Light antinuclei from Dark Matter

Fiorenza Donato
Torino University & INFN

"Light Anti-Nuclei as a Probe for New Physics" Workshop
Leiden, 15.10.2019

SIGNALS from RELIC WIMPs

Direct searches (deeply underground experiments) :

elastic scattering of a WIMP off detector nuclei

Measure of the recoil energy

Annual modulation and directionality of the measured rate

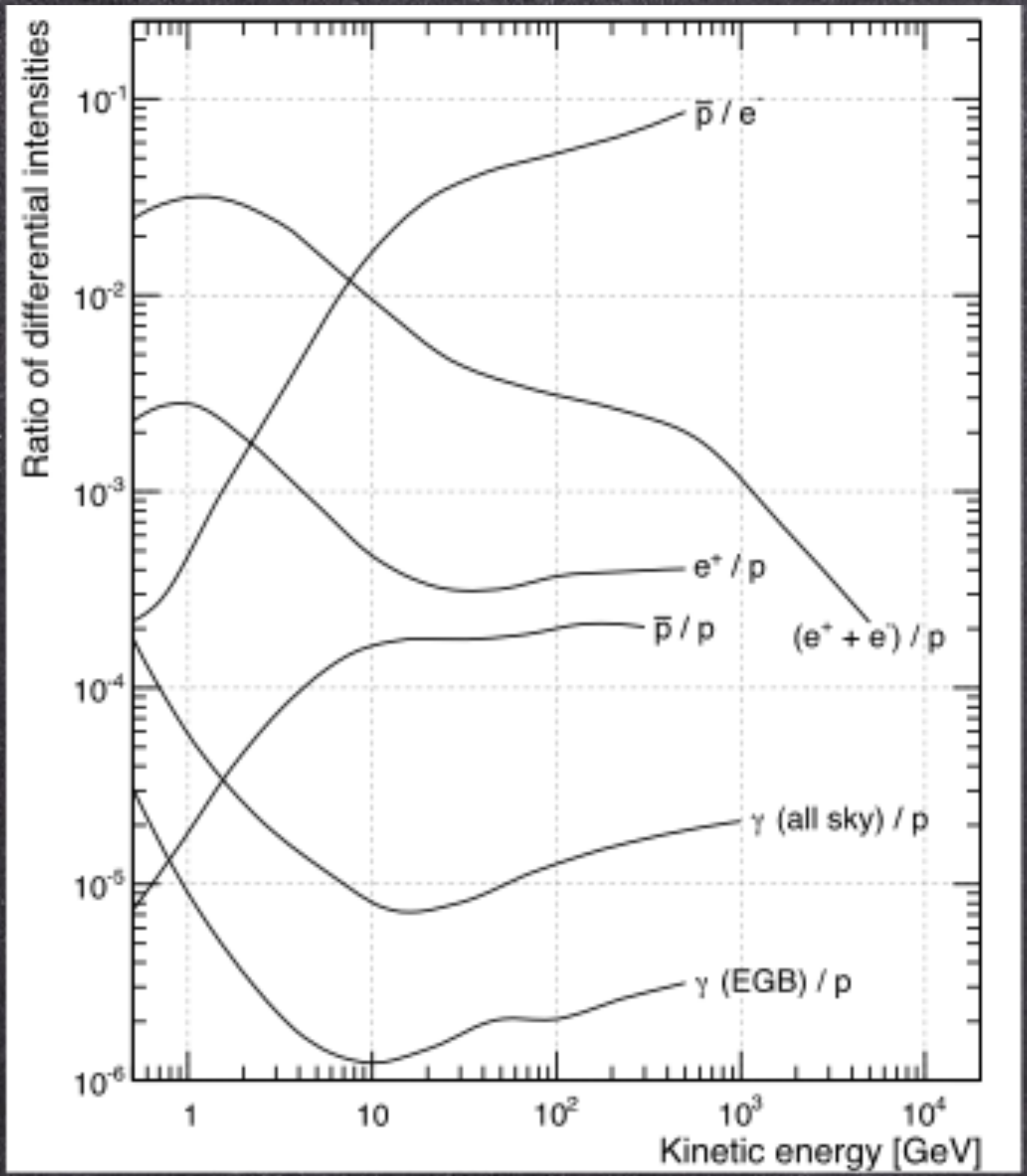
Indirect searches: in Cosmic Rays (mostly space based experiments)

signals due to annihilation of accumulated $\chi\chi$ in the of Sun/Earth (neutrinos)

signals due to $\chi\chi$ annihilation in the galactic halo (antimatter, gamma-rays)

New particles are searched at colliders but we cannot say anything about being the solution to the DM in the Universe!

The interest into rare cosmic rays



L Baldini, 1407.7631

Antimatter is highly suppressed

γ rays even more, but keep directionality

Antimattear or γ-rays sources from DARK MATTER

Annihilation

$$Q_{\rm ann}(\vec{x},E) = \epsilon \left(\frac{\rho(\vec{x})}{m_{DM}}\right)^2 \sum_f \langle\sigma v\rangle_f \frac{dN^f_{e^\pm}}{dE}$$

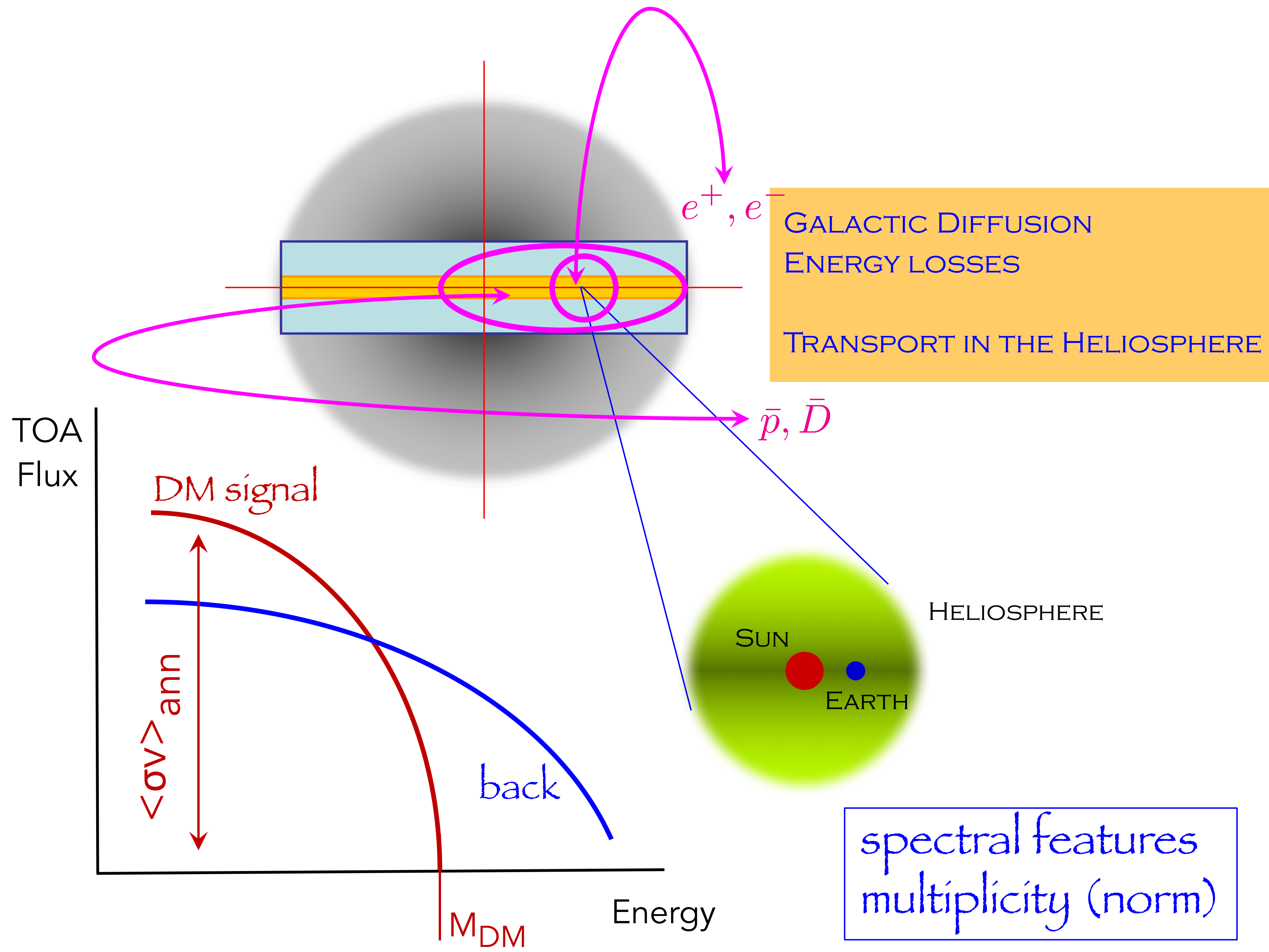
Decay

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

- ρ DM density in the halo of the MW
- m_{DM} DM mass
- $\langle\sigma v\rangle$ 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

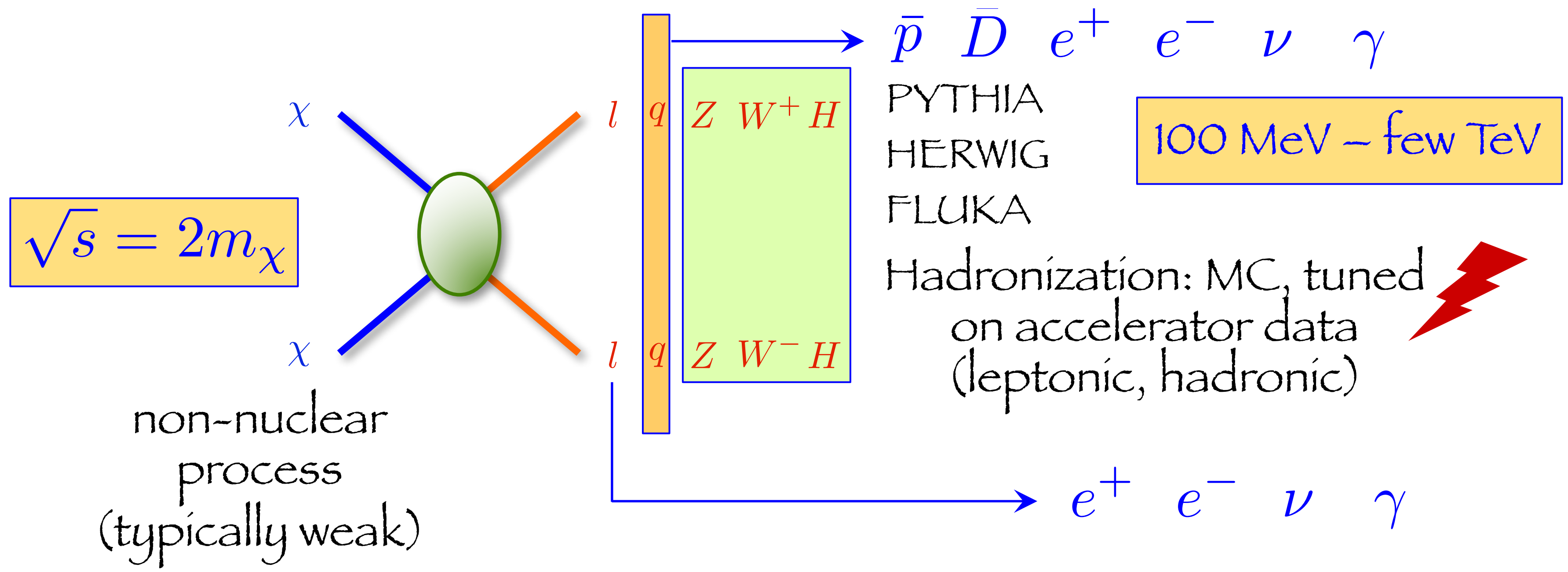
The case for antiprotons

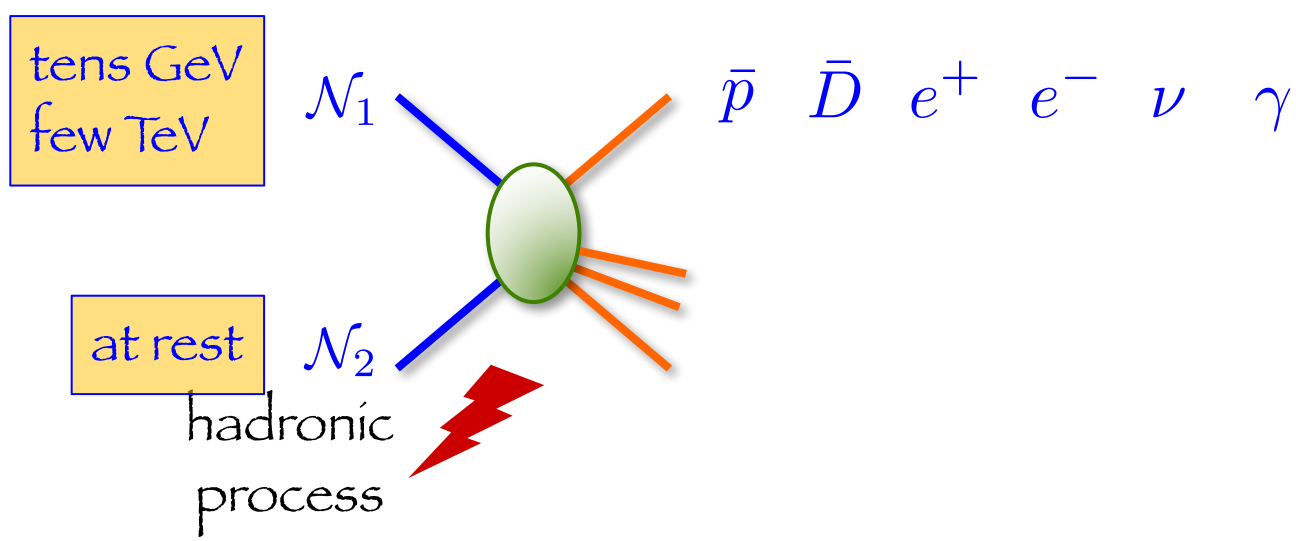
Antiproton fluxes at the Top-of-Atmosphere



spectral features
multiplicity (norm)

Injection spectra from DM and CRs

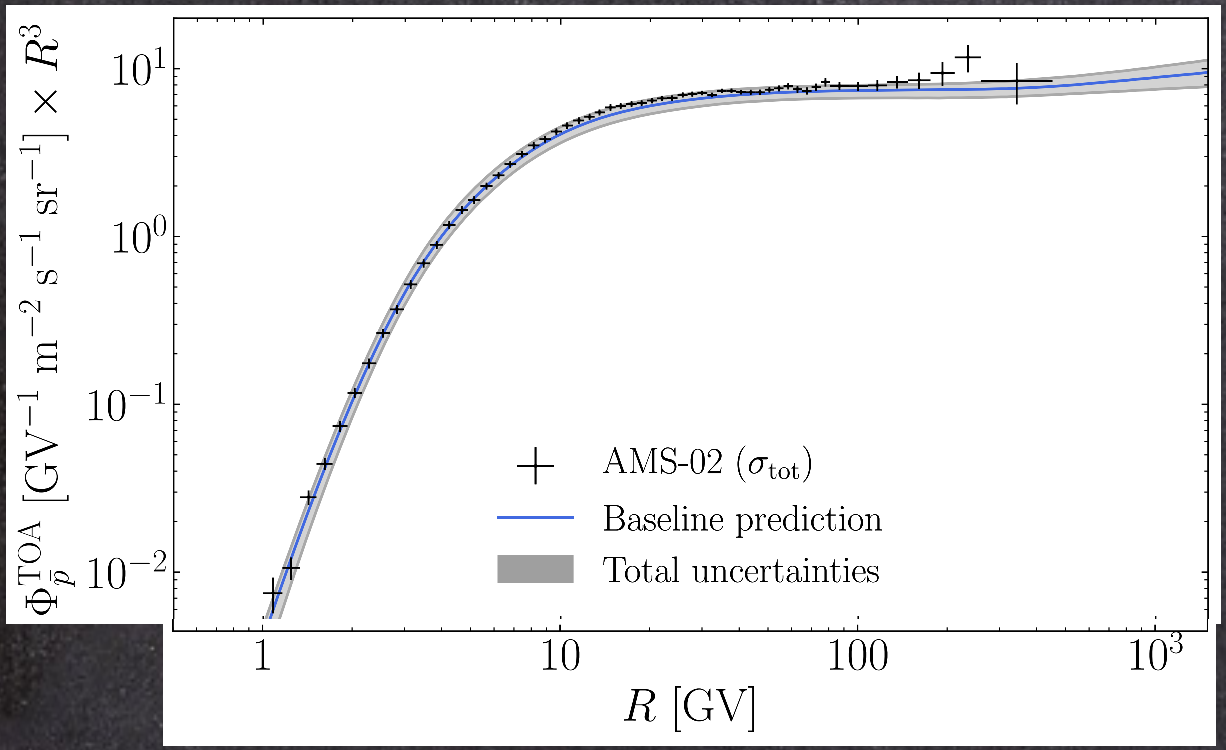


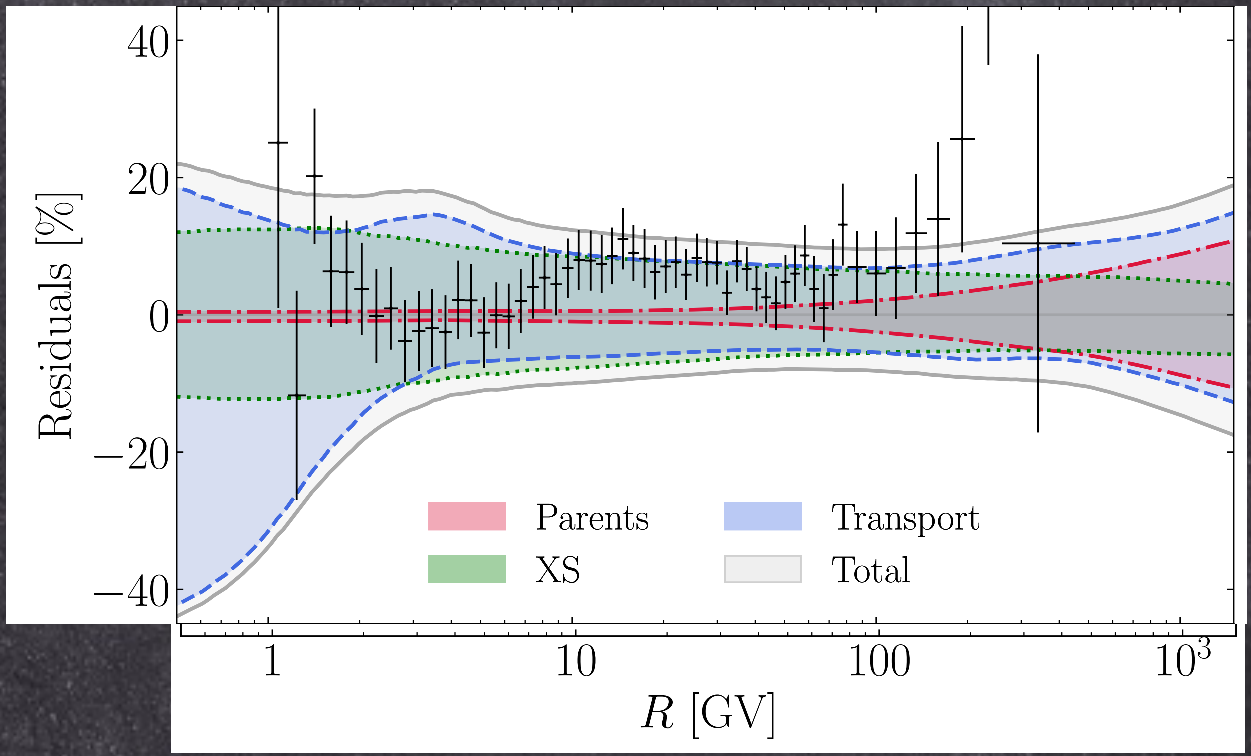


$p + p \longrightarrow \bar{p}$ ...
$p + \mathrm{He} \longrightarrow \bar{p}$ ...
$\mathrm{He} + p \longrightarrow \bar{p}$ ...
$\mathrm{He} + \mathrm{He} \longrightarrow \bar{p}$ ...
(...)

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

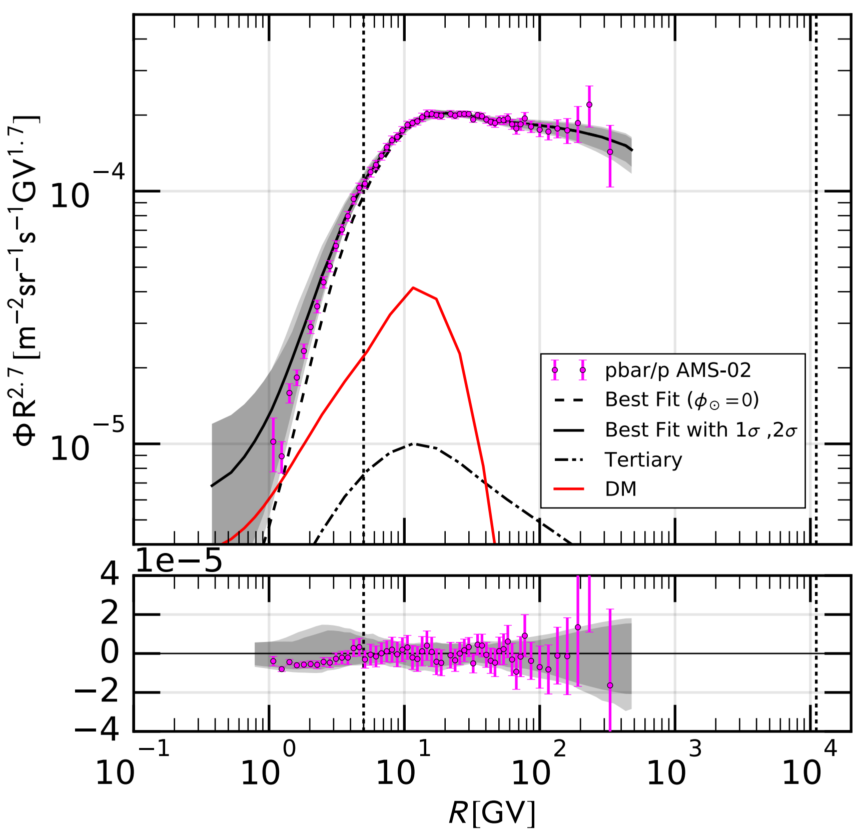


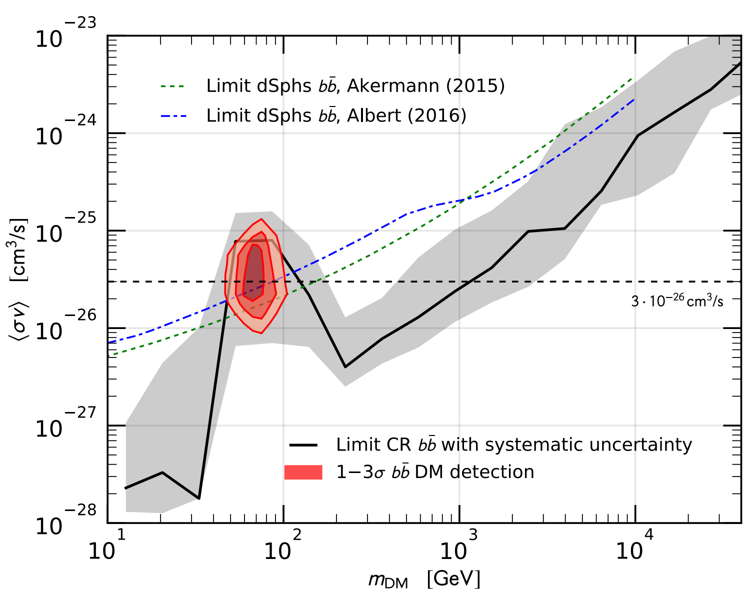


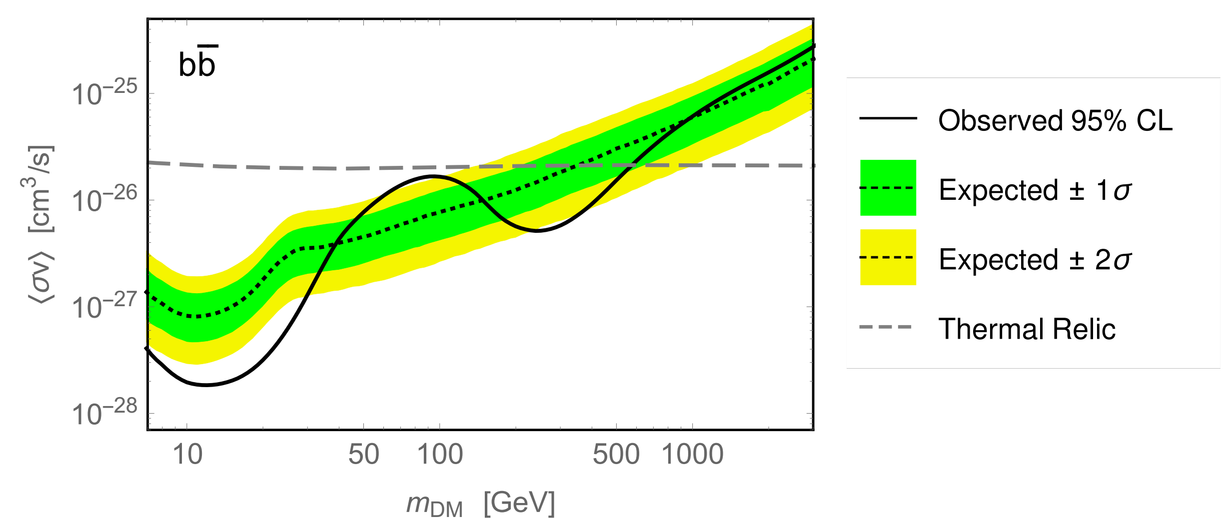
The secondary pbar flux is predicted to be consistent with AMS-02 data
Transport and cross section uncertainties are comparable

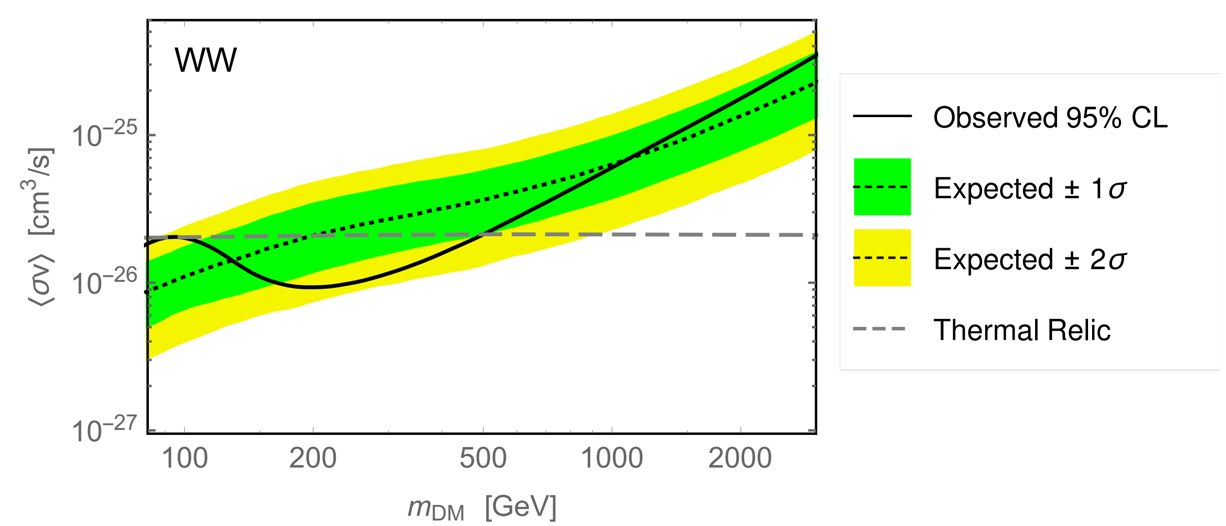
A dark matter contribution would come as a very tiny effect
Precise predictions are mandatory

Possible contribution from dark matter









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

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.

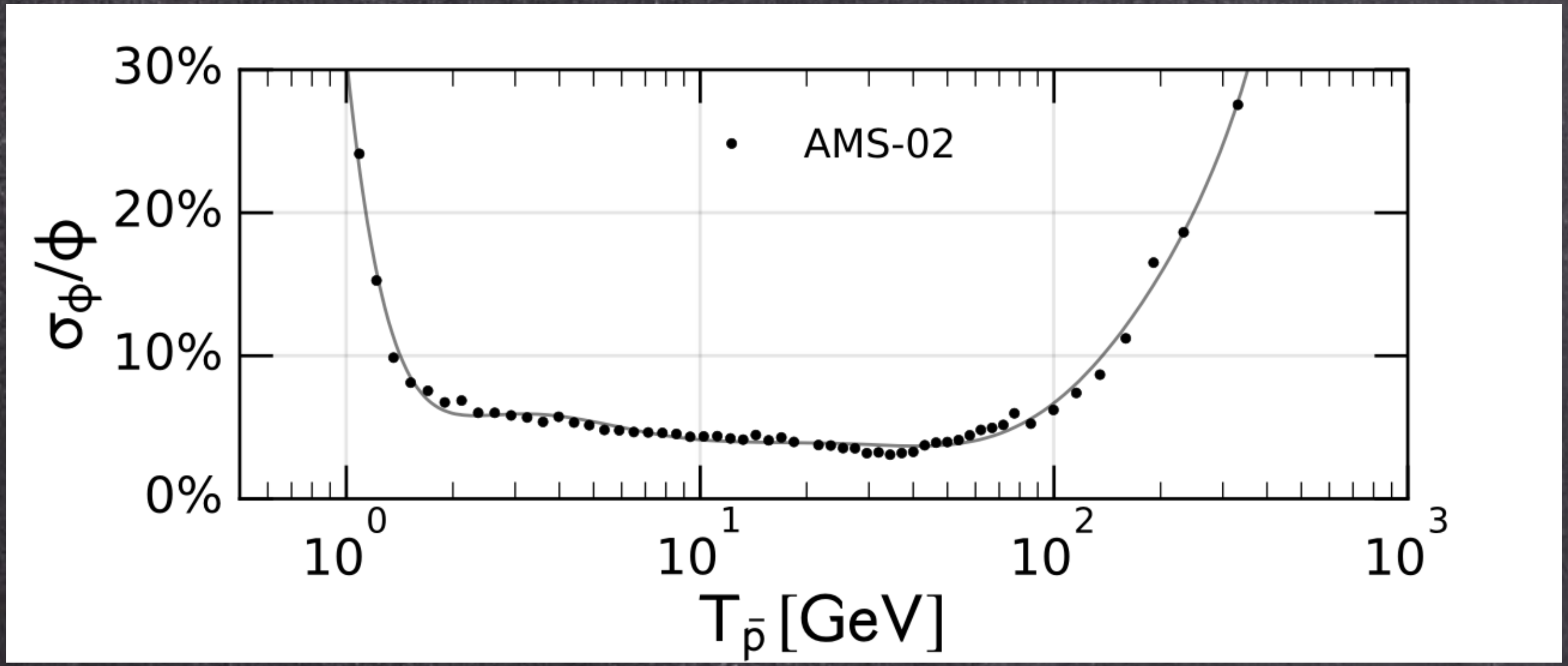
Antiproton production by inelastic scatterings

FD, Korsmeier, Di Mauro PRD 2017

$$q_{\bar{p}}^{pp}(E_{\bar{p}}) = \int_{E_{\rm th}}^{+\infty} \frac{d\sigma_{p\,p\to\bar{p}}}{dE_{\bar{p}}}(E_p, E_{\bar{p}}) n_H (4\pi\Phi_p(E_p)) dE_p$$

Source term

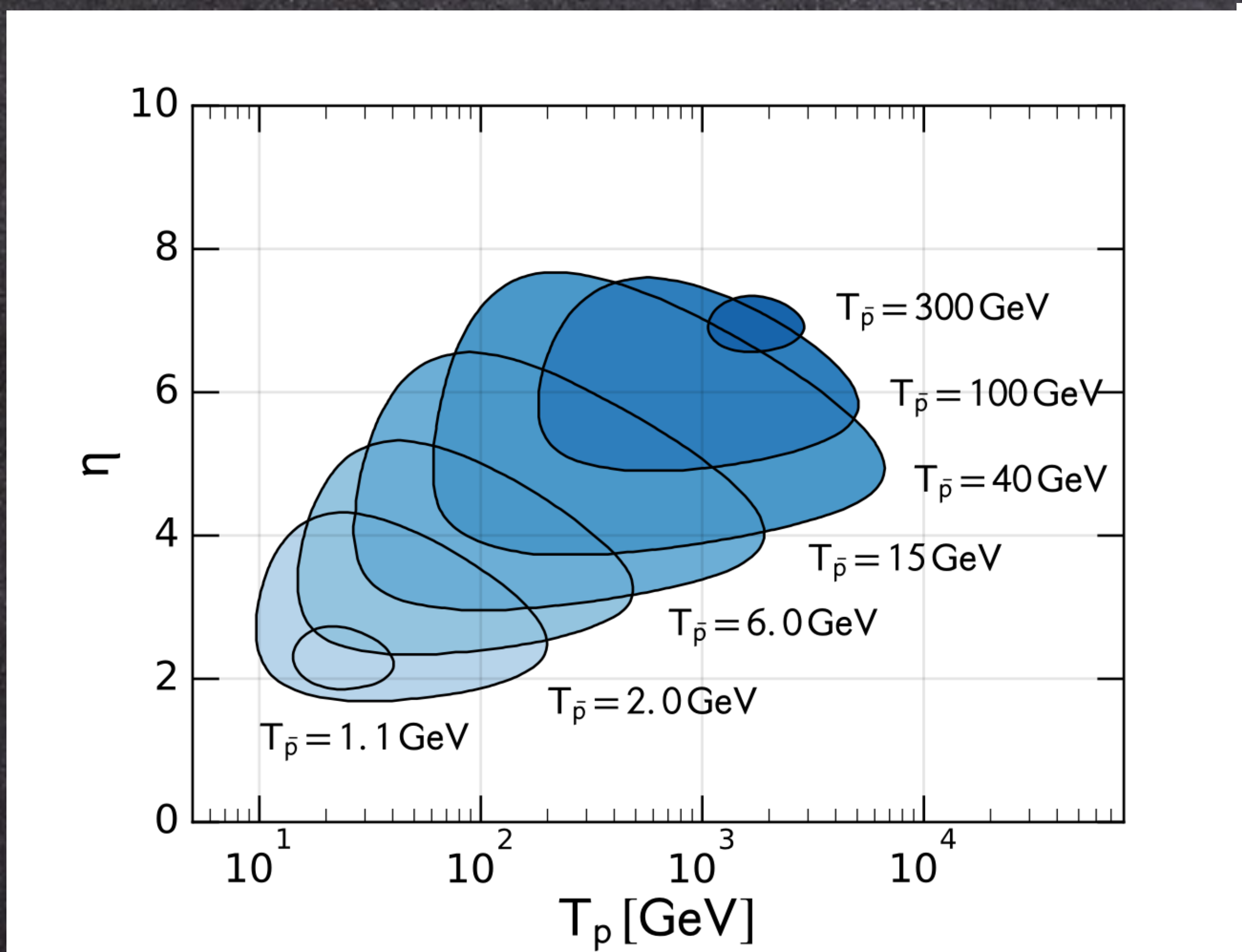
i, j = proton, helium
(both in the CRs and in the ISM)



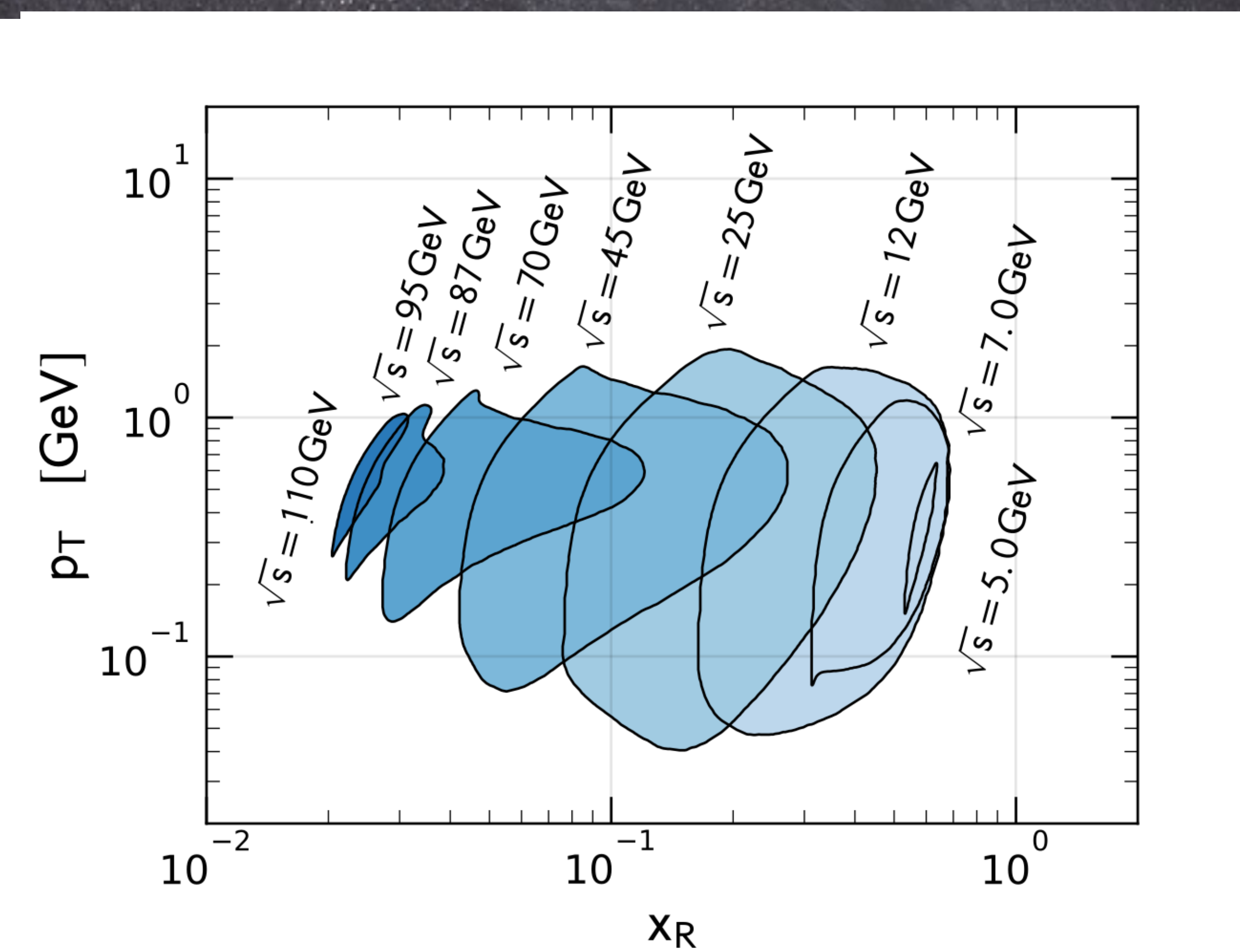
Cosmic antiproton data are very precise:
production cross sections should be known with high accuracy in order not to introduce high theoretical uncertainties

Parameter space to be covered

Fixed target



Lab frame

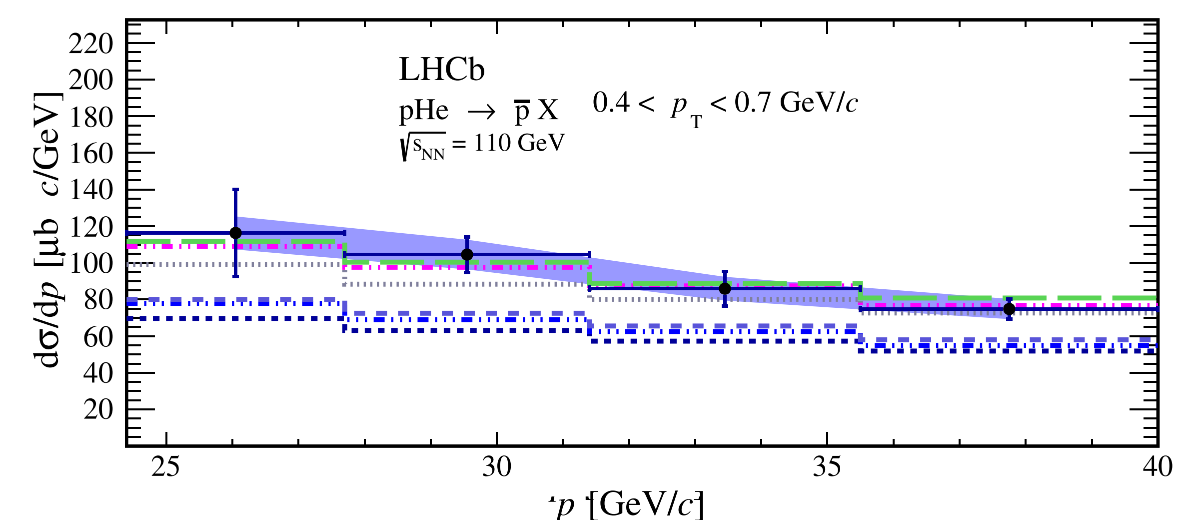


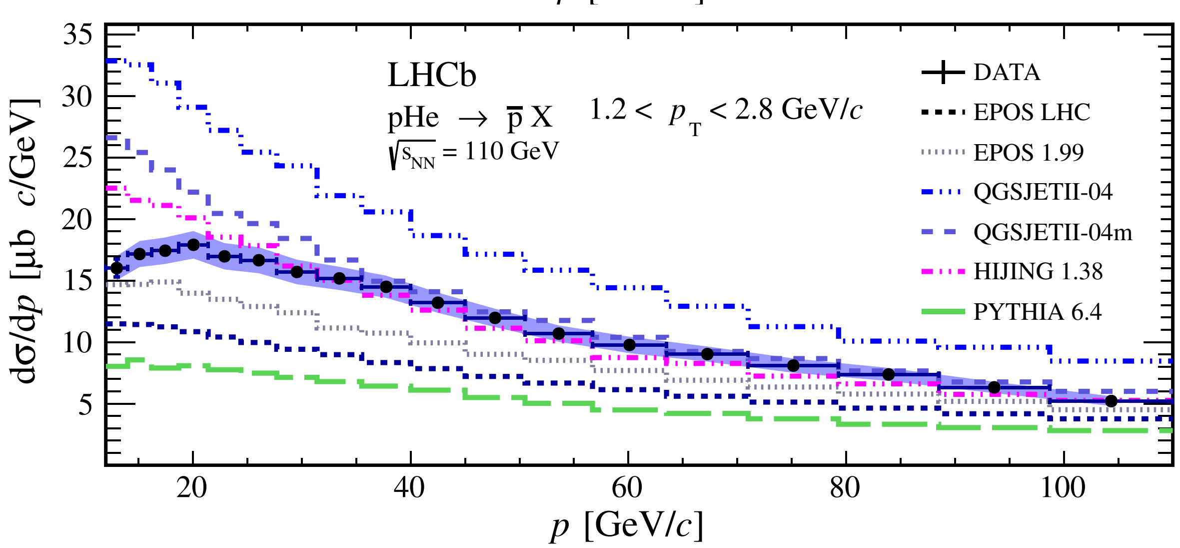
AMS02 accuracy is reached if pp -> pbar cross section is measured with 3% accuracy inside the regions, 30% outside.

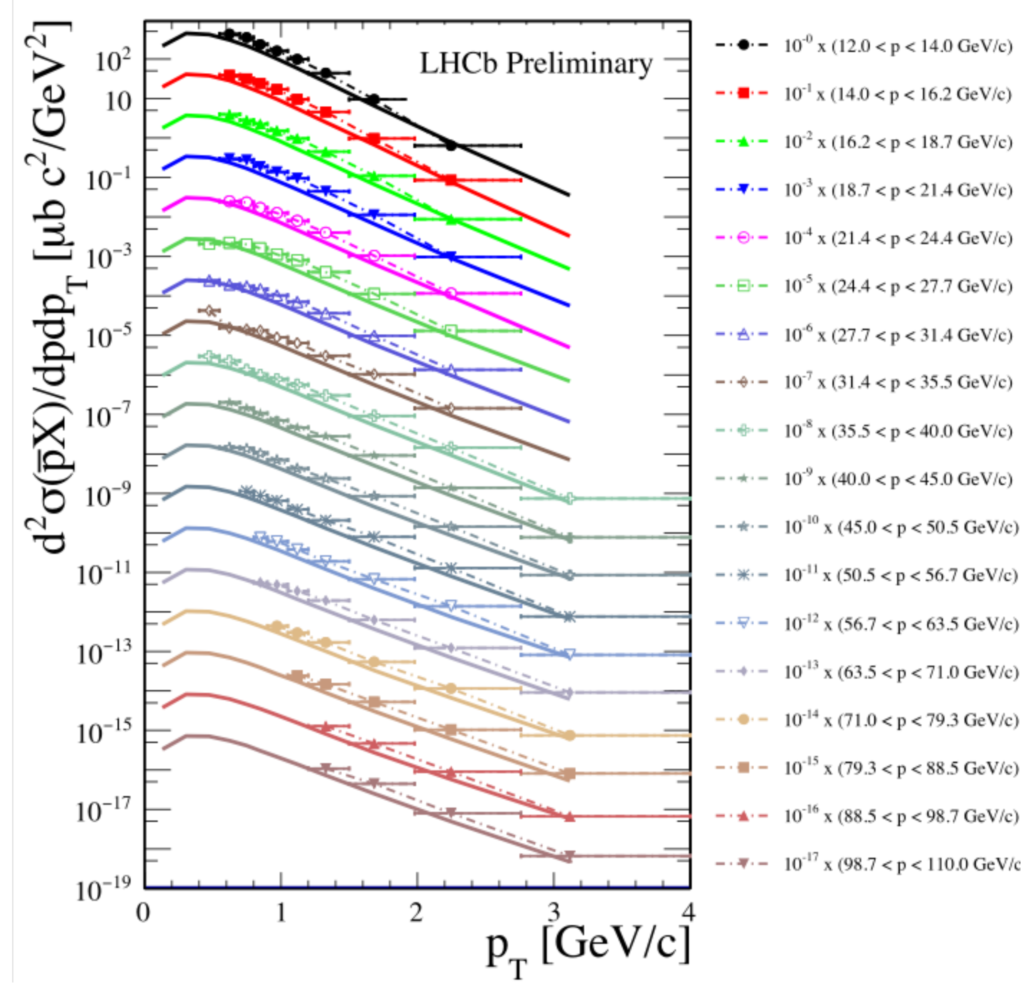
Measurement of Antiproton Production in p-He Collisions at $\sqrt{s_{NN}} = 110$ GeV

R. Aaij *et al.*[*]
(LHCb Collaboration)

The cross section for prompt antiproton production in collisions of protons with an energy of 6.5 TeV incident on helium nuclei at rest is measured with the LHCb experiment from a data set corresponding to an integrated luminosity of 0.5 nb^{-1}. The target is provided by injecting helium gas into the LHC beam line at the LHCb interaction point. The reported results, covering antiproton momenta between 12 and 110 GeV/c, represent the first direct determination of the antiproton production cross section in p-He collisions, and impact the interpretation of recent results on antiproton cosmic rays from space-borne experiments.



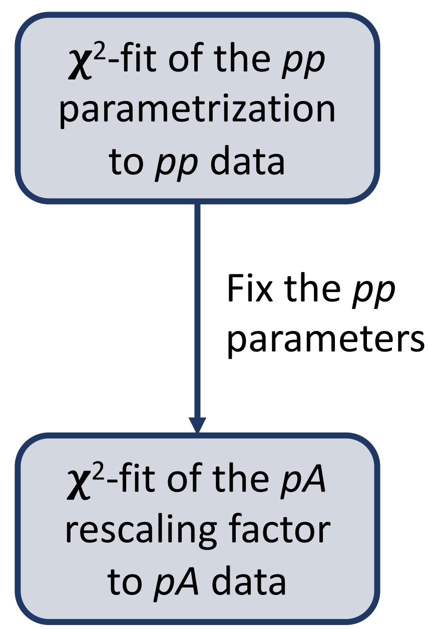




Re-analysis of the cross section parameterization

- 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*



Param. I

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

Param. II

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

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

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

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

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

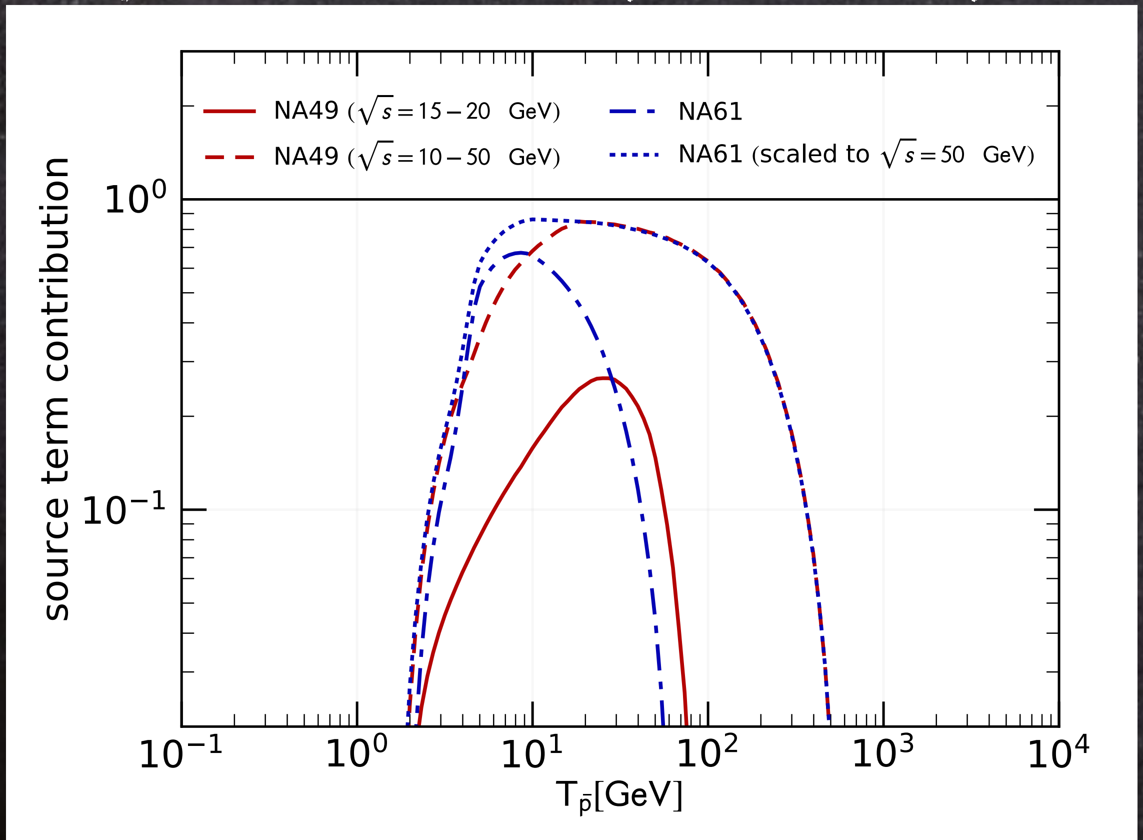
pHe -> pbar + X

LHCb (Graziani et al. Moriond 2017)

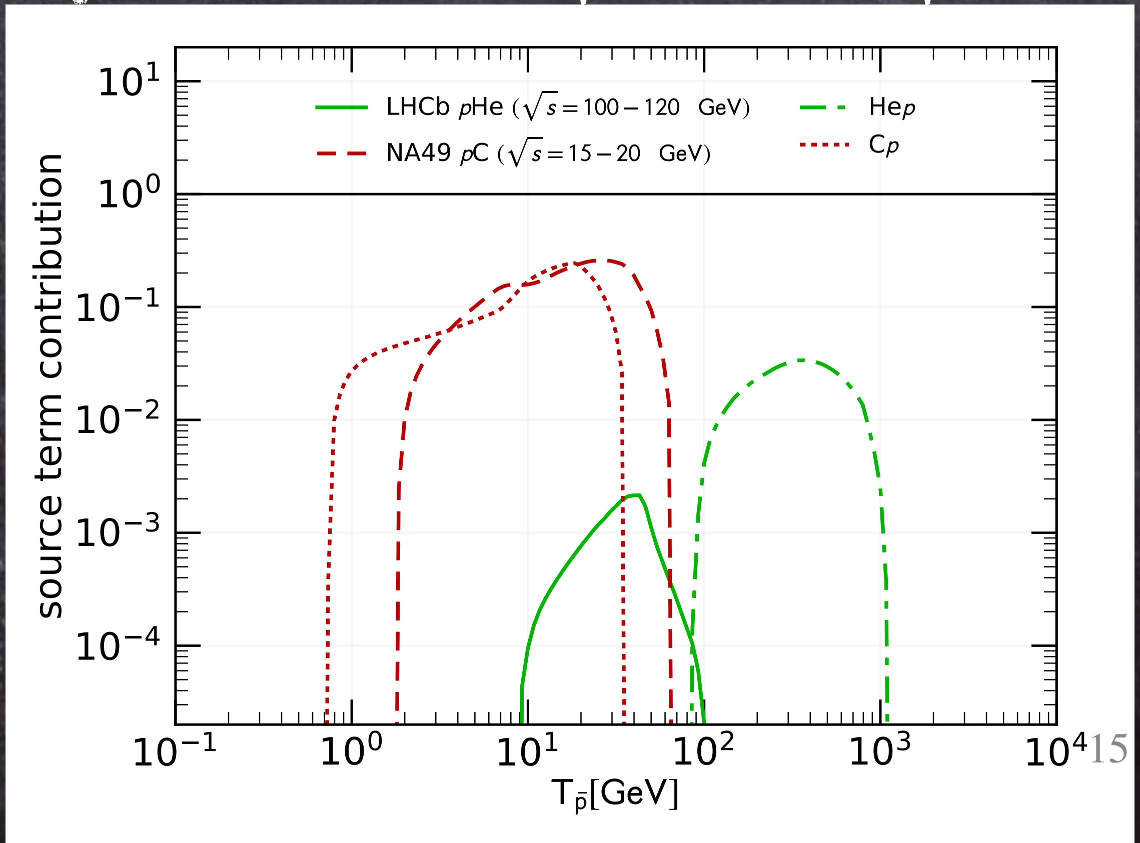
$\sqrt{s}$ = 110 GeV

T_p = 6.5 TeV

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



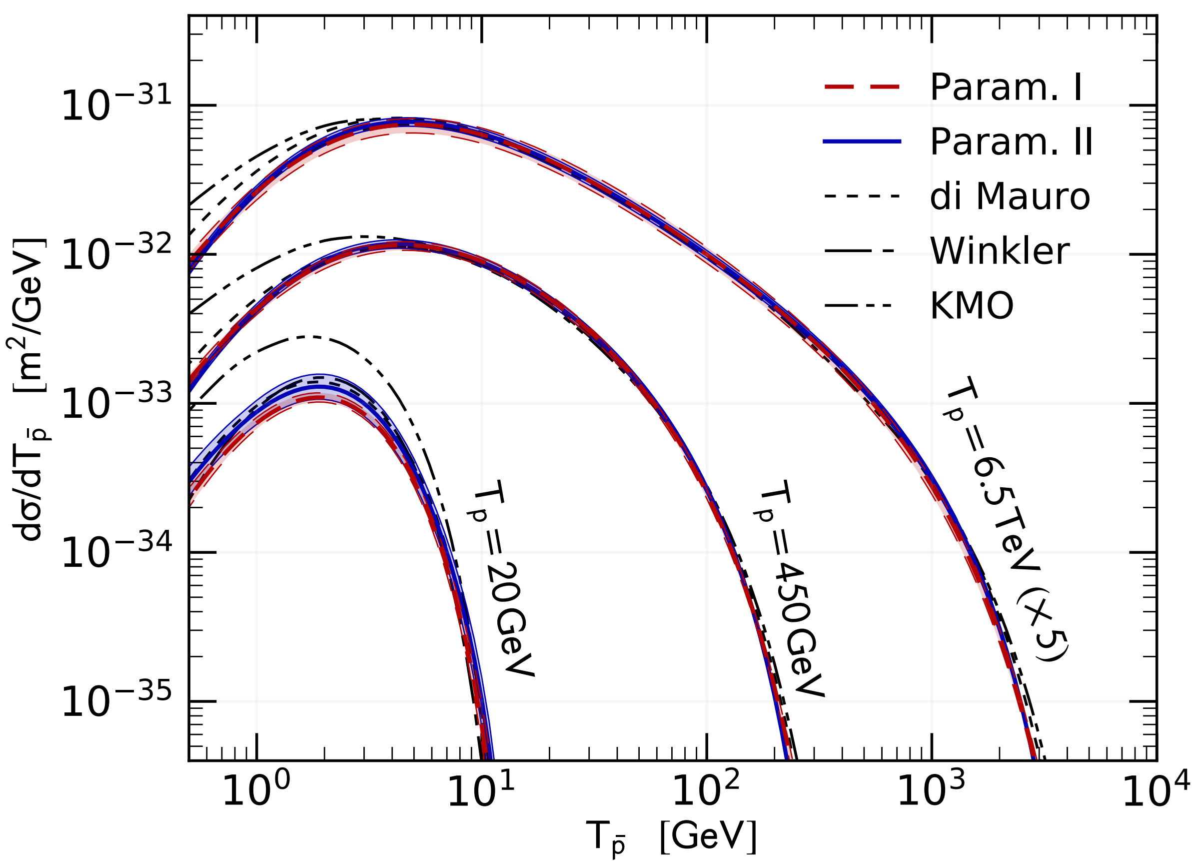
Fraction of the p-nucelus source term covered by the kinematical parameters space



pp—> pbar+X production cross sections

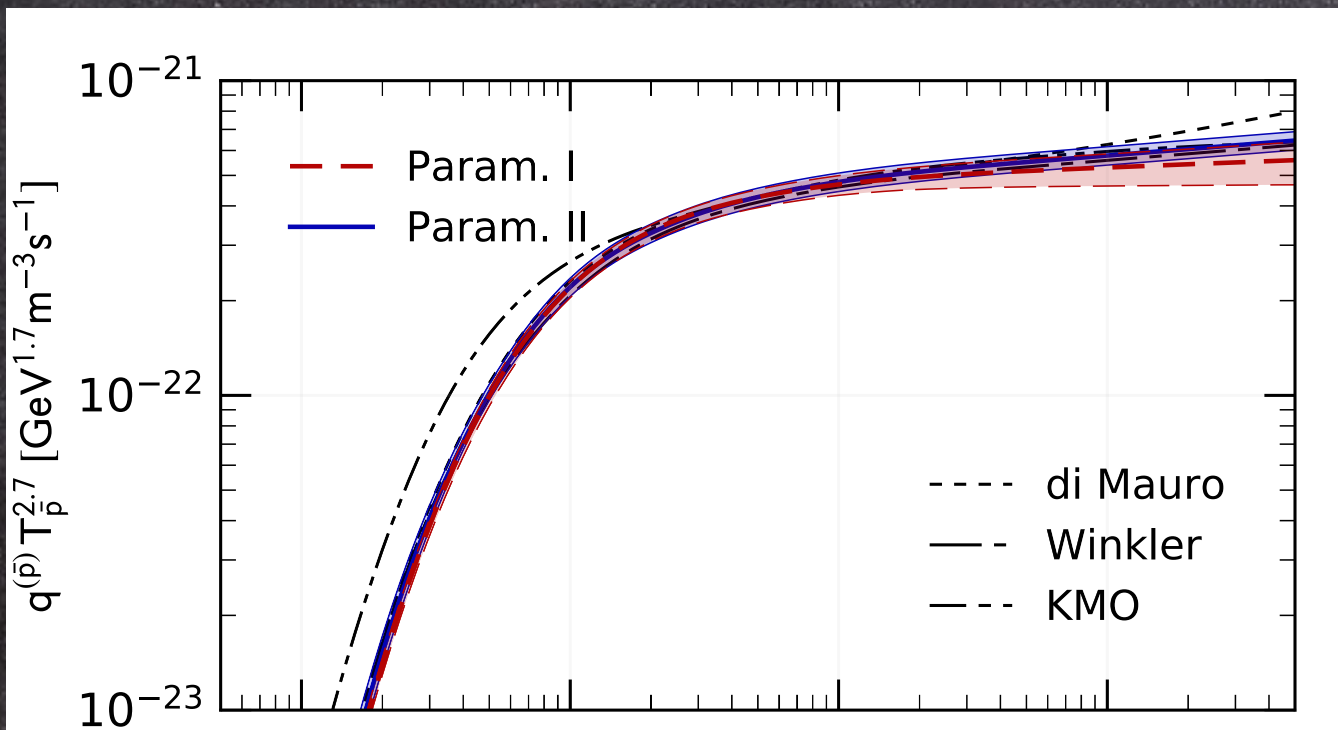
FD, Korsmeier, Di Mauro PRD 2018

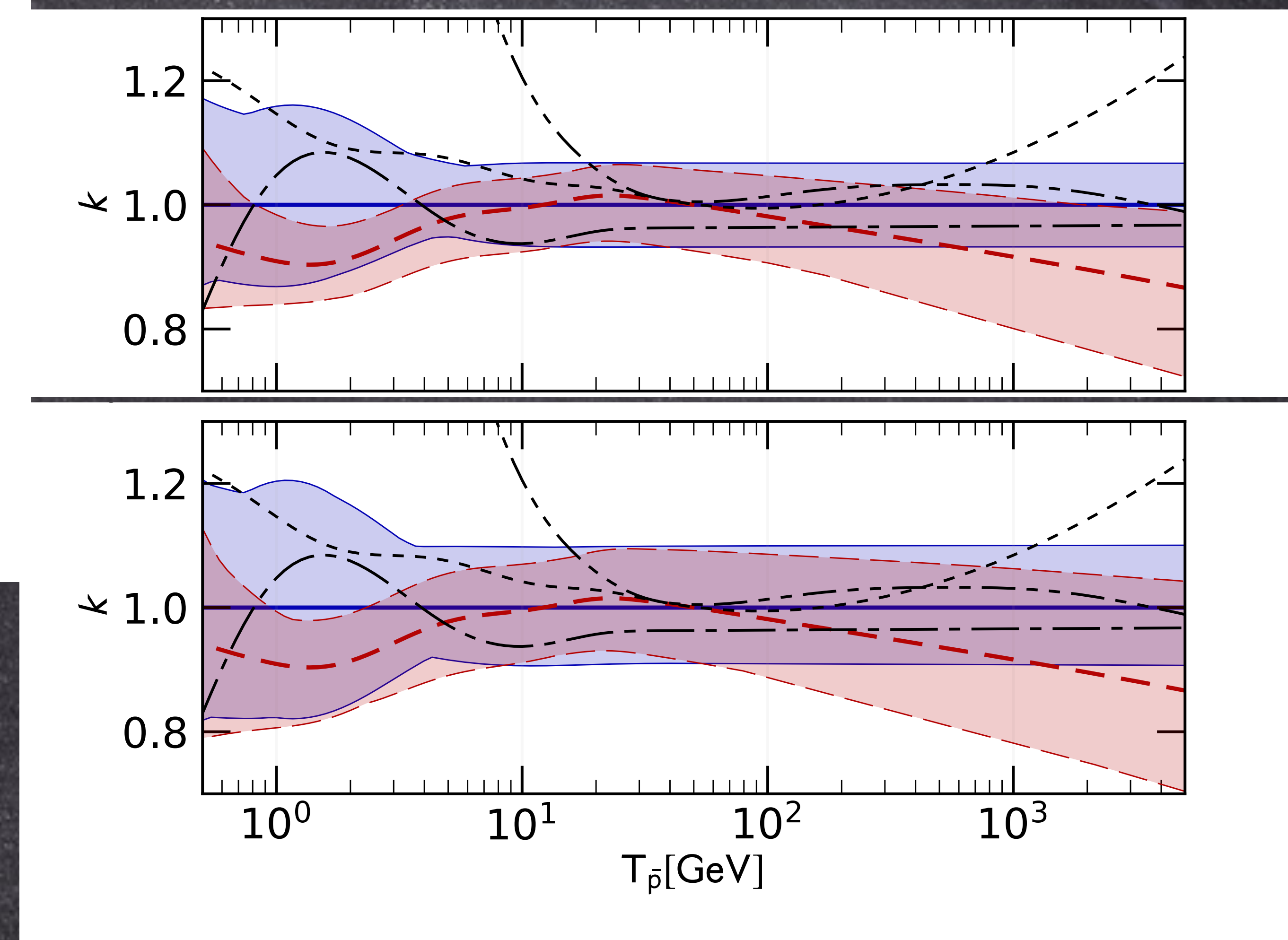
$$q_{ij}(T_{\bar{p}}) = \int_{T_{\rm th}}^{\infty} dT_i \; 4\pi \, n_{{\rm ISM},j} \, \phi_i(T_i) \, \boxed{\frac{d\sigma_{ij}}{dT_{\bar{p}}}(T_i, T_{\bar{p}})}$$



Good agreement for T > 10 GeV

proton-proton -> antiproton + X





	$\sqrt{s}$ [GeV]	σ_{scale}	I	II	Ref.
	17.3	6.5%	×	×	[26]
	7.7, 8.8, 12.3, 17.3	5%	×	×	[24]
t.	6.1, 6.7	10%	×	×	[36]
	200	10%	×		[38]

Still, the pp channel brings at least 10% uncertainty.

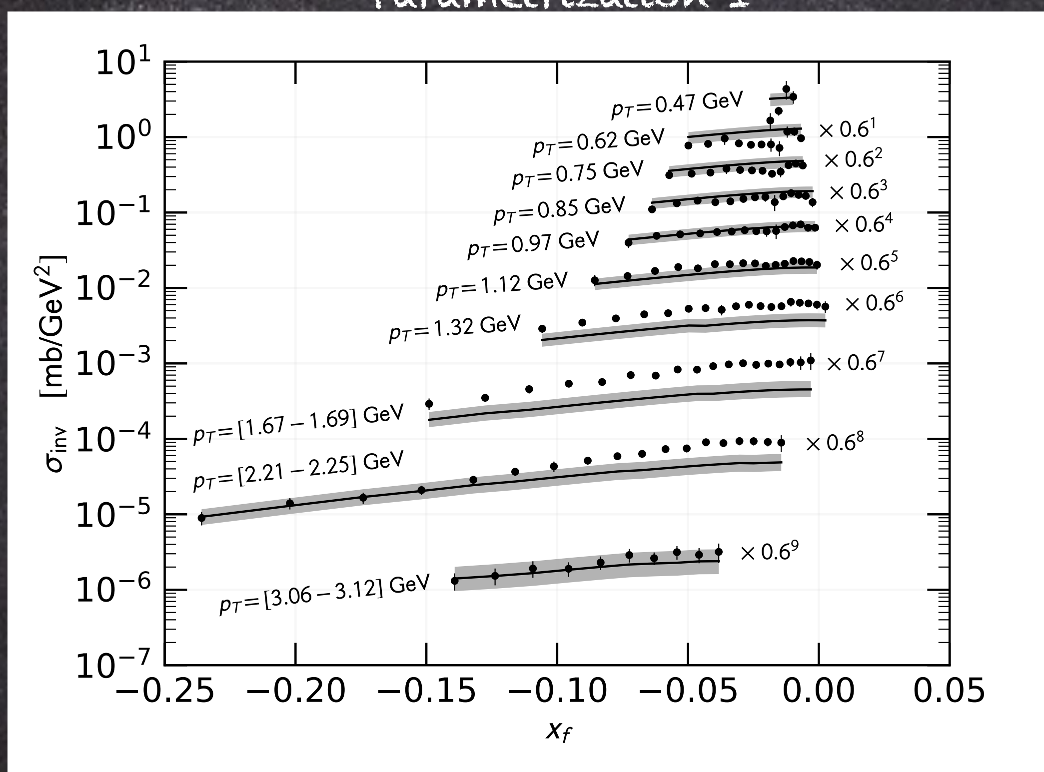
Systematics ...

High-energy data analysis

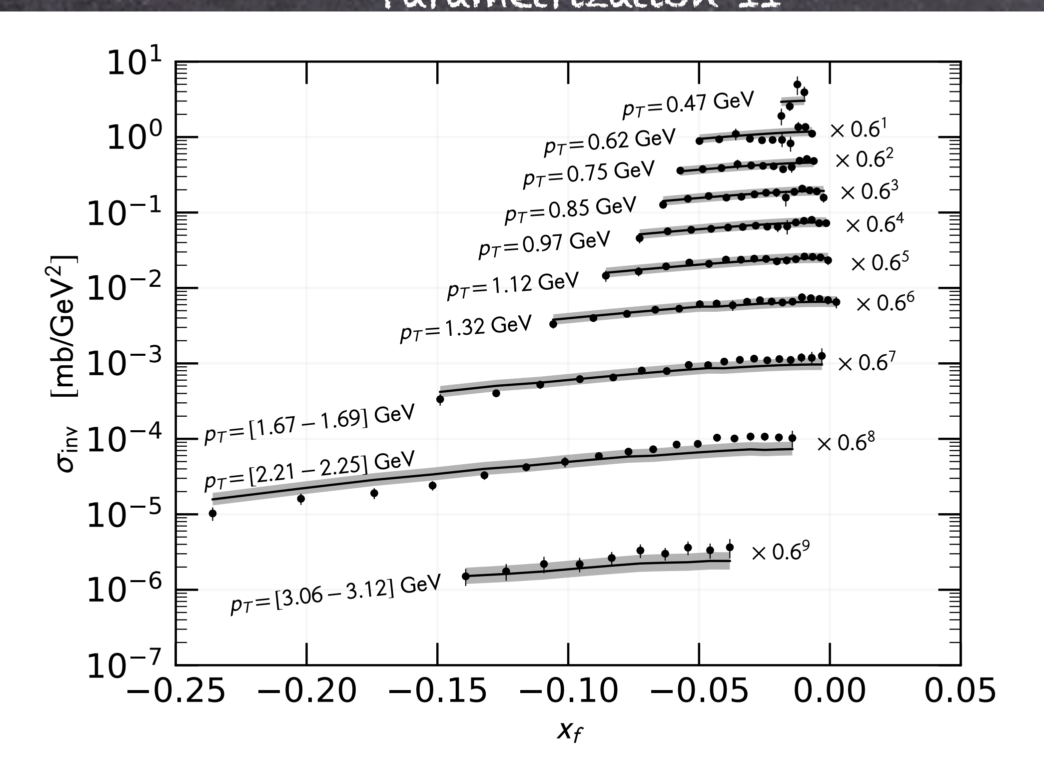
Korsmeier, FD, Di Mauro, PRD 2018

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



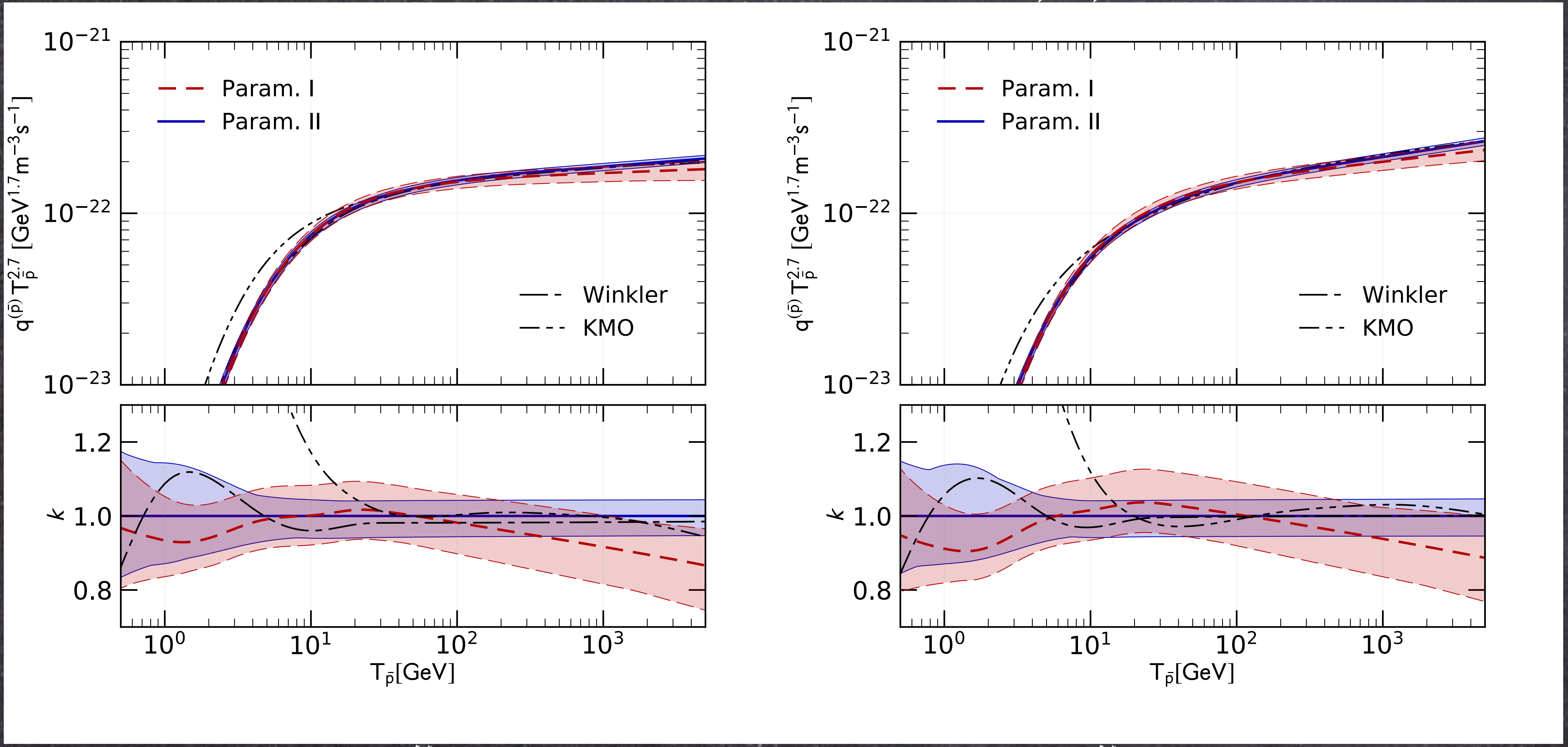
Parametrization II



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

The nuclear antiproton source spectrum

Korsmeier, FD, Di Mauro PRD i2018



p-He

He-p

Param II is preferred by the fits.

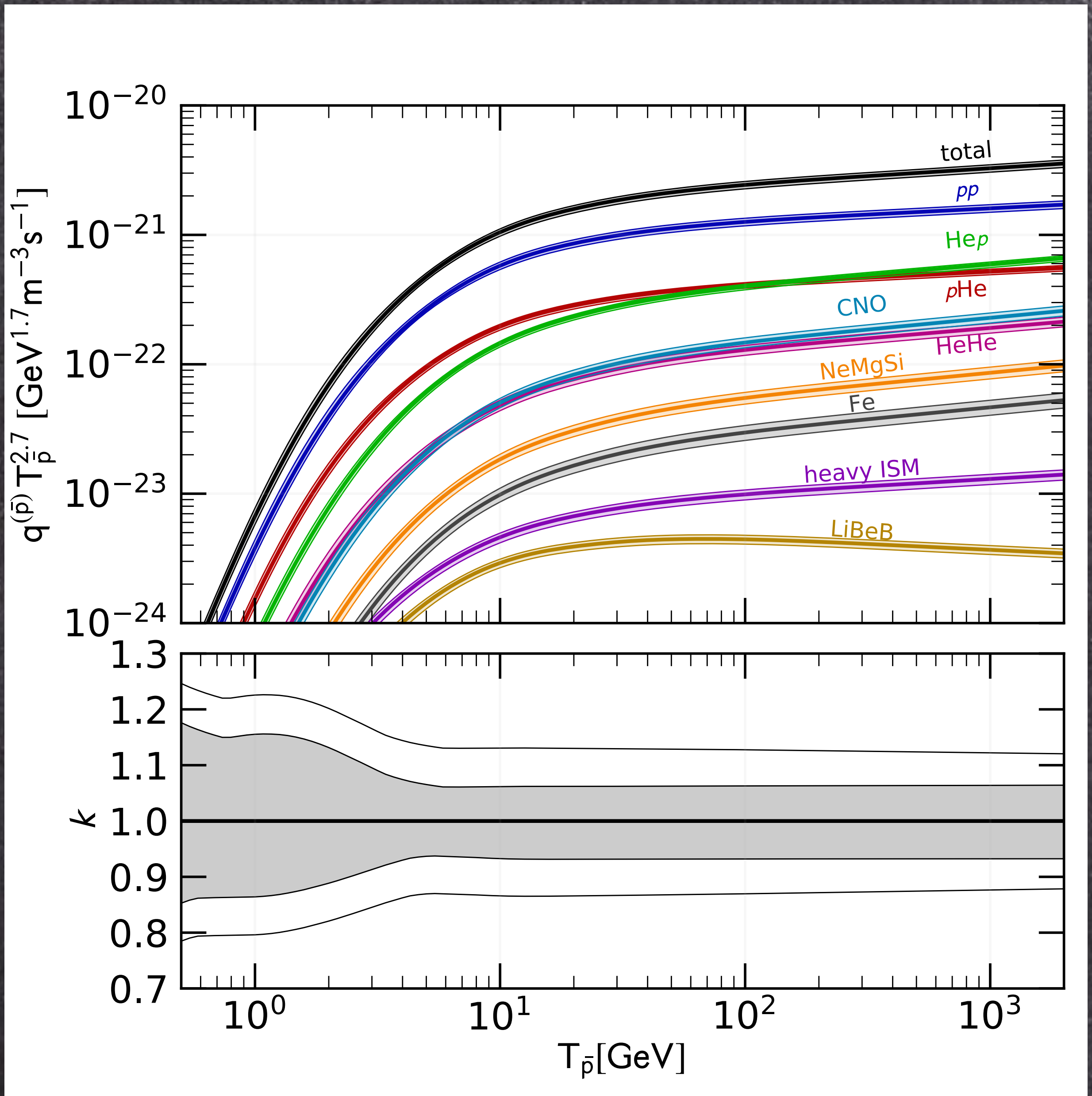
The effect of LHCb data is to select a h.e. trend of the pbar source term.

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



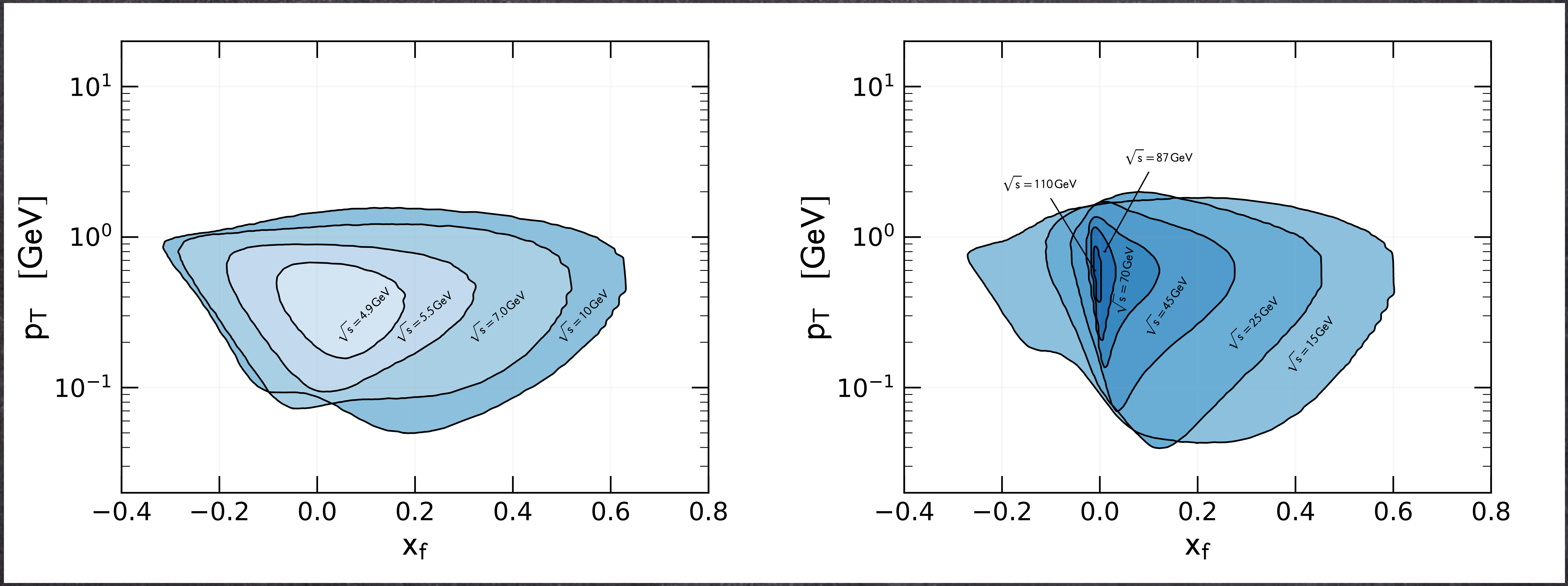
with uncertainties in the hyperon correction and isospin violation

$$\Delta_{\mathrm{IS}} = \frac{c_1^{\mathrm{IS}}}{1 + (s/c_2^{\mathrm{IS}})^{c_3^{\mathrm{IS}}}}$$

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

Higher uncertainties at low energies

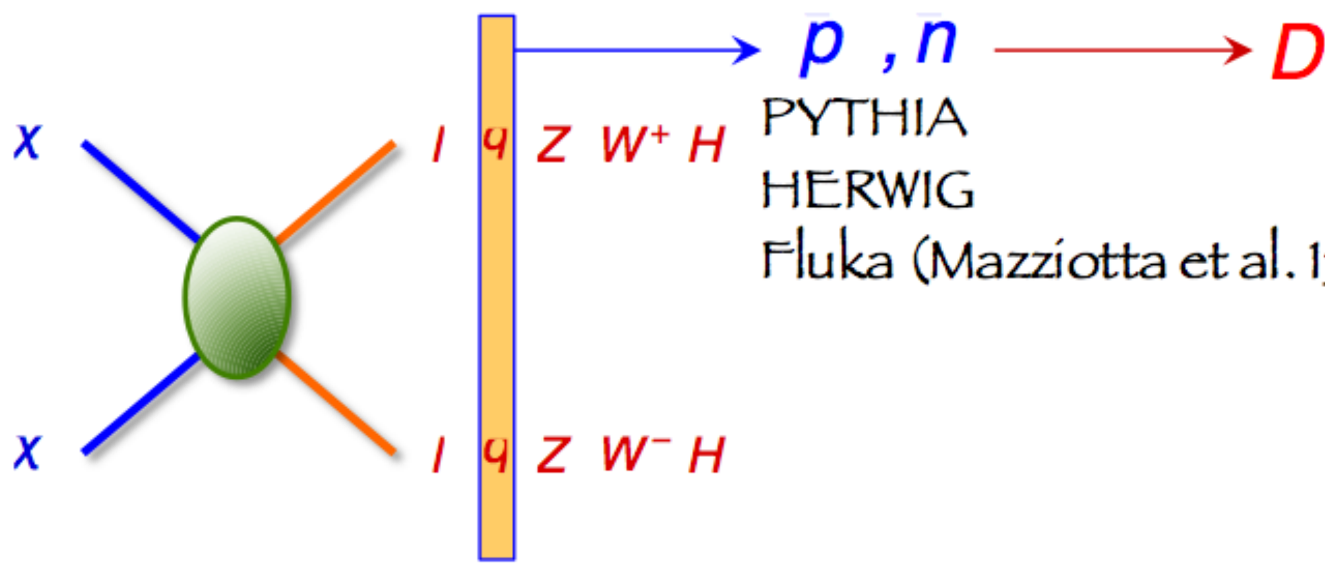
For next generation experiments



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

The case for antideuterons

Antideuteron from Dark Matter particles



PYTHIA
HERWIG
Fluka (Mazziotta et al. 1510.04623)

$$\frac{dN_{\bar d}}{dT_{\bar d}} = (4\pi E_{\bar d}\, k_{\bar d})\, F_{\bar d}(\sqrt{s}, k_{\bar d})$$

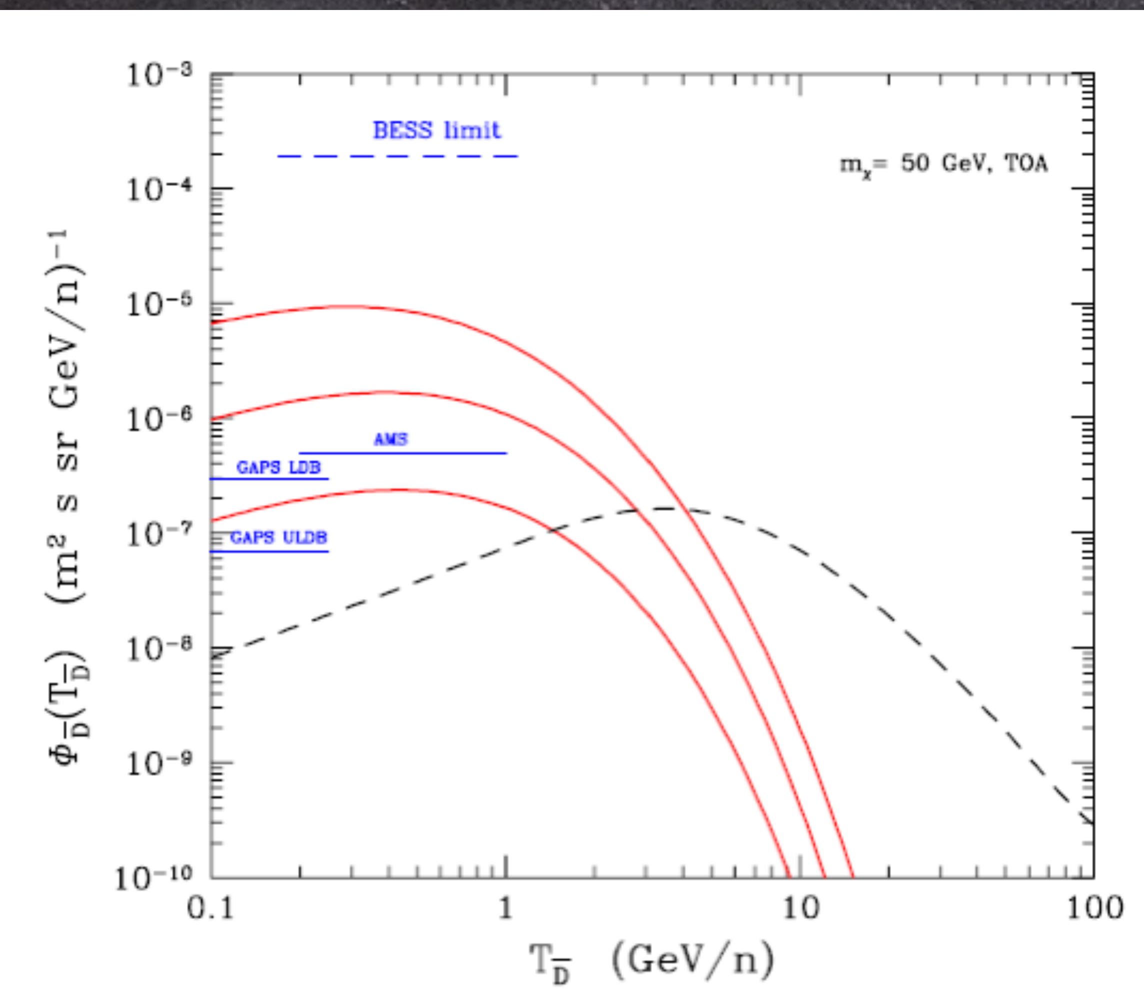
$$F_{\bar d}(\sqrt{s}, \vec{k}_{\bar d}) = \int F_{(\bar p \bar n)}(\sqrt{s}, \vec{k}_{\bar p}, \vec{k}_{\bar n})\, \mathcal{C}(\sqrt{s}, \vec{k}_{\bar p}, \vec{k}_{\bar n} | \vec{k}_{\bar d})\, d^3\vec{k}_{\bar n}\, d^3\vec{k}_{\bar n}$$

Coalescence function

Flux of antideuterons: DM vs secondary one

FD, Fornengo, SalFD, Fornengo, salati PRD 2001; FD, Fornengo, Maurin PRD 2008;
Kadastik, Raidal, Strumia PLB2010; Ibarra, Wild JCAP2013; Fornengo, Maccione, Vittino JCAP 2013; ...ati PRD (2000) ADD

In order for fusion to take place,
the two antinucleons must have low kinetic energy



$$\frac{dN_{\bar{D}}}{dE_{\bar{D}}} = \left(\frac{4\,P_{\rm coal}{}^3}{3\,k_{\bar{D}}}\right)\left(\frac{m_{\bar{D}}}{m_{\bar{p}}\,m_{\bar{n}}}\right)\sum_{\rm F,h} B_{\chi \rm h}^{(\rm F)}\left\{\frac{dN_{\bar{p}}^{\rm h}}{dE_{\bar{p}}}\left(E_{\bar{p}} = \frac{E_{\bar{D}}}{2}\right)\right\}^2$$

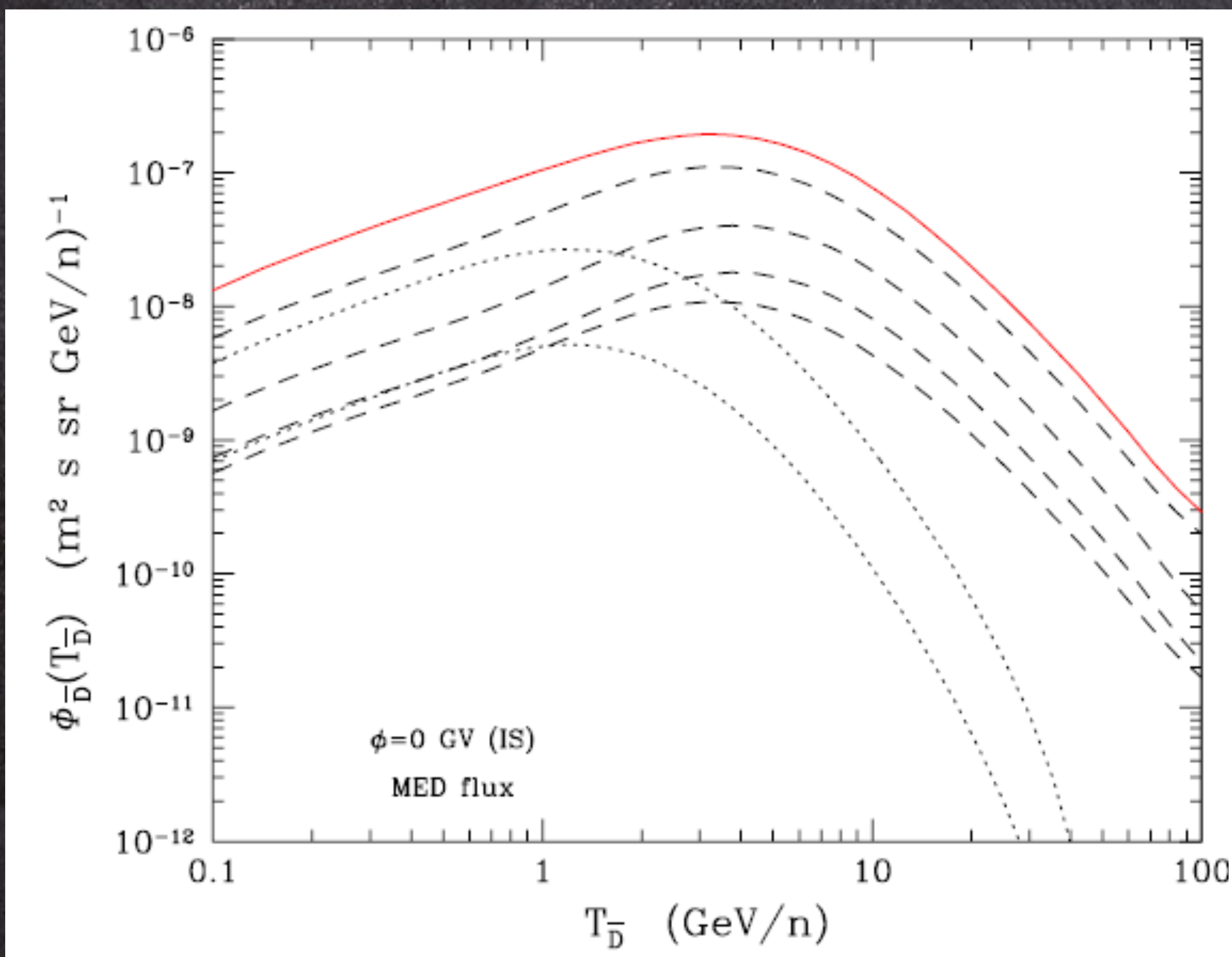
Kinematics of spallation reactions prevents the formation of very low antiprotons (antineutrons).

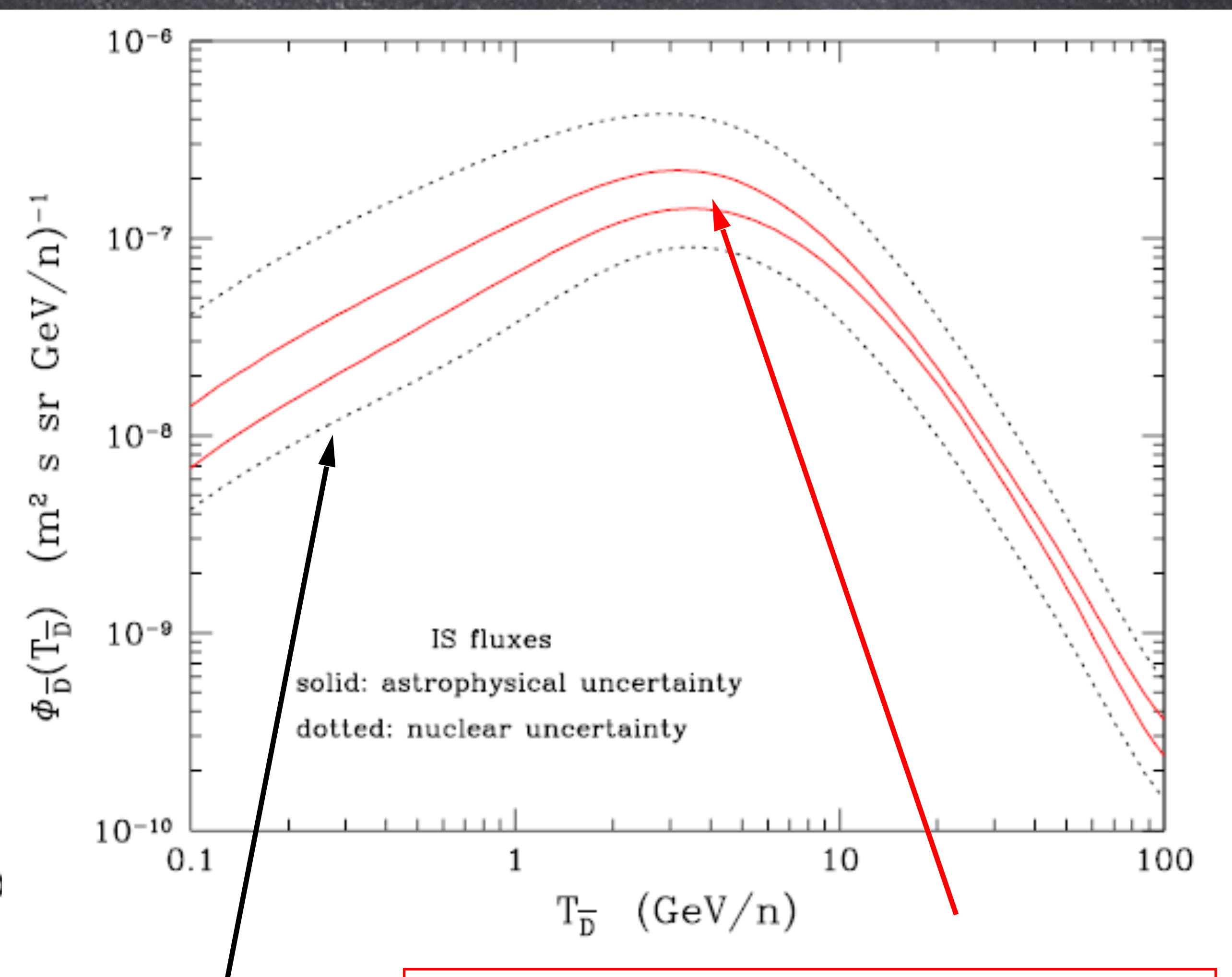
At variance, dark matter annihilates almost at rest

Secondary antideuterons

FD, Fornengo, Maurin PRD 2008

Contributions to secondaries



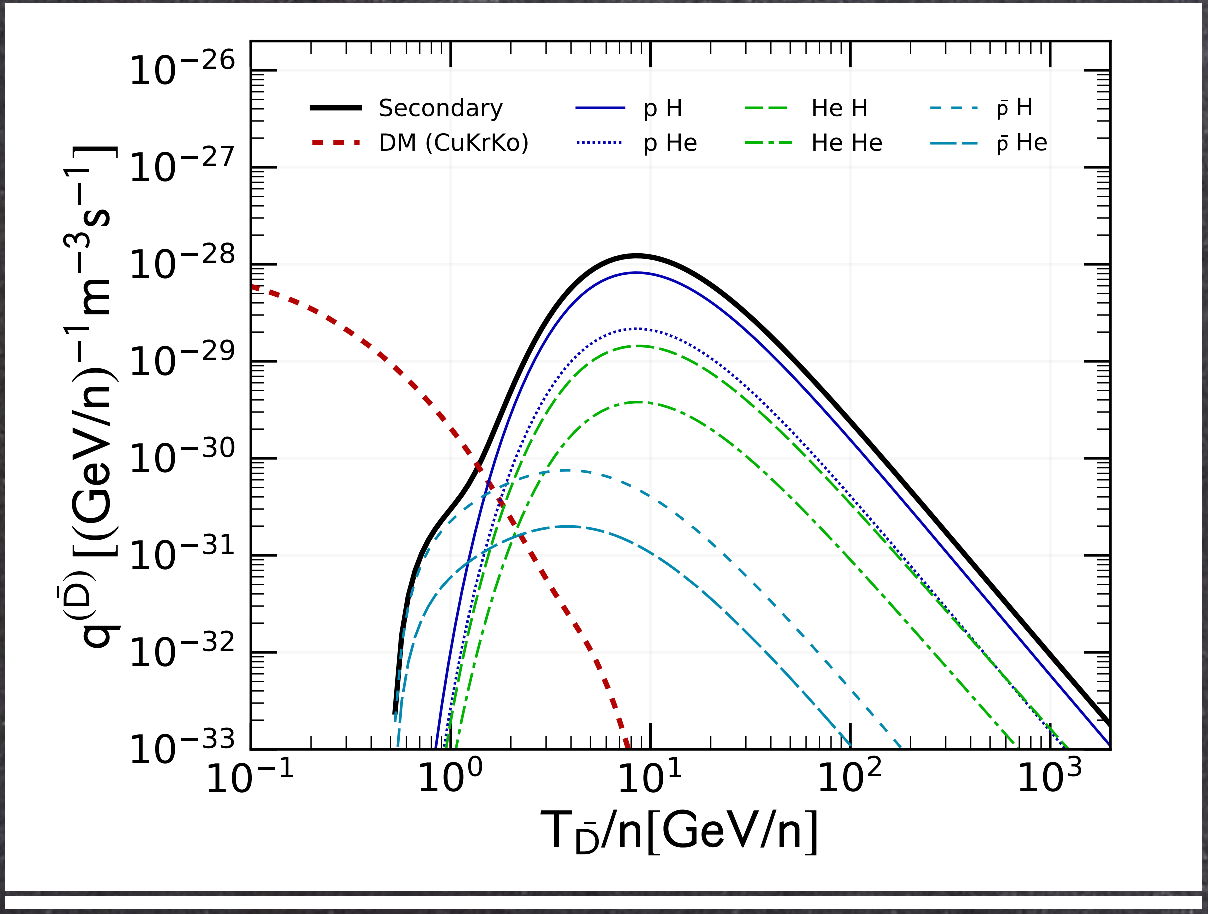


p-p, p-He,
He-H, He-He
H- pbar, He-pbar

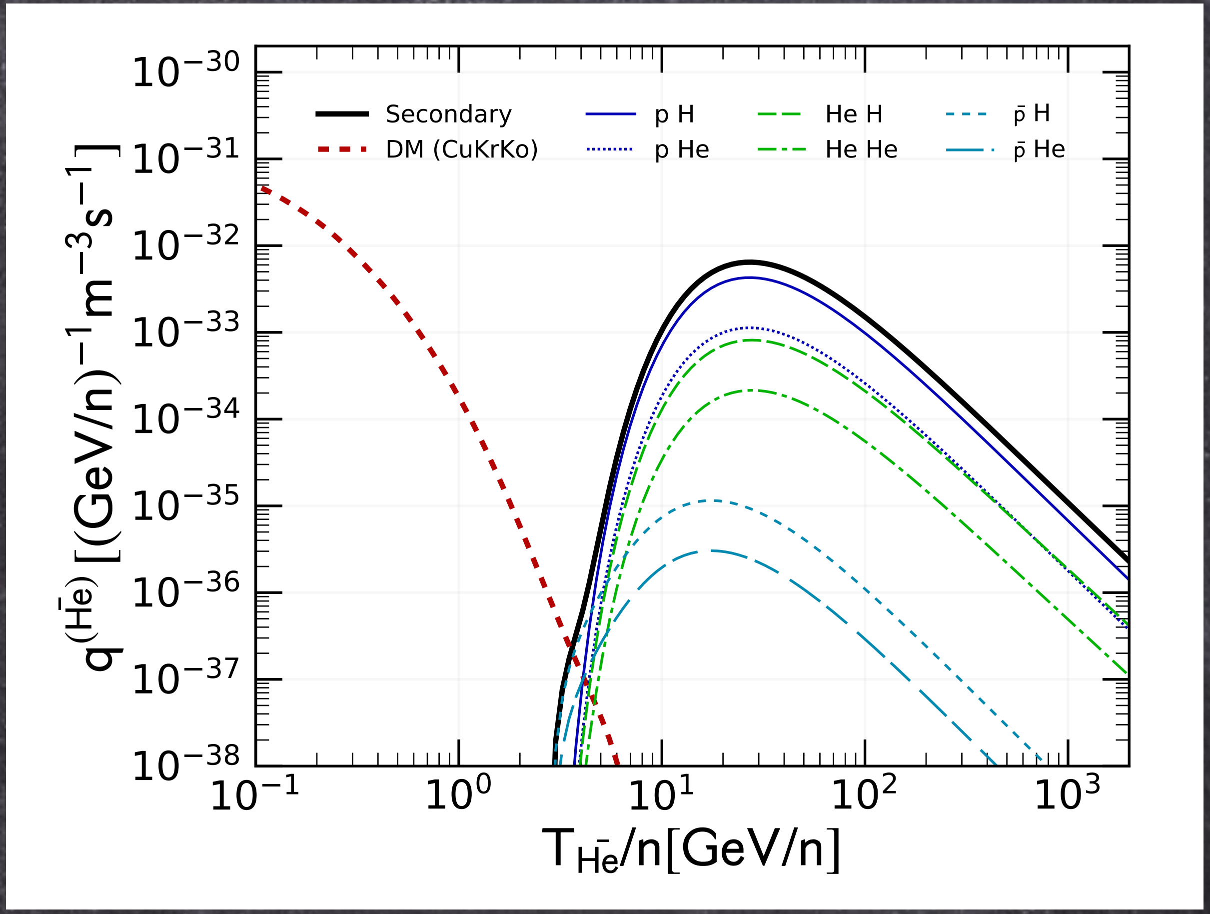
Propagation uncertainties
Compatibility with B/C

Nuclear uncertainties
Production cross sections & P_{coal}
Production from antiprotons
Non-annihilating cross sections

The antideuteron DM source



anti-D



anti-^{3}He

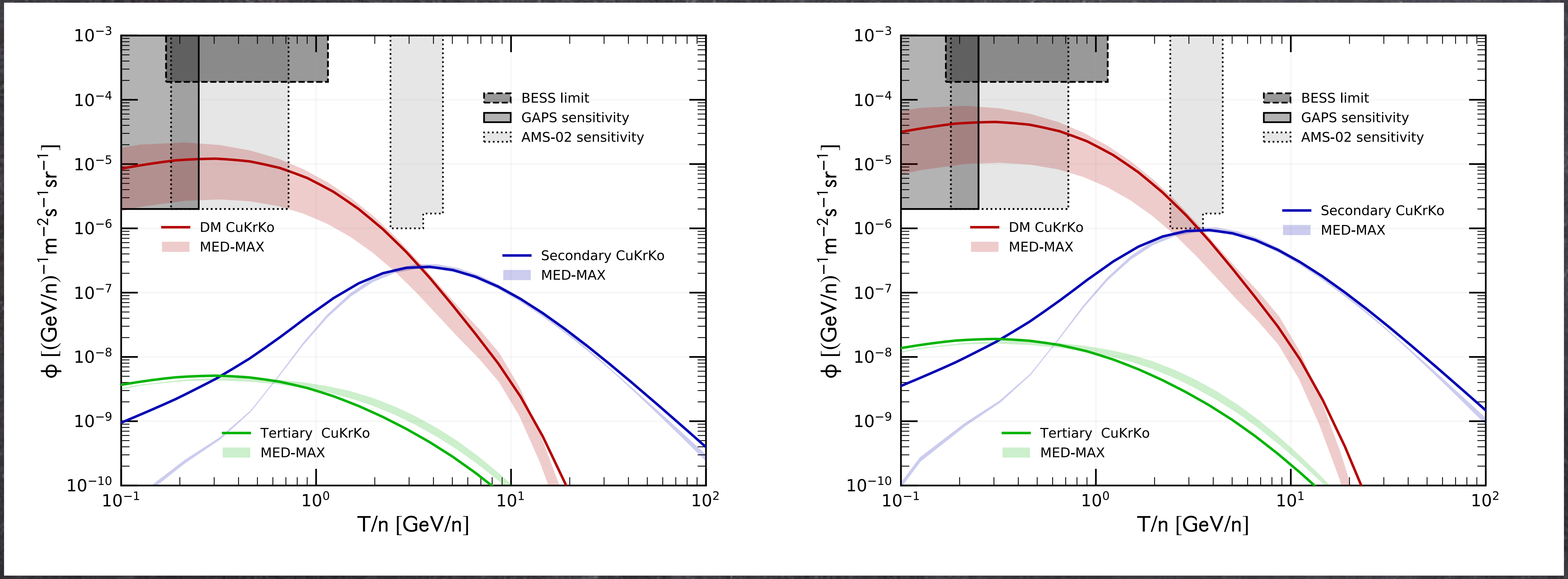
The window S/B is wider for ^{3}He, in spite of 4 o.o.f. lower spectra

Possible antideuteron verification of Dark Matter hint in antiprotons

FD, Fornengo, Korsmeier, PRD 2018

P_{coal} = 124 (62) MeV

P_{coal} = 248 (124) MeV



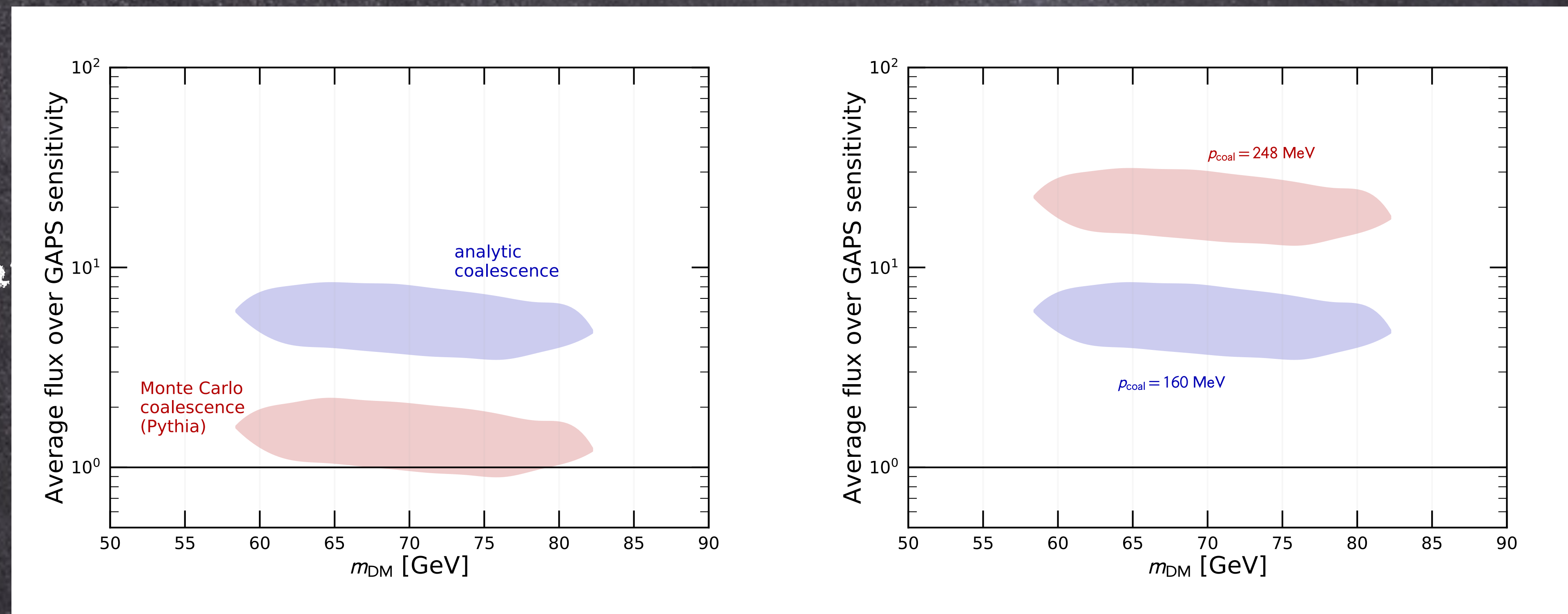
DM antiprotons possibly hidden in AMS data are potentially testable by AMS and GAPS

Uncertainties on the detection predictions

FD, Fornengo, Korsmeier, 1711.08465 subm

Coalescence Model:
a factor > 10
(does not affect pbar flu

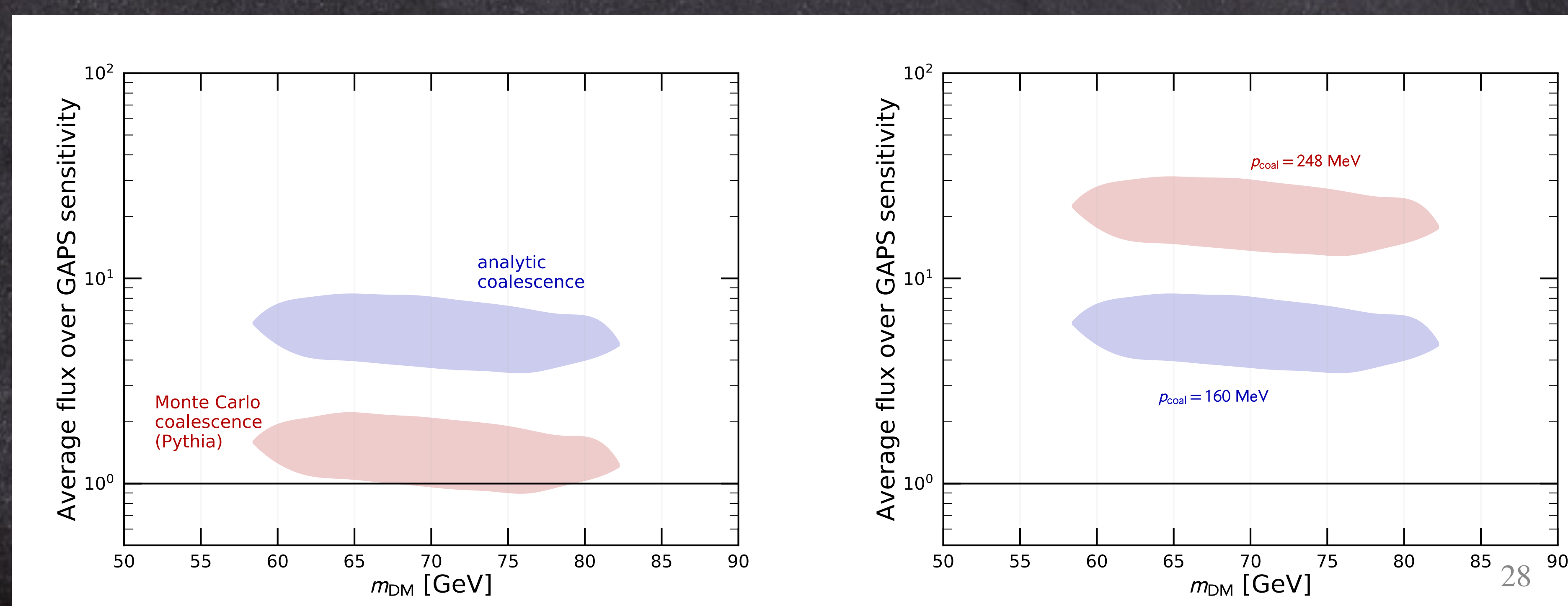
Propagation models:
a factor > 10
(affects pbar flux)



(a) Coalescence model

(b) Coalescence momentum

See talks by D. Maurin, Engelbrecht, De Felice



If it were DM

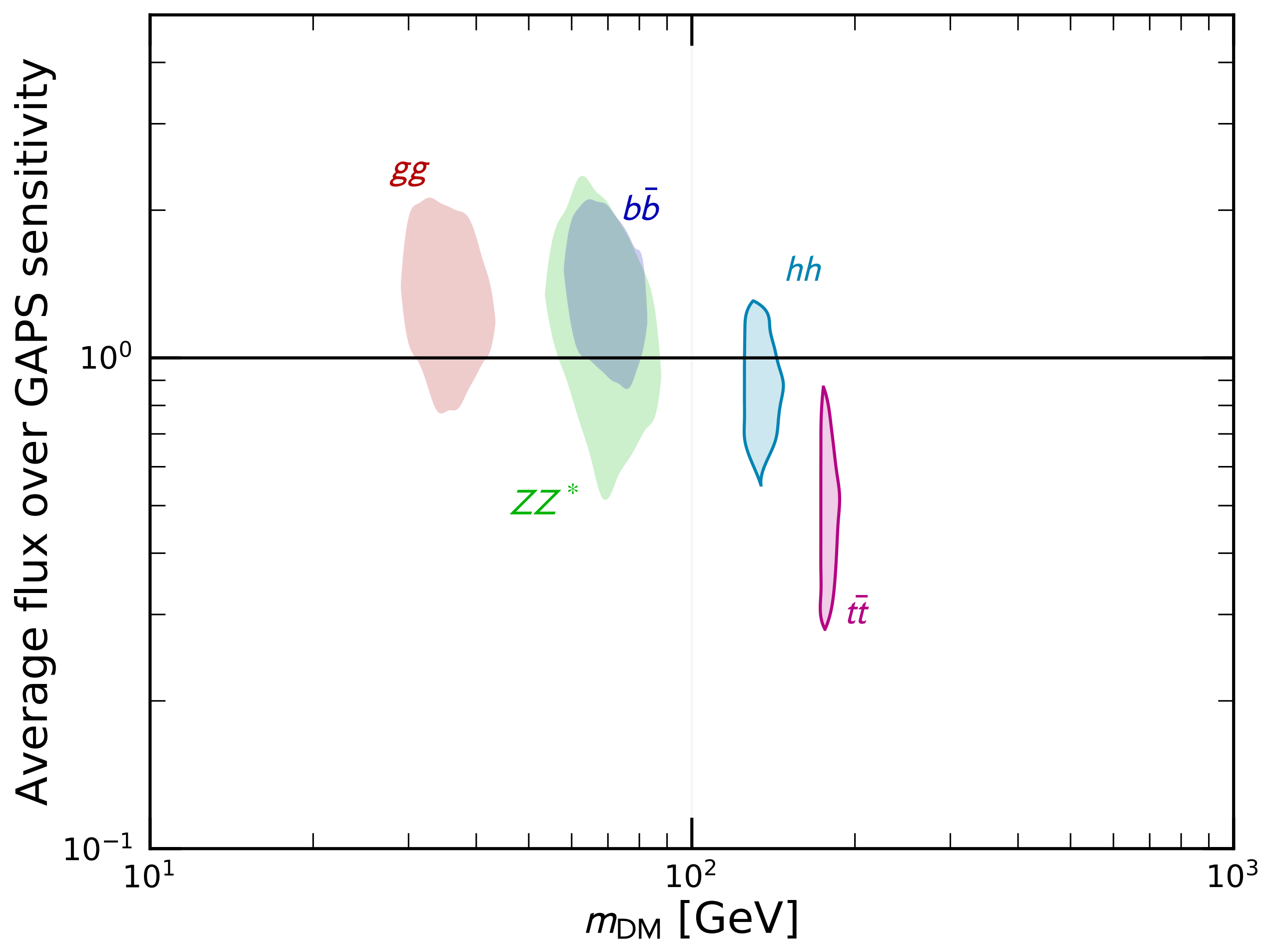
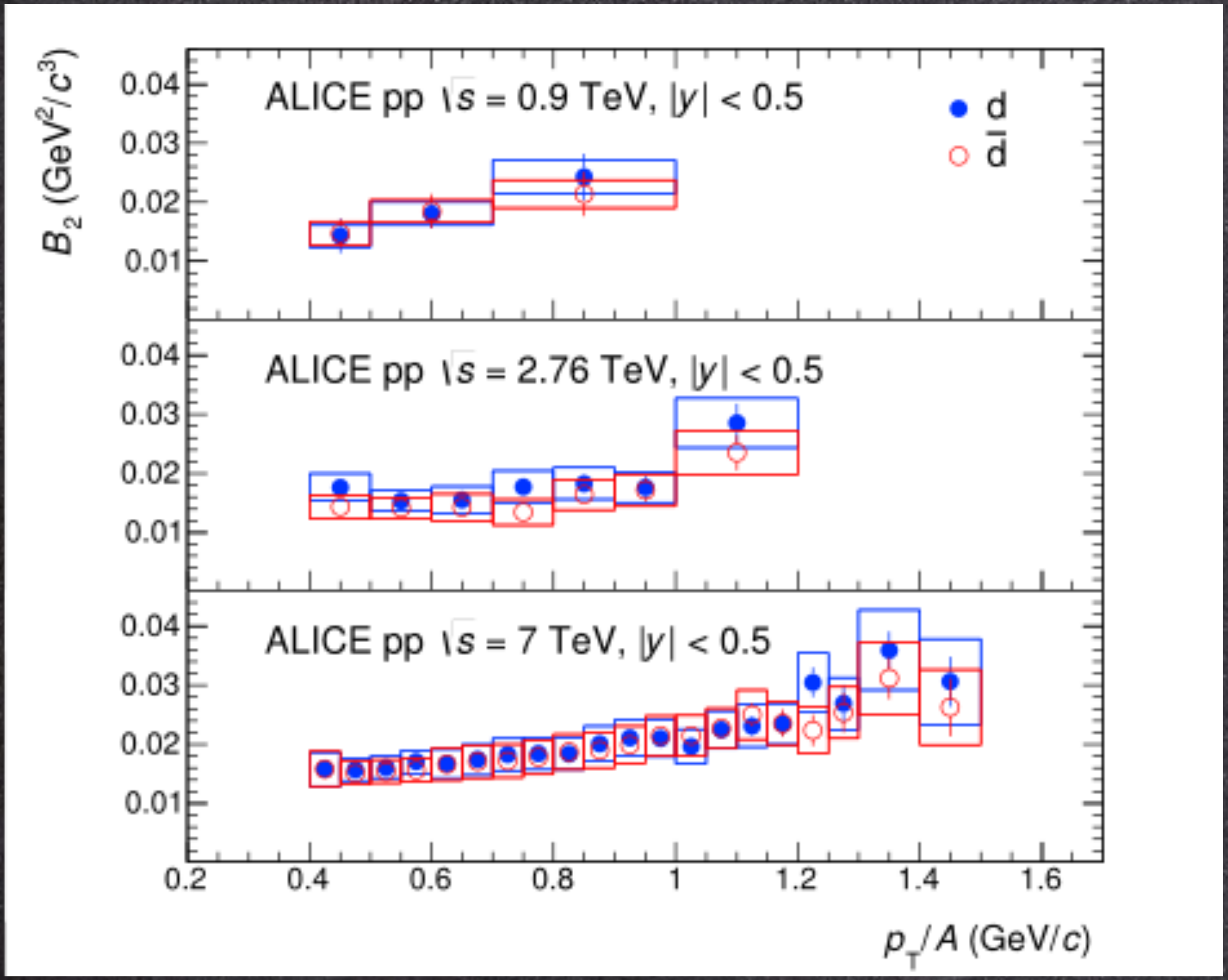


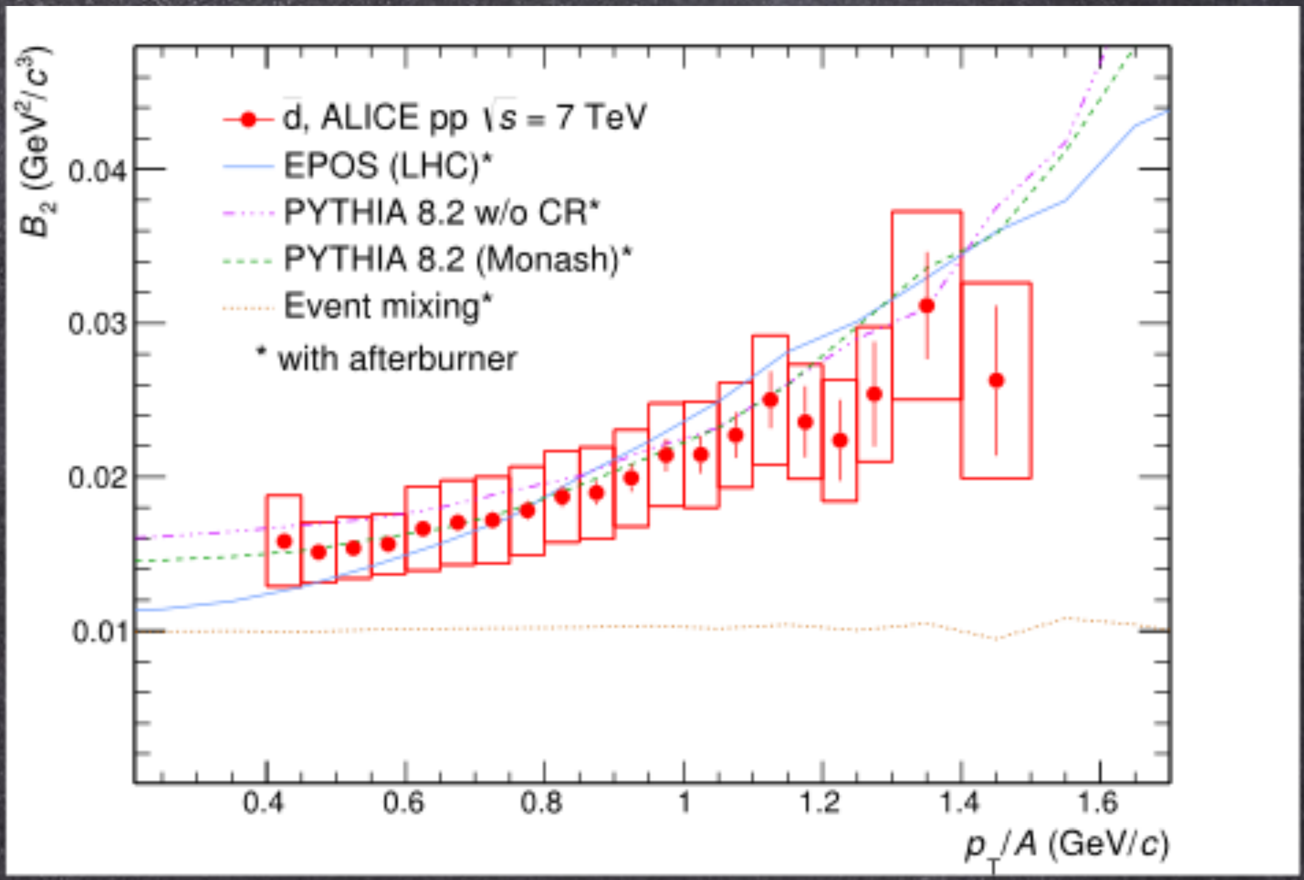
TABLE II. Summary of the best-fit DM mass and thermally averaged cross section for various standard model final states from the analyses [14, 56].

Final state	$m_{\rm DM}$ [GeV]	$\langle\sigma v\rangle$ [10^{-26} cm^3/s]
gg	34	1.9
$b\bar{b}$	71	2.6
ZZ^*	66	2.4
hh	128	5.7
$t\bar{t}$	173	3.8

Contribution from ALICE

Alice Coll. PRC 2018





Coalescence parameter measured also at LHC energies

See talk by M. Kachelriess

The case for antihelium

The production of anti helium

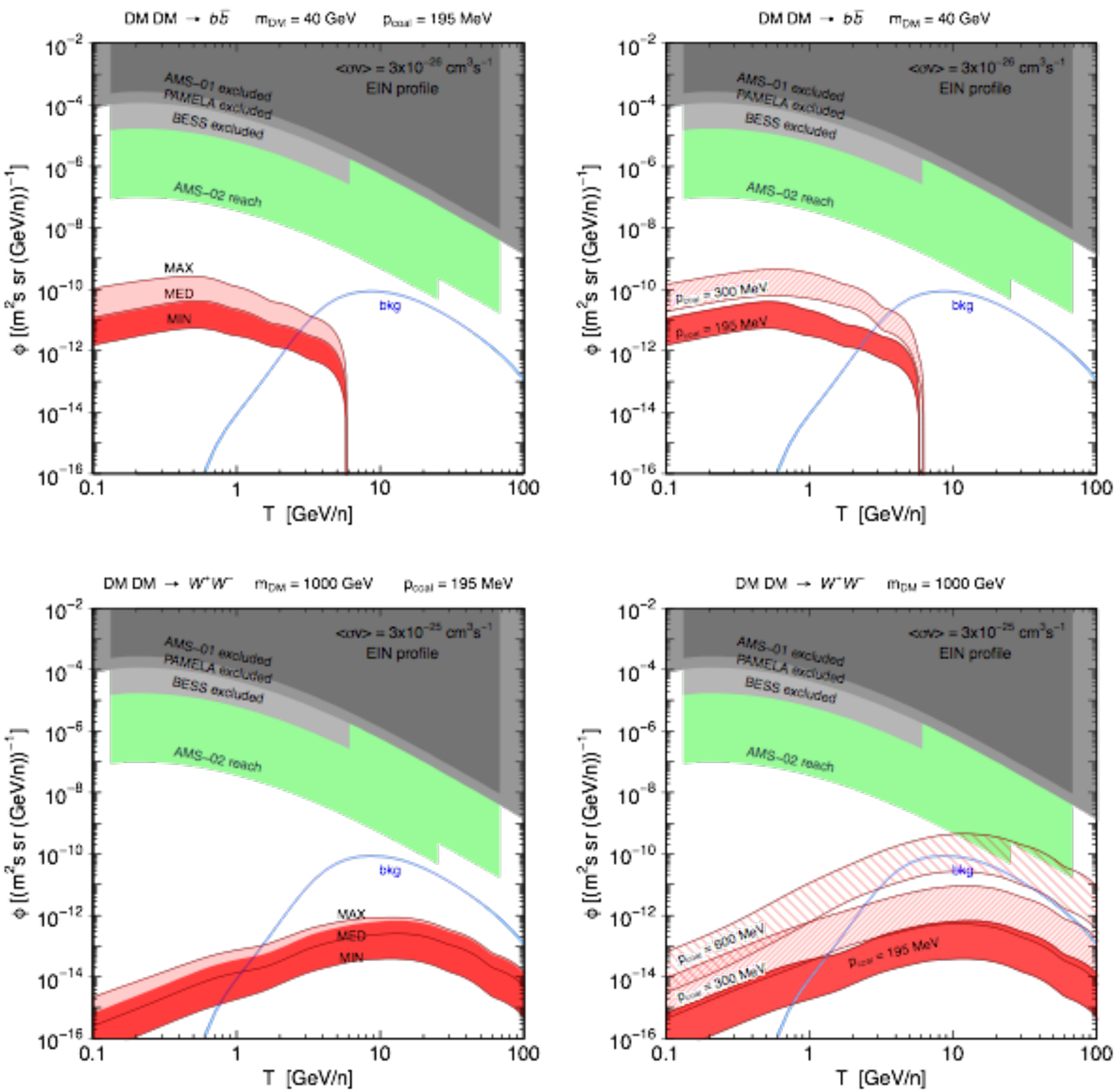
$$E_{\overline{\mathrm{He}}}\frac{d^3\sigma_{\overline{\mathrm{He}}}}{dk^3_{\overline{\mathrm{He}}}} = \frac{m_{\overline{\mathrm{He}}}}{m_p^2 m_n}\left(\frac{1}{\sigma_{\mathrm{tot}}}\frac{4\pi}{3}\frac{p_{\mathcal{C}}^3}{8}\right)^2 \times E_{\bar{p}}\frac{d^3\sigma_{\bar{p}}}{dk^3_{\bar{p}}}E_{\bar{p}}\frac{d^3\sigma_{\bar{p}}}{dk^3_{\bar{p}}}E_{\bar{n}}\frac{d^3\sigma_{\bar{n}}}{dk^3_{\bar{n}}},$$

$$\frac{dN_{\overline{\mathrm{He}}}}{dE_{\overline{\mathrm{He}}}} = \frac{m_{\mathrm{He}}}{m_p^2 m_n}3\left(\frac{p_{\mathcal{C}}^3}{8k_{\overline{\mathrm{He}}}}\right)^2\frac{dN_{\bar{p}}}{dE_{\bar{p}}}\frac{dN_{\bar{p}}}{dE_{\bar{p}}}\frac{dN_{\bar{n}}}{dE_{\bar{n}}}$$

which again relies the antiproton production cross section

The case for antihelium

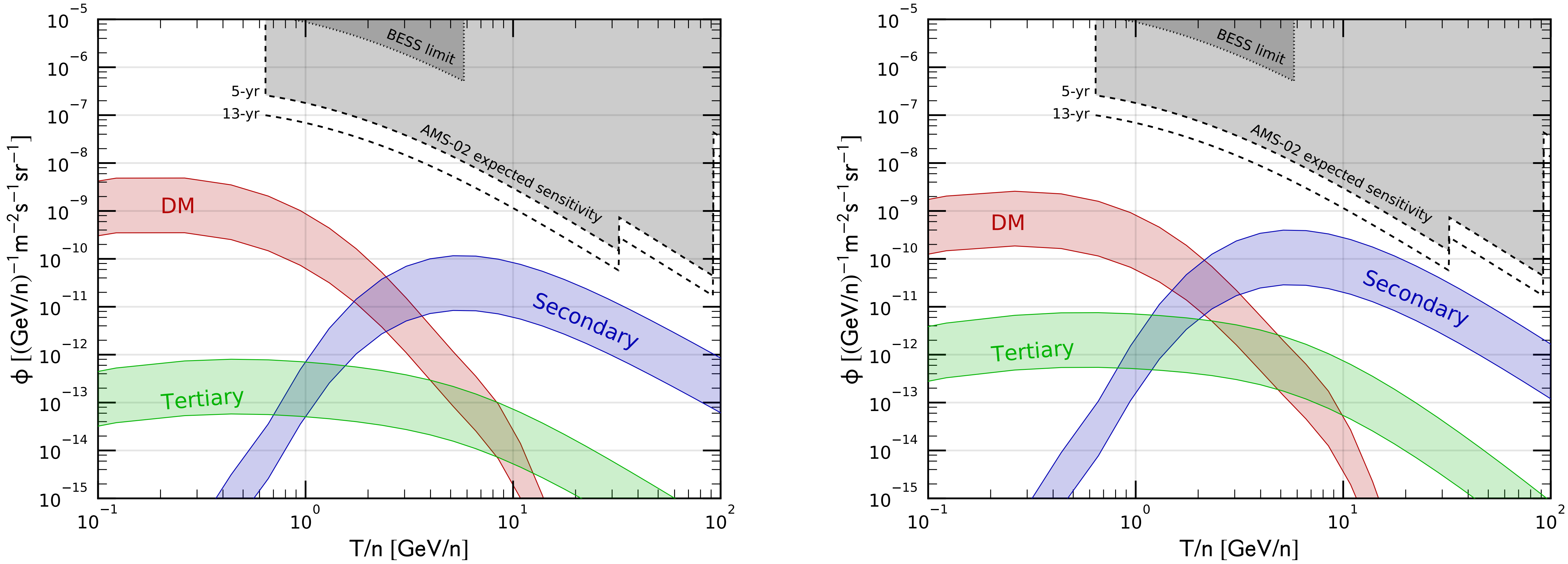
Cirelli, Fornengo, Taoso, Vittino, JCAP2014; Carlson, Coogan, Linden, Profumo, Ibarra, Wild et al. PRD2014



- Good signal-to-bkgd ratios
- Predictions for most DM models much lower than experimental reach
- Nuclear physics brings relevant effects through $(p_{coal})^6$

Perspectives with antihelium

FD, Fornengo, Korsmeier, PRD 2018



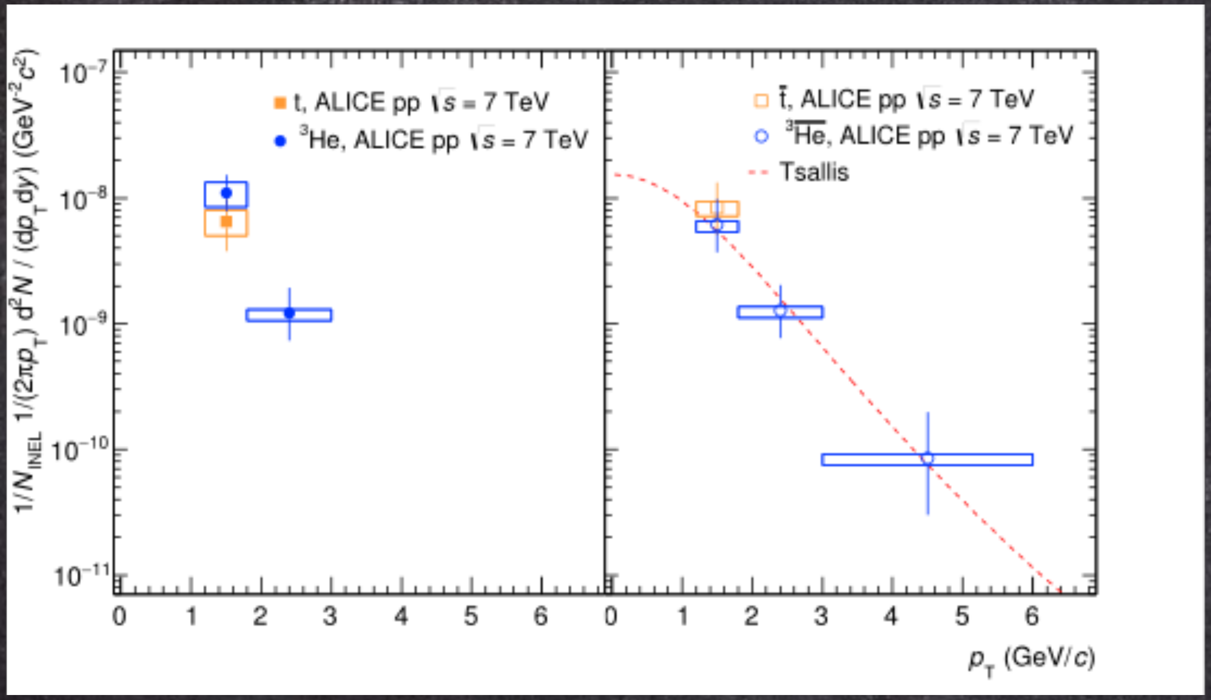
Challenging for present day experiments

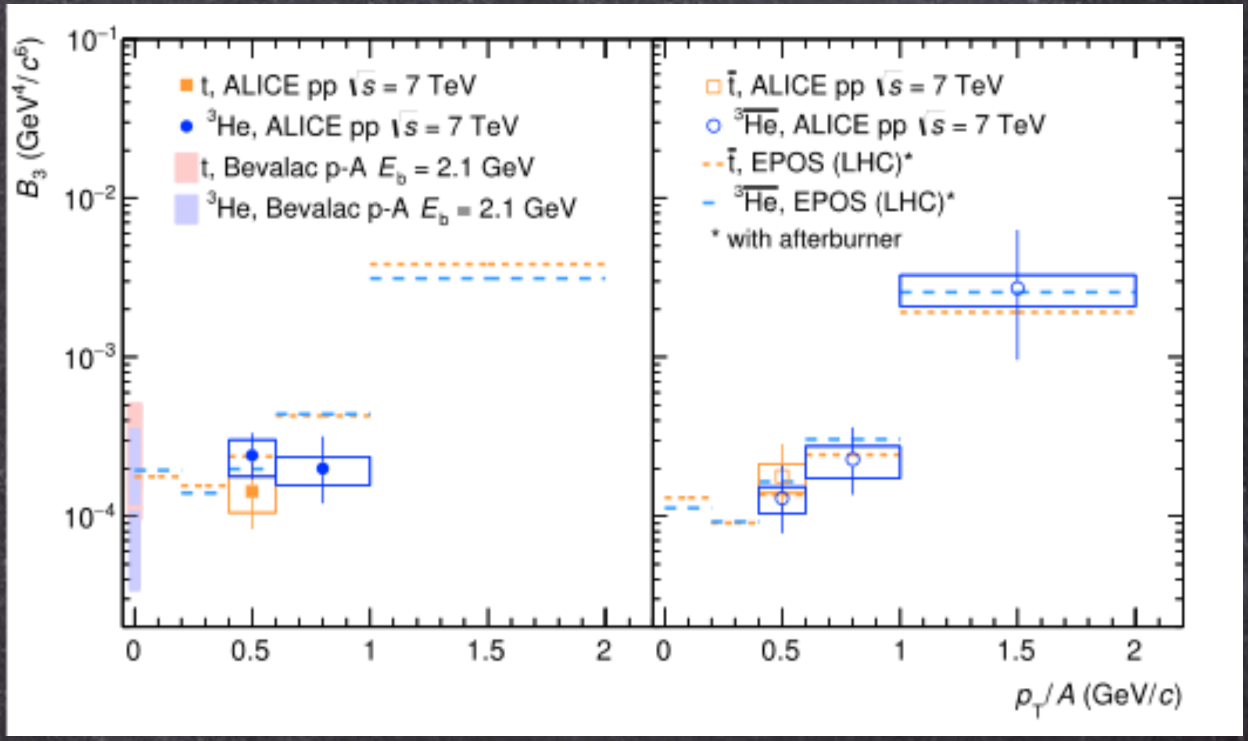
Antihelium ³He production

First data at LHC/Alice, Alice Coll. PRC 2018
Data at 0.9, 2.76, 7 TeV sqrt(s)

Invariant yields

Coalescence parameter





Previous data from Bevalac on ³He, consistent with Alice.
Measured a p_T dependence, but non very relevant in the Galaxy (see inv. yield)
P_{coal} greater (122 MeV vs 98 MeV) than in previous estimations ⍰ $(p_{coal})^6$

Conclusions

No clear evidence of DM in antimatter

If nature has hidden DM signals in antimatter, these signals are tiny

Unavoidable to handle this research as a precision physics problem:

- propagation in the Galaxy and in the heliosphere;
- cross section for secondary production

Antideuteron are, so far, the best signature.

Let's do not forget that antimatter from DMshould also produce γ rays

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