Prospects of detecting dark matter through cosmic-ray antihelium with the antiproton constraints

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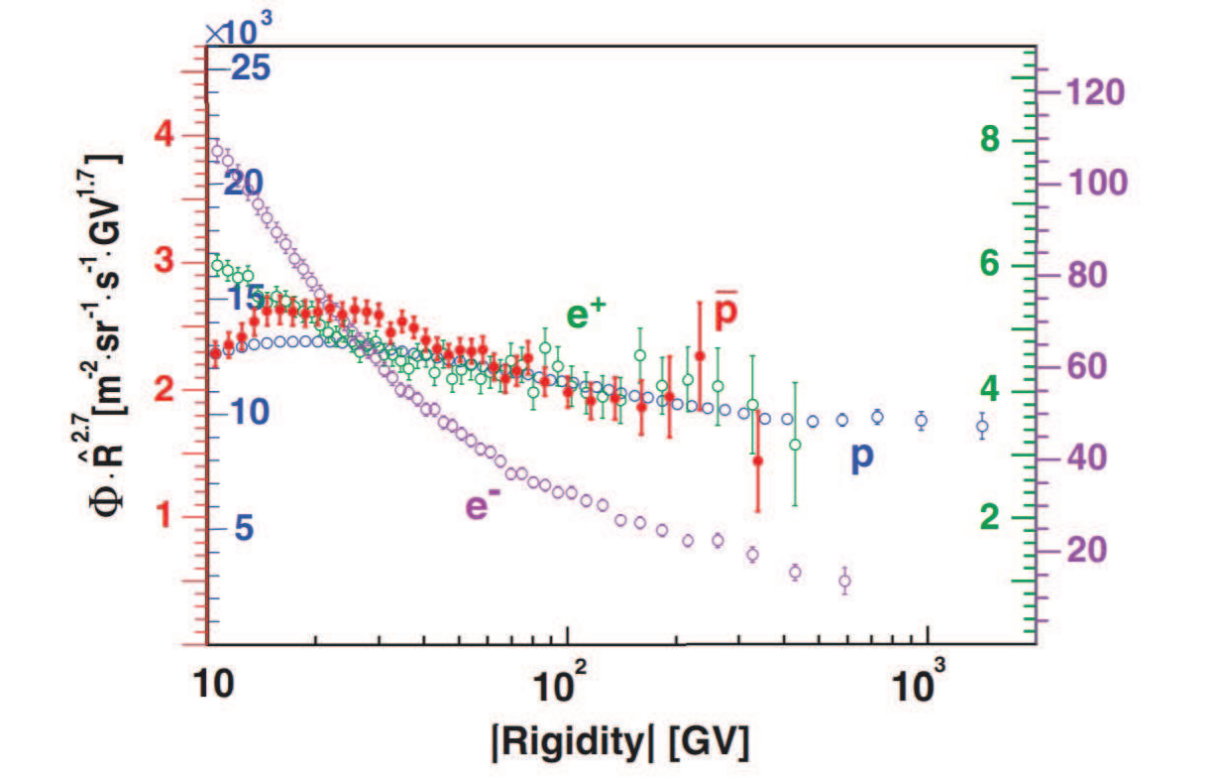
Outline:

- The coalescence model
- The propagation of anti-nuclei in cosmic rays
- The upper limit of dark matter annihilation cross sections from the AMS-02 $\bar{p}/p$ data
- The detecting prospects of anti-Helium on AMS-02
- Conclusions

Introduction

The existence of Dark Matter (DM) are supported by various observations, but the particle nature of DM is still largely unknown. High precision measurements of Cosmic Rays (CR) may shed light on the properties of DM.



AMS Coll., PRL 117 (2016) 091103

Anti-nuclei in cosmic rays

Anti-nuclei in CR are important probes in Dark Matter indirect detection.

- The high production threshold boosts the secondary productions to high kinetic energies, leaving a high signal to background ratio in low energy regions.
- The production of anti-nuclei are highly correlated with anti-protons, the uncertainties of CR anti-nuclei can be well constrained by the CR anti-proton observations.

coalescence model

Nucleons combine into a nucleus if the relative four-momenta of proper sets of nucleons is less than the coalescence momentum p_0.

The coalescence criterion

Coalescence criterion for $\overline{\mathrm{D}}$

$$||k_{\bar{p}} - k_{\bar{n}}|| = \sqrt{(\Delta\vec{k})^2 - (\Delta E)^2} < p_0^{\bar{D}}.$$

Coalescence criterion for $^3\overline{\mathrm{He}}$

- Requiring the relative four-momenta of each pair of anti-nucleons smaller than $p_0^{\overline{\mathrm{He}}}$. (*Nucleon Pair*)
- Using a circle with minimal radius to envelope the relative four-momenta of the anti-nucleons, and requiring the diameter of this circle less than $p_0^{\overline{\mathrm{He}}}$. (*Minimal Circle*)
- Boosting the set of anti-nucleons into their center-of-mass frame, and requiring the momentum of each anti-nucleon smaller than $p_0^{\overline{\mathrm{He}}}/2$. (*Afterburner*)

E. Carlson et al., PRD 89 (2014) 076005; ALICE Coll., ALICE-PUBLIC-2017-010

The coalescence momentum

The coalescence momentum of $^3\overline{\mathrm{He}}$:
Using the relation between $p_0^{\overline{\mathrm{He}}}$ and $p_0^{\bar{\mathrm{D}}}$:

E. Carlson et al., PRD 89 (2014) 076005

- The binding energy relation:

$$p_0^{\overline{\mathrm{He}}} = \sqrt{E_b^{^3\overline{\mathrm{He}}} / E_b^{\overline{\mathrm{D}}}}\; p_0^{\bar{\mathrm{D}}}$$

- Assuming $p_0^{\overline{\mathrm{He}}}/p_0^{\bar{\mathrm{D}}} = p_0^{\mathrm{He}}/p_0^{\mathrm{D}}$:

$$p_0^{\overline{\mathrm{He}}} = \langle p_0^{\mathrm{He}}/p_0^{\mathrm{D}} \rangle\; p_0^{\bar{\mathrm{D}}}$$

The ALICE group released the only $^3\overline{\mathrm{He}}$ data in pp collisions:
3 data points for $^3\overline{\mathrm{He}}$ in different p_T ranges and one data points for $\overline{\mathrm{T}}$, at $\sqrt{s} = 7$ TeV.

ALICE Coll., PRC 97 (2018) 024615

Fitting the ALICE data

Coalescence parameter B_3

$$E_{\overline{\mathrm{He}}}\frac{d^3N_{\overline{\mathrm{He}}}}{d\vec{p}^{\,3}_{\overline{\mathrm{He}}}} = B_3(E_{\bar{p}}\frac{d^3N_{\bar{p}}}{d\vec{p}^{\,3}_{\bar{p}}})^2(E_{\bar{n}}\frac{d^3N_{\bar{n}}}{d\vec{p}^{\,3}_{\bar{n}}}),\ \vec{p}_{\bar{p}} = \vec{p}_{\bar{n}} = \vec{p}_{\overline{\mathrm{He}}}/3.$$

Convert B_3 to coalescence momentum:

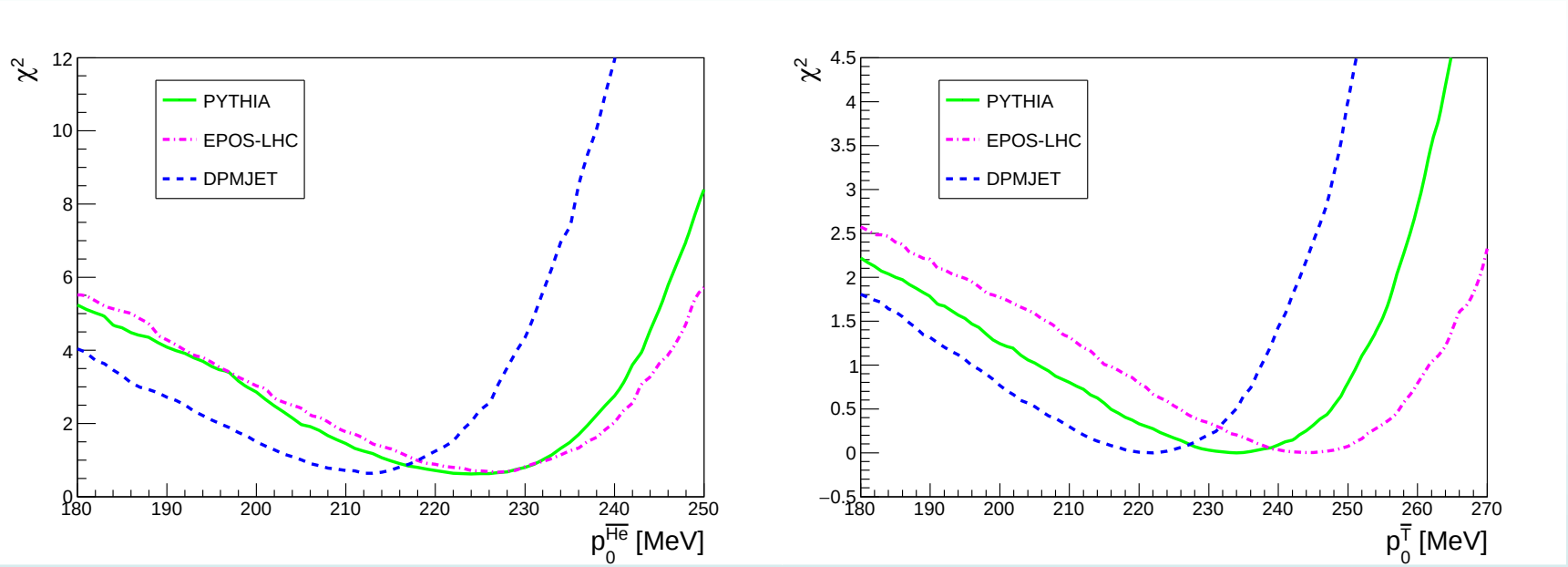
- Uncorrelated and isotropic momentum distributions:

$$B_3 = \frac{m_{\mathrm{He}}}{m_p^2 m_n}(\frac{\pi}{6}(p_0^{\overline{\mathrm{He}}})^3)^2$$

- Monte Carlo (MC) simulations:
  Calculate the spectrum of $\overline{\mathrm{He}}$ for a series of $p_0^{\overline{\mathrm{He}}}$, and make a χ^2 fitting to pick out the best-fit value.

MC generators: **PYTHIA, EPOS-LHC, DPMJET**

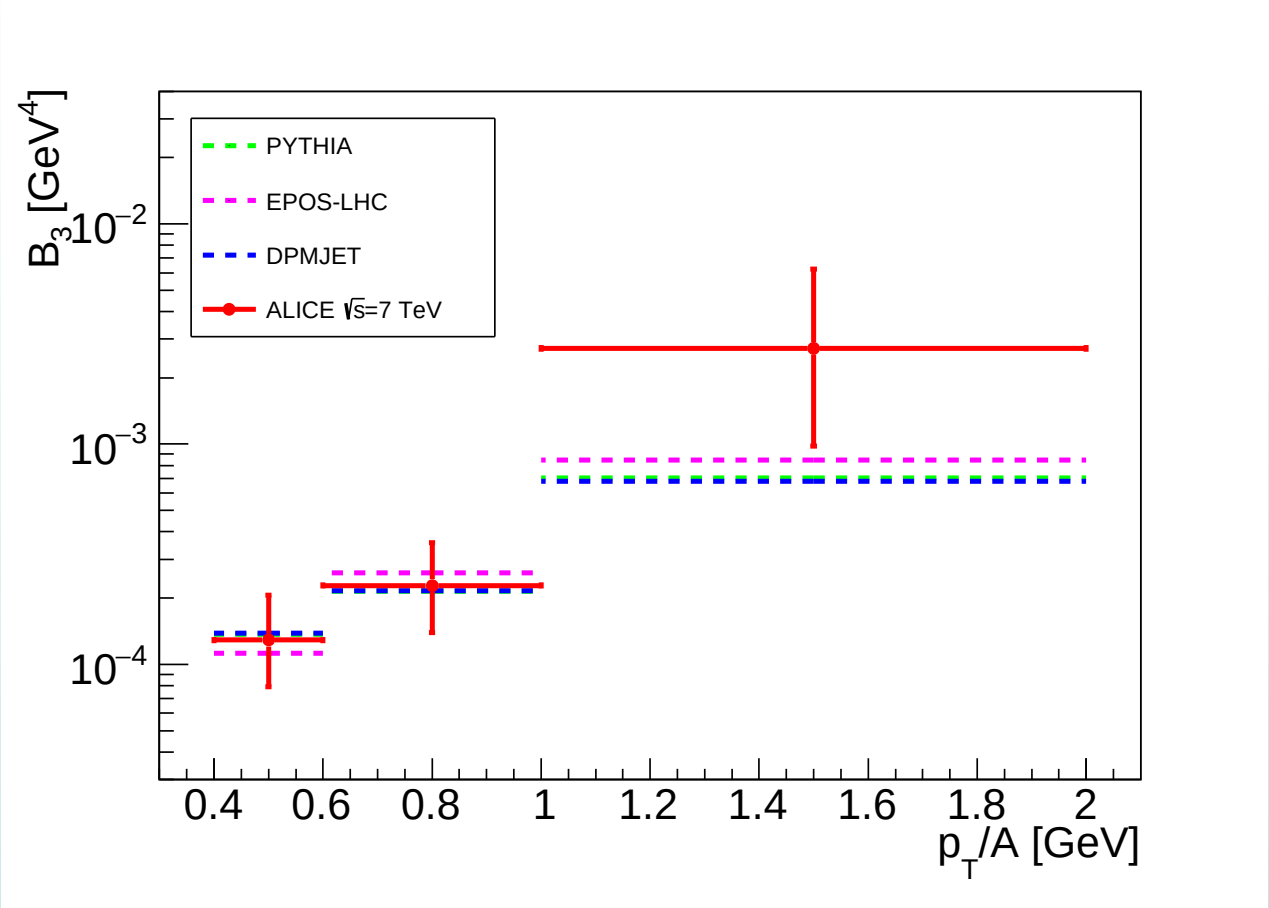
Fitting the ALICE data



$$\chi^2_{\mathrm{min}}/d.o.f \sim 0.6/2$$

MC generators:	PYTHIA	EPOS-LHC	DPMJET
$p_0^{\overline{\mathrm{He}}}$ [MeV]	$224^{+12}_{-16}\ (254 \pm 14)$	$227^{+11}_{-16}\ (254 \pm 14)$	212^{+10}_{-13}
$p_0^{\overline{\mathrm{T}}}$ [MeV]	$234^{+17}_{-29}\ (266 \pm 22)$	$245^{+17}_{-30}\ (268 \pm 22)$	222^{+16}_{-26}

Fitting the ALICE data



The p_T dependence are reproduced.

The formation of $^3\overline{\mathrm{He}}$

Two possible channel to form a $^3\overline{\mathrm{He}}$

- Direct formation ($\bar{p}\bar{p}\bar{n}$):
  expected to be suppressed by Coulombian repulsion between the two antiprotons.
- The β-decay of anti-Triton ($\bar{p}\bar{n}\bar{n}$):

$$\overline{\mathrm{T}} \longrightarrow {}^3\overline{\mathrm{He}} + e^+ + \nu_e + 18.6\ \mathrm{keV}$$

The Coulombian repulsion may not be significant:

- $p_0^{\overline{\mathrm{He}}}$ is only $4\% \sim 8\%$ smaller than $p_0^{\overline{\mathrm{T}}}$
- Gamow factor: $\mathcal{G} \sim \exp(-2\pi\alpha \frac{m_p}{p_0^{\overline{\mathrm{He}}}}) \sim 0.8$

Both channels are included in our work.

$^3\overline{\mathrm{He}}$ from DM annihilation

PYTHIA is used to simulate the hadronization after the DM annihilation.

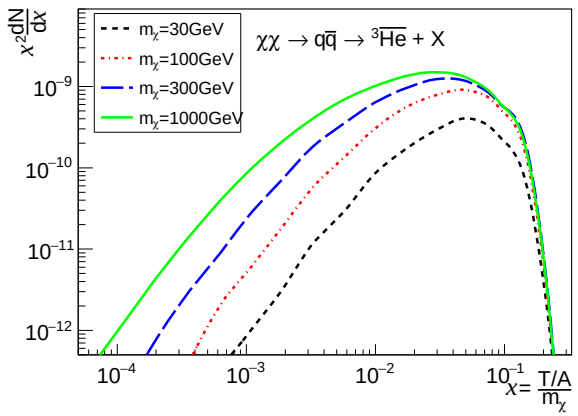
$$\chi\chi \rightarrow \text{Generic Resonance} \rightarrow q\bar{q}\ or\ b\bar{b}\ or\ W^+W^-$$

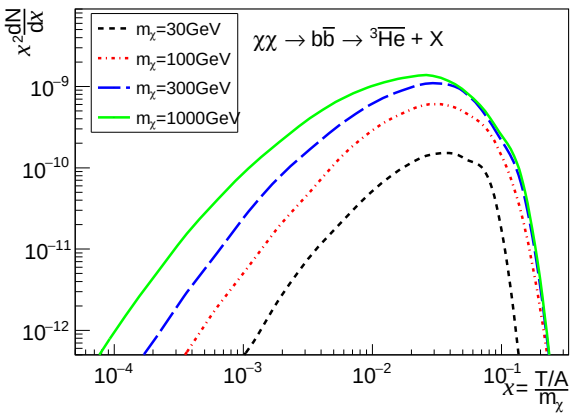
with $m_\chi = 30,\ 100,\ 300,\ 1000$ GeV.

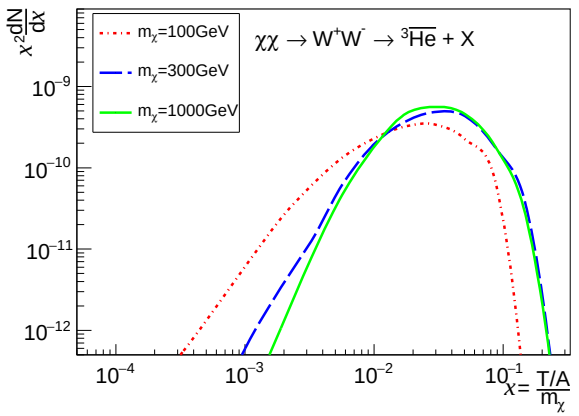
$\mathcal{O}(10^{11})$ collision events, $\mathcal{O}(10^4)$ $^3\overline{\mathrm{He}}$ produced for each case

The rescaled energy spectra of DM sourced $^3\overline{\mathrm{He}}$:

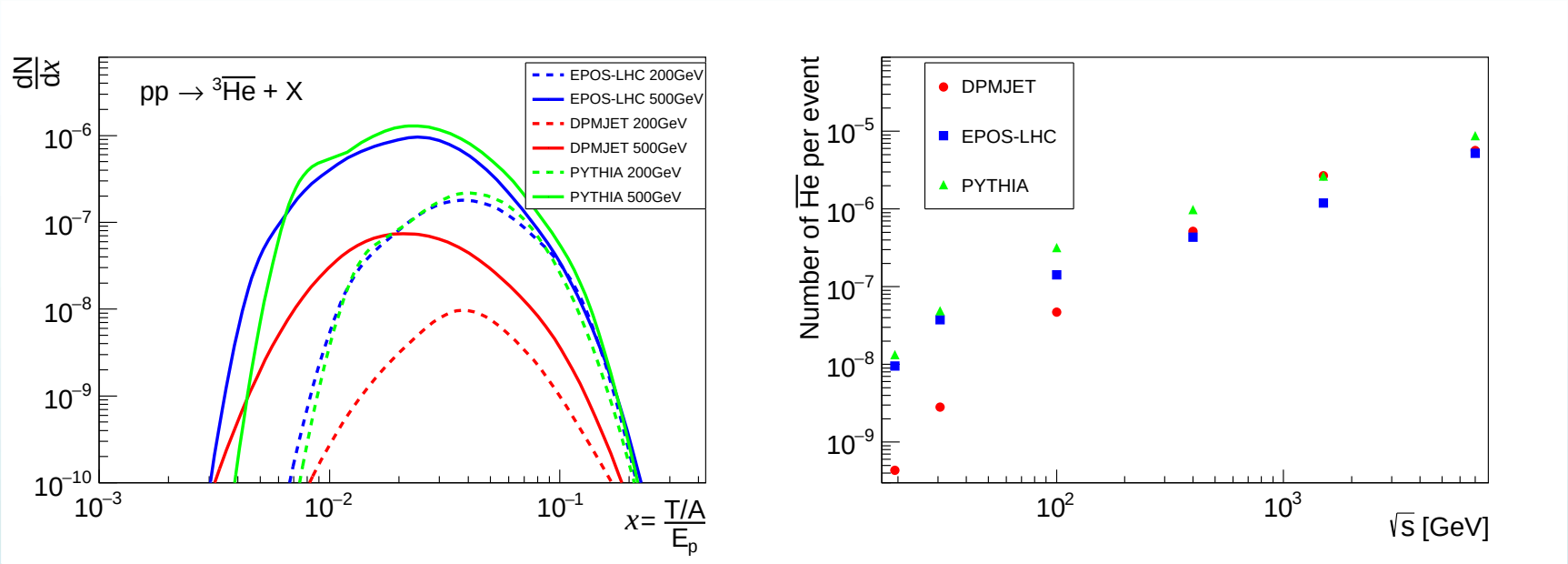
$$p_0^{\overline{\mathrm{He}}} = 224 \text{ MeV},\ p_0^{\overline{\mathrm{T}}} = 234 \text{ MeV}$$







$^3\overline{\mathrm{He}}$ from pp-collisions



Left) The energy spectra of $^3\overline{\mathrm{He}}$ from pp-collisions, with the incident proton energy $E = 200$ and 500 GeV, from **PYTHIA**, **EPOS-LHC** and **DPMJET**. *Right*) The total number of $^3\overline{\mathrm{He}}$ produced in pp-collisions at different $\sqrt{s}$, from the three MC generators.

The uncertainty form MC generators: $\mathcal{O}(10)$

The propagation of anti-nuclei in CR

The diffusion equation

$$\frac{\partial \psi}{\partial t} = q(\vec{r}, p) + \vec{\nabla} \cdot (D_{xx} \vec{\nabla} \psi - \vec{V}_c \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi$$

$$- \frac{\partial}{\partial p} \left[\dot{p} \psi - \frac{p}{3} (\vec{\nabla} \cdot \vec{V}_c) \psi \right] - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi$$

The equation is solved by the **GALPROP** v54 code.

Three propagation models:

A global Bayesian fitting to the AMS-02 B/C ratio and proton flux

Model	r_h(kpc)	z_h(kpc)	D_0	R_0(GV)	δ_1/δ_2	V_a(km/s)	R_{ps}(GV)	γ_{p1}/γ_{p2}
MIN	20	1.8	3.53	4.0	0.3/0.3	42.7	10.0	1.75/2.44
MED	20	3.2	6.50	4.0	0.29/0.29	44.8	10.0	1.79/2.45
MAX	20	6.0	10.6	4.0	0.29/0.29	43.4	10.0	1.81/2.46

H.-B. Jin et al., JCAP 09 (2015) 049

The source terms

The source term of DM $\bar{A}$ $(\bar{A} = \bar{p}, {}^3\overline{\mathrm{He}})$

$$q_{\overline{\mathrm{He}}}(\vec{r}, p) = \frac{\rho^2_{\mathrm{DM}}(\vec{r})}{2m^2_\chi} \langle \sigma v \rangle \frac{dN_{\bar{A}}}{dp}$$

Four DM profiles: Einasto, Isothermal, Moore, NFW

The source term of the secondary (tertiary) $\bar{A}$

$$q(\vec{r}, p) = \sum_{i=p,\mathrm{He}(\bar{p})} \sum_{j=\mathrm{H},\mathrm{He}} n_j(\vec{r}) \int \beta_i \, c \, \sigma^{\mathrm{inel}}_{ij}(p') \frac{dN_{\bar{A}}(p, p')}{dp} \, n_i(\vec{r}, p') \, dp'$$

The inelastic cross section $\sigma^{\mathrm{inel}}_{ij}$ are derived from MC generators.
Only pp contributions are included for ${}^3\overline{\mathrm{He}}$.

The interaction cross sections

The inelastic interaction rate $\Gamma_{\rm int} = 1/\tau_f$,
scattering rate between $\bar{A}$ and the interstellar gas:

$$\Gamma_{\rm int} = (n_{\rm H} + 4^{2/3} n_{\rm He})\, v\, \sigma_{\bar{A}p}$$

$n_{\rm He}/n_{\rm H} = 0.11$ (GALPROP default)

$\sigma_{\overline{\rm He}p}$ data are not available, $\sigma_{\overline{\rm He}p} = \sigma_{{\rm He}\bar{p}}$ assumed by CP-invariance

A parametrization of $\sigma_{A\bar{p}}$

$$\sigma_{A\bar{p}} = A^{2/3}\left[48.2 + 19\, x^{-0.55} + (0.1 - 0.18\, x^{-1.2})Z + 0.0012\, x^{-1.5}\, Z^2\right] {\rm mb}$$

where $x = T/(A \cdot {\rm GeV})$. For $\sigma_{\overline{\rm He}p}$, $A = 3, Z = 2$.

The solar modulation

The spectra of CR particles are effected by the solar wind and the magnetic field of solar system.

Force Field Approximation

$$\Phi_{A,Z}^{TOA}(T_{TOA}) = \left(\frac{2m_A A T_{TOA} + A^2 T_{TOA}^2}{2m_A A T_{IS} + A^2 T_{IS}^2} \right) \Phi_{A,Z}^{IS}(T_{IS})$$

where $T_{IS} = T_{TOA} + (e\phi_F |Z|/A)$.
The Fisk potential $\phi_F = 550$ MV.

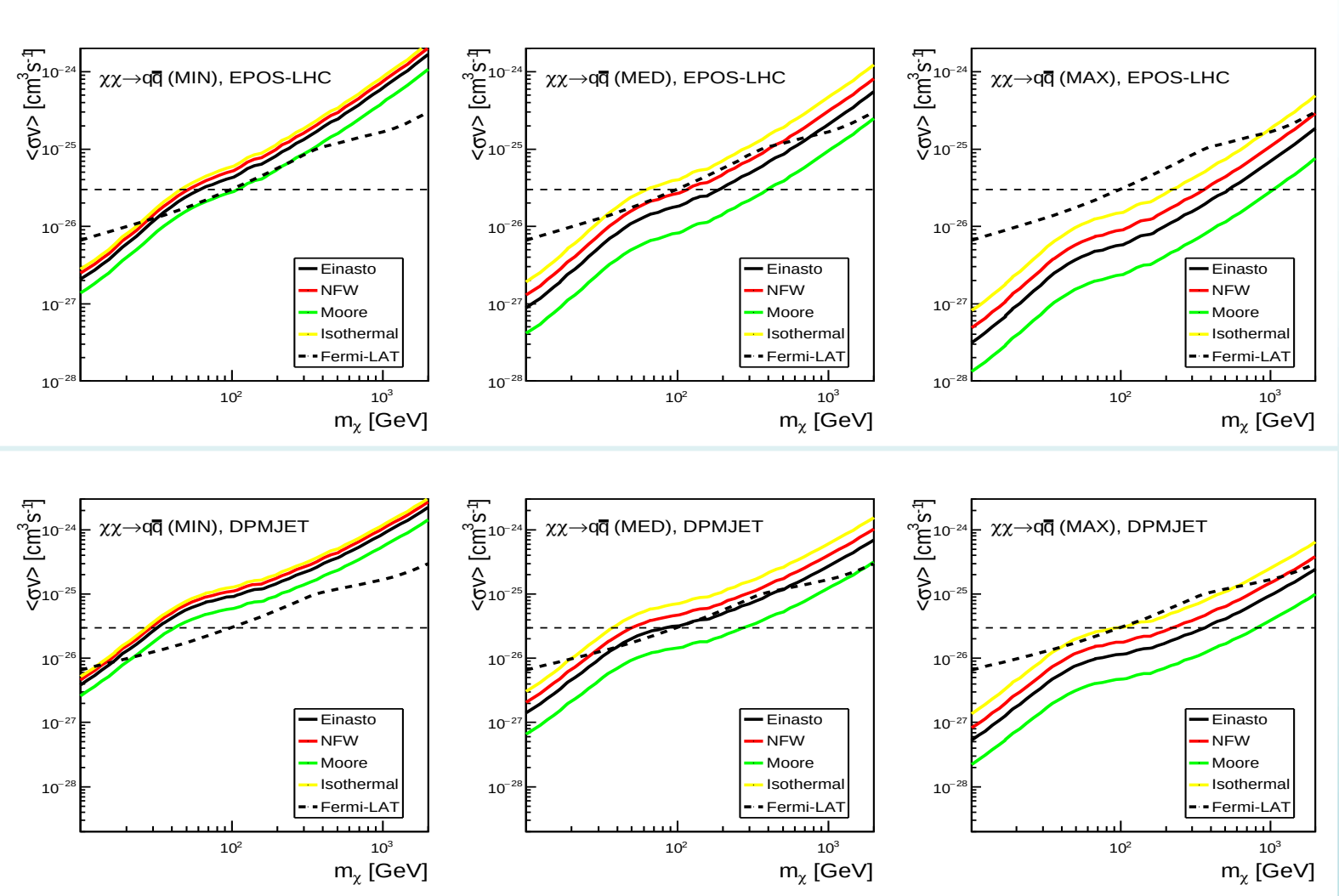
Upper limit of DM annihilation cross section

AMS-02 published the so far most accurate antiproton flux, and this measurement would give a stringent limitation on the DM annihilation cross section.
We use the frequentist χ^2-analyse to derive the 95% CL upper limits on the DM annihilation cross section from the AMS-02 $\bar{p}/p$ data.
First calculate the minimal value χ_{min}, 95% CL corresponding to $\Delta\chi^2 = 3.84$ for one parameter.

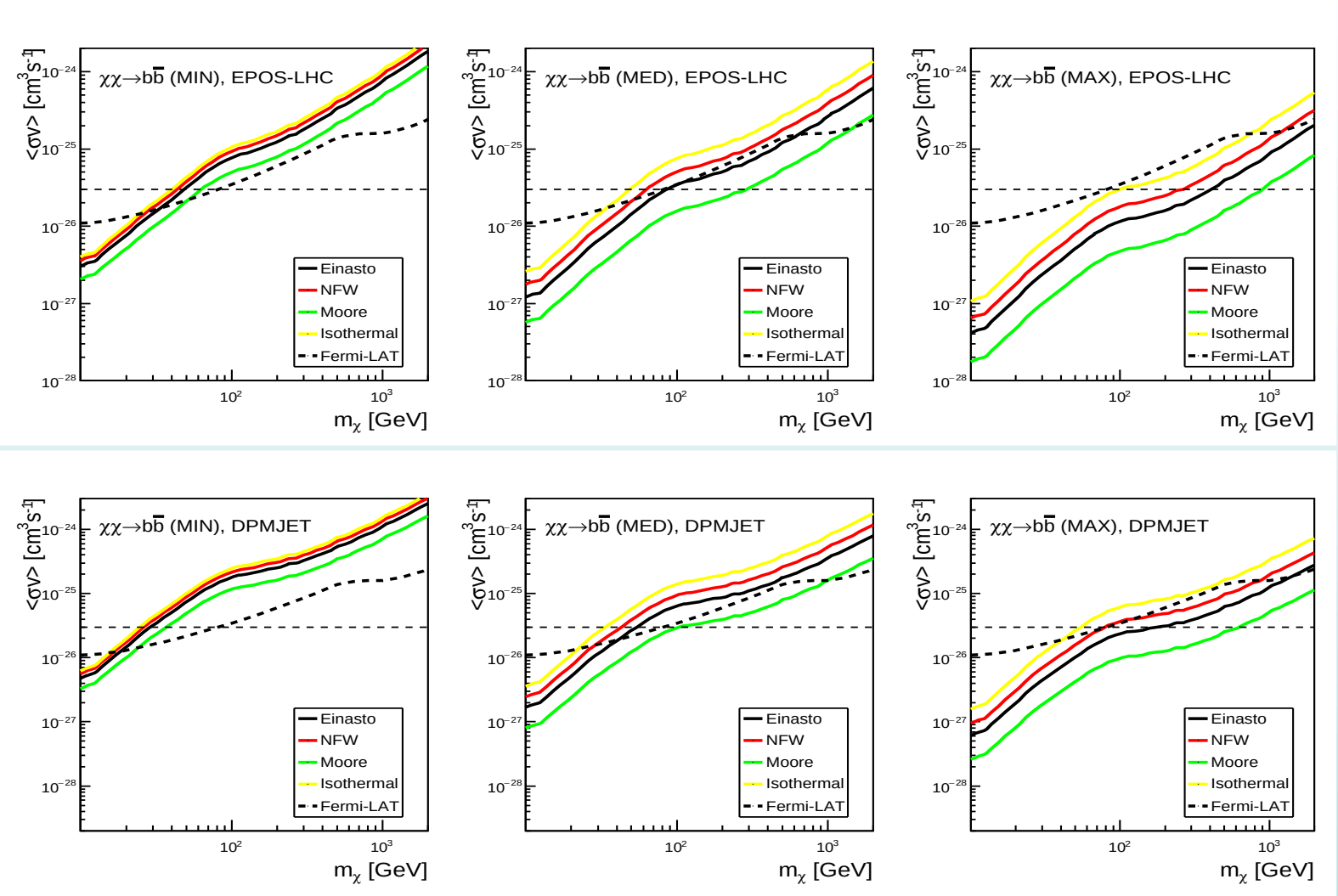
NA49 data: *NA49 Coll., Eur.Phys.J.C65:9-63 (2010)*

PYTHIA overestimate the production of $\bar{p}$ from pp collisions at low $\sqrt{s}$, **EPOS-LHC** and **DPMJET** consist with the NA49 data.

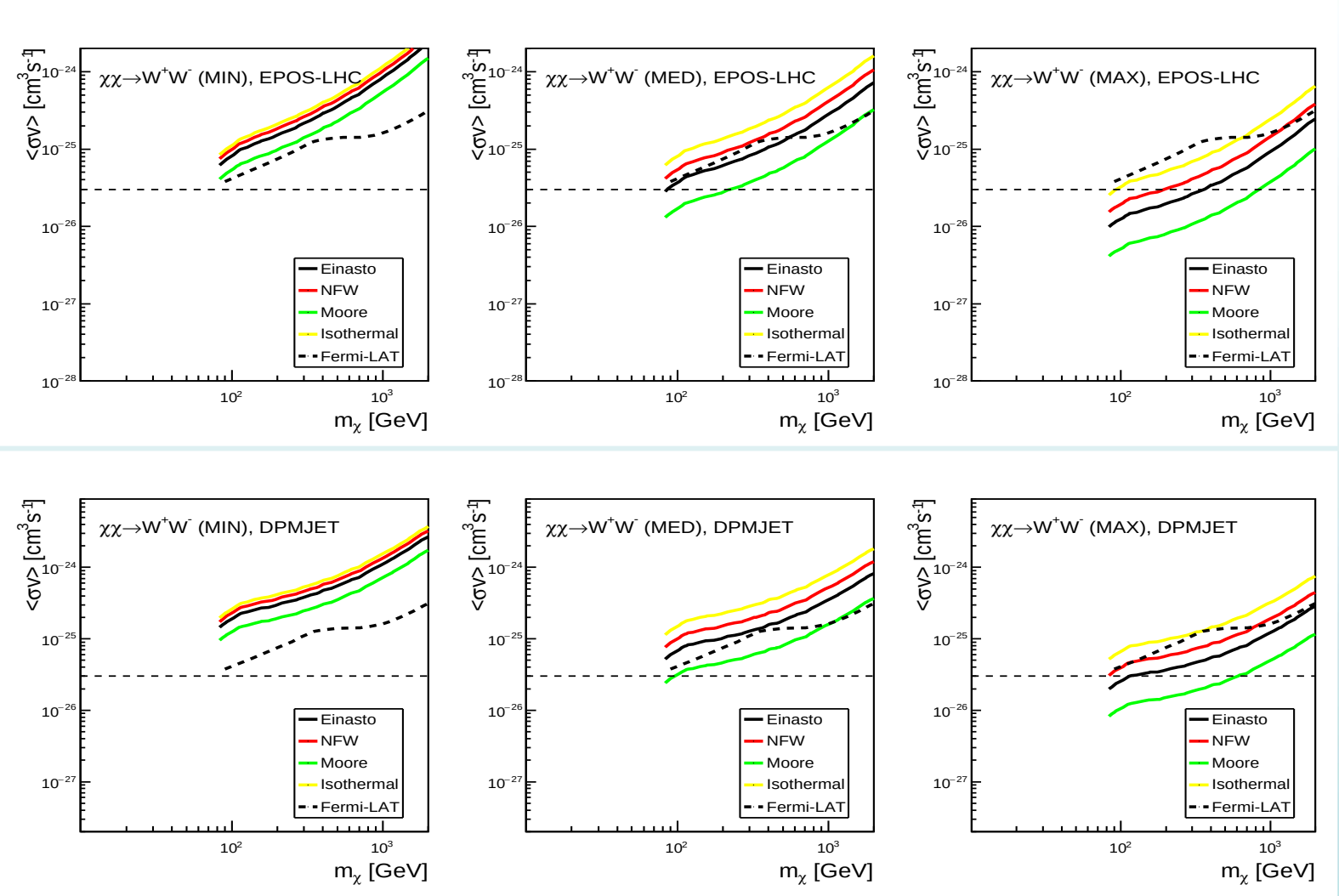
The upper limit of DM cross sections ($q\bar{q}$)



The upper limit of DM cross sections ($b\bar{b}$)



The upper limit of DM cross sections (W^+W^-)

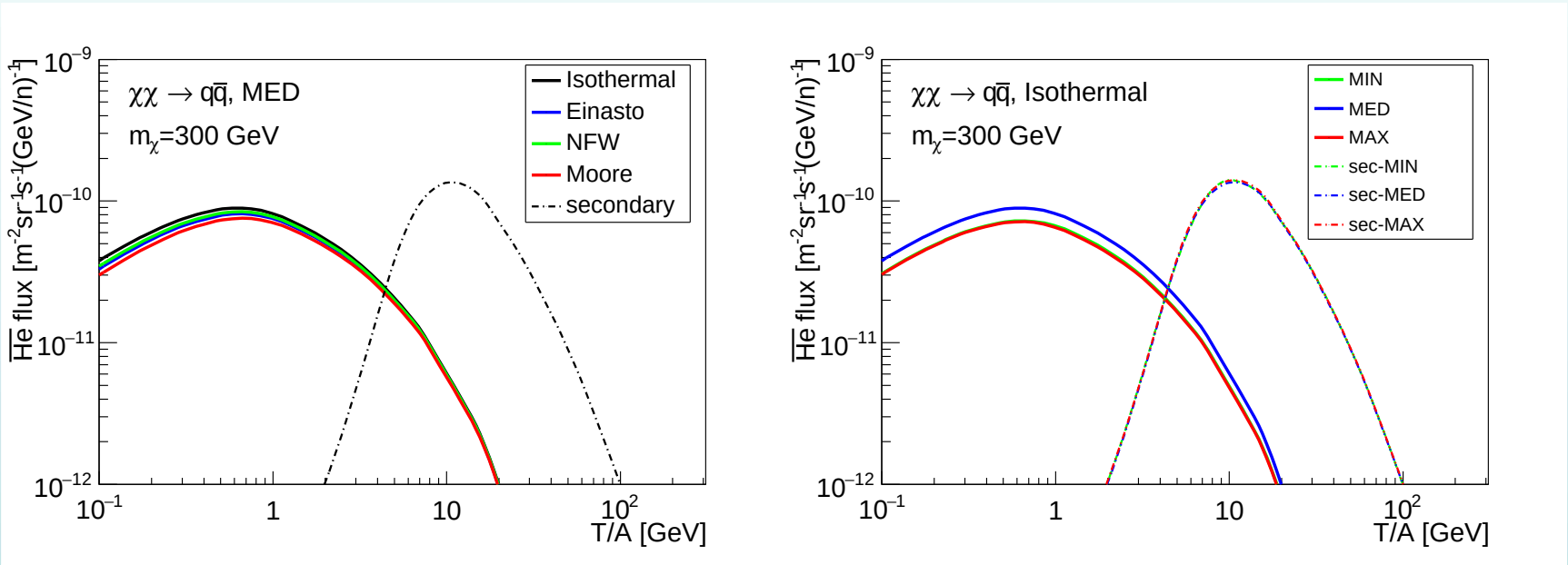


The flux of $^3\overline{\mathrm{He}}$

An advantage of constraining $^3\overline{\mathrm{He}}$ with $\bar{p}$: greatly reducing the uncertainties.

Fixed $< \sigma v >$: propagation models $\mathcal{O}(10)$ DM profiles $\mathcal{O}(10)$

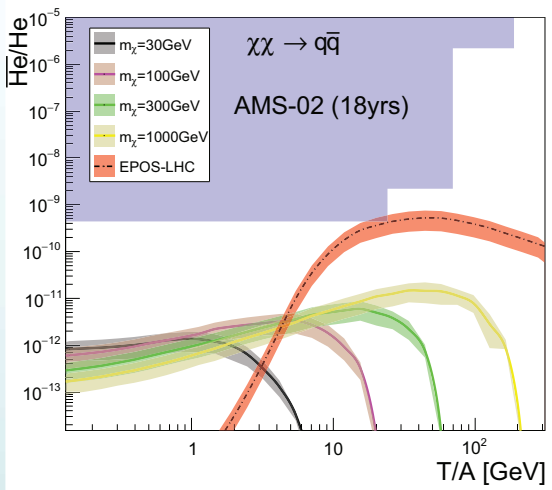
$\bar{p}$ constrained $< \sigma v >$: propagation models 30% DM profiles 30%

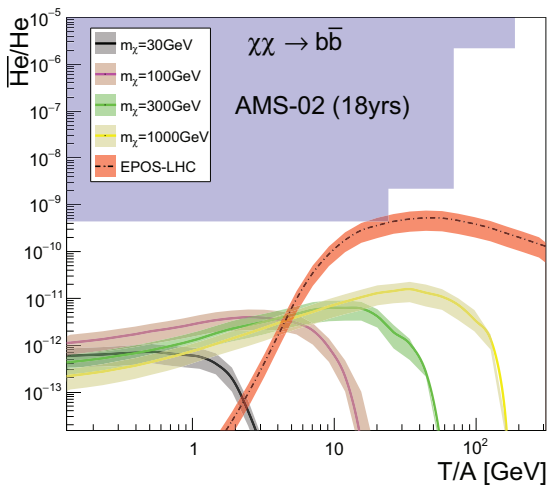


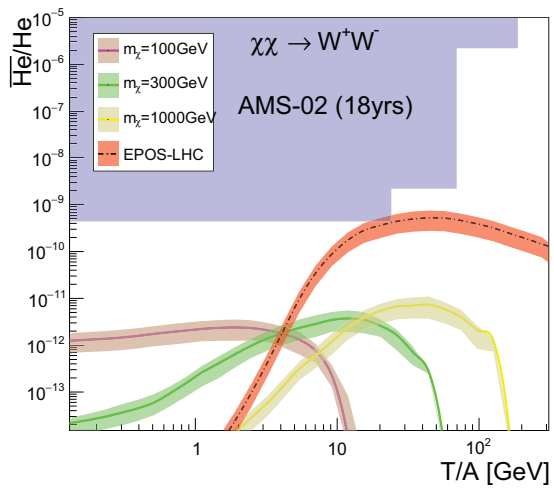
Left) Differences between the DM profiles. *Right*) Differences between the propagation models.

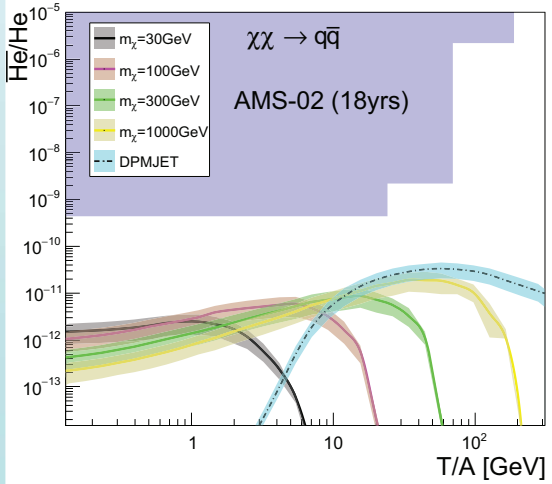
The detecting prospects on AMS-02

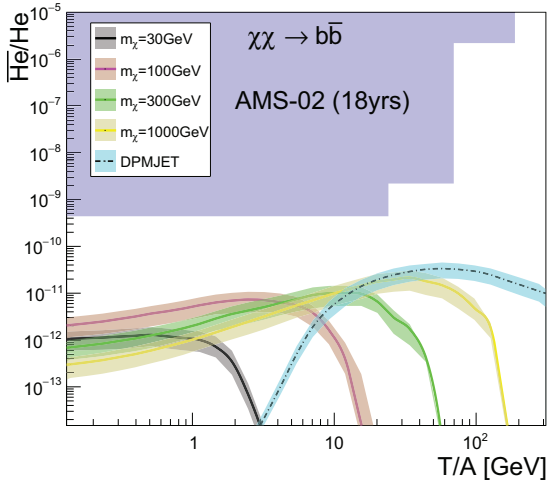
Propagation model: MED DM profile: Isothermal

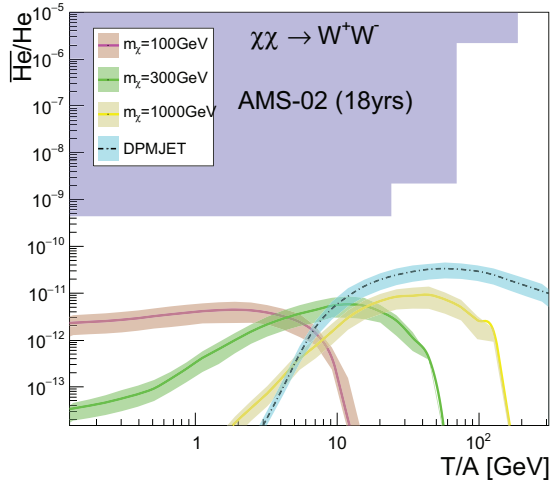












The prospective $^3\overline{\mathrm{He}}$ number on AMS-02

The number of $^3\overline{\mathrm{He}}$ observed on AMS-02:

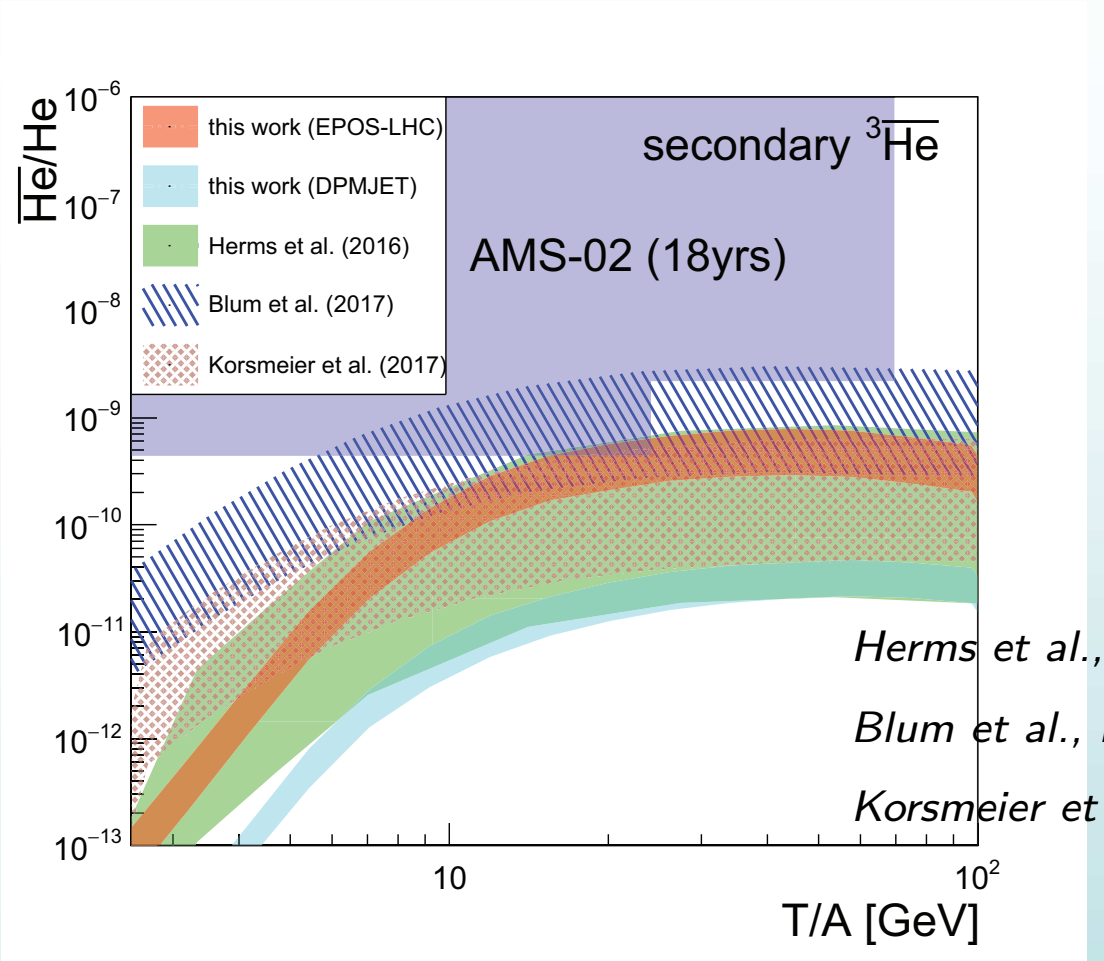
$$N = \int_{T_{\mathrm{min}}}^{T_{\mathrm{max}}} \eta \, \Phi_{\overline{\mathrm{He}}} \, \mathcal{A} \, t \, d \, T$$

Most optimistic assumption:

$$\eta = 1, \, \mathcal{A} = 0.5 \mathrm{m}^2 \, \mathrm{sr} \text{ (geometric acceptance)},$$
$$t = 18 \text{ years}, \; T_{\mathrm{min(max)}}/A = 0.1 \text{ GeV } (1 \text{ TeV}).$$

	m_χ (GeV)	$\chi\chi \to q\bar{q}$	$\chi\chi \to b\bar{b}$	$\chi\chi \to W^+W^-$
DM	30	$0.084^{+0.038}_{-0.040}$ $(0.153^{+0.070}_{-0.073})$	$0.041^{+0.020}_{-0.018}$ $(0.073^{+0.036}_{-0.032})$	—
	100	$0.153^{+0.065}_{-0.072}$ $(0.269^{+0.114}_{-0.127})$	$0.227^{+0.107}_{-0.103}$ $(0.419^{+0.198}_{-0.190})$	$0.164^{+0.077}_{-0.076}$ $(0.304^{+0.143}_{-0.141})$
	300	$0.122^{+0.055}_{-0.056}$ $(0.179^{+0.081}_{-0.082})$	$0.160^{+0.074}_{-0.074}$ $(0.256^{+0.118}_{-0.118})$	$0.054^{+0.025}_{-0.025}$ $(0.084^{+0.039}_{-0.039})$
	1000	$0.106^{+0.048}_{-0.048}$ $(0.138^{+0.063}_{-0.063})$	$0.131^{+0.058}_{-0.061}$ $(0.179^{+0.079}_{-0.083})$	$0.015^{+0.007}_{-0.007}$ $(0.019^{+0.009}_{-0.009})$
Secondary		$0.986^{+0.437}_{-0.455}$	$(0.054^{+0.021}_{-0.021})$	

A comparison of secondary $^3\overline{\mathrm{He}}$



Herms et al., JCAP 1702 (2017) 018

Blum et al., PRD 96 (2017) 103021

Korsmeier et al., PRD 97 (2018) 103011

Fluxes overlap at $T/A > 10$ GeV !

A candidate event of $^3\overline{\mathrm{He}}$ with momentum 40.3 ± 2.9 GeV

S. Ting, https://indico.cern.ch/event/592392

Conclusions

- AMS-02 is likely to detect the secondary $^3\overline{\mathrm{He}}$
- AMS-02 is unlikely to detect the $^3\overline{\mathrm{He}}$ from DM
- The sensitivity of next generation of detectors should improve about two order of magnitude to detect the $^3\overline{\mathrm{He}}$ from DM

Thank You!