picture: Wikipedia

Cross sections for cosmic-ray antiprotons

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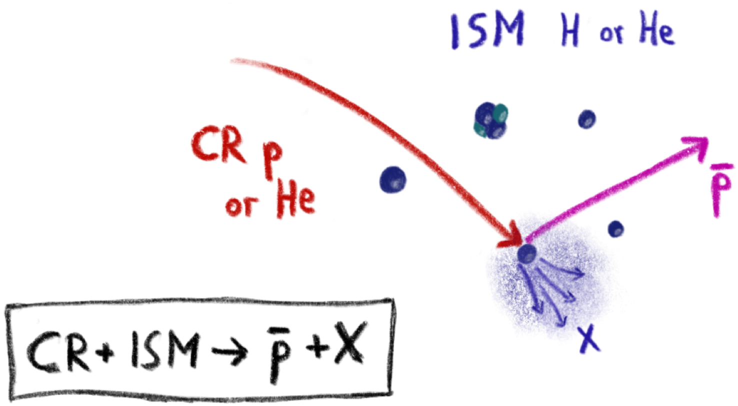
Outline

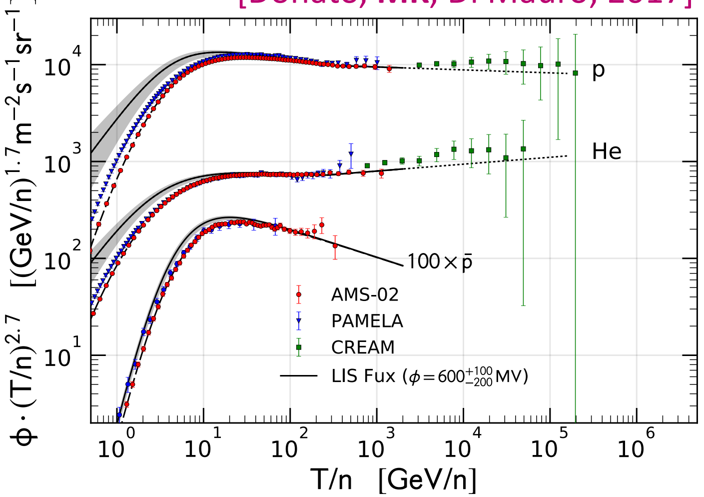
- Introduction to cosmic rays
- Cosmic-ray propagation
- Cosmic-ray antiprotons
- Antiproton production
- Conclusion



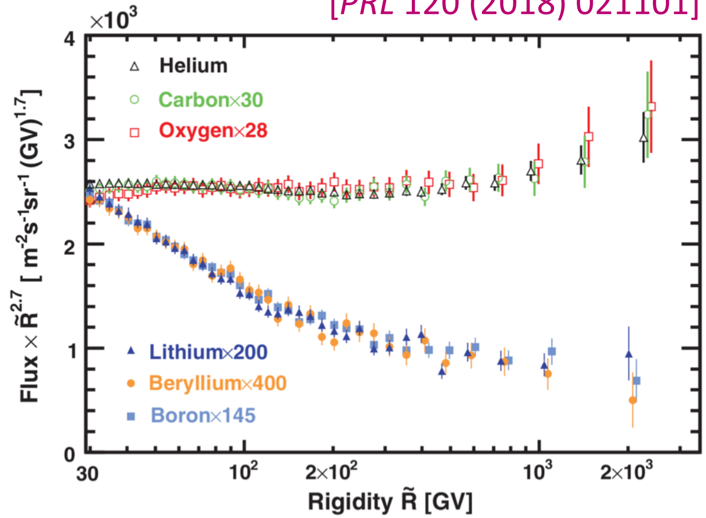
Cosmic rays in the precision era

- Space-based experiments PAMELA and AMS-02 determine cosmic-ray spectra with increasing precision
- Interpretation of the CR data requires understanding of:
  - Production
  - Propagation in the Galaxy
  - Solar effects
- AMS-02 measures the antiproton flux at about 5% precision between 1 and 400 GeV

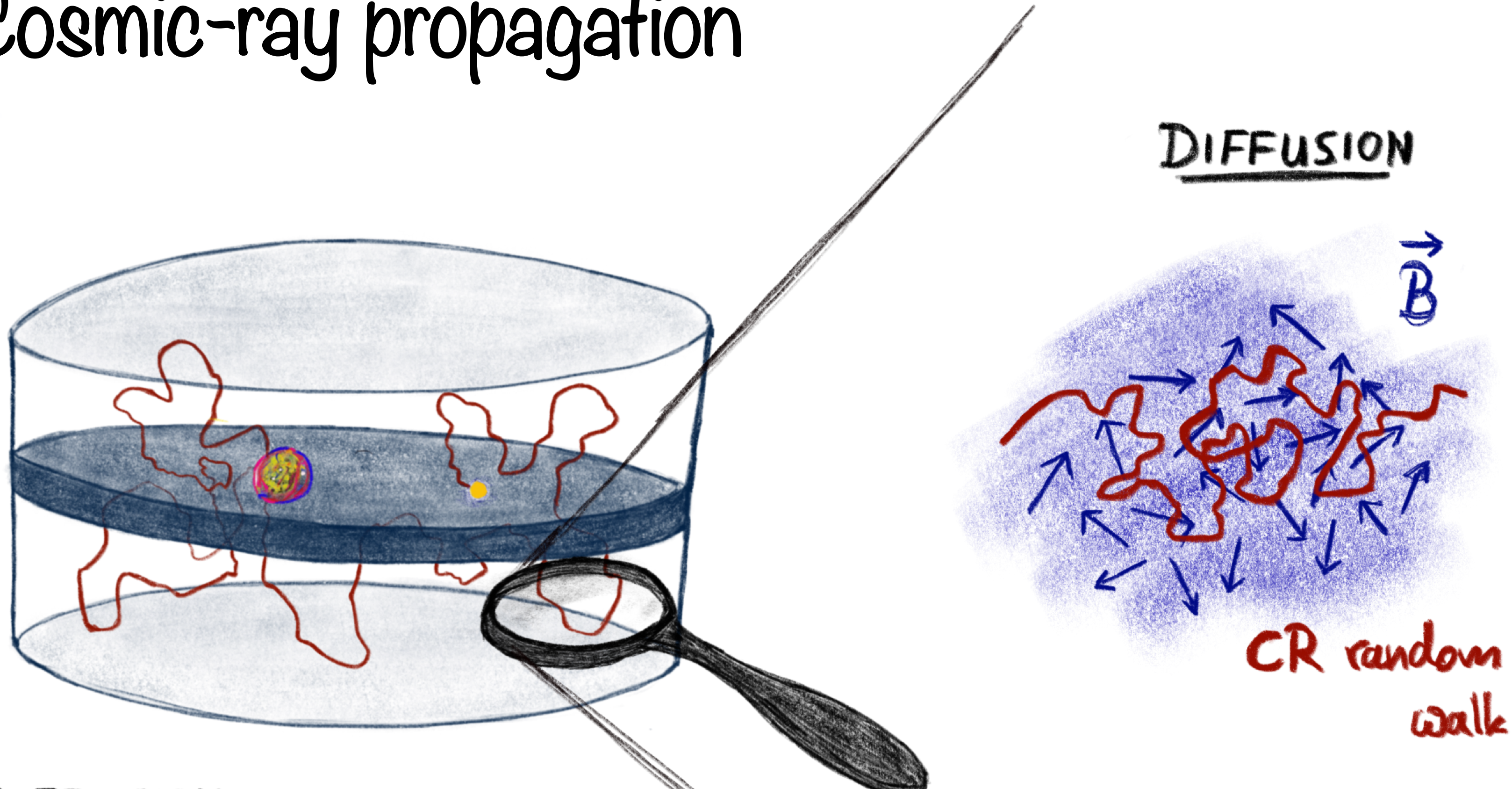
[Donato, **MK**, Di Mauro; 2017]



[*PRL* 120 (2018) 021101]



Cosmic-ray propagation



DIFFUSION

$$\vec{j} = -D\vec{\nabla}\phi$$

$$\partial_t \phi = -\vec{\nabla}\cdot\vec{j}$$

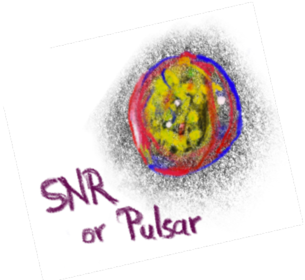
$$\boxed{\partial_t \phi = +\vec{\nabla}\cdot D\vec{\nabla}\phi}$$

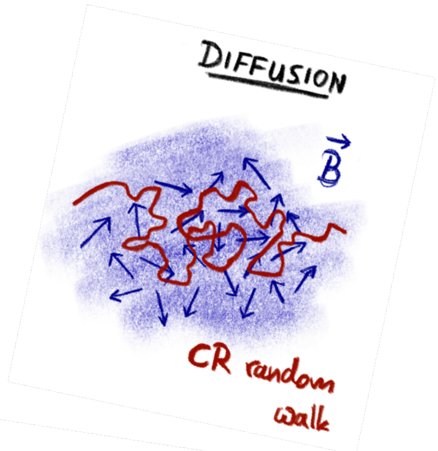
Cosmic-ray propagation

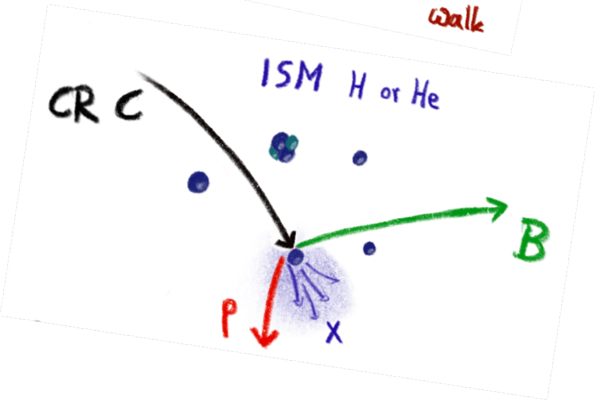
- Charged particles in our Galaxy described by a diffusion equation:

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

- AMS-02 measures fluxes from 1 GeV to a few TeV
- Primaries (p, He, CNO, …) produced and accelerated in astrophysical sites
- Secondaries (Li, B, $\overline{\mathrm{p}}$, …) constrain propagation
- Antiprotons might give rise to DM







Constrain CR propagation

- Secondary-to-primary ratios constrain propagation since secondaries “undergo propagation twice”
- Standard rulers: B/C and $^{9}Be/^{10}Be$

  [Donato, Fornengo, Maurin, Slati; 2004]

  [Putze, Derome, Maurin; 2010]

  [Kappel, Reinert, Winkler; 2014]

  [Johannesson, et al.; APJ; 2016]

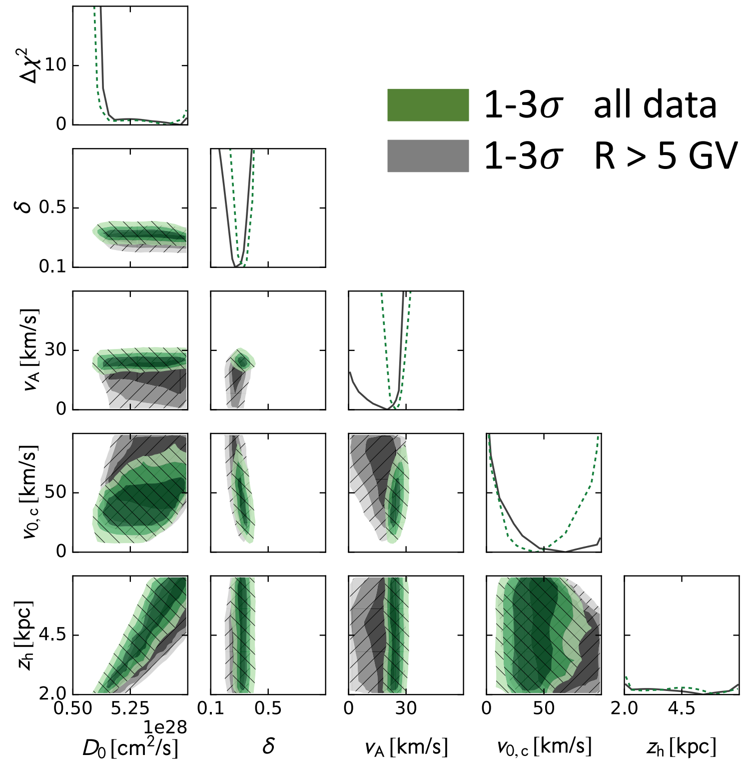
  [Feng, Tomassetti, Oliva; 2016]

  …
- Light nuclei: D and $^{3}He/^{4}He$

  [Coste, Derome, Maurin, Putze; 2010]
- Antiprotons

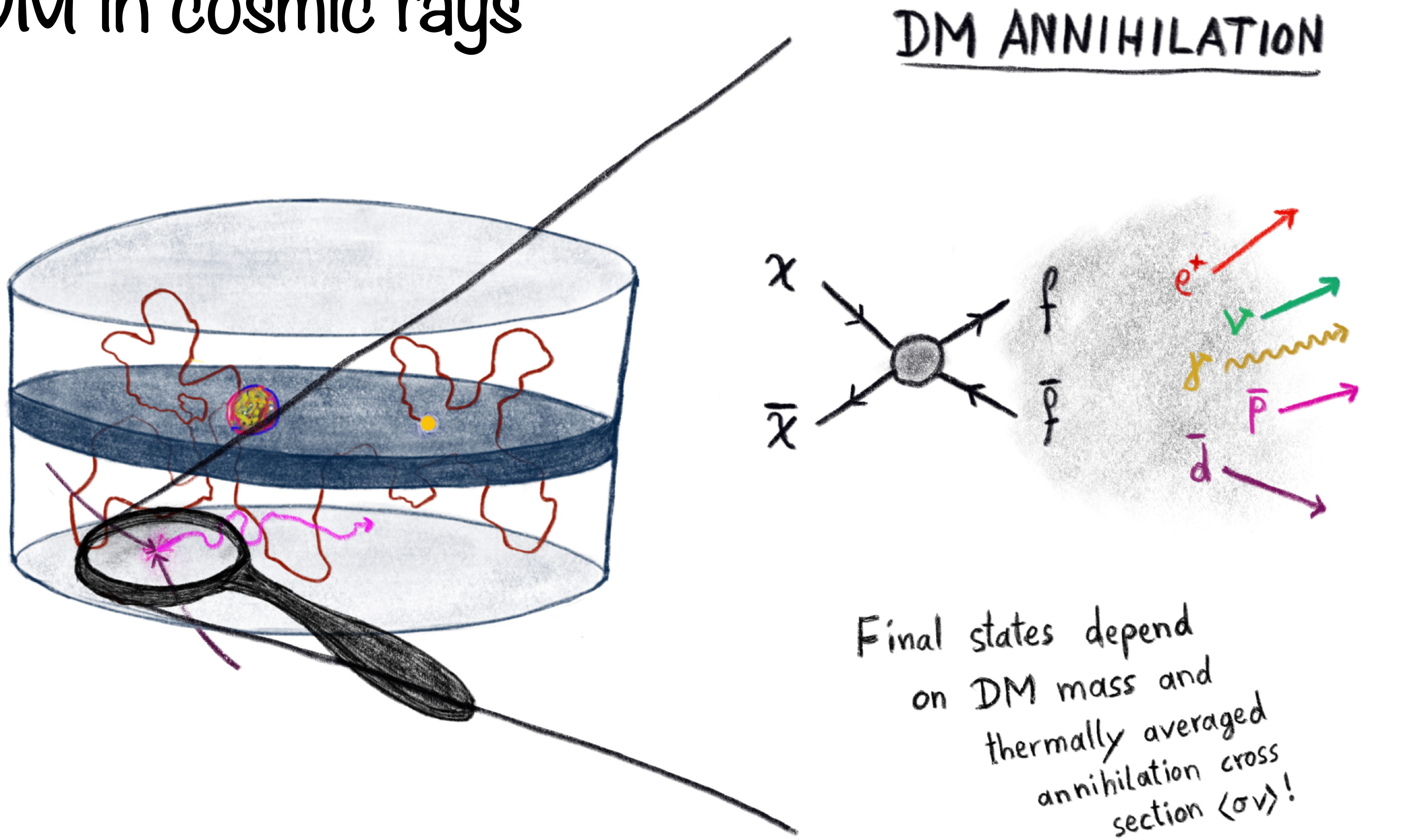
  [Korsmeier, Cuoco; 2016]

Fit to AMS-02 data p, He, $\bar{p}$



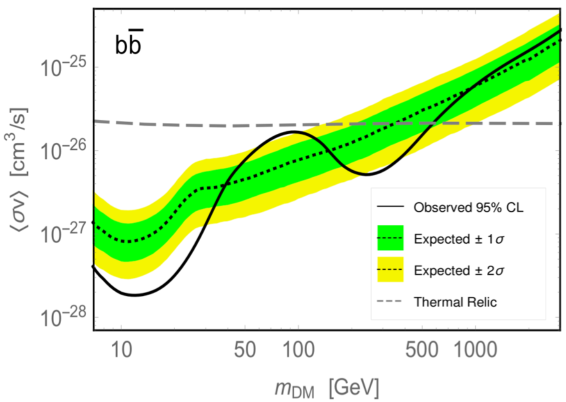
[MK, Cuoco; 2016]

DM in cosmic rays

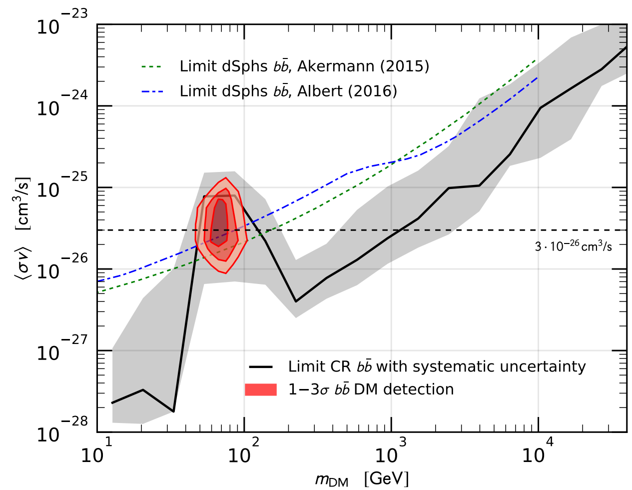


DM and CR antiprotons

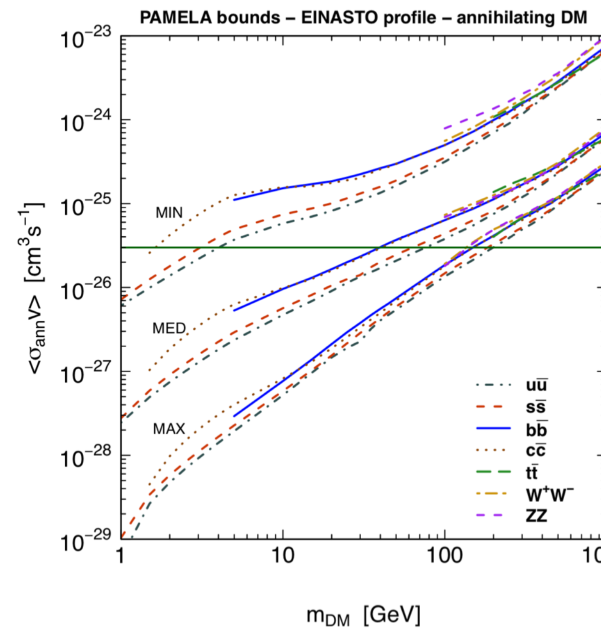
[Reinert, Winkler; 2018]



[Cuoco , Krämer, **MK**; 2017]

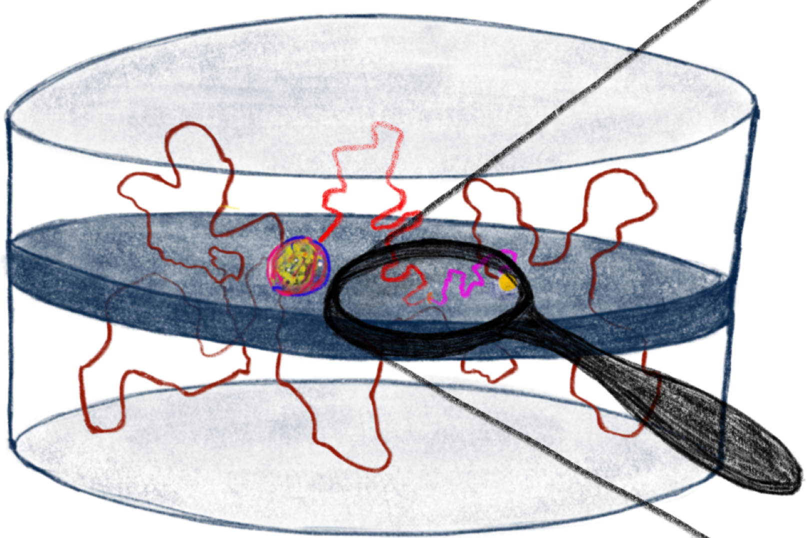


[Fornengo, Maccione, Vittino; 2014]

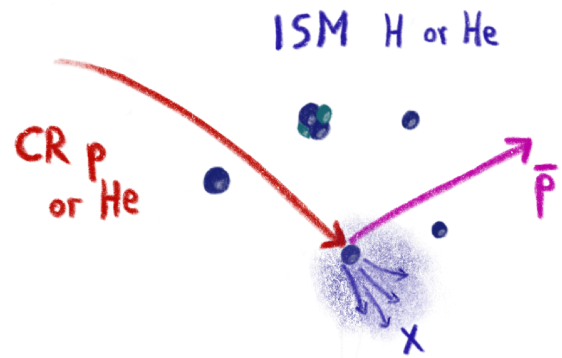


- CR antiprotons constrain WIMP DM parameter space
- Signatures in the antiproton flux might reveal hints for DM
- **But:** the estimation of systematic uncertainties is non-trivial

Cosmic-rays antiprotons



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

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

$$E \frac{d^3\sigma}{dp^3} \sim R(s, x_R) \, (1 - x_R)^{C_1} \, e^{-C_2 p_T} \xrightarrow{\text{Lorentz transformation + angular integration}} \frac{d\sigma(T, T_{\bar{p}})}{dT_{\bar{p}}}$$

- $R(s, x_R)$: scaling violation
- $(1 - x_R)^{C_1}$: Feynman scaling invarianz
- $e^{-C_2 p_T}$: p_T suppression

M. Korsmeier ©

Antiproton production

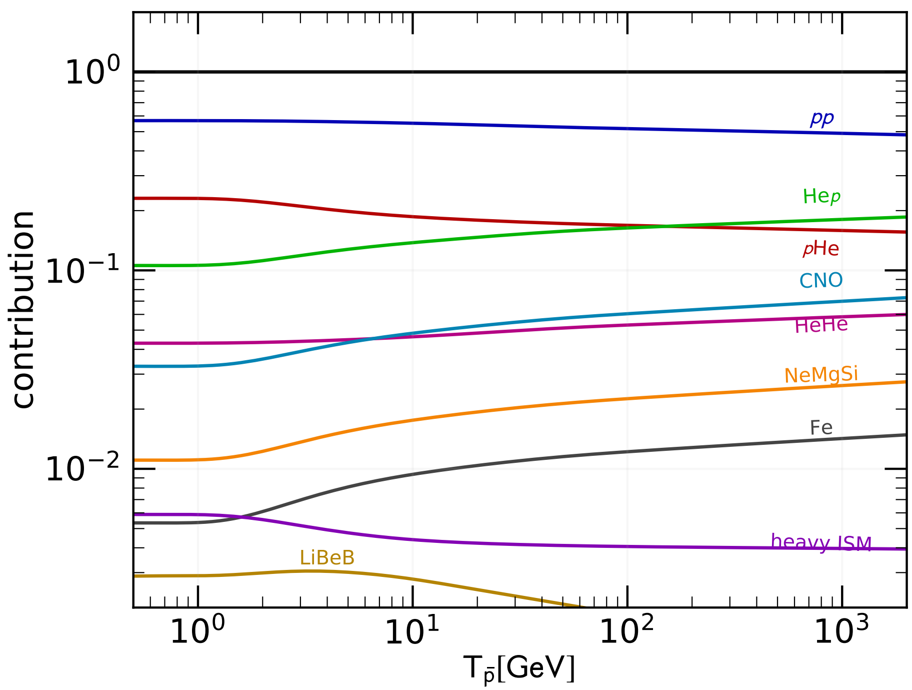
Antiprotons are produced by interaction of CR p and He with the ISM of mostly H and He.

$$\mathrm{CR}_i + \mathrm{ISM}_j \to \bar{p} + X$$

Main production channels:

- *pp* 50%-60%
- *p* He 15%-20%
- He*p* 10%-20%

[**MK**, Donato, Di Mauro; 2018]



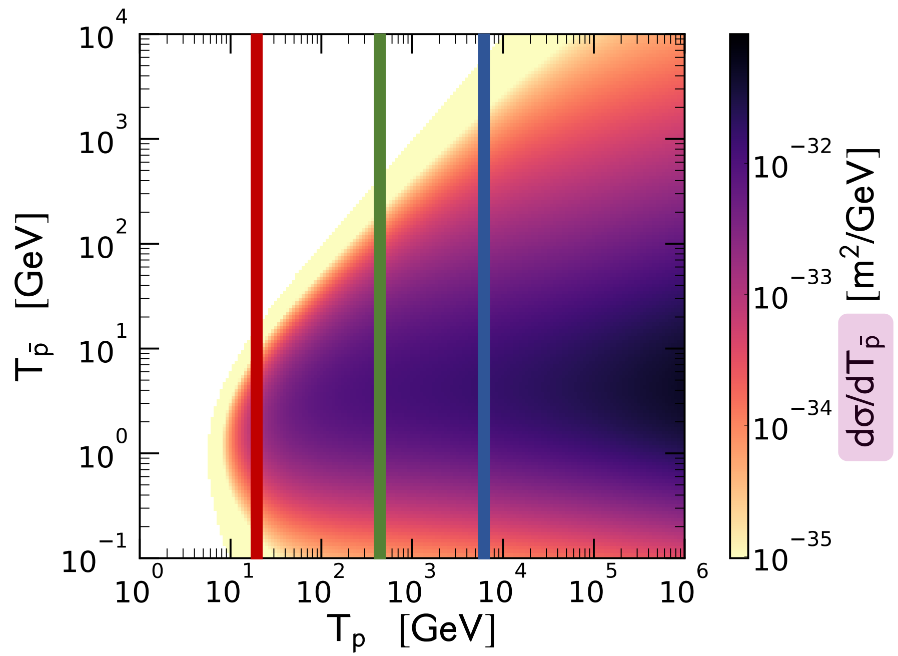
Cross section parametrization

Parameterizations	Channels	Info
[Tan & Ng 1983]	*pp*	parameterization
DTUNUC (1998-2001)	*p*He, He*p*, HeHe	MC (low energy)
[Duperray, et al.; 2003]	*pp*, *p*A	parameterization
[di Mauro, et al.; 2014]	*pp*	parameterization
[Kachelriess, et al.; 2015]	*pp*, *p*A, A*p*, AA	MC (high energy)
[Winkler, et al.; 2014, 2017]	*pp*, *p*He, He*p*, HeHe	parameterization
[Korsmeier, et al. 2018]	***pp*, *p*A, A*p*, AA**	**parameterization**

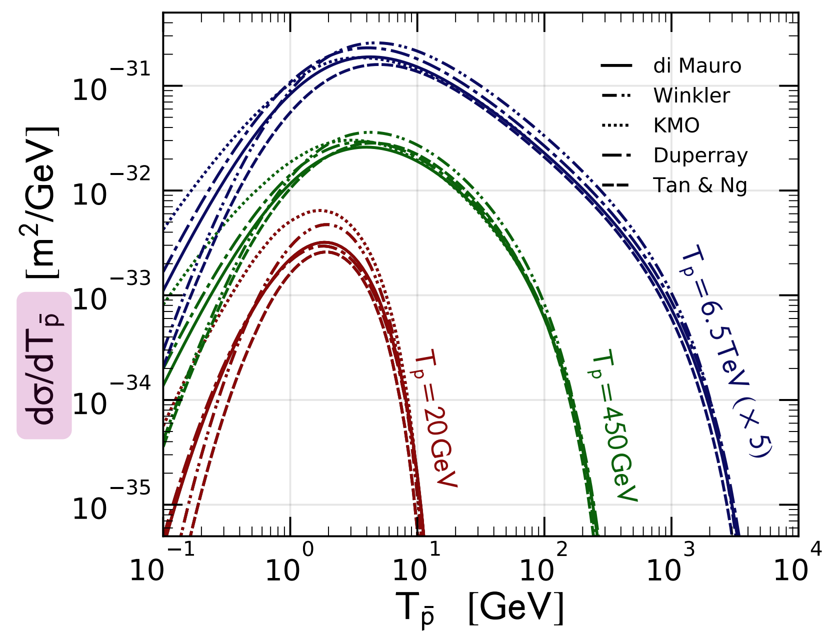
Comparison of cross section parametrizations

$$q_{ij}(T_{\bar{p}}) = \int_0^\infty dT_i \; 4\pi \, n_{\mathrm{ISM},j} \, \phi_i(T_i) \, \frac{d\sigma_{ij}}{dT_{\bar{p}}}(T_i, T_{\bar{p}})$$

***pp* channel**



[Donato, **MK**, Di Mauro; 2017]



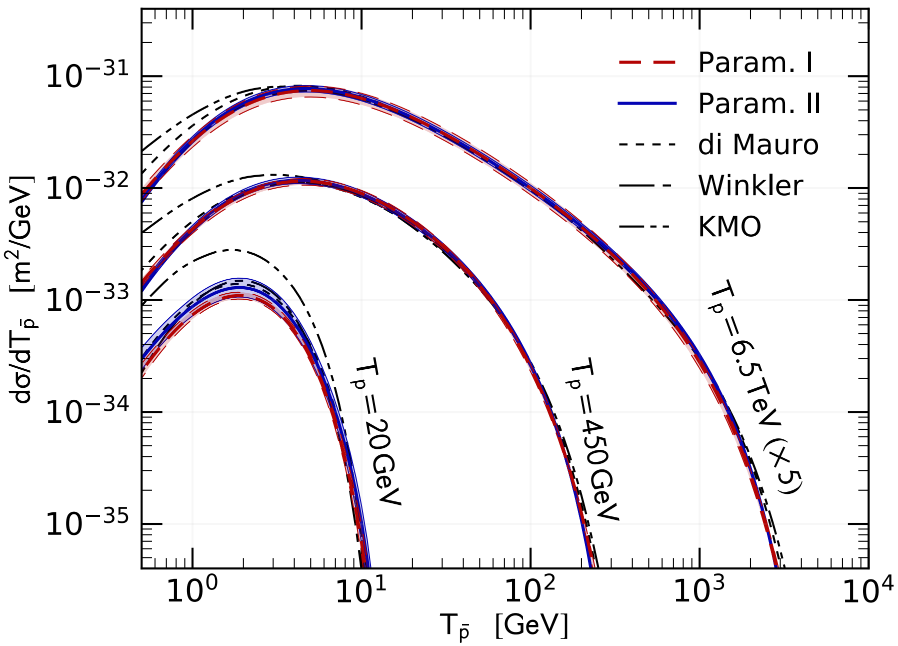
Large discrepancies between different parametrizations!

Fits of cross section parametrizations

- Reevaluation of two parametrizations
  - Param. I [Di Mauro, et al.; 2014]
  - Param. II [Winkler; 2017]

  for *pp* and *pA* collisions
- Focus on cross section data from NA49 and NA61 in the *pp* channel
- Fit of *pA:*
  - Rescaling from *pp*
  - With *p* He data from LHCb **(recent first-ever determination!)** and *p*C data from NA49

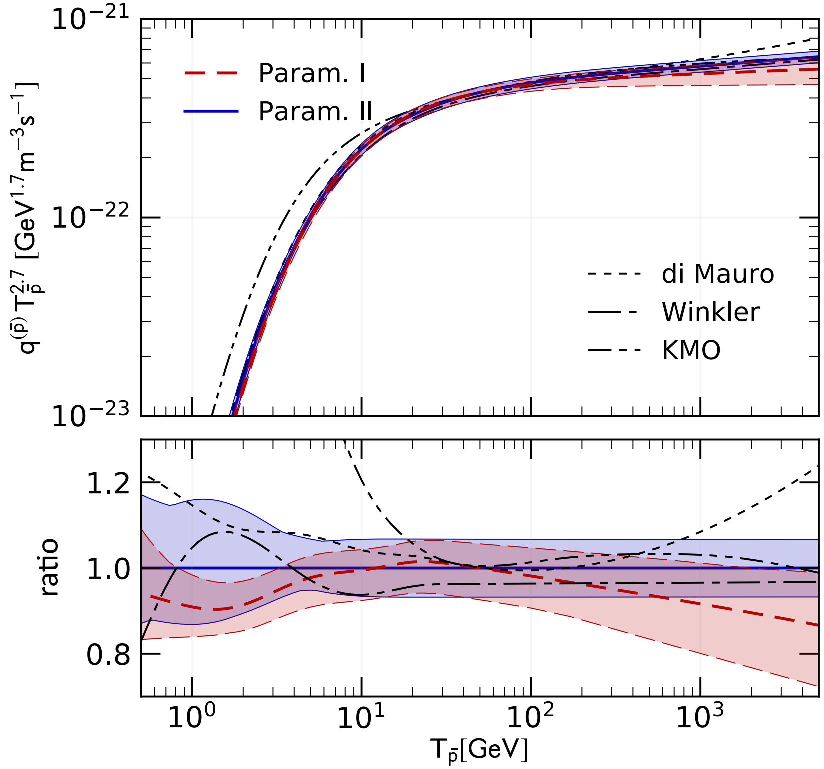
[**MK**, Donato, Di Mauro; 2018]



Comparison at the source term level

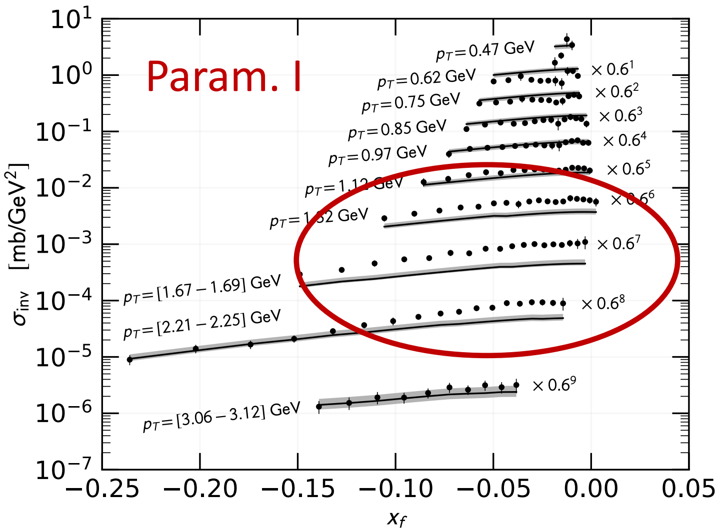
[**MK**, Donato, Di Mauro; 2018]

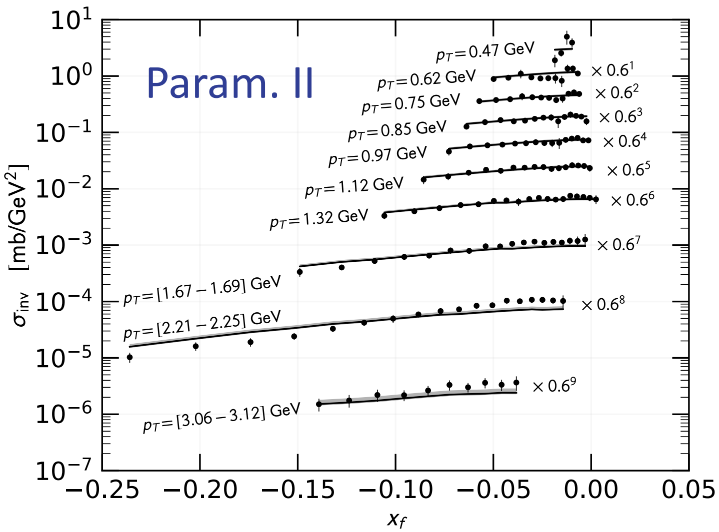
- 8% uncertainty (2σ confidence) increasing to 15% at 1 GV
- Agreement of the two parametrizations and with previous analyses
- Kachelriess, et al. overpredicts antiprotons below 10 GeV



Fitting the proton-nuclei channels

- Data in *pA* channels is scarce
  => No stand-alone parametrization
- Our Ansatz: fit a rescaling of the pp channel
- LHCb provides the first ever measurement of antiproton production from a proton beam at T_p = 6.5 TeV on fix-target helium
- LHCb data gives preference for Param. II at large energies





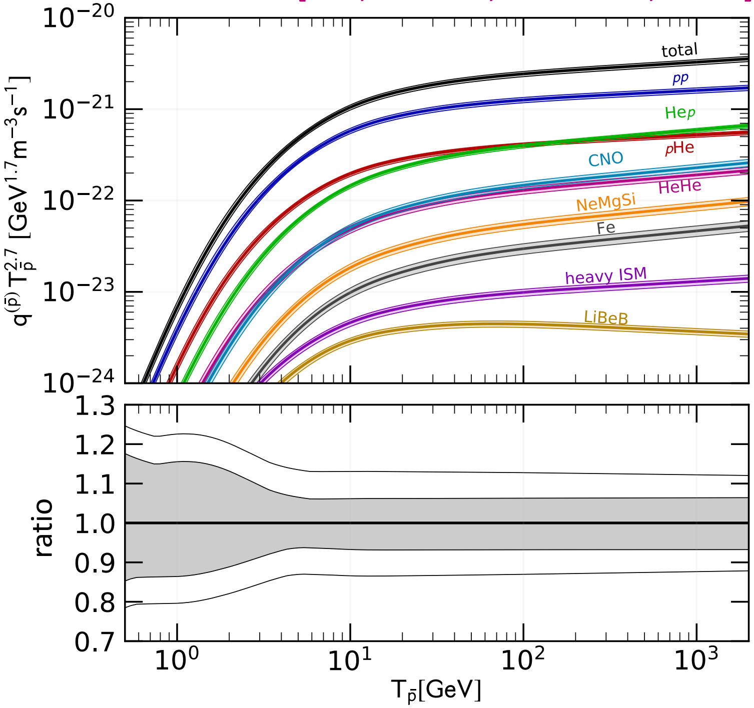
[**MK**, Donato, Di Mauro; 2018]

Total antiproton source term

- Uncertainties from *pp* translate into all channels

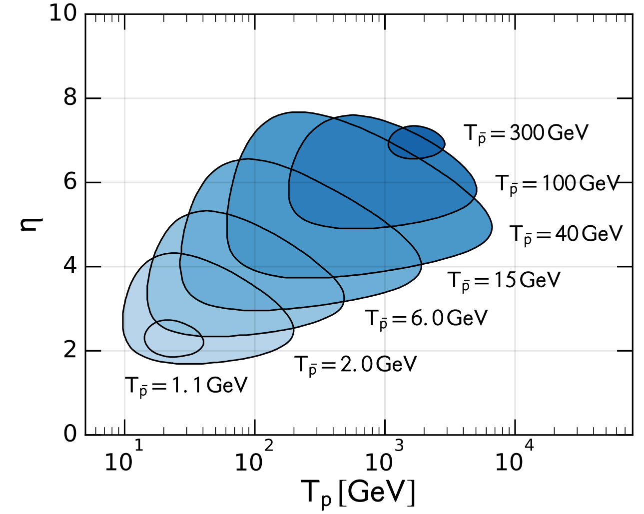
- Antiproton production from antineutron or antihyperon decay adds 5% uncertainty

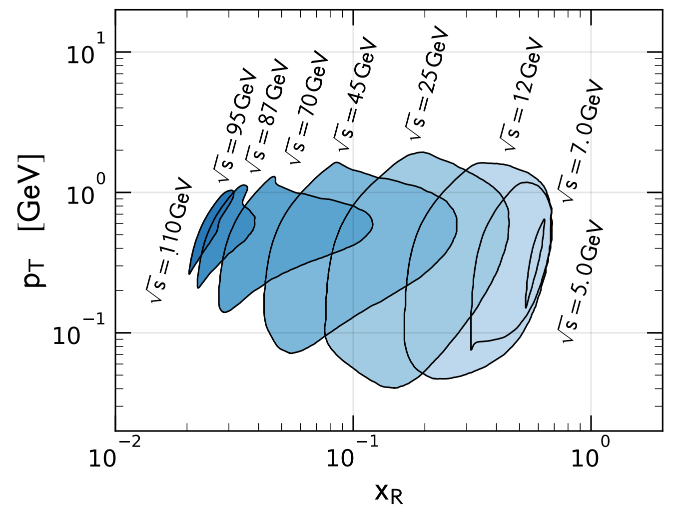
[**MK**, Donato, Di Mauro; 2018]



How to improve cross section uncertainties

[Donato, **MK,** Di Mauro; 2017]



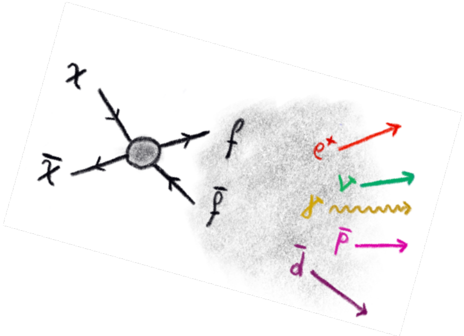


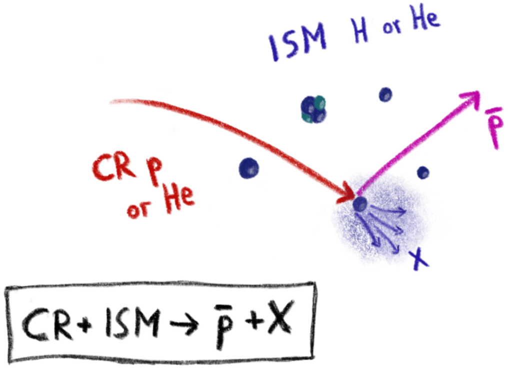
What is the required precision of the antiproton production cross sections to match the accuracy of AMS-02 flux measurements?

- We provide a guideline for future experiments concerning the most relevant kinematic parameter space
- If the cross sections $E\frac{d^3\sigma}{dp^3}(\sqrt{s}, x_\mathrm{R}, p_\mathrm{T})$ are known by 3% inside the blue contours we reach AMS-02 accuracy

Conclusion

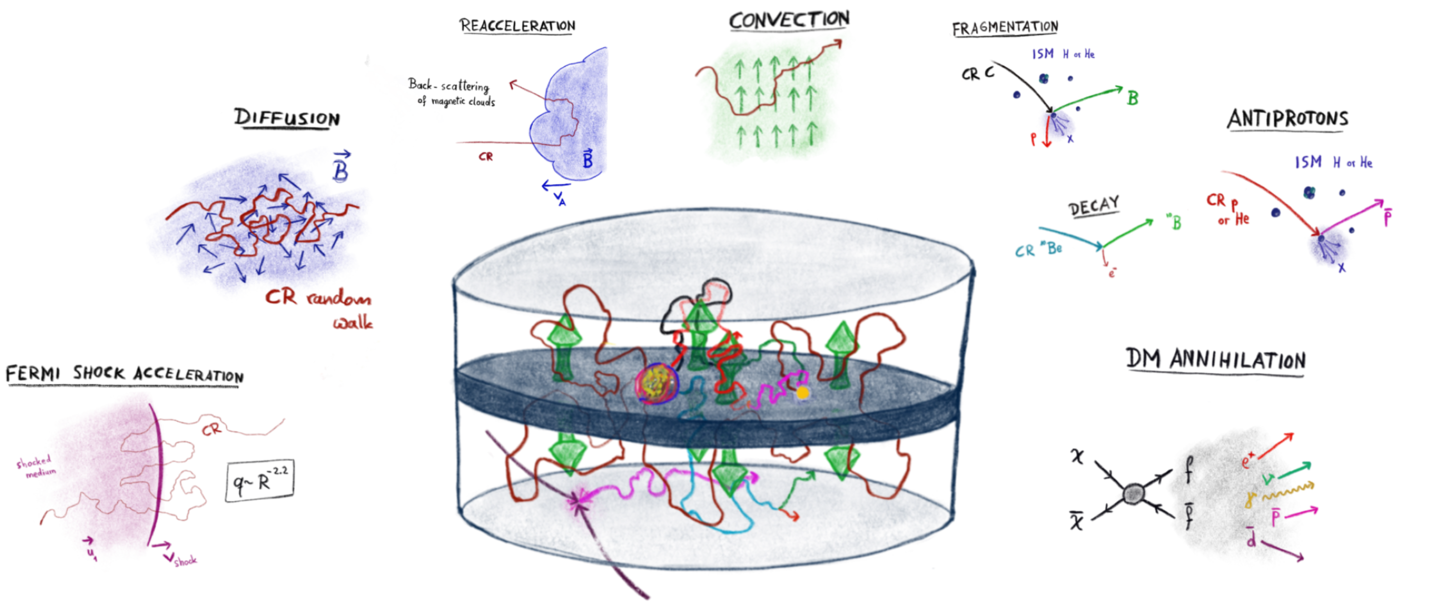
- We provide a description of cross sections and uncertainties for antiproton production in proton-proton and proton-nucleus collisions
- Further efforts are required to reach AMS-02 flux accuracy
- We determine the the most relevant parameter space for future cross section measurements





Thank you for your attention!

Backup



REACCELERATION
Back-scattering of magnetic clouds
CR
CONVECTION
FRAGMENTATION
ISM H or He
CR C
B
DIFFUSION
CR random walk
ANTIPROTONS
DECAY
FERMI SHOCK ACCELERATION
CR
shocked medium
DM ANNIHILATION

XS parametrizations

Parametrization I

$$\sigma_{\rm inv}(\sqrt{s}, x_{\rm R}, p_{\rm T}) = \sigma_{\rm in}(1-x_{\rm R})^{C_1}\exp(-C_2 x_{\rm R}) \times \left[C_3\left(\sqrt{s}\right)^{C4}\exp(-C_5 p_{\rm T}) + C_6\left(\sqrt{s}\right)^{C7}\exp\left(-C_8 p_{\rm T}^2\right)\right]$$

Parametrization II

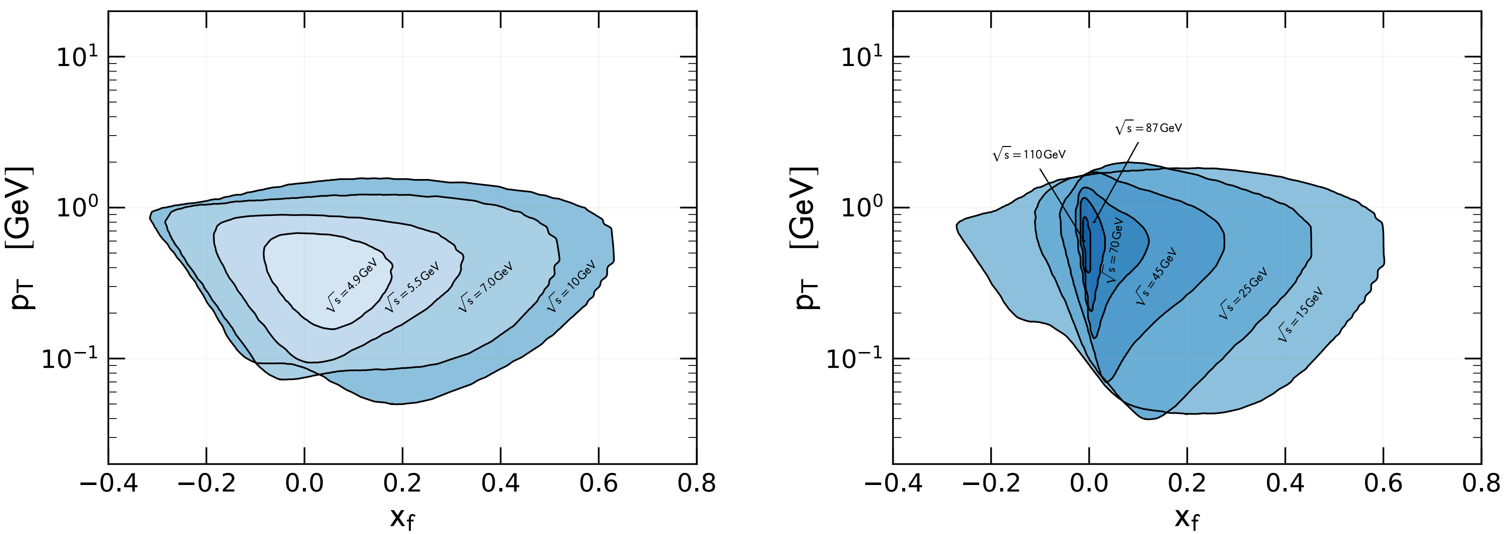
$$\sigma_{\rm inv}(\sqrt{s}, x_{\rm R}, p_{\rm T}) = \sigma_{\rm in} R\, C_1 (1-x_{\rm R})^{C_2} \times \left[1 + \frac{X}{\rm GeV}(m_T - m_p)\right]^{\frac{-1}{C_3 X}}$$

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

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

Most relevant kinematic parameter space for XS measurements

[**MK**, Donato, Di Mauro; 2018]



XS coverage of the source term

[MK, Donato, Di Mauro; 2018]