Antiproton production cross sections and the search for dark matter

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Primary and secondary cosmic rays in the Galaxy

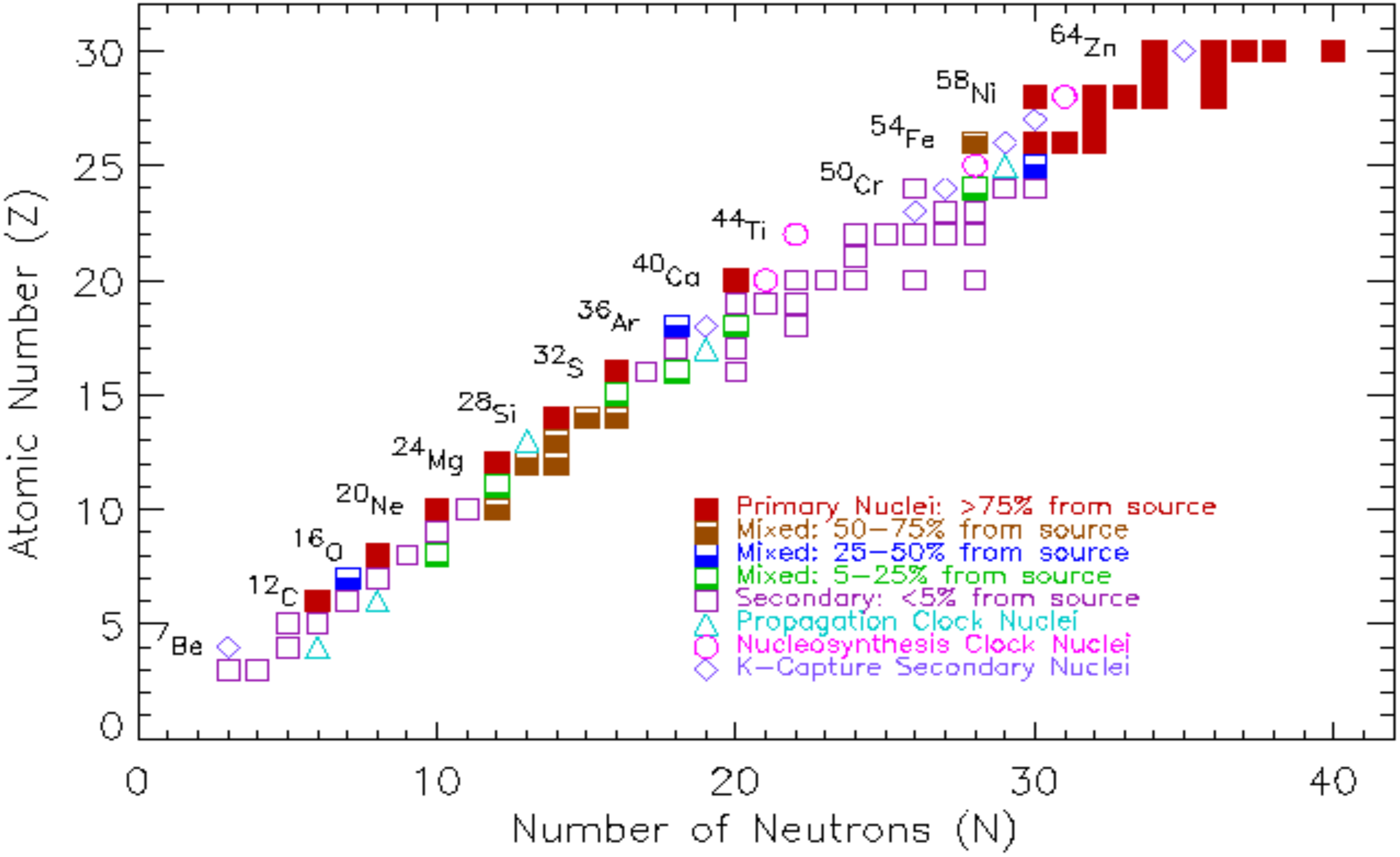
Primaries: produced in the sources (SNR and Pulsars)
H, He, CNO, Fe; e-, e+
Possibly e^+, p^-, d^- from Dark Matter annihilation

Secondaries : produced by **spallation of primary CRs (p, He,C, O, Fe) on the interstellar medium (ISM)**
LiBeB, sub-Fe; e^+, p^-, d^-

All primary and secondary species propagate in the Galaxy, dominated by diffusion on the magnetic fields and/or by intense energy losses (leptons)

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



Production cross sections in the galactic cosmic ray modeling

H, He, C, O, Fe,… are present in the supernova remnant surroundings, and directly accelerated into the the interstellar medium (ISM)

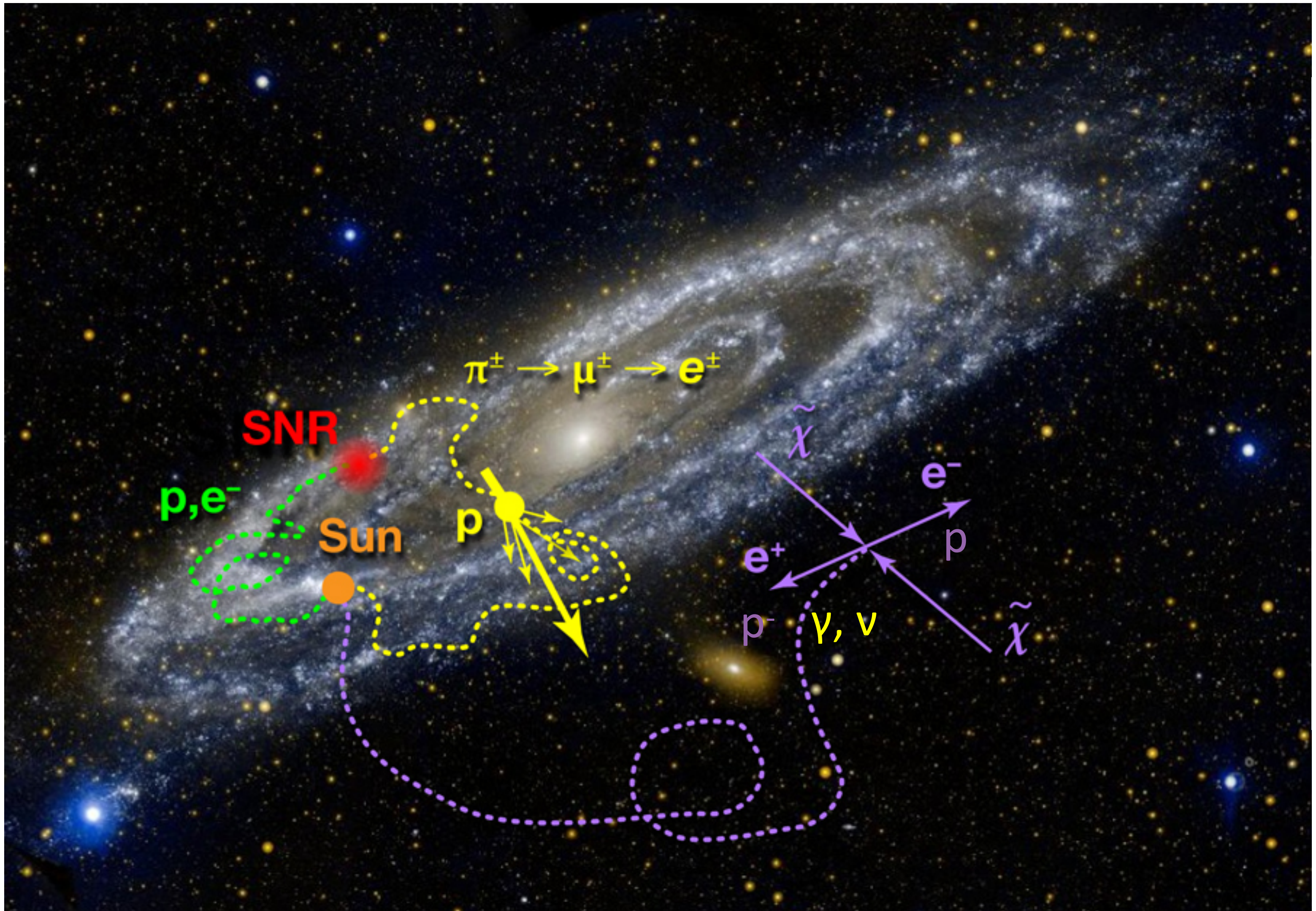
All the other nuclei (Li, Be, B, p-, and e+, gamma, …) are produced by spallation of heavier nuclei with the atoms (H, He) of the ISM

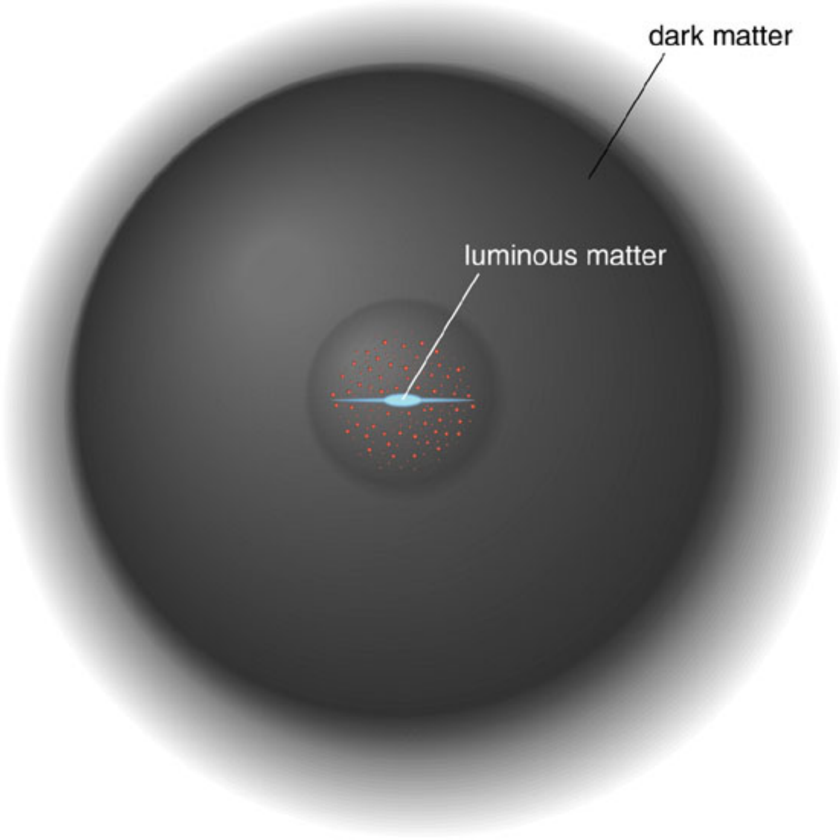
We need all the cross sections σ^{kj} - from Nichel down to proton - for the production of the j-particle from the heavier k-nucleus scattering off the H and He of the ISM

Remarkable for DARK MATTER signals is productions of: antiproton, antideuteron, positron and gamma rays.

Indirect DARK MATTER searches

Dark matter can annihilate in pairs with standard model final states.
Low background expected for cosmic **ANTIMATTER**, and for **NEUTRINOS** and **GAMMA RAYS** coming from dense DM sites





WIMP INDIRECT SIGNALS

Annihilation inside celestial bodies (Sun, Earth):

- ν at neutrino telescopes as up-going muons

Annihilation in the galactic halo:

- γ-rays (diffuse, monochromatic line), multiwavelength
- antimatter, searched as rare components in cosmic rays (CRs)

$$e^{+},\ \overline{p},\ \overline{D}$$

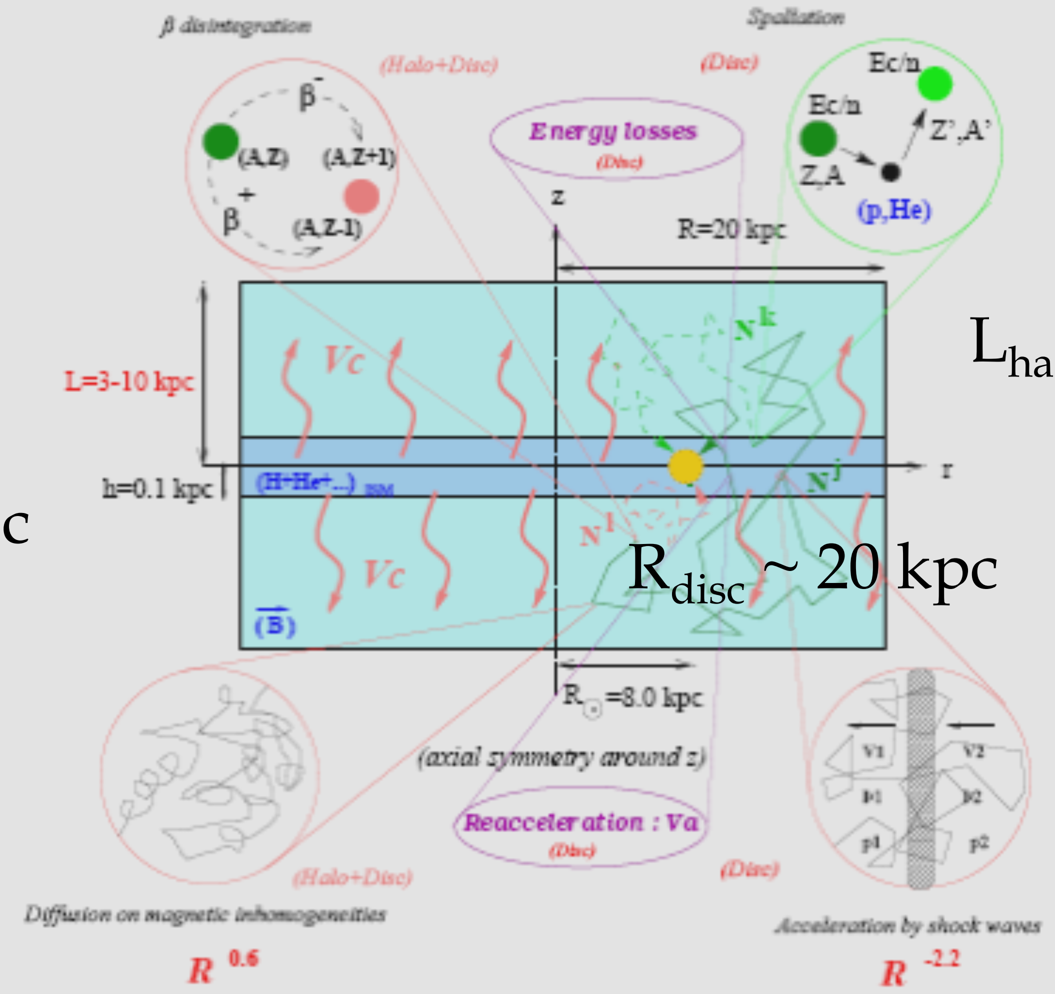
ν and γ keep directionality

→ SOURCE DENSITY

Charged particles diffuse in the galactic halo

→ ASTROPHYSICS OF COSMIC RAYS!

DM Sources are also



DM halo~ 200 kpc

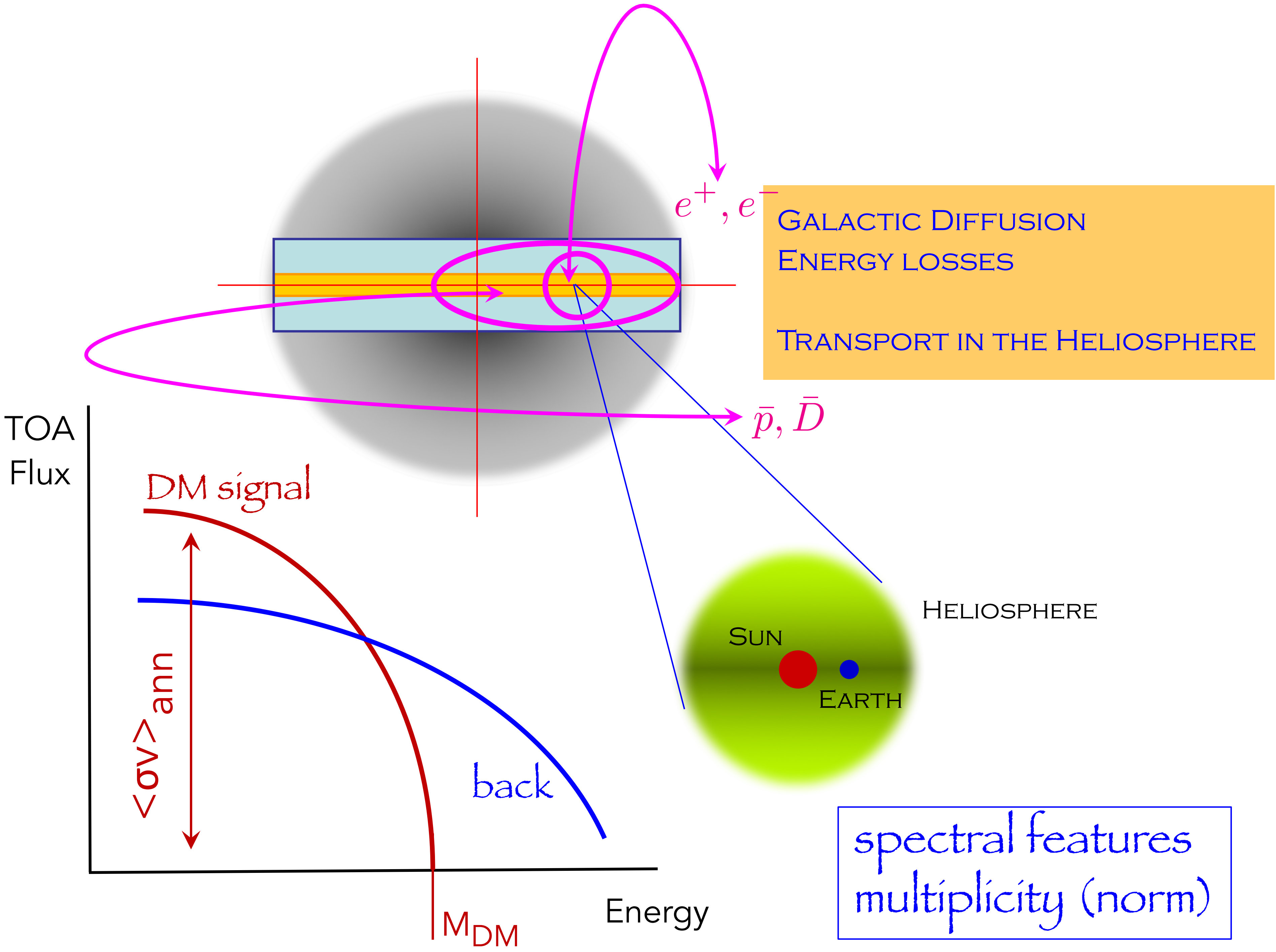
L_{halo} ~4-10 kpc

h_{disc} ~ 0.2 kpc

R_{disc} ~ 20 kpc

in the diffusive halo

Antiproton fluxes at the Top-of-Atmosphere

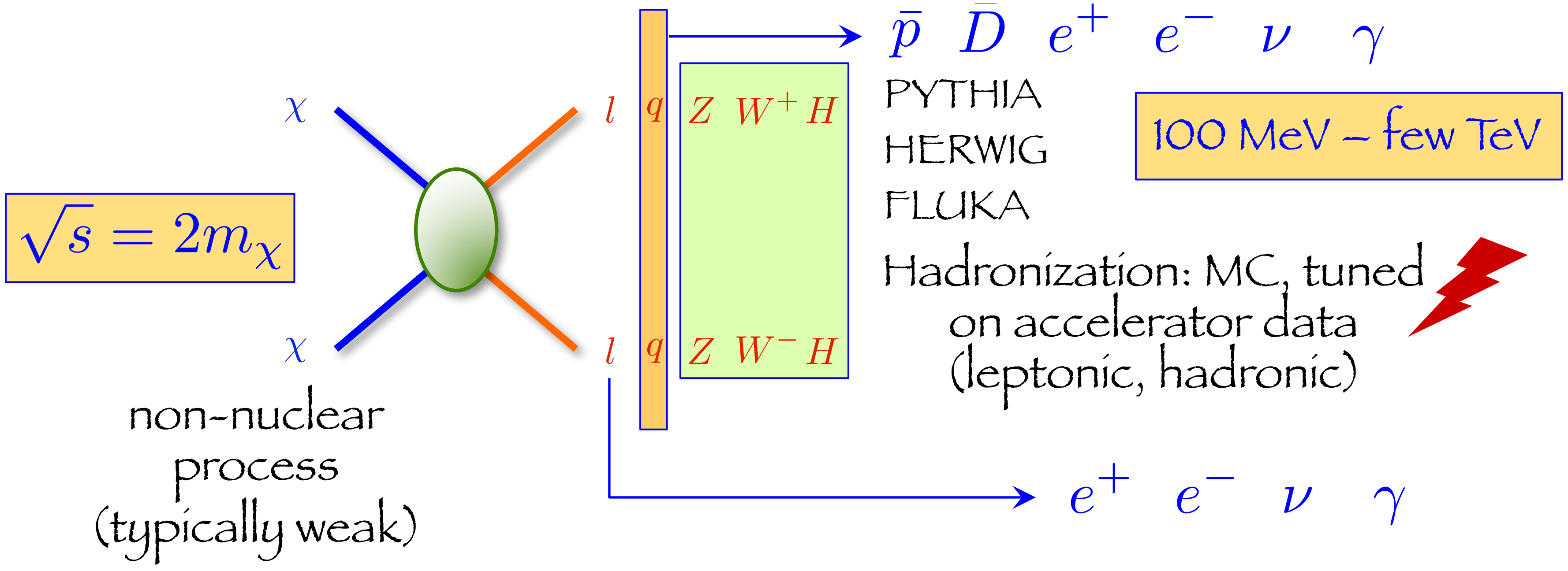


GALACTIC DIFFUSION
ENERGY LOSSES

TRANSPORT IN THE HELIOSPHERE

spectral features
multiplicity (norm)

Injection spectra from DM and CRs



$\sqrt{s} = 2m_\chi$

χ

χ

l q Z W^+ H

l q Z W^- H

$\bar{p}$ $\bar{D}$ e^+ e^- ν γ

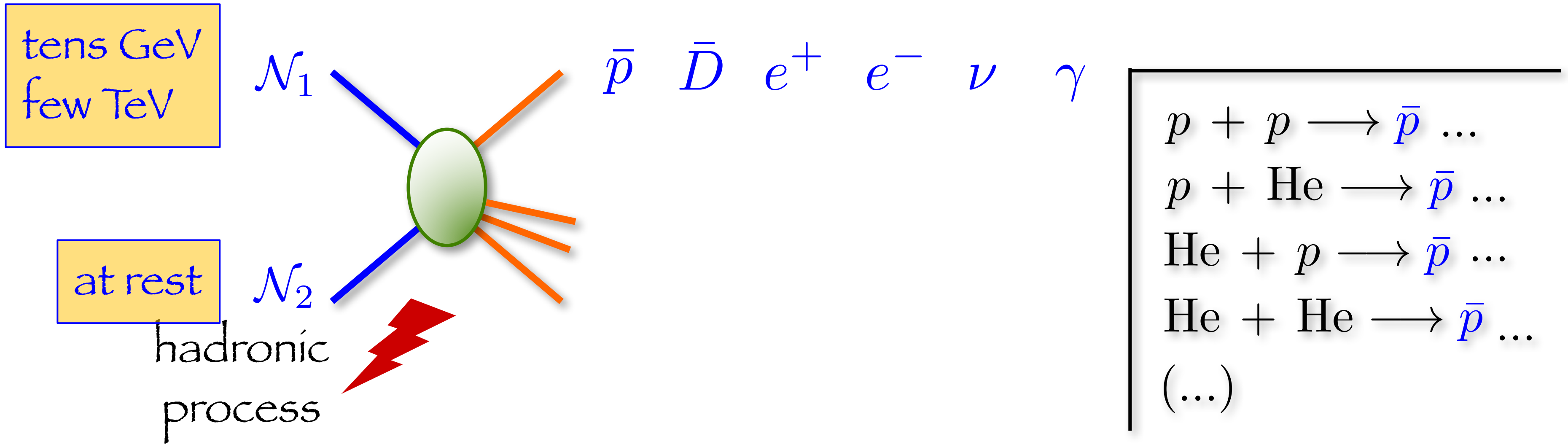
PYTHIA
HERWIG
FLUKA

100 MeV – few TeV

Hadronization: MC, tuned
on accelerator data
(leptonic, hadronic)

e^+ e^- ν γ

non-nuclear
process
(typically weak)



tens GeV
few TeV

$\mathcal{N}_1$

at rest

$\mathcal{N}_2$

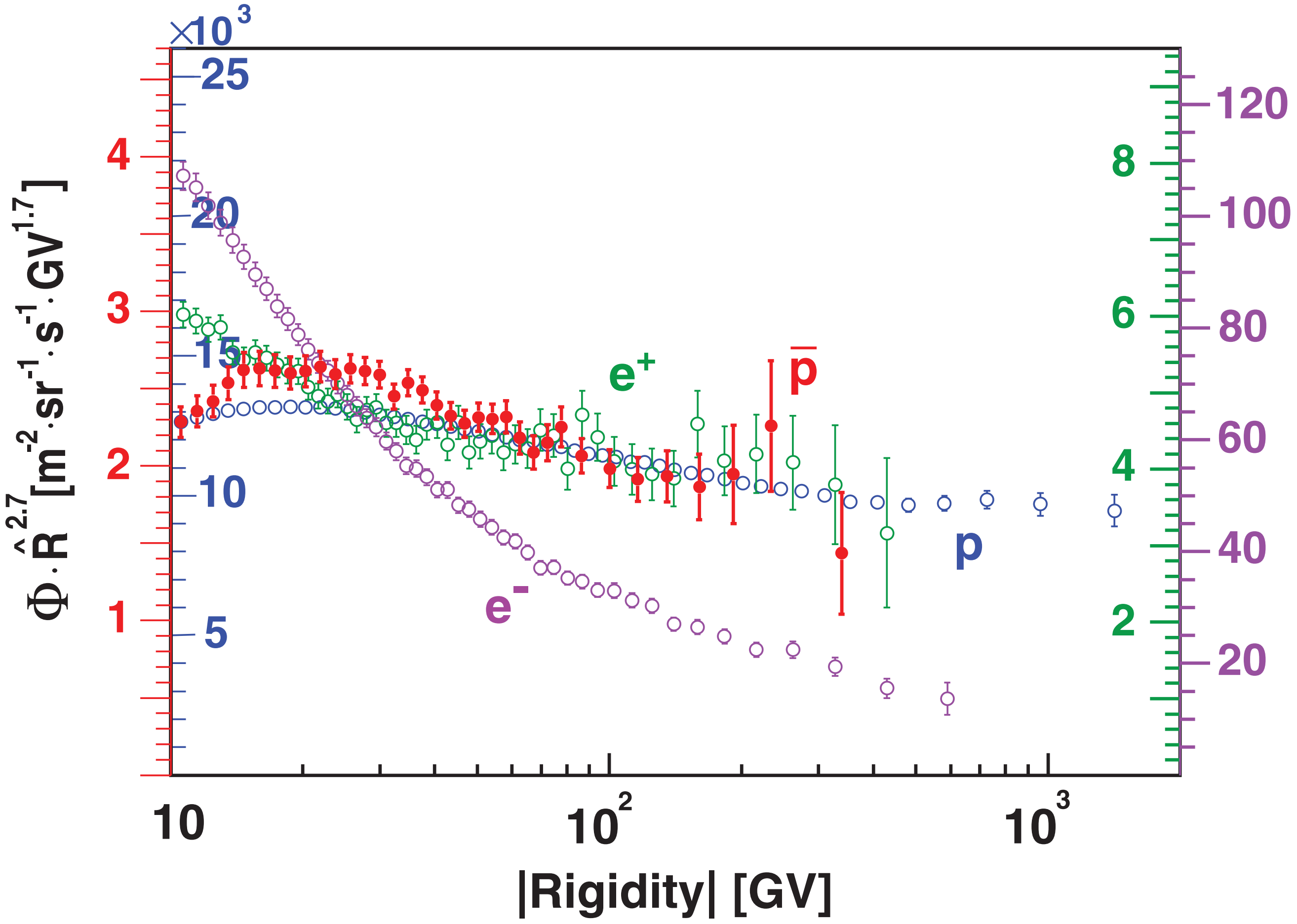
hadronic
process

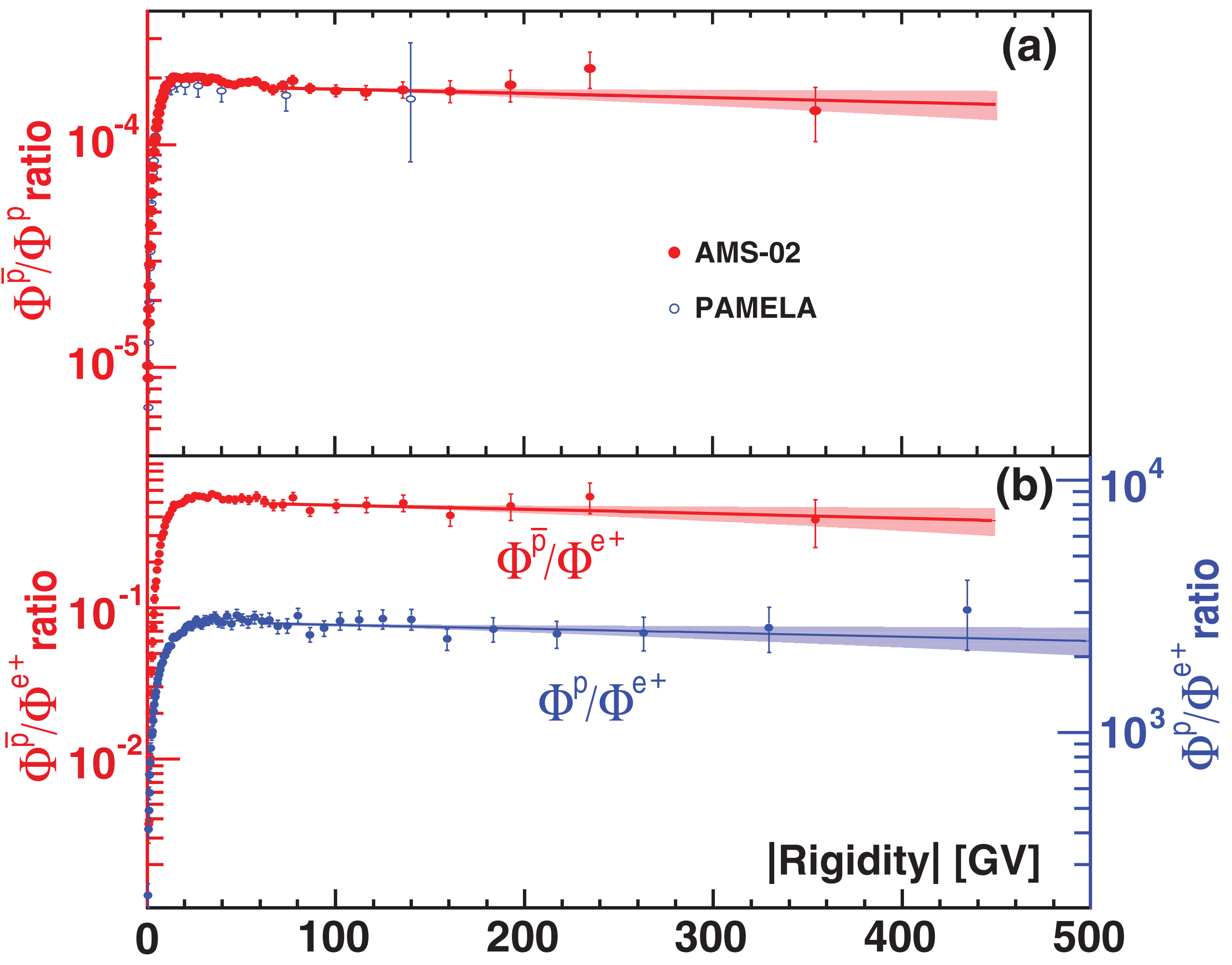
$\bar{p}$ $\bar{D}$ e^+ e^- ν γ

$p + p \longrightarrow \bar{p}$ ...
$p + \mathrm{He} \longrightarrow \bar{p}$ ...
$\mathrm{He} + p \longrightarrow \bar{p}$ ...
$\mathrm{He} + \mathrm{He} \longrightarrow \bar{p}$ ...
(...)

Cosmic antiproton data

AMS Coll. PRL 2016

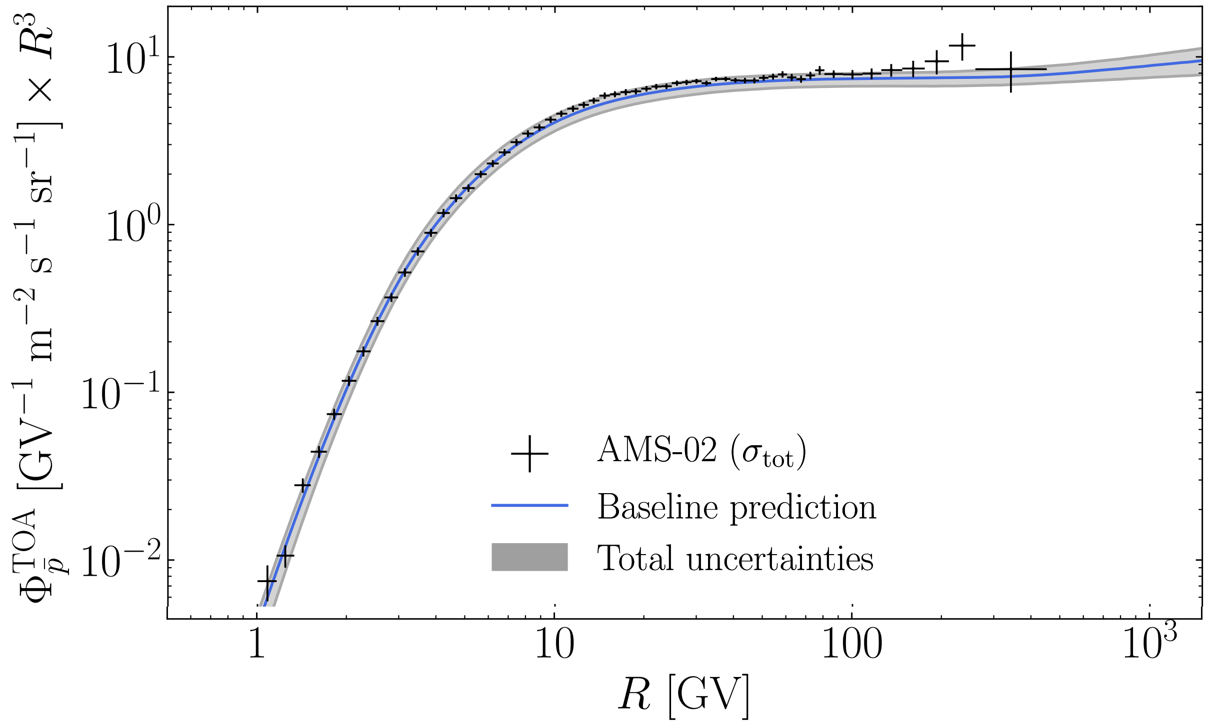


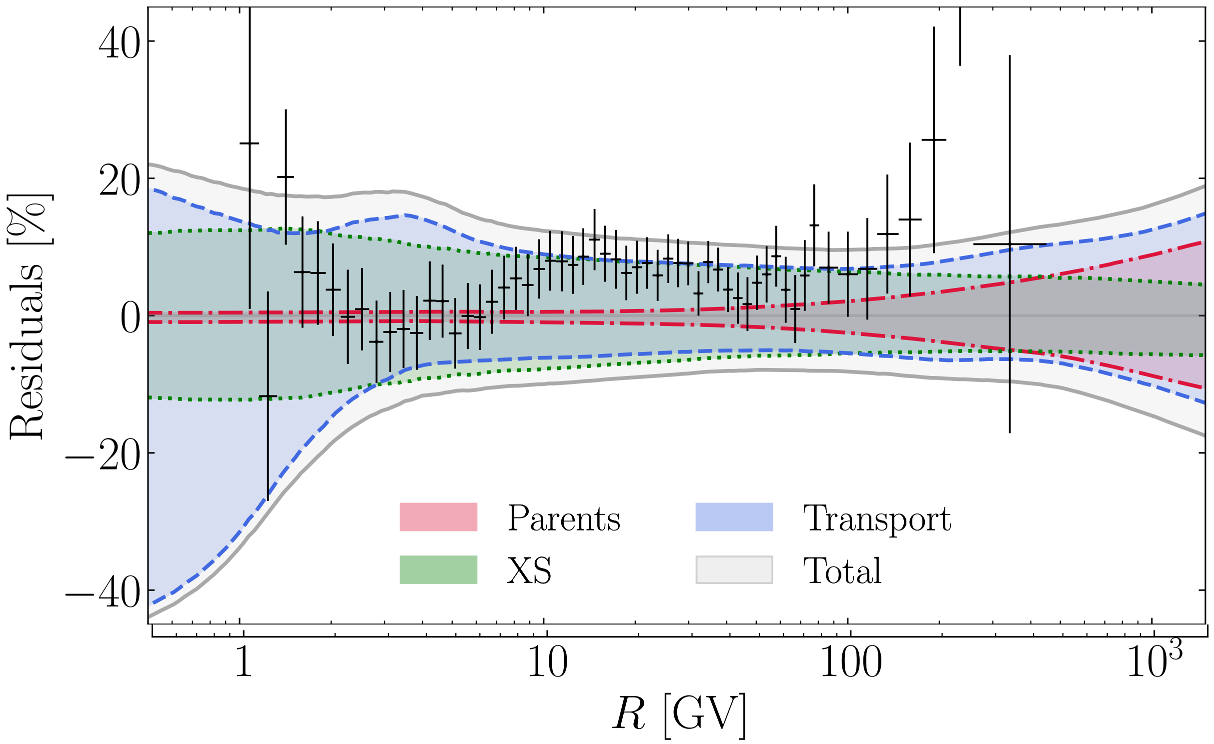


Data are very precise, and over almost 3 o.o.m.

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 1906.07119

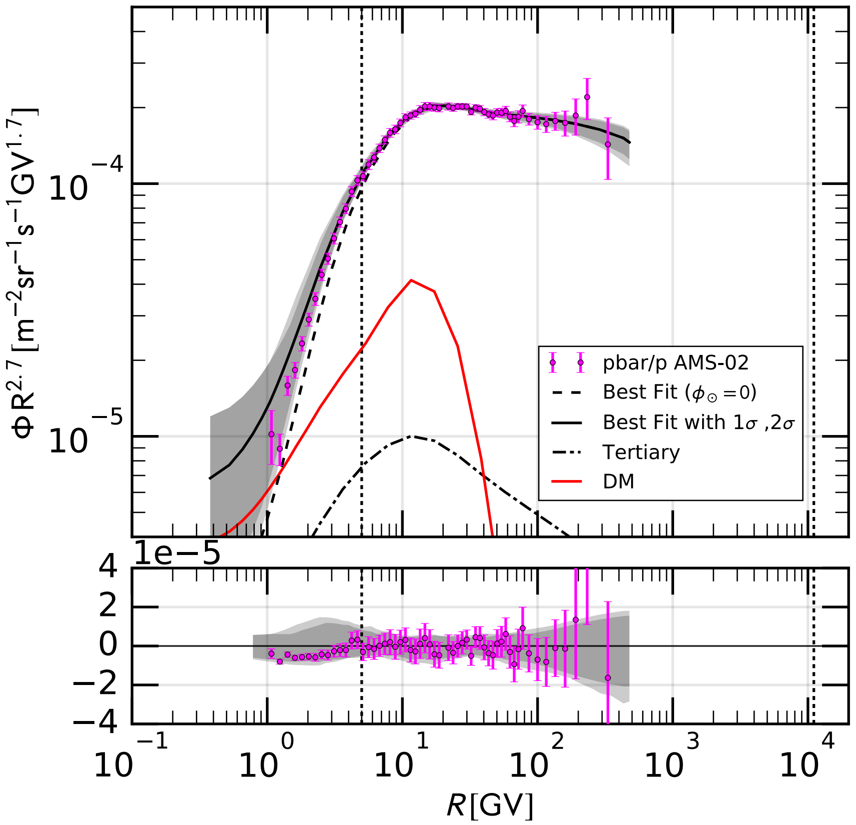


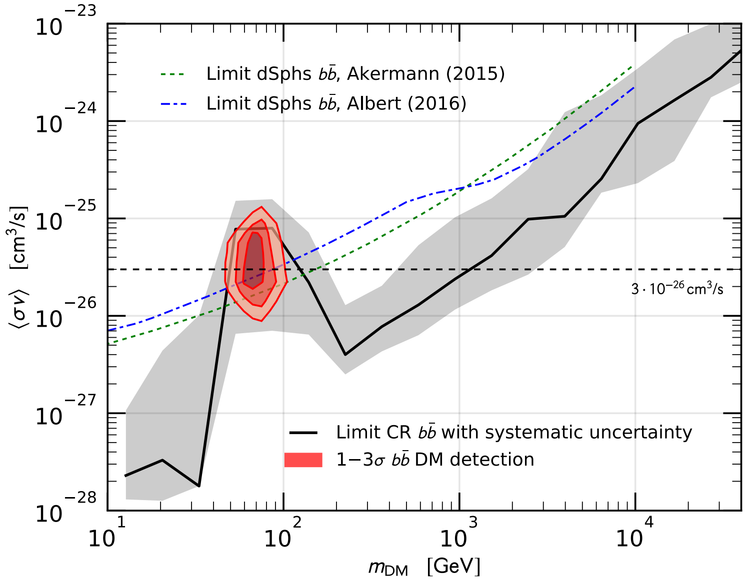


- The secondary bar flux is **predicted** to be consistent with AMS-02 data
- Transport and cross section uncertainties are comparable
- A **dark matter** contribution would come as a tiny effect
- Precise predictions are mandatory

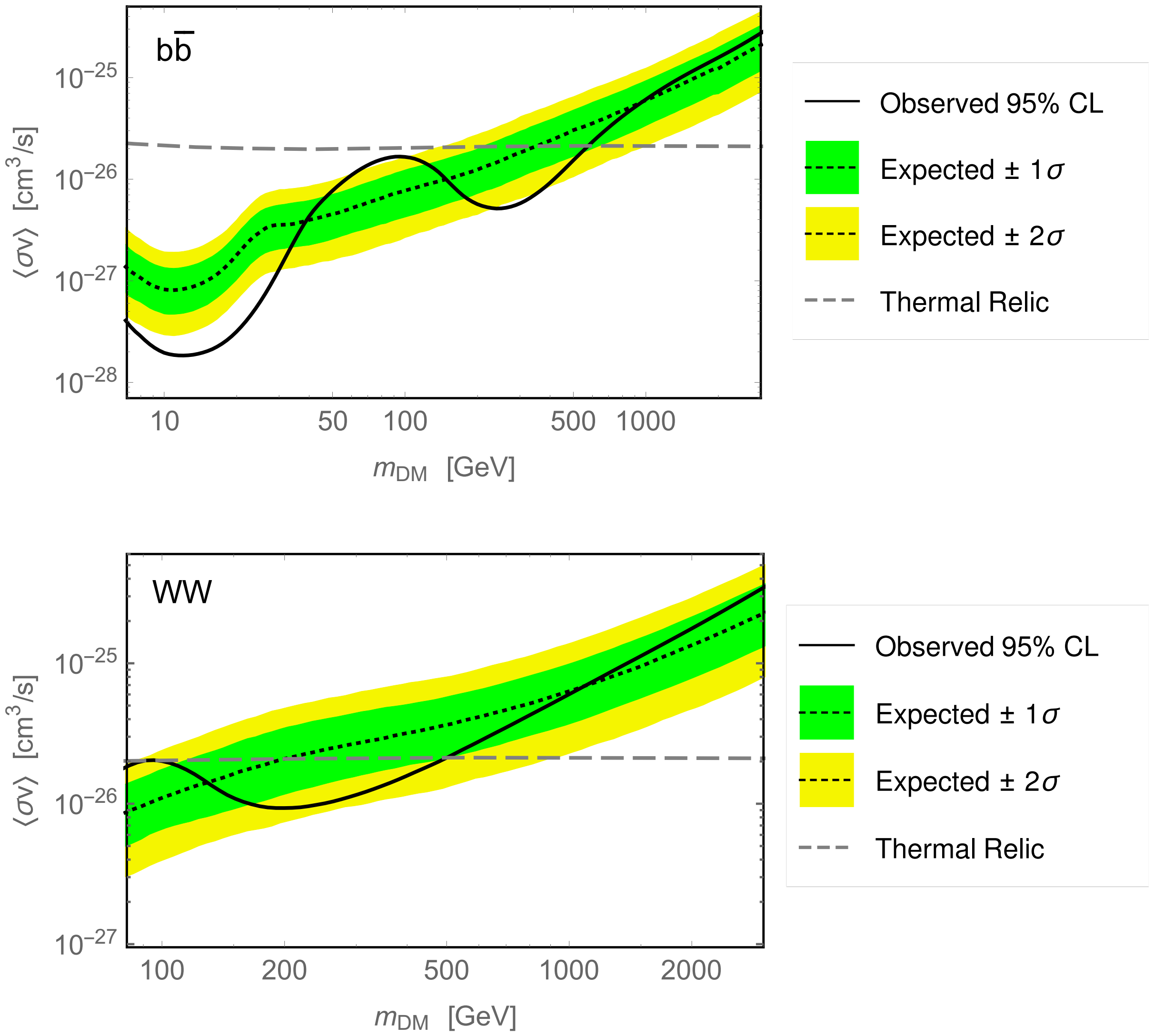
Possible contribution from dark matter

Cuoco, Korsmeier, Kraemer PRL 2017





Reinert & Winkler JCAP2018



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

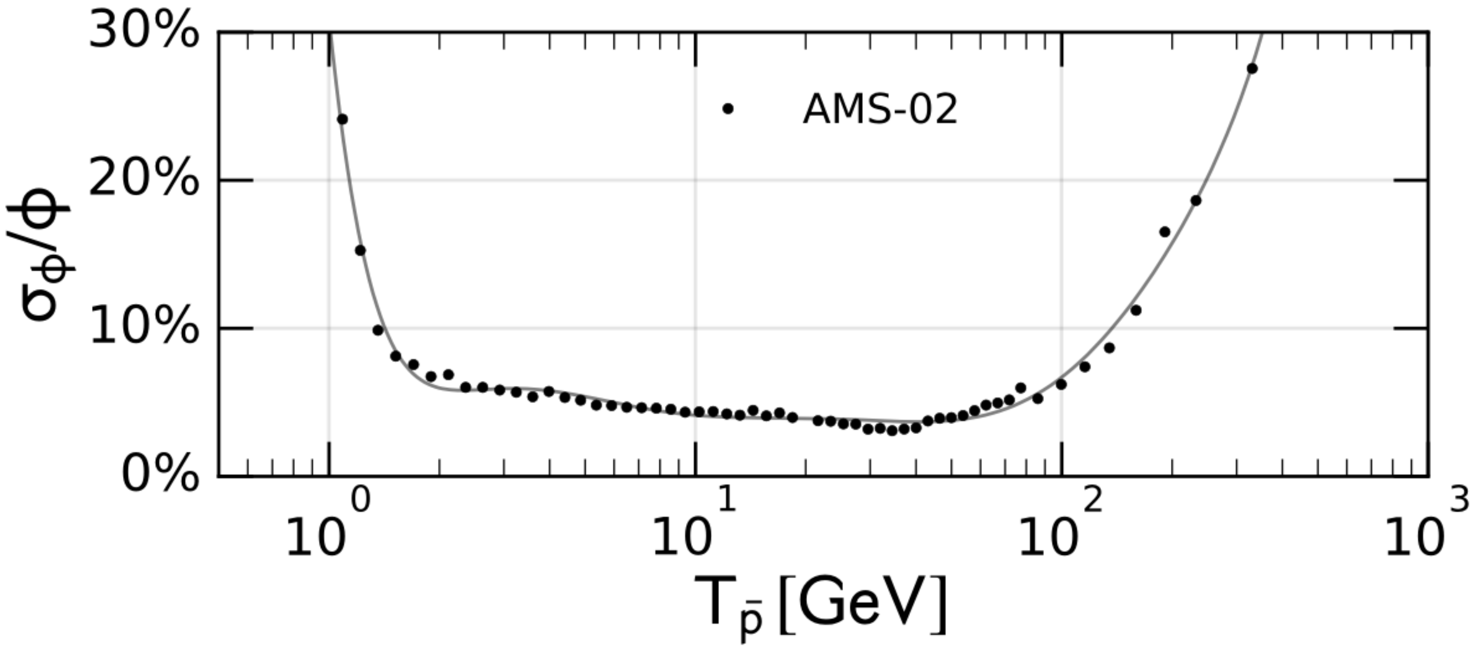
Antiproton production by inelastic scatterings

FD, Korsmeier, Di Mauro PRD 2017

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

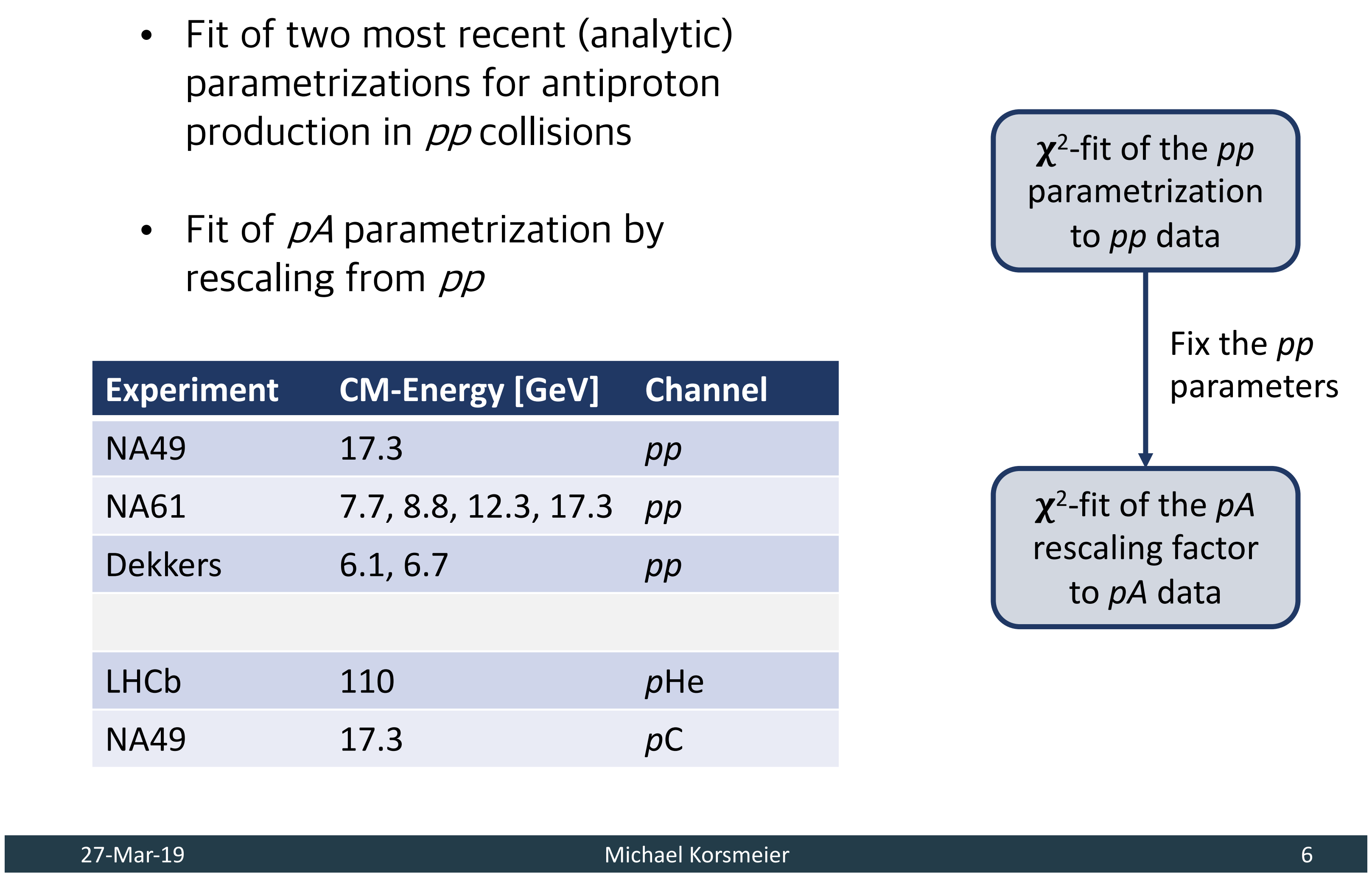
Source term

i, j = proton, helium
(both in the CRs and in the ISM)



Cosmic antiproton data are very precise:
production cross sections should be known with high accuracy
in order not to introduce high **theoretical** uncertainties

Re-analysis of the cross section parameterization



- Fit of two most recent (analytic) parametrizations for antiproton production in *pp* collisions
- Fit of *pA* parametrization by rescaling from *pp*

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	*pHe*
NA49	17.3	*pC*

χ^2-fit of the *pp* parametrization to *pp* data

Fix the *pp* parameters

χ^2-fit of the *pA* rescaling factor to *pA* data

27-Mar-19 Michael Korsmeier 6

Param. I

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

Param. II

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

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

$$\sigma_{\text{inv}}^{pA}(\sqrt{s}, x_f, p_{\text{T}}) = f^{pA}(A, x_f, \mathcal{D})\ \sigma_{\text{inv}}^{pp}(\sqrt{s}, x_{\text{R}}, p_{\text{T}})$$

$$\sigma_{\text{inv}}^{\text{Galaxy}} = \sigma_{\text{inv}}(2 + \Delta_{\text{IS}} + 2\Delta_{\Lambda}$$

New fixed-target data for the antiproton XS

FD, Korsmeier, Di Mauro PRD 2018

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

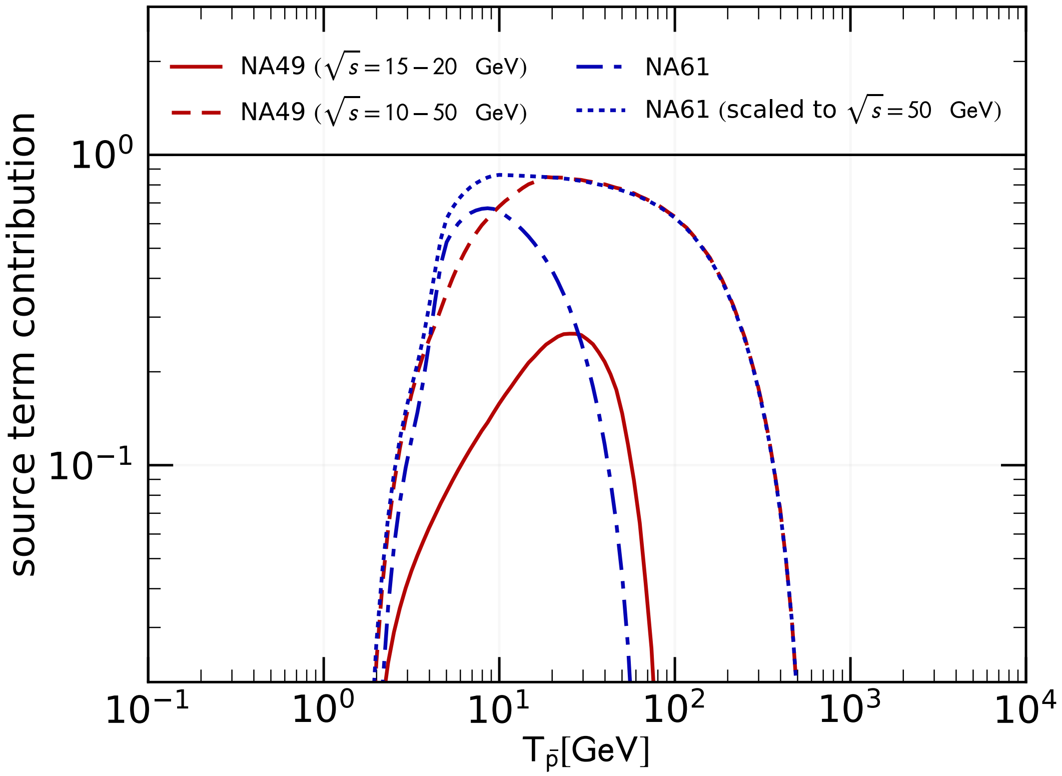
pHe —> pbar + X

LHCb (Graziani et al. Moriond 2017)

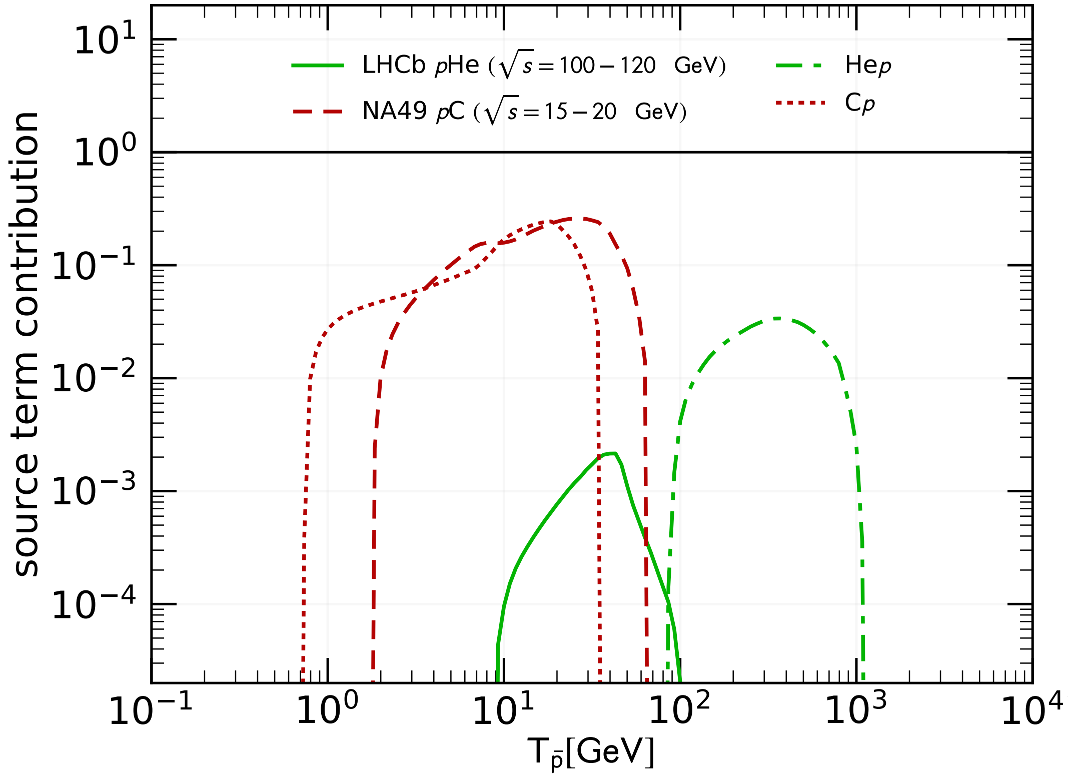
$\sqrt{s} = 110$ GeV

T_p = 6.5 TeV

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



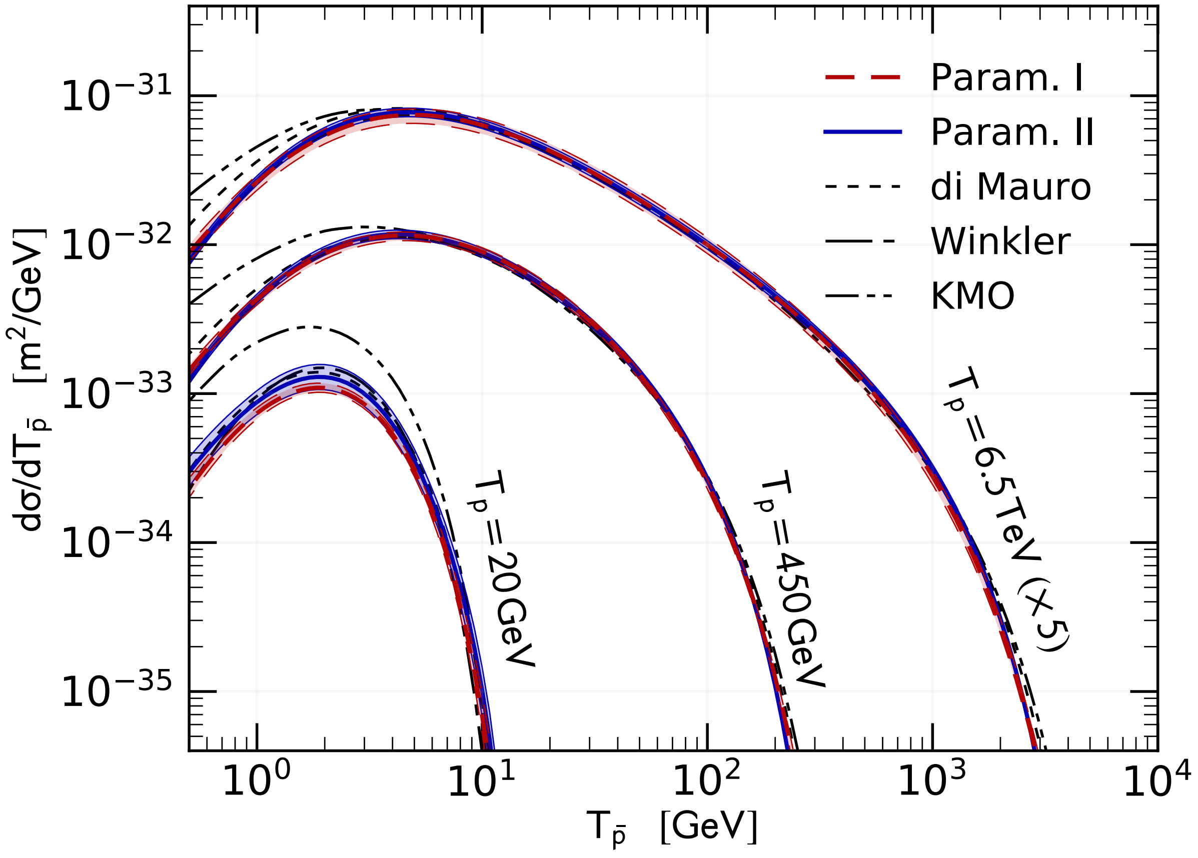
Fraction of the p-nucelus source term covered by the kinematical parameters space



pp—> pbar+X production cross sections

FD, Korsmeier, Di Mauro PRD 2018

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



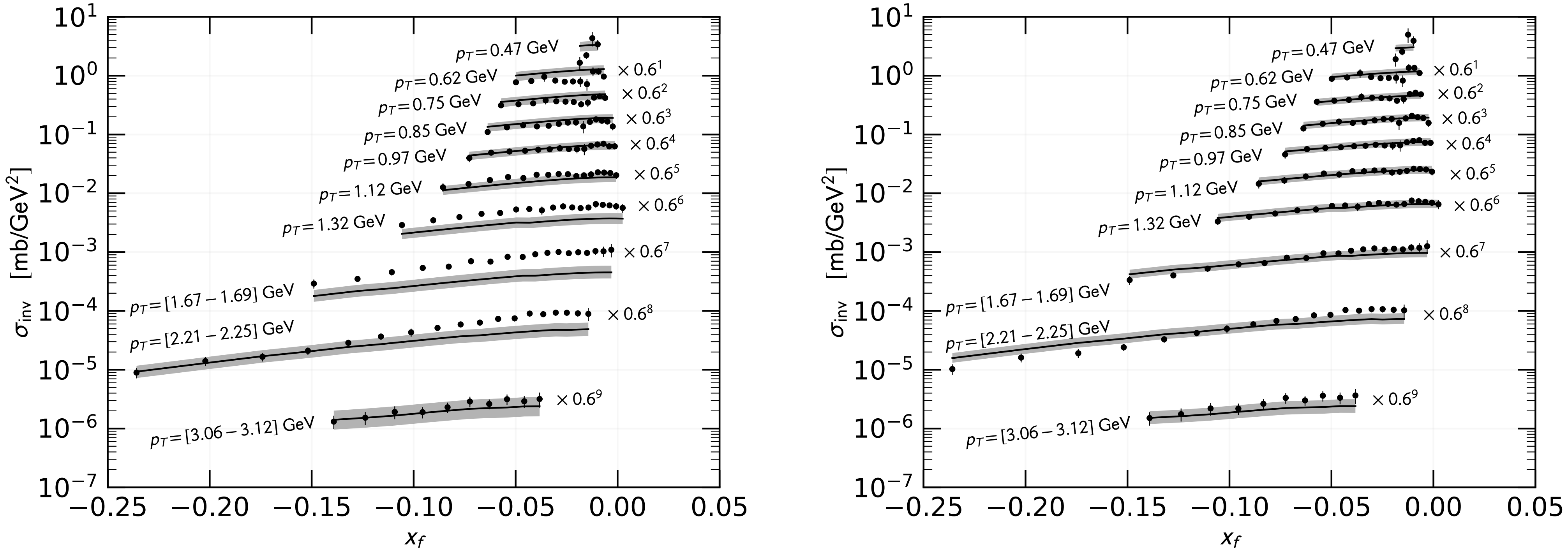
Good agreement for T > 10 GeV

High-energy data analysis

Korsmeier, FD, Di Mauro, PRD 2018

1. Fit to NA61 pp —> pbar + X data
2. Calibration of pA XS on NA49 pC —> pbar + X data
3. Inclusion of LHC pHe —> pbar + X data

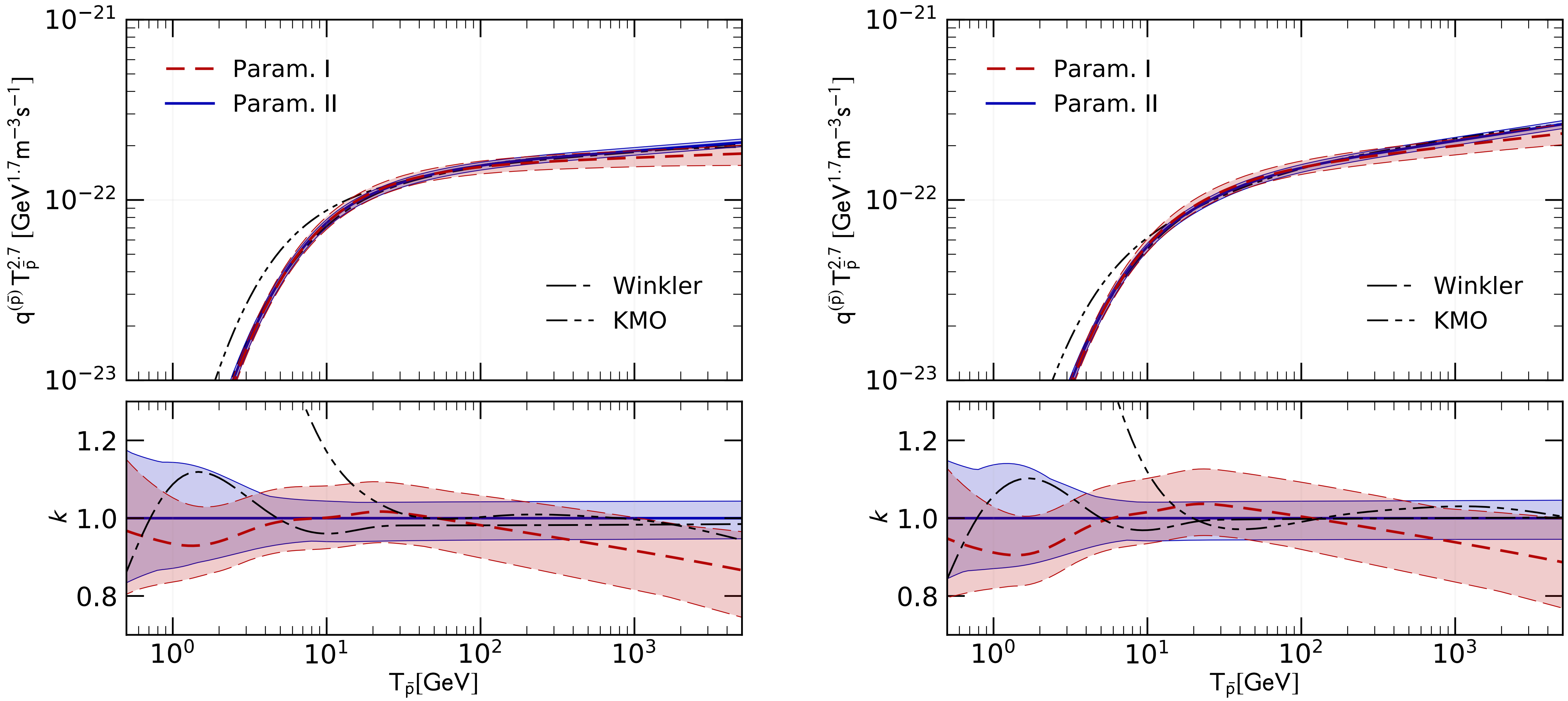
Parametrization I



LHCb data agree better with one of the two pp parameterizations.
They select the high energy behavior of the Lorentz invariant cross section

The antiproton source spectrum

Korsmeier, FD, Di Mauro, 1802.03030, PRD i2018



Param II is preferred by the fits.

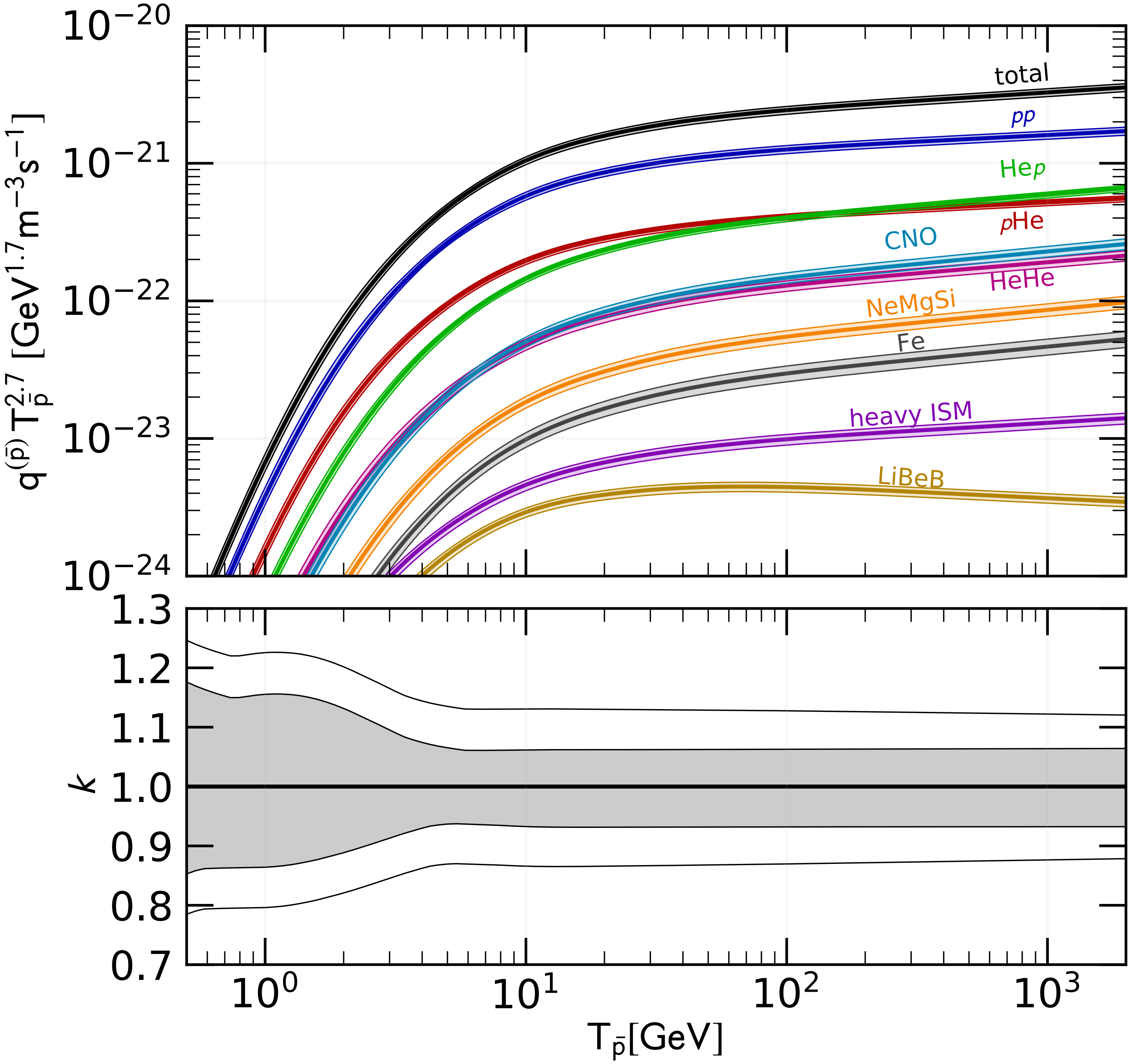
The effect of LHCb data is to select a h.e. trend of the pbar source term.

A harder trend is preferred.

Uncertainties still range about 10-15%, and increase at low energies.

Effects on the total pbar production

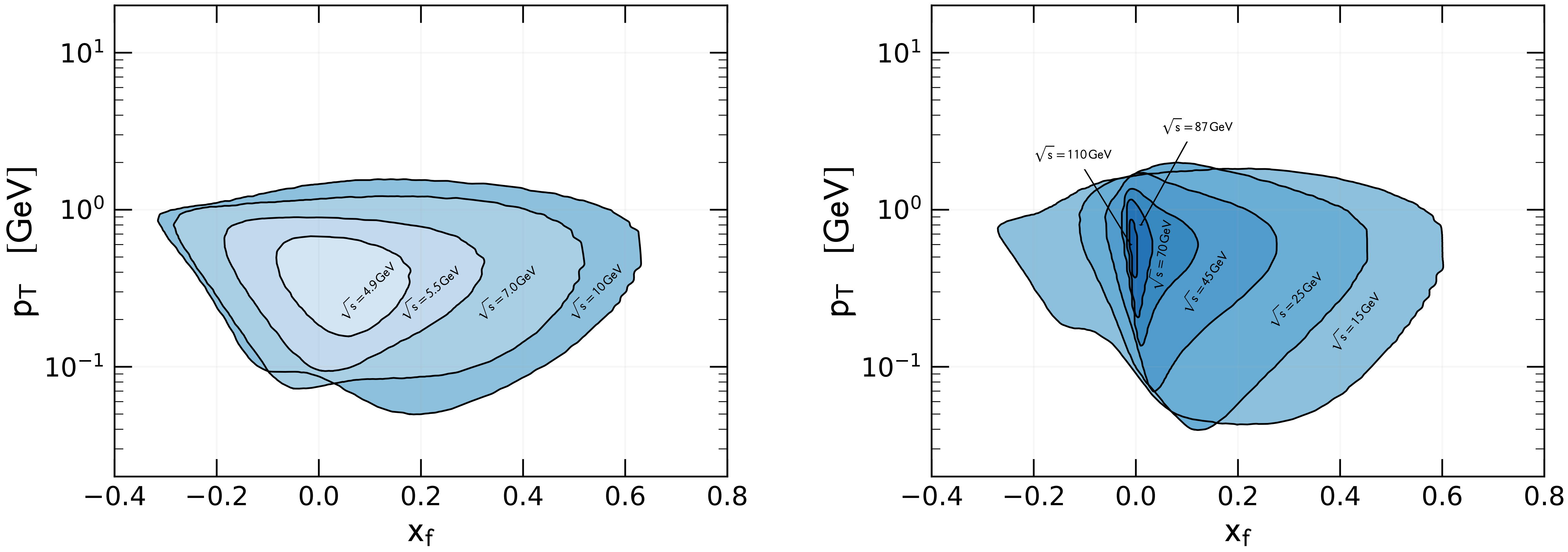
Korsmeier, FD, Di Mauro, 1802.03030, PRD 2018



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

For next generation experiments



AMS02 accuracy is reached if pp→pbar cross section is measured with 3% accuracy inside the regions, 30% outside.

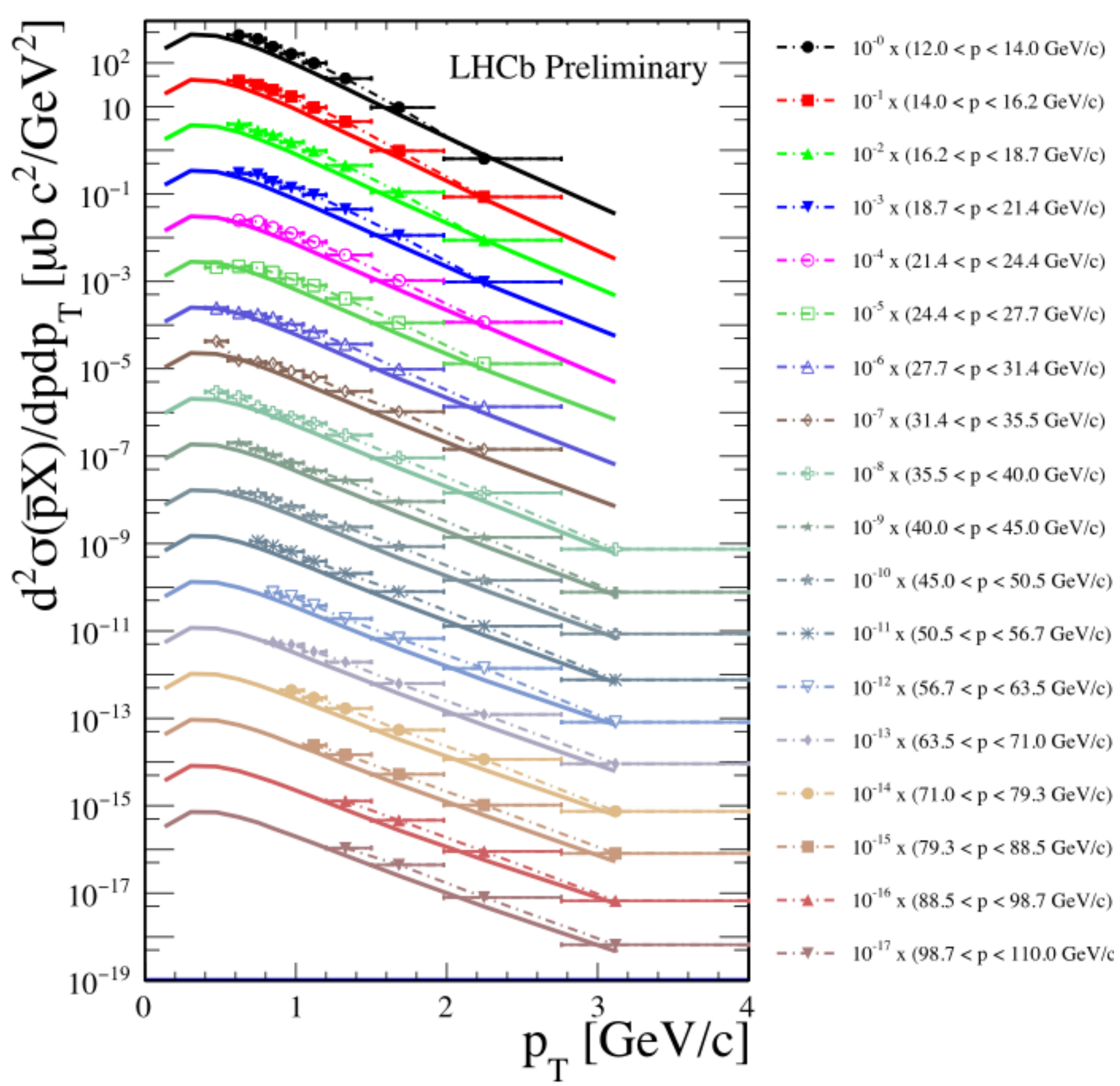
Conclusions

- The AMS data induce a remarkable progress in understanding our Galaxy. Its data reach unprecedented precision (few %).
- The production cross sections for secondary nuclei are often the main source of theoretical uncertainty
- High energy physics is addressing new data at the service of high precision cosmic ray data
- Improvements in calculations of the nuclear cross sections will certainly remain **data driven** in the near future

LHCb pHe —> $p^{-}X$ cross section data

G Graziani for LHCb, Moriond 2017

First data ever has been collected by LHCb in fixed target mode



Result for **prompt** production (excluding weak decays of hyperons)

The total inelastic cross section is also measured to be

$$\sigma_{inel}^{\text{LHCb}} = (140 \pm 10)\ \text{mb}$$

The EPOS LHC prediction

[T. Pierog at al, Phys. Rev. C92 (2015), 034906]

is 118 mb, ratio is 1.19 ± 0.08.

Run at 4 TeV p beam energy is under analysis by the collaboration

General idea for matching the accuracy

- Determine the contribution to the antiproton source spectrum from the whole parameter space

$$\{\sqrt{s}, x_{\mathrm{R}}, p_{\mathrm{T}}\} \qquad \{T, T_{\bar{p}}, \cos(\theta)\}$$

- Assign the maximal uncertainty that the cross section should have in order to address the following requirements:

1. The total uncertainty shall match the AMS-02 accuracy
2. The parameter space with larger contribution to the source spectrum, should have the smaller uncertainties in the cross section measurements

$$\frac{d\sigma}{dT_{\bar{p}}}(T, T_{\bar{p}}) = 2\pi p_{\bar{p}} \int_{-1}^{1} d\cos(\theta)\ \sigma_{\mathrm{inv}}$$

$$= 2\pi p_{\bar{p}} \int_{-\infty}^{\infty} d\eta\ \frac{1}{\cosh^2(\eta)}\ \sigma_{\mathrm{inv}} \qquad \eta = -\ln\left(\tan\left(\frac{\theta}{2}\right)\right)$$

Predictions for future extensions of experiments