Phenomenology of antiproton production in the Galaxy

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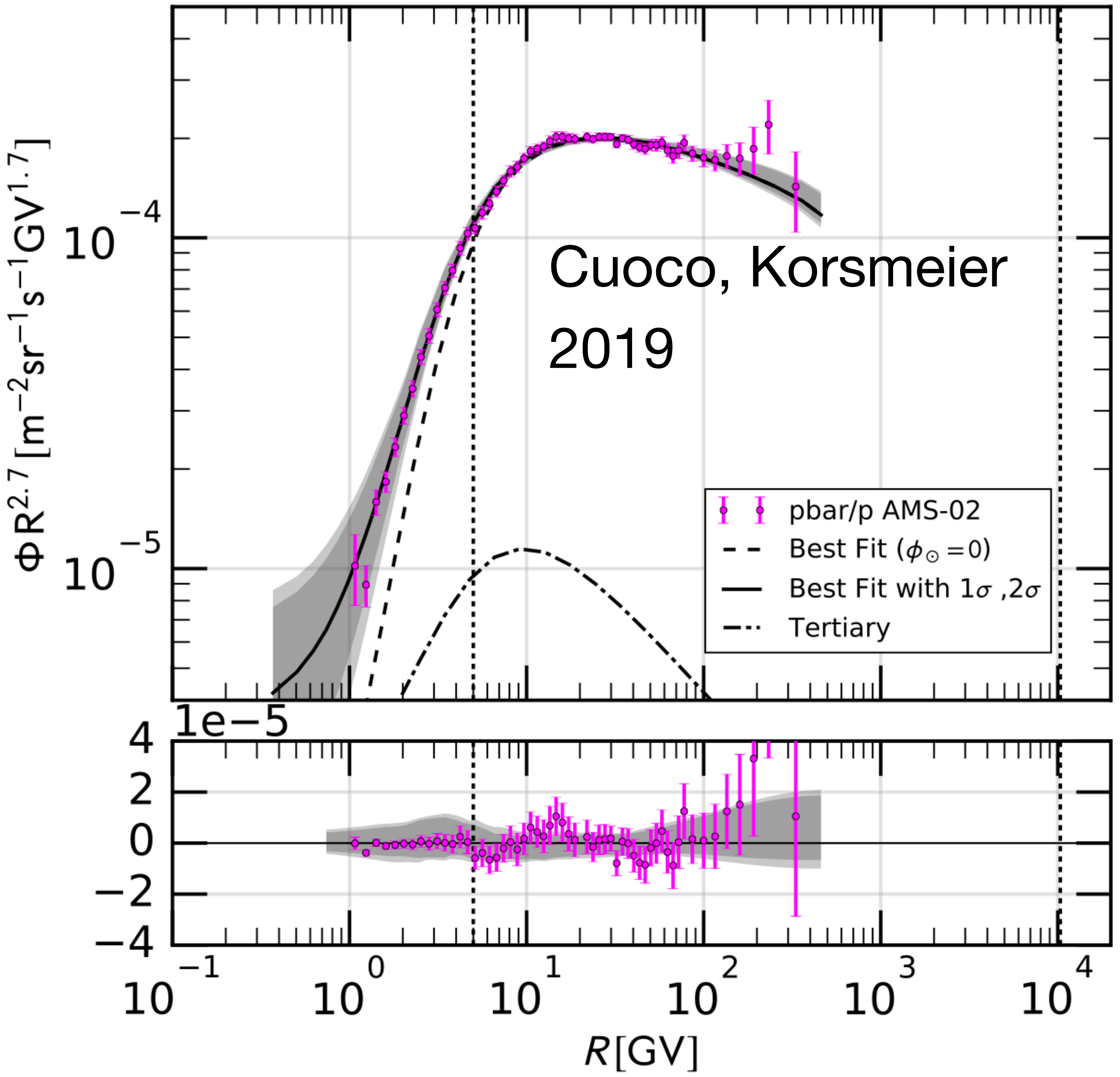
Outline of the talk

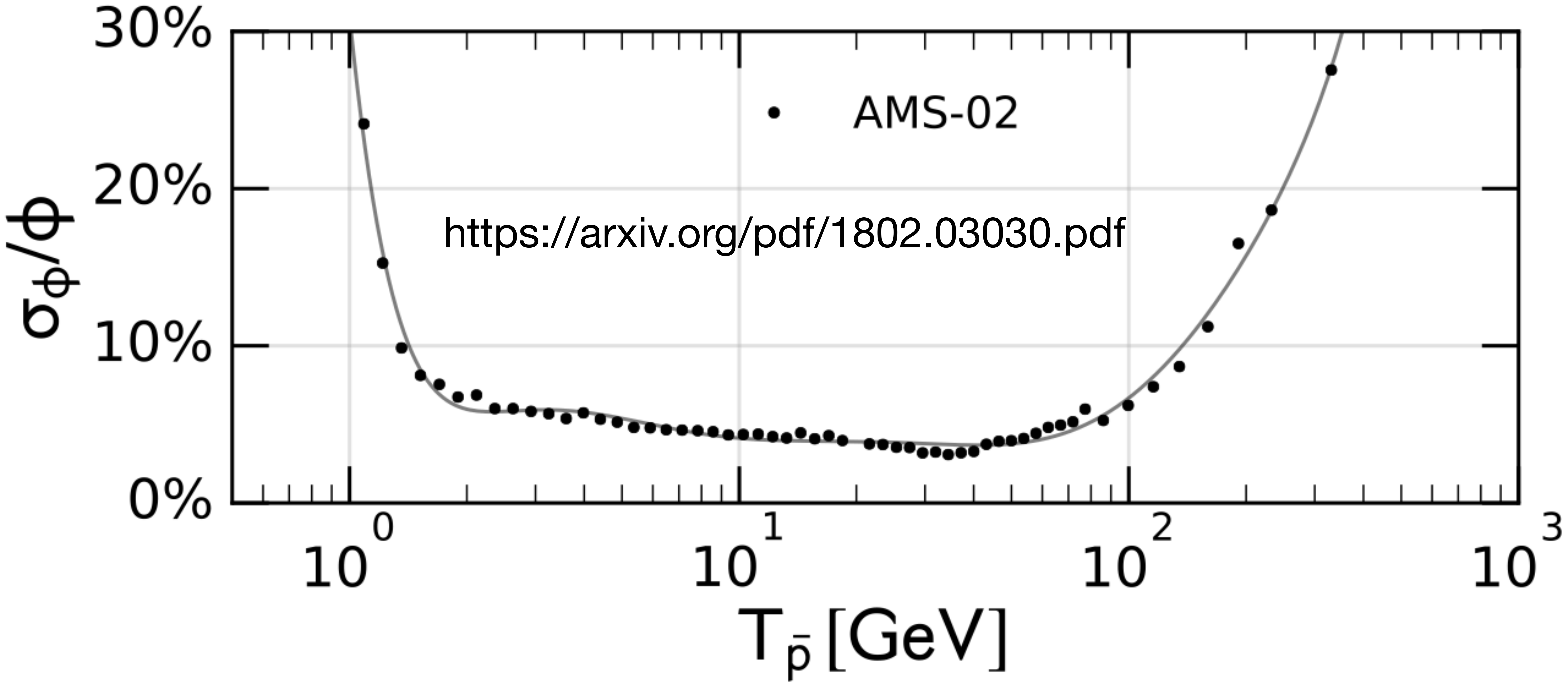
- Motivation for pursing precise measurements for the antiproton production cross sections.
- Parametrizations of the cross sections.
    - Di Mauro et al. *Phys.Rev.D* 90 (2014) 8, 085017
    - Korsmeier et al. *Phys.Rev.D* 97 (2018) 10, 103019
- Uncertainties on the theoretical model.
- Prescriptions for future measurements.
    - Donato et al. *Phys.Rev.D* 96 (2017) 4, 043007

AMS-02 antiprotons flux data

- AMS-02 data reach a precision of about 3-6% between 2-100 GeV.
- In order to study cosmic-ray (CR) physics and search for dark matter signals errors of cross section data should reach about the same precision.
- *Antiproton flux data between 10-500 GeV —>sqrt(s) = 5-100 GeV*

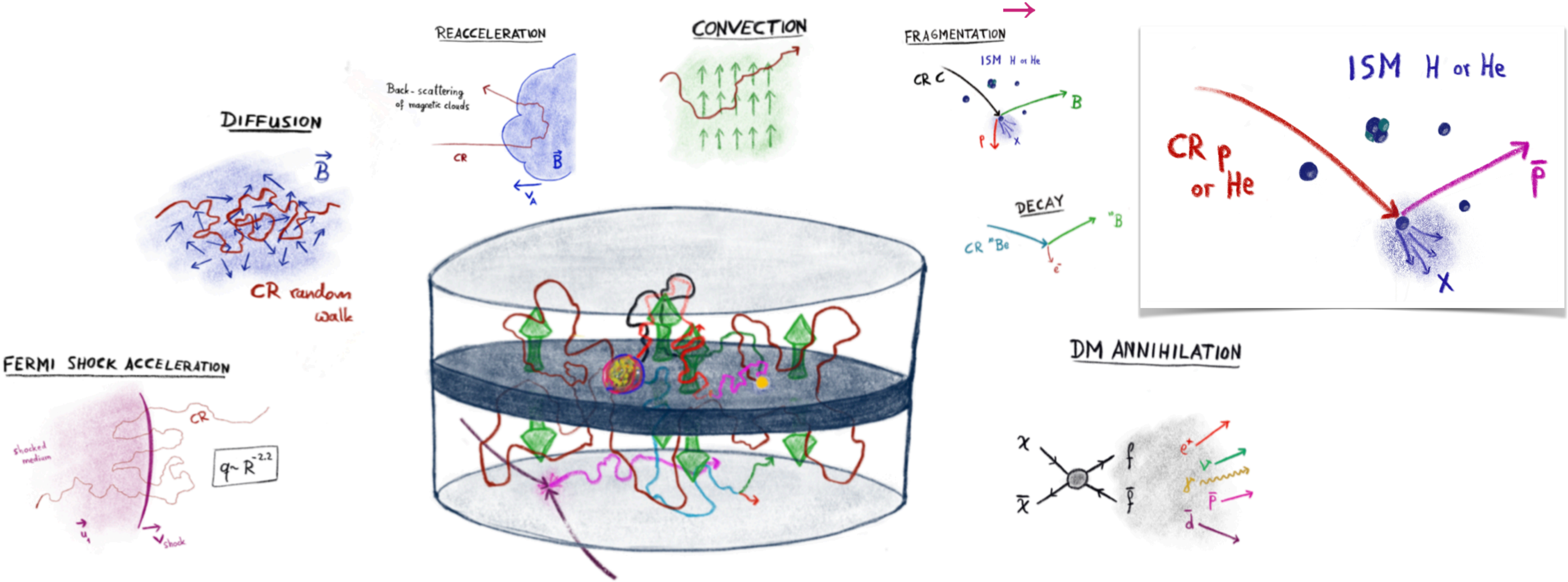


Cuoco, Korsmeier 2019



https://arxiv.org/pdf/1802.03030.pdf

Cosmic-ray propagation



Courtesy of M. Korsmeier

$$\frac{\mathrm{d}\psi}{\mathrm{d}t} = q(\boldsymbol{x}, p) + \boldsymbol{\nabla} \cdot (D_{xx} \boldsymbol{\nabla}\psi - \boldsymbol{V}\psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2}\psi - \frac{\partial}{\partial p}\left(\frac{\mathrm{d}p}{\mathrm{d}t}\psi - \frac{p}{3}\boldsymbol{\nabla}\cdot\boldsymbol{V}\psi\right) - \frac{1}{\tau_f}\psi - \frac{1}{\tau_r}\psi$$

Theoretical model

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

$$\frac{d\sigma}{dT_{\bar{p}}}(T_p, T_{\bar{p}}) = p_{\bar{p}} \int d\Omega \left(E \frac{d^3\sigma}{dp^3} \right)(T_p, T_{\bar{p}}, \theta)$$

$$x_{\mathrm{R}} = E^*_{\bar{p}} / E^{\max *}_{\bar{p}}$$

$$\sigma_{\mathrm{inv}} = E \frac{d^3\sigma}{dp^3}(\sqrt{s}, x_{\mathrm{R}}, p_{\mathrm{T}})$$

$$x_f = 2p^*_{\mathrm{L}} / \sqrt{s}$$

Antiproton production

$p + p \to \bar{p} + X$

$$E\frac{d^3\sigma}{dp^3} \sim R(s,x_R)\,(1-x_R)^{c_1} e^{-c_2 p_T} \xrightarrow{\text{Lorentz transformation + angular integration}} \frac{d\sigma(T,T_{\bar{p}})}{dT_{\bar{p}}}$$

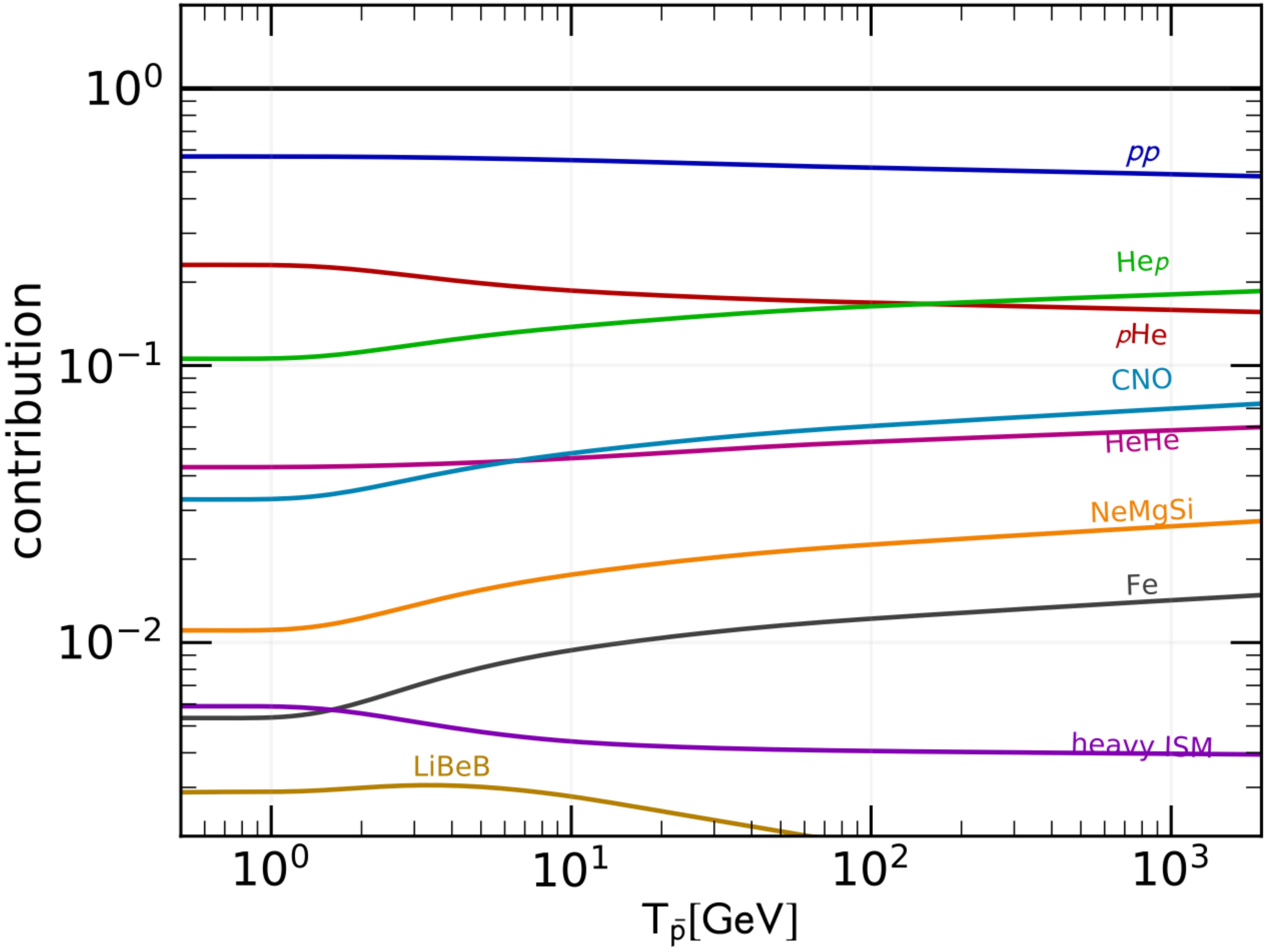
scaling violation

Feynman scaling invarianz

p_T suppression

Korsmeier et al. *Phys.Rev.D* 97 (2018) 10, 103019

Different channels for the antiproton production

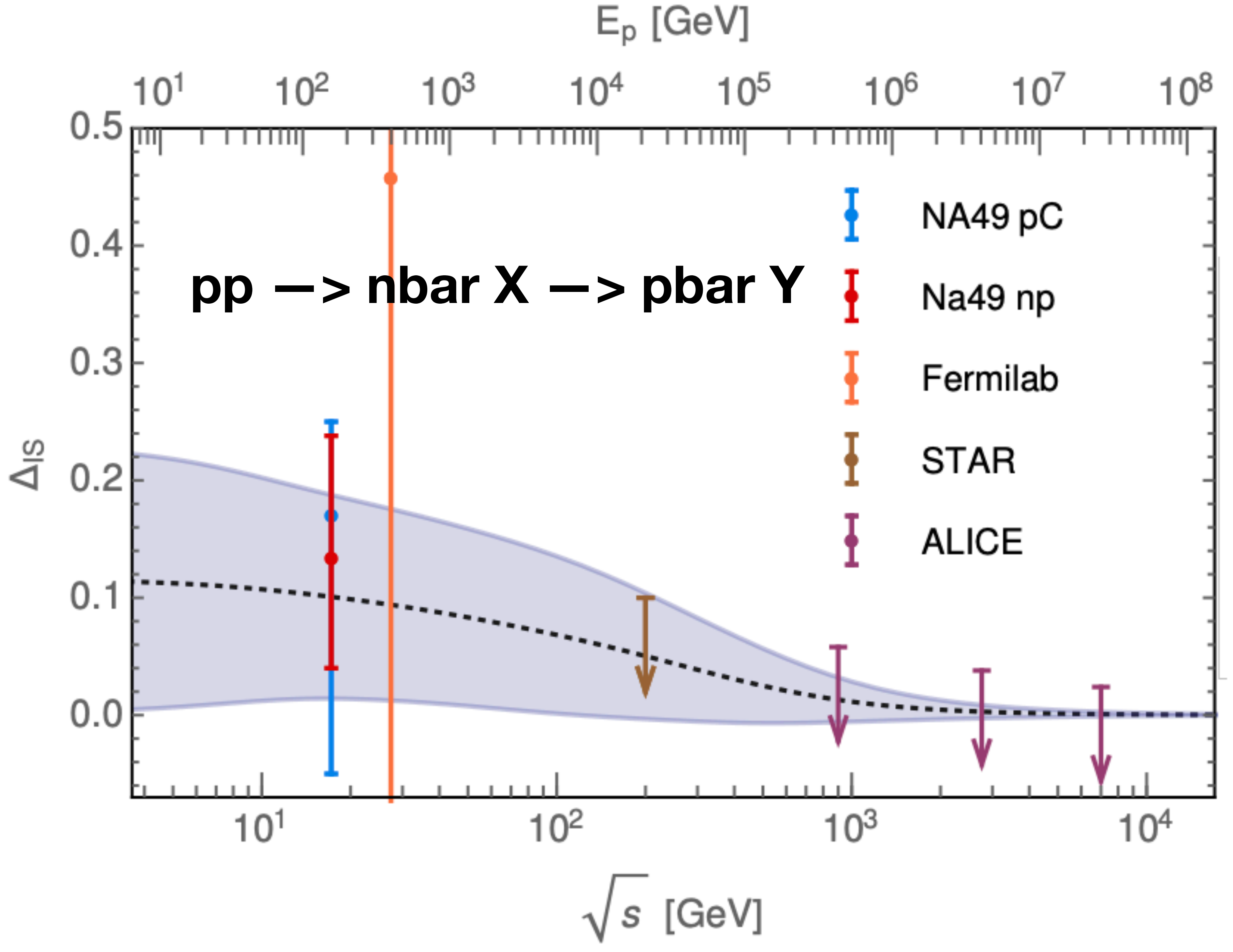


- *pp* (50% - 60%)
- *p*He (15% - 20%)
- He*p* (10% - 20%)
- HeHe few percent
- CNO + ISM few percent

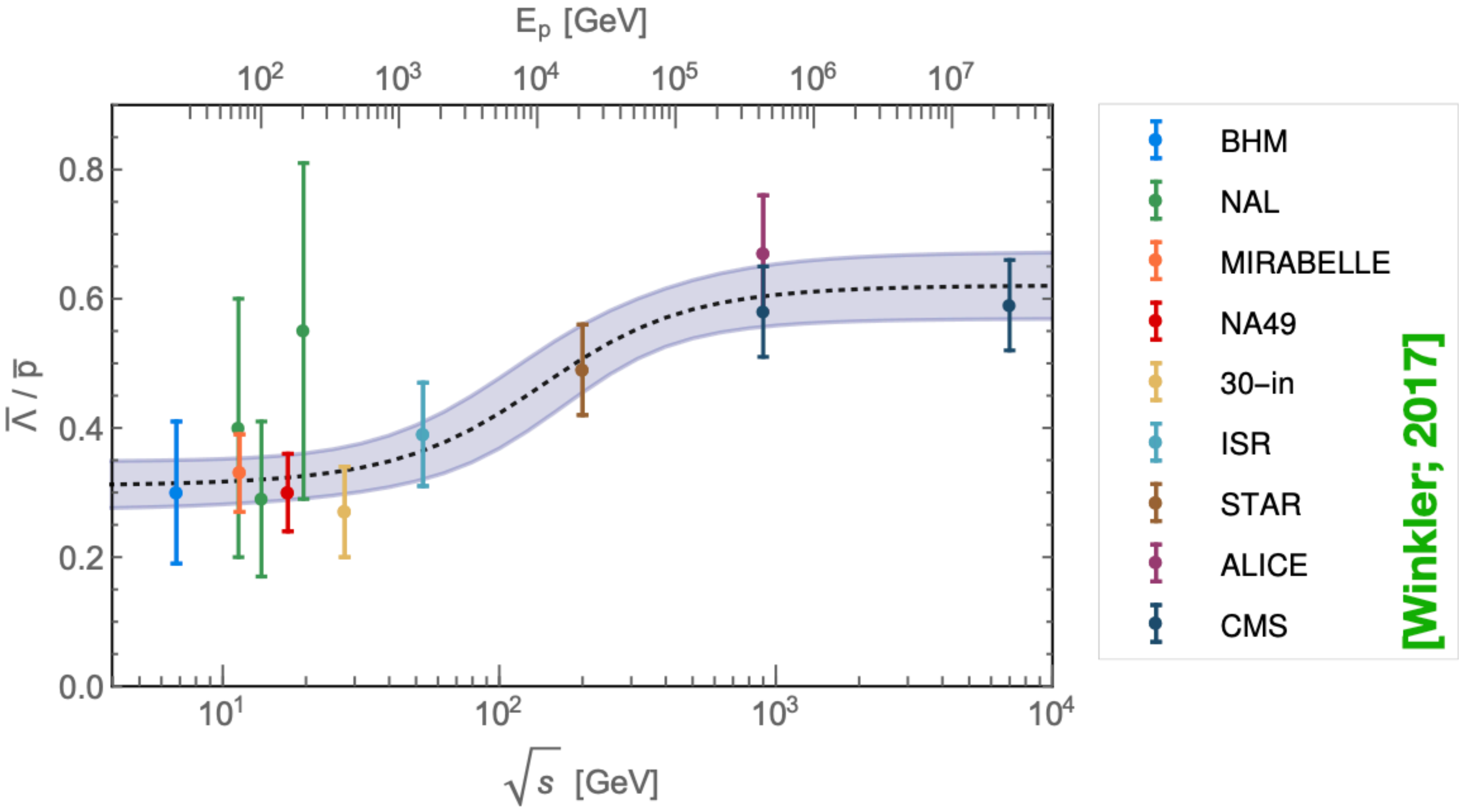
Korsmeier et al. *Phys.Rev.D* 97 (2018) 10, 103019

Antineutrons and Hyperons

Isospin asymmetry



Antihyperons



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

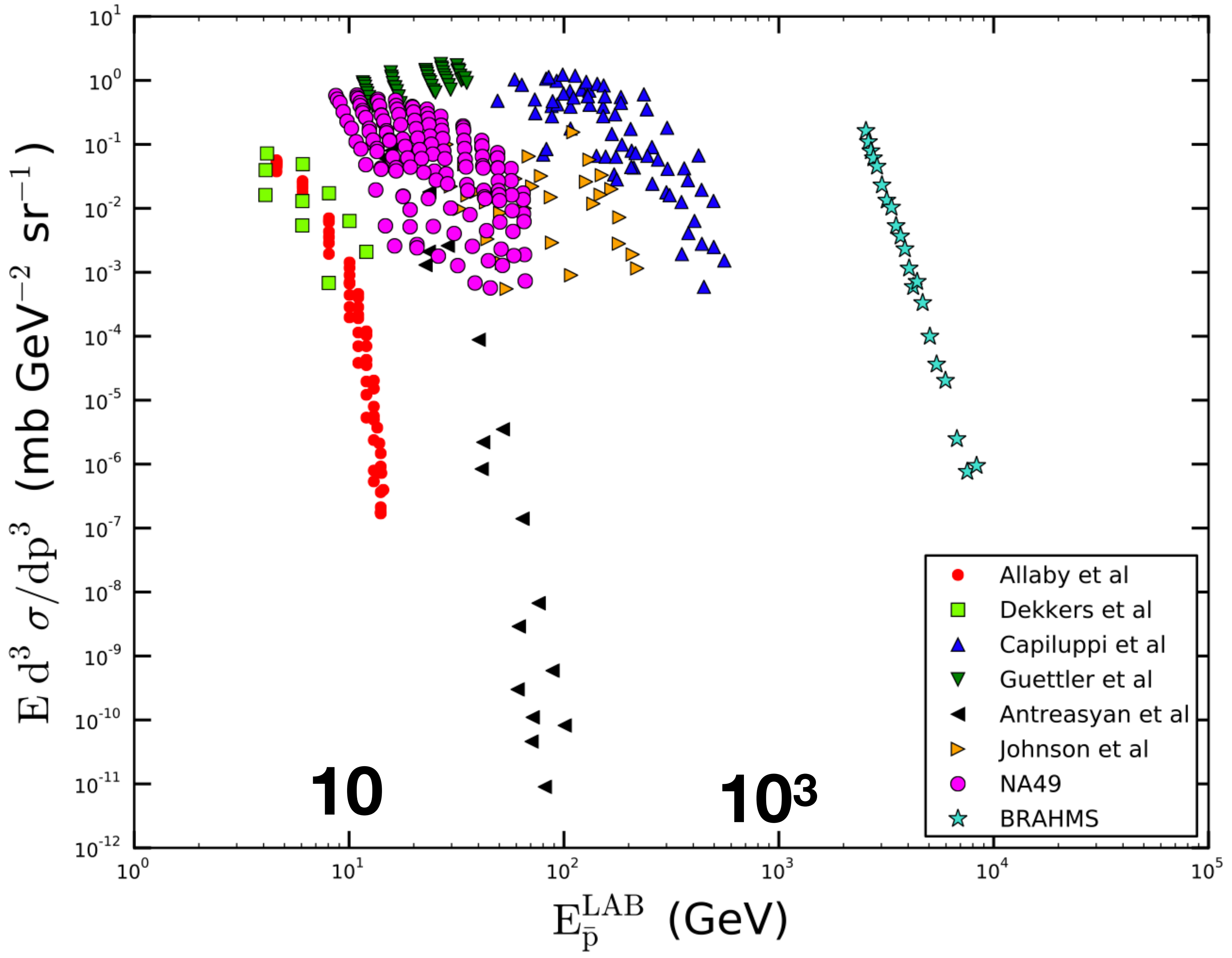
Antineutrons
Isospin asymmetry
Antihyperons

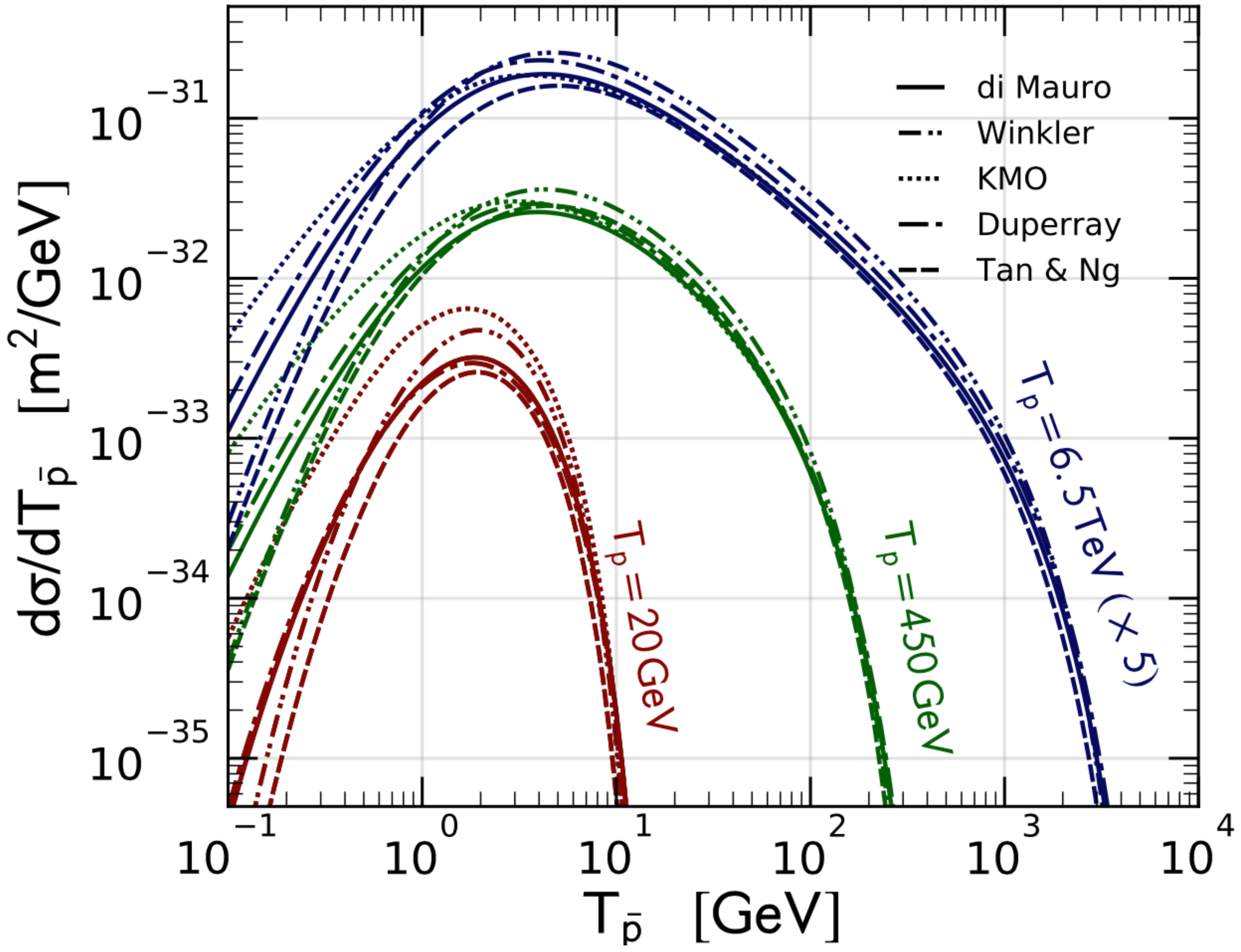
Di Mauro et al. *Phys.Rev.D* 90 (2014) 8, 085017

Experiment	$\sqrt{s}$ (GeV)	p_T (GeV)	x_R
Dekkers *et al*, CERN 1965 [18]	6.1, 6.7	$(0., 0.79)$	$(0.34, 0.65)$
Allaby *et al*, CERN 1970 [19]	6.15	$(0.05, 0.90)$	$(0.40, 0.94)$
Capiluppi *et al*, CERN 1974 [20]	23.3, 30.6, 44.6, 53.0, 62.7	$(0.18, 1.29)$	$(0.06, 0.43)$
Guettler *et al*, CERN 1976 [21]	23.0, 31.0, 45.0, 53.0, 63.0	$(0.12, 0.47)$	$(0.036, 0.092)$
Johnson *et al*, FNAL 1978 [22]	13.8, 19.4, 27.4	$(0.25, 0.75)$	$(0.31, 0.55)$
Antreasyan *et al*, FNAL 1979 [23]	19.4, 23.8, 27.4	$(0.77, 6.15)$	$(0.08, 0.58)$
BRAHMS, BNL 2008 [13]	200	$(0.82, 3.97)$	$(0.11, 0.39)$
NA49, CERN 2010 [14]	17.3	$(0.10, 1.50)$	$(0.11, 0.44)$

Antiproton data from AMS-02 are between 10-1000 GeV —> sqrt(s) = 5-50 GeV

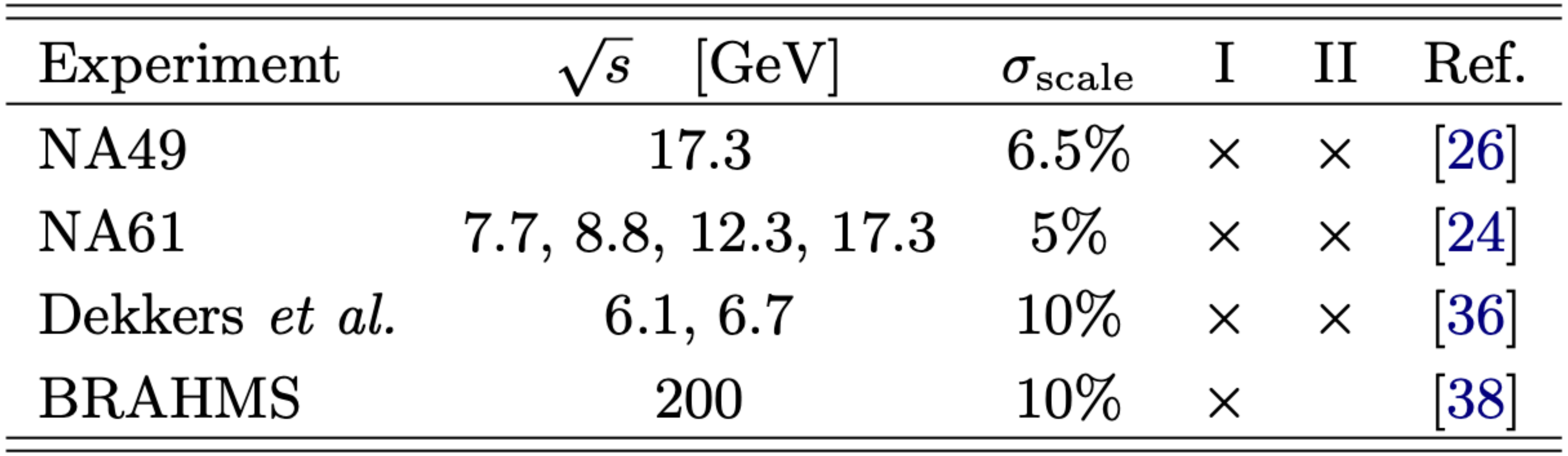
→ **Feed-down correction applied!**





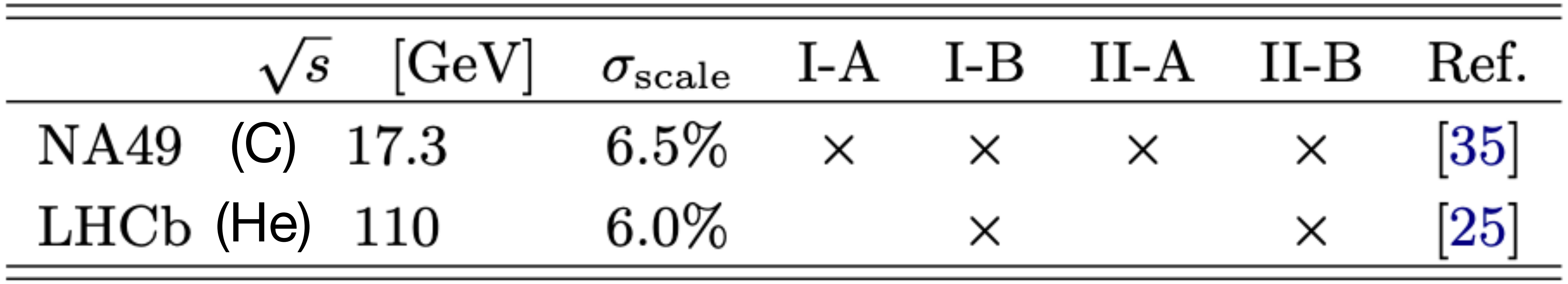
Data used in Korsmeier et al. *Phys.Rev.D* 97 (2018) 10, 103019

pp—> anti-p X



Experiment	$\sqrt{s}$ [GeV]	σ_{scale}	I	II	Ref.
NA49	17.3	6.5%	×	×	[26]
NA61	7.7, 8.8, 12.3, 17.3	5%	×	×	[24]
Dekkers *et al.*	6.1, 6.7	10%	×	×	[36]
BRAHMS	200	10%	×		[38]

pA—> anti-p X



	$\sqrt{s}$ [GeV]	σ_{scale}	I-A	I-B	II-A	II-B	Ref.
NA49 (C)	17.3	6.5%	×	×	×	×	[35]
LHCb (He)	110	6.0%		×		×	[25]

E_p=6.5 TeV

We updated the two most recent analytic cross section parametrizations

Param. I: [Di Mauro+, 2014]
Param. II: [Winkler, 2017]

Korsmeier et al. *Phys.Rev.D* 97 (2018) 10, 103019

Proton Nucleus channel

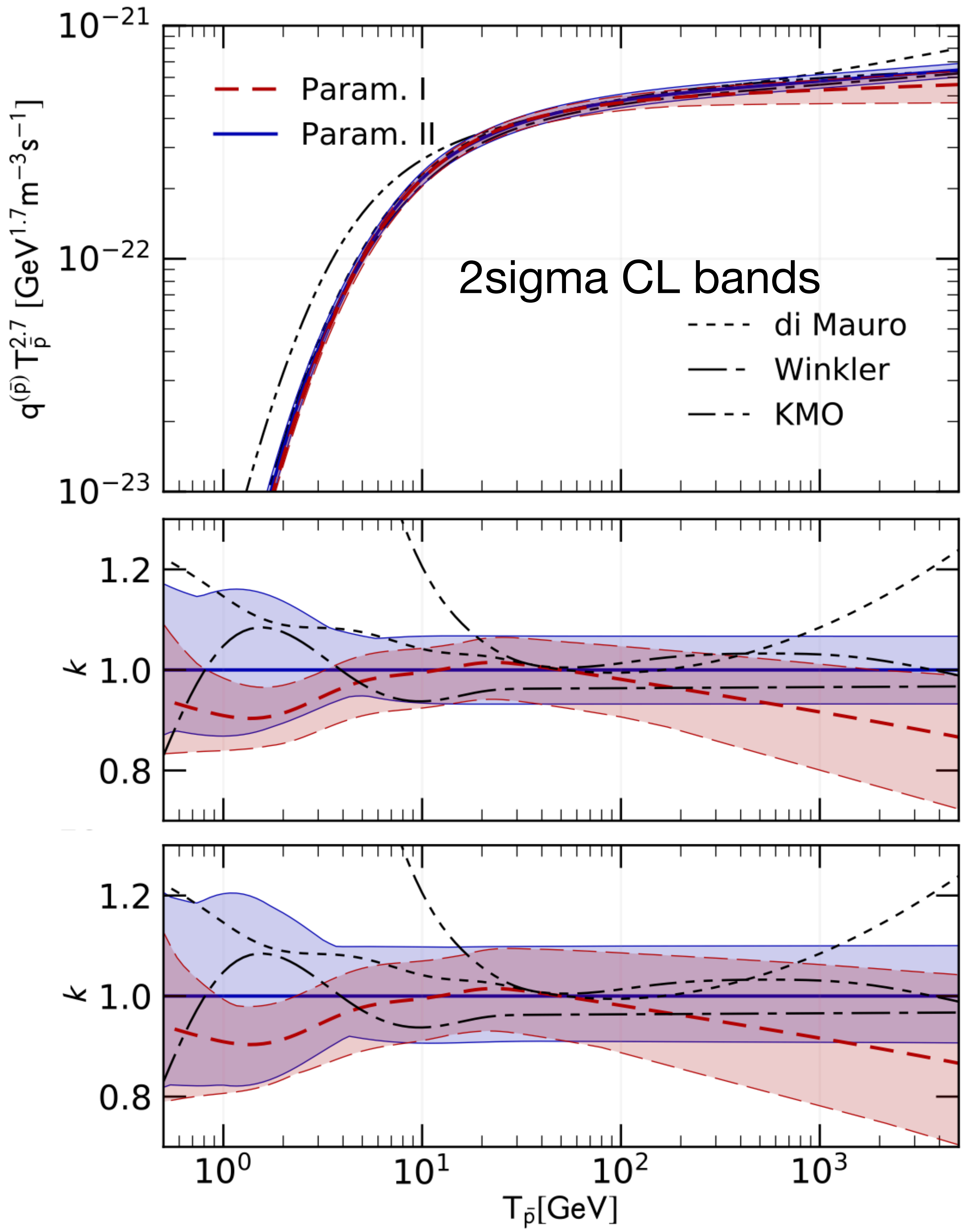
- Data in the proton nucleus channel is scarce and a standalone parametrization is not possible
- We assume that *p*A channels are proportional to *pp*
- We allow for an x_f dependence to incorporate forward-backward asymmetry

$$\left(E\frac{d^3\sigma}{dp^3}\right)^{pA}(\sqrt{s}, x_f, p_T) = f^{pA}(A, x_f, \mathscr{D})\left(E\frac{d^3\sigma}{dp^3}\right)^{pp}(\sqrt{s}, x_f, p_T)$$

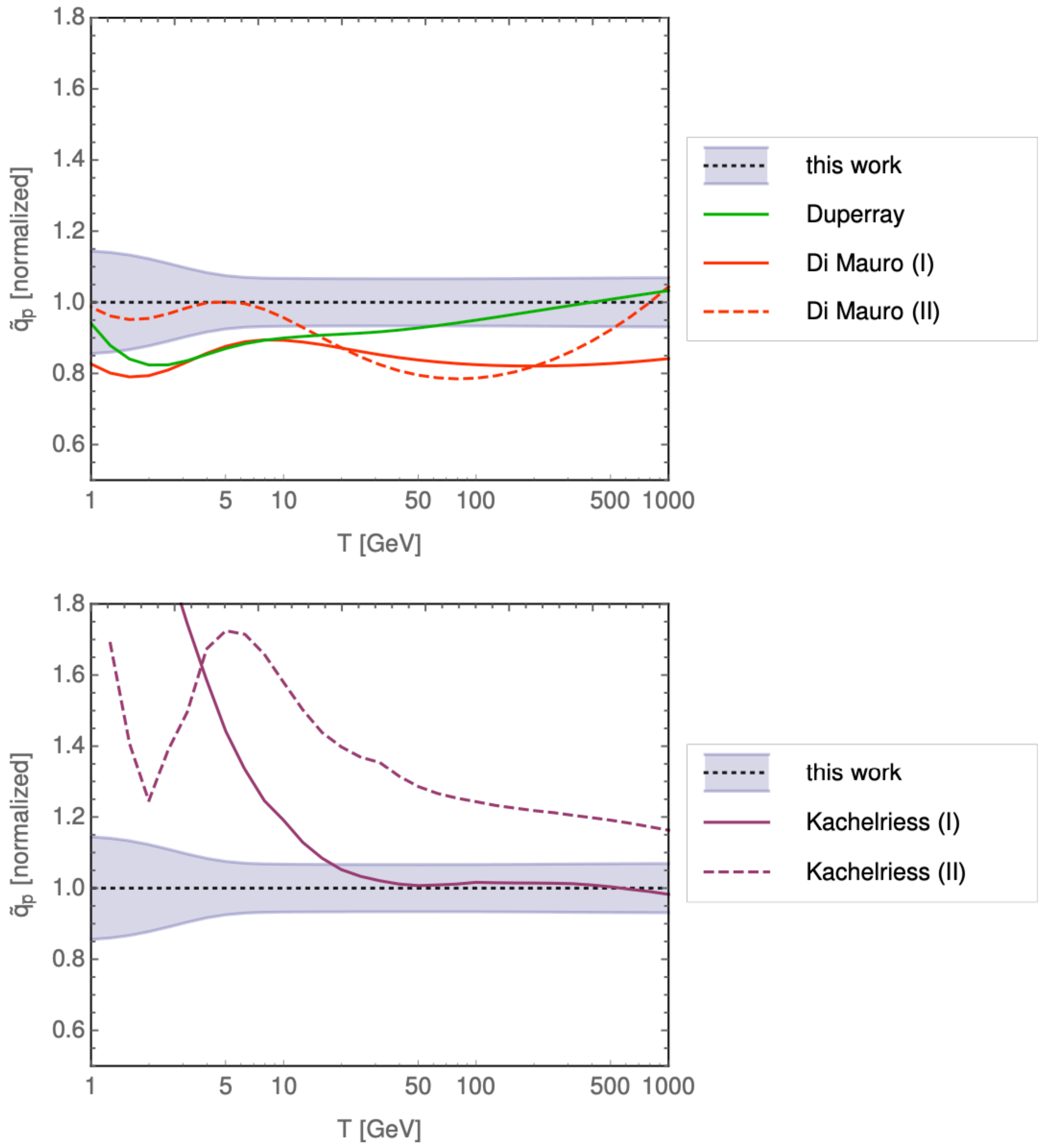
$$f^{pA}(A, x_f) = A^{D_1}\left[A^{D_2}\left(1+\frac{N}{A}\Delta_{\mathrm{IS}}\right)F_{\mathrm{tar}}(x_f) + F_{\mathrm{pro}}(x_f)\right]$$

$F_{pro}(x_f)$ and $F_{tar}(x_f)$ are the projectile and target overlap functions.

Antiproton production cross section: prompt pp channel



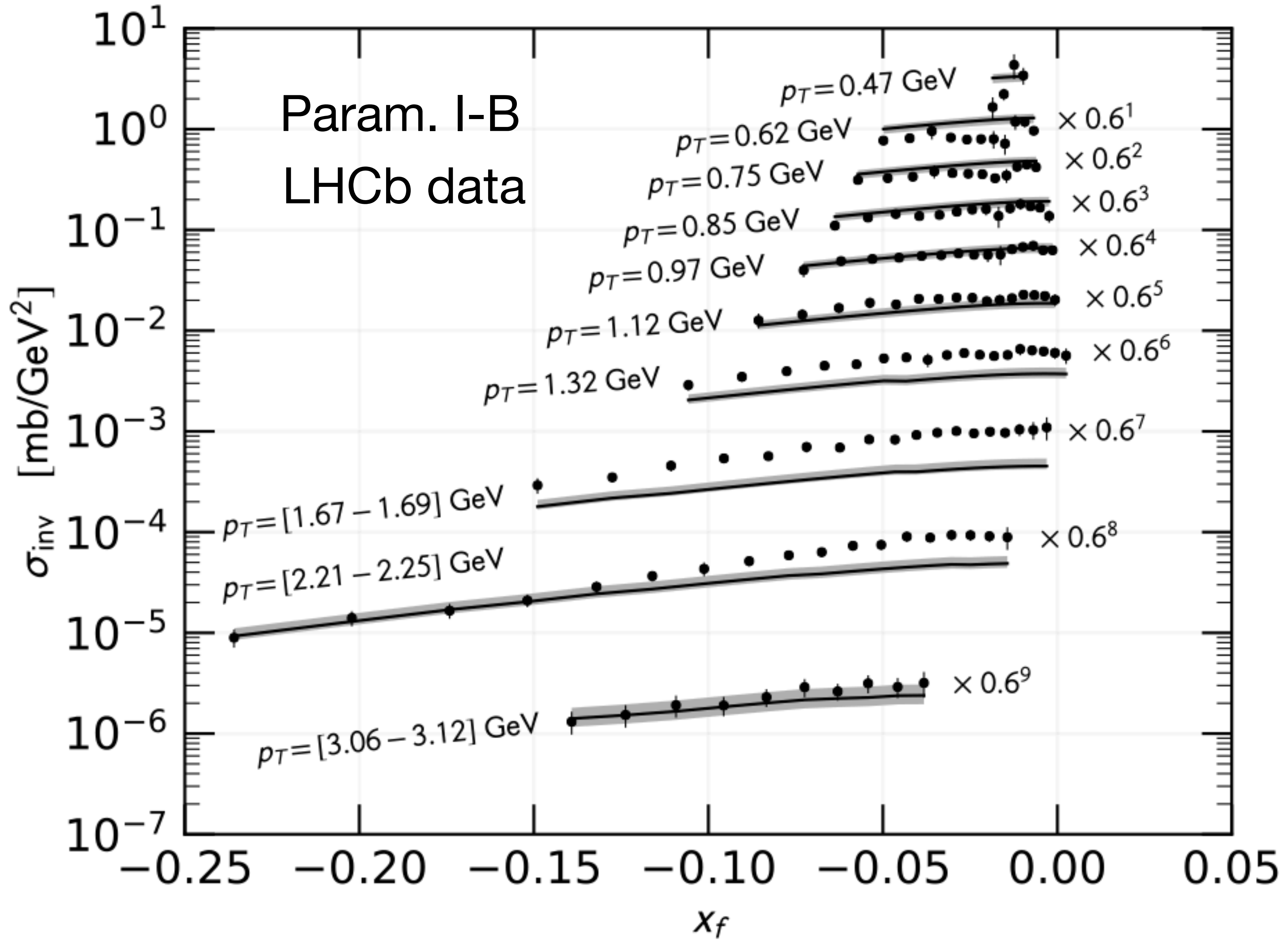
Korsmeier et al. *Phys.Rev.D* 97 (2018) 10, 103019

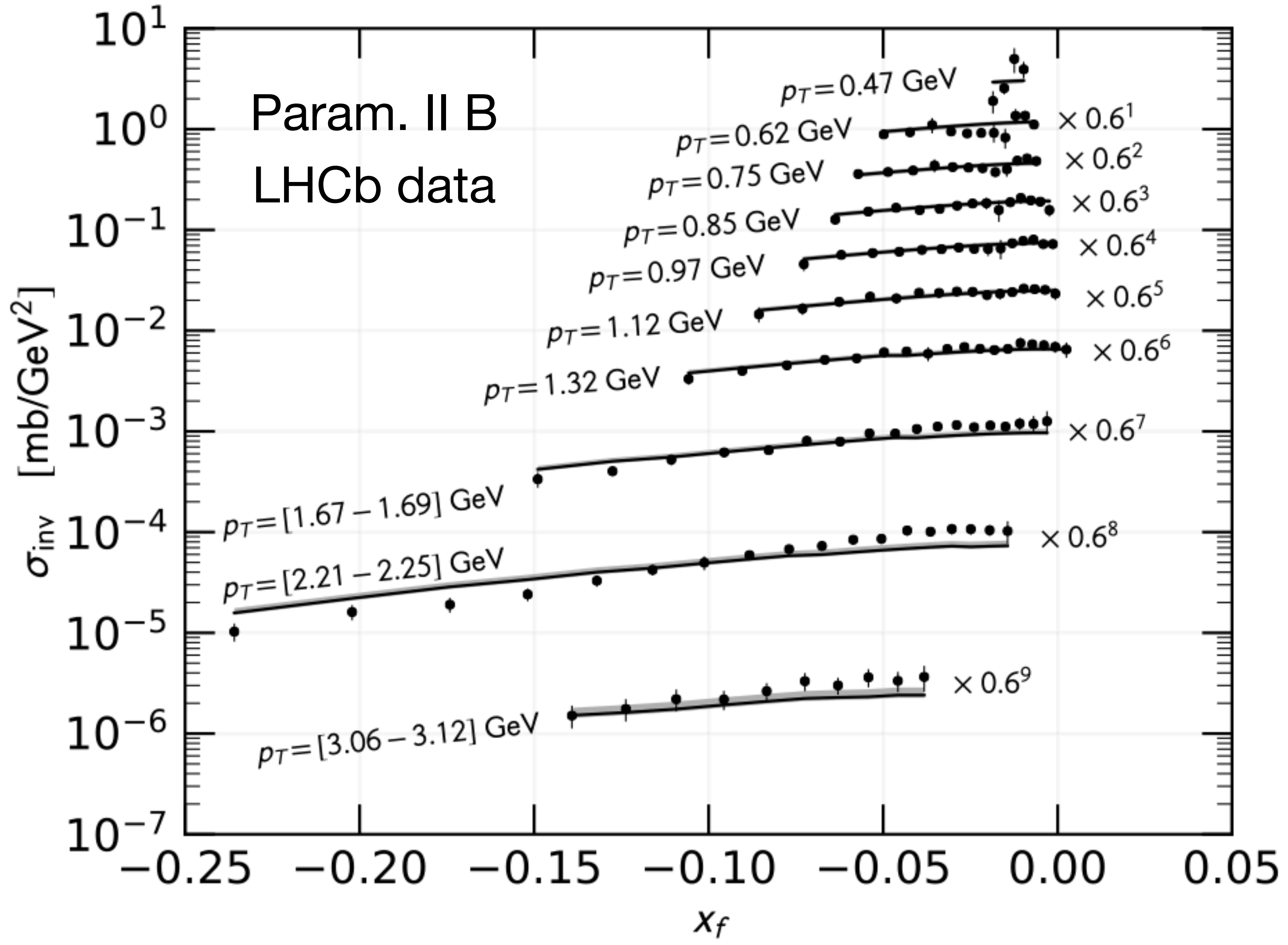


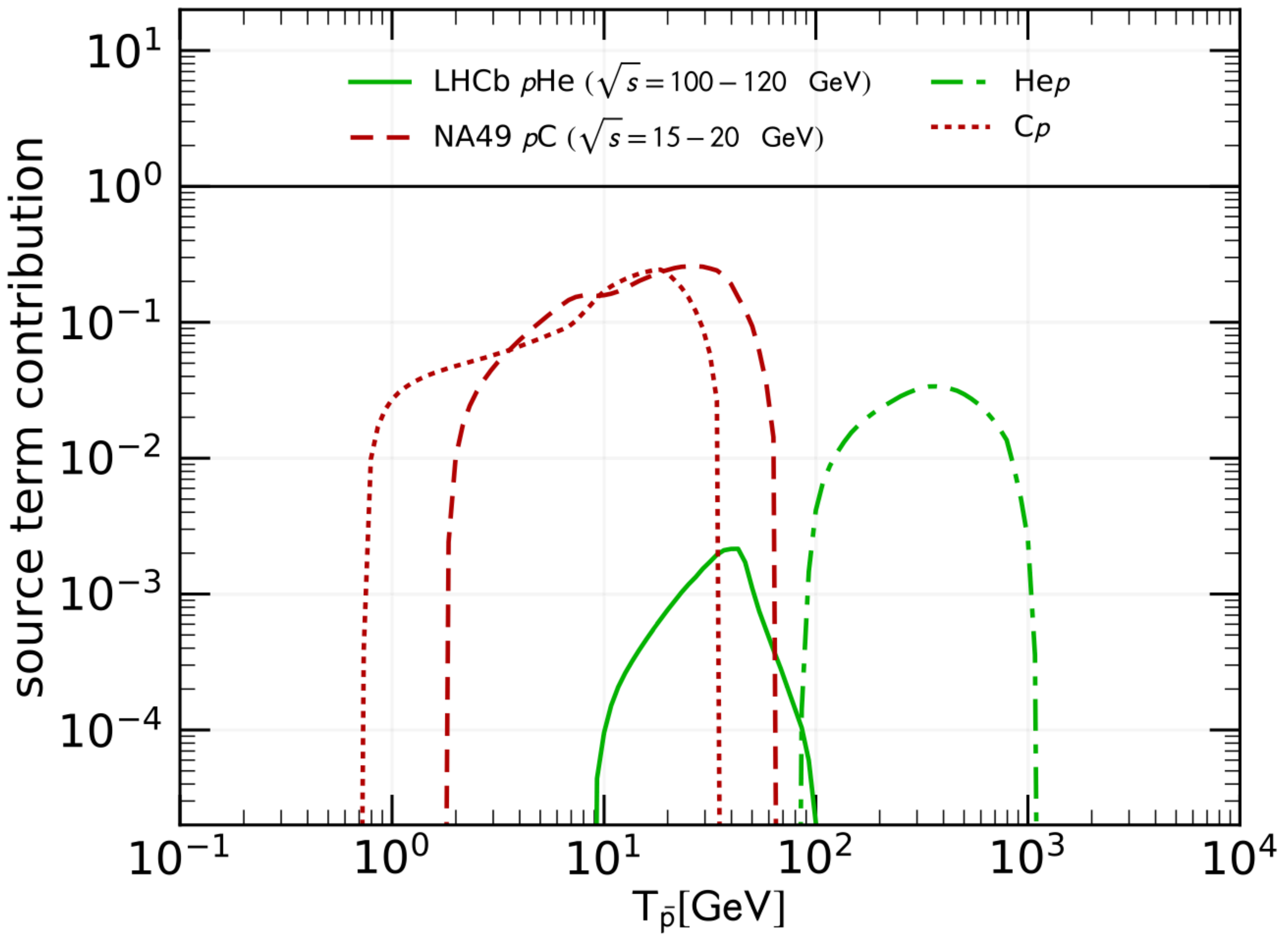
Winkler *JCAP* 02 (2017) 048

Different papers agree on the fact that the prompt pp channel has an uncertainty between 15-20%

Antiproton production cross section: prompt pHe, Hep, HeHe channel



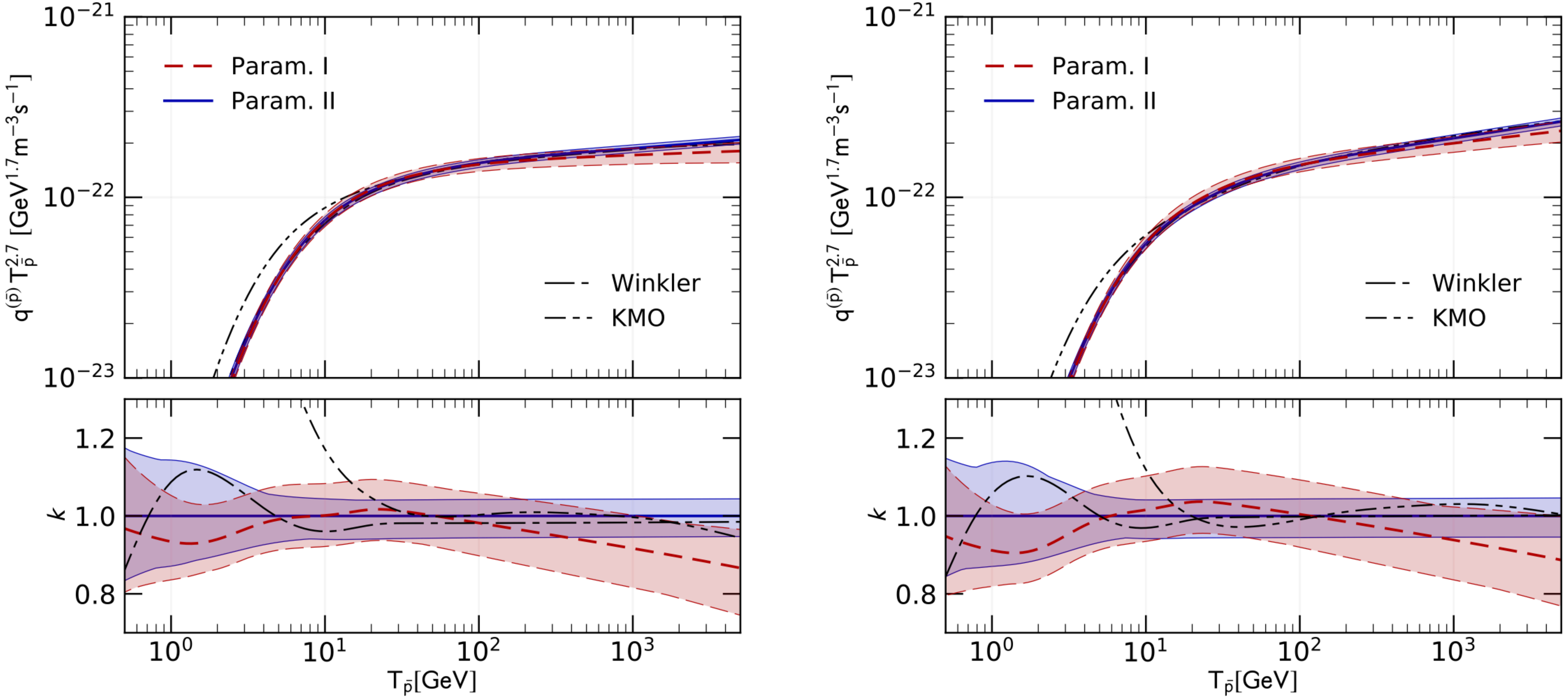




Param. II provides a much better fit to the LHCb data.

Korsmeier et al. *Phys.Rev.D* 97 (2018) 10, 103019

Antiproton production cross section: prompt pHe, Hep, HeHe channel



CR pHe (left panel) and Hep (right panel) antiproton source term

The uncertainty for the He part is about 15-20%

Korsmeier et al. *Phys.Rev.D* 97 (2018) 10, 103019

Uncertainty related to antineutron decay

- ***pp—>anti-n X —> anti-p Y*** usually taken to be the same of pp—>anti-p X.
- NA49 proceeding found an isospin asymmetry at the level of 20-30% at xf=0.
- **This is the main source of uncertainty in antiproton production cross sections.**

[….] Very recently a small (120 kevents) pilot sample of n + p collisions has been obtained. These are derived from d + p reactions by tagging the spectator proton, where the deuterons in turn are produced by fragmentation of a Pb beam in a C target. [….]

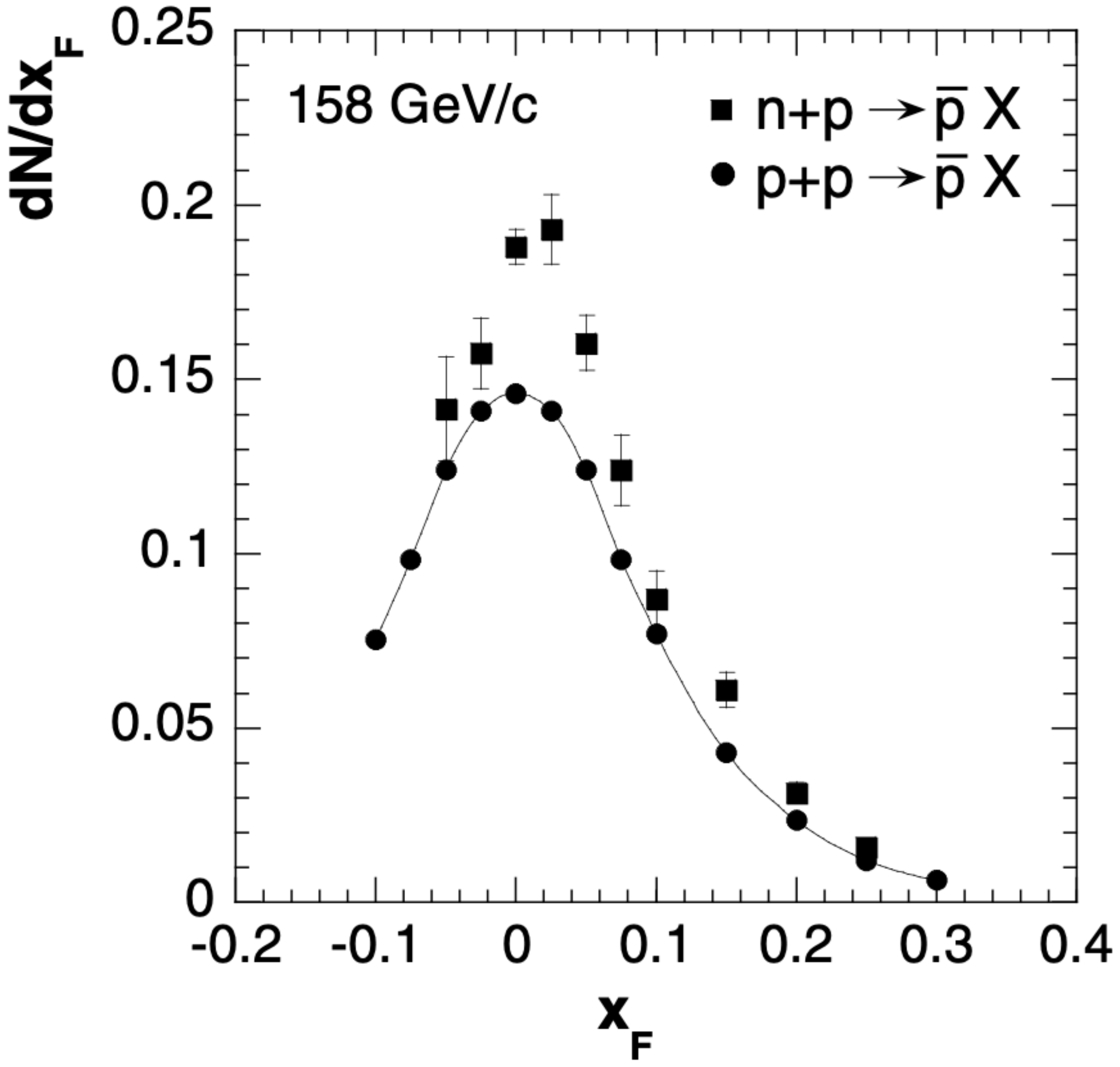
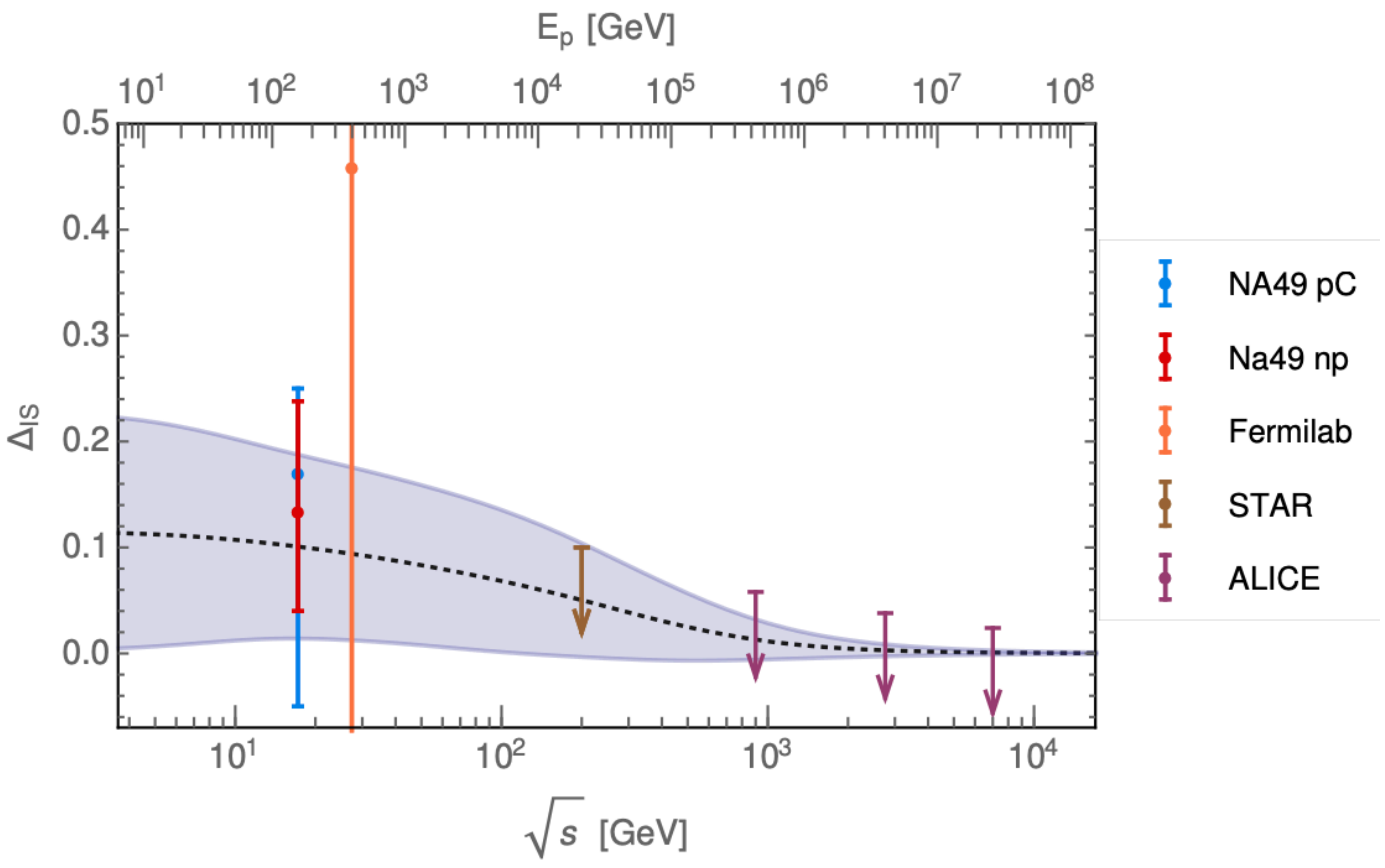


Fig. 3. Anti-proton density distribution as a function of x_F for p + p and n + p interactions

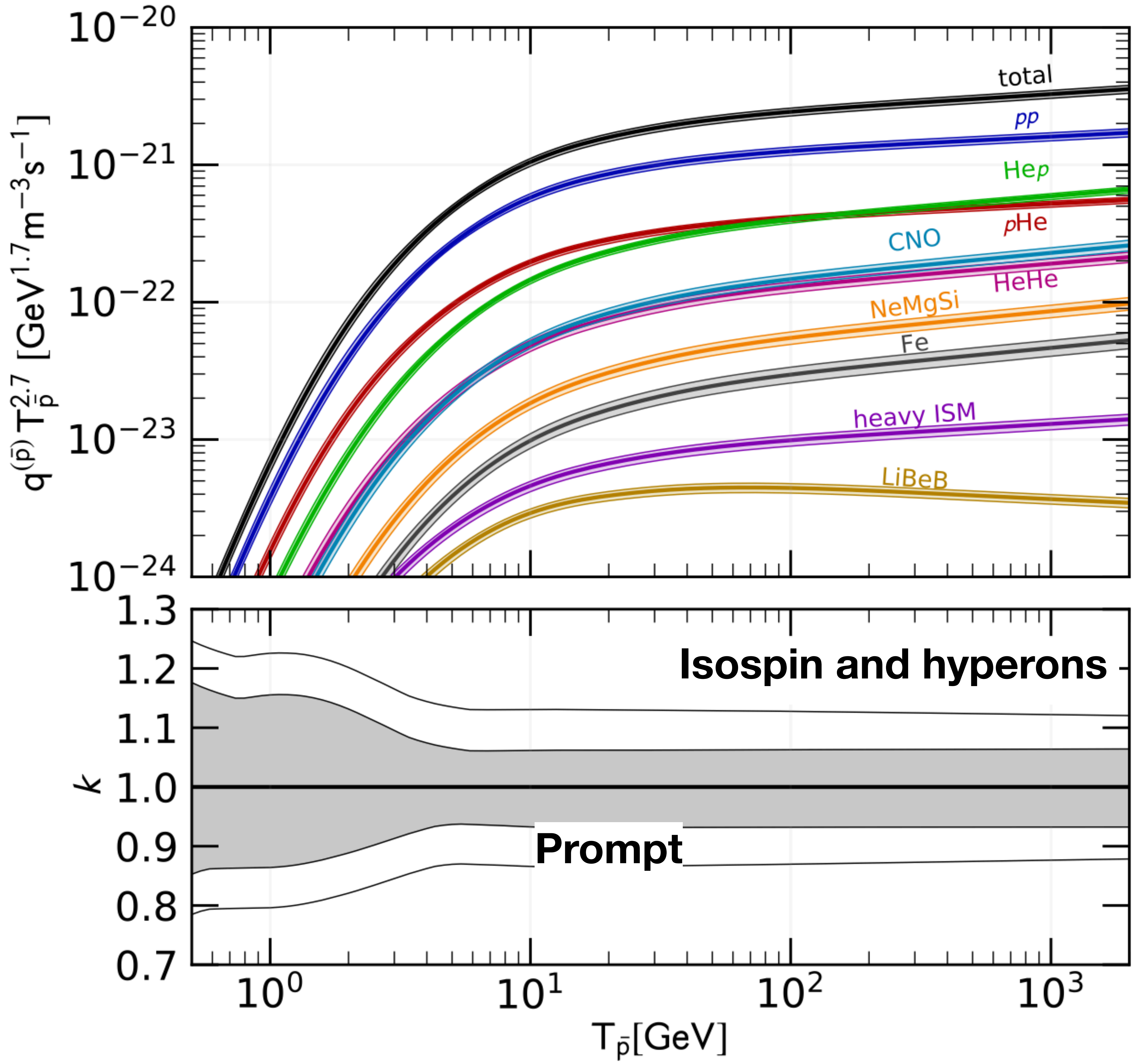
Isospin asymmetry

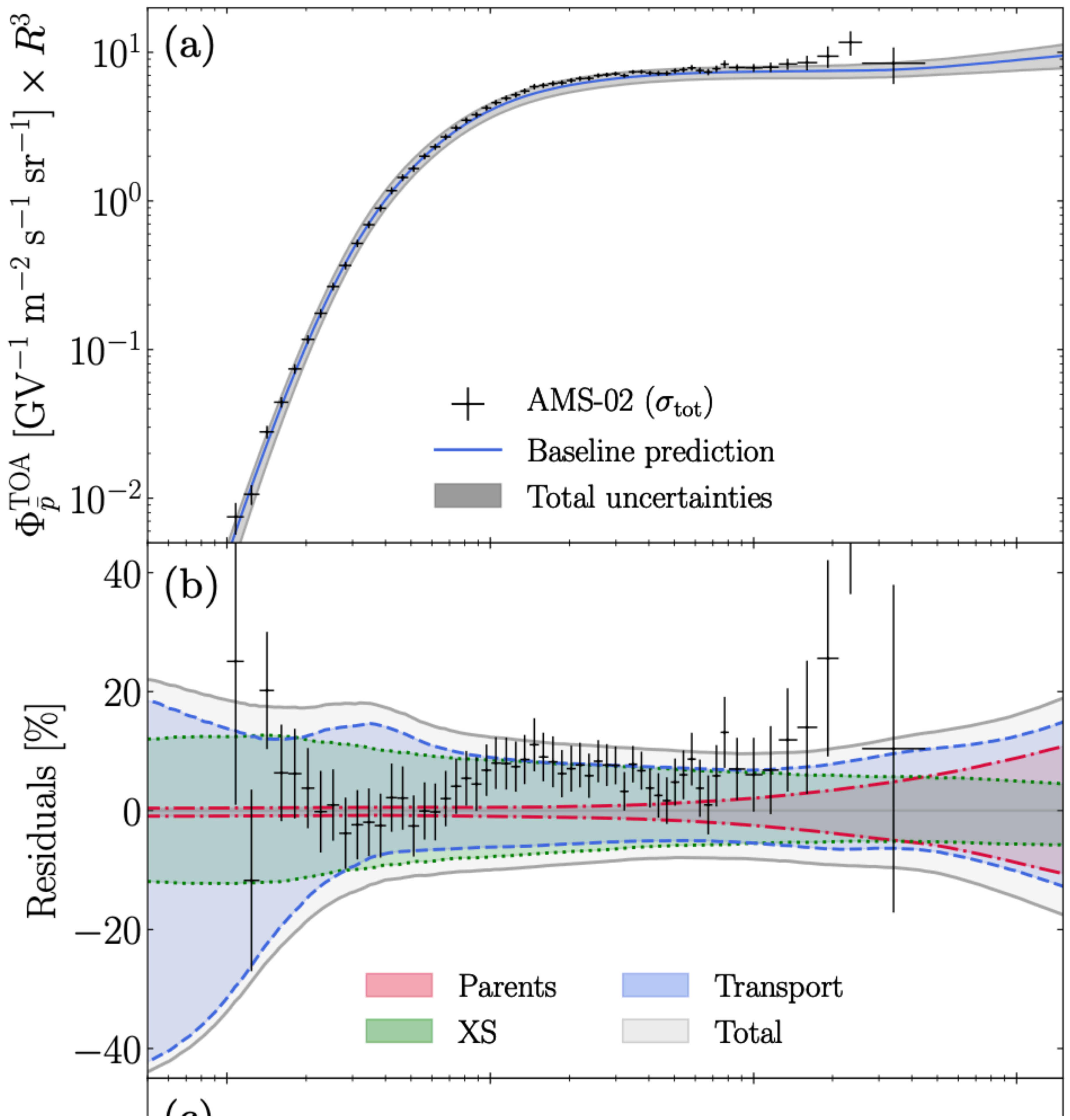
- It is more relevant at low energy wrt high energies (similarly to pions).
- Pythia produce same amount of anti-n and anti-p contrary to Herwig.
- This is a theoretical challenge to overcome.



Winkler *JCAP* 02 (2017) 048

Final uncertainty at the moment





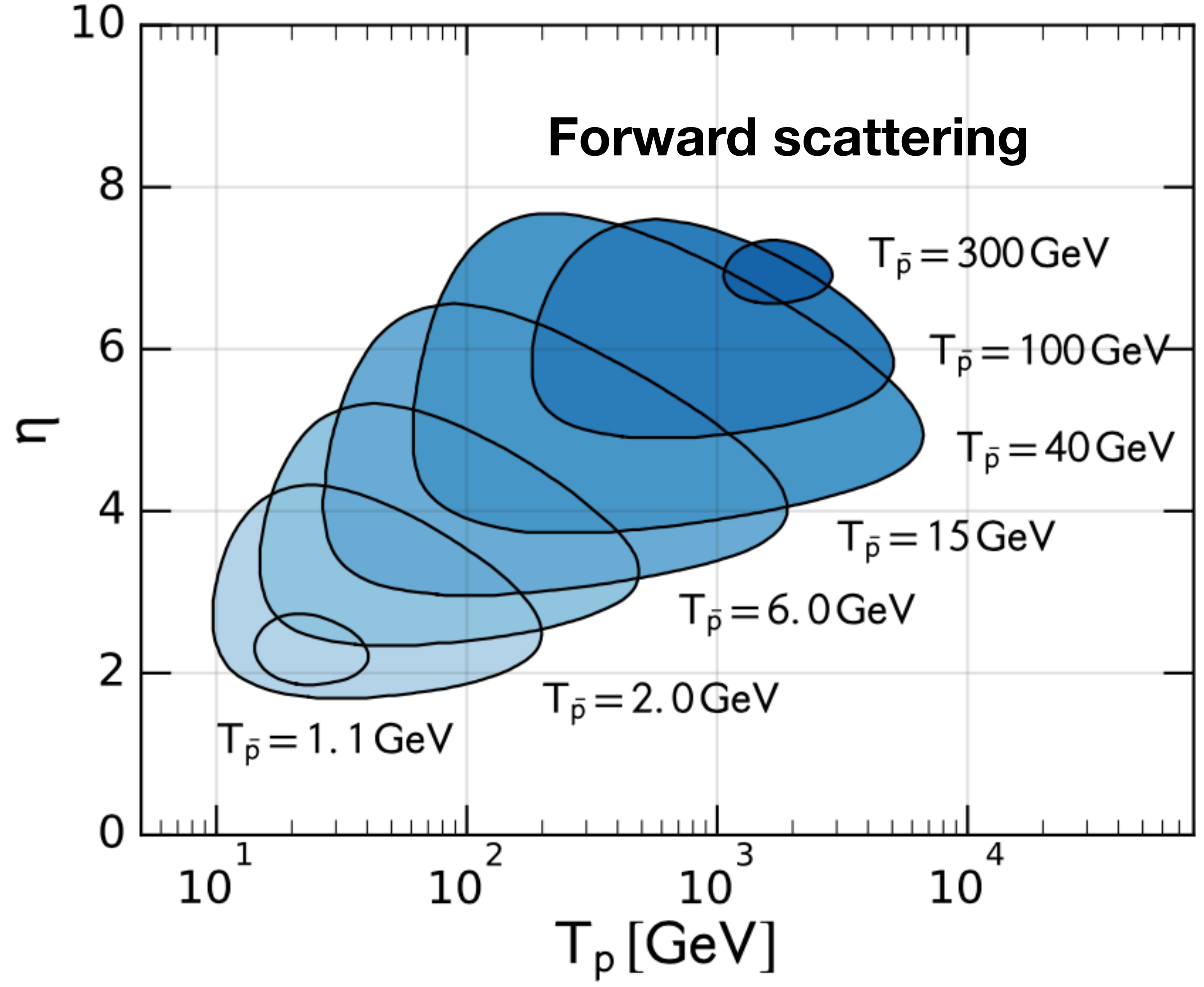
Korsmeier et al. *Phys.Rev.D* 97 (2018) 10, 103019

Calore et al. *SciPost Phys.* 12 (2022) 5, 163

Prescriptions for CS measurements

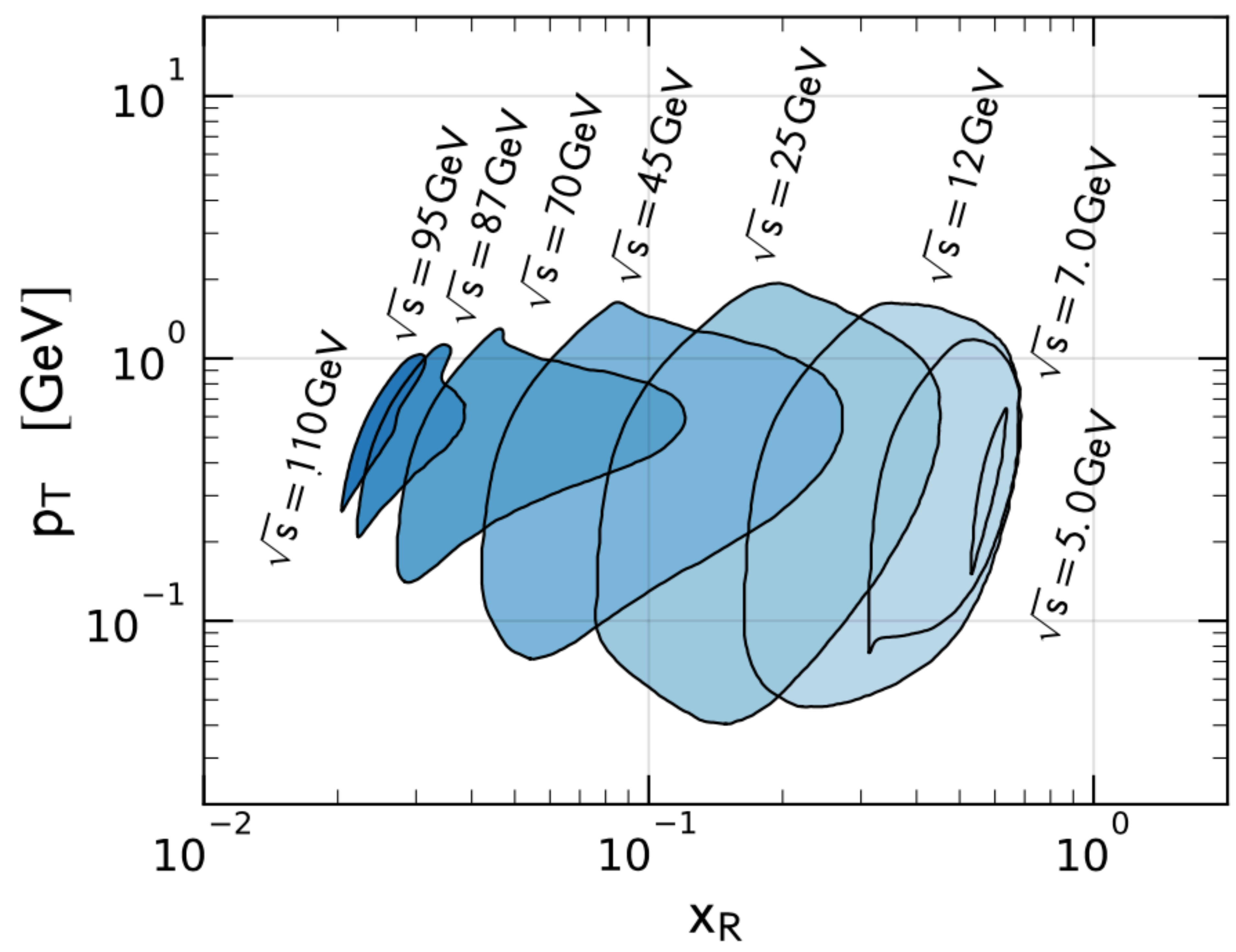
Fix target experiment

$$\left(E\frac{d^3\sigma}{dp^3}\right)(T_p, T_{\bar{p}}, \eta)$$



Collider experiment

$$\left(E\frac{d^3\sigma}{dp^3}\right)(\sqrt{s}, x_R, p_T)$$

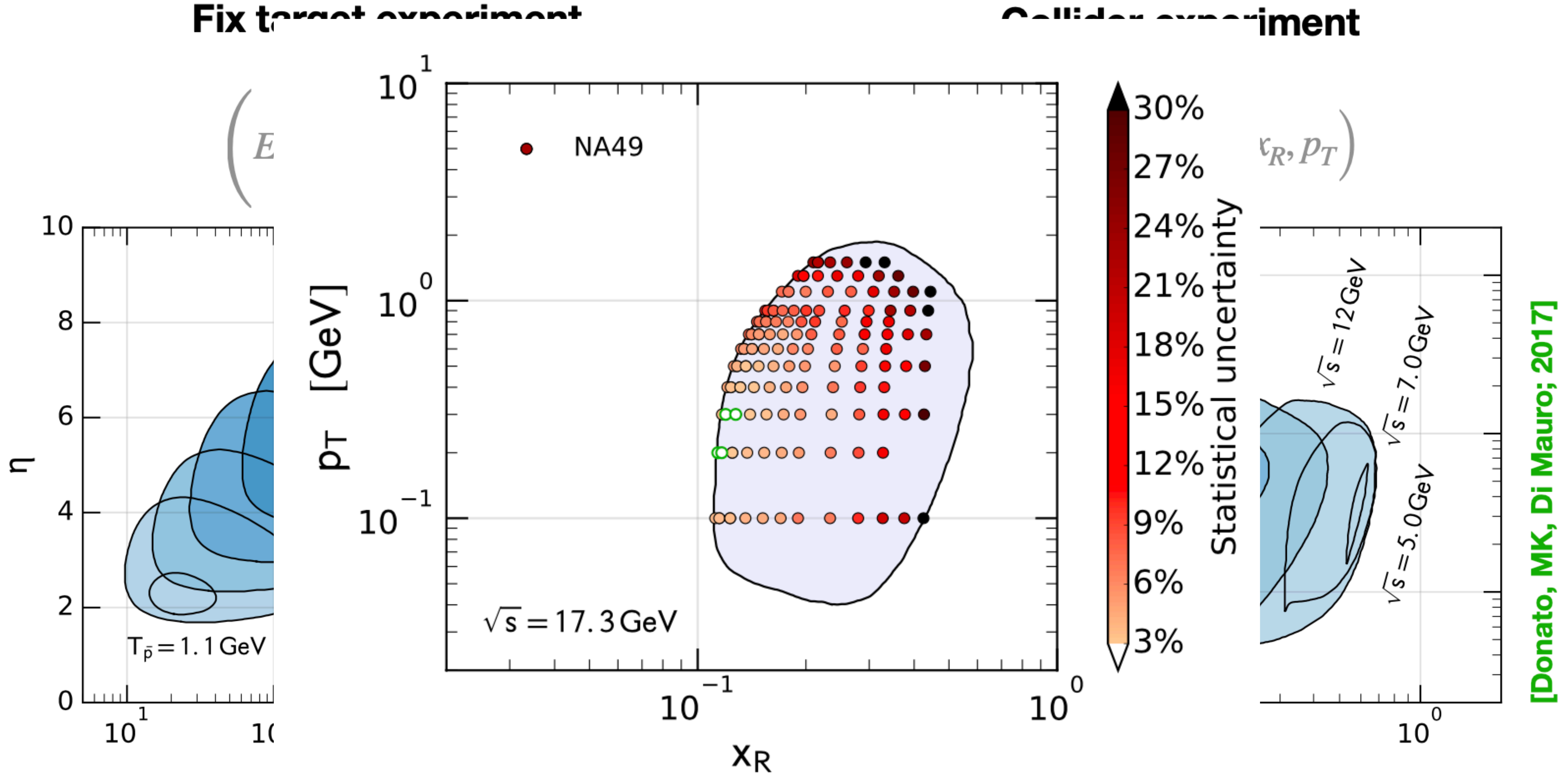


[Donato, MK, Di Mauro; 2017]

If the source term is measured with 3% accuracy inside the blue contours and with 30% outside the contours we can reach the measurement uncertainties of the AMS-02 antiproton flux.

Donato et al. *Phys.Rev.D* 96 (2017) 4, 043007

Prescriptions for CS measurements



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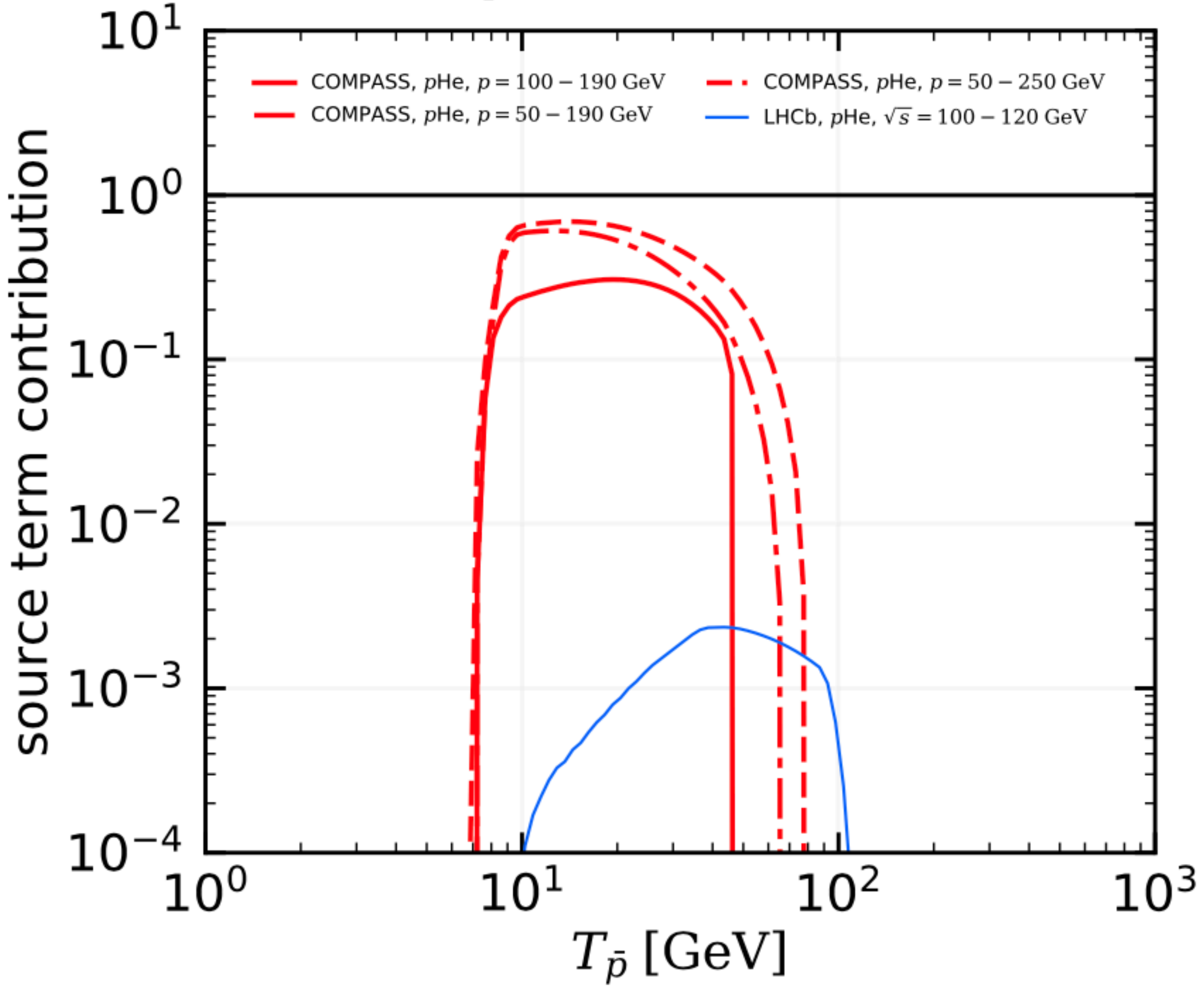
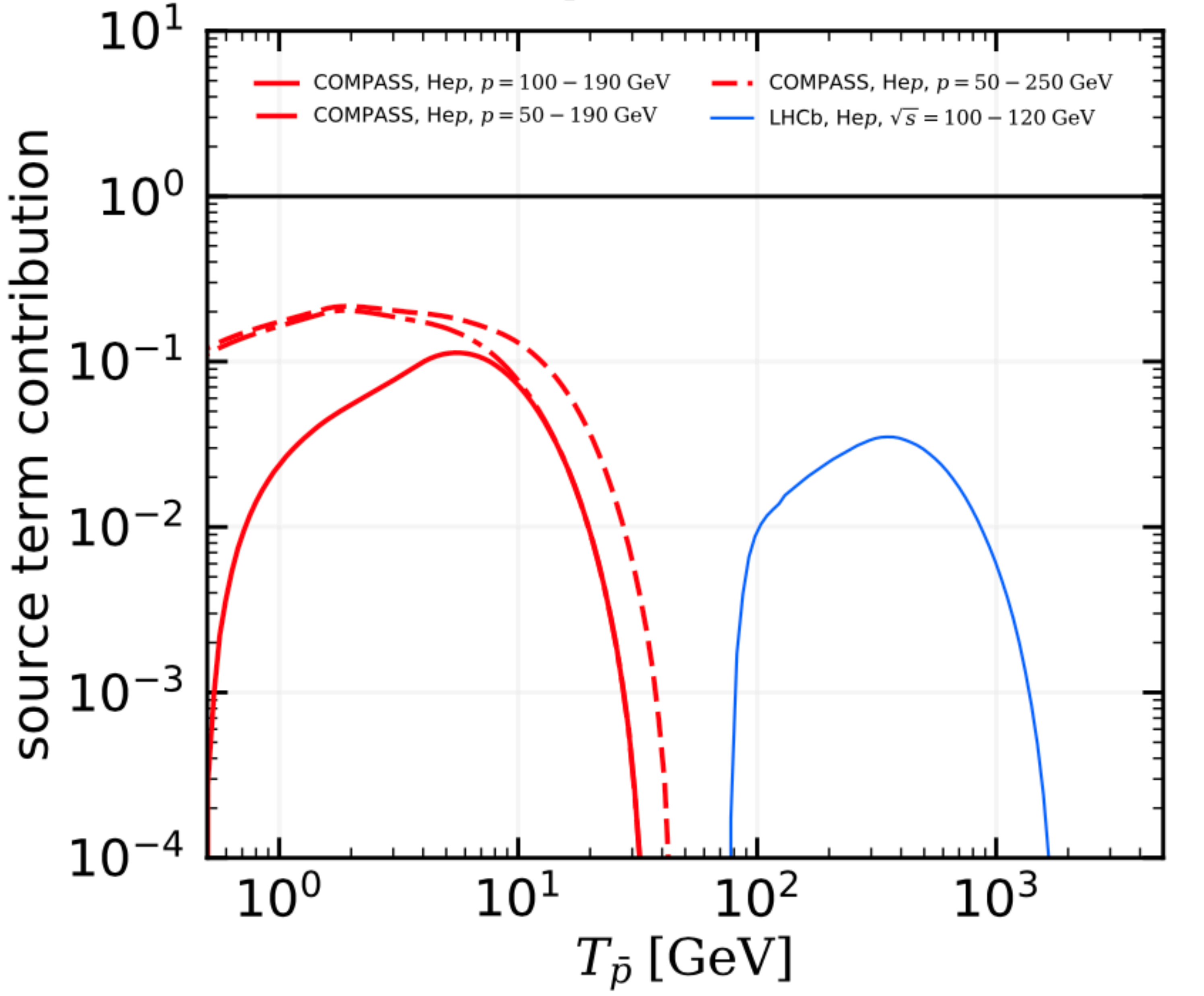
Donato et al. *Phys.Rev.D* 96 (2017) 4, 043007

Prospects for COMPASS++/AMBER

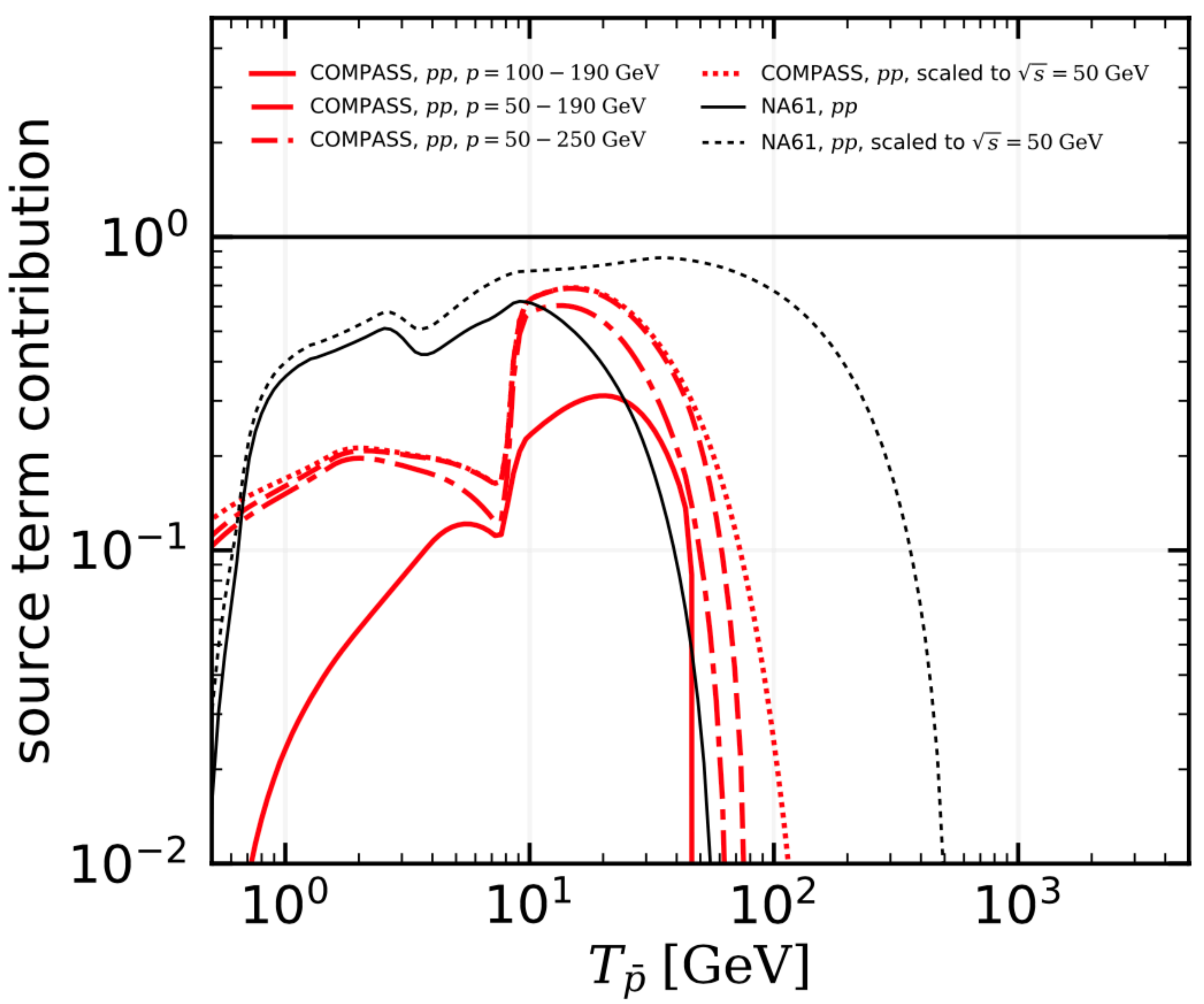
pHe channel



Hep channel



pp channel



The COMPASS++/AMBER collaboration has the potential to significantly improve cross section measurements in the *p*He channel.

See Davide Giordano's Talk!

Taken from https://indico.cern.ch/event/1021402/contributions/4311146/attachments/2234195/3786365/PZ_AMBER_Workshop_April21.pdf

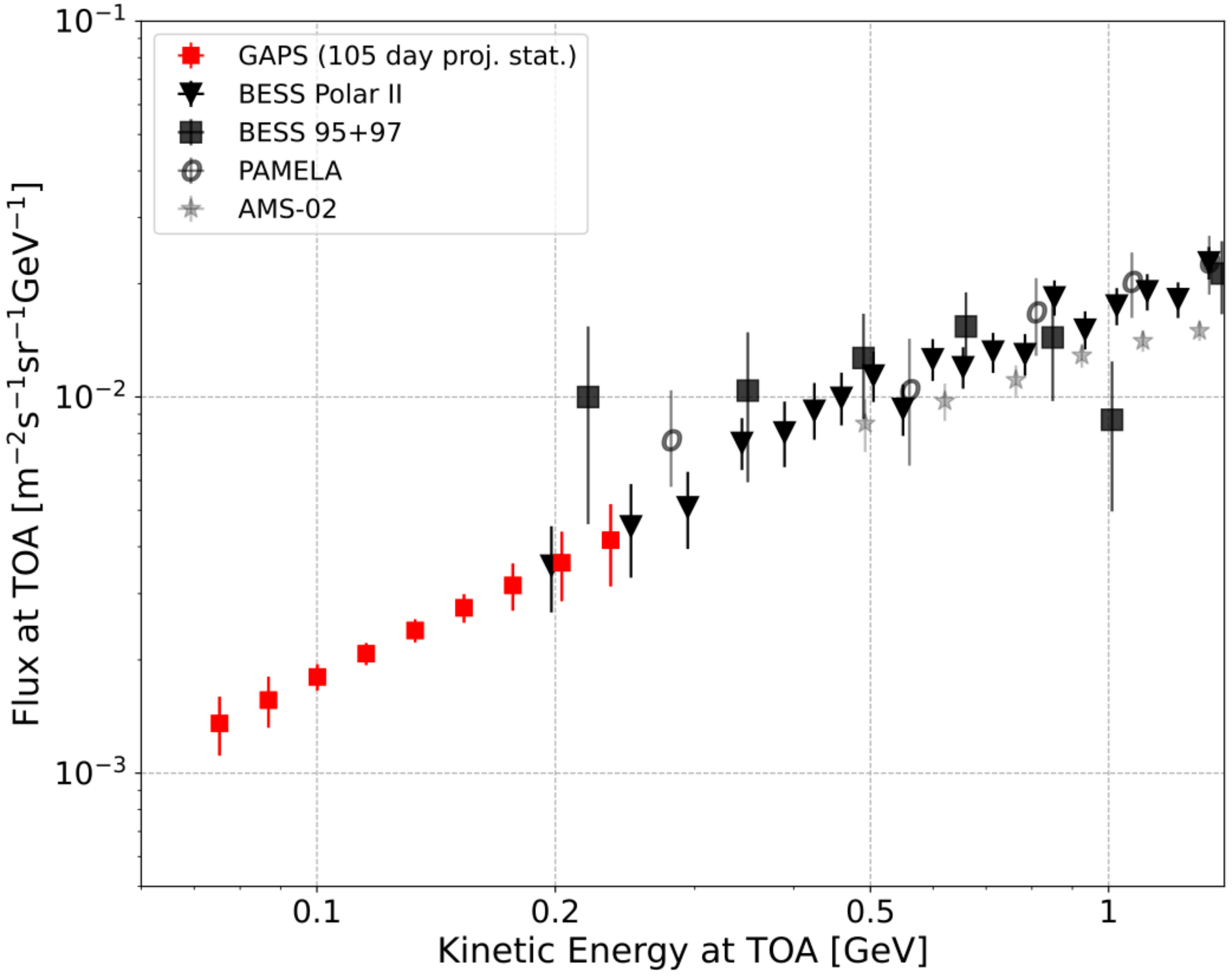
Conclusions

- AMS-02 antiproton flux data are measured with a precision as low as 3-6%.
- Antiproton production cross sections are an important ingredient to understand the recent and precise flux measurements by AMS-02
- Uncertainties of cross sections in prediction of the antiproton source term are between 15% and 20%
- Future cross section measurements are necessary to improve our understanding of antiproton production in cosmic rays

Backup slides

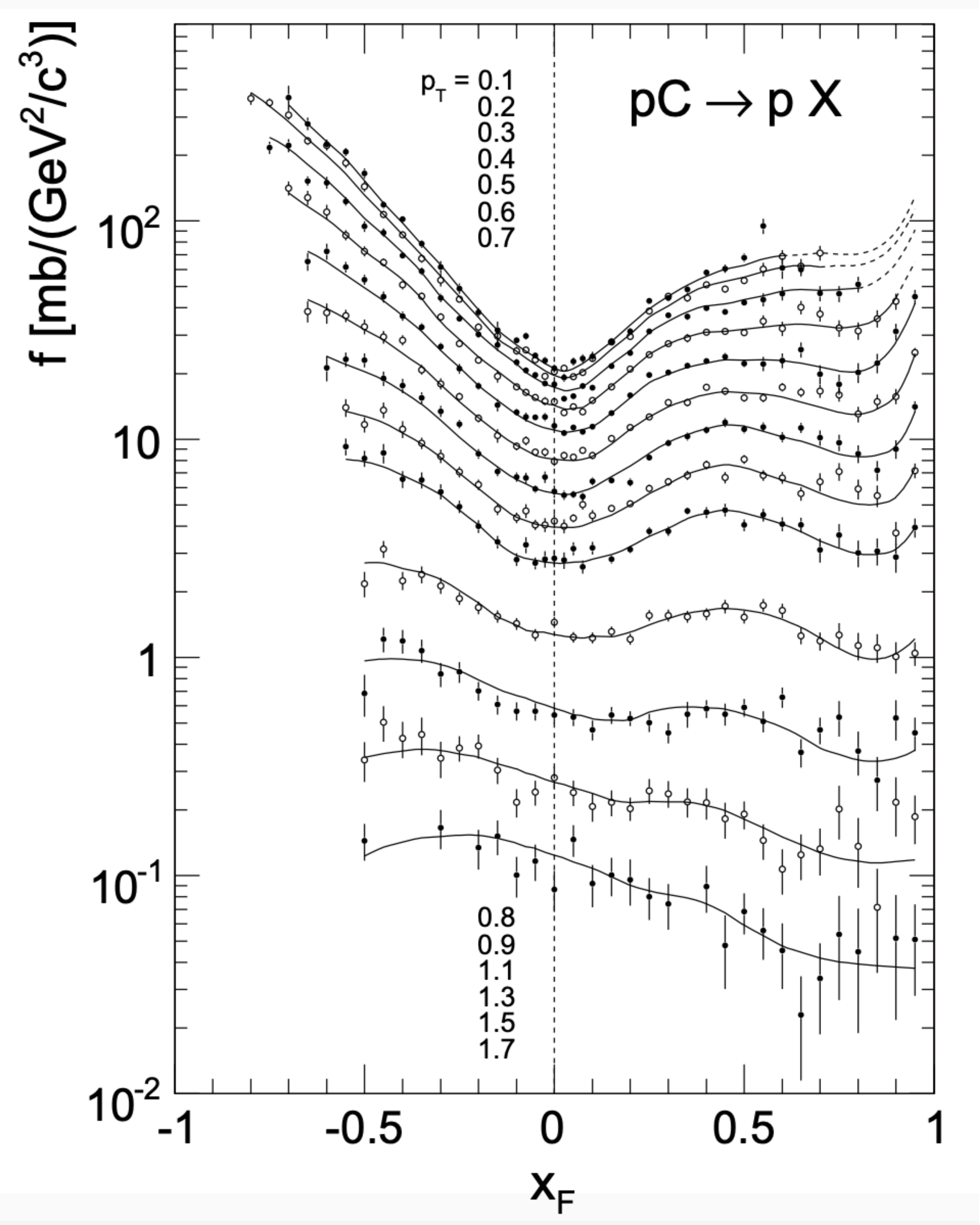
P-bar cosmic measurements below 1 GeV

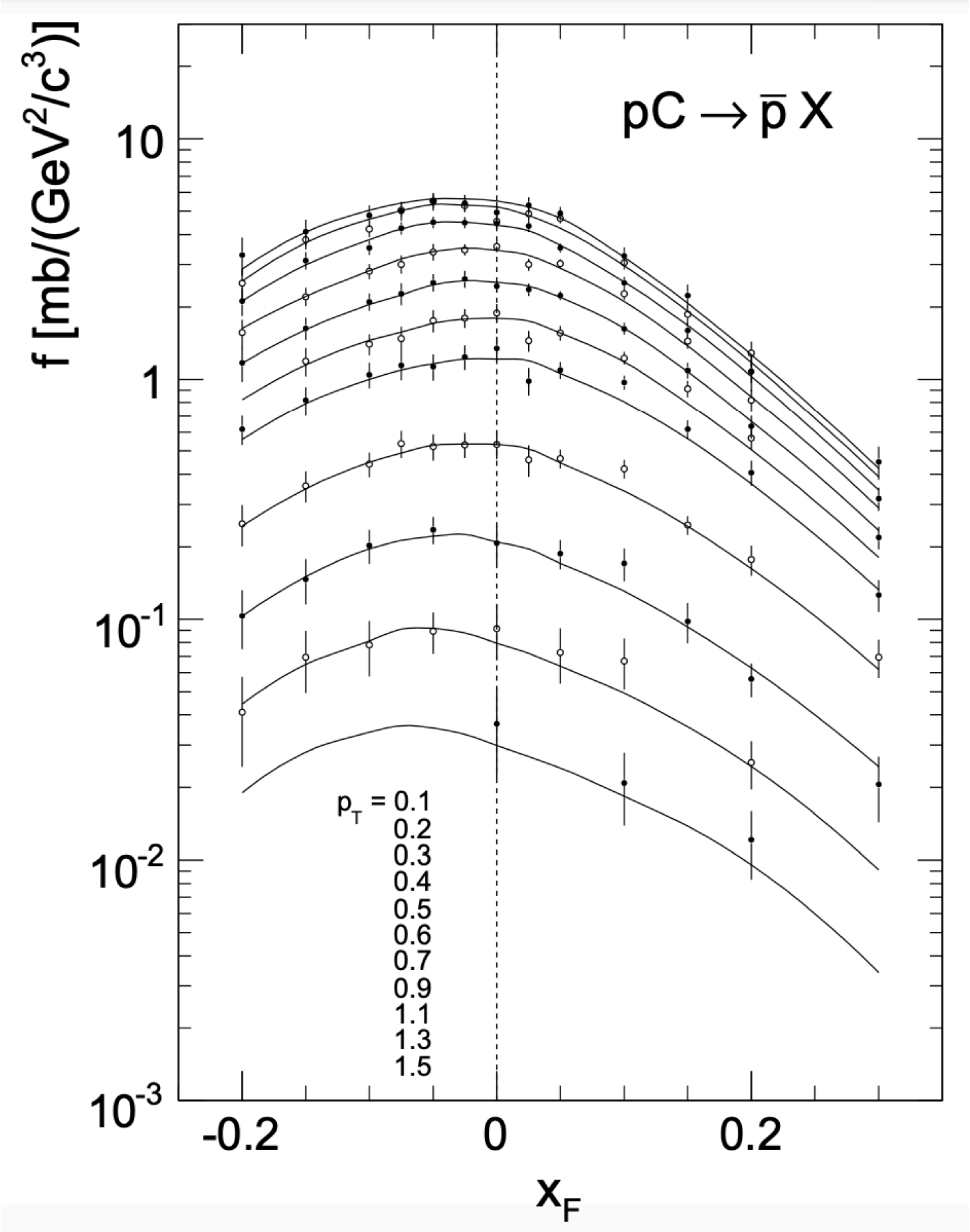
- GAPS will measure with the best sensitivity ever the antiproton cosmic flux below 1 GeV of kinetic energy.
- This energy range is very important for understanding the CR propagation and solar modulation effects.



https://arxiv.org/pdf/2206.12991.pdf

Forward-backward asymmetry in pC NA49





Cross section parametrizations

Param I (di Mauro):

$$\left(E\frac{d^3\sigma}{dp^3}\right)_{pp}(\sqrt{s}, x_R, p_T) = \sigma_{\text{in}}(1-x_R)^{C_1}\exp(-C_2 x_R)\left[C_3\left(\sqrt{s}\right)^{C4}\exp(-C_5 p_T) + C_6\left(\sqrt{s}\right)^{C7}\exp\left(-C_8 p_T^2\right)\right]$$

8 free parameters in the fit!

Param. II (Winkler):

$$\left(E\frac{d^3\sigma}{dp^3}\right)_{pp}(\sqrt{s}, x_R, p_T) = \sigma_{\text{in}}R(\sqrt{s}, x_R, p_T)\, C_1(1-x_R)^{C_2}\left[1+\frac{X}{\text{GeV}}(m_T - m_p)\right]^{-\frac{1}{C_3 X}}$$

$$R = \begin{cases} 1 & , \sqrt{s}10\,\text{GeV} \\ \left[1 + C_5\left(10 - \frac{\sqrt{s}}{\text{GeV}}\right)^5\right]\exp\left[C_6\left(10-\frac{\sqrt{s}}{\text{GeV}}\right)^2(x_R - x_{R,\min})\right] & , \text{elsewhere} \end{cases}$$

and

$$X = C_4 \log^2\left(\frac{\sqrt{s}}{4m_p}\right)$$

5 free parameters in the fit!

Both parametizations exploit the scaling invariance of the antiproton production cross section in $x_R = E^*_{\bar{p}}/E^*_{\bar{p},\max}$ for CM energies between ~10 GeV to 50 GeV.

Cross section parametrizations

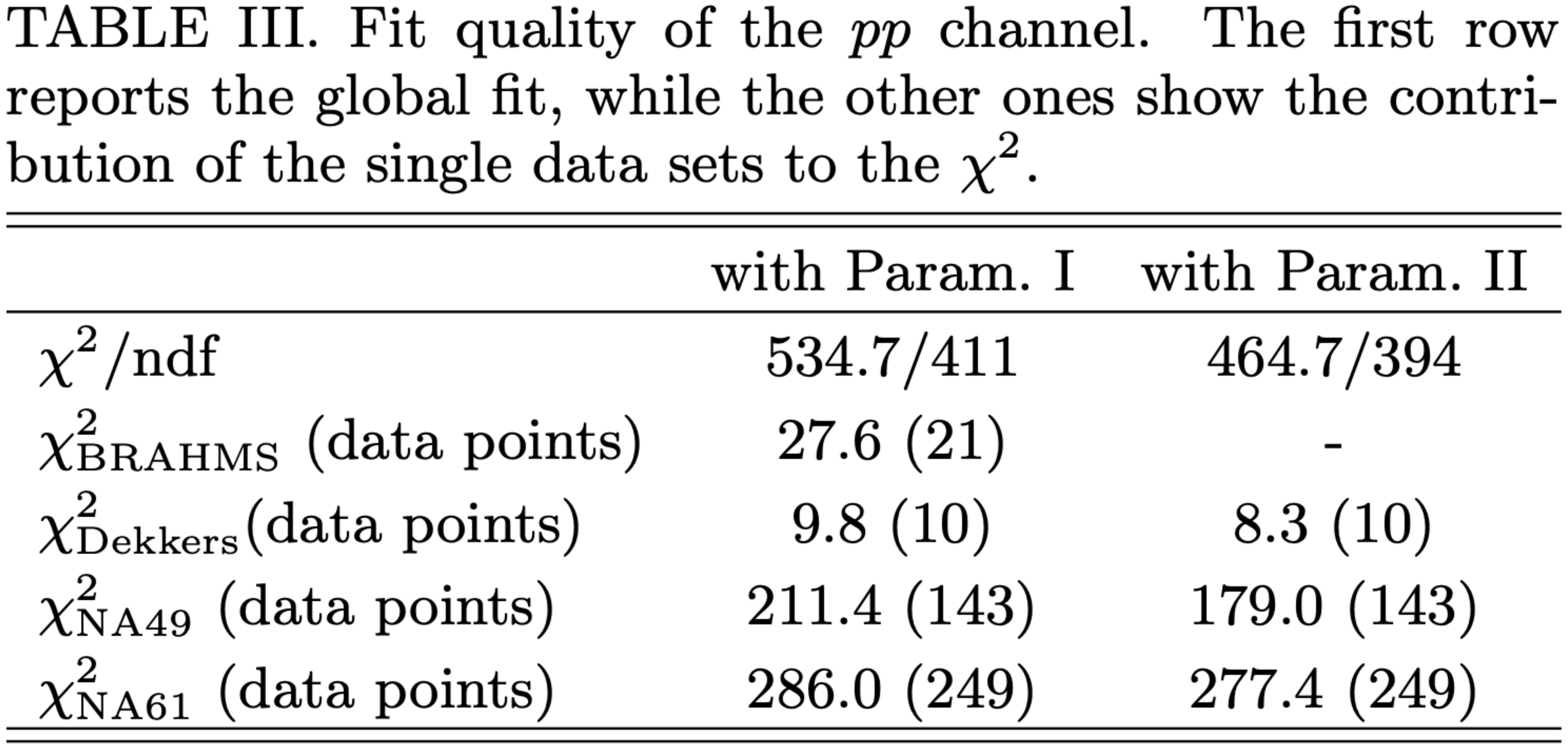


TABLE III. Fit quality of the pp channel. The first row reports the global fit, while the other ones show the contribution of the single data sets to the χ^2.

	with Param. I	with Param. II
χ^2/ndf	534.7/411	464.7/394
χ^2_{BRAHMS} (data points)	27.6 (21)	-
χ^2_{Dekkers}(data points)	9.8 (10)	8.3 (10)
χ^2_{NA49} (data points)	211.4 (143)	179.0 (143)
χ^2_{NA61} (data points)	286.0 (249)	277.4 (249)

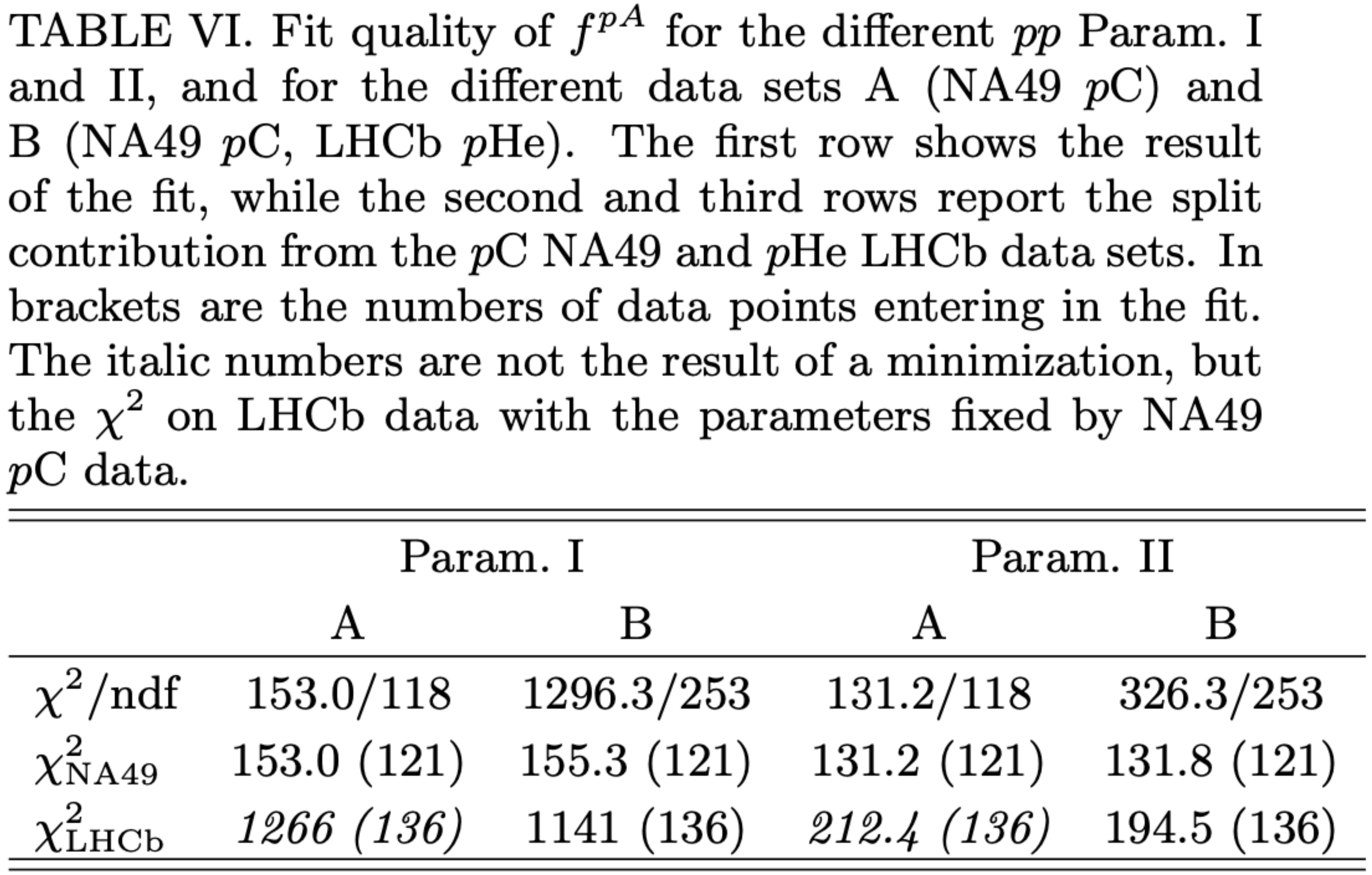
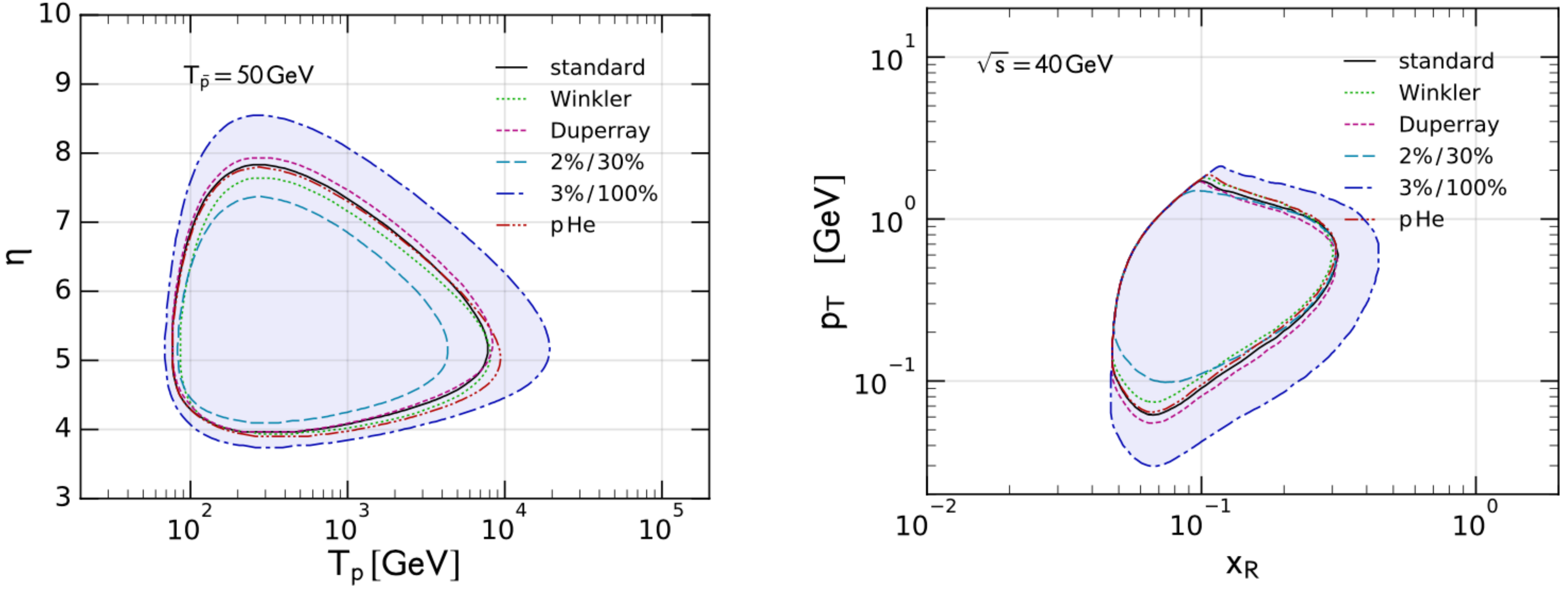


TABLE VI. Fit quality of f^{pA} for the different pp Param. I and II, and for the different data sets A (NA49 pC) and B (NA49 pC, LHCb pHe). The first row shows the result of the fit, while the second and third rows report the split contribution from the pC NA49 and pHe LHCb data sets. In brackets are the numbers of data points entering in the fit. The italic numbers are not the result of a minimization, but the χ^2 on LHCb data with the parameters fixed by NA49 pC data.

	Param. I		Param. II	
	A	B	A	B
χ^2/ndf	153.0/118	1296.3/253	131.2/118	326.3/253
χ^2_{NA49}	153.0 (121)	155.3 (121)	131.2 (121)	131.8 (121)
χ^2_{LHCb}	*1266 (136)*	1141 (136)	*212.4 (136)*	194.5 (136)

Prescriptions with different models

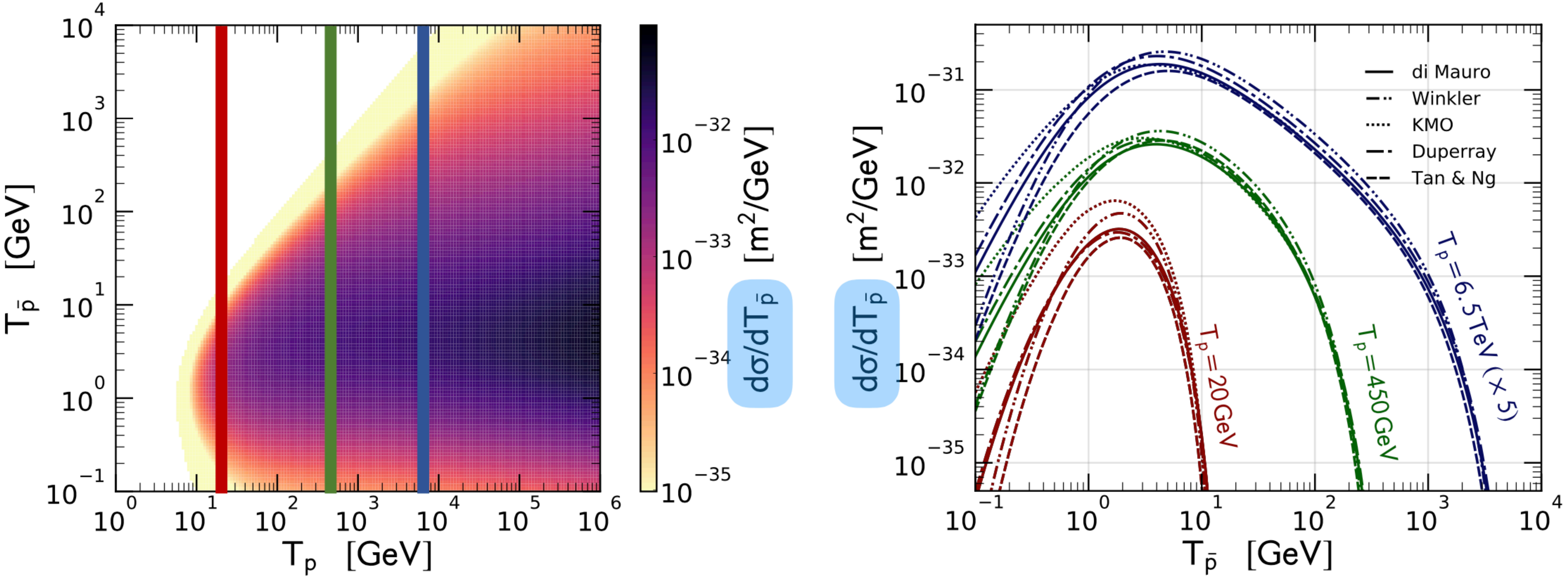


(a) LAB frame

(b) CM frame

Results for the antiproton cross sections

$$\frac{d\sigma}{dT_{\bar{p}}}(T_p, T_{\bar{p}}) = p_{\bar{p}} \int d\Omega \left(E \frac{d^3\sigma}{dp^3} \right)(T_p, T_{\bar{p}}, \theta)$$

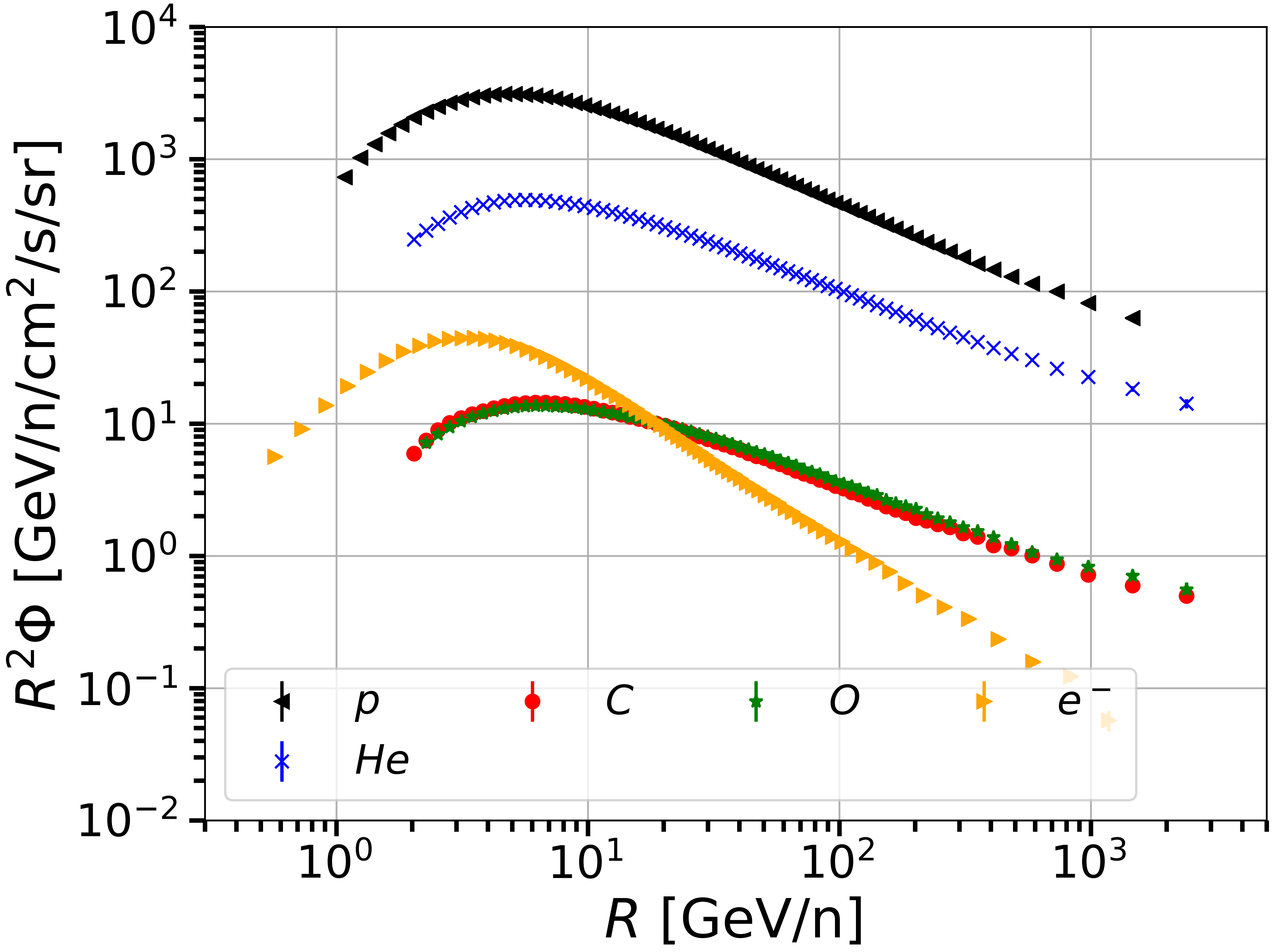


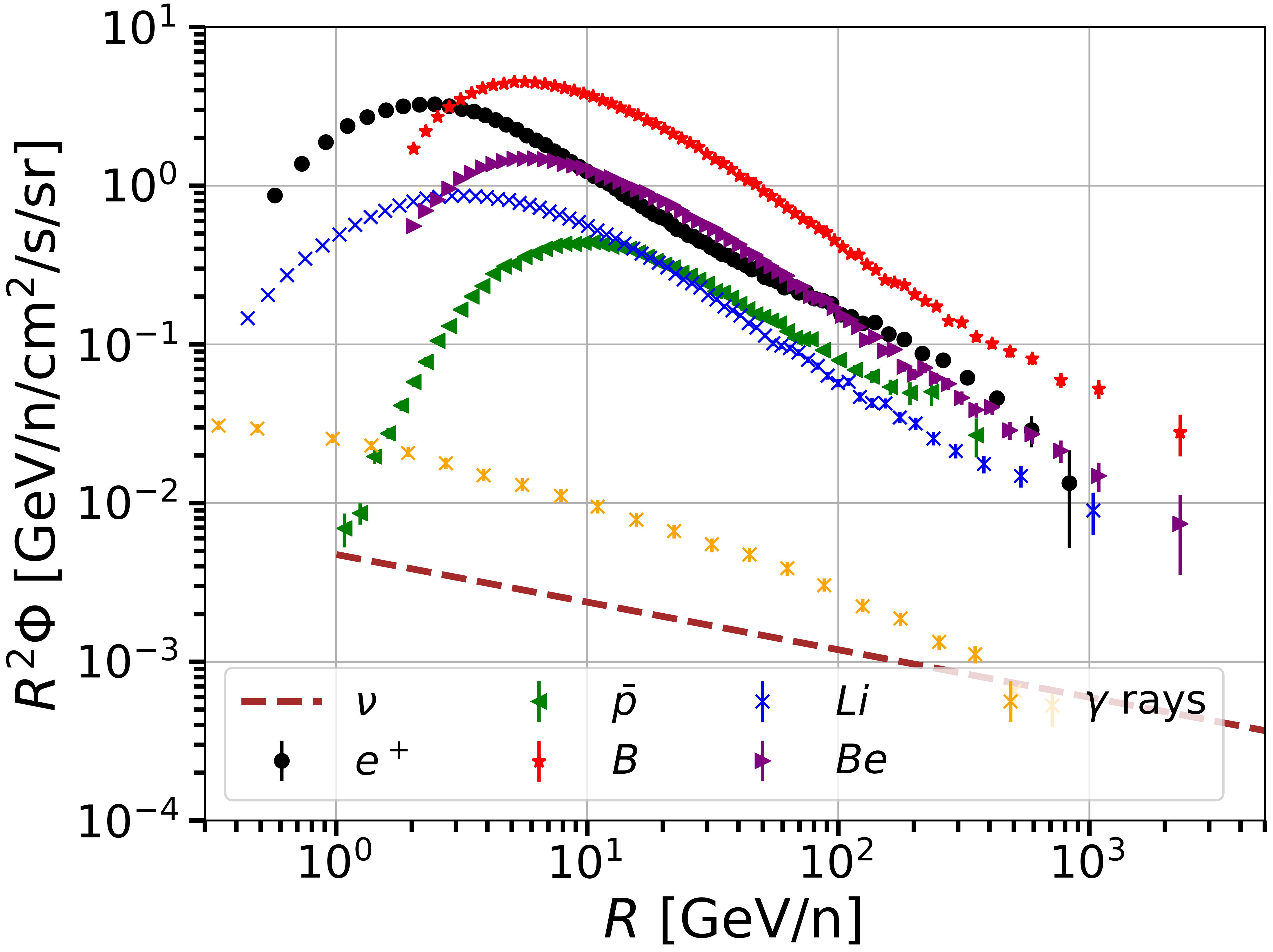
[Donato, MK, Di Mauro; 2017]

There are large differences between various cross section parametrizations used to predict CR antiprotons.

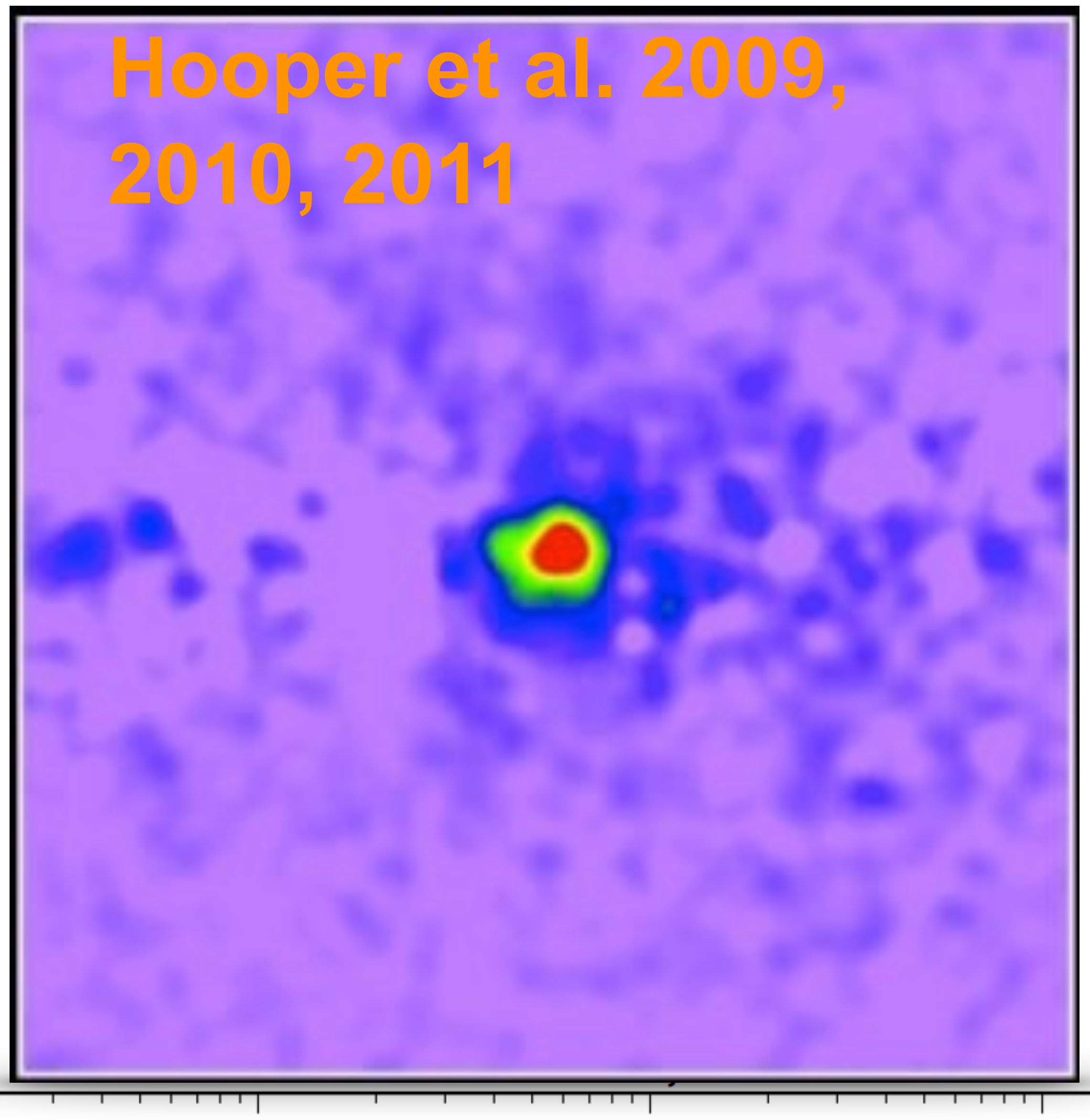
Cosmic-ray particles

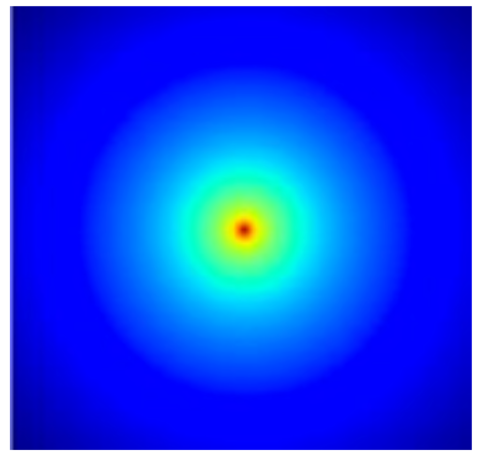
- Among all cosmic rays, secondaries are the most interesting for DM searches.
- In particular antiprotons, positrons, gamma rays and neutrinos are the most studied.
- Antinuclei are also considered because the DM production should exceed the secondary one at low energy.



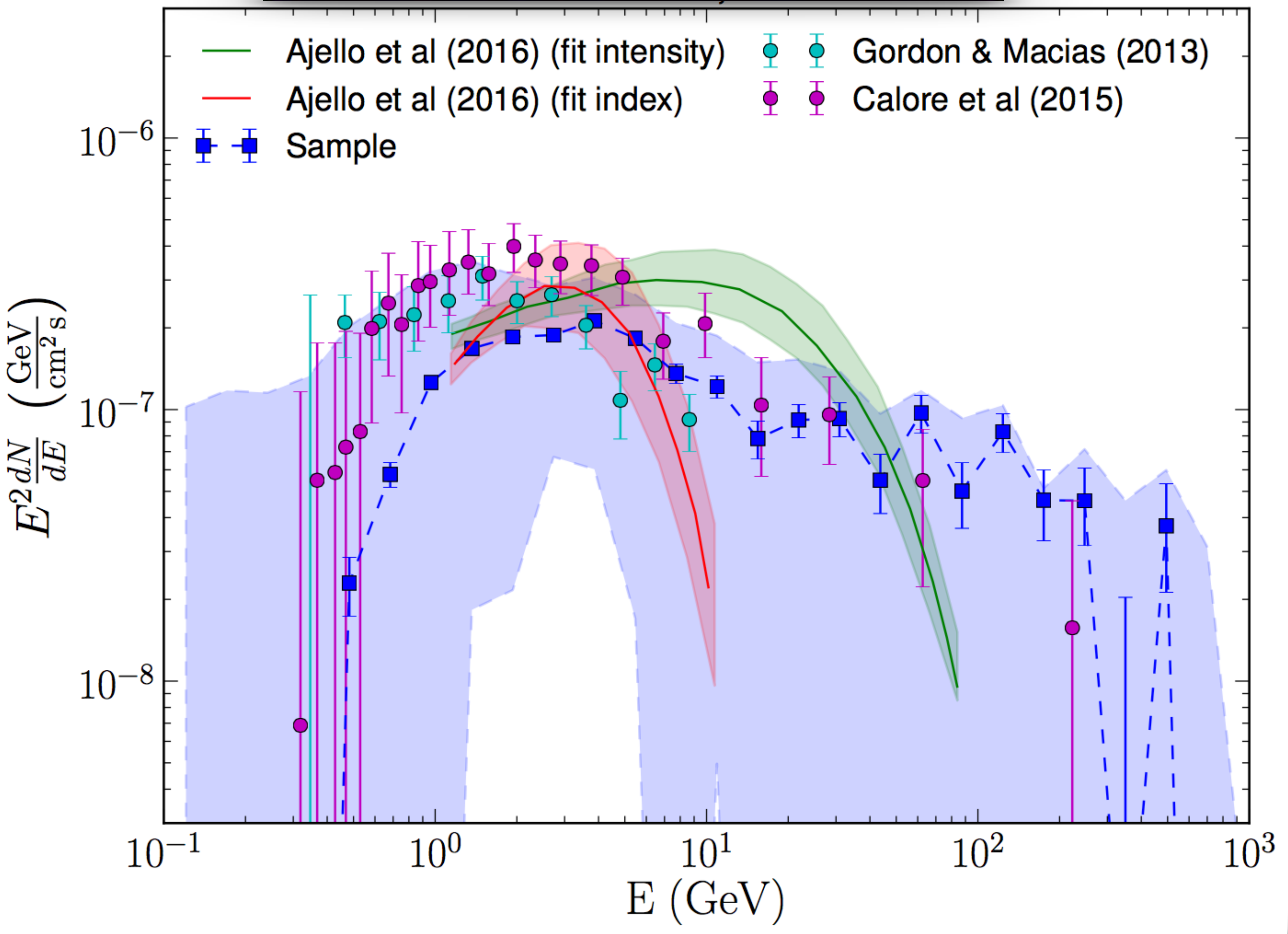


Possible excesses in cosmic-ray data

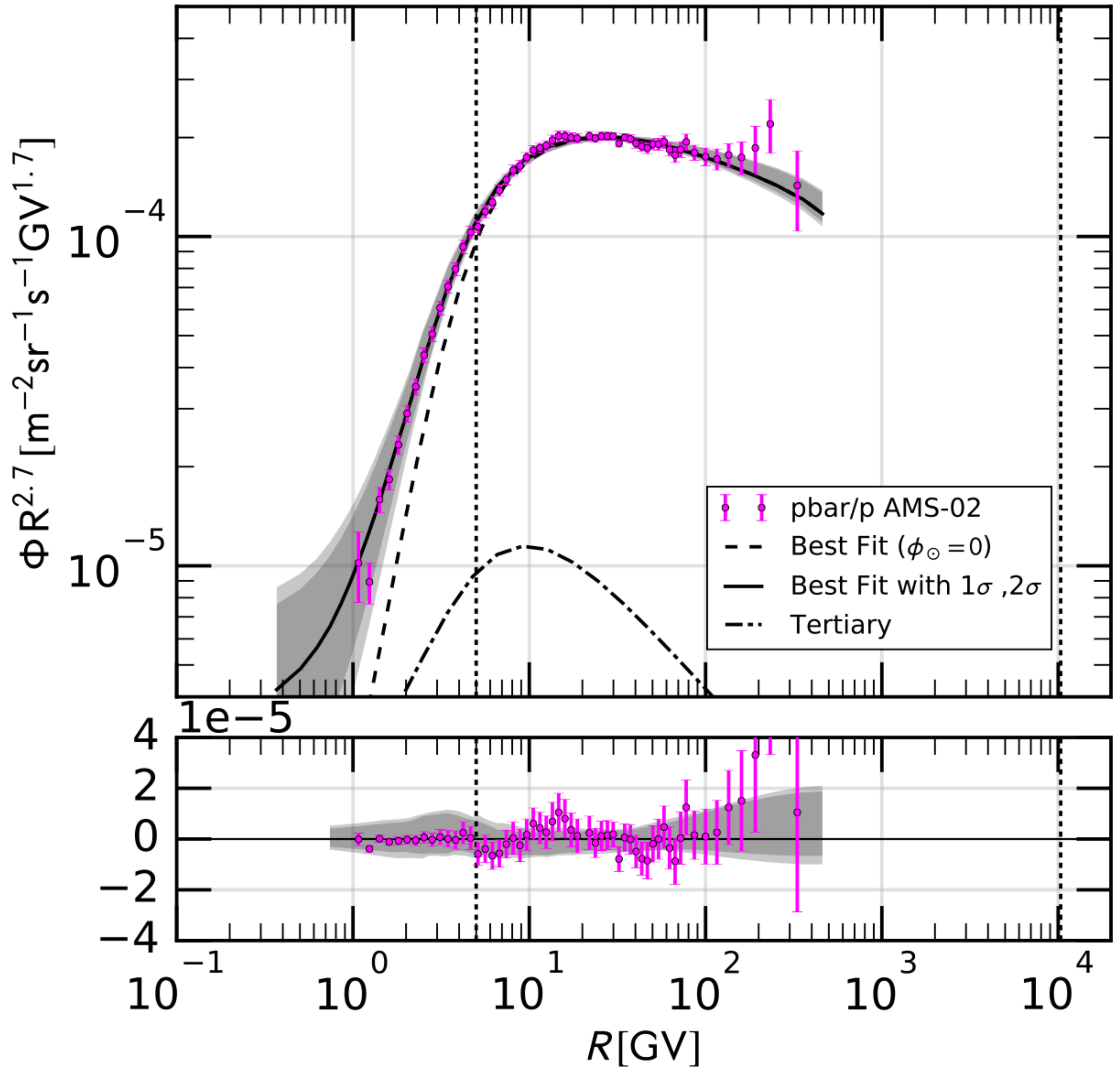


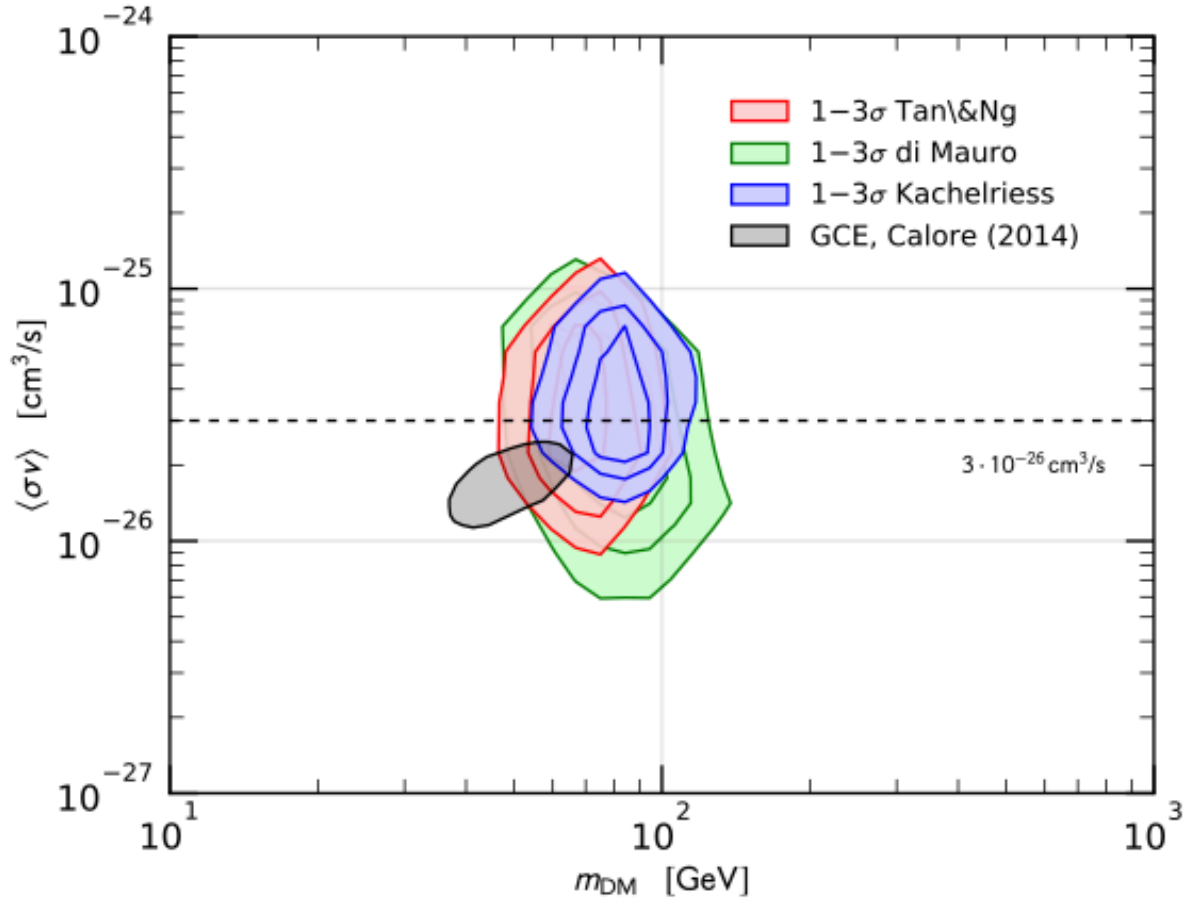


The GeV Galactic center excess



The AMS-02 antiproton excess





The two excesses can be both a signal from DM…