Recent ALICE results on antinuclei inelastic c.s. and the implications for antinuclei fluxes near Earth

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On behalf of ALICE collaboration
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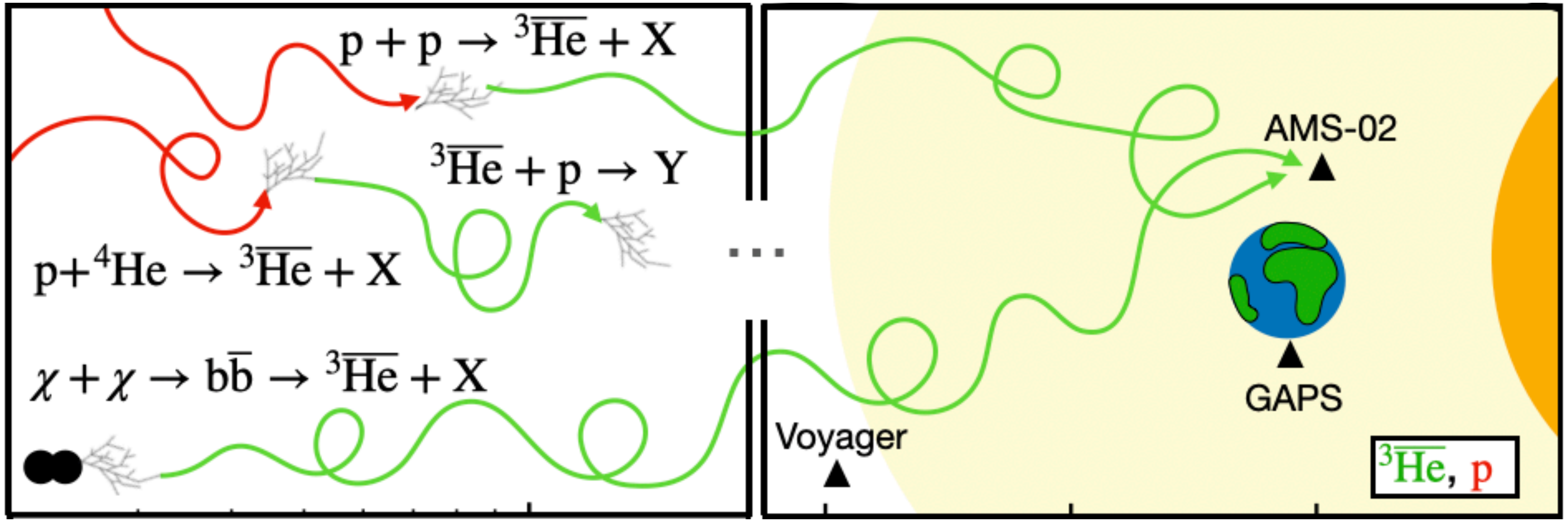
ISCRA-2021

Motivation

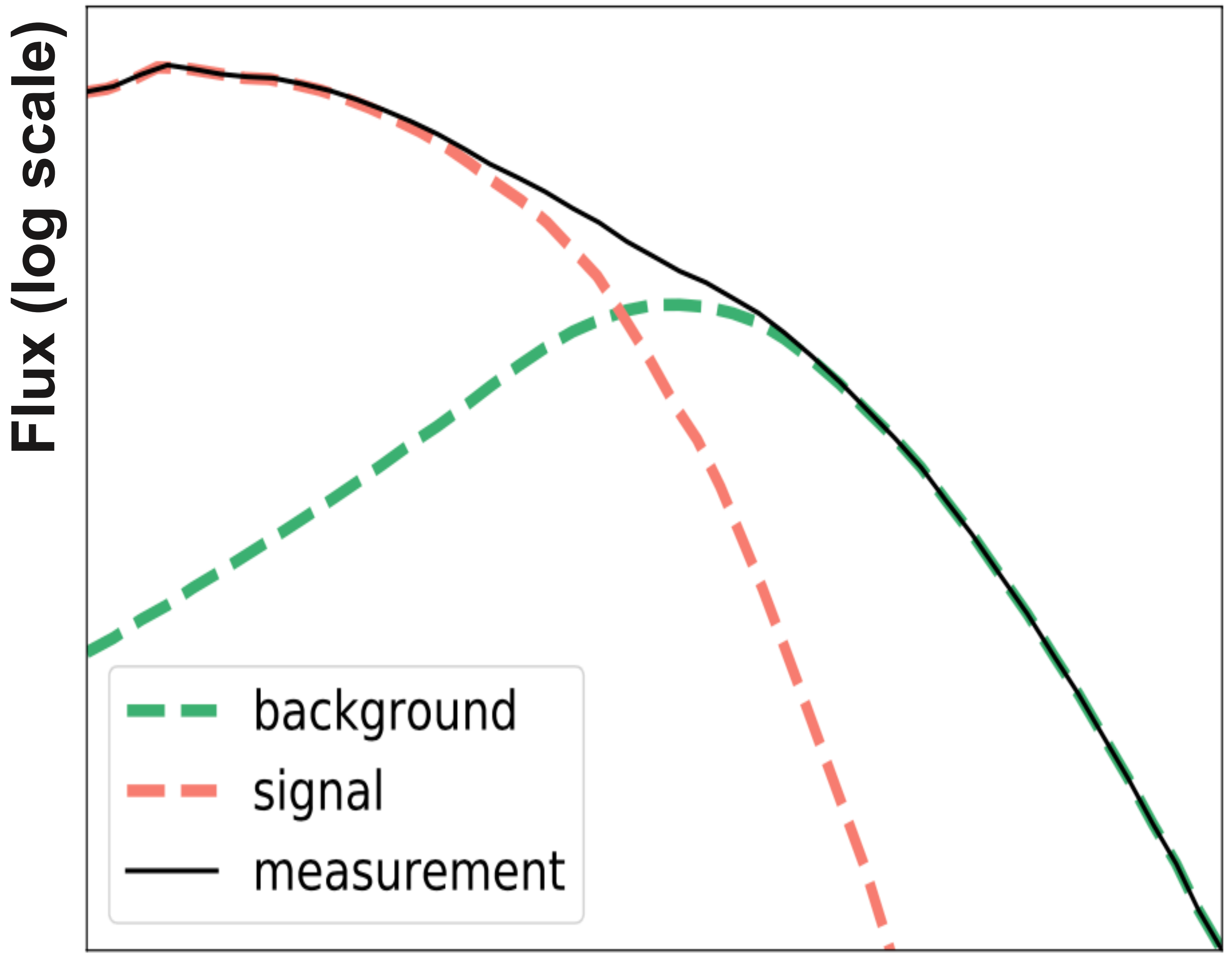
Antinuclei in cosmic rays ($\overline{d}$, $^3\overline{He}$, $^4\overline{He}$) - unique probe for indirect dark matter searches

- Low background from secondary production is expected in the low-energy range
- *Vital to determine primary and secondary antinuclei fluxes as precisely as possible!*

$^3\overline{He}$ production and propagation in the Galaxy



Schematic antinuclei fluxes near Earth



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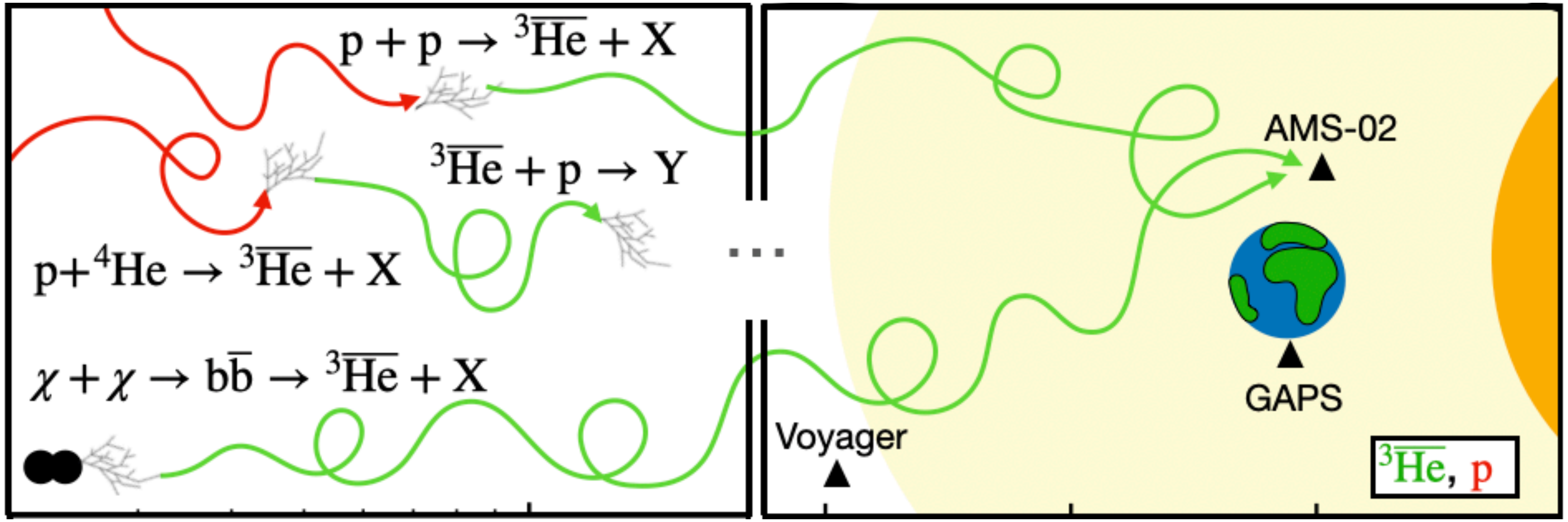
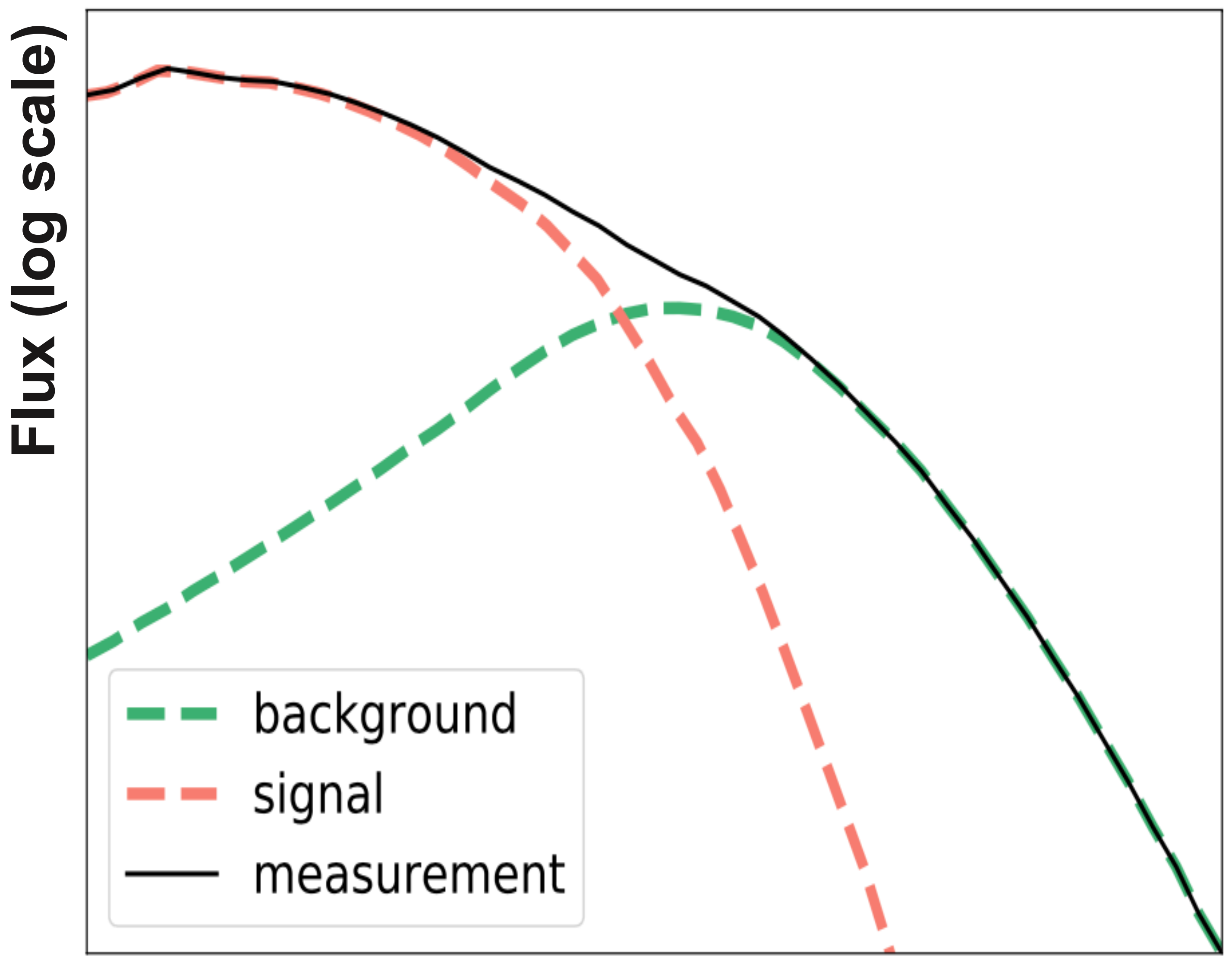


Distance to the galactic centre (a.u.)

Schematic antinuclei fluxes near Earth



Many effects on the long way to the detectors near Earth:

- Diffusion, convection: common for all (anti)particles
- *Inelastic interactions with interstellar medium - essential part of calculations!*

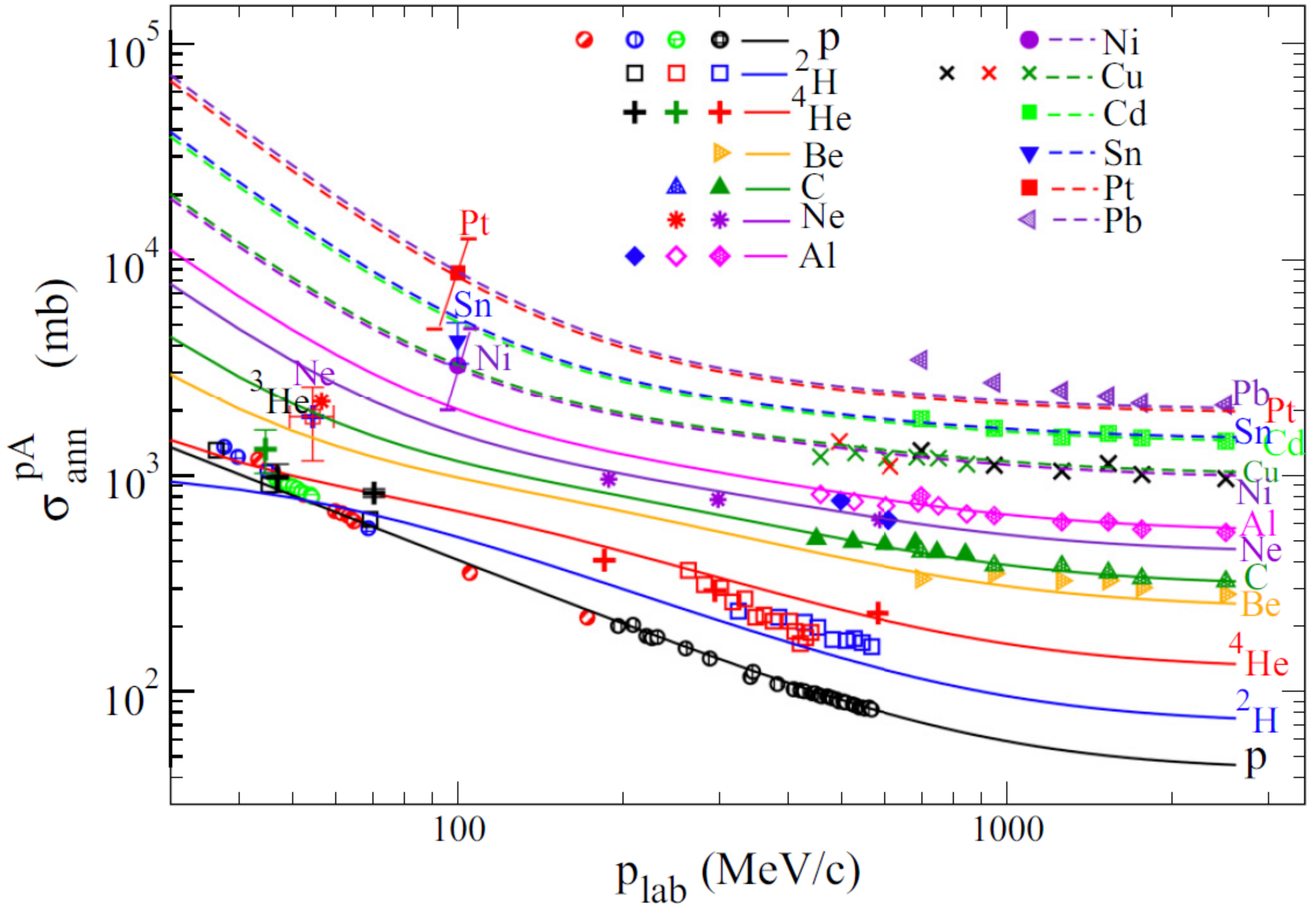
ALICE

Status of antinuclei σ_{inel} measurements (before ALICE)

Antinuclei inelastic cross sections are poorly (or not) known at low energies

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

Antiprotons [1]



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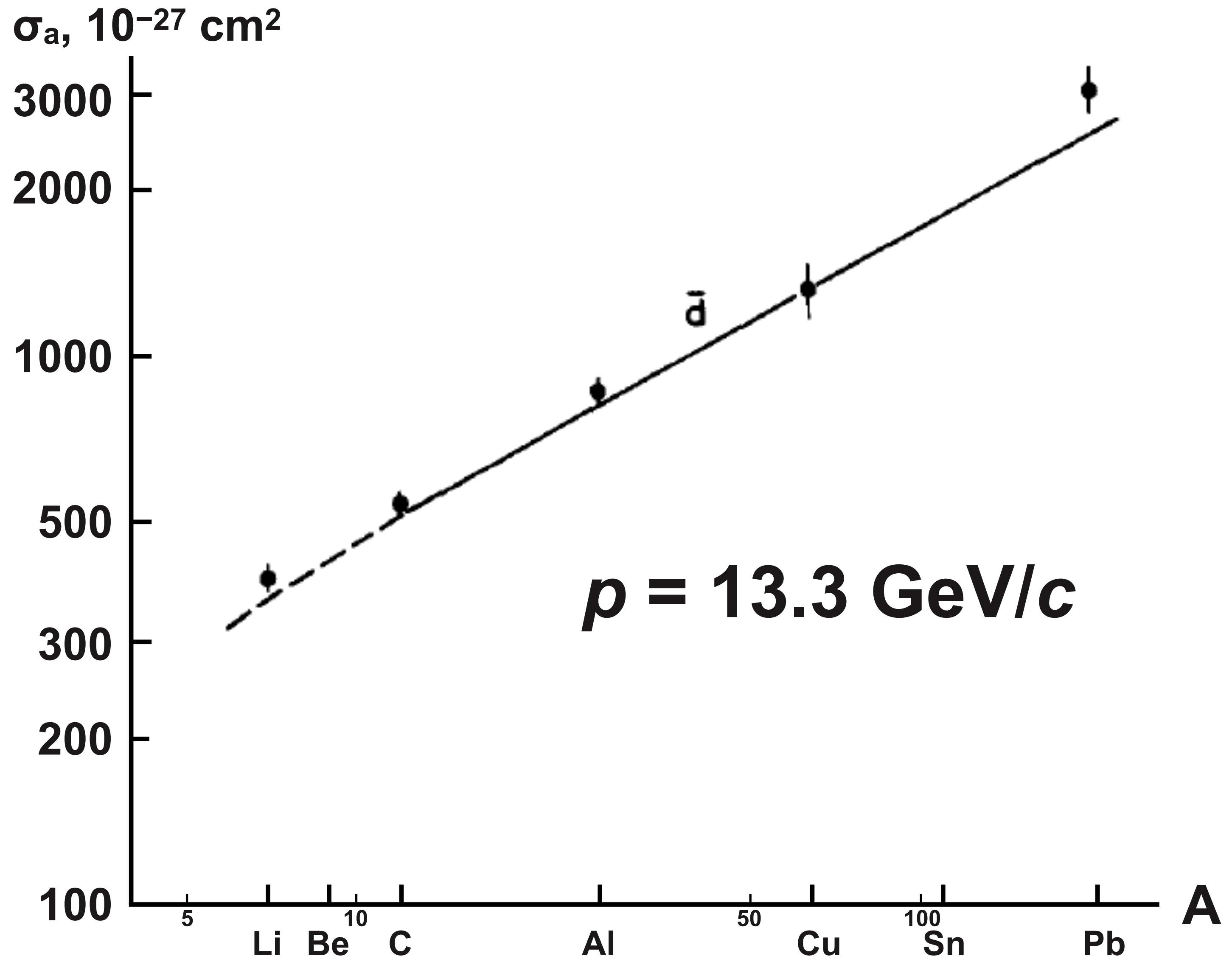
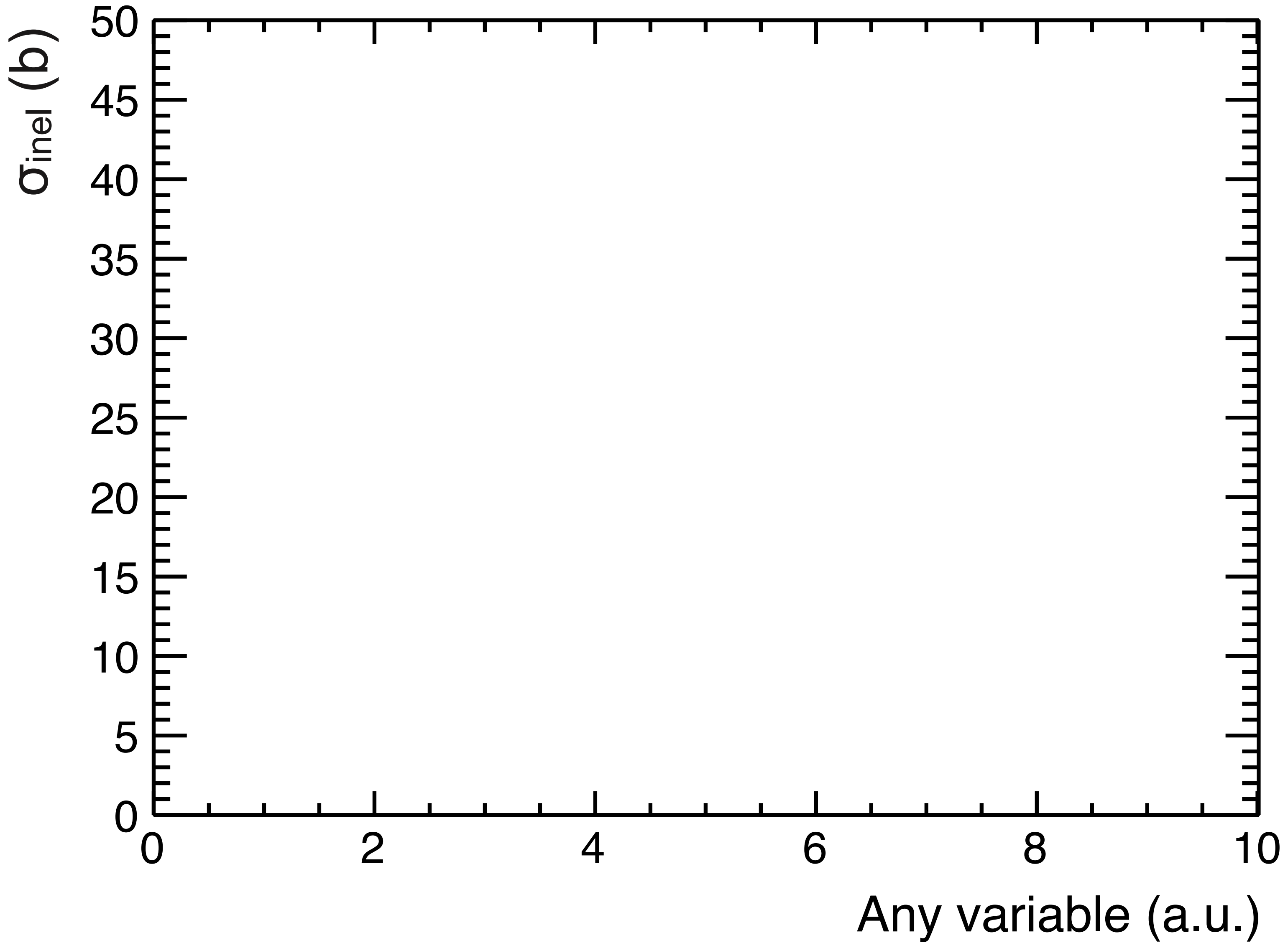


Antihelium



[1] Lee et al., Phys. Rev. C 89, 054601 (2014)
[2] Denisov et al., Nuclear Physics B 31 (1971) 253

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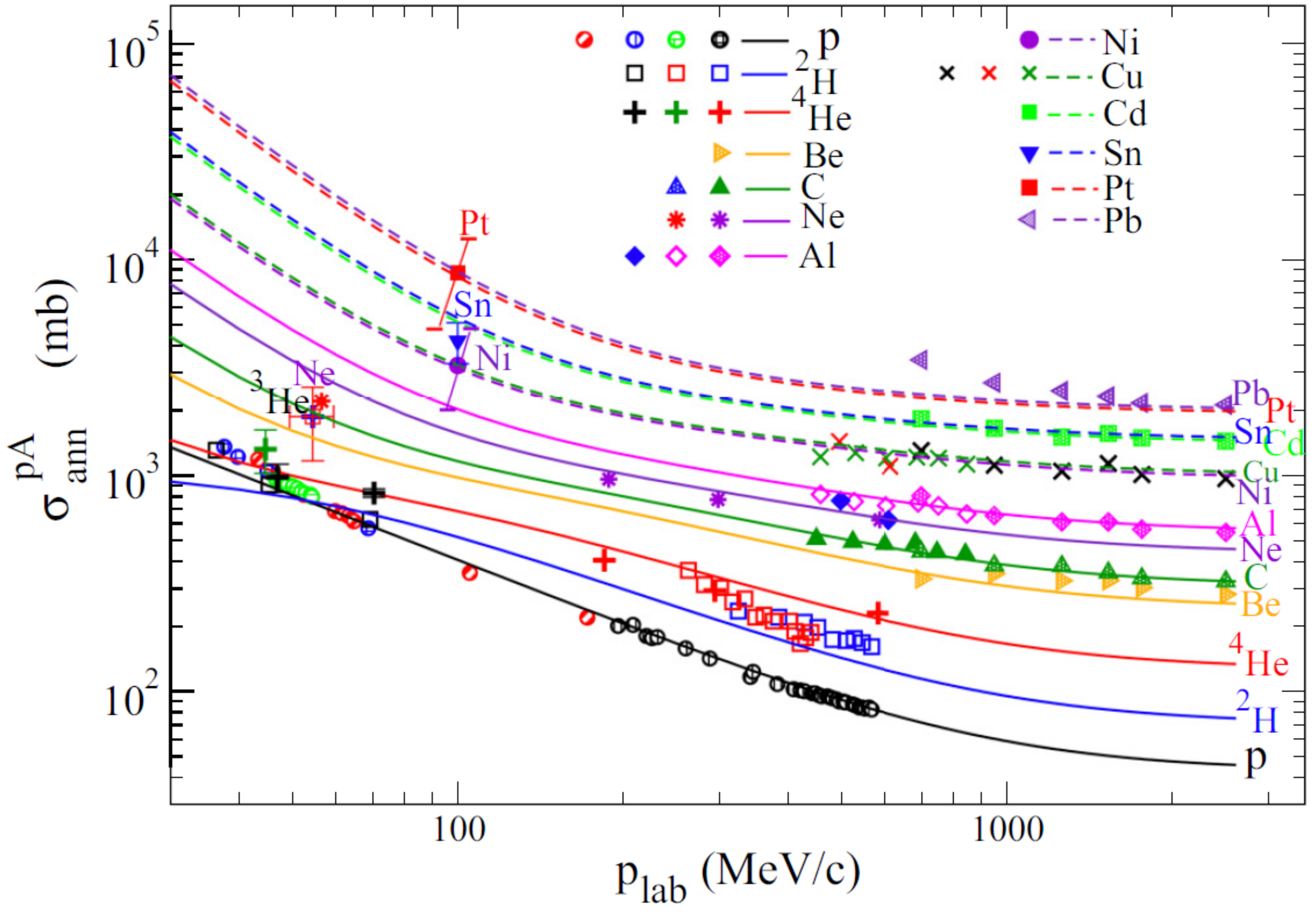

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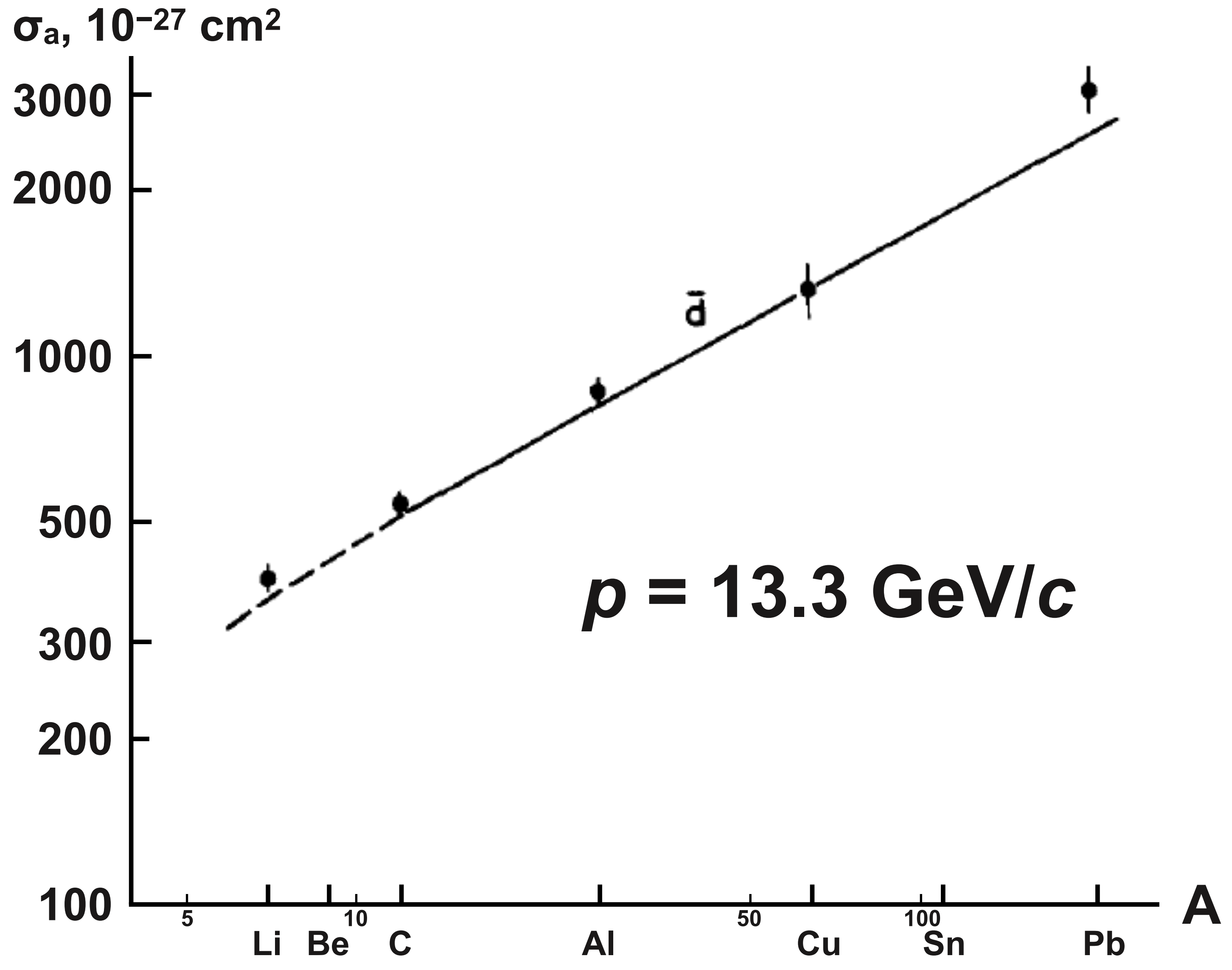

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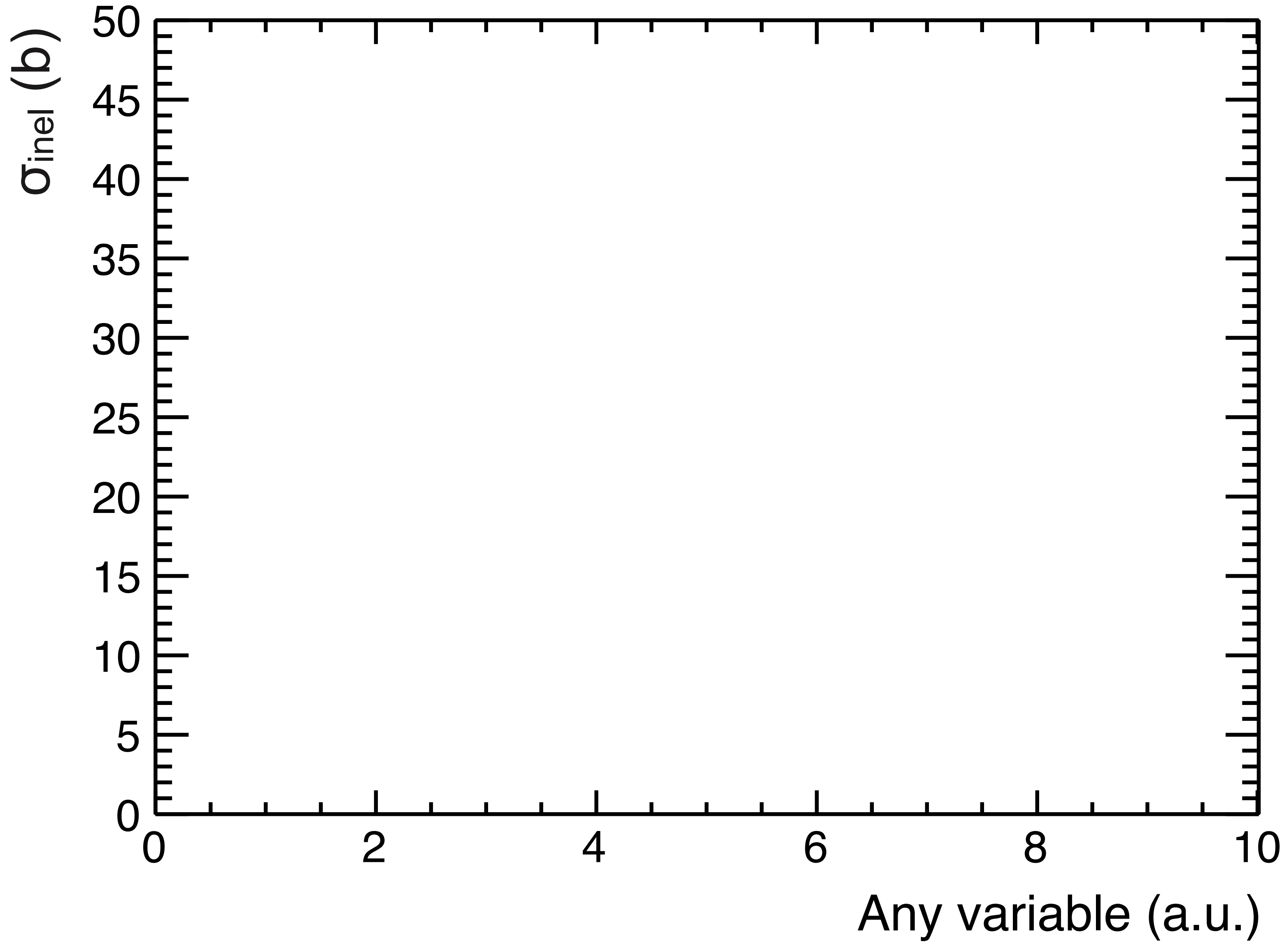

High-energy collisions at LHC produce a lot of antinuclei

- *We can use this to study antinuclei inelastic interaction with the detector material!*

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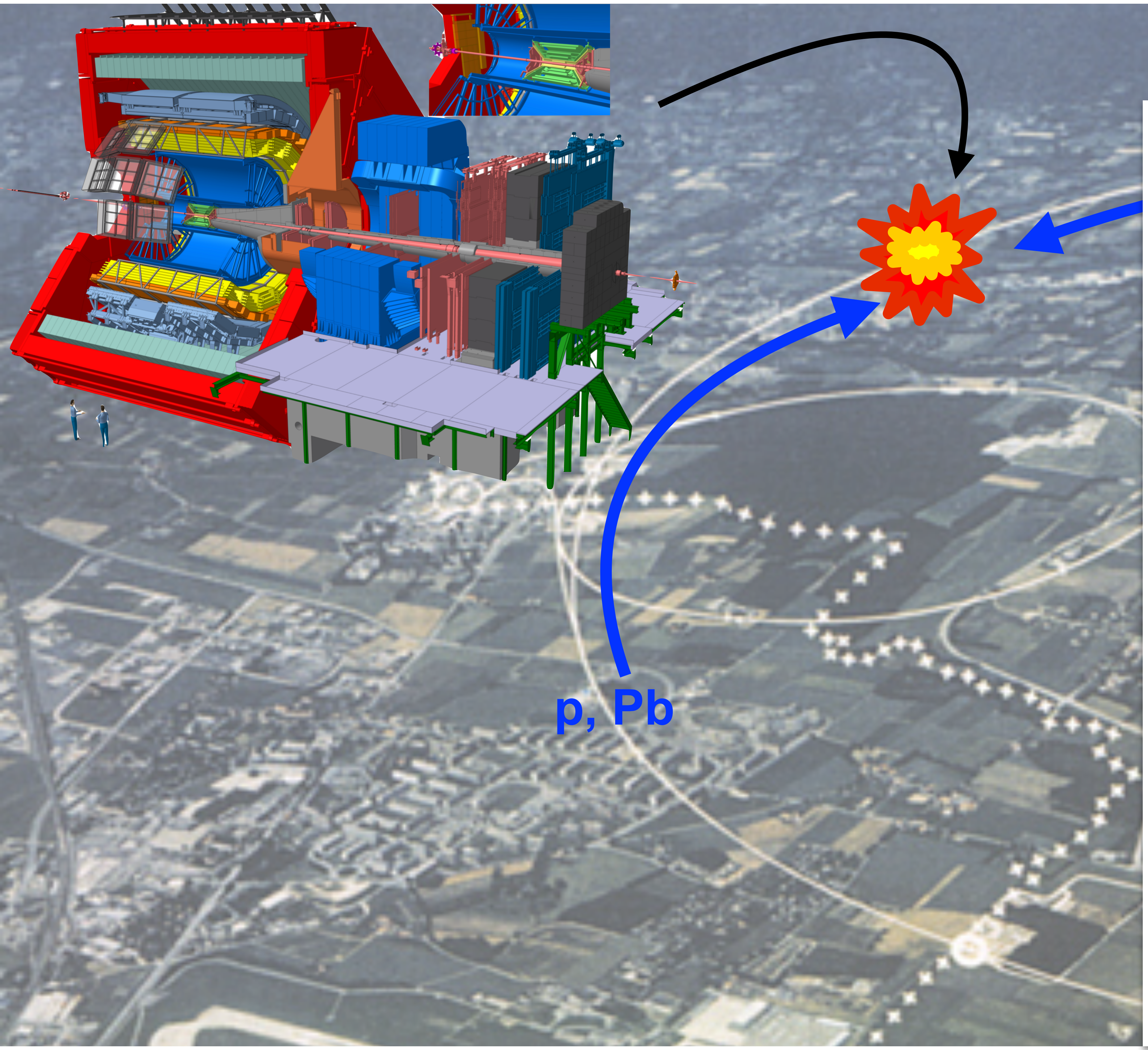
LHC as an antimatter factory

At LHC energies, (anti)nuclei are abundantly produced in collisions of protons and Pb ions

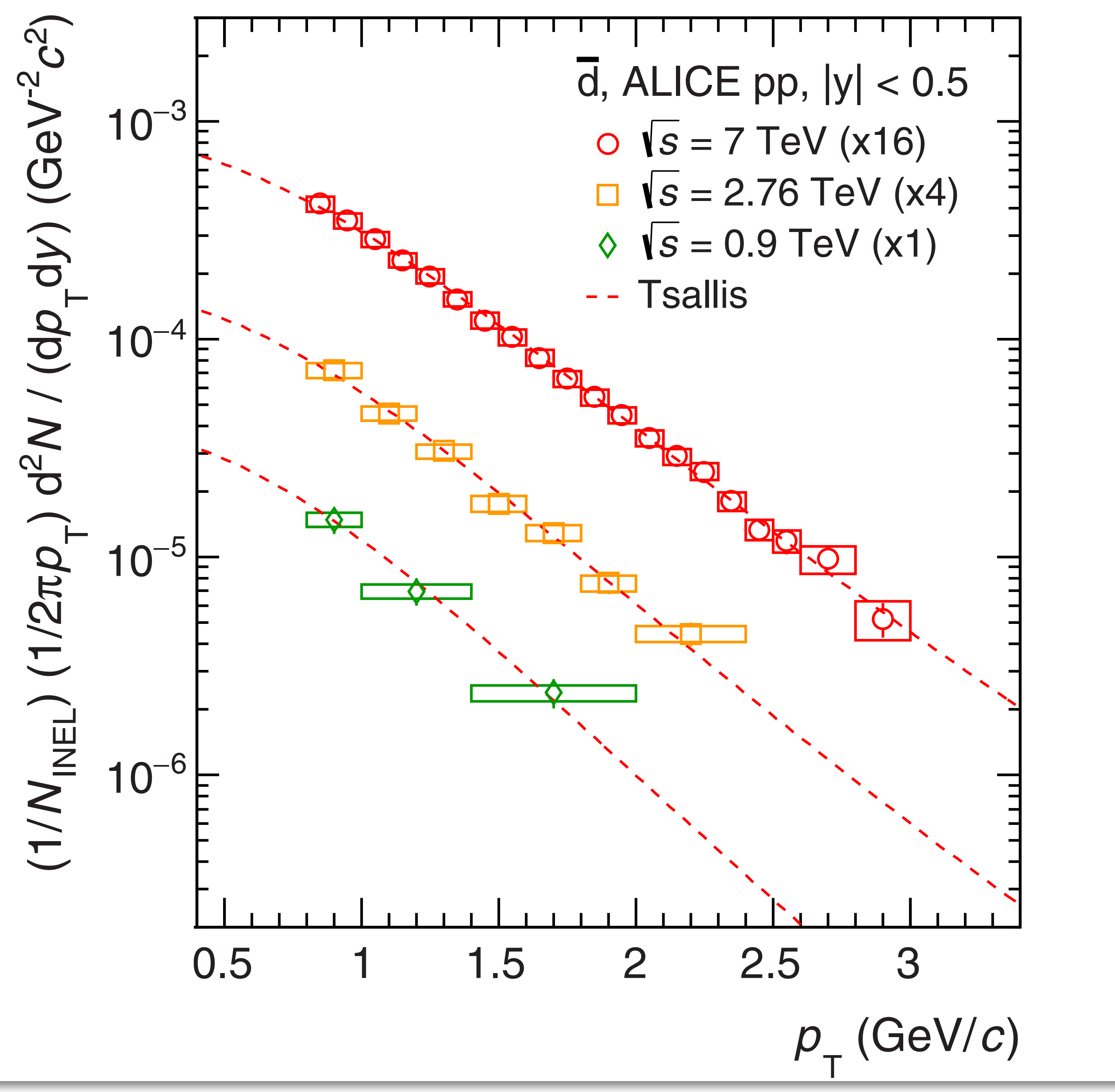
LHC as an antimatter factory

At LHC energies, (anti)nuclei are abundantly produced in collisions of protons and Pb ions

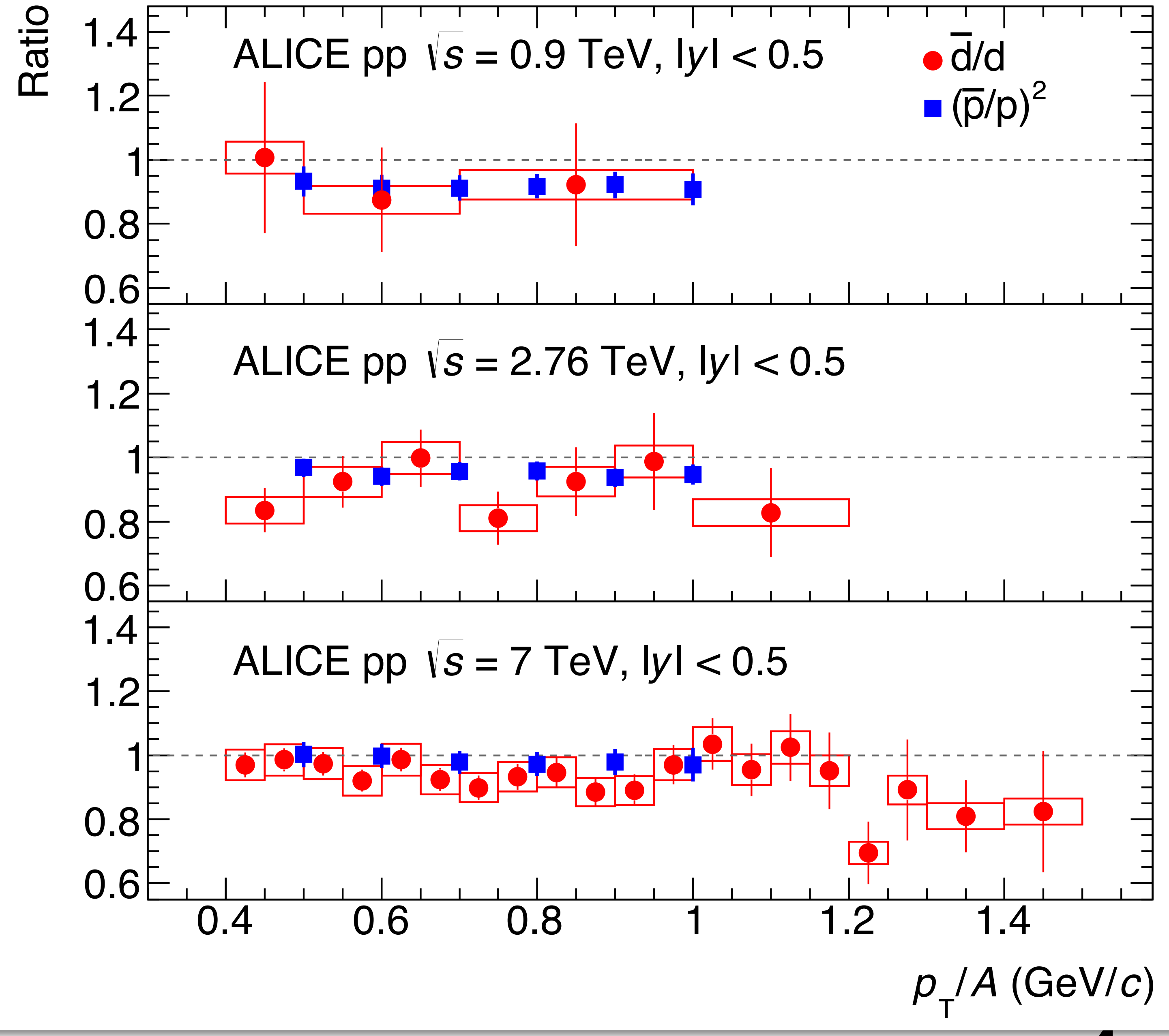
- Perfect place to study the production and annihilation of antinuclei at low momenta
- Primordial antimatter-to-matter ratio approaches unity with increasing $\sqrt{s}$



p_T spectra of $\bar{d}$ in pp collisions [1]



$\bar{d}$/d and $(\bar{p}/p)^2$ ratios vs p_T [1]



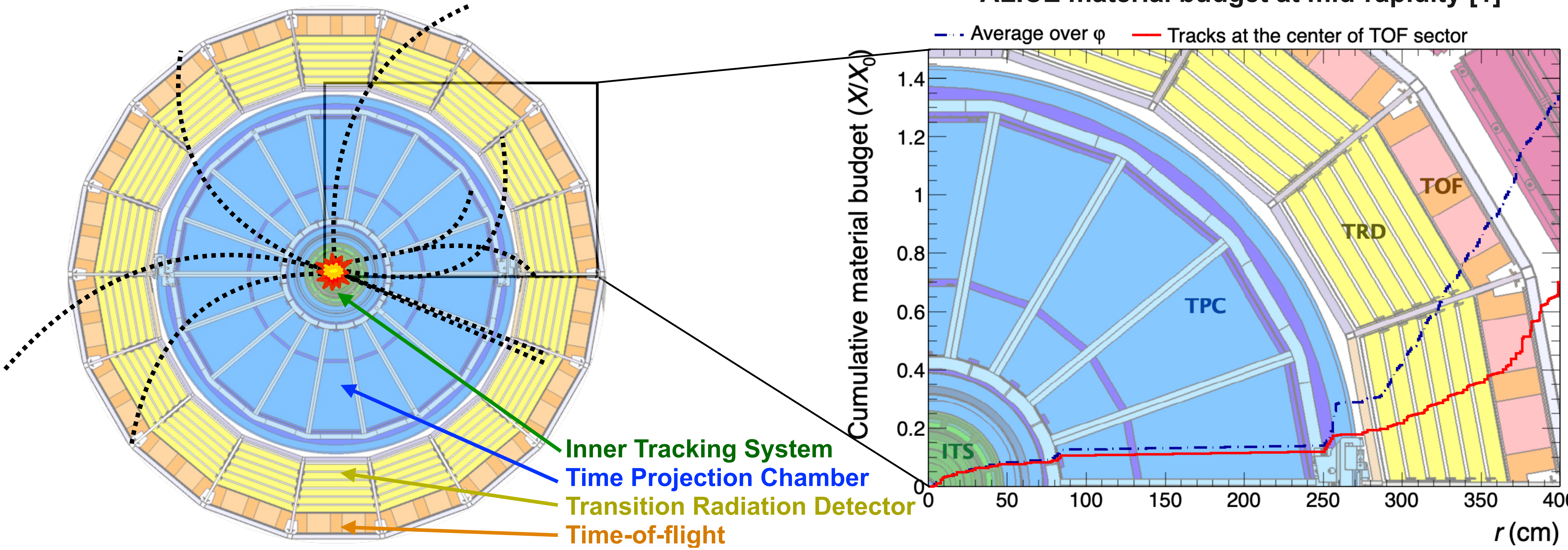
[1] ALICE, Phys. Rev. C 97, 024615 (2018)

…and ALICE detector material as a target

Many different materials are used in the detector construction

- Averaged $\langle A \rangle$ value of material crossed by an (anti)particle can be calculated as: $\langle A \rangle = \frac{\sum_{i=1}^{R} A_i \rho_i}{\sum_{i=1}^{R} \rho_i}$

ALICE material budget at mid-rapidity [1]

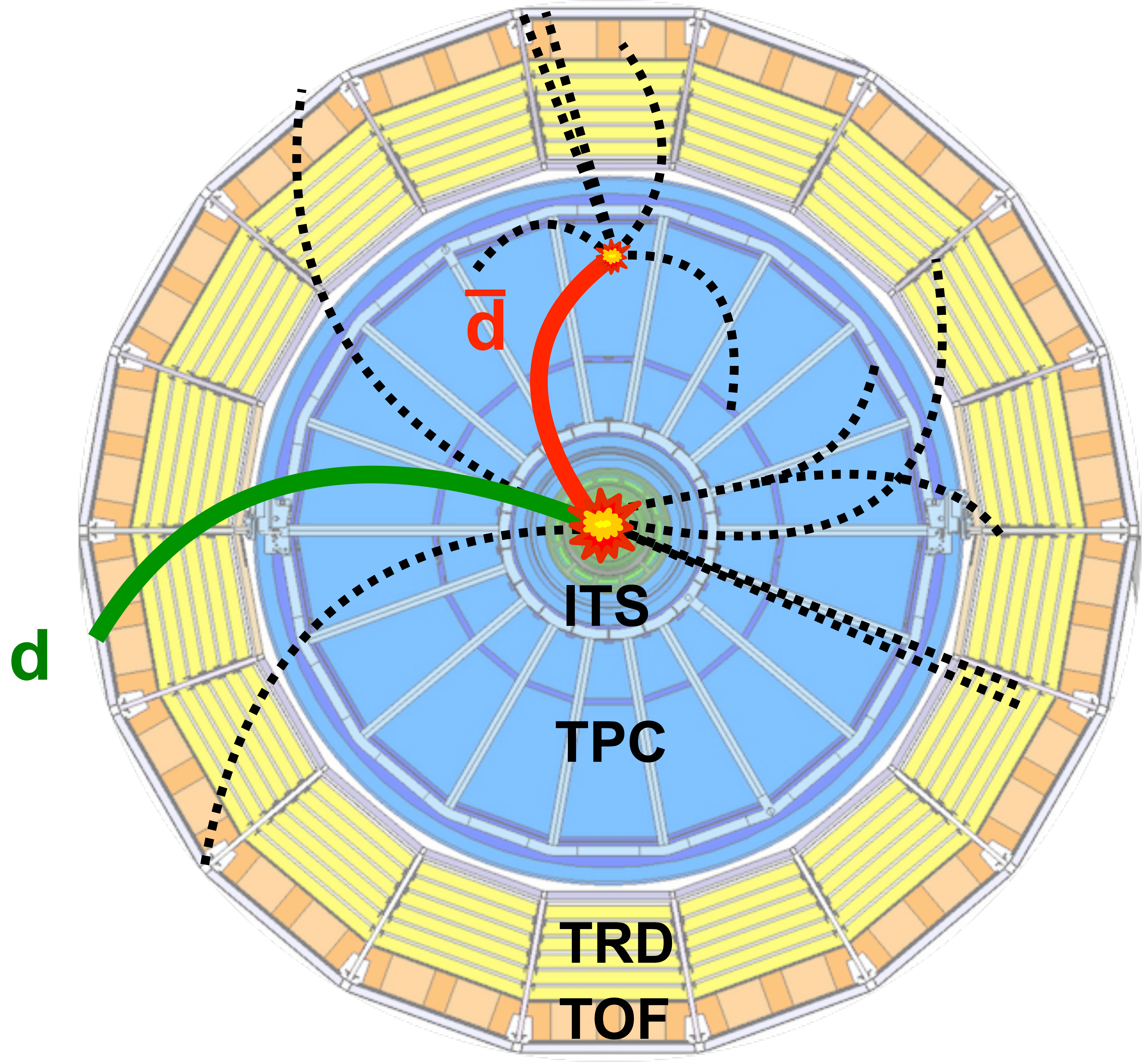


[1] ALICE, Phys. Rev. Lett. 125, 162001 (2020)

Methods used to obtain σ_{inel} of antinuclei

Antimatter-to-matter ratio [1]

- Measure reconstructed “antinuclei/nuclei” and compare results with MC simulations
- Used for analyses of $\sigma_{inel}(\overline{d})$ and $\sigma_{inel}(^{3}\overline{He})$



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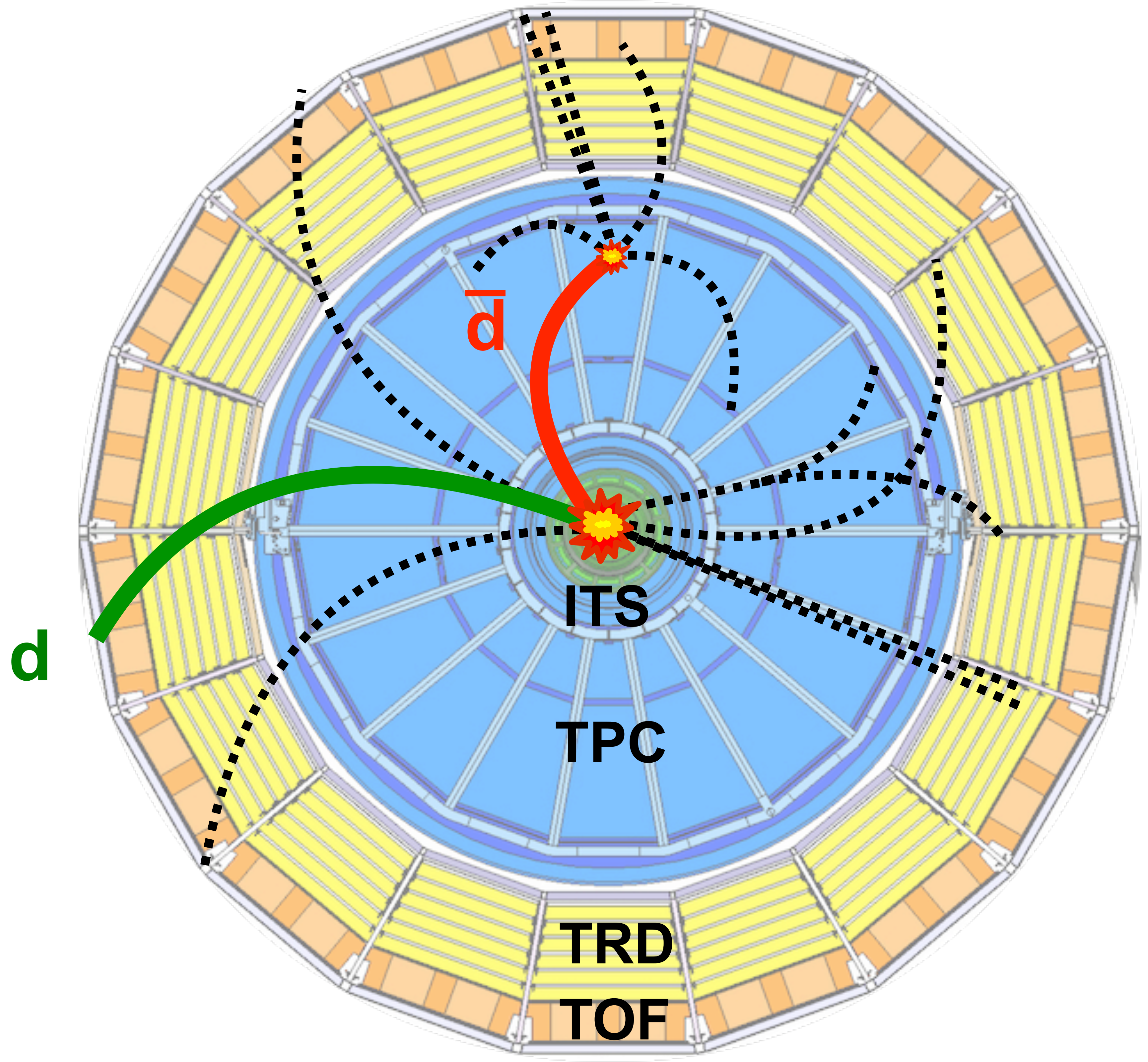
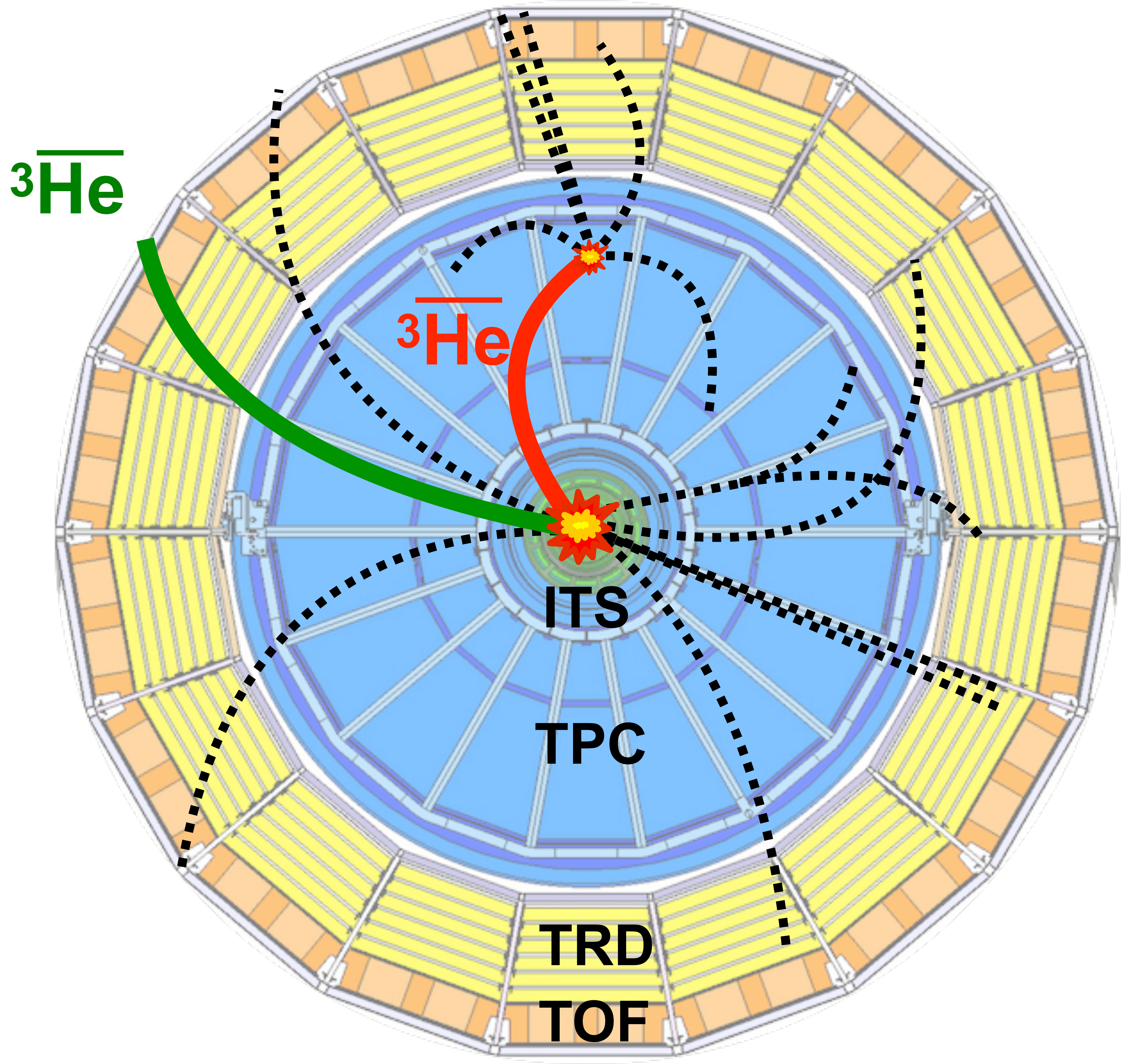
TPC-to-TOF matching

- Measure "antinuclei in TOF/antinuclei in TPC" and compare results with MC simulations
- Applicable for $^{3}\overline{He}$ in a broad momentum range





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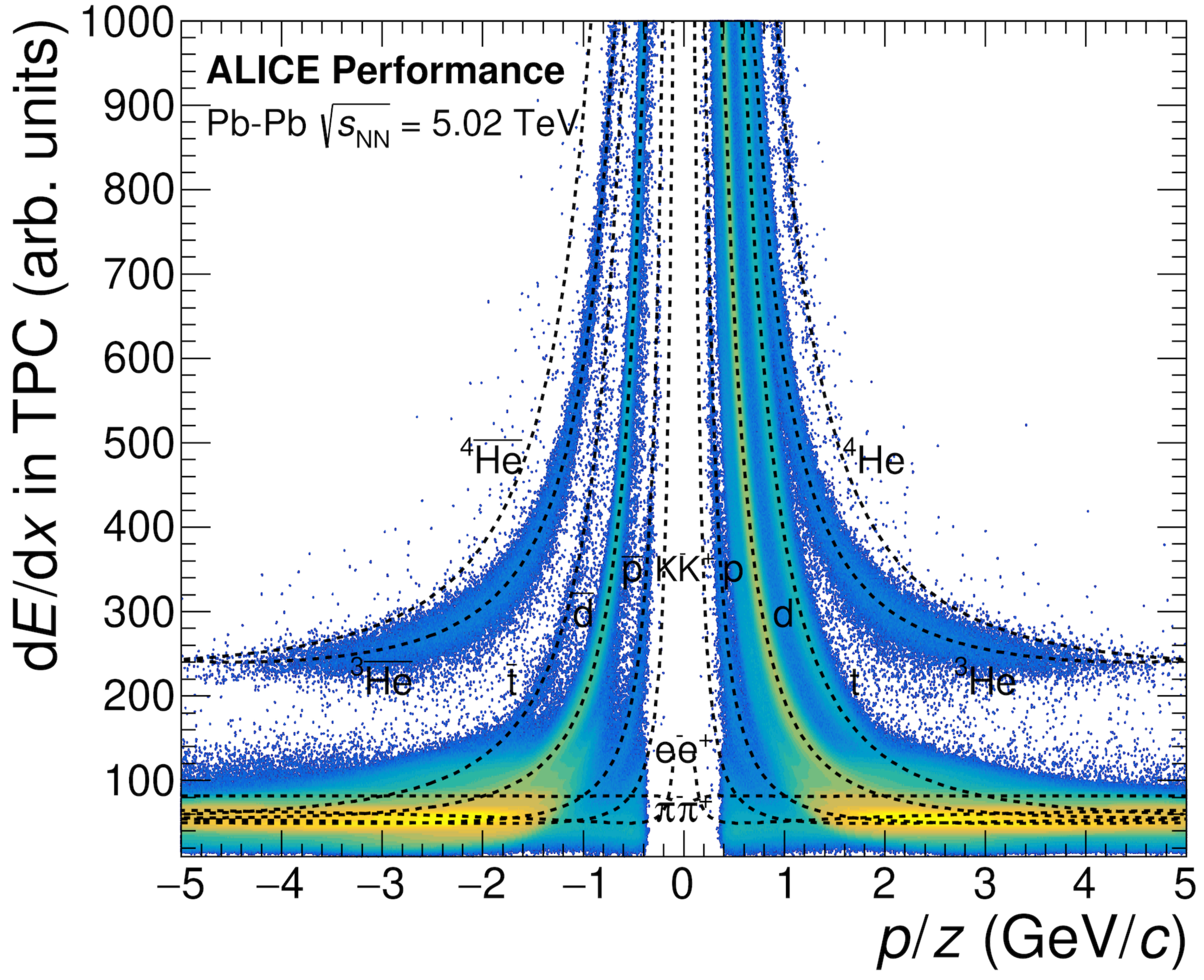
Particle identification in TPC and TOF

Complementary information from TPC and TOF detectors allows selection of high-purity (anti)nuclei

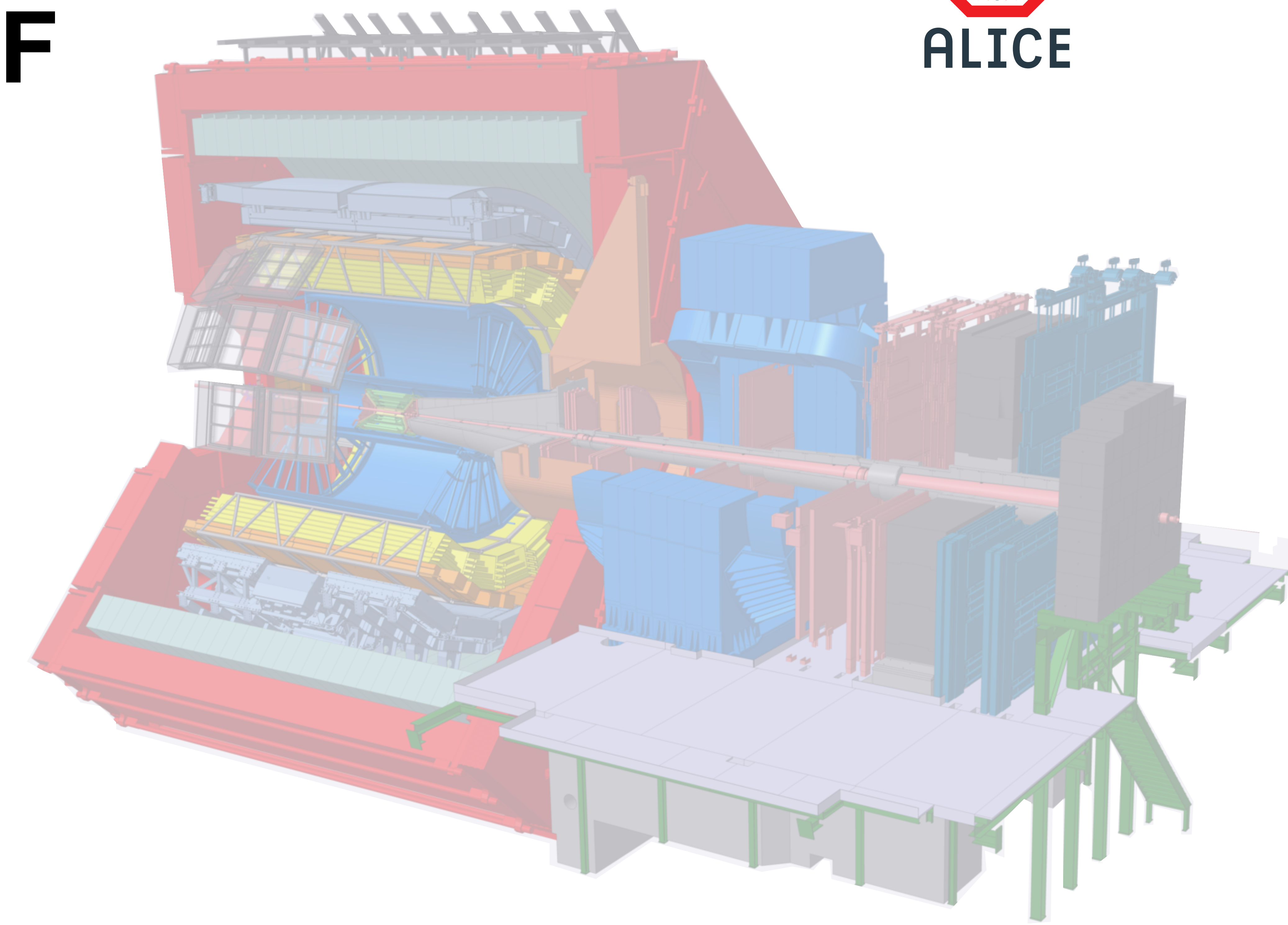
TPC: dE/dx in gas (Ar/CO_2)

- Clear identification of (anti)^{3}He thanks to large mass and double charge

d*E*/dx in ALICE TPC



ALI-PERF-341664



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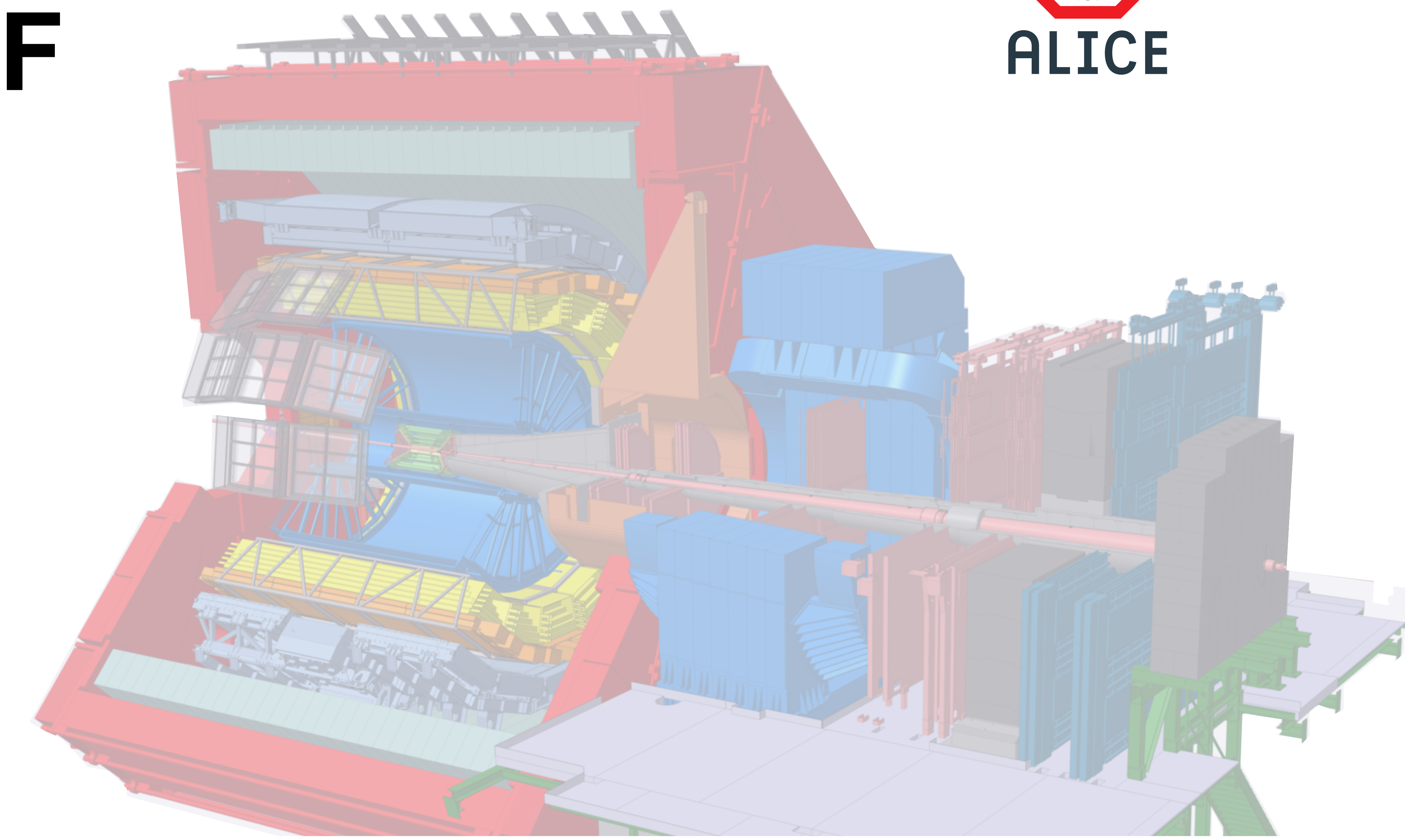

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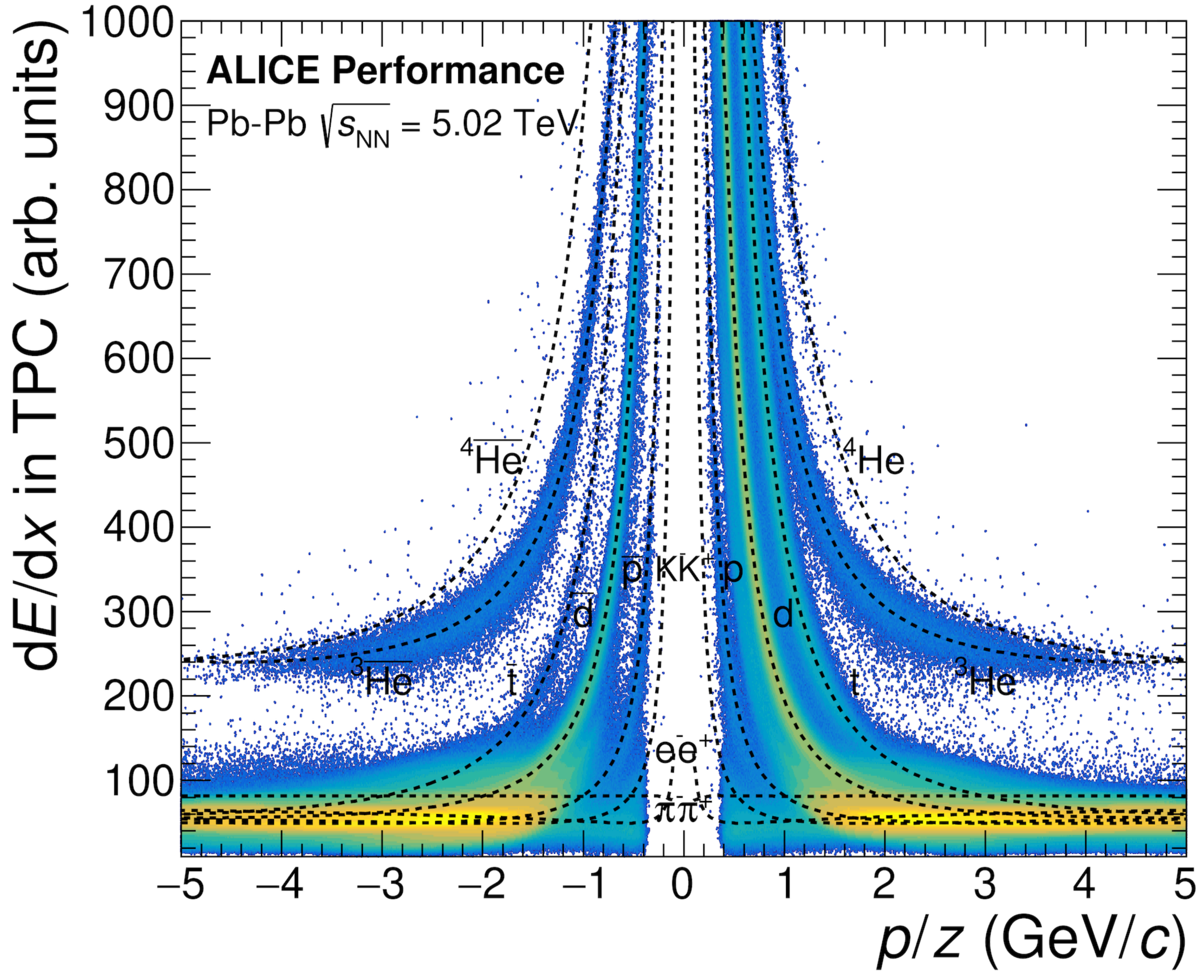
TOF measurements: $\beta = v/c$

- $p = \gamma\beta m \rightarrow$ mass

d*E*/dx in ALICE TPC



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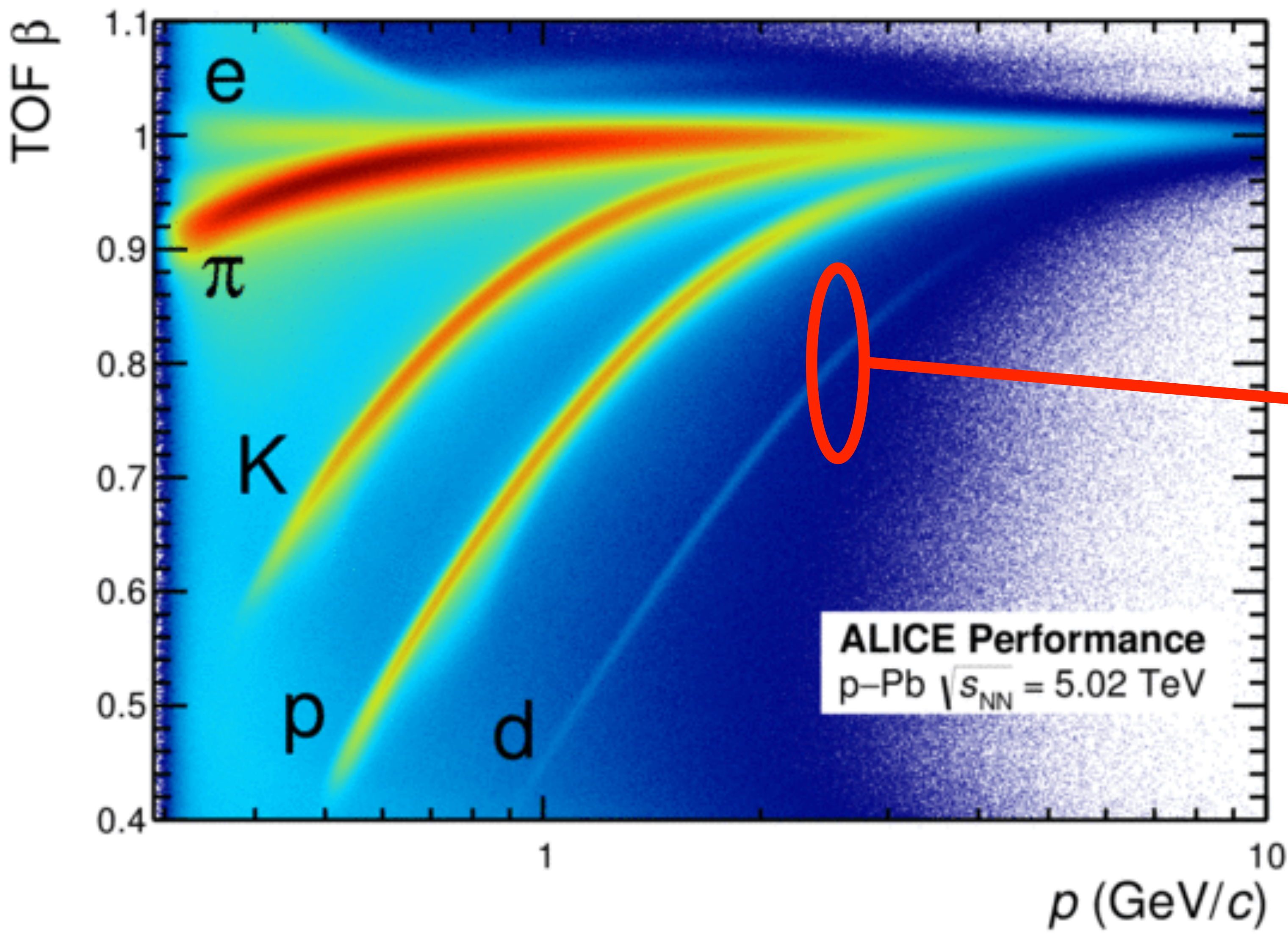
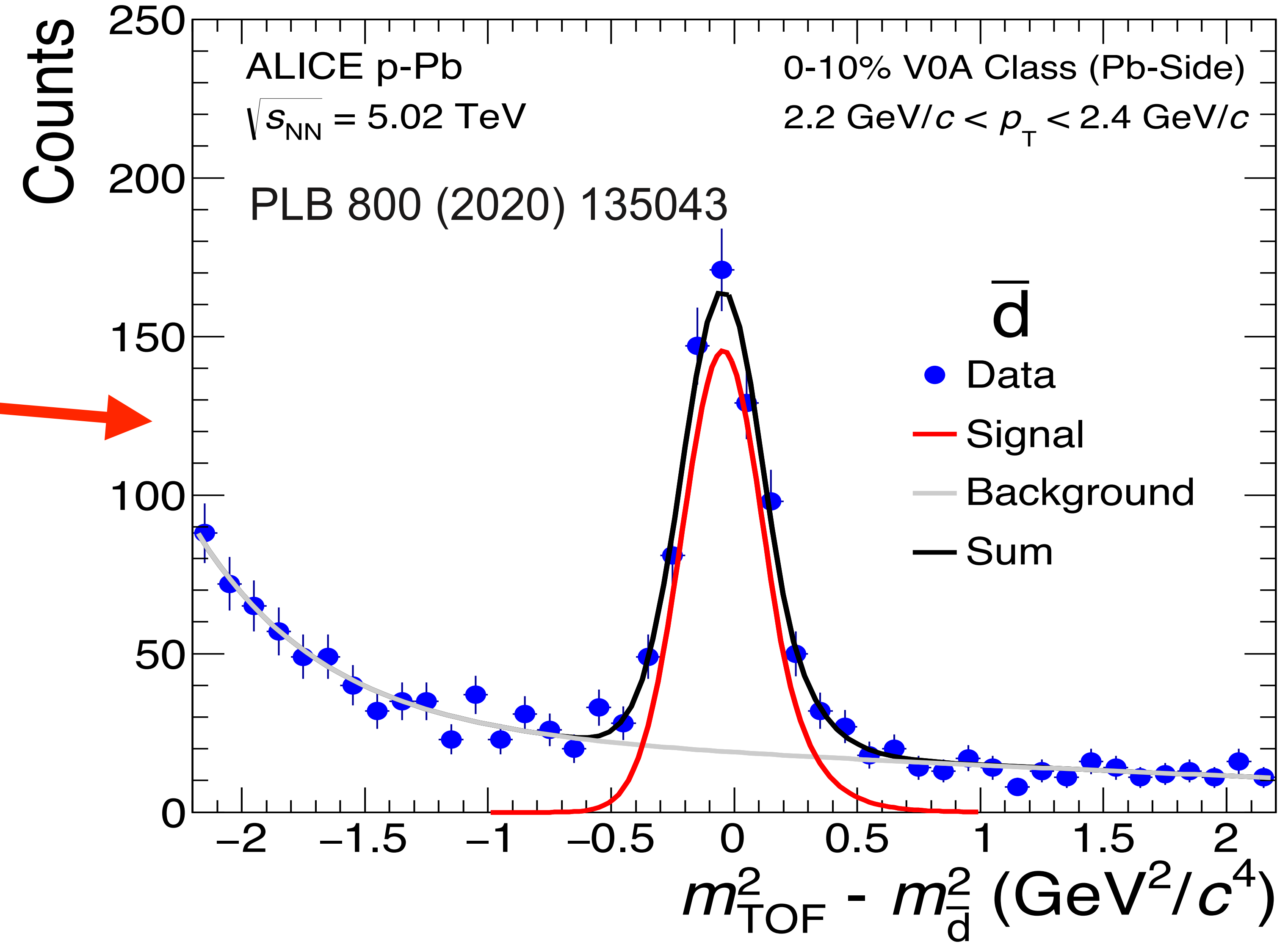
TOF β

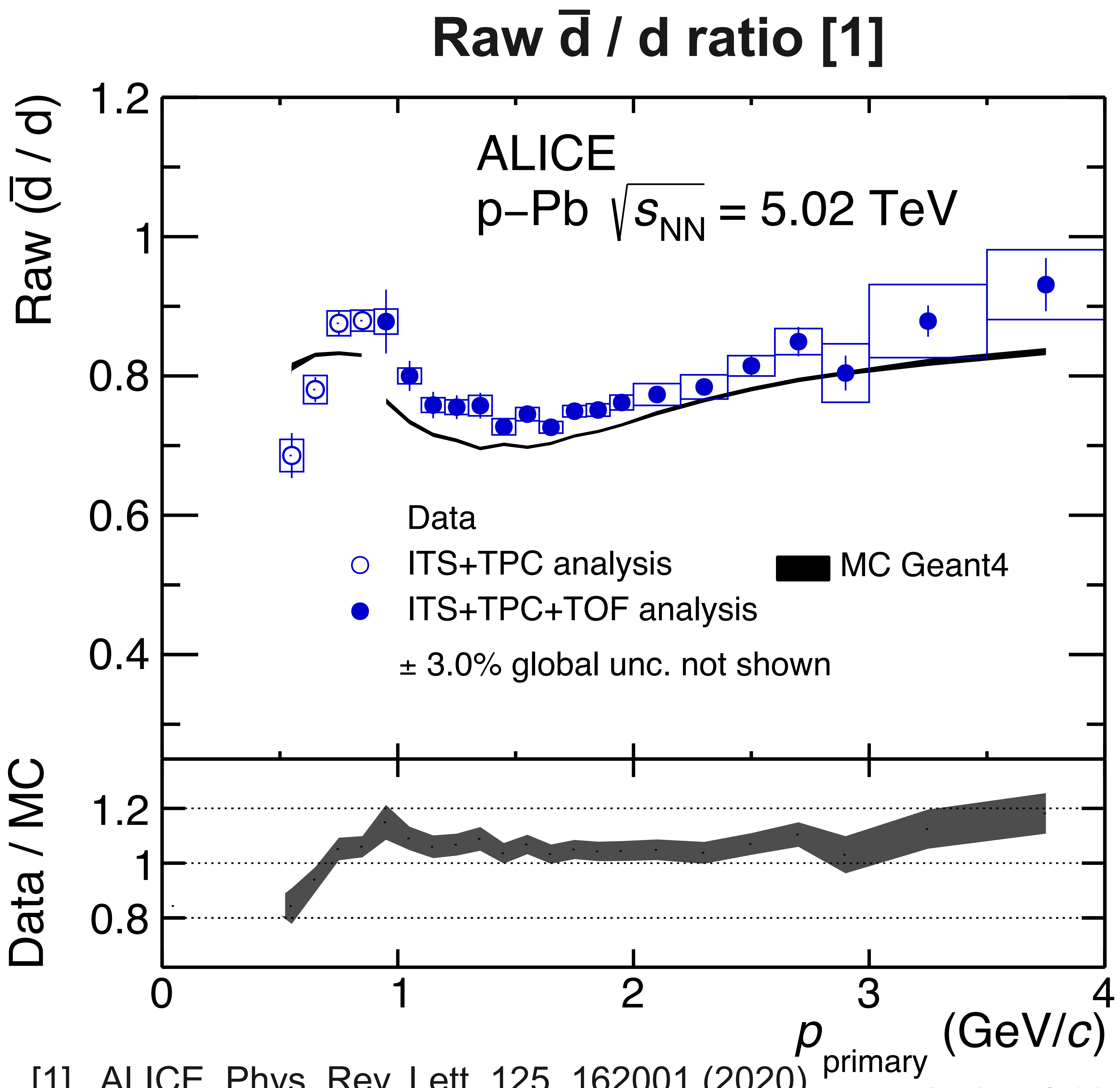


ALI-PERF-149520



Raw ratio of primary (anti)deuterons

Raw d̄ / d ratio compared to ALICE Geant4 MC simulations



- Higher loss of antideuterons in detector material as expected

Monte Carlo data: detailed simulation of ALICE detector performance

- Propagation of (anti)particles and interaction with matter with Geant4
- Inelastic c.s.: Glauber model simulations parametrised vs *A* as described in [2]

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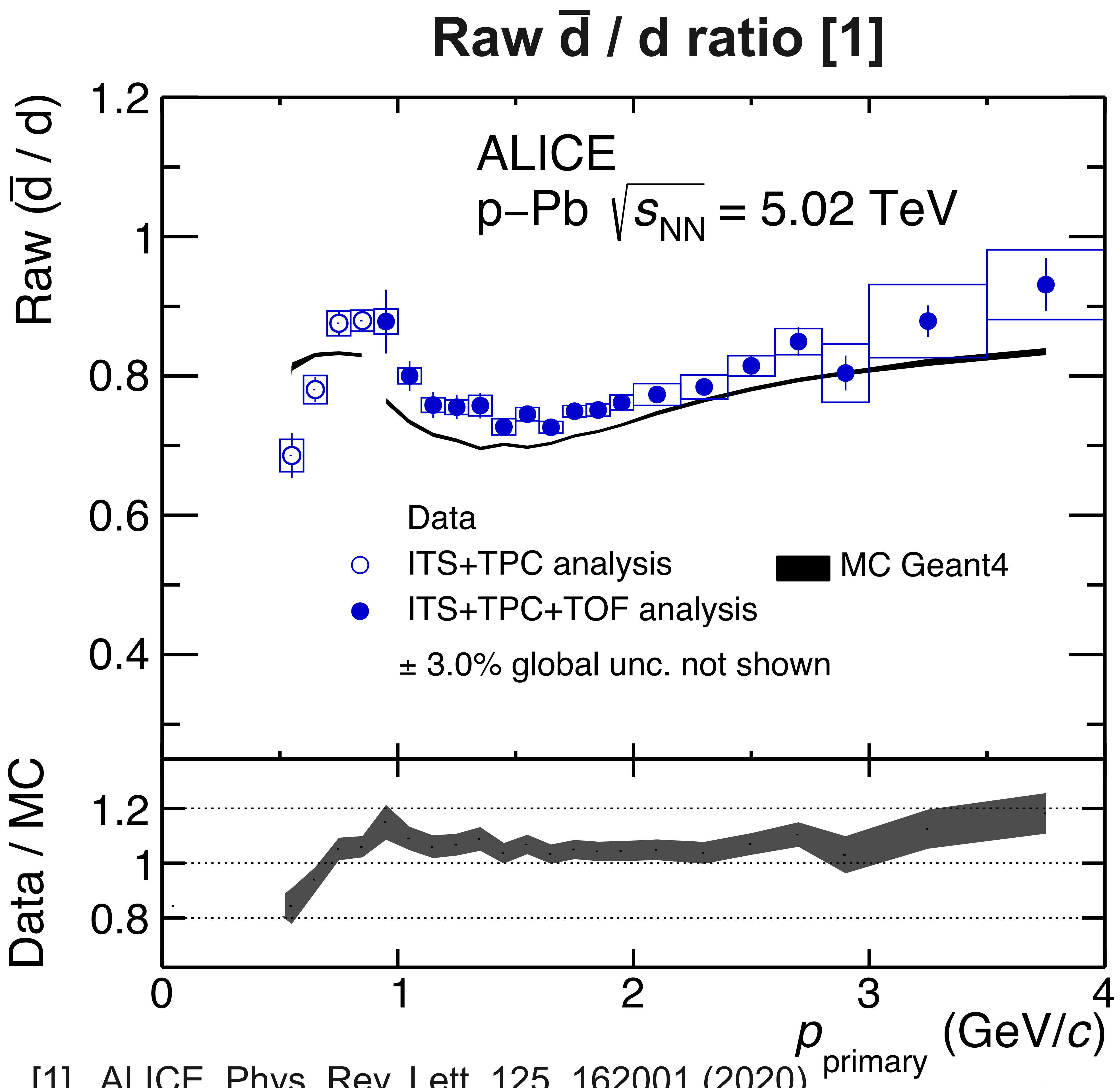

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Vary $\sigma_{inel}(\bar{d})$ in simulations until MC describes the experimental results → constraints on $\sigma_{inel}(\bar{d})$

- σ_{inel}(d) is fixed to the Geant4 parameterisations (describe well exp. data on σ_{inel}(d))

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Extraction of $\sigma_{inel}(\bar{d})$

In each momentum bin, exp. data are compared to MC simulations with varied $\sigma_{inel}(\bar{d})$

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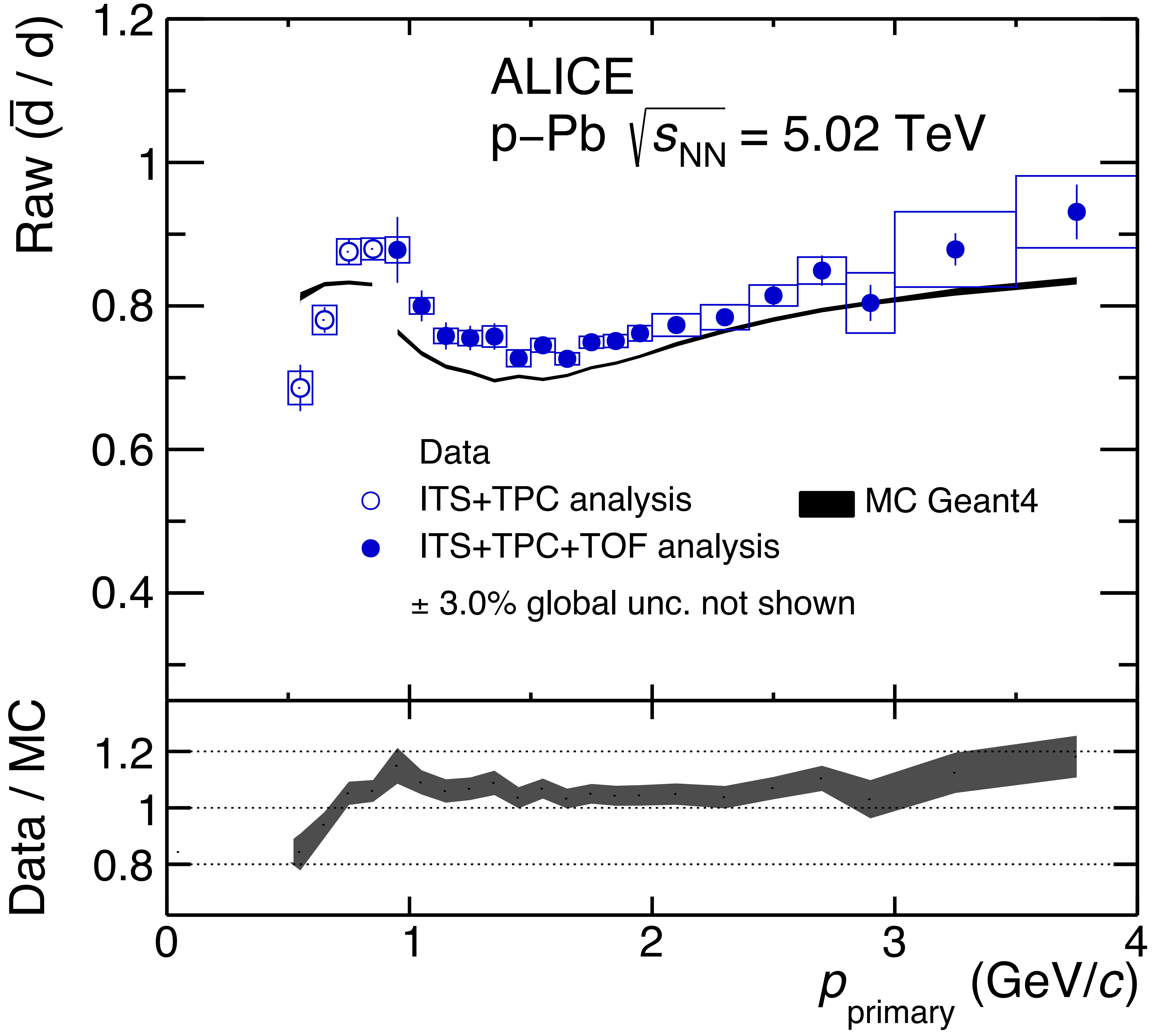

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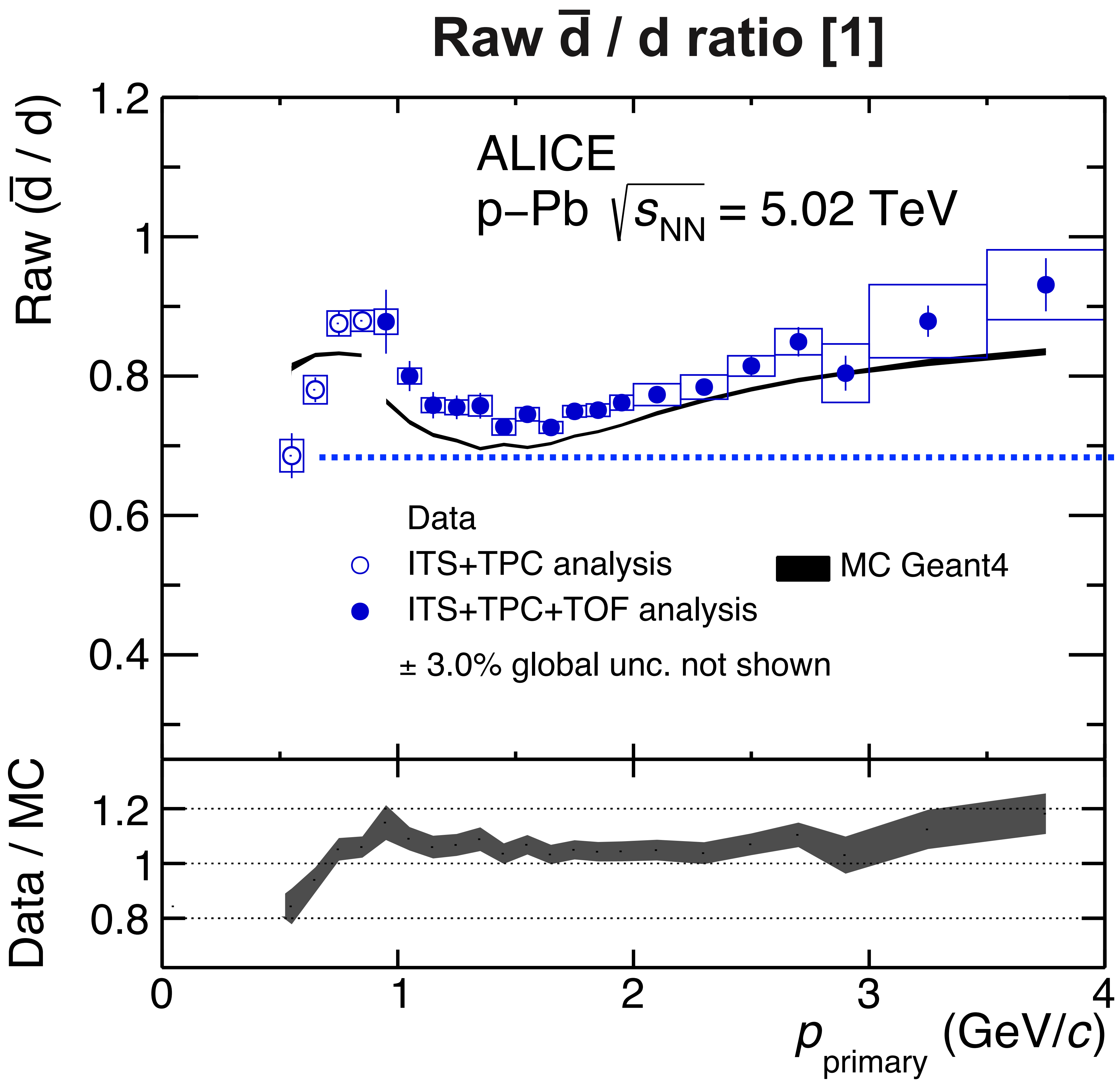

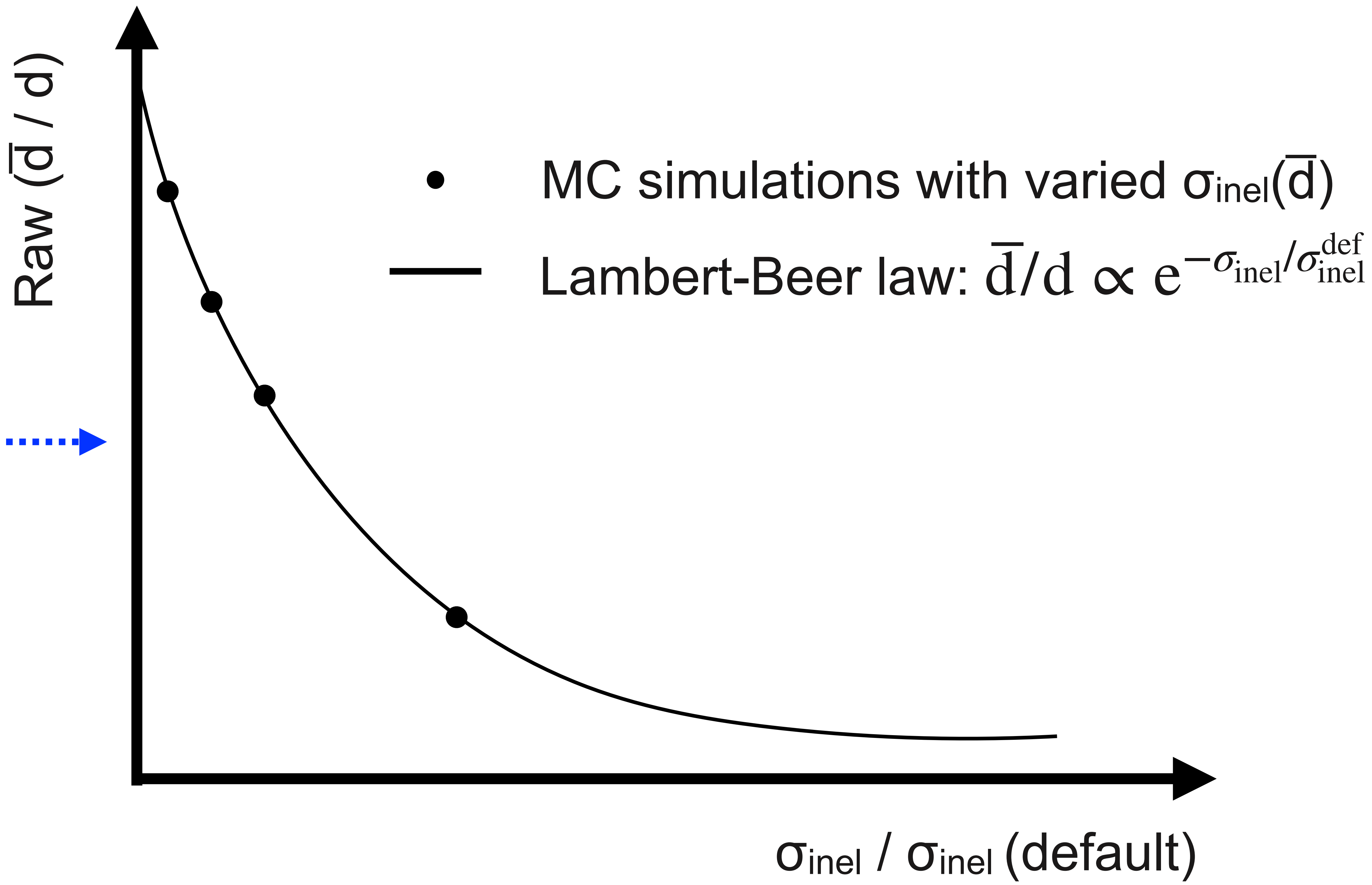

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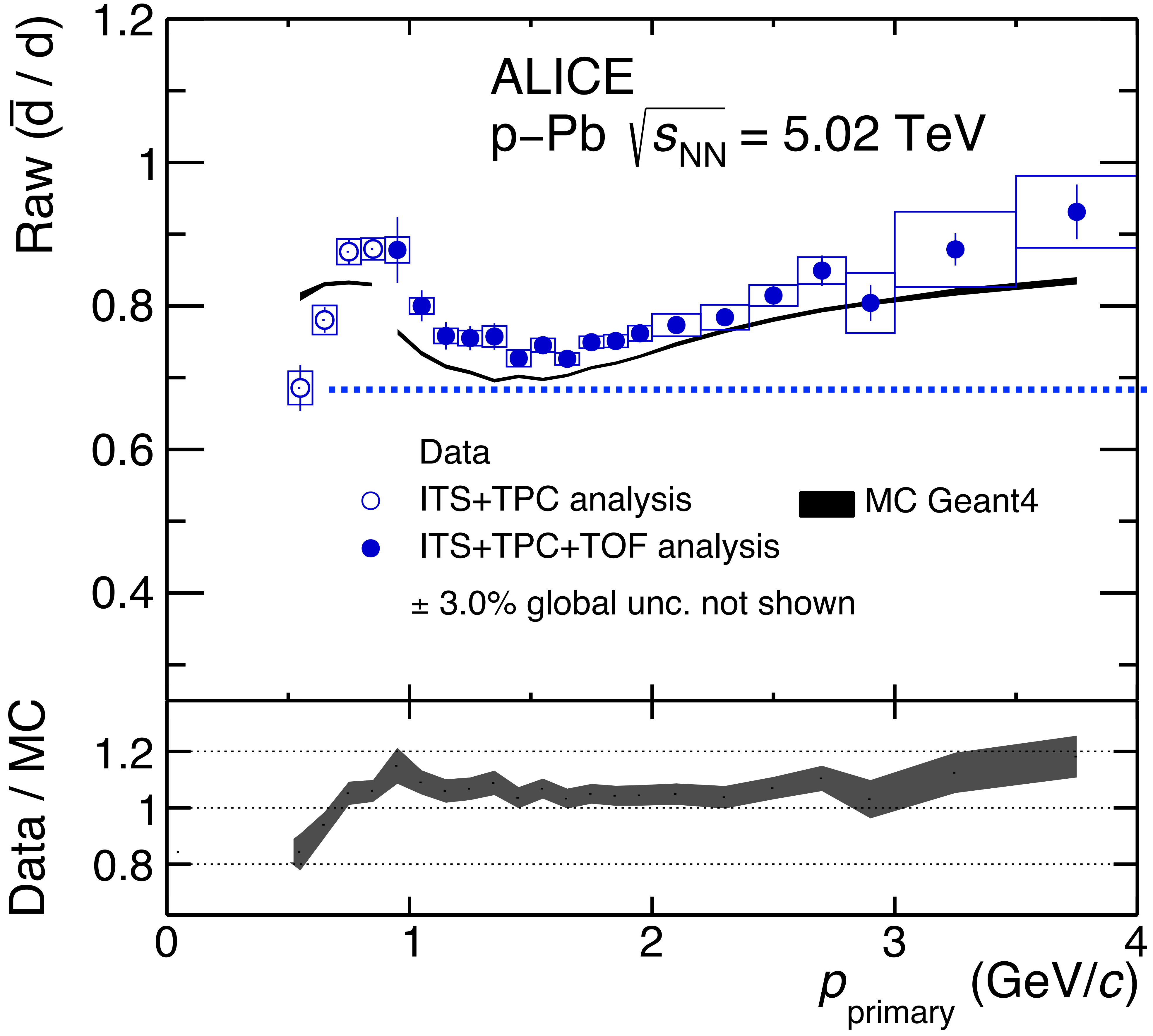

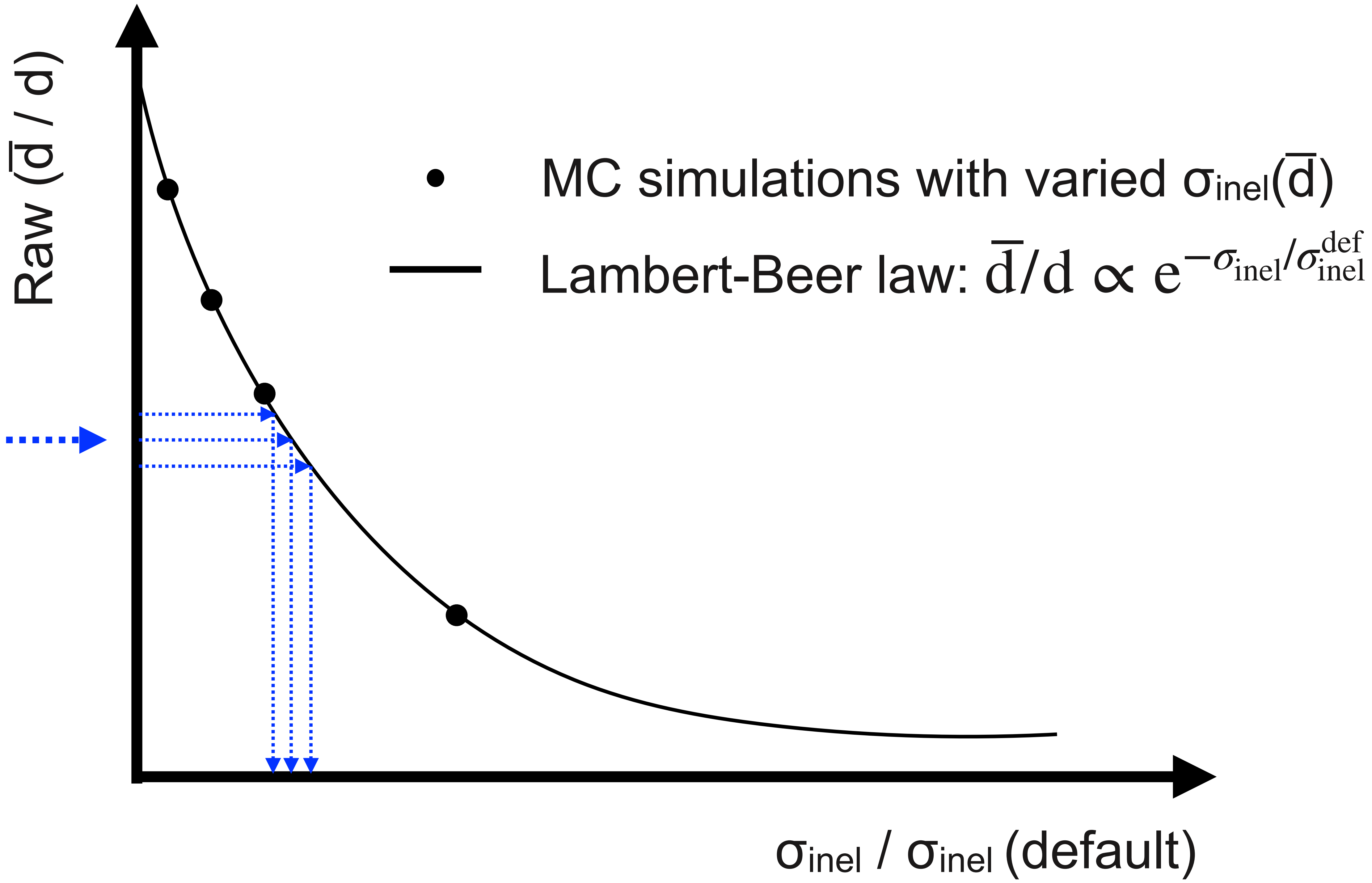

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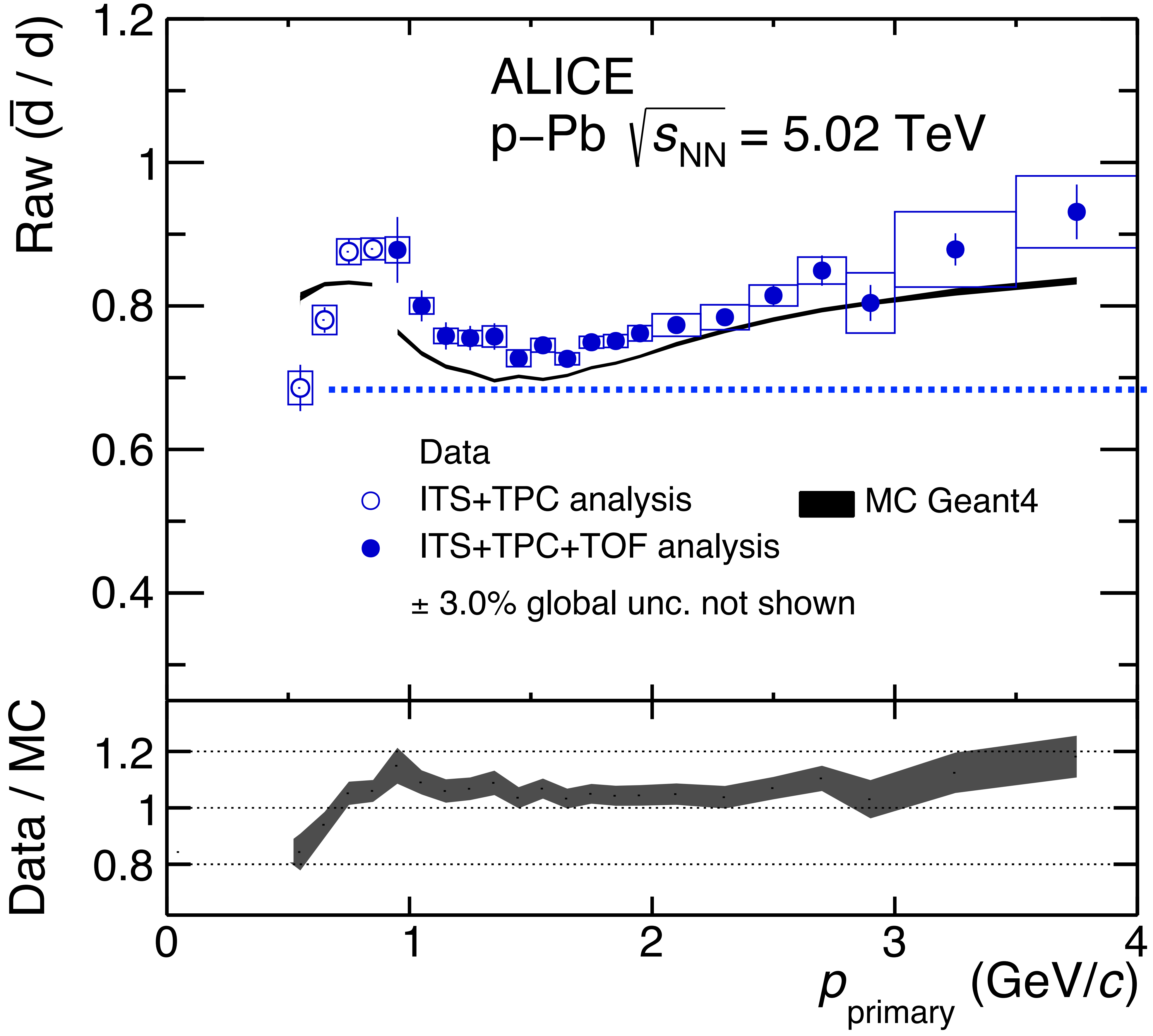

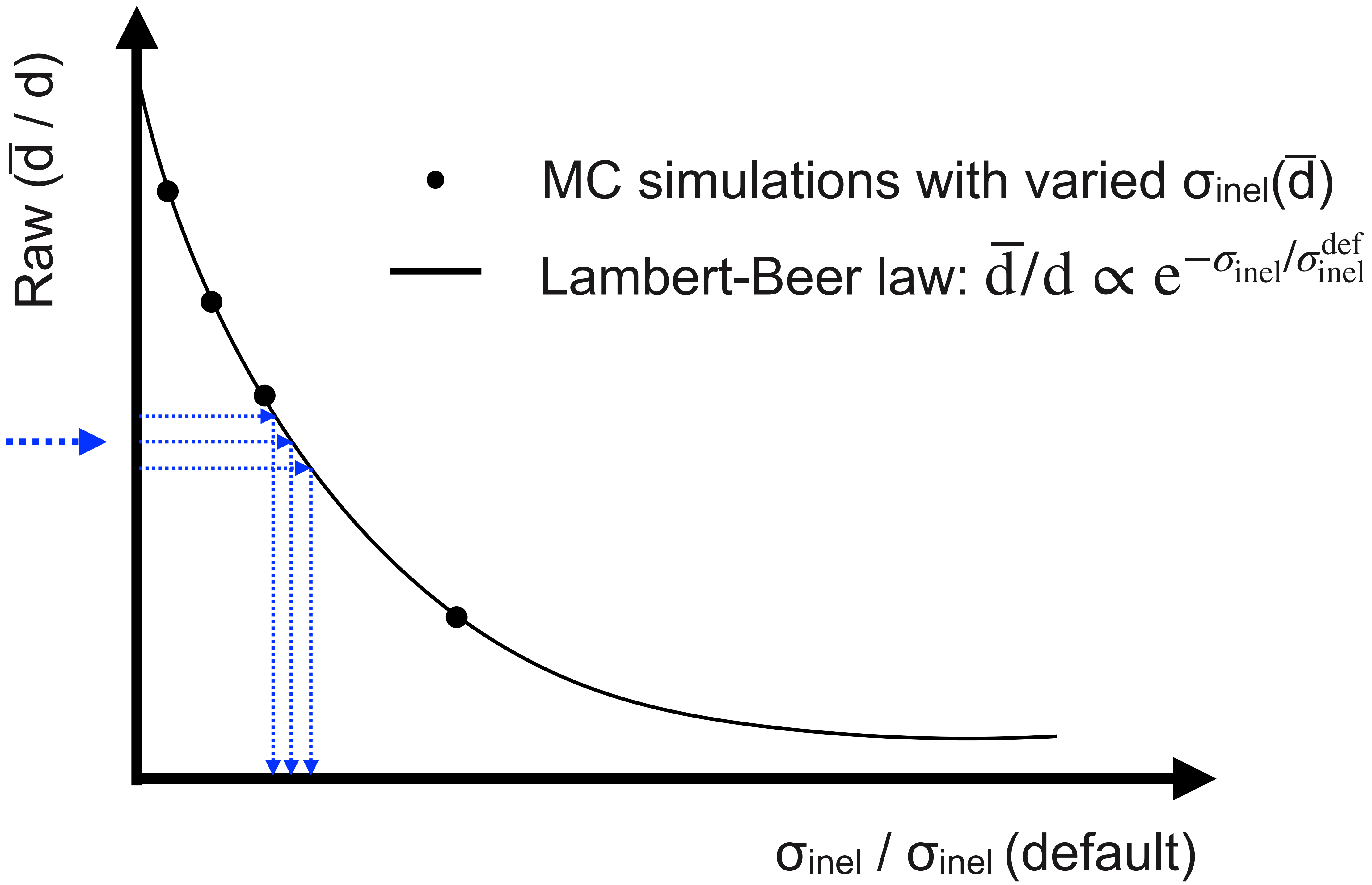

$$\sigma_{inel}(\bar{d}+\langle A\rangle) = \sigma_{inel}^{Geant4}(\bar{d}+\langle A\rangle)\times \text{ corr. factor}$$

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Results for $\sigma_{inel}(\bar{d})$

High p region (TOF analysis): good agreement with Geant4 parameterisations

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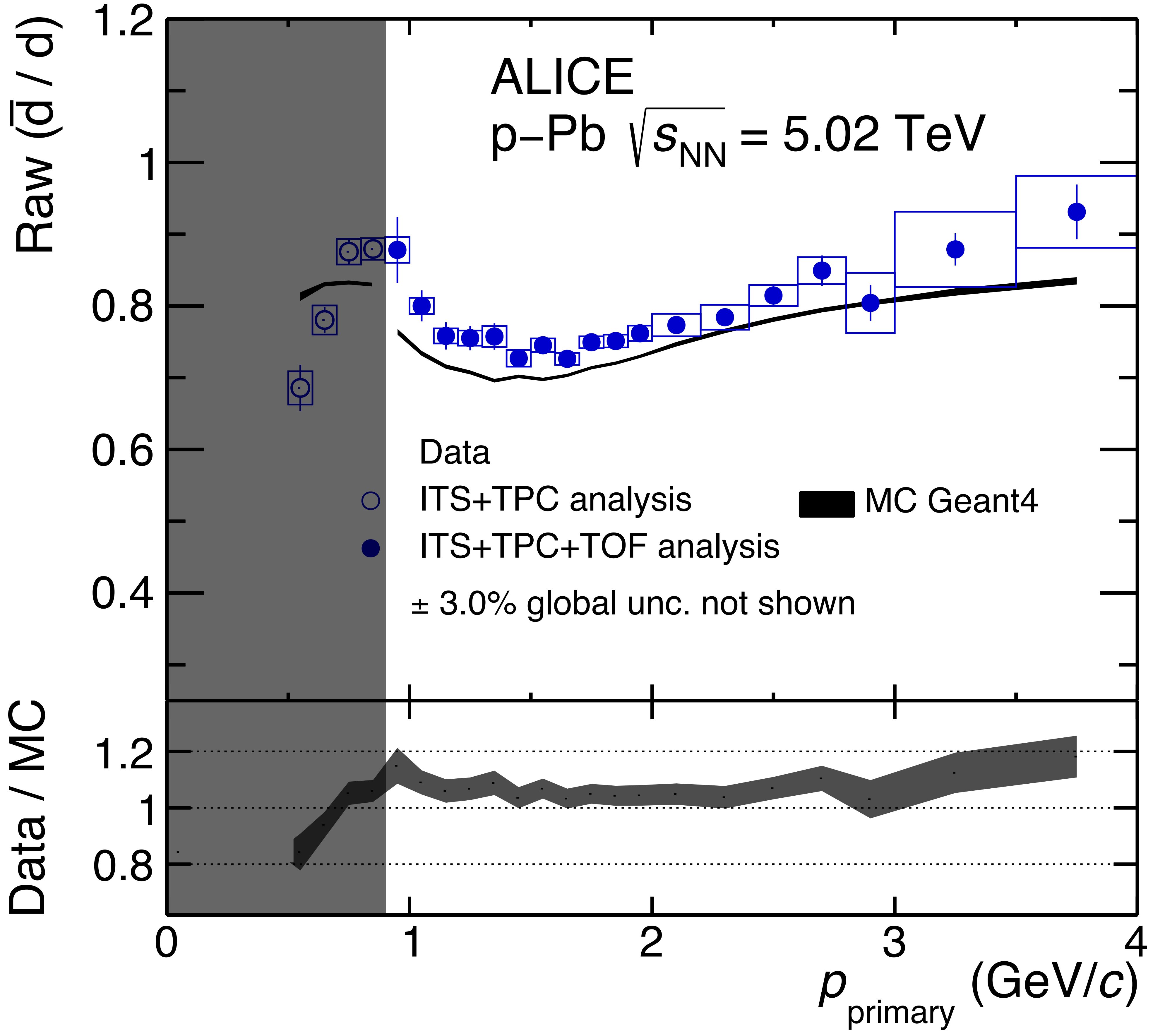
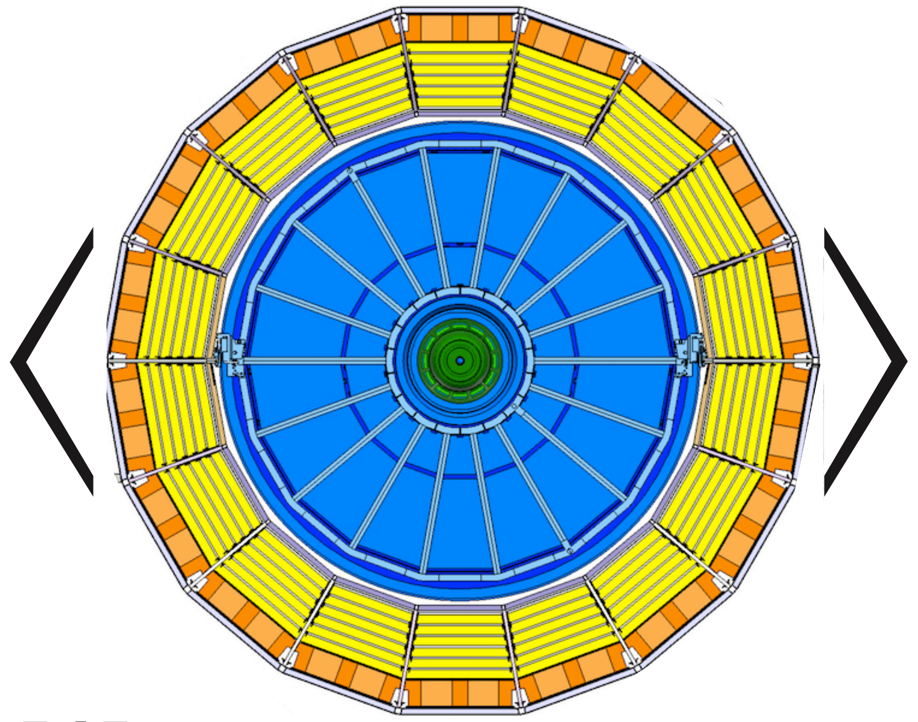
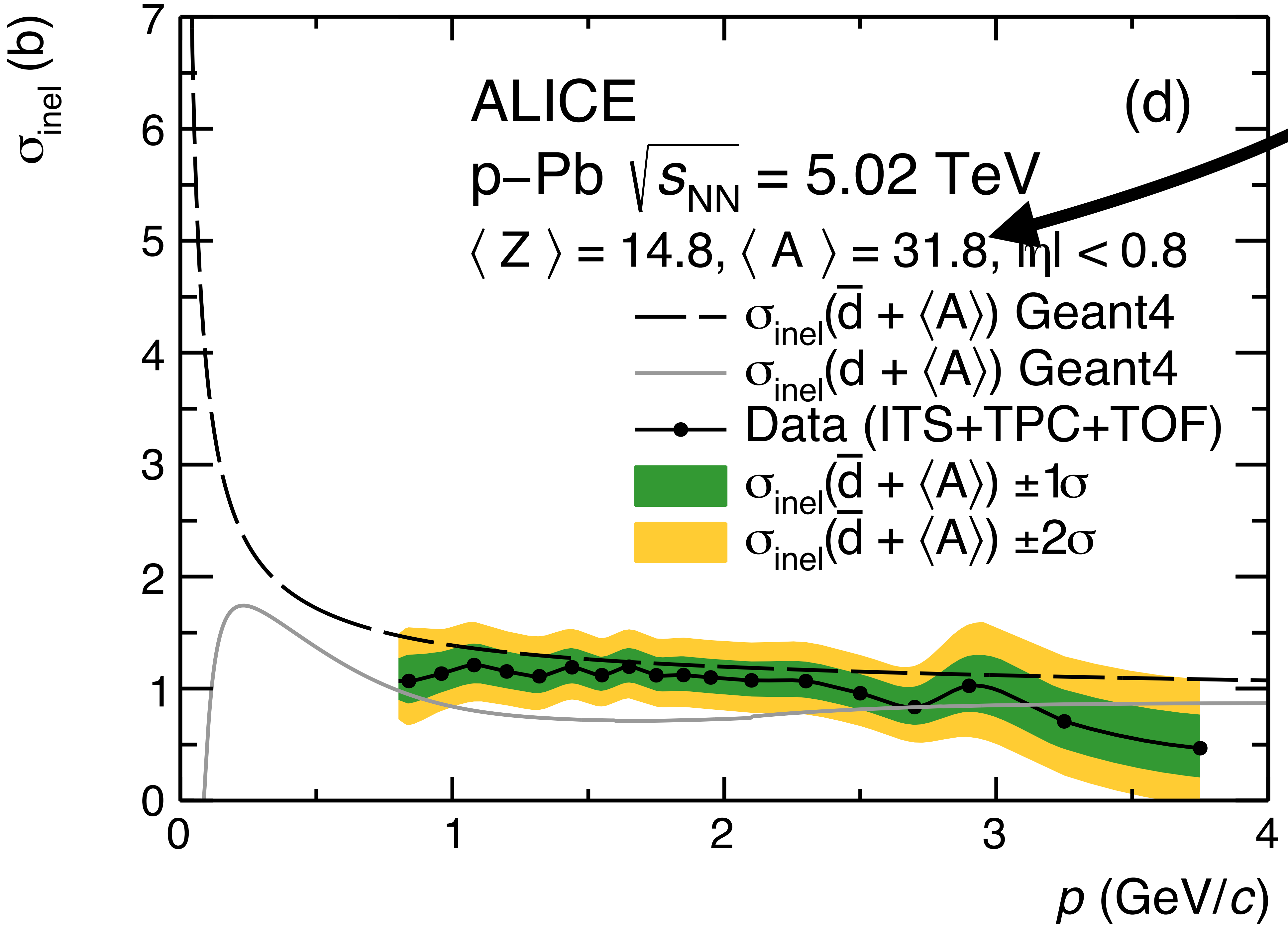


First experimental information on $\sigma_{inel}(\bar{d})$ at low momentum!



$\sigma_{inel}(\bar{d})$ on averaged ALICE material [1]



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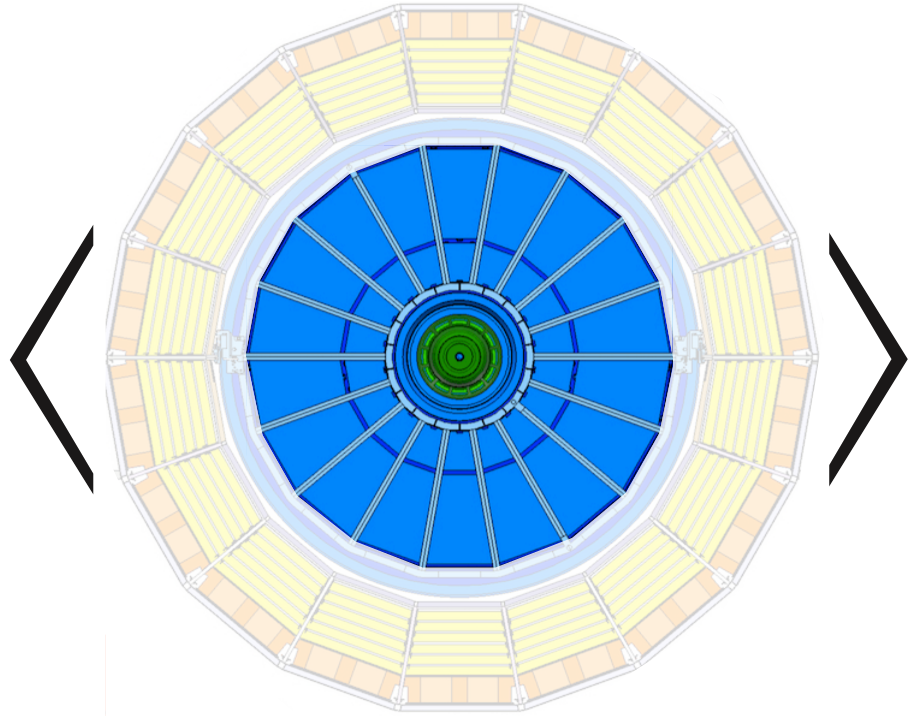
Low p region (ITS-TPC analysis): hint for steeper rise of $\sigma_{inel}(\bar{d})$ than in Geant4!



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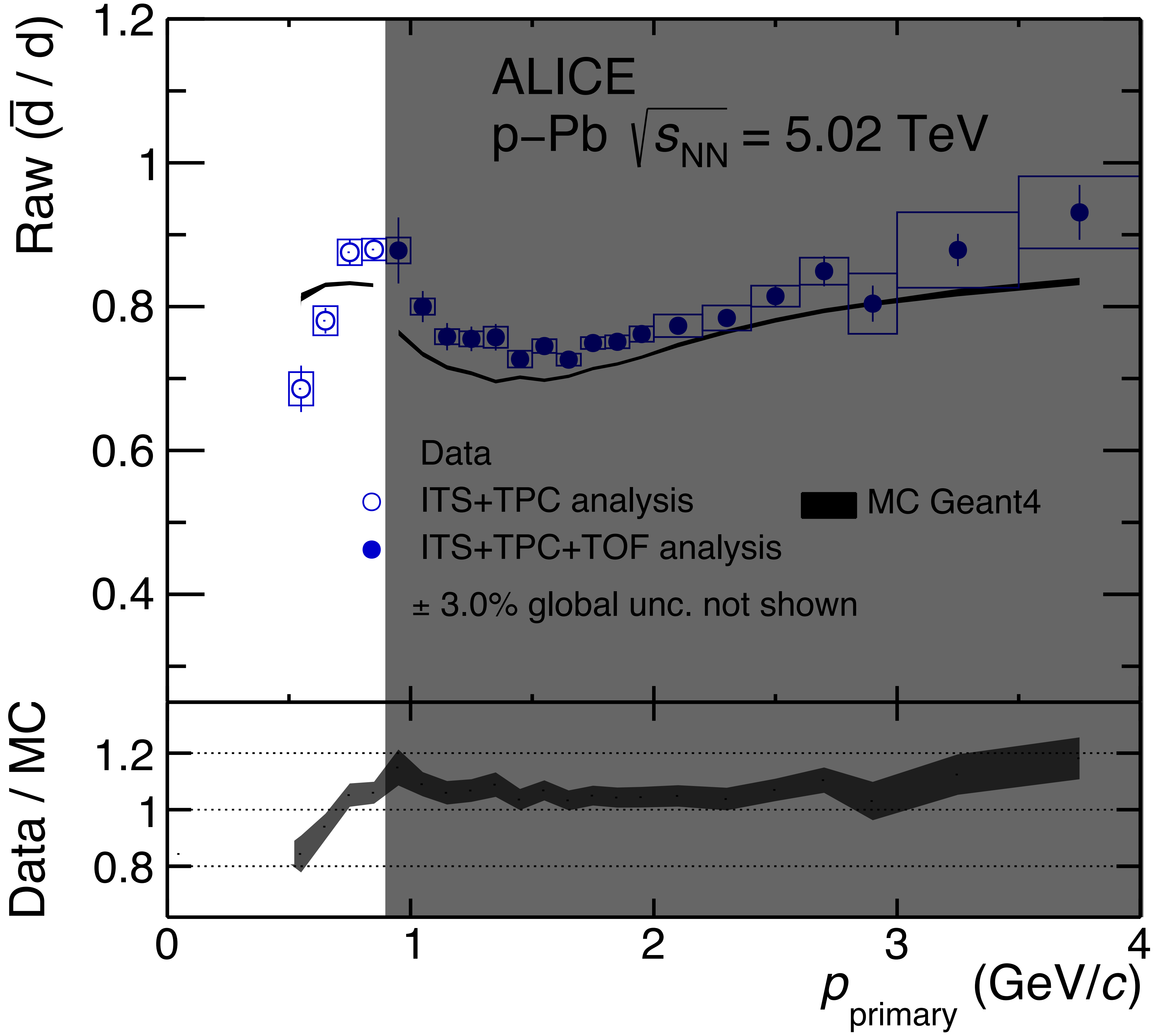

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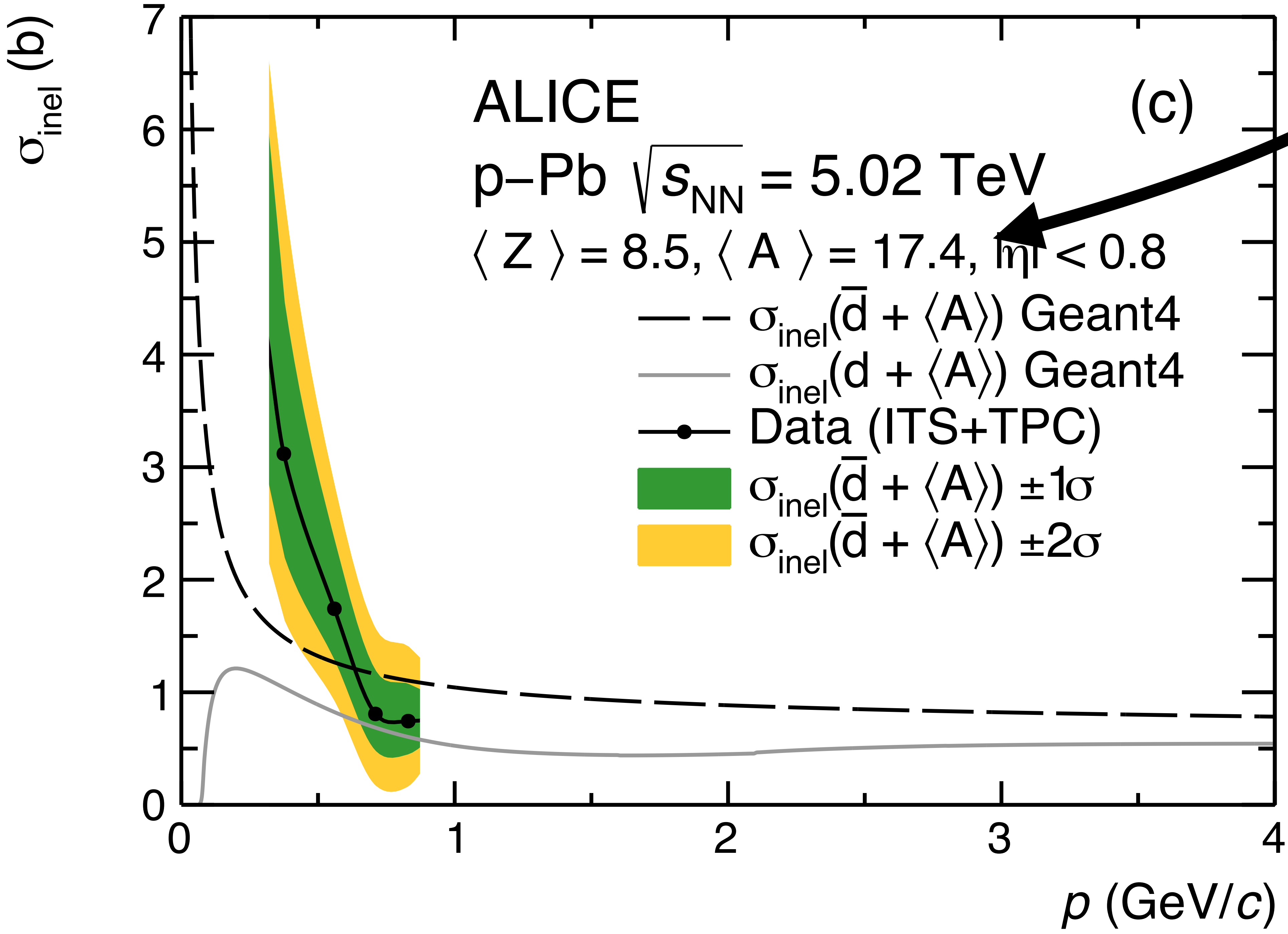

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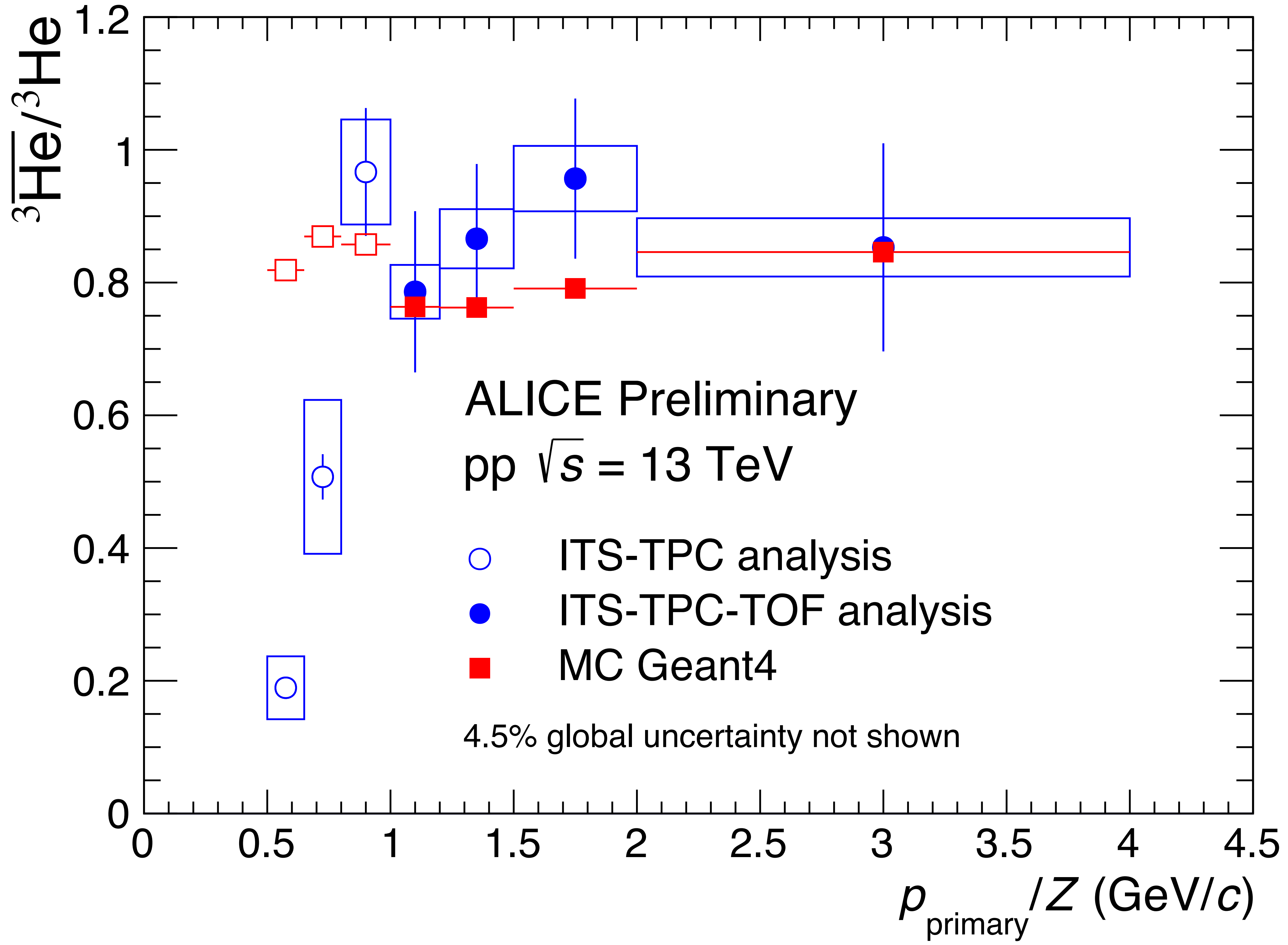
Results for $\sigma_{inel}(^3\overline{He})$

- Antimatter-to-matter ratio method (used in pp collisions) or TPC-to-TOF matching (for PbPb collisions)
- Low-momentum range: much steeper rise of $\sigma_{inel}(^3\overline{He})$ than predicted by Geant4
- *First experimental information on* $\sigma_{inel}(^3\overline{He})$*!*

Raw $^3\overline{He}$ / ^3He ratio in pp collisions



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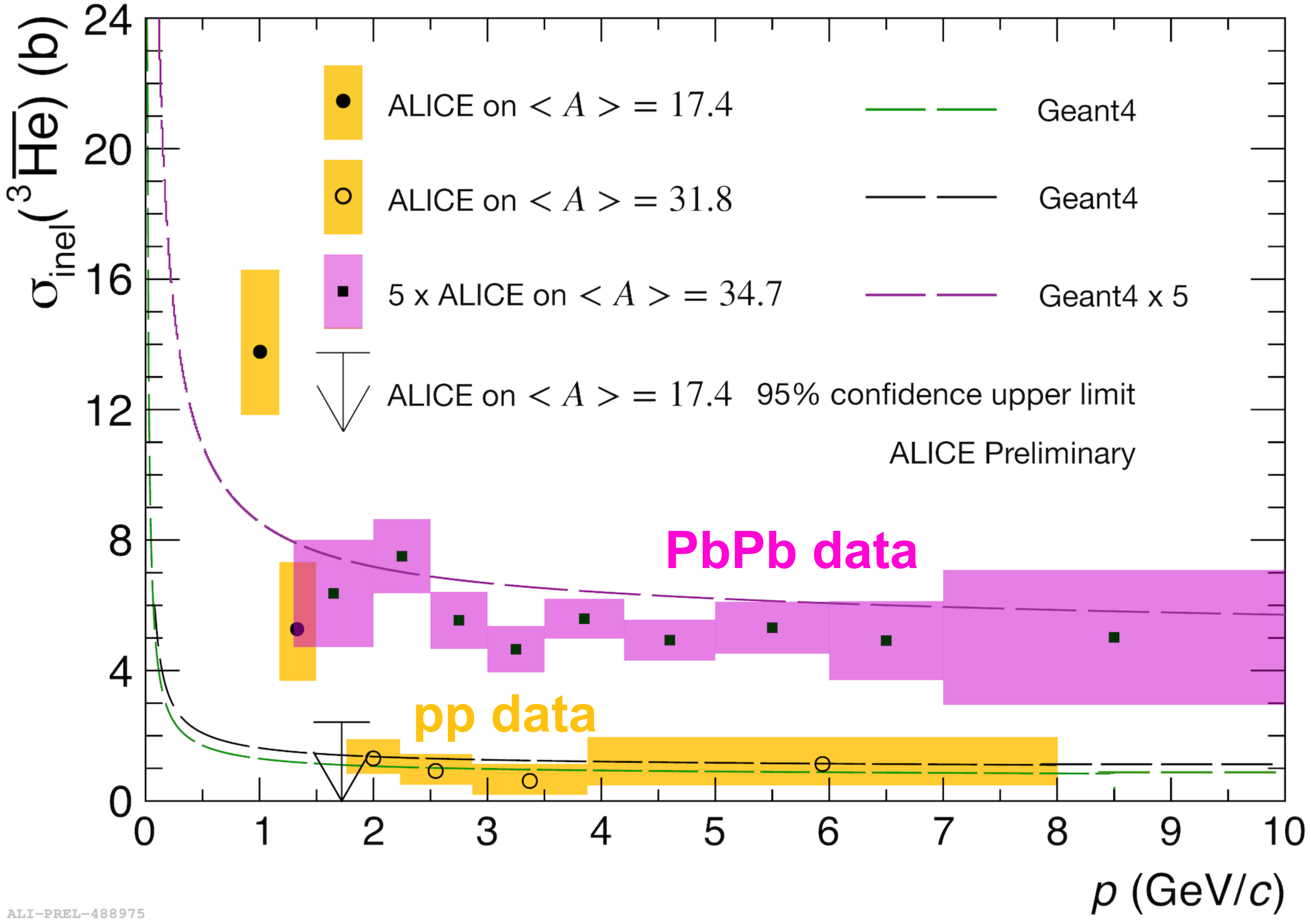

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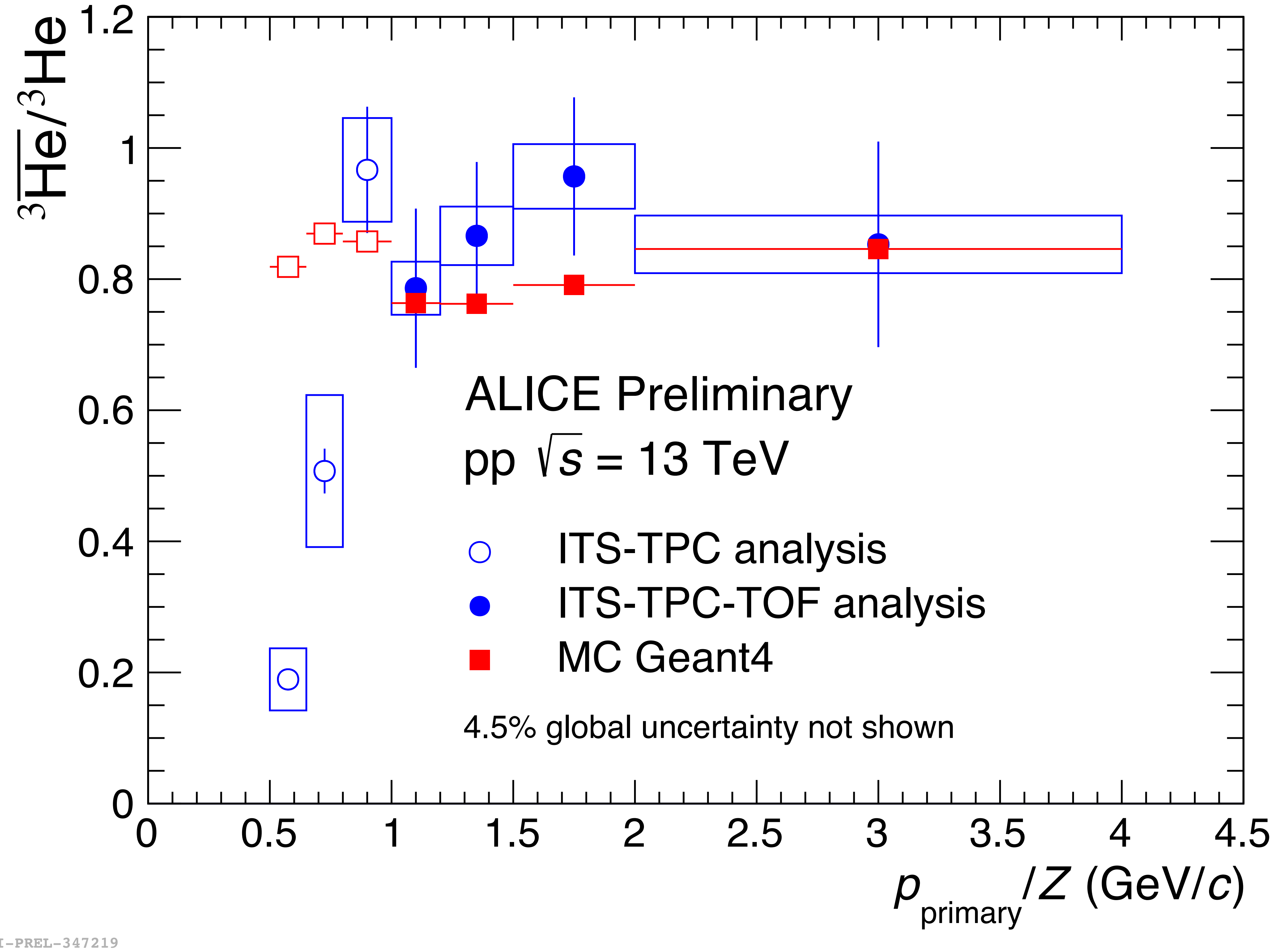

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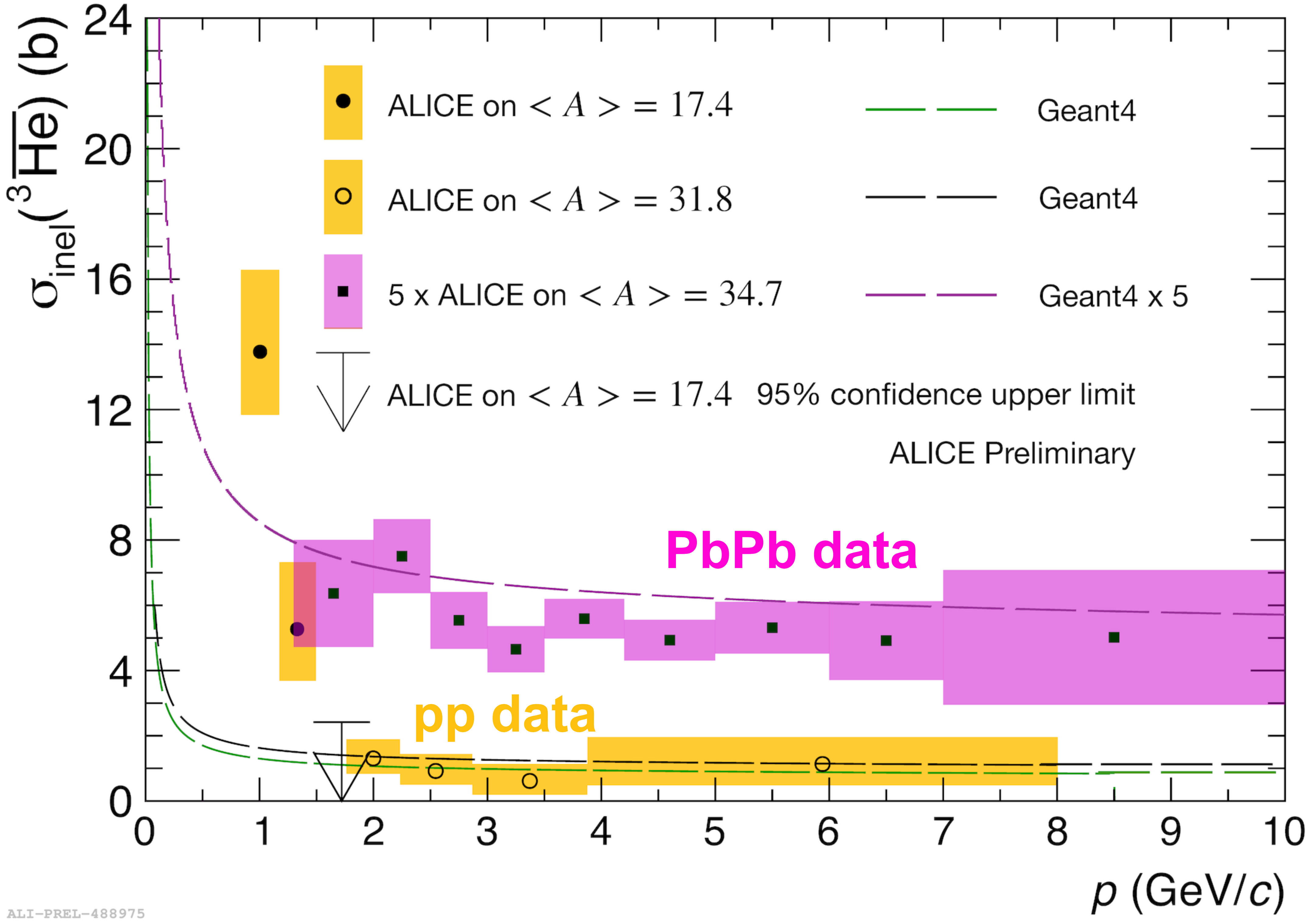


What is the impact of these measurements on the antinuclei fluxes near Earth?

Recipe to cook antinuclei fluxes

ALICE

Propagation of $^{3}\overline{\text{He}}$ in the Galaxy

Transport equation to be solved:

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

Source Function

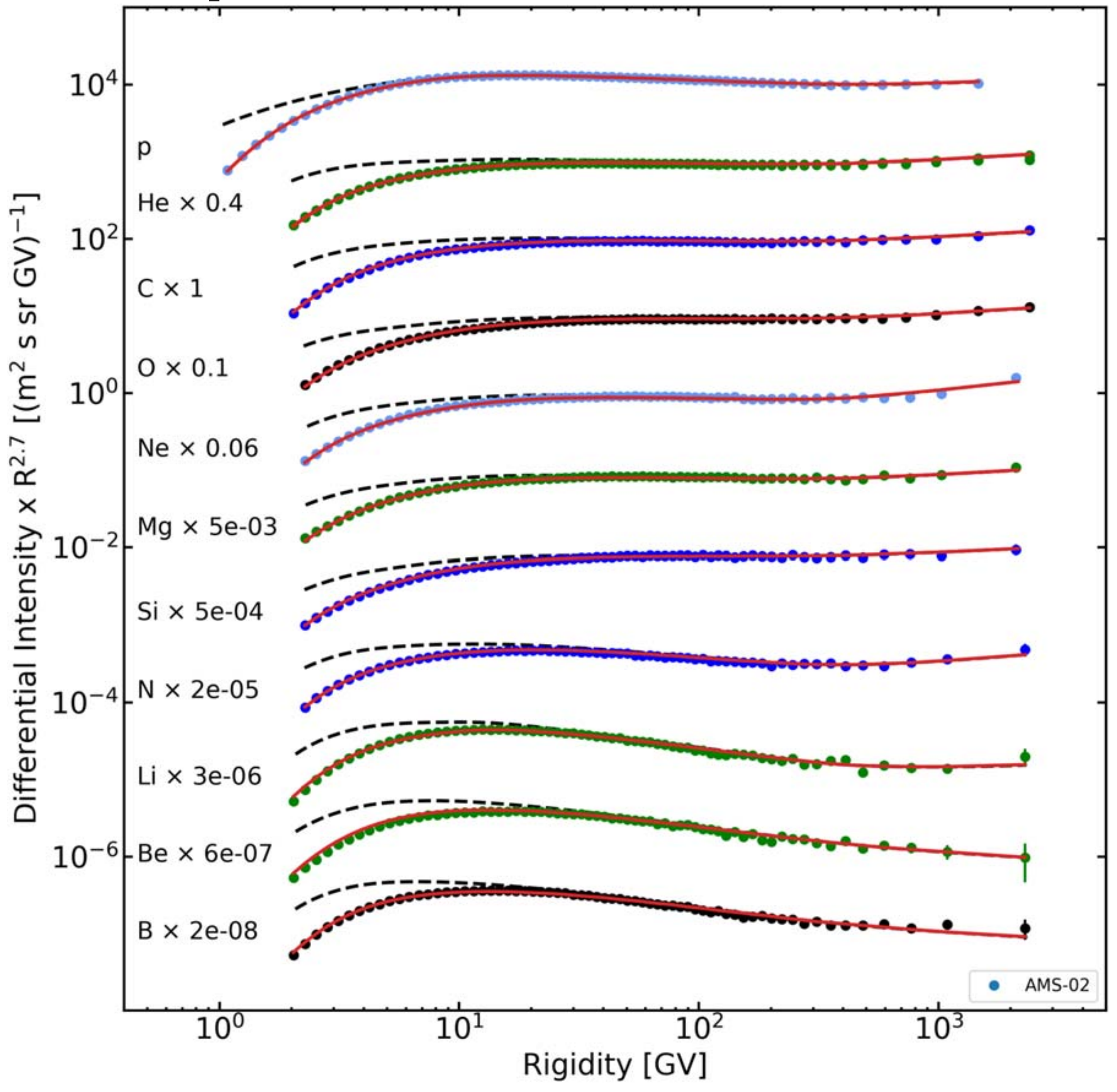
Propagation: diffusion, convection…

Fragmentation, inel. interactions

Can be numerically solved using **GALPROP** code [1]

Propagation parameters (common for all (anti)nuclei) can be constrained from available cosmic ray measurements

Comparison with AMS-02 data [2]



[1] https://galprop.stanford.edu
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The calculation of $^3\overline{\text{He}}$ flux requires:

- source function: differential production cross section [3, 4]
- inelastic cross section (from ALICE measurements)

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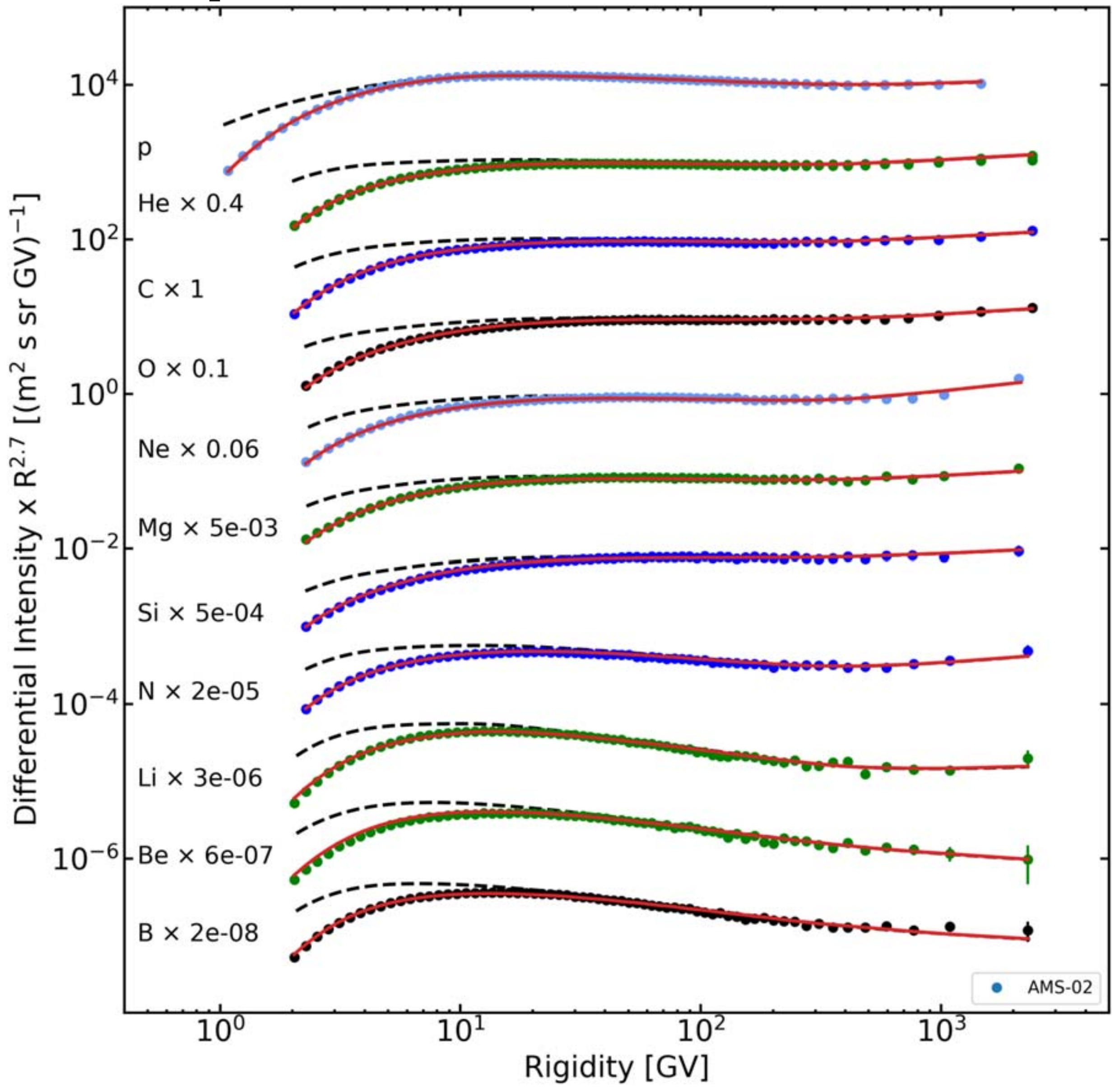

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[3] Shukla et al., Phys. Rev. D. 102, 063004 (2020)
[4] Carlson et al., Phys. Rev. D. 89, 076005 (2014)

ALICE

$^{3}\overline{\mathrm{He}}$ source function: dark matter

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

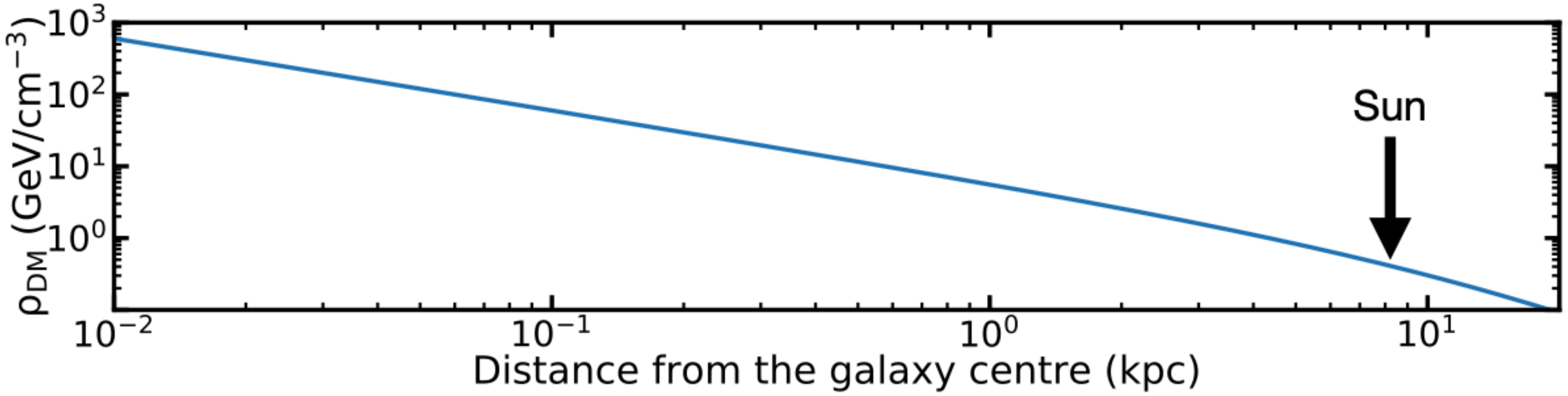
- ρ_{DM} - according to NFW profile [1]
- m_χ = 100 GeV, annihilation into W^+W^-
- $\langle\sigma v\rangle$ = 2.6x10^{-26} $\mathrm{cm^3 s^{-1}}$ [2]
- dN/dE_{kin} from [1] (PYTHIA 8 with event-by-event coalescence afterburner)

[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 function: dark matter

ALICE

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



- ρ_{DM} - according to NFW profile [1]
- m_χ = 100 GeV, annihilation into W^+W^-
- $\langle \sigma v \rangle$ = 2.6x10^{-26} $\mathrm{cm}^3\mathrm{s}^{-1}$ [2]
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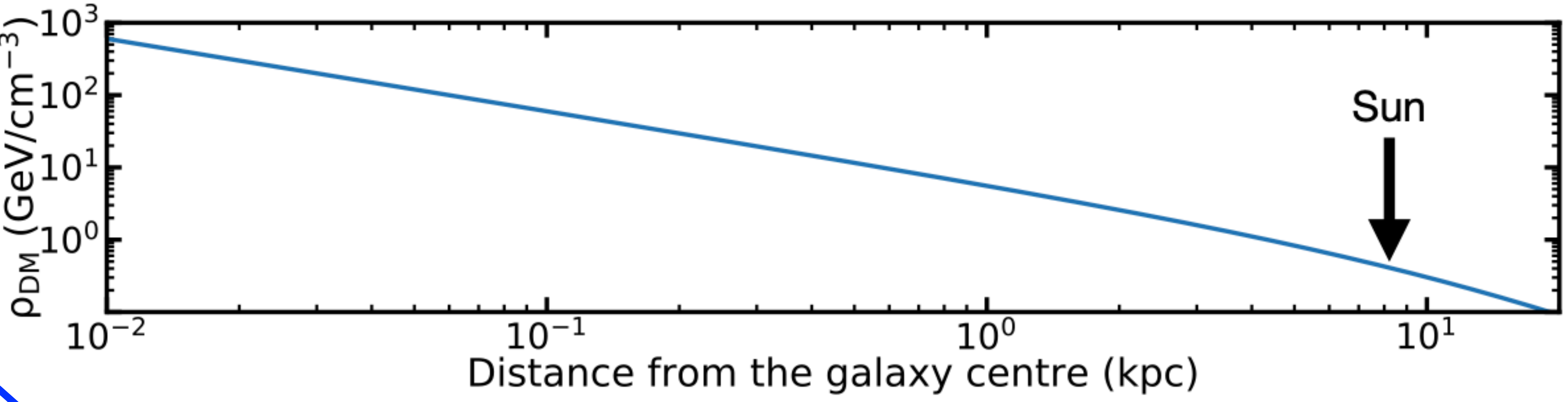

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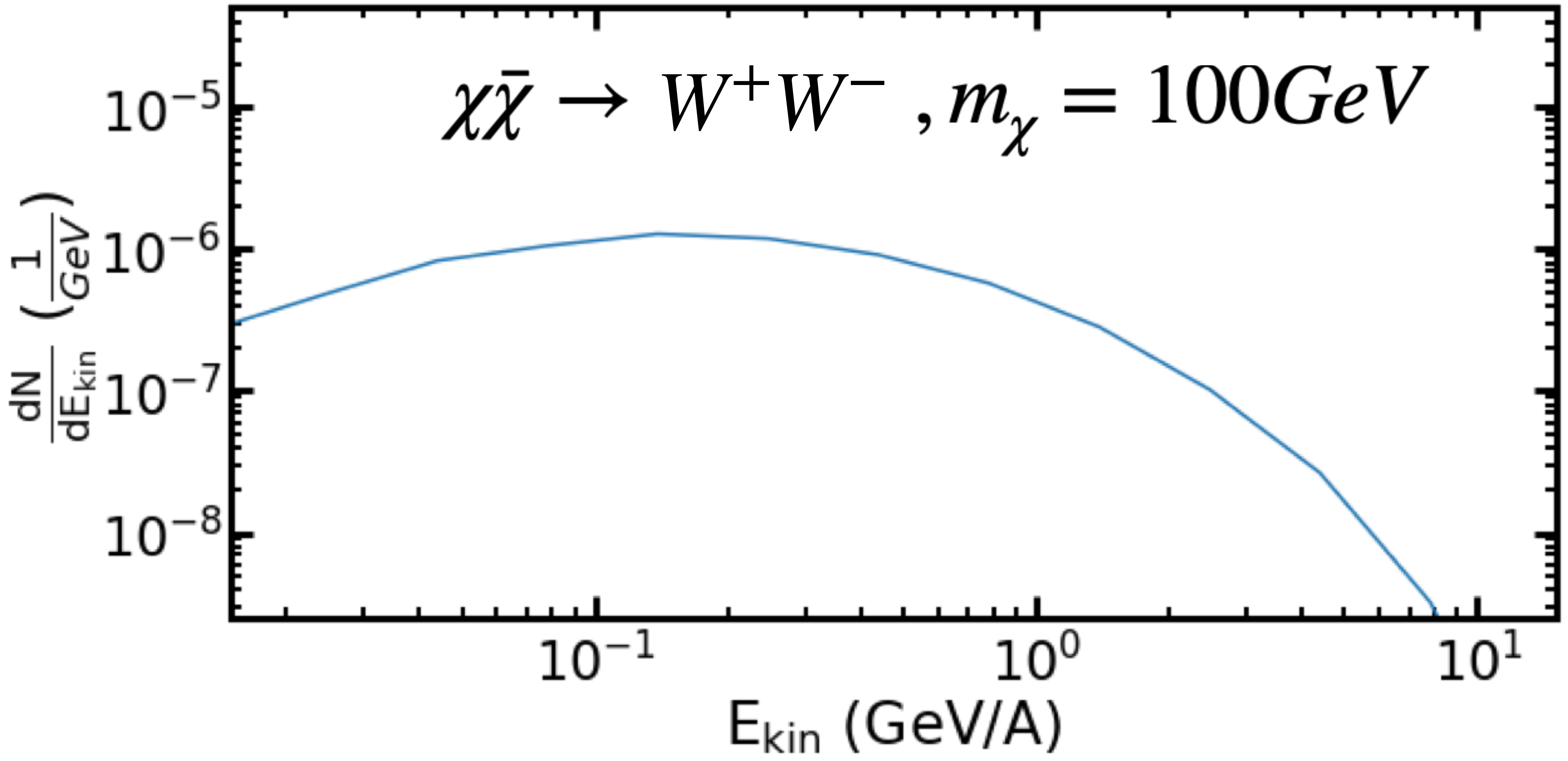
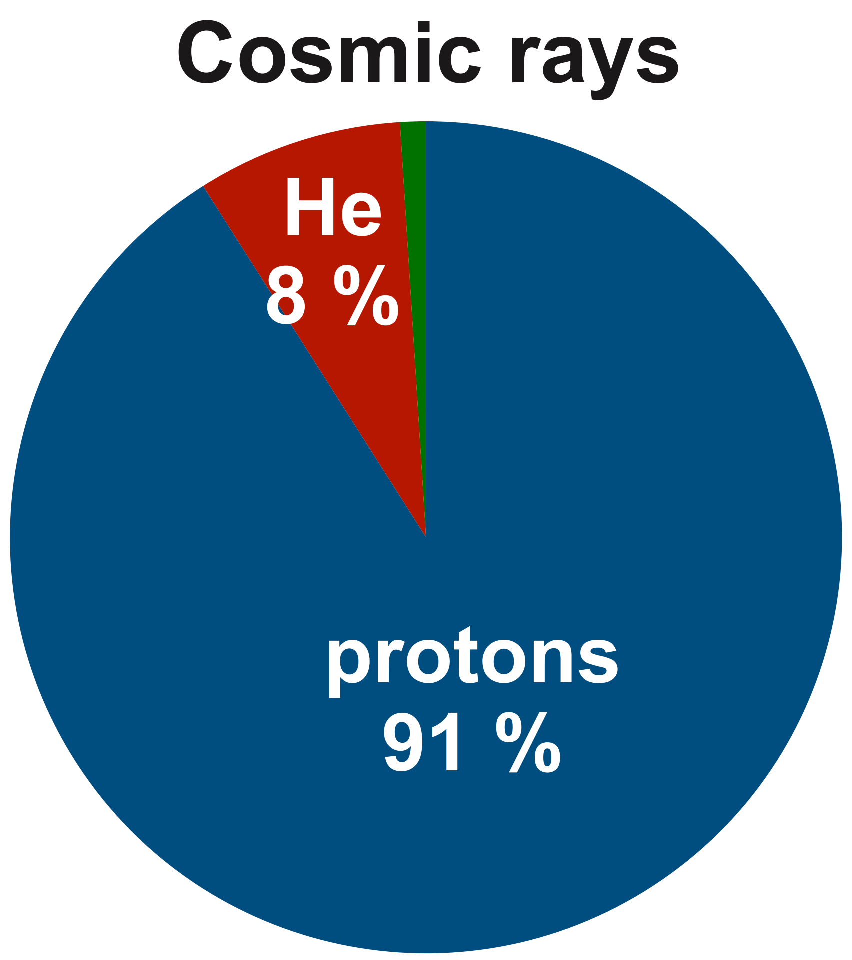
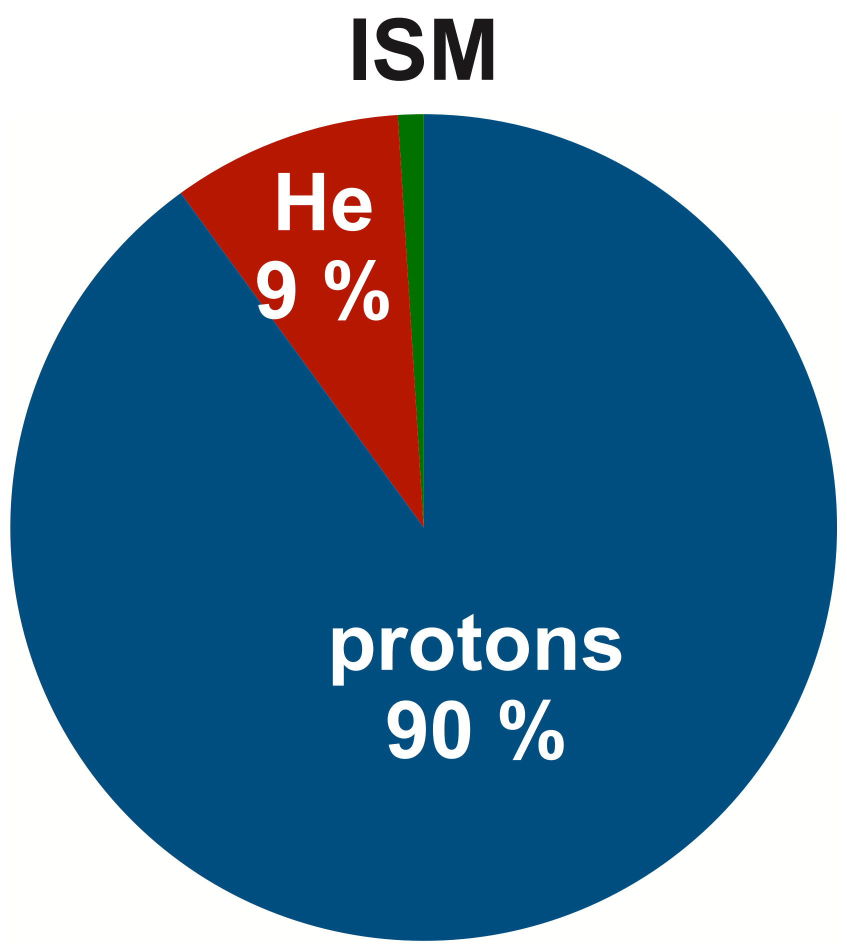


[1] Carlson et al., Phys. Rev. D. 89, 076005 (2014)
[2] Korsmeier et al., Phys. Rev. D. 97, 103011 (2018)

$^{3}\overline{\text{He}}$ source function: cosmic rays + ISM

Relevant collision systems: pp, p−He, He−p, He−He





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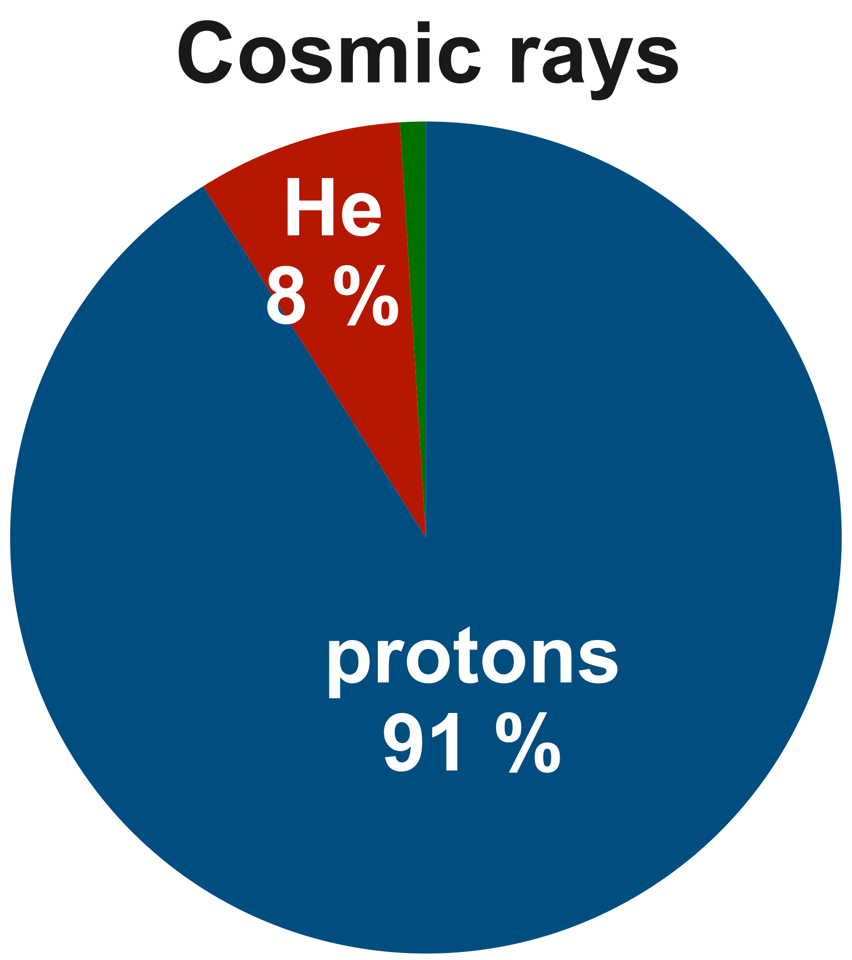
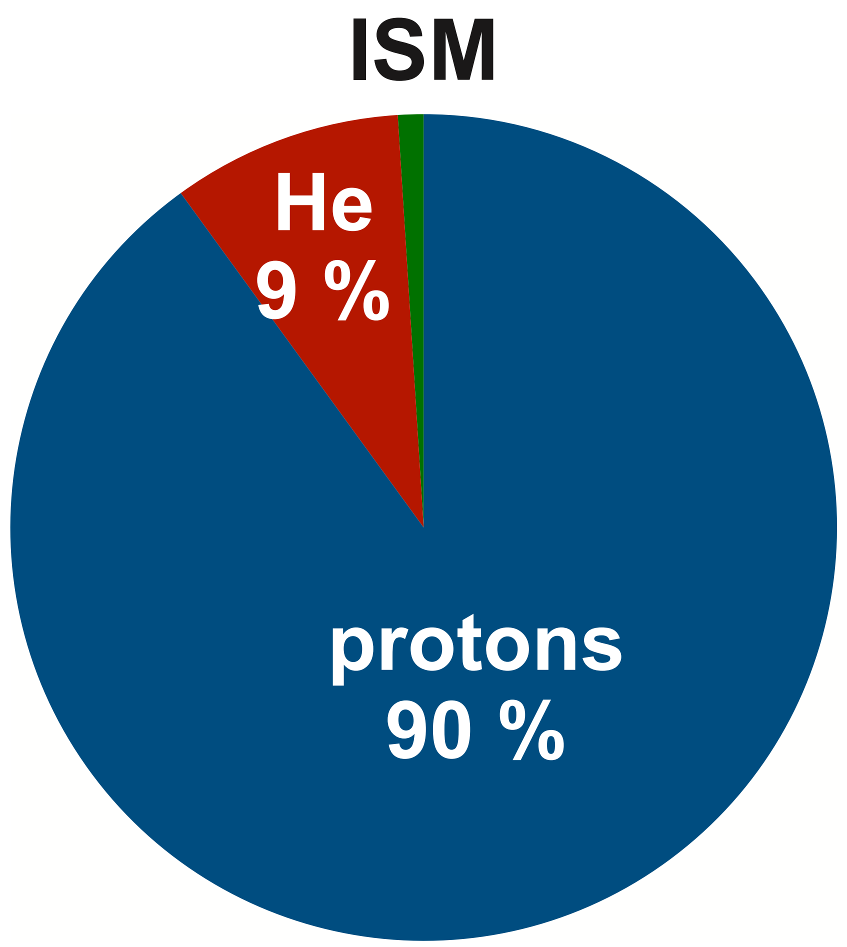
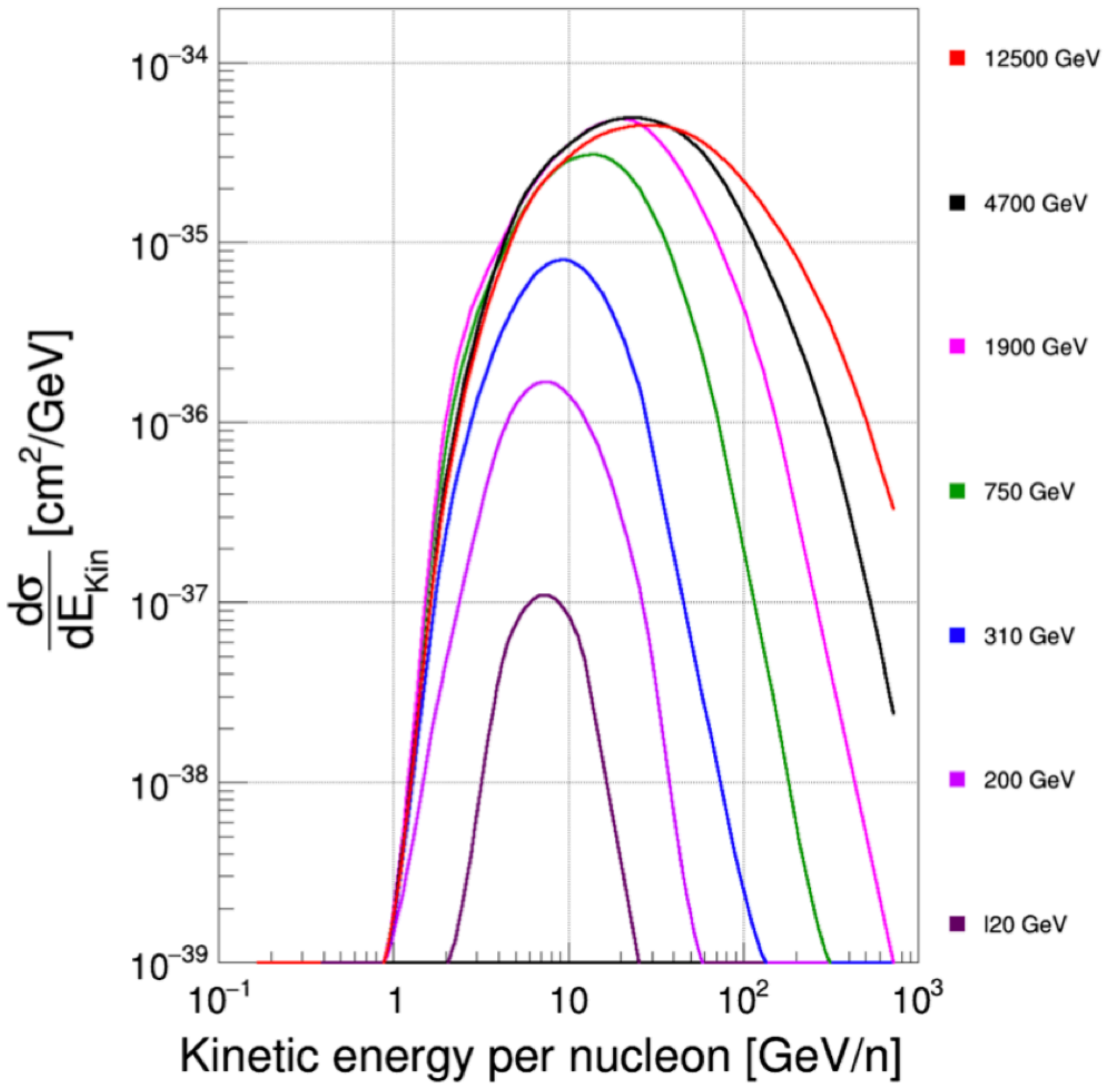
- Production cross section in pp collisions: from [1] (EPOS LHC + even-by-event coalescence afterburner)
- Other collision types scaled by $(A_T A_P)^{2.2/3}$





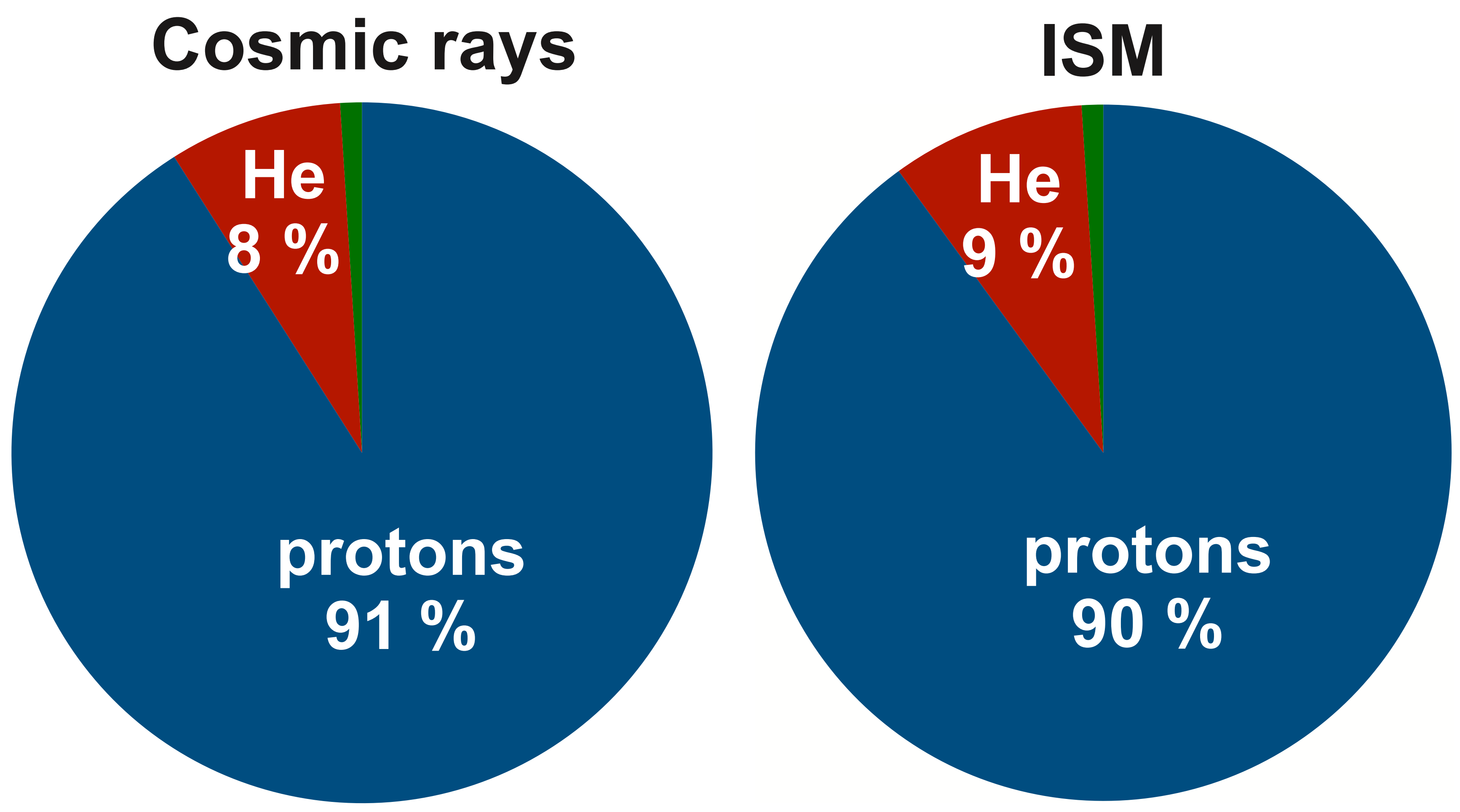
$^{3}\overline{\mathrm{He}}$ production in pp [1]



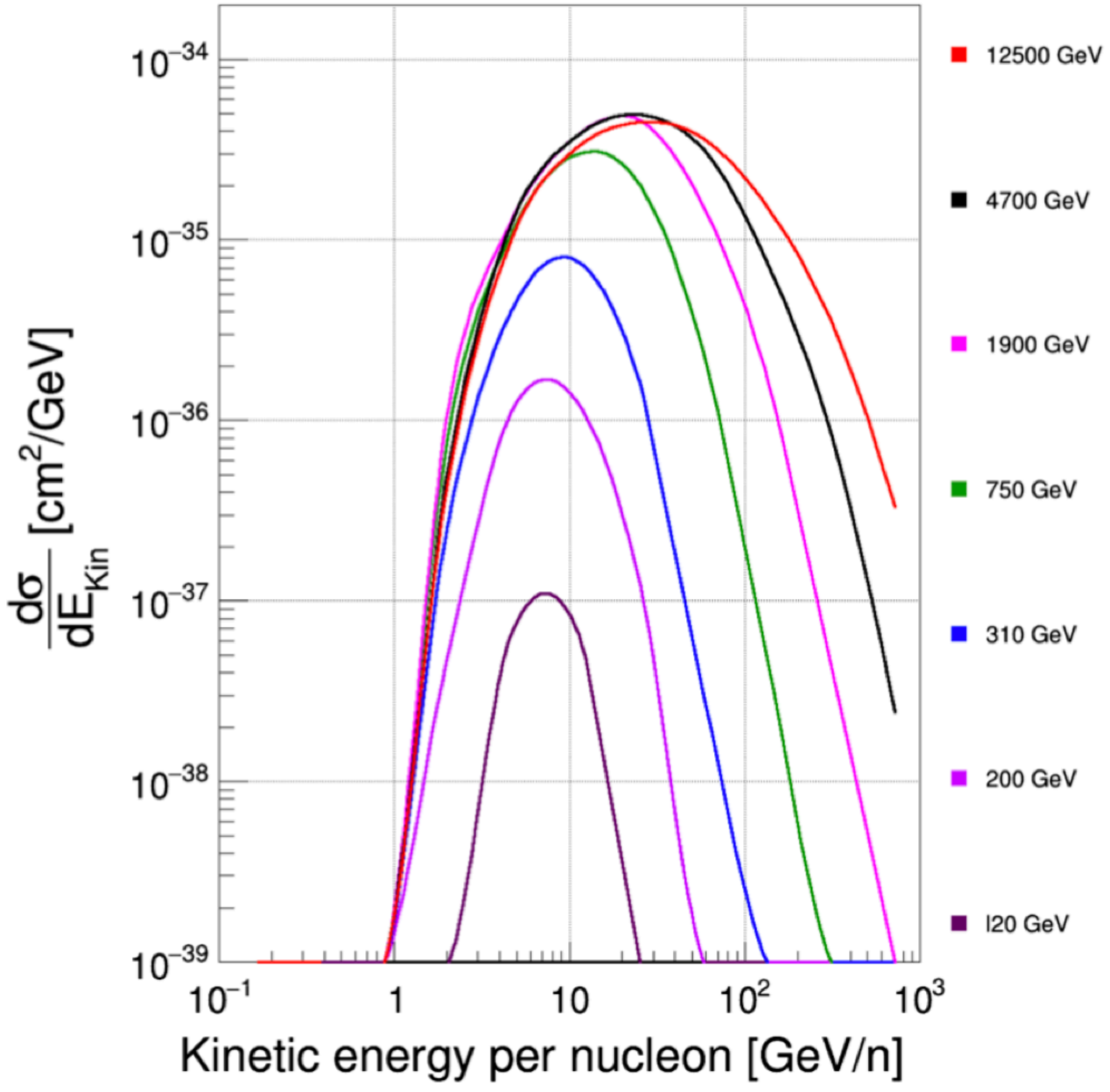
[1] Shukla et al., Phys. Rev. D. 102, 063004 (2020)

$^{3}\overline{\text{He}}$ source function: cosmic rays + ISM

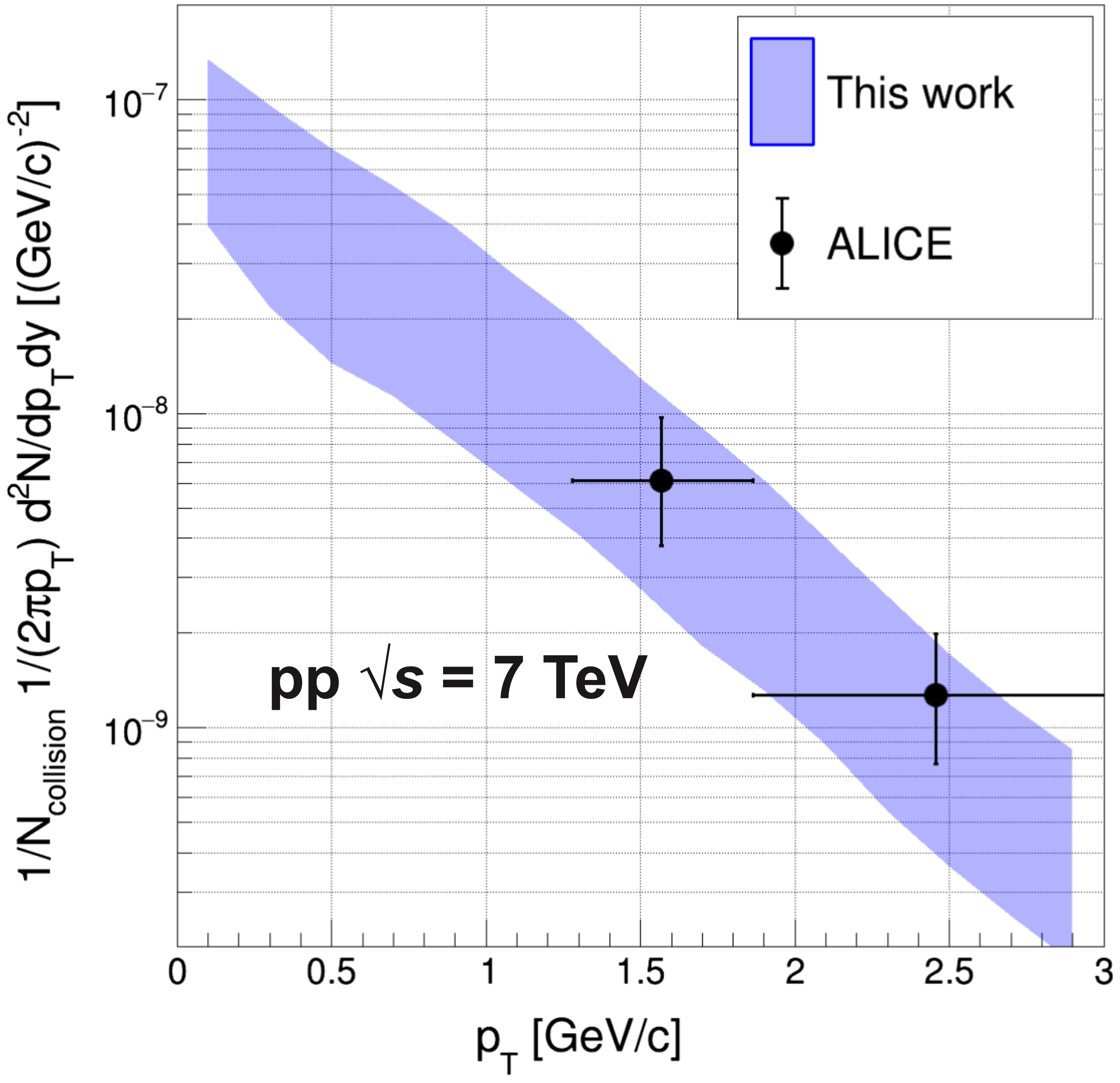
Relevant collision systems: pp, p−He, He−p, He−He
- Production cross section in pp collisions: from [1] (EPOS LHC + even-by-event coalescence afterburner)
- Other collision types scaled by $(A_T A_P)^{2.2/3}$
- Validated with the ALICE data [2]



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



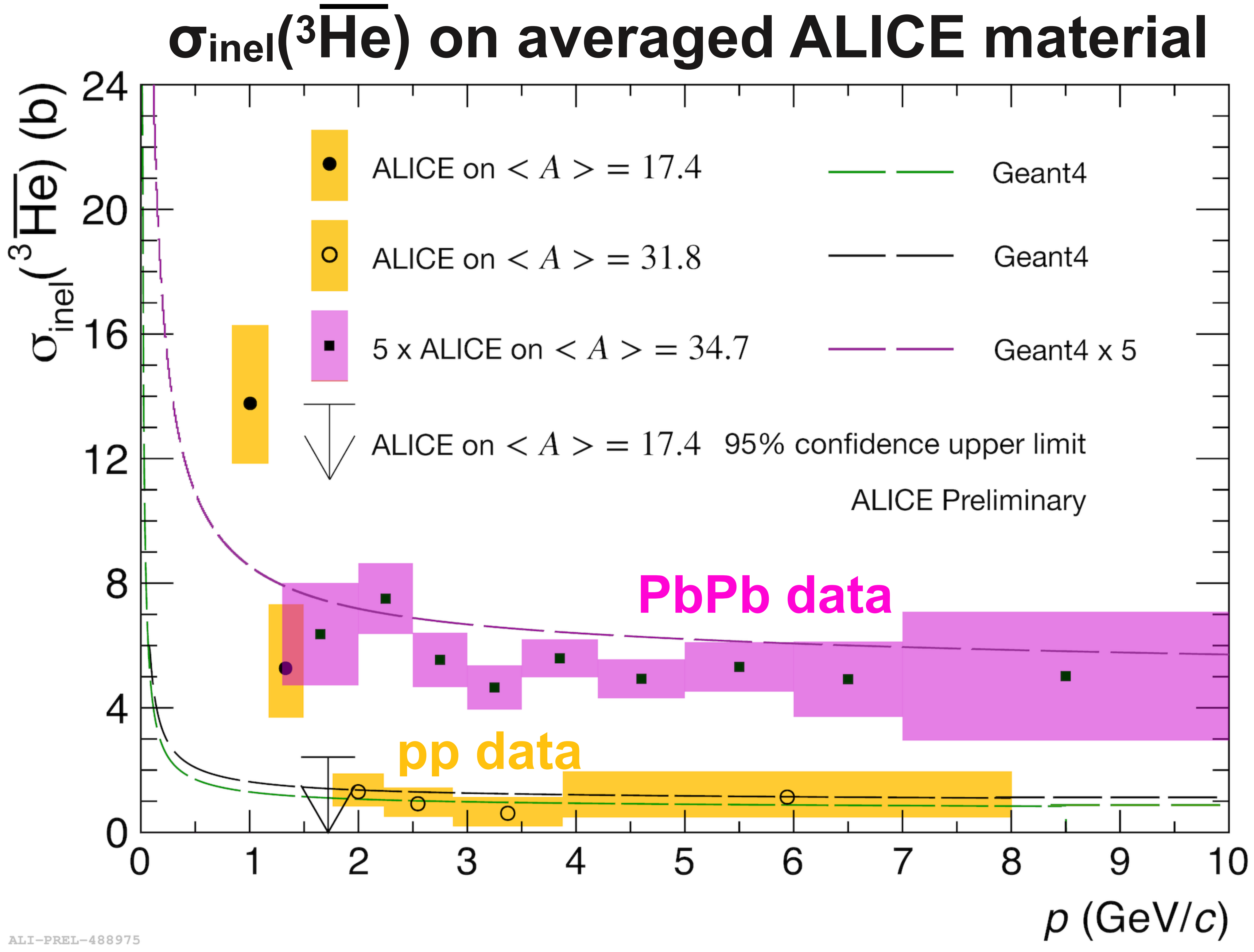
Comparison with ALICE results [1,2]



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

Inelastic interactions

ALICE measurements on $\sigma_{inel}(^3\overline{He})$ are for heavy elements with $\langle A \rangle$ = 17.4 to 34.7
Need to be scaled for proton and helium targets (ISM)



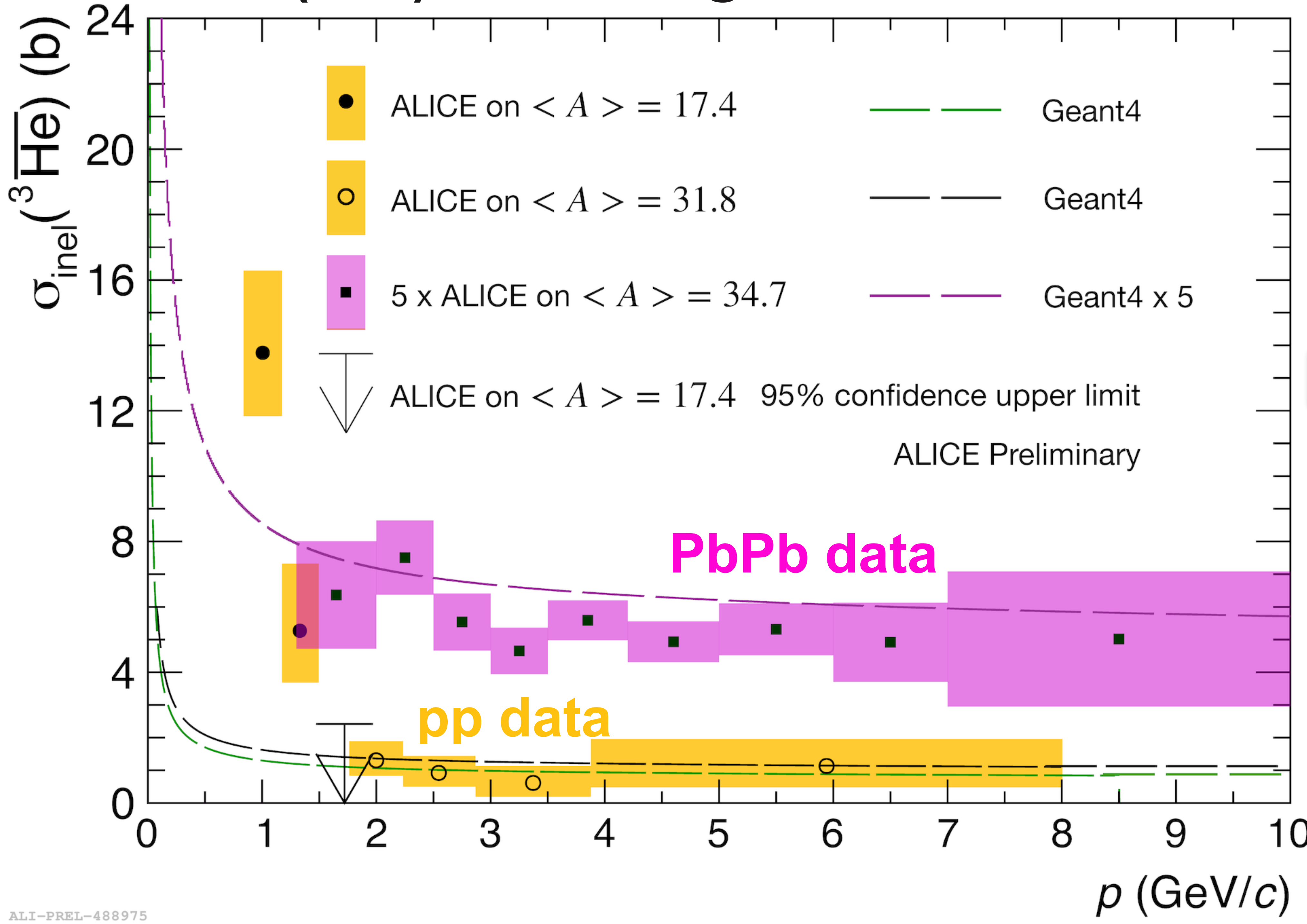
Inelastic interactions

ALICE measurements on $\sigma_{inel}(^3\overline{He})$ are for heavy elements with $\langle A \rangle = 17.4$ to 34.7

Need to be scaled for proton and helium targets (ISM)

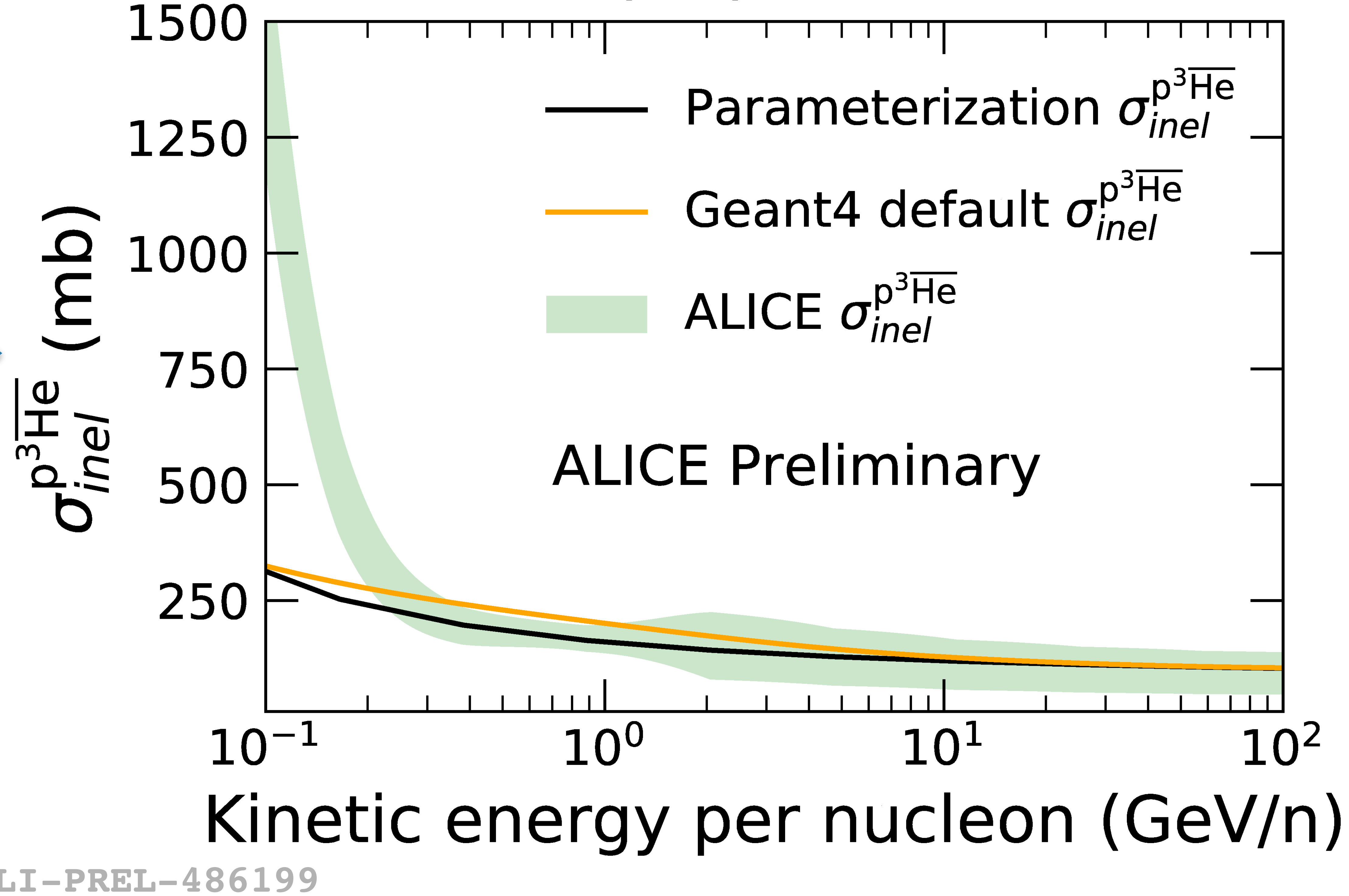
- Obtain correction factor for Geant4 parametrisation using ALICE measurements
- Use this correction factor for all targets, with additional 8% uncertainty on possible *A* scaling [1]

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



$$corr. = \frac{\sigma_{inel}^{ALICE}}{\sigma_{inel}^{Geant4}}$$

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



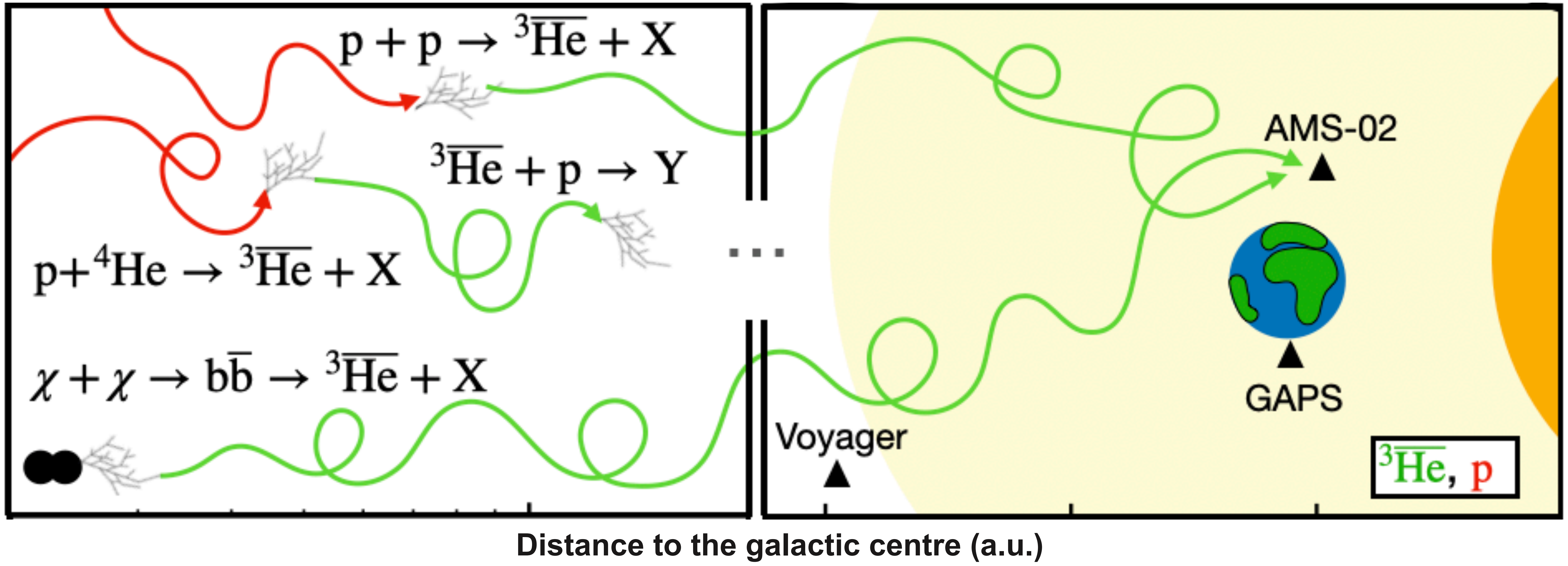
[1] Uzhinsky et al., Phys. Lett. B 705 (2011) 235

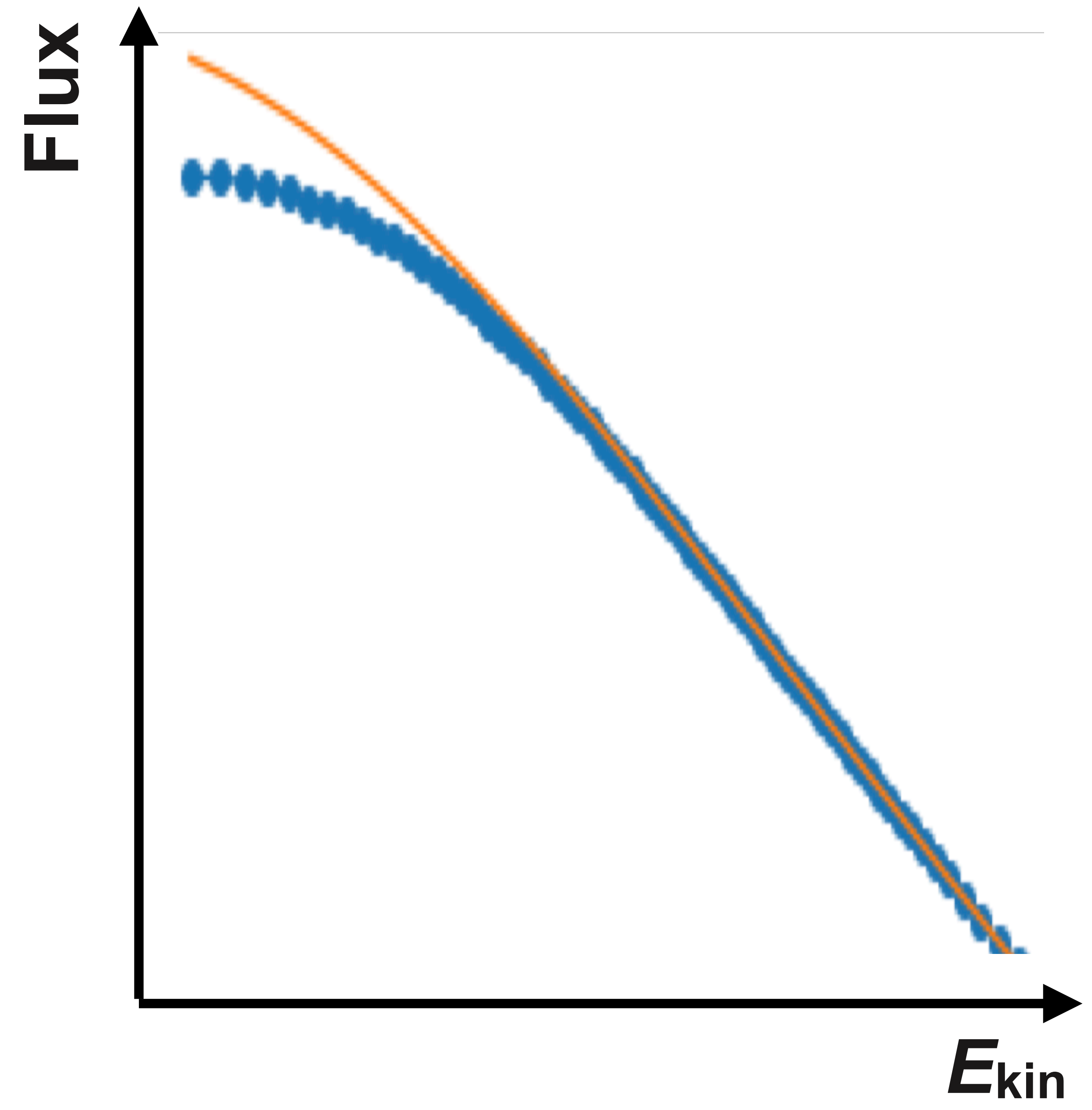
ALICE

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

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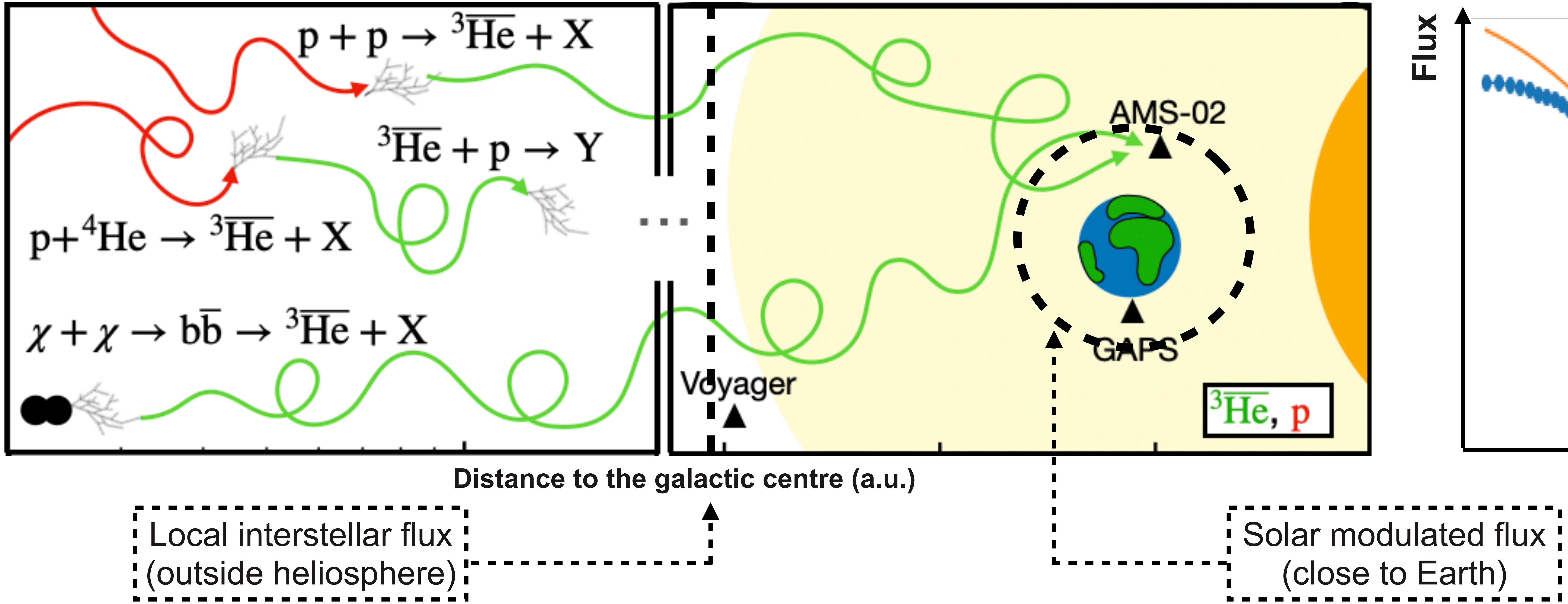
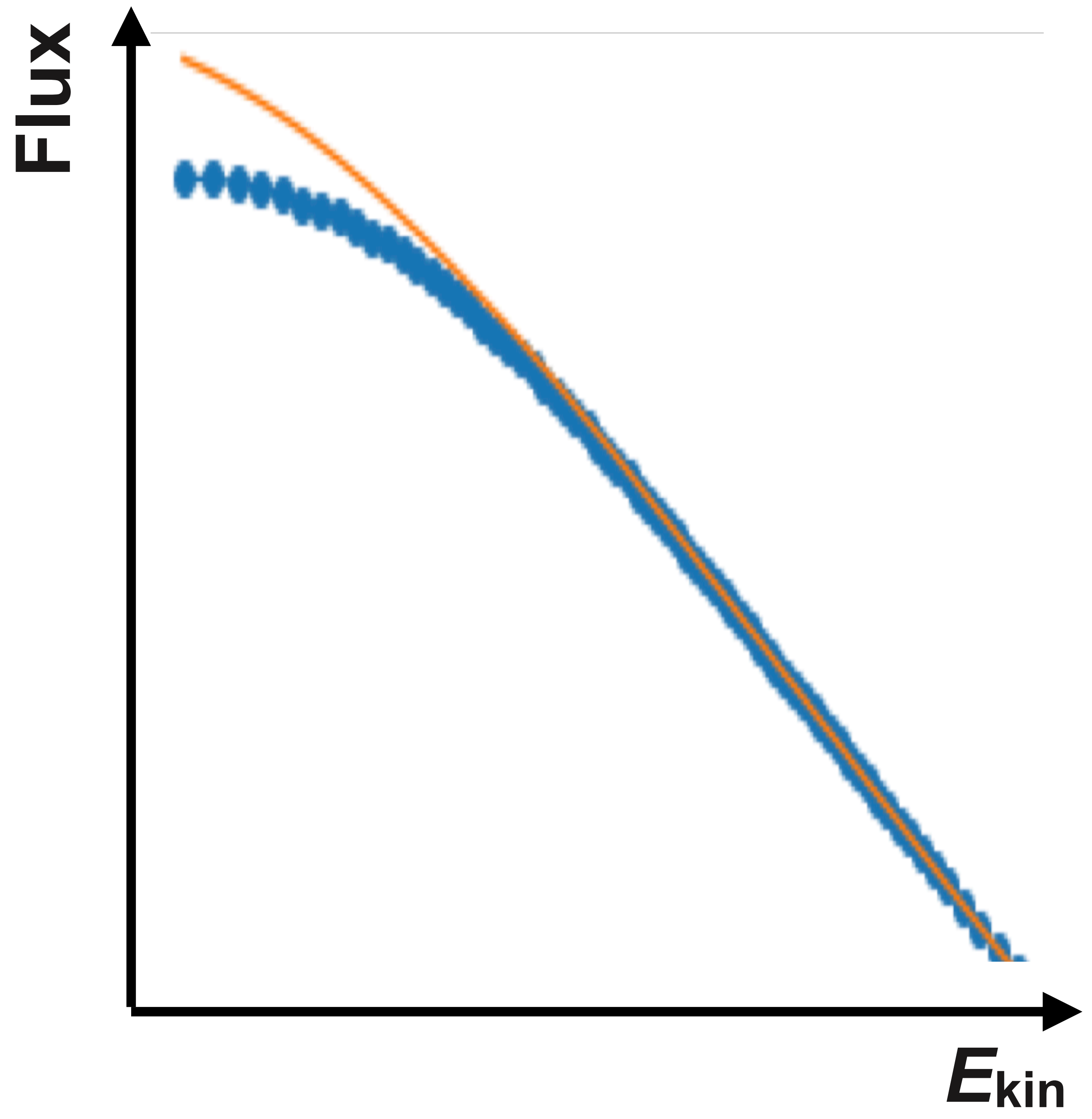




[1] Gleeson, Axford, Astrophys.J. 154 (1968) 1011

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

Various $\sigma_{inel}(^{3}\overline{\text{He}})$ used in the calculations

- $\sigma_{inel}(^{3}\overline{\text{He}}) = 0$
- $\sigma_{inel}(^{3}\overline{\text{He}})$ from Geant4
- $\sigma_{inel}(^{3}\overline{\text{He}})$ from [1]
- $\sigma_{inel}(^{3}\overline{\text{He}})$ from ALICE

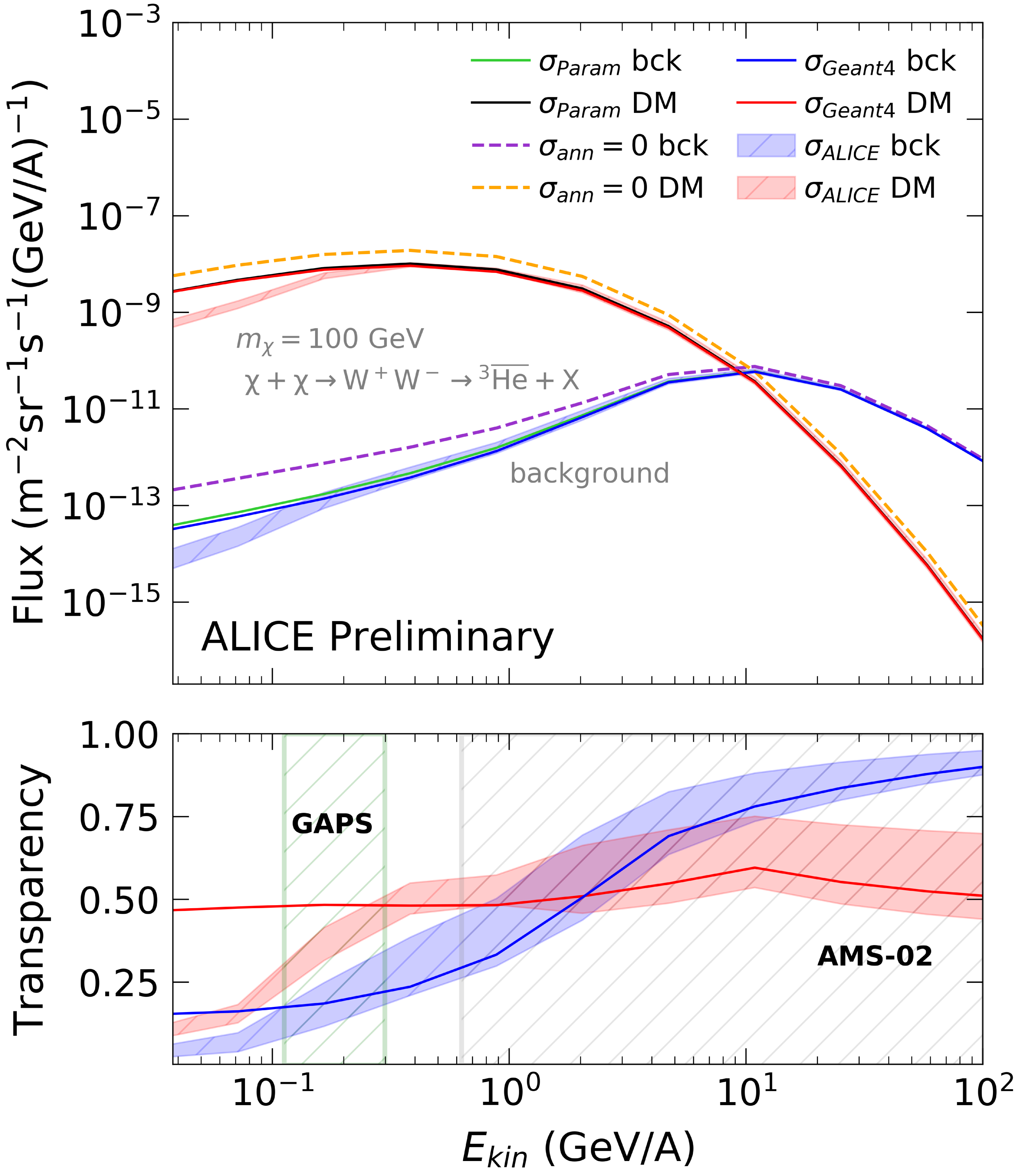
Uncertainties are only from ALICE measurement on σ_{inel}

- **Small compared to other uncertainties in the field!**

Rather constant transparency of 50% for typical DM scenario and 25-90% for background

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

Local interstellar flux



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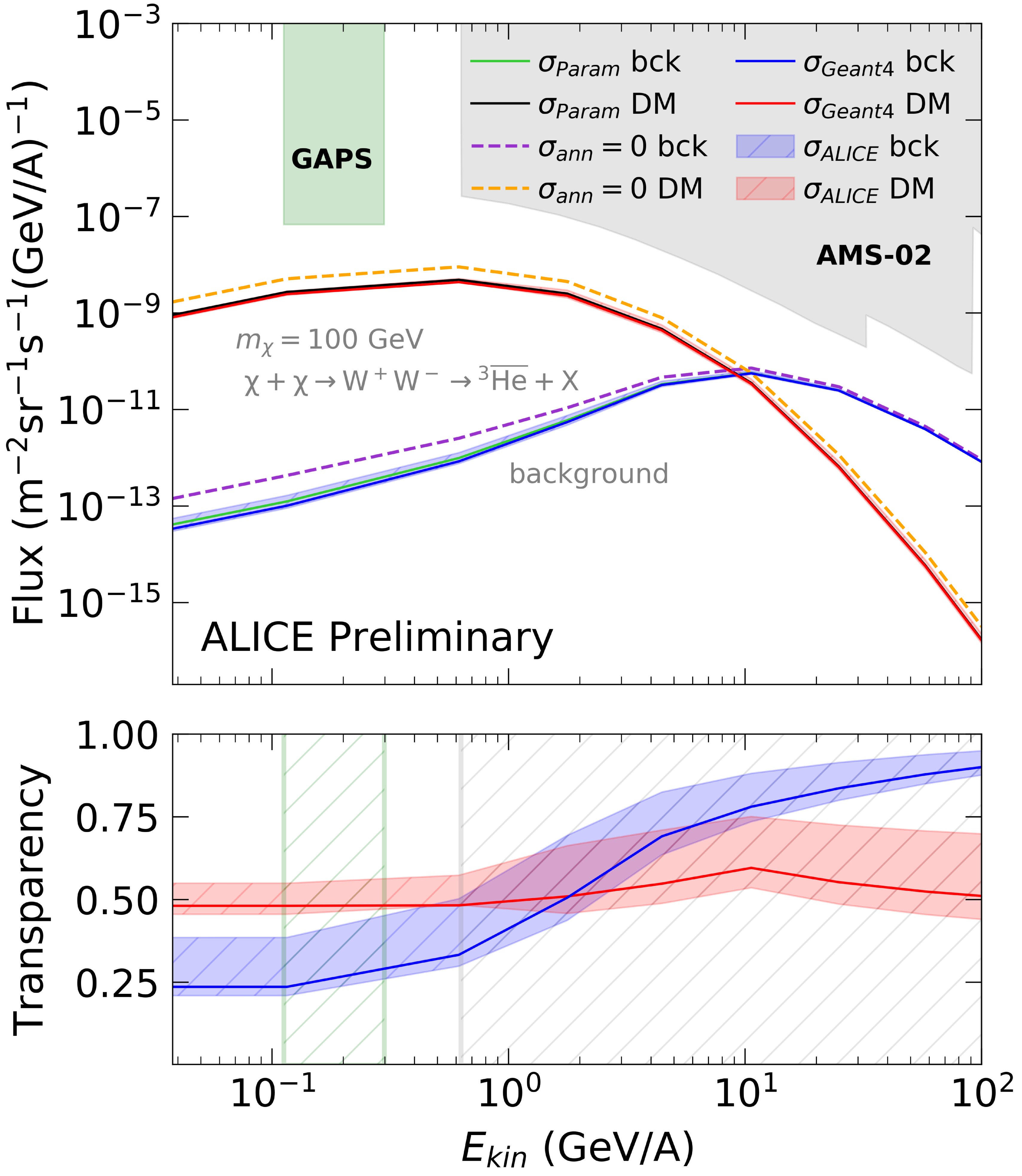
Solar modulated flux



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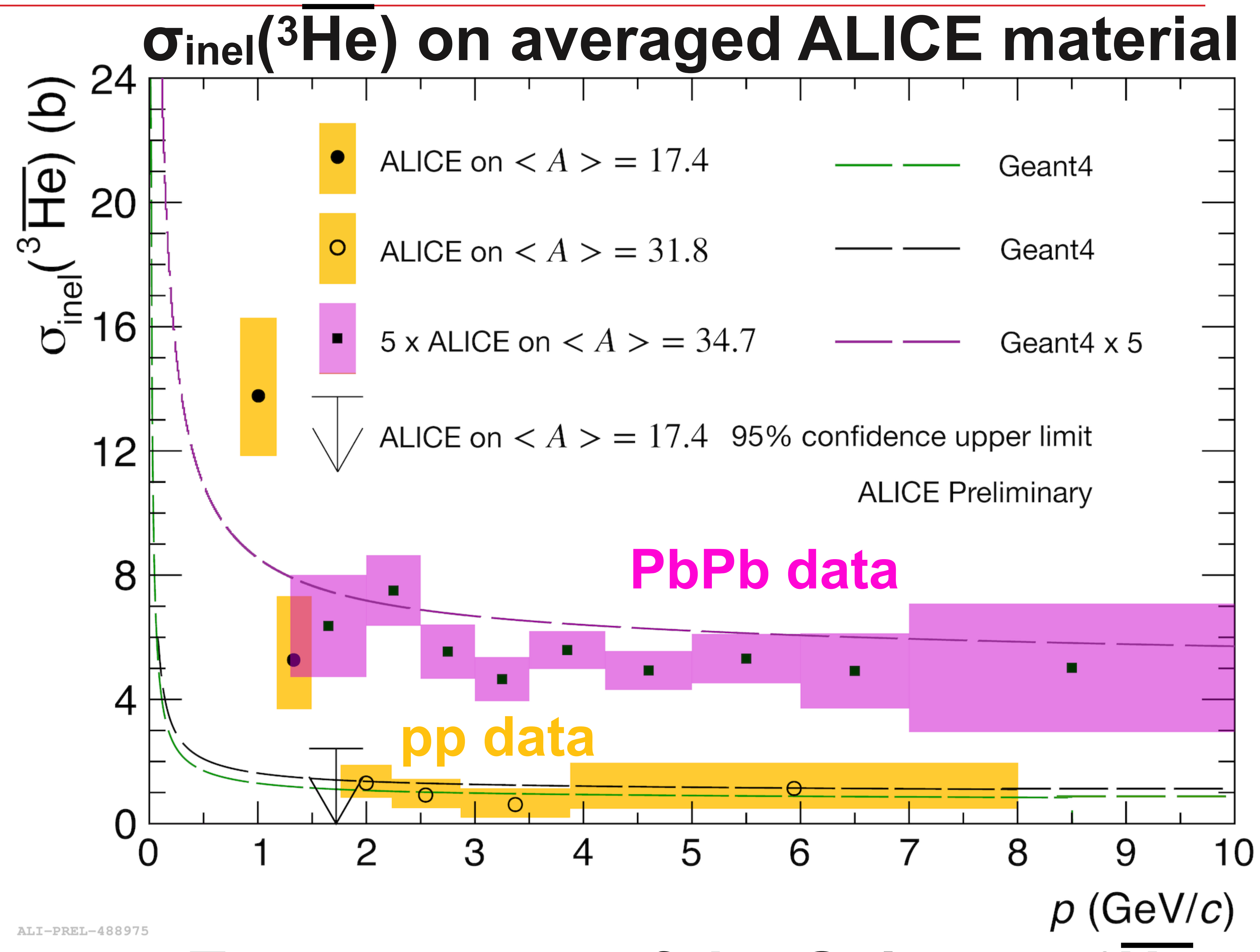
[1] Korsmeier et al., Phys.Rev.D 97 (2018) 10, 103011

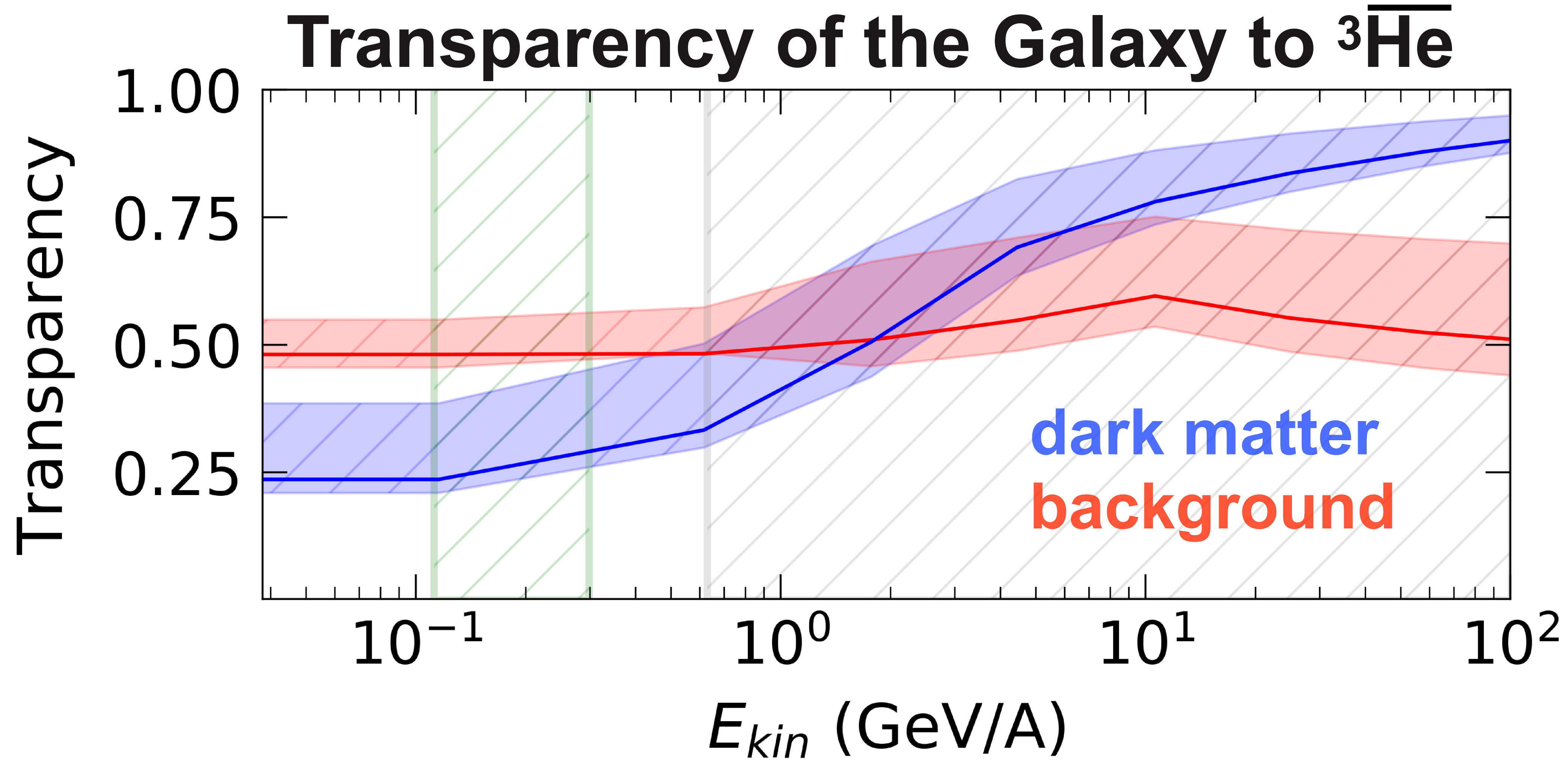
Summary and outlook

First measurements of antinuclei inelastic cross section in low kinetic energy range

Impact of the ALICE measurements on $^{3}\overline{\mathrm{He}}$ fluxes near Earth has been studied:
- High transparency of the Galaxy to $^{3}\overline{\mathrm{He}}$
- Uncertainties on cosmic ray fluxes from $\sigma_{\mathrm{inel}}(^{3}\overline{\mathrm{He}})$ measurements are small compared to other uncertainties in the field

The analysis of the impact on antideuteron cosmic ray fluxes is ongoing





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Essential reference for any studies of antinuclei in space!