The dark side of ALICE: from antinuclei interactions to dark matter searches in space

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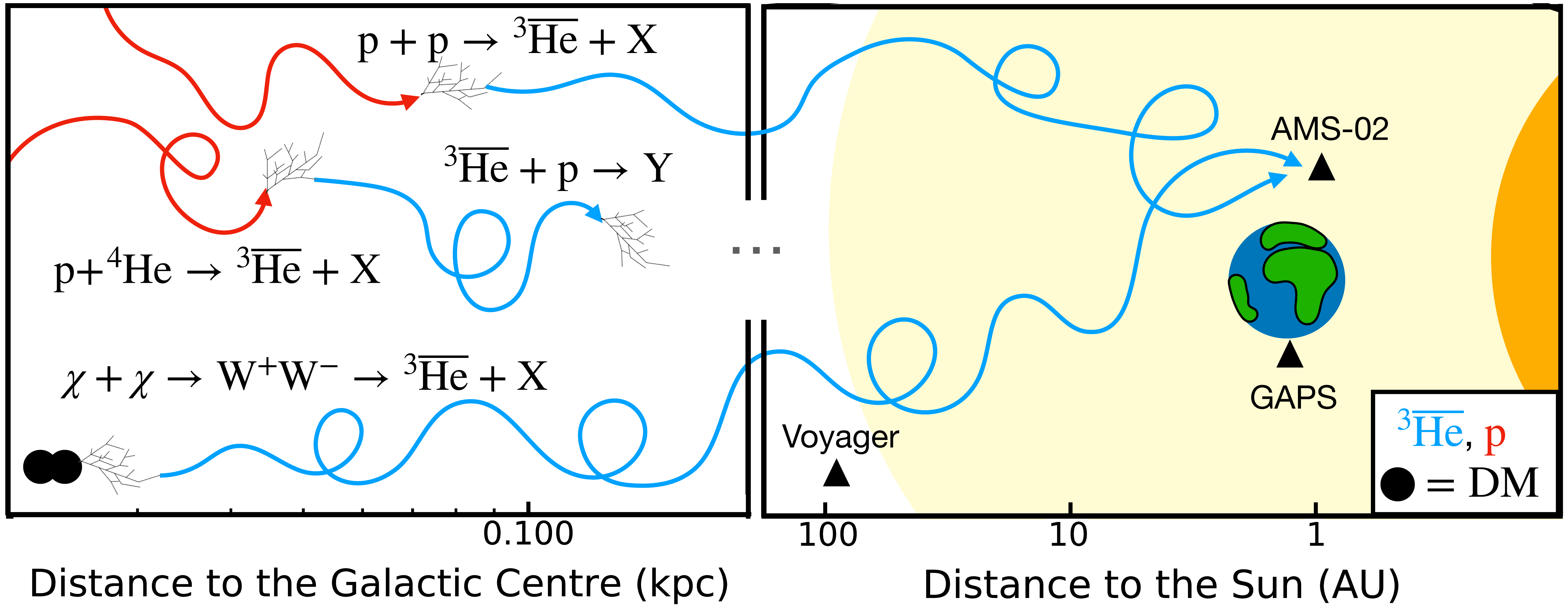
Introduction and motivation

Antinuclei ($\overline{d}$, $^{3}\overline{He}$, $^{4}\overline{He}$) in space (studied by **AMS-02, GAPS**) may result from:

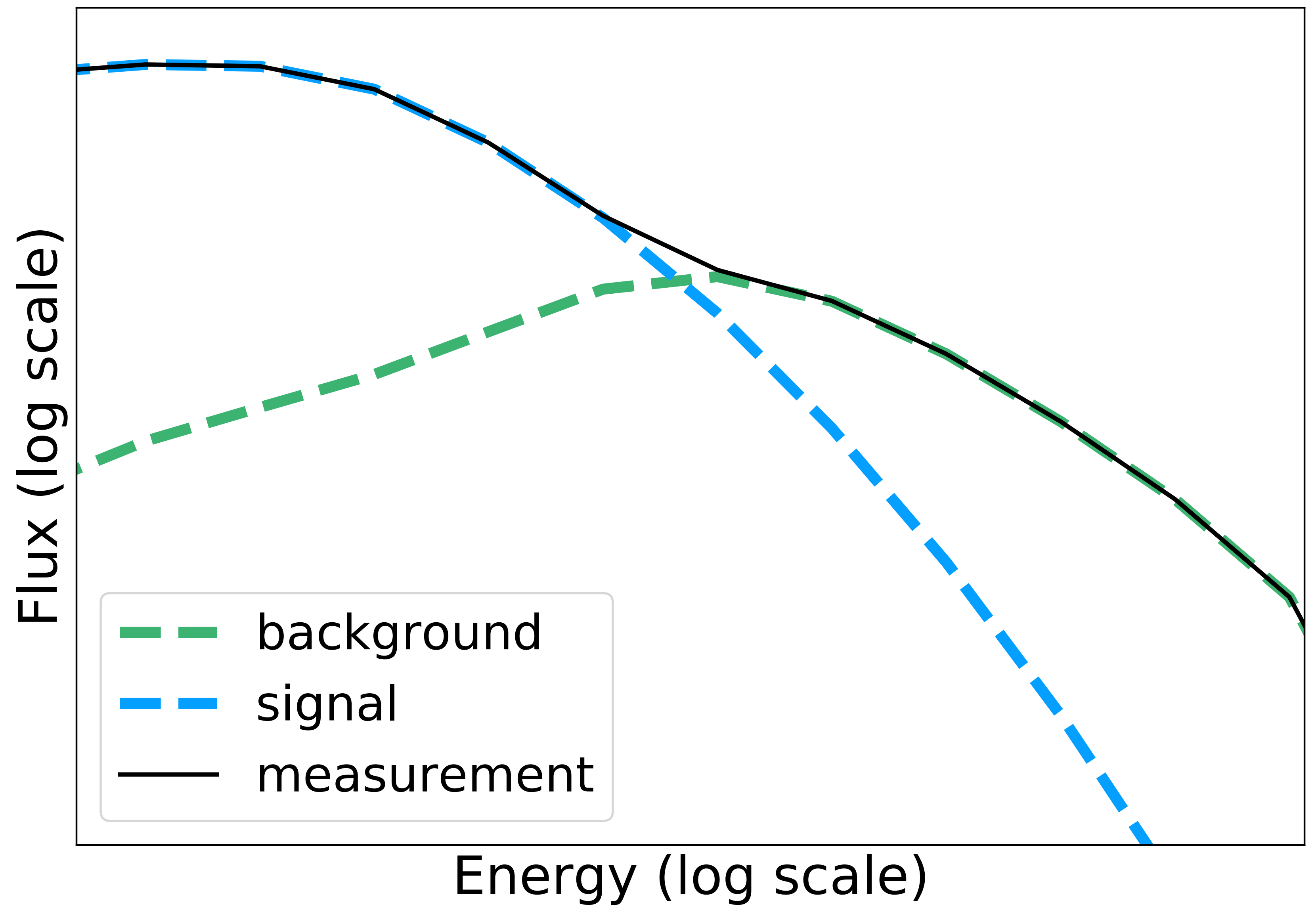
- Dark matter annihilation (or decay) → signal
- Interaction of high energy cosmic rays with the interstellar gas → background

– Low background is expected in the low energy range
– Vital to determine exact primary and secondary antinuclei fluxes
– *Requires precise knowledge of antinuclei inelastic interaction with interstellar gas*

Unique probe for indirect dark matter searches!



Schematic of expected antinuclei fluxes

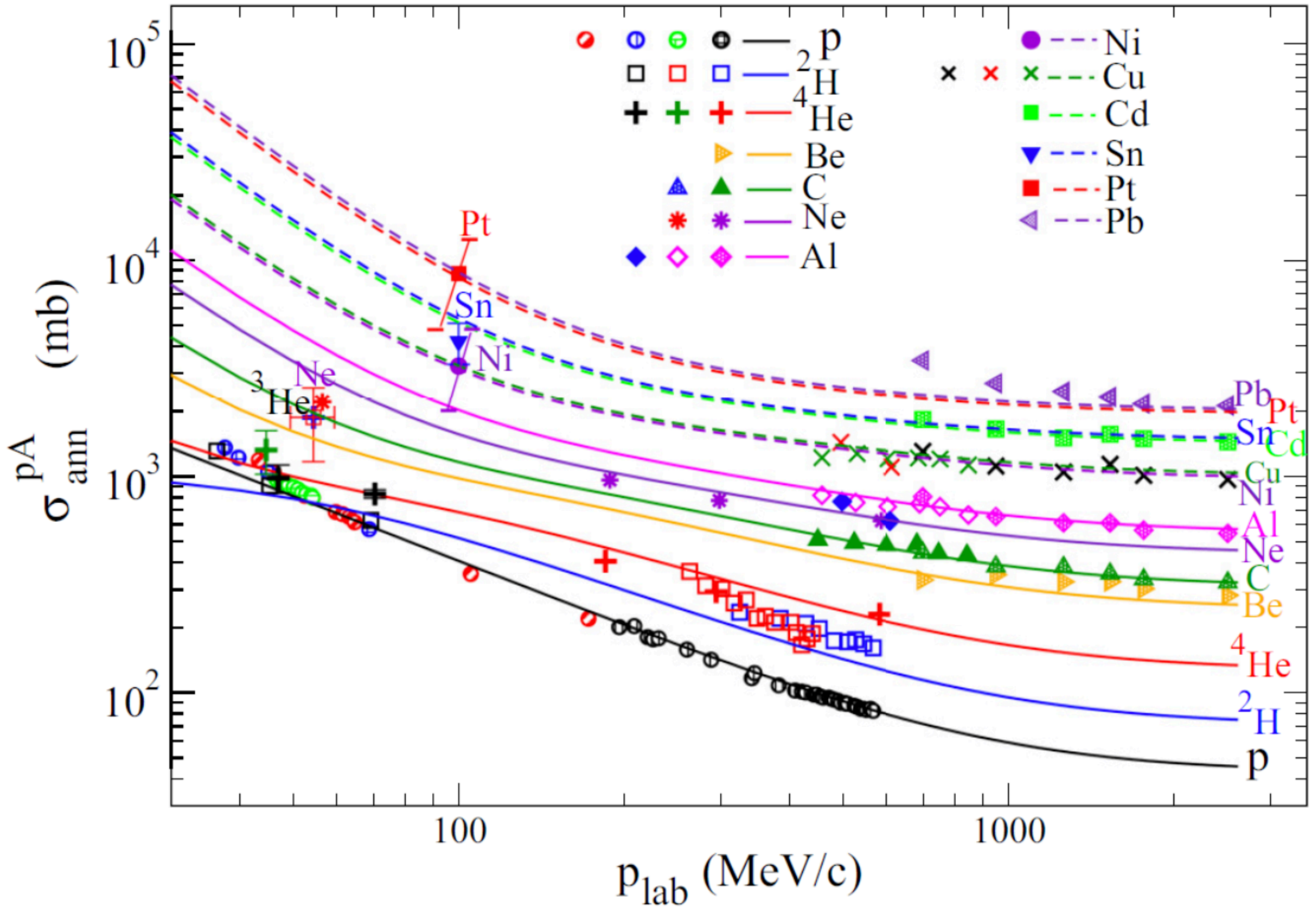


Antinuclei σ_{inel} measurements (before ALICE)

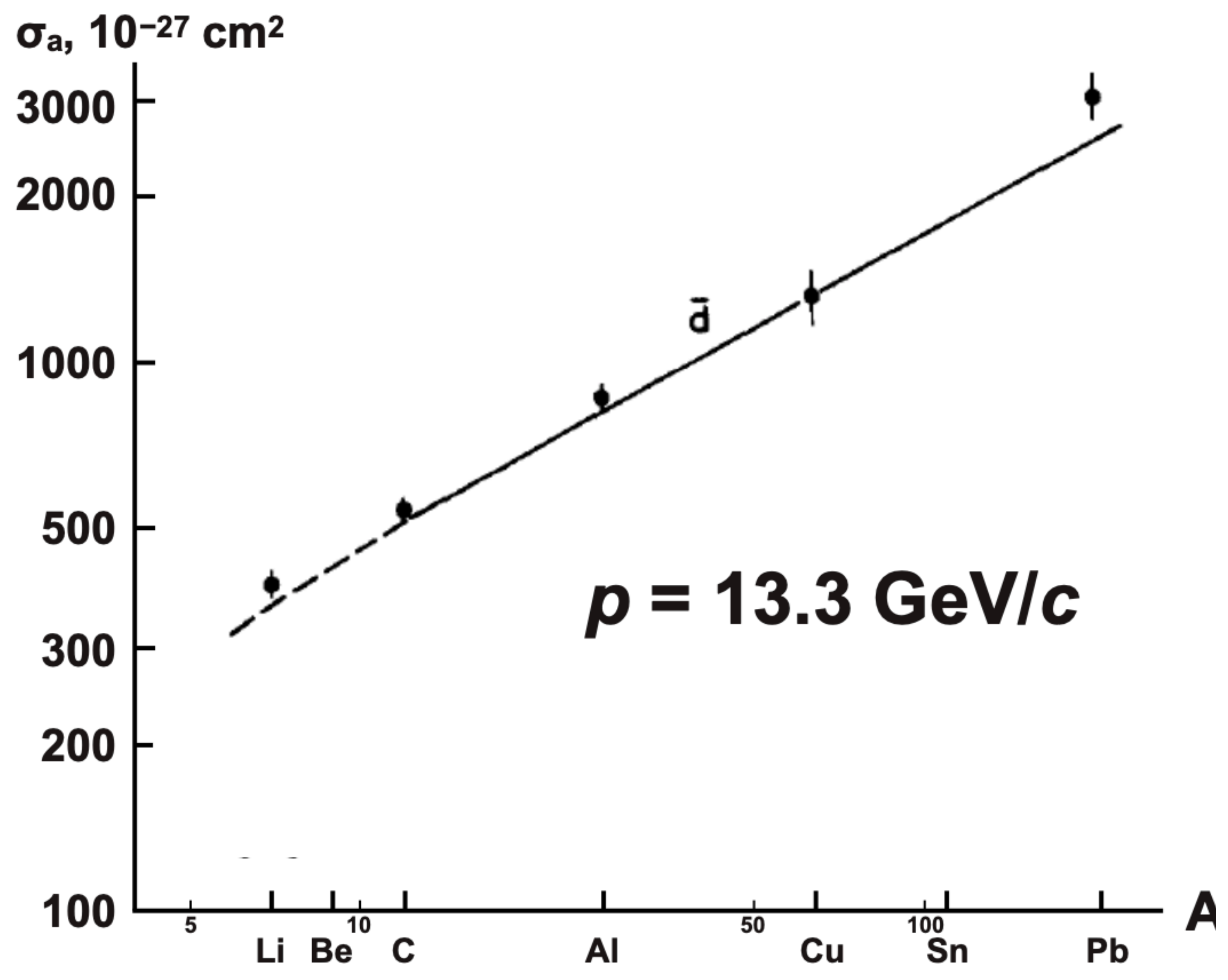
Relevant inelastic cross sections (σ_{inel}) only poorly constrained for antinuclei heavier than $\overline{\text{p}}$:

- Antideuterons: no experimental data below p = 13.3 GeV/c [2]
- **Antihelium inelastic c.s. have never been measured at any momenta**

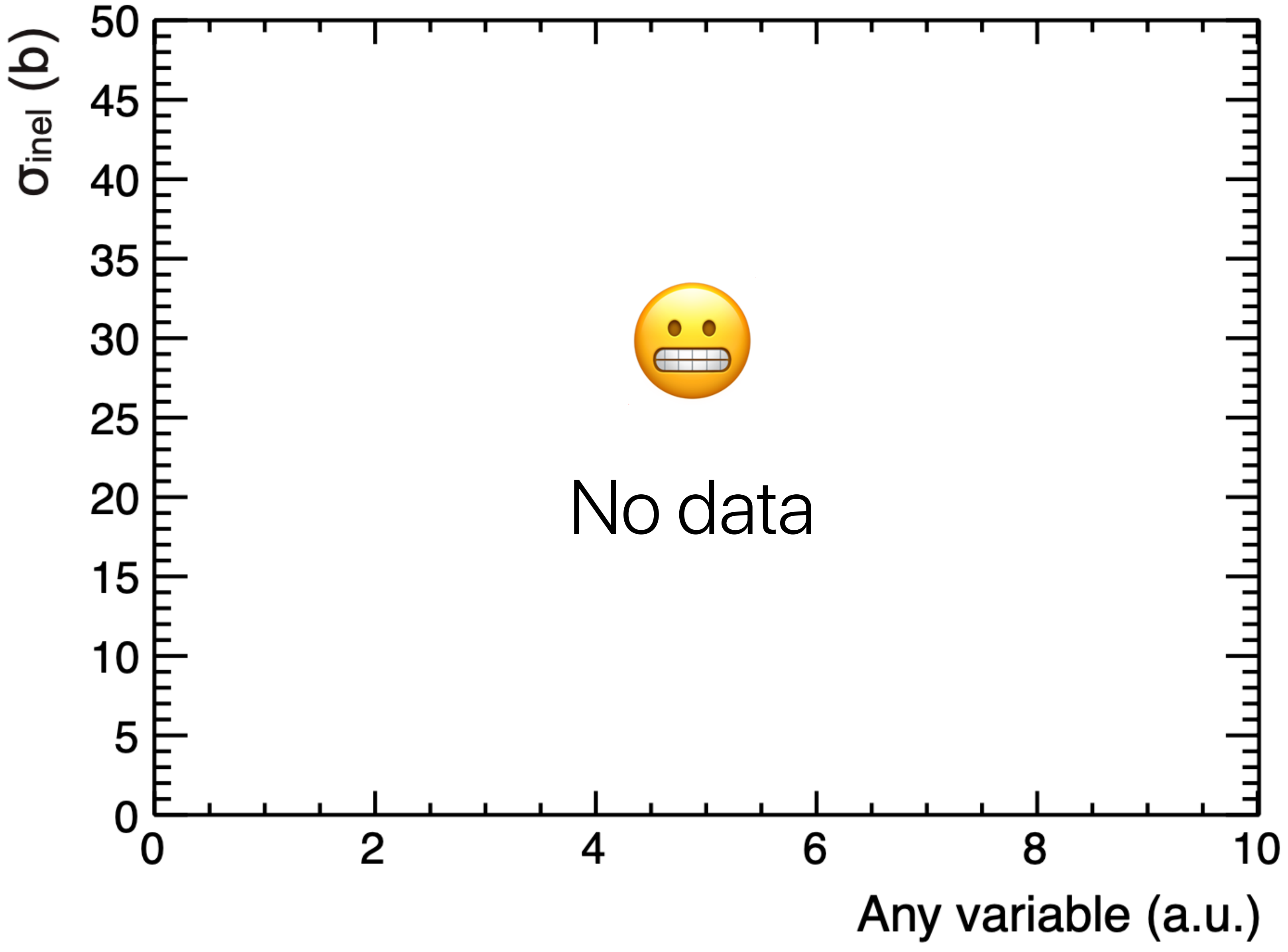
$\overline{\text{p}}$ [1]



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



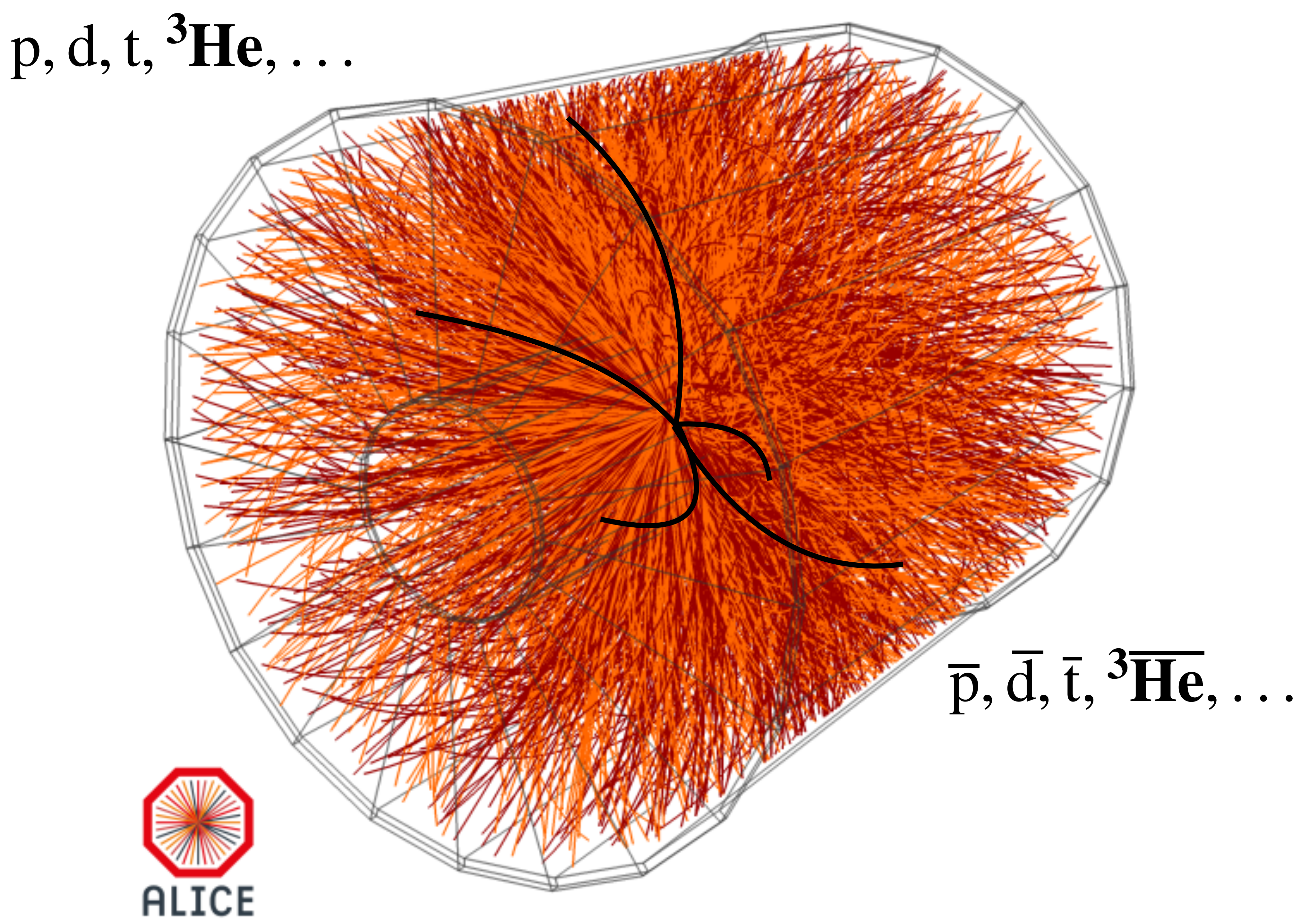
$^3\overline{\text{He}}$



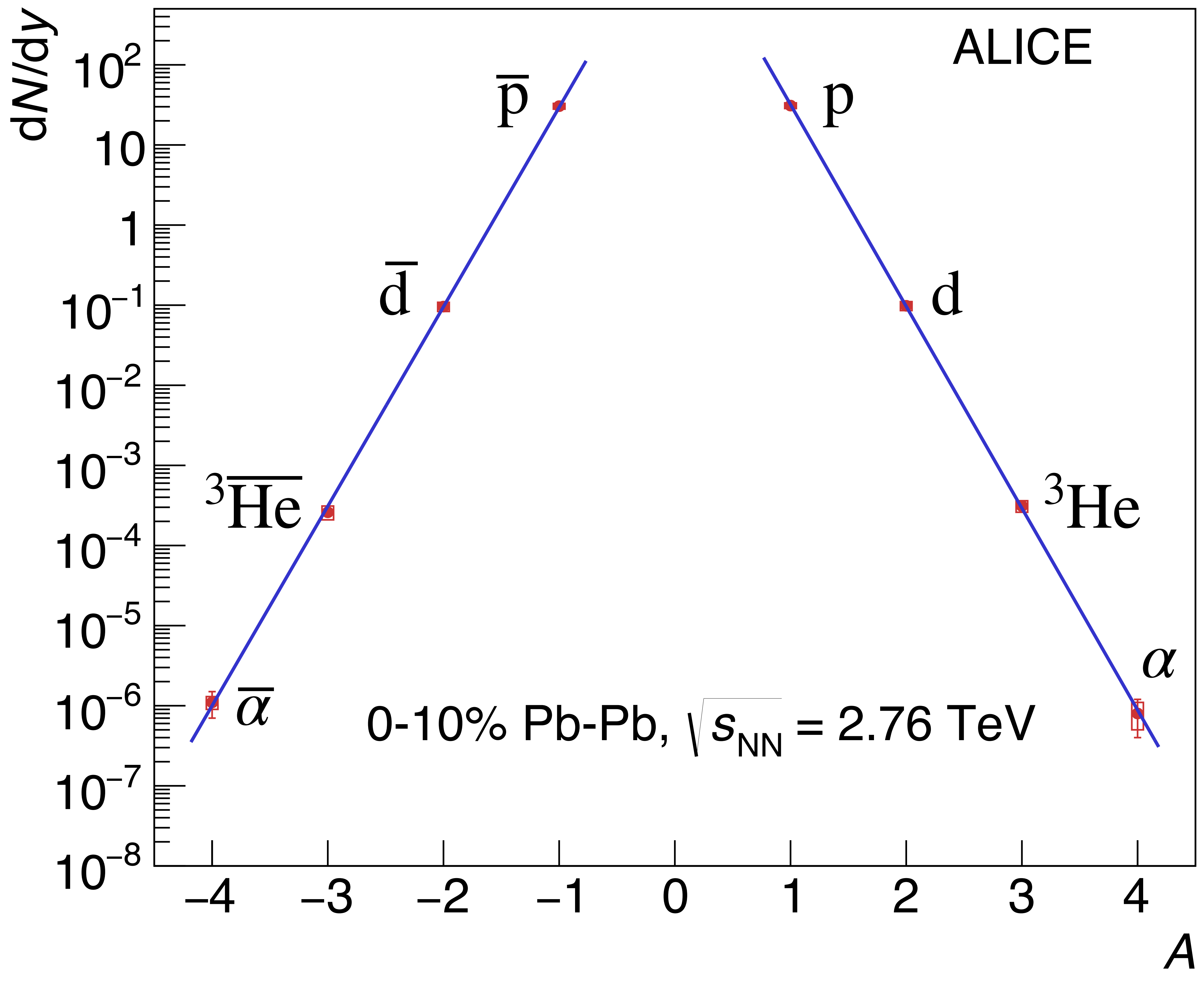
[1] Lee et al., Phys. Rev. C 89, 054601 (2014)

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

LHC as an antimatter factory



Nucl. Phys. A 971 (2018) 1-20

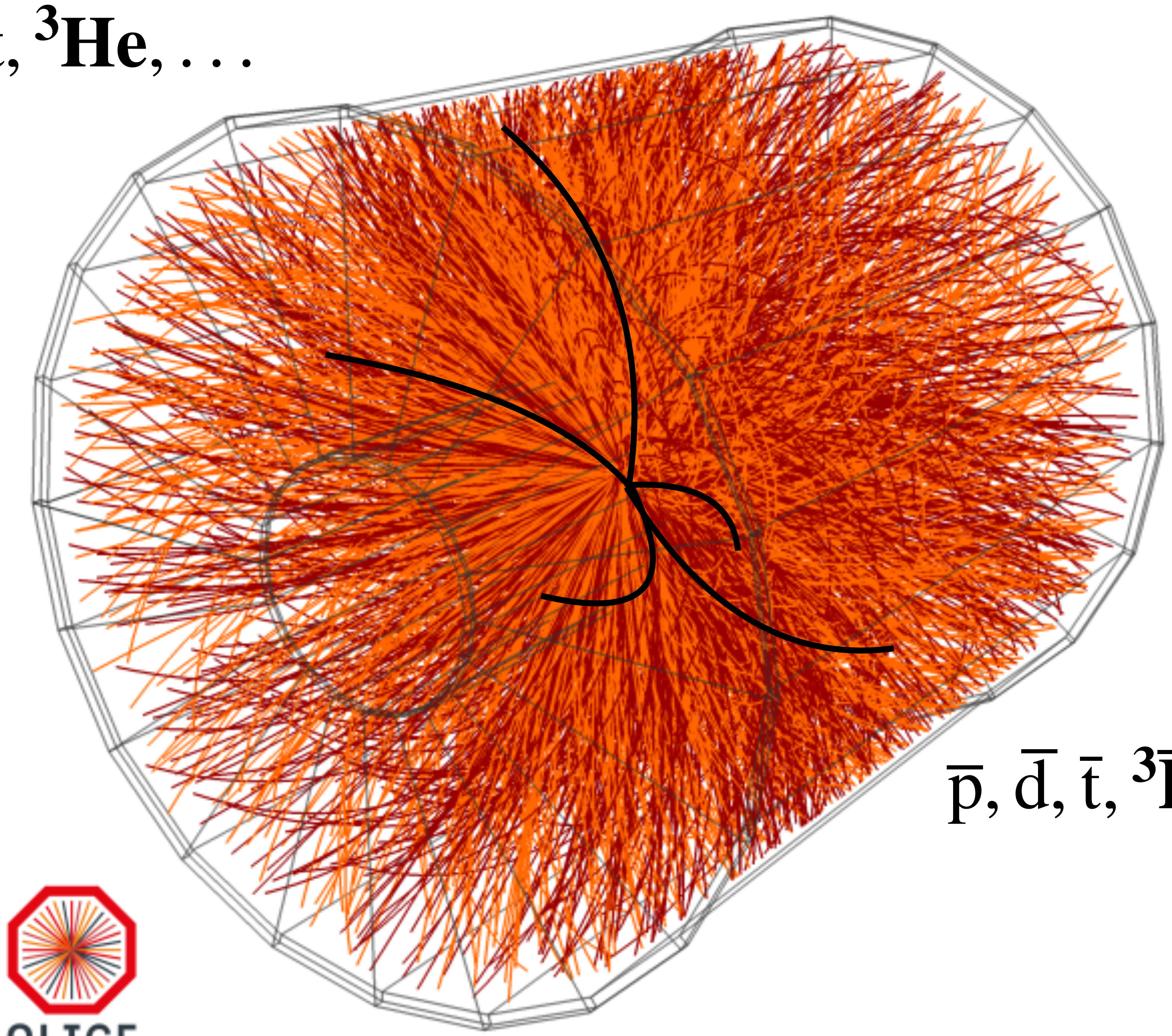


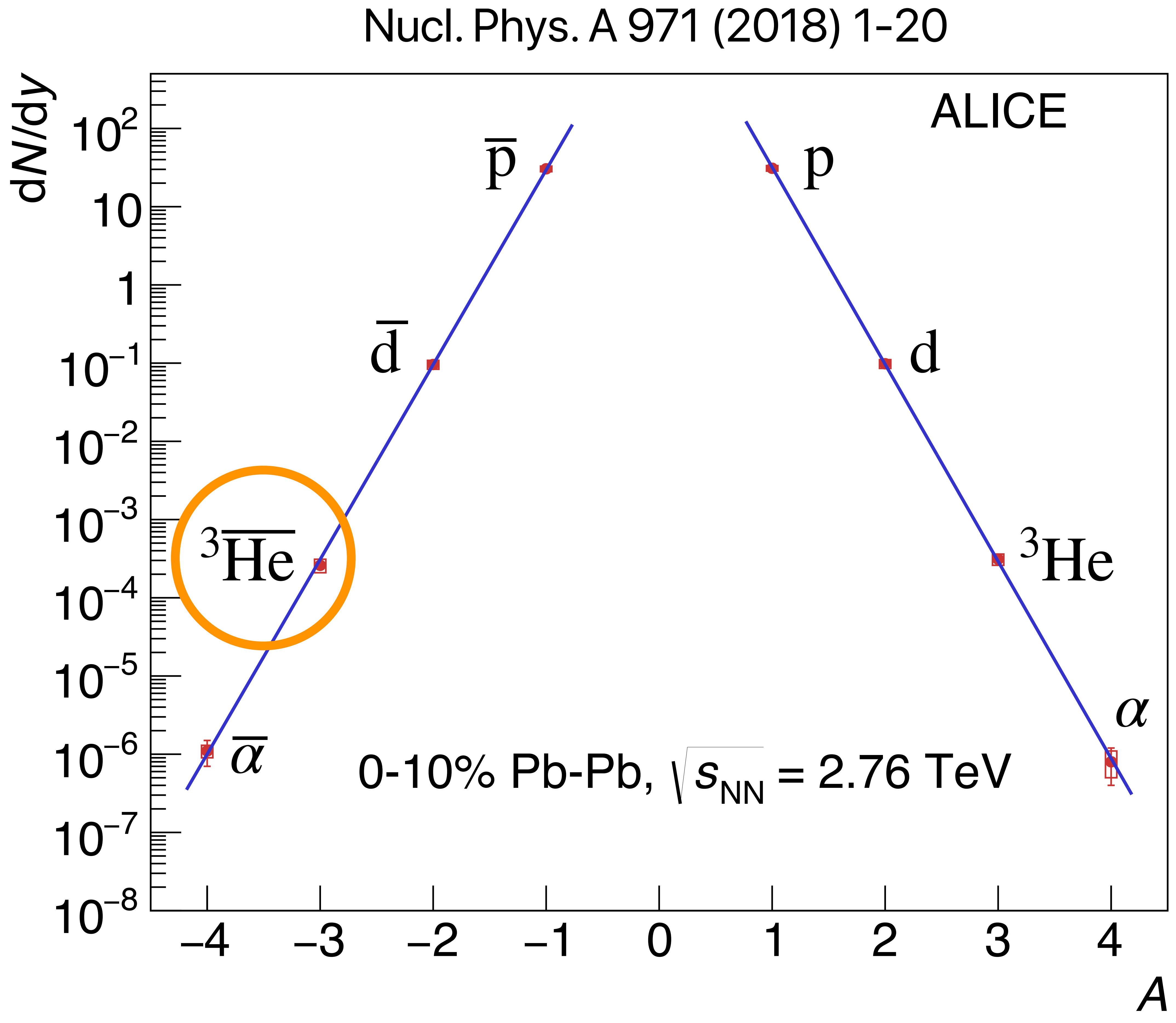
High energy collisions at LHC = the most suitable environment to study production of (anti)nuclei and their annihilation

- At LHC energies matter and antimatter are produced in almost equal amounts
- … propagate through detector material
- … and get absorbed inside the detector

→ in ALICE we are in a unique position to quantify σ_{inel} !

LHC as an antimatter factory

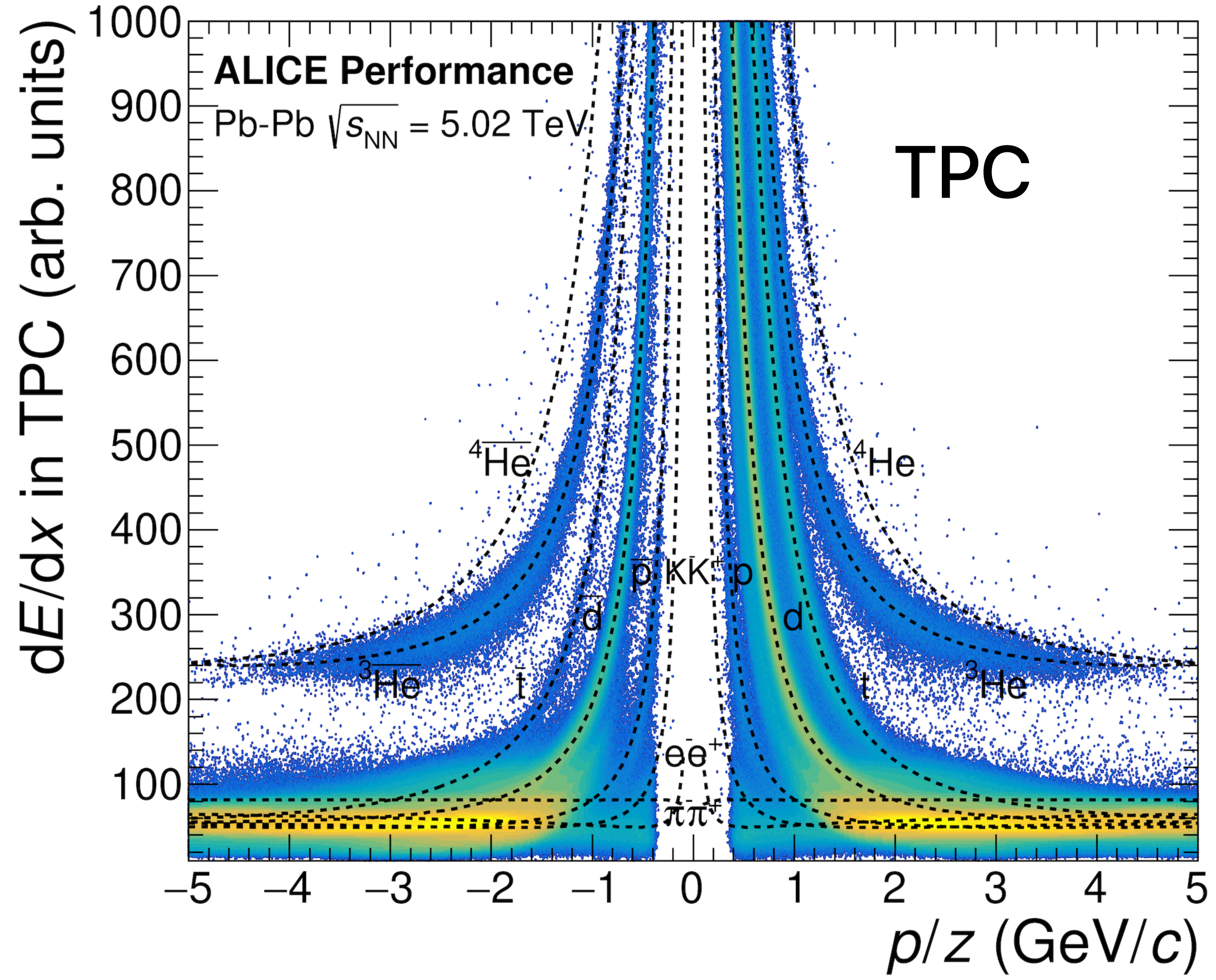




High energy collisions at LHC = the most suitable environment to study production of (anti)nuclei and their annihilation

This talk: focus on A = 3

ALICE apparatus and its particle identification capabilities



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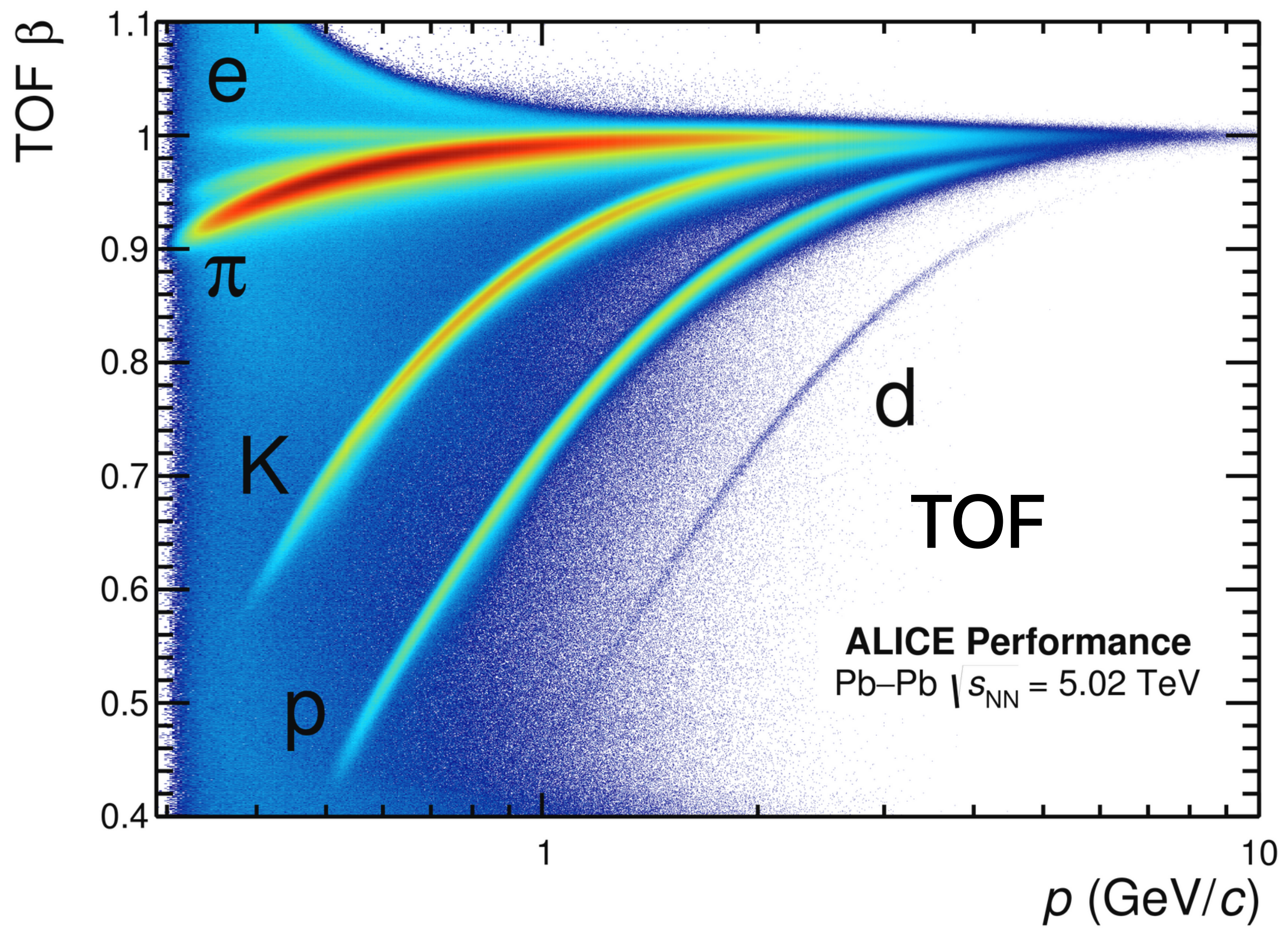
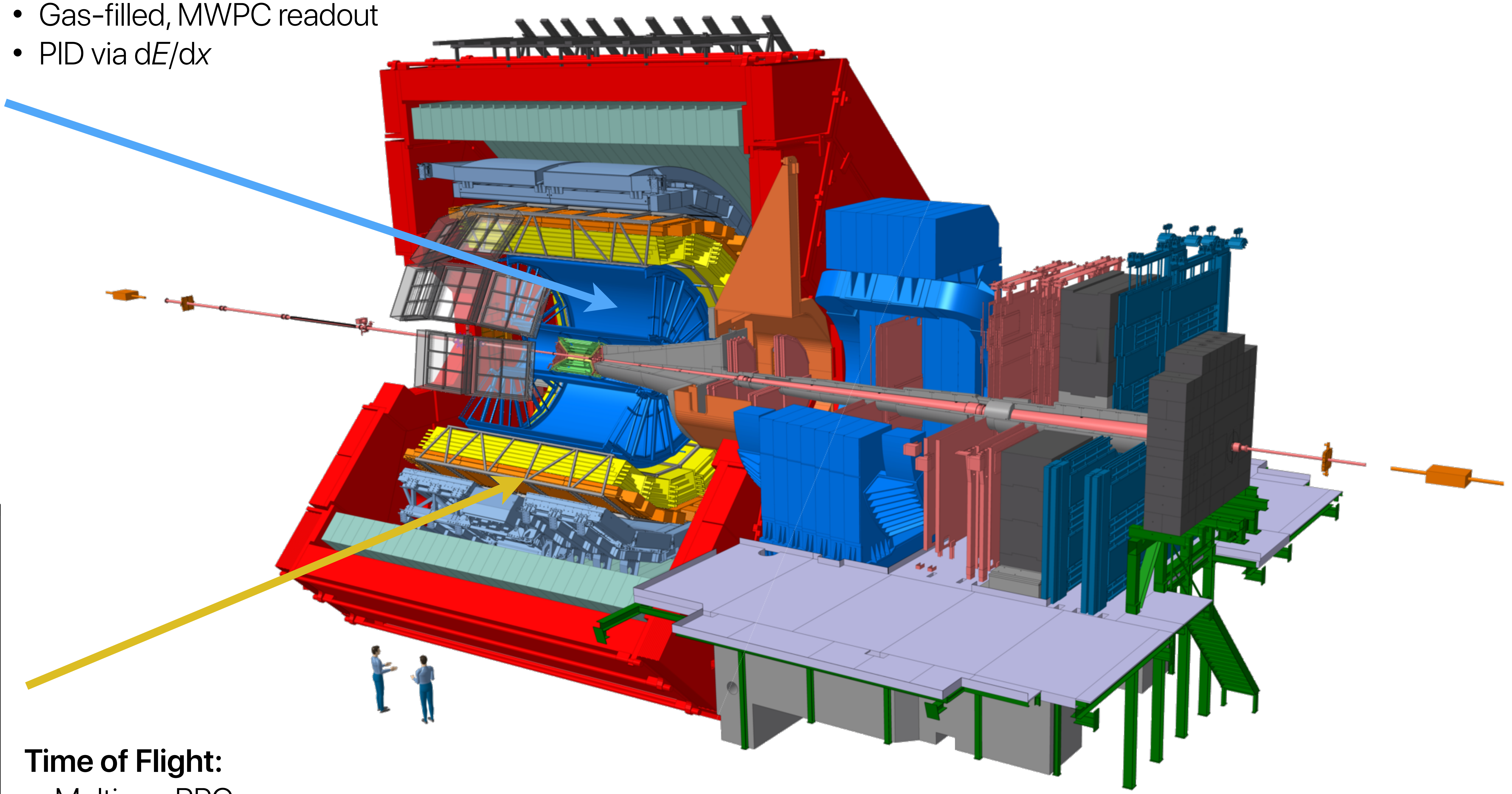


ALI-PERF-106336

Time Projection Chamber:

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



Time of Flight:

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

Methods to measure σ_{inel}

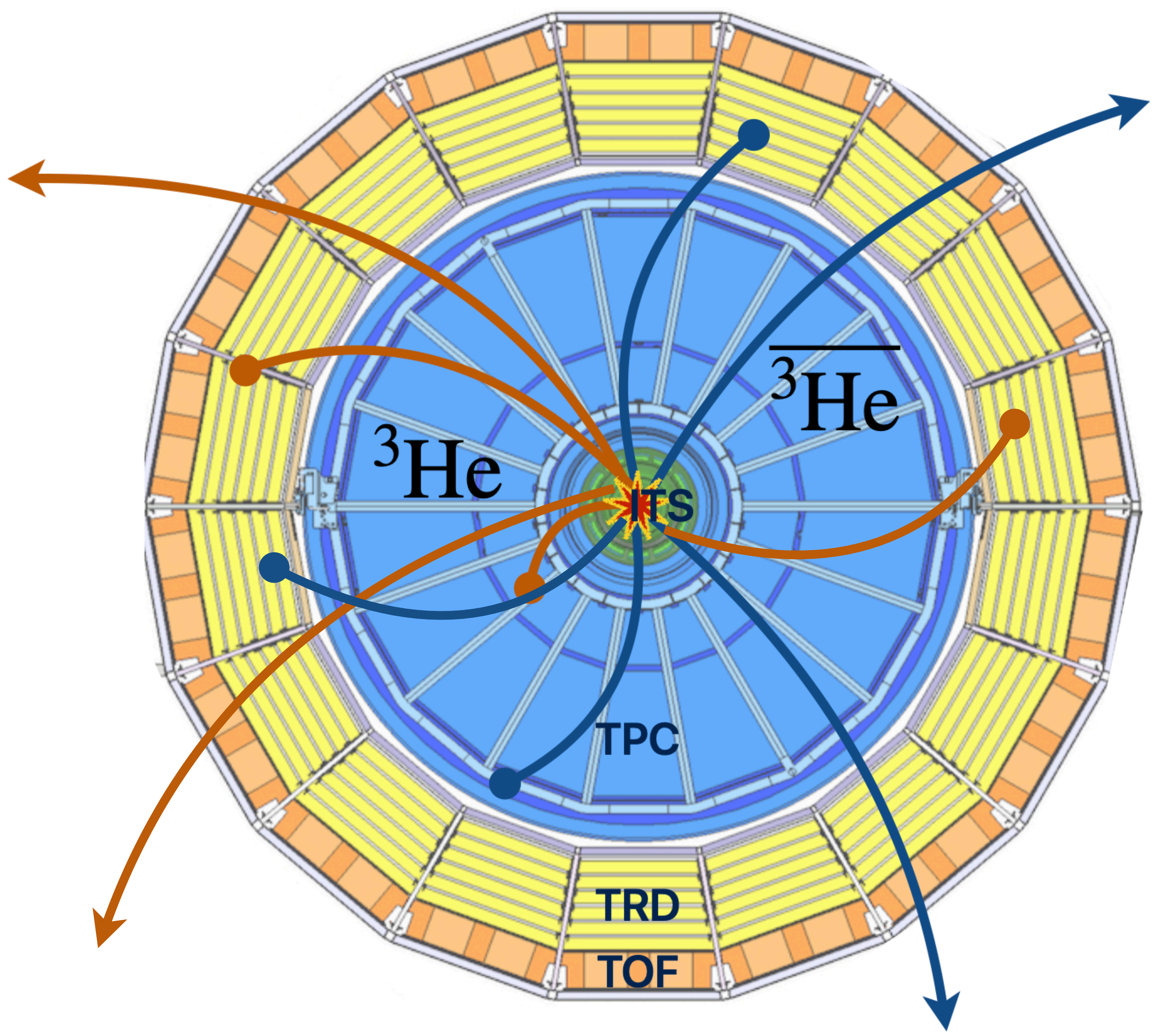
Antiparticle/particle raw ratio (pp, p-Pb collisions):

- 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 $\sigma_{\mathrm{inel}}(\mathrm{nuclei})$

\- Background from secondary particles



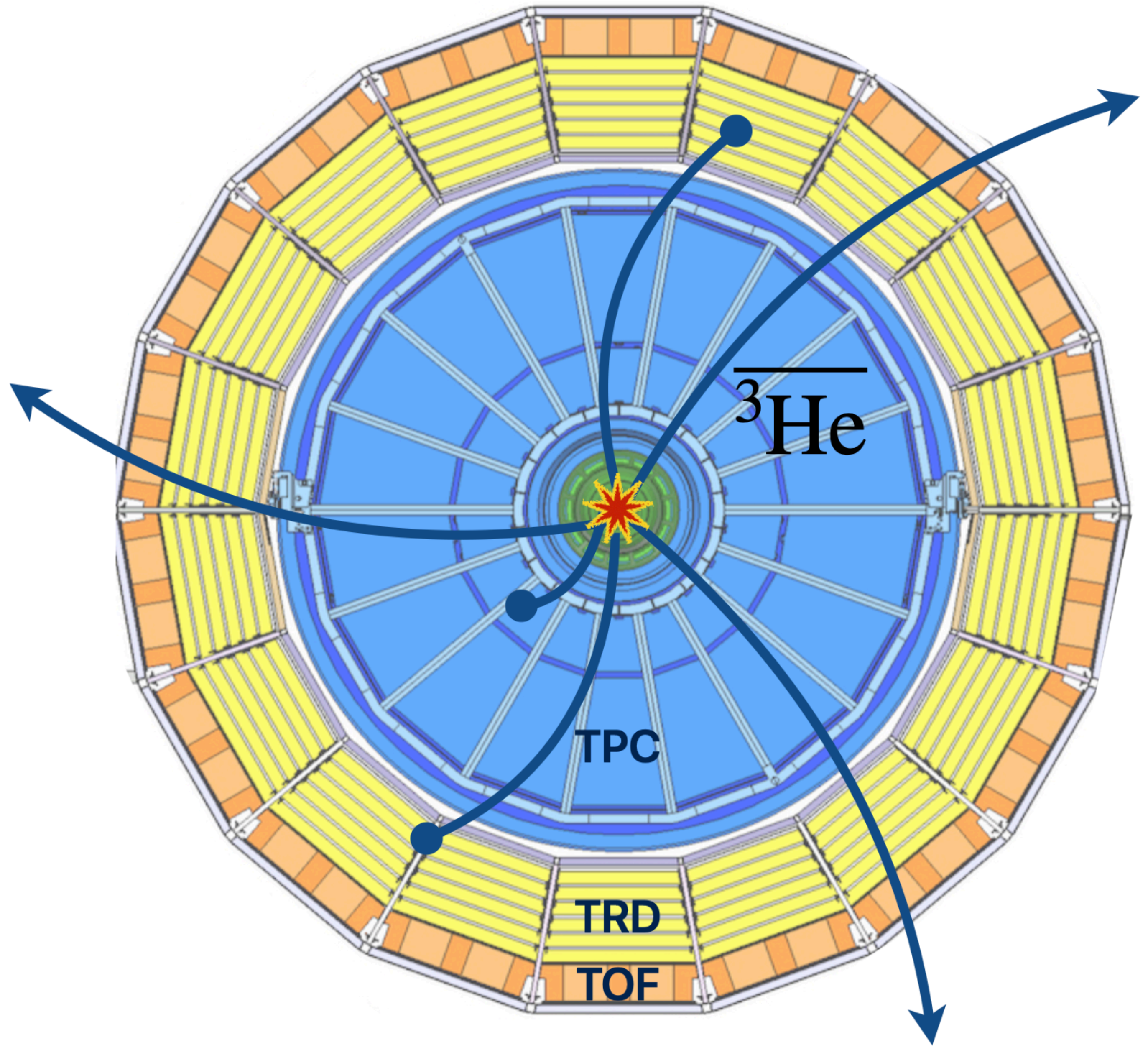
TOF/TPC ratio (Pb-Pb collisions):

- 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

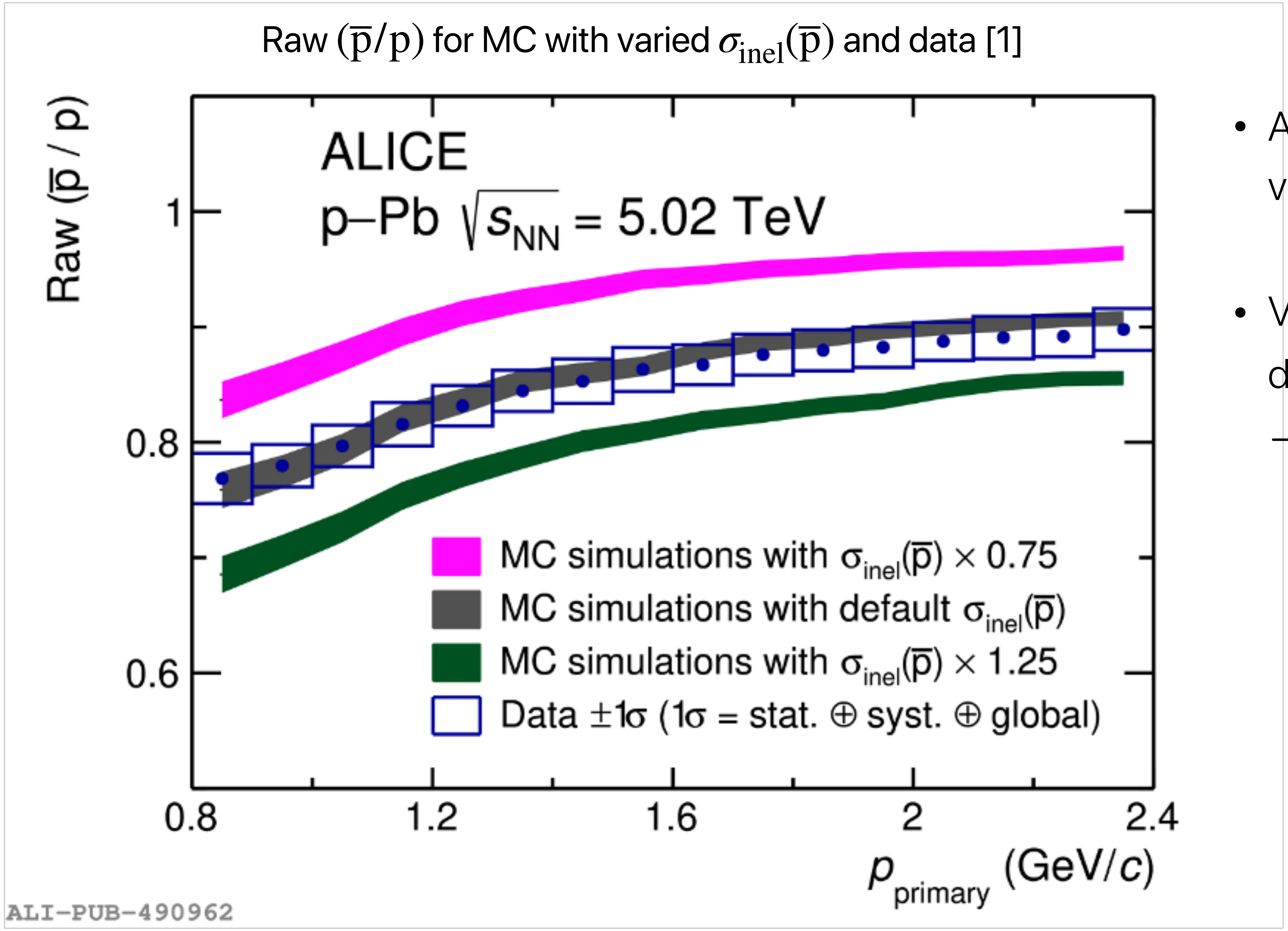
\+ Independent of $\sigma_{\mathrm{inel}}(\mathrm{nuclei})$

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



Antiparticle/particle raw ratio

Method 1

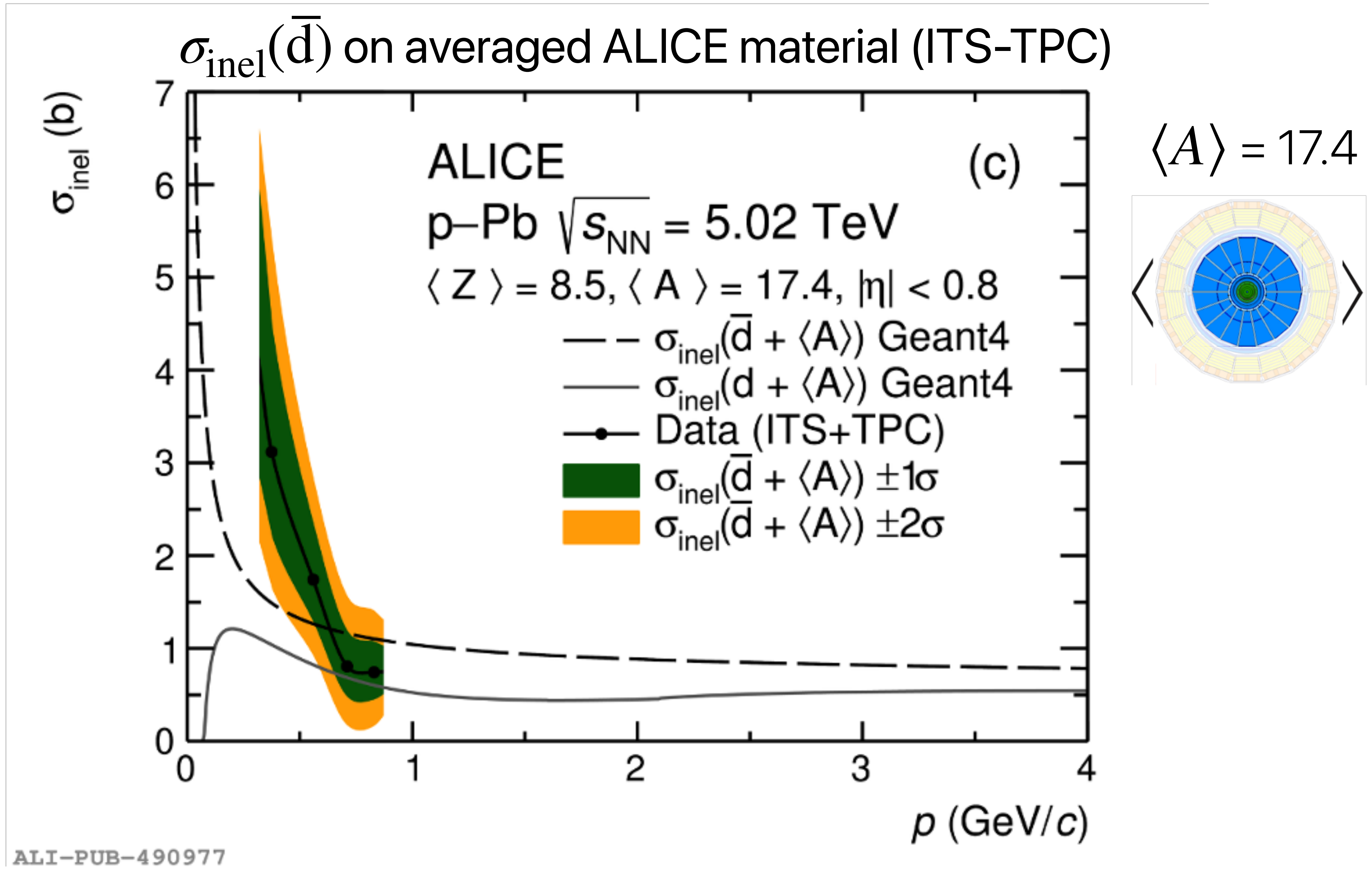


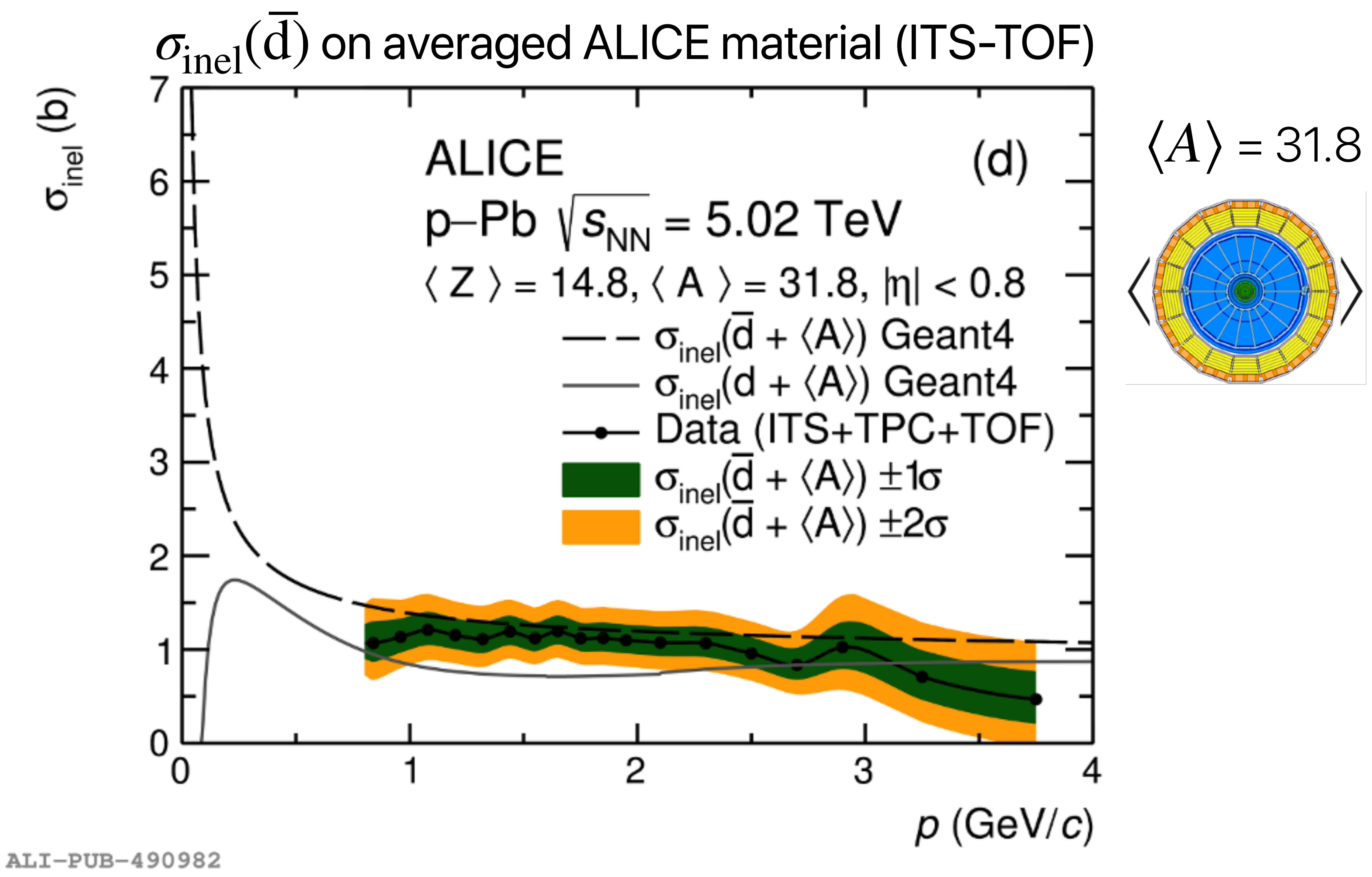
- Antiparticle-to-particle ratios are sensitive to the variation of the inelastic cross section
- Vary $\sigma_{inel}(\bar{d},\ ^{3}\overline{He})$ in simulations until MC describes the experimental results
  → constraints on $\sigma_{inel}(\bar{d},\ ^{3}\overline{He})$

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

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

Method 1





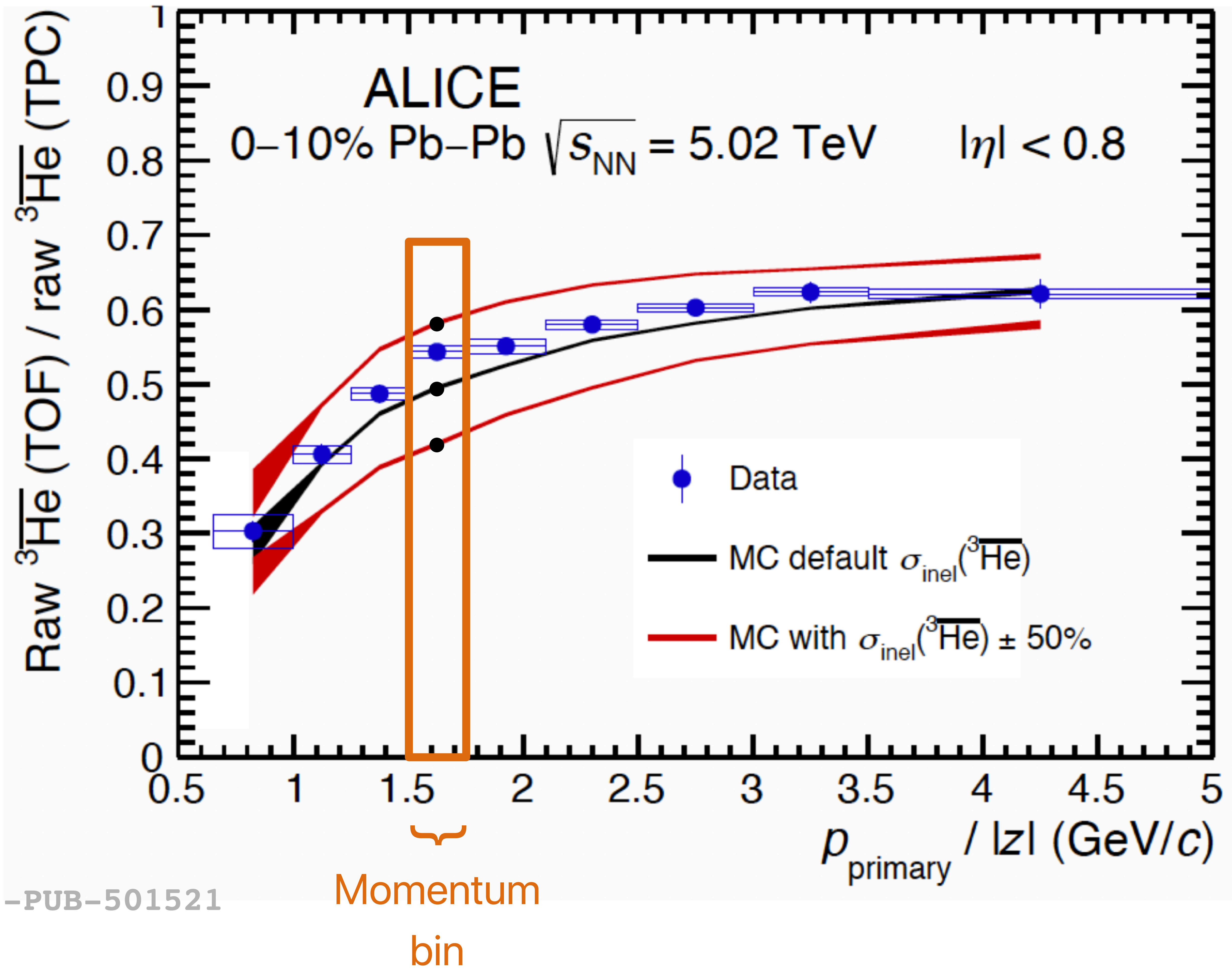
- First measurement of antideuteron inelastic cross section at low momenta!
- Exp. σ_{inel} is approx. 15% smaller w.r.t. Geant4 at high momenta, steeper rise in low p region
- Published: PRL 125, 162001 (2020)

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

Method 2

- 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

[arXiv:2202.01549]



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

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ALICE

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- In each momentum bin compare the TOF-TPC ratio in MC to the one in data

↓

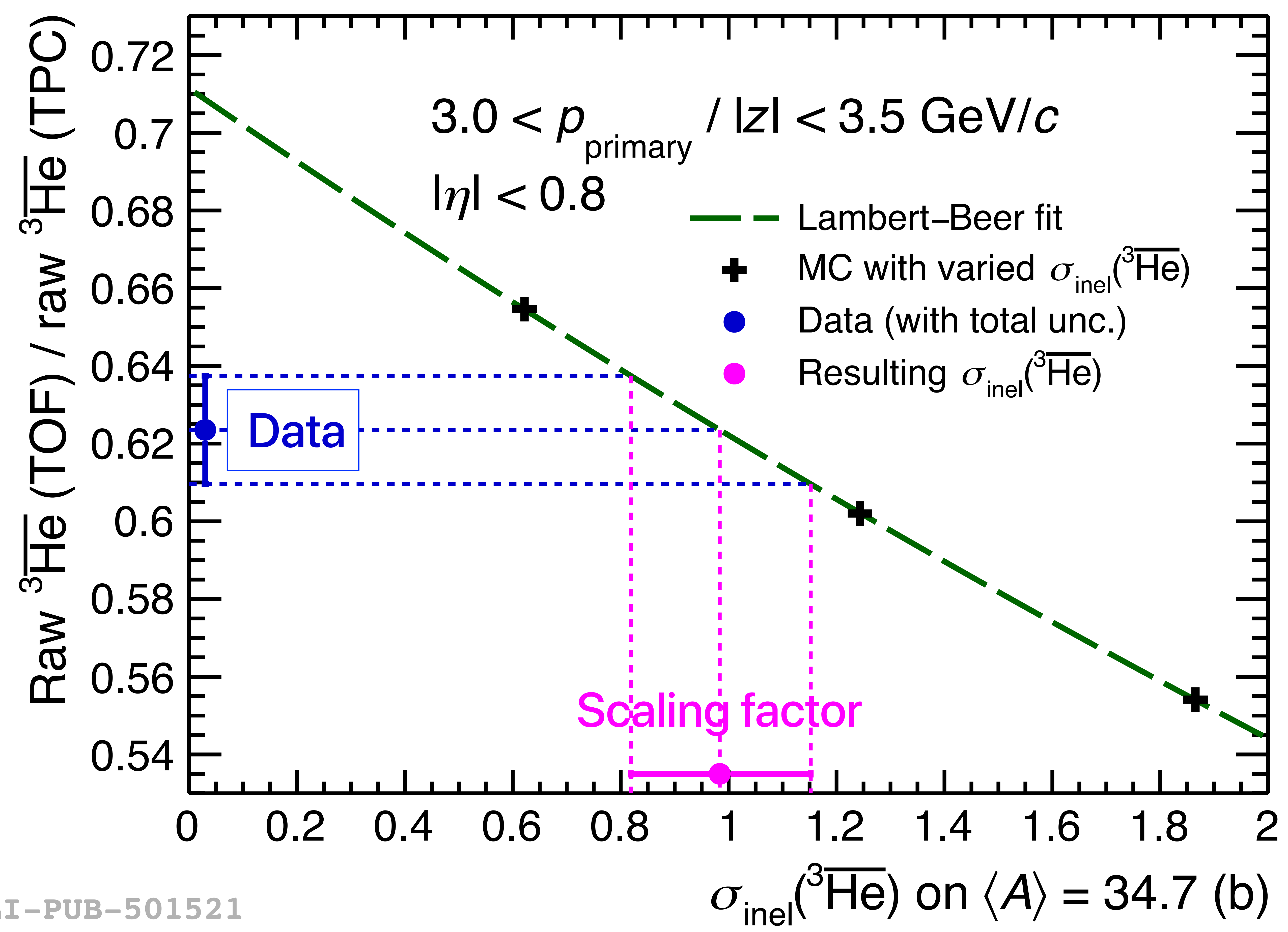
- Fit MC points with an exponential according to the Lambert-Beer law:

$$N = N_0 \times \exp(-\sigma\rho L)$$

- extract $\sigma_{inel}/\sigma_{inel}^{def}$ scaling factor
- calculate the inelastic cross section on $\langle A \rangle$:

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

[arXiv:2202.01549]



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

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

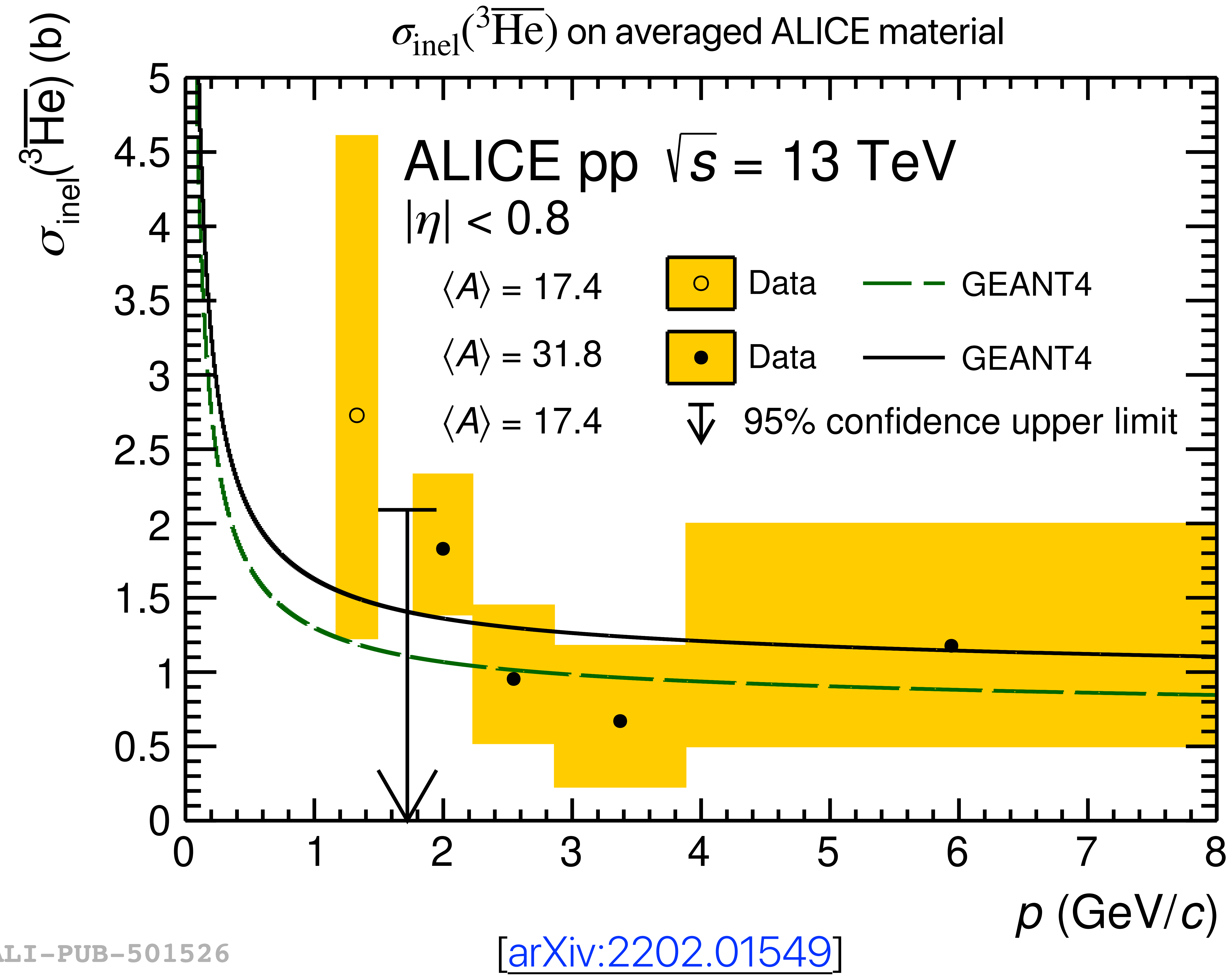
Method 1

ALICE

- $\sigma_{\text{inel}}(^{3}\overline{\text{He}})$: Results for **antiparticle-to-particle raw ratio** and **TOF-to-TPC ratio**:

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

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



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

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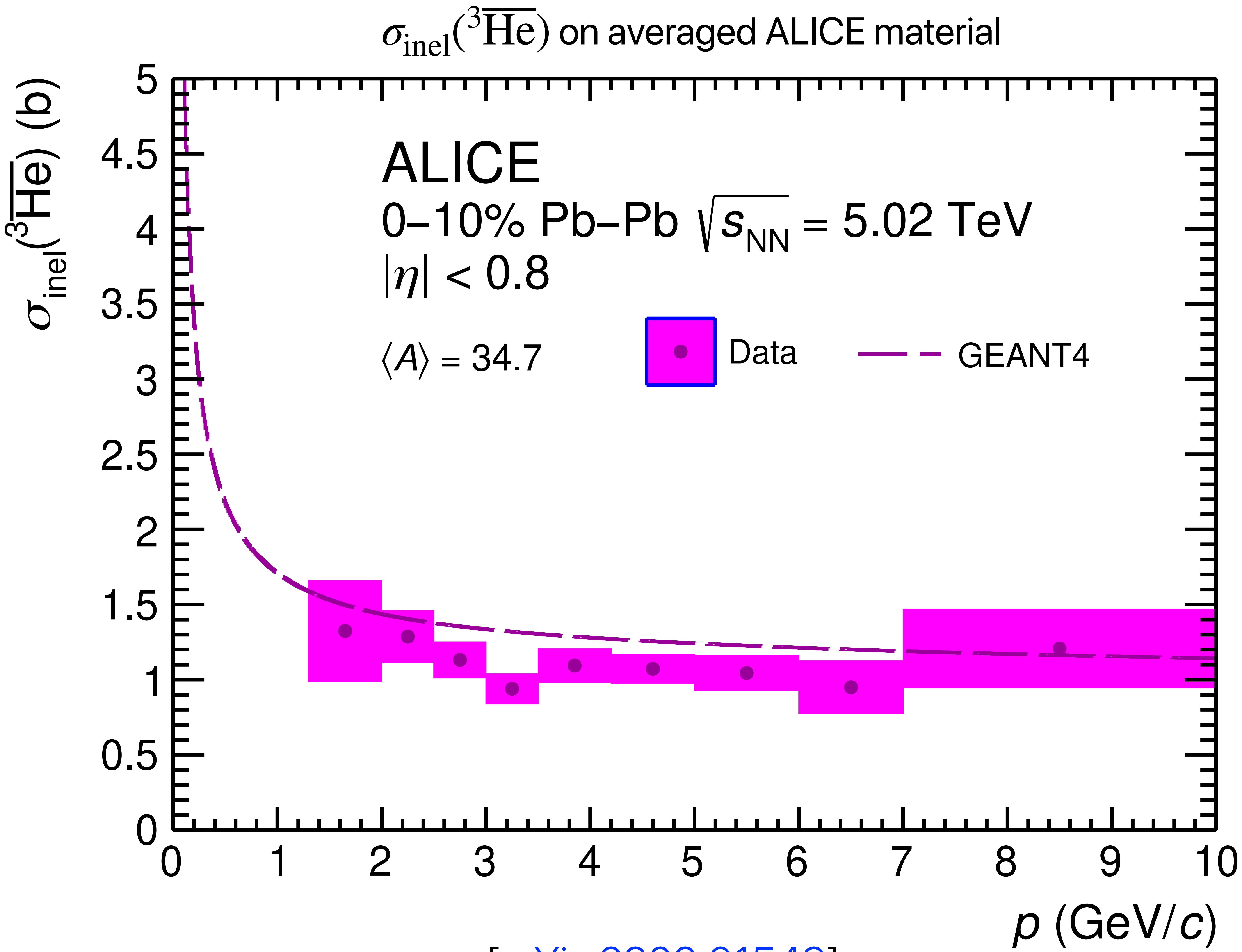

ALI-PUB-501531

[arXiv:2202.01549]

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

Method 2

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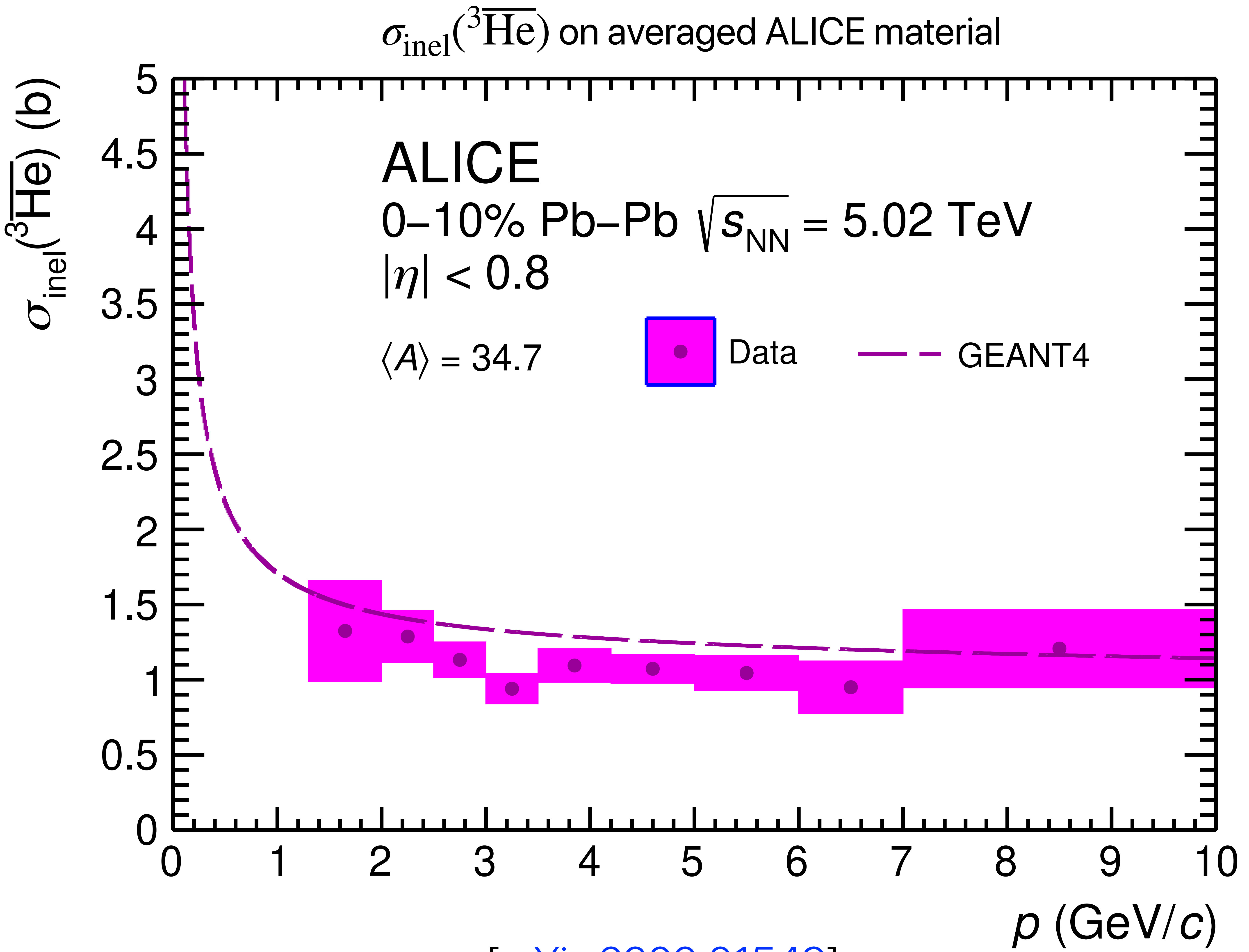
→ Next: impact on $^{3}\overline{\mathrm{He}}$ propagation in space



ALI-PUB-501531

[arXiv:2202.01549]

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

ALICE

Transport equation

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

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**

[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)

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

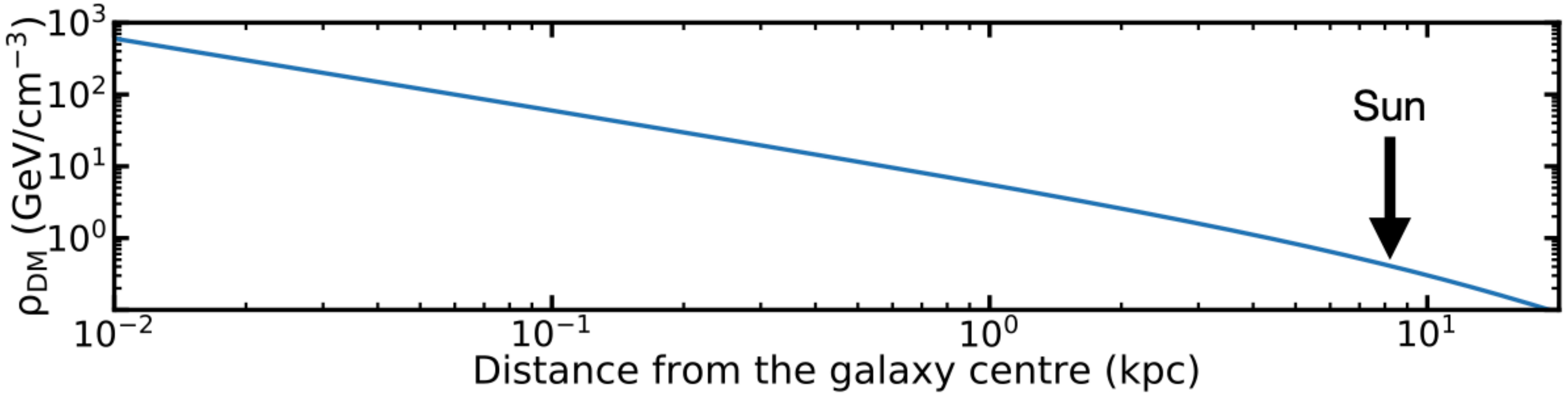
Source (1) ✅ Propagation ✅ Annihilation ❌

ALICE

DM density distr.

Source function

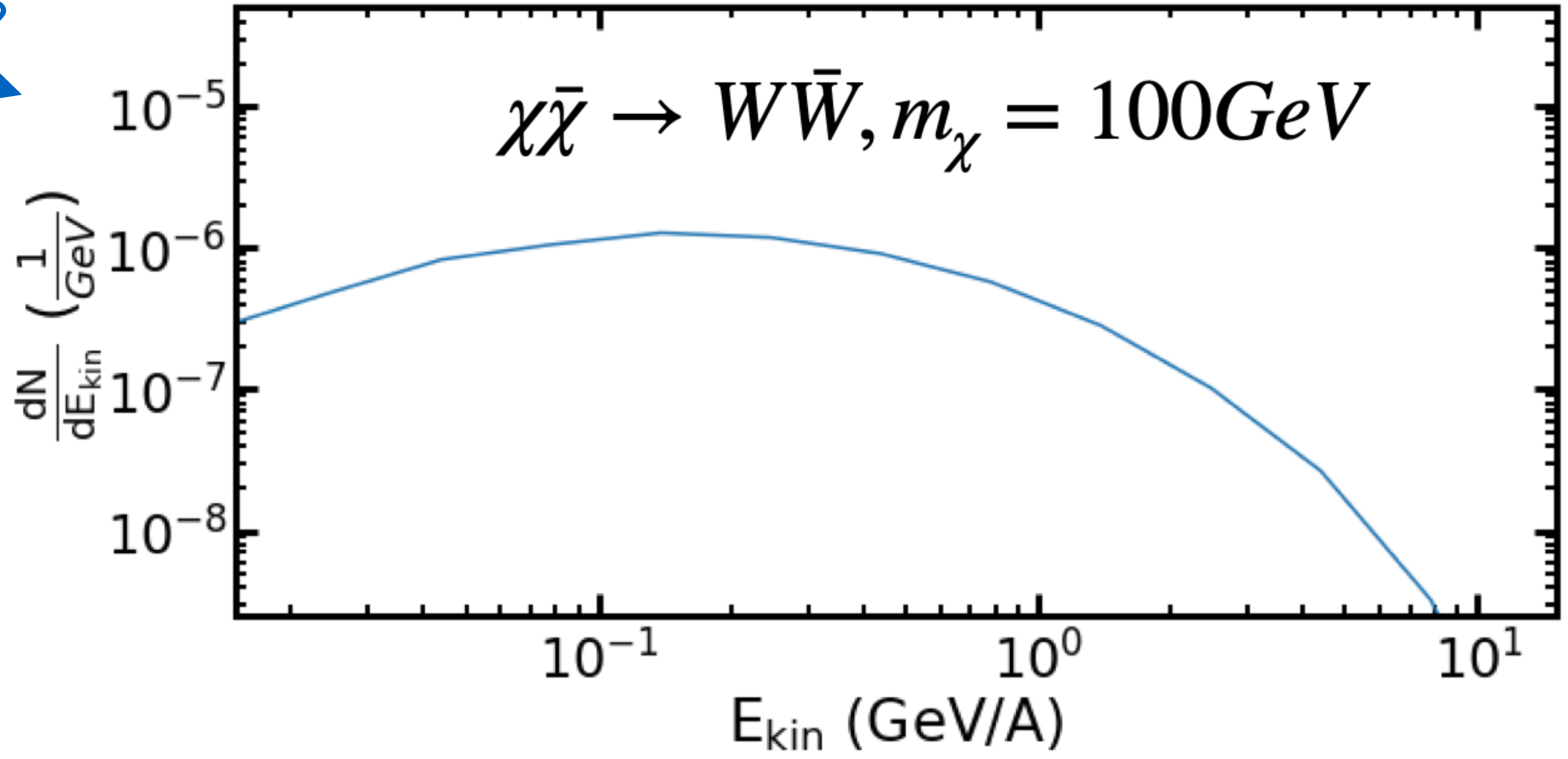
$$q(\mathrm{r}, E_{kin}) = \frac{1}{2}\frac{\rho^2_{\mathrm{DM}}(\mathrm{r})}{m^2_\chi}\langle\sigma v\rangle(1+\epsilon)\frac{dN}{dE_{kin}}$$



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

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

→ peak at E_{kin} ~ 0.1 GeV/A



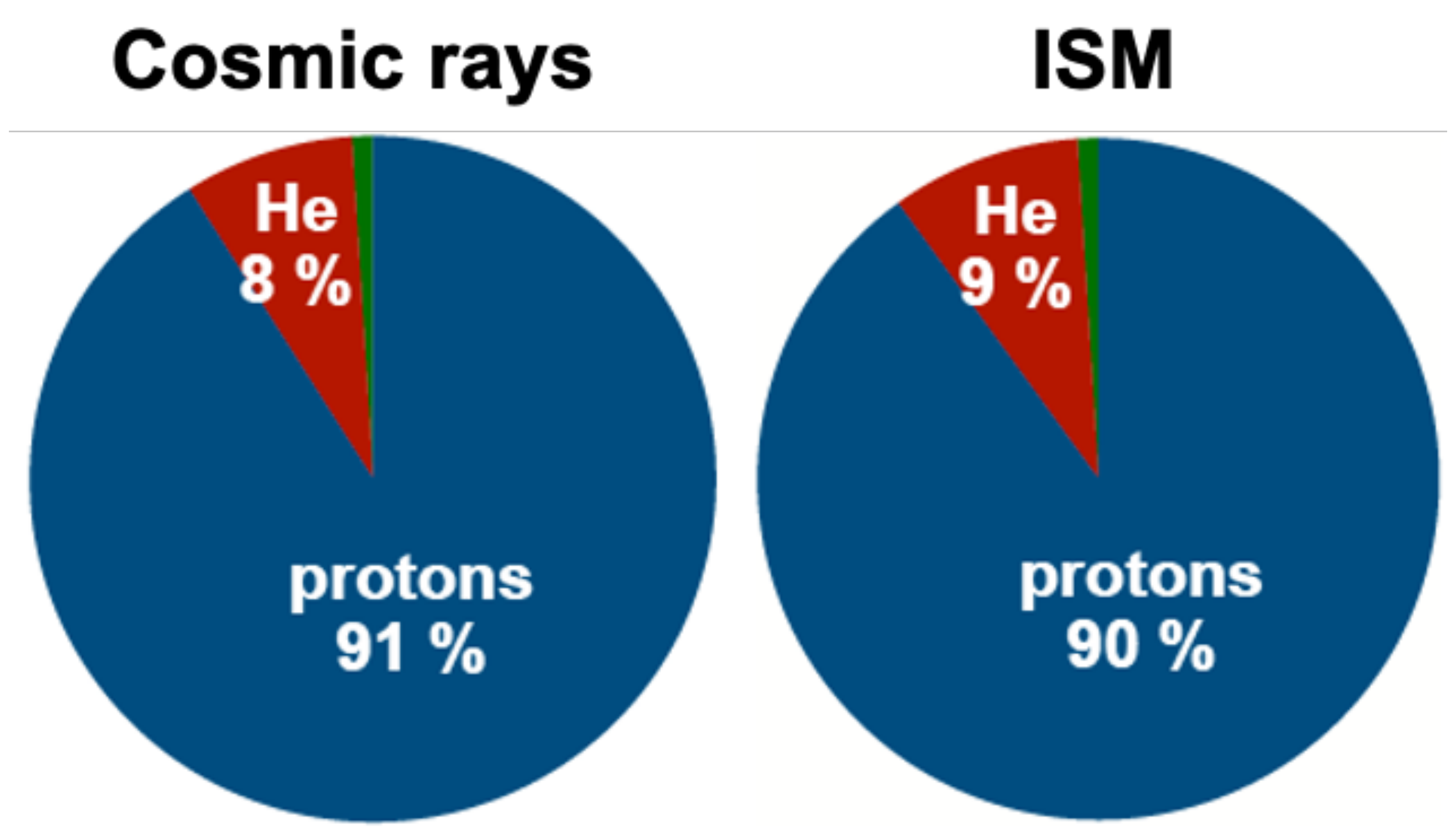
[1] Carlson et al, Phys. Rev. D. 89, 076005 (2014)
[2] Korsmeier et al, Phys. Rev. D. 97, 103011 (2018)

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

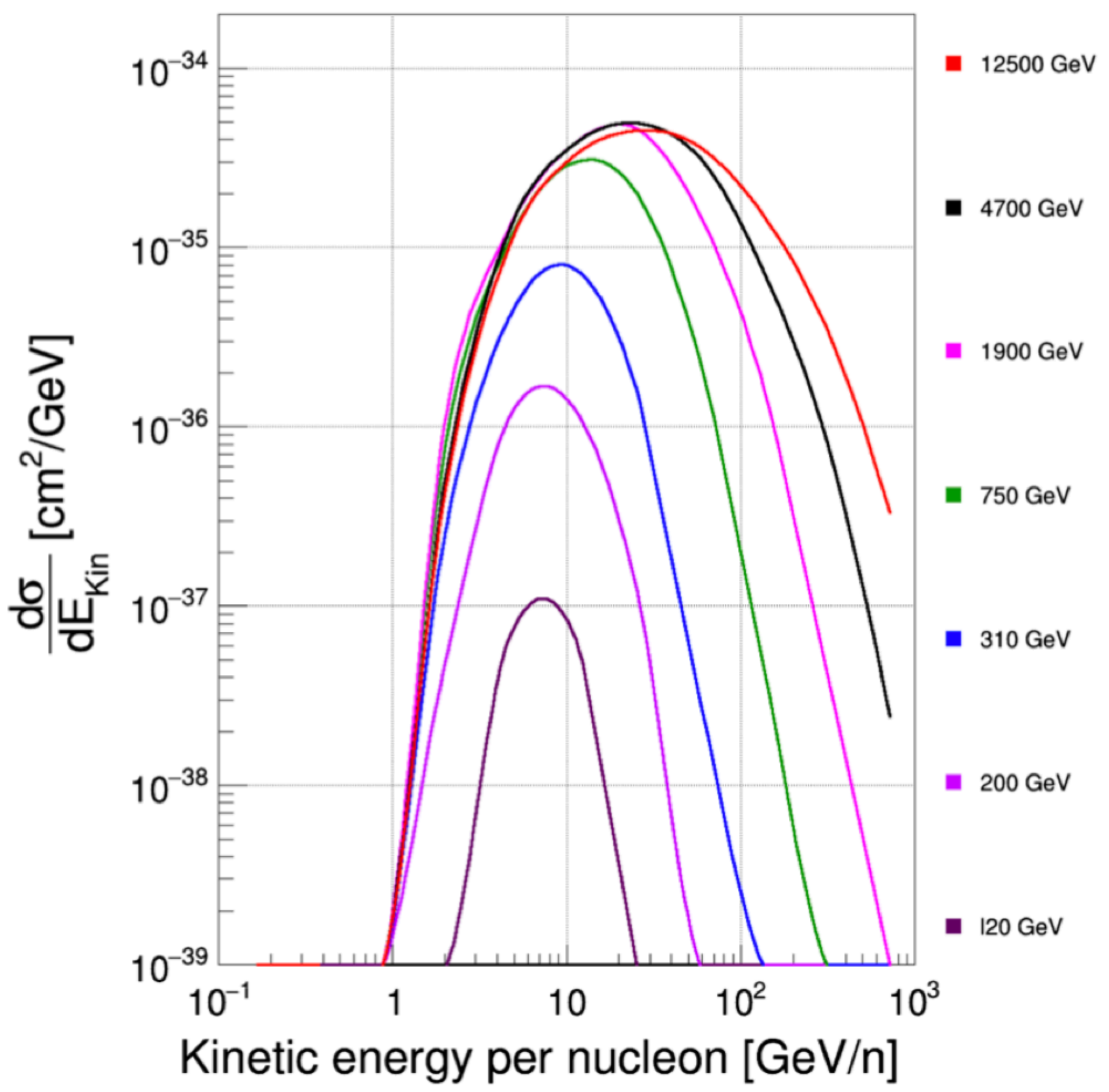
Source (2) ✅ Propagation ✅ Annihilation ❌

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

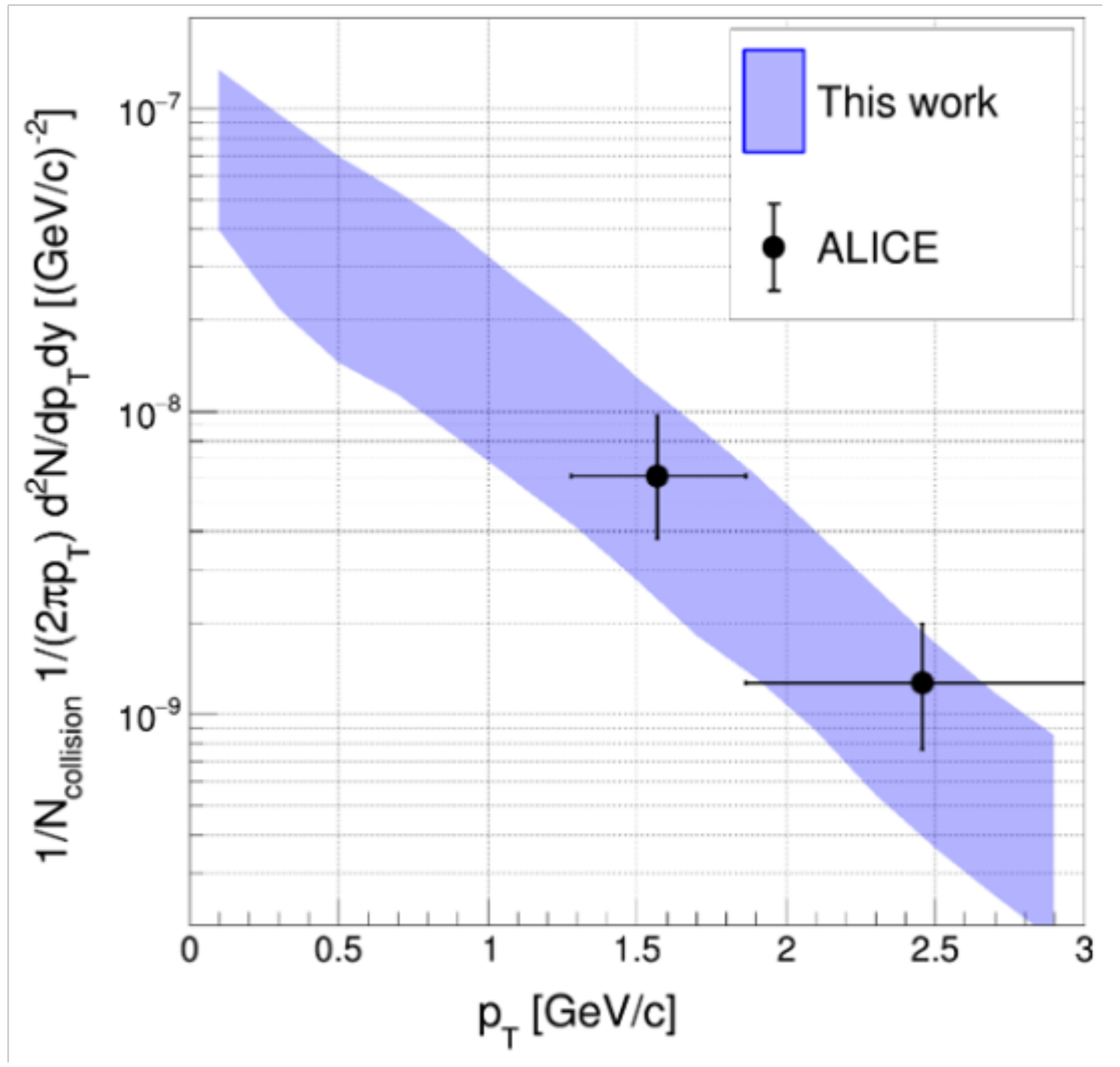
- Collision systems: pp, p-^{4}He, ^{4}He-p, ^{4}He-^{4}He
- Production cross section in pp from [1]: EPOS LHC + coalescence afterburner
- Scaling factor $(A_T A_P)^{2.2/3}$ for the other collision systems
- Validated by ALICE data [2] ✅



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

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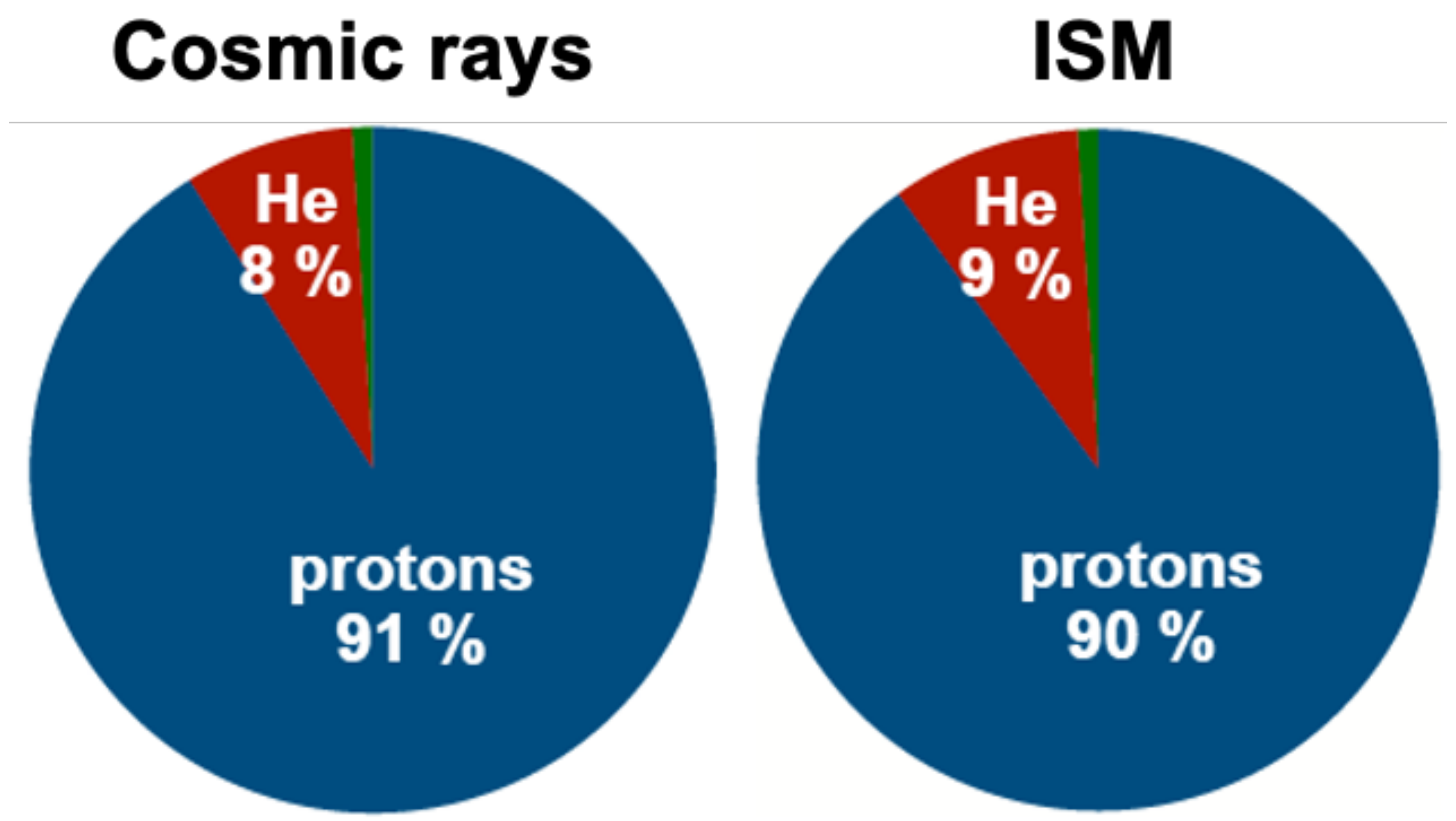
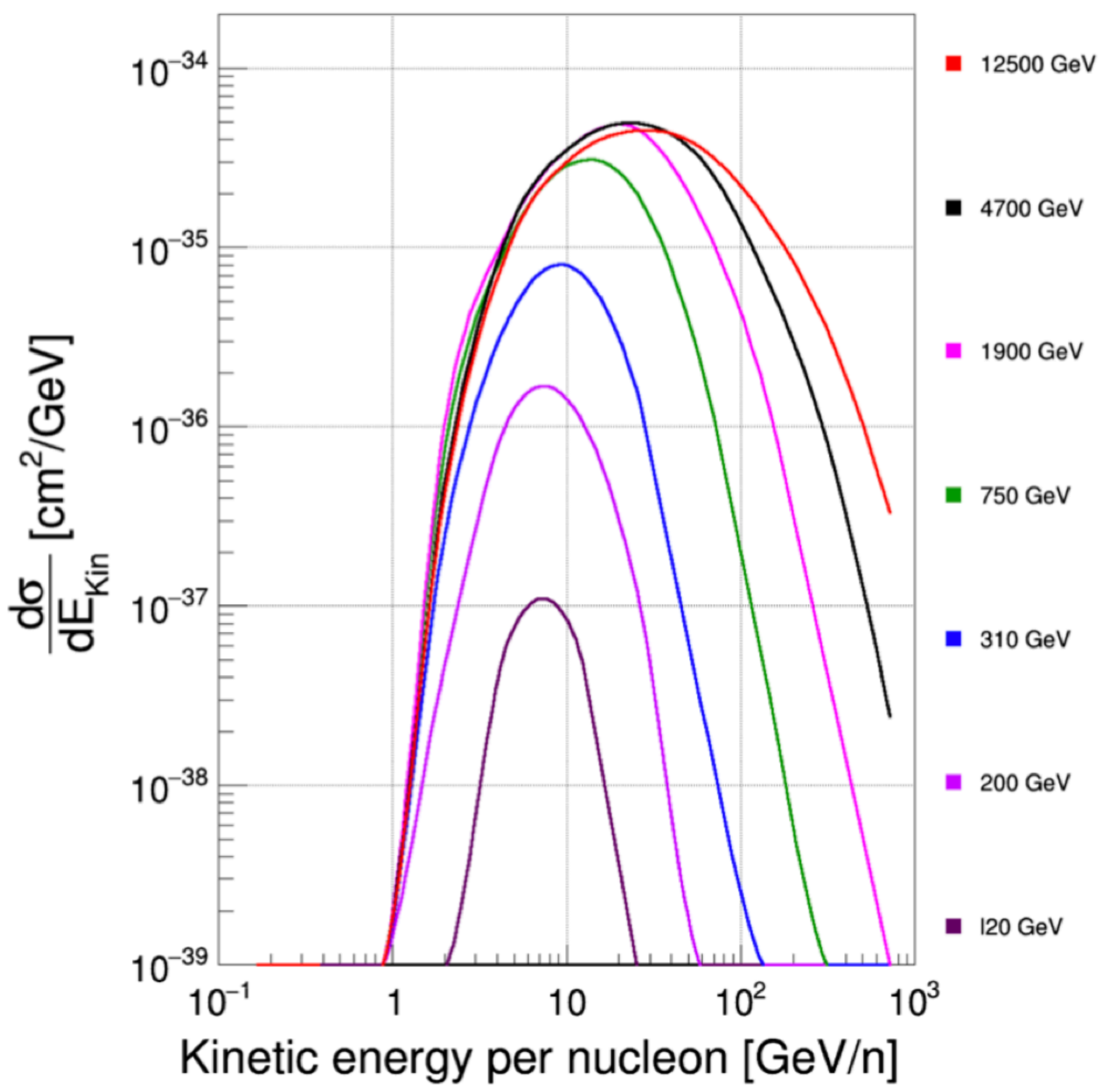
See talk by Chiara Pinto
Tue 14.06 at 9:20



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



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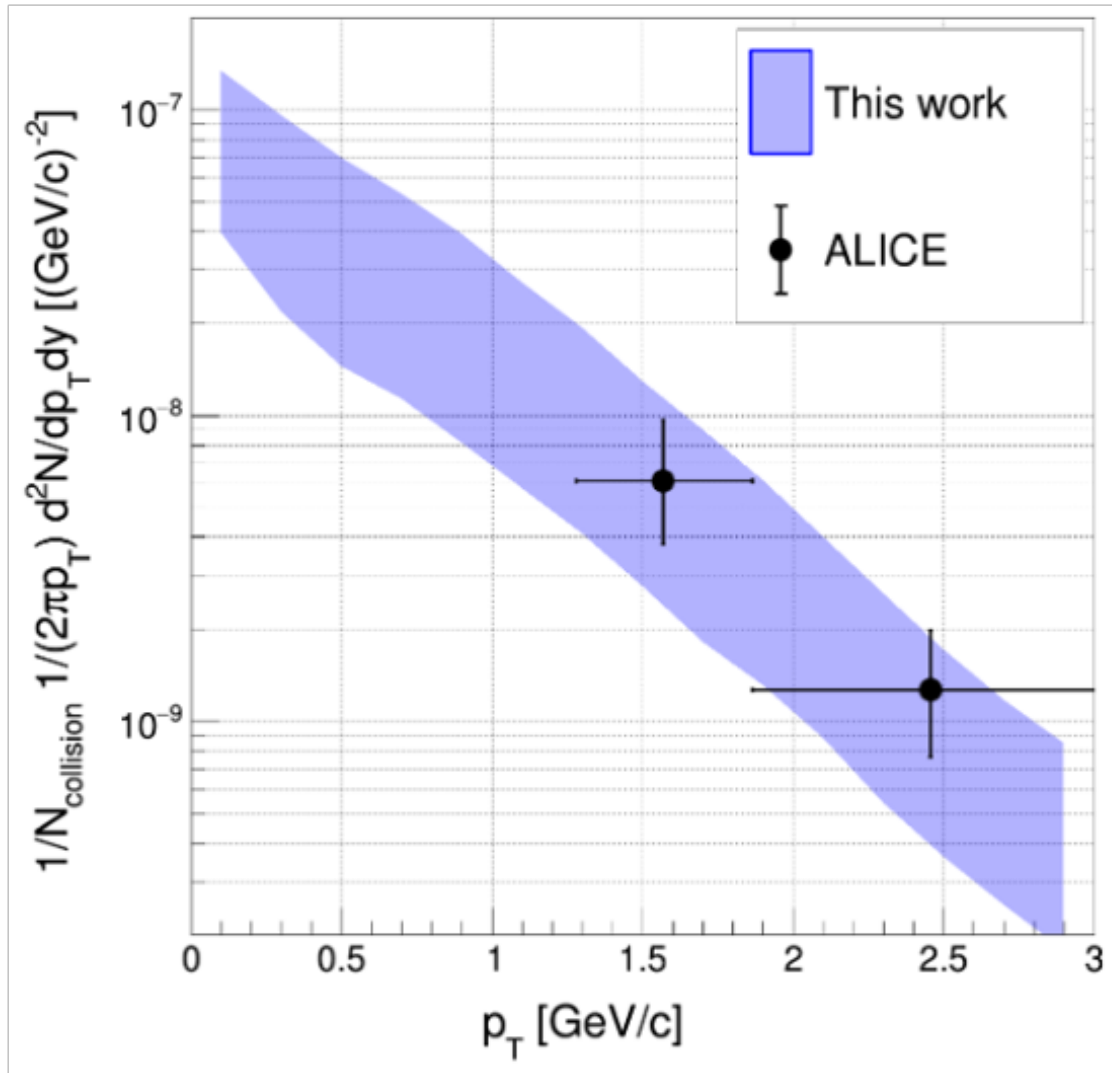

[1] Shukla et al, Phys. Rev. D. 102, 063004 (2020)
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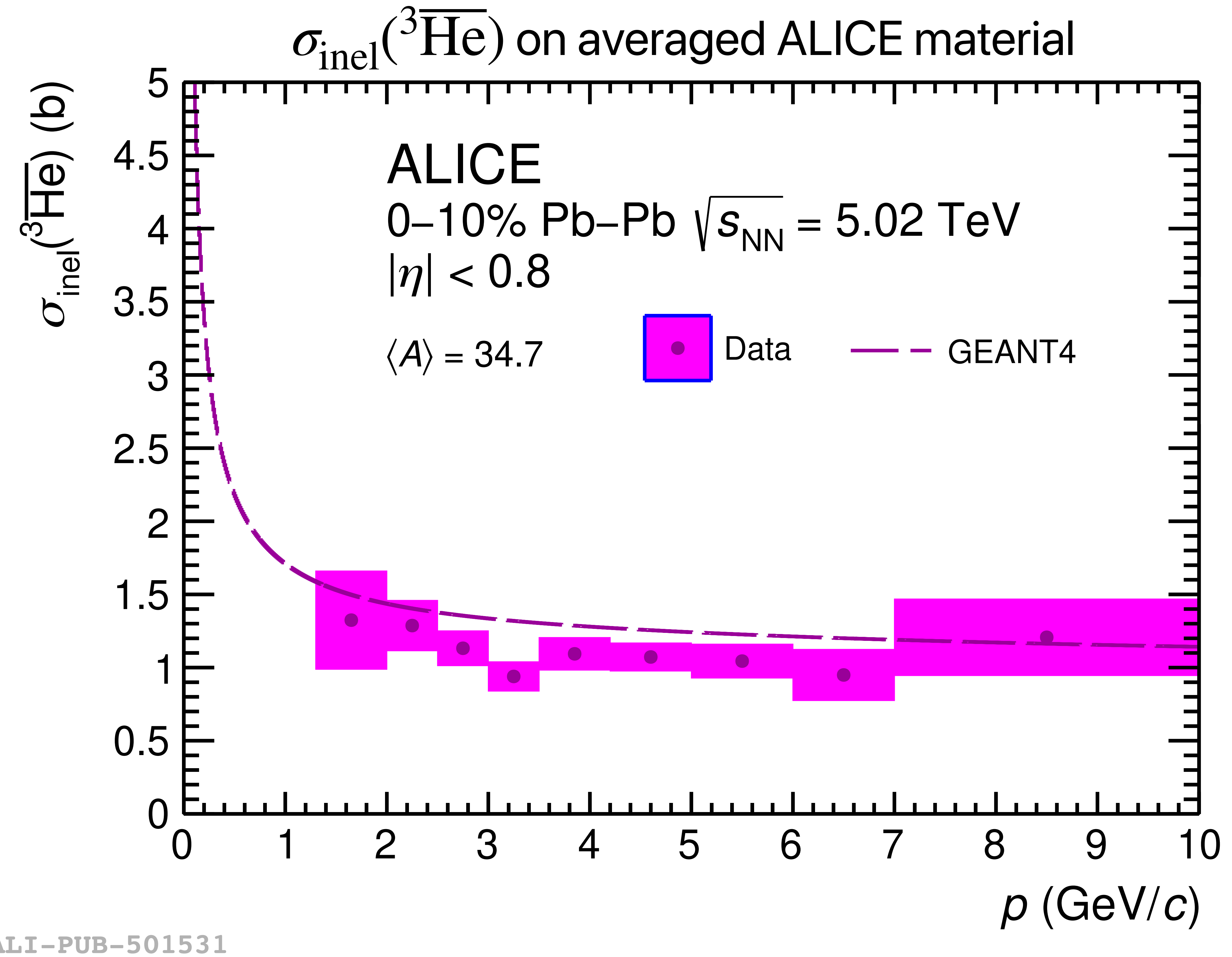
Annihilation

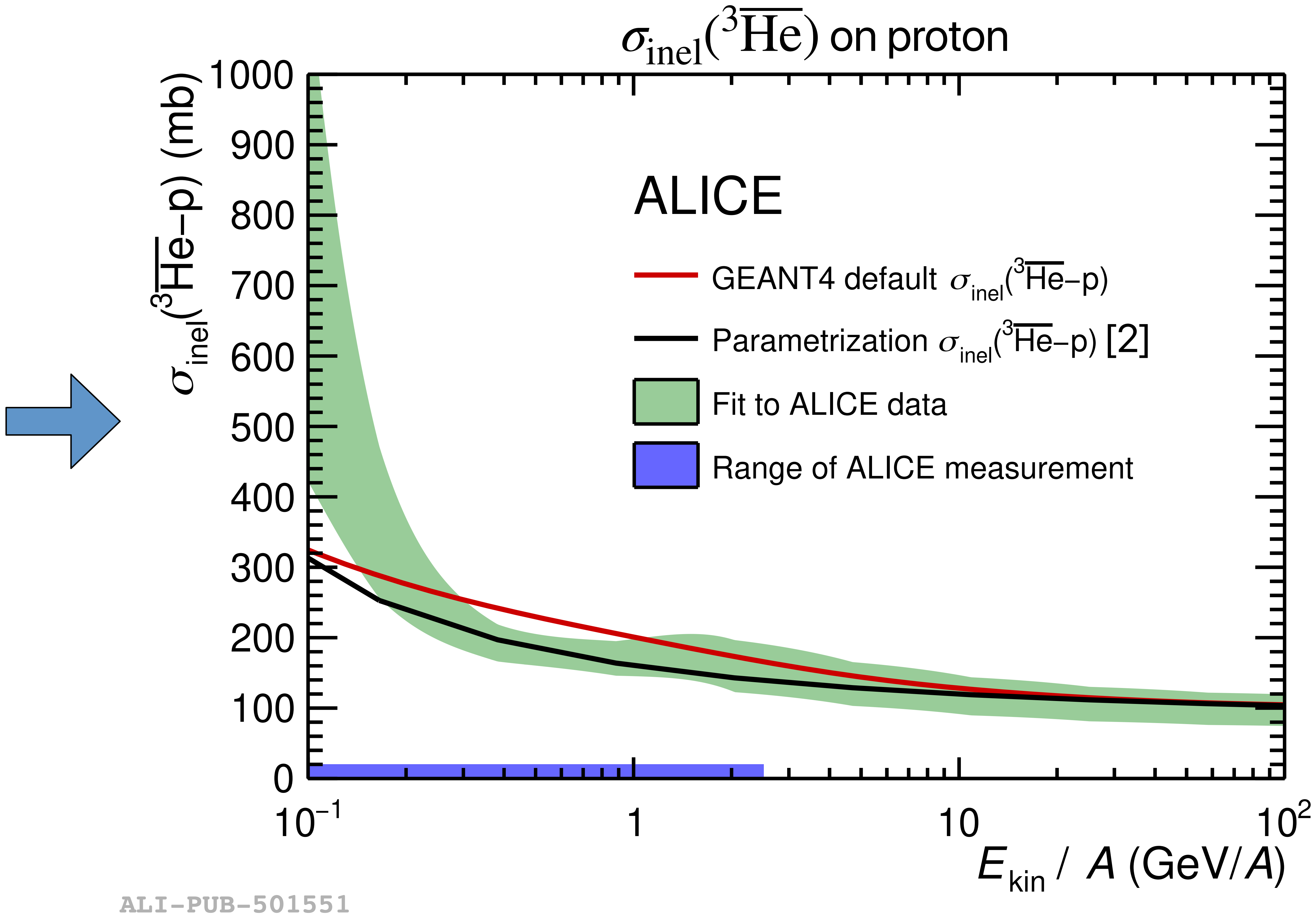
Sources ✅ Propagation ✅ Annihilation ✅

ALICE

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





[1] Uzhinsky et al. Phys. Lett. B 705 (2011) 235
[2] Korsmeier et al, Phys. Rev. D. 97, 103011 (2018)

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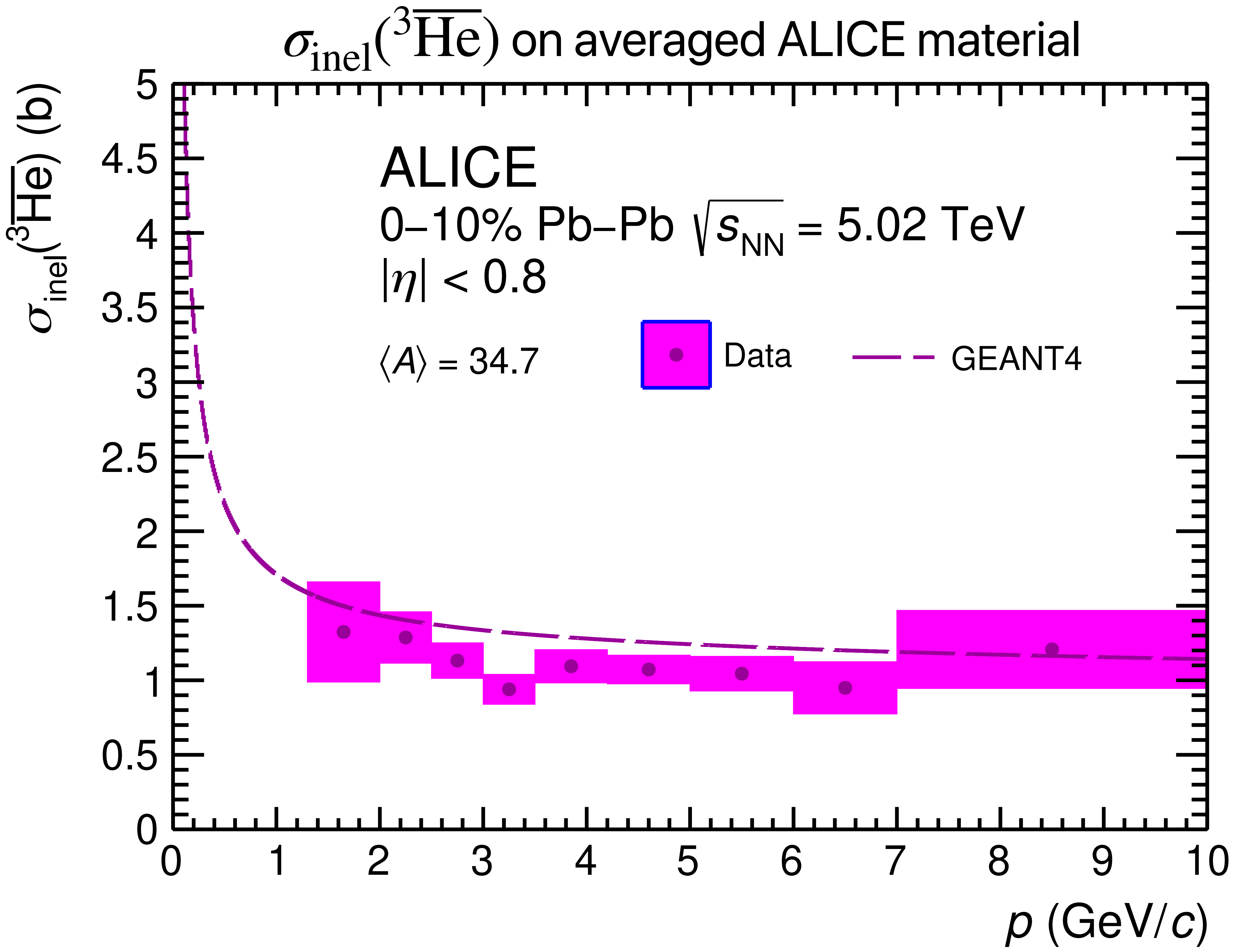

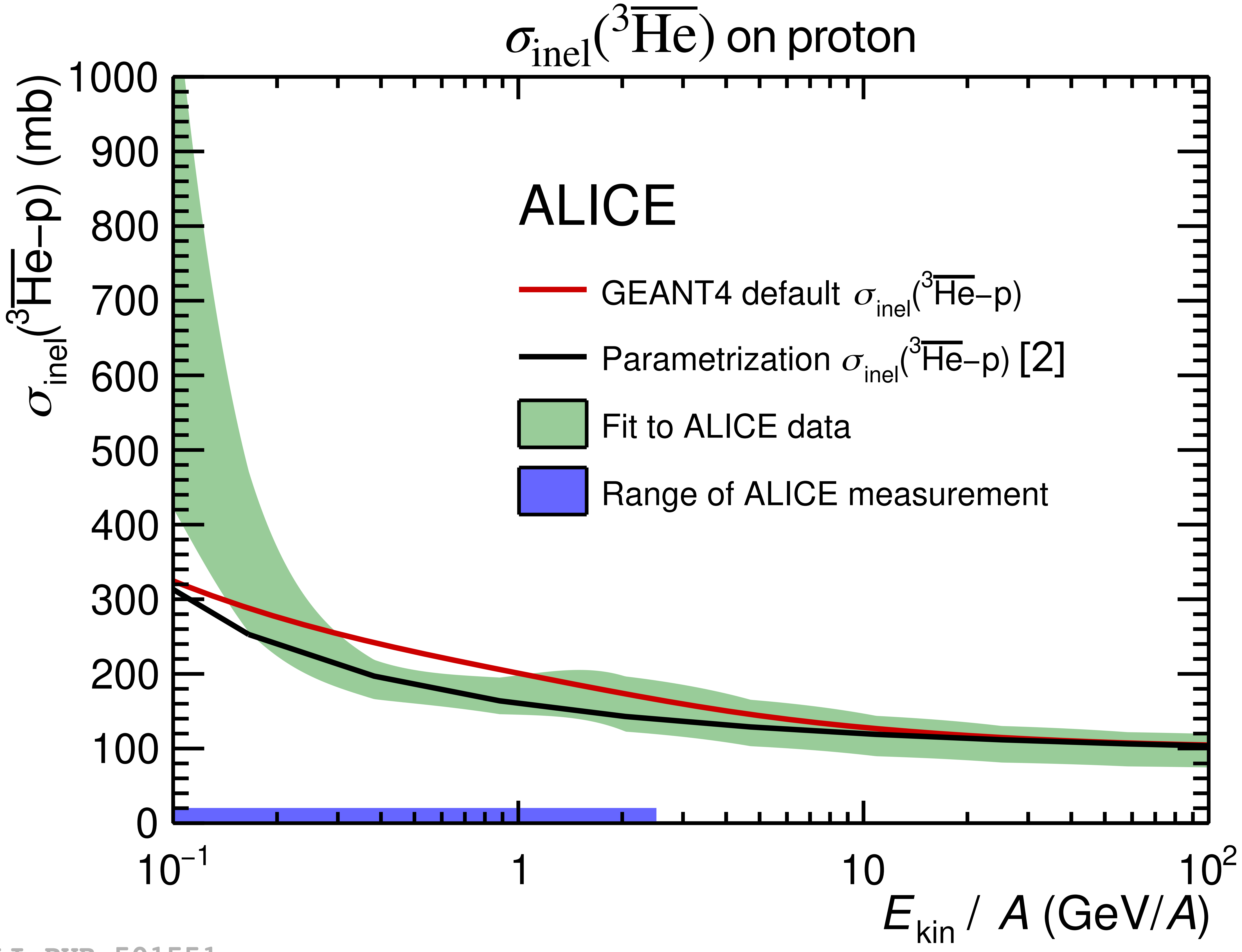

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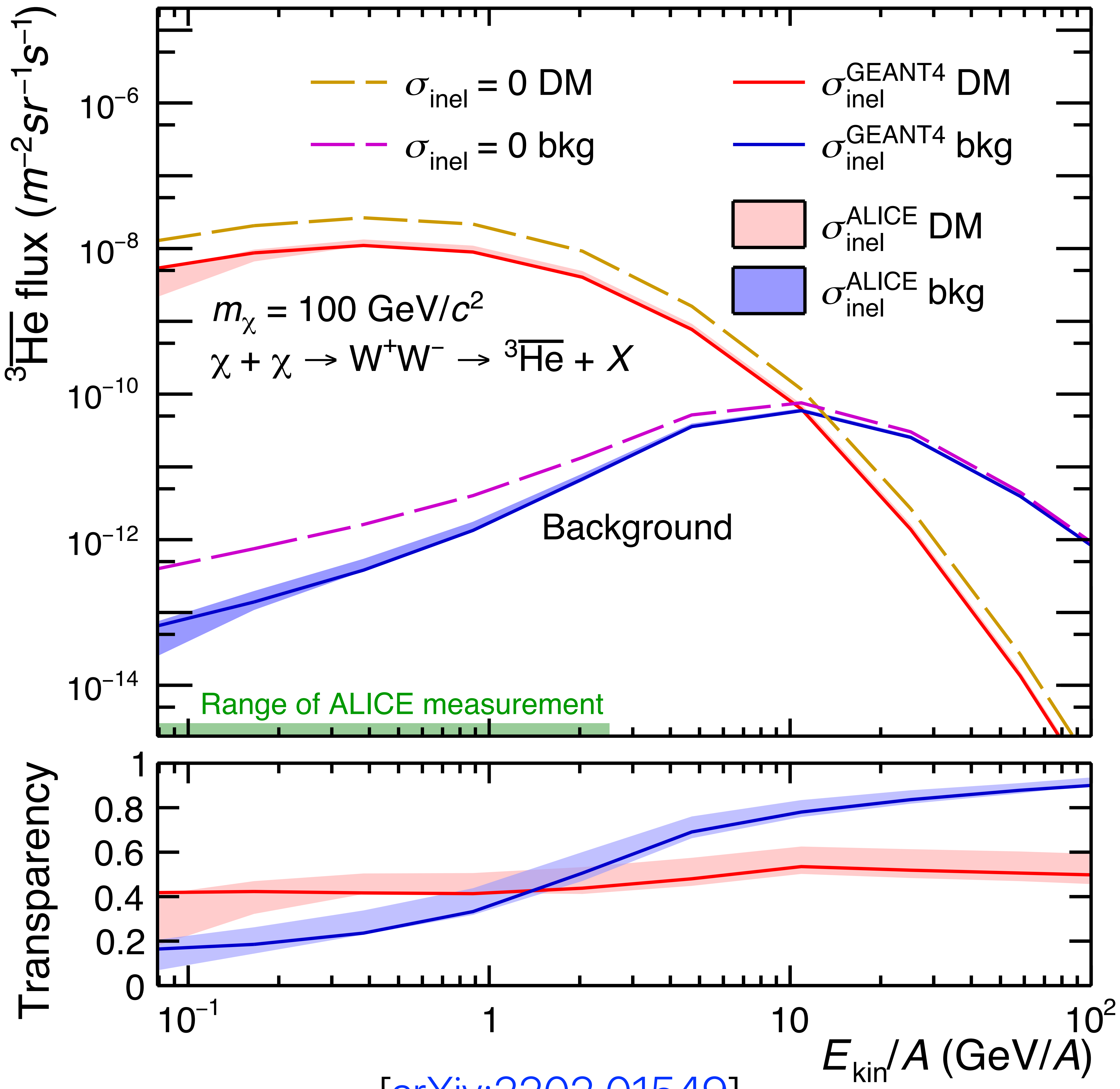
Results: $^{3}\overline{\mathrm{He}}$ fluxes

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

Outside heliosphere

- 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**

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



[arXiv:2202.01549]

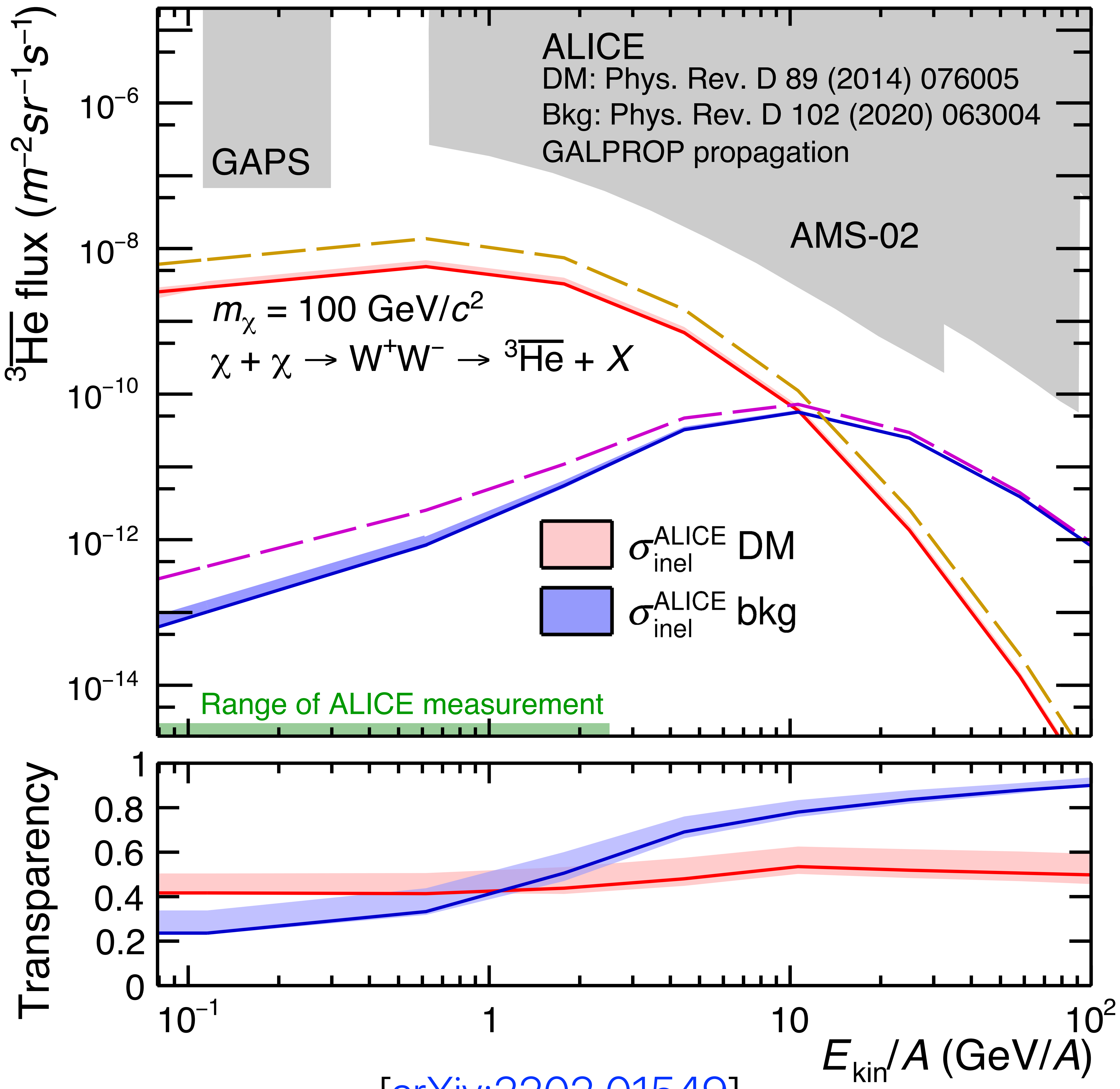
[1] Korsmeier et al, Phys. Rev. D. 97, 103011 (2018)

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

Near Earth

- 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
- **Solar modulation: flux near Earth**

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



[arXiv:2202.01549]

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

Summary and outlook

ALICE performed **groundbreaking measurements** of antinuclei inelastic cross sections:

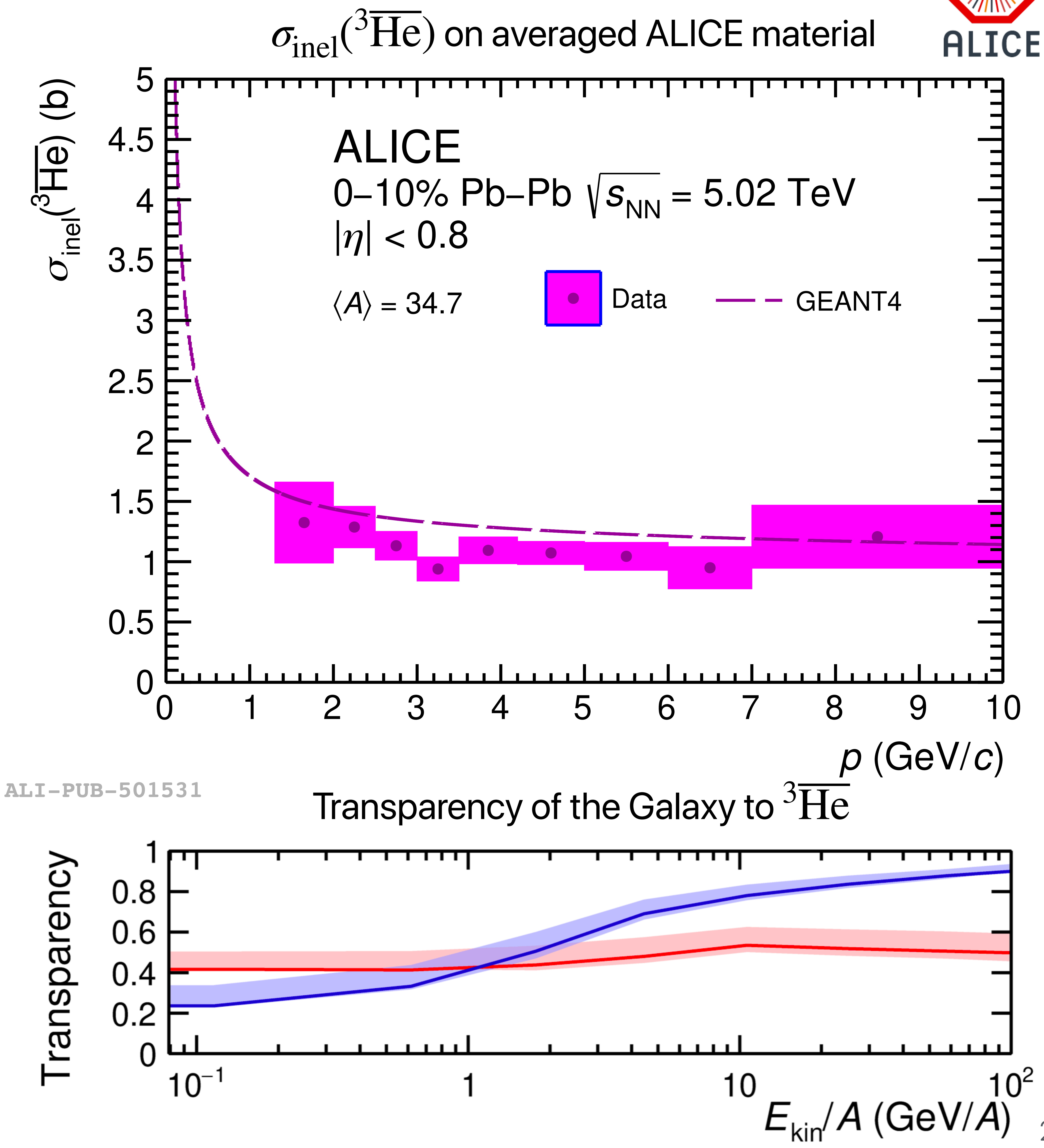
- ✅ $\overline{\mathrm{d}}$ at low energy published: [PRL 125, 162001 (2020)]
- ✅ $^{3}\overline{\mathrm{He}}$ paper submitted: [arxiv.org/2202.01549]

↓

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
- $\sigma_{\mathrm{inel}}(\overline{\mathrm{d}})$ used to re-evaluate the antideuteron cosmic ray fluxes: [Phys. Rev. D 105 (2022) 8, 083021]

Thank you for your attention!

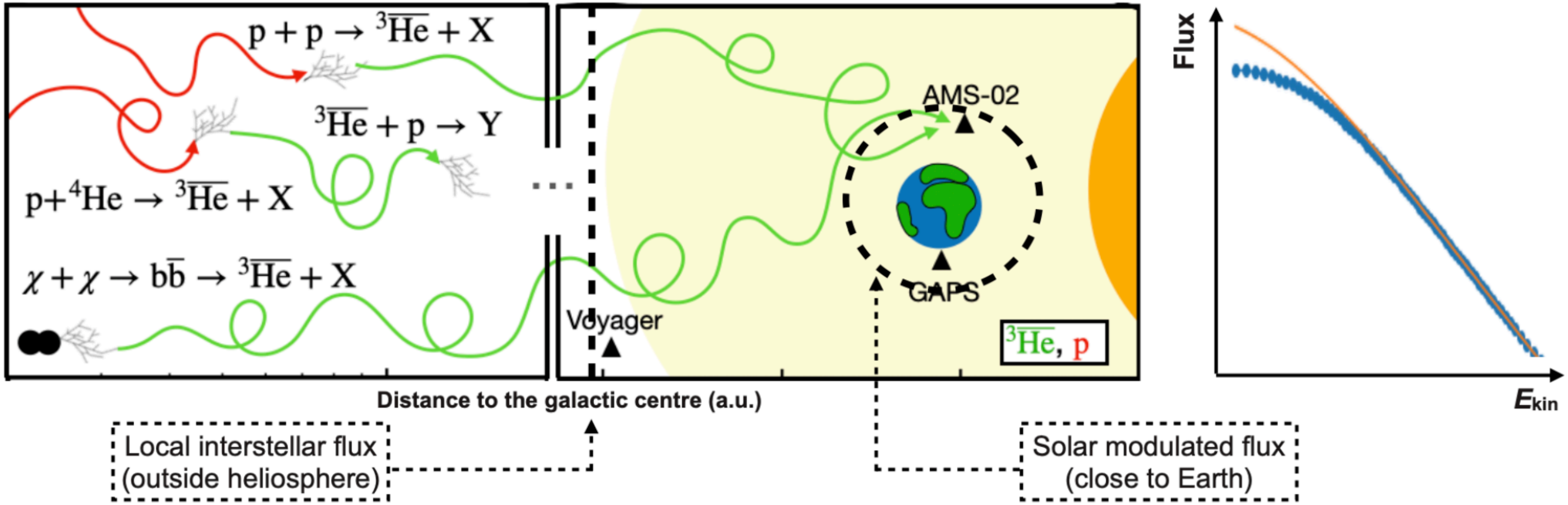


Backup slides

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:

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



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