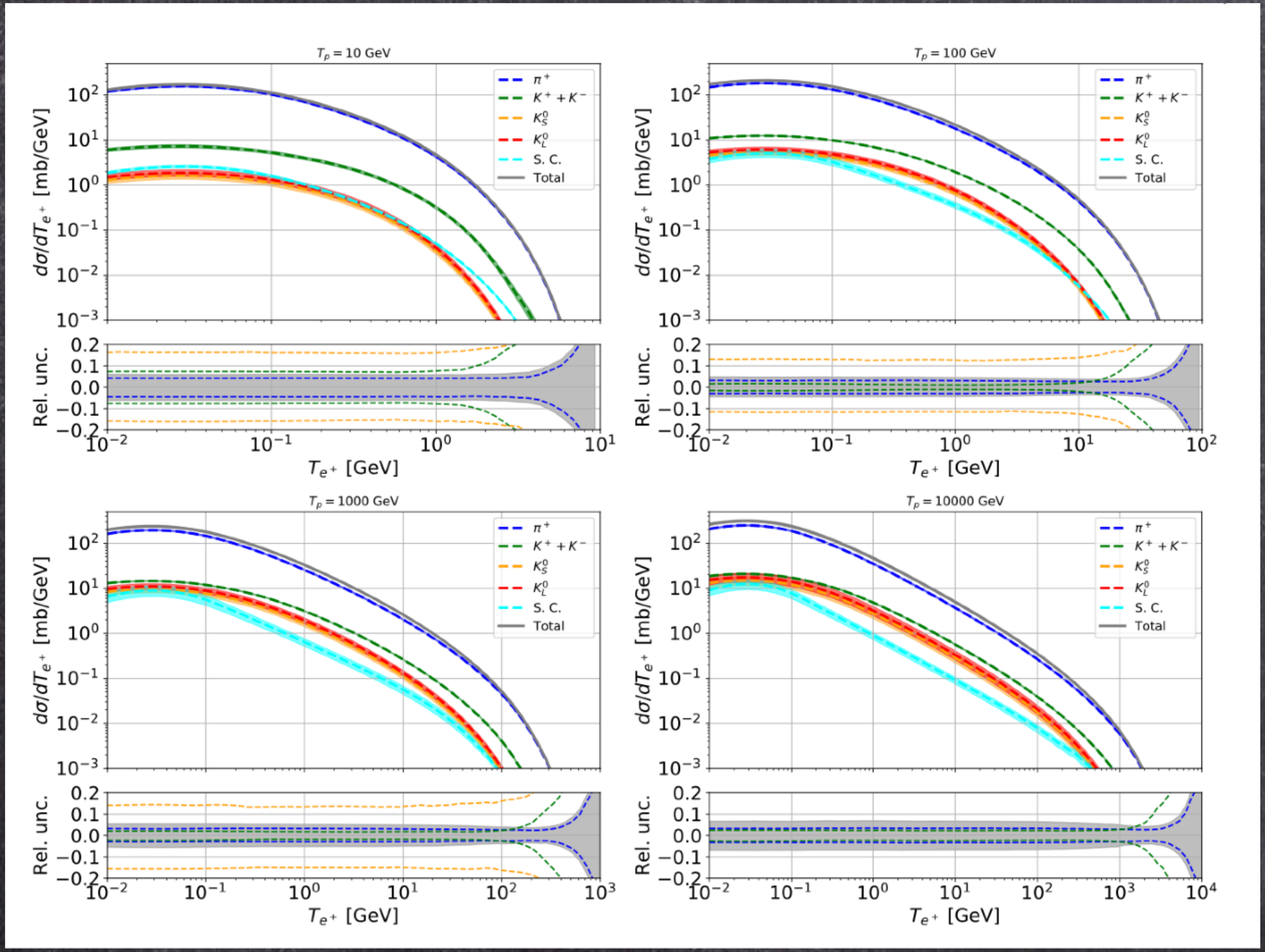


Data are fitted with very small uncertainties

Our parameterizations result appropriate, data are very precise

Total cross section from pp—> e⁺ + X

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



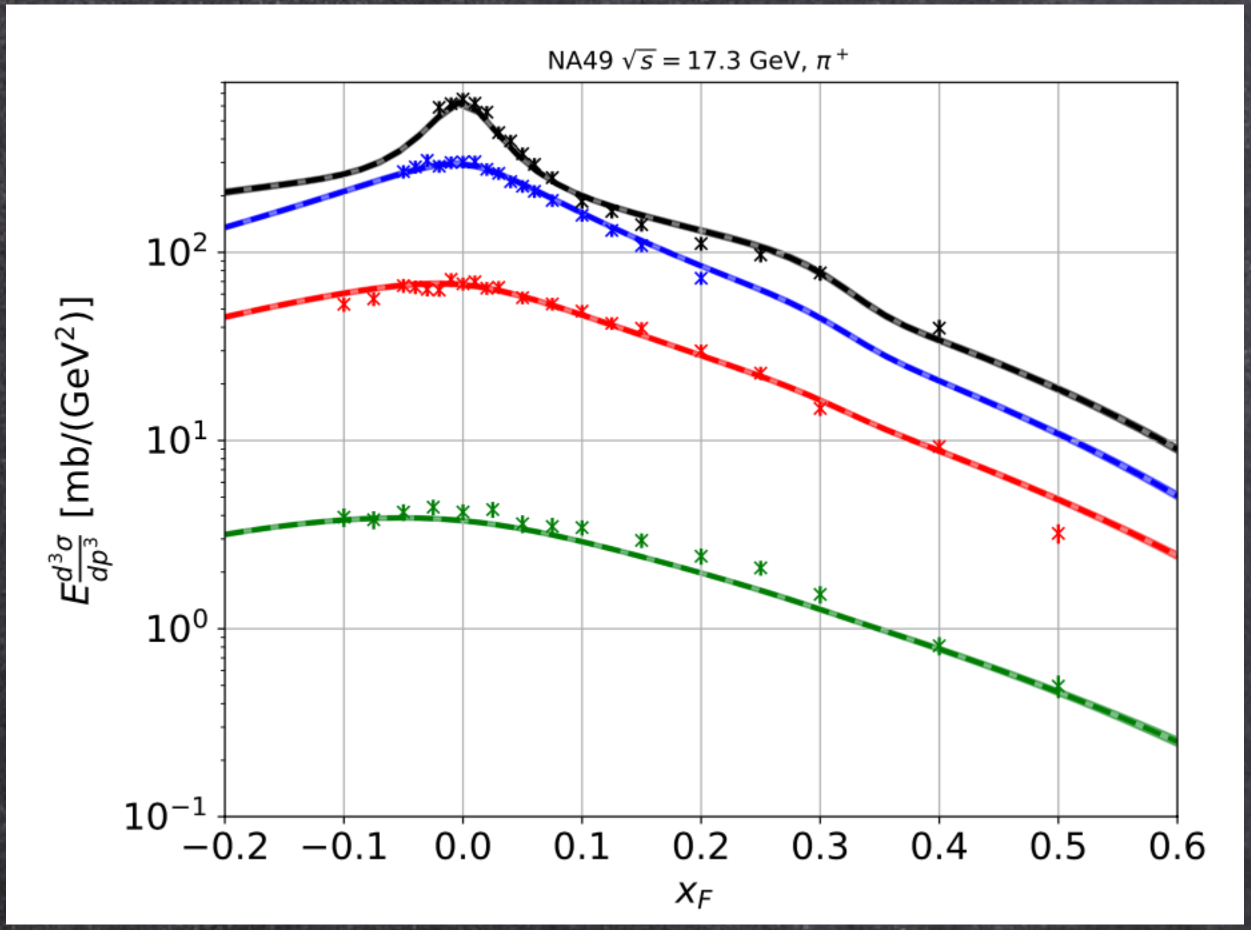
All channels contributing >0.5% are included.

Uncertainty globally contained to <10%

Effect of scattering off nuclei

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

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 true

Data on He are necessary

Final results on e+ cross section

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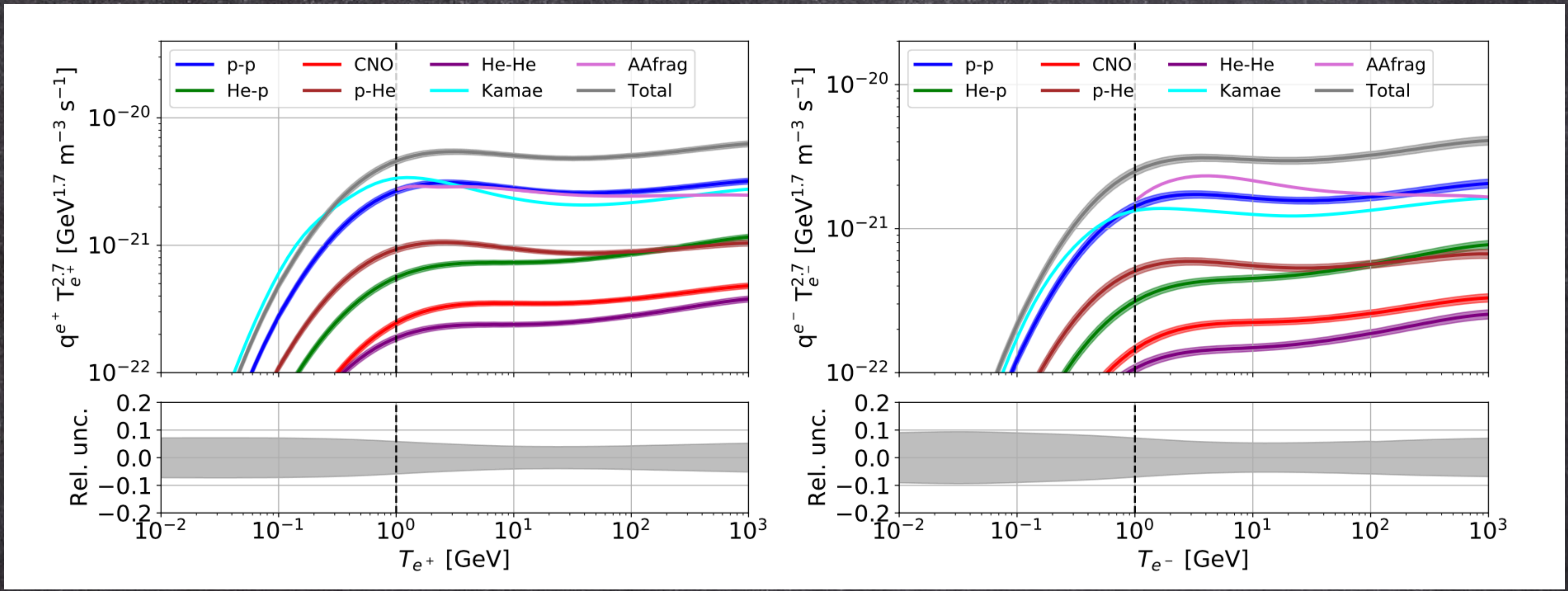
Positrons Electrons



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

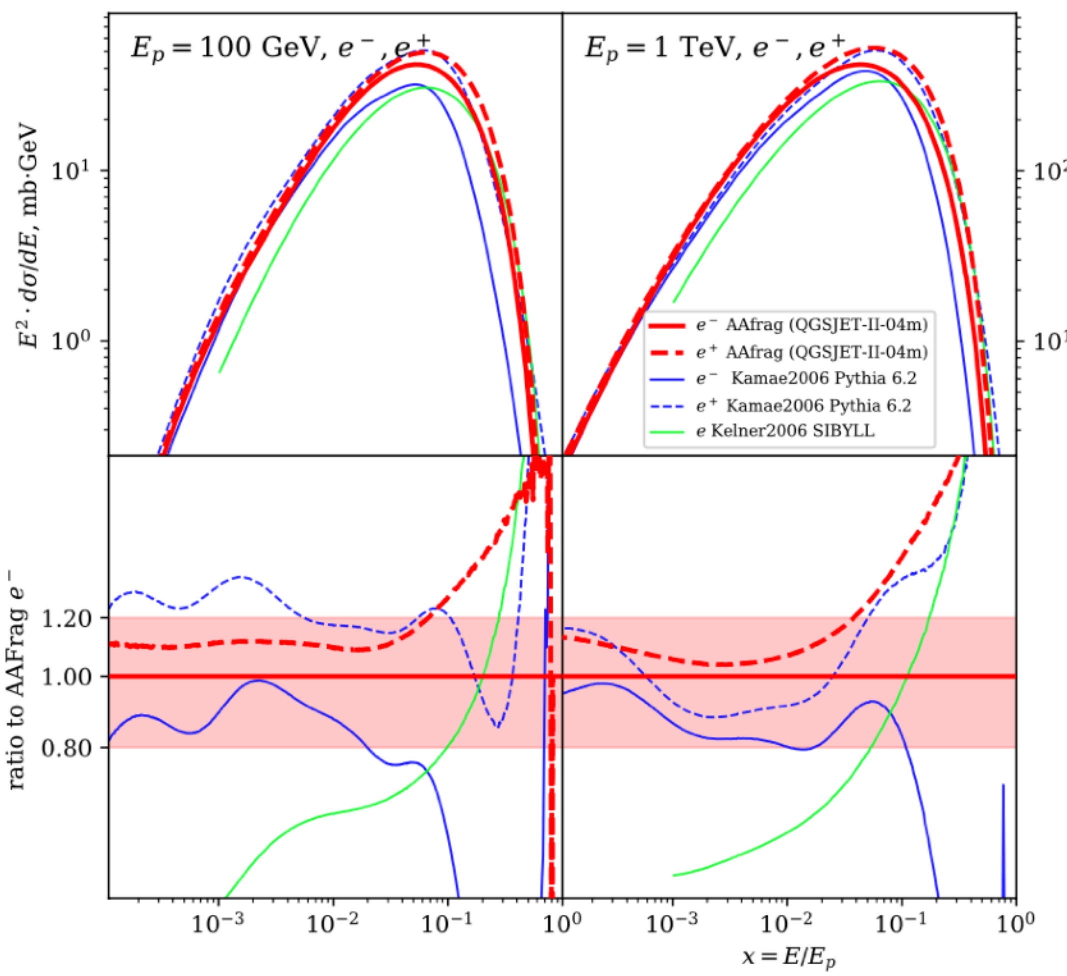
Comparison with MonteCarlo computations is done for p-p.

Similar results for e-.

Comparison with Monte Carlo generators

Koldobskiy et al., PRD 2021, 2110.00496

Results with Aafrag



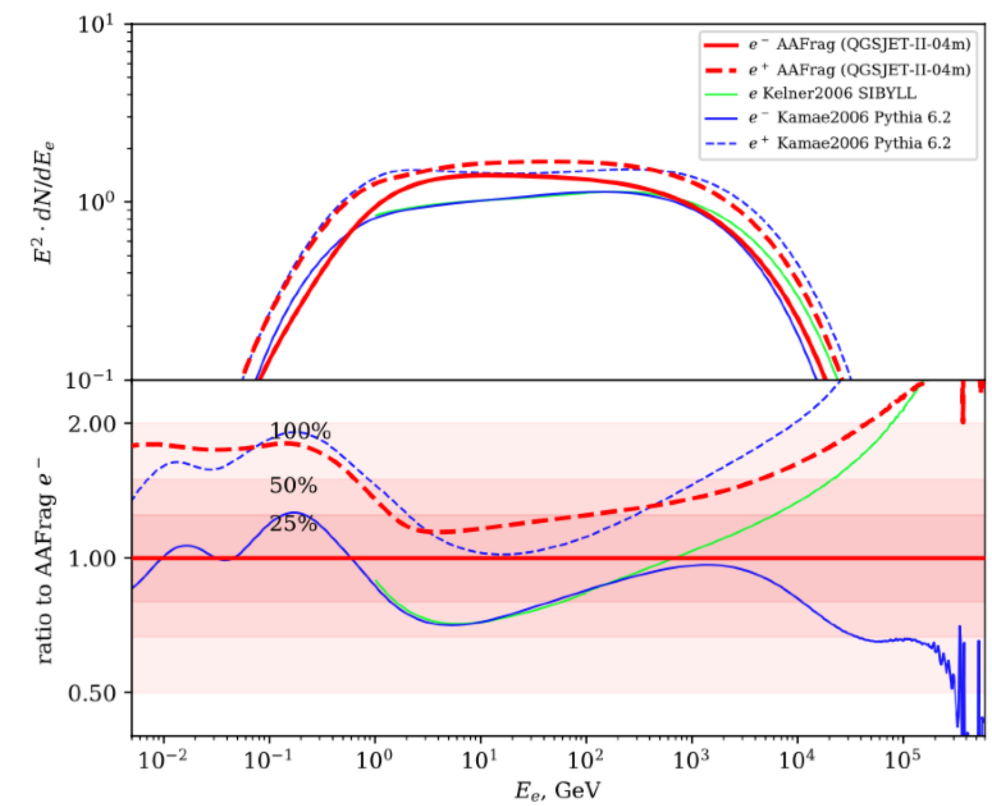
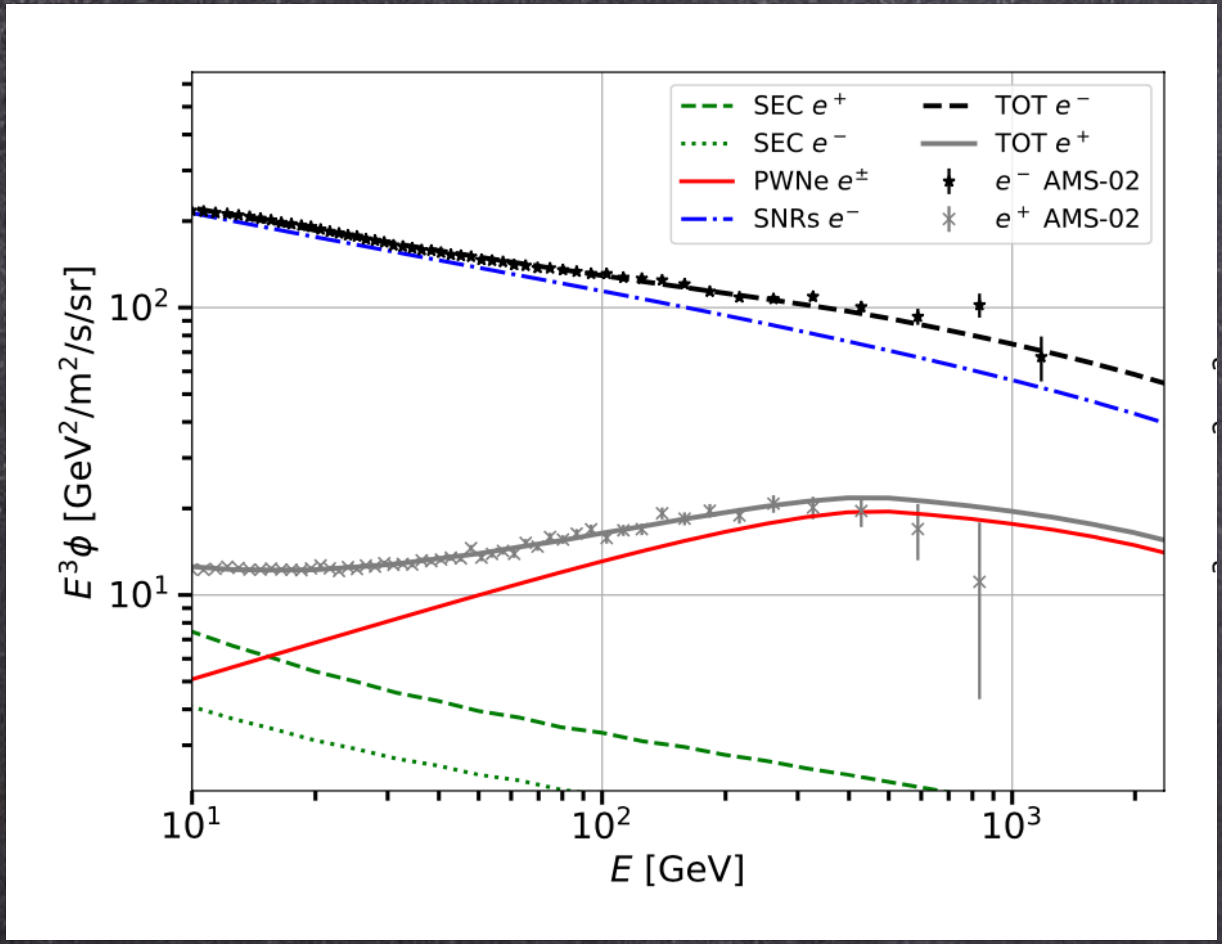


FIG. 9: Electron and positron fluxes for a power-law cosmic ray spectrum ($\propto 1/p^2 \exp(-p/p_0)$) .

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

The role of e± secondaries

M. Di Mauro, FD, S. Manconi PRD 2021



e+ secondaries contribute significantly to shape the spectrum at Earth.

The flux in the GeV region is likely dominated by secondaries

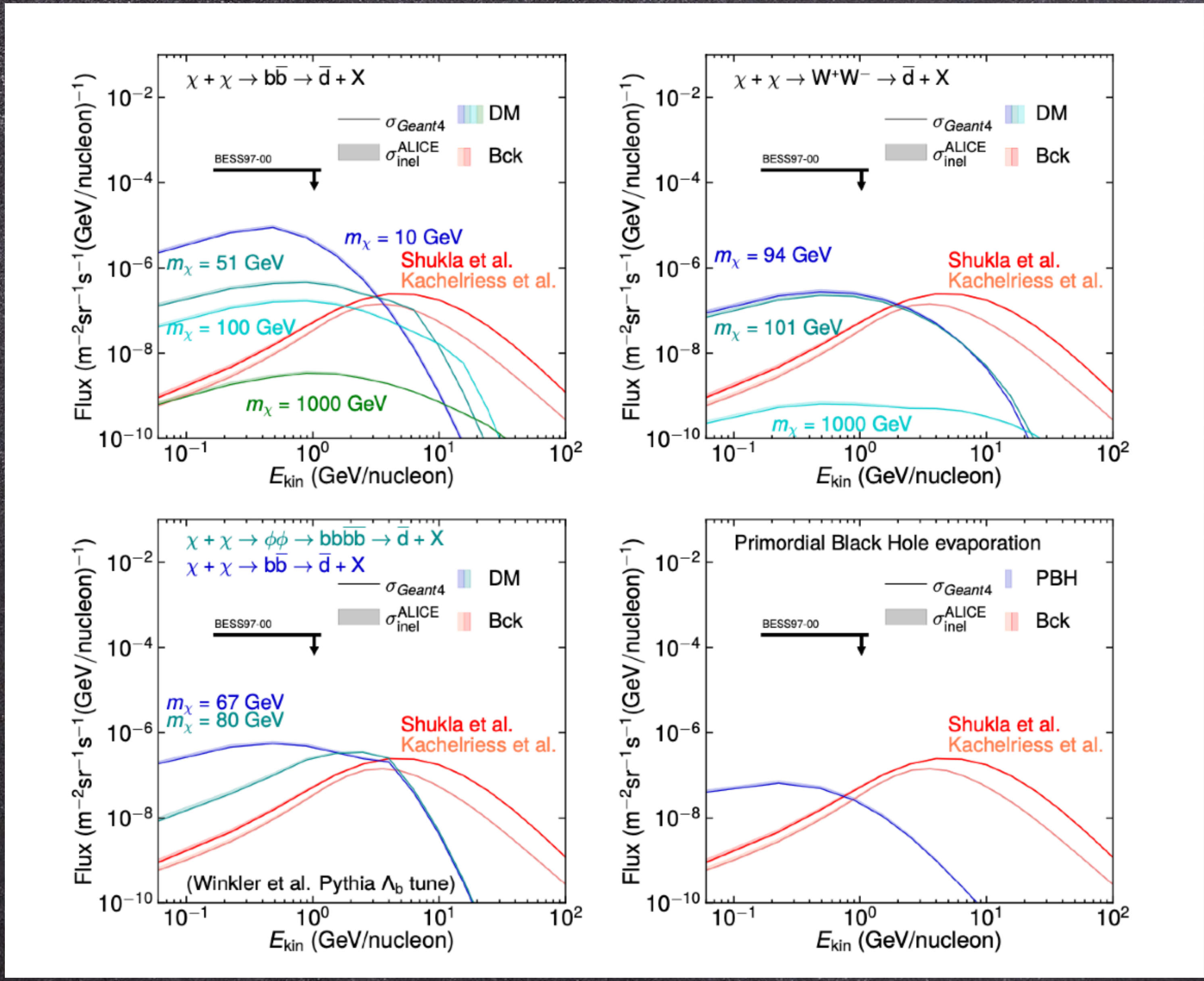
A PRIMARY component is surely there at high energies

The case for Antideuterons

See M. Kachelriess' talk

Antideuterons persepctives

Serksnyte et al,PRD 2022



Low energy window keeps being a discovery field

Uncertainties on P_c is ± 70%

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!

Conclusions

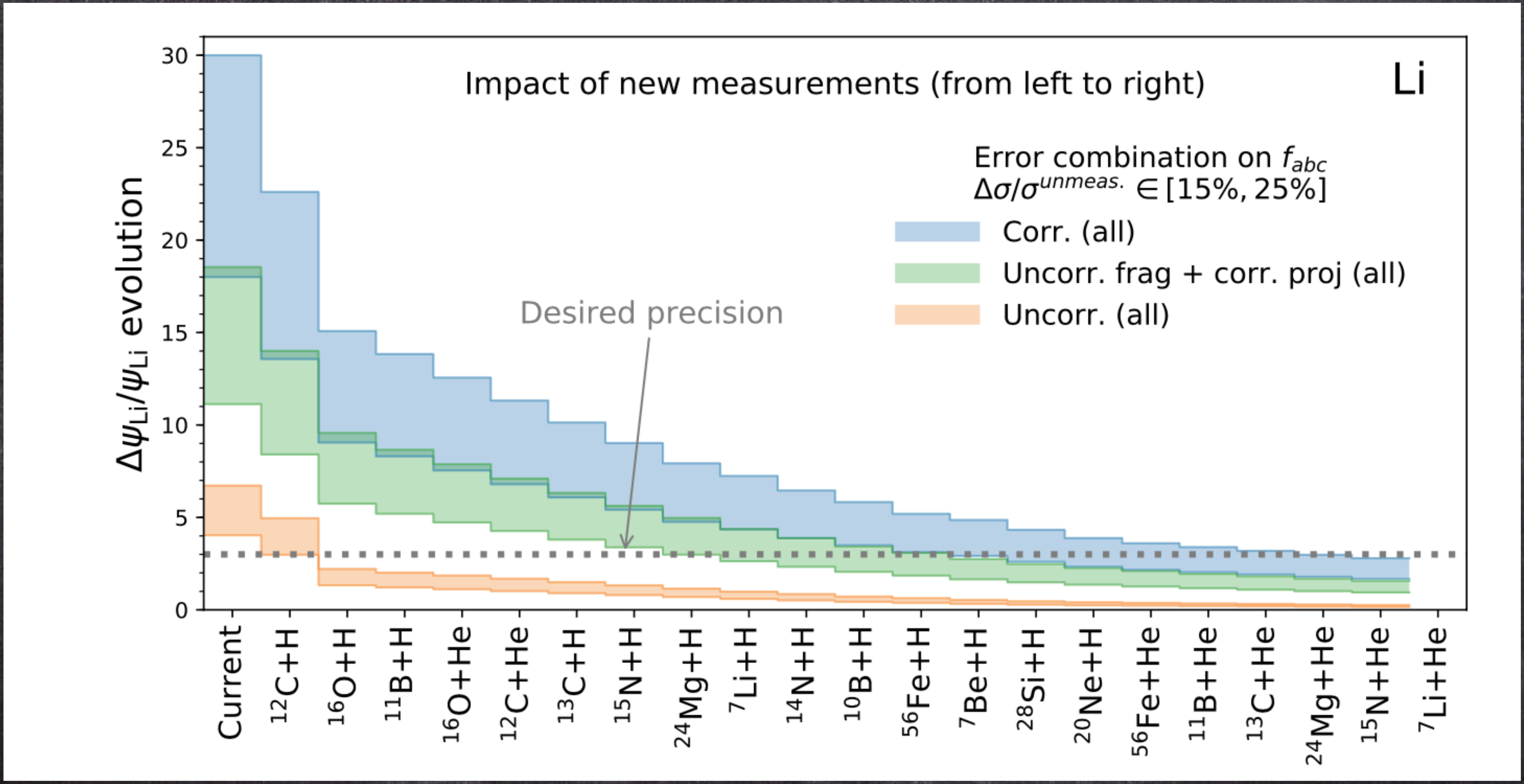
Great efforts to better understand nuclei and antinuclei in CRS: theory models, data from space, data from colliders.

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

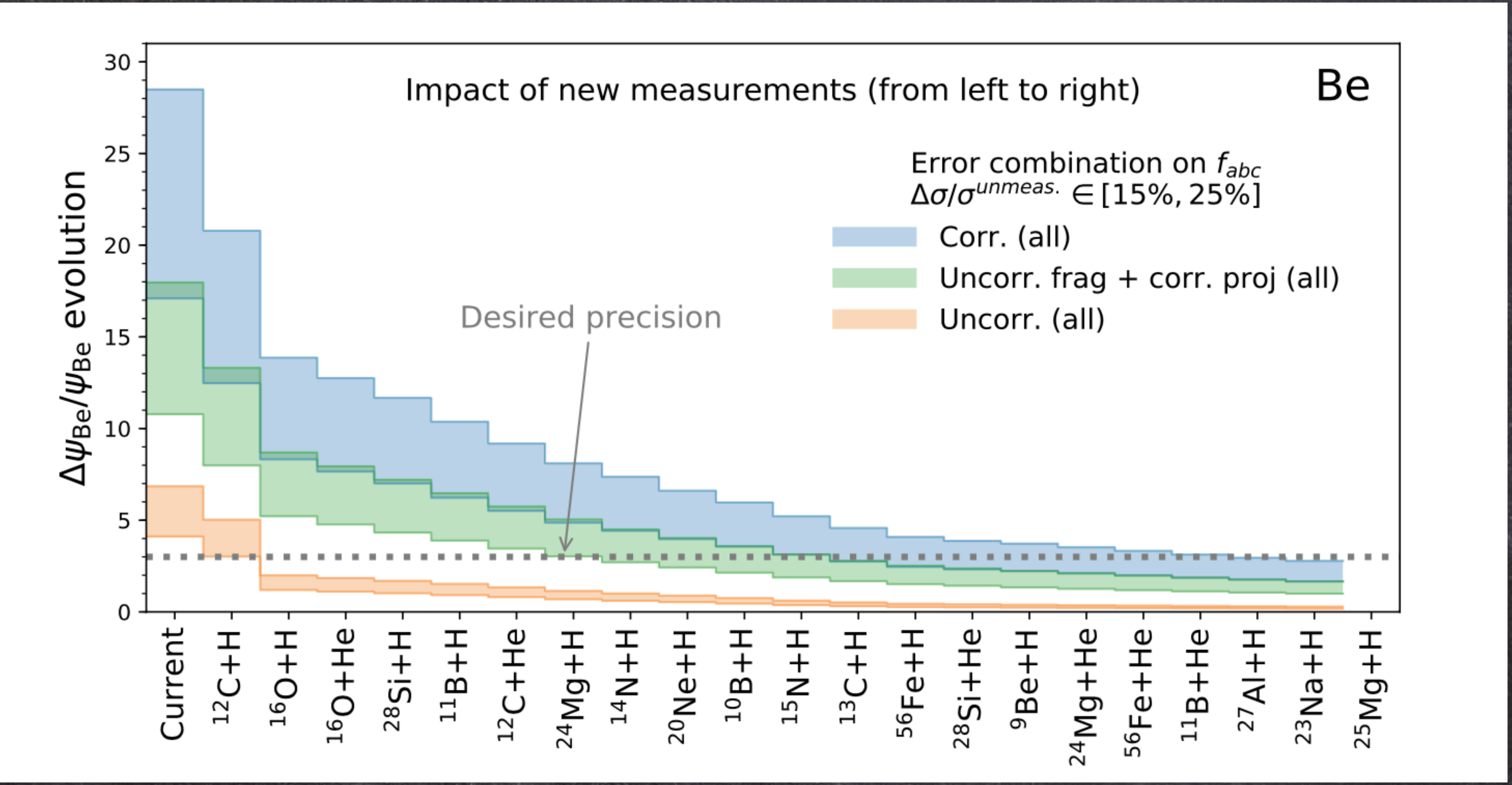
Most relevant physics cases

Improve Lithium production cross sections



Genolini, Moskalenko, Maurin, Unger PRC 2018

Improve Beryllium production cross sections

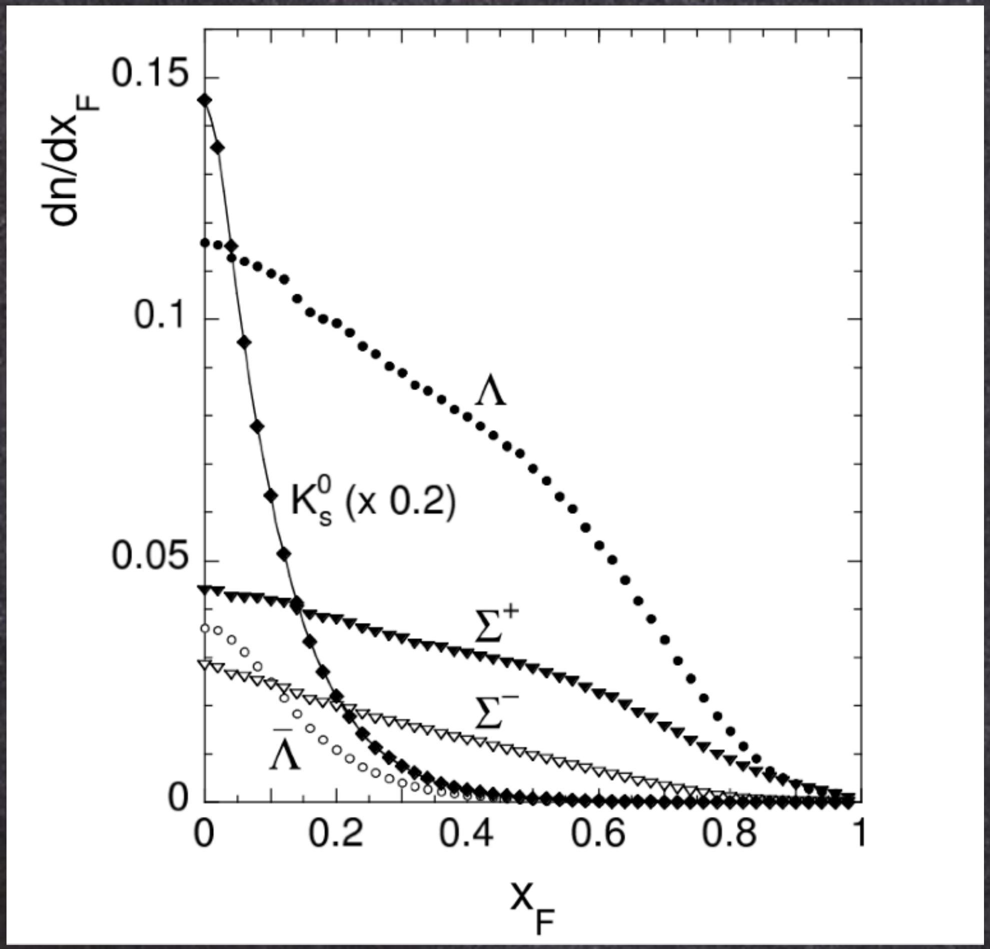


Genolini, Moskalenko, Maurin, Unger PRC 2018

Data correction for feed-down

The pion production cross section can contain (or not) the pions From weak decays of strange particles.

C. Alt et al., Eur. Phys. J. C, 2005

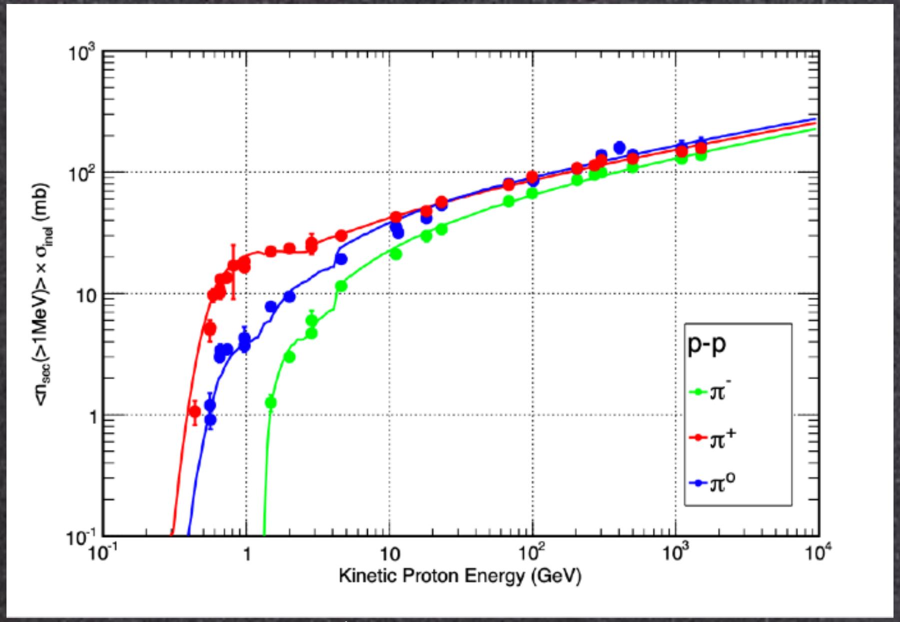


NA49 p_T integrated, MC

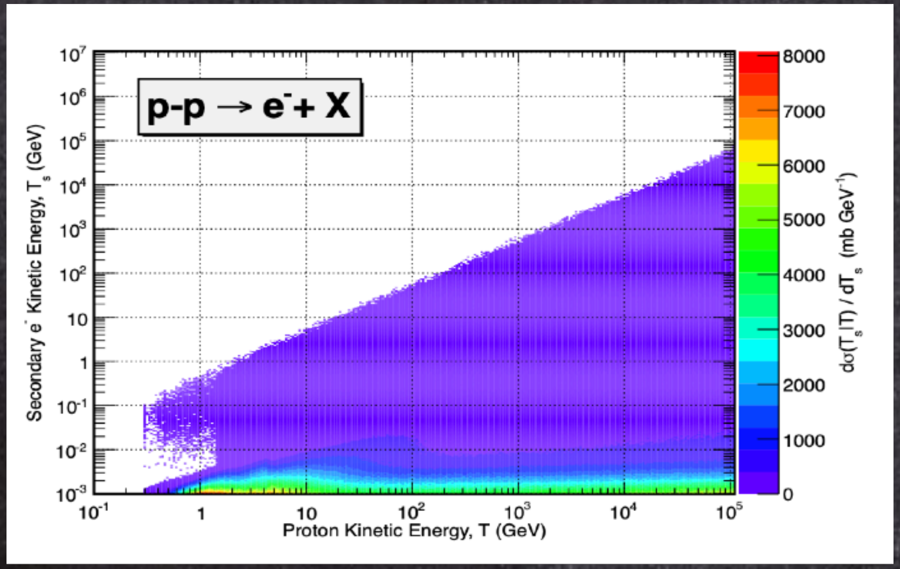
Almost all the data except the older ones are feed-down corrected.
When not, we correct for it.

Fluka MC generator

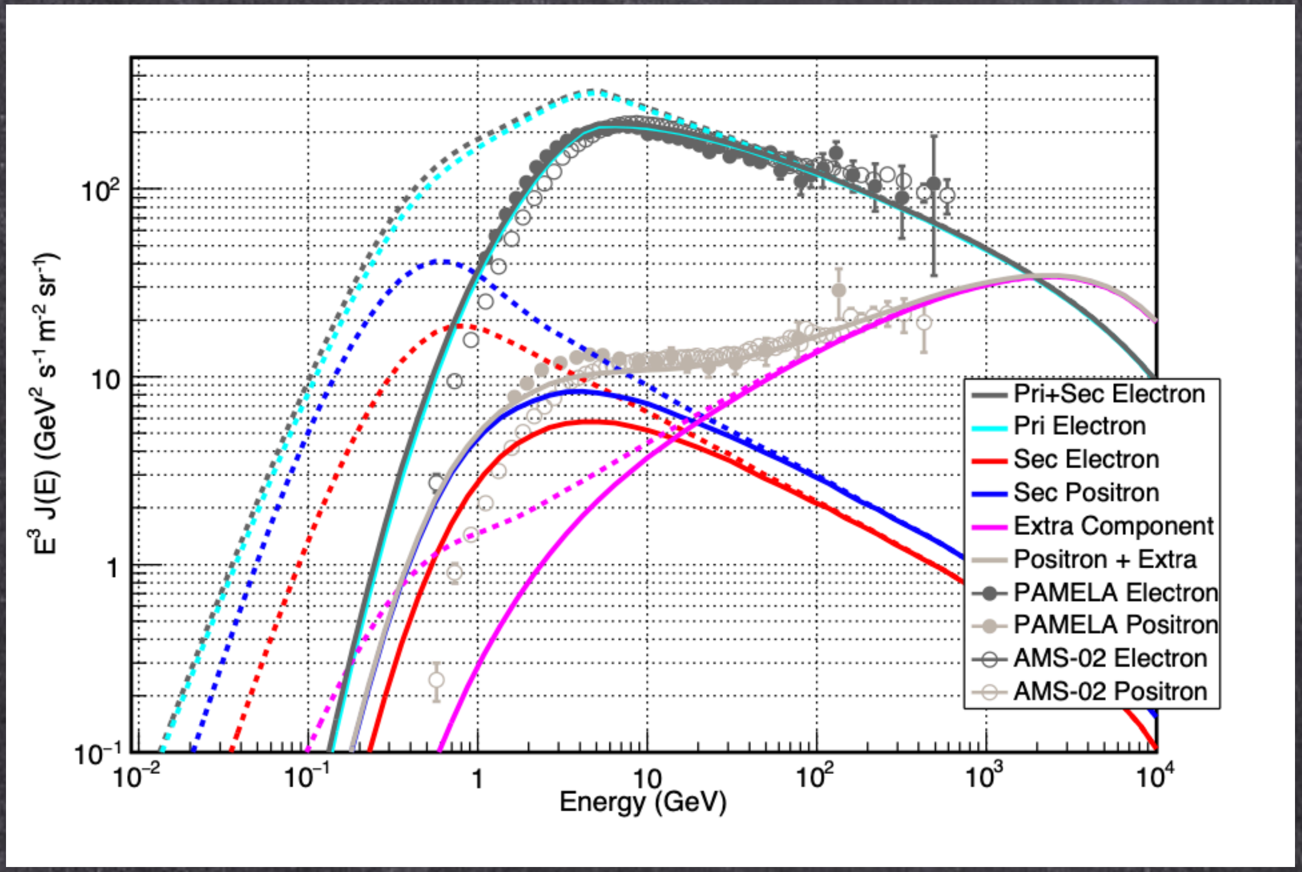
N. Mazziotta+, AP 2017



Points are from Dermer 1986



T_e is severely degraded from Projectile energy



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

Light nuclei: primaries and secondaries

Genolini, Moskalenko, Maurin, Unger PRC 2018

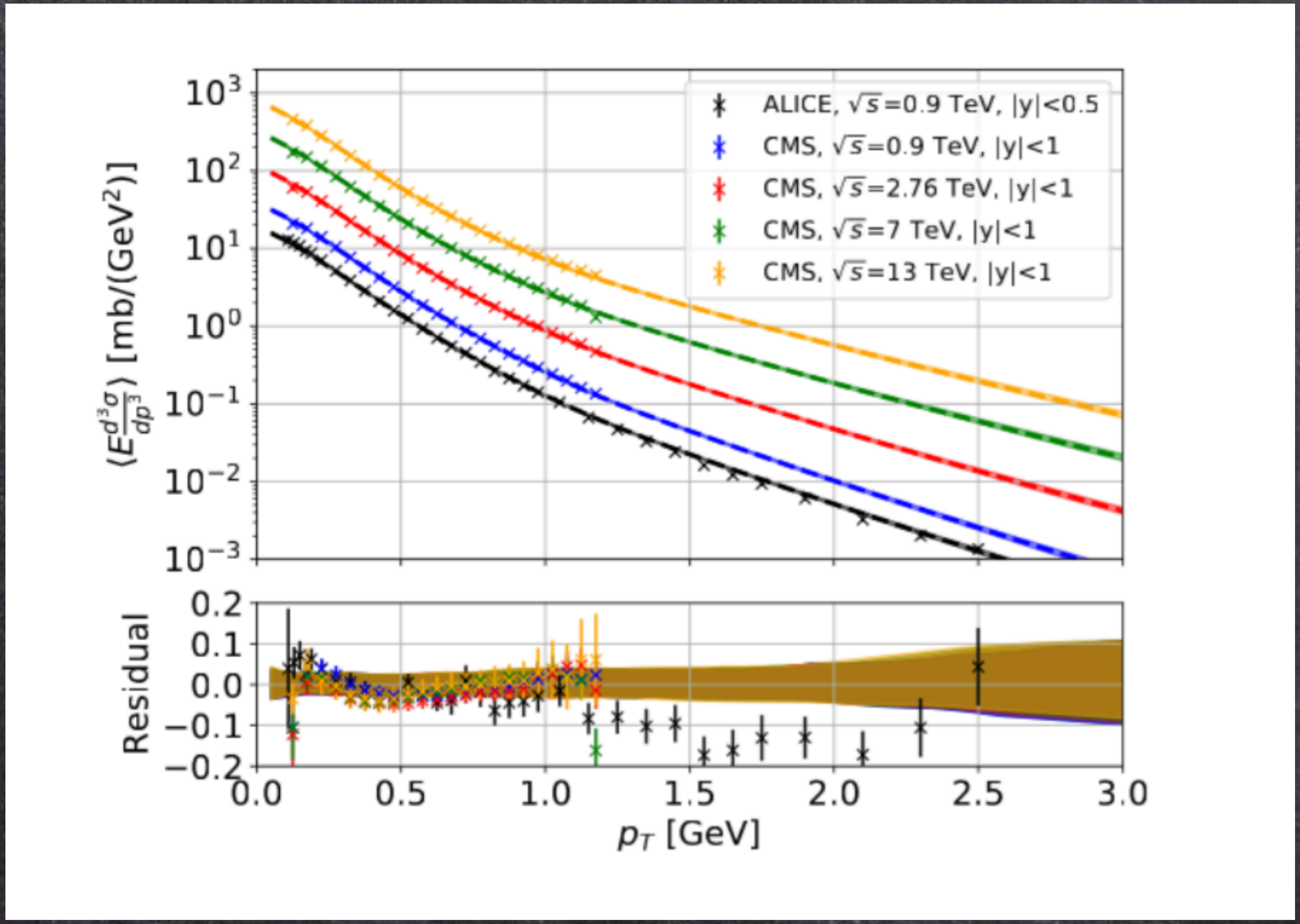
TABLE I. Fractions of primary/fragmentation/radioactive origin (w.r.t. total flux), and contributions of 1-/2-/'more-than-2' step channels (w.r.t. total secondary production) at 10 GeV/n. These numbers are independent of the propagation model if sources have the same spectral index.

CR	% isotope	% of total flux prim.	frag.	rad.	% of multi-step secondaries 1	2	>2
Li		0	100	0	66	25	9
(56%)	^{6}Li	0	100	0	66	25	9
(44%)	^{7}Li	0	100	0	66	26	8
Be		0	100	0	73	20	7
(63%)	^{7}Be	0	100	0	78	17	6
(30%)	^{9}Be	0	100	0	65	26	9
(6%)	^{10}Be	0	100	0	66	26	7
B		0	95	5	79	17	5
(33%)	^{10}B	0	85	15	70	24	6
(67%)	^{11}B	0	100	0	82	14	4
C		79	21	0	77	17	5
(90%)	^{12}C	88	12	0	72	21	6
(10%)	^{13}C	7	93	0	83	13	4
(0.02%)	^{14}C	0	100	0	56	35	9
N		27	72	2	87	9	4
(54%)	^{14}N	49	48	3	83	13	4
(46%)	^{15}N	0	100	0	89	7	3

Results at large sqrt(s)

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

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

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

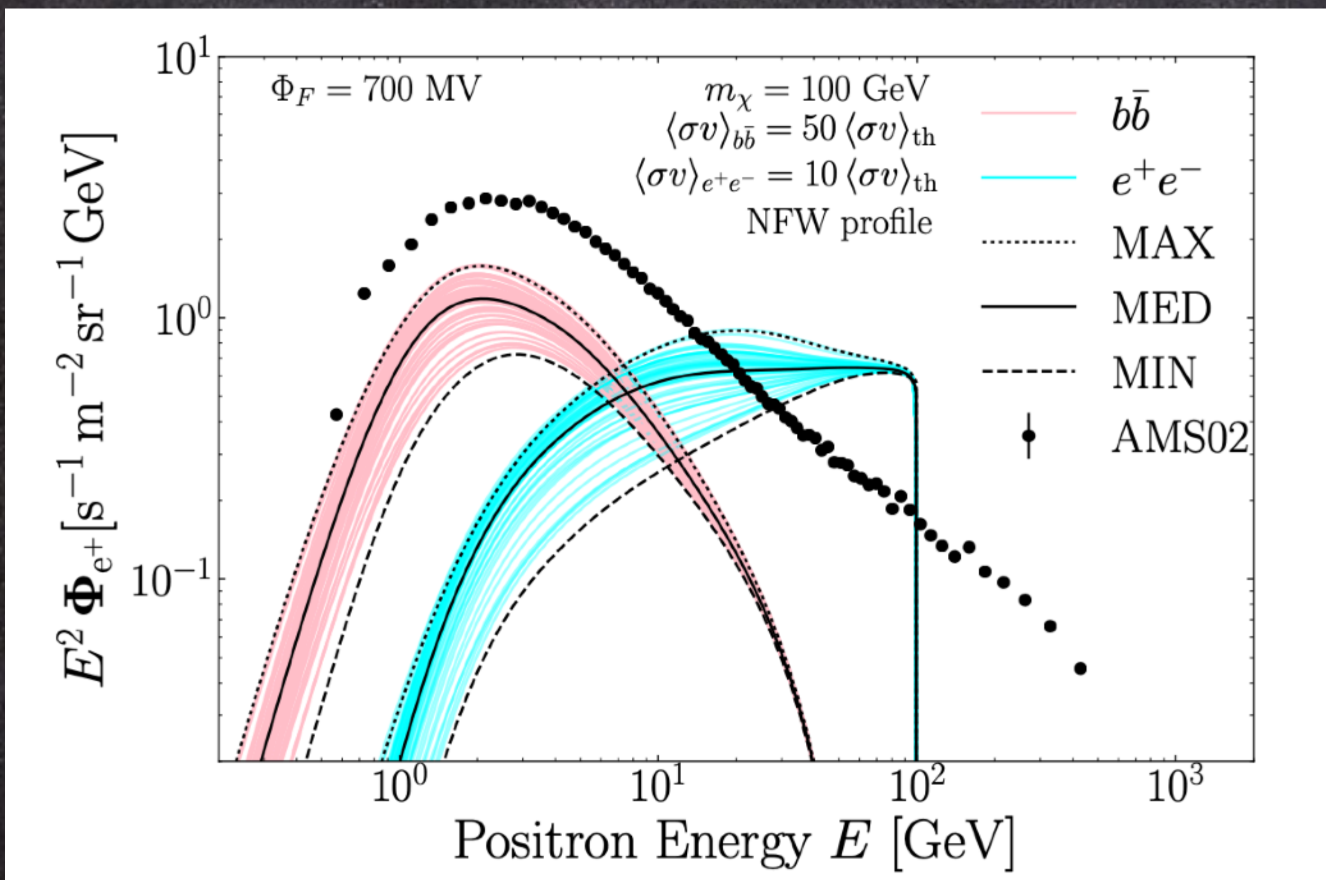
- ρ DM density in the halo of the MW
- m_{DM} DM mass
- $\langle\sigma v\rangle$ thermally averaged annihilation cross section in SM channel f
- Γ DM decay time
- e+, e- energy spectrum generated in a single annihilation or decay event

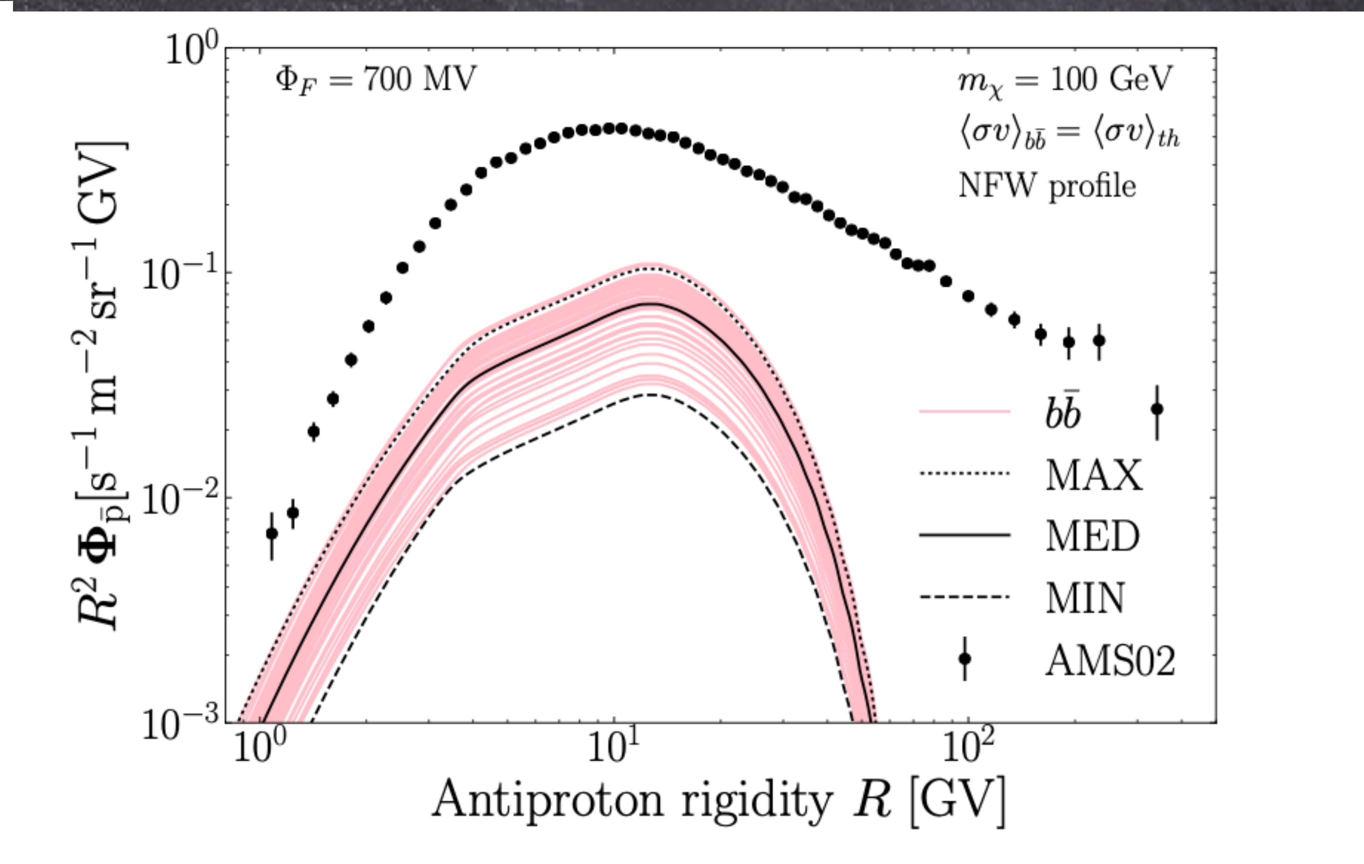
Annihilations take place in the whole diffusive halo

Effect of galactic propagation

Genolini+ 2103.04108

Galactic propagation has strong impact on Dark Matter induced fluxes

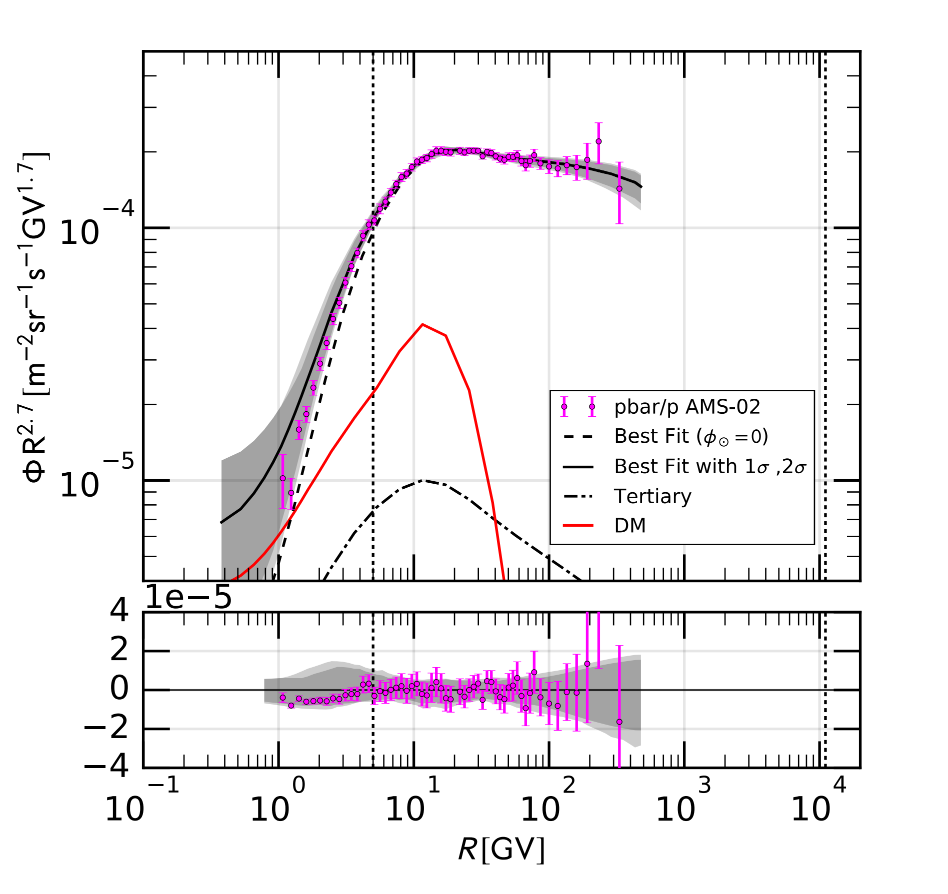




New AMS-02 sec/prim data allow reduction of propagation uncertainties

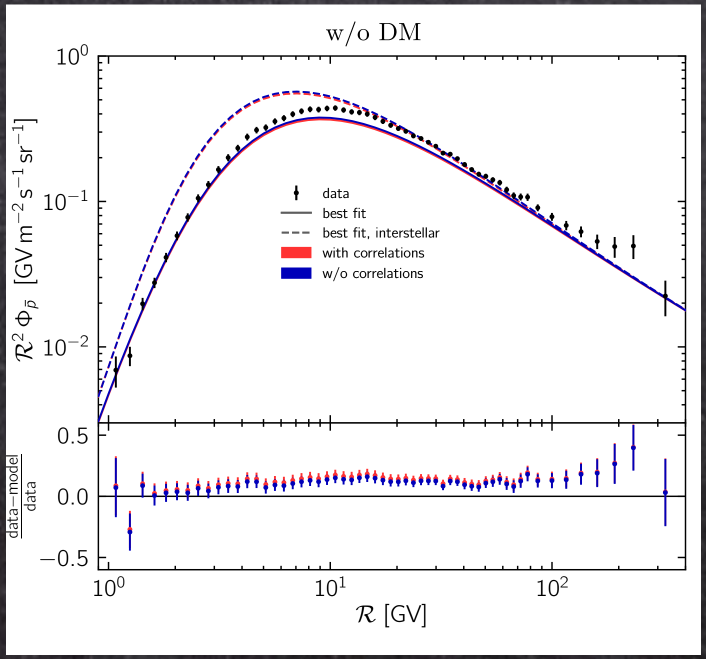
Possible contribution from dark matter

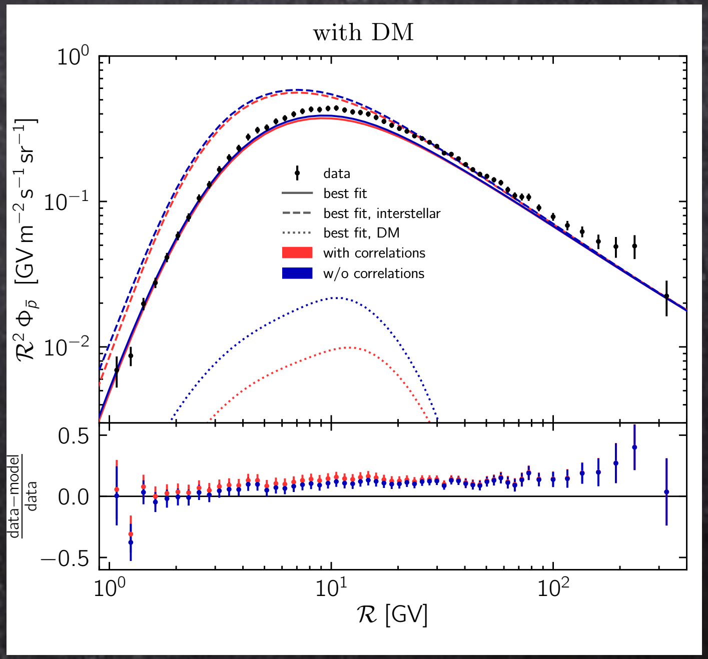
Cuoco, Korsmeier, Kraemer PRL 2017



Antiproton data are so precise that permit to set strong upper bounds on the dark matter annihilation cross section, or to improve the fit w.r.t. to the secondaries alone adding a tine DM contribution

Heisig, Korsmeier, Winkler PRD2020 2020





Derivation of covariance matrix for systematic errors (dominated by p(bar)C absorption cross section) The significance for DM drops below 1sigma