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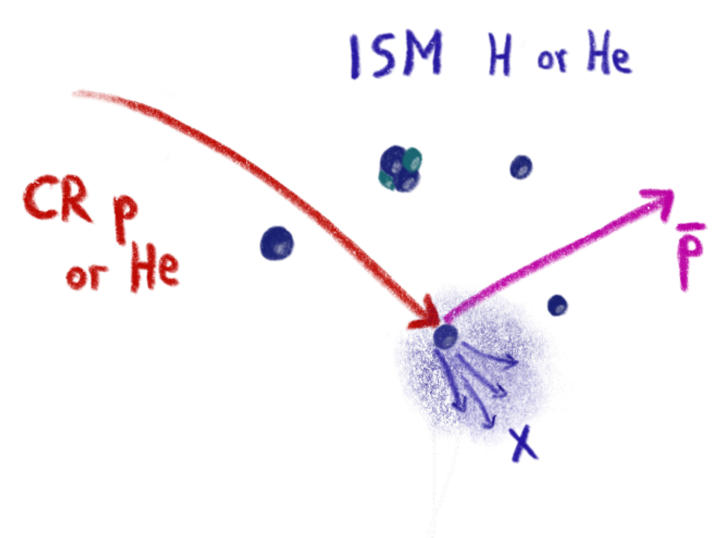
Antiproton production cross sections in cosmic rays

Michael Korsmeier



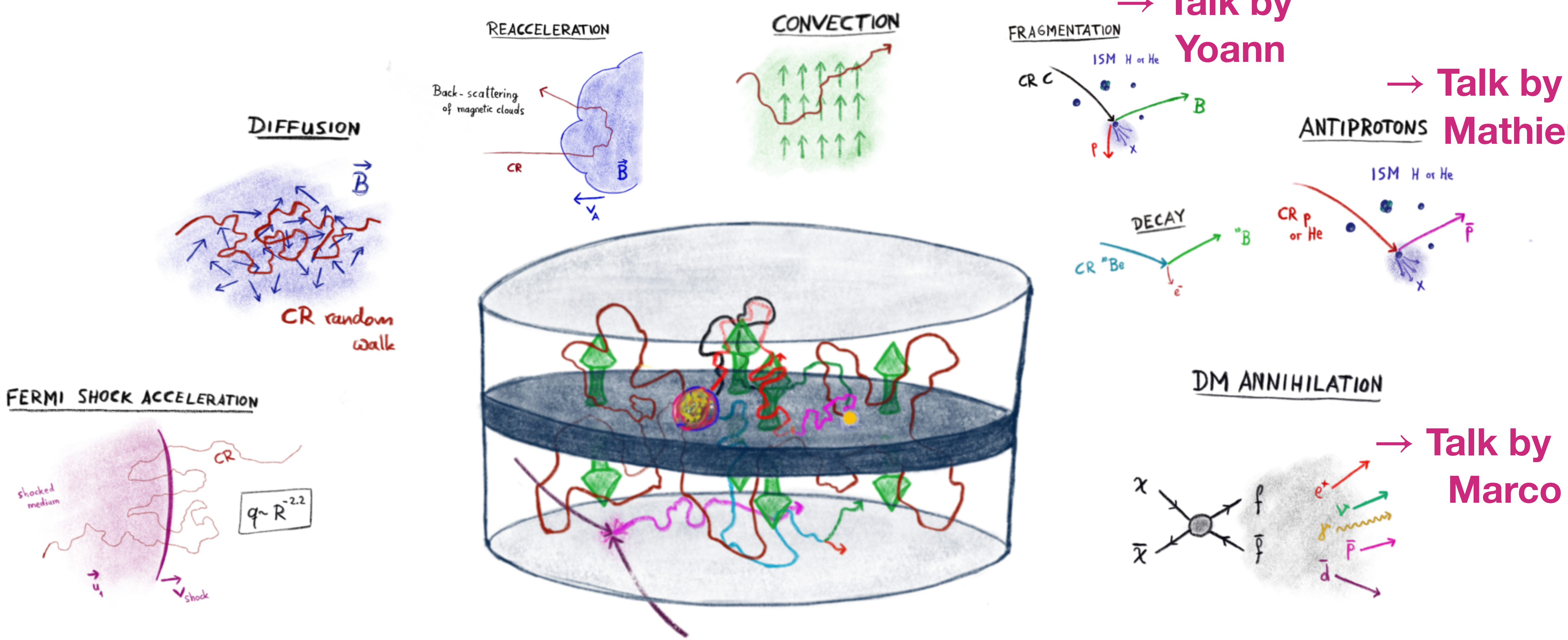
13-Nov-19

XSCRC 2019 - CERN

Outline

- Motivation to study antiprotons in cosmic rays
- Parameterizing the secondary antiproton production cross section
  Based on: Korsmeier, Donato, di Mauro; **Phys.Rev. D97 (2018) no.10, 103019**
- Requirements for future cross section measurements
  Based on: Donato, Korsmeier, di Mauro; **Phys. Rev. D96 (2017) 043007**

Introduction CR propagation



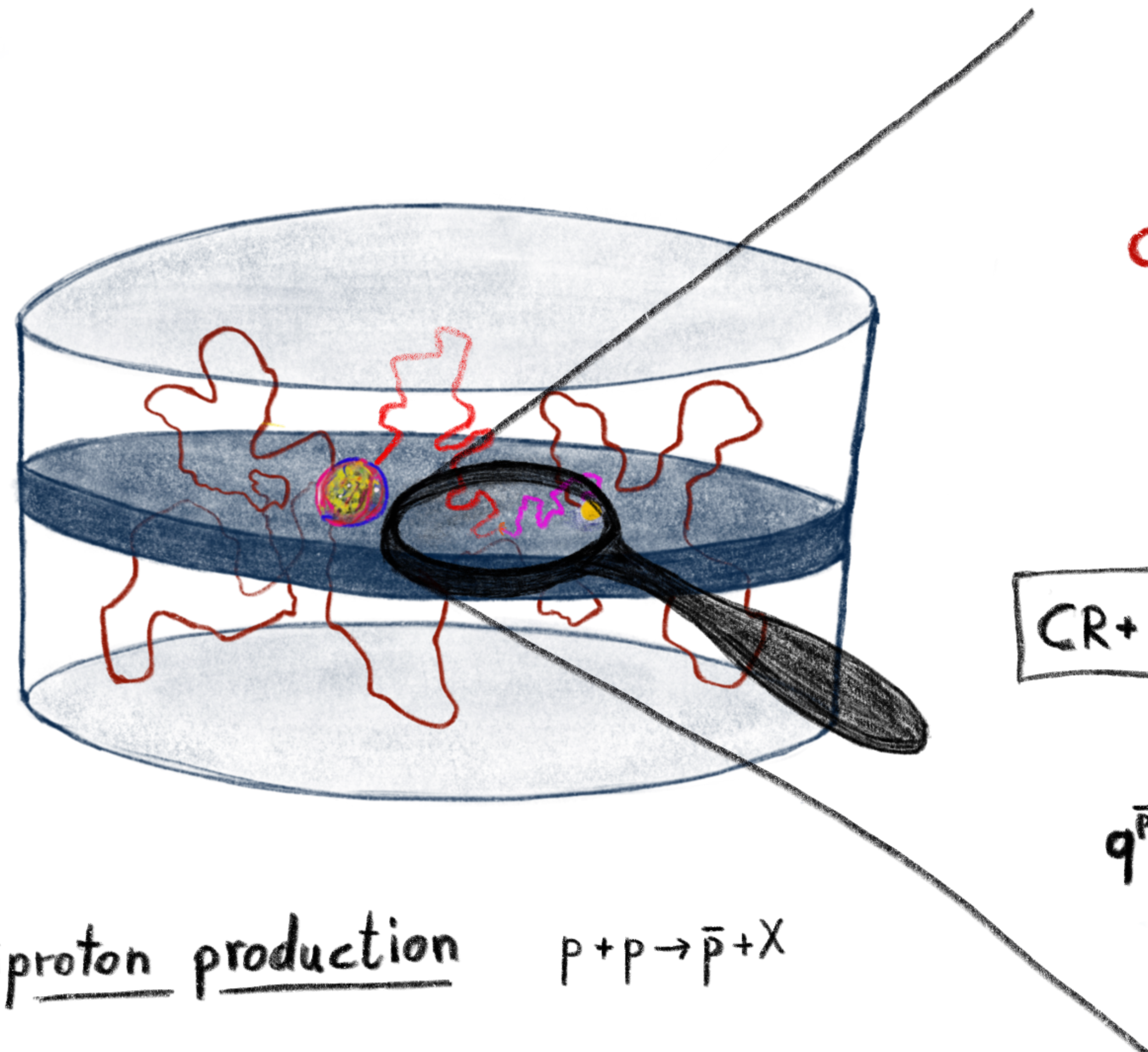
→ Talk by Yoann

→ Talk by Mathieu

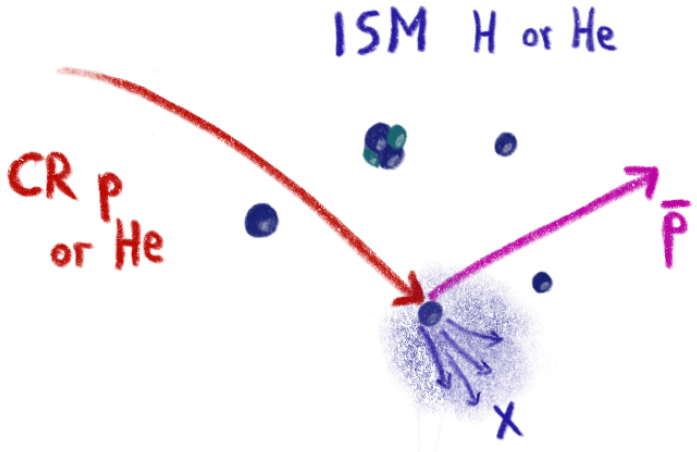
→ Talk by Marco

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

Introduction CR propagation



ANTIPROTONS



$CR + ISM \rightarrow \bar{p} + X$

$$q^{\bar{p}}(T_{\bar{p}}) = \int dT \, 4\pi \, n_{ISM} \, \phi_{CR}(T) \, \frac{d\sigma(T, T_{\bar{p}})}{dT_{\bar{p}}}$$

Antiproton production

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

$$E \frac{d^3\sigma}{dp^3} \sim R(s, x_R) \, (1 - x_R)^{c_1} \, e^{-c_2 p_T}$$

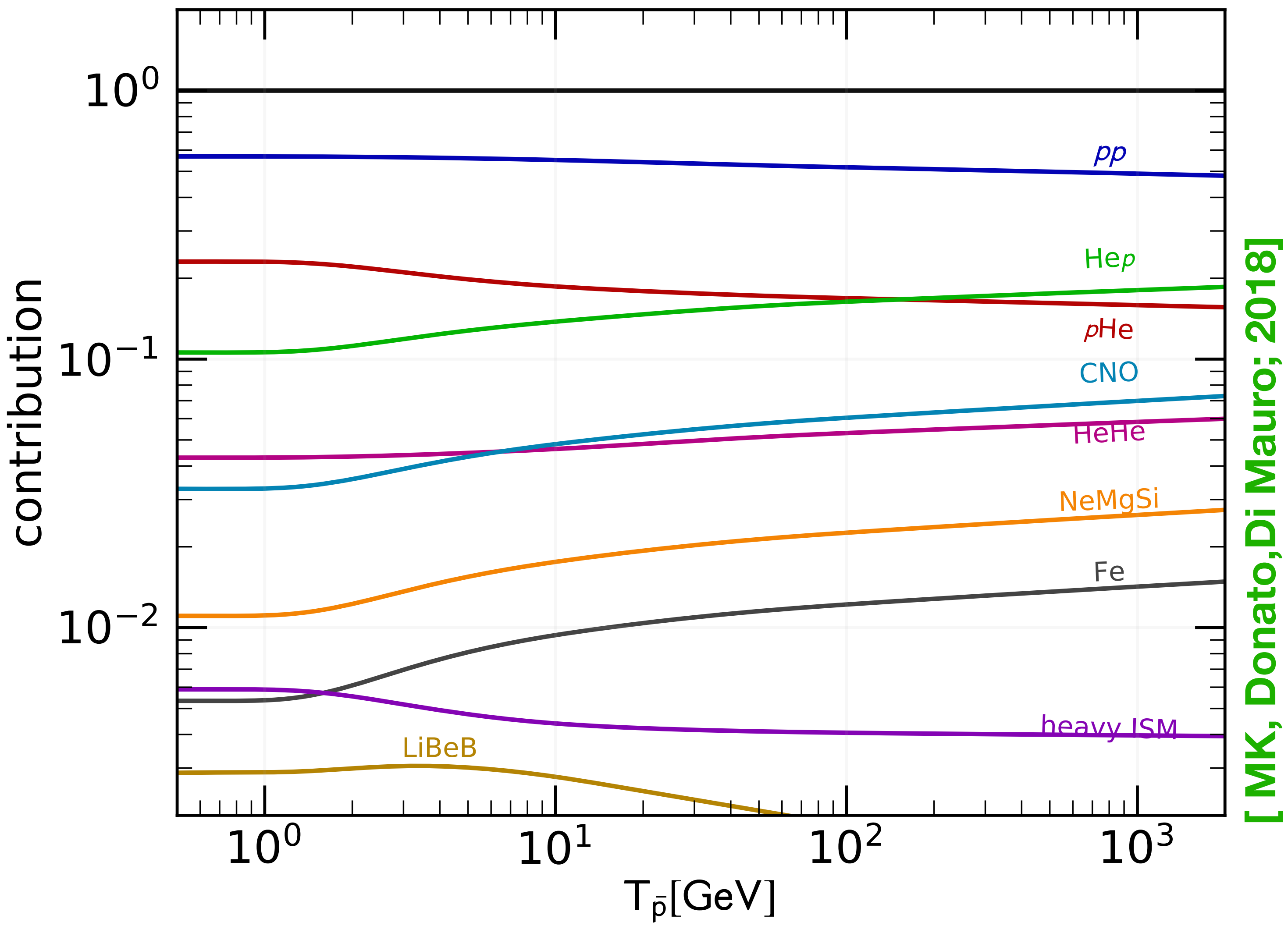
Lorentz transformation + angular integration →

$$\frac{d\sigma(T, T_{\bar{p}})}{dT_{\bar{p}}}$$

- $R(s, x_R)$: scaling violation
- $(1 - x_R)^{c_1}$: Feynman scaling invarianz
- $e^{-c_2 p_T}$: p_T suppression

Contribution of various CR+ISM channels

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



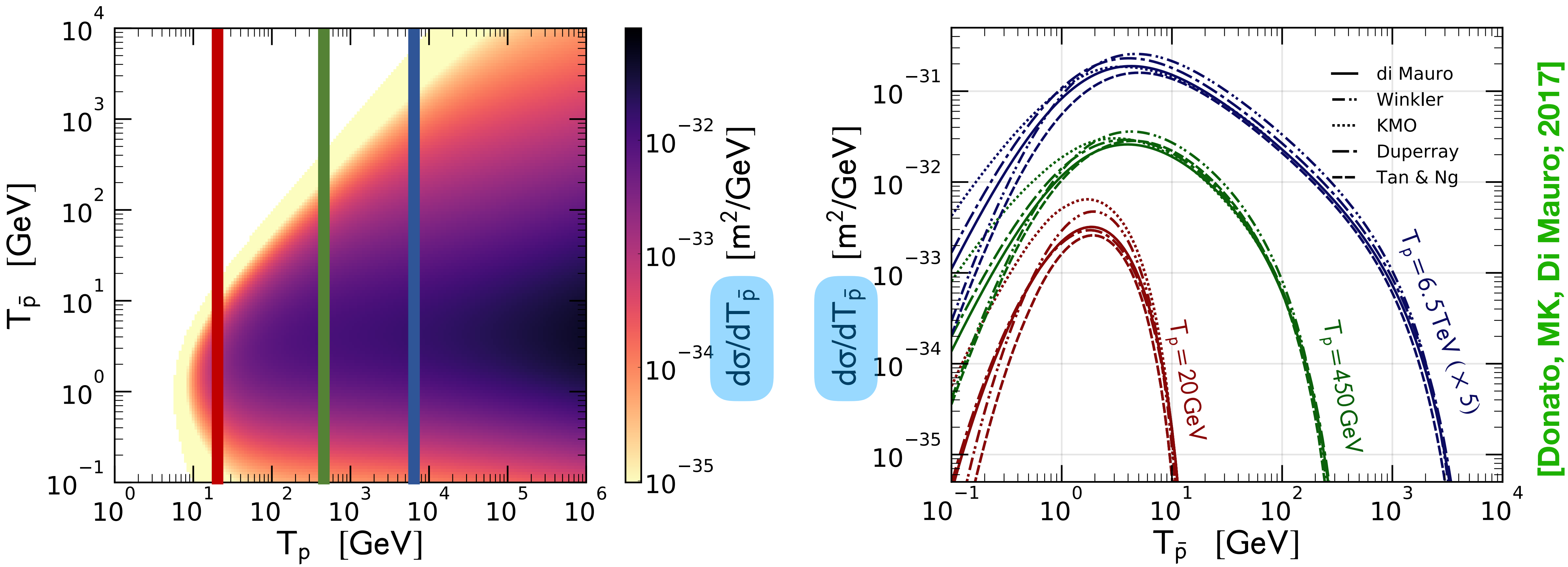
Dominant antiproton production channels in CRs:

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

Channels with secondary CRs or heavy ISM can slightly change the energy behavior, but these channels are suppressed below the percent level.

Uncertainties in $\bar{p}$ cross sections

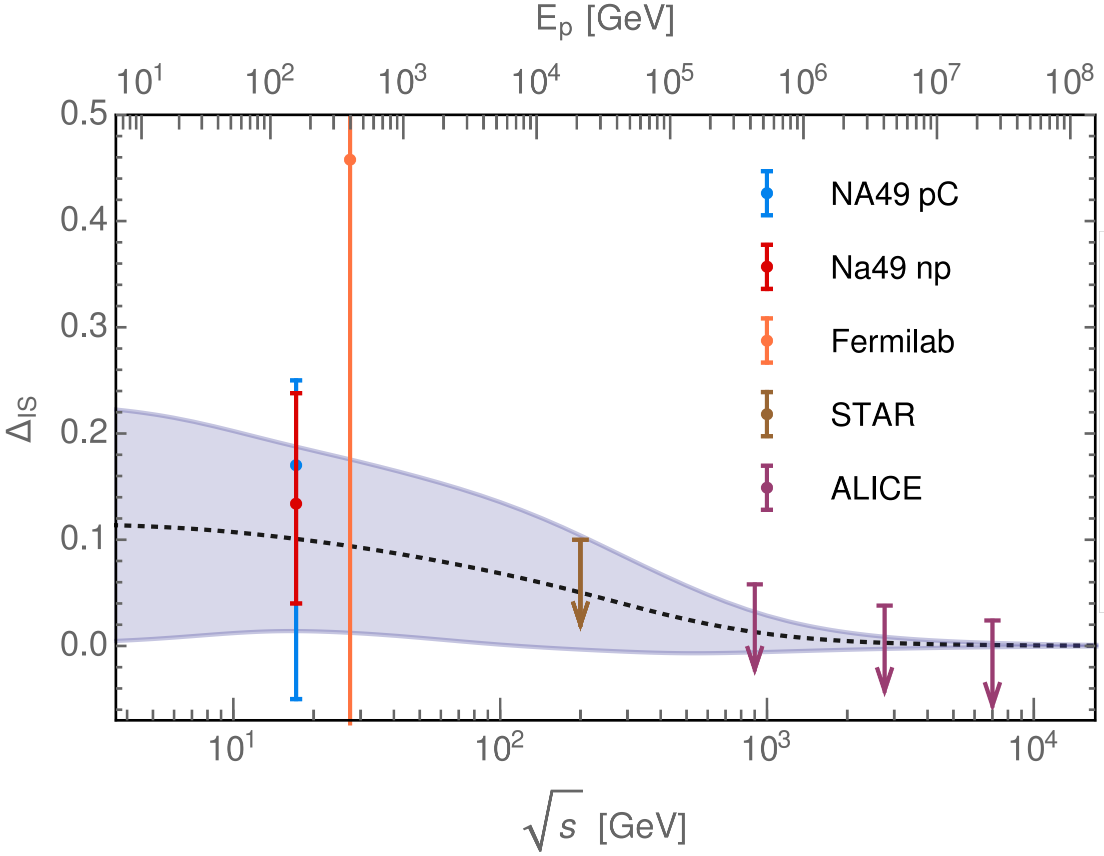
$$\frac{d\sigma}{dT_{\bar{p}}}(T_p, T_{\bar{p}}) = p_{\bar{p}} \int d\Omega \left(E \frac{d^3\sigma}{dp^3} \right)(T_p, T_{\bar{p}}, \theta)$$



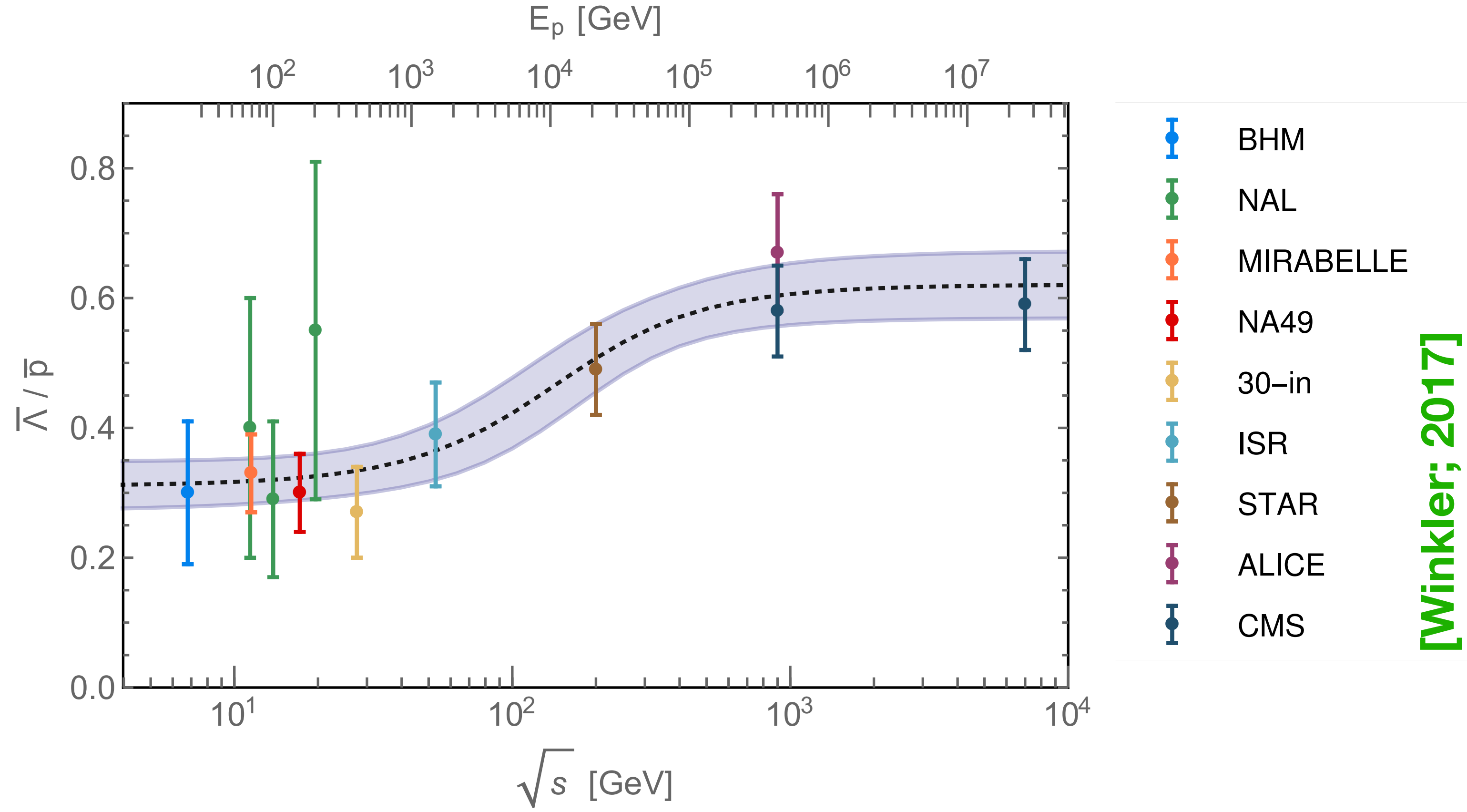
There are large differences between various cross section parametrizations used to predict CR antiprotons.

Antineutrons and antihyperons

Isospin asymmetry



Antihyperons



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

Antineutrons
Isospin asymmetry
Antihyperons

Part I

Parameterizing the secondary antiproton production cross section

Roadmap to update the recent XS parametrizations

- We update the two most recent analytic cross section parametrizations

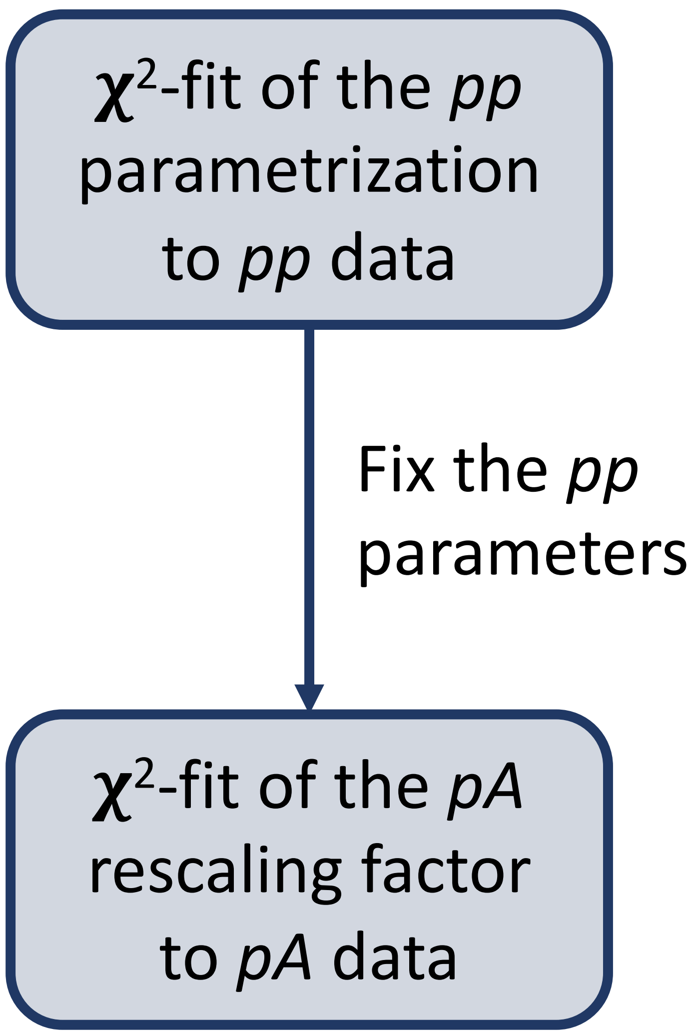
  Param. I: [Di Mauro+, 2014]
  Param. II: [Winkler, 2017]

  using data from NA61 and LHCb

- We use for the first time the data in the *p*He channel

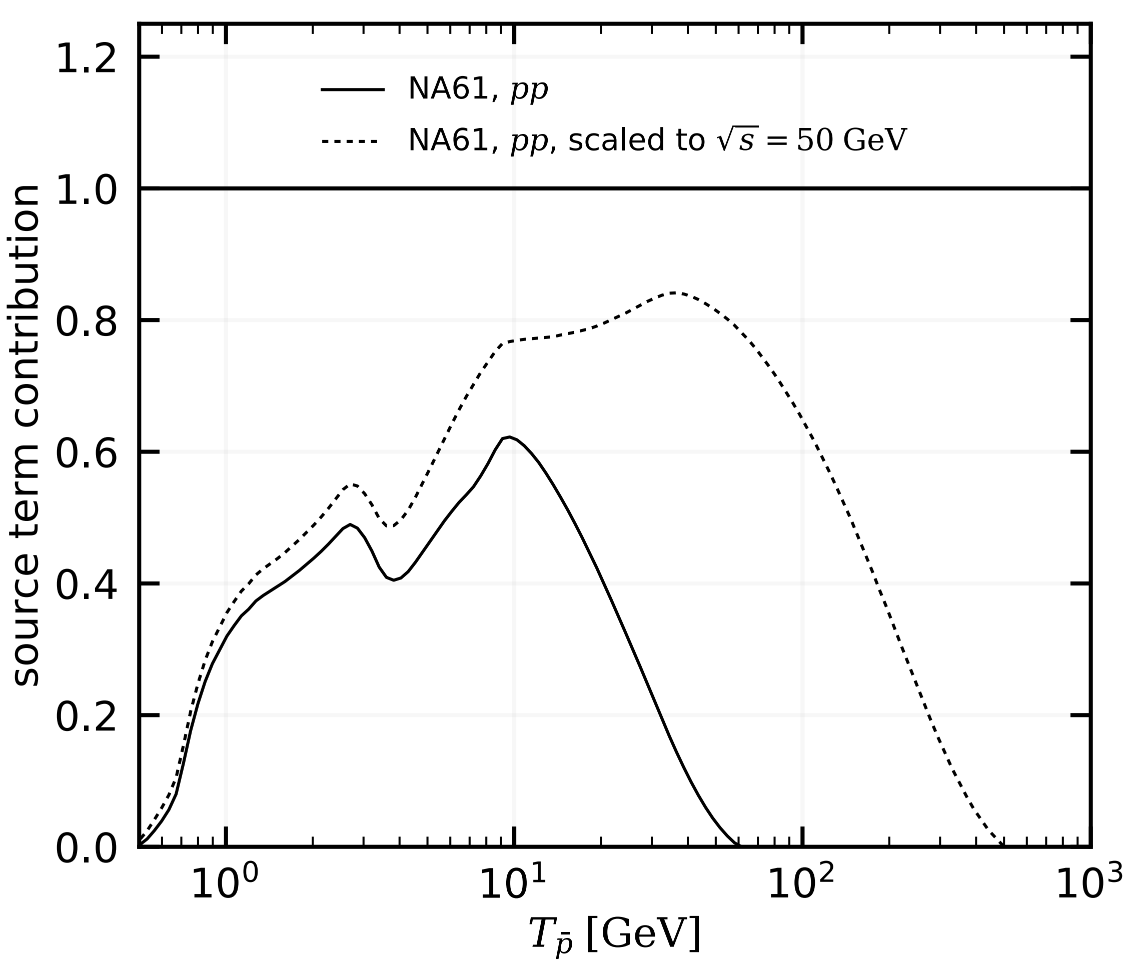
- We derive uncertainties from cross sections on the CR source term

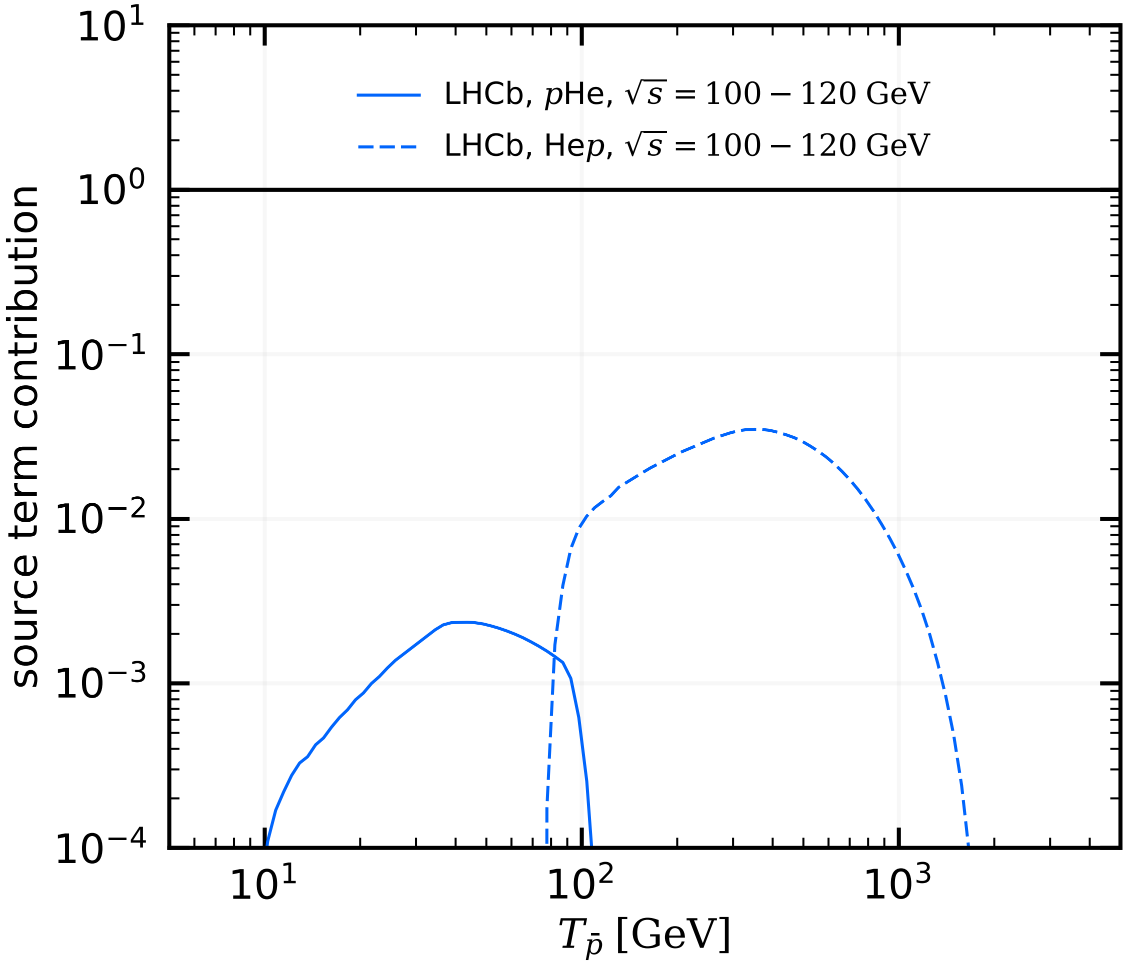
Fit strategy and important data sets



Experiment	CM-energy [GeV]	Channel
NA49	17.3	*pp*
NA61	7.7, 8.8, 12.3, 17.3	*pp*
Dekkers	6.1, 6.7	*pp*
LHCb	110	*p*He
NA49	17.3	*p*C

Fractional source term contribution





NA61 covers a large range and a high fraction of the antiproton source term in the *pp* channel. On the other hand, the contribution of LHCb in the *p*He and He*p* channel is almost negligible.

Cross section parametrization

Param I (di Mauro):

$$\left(E\frac{d^3\sigma}{dp^3}\right)_{pp}(\sqrt{s}, x_R, p_T) = \sigma_{\rm in}(1-x_R)^{C_1}\exp(-C_2x_R)\left[C_3\left(\sqrt{s}\right)^{C4}\exp(-C_5p_T) + C_6\left(\sqrt{s}\right)^{C7}\exp\left(-C_8p_T^2\right)\right]$$

8 free parameters in the fit!

Param. II (Winkler):

$$\left(E\frac{d^3\sigma}{dp^3}\right)_{pp}(\sqrt{s}, x_R, p_T) = \sigma_{\rm in}R(\sqrt{s}, x_R, p_T)\, C_1(1-x_R)^{C_2}\left[1 + \frac{X}{\rm GeV}(m_T - m_p)\right]^{-\frac{1}{C_3X}}$$

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

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

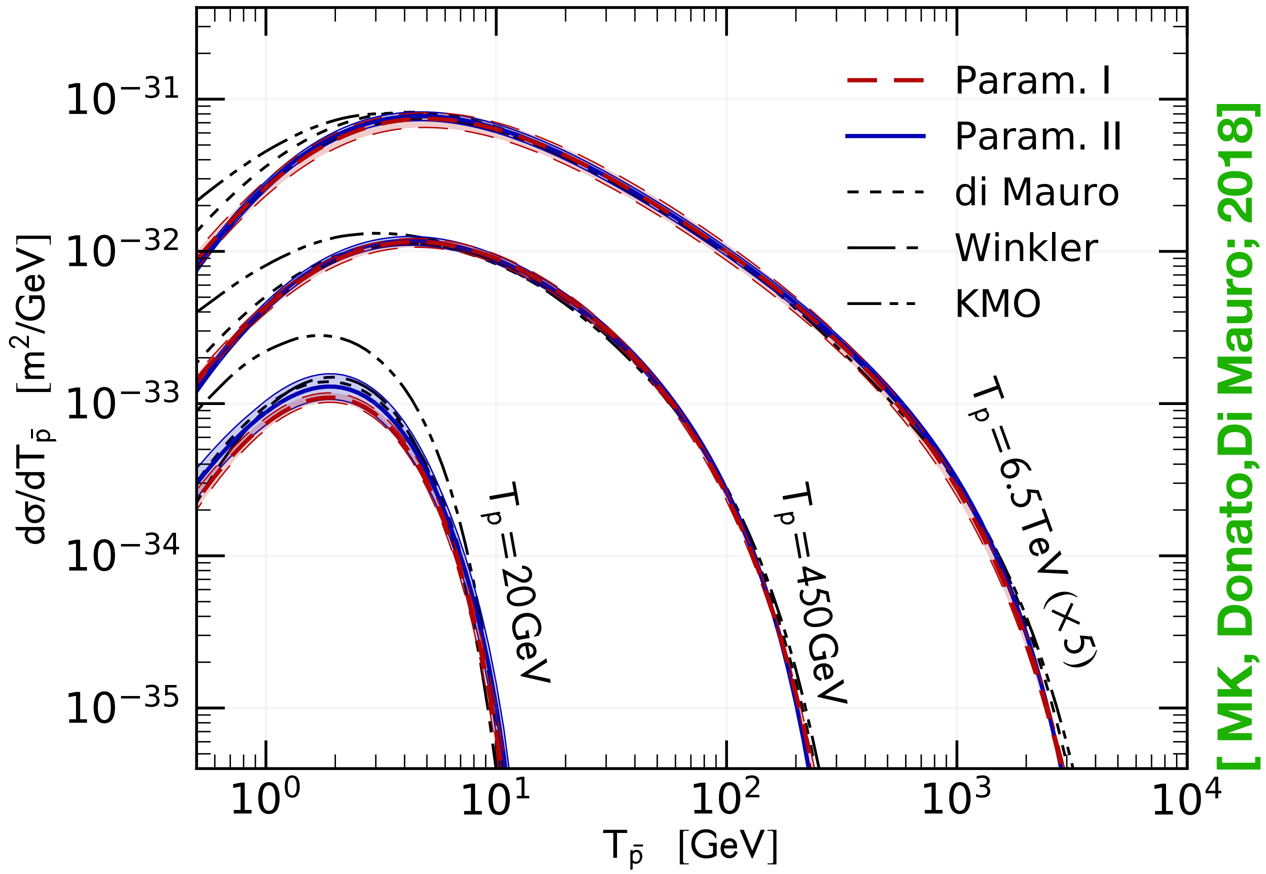
5 free parameters in the fit!

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

Result in the *pp* channel

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

Energy-differential cross section



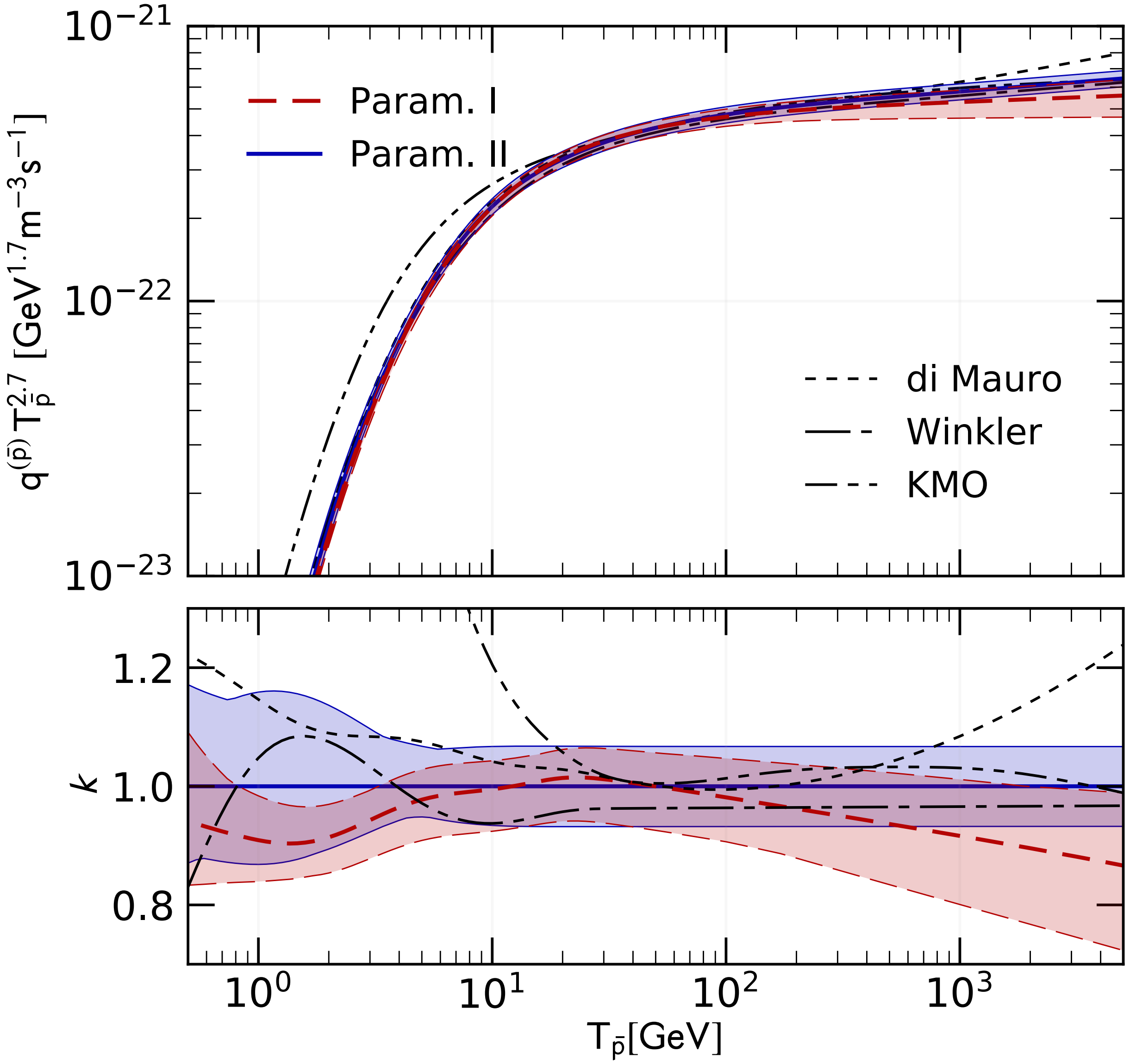
Param. I: [Di Mauro+, 2014]
Param. II: [Winkler, 2017]

- Both parametrizations provide a good fit to the available data
- The results are compatible within uncertainties
- MC generators like EPOS-LHC and QGSJET (KMO) overpredict $\bar{p}$ at low energies

The secondary antiproton source term

$$q_{pp\to\bar{p}}(T_{\bar{p}}) = \int_0^\infty dT_p 4\pi n_{\mathrm{ISM,p}} \Phi_p(T_p) \frac{d\sigma_{pp\to\bar{p}}}{dT_{\bar{p}}}(T_p, T_{\bar{p}})$$

***pp* channel: prompt production**



[MK, Donato,Di Mauro; 2018]

- The uncertainty of the secondary source term of $\bar{p}$ imposed by cross section is 8% to 15%
- At $T_{\bar{p}} > 5$ GeV the uncertainty is mostly a normalisation while at lower energies also the shape is uncertain

The proton nucleus channels

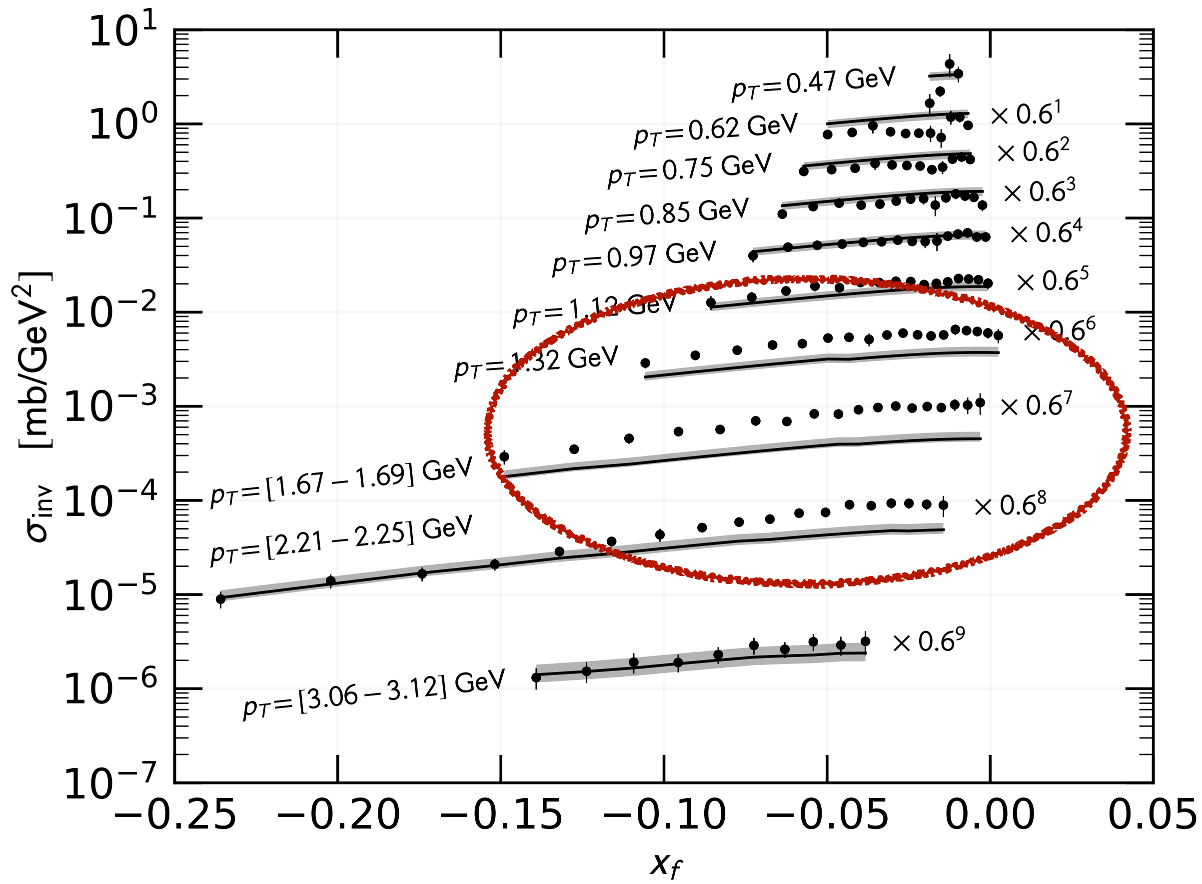
- Data in the proton nucleus channel is scarce and a standalone parametrization is not possible
- We assume that *p*A channels are proportional to *pp*
- We allow for an x_f dependence to incorporate forward-backward asymmetry

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

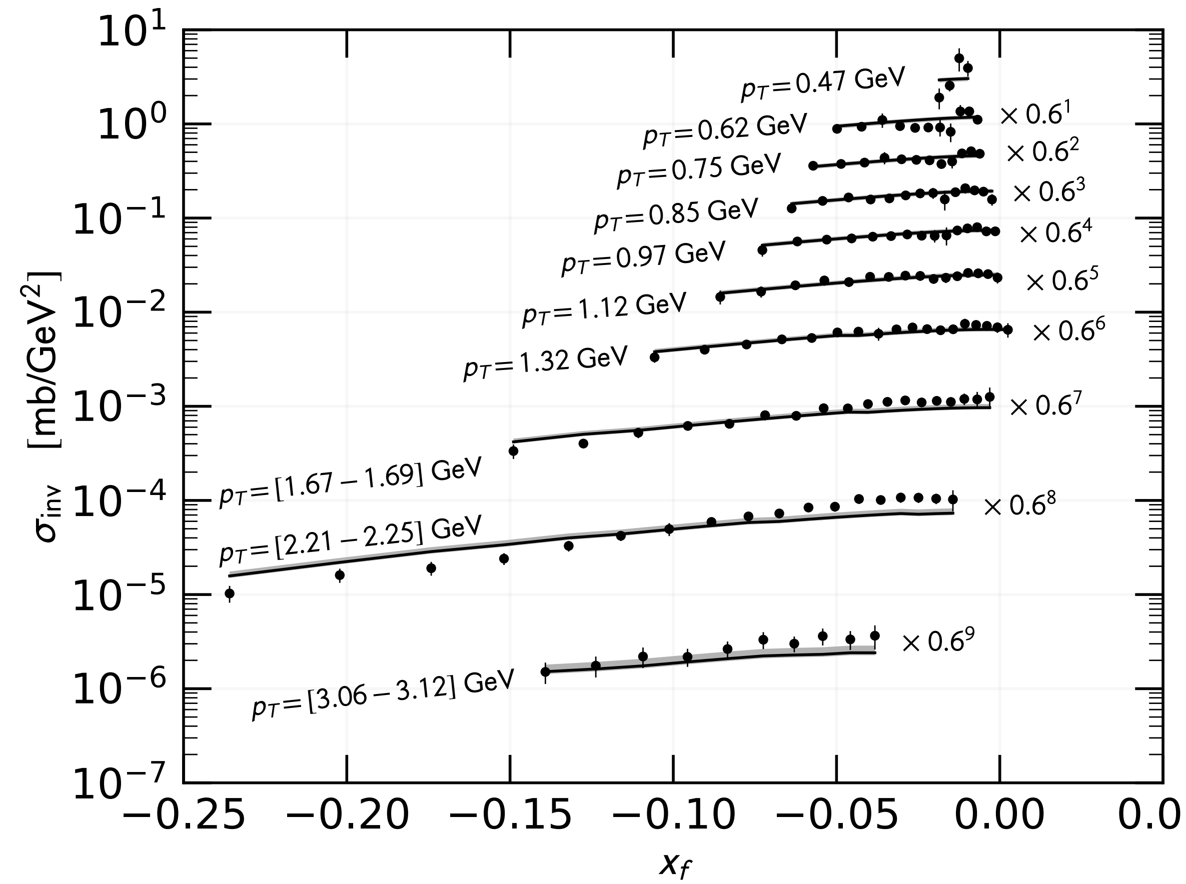
$$f^{pA}(A, x_f) = A^{D_1}\left[A^{D_2}\left(1 + \frac{N}{A}\Delta_{\rm IS}\right)F_{\rm tar}(x_f) + F_{\rm pro}(x_f)\right]$$

The impact of LCHb data

Param. I: [Di Mauro+, 2014]



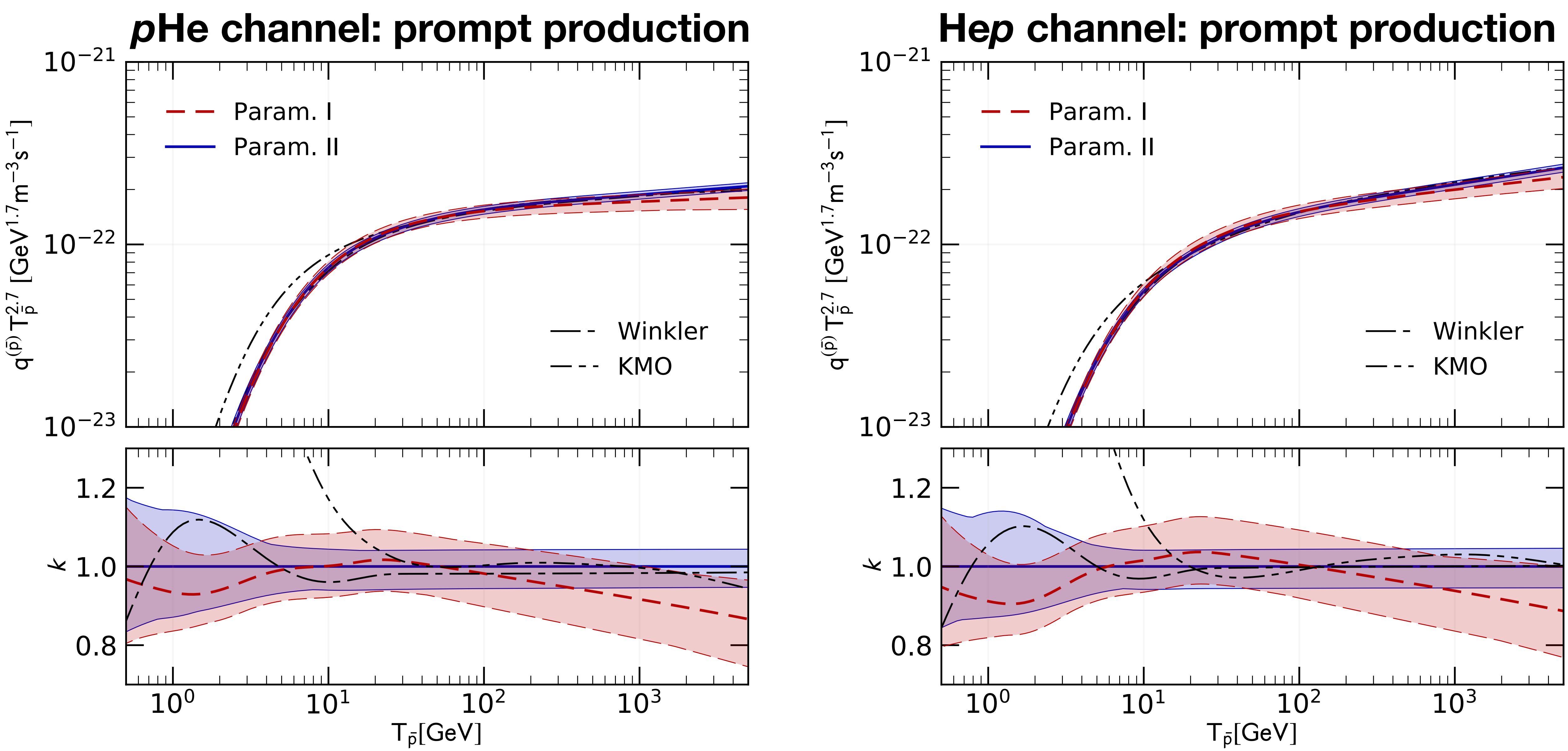
Param. II: [Winkler, 2017]



[MK, Donato,Di Mauro; 2018]

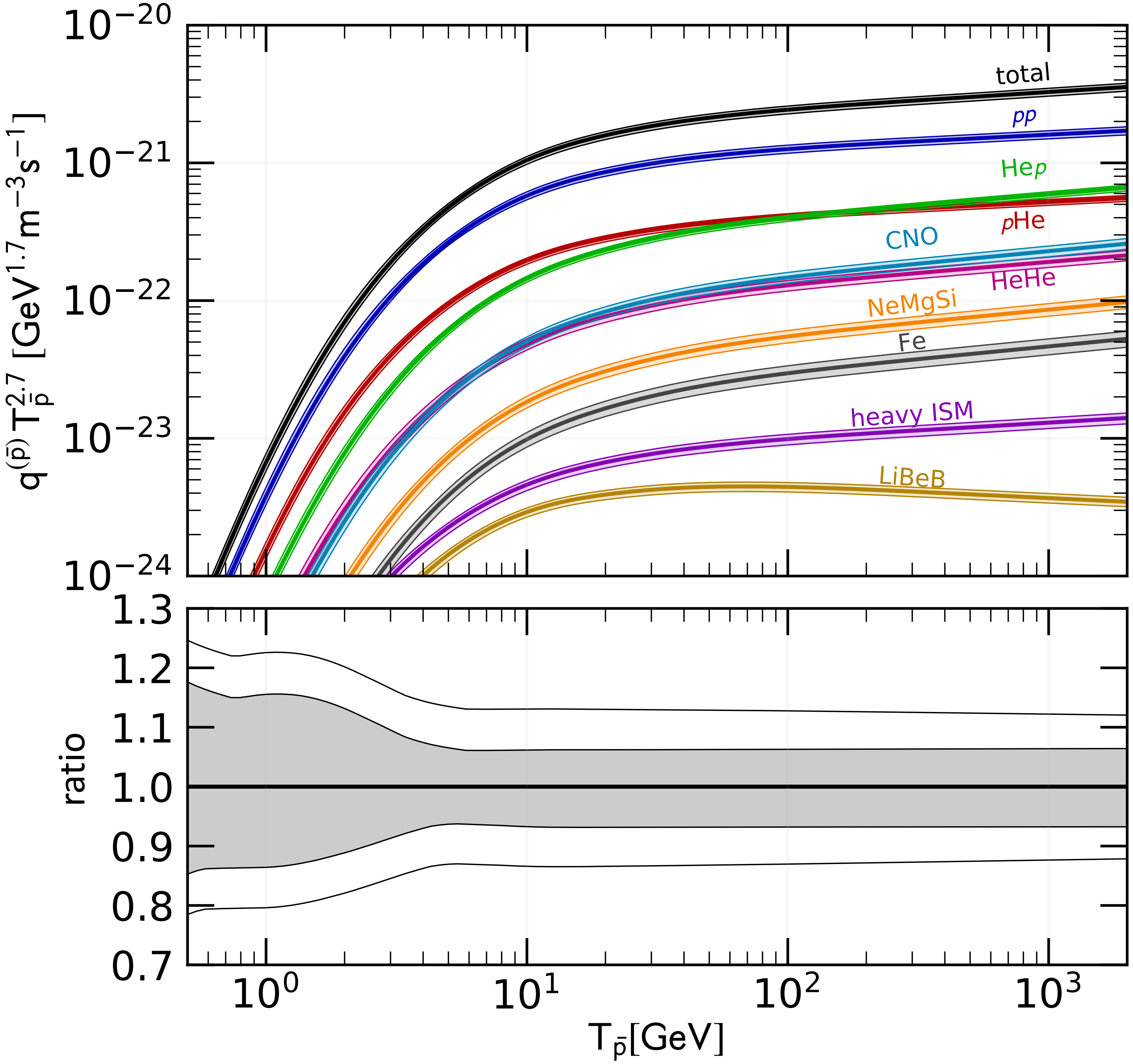
Param. II provides a much better fit to the LHCb data.

Source terms in the proton nucleus channels



[MK, Donato,Di Mauro; 2018]

Total secondary antiproton source term



[MK, Donato,Di Mauro; 2018]

Cross section uncertainties are up to 20% at low energies.

Isospin and hyperons

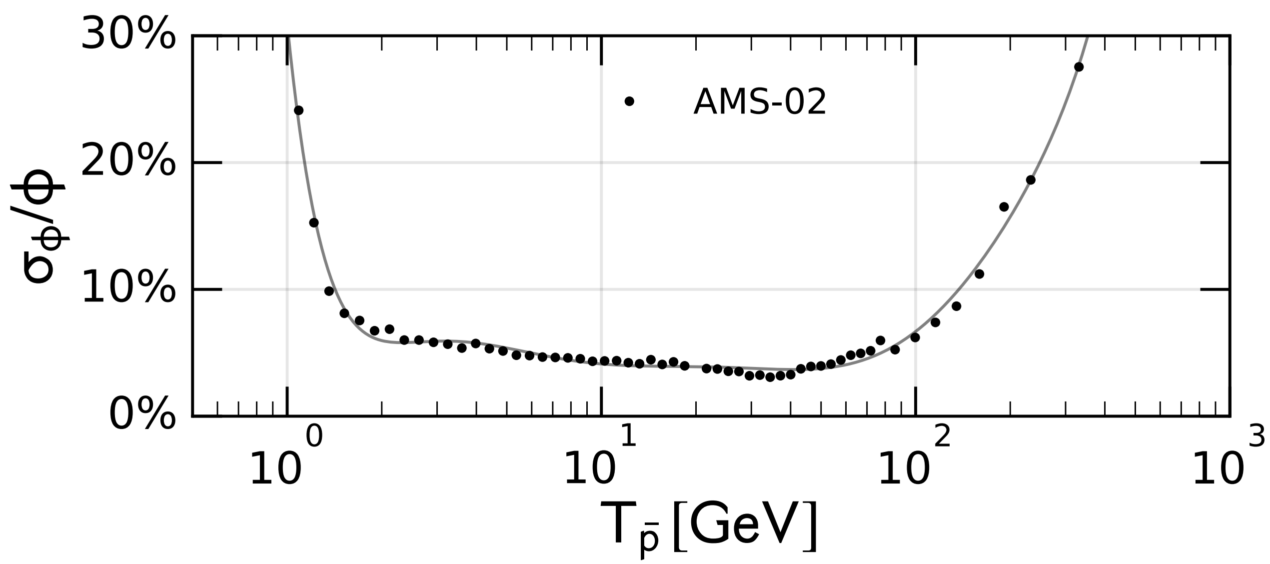
Prompt antiprotons

Part II

Requirements for future cross section measurements

Precision of AMS-02 flux measurements

Relative uncertainty of the AMS-02 antiproton flux



What is the required parameter space and precision for cross section measurements?

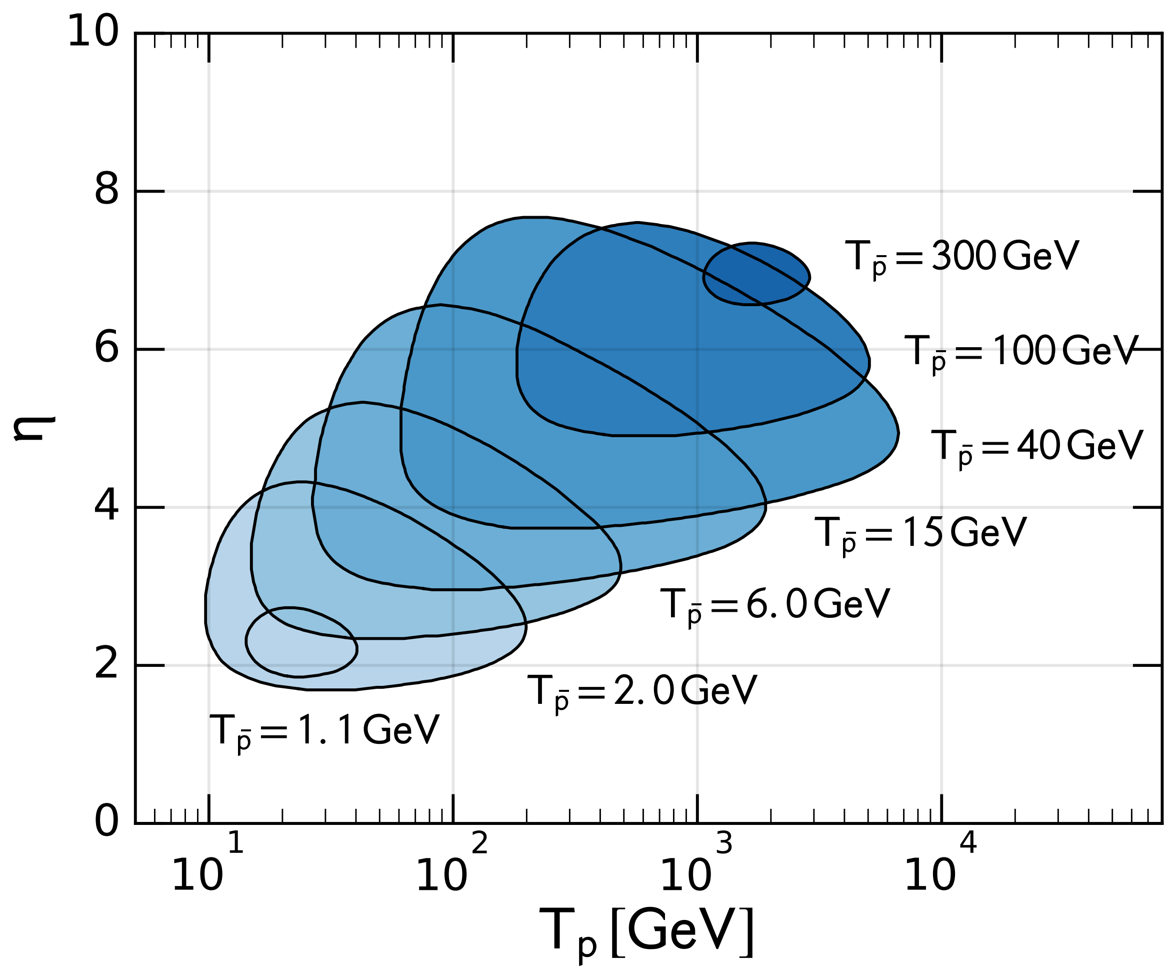
Our guiding principles:

- The uncertainty of cross section in the prediction of the antiproton flux shall match (not exceed) AMS-02 accuracy
- Cross sections have to be measured more precisely where their contribution to the source term is large

Guidance for future XS measurements

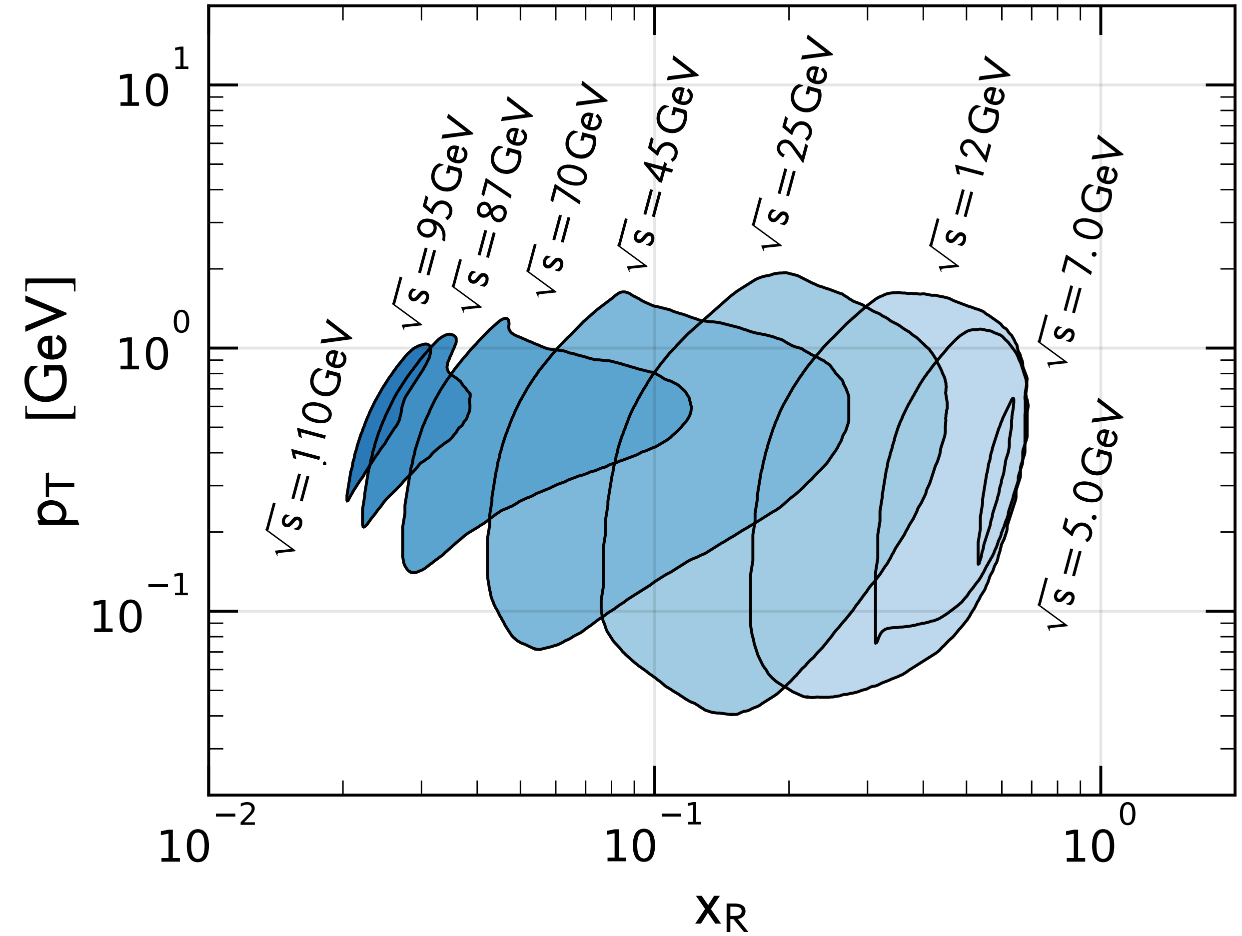
Fix target experiment

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



Collider experiment

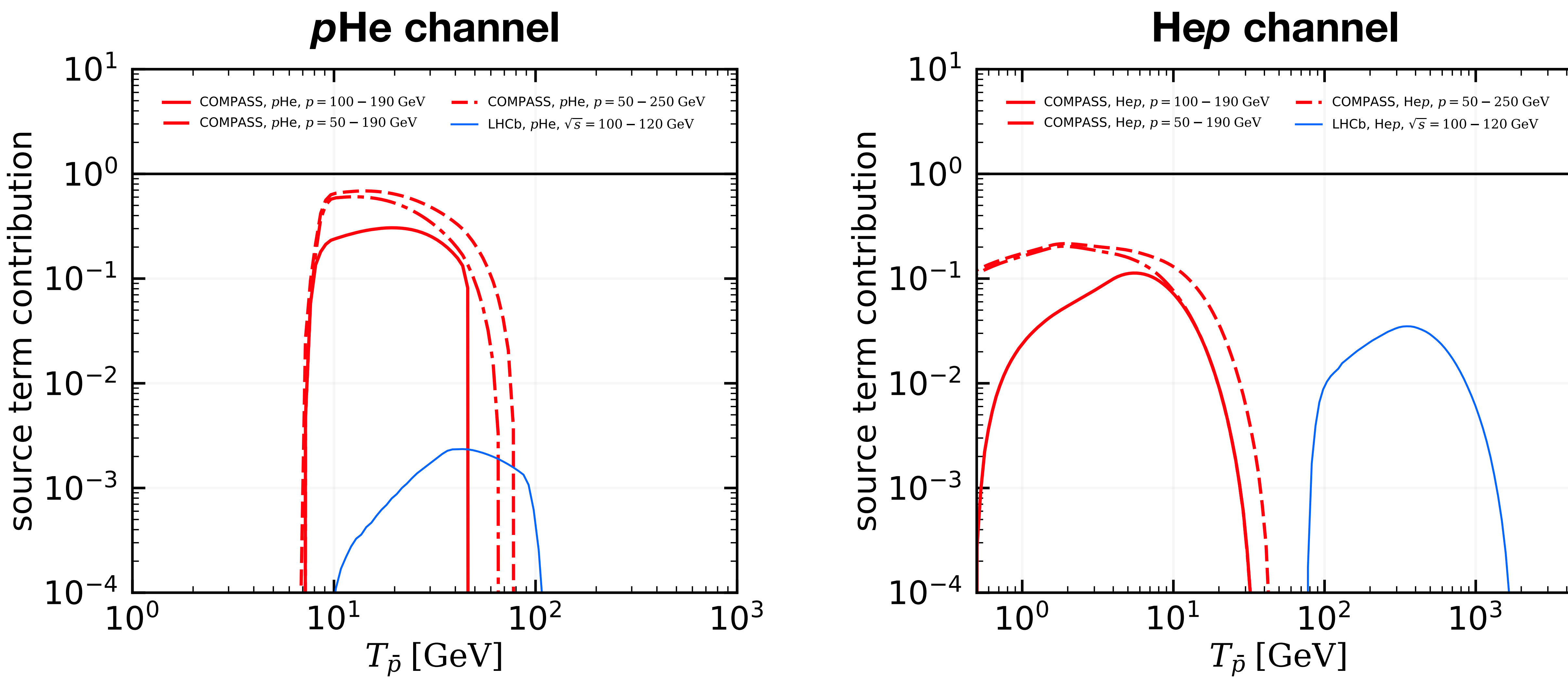
$$\left(E\frac{d^3\sigma}{dp^3}\right)\left(\sqrt{s}, x_R, p_T\right)$$



[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.

Prospects of COMPASS++/AMBER



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

→ Talk by Paolo on Friday

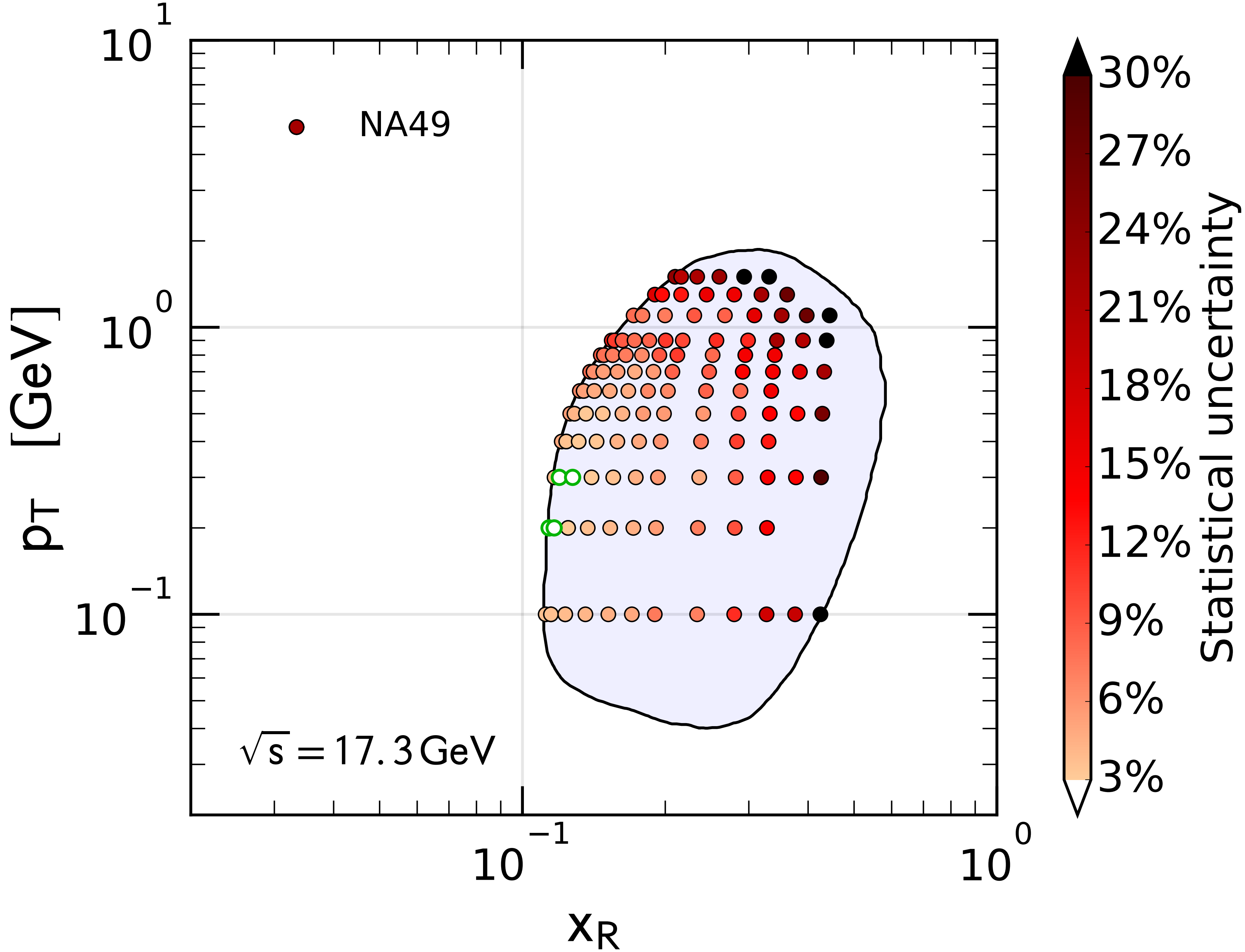
Conclusion

- 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 12% and 20%
- Future cross section measurements can improve our understanding of antiproton production in cosmic rays

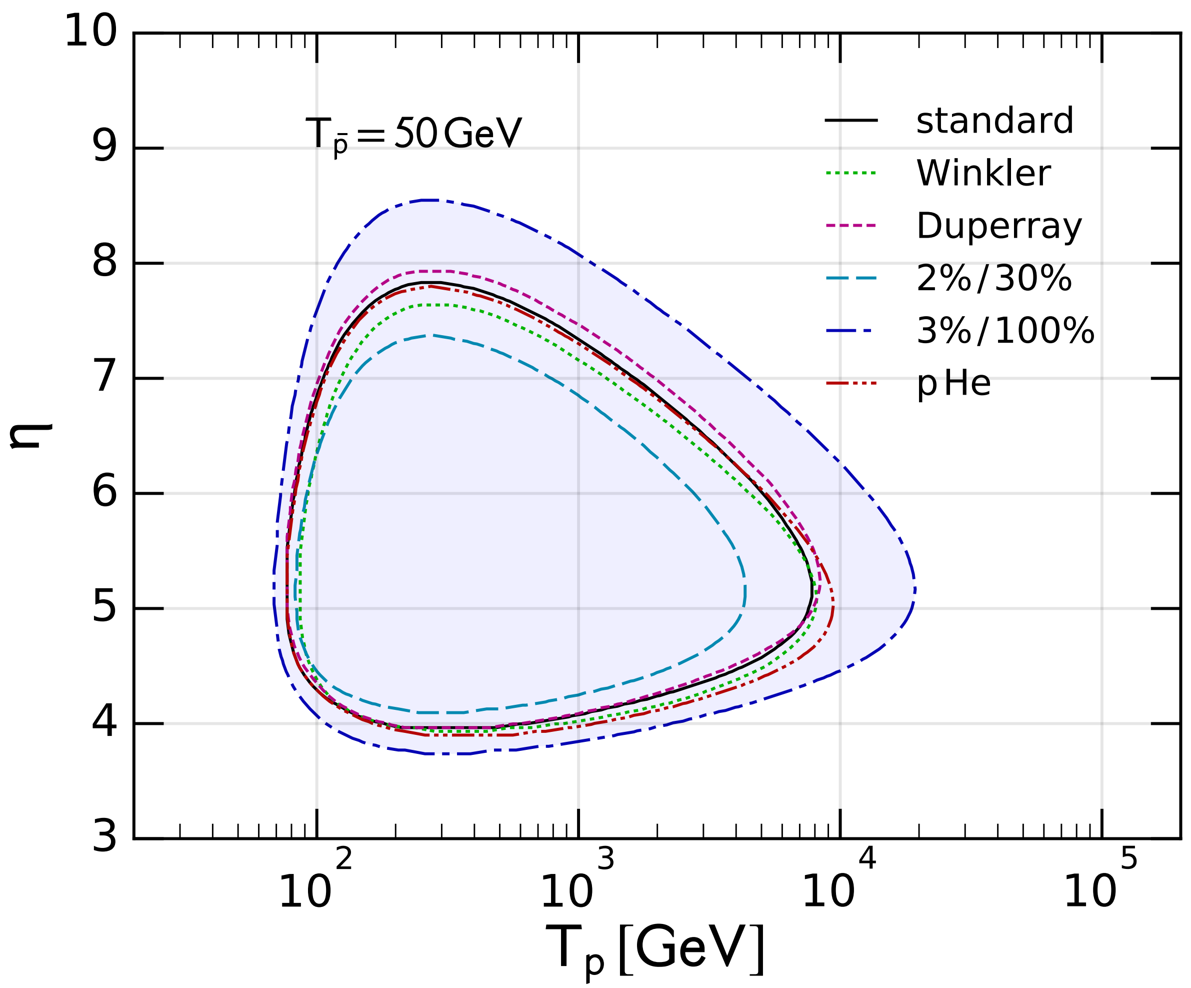
Thank you for your attention!

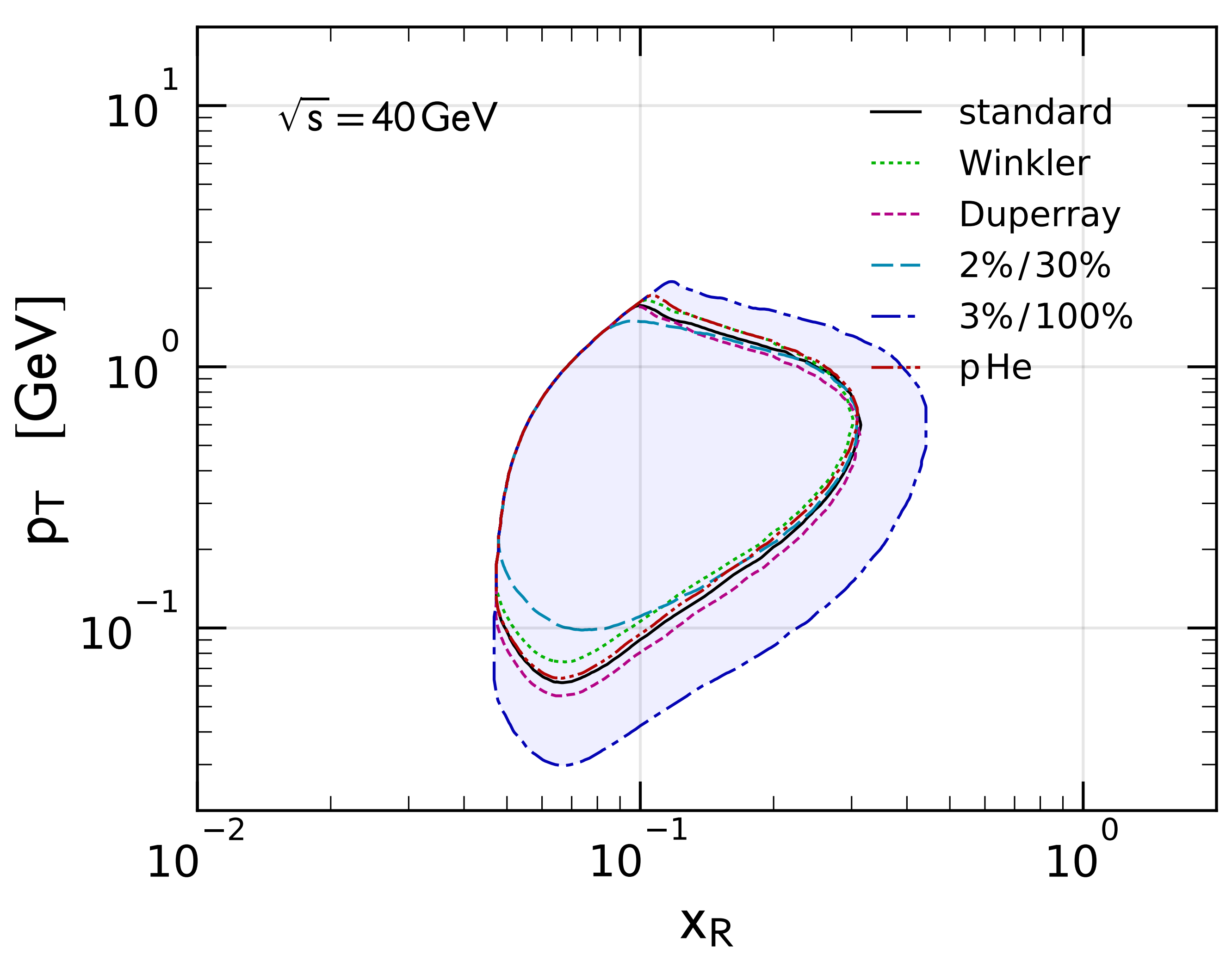
Backup

Precision of current XS measurements



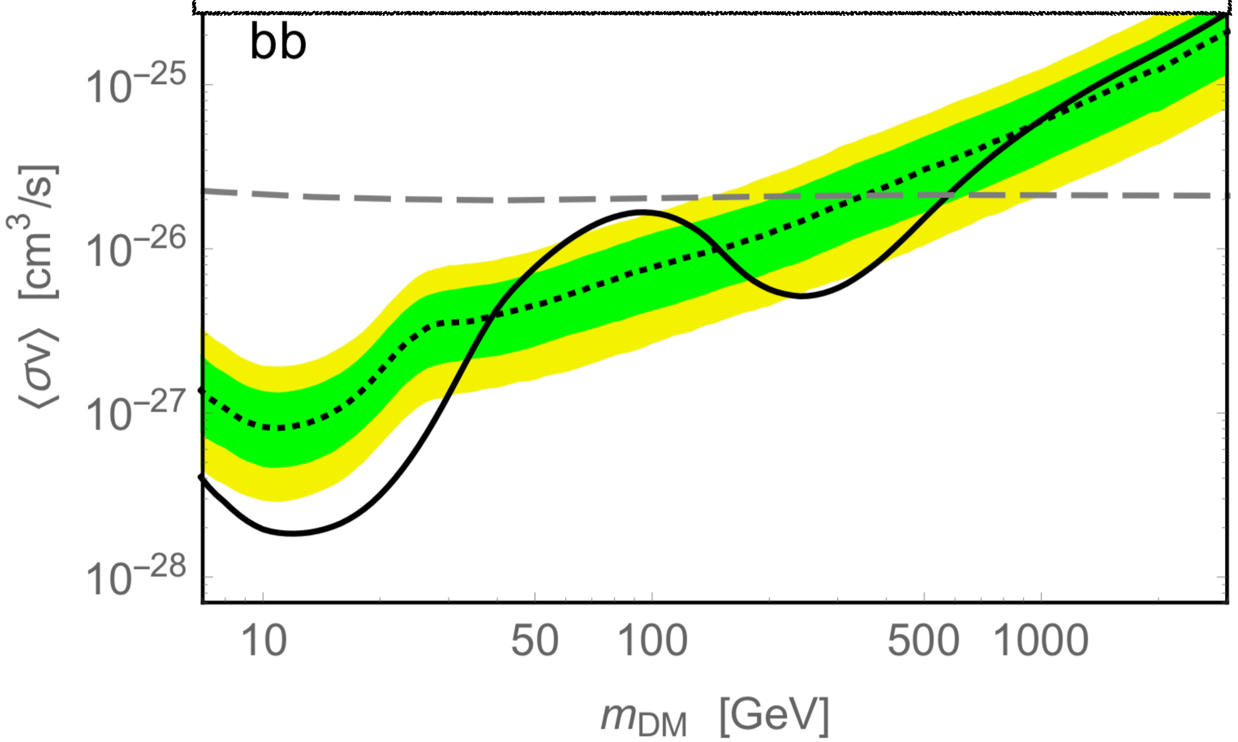
Guidance for future XS measurements





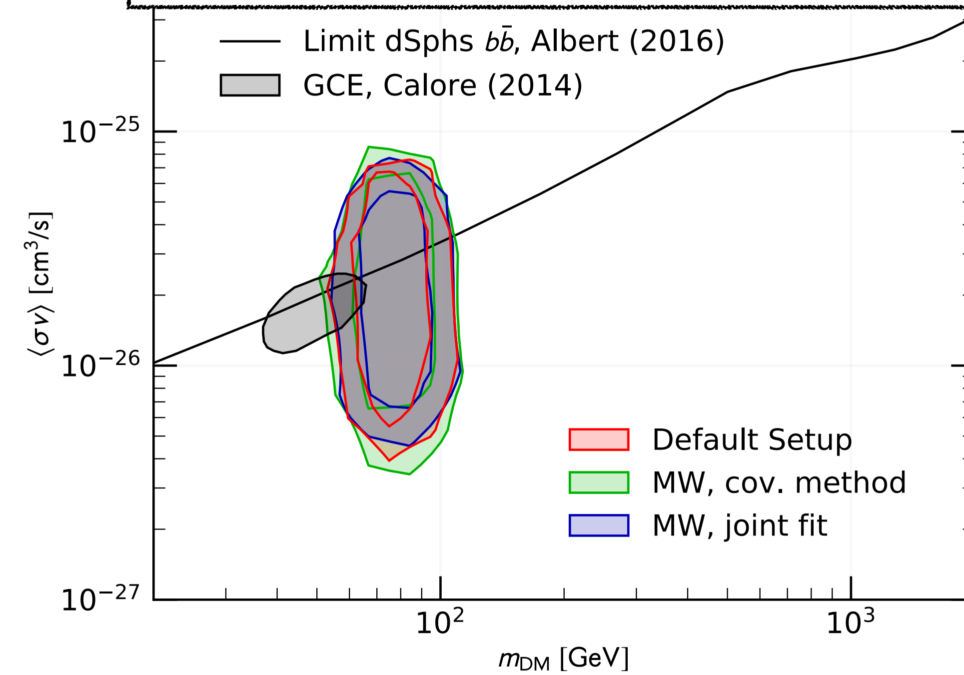
Precision analyses with CR antiprotons

1.1σ excess is not significant



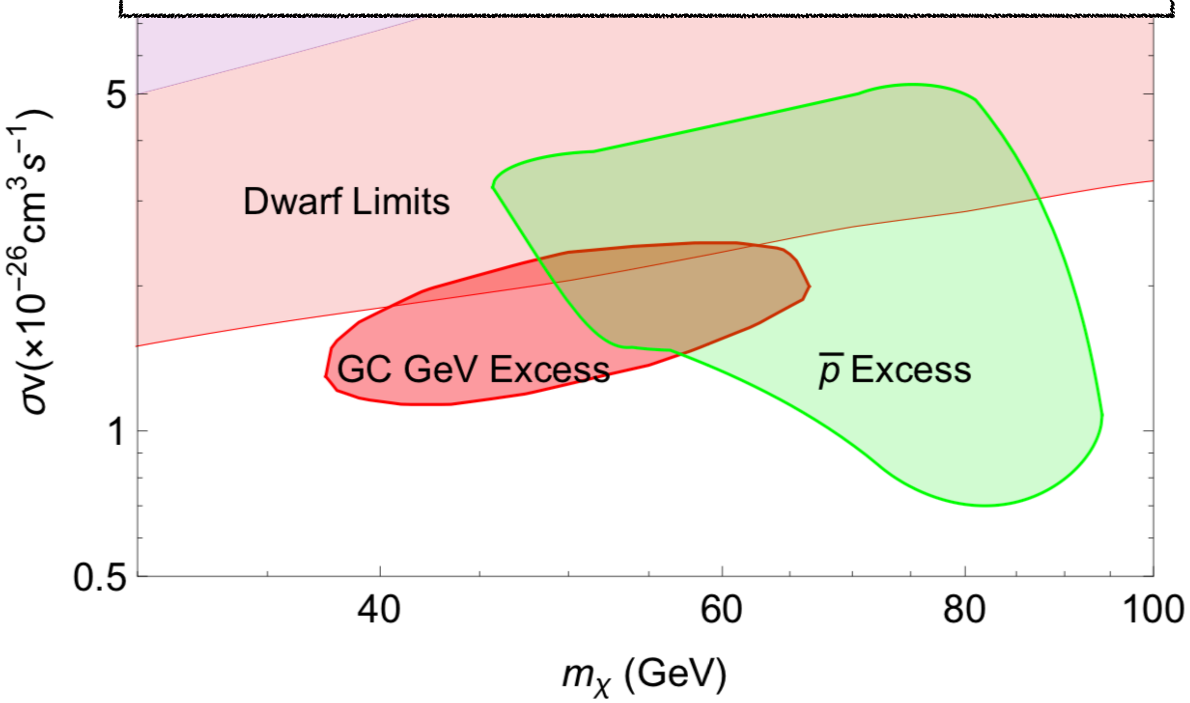
[Reinert, Winkler; 2018]

Significance at 2.9σ



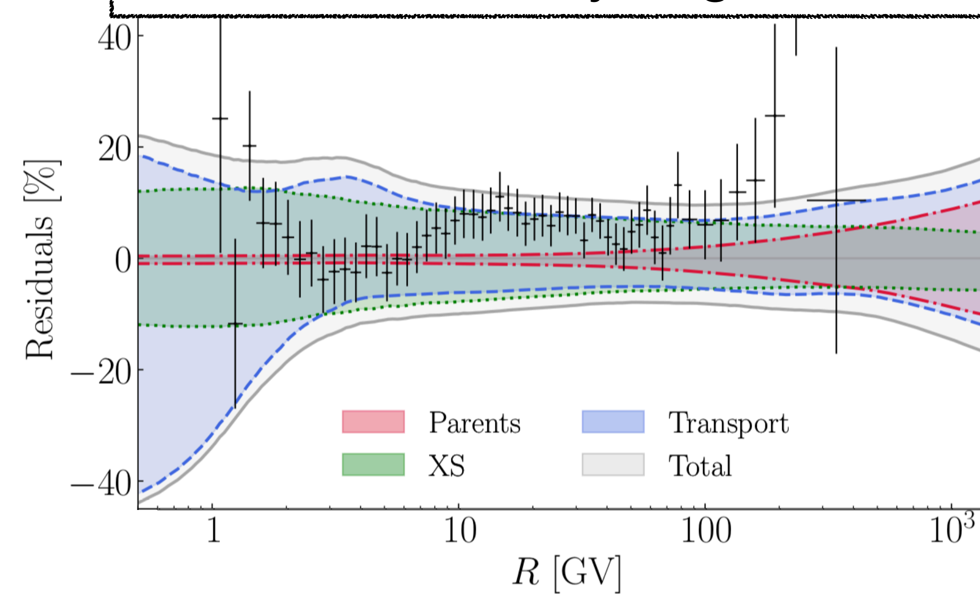
[Cuoco, MK, +; 2019]

3.3σ to 4.7σ: robust excess



[Cholis, Linden, Hooper; 2019]

Antiprotons are consistent with secondary origin



[Boudaud, Genolini, +; 2019]

→ Talk by Mathieu