(Anti)nuclei production at colliders relevant for astroparticle physics

P. Larionov[1,2], on behalf of the ALICE collaboration

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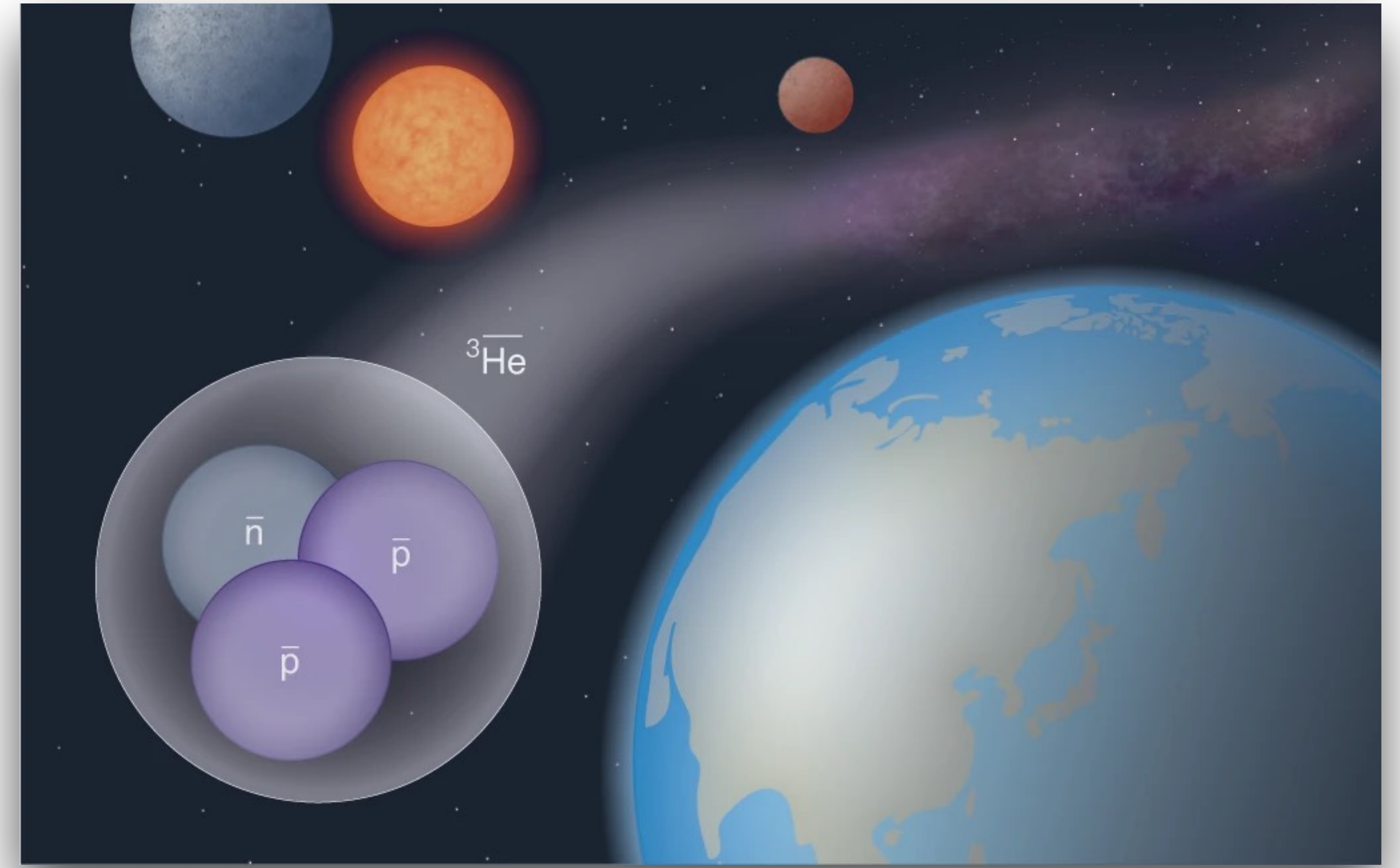
Antinuclei in astroparticle physics



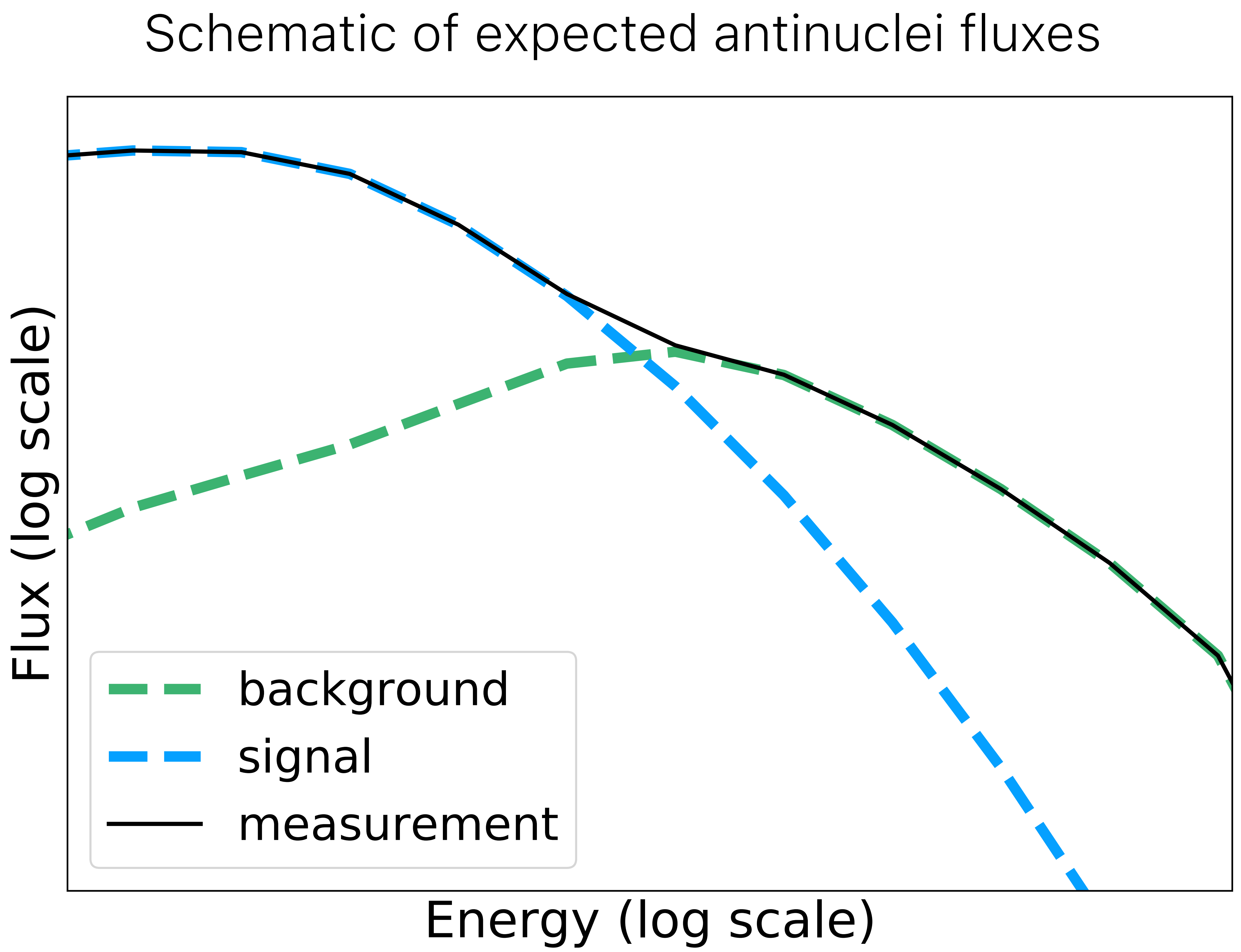
An $^{3}\overline{\mathrm{He}}$ nuclei reaches our solar neighbourhood after travelling through our Galaxy.

Figure: YouTube video

Cosmic ray antinuclei ($\bar{\mathrm{d}}$, $^{3}\overline{\mathrm{He}}$, $^{4}\overline{\mathrm{He}}$):

- Potential signal of dark matter annihilation
- Expected to be produced by the interaction of primary cosmic rays (CR) with the interstellar medium (ISM) — background / secondary production
- Studied by **AMS-02, GAPS** experiments
  - ▷ Measurement of cosmic (anti)nuclei flux

Antinuclei in astroparticle physics



☞ Low background is expected in the low energy range

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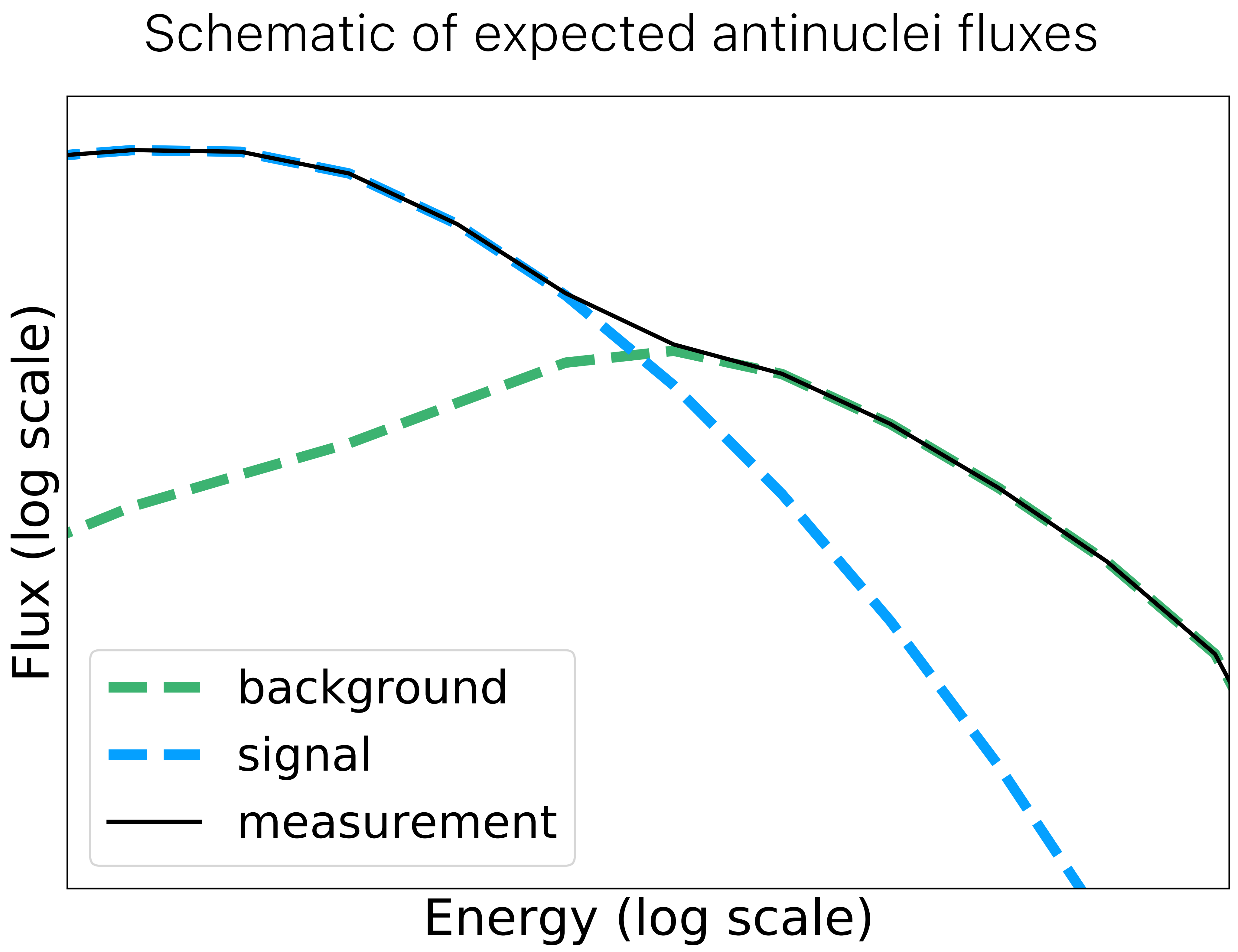
Antinuclei in astroparticle physics


Schematic of expected antinuclei fluxes

☞ Low background is expected in the low energy range

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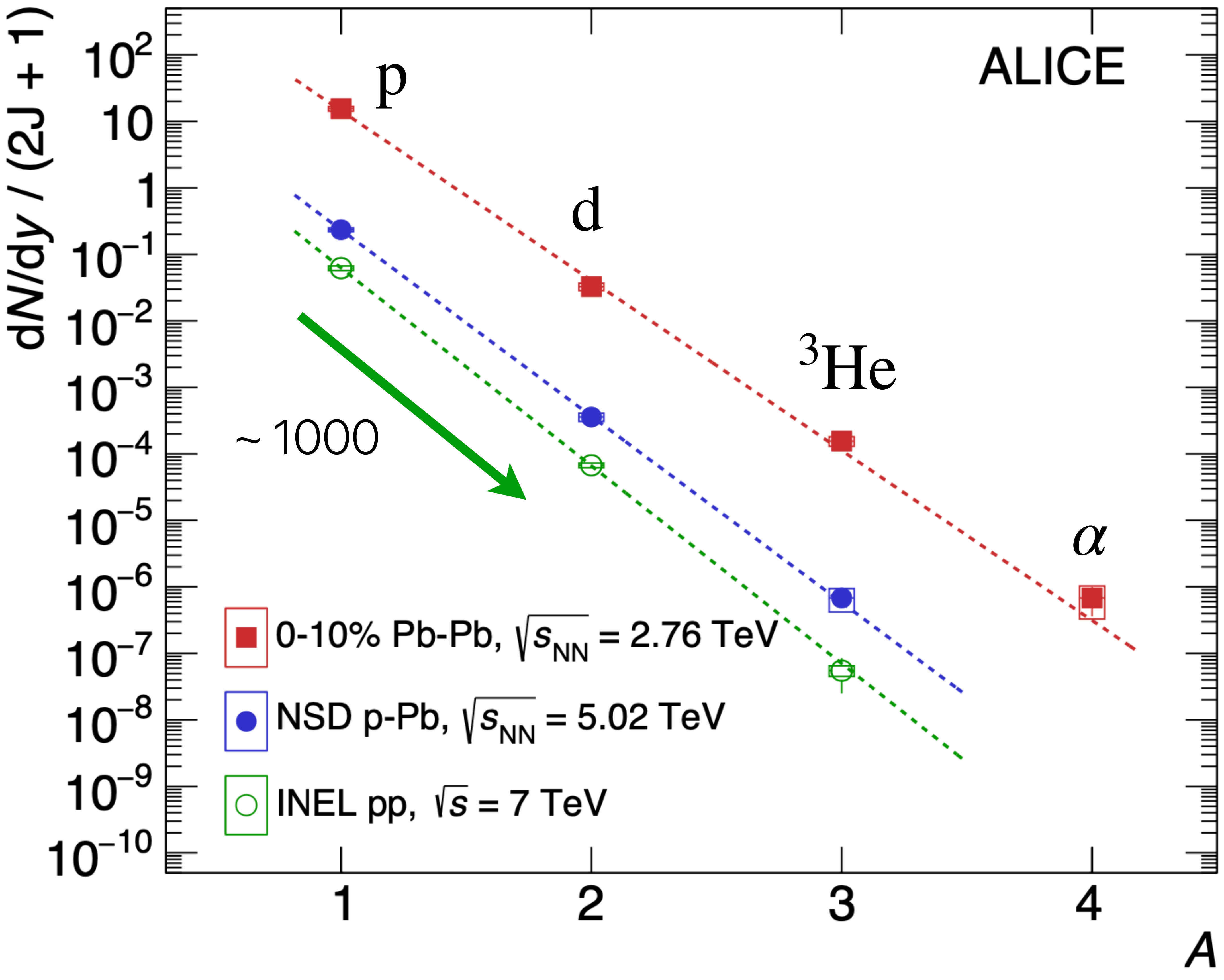
🤔

How do we contribute with collider data?

LHC — antimatter factory

- On Earth, antinuclei are produced at colliders
- Rare: reduction factor 300 for each additional nucleon (Pb-Pb) and 1000 (pp) collisions at LHC energies
- Models attempt to describe the production:
  - Statistical hadronization model (SHM)
  - Coalescence
- Relevant for secondary flux studies:
  - data from pp collisions as CR and ISM is mostly protons, H and He

ALICE collab., Phys. Lett. B **800**, 135043 (2020)



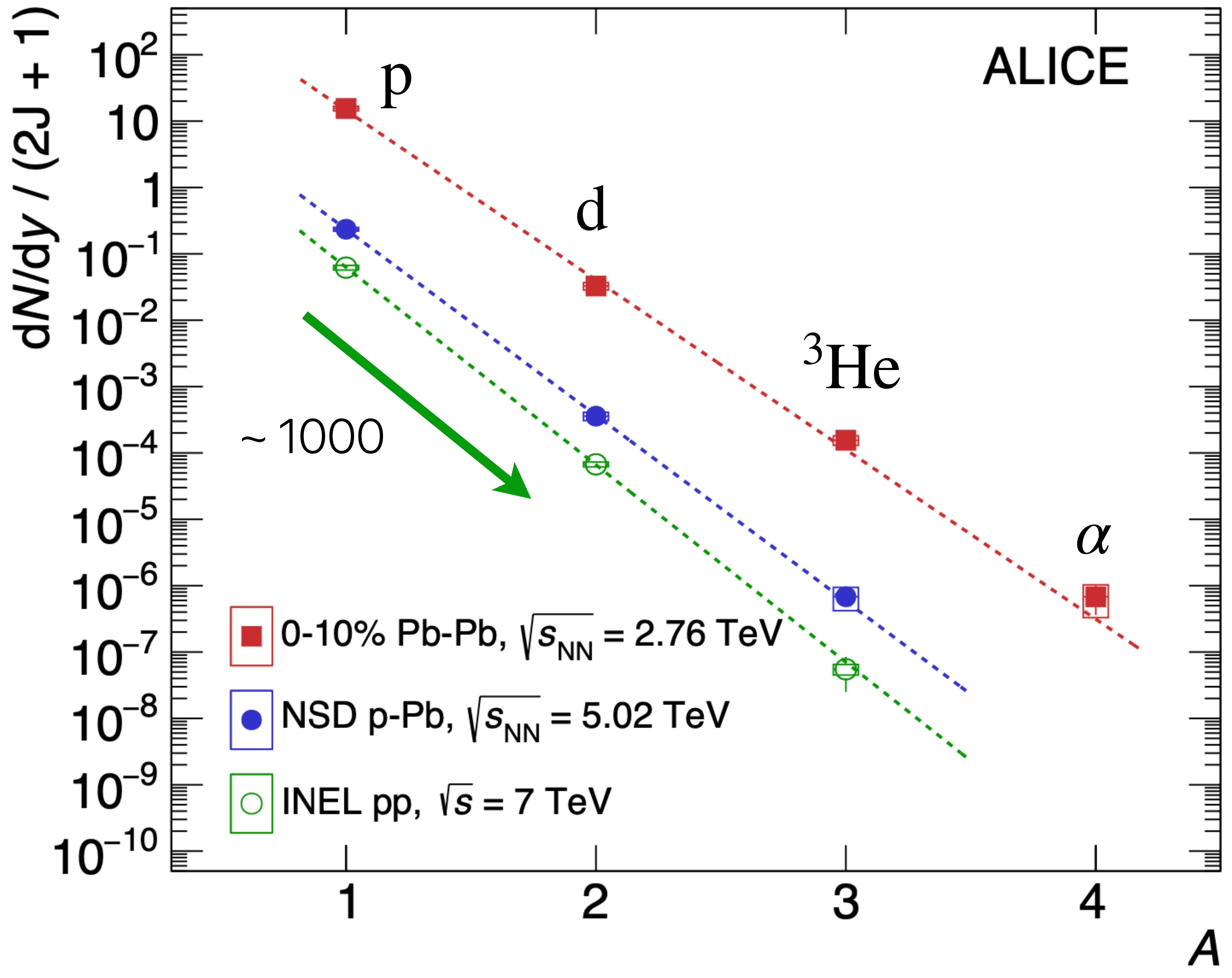
$$\frac{\text{antimatter}}{\text{matter}} \approx 1$$

LHC — antimatter factory

- ALICE experiment has been very active in measuring (anti)nuclei production cross section and coalescence parameters

Talk on (anti)nuclei production in small systems with ALICE by Rutuparna Rath
Thu 25th @15:20 Heavy Ion Physics

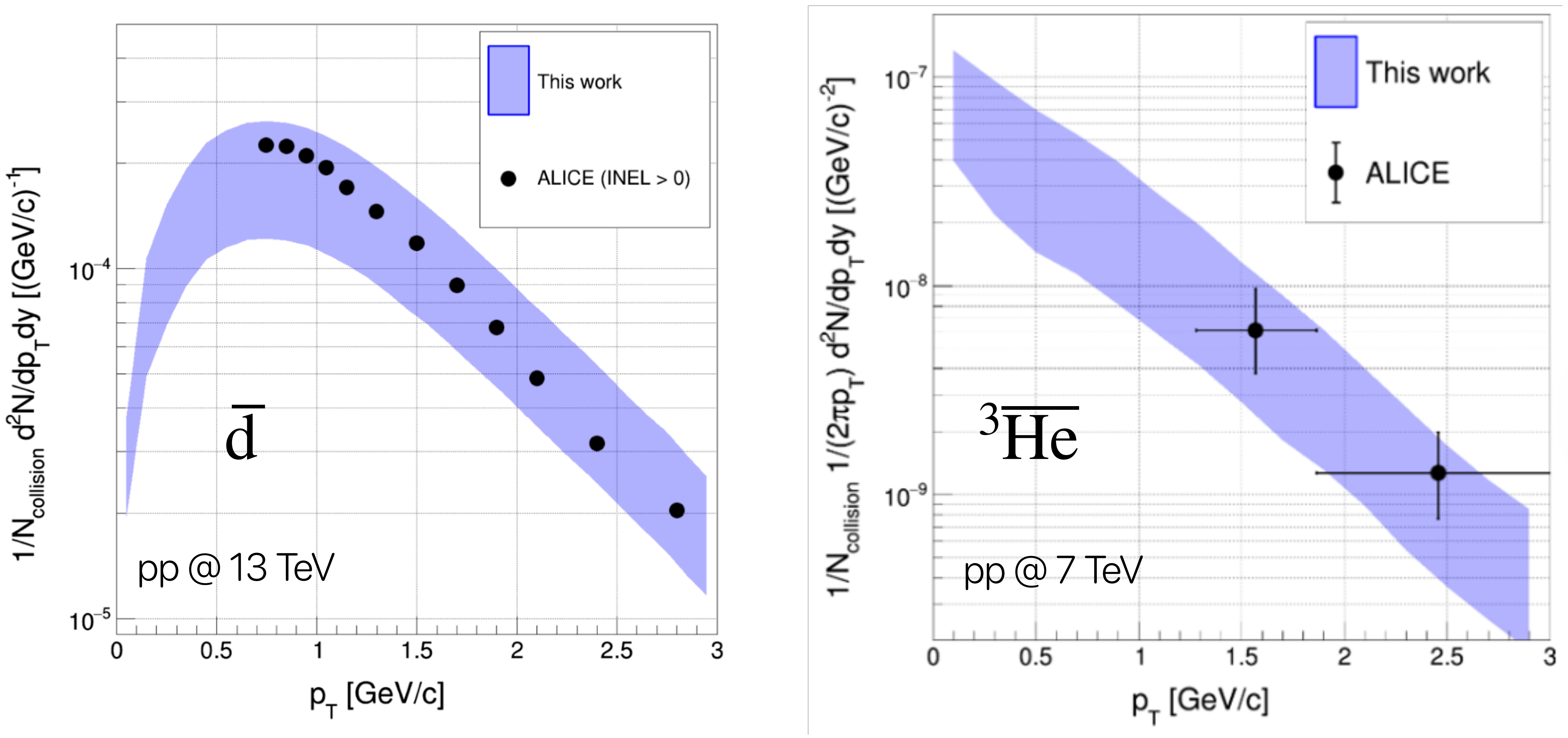
ALICE collab., Phys. Lett. B **800**, 135043 (2020)

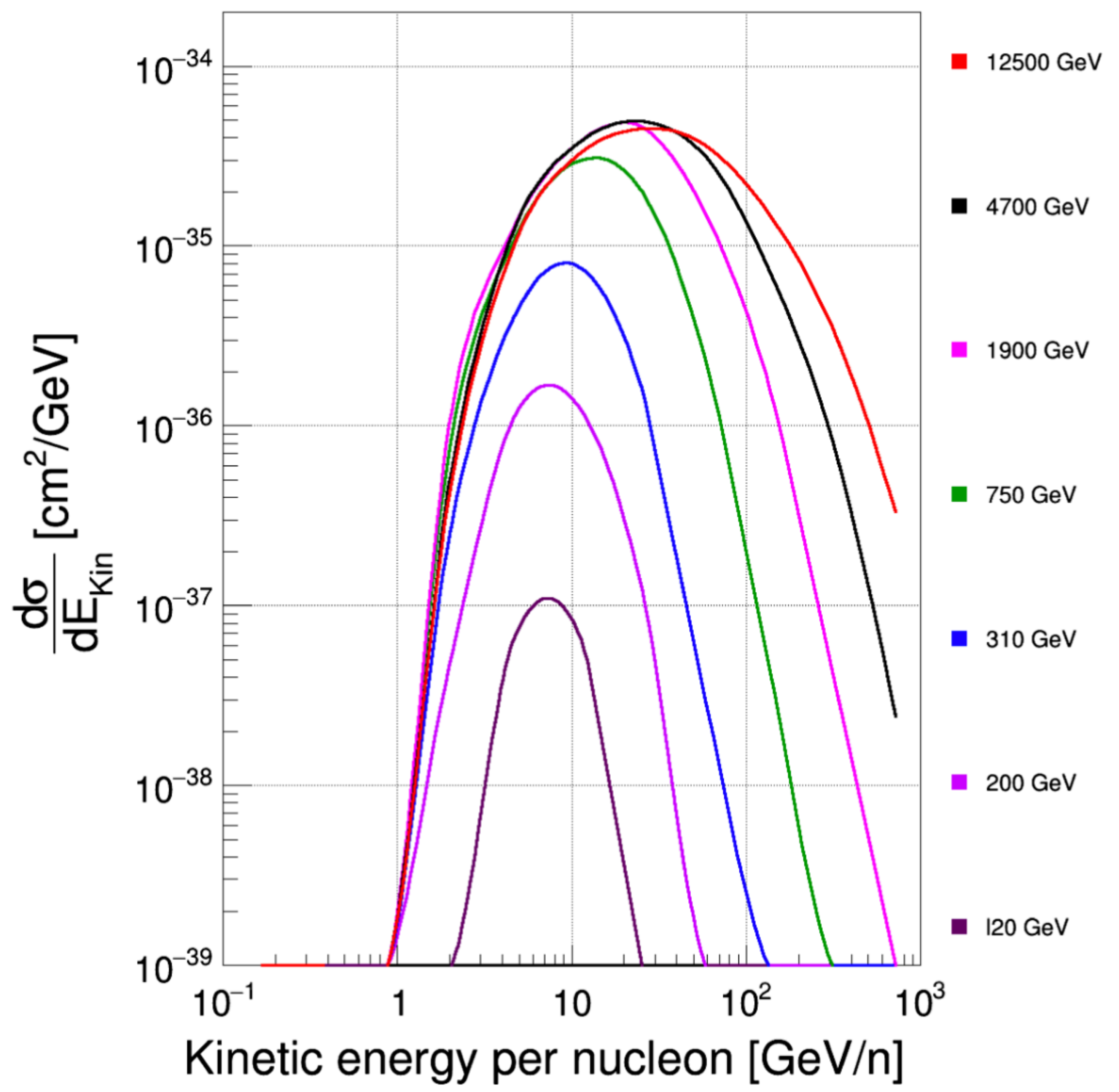


$$\frac{\text{antimatter}}{\text{matter}} \approx 1$$

Collider data input to validate the coalescence models

Number density of $\overline{\mathrm{d}}$, $^{3}\overline{\mathrm{He}}$ production from coalescence mechanism shown with ALICE data [1].





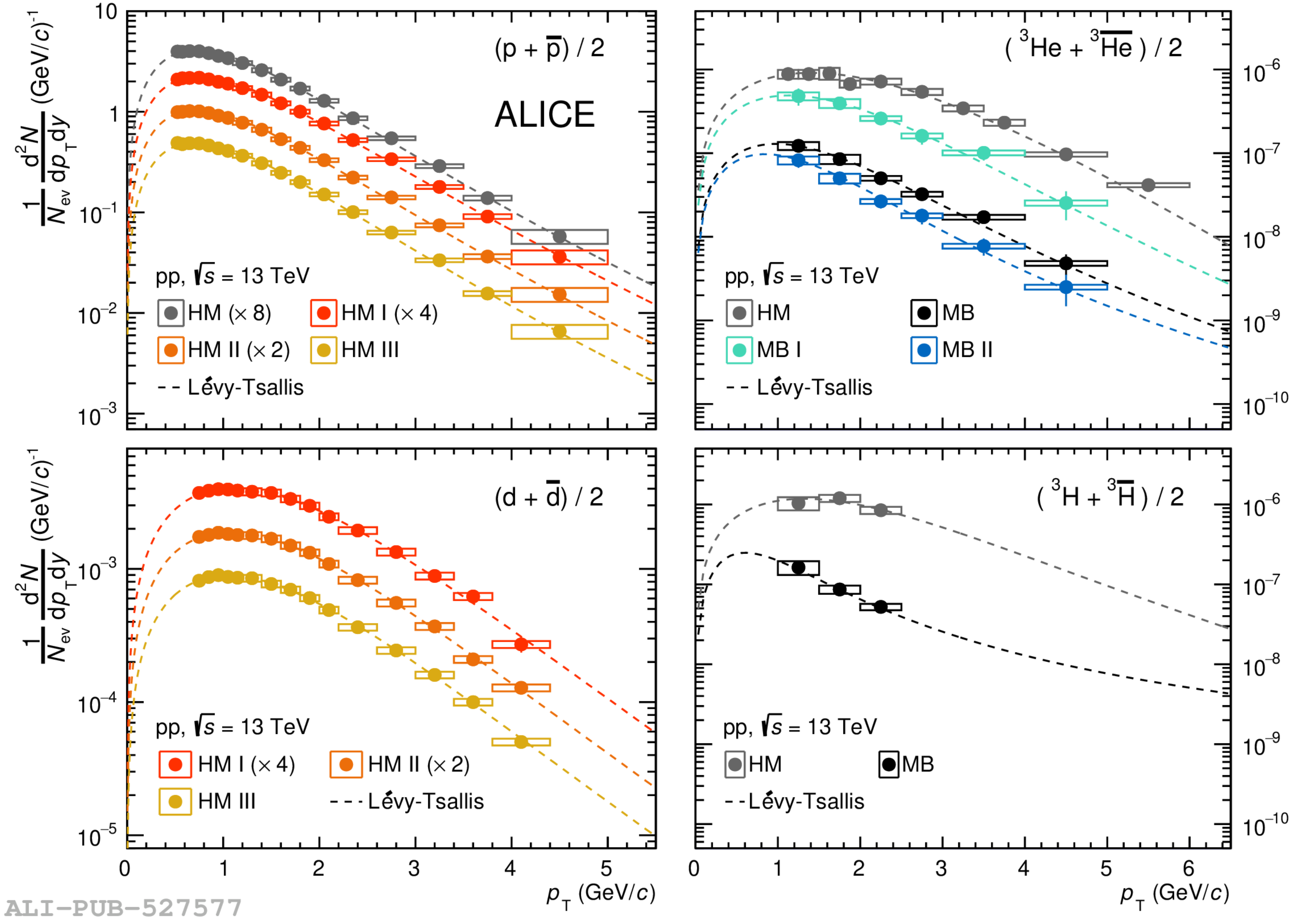
Production cross-section for $^{3}\overline{\mathrm{He}}$ for different pp collision energies, using the coalescence mechanism [1].

- Coalescence model based calculations of the production yields of antinuclei in space: used to calculate secondary flux
- Validation with LHC data (pp collisions at $\sqrt{s}$ = 7 and 13 TeV)

[1] Shukla et. al., Phys. Rev. D **102**, 063004 (2020)

New data on the (anti)nuclei production by ALICE

ALICE collaboration, *J. High Energ. Phys.* **2022**, 106 (2022)



- New results from ALICE on light (anti)nuclei production in pp collisions at $\sqrt{s}$ = 13 TeV

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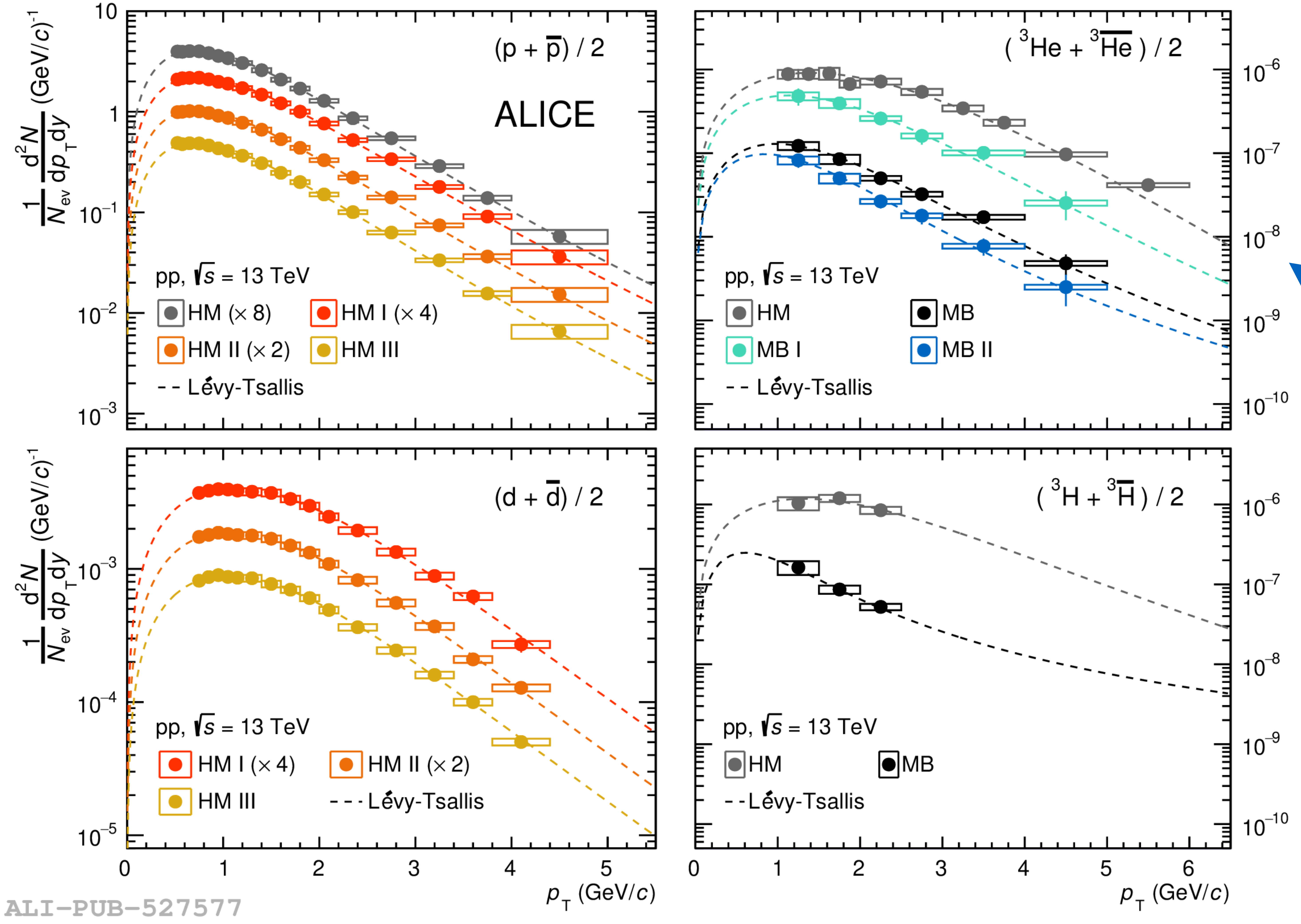

- New results from ALICE on light (anti)nuclei production in pp collisions at $\sqrt{s}$ = 13 TeV
- Extended p_T range for antihelium

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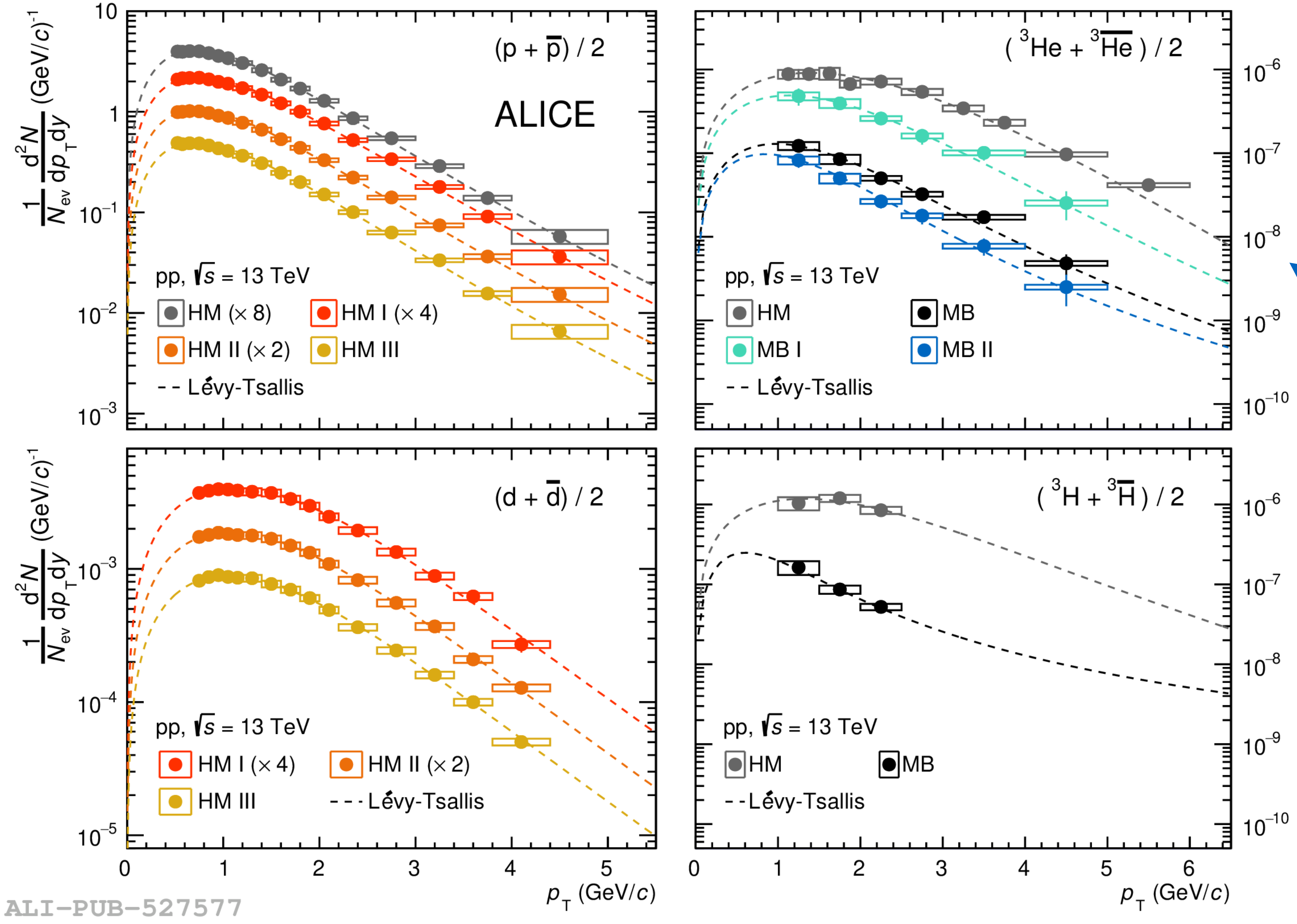
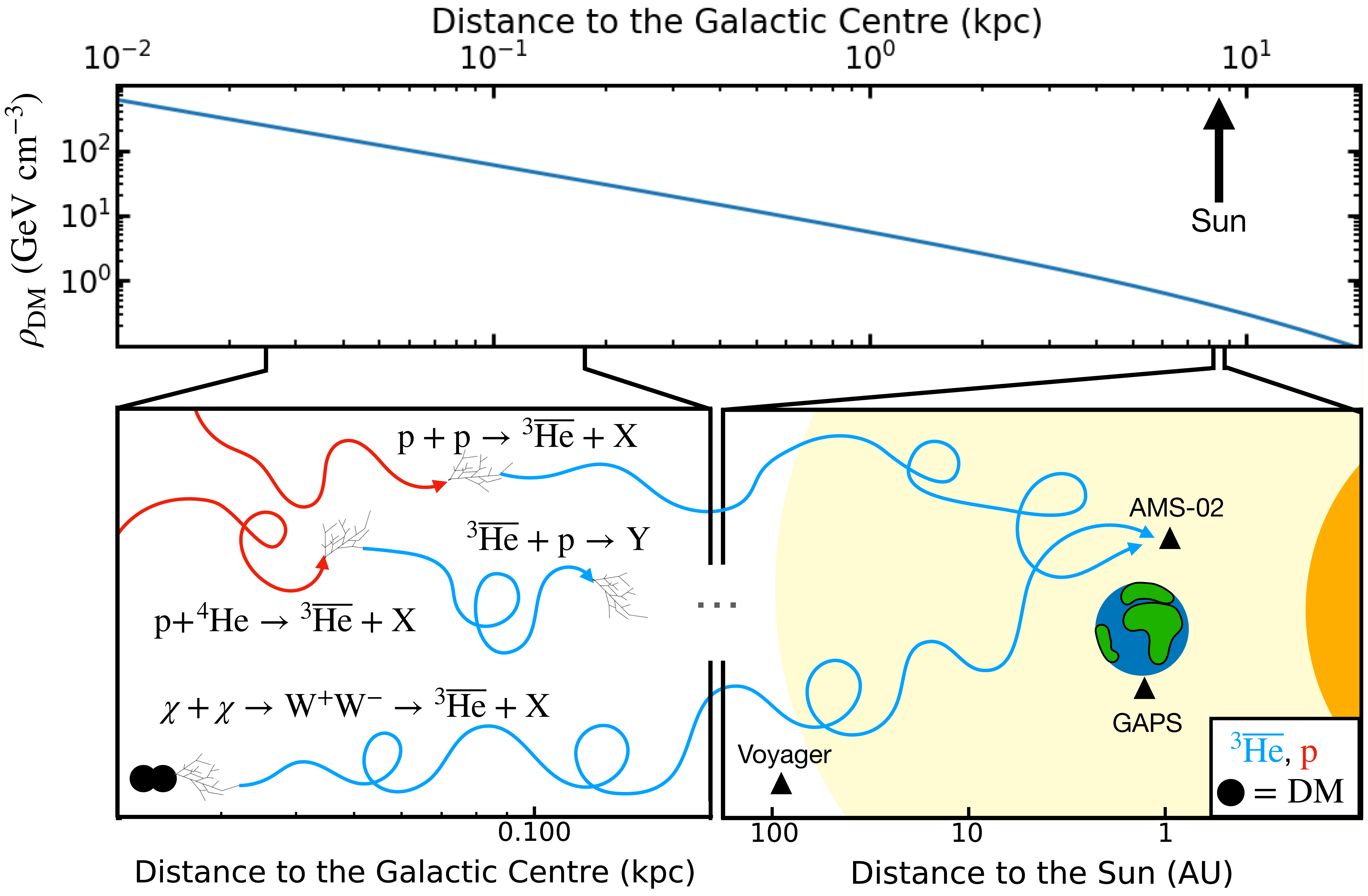


- New results from ALICE on light (anti)nuclei production in pp collisions at $\sqrt{s}$ = 13 TeV
- Extended p_T range for antihelium

What else can we learn with the produced (anti)nuclei at colliders ?

Antinuclei inelastic interaction in the Galaxy

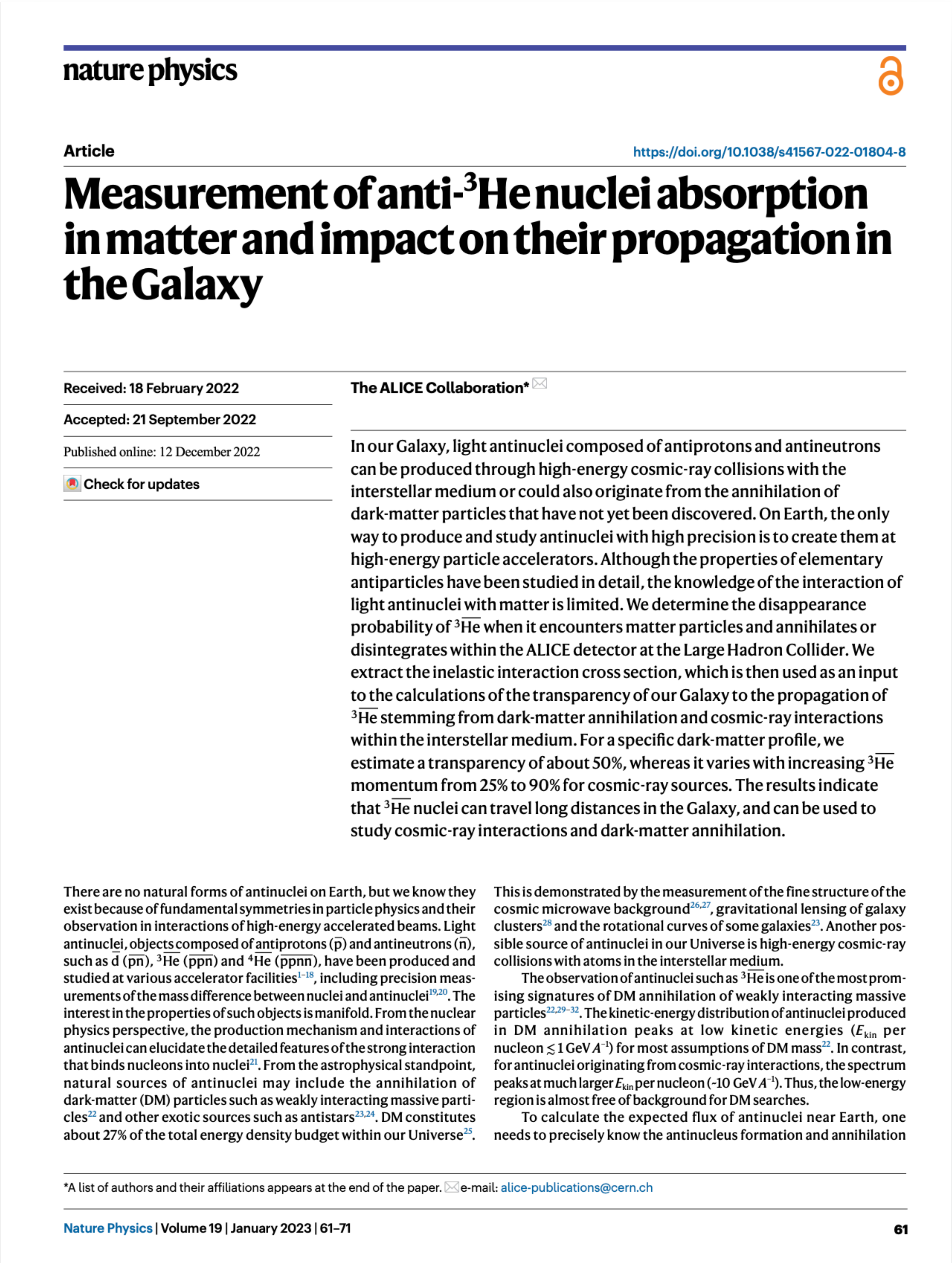


Calculation of primary and secondary fluxes near Earth:

- Requires precise knowledge of **antinuclei inelastic interaction** with interstellar gas
- We can quantify it!

ALICE already measured $\sigma_{\rm inel}(\overline{\rm d})$:
[PRL 125, 162001 (2020)](PRL 125, 162001 (2020))
This talk: focus on ${}^{3}\overline{\rm He}$

Measurement of the transparency of the Galaxy to $^{3}\overline{\mathrm{He}}$



nature physics

Article

https://doi.org/10.1038/s41567-022-01804-8

Measurement of anti-^{3}He nuclei absorption in matter and impact on their propagation in the Galaxy

Received: 18 February 2022

Accepted: 21 September 2022

The ALICE Collaboration*

In our Galaxy, light antinuclei composed of antiprotons and antineutrons can be produced through high-energy cosmic-ray collisions with the interstellar medium or could also originate from the annihilation of dark-matter particles that have not yet been discovered. On Earth, the only way to produce and study antinuclei with high precision is to create them at high-energy particle accelerators. Although the properties of elementary antiparticles have been studied in detail, the knowledge of the interaction of light antinuclei with matter is limited. We determine the disappearance probability of $^{3}\overline{\mathrm{He}}$ when it encounters matter particles and annihilates or disintegrates within the ALICE detector at the Large Hadron Collider. We extract the inelastic interaction cross section, which is then used as an input to the calculations of the transparency of our Galaxy to the propagation of $^{3}\overline{\mathrm{He}}$ stemming from dark-matter annihilation and cosmic-ray interactions within the interstellar medium. For a specific dark-matter profile, we estimate a transparency of about 50%, whereas it varies with increasing $^{3}\overline{\mathrm{He}}$ momentum from 25% to 90% for cosmic-ray sources. The results indicate that $^{3}\overline{\mathrm{He}}$ nuclei can travel long distances in the Galaxy, and can be used to study cosmic-ray interactions and dark-matter annihilation.

There are no natural forms of antinuclei on Earth, but we know they exist because of fundamental symmetries in particle physics and their observation in interactions of high-energy accelerated beams. Light antinuclei, objects composed of antiprotons ($\overline{\mathrm{p}}$) and antineutrons ($\overline{\mathrm{n}}$), such as $\overline{\mathrm{d}}$ ($\overline{\mathrm{pn}}$), $^{3}\overline{\mathrm{He}}$ ($\overline{\mathrm{ppn}}$) and $^{4}\overline{\mathrm{He}}$ ($\overline{\mathrm{ppnn}}$), have been produced and studied at various accelerator facilities[1–18], including precision measurements of the mass difference between nuclei and antinuclei[19,20]. The interest in the properties of such objects is manifold. From the nuclear physics perspective, the production mechanism and interactions of antinuclei can elucidate the detailed features of the strong interaction that binds nucleons into nuclei[21]. From the astrophysical standpoint, natural sources of antinuclei may include the annihilation of dark-matter (DM) particles such as weakly interacting massive particles[22] and other exotic sources such as antistars[23,24]. DM constitutes about 27% of the total energy density budget within our Universe[25]. This is demonstrated by the measurement of the fine structure of the cosmic microwave background[26,27], gravitational lensing of galaxy clusters[28] and the rotational curves of some galaxies[23]. Another possible source of antinuclei in our Universe is high-energy cosmic-ray collisions with atoms in the interstellar medium.

The observation of antinuclei such as $^{3}\overline{\mathrm{He}}$ is one of the most promising signatures of DM annihilation of weakly interacting massive particles[22,29–32]. The kinetic-energy distribution of antinuclei produced in DM annihilation peaks at low kinetic energies (E_{kin} per nucleon $\lesssim 1\,\mathrm{GeV}\,A^{-1}$) for most assumptions of DM mass[22]. In contrast, for antinuclei originating from cosmic-ray interactions, the spectrum peaks at much larger E_{kin} per nucleon (~$10\,\mathrm{GeV}\,A^{-1}$). Thus, the low-energy region is almost free of background for DM searches.

To calculate the expected flux of antinuclei near Earth, one needs to precisely know the antinucleus formation and annihilation

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Nature Physics | Volume 19 | January 2023 | 61–71

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ALICE experiment measures the absorption cross section of $^{3}\overline{\mathrm{He}}$ and calculates the transparency of the Galaxy to this antinuclei

- First measurement of the $^{3}\overline{\mathrm{He}}$ absorption cross section
- Calculation of the expected antihelium flux near Earth for both dark matter and secondary fluxes

📌 Nat. Phys. 19, 61–71 (2023)

Propagation of $^{3}\overline{\mathrm{He}}$ in the Galaxy: ingredients

Transport equation

$$\frac{\partial\psi}{\partial t} = \boxed{q(\mathbf{r},p)} + \boxed{\nabla\cdot(D_{xx}\nabla\psi - \mathbf{V}\psi) + \frac{\partial}{\partial p}p^{2}D_{pp}\frac{\partial}{\partial p}\frac{\psi}{p^{2}} - \frac{\partial}{\partial p}\left[\psi\frac{dp}{dt} - \frac{p}{3}(\nabla\cdot\mathbf{V})\psi\right]} - \boxed{\frac{\psi}{\tau_f} - \frac{\psi}{\tau_r}}$$

Source Function

Propagation: diffusion, convection...

Fragmentation, annihilation

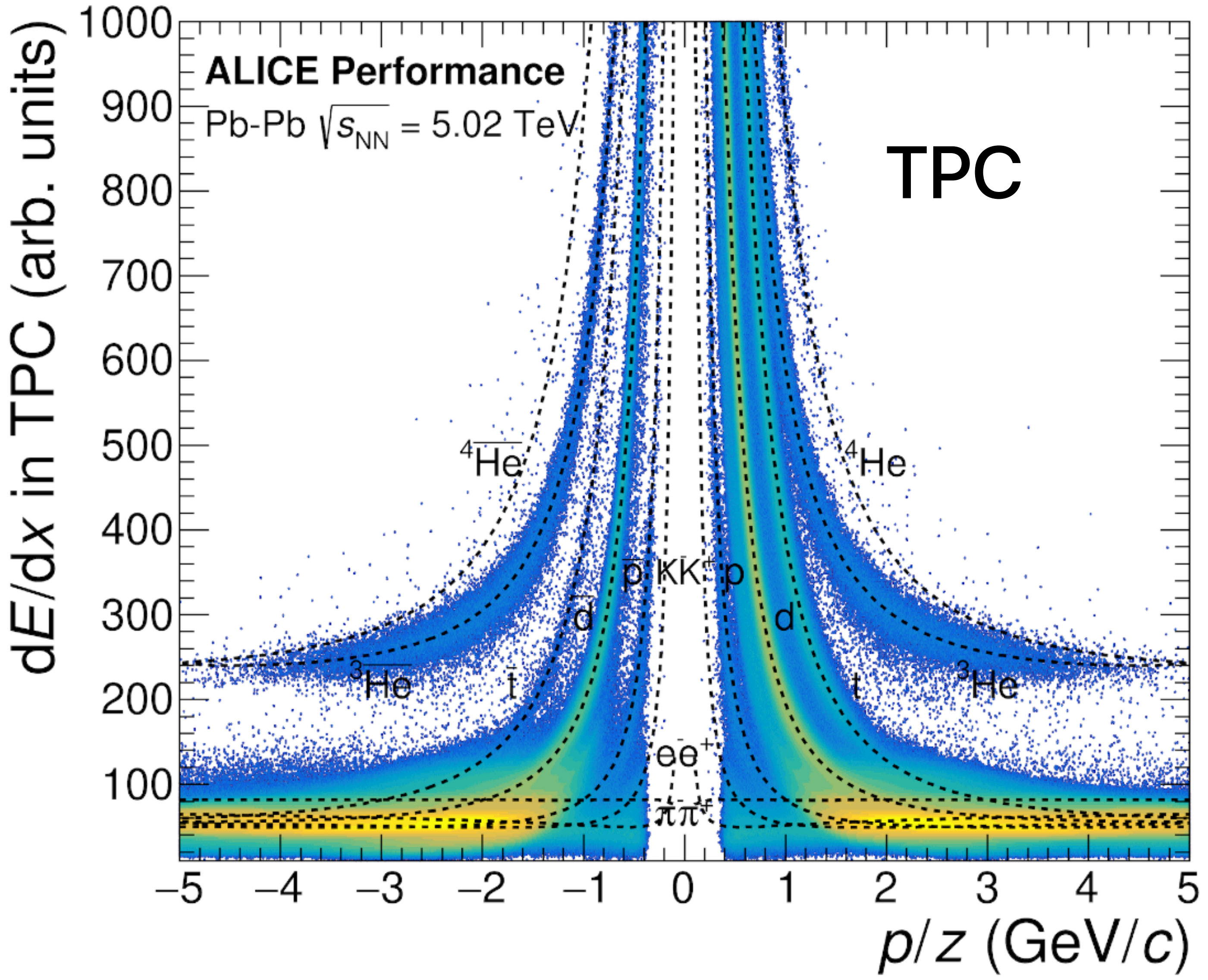
- Can be numerically solved using publicly available GALPROP package
- **Propagation parameters** (common for all (anti)nuclei) can be constrained using available cosmic ray measurements [1]

- Calculation of antinuclei flux requires:
  - **source function**: differential production cross section [2, 3]
  - **annihilation cross section**

Input:
ALICE
measurements

[1] M. J. Boschini et. al. 2020 (*ApJS* 250 27)
[2] Shukla et. al., Phys. Rev. D 102, 063004 (2020)
[3] Carlson et. al., Phys. Rev. D 89, 076005 (2014)

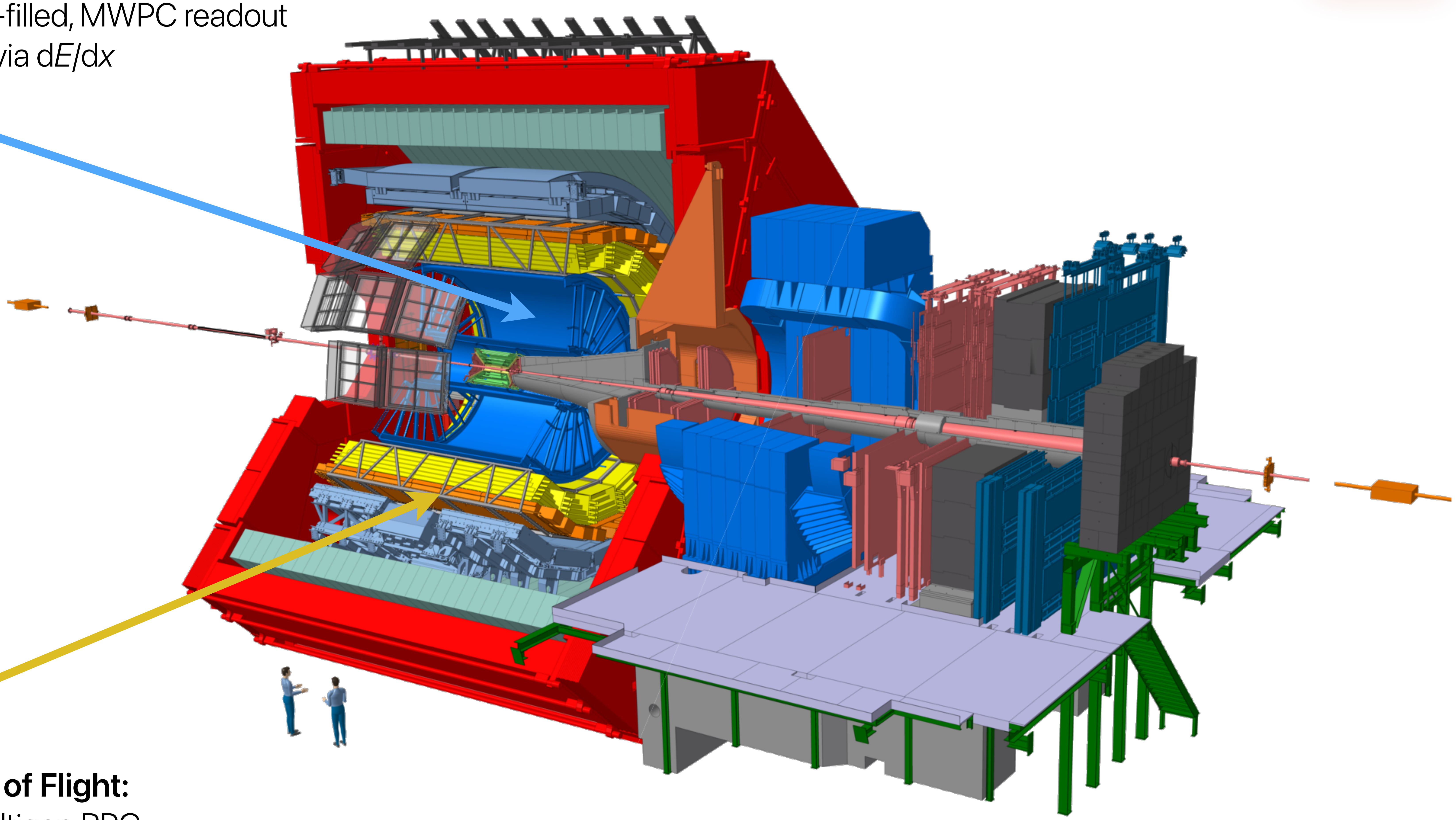
ALICE apparatus and its particle identification capabilities

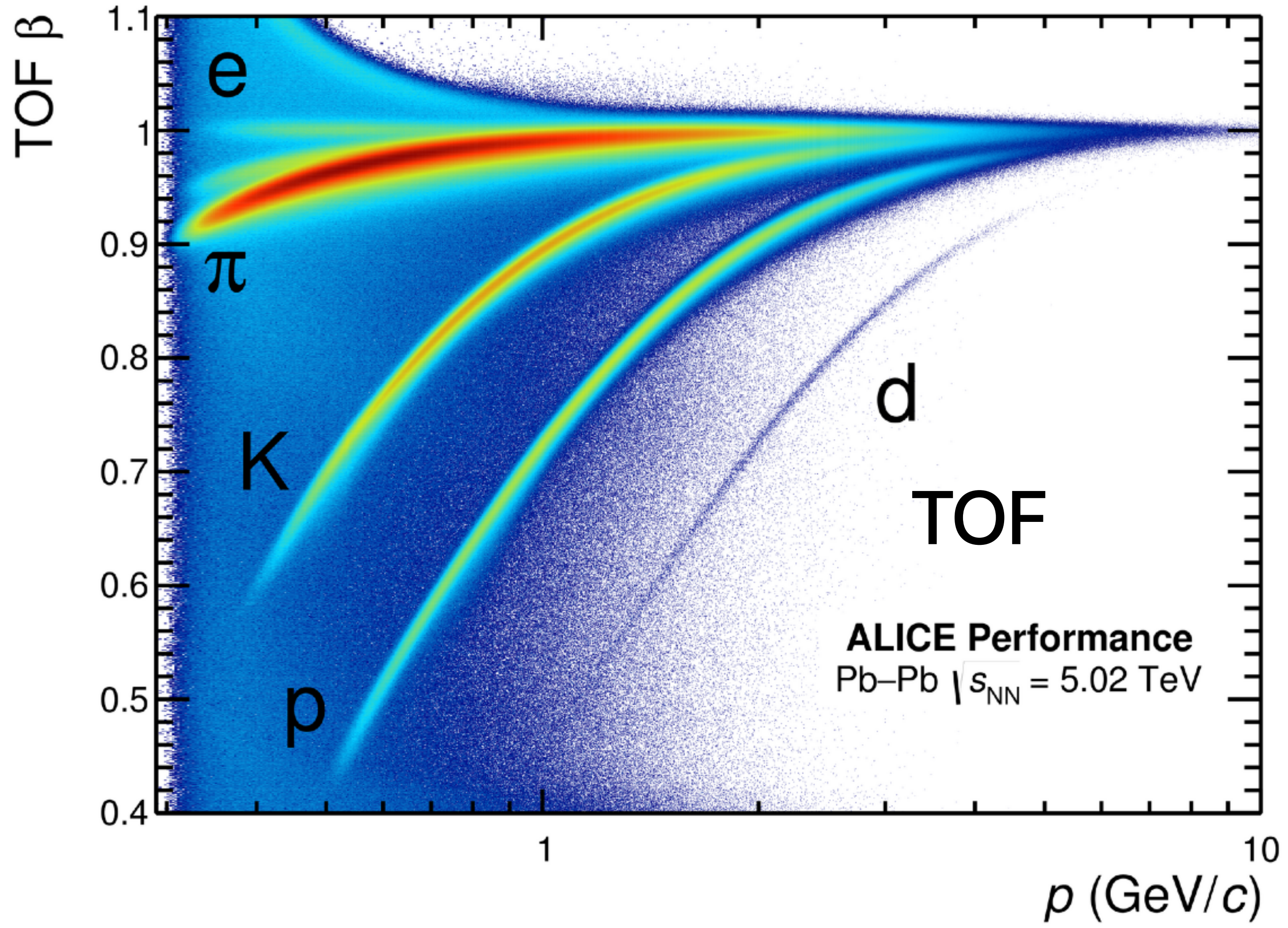


ALI-PERF-341664

Time Projection Chamber:

- Gas-filled, MWPC readout
- PID via dE/dx





ALI-PERF-106336

Time of Flight:

- Multigap RPC
- PID via time-of-flight measurement

Methods to measure σ_{inel}

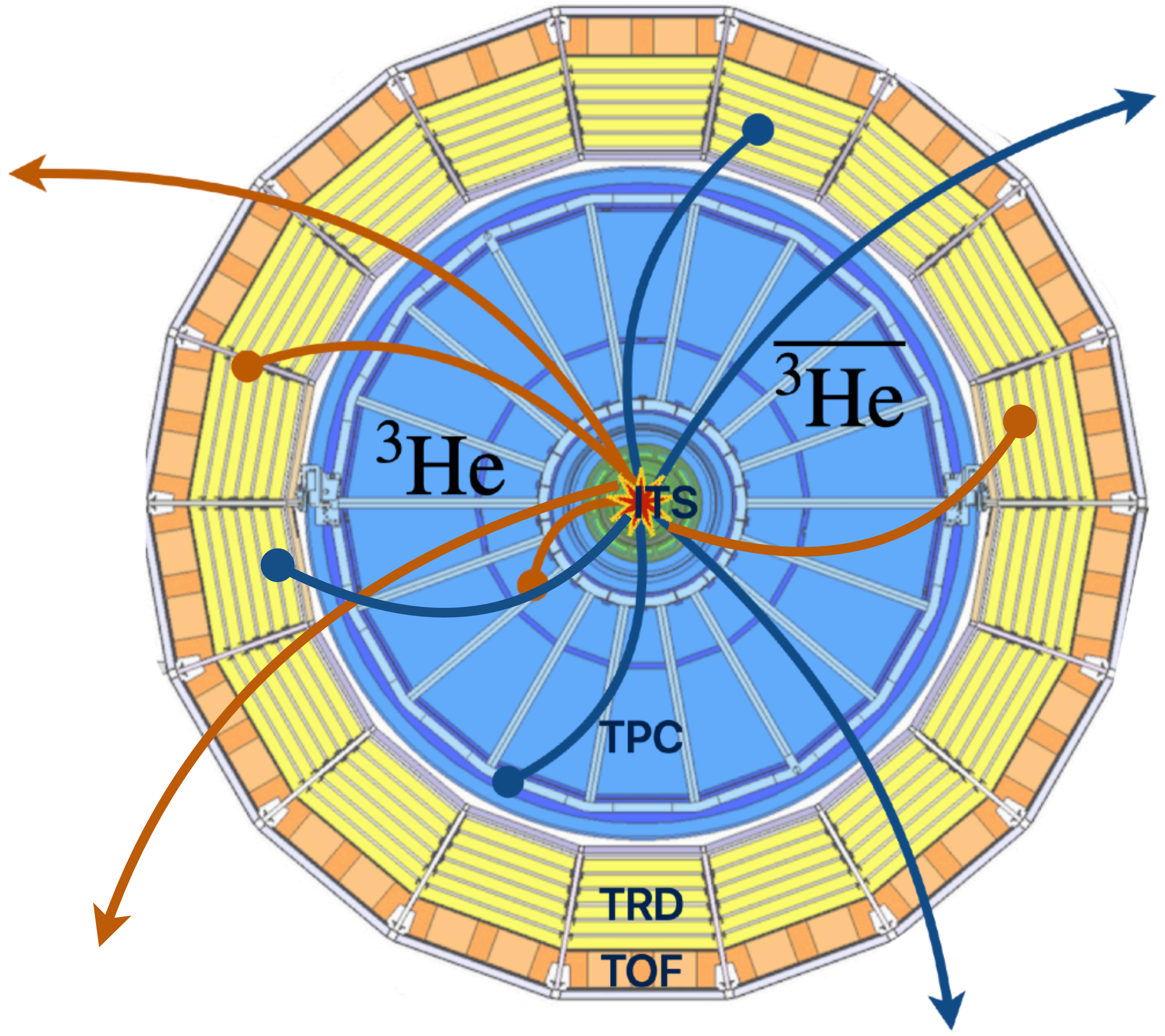
Antiparticle/particle raw ratio: Method 1

- Measure reconstructed $\overline{\mathrm{d}}/\mathrm{d}$, $^{3}\overline{\mathrm{He}}/^{3}\mathrm{He}$... and compare with MC simulations

\+ Access to low momenta ($p \lesssim 1$ GeV/c)

\- Relies on $\sigma_{\text{inel}}(\text{nuclei})$

\- Background from secondary particles



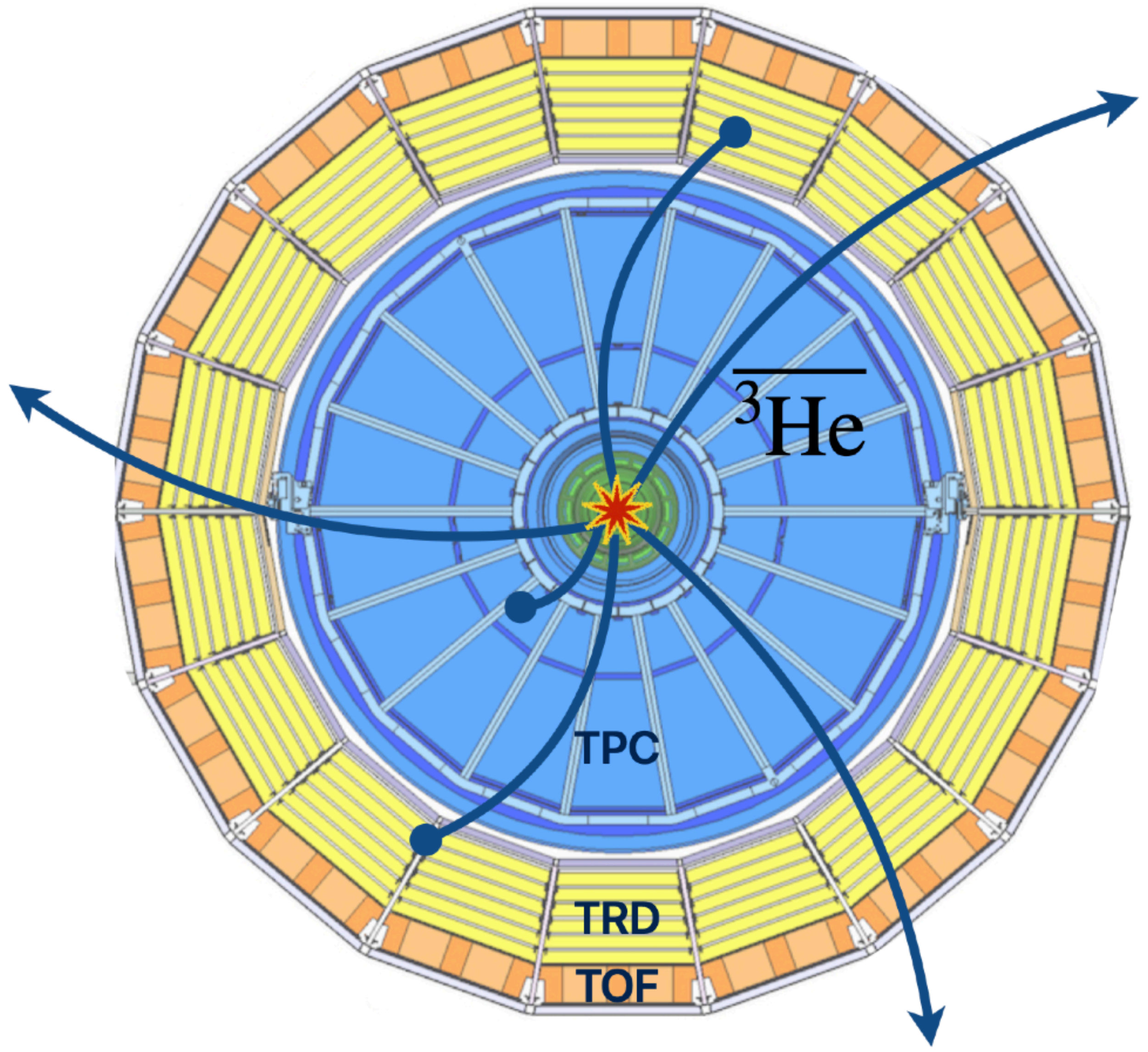
TOF/TPC ratio: Method 2

- Measure reconstructed $N^{\mathrm{TOF}}_{^{3}\overline{\mathrm{He}}}/N^{\mathrm{TPC}}_{^{3}\overline{\mathrm{He}}}$ and compare with MC simulations

\+ High statistics, wide momentum range

\+ Independent of $\sigma_{\text{inel}}(\text{nuclei})$

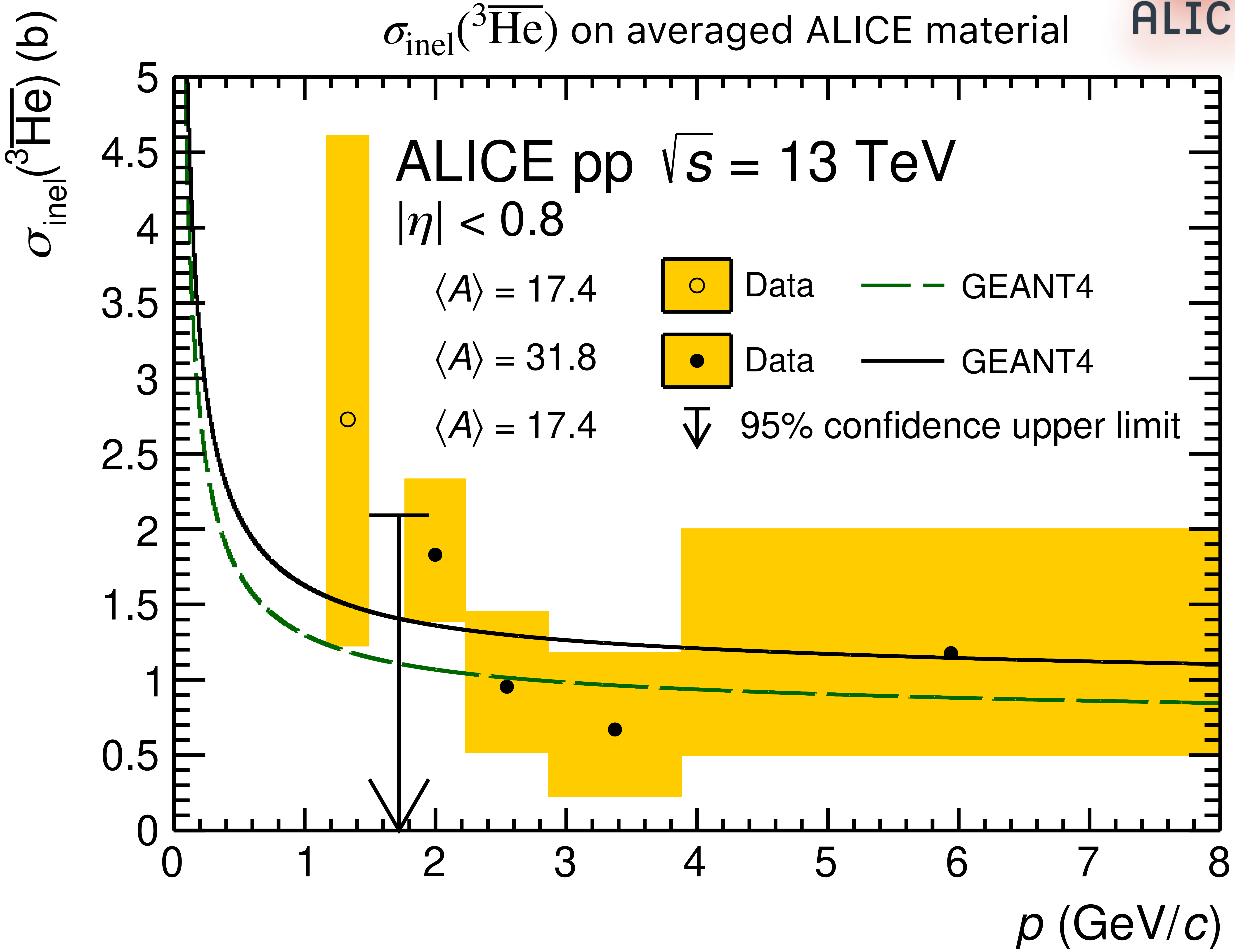
\- No access to very-low momenta ($p \lesssim 1$ GeV/c)



Results: $^{3}\overline{\mathrm{He}}$ inelastic cross section

Method 1

- $\sigma_{\mathrm{inel}}(^{3}\overline{\mathrm{He}})$: Results for **antiparticle-to-particle raw ratio method**



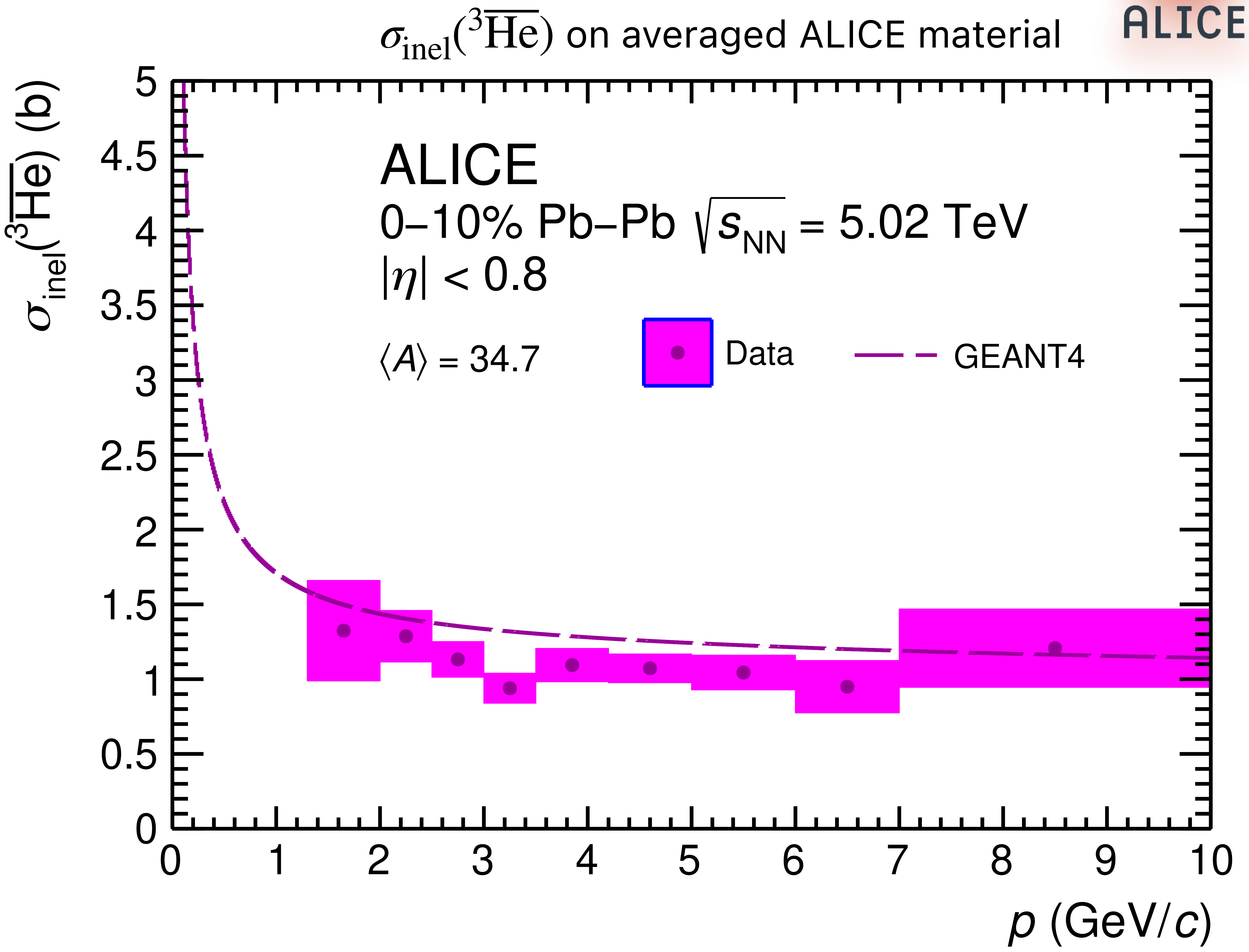
ALI-PUB-501526

Nat. Phys. 19, 61–71 (2023)

Results: ${}^{3}\overline{\mathrm{He}}$ inelastic cross section

Method 2

- $\sigma_{\mathrm{inel}}({}^{3}\overline{\mathrm{He}})$: Results for **TOF-to-TPC ratio method**



ALI-PUB-501531

Nat. Phys. 19, 61–71 (2023)

Results: $^{3}\overline{\mathrm{He}}$ inelastic cross section

Method 2

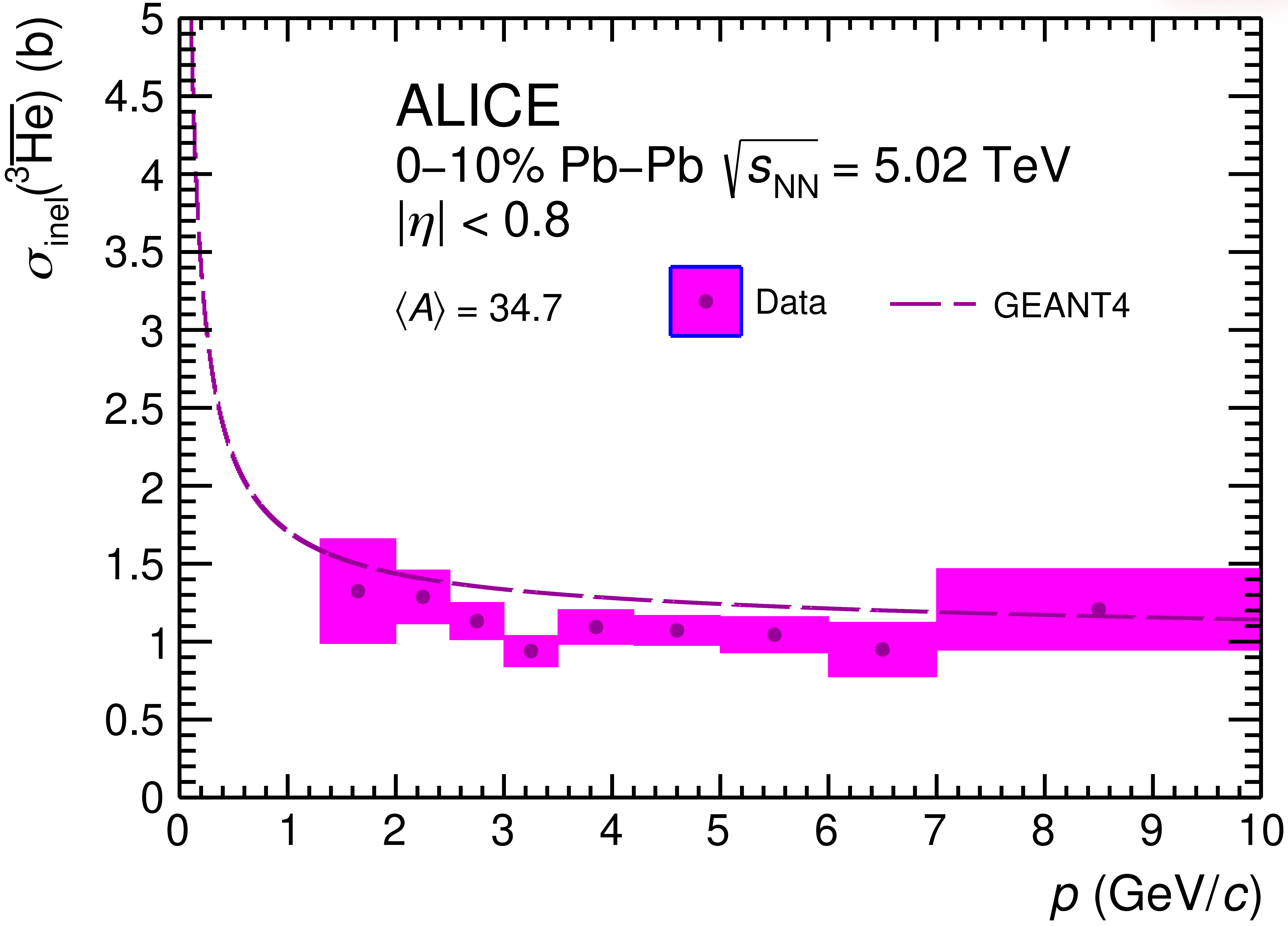
- $\sigma_{\mathrm{inel}}(^{3}\overline{\mathrm{He}})$: Results for **TOF-to-TPC ratio method**

First ever measurement of $^{3}\overline{\mathrm{He}}$ inelastic cross section!

- Results from both methods are compatible (higher precision in TOF-to-TPC ratio)
- Bands: statistical ⊕ systematic uncertainties

→ impact on $^{3}\overline{\mathrm{He}}$ propagation in space

$\sigma_{\mathrm{inel}}(^{3}\overline{\mathrm{He}})$ on averaged ALICE material



ALI-PUB-501531

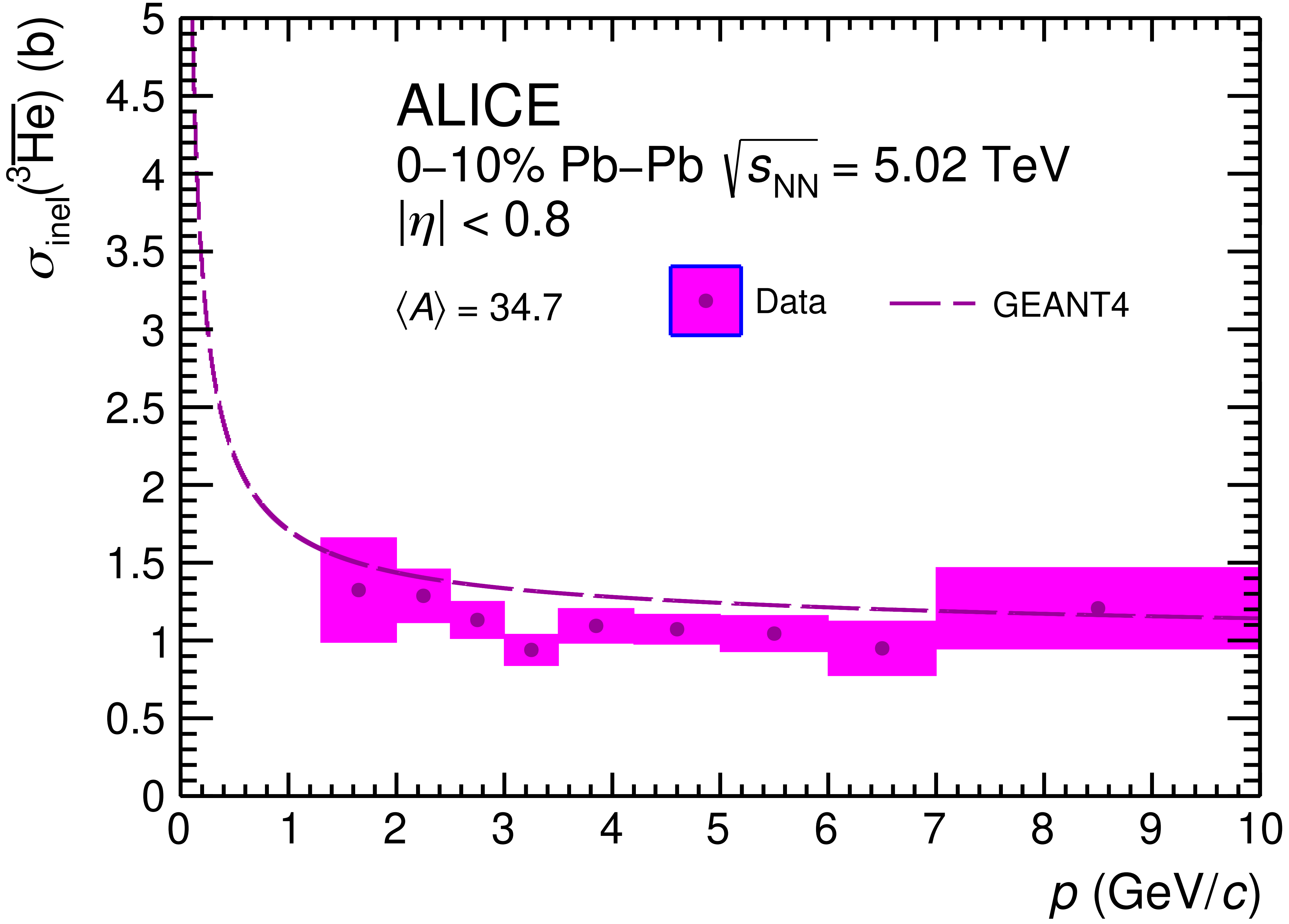
Nat. Phys. 19, 61–71 (2023)

Annihilation

$^{3}\overline{\mathrm{He}}$ nuclei may interact inelastically with the interstellar gas ($A = 1$, $A = 4$)

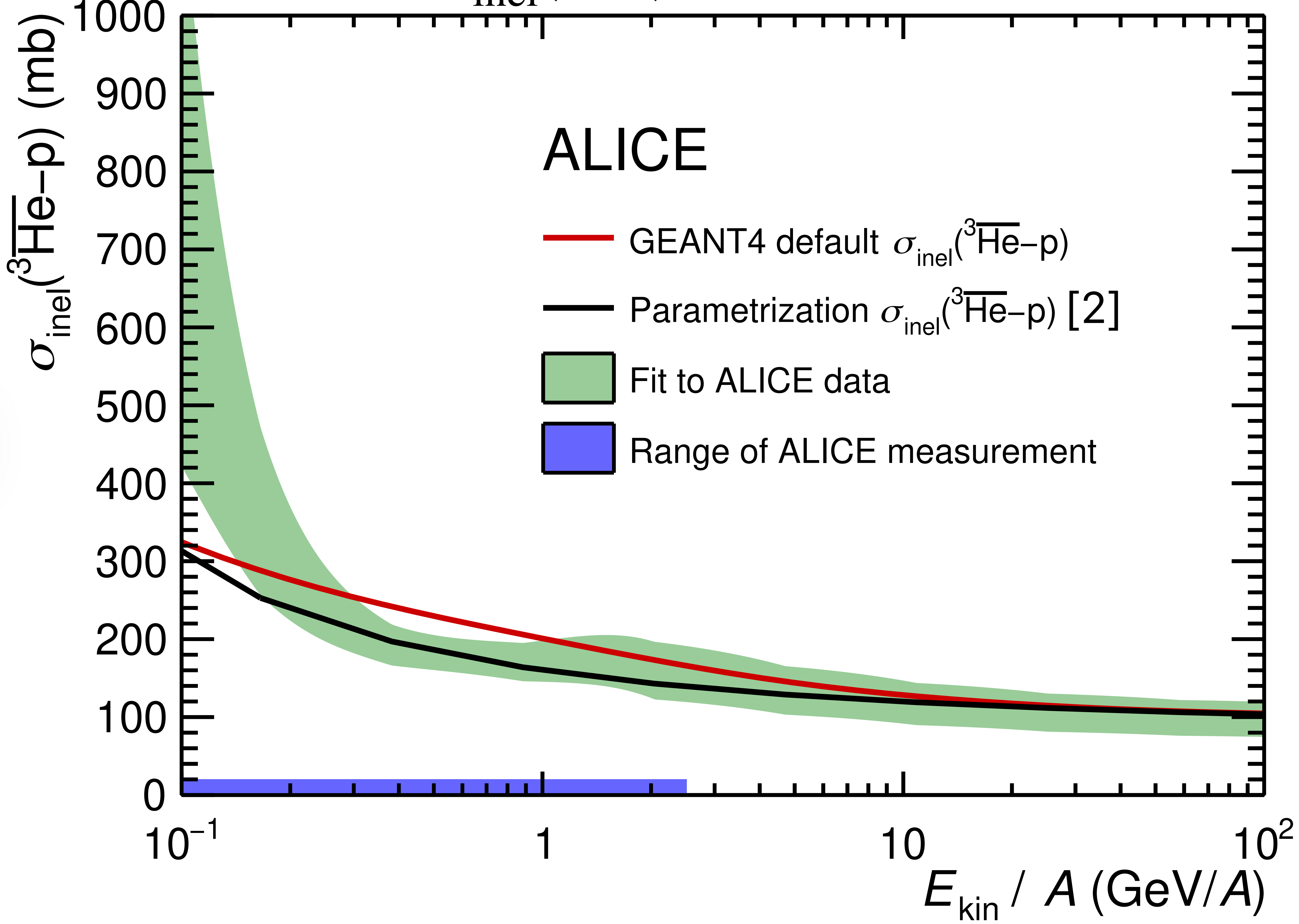
- ALICE results for $\sigma_{\mathrm{inel}}(^{3}\overline{\mathrm{He}})$ are for heavy elements with $\langle A \rangle$ = 17.4 to 34.7
- Rescaled for proton and helium targets
- 8% uncertainty from A scaling [1] is valid for all targets

$\sigma_{\mathrm{inel}}(^{3}\overline{\mathrm{He}})$ on averaged ALICE material



ALI-PUB-501531

$\sigma_{\mathrm{inel}}(^{3}\overline{\mathrm{He}})$ on proton



ALI-PUB-501551

[1] Uzhinsky et al. Phys. Lett. B 705 (2011) 235

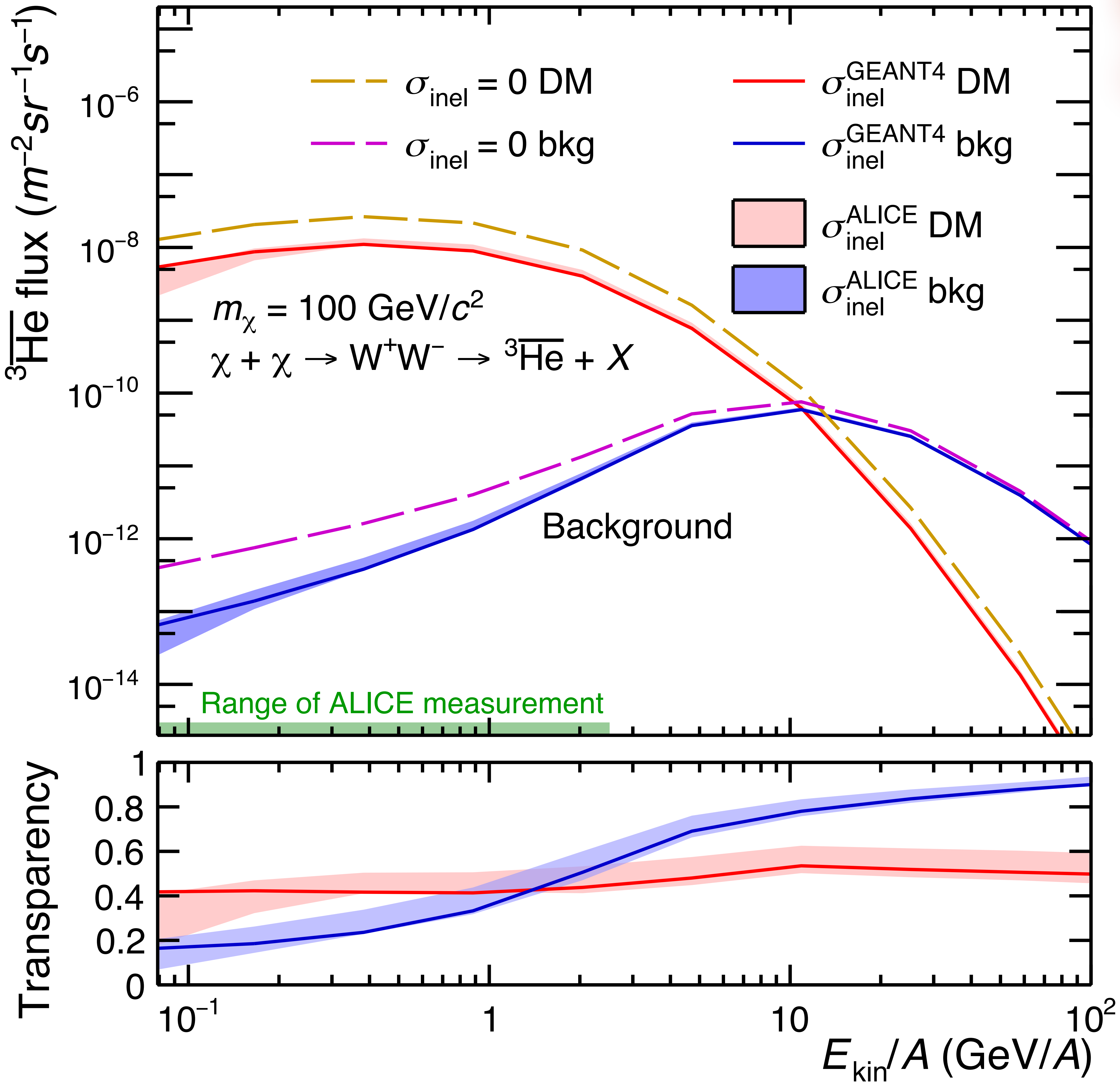
[2] Korsmeier et al, Phys. Rev. D. 97, 103011 (2018)

Results: $^3\overline{\mathrm{He}}$ fluxes

- Effect of various inelastic cross sections on $^3\overline{\mathrm{He}}$ fluxes
- Uncertainty only from σ_{inel} from ALICE data: **small compared to other uncertainties in the field!**
- $^3\overline{\mathrm{He}}$ transparency (at low E_{kin}): 25% from CR interactions, 50% from typical DM candidates
- **Flux outside heliosphere**

$$\text{Transparency} = \frac{\text{Flux}(\sigma_{\mathrm{inel}})}{\text{Flux}(\sigma_{\mathrm{inel}} = 0)}$$

Outside heliosphere



[1] Korsmeier et al, Phys. Rev. D. 97, 103011 (2018)

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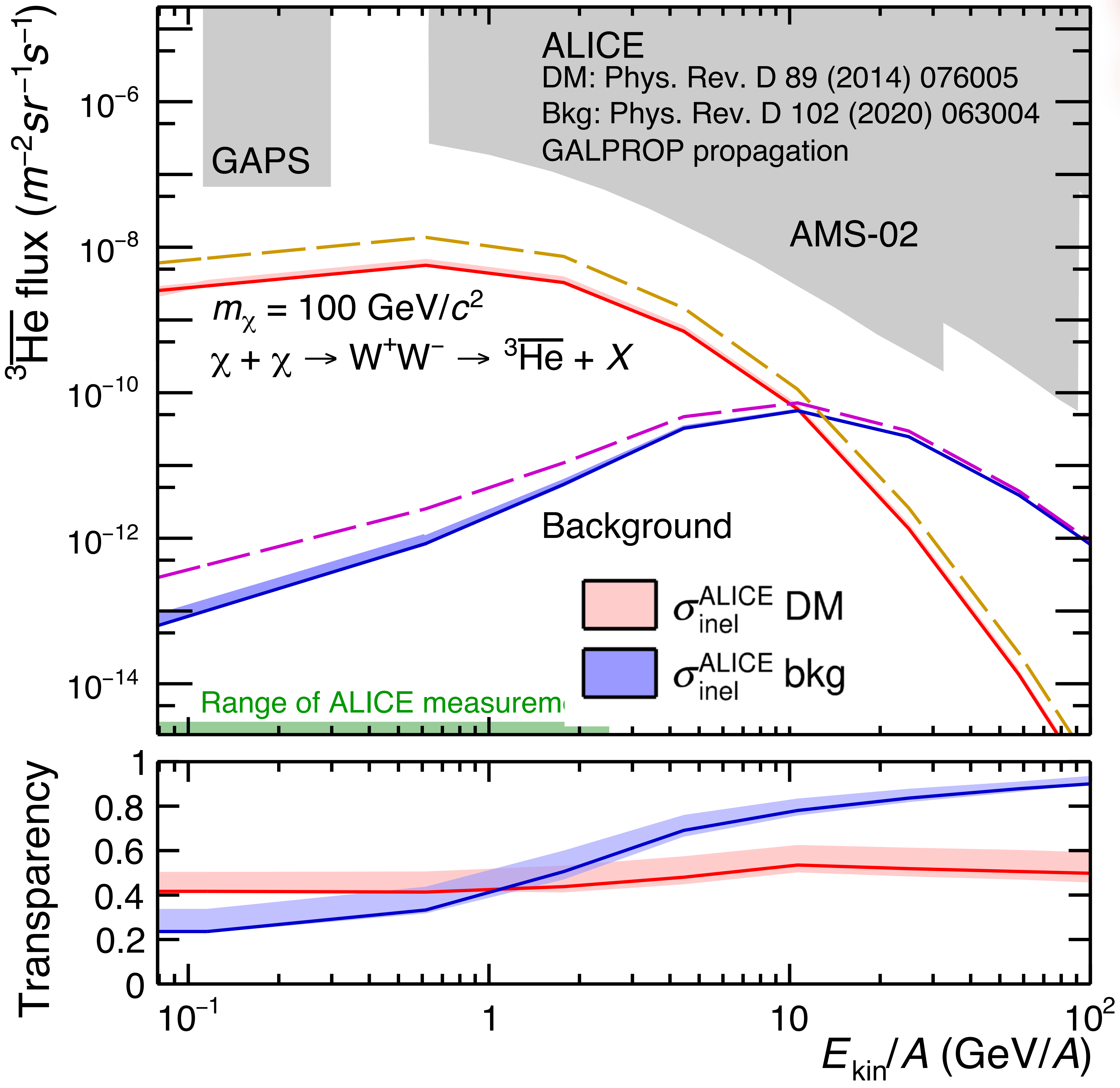
High transparency of the Galaxy to $^{3}\overline{\text{He}}$ nuclei!

Near Earth



[1] Korsmeier et al, Phys. Rev. D. 97, 103011 (2018)

Summary

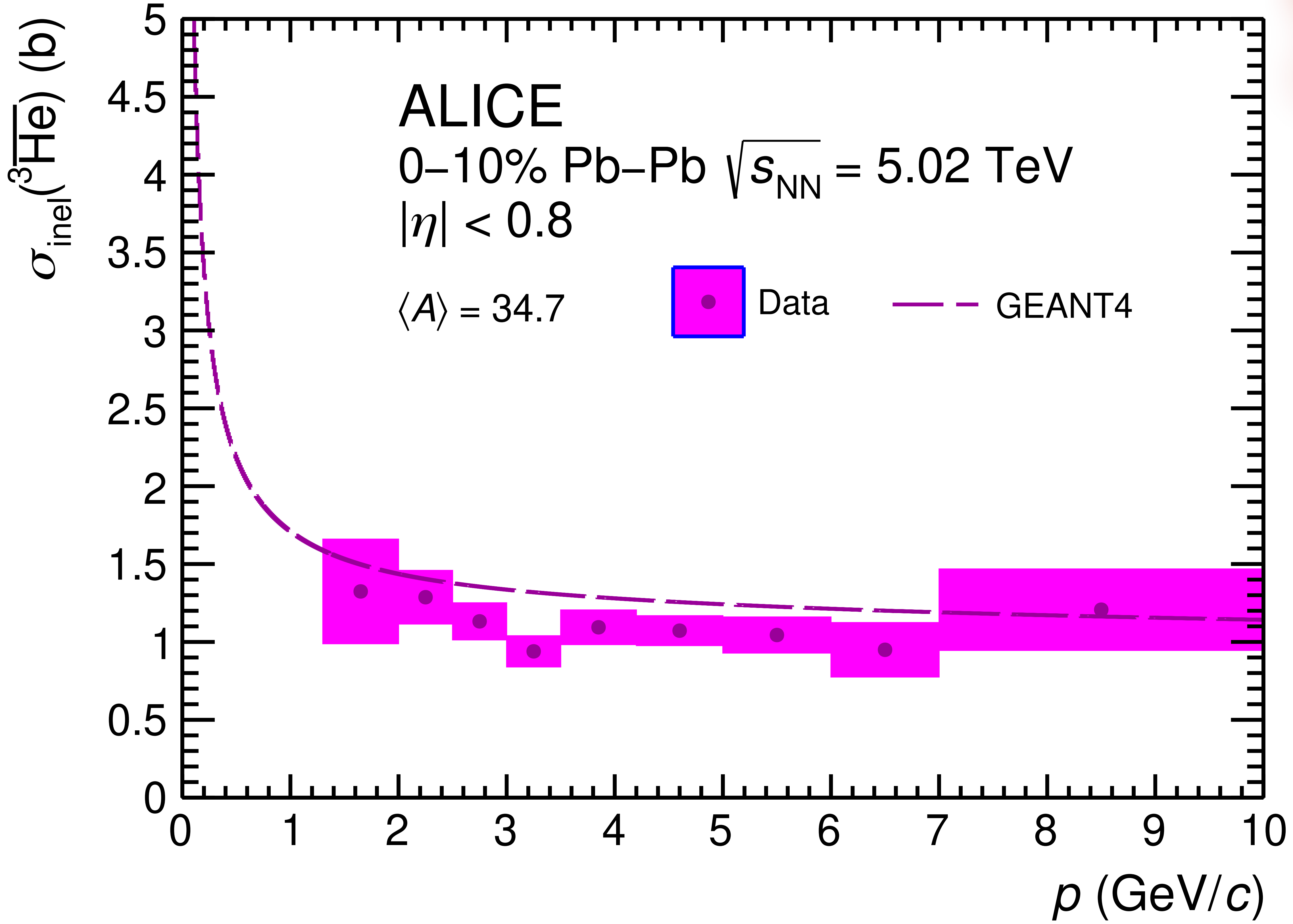
Production of (anti)nuclei at colliders provides important input to:

- Understand their production mechanism
- Validate the models used for calculation of (anti)nuclei fluxes
- New! ALICE performed **groundbreaking measurements** of antinuclei inelastic cross sections:
  ✅ $^{3}\overline{\mathrm{He}}$ [Nat. Phys. 19, 61–71 (2023)]

Impact on antinuclei flux near Earth:

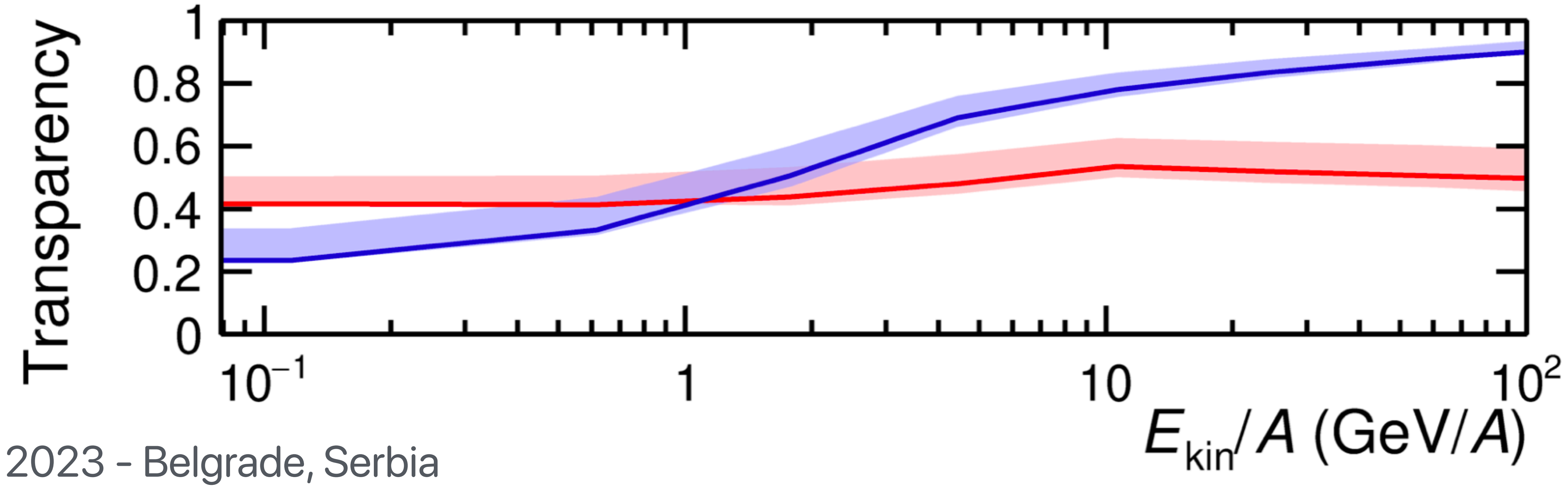
- **High transparency of the Galaxy to $^{3}\overline{\mathrm{He}}$**
- Small uncertainties on cosmic ray fluxes from $\sigma_{\mathrm{inel}}(^{3}\overline{\mathrm{He}})$ compared to other uncertainties in the field

$\sigma_{\mathrm{inel}}(^{3}\overline{\mathrm{He}})$ on averaged ALICE material



ALI-PUB-501531

Transparency of the Galaxy to $^{3}\overline{\mathrm{He}}$

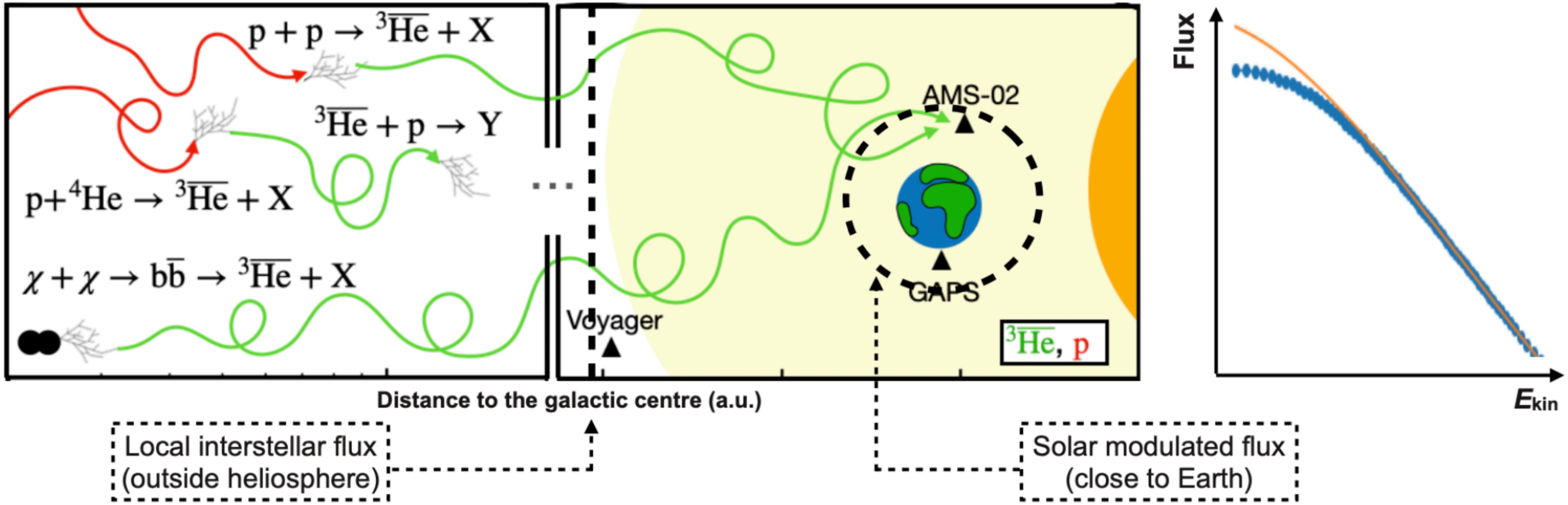


Backup slides

Solar environment effects

- Solar magnetic field forms heliosphere which shields cosmic rays
- Solar modulation is accounted for using Force-Field approximation [1] with Fisk potential ϕ = 0.4 GV:

$$F_{mod}(E_{mod}, \phi) = F(E)\frac{(E - Z\phi)^2 - m^2_{^3He}}{E^2 - m^2_{^3He}} \text{, where } E_{mod} = E - Z\phi$$



Local interstellar flux (outside heliosphere)

Solar modulated flux (close to Earth)

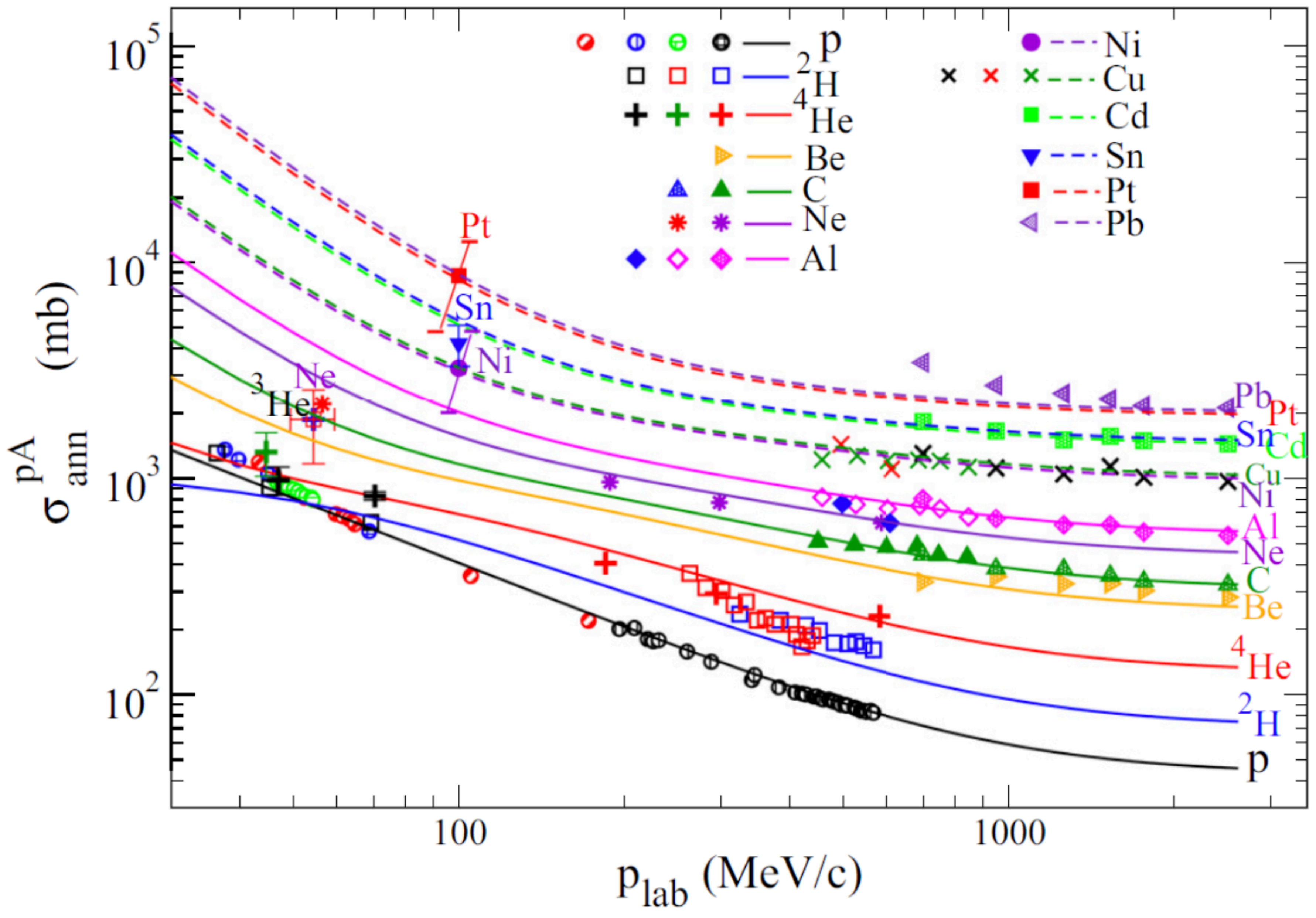
[1] Gleeson, Axford, Astrophys.J. 154 (1968) 1011

Antinuclei σ_{inel} measurements (before ALICE)

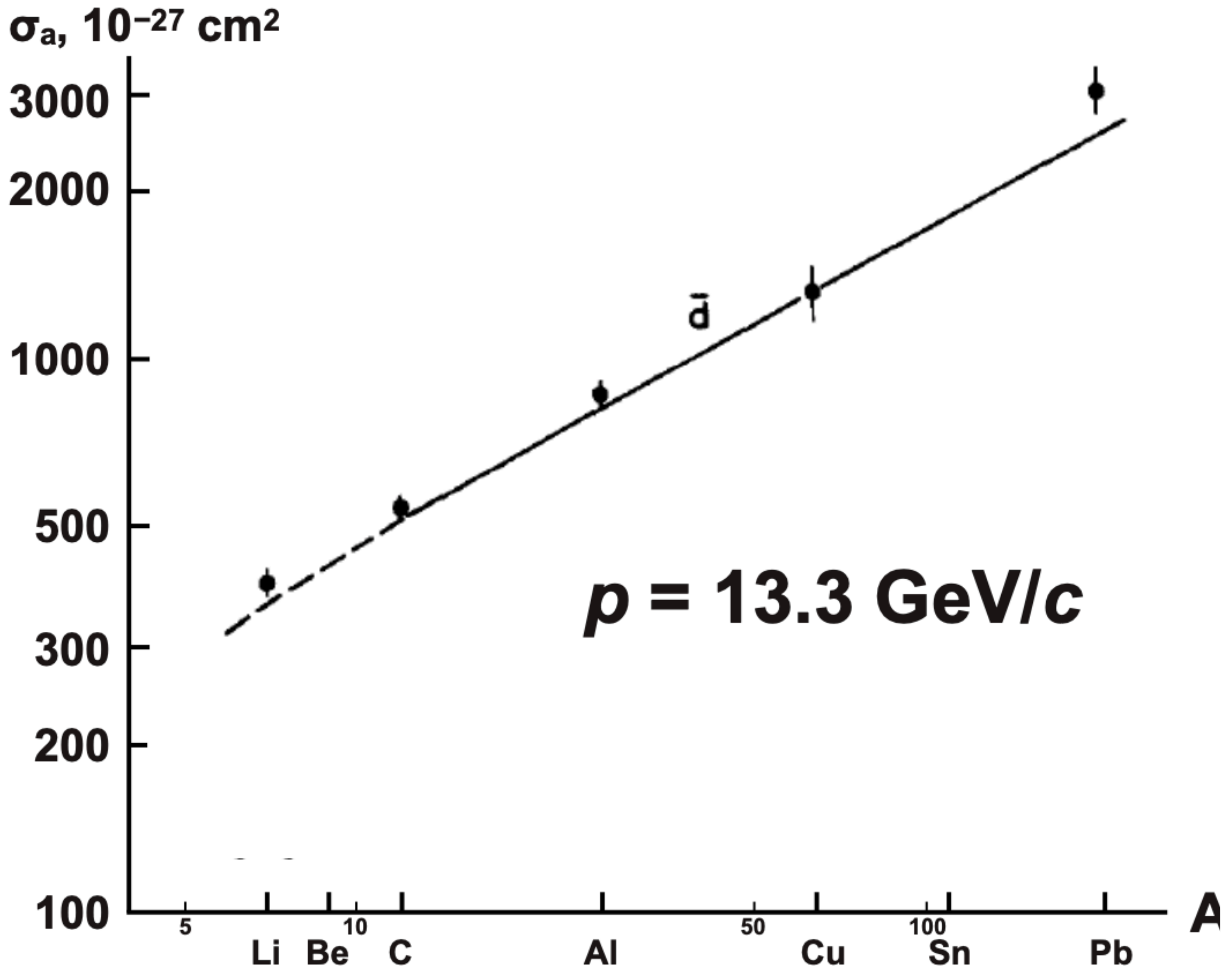
Relevant inelastic cross sections (σ_{inel}) only poorly constrained for antinuclei heavier than $\overline{\text{p}}$:

- $\overline{\text{d}}$: no experimental data below *p* = 13.3 GeV/*c* [2]
- **$^{3}\overline{\text{He}}$ inelastic c.s. have never been measured at any momenta**

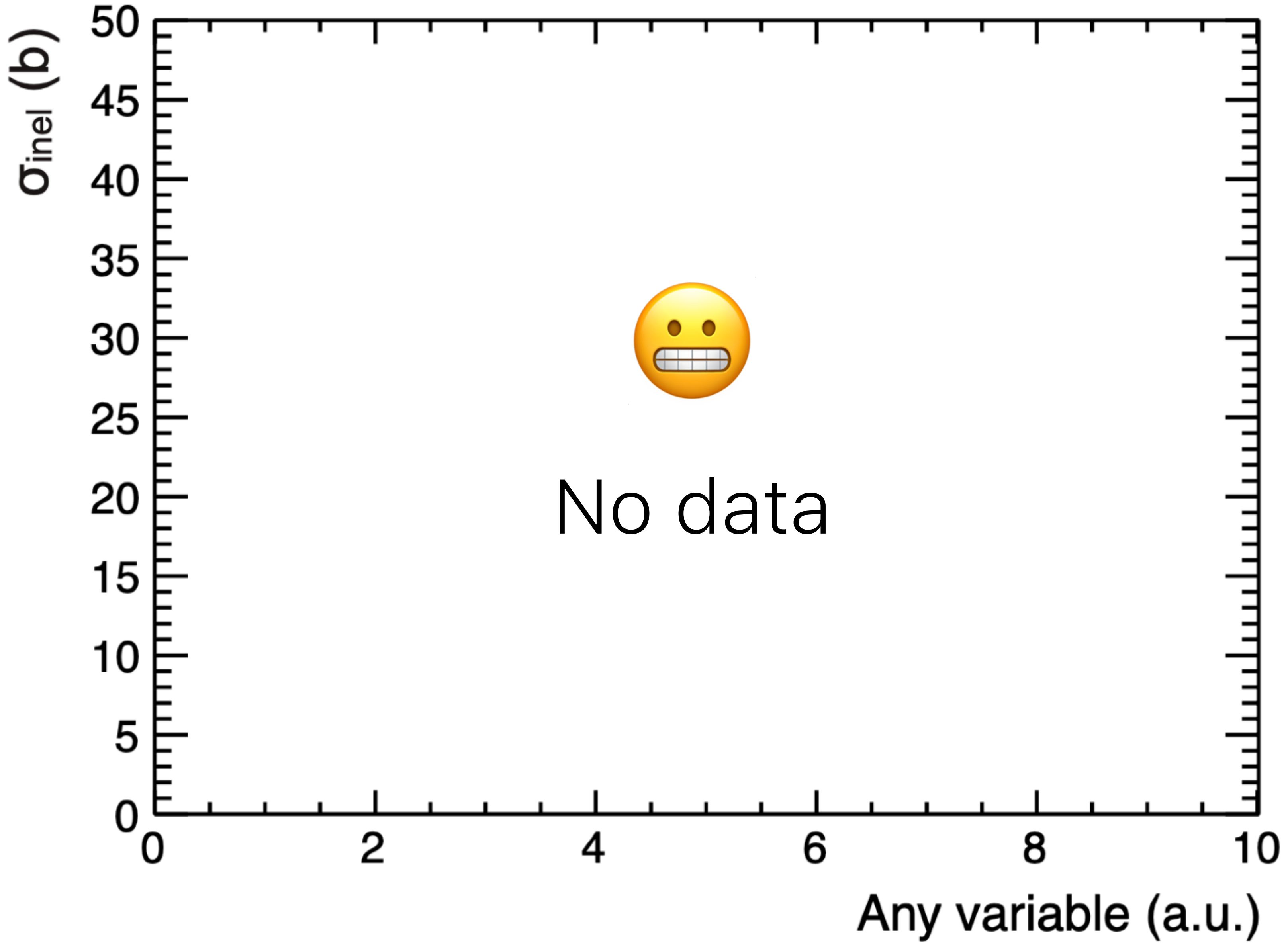
$\overline{\text{p}}$ [1]



$\overline{\text{d}}$ [2]



$^{3}\overline{\text{He}}$



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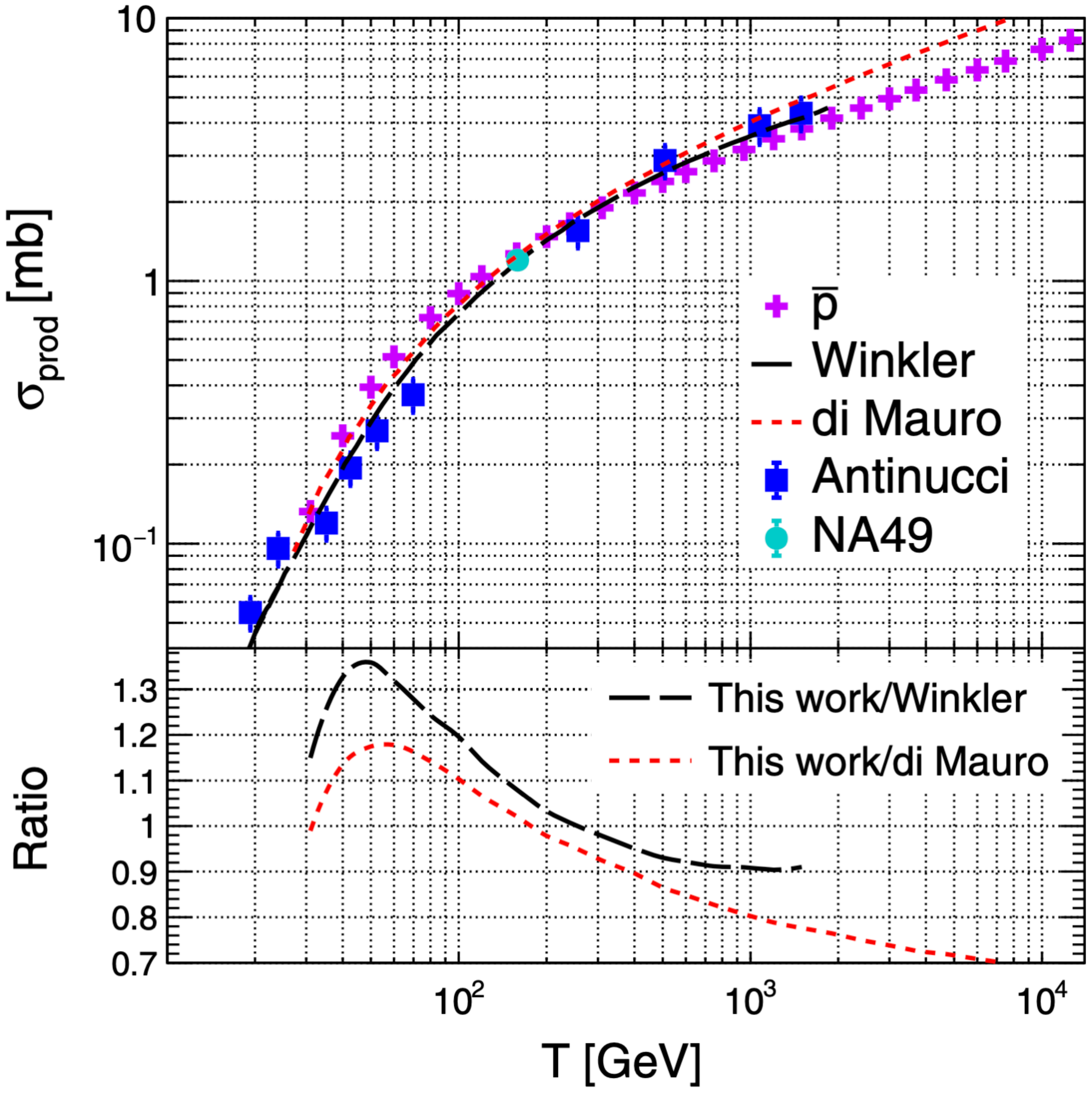
[1] Lee et. al., Phys. Rev. C 89, 054601 (2014)

[2] Denisov et. al., Nuclear Physics B 31 (1971) 253

Models [1] validation with low-energy antiproton data



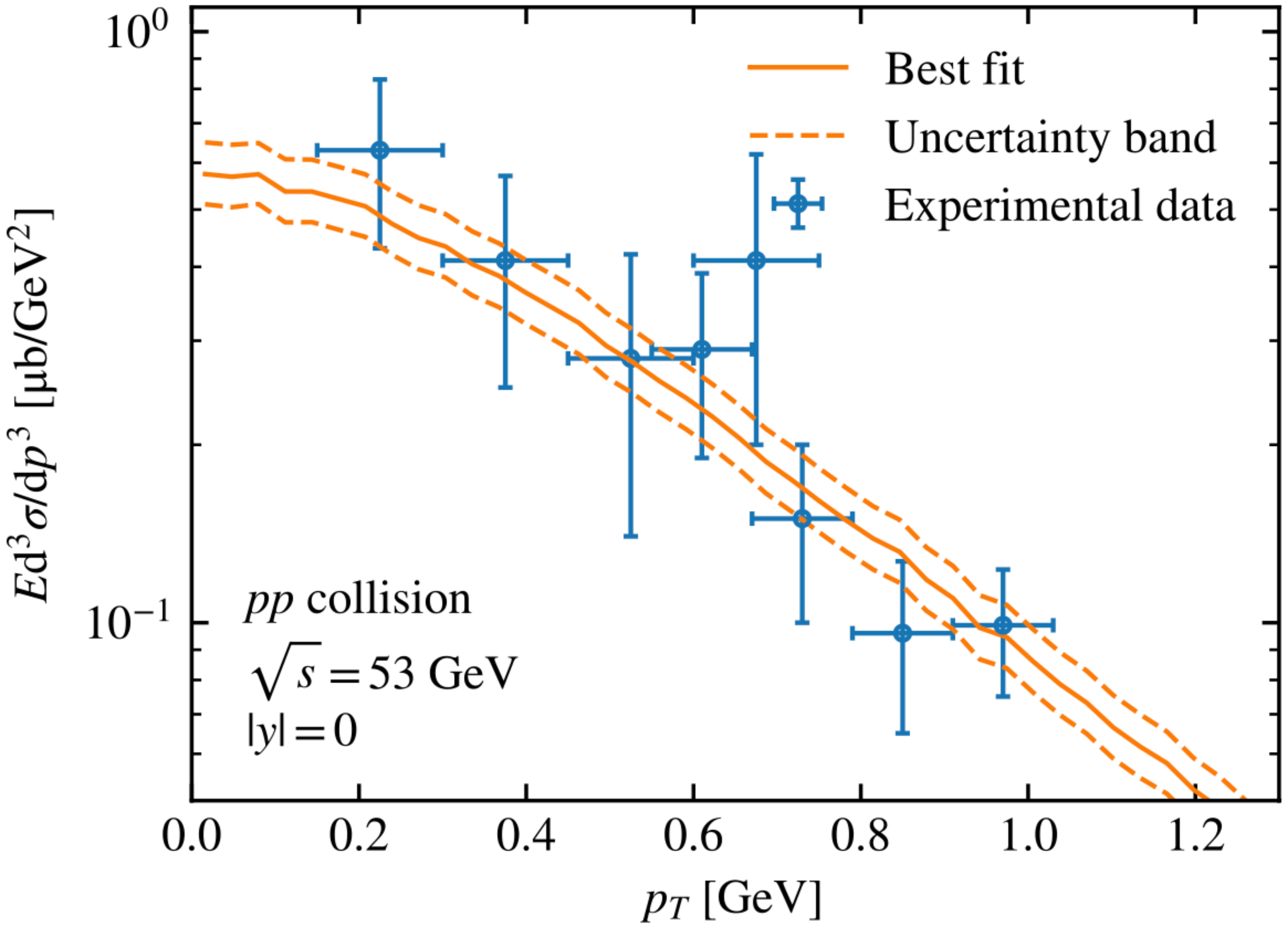
- Experimental data from [2, 3]

[1] Shukla et. al., Phys. Rev. D **102**, 063004 (2020)

[2] Eur. Phys. J. C 65, 9 (2009)

[3] Lett. Nuovo Cimento 6, 121 (1973)

Models [1] validation with antideuteron data



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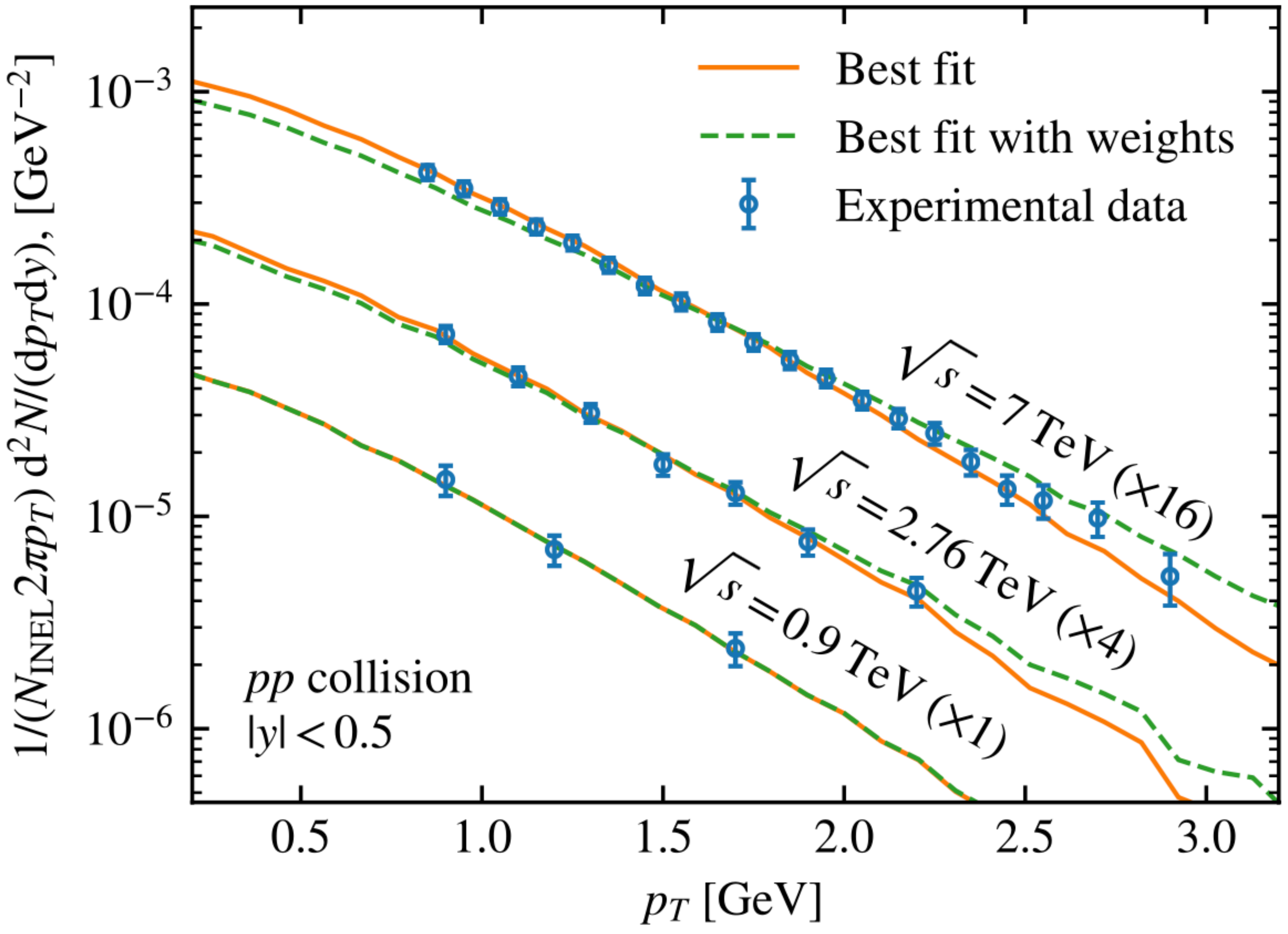


Experimental data from ALICE [4]

[1] M. M. Kachelrieß et. al., JCAP08 (2020) 048

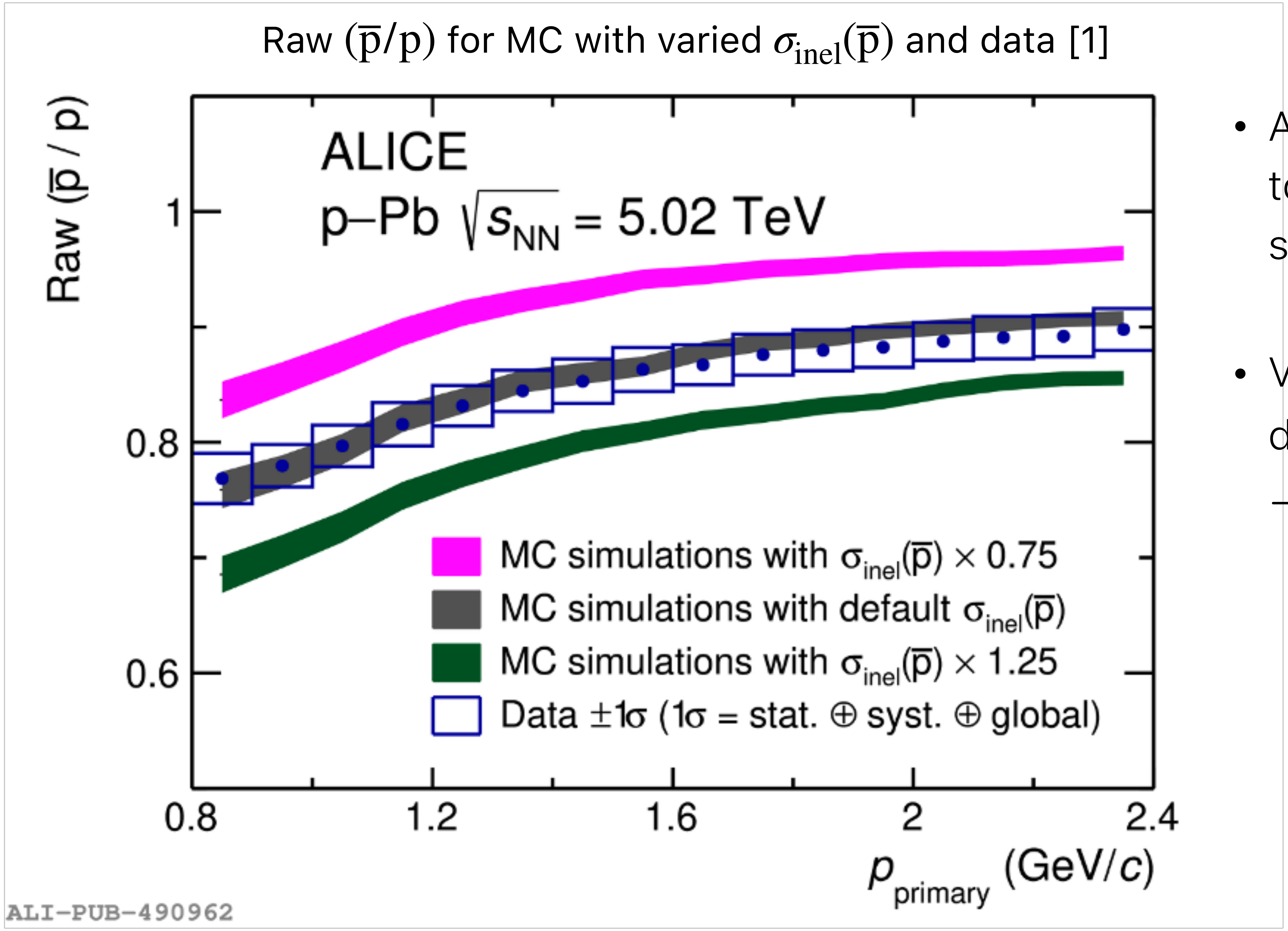
[2] B. Alper et al., Phys. Lett. 46B (1973) 265

[3] British-Scandinavian-MIT collaboration, Lett. Nuovo Cim. 21 (1978) 189

[4] ALICE collaboration, Phys. Rev. C97 (2018) 024615

Antiparticle/particle raw ratio

Method 1



- Antiparticle-to-particle ratios are sensitive to the variation of the inelastic cross section

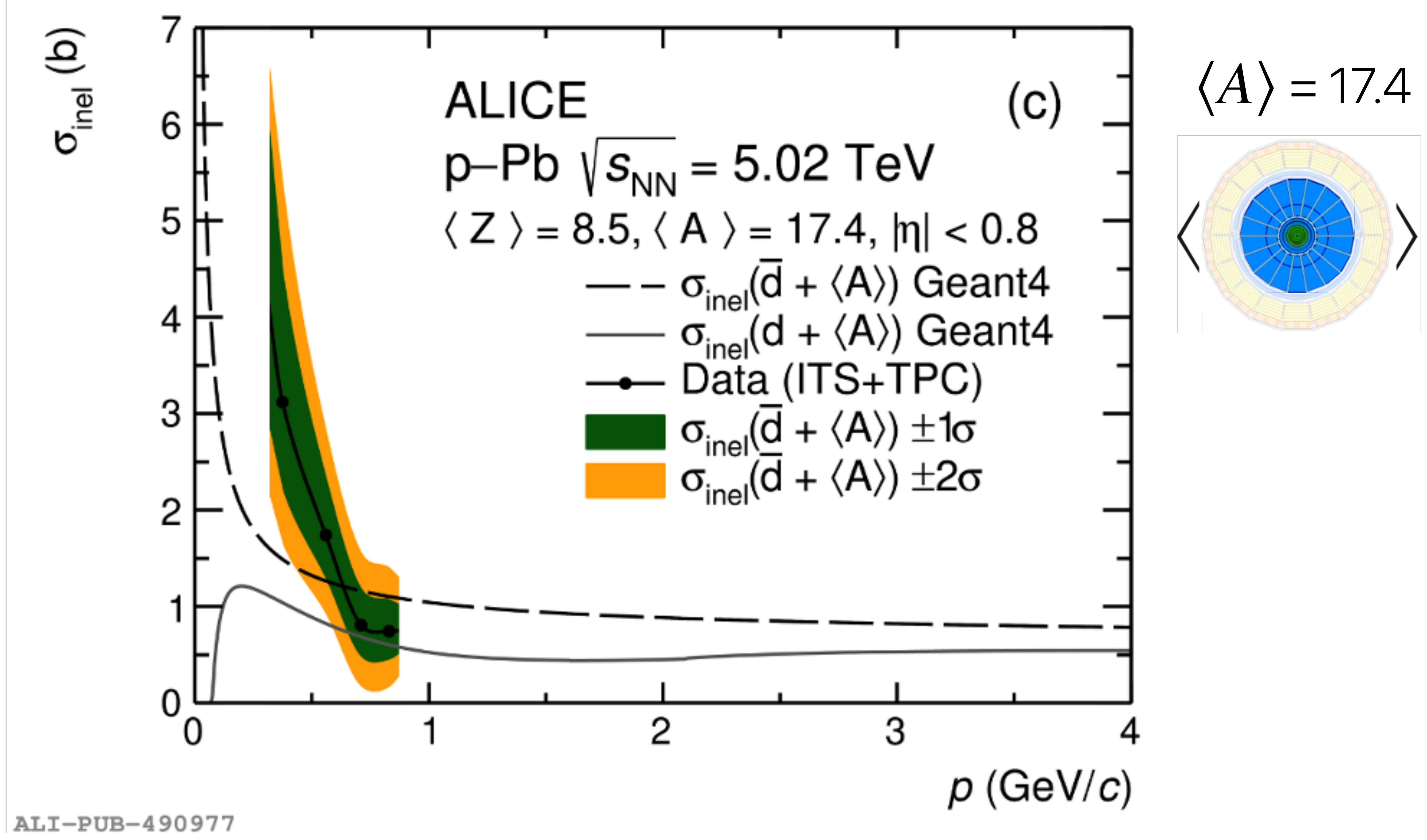
- Vary $\sigma_{\mathrm{inel}}(\overline{\mathrm{d}},\ {}^{3}\overline{\mathrm{He}})$ in simulations until MC describes the experimental results
  → constraints on $\sigma_{\mathrm{inel}}(\overline{\mathrm{d}},\ {}^{3}\overline{\mathrm{He}})$

[1] ALICE, PRL 125, 162001 (2020)

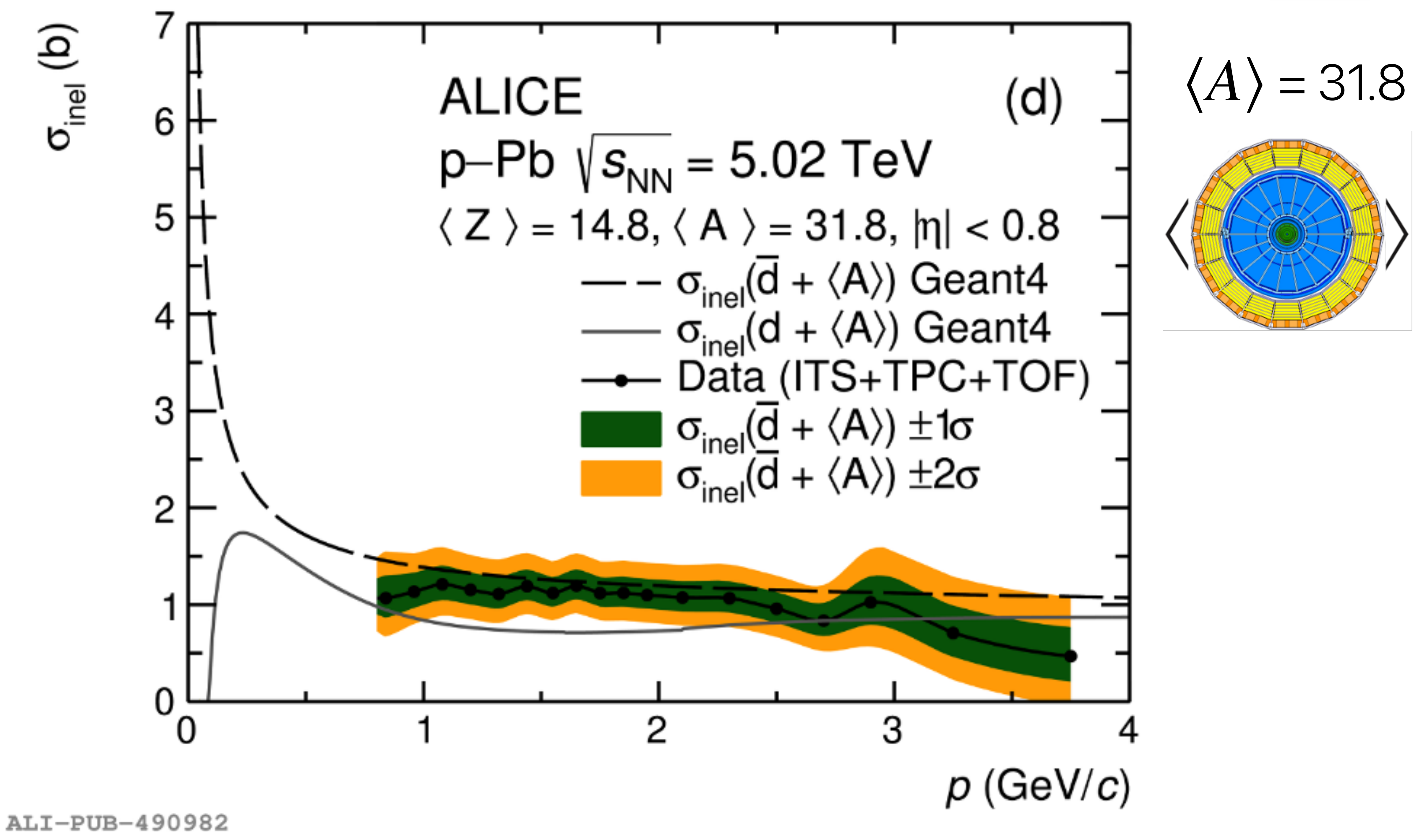
Antiparticle/particle raw ratio: $\sigma_{\mathrm{inel}}(\bar{\mathrm{d}})$

Method 1

$\sigma_{\mathrm{inel}}(\bar{\mathrm{d}})$ on averaged ALICE material (ITS-TPC)



$\sigma_{\mathrm{inel}}(\bar{\mathrm{d}})$ on averaged ALICE material (ITS-TOF)



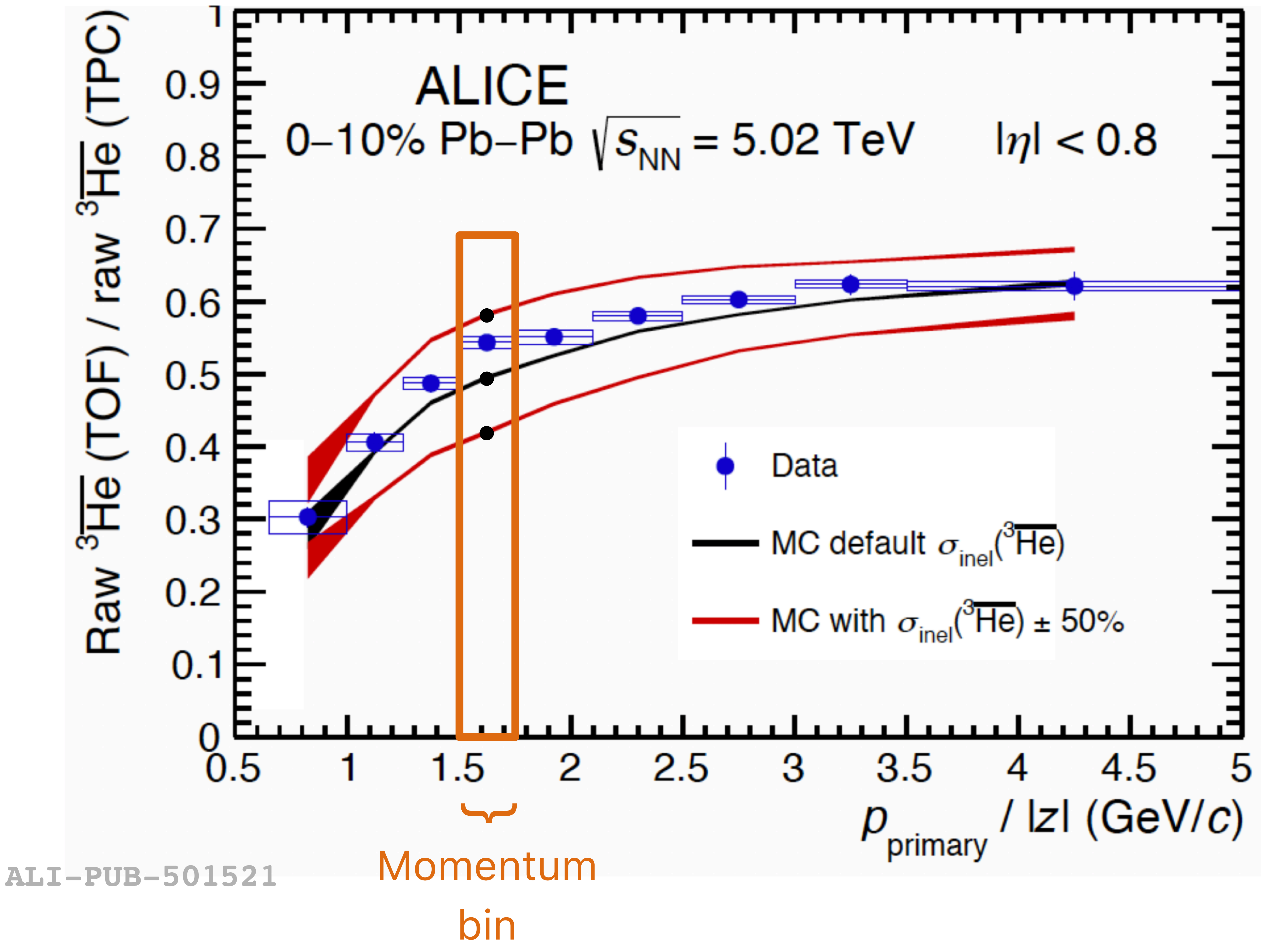
- First measurement of antideuteron inelastic cross section at low momenta!
- Exp. σ_{inel} is approx. 15% smaller w.r.t. `Geant4` at high momenta, steeper rise in low p region
- Published: PRL 125, 162001 (2020)

How we measure σ_{inel} with TPC-TOF matching

Method 2

Nat. Phys. 19, 61–71 (2023)

- Identify $N^{\mathrm{TOF}}_{\mathrm{track}} / N^{\mathrm{TPC}}_{\mathrm{track}}$ in data and simulations
- Monte Carlo simulations with scaled σ_{inel} (0.5x, 1x, 1.5x)
- In each momentum bin compare the TOF-TPC ratio in MC to the one in data



How we measure σ_{inel} with TPC-TOF matching

Method 2

- Identify $N^{\mathrm{TOF}}_{\mathrm{track}} / N^{\mathrm{TPC}}_{\mathrm{track}}$ in data and simulations
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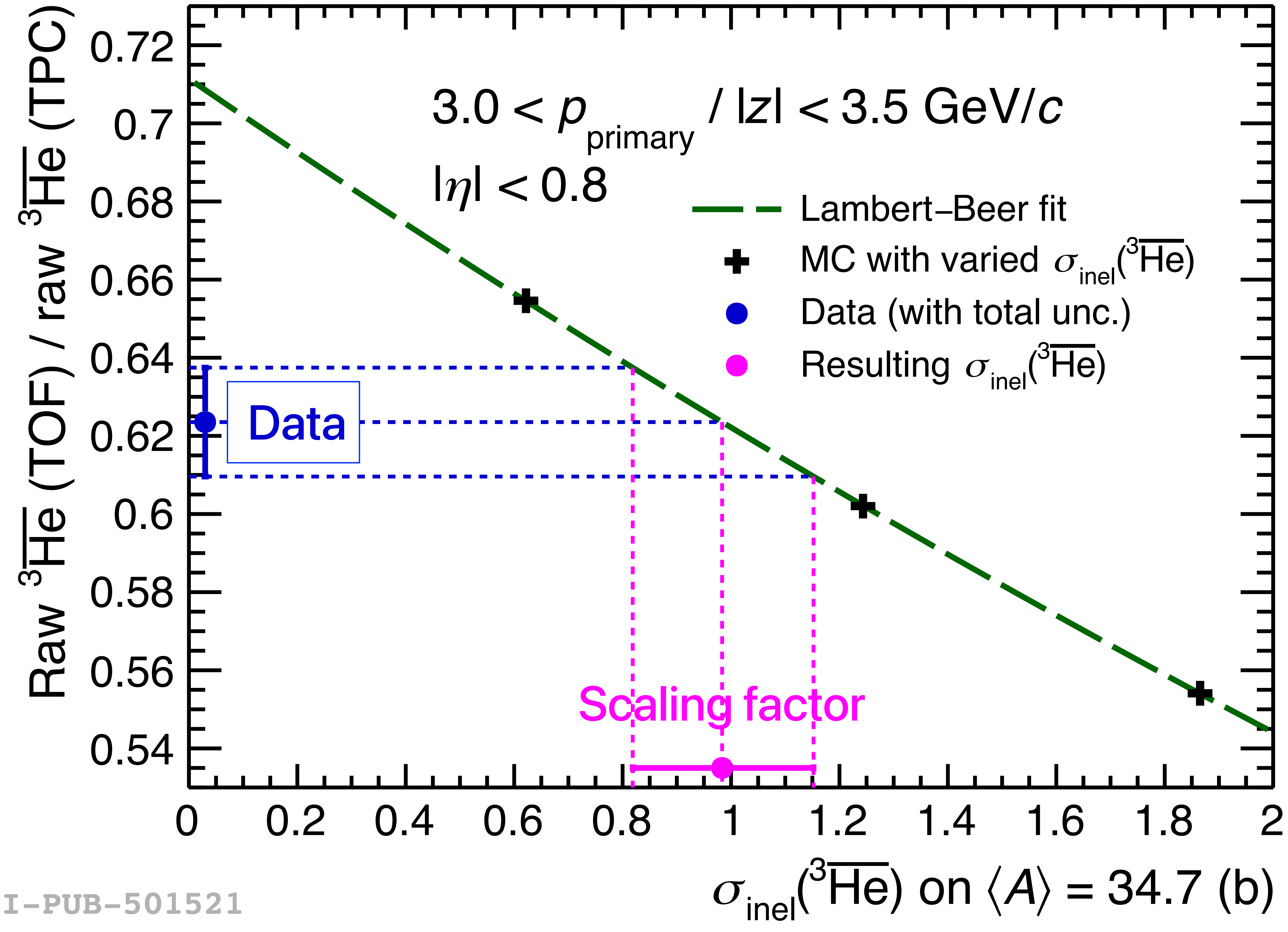
↓

- Fit MC points with an exponential according to the Lambert-Beer law:
  $N = N_0 \times \exp(-\sigma\rho L)$
- extract $\sigma_{\mathrm{inel}}/\sigma_{\mathrm{inel}}^{\mathrm{def}}$ scaling factor
- calculate the inelastic cross section on $\langle A \rangle$:

$$\boxed{\sigma_{\mathrm{inel}}(^{3}\overline{\mathrm{He}}) = \sigma_{\mathrm{inel}}^{\mathbf{Geant4}}(^{3}\overline{\mathrm{He}}) \times \text{scaling factor}}$$

Nat. Phys. 19, 61–71 (2023)



ALI-PUB-501521

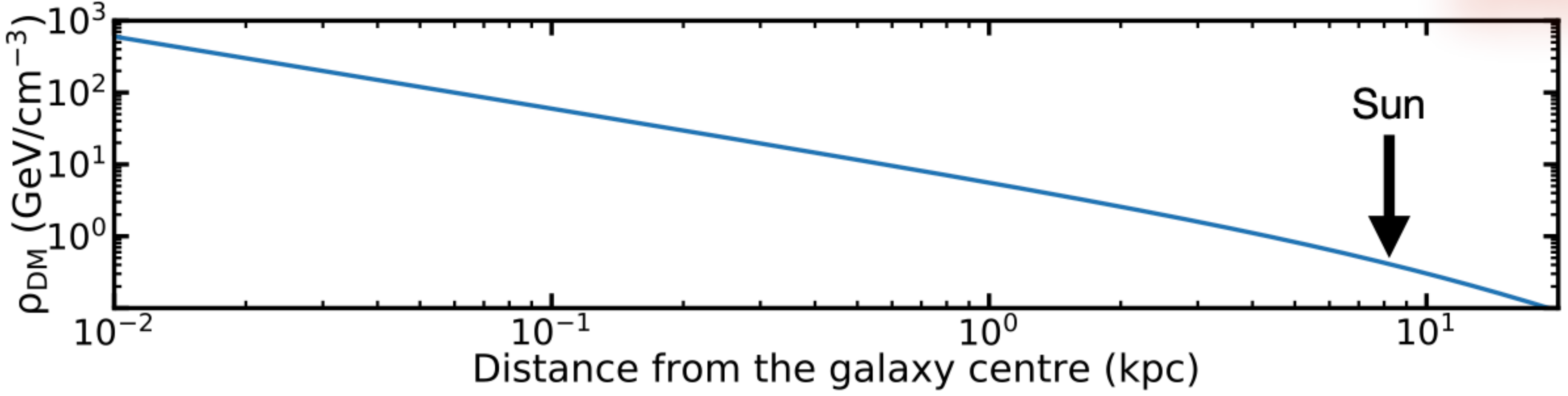
$^{3}\overline{\mathrm{He}}$ source (I): dark matter

Source (1) ✅ Propagation ✅ Annihilation ❌

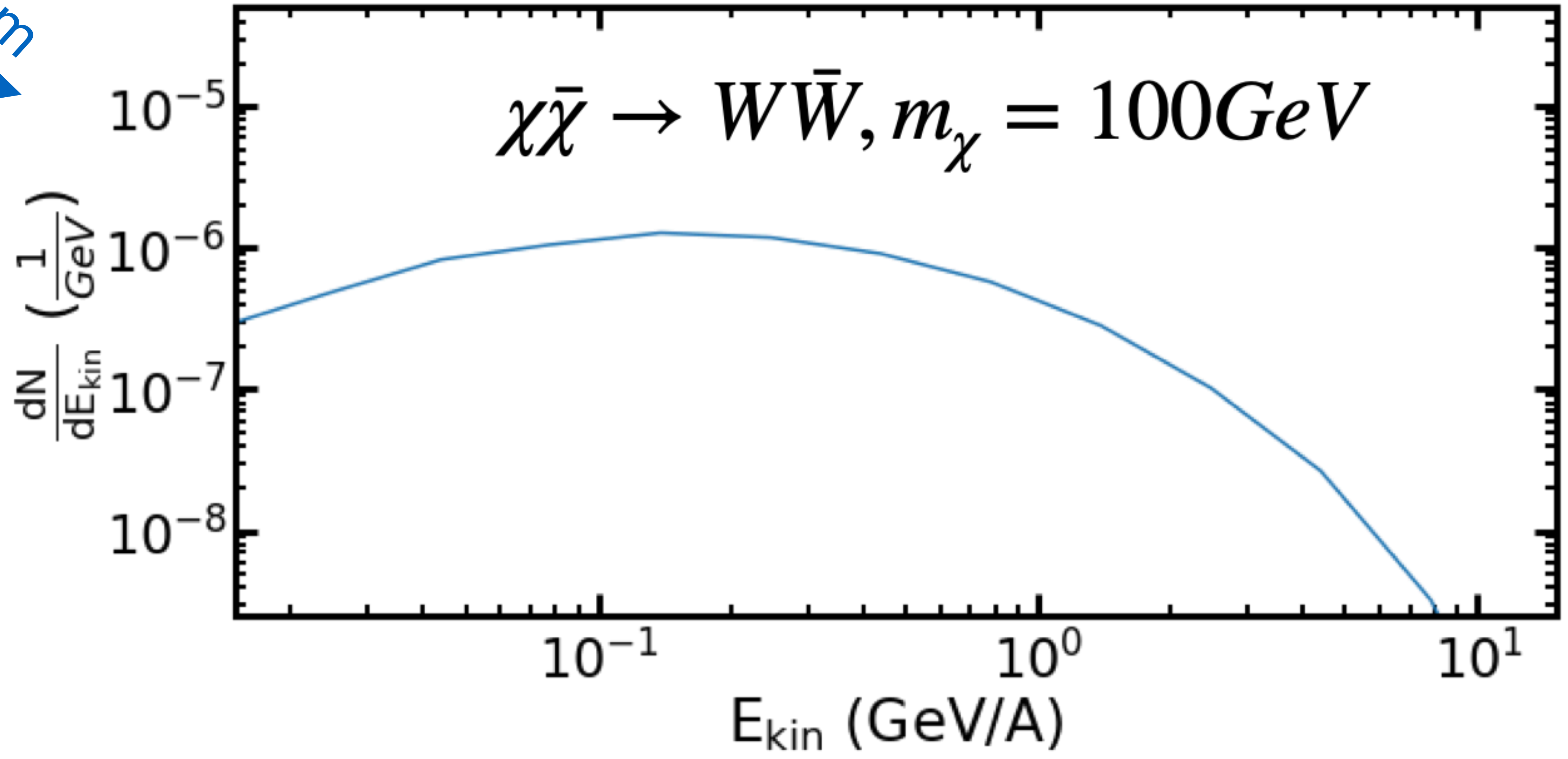
Source function

$$q(\mathrm{r}, E_{kin}) = \frac{1}{2}\frac{\rho_{\mathrm{DM}}^{2}(\mathrm{r})}{m_{\chi}^{2}}\langle\sigma v\rangle(1+\epsilon)\frac{dN}{dE_{kin}}$$

DM density distr.



$^{3}\overline{\mathrm{He}}$ spectrum



- ρ_{DM} - Navarro–Frenk–White profile [1]
- m_{χ} = 100 GeV for $\mathrm{W}^{+}\mathrm{W}^{-}$
- $\langle\sigma v\rangle$ = 2.6x10^{-26} $\mathrm{cm}^{3}\mathrm{s}^{-1}$ [2]
- $(1+\epsilon)$ = 2 [1]
- $^{3}\overline{\mathrm{He}}$ spectrum from [1] PYTHIA 8 + coalescence afterburner

→ peak at E_{kin} ~ 0.1 GeV/A

[1] Carlson et al, Phys. Rev. D. 89, 076005 (2014)

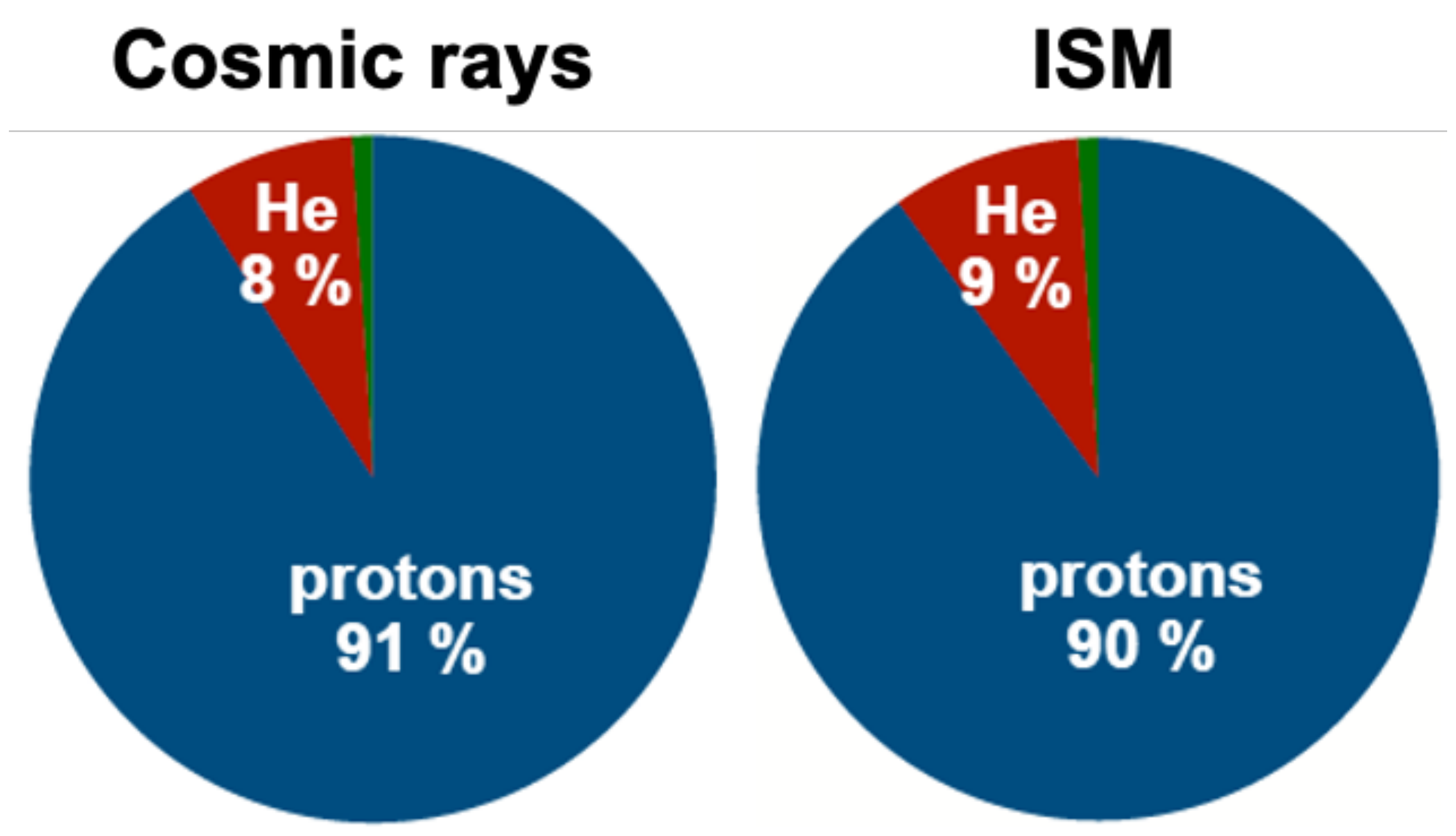
[2] Korsmeier et al, Phys. Rev. D. 97, 103011 (2018)

$^{3}\overline{\text{He}}$ source (II): CR + ISM

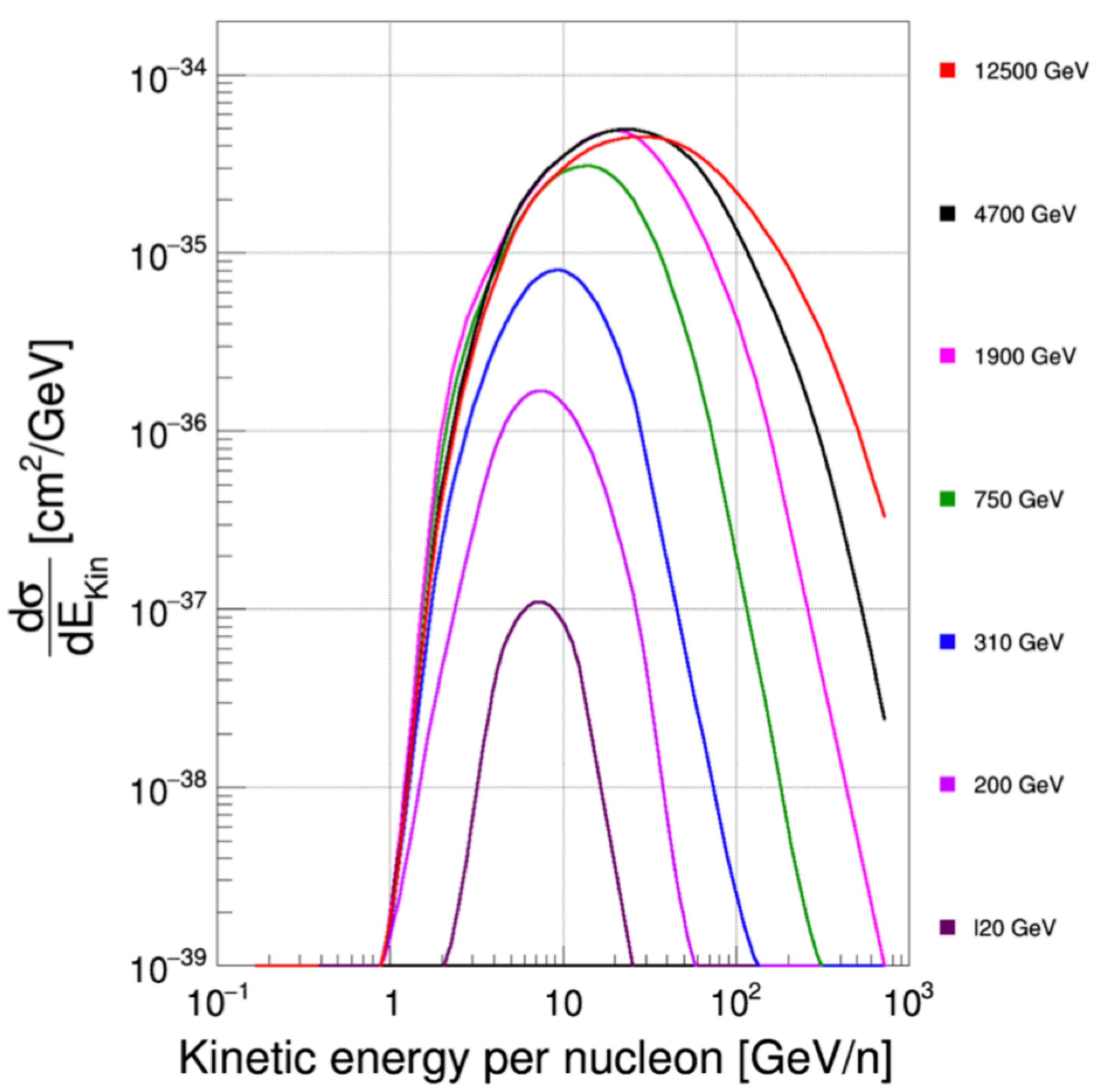
Source (2) ✅ Propagation ✅ Annihilation ❌

Another relevant $^{3}\overline{\text{He}}$ source from interactions of cosmic rays (CR) with interstellar medium (ISM)

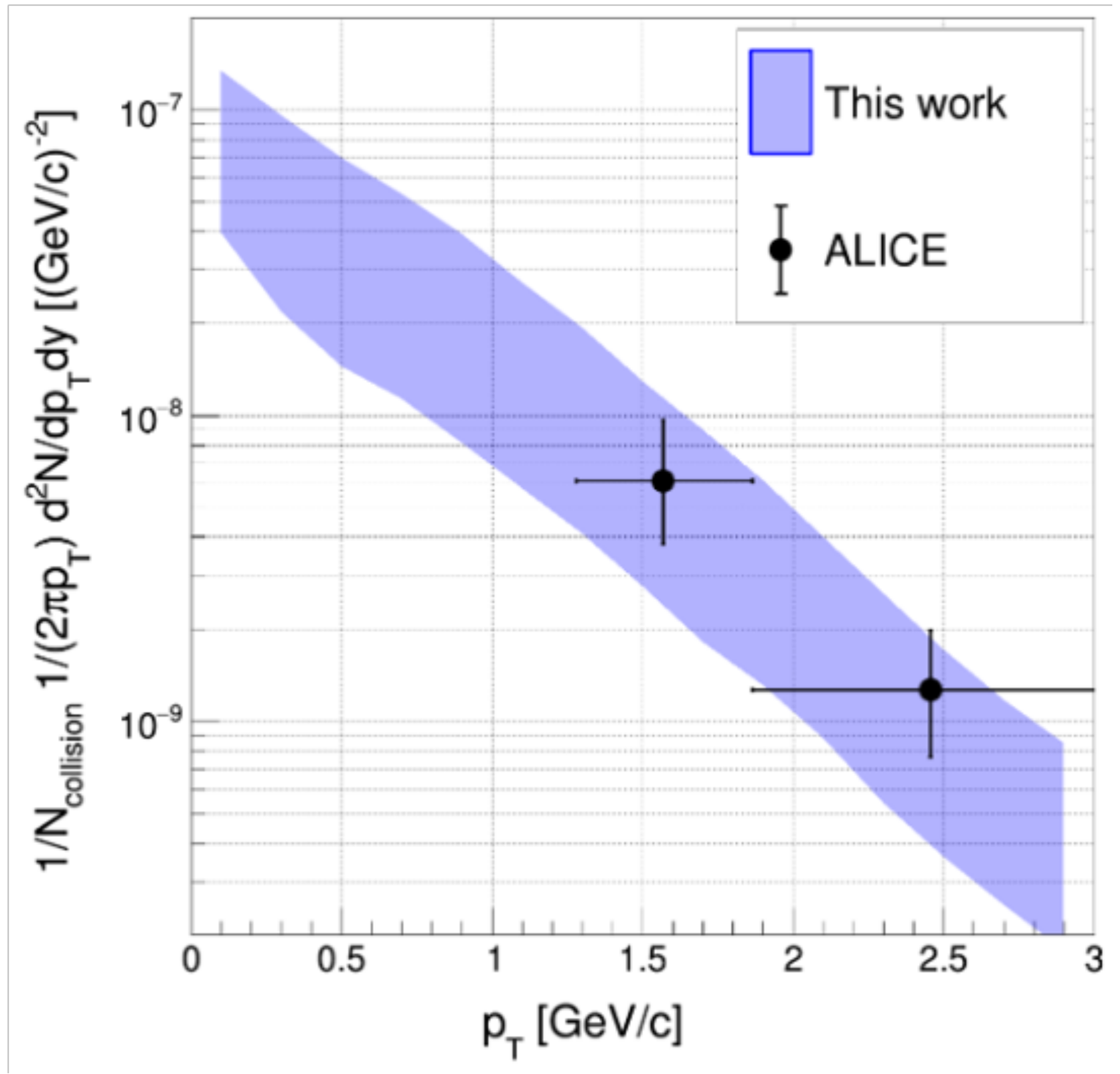
- Collision systems: pp, p-^{4}He, ^{4}He-p, ^{4}He-^{4}He
- Production cross section in pp from [1]: EPOS LHC + coalescence afterburner
- Scaling factor $(A_T A_P)^{2.2/3}$ for the other collision systems
- Validated by ALICE data [2] ✅



$^{3}\overline{\text{He}}$ production in pp [1]



Comparison with ALICE results [1,2]



[1] Shukla et al, Phys. Rev. D. 102, 063004 (2020)
[2] ALICE, Phys. Rev. C 97, 024615 (2018)