Cosmic ray anti-particles

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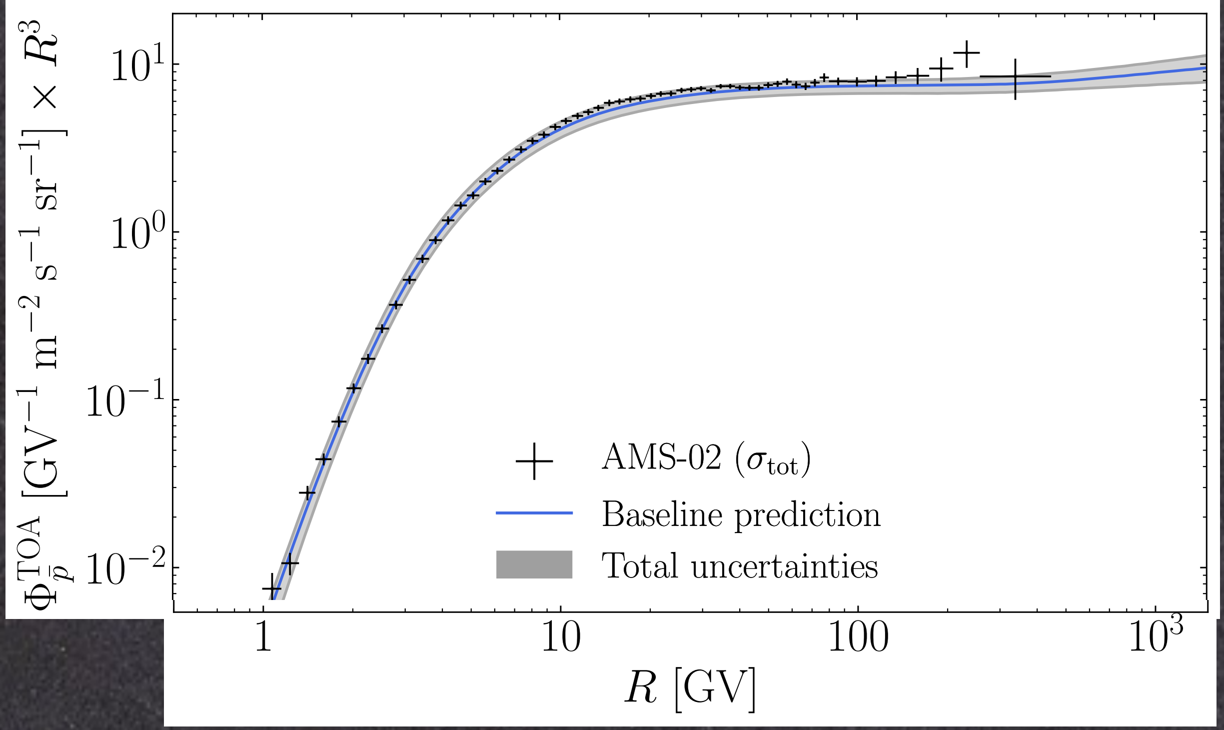
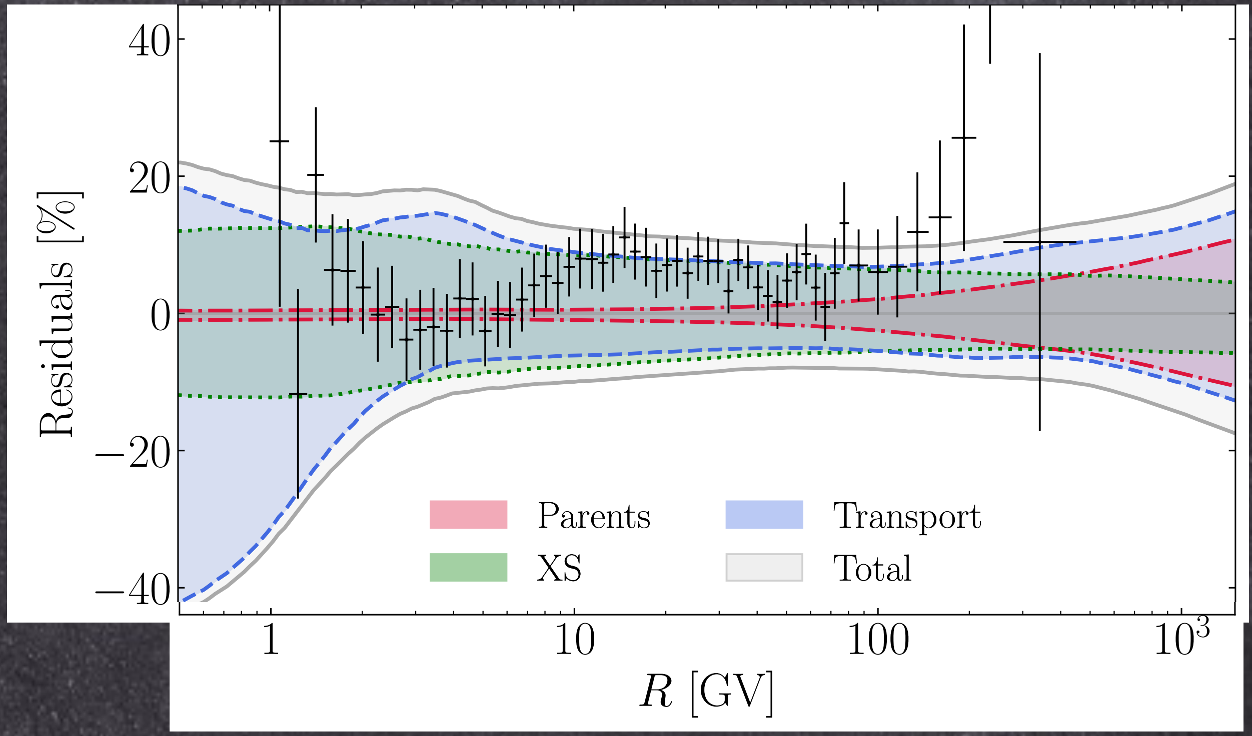
Cern 16.12.2022 - NA61++/Shine workshop

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

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

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

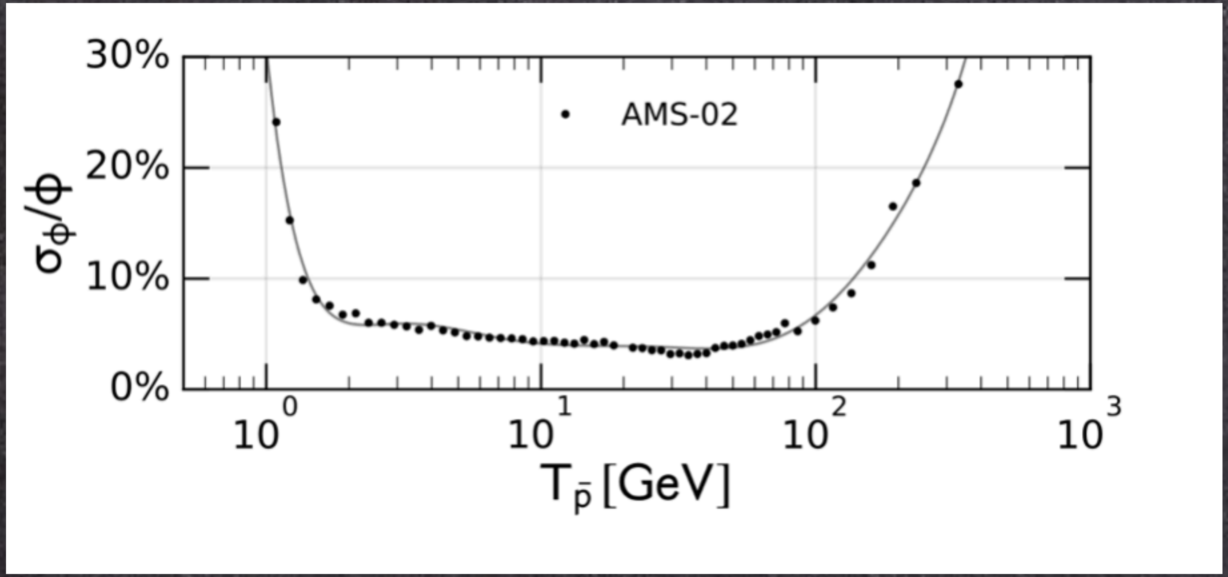
- ρ DM density in the halo of the MW
- m_{DM} DM mass
- <σv> thermally averaged annihilation cross section in SM channel f
- Γ DM decay time
- e+, e- energy spectrum generated in a single annihilation or decay event

Annihilations take place in the whole diffusive halo

Antiproton production by inelastic scatterings

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

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



Data from space are very precise

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

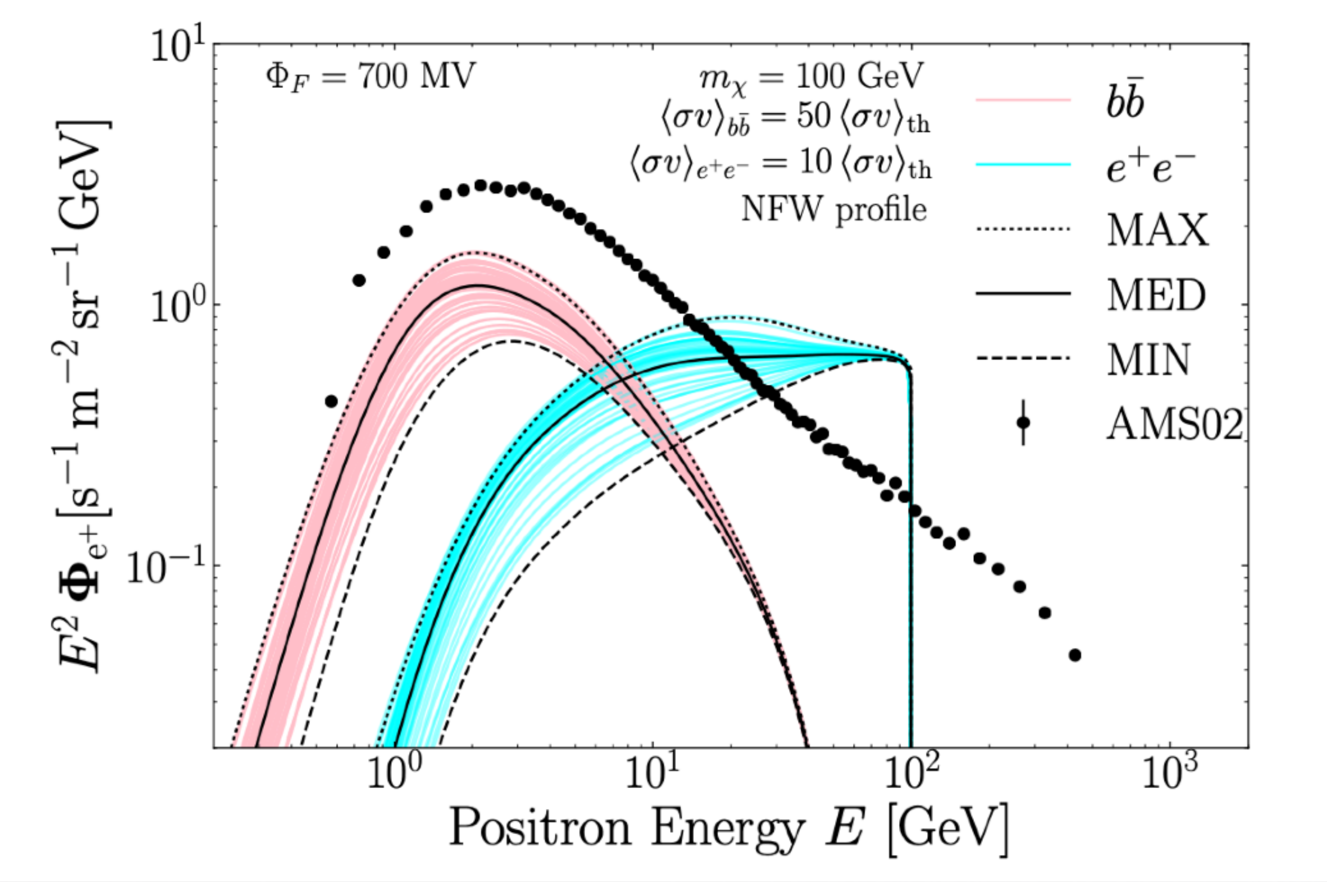
T_p = 6.5 TeV

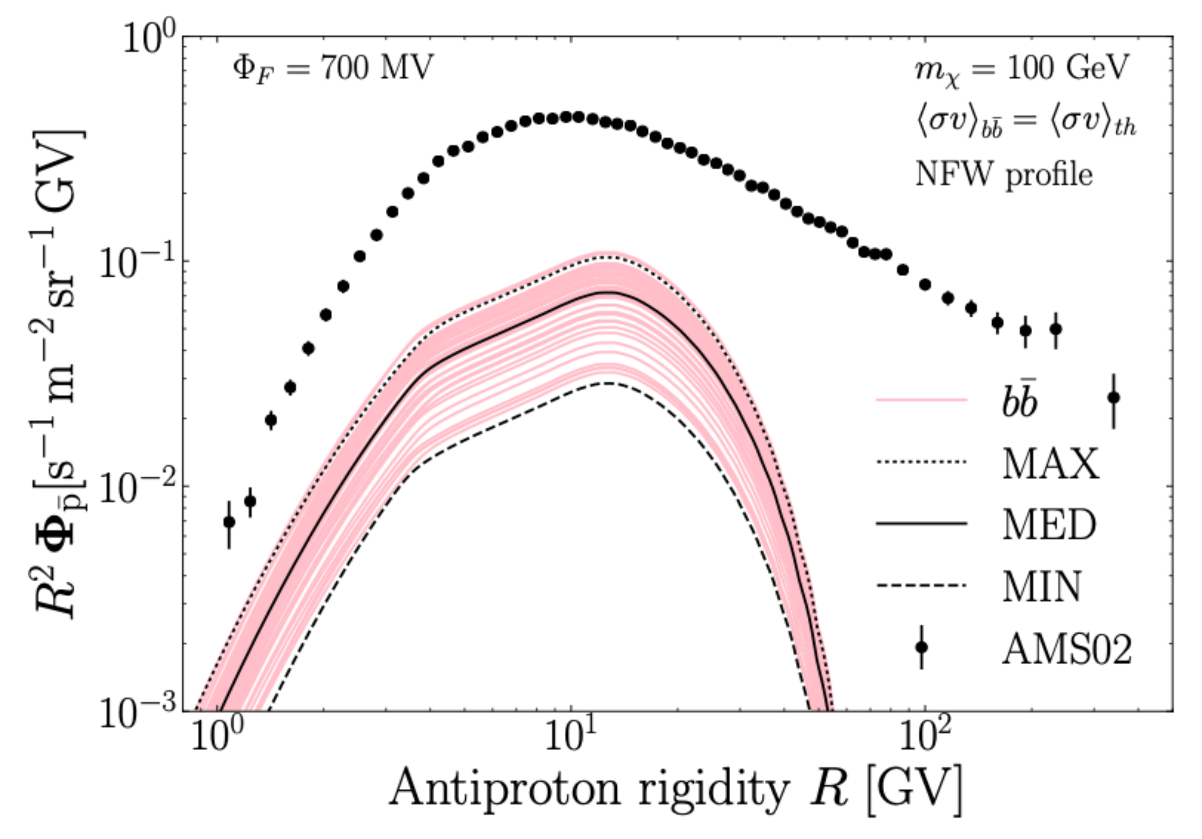
Most recent cross section data

Effect of galactic propagation

Genolini+ 2103.04108

Galactic propagation has strong impact on Dark Matter induced fluxes



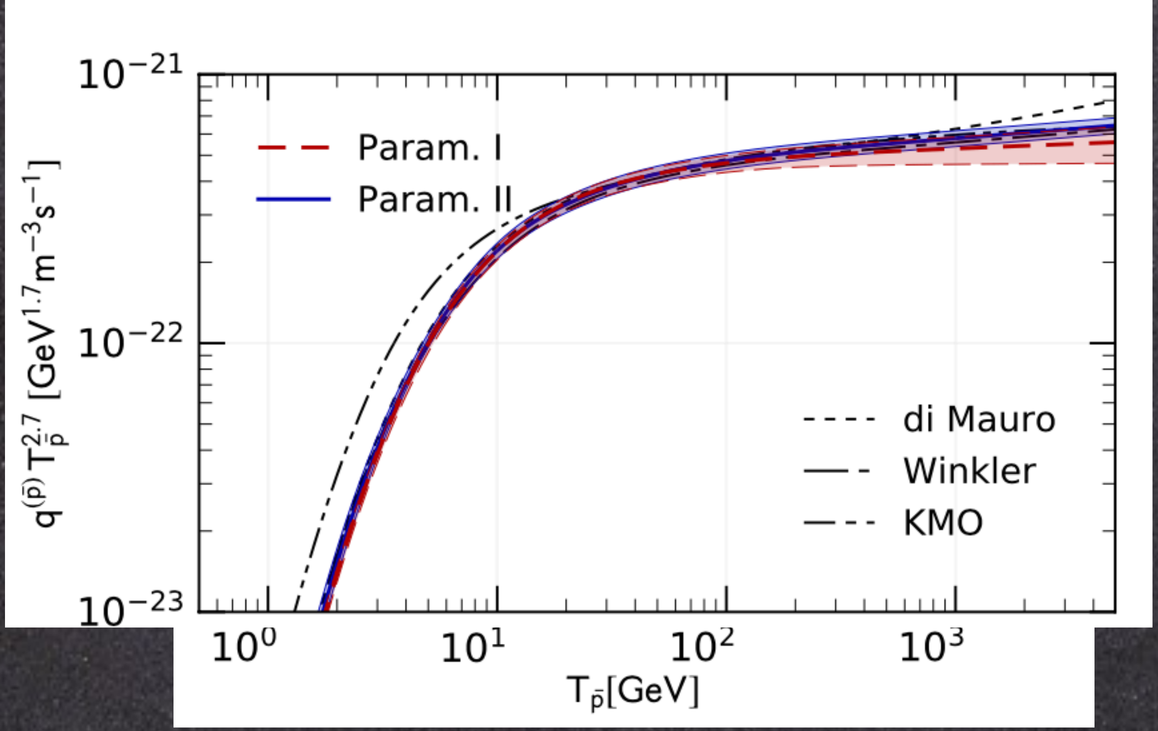


New AMS-02 sec/prim data allow reduction of propagation uncertainties

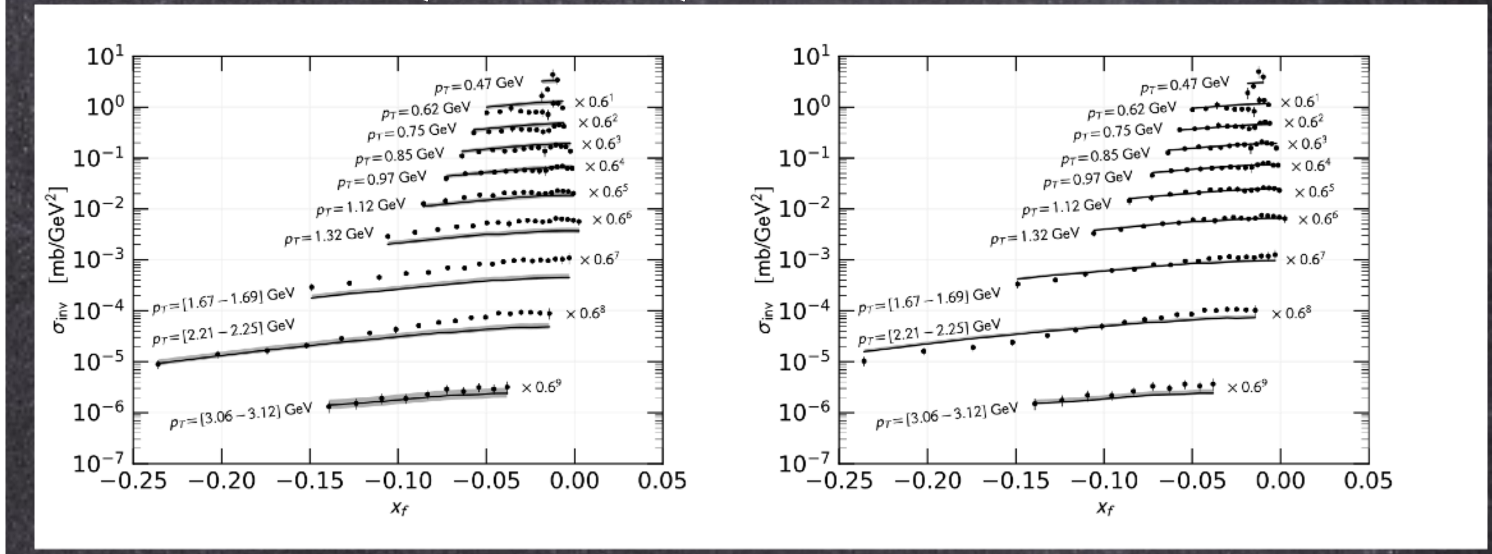
The prompt antiproton source spectrum

Korsmeier, FD, Di Mauro, PRD 2018

pp --> p- X source term



LHCb pHe --> p- X data & our fit

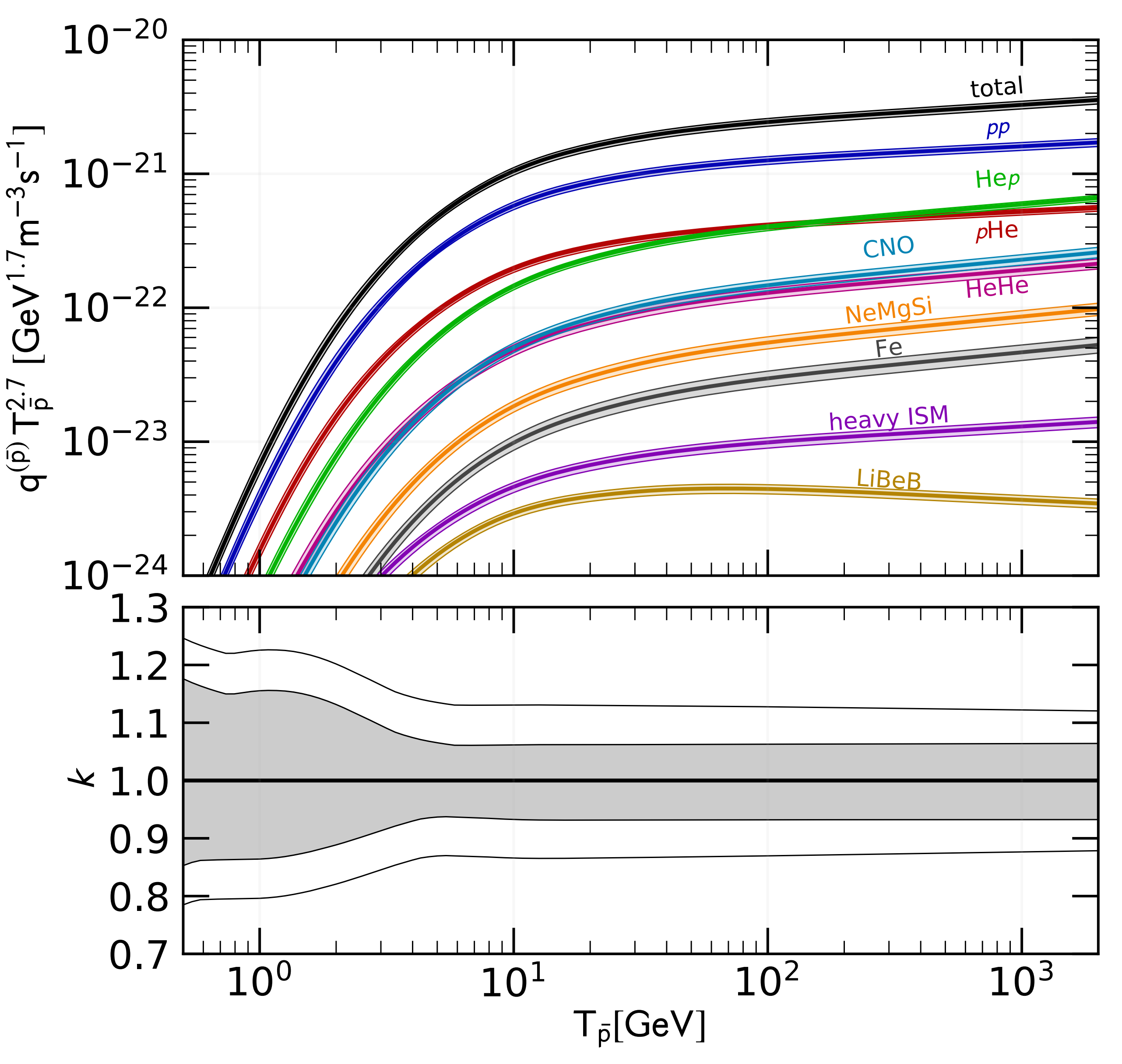


The effect of LHCb data is to select a high energy trend of the pbar source.

A harder trend is preferred.

Effects on the total pbar production

Korsmeier, FD, Di Mauro, 1802.03030, PRD 2018



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

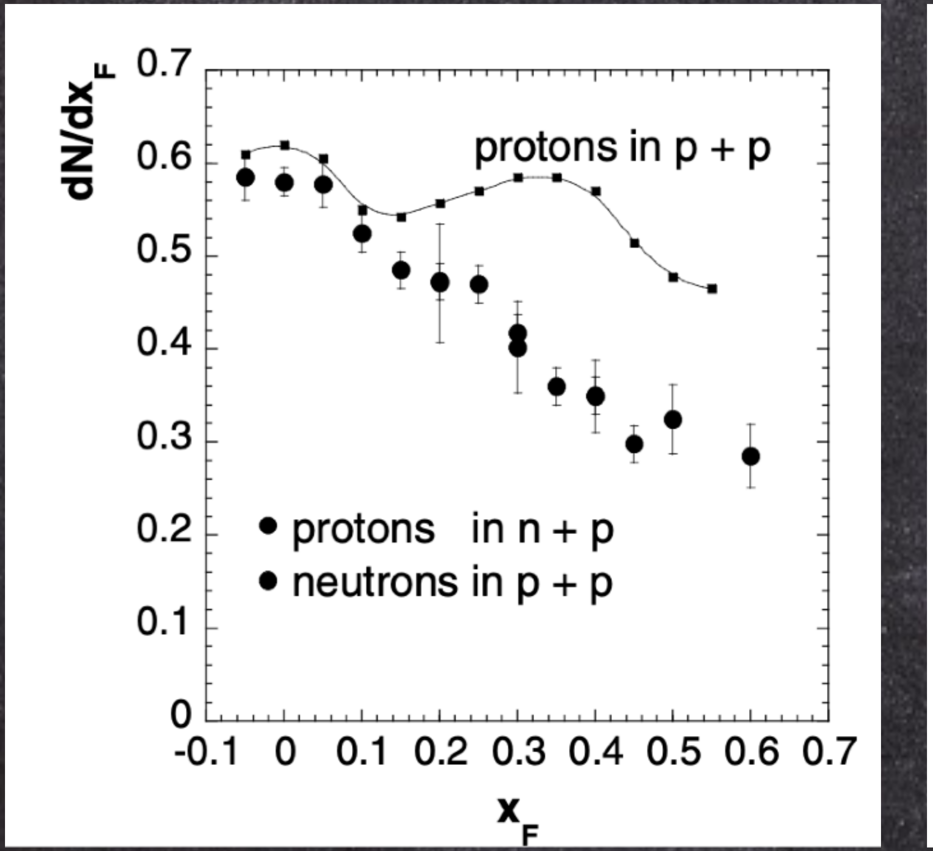
Higher uncertainties at very low energies

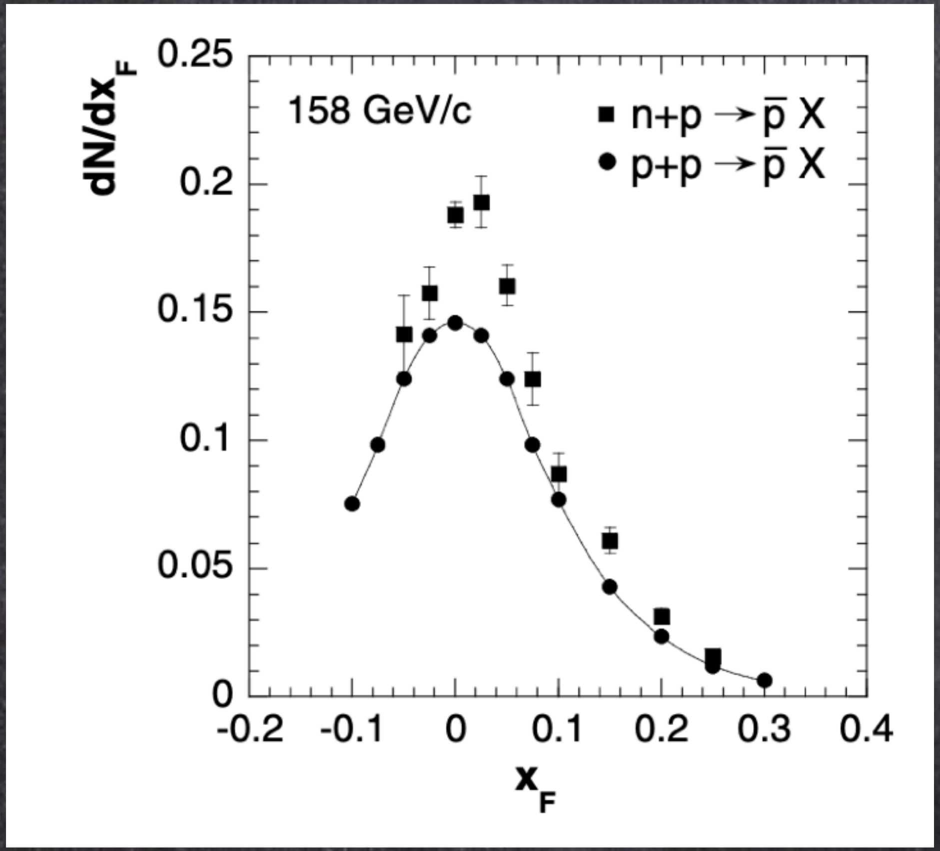
Result with uncertainties in the hyperon correction and isospin violation

Isospin violation?

$$\sigma_{\rm inv}^{\rm Galaxy} = \sigma_{\rm inv}(2 + \Delta_{\rm IS} + 2\Delta_{\Lambda}).$$

Traditionally, one multiplies by 2 for antineutron in pp scatterings.
In H.Fischer (for NA49 Coll.) Acta Phys. Hung A17, 369 (2003) isospin asymmetry is claimed. Enhancement in antineutron production.

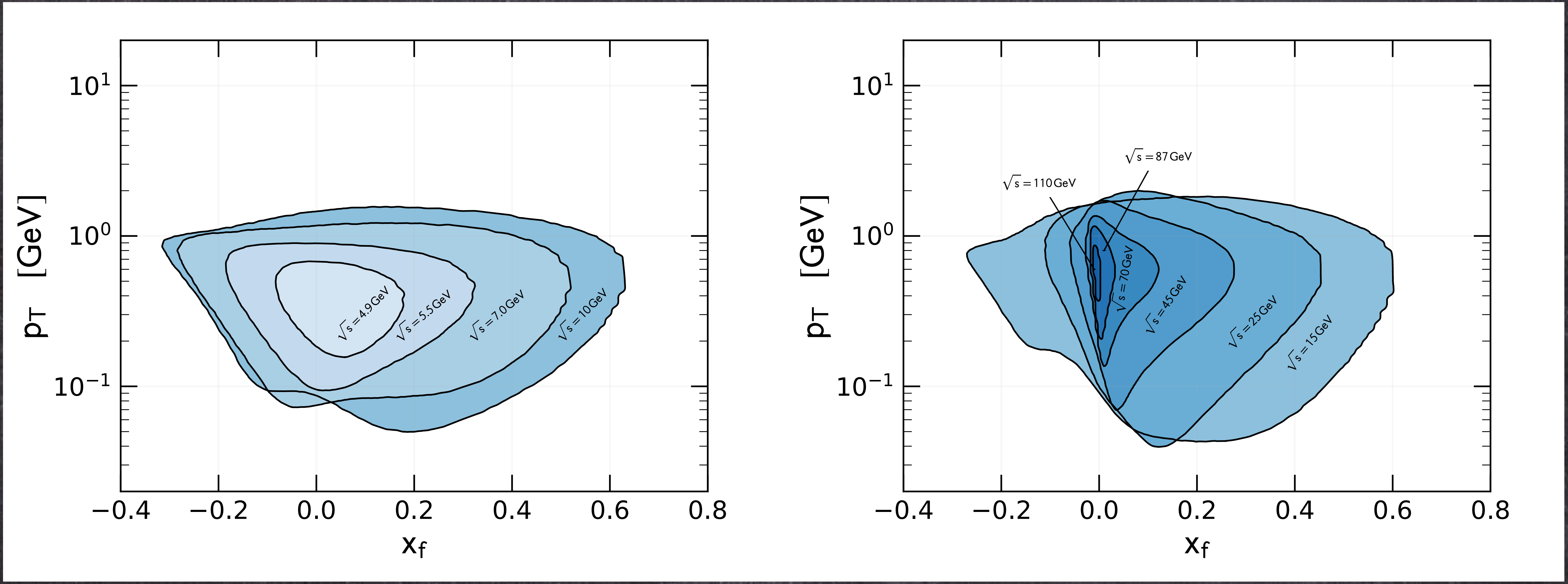




This asymmetry should be tested. NA61?

For next generation experiments

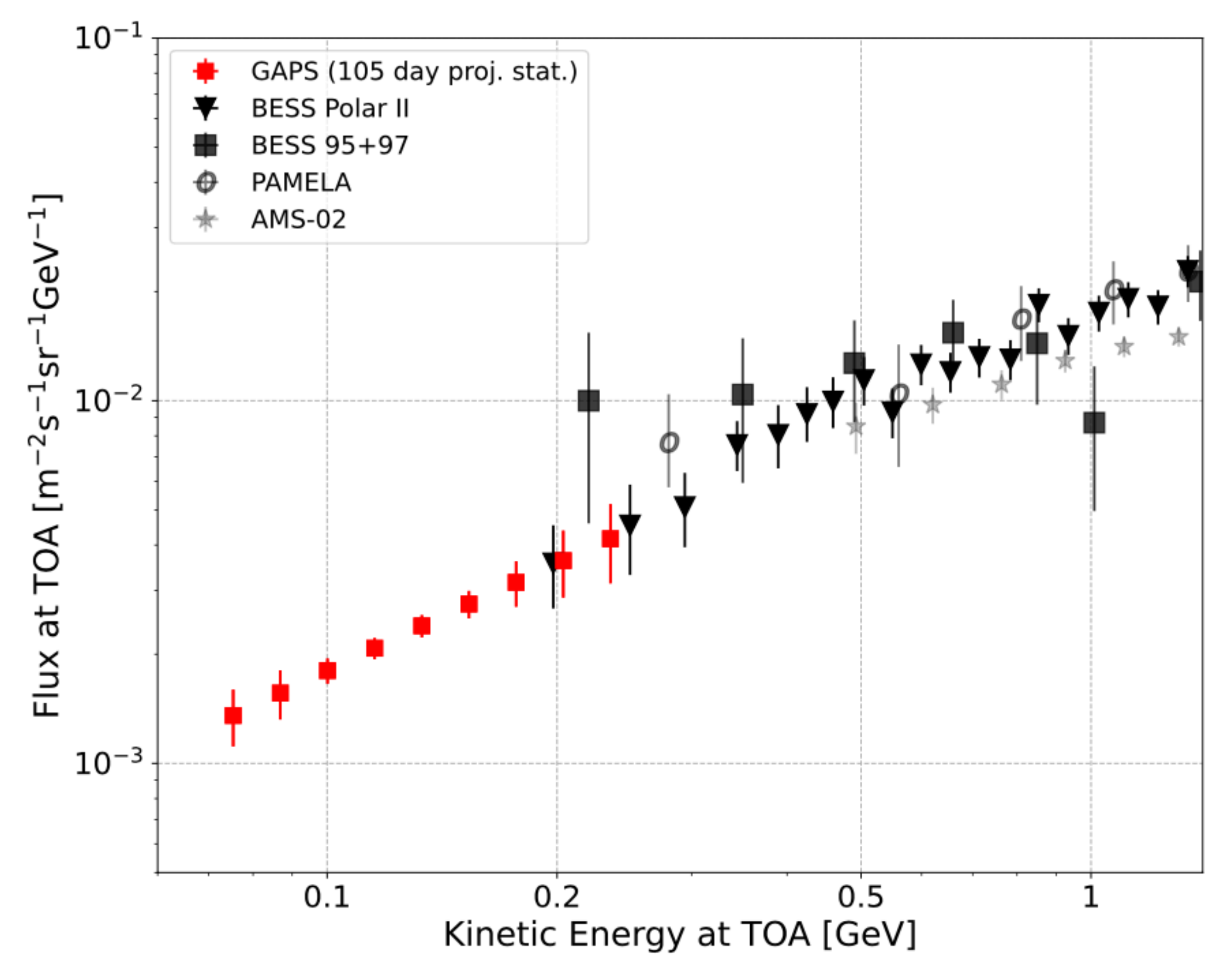
Korsmeier, FD, Di Mauro, 1802.03030, PRD 2018



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

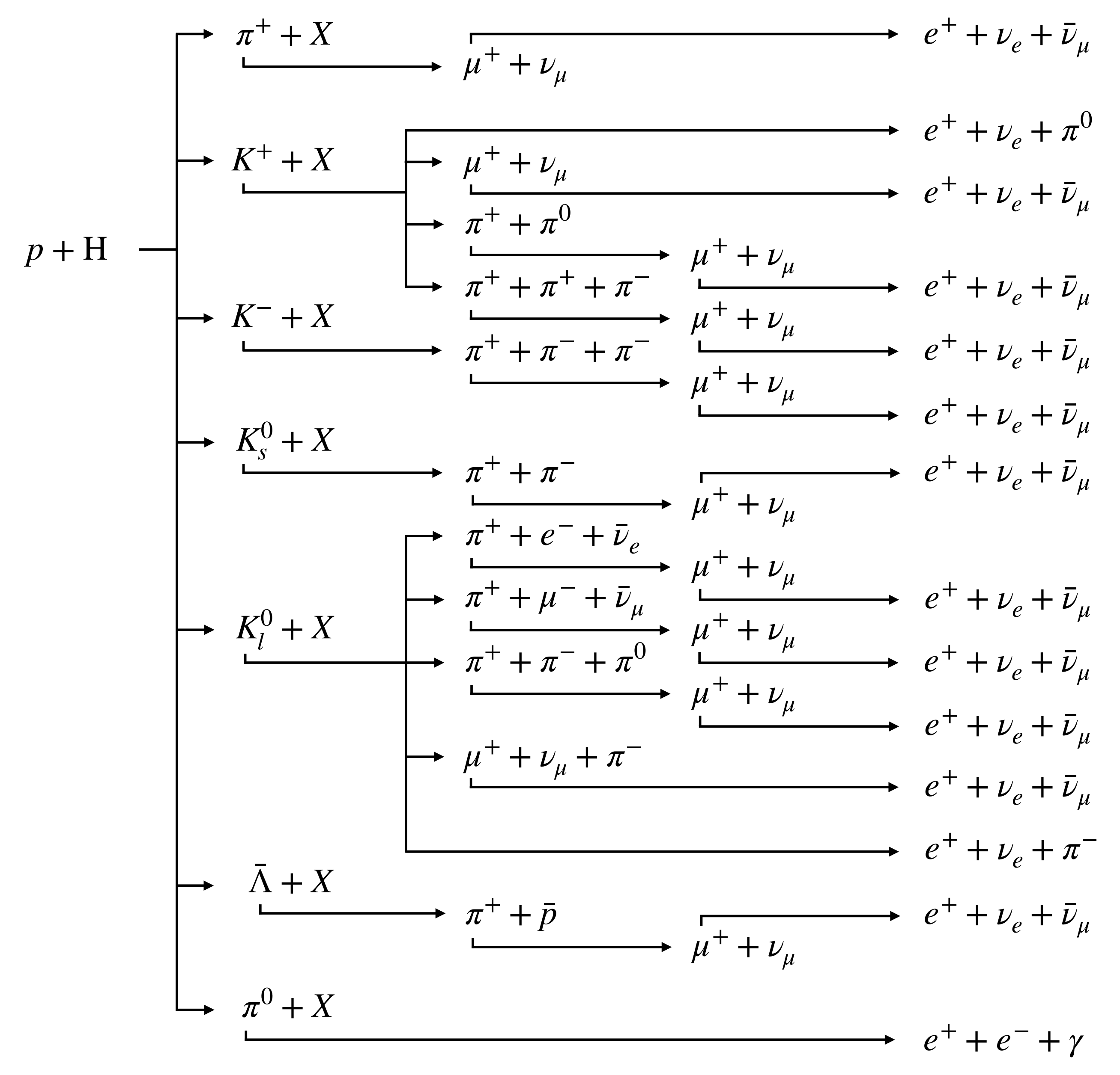


Sub-GeV antiprotons will be measured in 2023 (and 2025, 2027) by GAPS. Robust predictions are needed:
cross sections, propagation, solar modulation

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

e+ production channels

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



$p + \mathrm{H}$

$\pi^+ + X$ → $\mu^+ + \nu_\mu$ → $e^+ + \nu_e + \bar{\nu}_\mu$

$K^+ + X$ → $e^+ + \nu_e + \pi^0$

$K^+ + X$ → $\mu^+ + \nu_\mu$ → $e^+ + \nu_e + \bar{\nu}_\mu$

$K^+ + X$ → $\pi^+ + \pi^0$ → $\mu^+ + \nu_\mu$ → $e^+ + \nu_e + \bar{\nu}_\mu$

$K^+ + X$ → $\pi^+ + \pi^+ + \pi^-$ → $\mu^+ + \nu_\mu$ → $e^+ + \nu_e + \bar{\nu}_\mu$

$K^- + X$ → $\pi^+ + \pi^- + \pi^-$ → $\mu^+ + \nu_\mu$ → $e^+ + \nu_e + \bar{\nu}_\mu$

$K^0_s + X$ → $\pi^+ + \pi^-$ → $\mu^+ + \nu_\mu$ → $e^+ + \nu_e + \bar{\nu}_\mu$

$K^0_l + X$ → $\pi^+ + e^- + \bar{\nu}_e$ → $\mu^+ + \nu_\mu$ → $e^+ + \nu_e + \bar{\nu}_\mu$

$K^0_l + X$ → $\pi^+ + \mu^- + \bar{\nu}_\mu$ → $\mu^+ + \nu_\mu$ → $e^+ + \nu_e + \bar{\nu}_\mu$

$K^0_l + X$ → $\pi^+ + \pi^- + \pi^0$ → $\mu^+ + \nu_\mu$ → $e^+ + \nu_e + \bar{\nu}_\mu$

$K^0_l + X$ → $\mu^+ + \nu_\mu + \pi^-$ → $e^+ + \nu_e + \bar{\nu}_\mu$

$K^0_l + X$ → $e^+ + \nu_e + \pi^-$

$\bar{\Lambda} + X$ → $\pi^+ + \bar{p}$ → $\mu^+ + \nu_\mu$ → $e^+ + \nu_e + \bar{\nu}_\mu$

$\pi^0 + X$ → $e^+ + e^- + \gamma$

We include all these contributions.

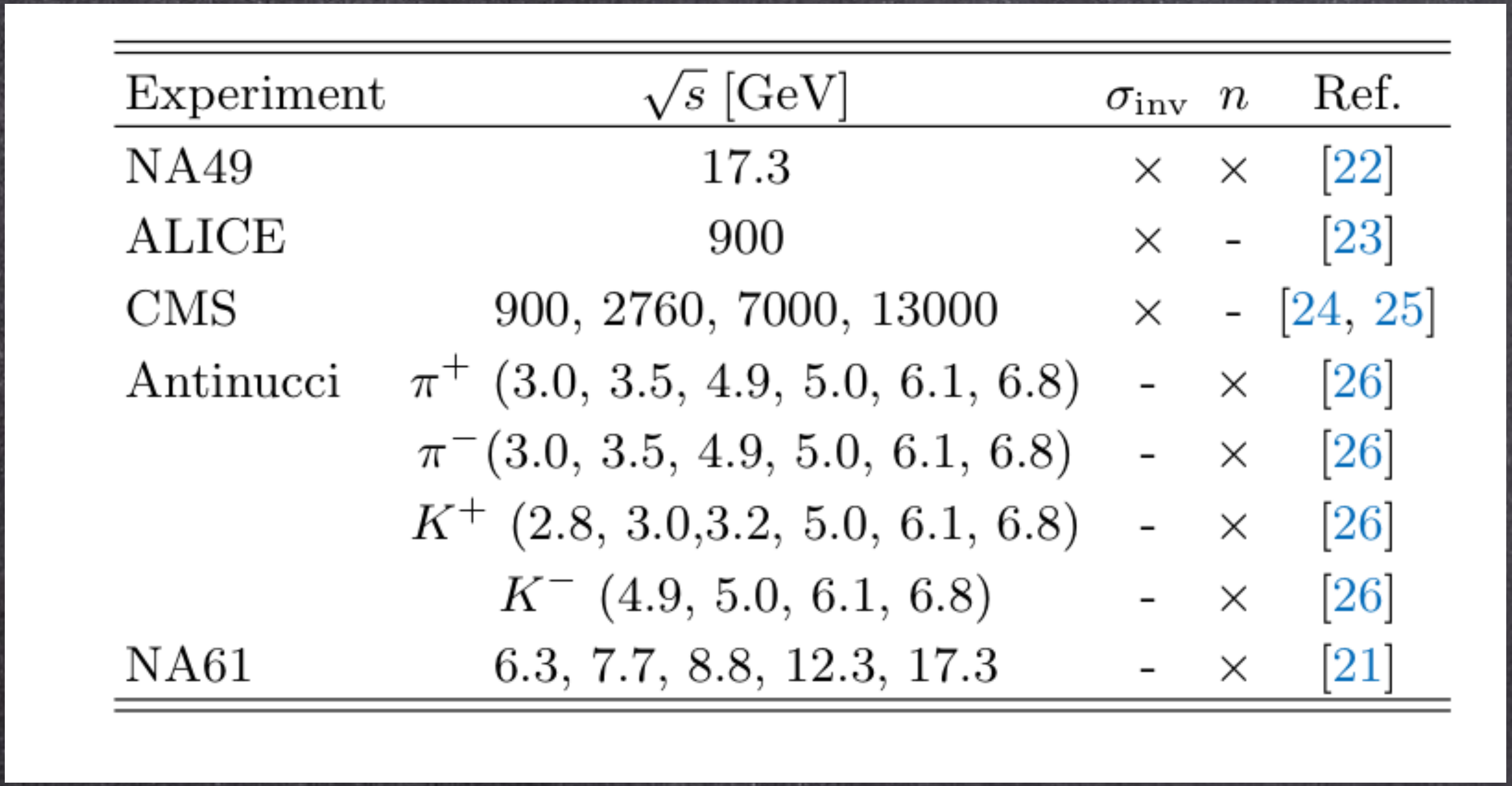
Similarly for collisions with nuclei.

We repeat ALL the analysis for e- under charge conjugation

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

A fit is performed on the σ_{inv} data

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

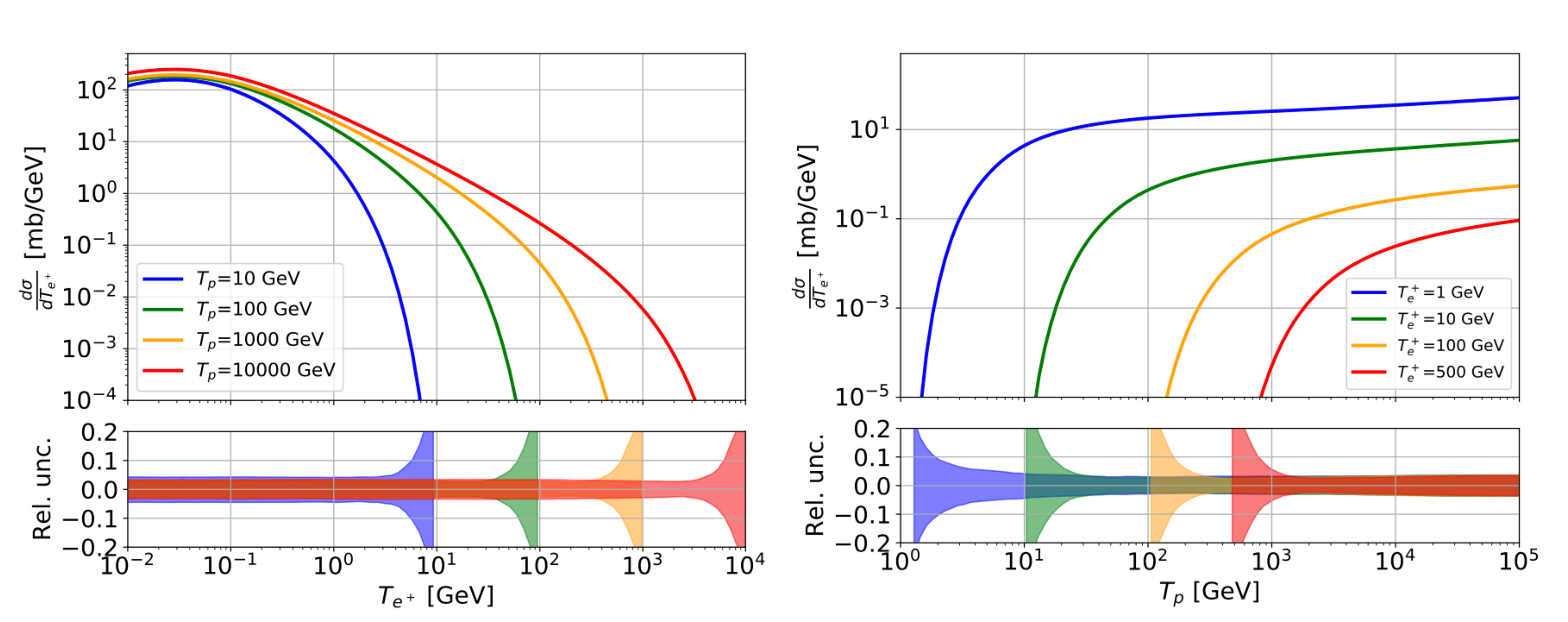


Experiment	$\sqrt{s}$ [GeV]	$\sigma_{\rm inv}$	n	Ref.
NA49	17.3	×	×	[22]
ALICE	900	×	-	[23]
CMS	900, 2760, 7000, 13000	×	-	[24, 25]
Antinucci	π^+ (3.0, 3.5, 4.9, 5.0, 6.1, 6.8)	-	×	[26]
	π^-(3.0, 3.5, 4.9, 5.0, 6.1, 6.8)	-	×	[26]
	K^+ (2.8, 3.0,3.2, 5.0, 6.1, 6.8)	-	×	[26]
	K^- (4.9, 5.0, 6.1, 6.8)	-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

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

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

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

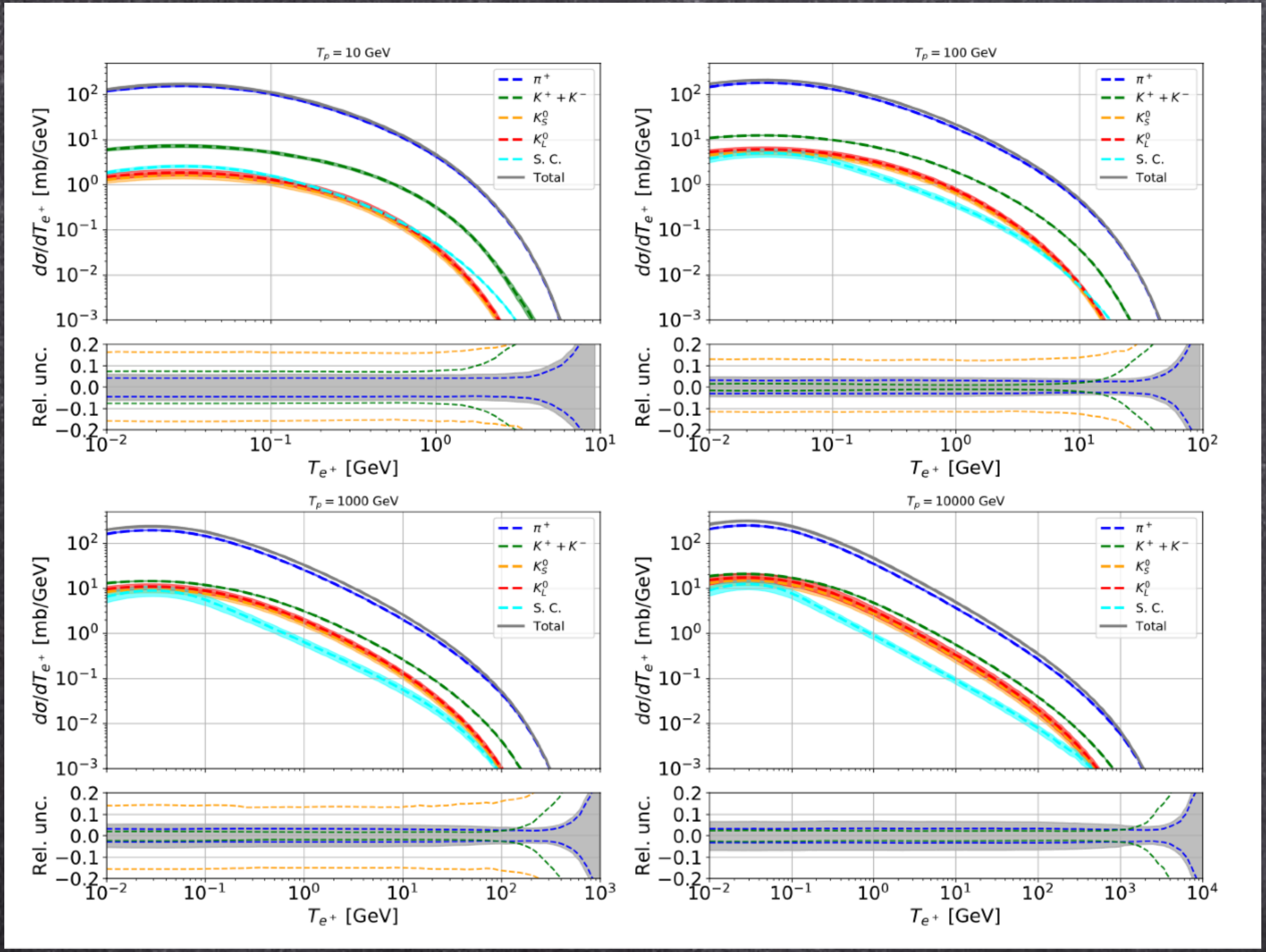


Data are fitted with very small uncertainties

Our parameterizations result appropriate, data are very precise

Total cross section from $pp \to e^+ + X$

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



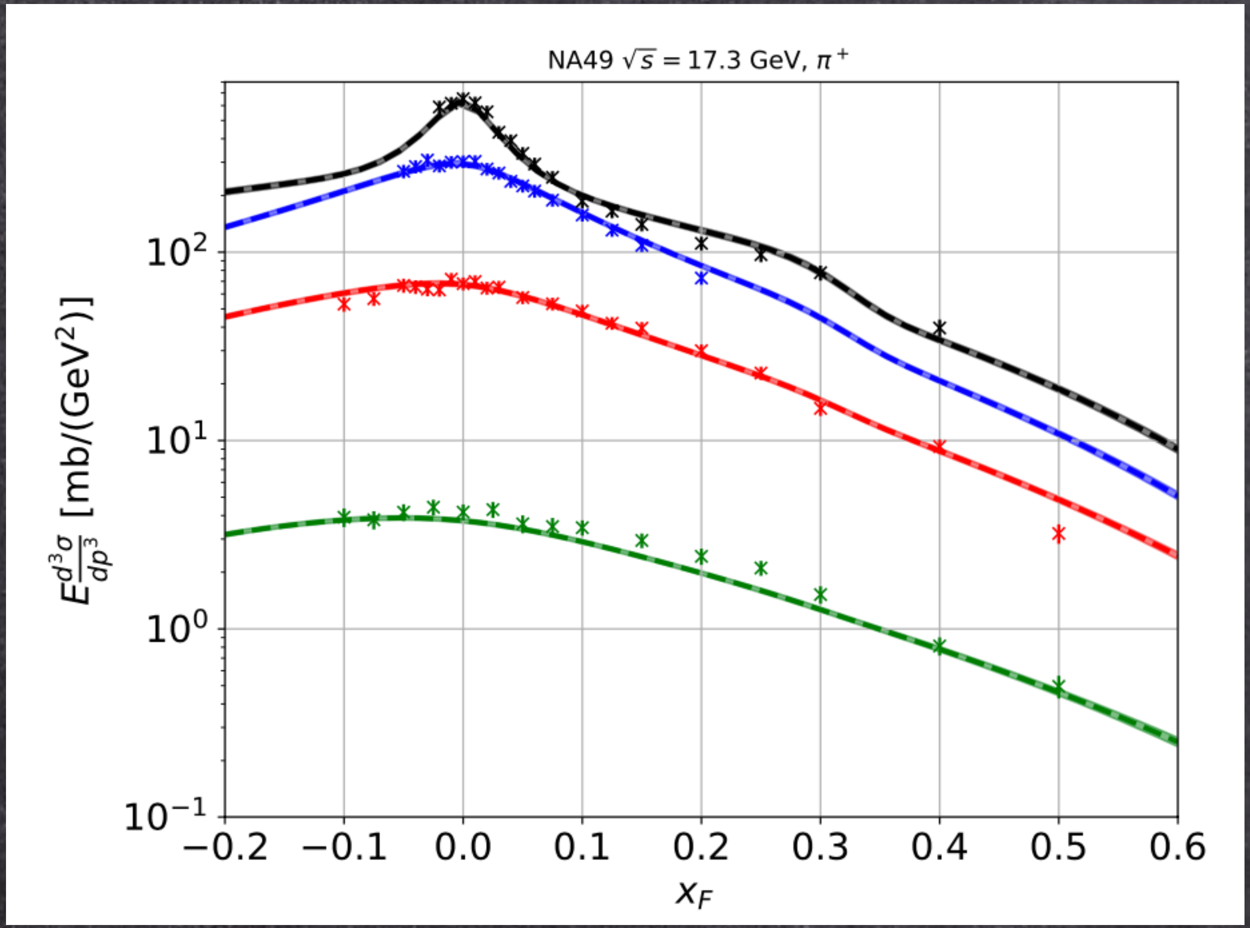
All channels contributing >0.5% are included.

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

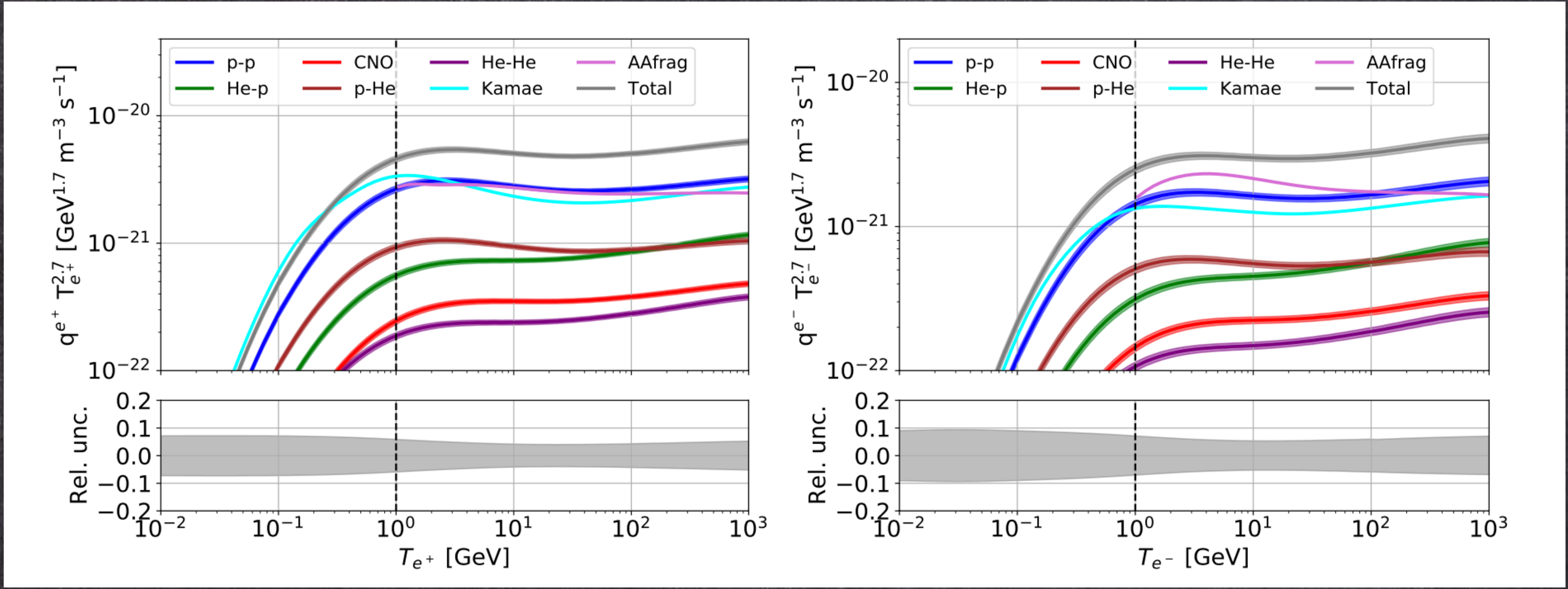


Uncertainty is small, but very likely is not true

Data on He are necessary

Final results on e+ cross section

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



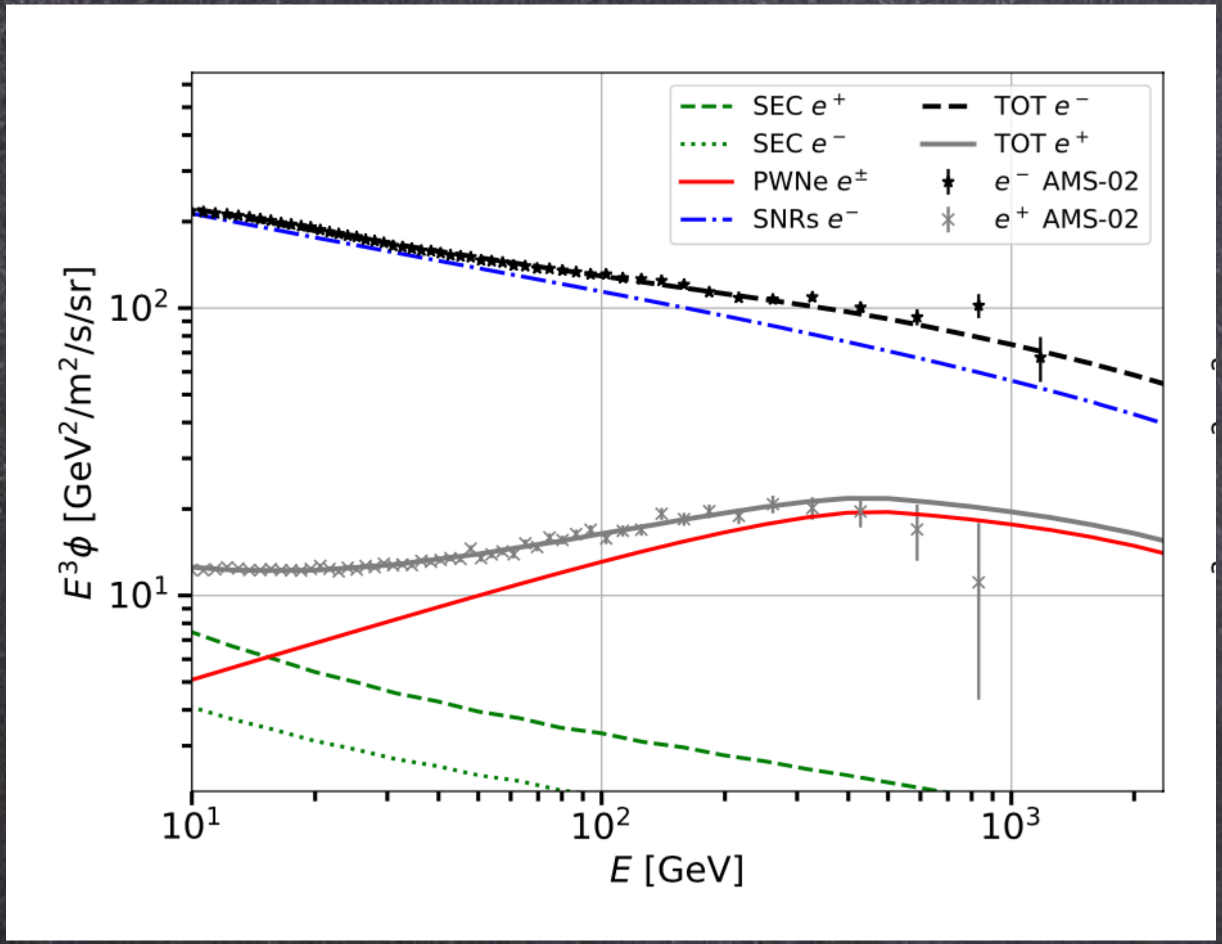
Positrons

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

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

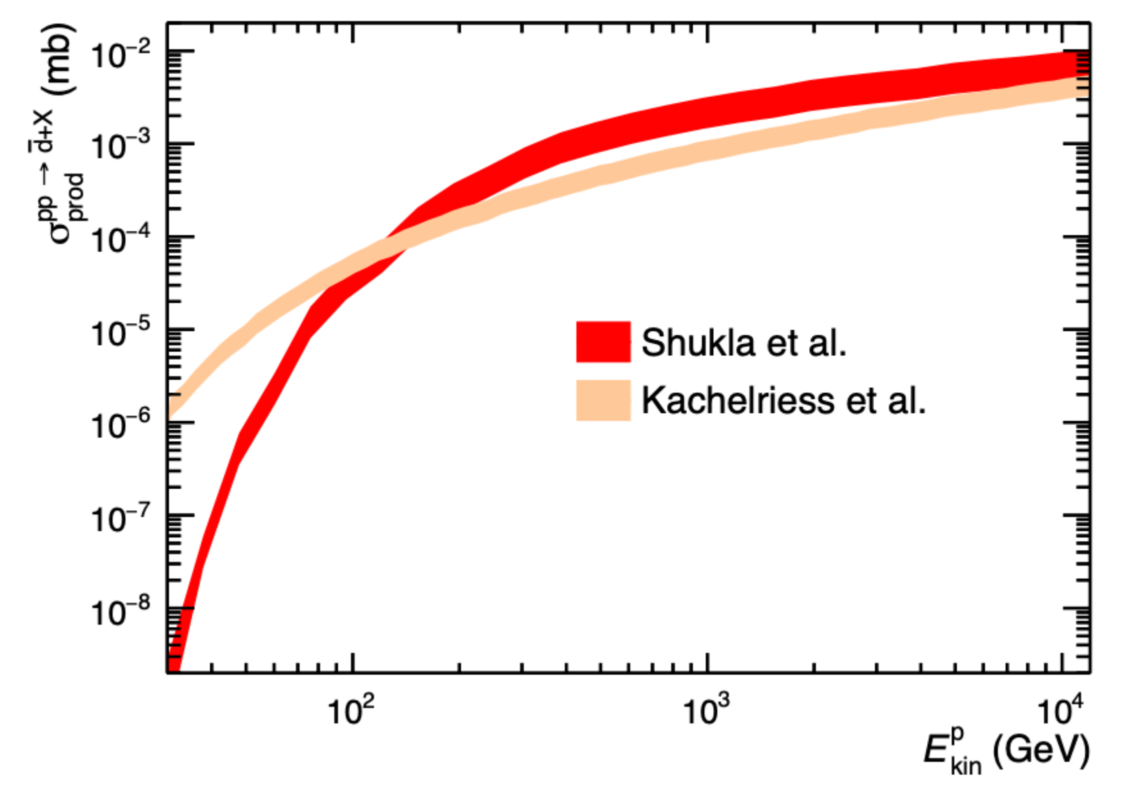
A PRIMARY component is surely there at high energies

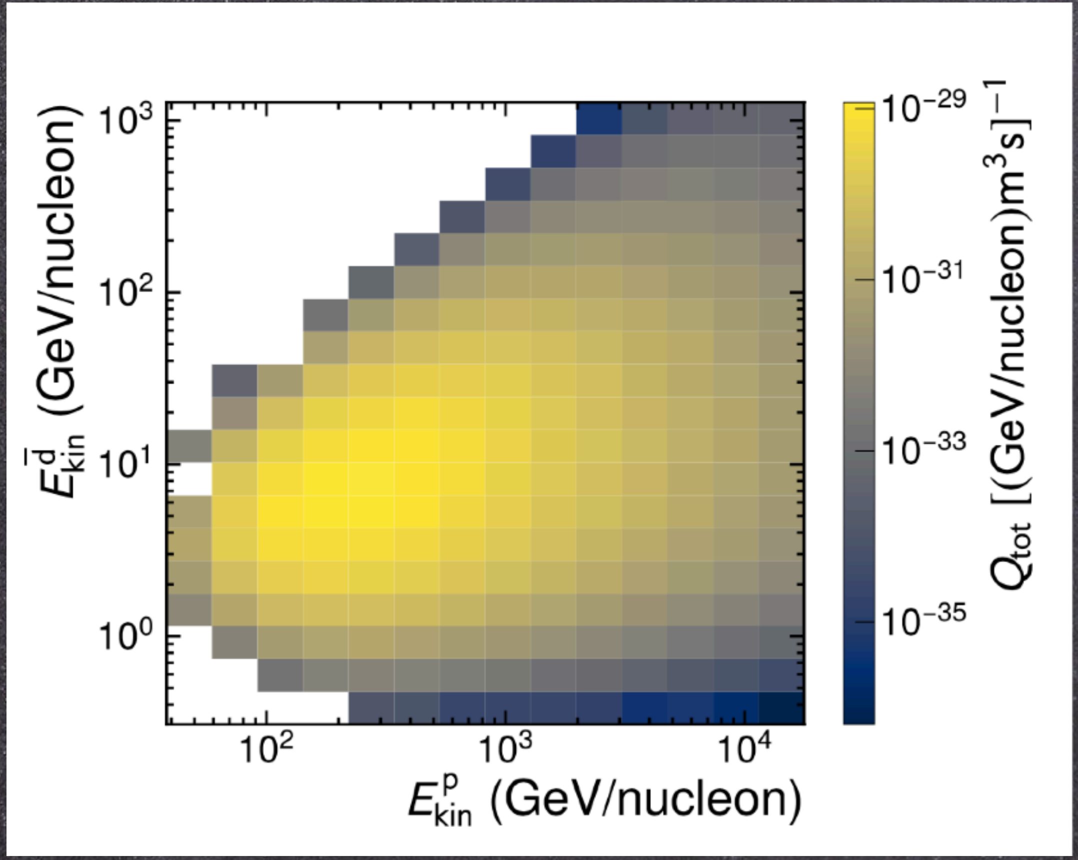
The case for

Antideuterons

Antideuteron production in p-p collisions

Serksnyte et al,PRD 2022





(L) Event-by-event (Monte Carlo) generators and coalescence models different generators may lead to significantly different predictions for low energy antideuterons.

(R) Secondary antideuterons below 1GeV/n are strongly suppressed

Models for p-n fusion into D

Statistical models, but they do not provide any dynamical clue

COALESCENCE models predict momentum distributions

- Uncorrelated $$E_{\overline{\mathrm{d}}}\frac{\mathrm{d}^3N_{\overline{\mathrm{d}}}}{\mathrm{d}p^3_{\overline{\mathrm{d}}}} \simeq B_2\left(E_{\overline{\mathrm{p}}}\frac{\mathrm{d}^3N_{\overline{\mathrm{p}}}}{\mathrm{d}p^3_{\overline{\mathrm{p}}}}\right)\left(E_{\overline{\mathrm{n}}}\frac{\mathrm{d}^3N_{\overline{\mathrm{n}}}}{\mathrm{d}p^3_{\overline{\mathrm{n}}}}\right)$$

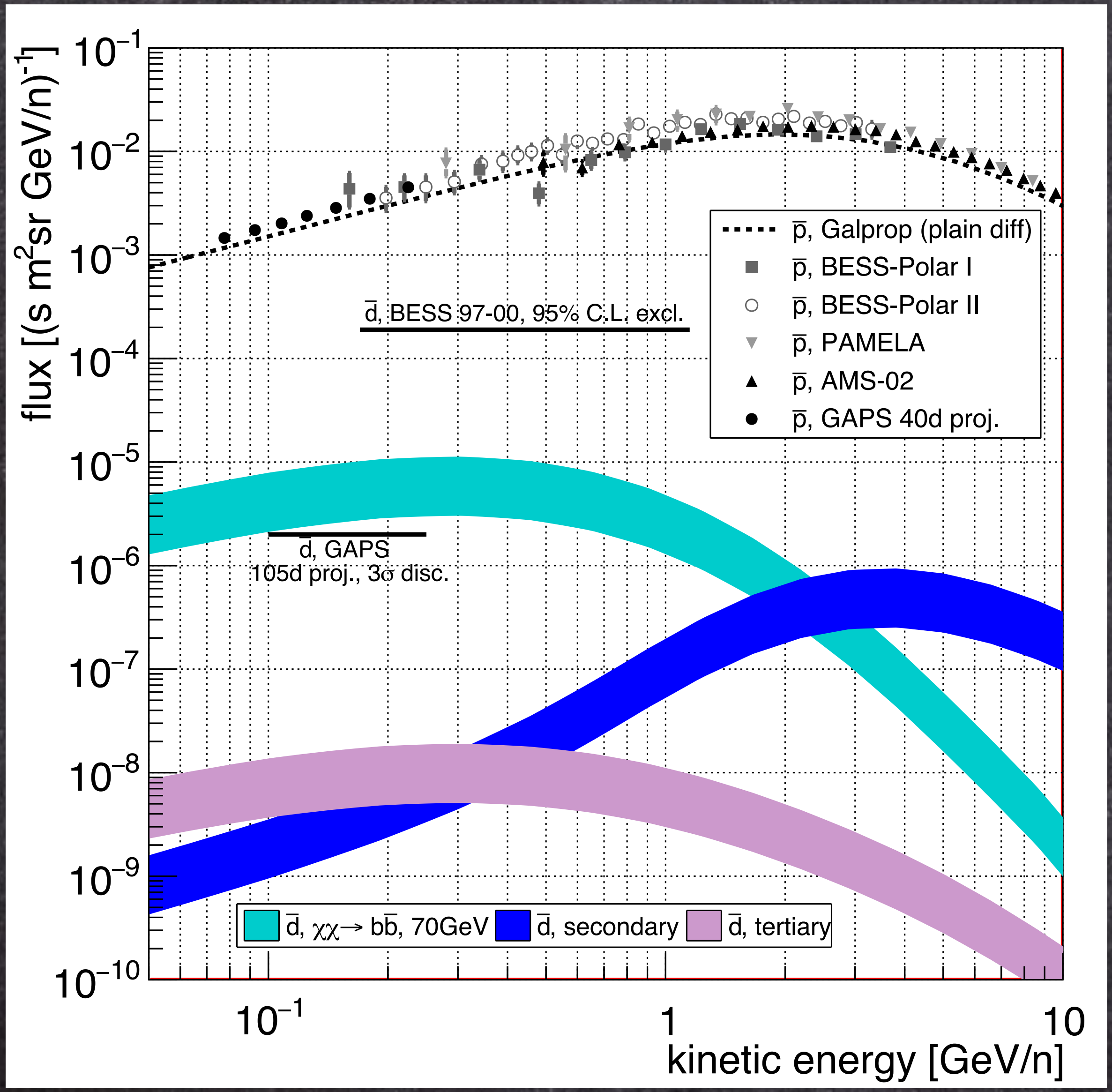
Simplest requirement: $|\vec{p}_{\overline{\mathrm{p}}} - \vec{p}_{\overline{\mathrm{n}}}| < p_0$ -> factorized coalescence (B_2 or P_C)

- Correlated, Monte Carlo based models. Particles close in momentum and physical space.

- Wigner function representations - semi-classical, wave functions

Antideuterons persepctives

P. Von Doetinchem et al. Phys. Rep. 2021



AMS-02 antiproton data

Antideuteron predictions for DM model indicated by pbar AMS-02 data

Bands are for coalescence uncertainty

Uncertainties on P_c is ± 70%

Conclusions

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

The low energy (< 1 GeV/n) window keeps very exciting for discoveries by antiprotons

Propagation uncertainties are reduced to a factor 5, and close to be further sized

Fusion has been studied both theoretically and phenomenologically And the uncertainties on Pc is ± 70%

Antiprotons: Low energies, isospin violation, He target
Positrons or π^+ and K^+: good state

PS. $\pi^0 \rightarrow 2\gamma$ almost no data

Analytical formulae for e± production XS

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

The procedure is fully data driven

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

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

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

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

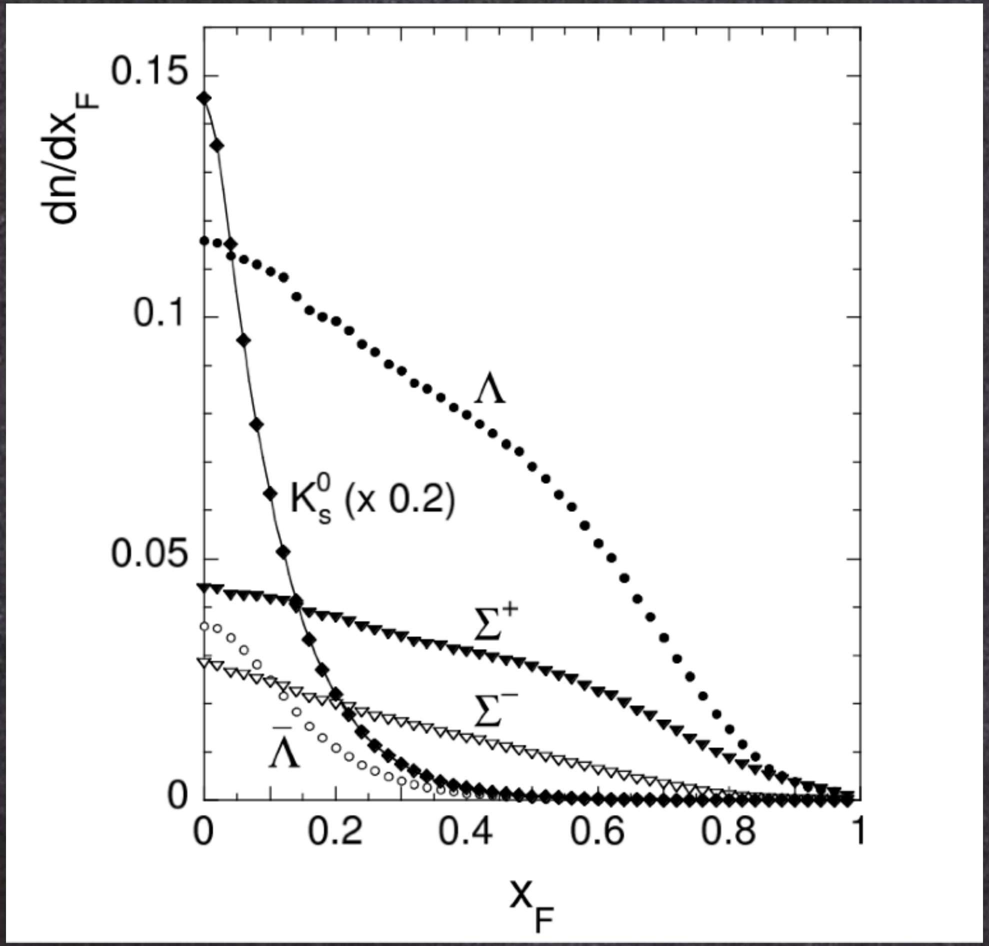
F_s and F_r mainly driven by NA49 data

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

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



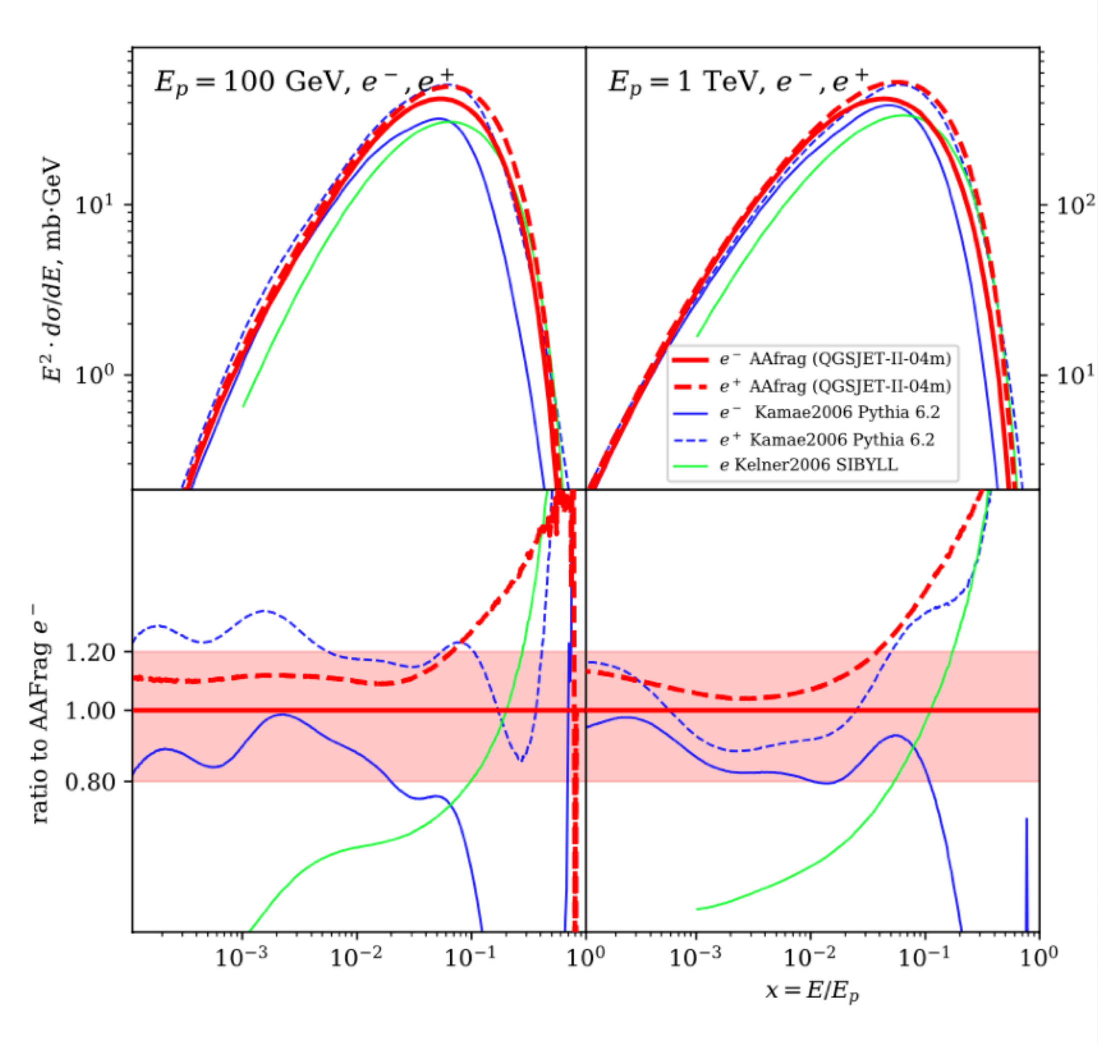
NA49 p_T integrated, MC

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

Comparison with Monte Carlo generators

Koldobskiy et al., PRD 2021, 2110.00496

Results with Aafrag



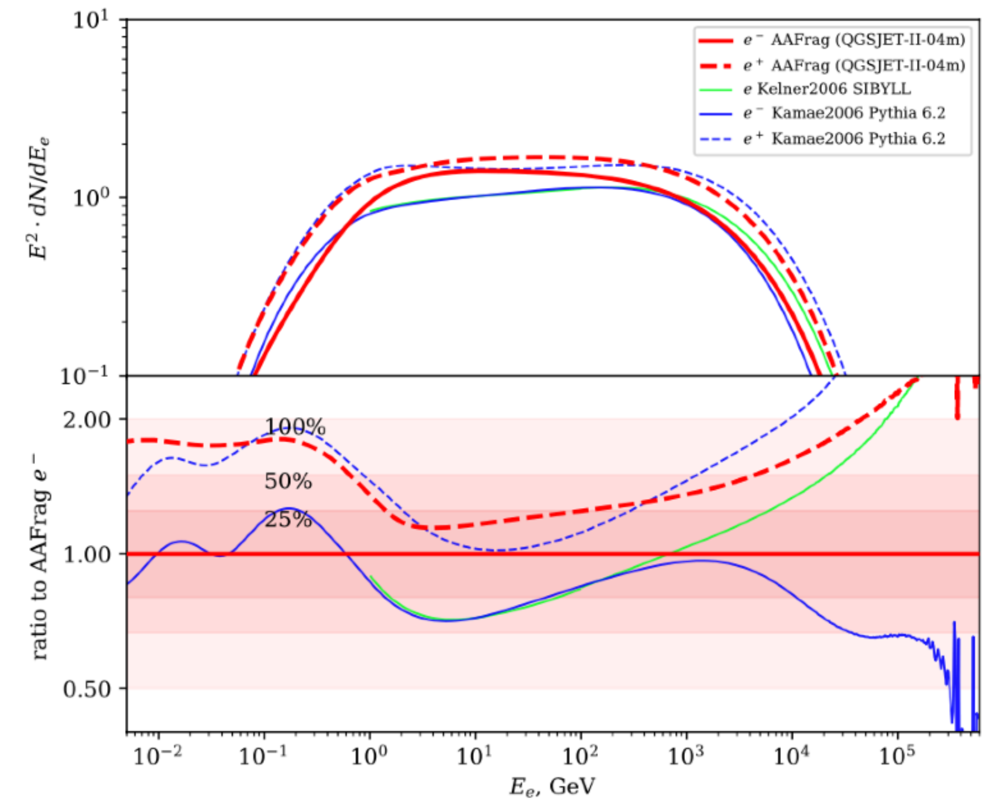


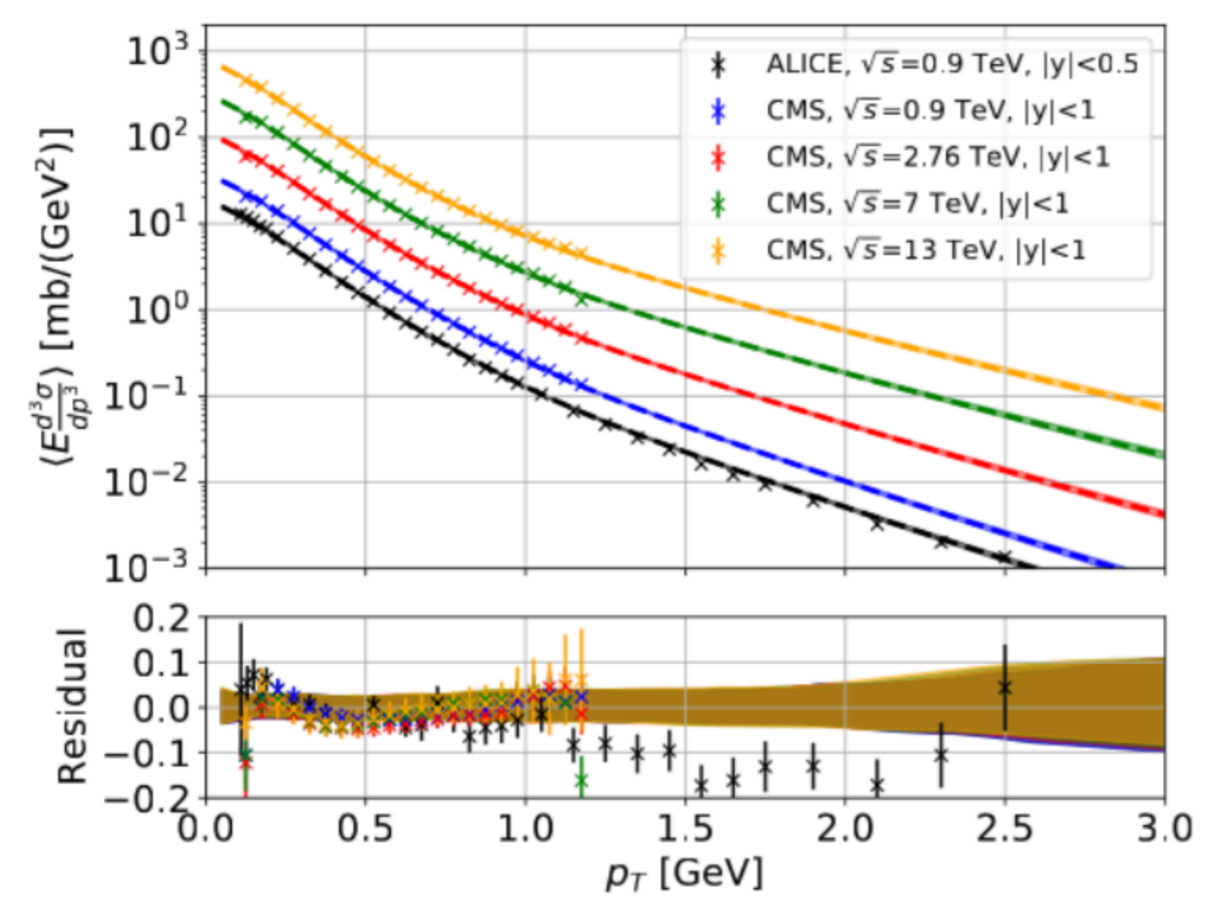
FIG. 9: Electron and positron fluxes for a power-law cosmic ray spectrum ($\propto 1/p^2 \exp(-p/p_0)$) .

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

Results at large sqrt(s)

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

We use σ_{inv} or multiplicity



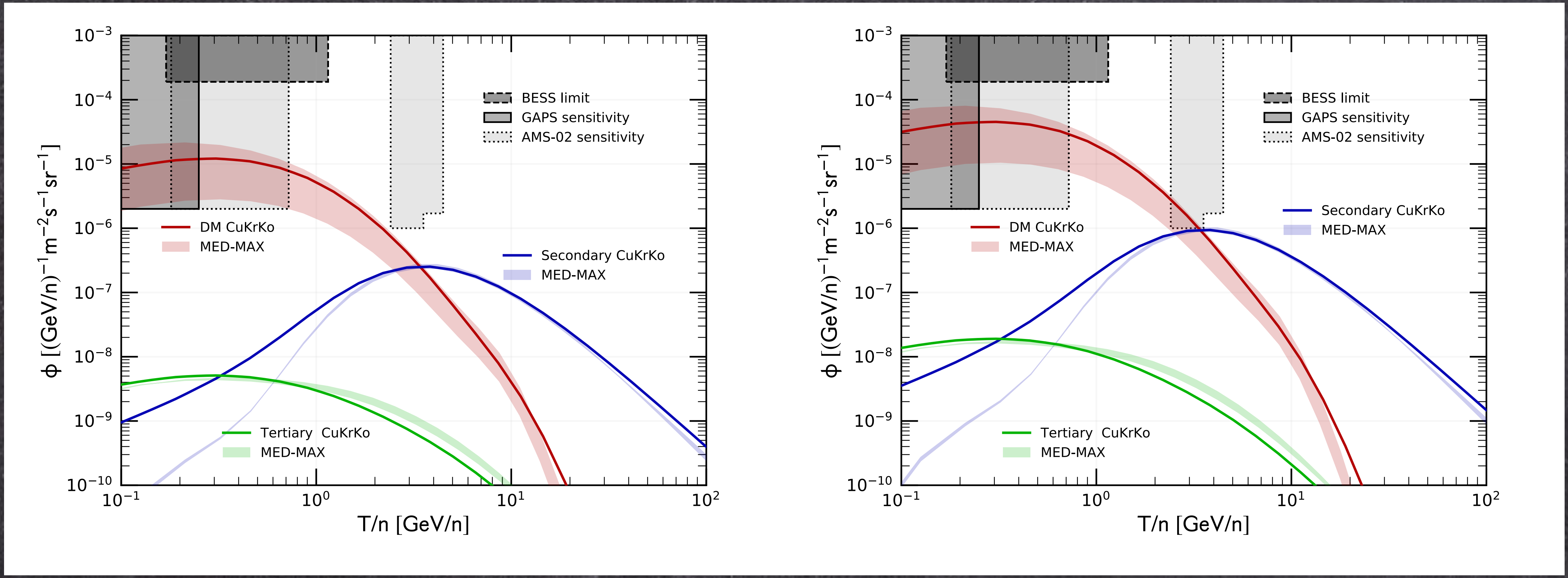
Uncertainties between 5% and 10% - most relevant is 5% at low p_T

Possible antideuteron verification of Dark Matter hint in antiprotons

FD, Fornengo, Korsmeier, PRD 2018

P_{coal} = 124 (62) MeV

P_{coal} = 248 (124) MeV



DM antiprotons possibly hidden in AMS data are potentially testable by AMS and GAPS