Measurement of the antinuclei inelastic cross sections with ALICE and implications for indirect Dark Matter searches

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

[1]CERN,

[2]Laboratori Nazionali di Frascati - INFN

pavel.larionov@cern.ch

NUCLEUS 2021 - 24 September 2021

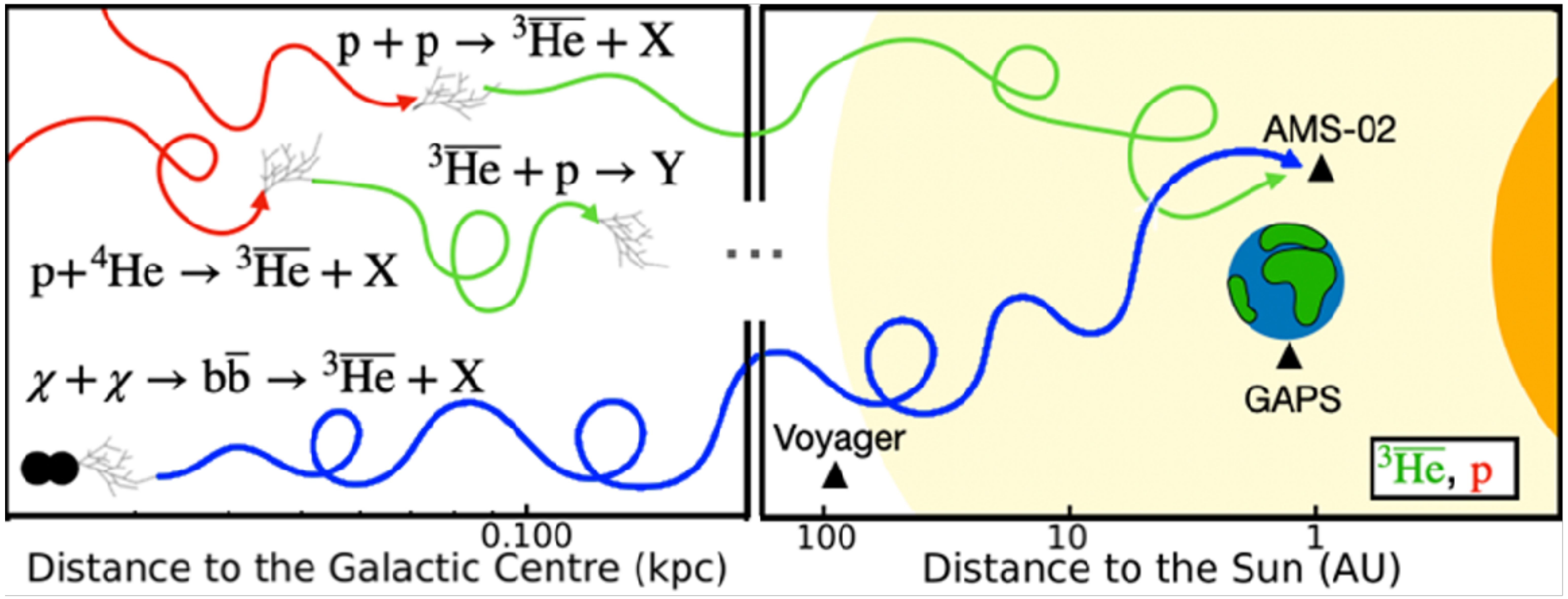
Introduction and motivation

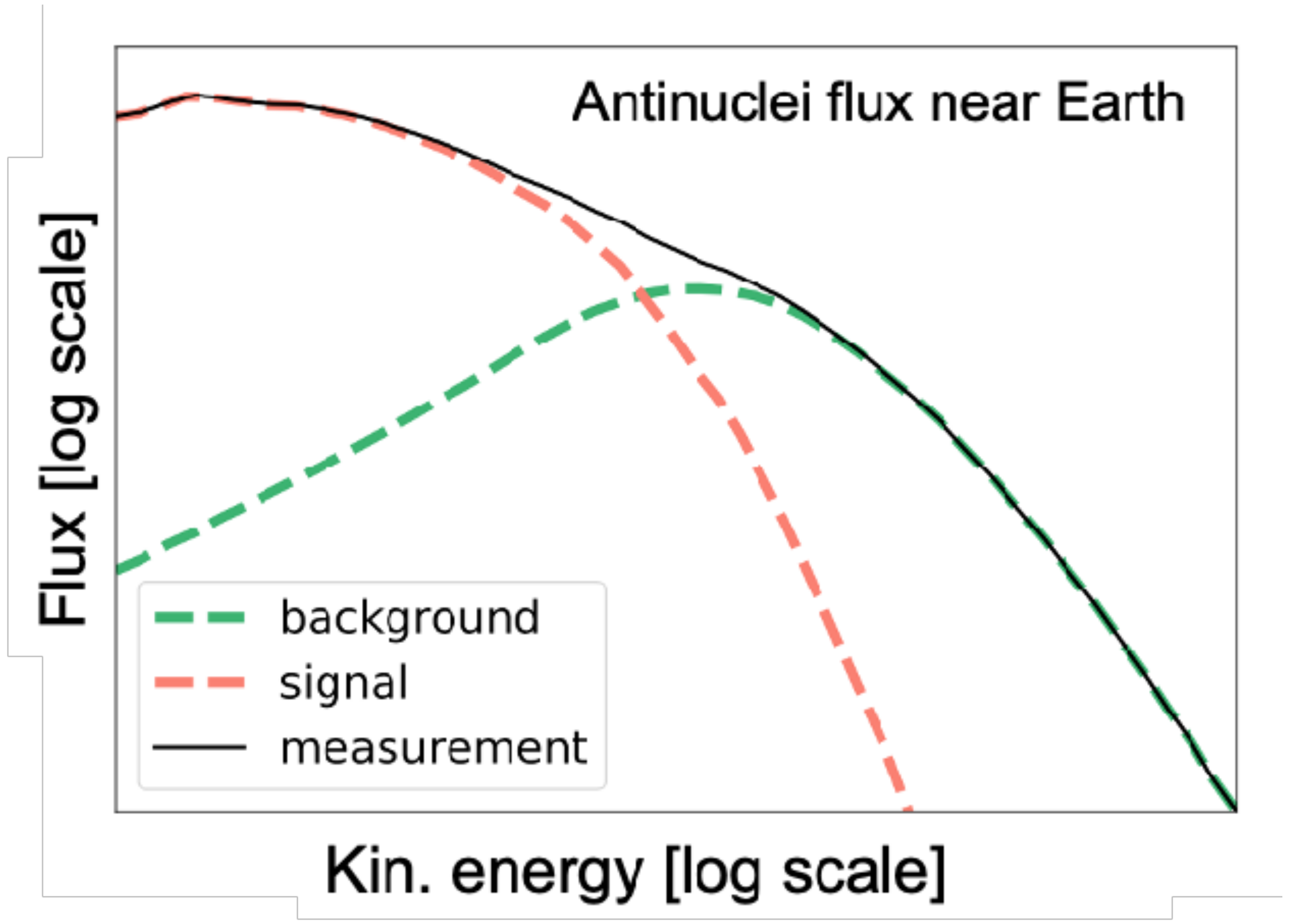
Antinuclei ($\overline{d}$, $^3\overline{He}$, $^4\overline{He}$) in space (searched by **AMS-02, GAPS**) may result from:

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

Unique probe for indirect Dark Matter searches!

– 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*



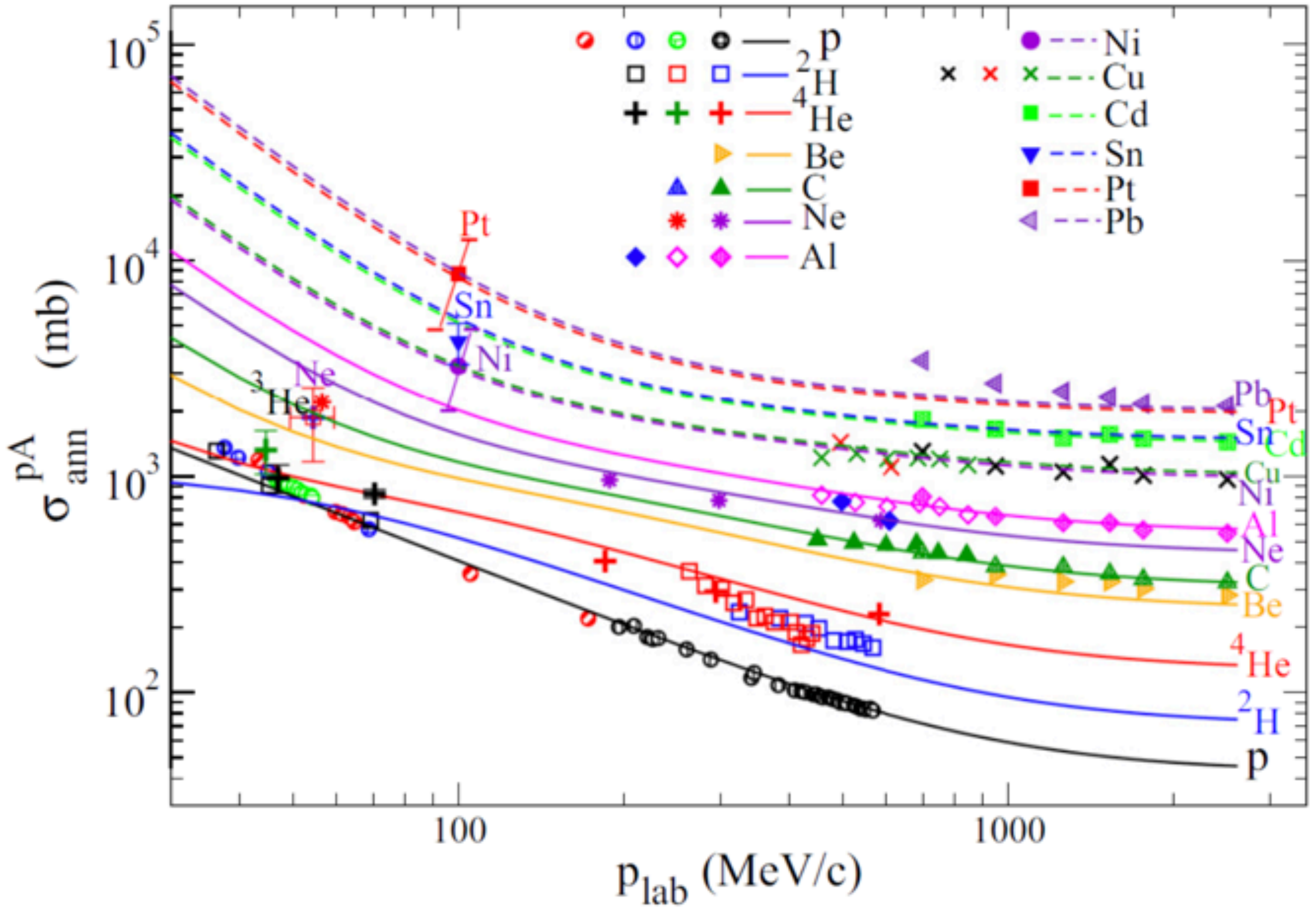


Current antinuclei σ_{inel} measurements (before ALICE)

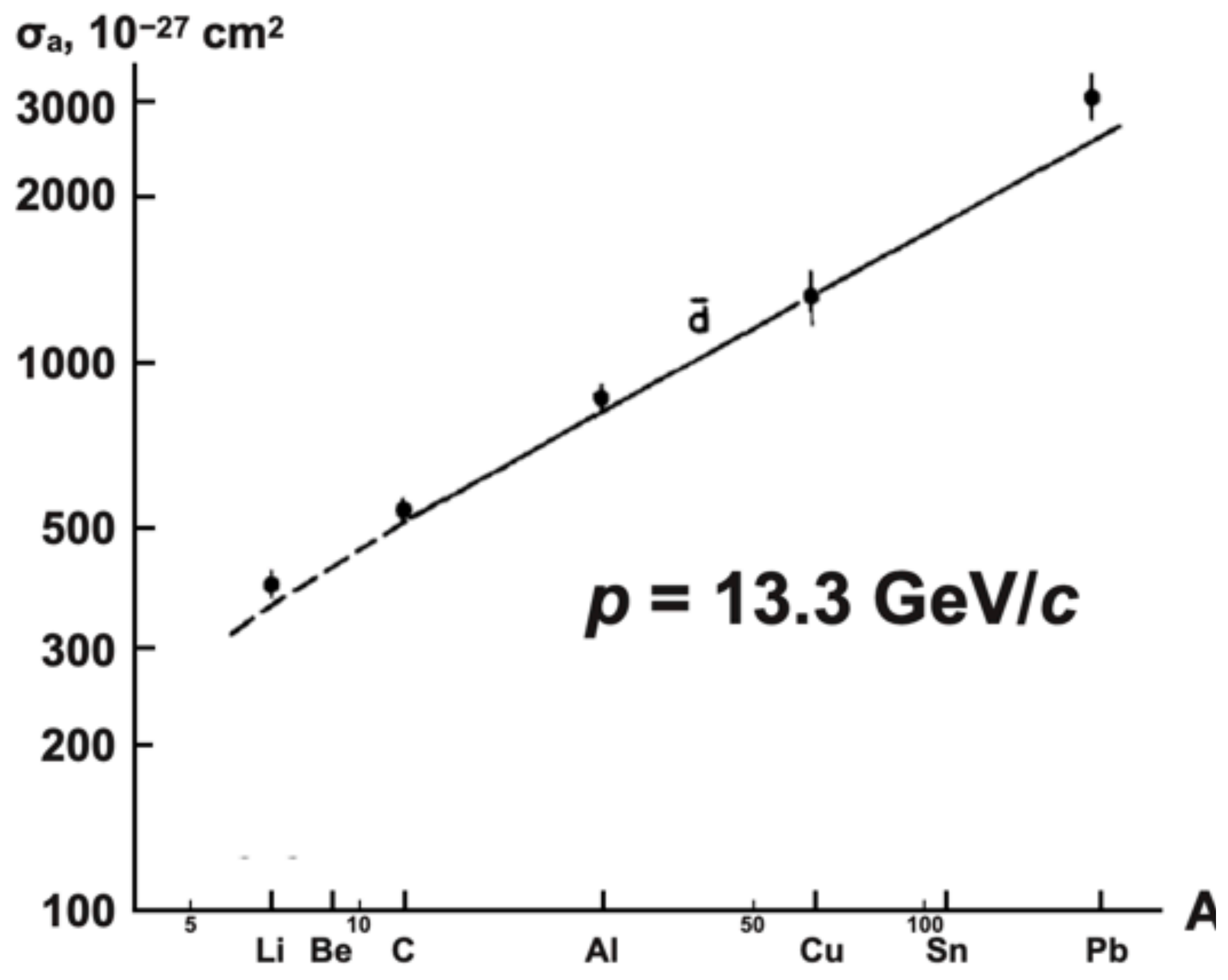
Relevant inelastic cross sections (σ_{inel}) only poorly constrained for antinuclei heavier than $\overline{\mathrm{p}}$:

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

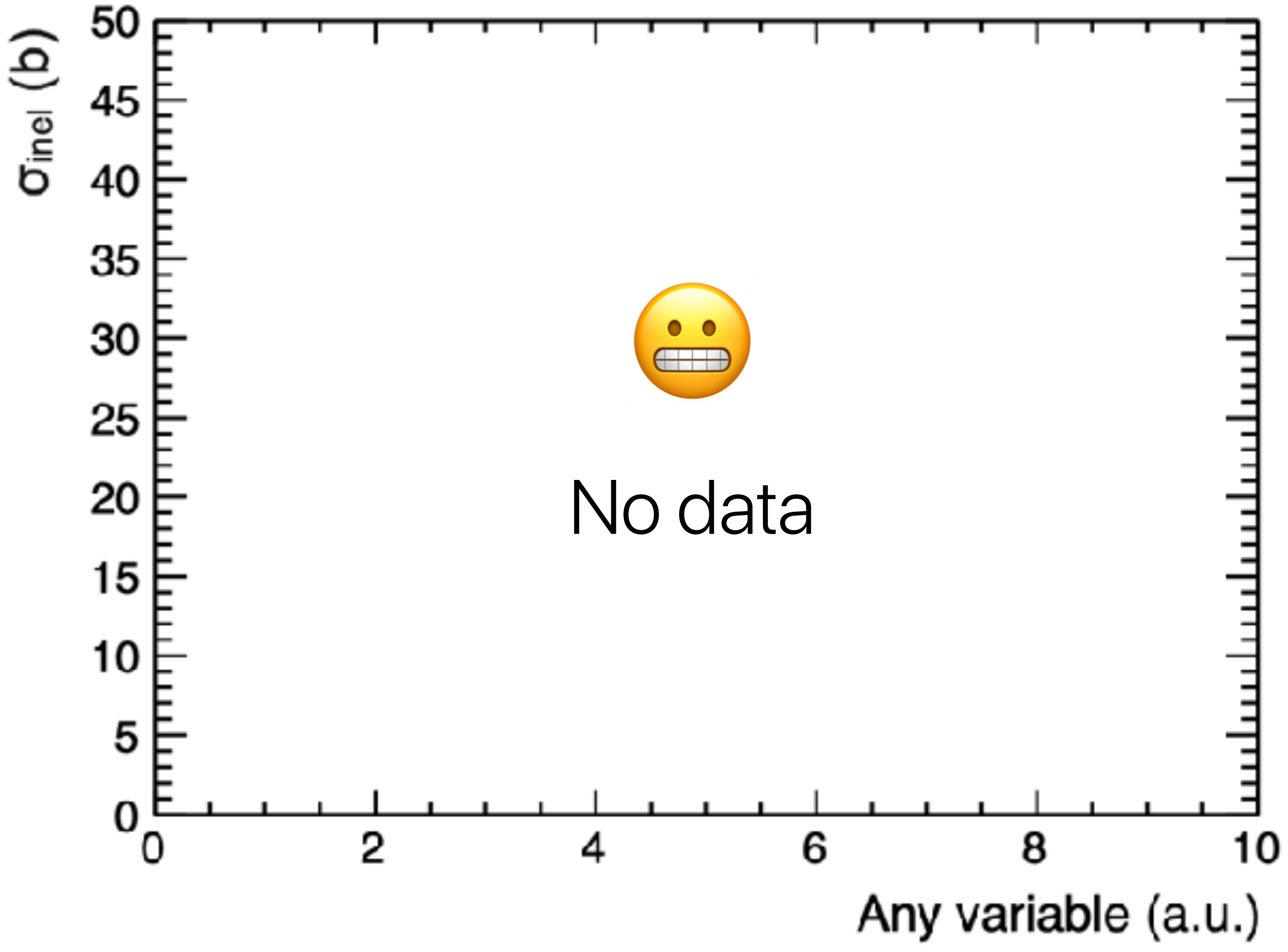
$\overline{\mathrm{p}}$ [1]



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



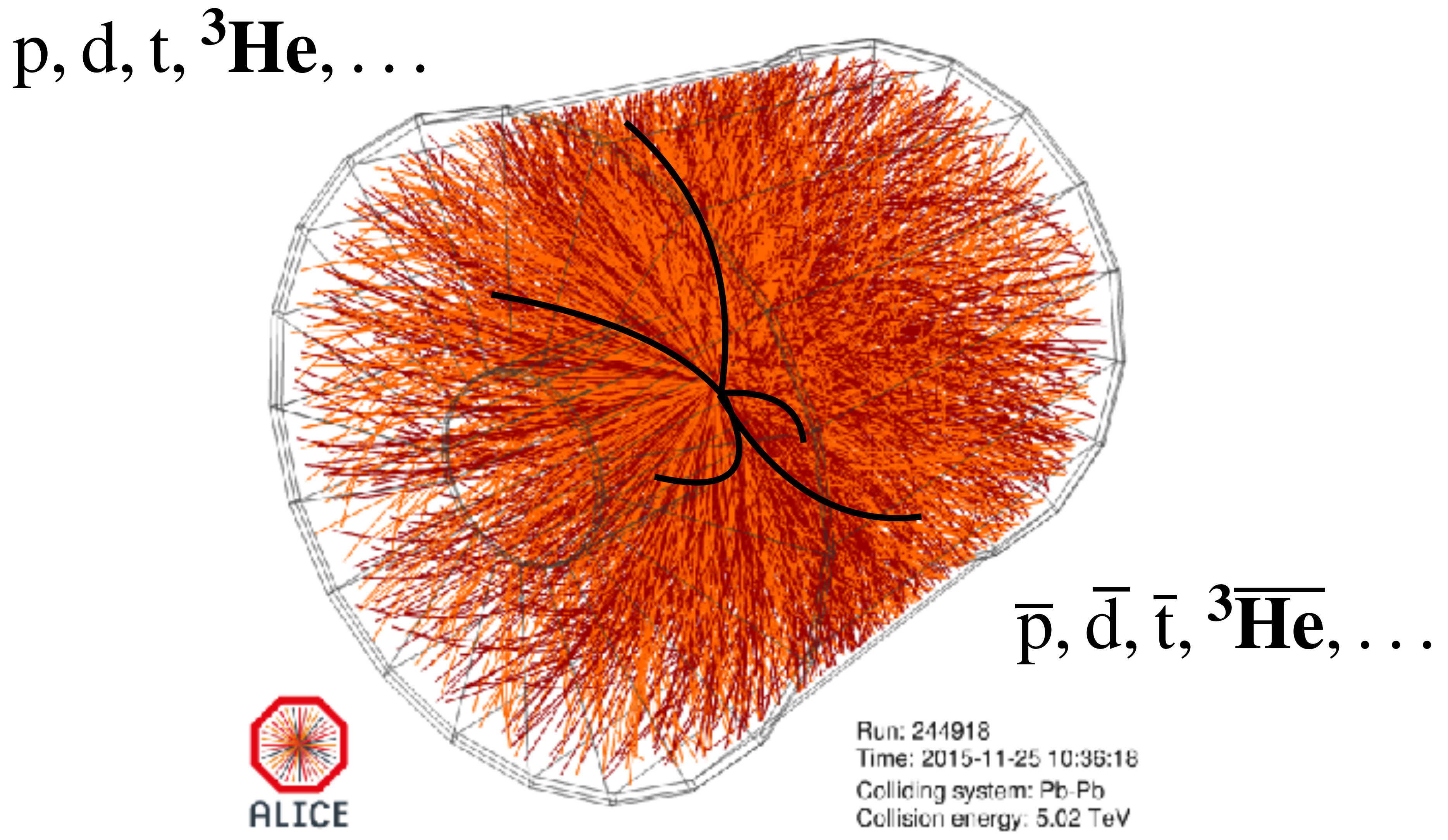
$^3\overline{\mathrm{He}}$



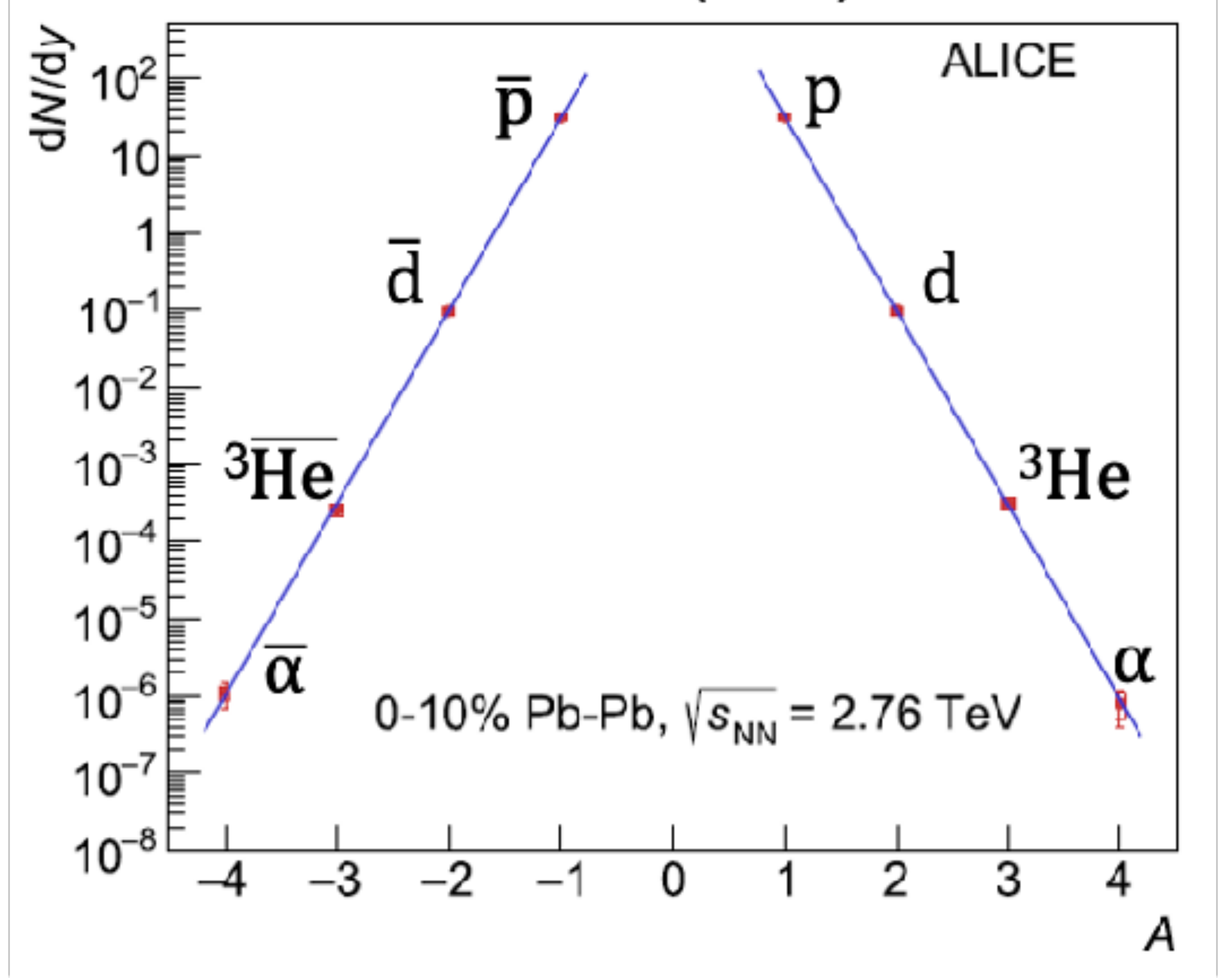
[1] Lee et al., Phys. Rev. C 89, 054601 (2014)

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

LHC as an antimatter factory

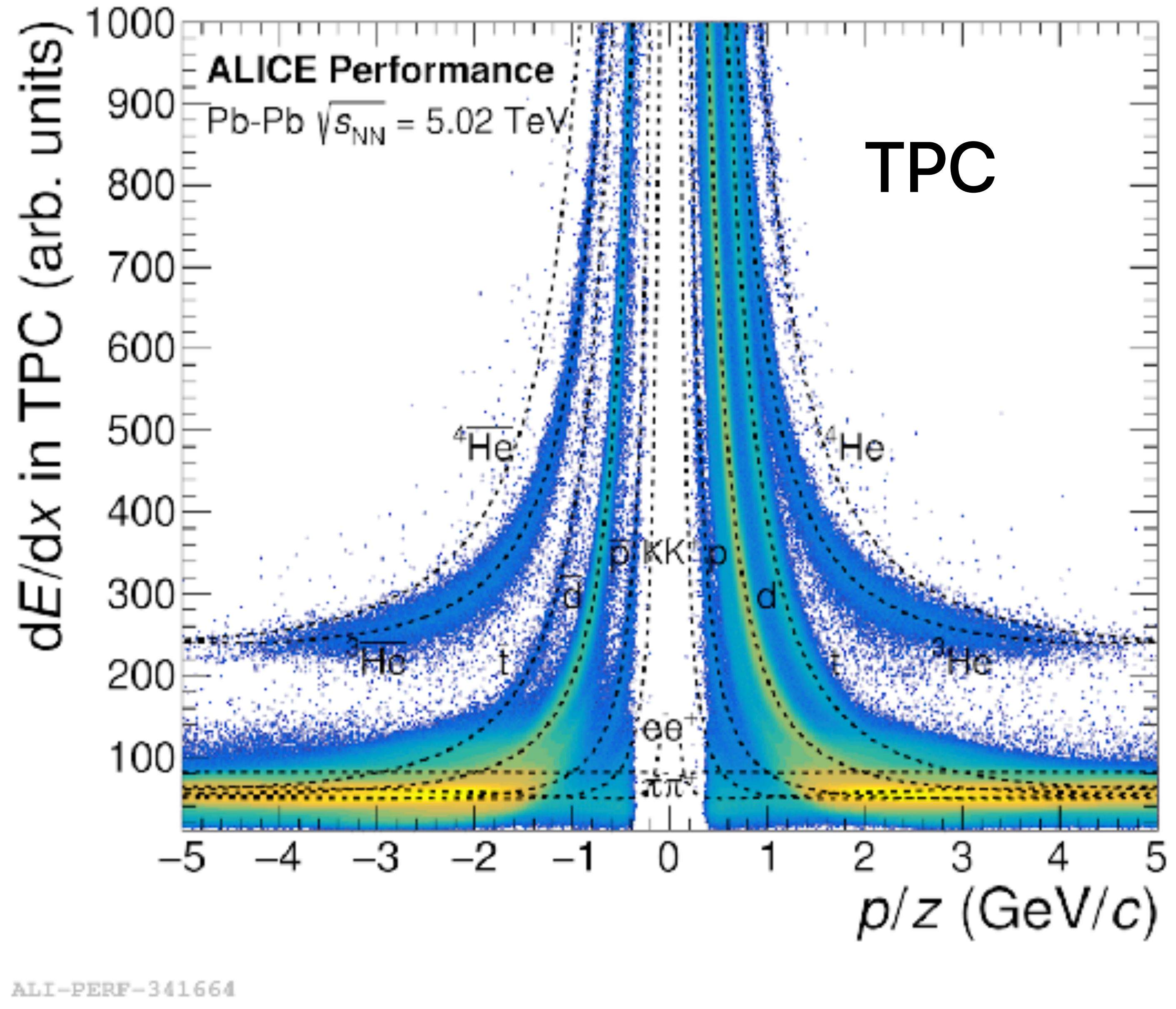


ALICE, PRC 97 (2018) 024615

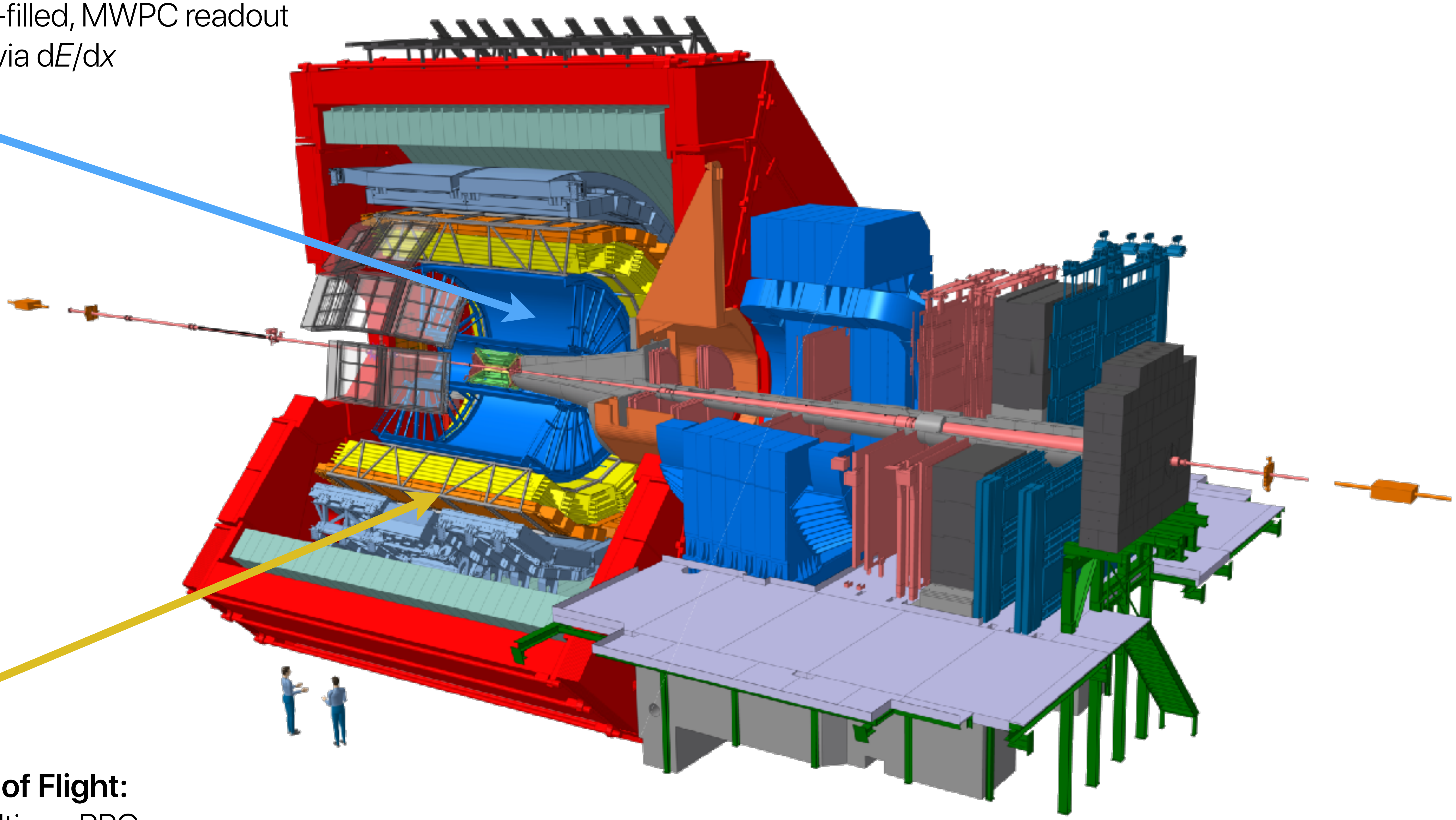


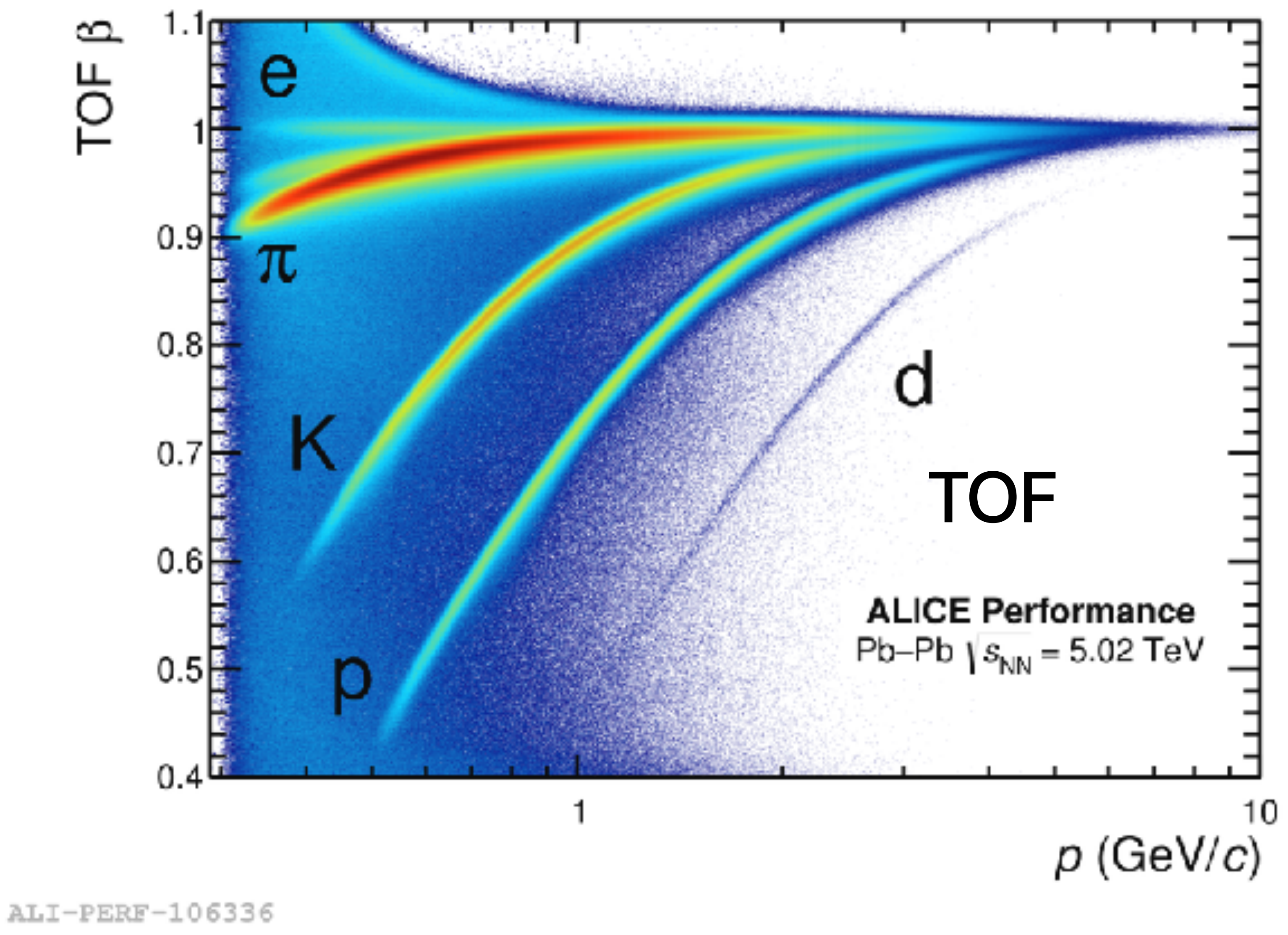
- High energy collisions at LHC = the most suitable environment to study production of (anti)nuclei and their annihilation
- At LHC energies matter and antimatter are produced in almost equal amounts
- ... and propagate through detector material ->
- (anti)nuclei get absorbed inside the detector → in ALICE we are in a unique position to quantify it!

ALICE apparatus and its particle identification capabilities



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}

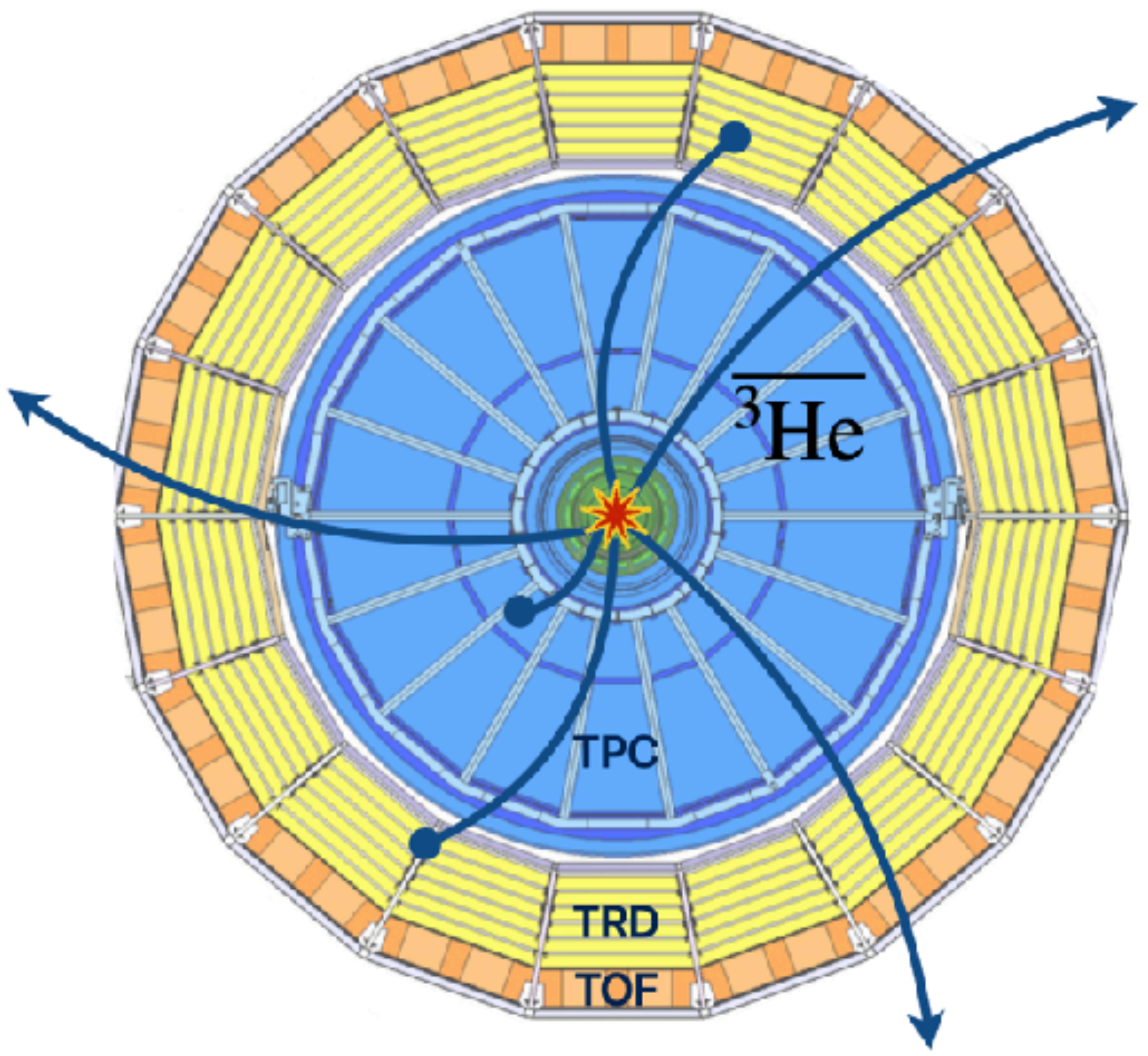
TOF/TPC ratio (Pb-Pb collisions):

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

\+ High statistics

\+ Independent on $\sigma_{\text{inel}}(^3\text{He})$

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



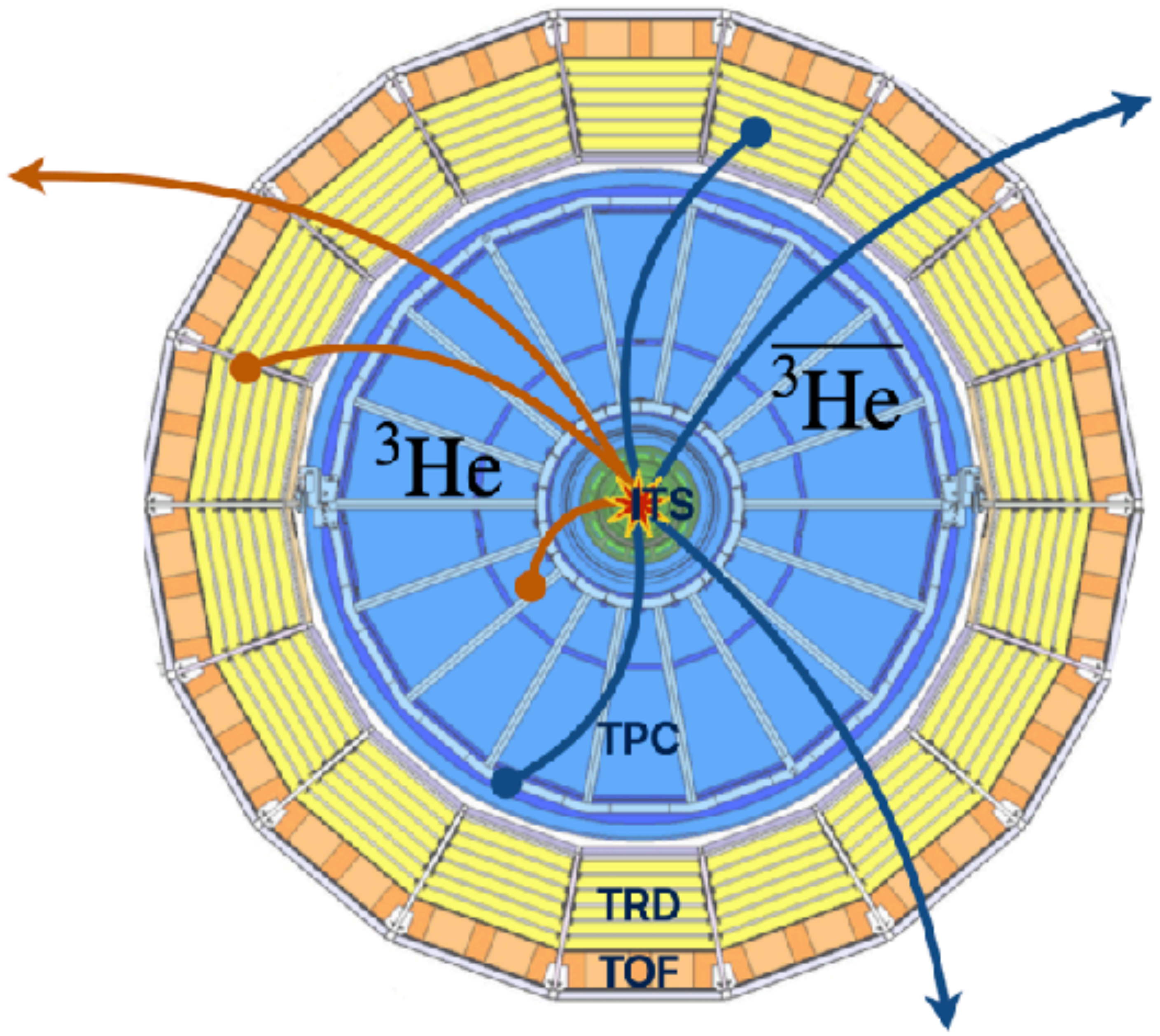
Antiparticle/particle raw ratio (pp, p-Pb collisions):

- Measure reconstructed $^3\overline{\text{He}}/^3\text{He}$ and compare with MC simulations

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

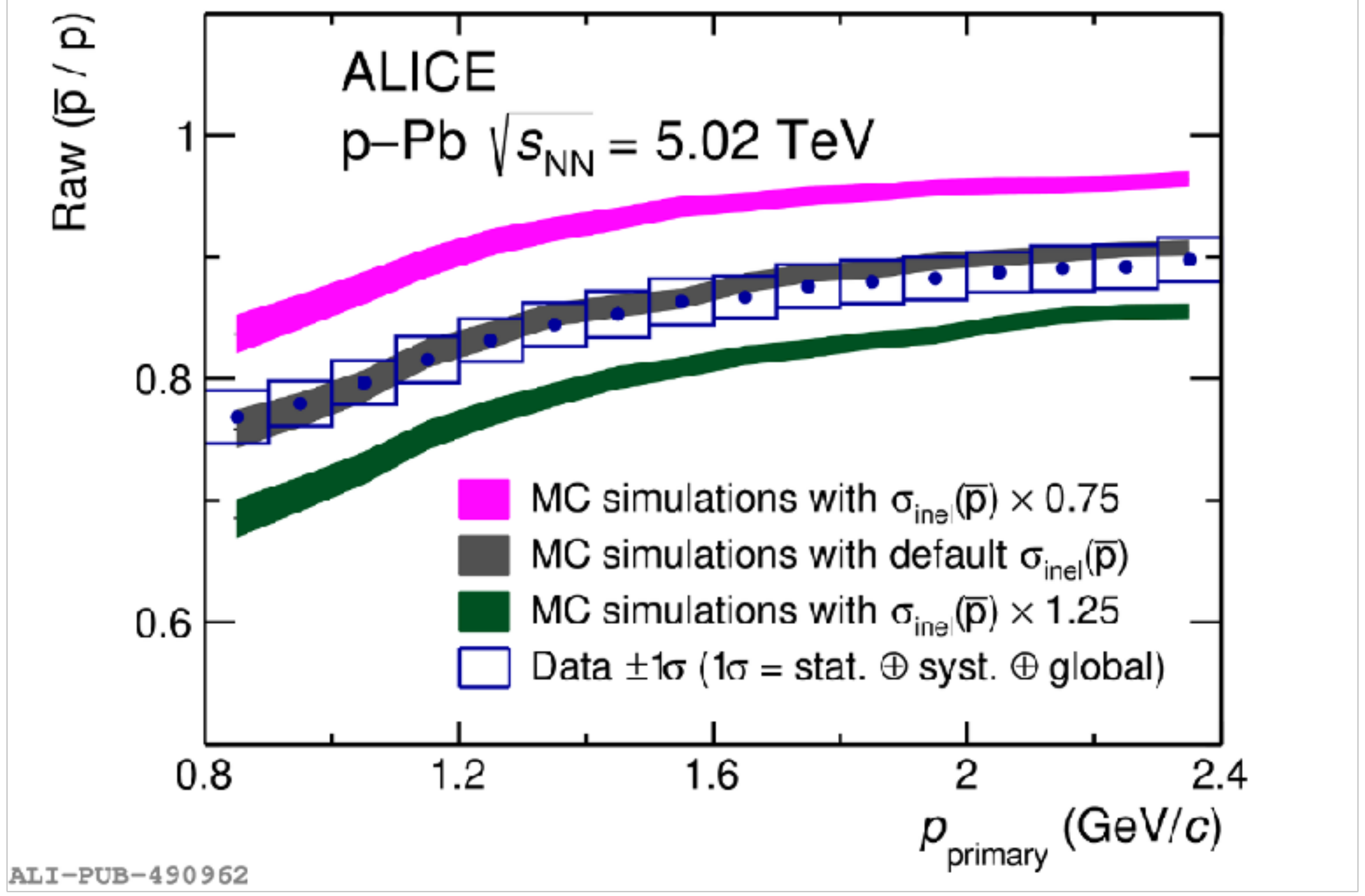
\- Relies on $\sigma_{\text{inel}}(^3\text{He})$

\- Background from secondary particles



Antiparticle/particle raw ratio

Raw $(\overline{p}/p)$ for MC with varied $\sigma_{inel}(\overline{p})$ and data [1]

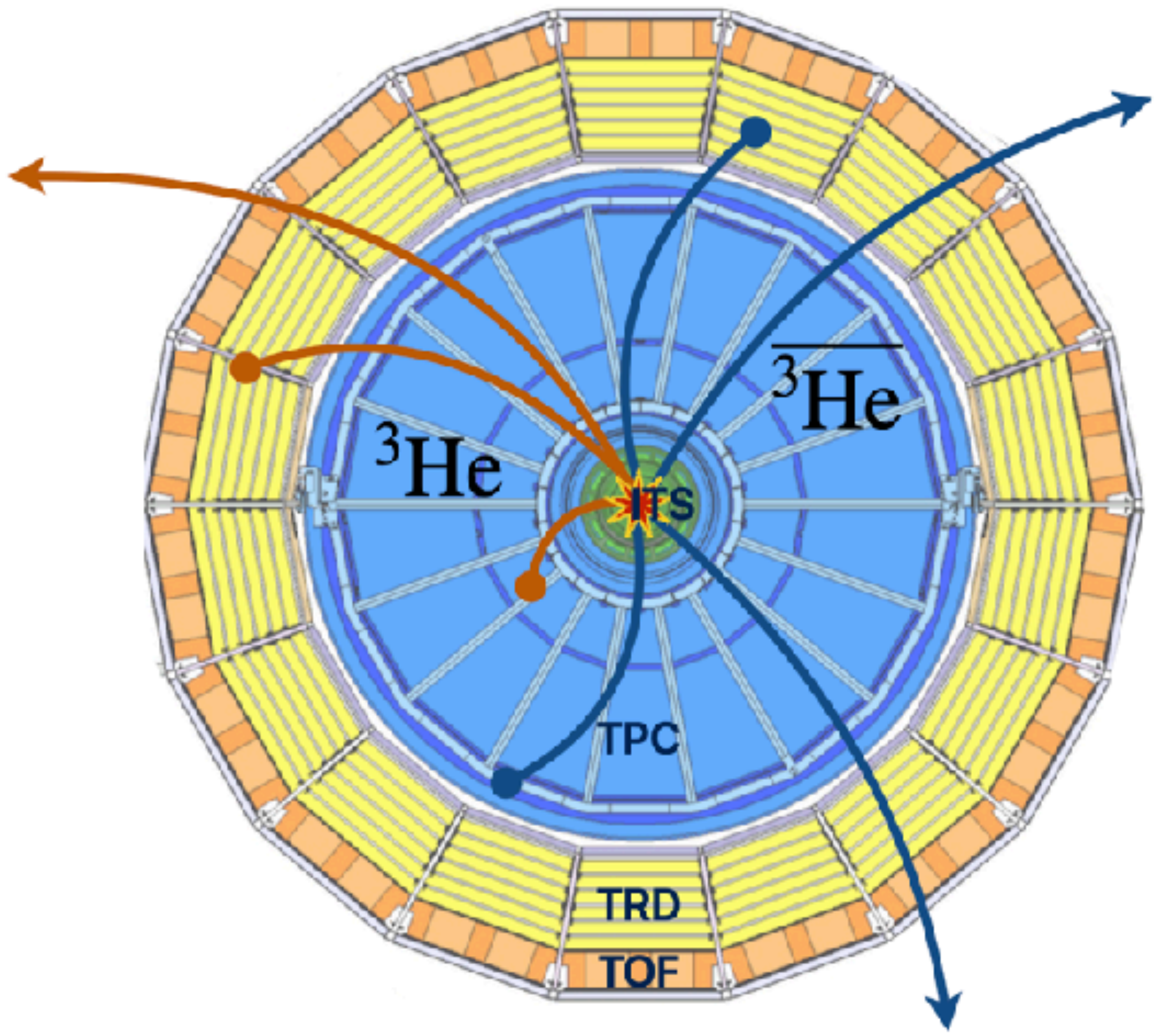


- Antiparticle-to-particle ratios are mainly sensitive to the variation of the inelastic cross section
- Vary $\sigma_{inel}(\overline{d},\ ^{3}\overline{He})$ in simulations until MC describes the experimental results → constraints on $\sigma_{inel}(\overline{d},\ ^{3}\overline{He})$

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

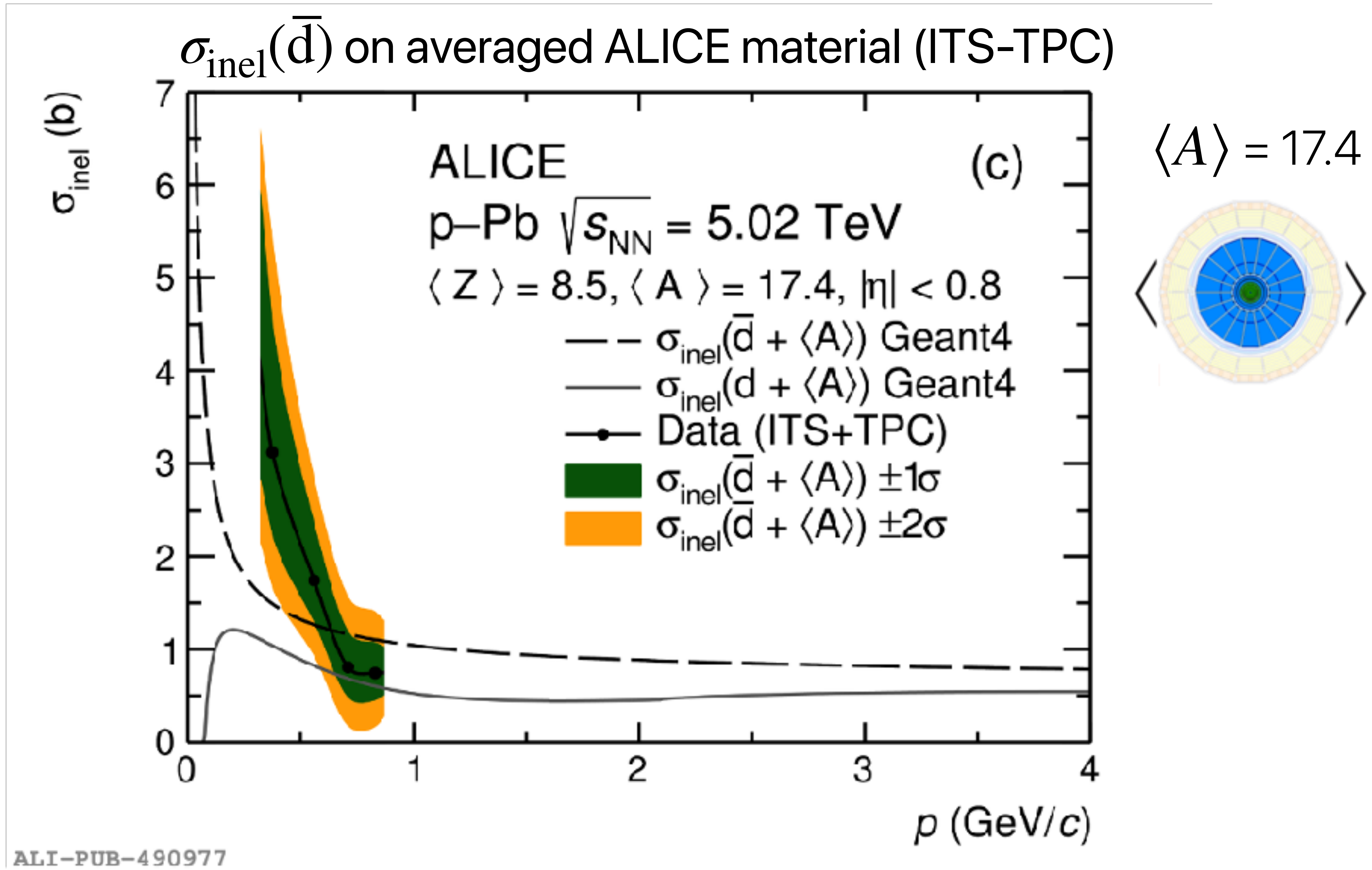
- Measure reconstructed $^{3}\overline{He}/^{3}He$ and compare with MC simulations

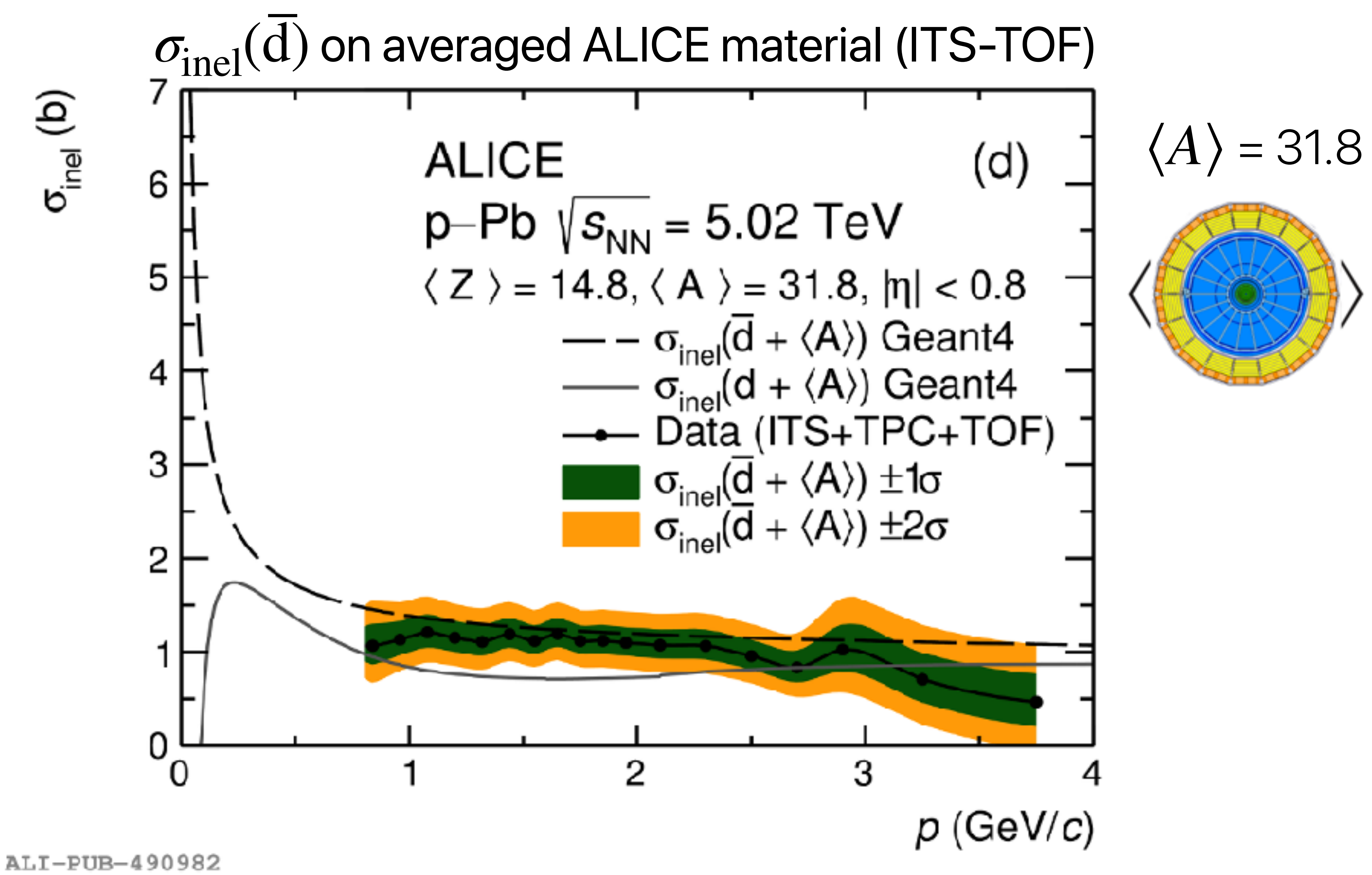
+ Access to low momenta ($p \lesssim 1$ GeV/c)
- Relies on $\sigma_{inel}(^{3}He)$
- Background from secondary particles



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

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

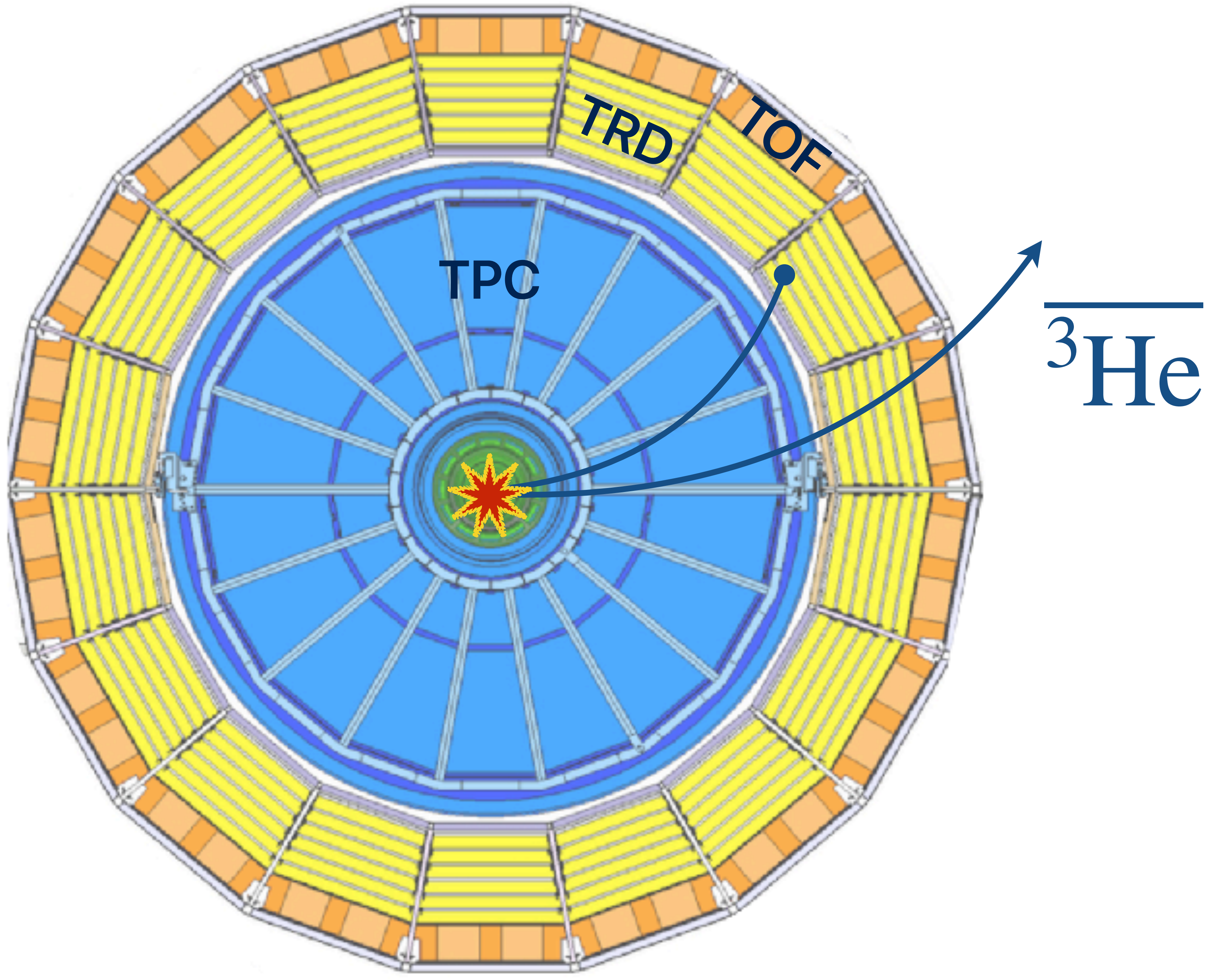


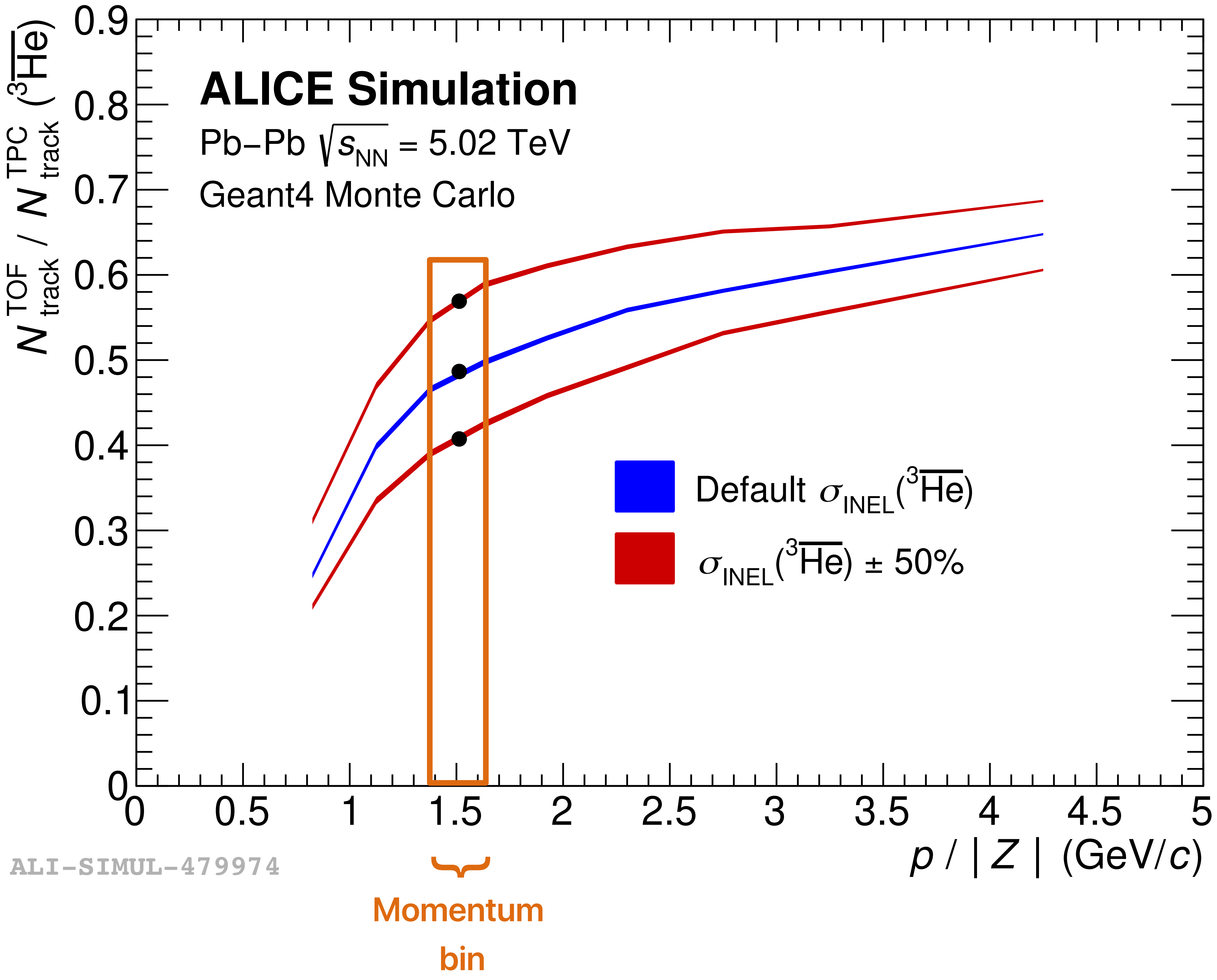


- First measurement of antideuteron inelastic cross section at low momenta!
- Exp. σ_{inel} is approx. 15% smaller w.r.t. Geant4 at high momenta, steeper rise in low p region
- Published: PRL 125, 162001 (2020)

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

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





How we measure $\sigma_{\rm inel}$ with TPC-TOF matching

ALICE

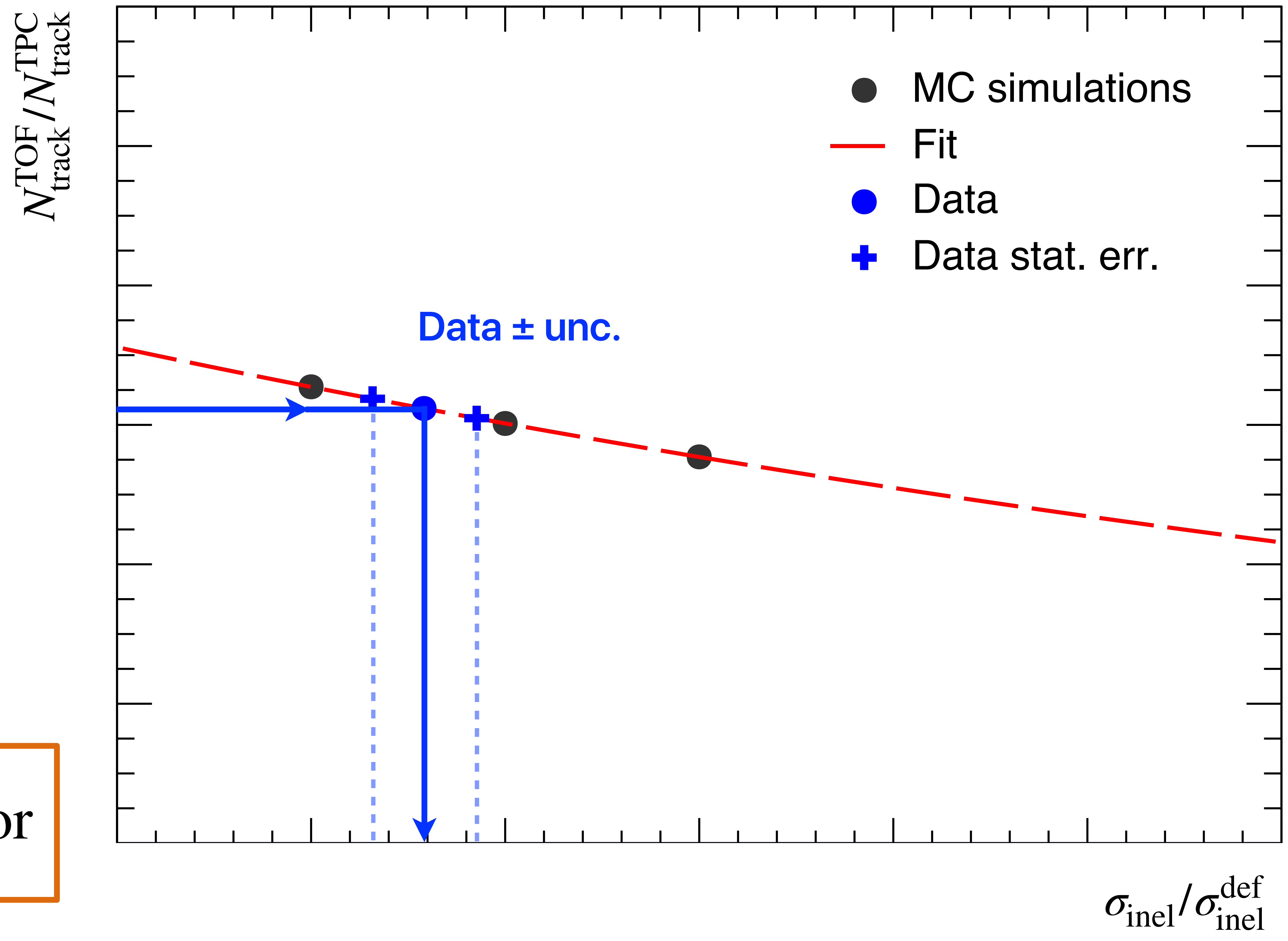
- Identify $N^{\rm TOF}_{\rm track}$ / $N^{\rm TPC}_{\rm track}$ in data and Monte Carlo
- In each momentum bin compare the TOF-TPC ratio in MC to the one in data
- Monte Carlo simulations with scaled $\sigma_{\rm inel}$ (0.5x, 1x, 1.5x)

→ extract $\sigma_{\rm inel}/\sigma^{\rm def}_{\rm inel}$ scaling factor

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

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

$$\sigma_{\rm inel}(^3\overline{\rm He} - \langle A\rangle) = \sigma^{\bf Geant4}_{\rm inel}(^3\overline{\rm He} - \langle A\rangle) \times \text{scaling factor}$$



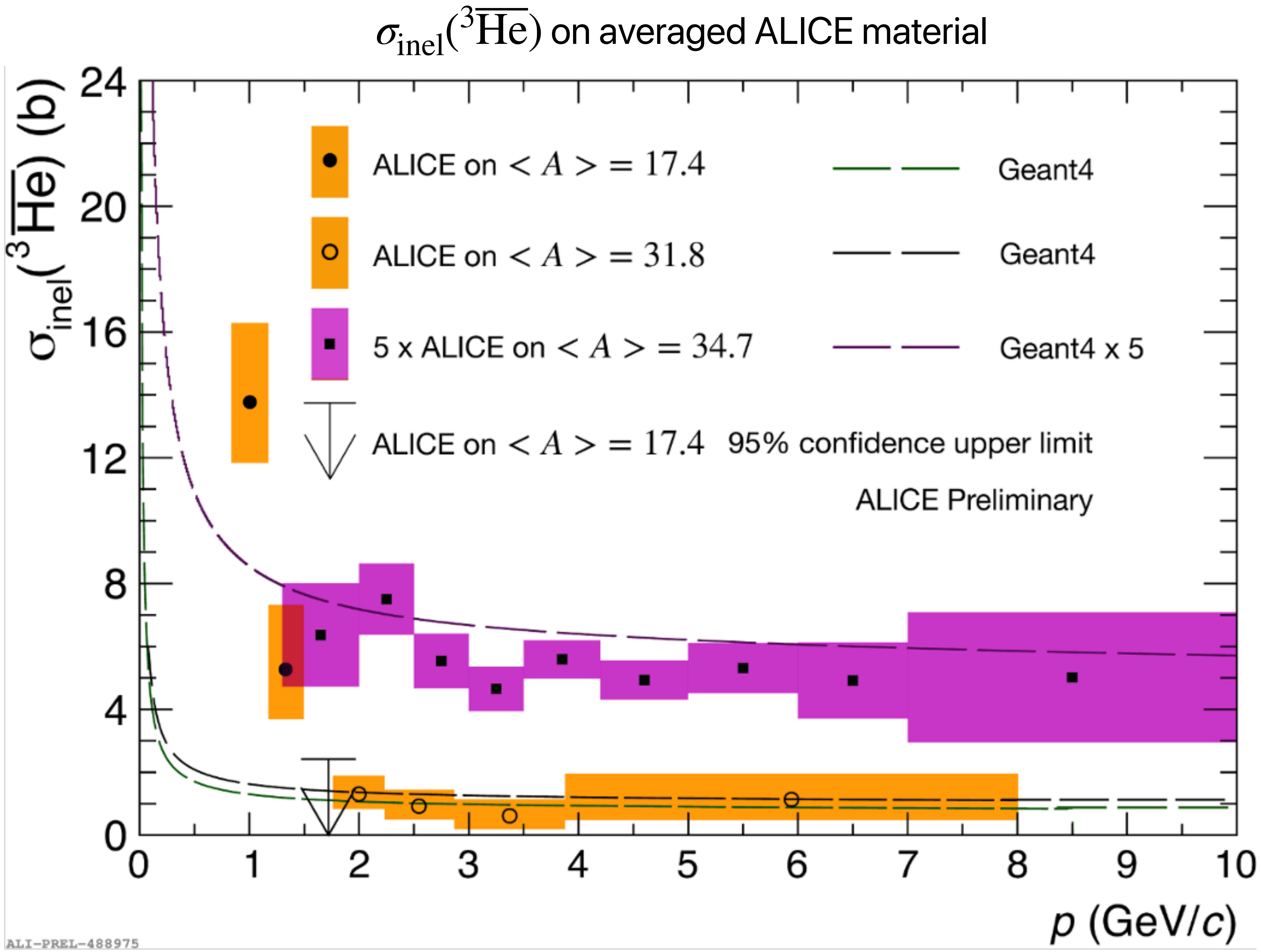
Results: $^{3}\overline{\mathrm{He}}$ inelastic cross-section

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

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

- Results from both methods are compatible (higher precision in TOF-to-TPC ratio)
- Exp. data at very low momentum ($p < 1.5$ GeV/c) show large discrepancy w.r.t. Geant4 parametrization

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



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

Transport equation

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

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)

$^{3}\overline{\mathrm{He}}$ source (I): Dark Matter

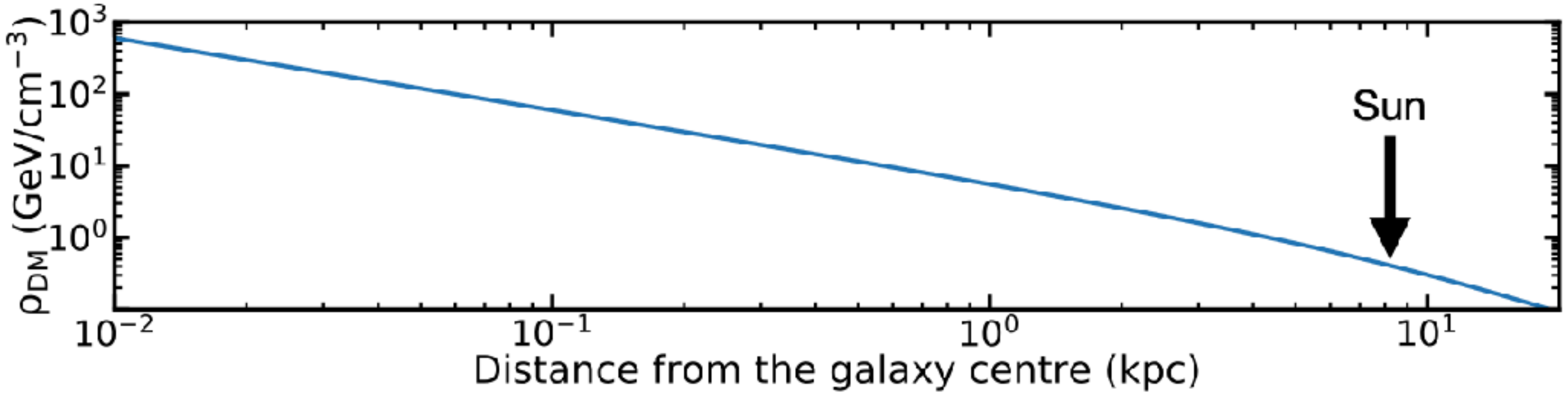
Source (I) ✅ Propagation ✅ Annihilation ❌

ALICE

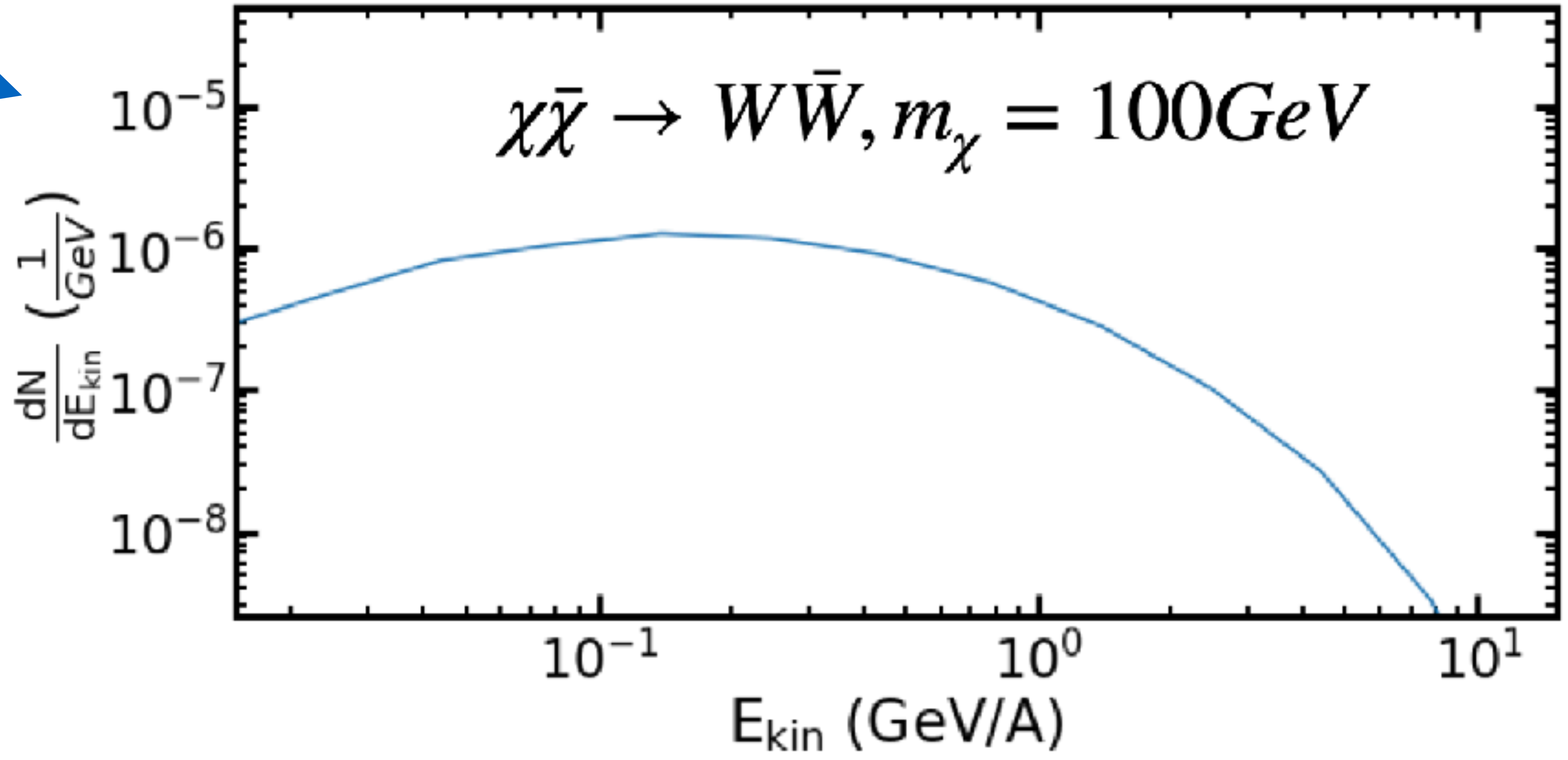
Source function

DM density distr.

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



$^{3}\overline{\mathrm{He}}$ 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]
- $^{3}\overline{\mathrm{He}}$ spectrum from [1] PYTHIA 8 + coalescence afterburner

→ peak at E_{kin} ~ 0.1 GeV/A

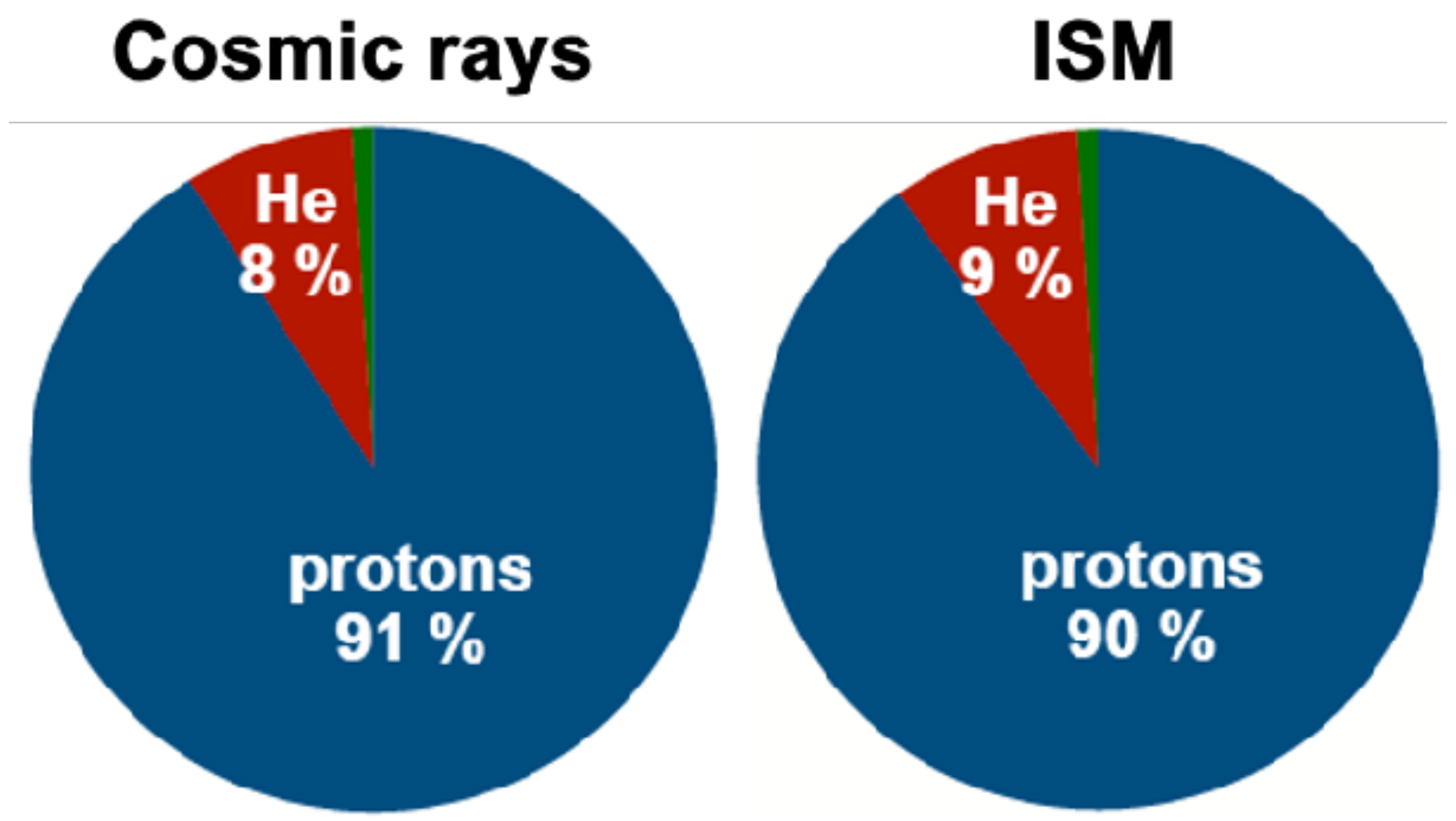
[1] Carlson et al, Phys. Rev. D. 89, 076005 (2014)
[2] Korsmeier et al, Phys. Rev. D. 97, 103011 (2018)

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

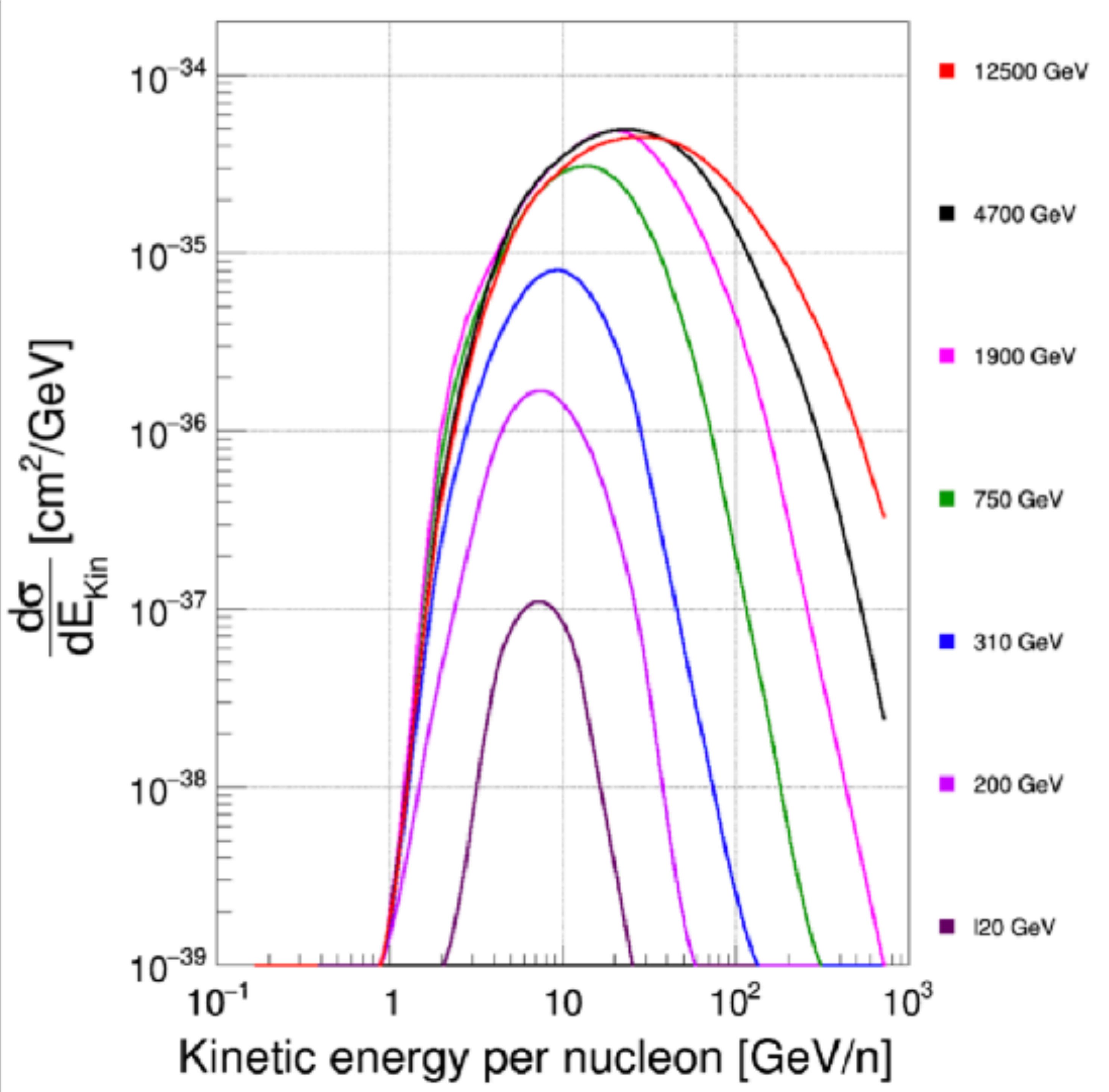
Sources ✅ Propagation ✅ Annihilation ❌

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

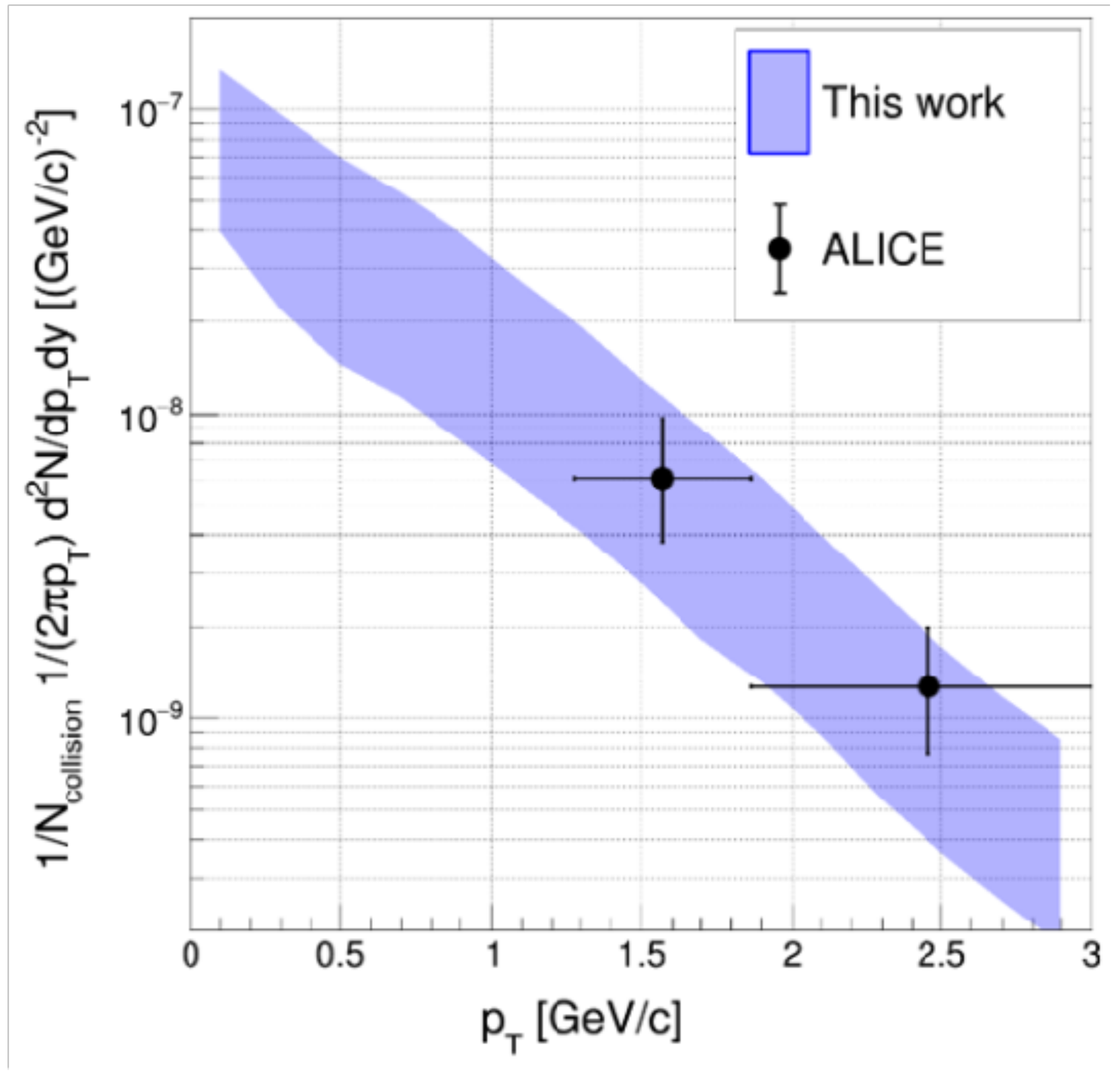
- Collision systems: pp, p-^{3}He, ^{3}He-p, ^{3}He-^{3}He
- Production cross section in pp from [1]: EPOS LHC + coalescence afterburner
- Scaling factor $(A_T A_P)^{11/15}$ for the other collision systems
- Validated by ALICE data [2] ✅



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

Annihilation

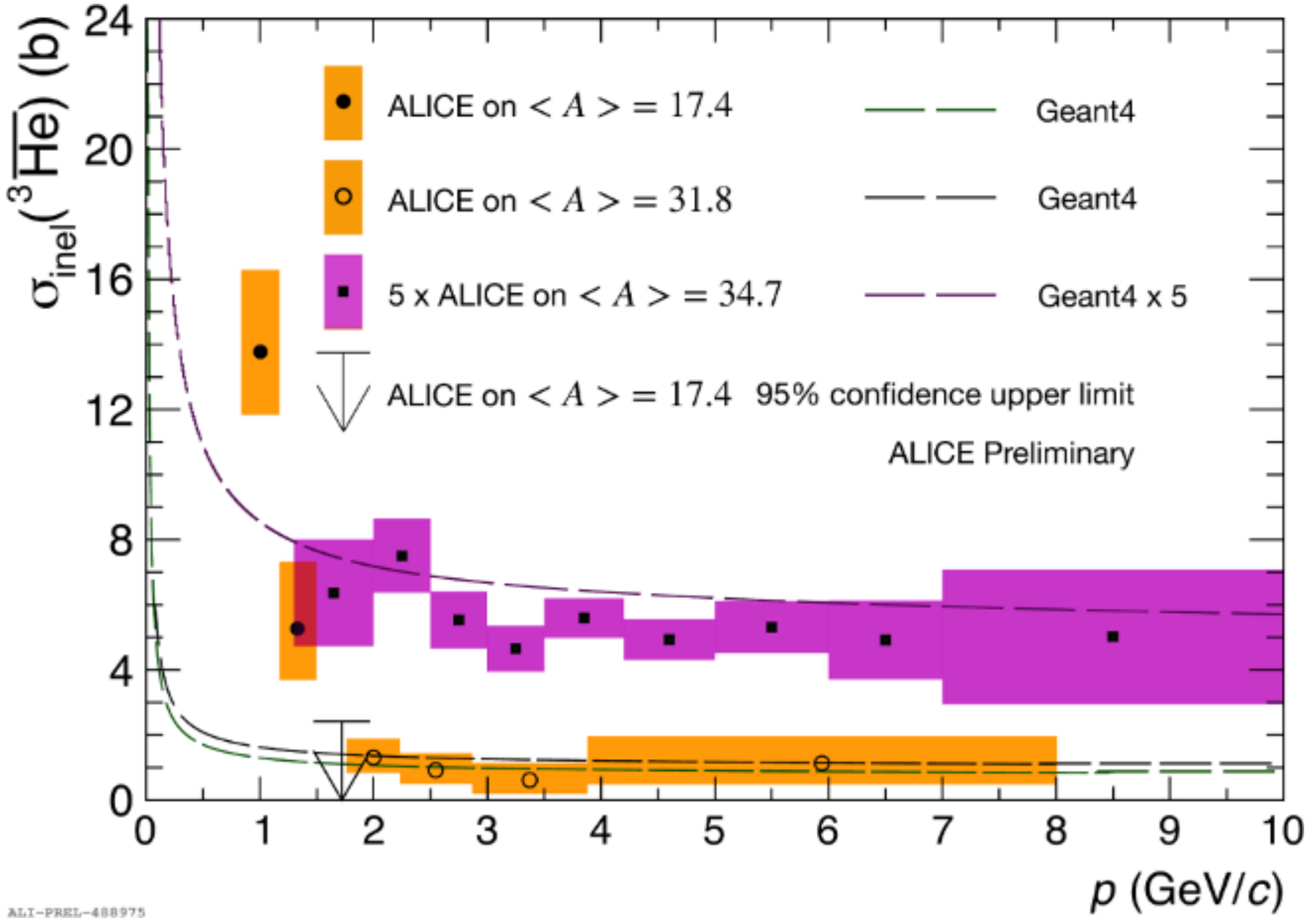
Sources ✅ Propagation ✅ Annihilation ✅

ALICE

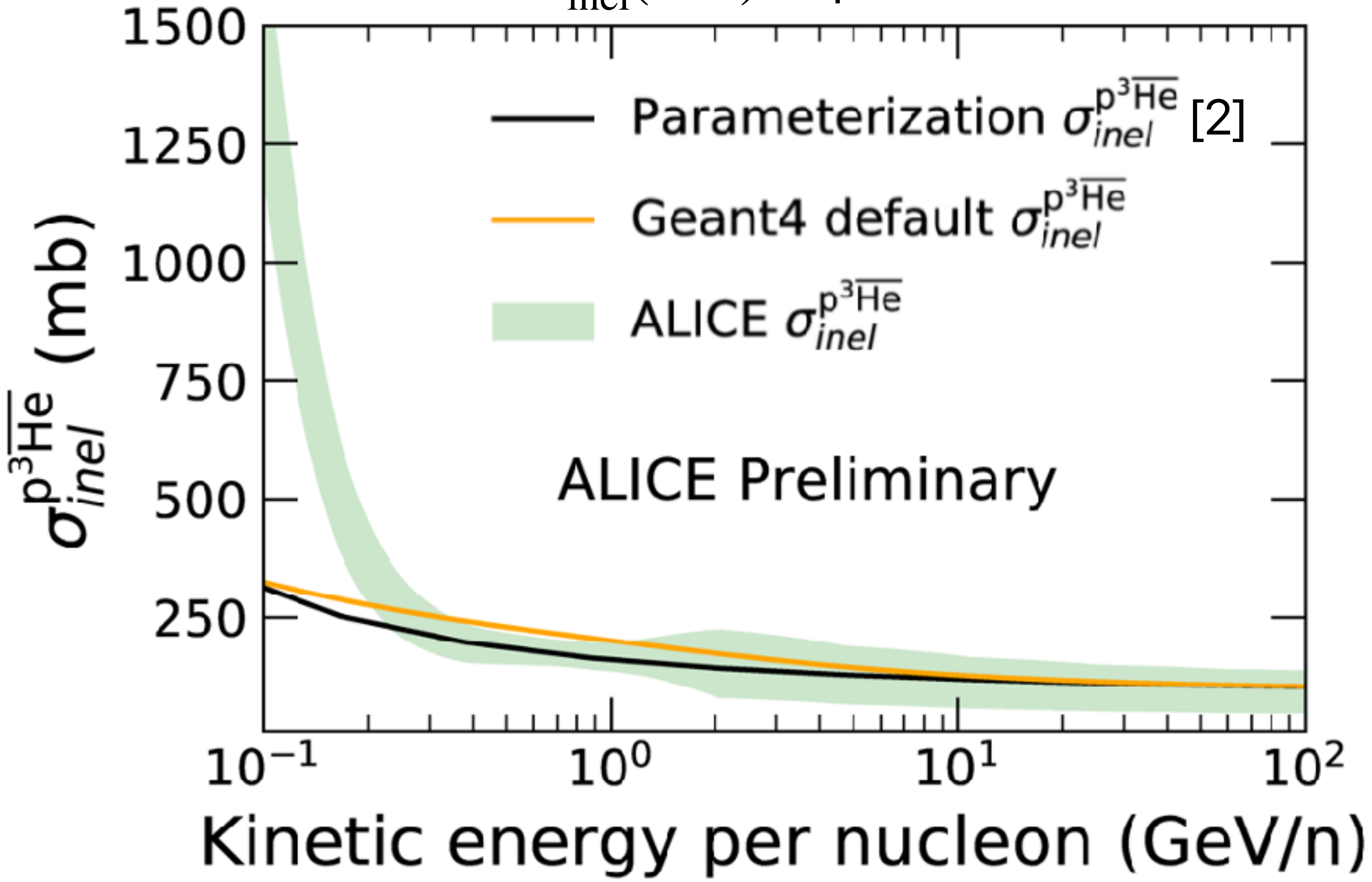
$^3\overline{\mathrm{He}}$ nuclei may interact inelastically with the interstellar gas

- ALICE results for $\sigma_{\mathrm{inel}}(^3\overline{\mathrm{He}})$ are for heavy elements with $\langle A \rangle$ = 17.4 to 34.7
- Rescaled using ALICE experimental data 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



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



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

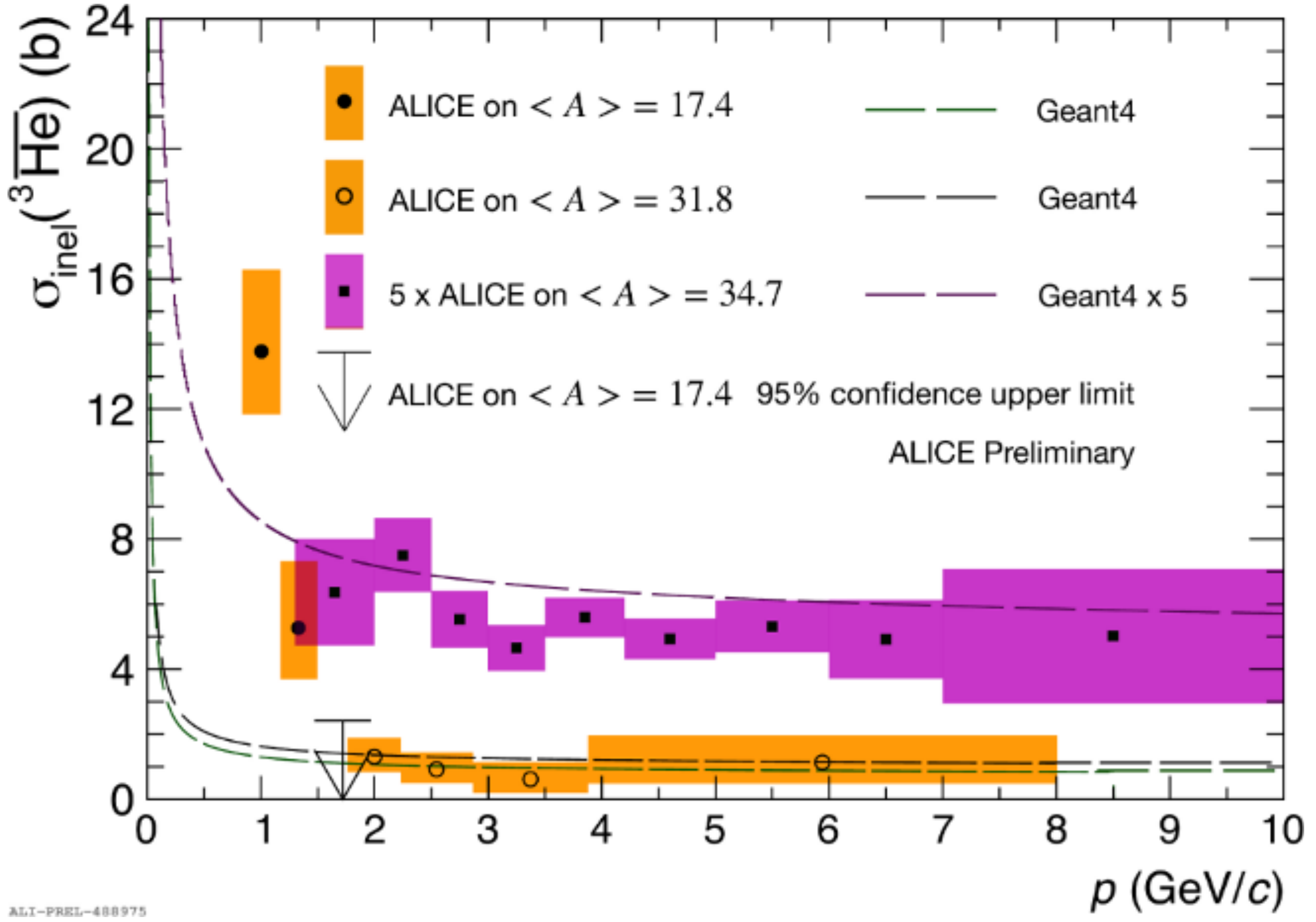
Annihilation

Sources ✅ Propagation ✅ Annihilation ✅

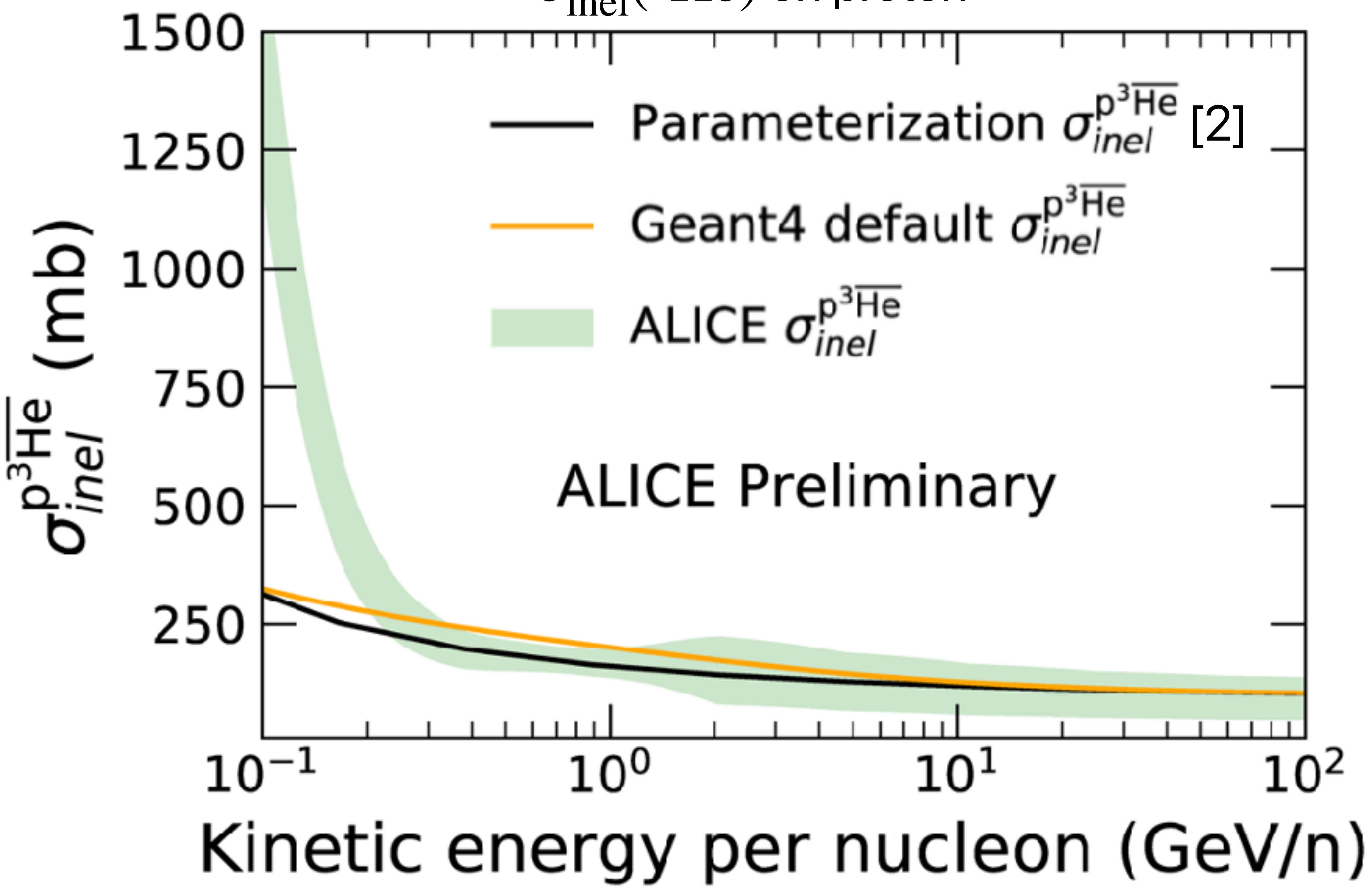
$^3\overline{\mathrm{He}}$ nuclei may interact inelastically with the interstellar gas

- ALICE results for $\sigma_{\mathrm{inel}}(^3\overline{\mathrm{He}})$ are for heavy elements with $\langle A \rangle$ = 17.4 to 34.7
- Rescaled using ALICE experimental data 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



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

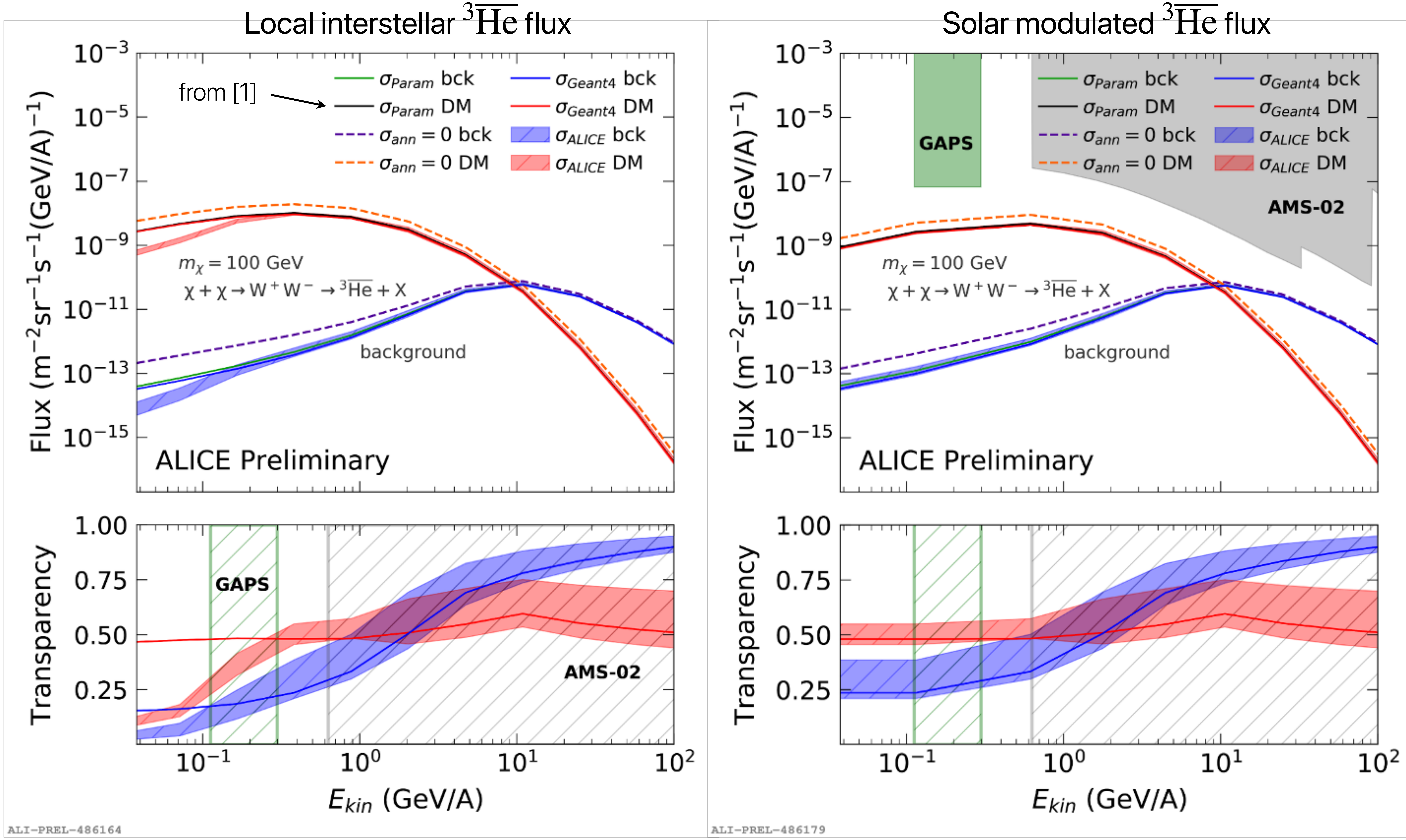


[1] Uzhinsky et al. Phys. Lett. B 705 (2011) 235
[2] Korsmeier et al, Phys. Rev. D. 97, 103011 (2018)

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

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

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



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

Summary and outlook

First measurements of antinuclei inelastic cross sections:

- ✅ $\overline{\mathrm{d}}$ at low energy (published)
- ✅ $^{3}\overline{\mathrm{He}}$ (paper in preparation)

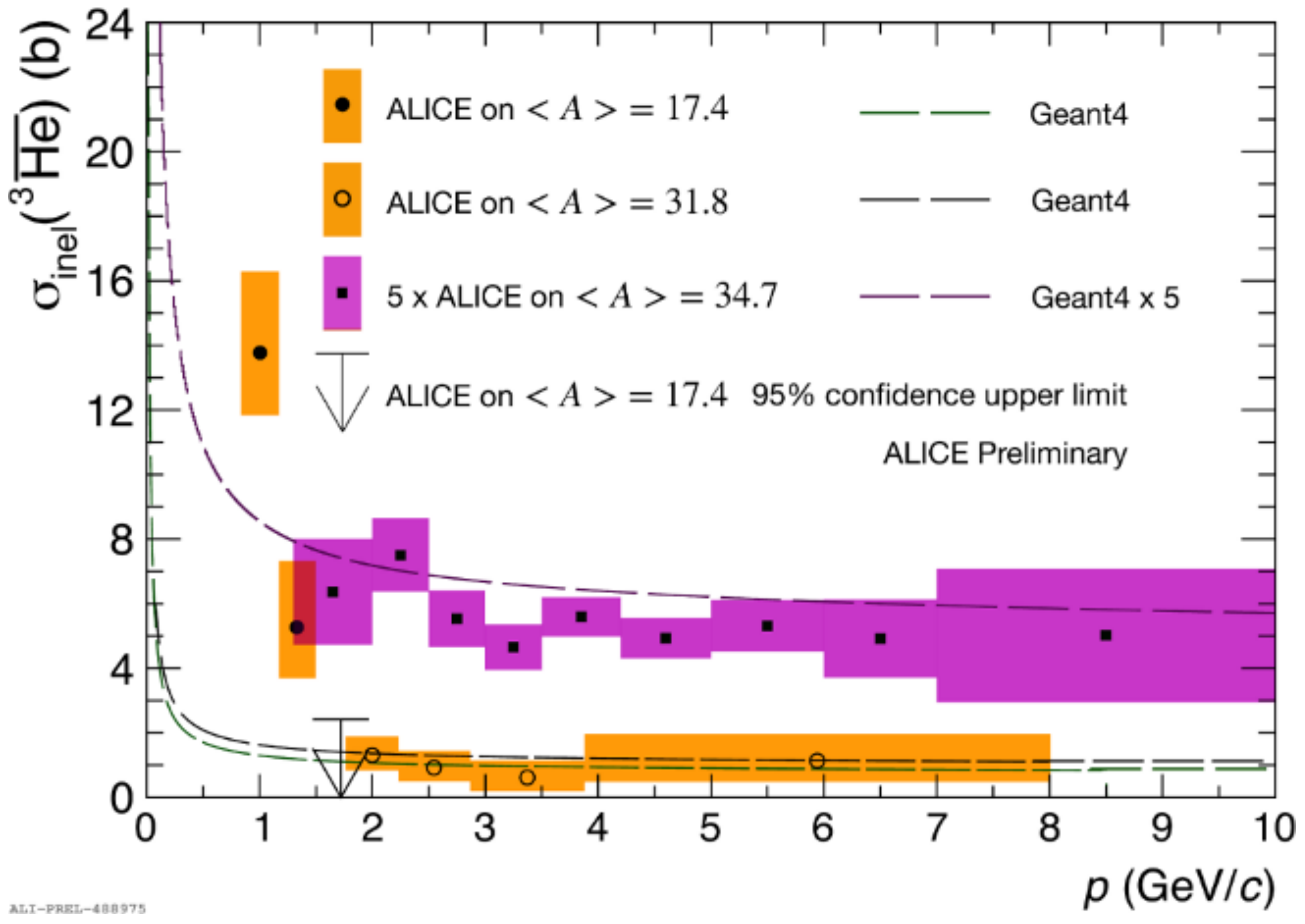
↓

Impact on $^{3}\overline{\mathrm{He}}$ flux near Earth:

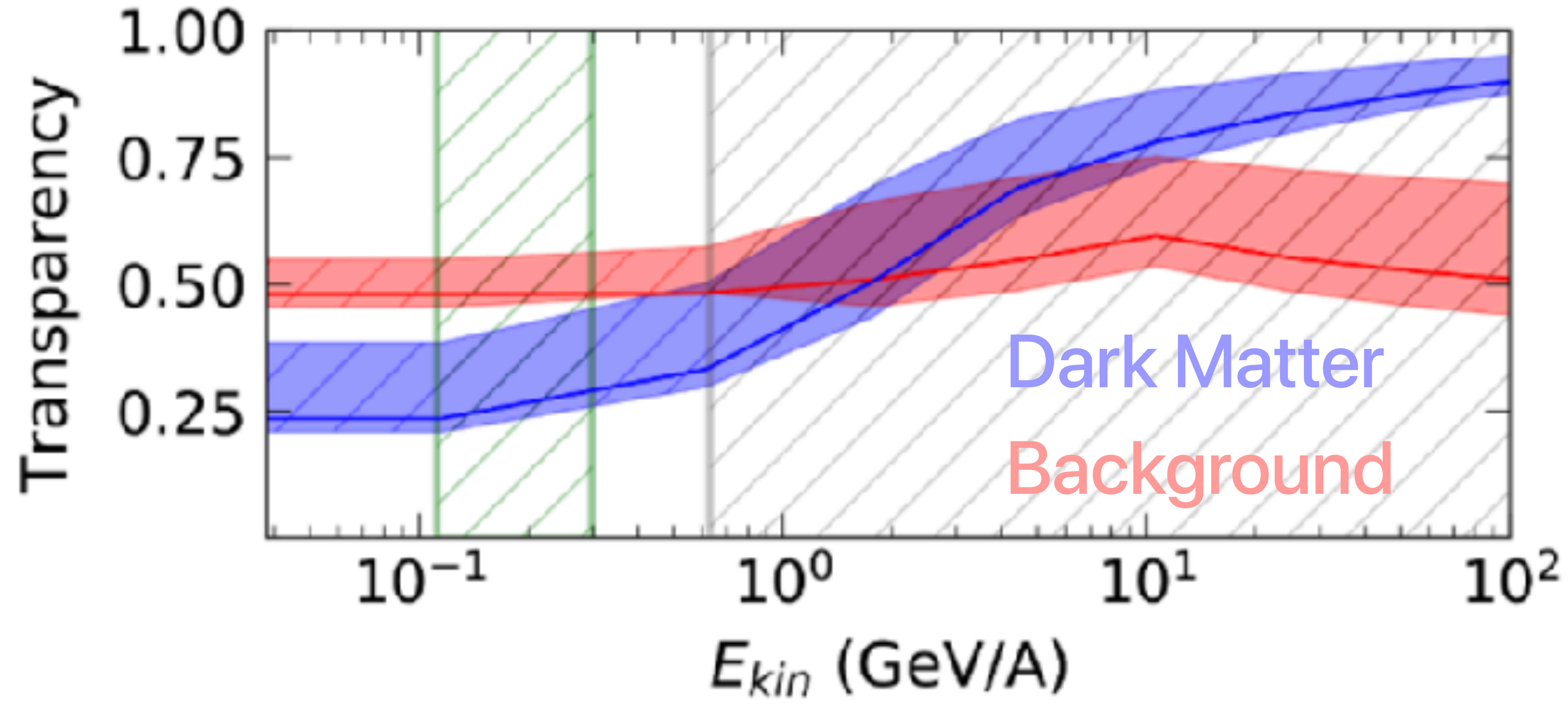
- **High transparency of the Galaxy to $^{3}\overline{\mathrm{He}}$**
- Small uncertainties on cosmic ray fluxes from $\sigma_{\mathrm{inel}}(^{3}\overline{\mathrm{He}})$ compared to other uncertainties in the field

Thank you for your attention!

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



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

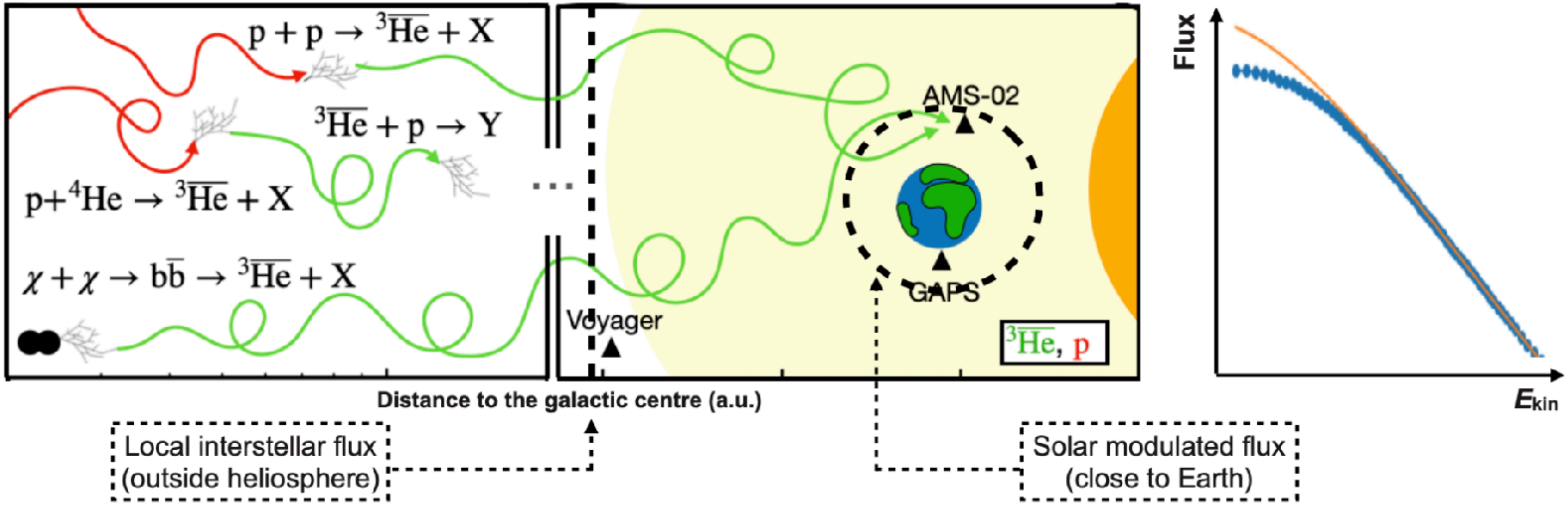


Backup slides

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:

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



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