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

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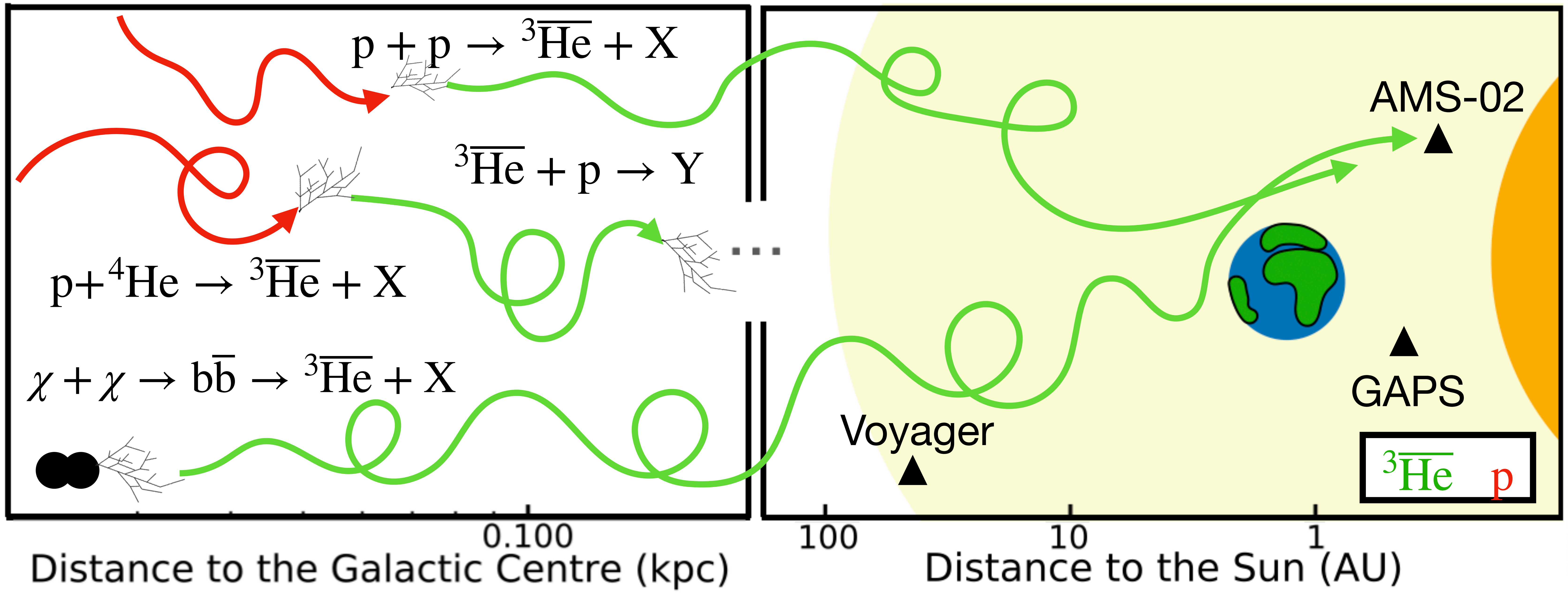
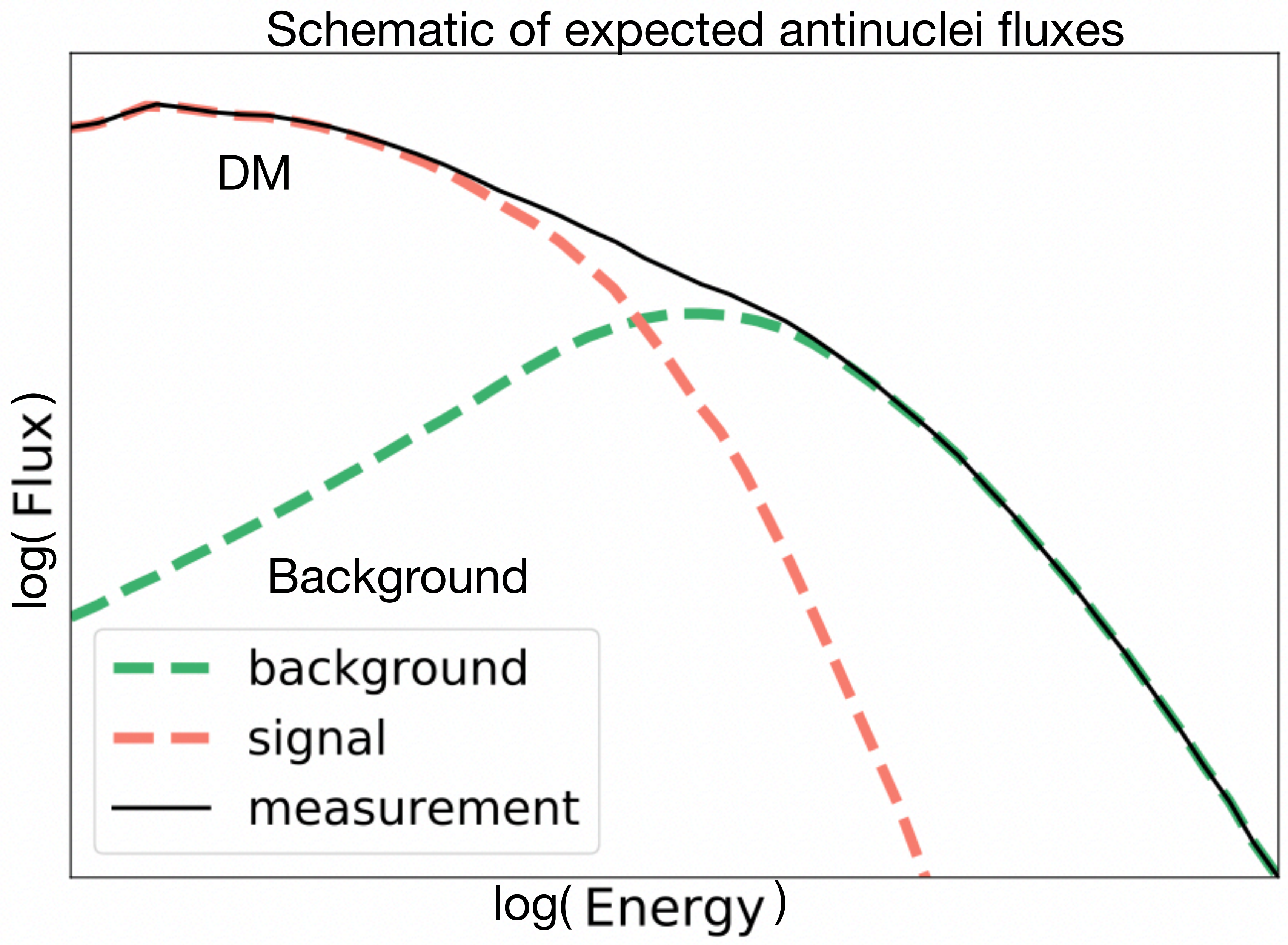
# Introduction

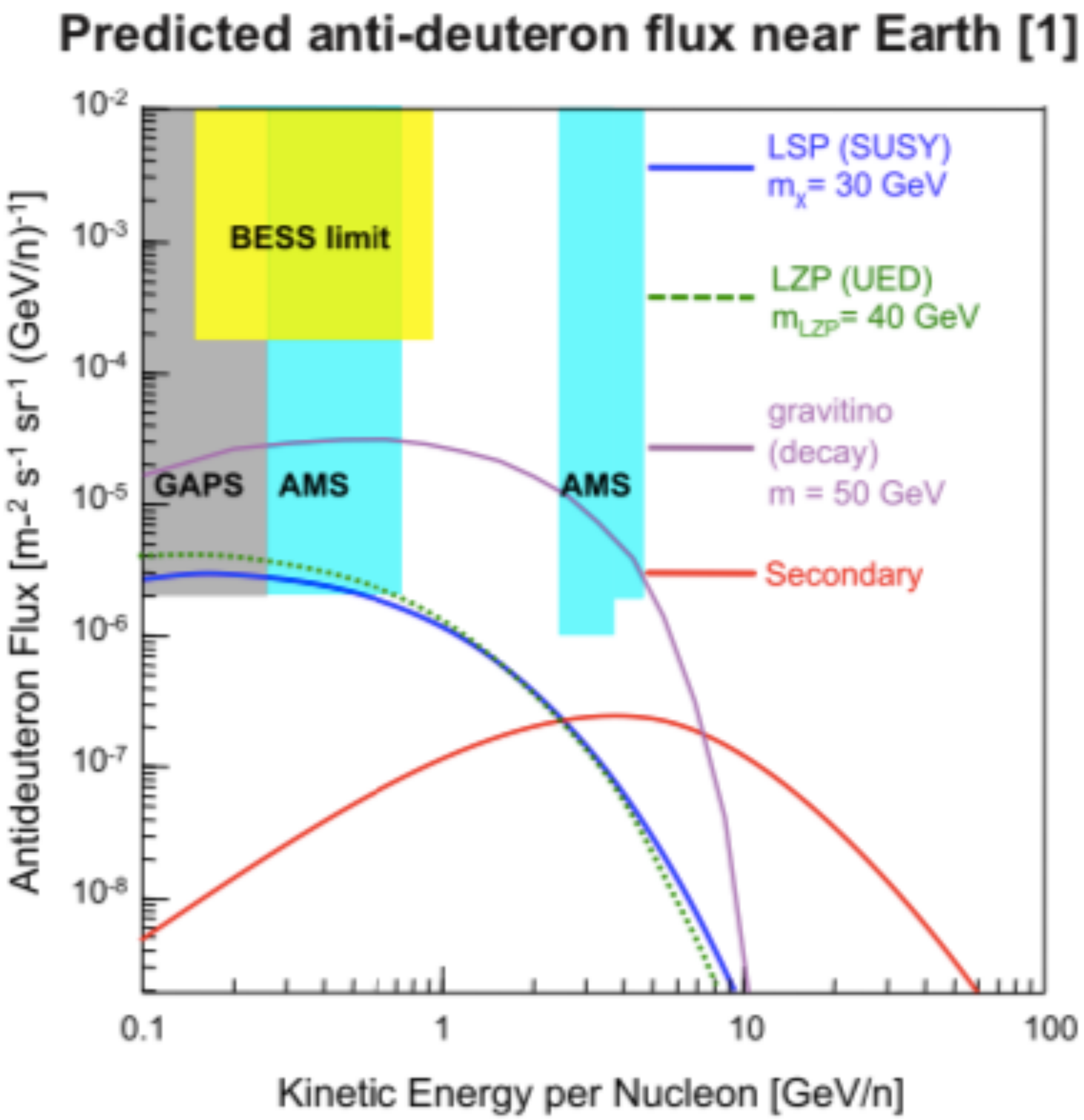
Cosmic ray antinuclei - unique dark matter probe

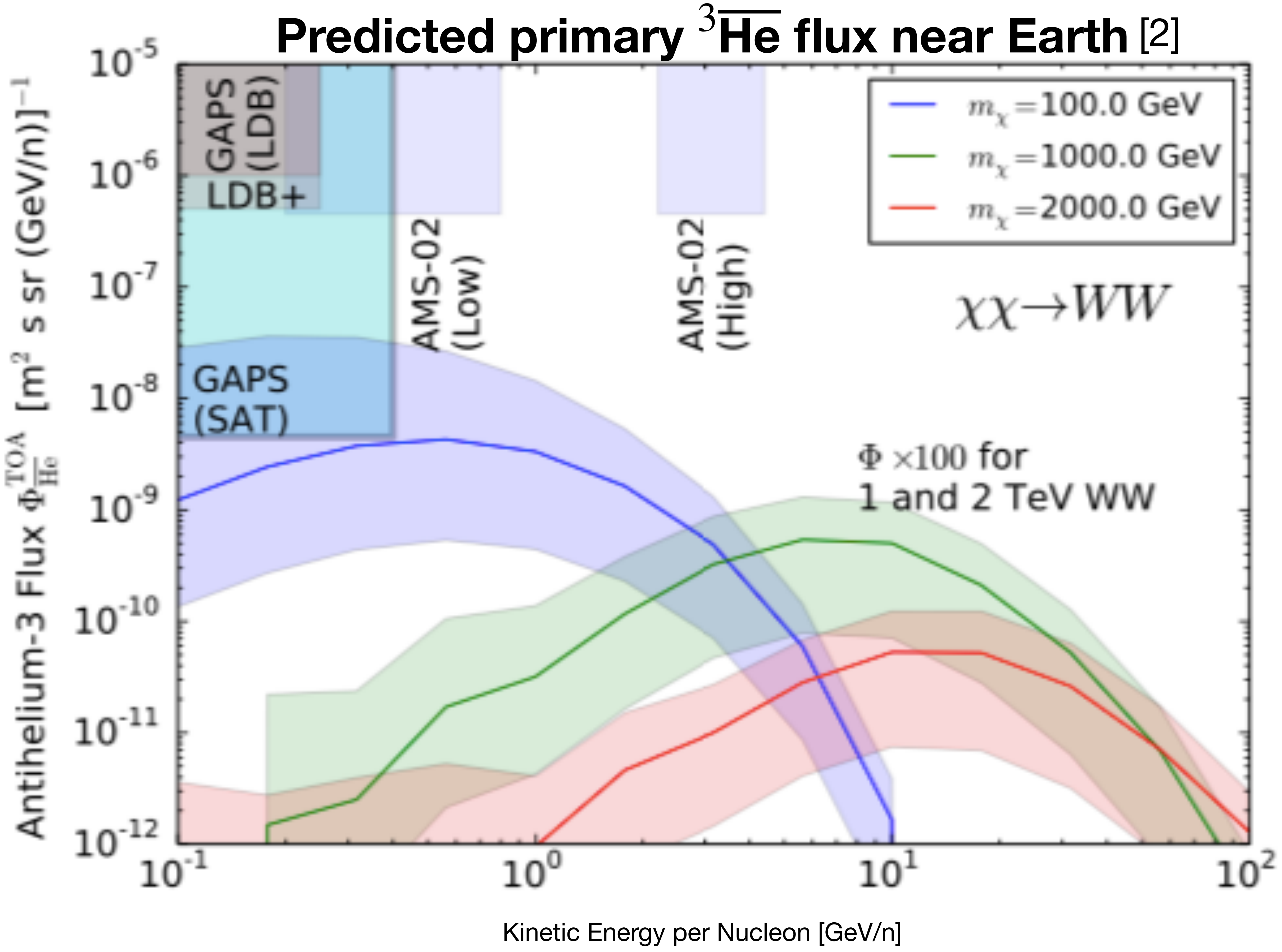
- Low background from astrophysical processes is expected
- Need to determine exact primary and secondary fluxes, which requires precise knowledge of antinuclei production, propagation and annihilation



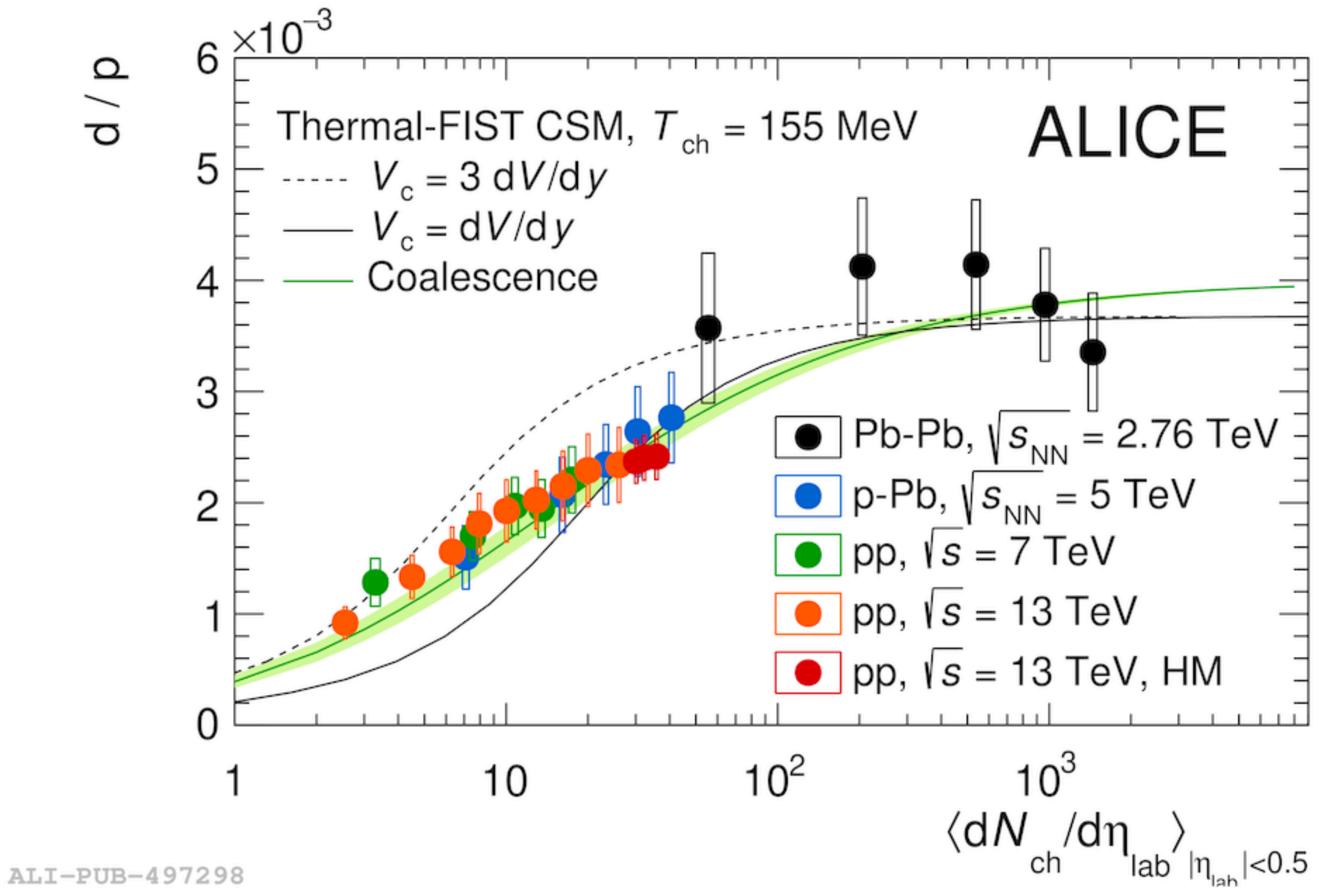
# Predicted antinuclei fluxes near earth



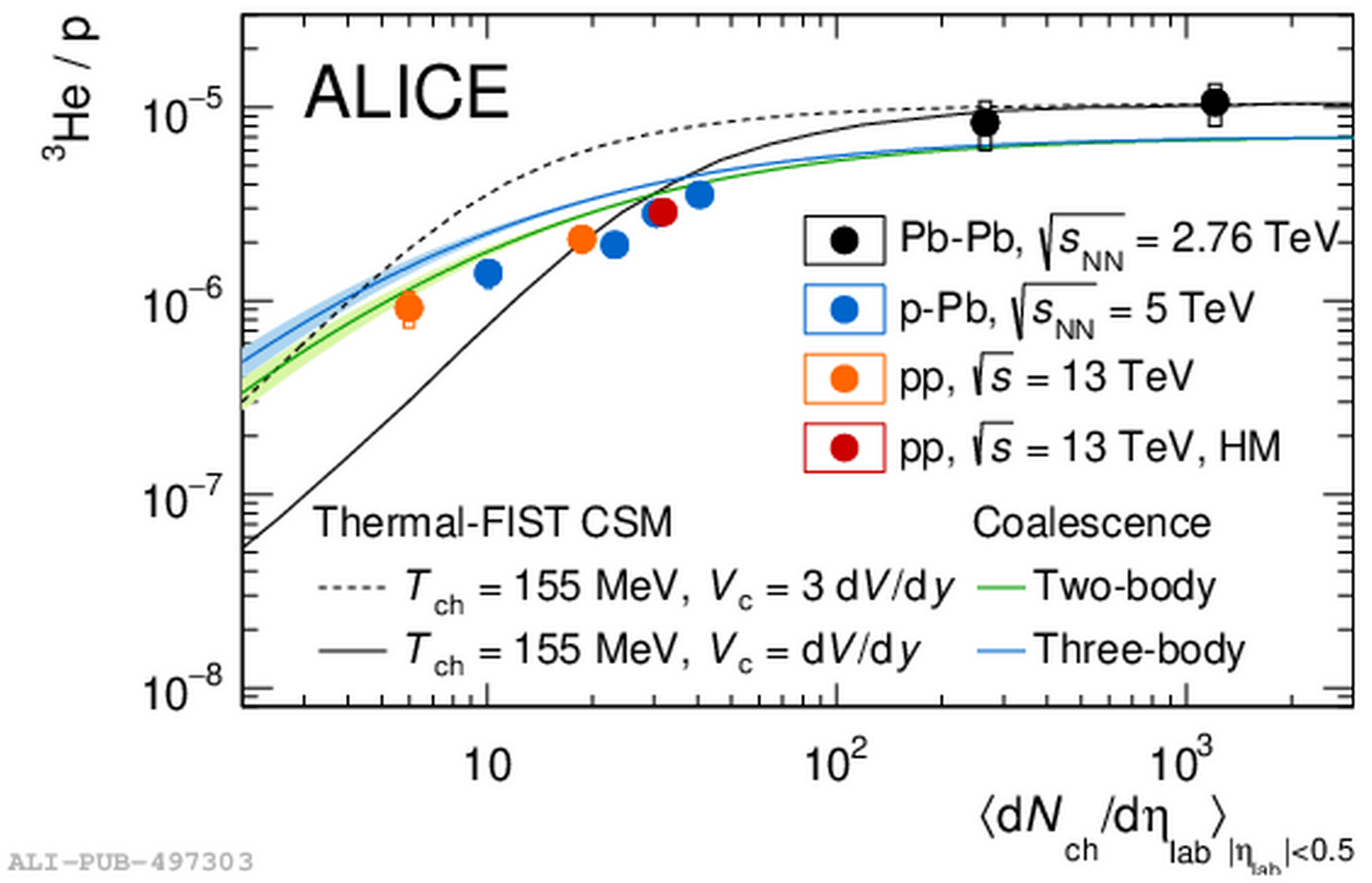




[1] Physics Report 618, 1 (2016) [2] Phys. Rev. D 89, 076005
[2] Korsmeier et.al. arXiv:1711.08465

# Measurements of (anti-)nuclei production




JHEP 01 (2022) 106

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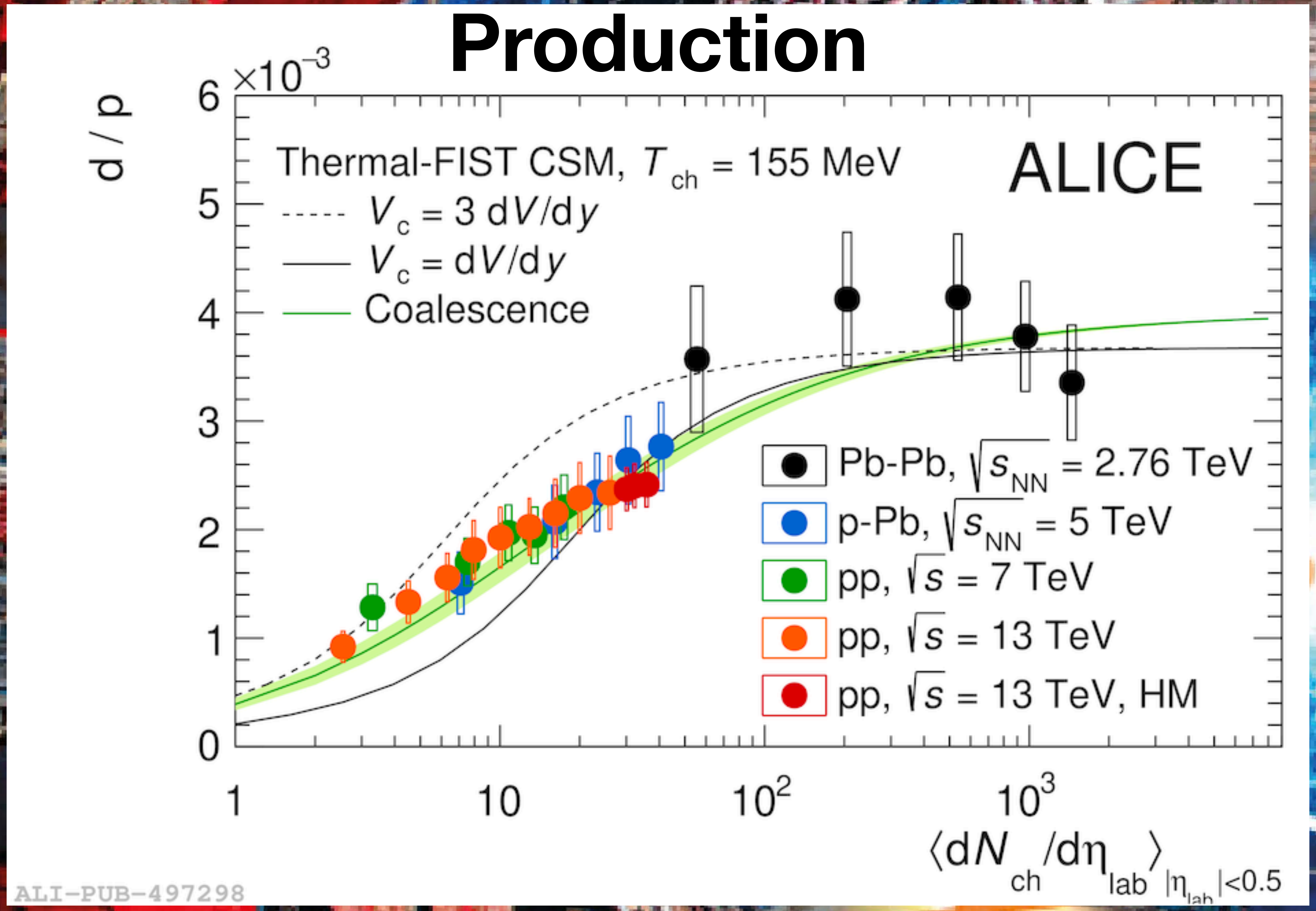
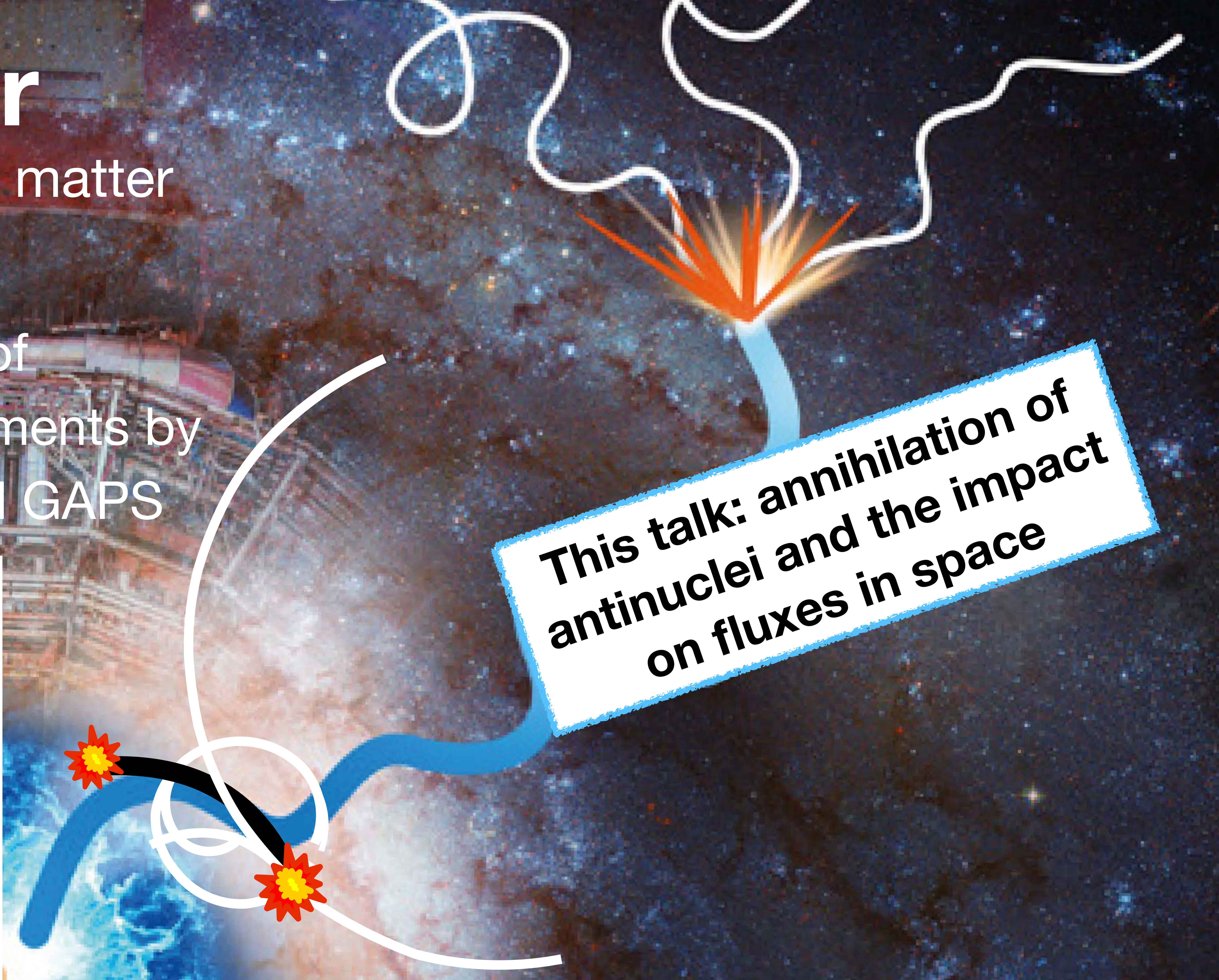
**This talk: annihilation of antinuclei and the impact on fluxes in space.**

# Space: the final frontier

How can ALICE help the search for a dark matter signal in space?

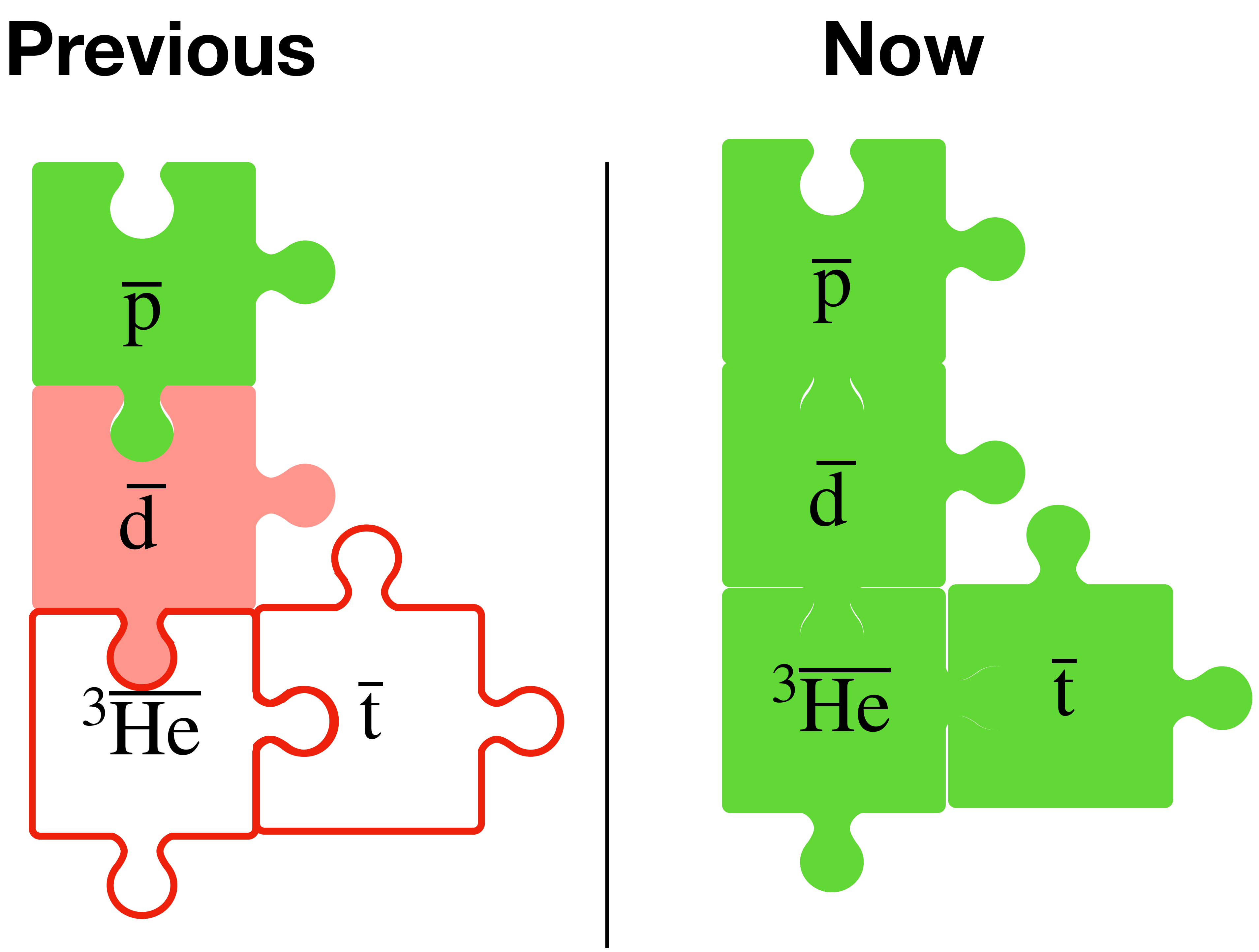
- Measure the production and annihilation of antinuclei => this helps interpret measurements by space bourne experiments, e.g.: AMS and GAPS



# Annihilation: pieces of the puzzle

- Antinuclei (A≥2) $\sigma_{inel}$ remained poorly known since the 70s – only 2 papers on $\overline{d}$ at high energies from ’70, ’71 [1-2]
- 3 years ago, ALICE started contributing to this field by measuring the inelastic cross sections of $\overline{d}$, $\overline{t}$ and $^{3}\overline{He}$ [3-4]
- Studied the impact of these measurements on cosmic ray antinuclei
- This talk focuses mainly on A=3 results



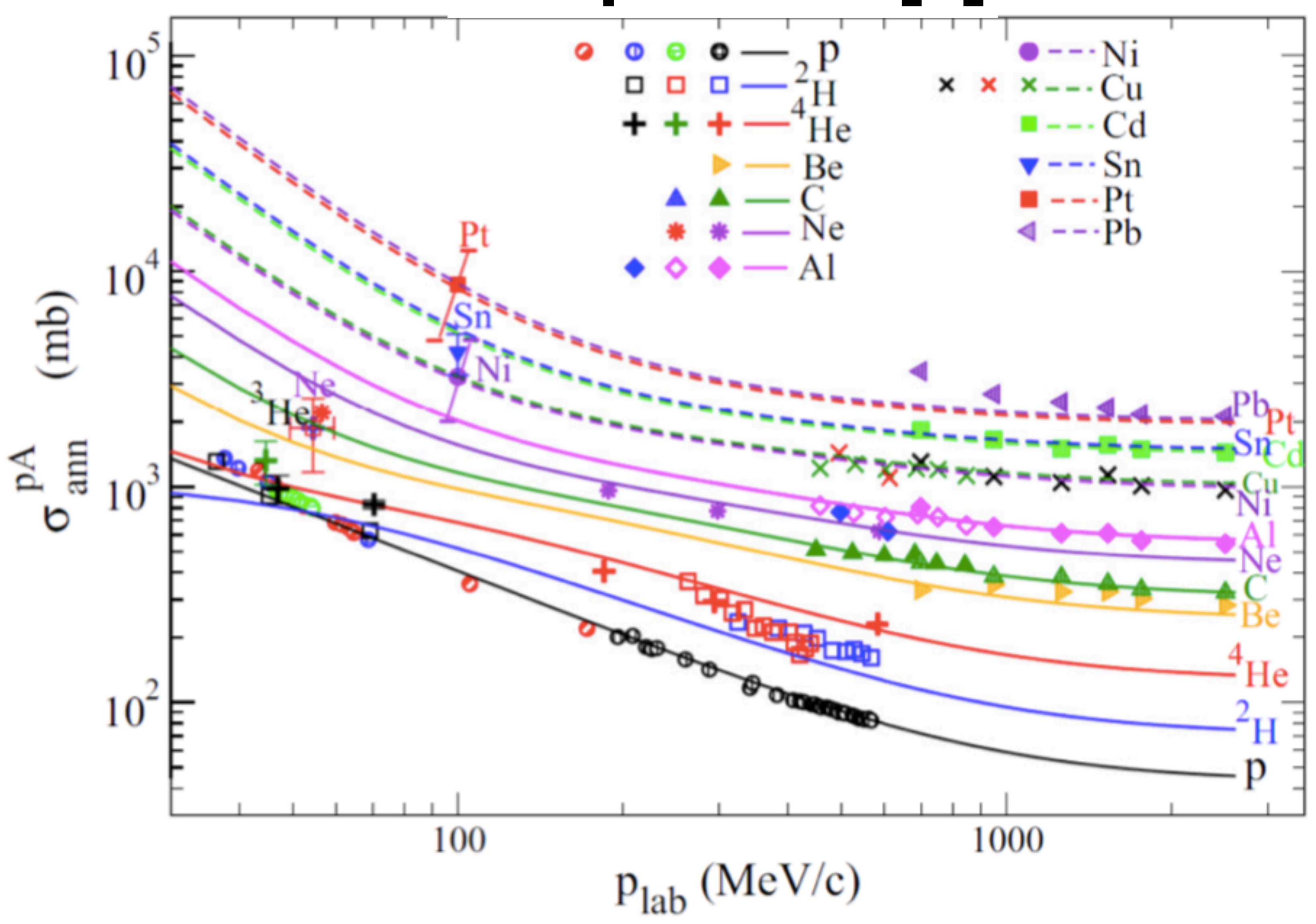

[1] Binon et al. PLB 31 (1970) [2] Denisov et. al. Nuc. Phys. B 31 (1971)
[3] PRL 125, 162001 (2020) [4] arxiv.org/2202.01549

# Current status of antinuclei inelastic cross sections

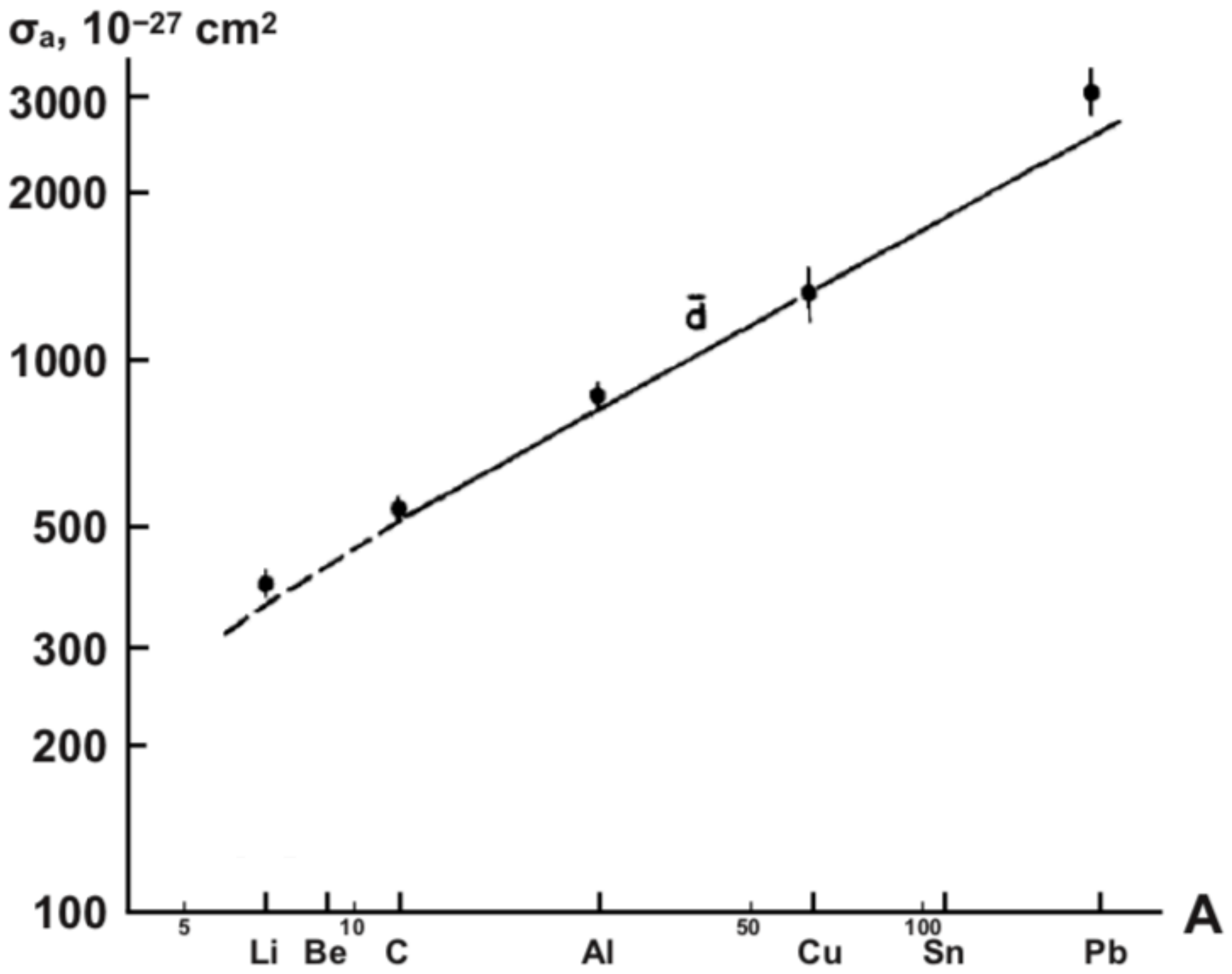
- **Antiproton** inelastic cross section is **well known**.
- **Antideuteron** inelastic cross section is **poorly known at low energies**.
- **Antihelium/antitriton** inelastic cross section has **never been measured** before.

➡ *Use ALICE to measure antinuclei inelastic cross sections!*

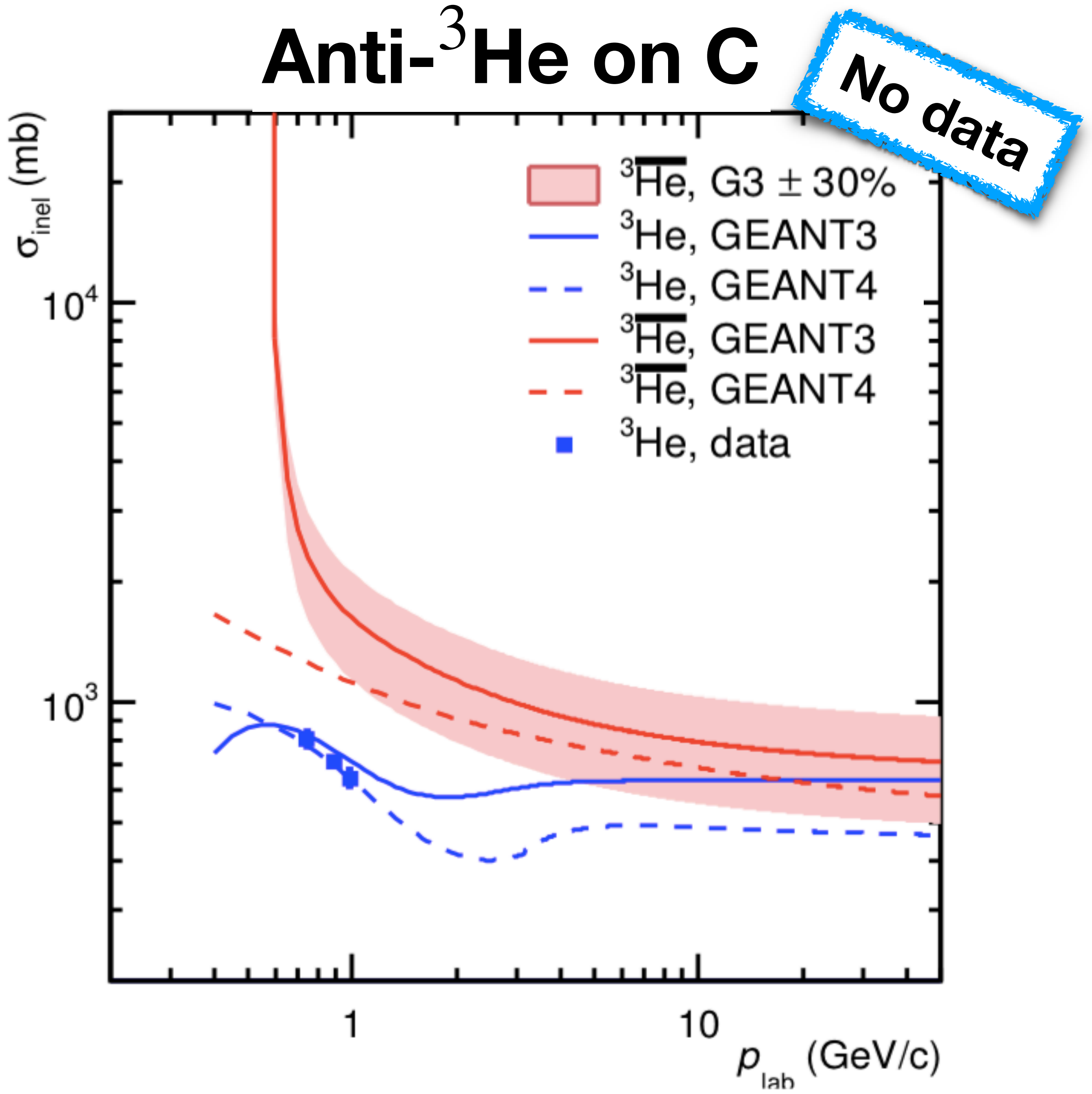
**Antiprotons [1]**



**Antideuterons [2]**



**Anti-$^3$He on C**




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

# The ALICE experiment at CERN

- Excellent **tracking and particle identification (PID)** capabilities
- Most suitable detector at the LHC to study the physics of (anti)nuclei

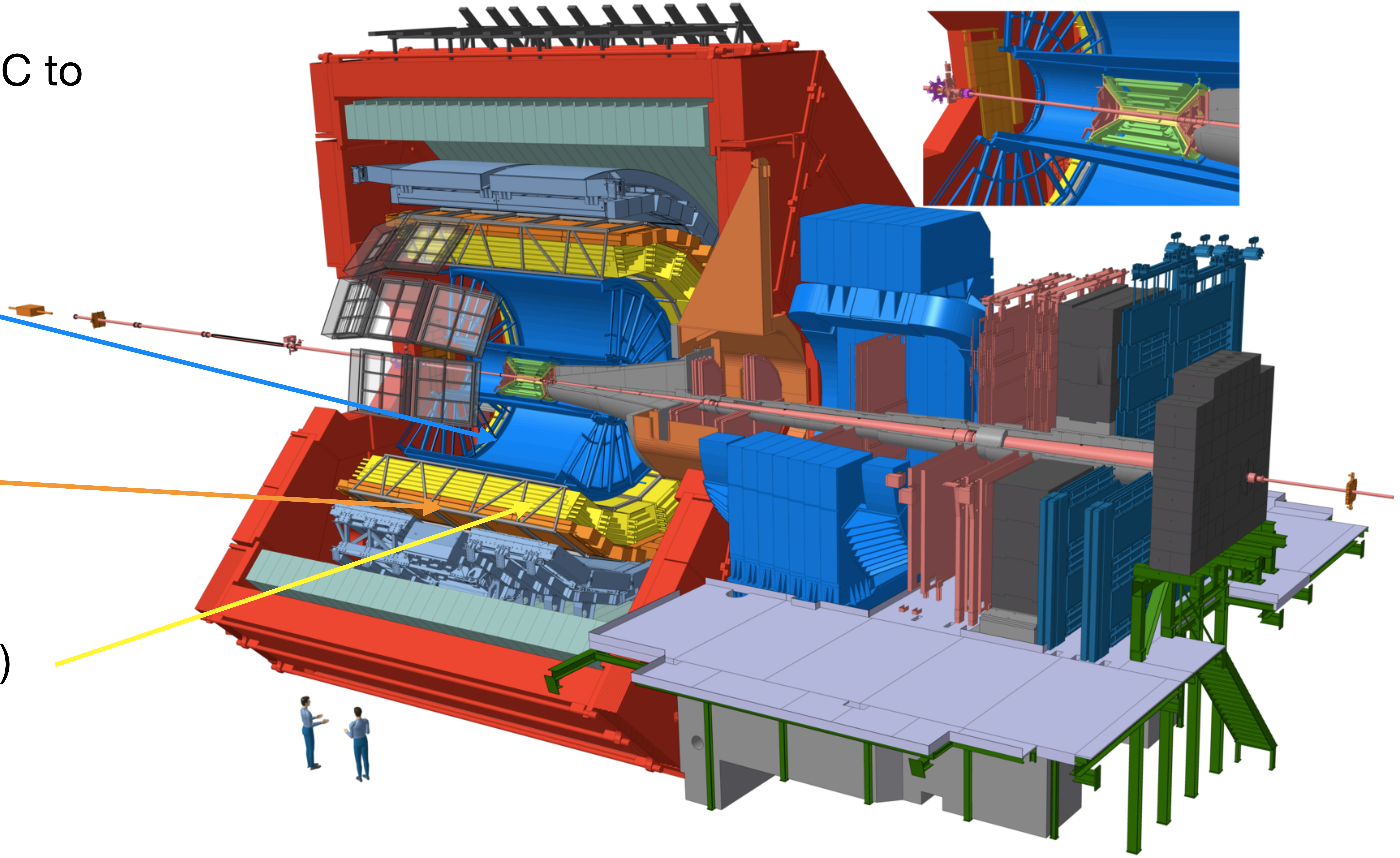
Time Projection Chamber (TPC)

- Tracking, PID (d$E$/dx)

Time of Flight detector (TOF)

- PID (TOF measurement)

Transition Radiation Detector (TRD)



# Use the LHC as an antimatter factory…

At LHC energies, particles and antiparticles are produced in almost equal amounts.

**This talk has results from:**

- High multiplicity pp collisions at $\sqrt{s} = 13$ TeV.
- Pb—Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.
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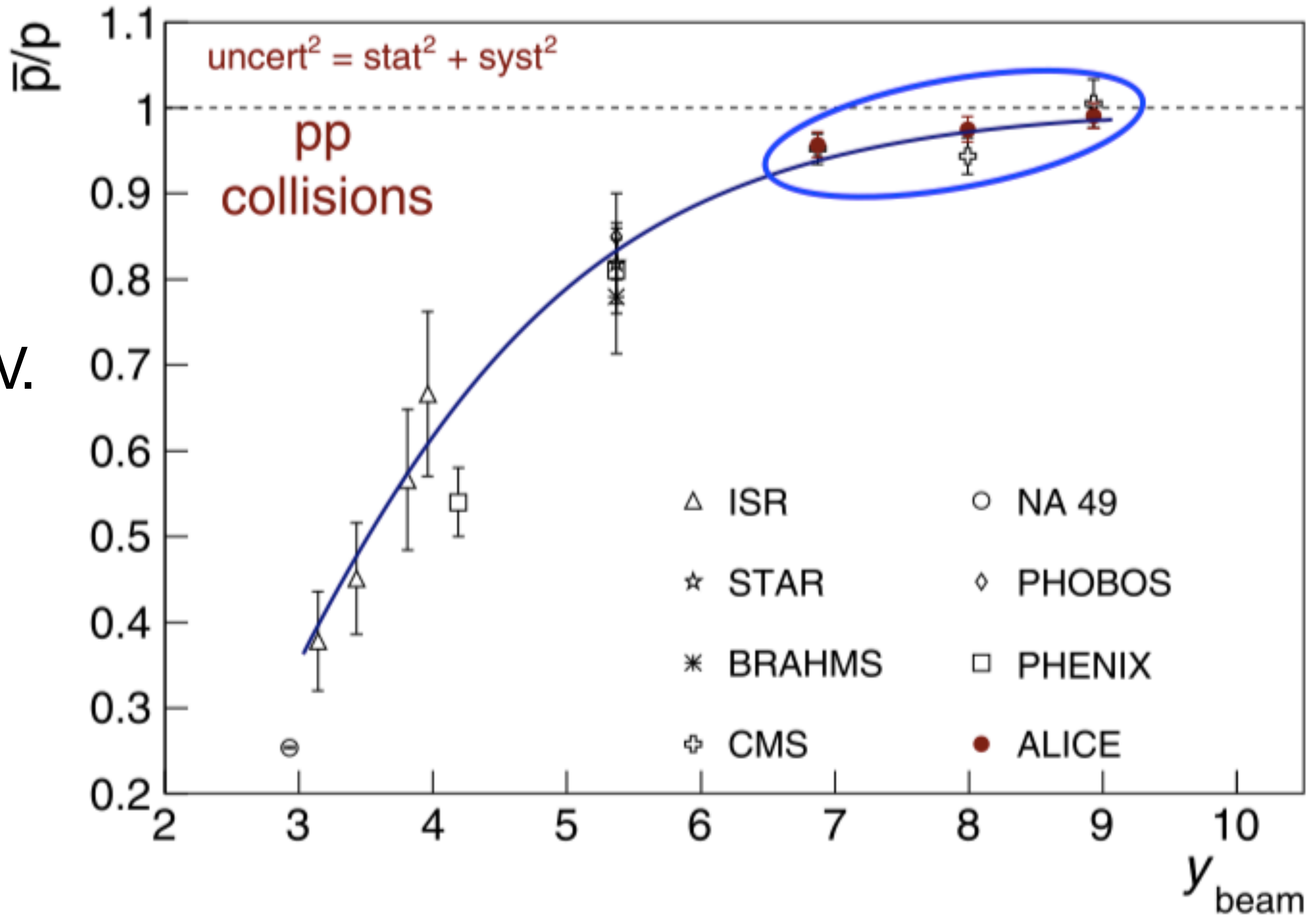
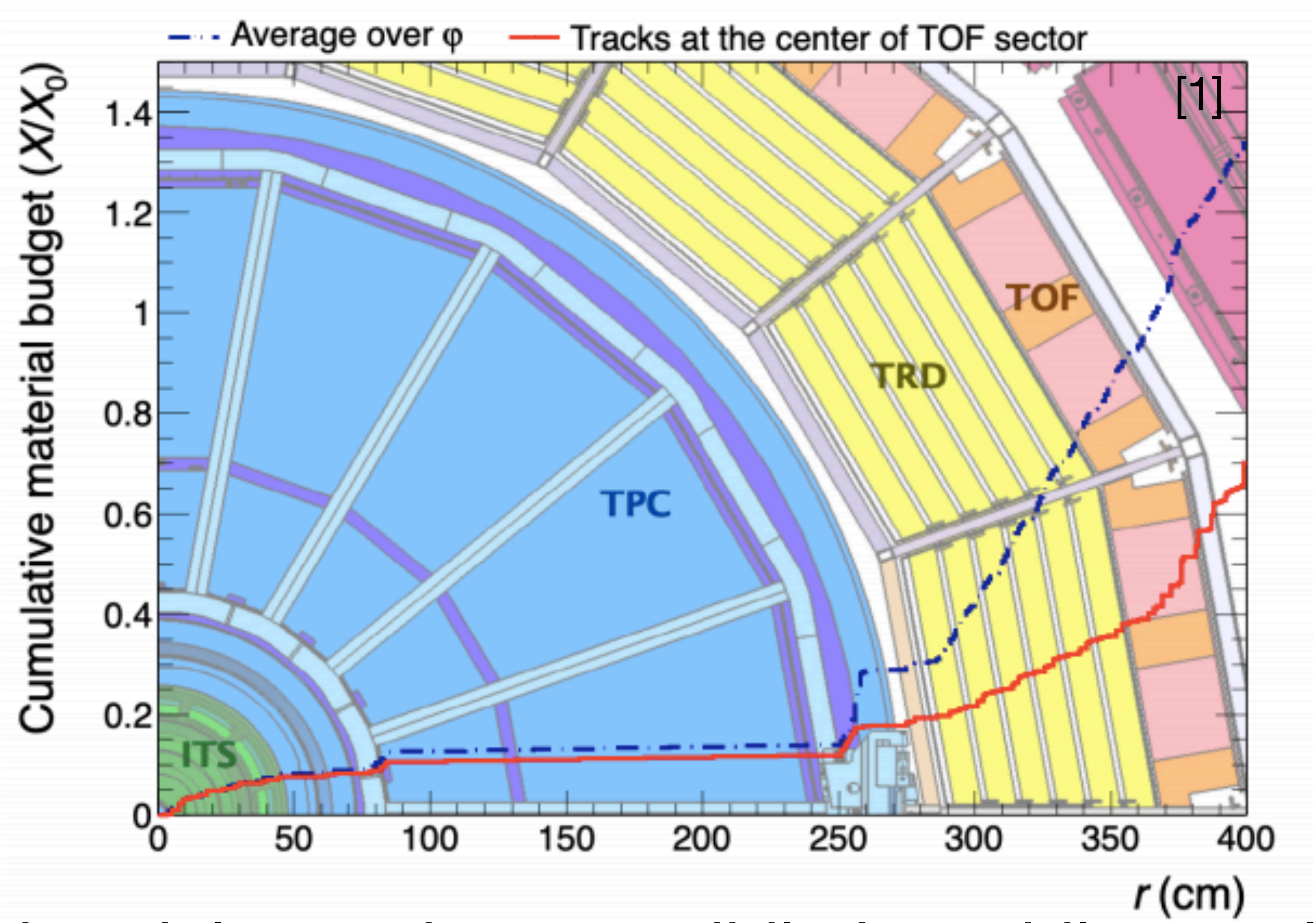
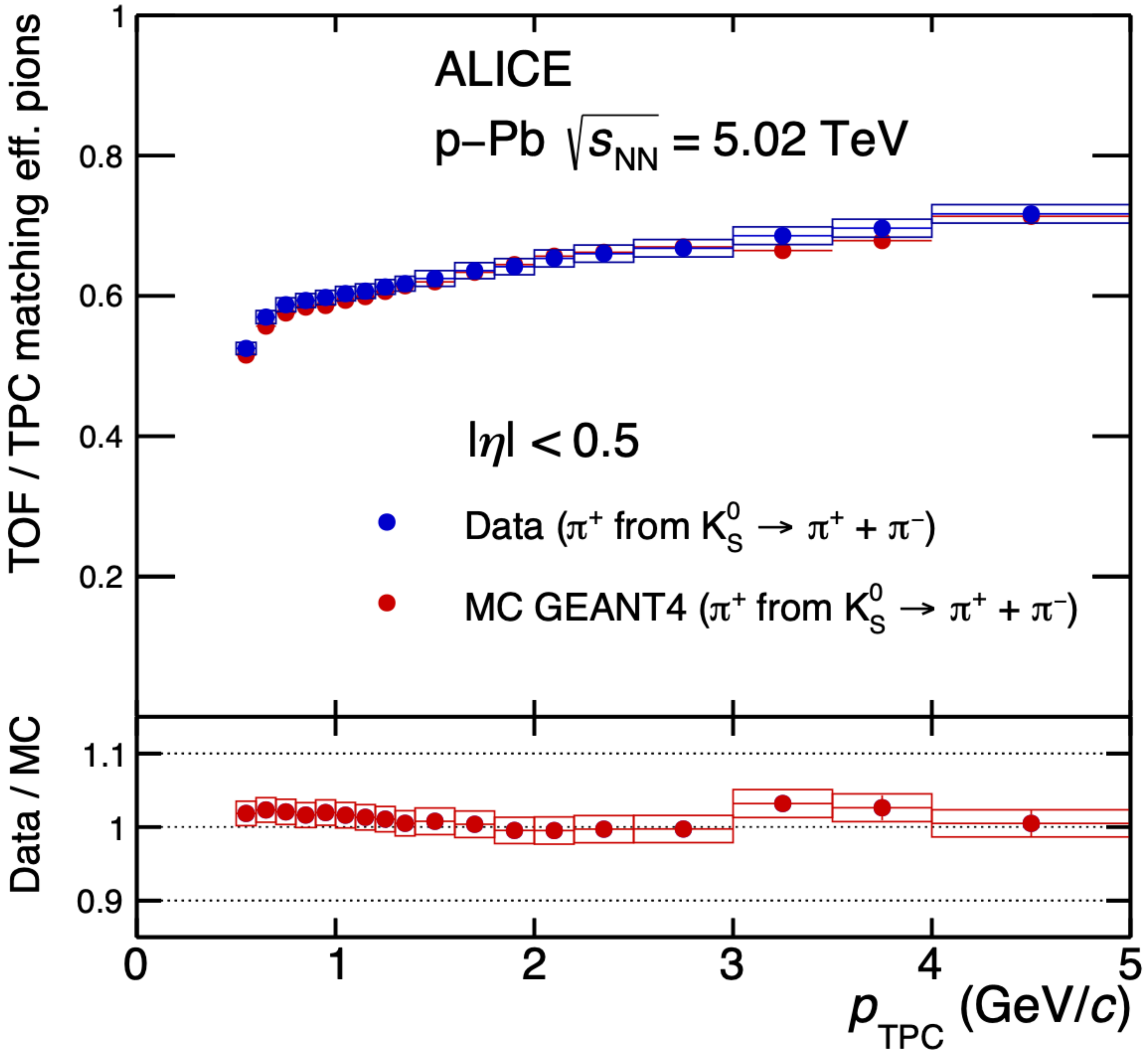
**p̄/p ratio at mid-rapidity vs √s [1]**




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

# … and the ALICE detector material as a target




- Antiparticles undergo annihilation while traveling through the detector material
- By quantifying this loss, we can measure the inelastic cross section of antinuclei!
- But: need to know our material budget very accurately

Details in CERN public note

[1] PRL 125, 162001 (2020)

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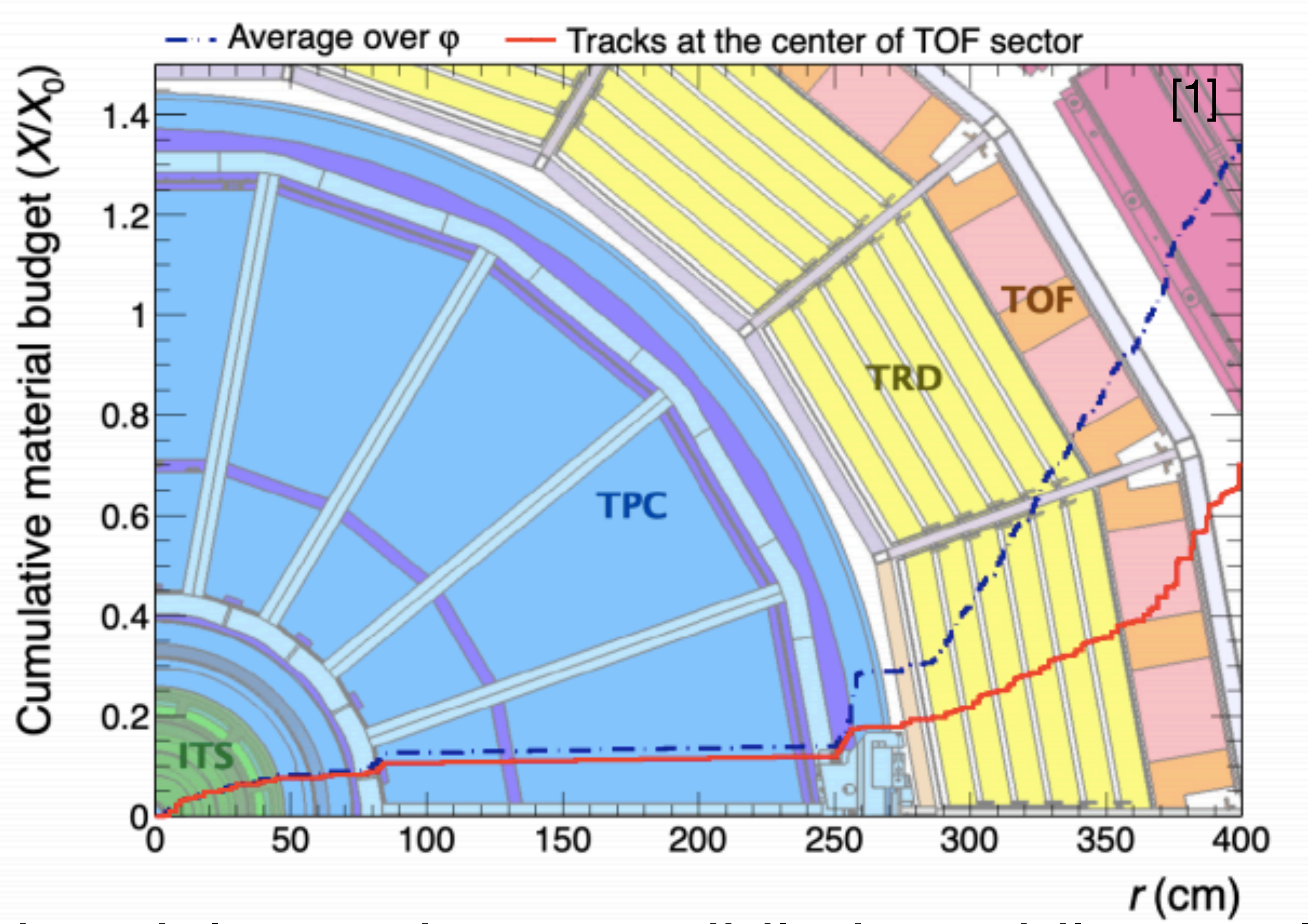


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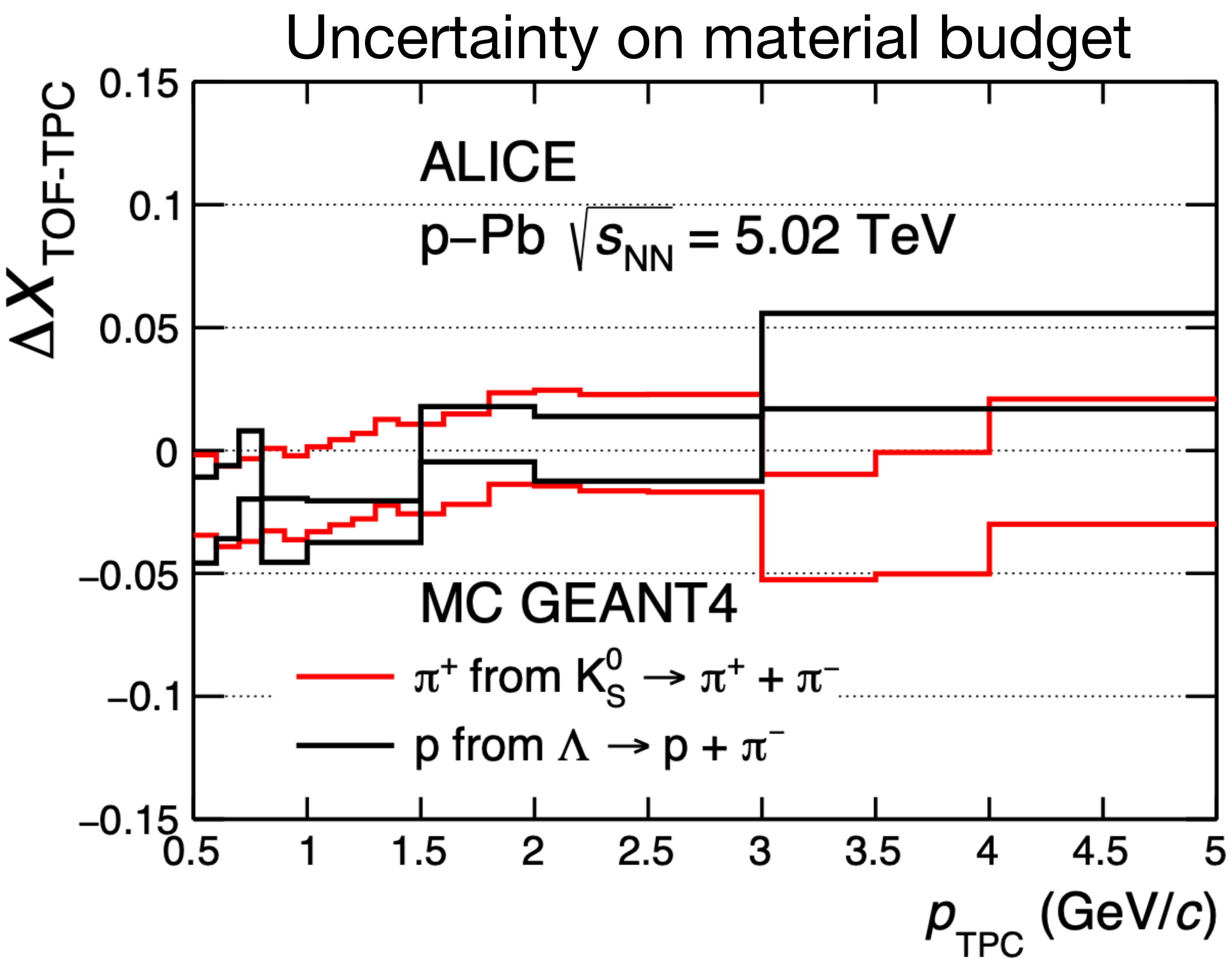


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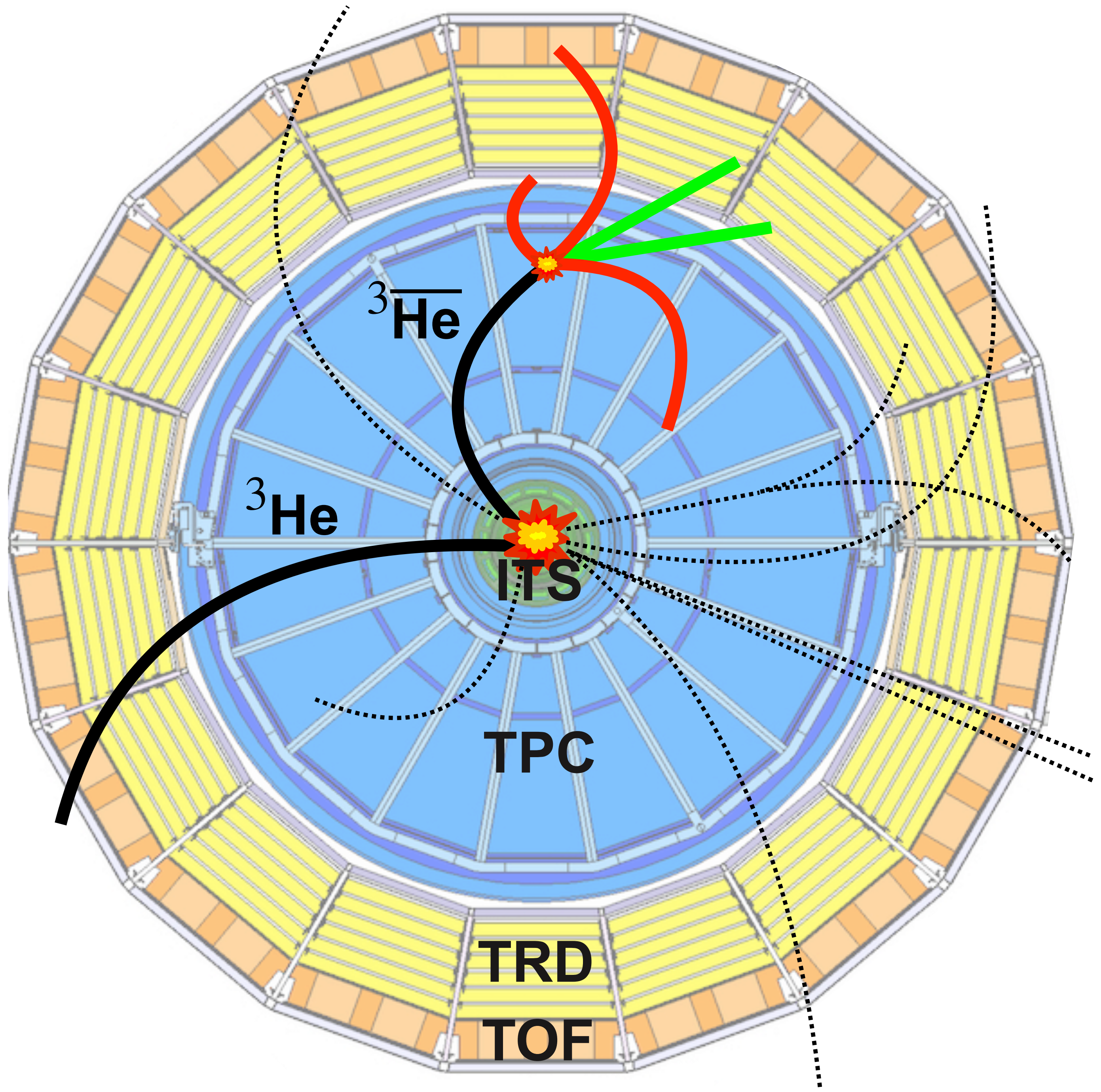
# The observables: antimatter-to-matter and TOF/TPC ratio

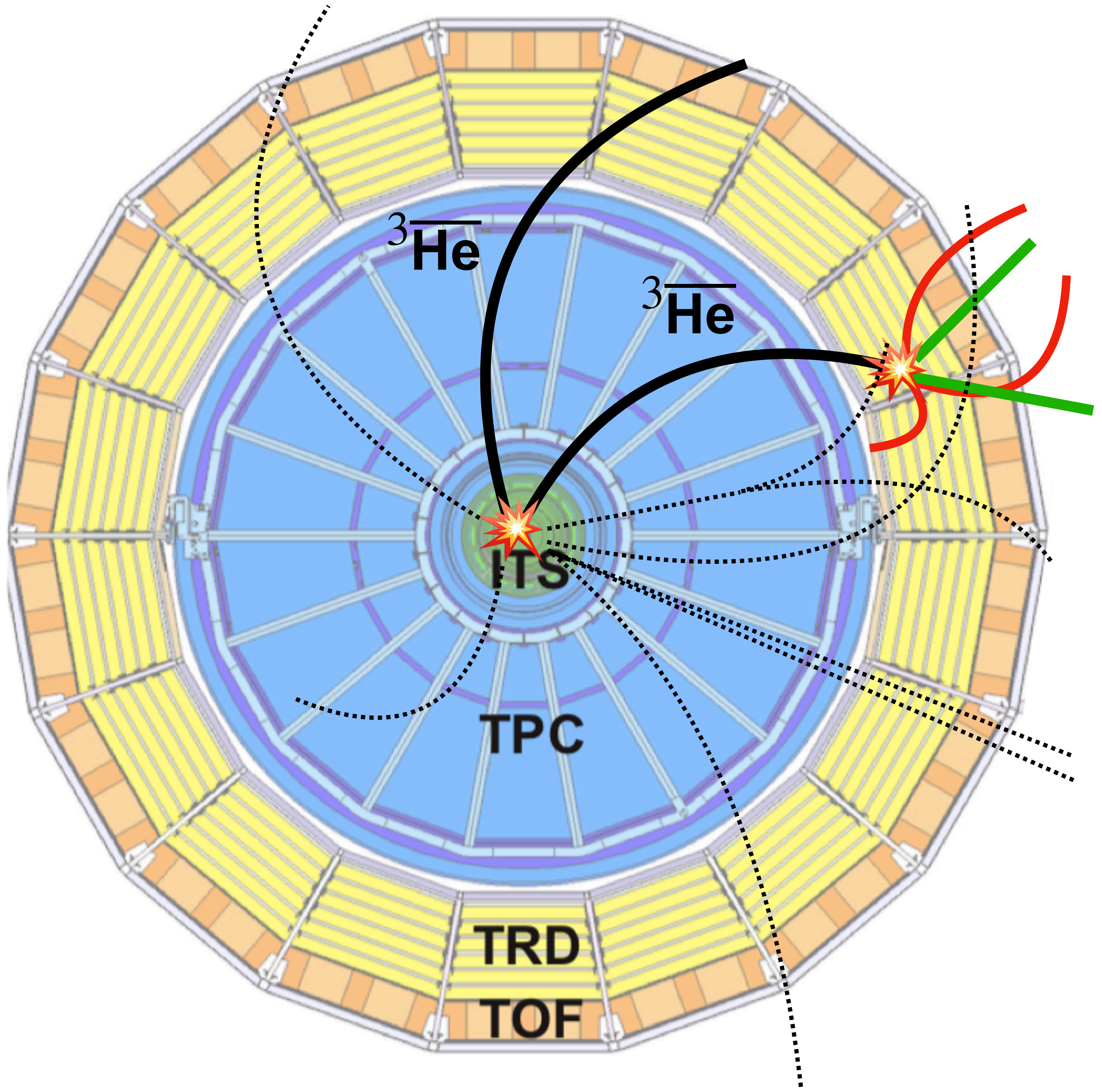
## Antimatter-to-matter ratio

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




## TOF-TPC-matching

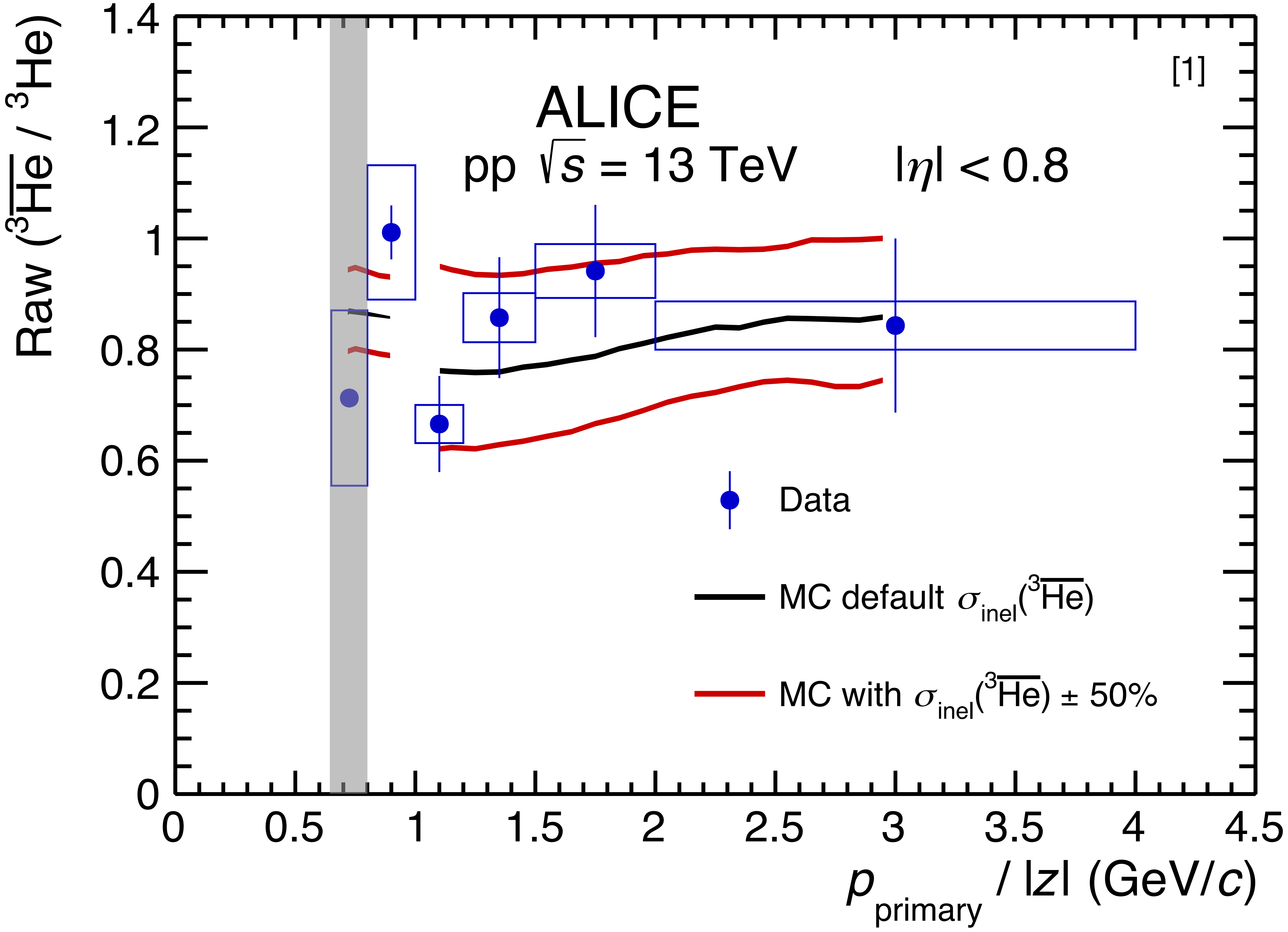
- Measure reconstructed $^3\overline{\rm He}_{TOF}/^3\overline{\rm He}_{TPC}$ and compare with MC simulations



# Extracting $\sigma_{inel}$ from data and Monte Carlo

- Monte Carlo (MC) simulations with varied $\sigma_{inel}$
- In each momentum bin, compare the antiparticle-to-particle ratio in MC to the one in data
- MC points are fit with an exponential, according to the Lambert-Beer law:

$$\overline{\text{B}}/\text{B} \propto \exp(-\sigma_{inel}/\sigma_{inel}^{def})$$




[1] arxiv.org/2202.01549

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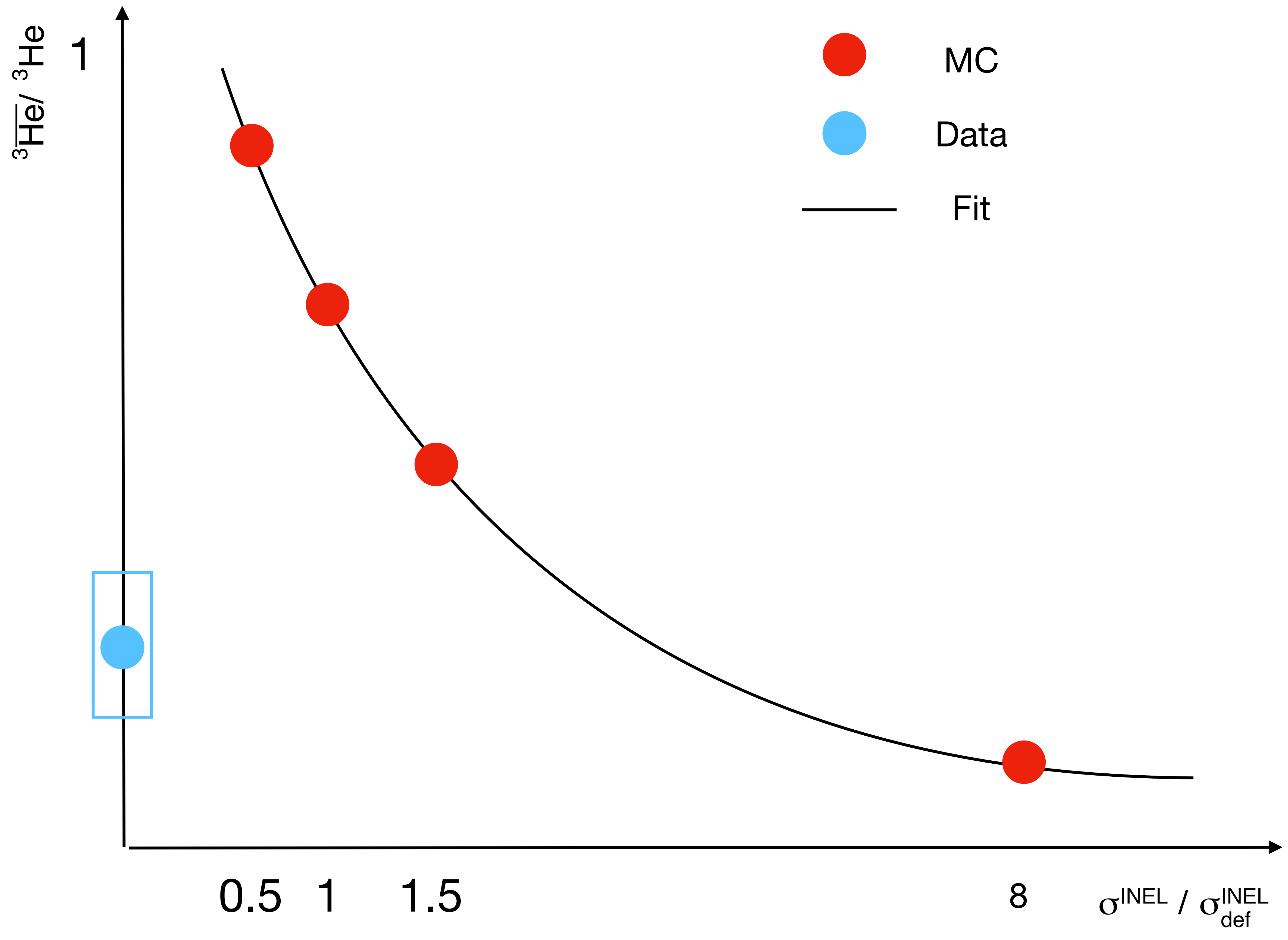


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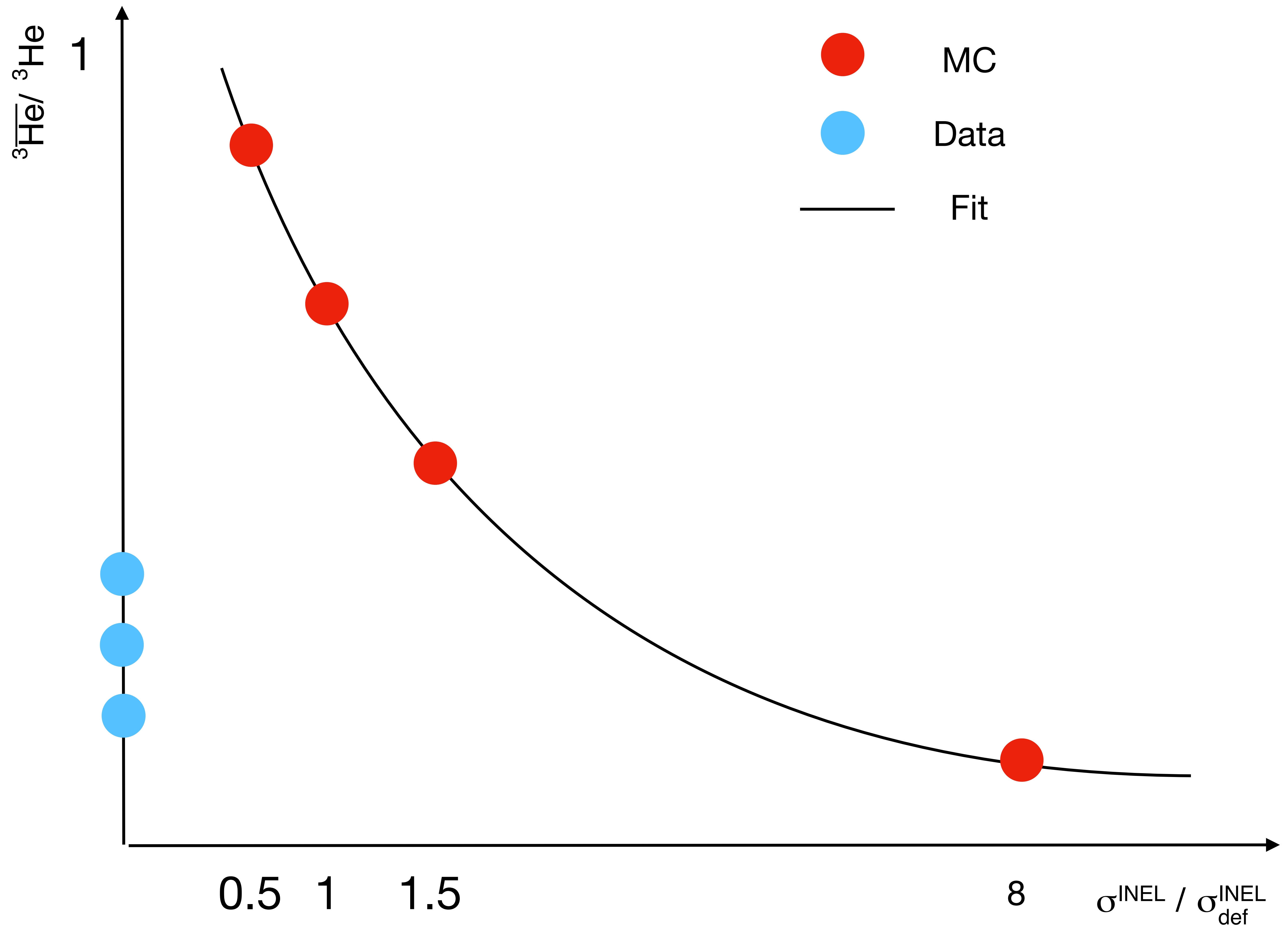


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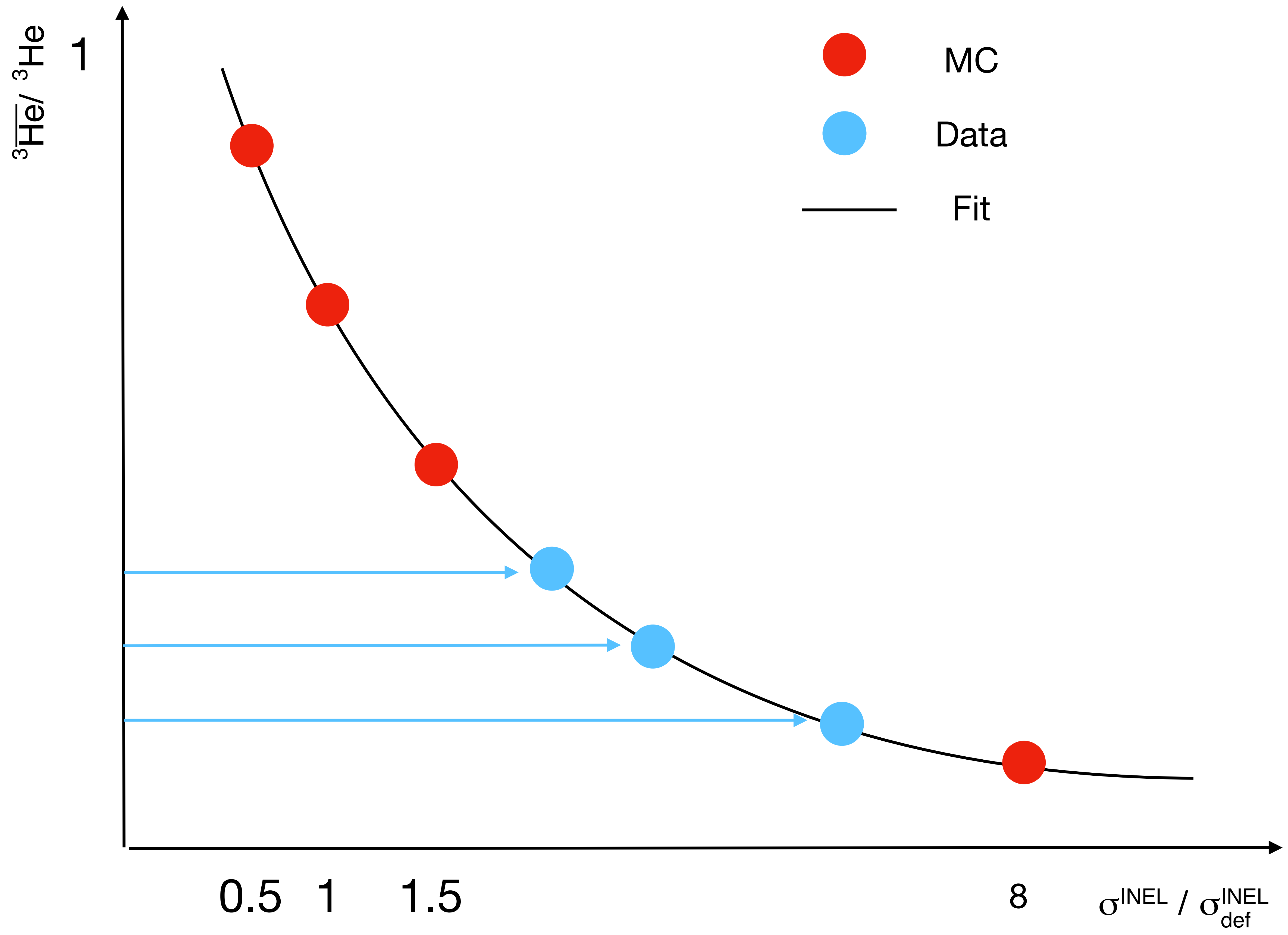


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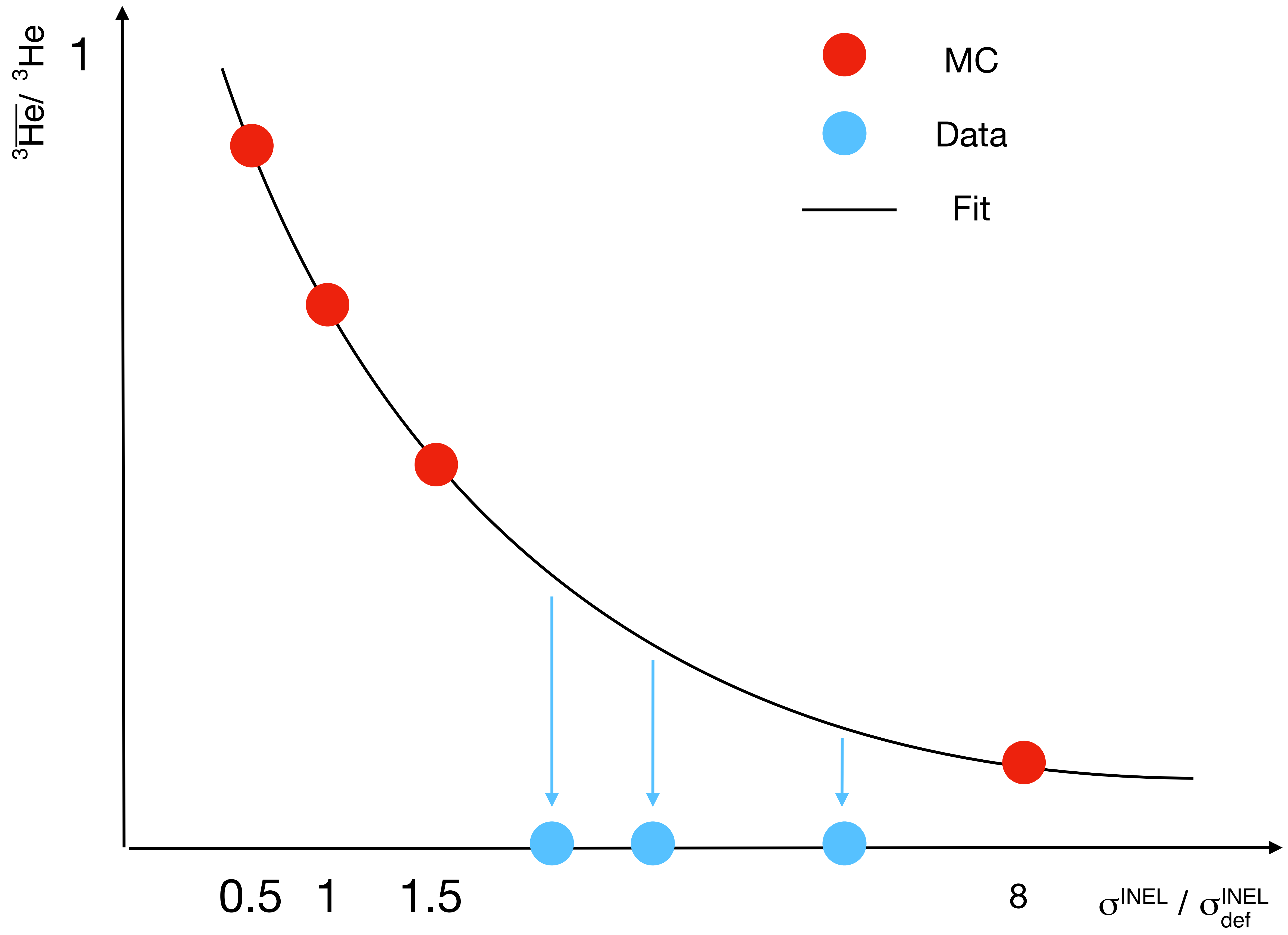


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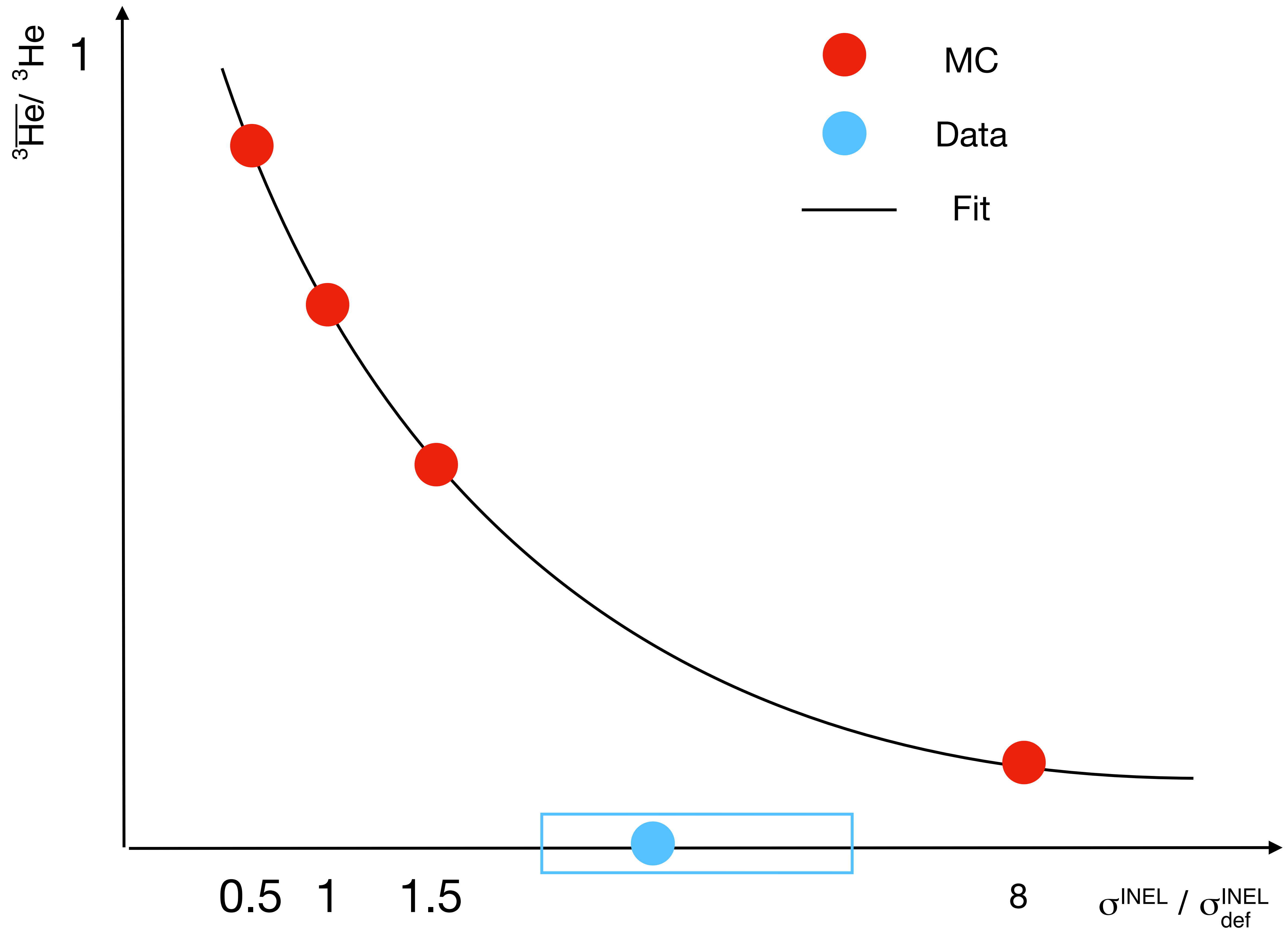


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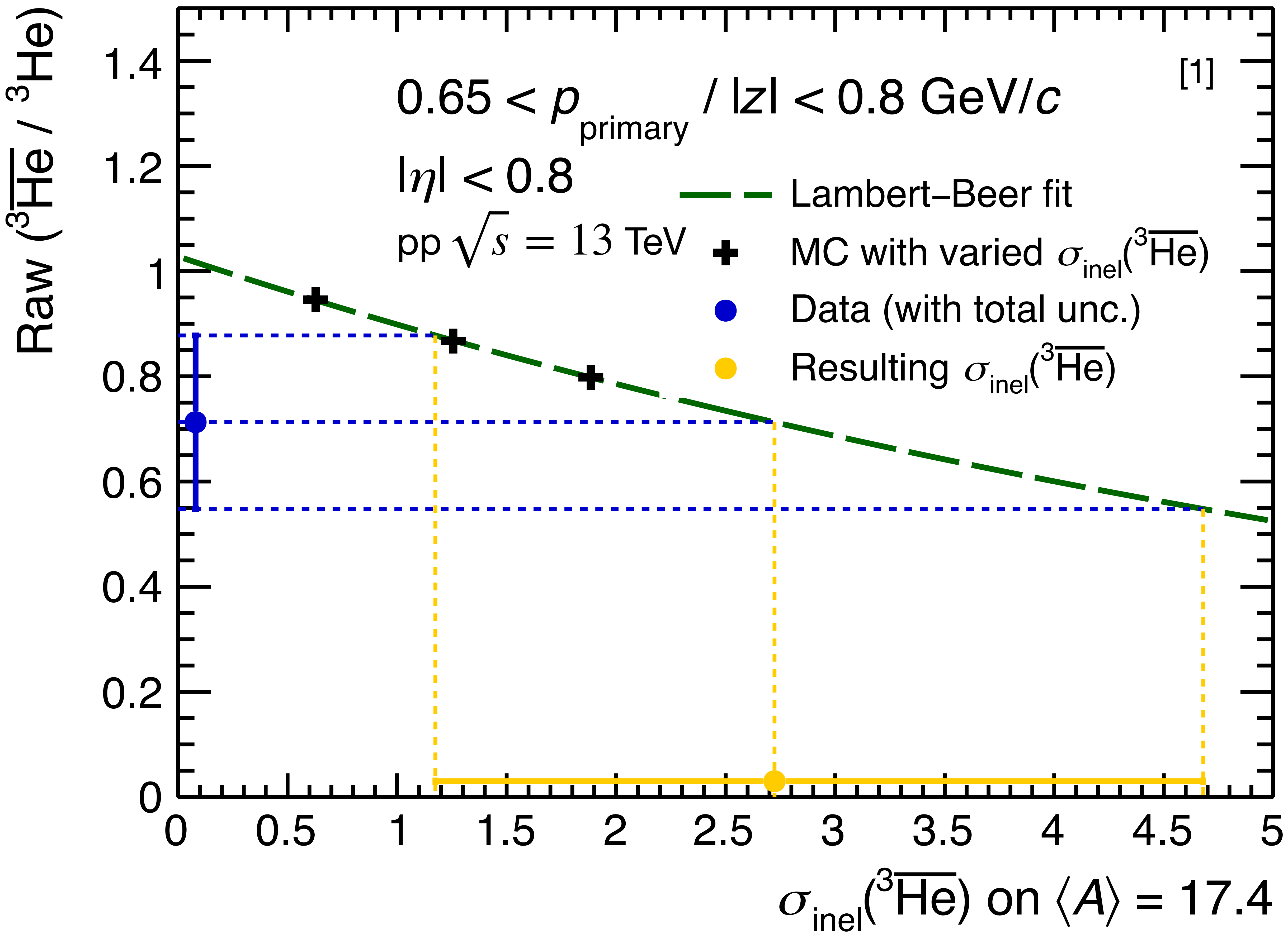



[1] arxiv.org/2202.01549

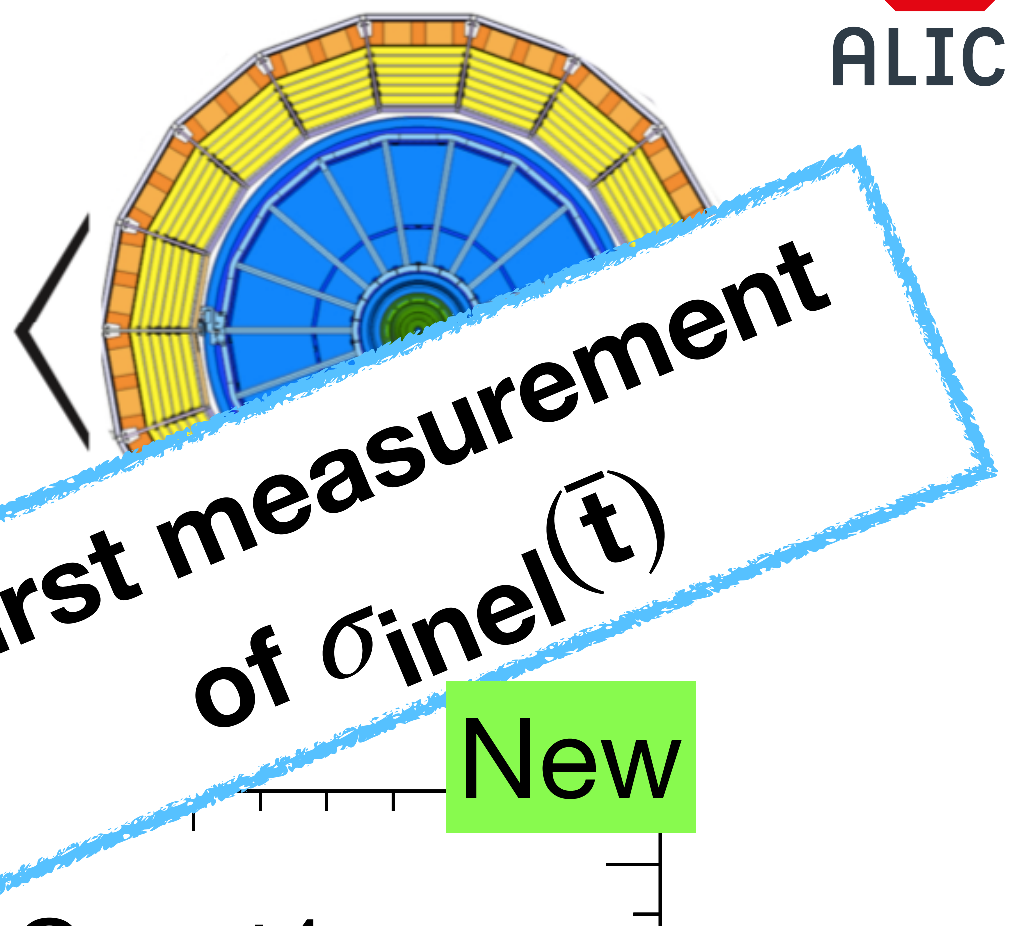
# Antideuteron inelastic cross section

$\sigma_{inel}(\overline{d})$ on average ALICE detector material
Hint of a steeper rise at low momentum

**First low-energy measurement of $\sigma_{inel}(\overline{d})$**

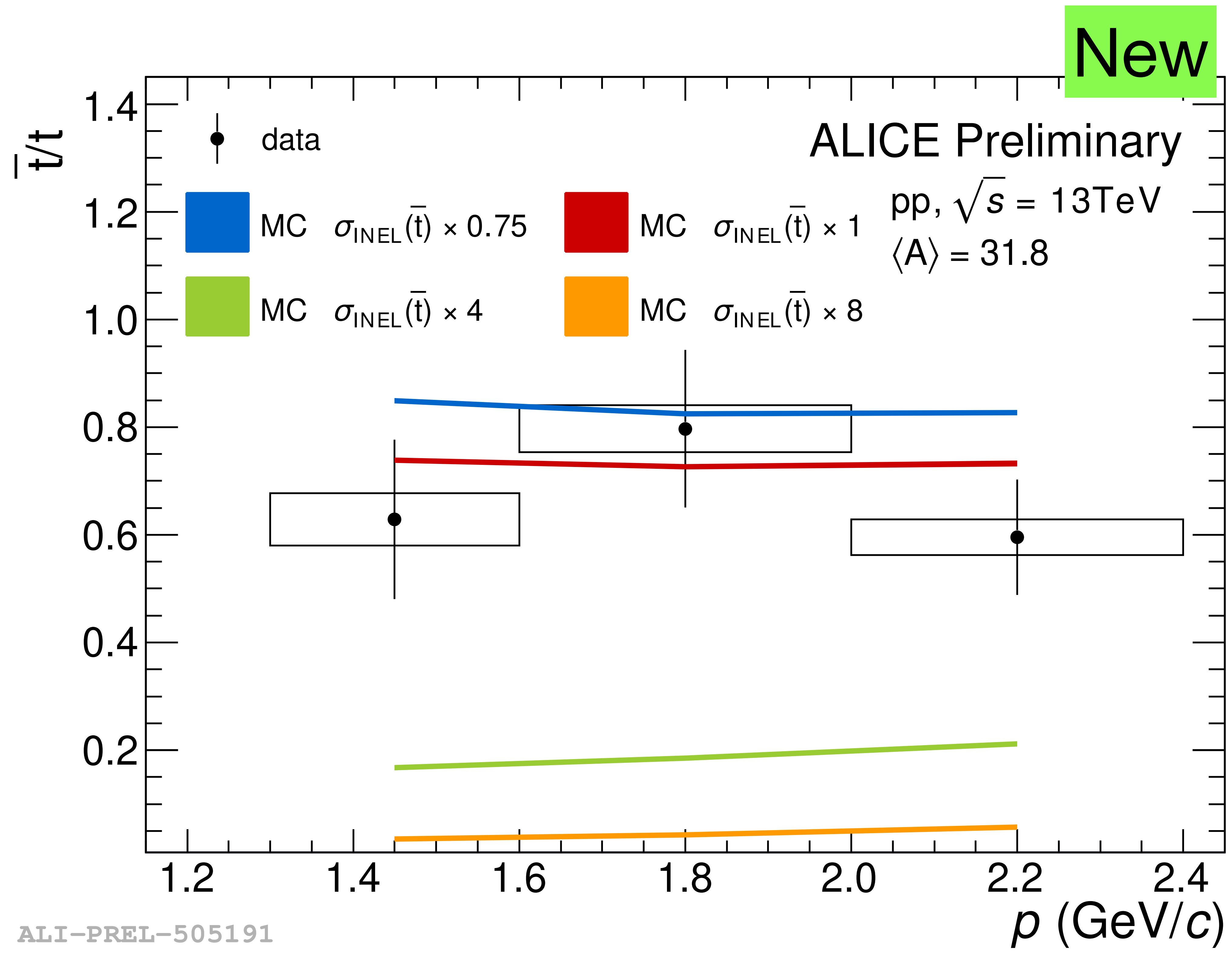

PRL 125, 162001 (2020)

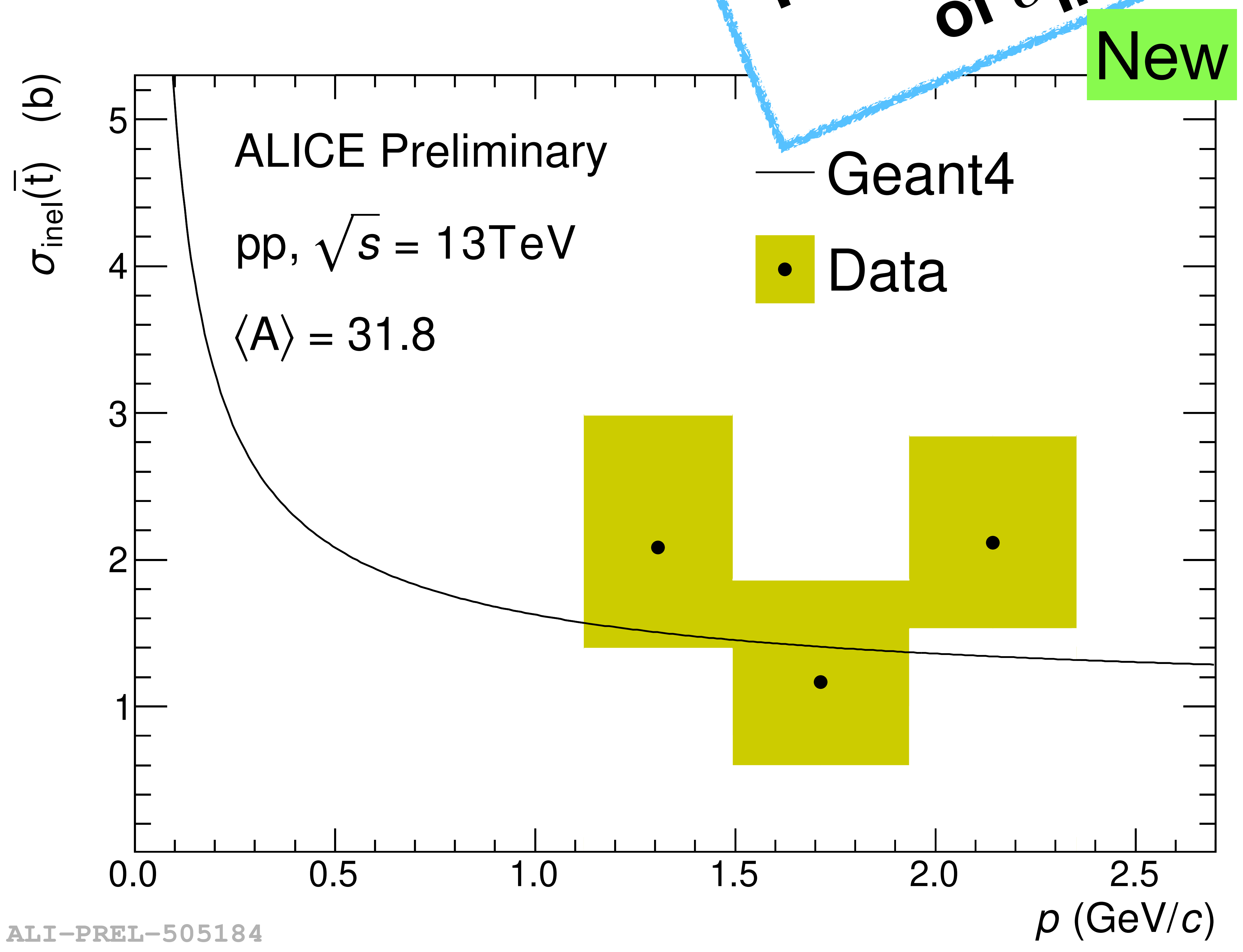
# Antitriton inelastic cross section



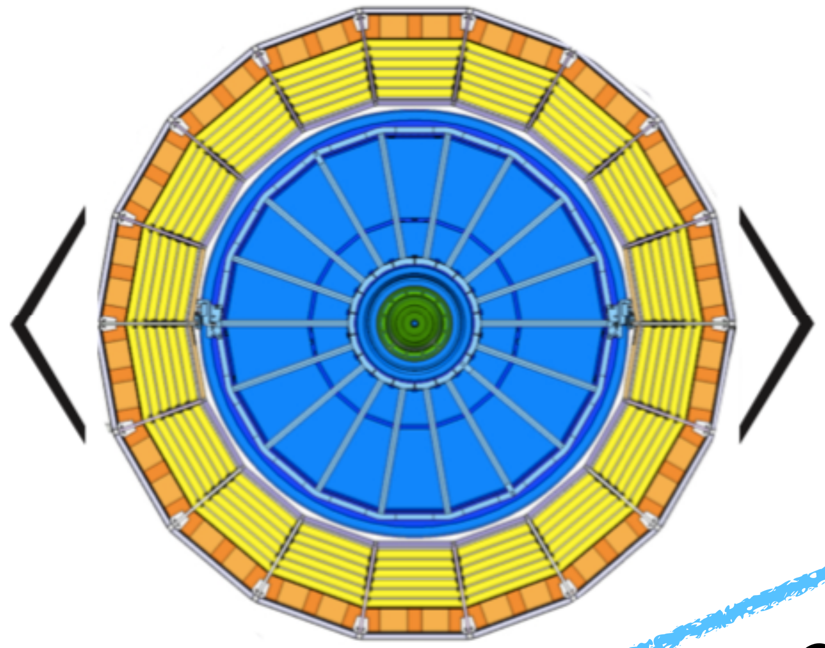

$\sigma_{inel}(\bar{t})$ on average ALICE detector material

Good agreement with Geant4, but with significant uncertainties



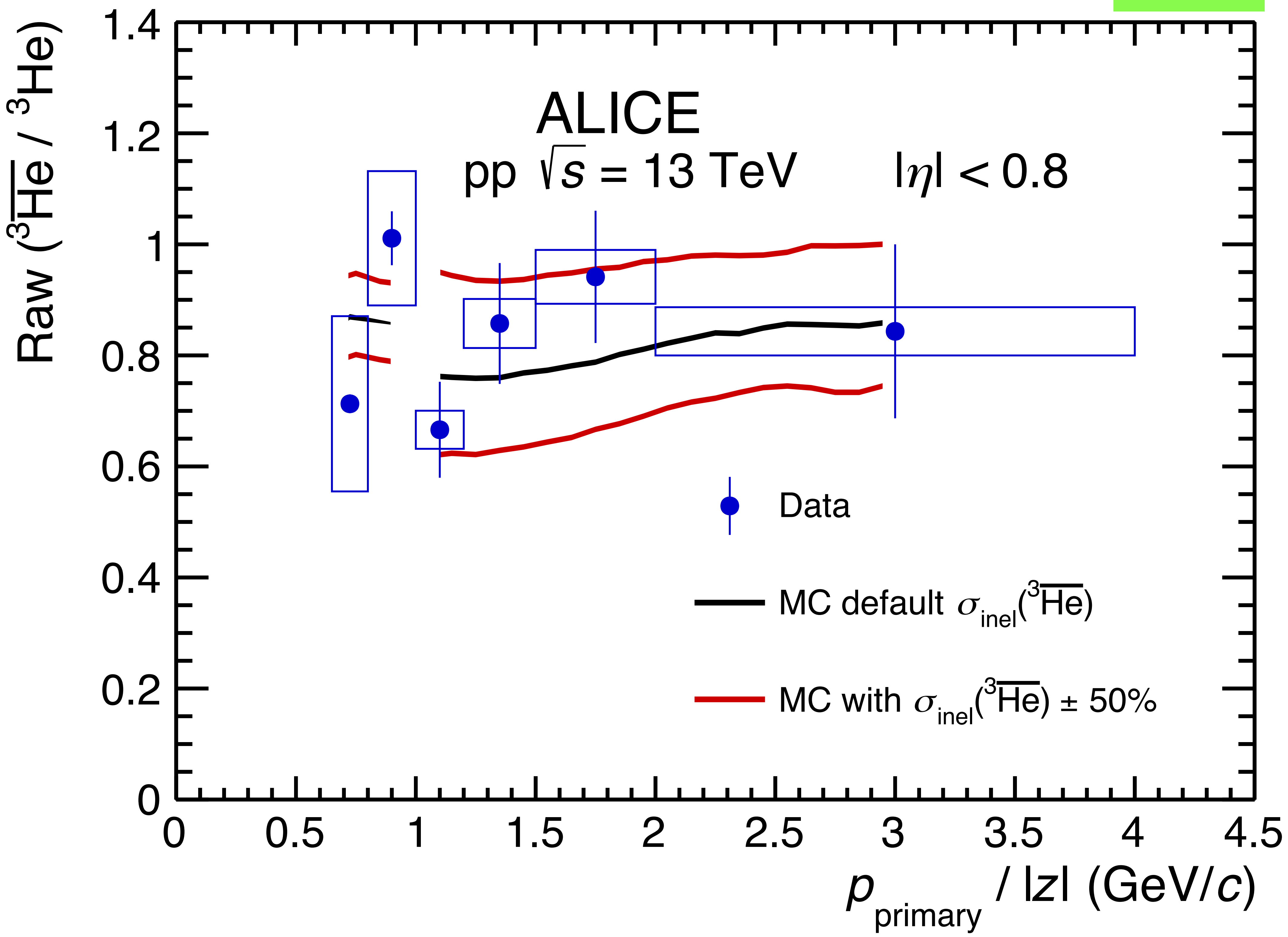
# $^3\overline{\text{He}}$ inelastic cross section



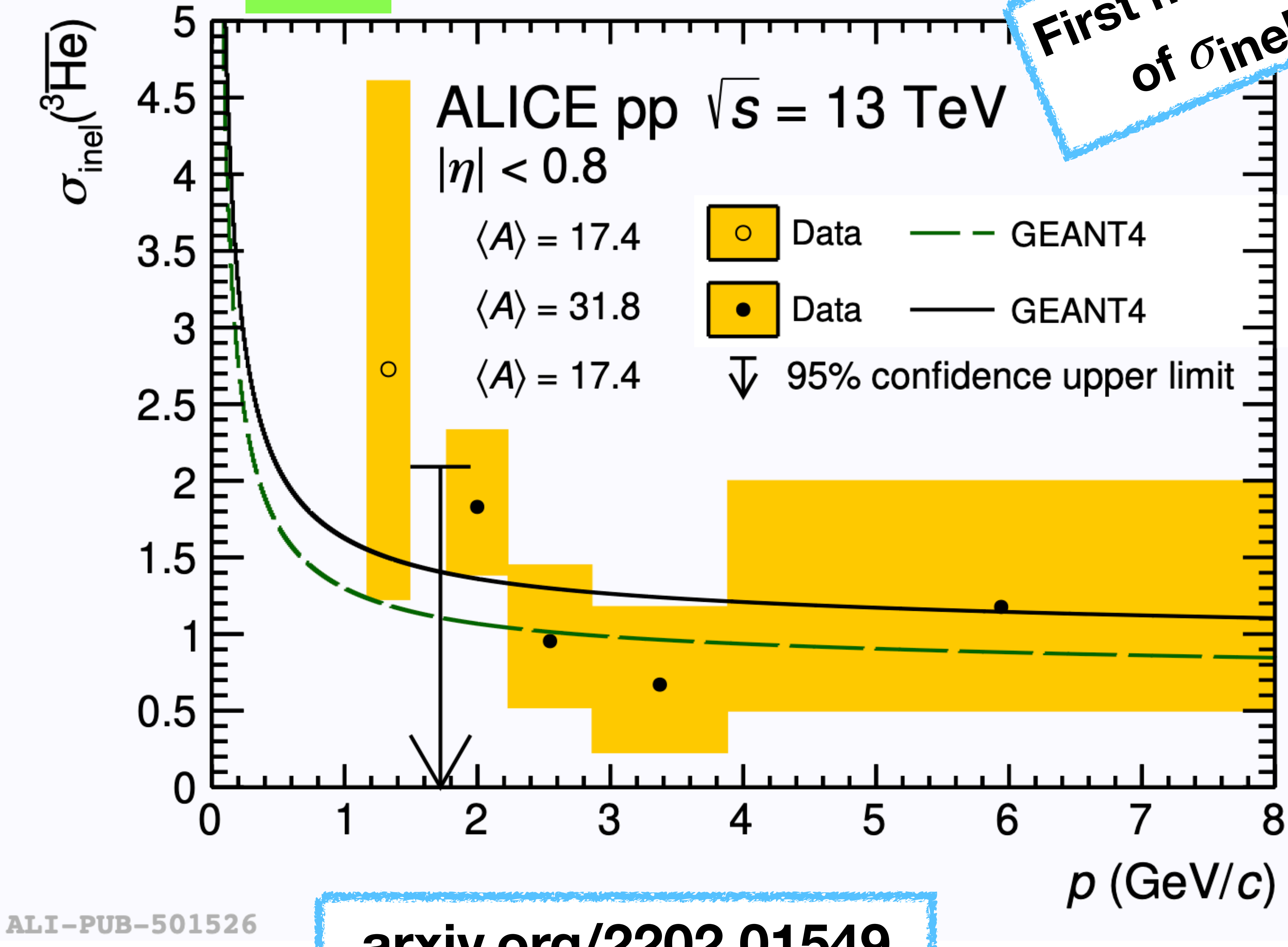
## $\sigma_{inel}(^3\overline{He})$ on average ALICE detector material

- Good agreement between the measurements and the Geant4 parameterizations

New



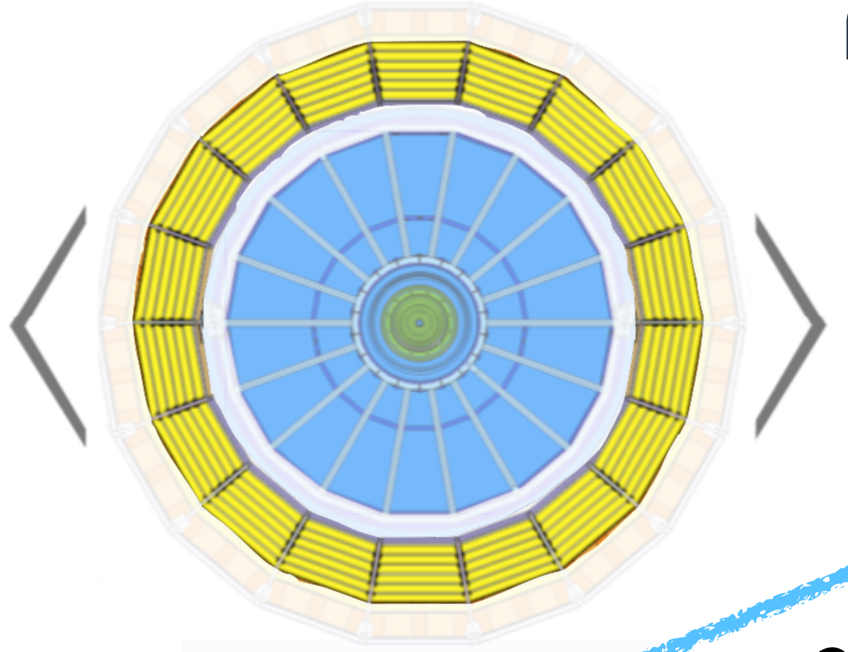

New




**First measurement of $\sigma_{inel}(^3\overline{He})$**

**arxiv.org/2202.01549**

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



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

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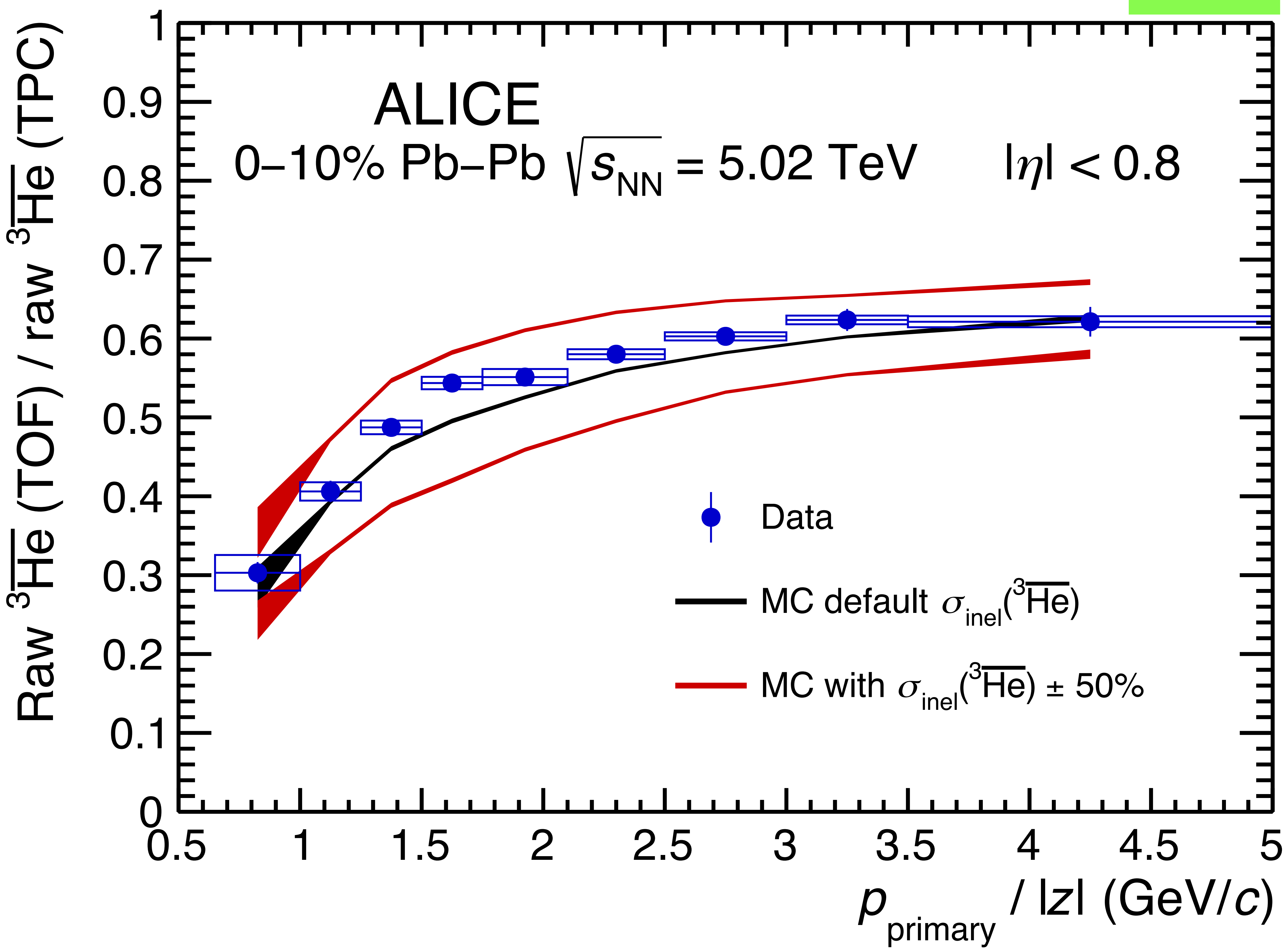


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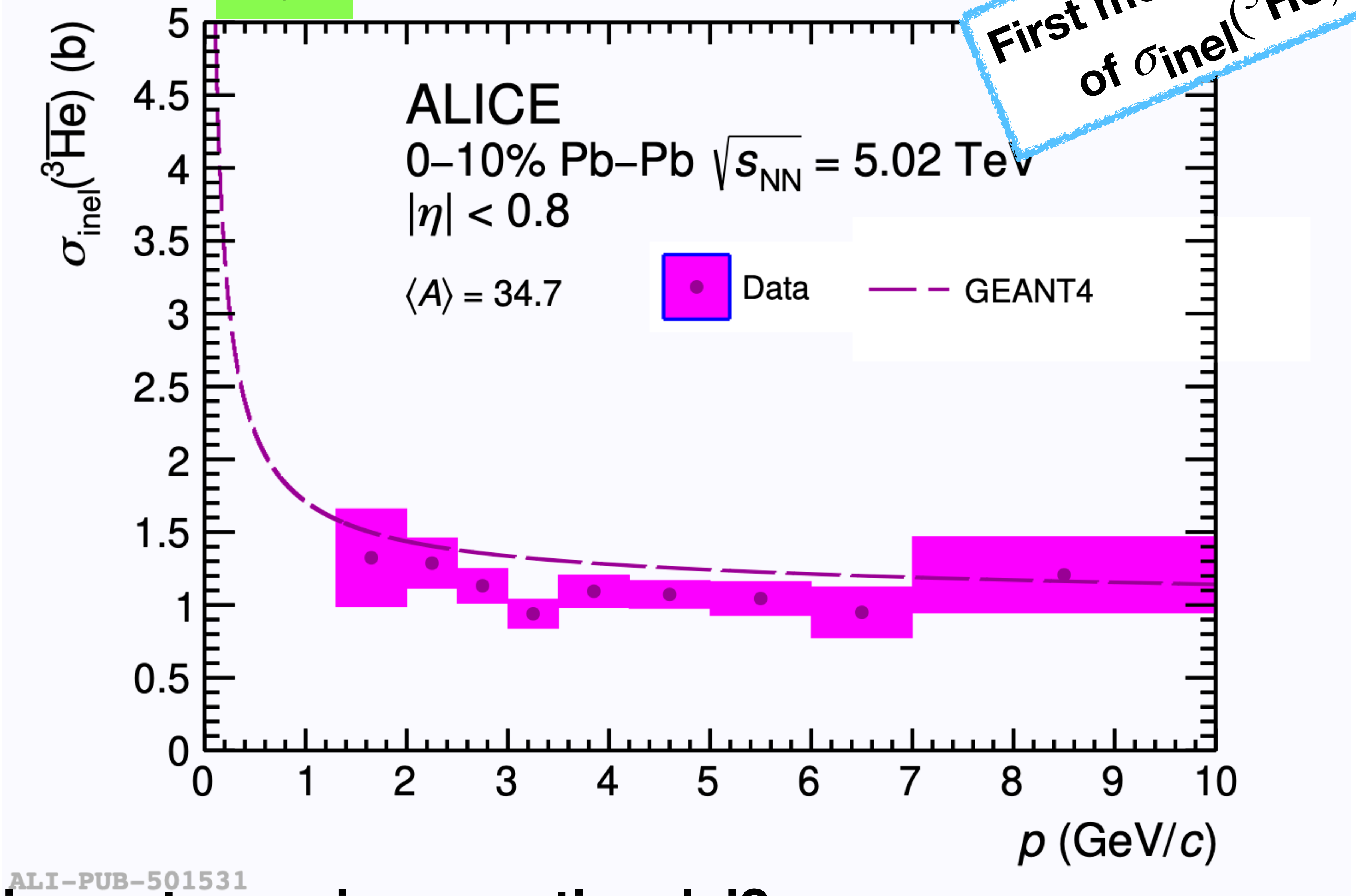



First measurement of $\sigma_{\mathrm{inel}}(^{3}\overline{\mathrm{He}})$

**How do these measurements impact cosmic ray antinuclei?**

# Recipe to cook antinuclei fluxes

# Galprop

**Transport equation**

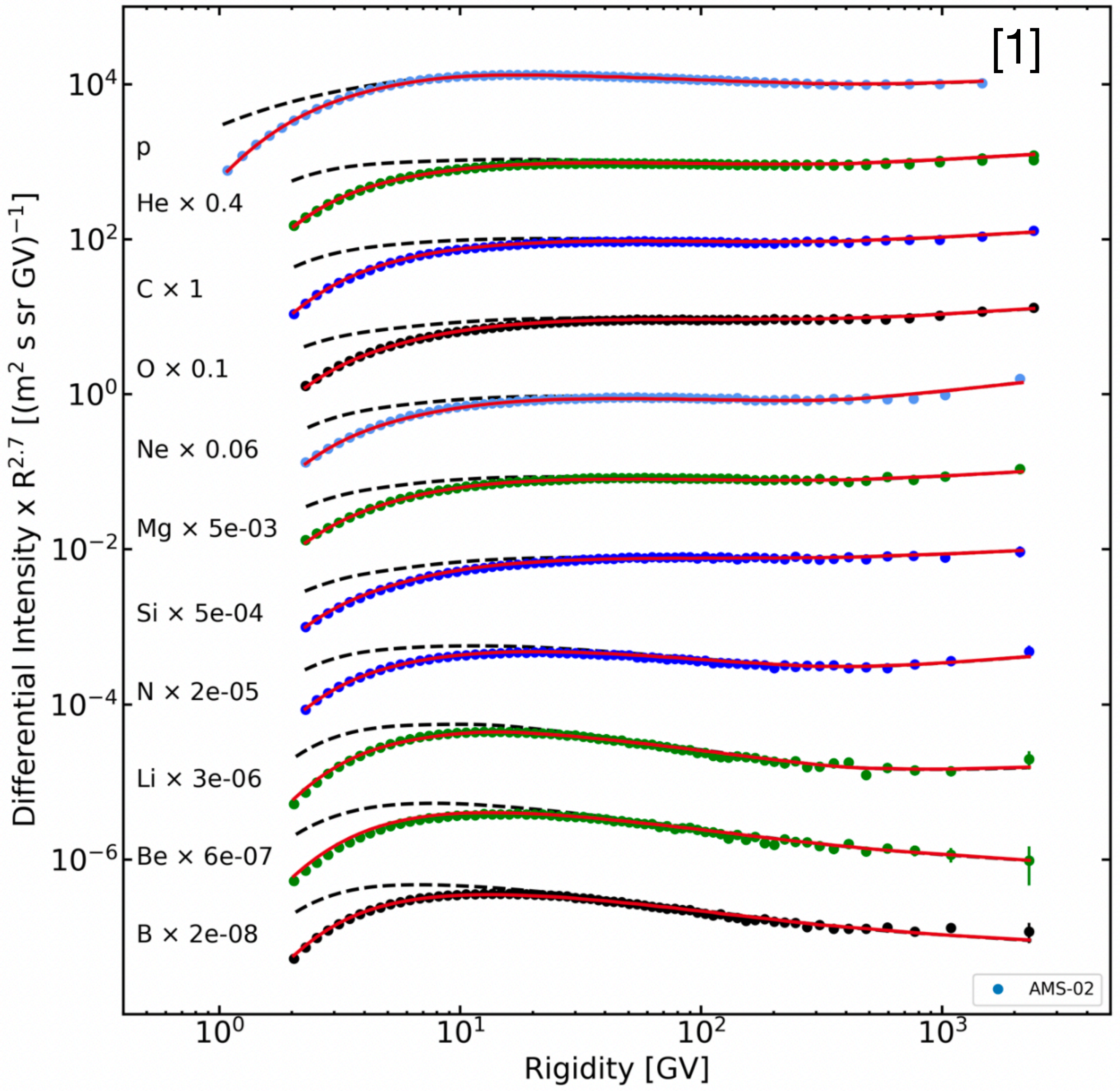
$$\frac{\partial \psi}{\partial t} = q(\mathbf{r}, p) + \mathbf{div}(D_{xx}\mathbf{grad}\psi - \mathbf{V}\psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{\psi}{p^2} - \frac{\partial}{\partial p}\left[\psi \frac{dp}{dt} - \frac{p}{3}(\mathbf{div} \cdot \mathbf{V})\psi\right]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

Source Function

Propagation: diffusion, convection…

Fragmentation, annihilation

Propagation can be constrained using proton and heavier nuclei cosmic ray measurements

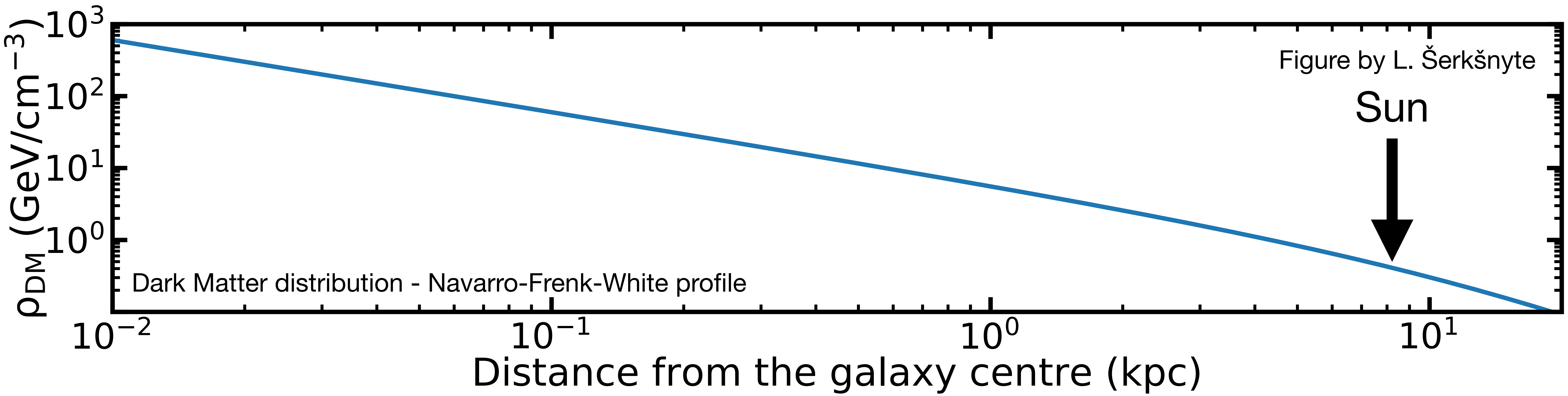



[1] *Boschini et al. ApJS 250 27 (2020)*
A. Strong, et. al. Nuclear and Particle Physics Proceedings, 297-299, 2018

# Antinuclei source terms

- The source term for antinuclei from dark matter can be written as:

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



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This is the thermally averaged annihilation cross section.

We can use $<\sigma v> = 2.6\mathrm{x}10^{-26}\mathrm{cm^3s^{-1}}$

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

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This accounts for anti-tritons which will then decay into $^{3}\overline{\rm He}$. $\epsilon \approx 1$

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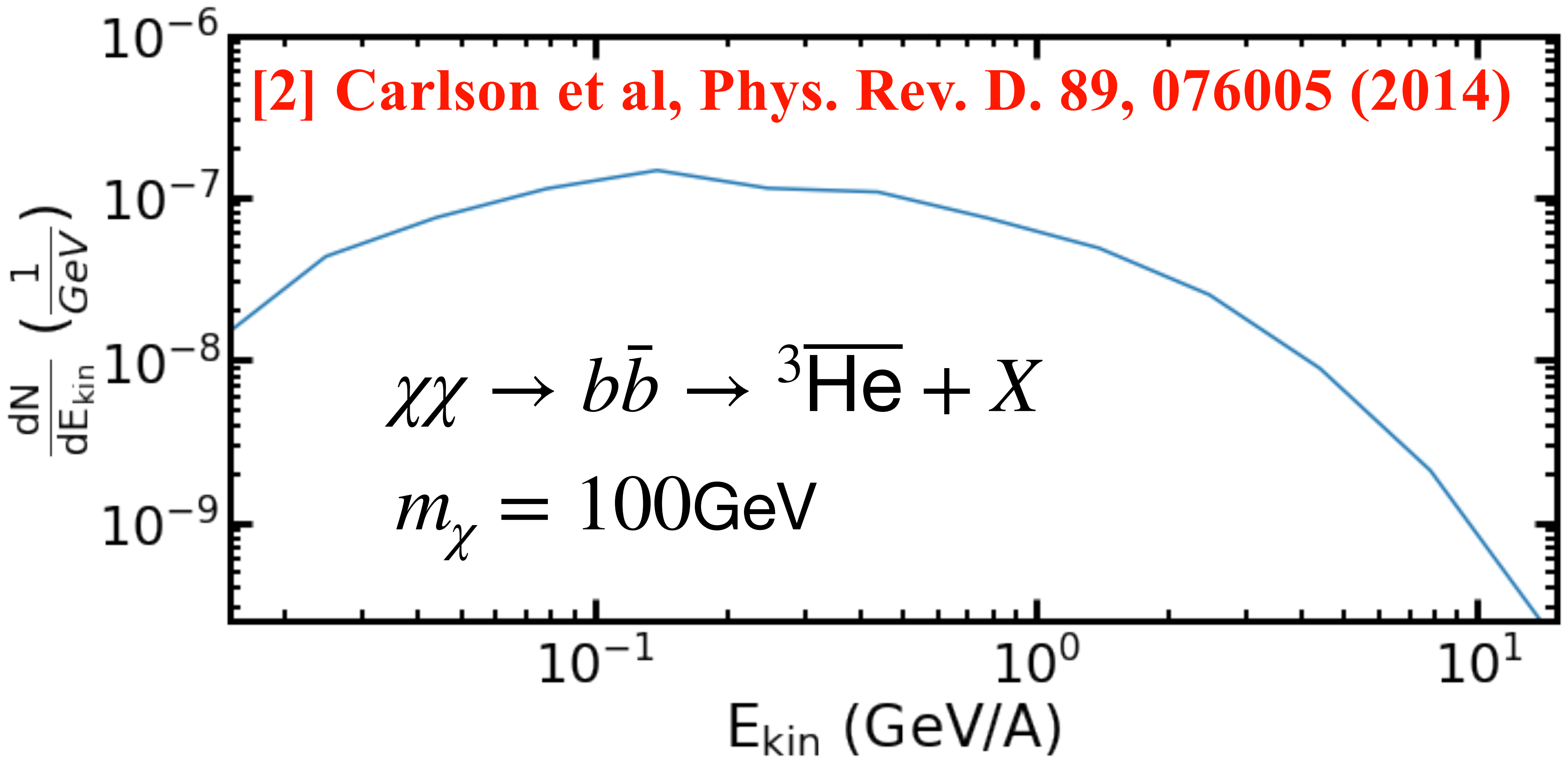
- The final term is the spectra of produced antinuclei, normalized to each dark matter annihilation.
- This can be calculated using a coalescence model. [3]

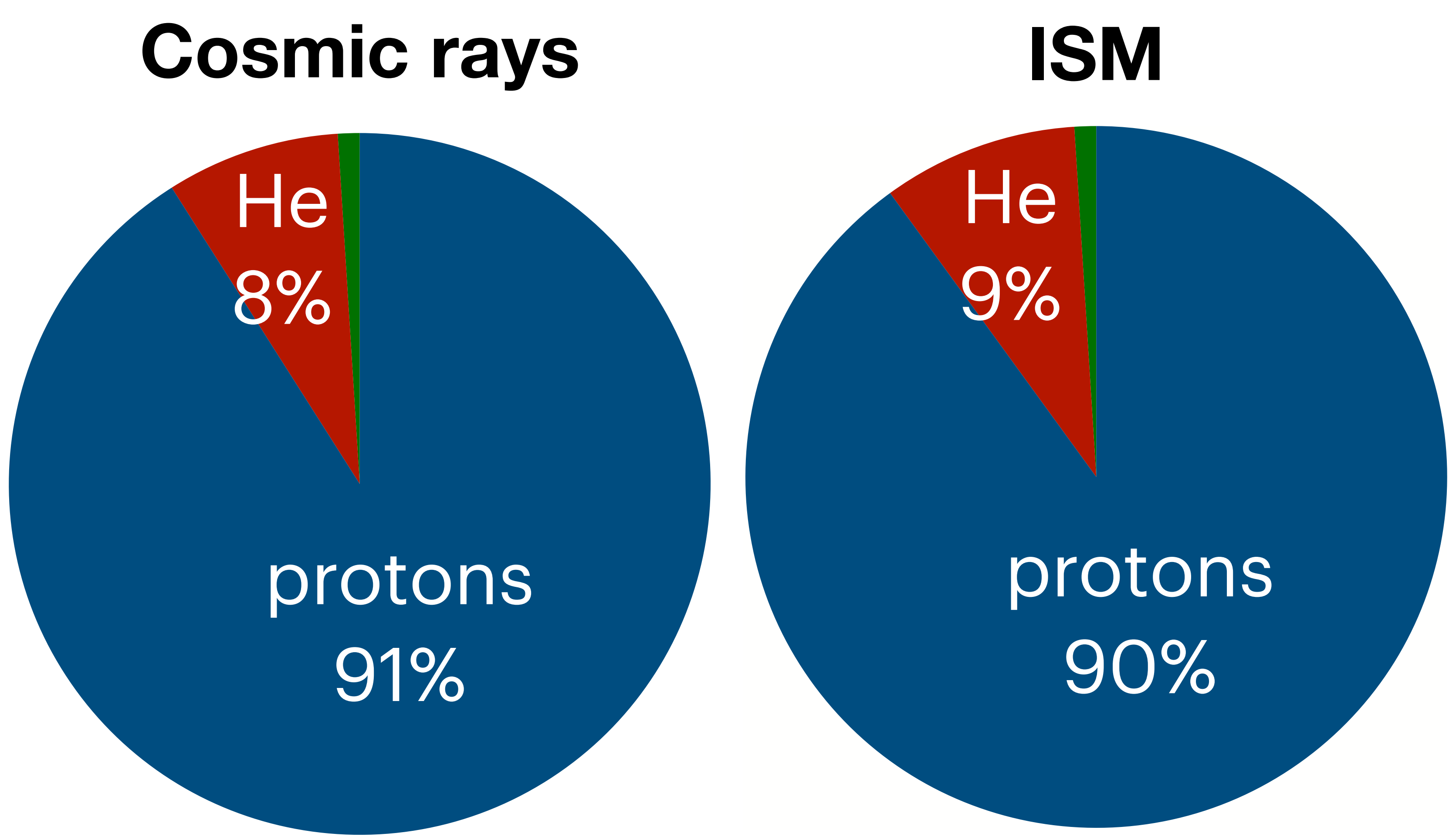



[3] F. Bellini, A. Kelweit, Phys.Rev.C pp (2019)

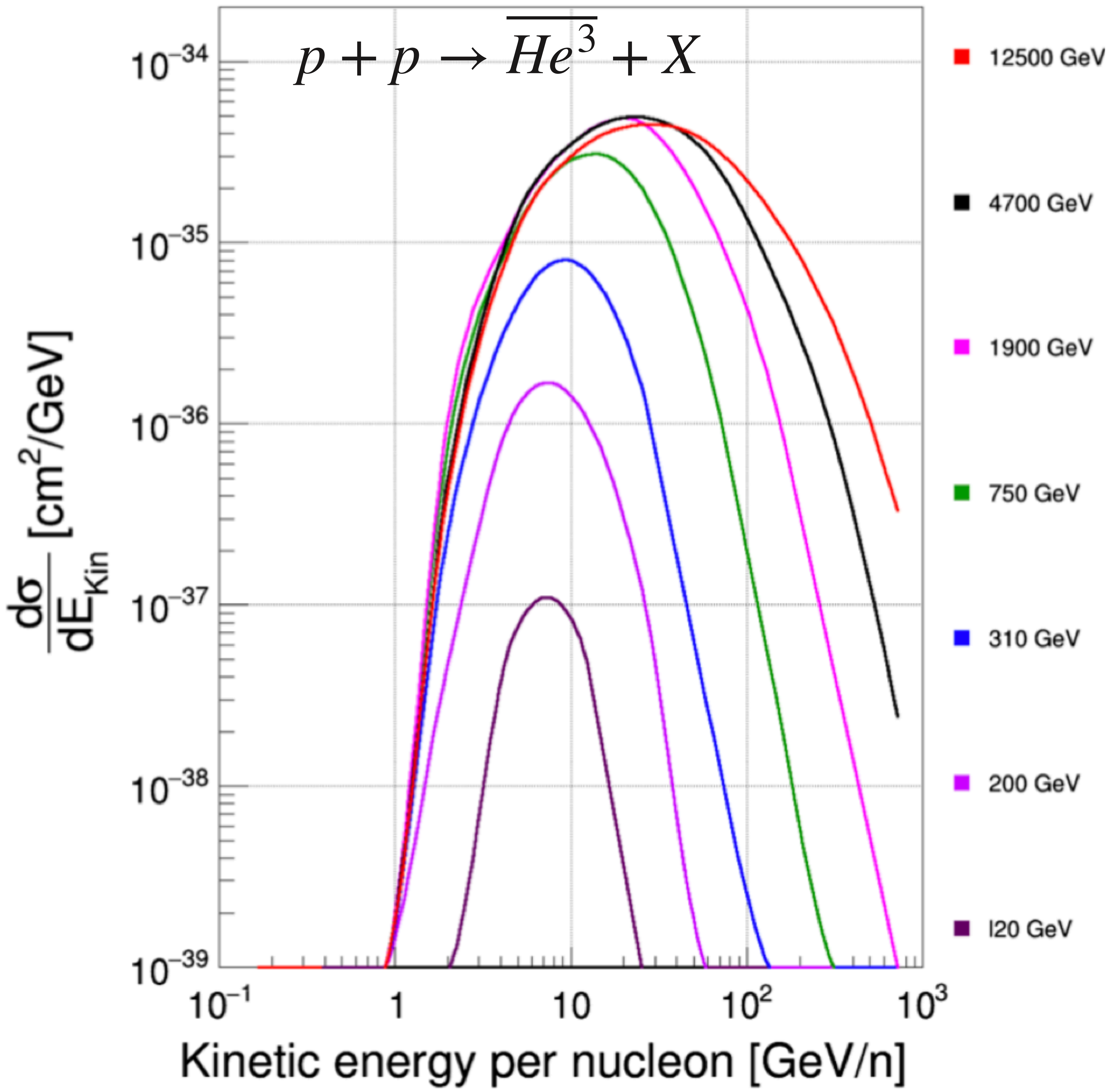
# $^3\overline{He}$ source function: Cosmic rays + Interstellar medium

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

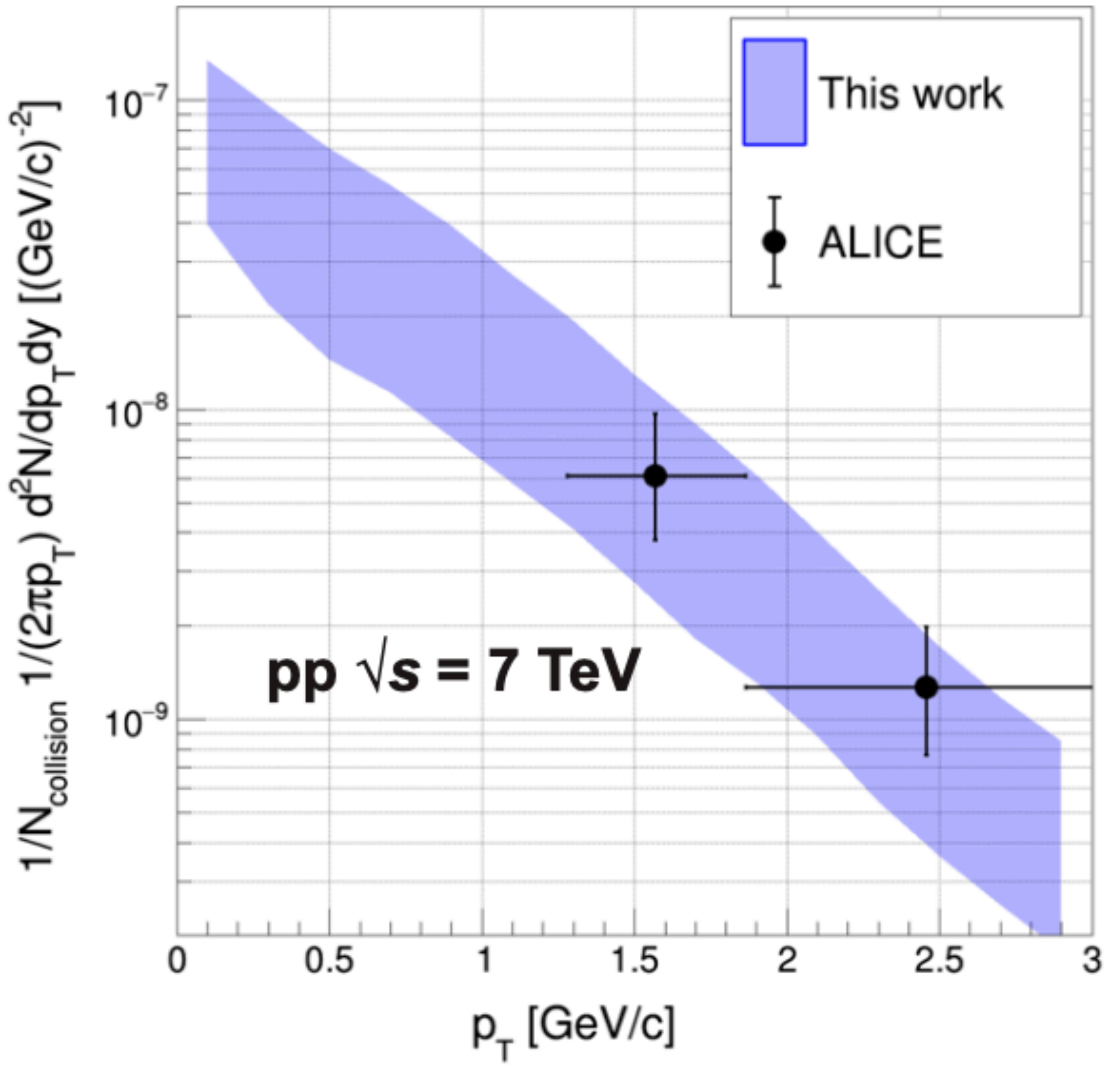
- Production cross section in pp collisions from [1] (EPOS LHC + event-by-event coalescence)
- Other collision types scaled $(A_T A_P)^{2.2/3}$
- Validated by ALICE data




**$^3\overline{He}$ production in pp**




**Comparison with ALICE results [1,2]**



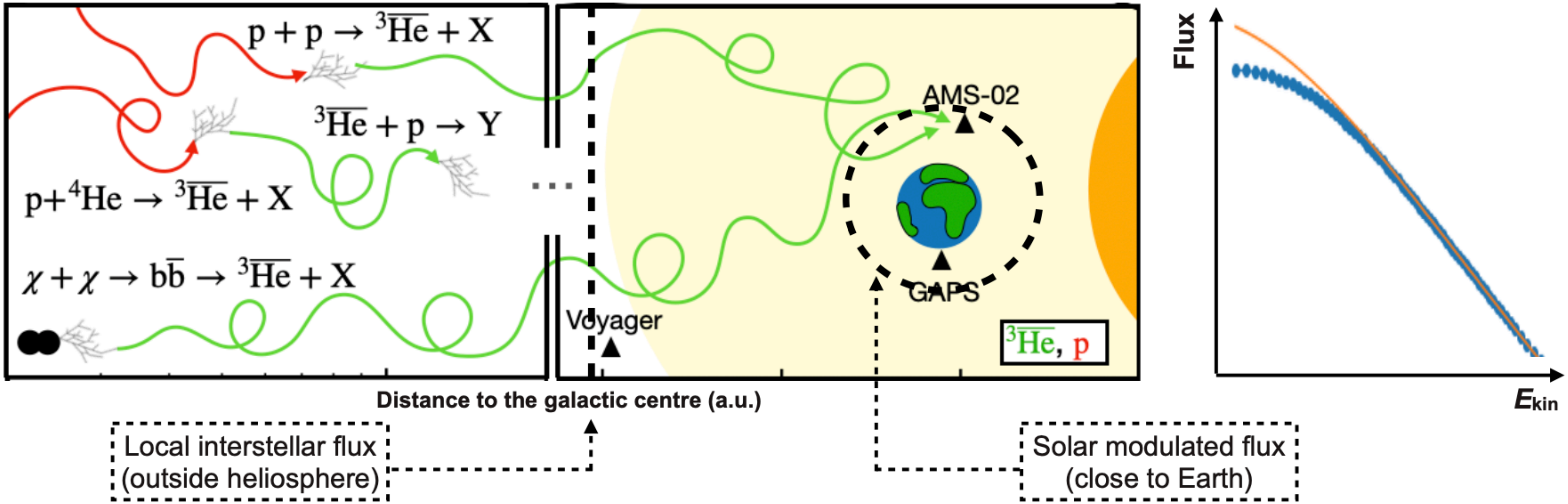

[1] Shukla et al, Phys. Rev. D. 102, 063004 (2020)
[2] ALICE, Phys. Rev. C 97, 024615 (2018)

# Solar environment effects

Solar magnetic field forms heliosphere which shields cosmic rays.

Solar modulation is accounted for using the Force-Field approximation [1] with Fisk potential $\phi$ = 0.4 GV:

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

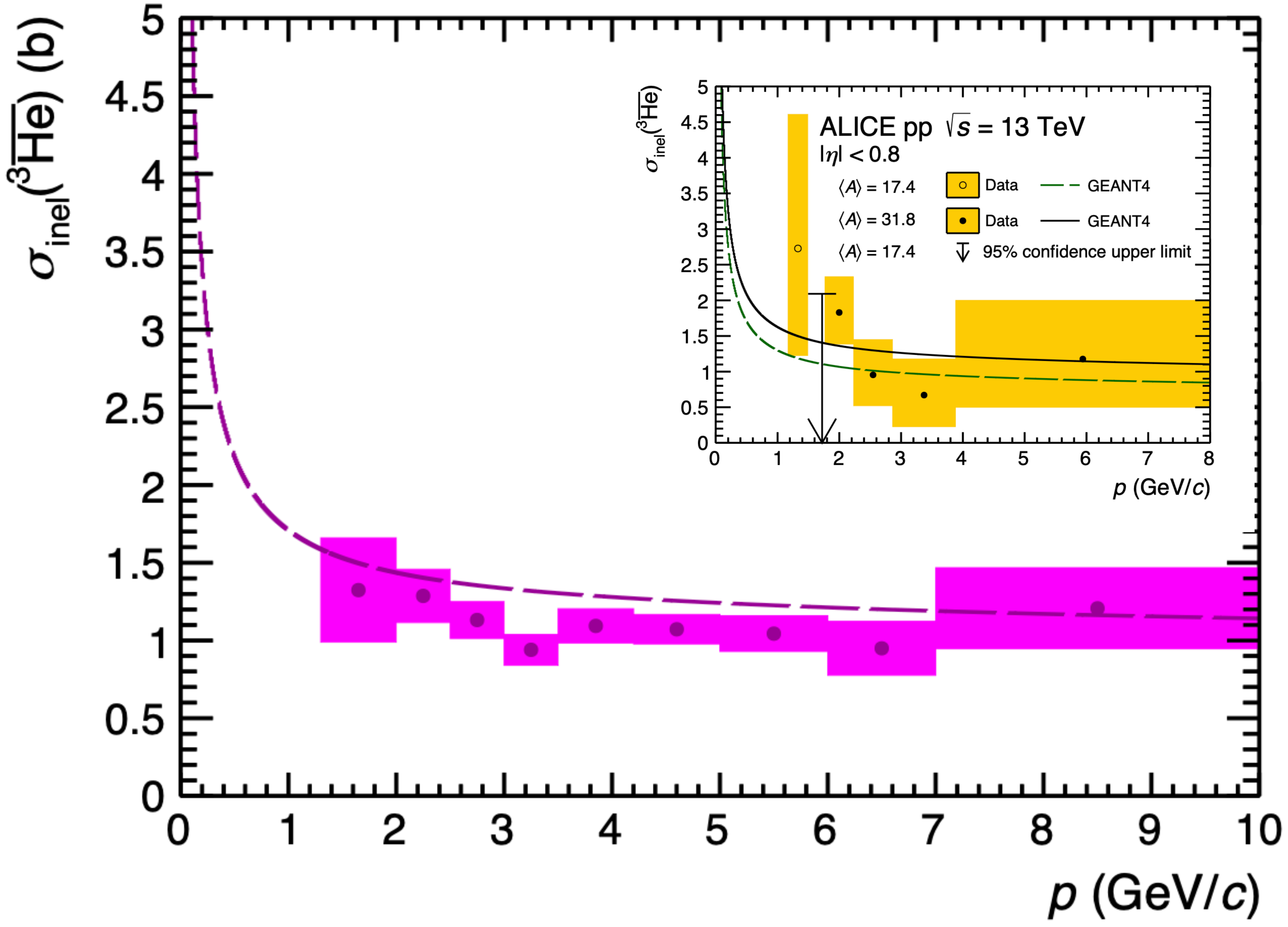


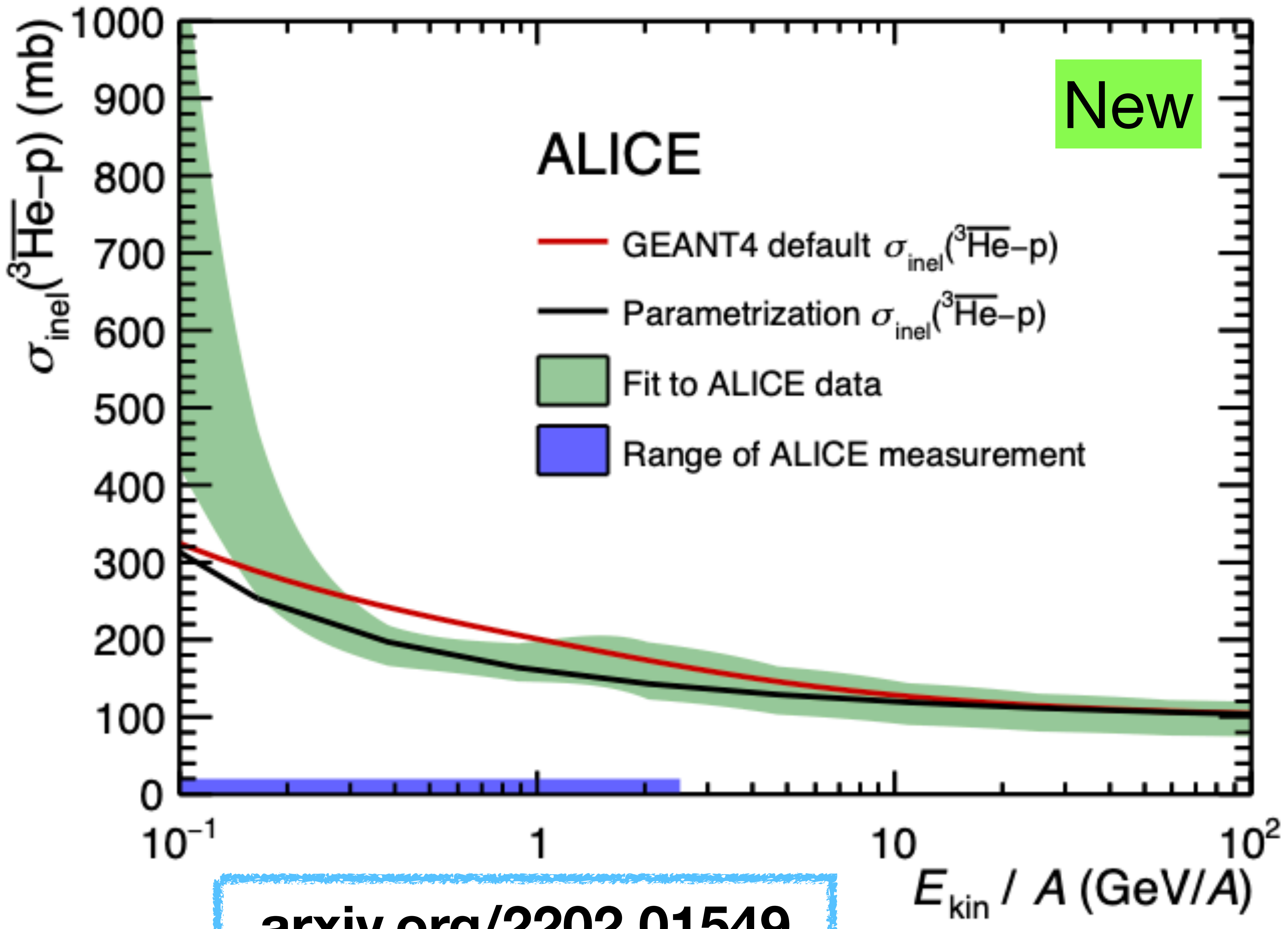

[1] Gleeson, Axford, Astrophys. J. 154 (1968) 1011

# Inelastic interactions

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

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




arxiv.org/2202.01549

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

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

Effect of various inelastic cross sections on $^3\overline{\mathrm{He}}$ fluxes

Solar modulated flux shifts particles to lower energies

Uncertainties only from ALICE measurement on $\sigma_{\mathrm{inel}}$

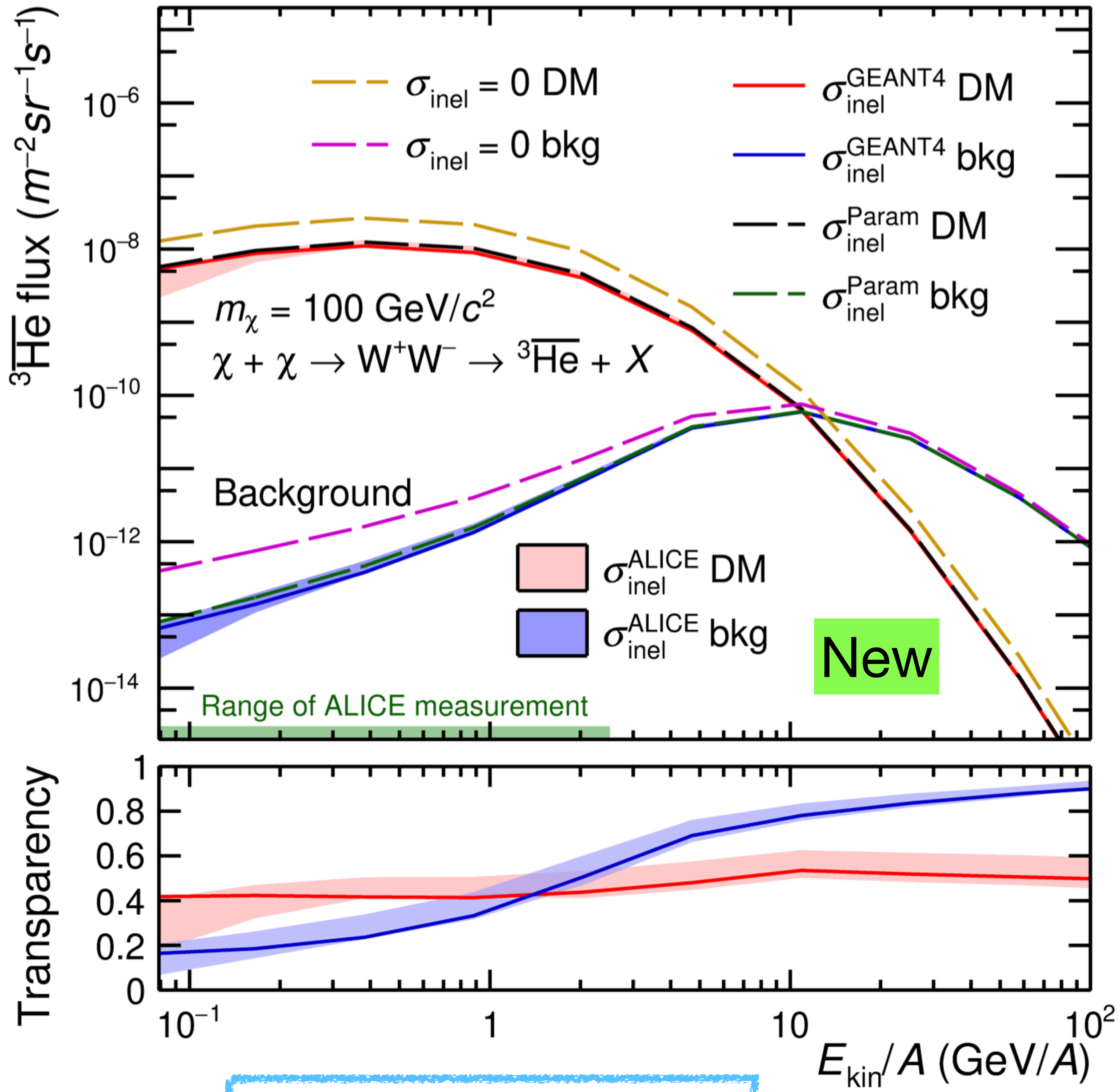
- **Small compared to other uncertainties in the field!**

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

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

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

**Outside heliosphere**




ALI-PUB-501541

**arxiv.org/2202.01549**

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

Effect of various inelastic cross sections on $^3\overline{\text{He}}$ fluxes

Solar modulated flux shifts particles to lower energies

Uncertainties only from ALICE measurement on $\sigma_{inel}$

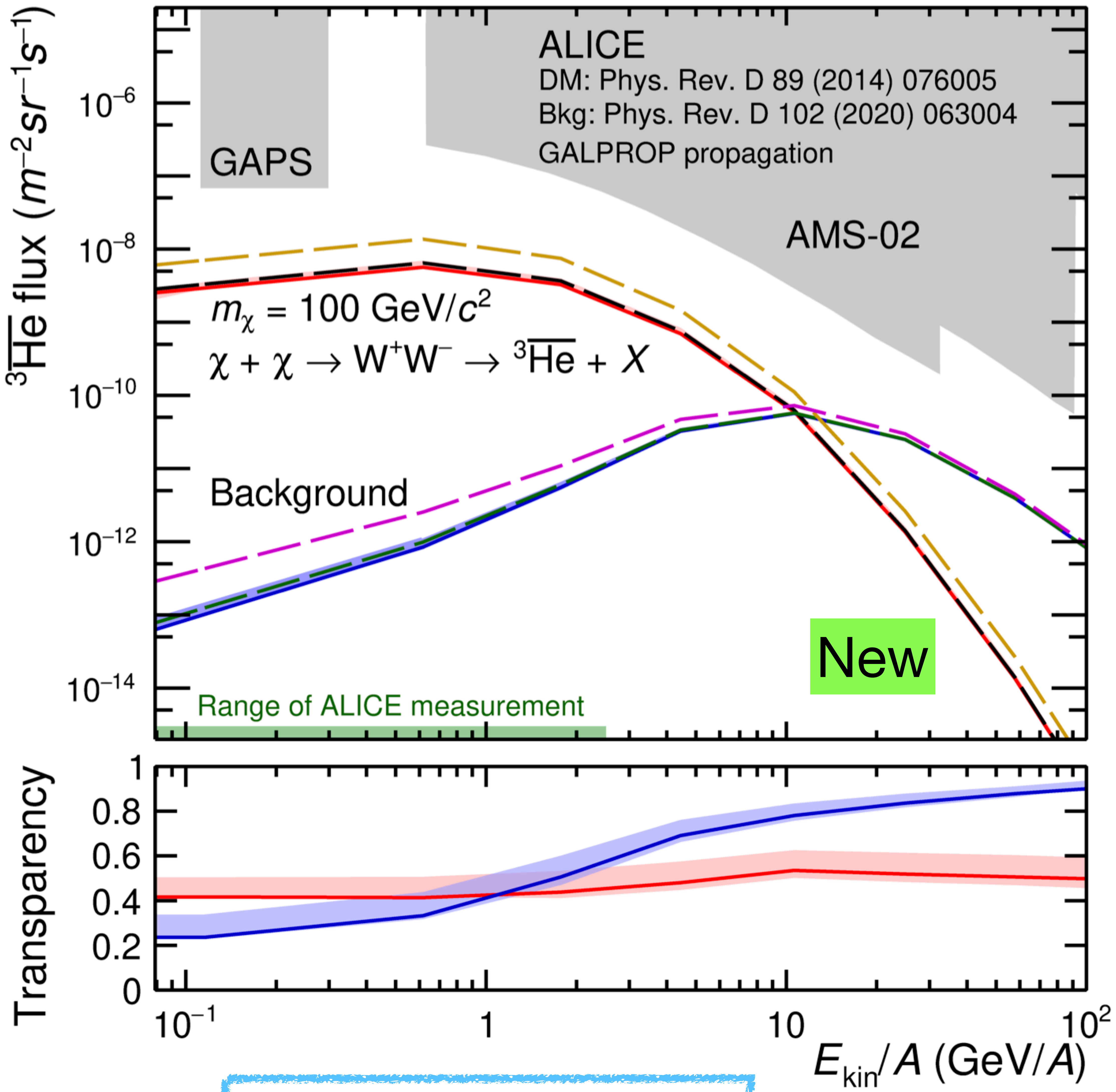
- **Small compared to other uncertainties in the field!**

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!**

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

Near earth




arxiv.org/2202.01549

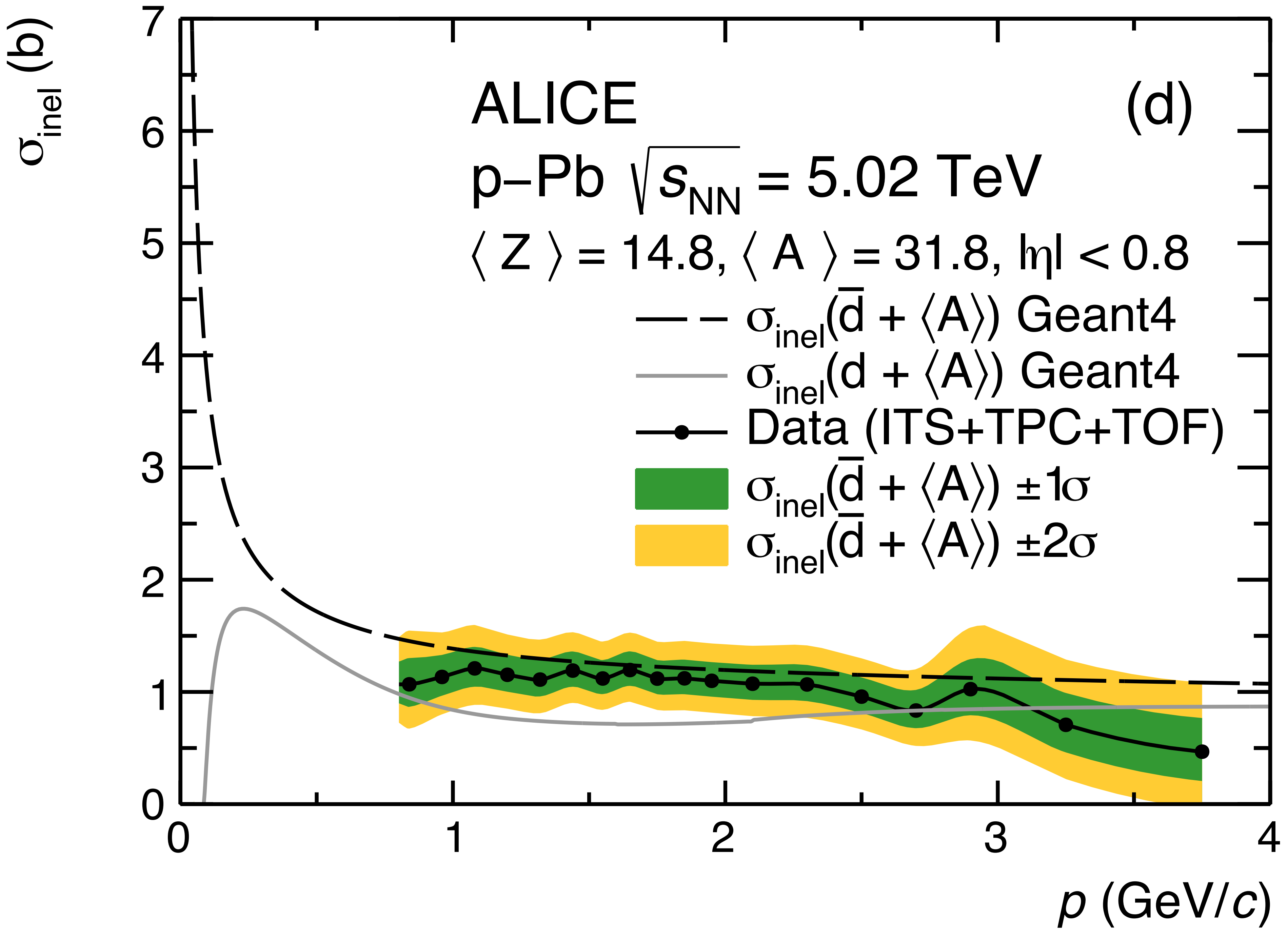
# Summary and outlook

Analysis of raw reconstructed $\overline{\mathrm{p}}$/p, $\overline{\mathrm{d}}$/d, $\overline{\mathrm{t}}$/t and $^3\overline{\mathrm{He}}/^3\mathrm{He}$ ratios and $^3\overline{\mathrm{He}}_{TOF}/^3\overline{\mathrm{He}}_{TPC}$ ratio

- Measurement of $\sigma_{\mathrm{inel}}$ via comparison with detailed ALICE Monte Carlo simulations using Geant4

First low energy measurement of the antideuteron inelastic cross section

- Paper: PRL 125, 162001 (2020)



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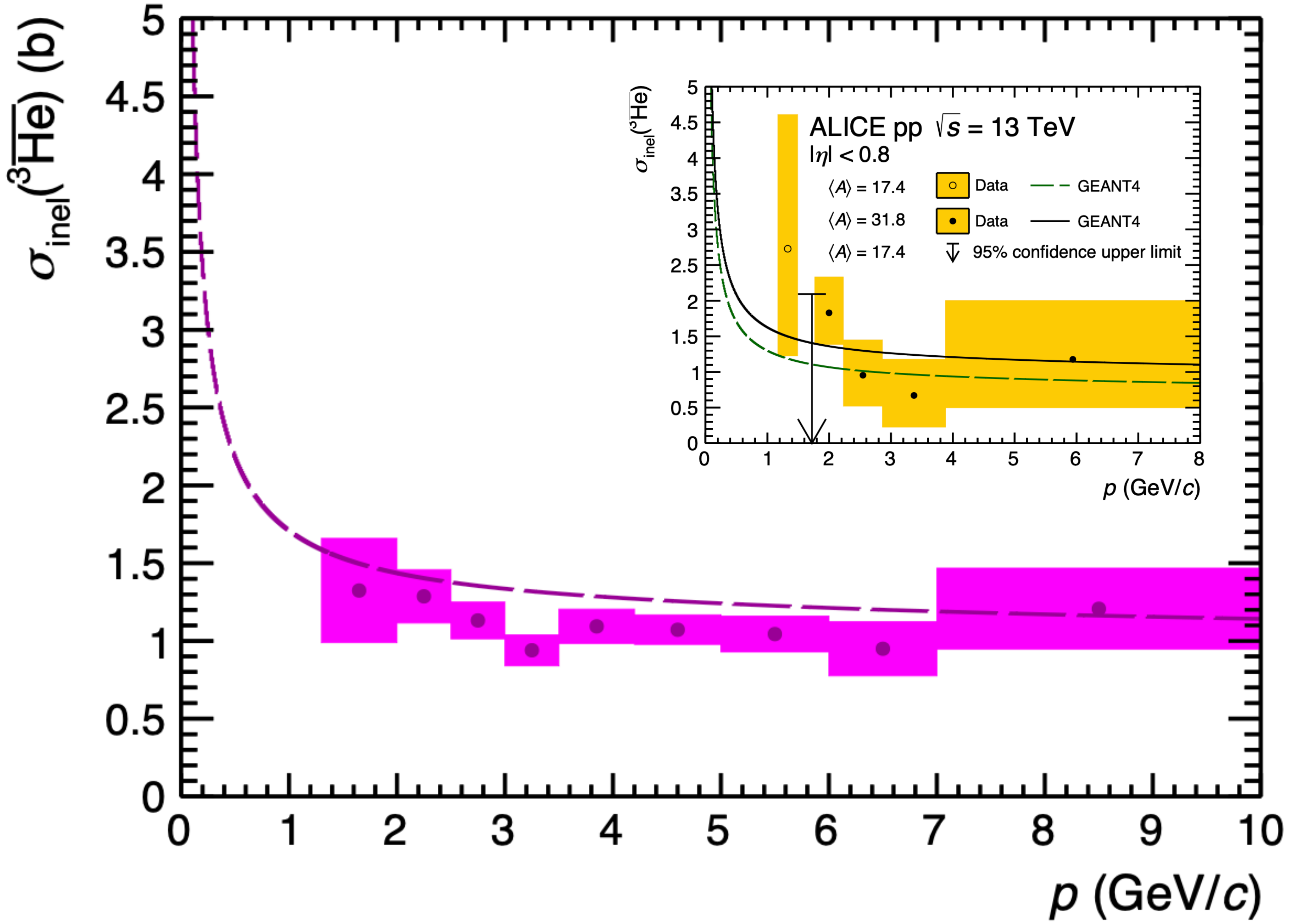

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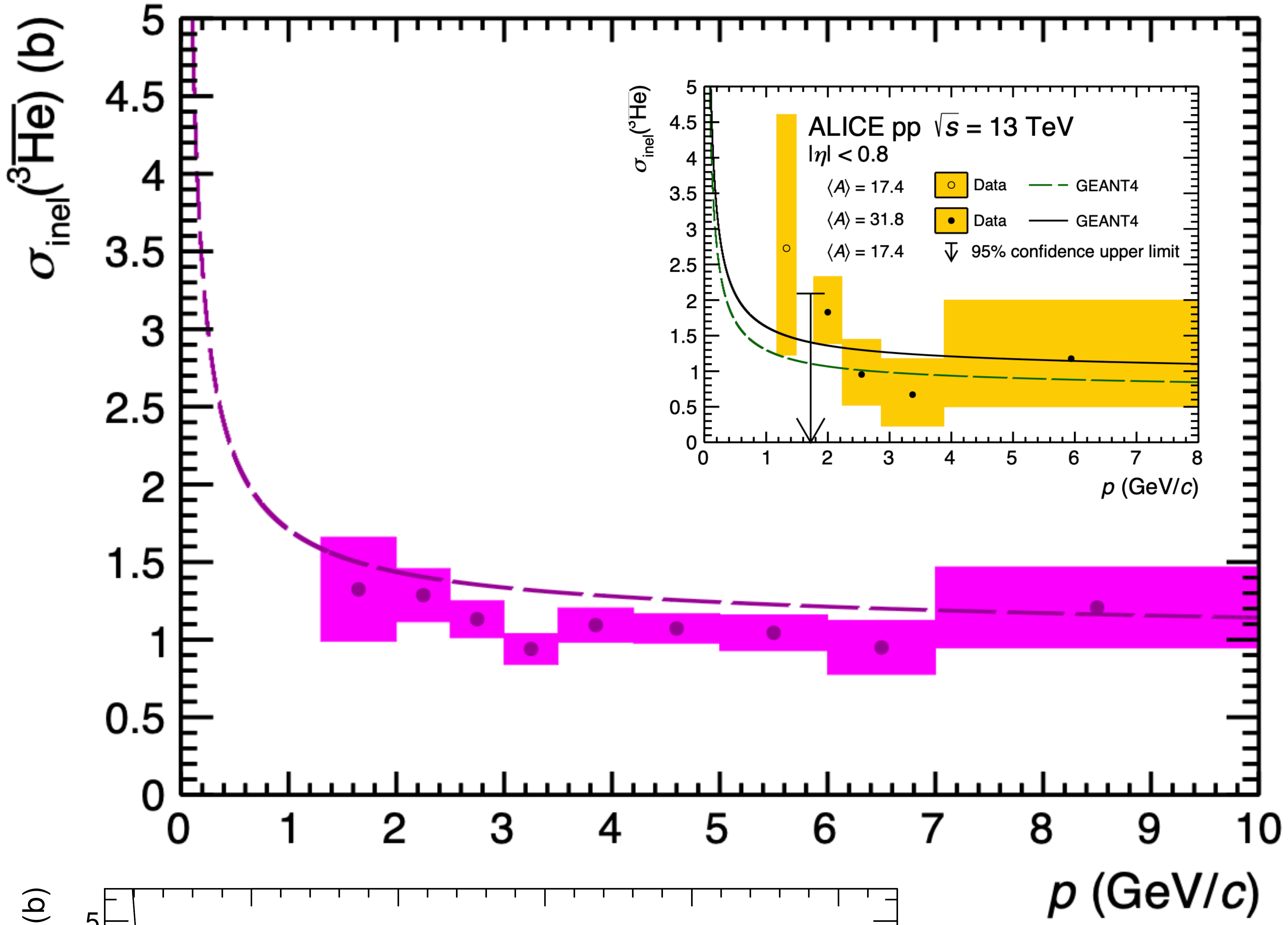


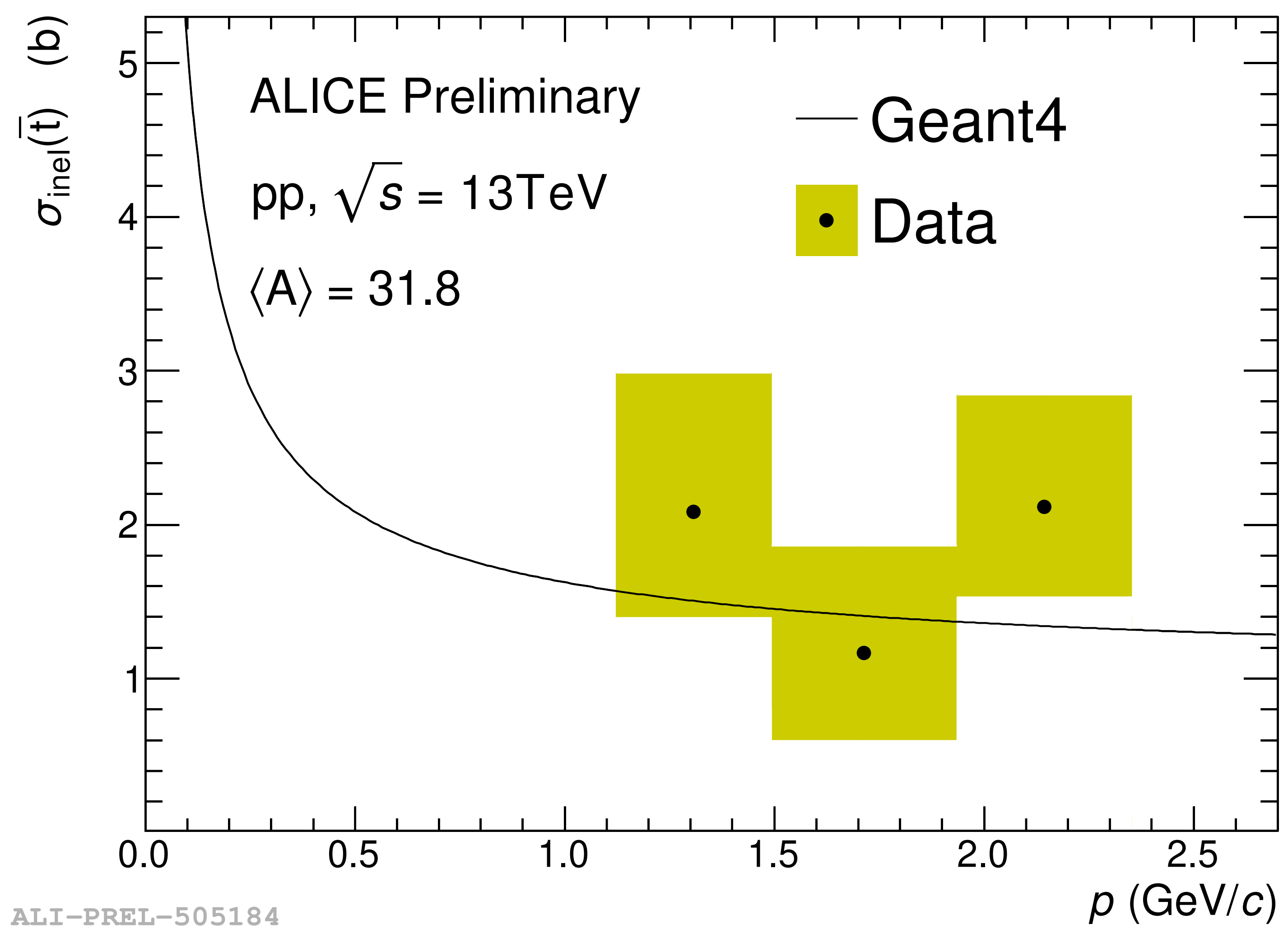

# Summary and outlook

Thank you for your attention!

Analysis of raw reconstructed $\overline{p}$/p, $\overline{d}$/d, $\overline{t}$/t and $^3\overline{He}/^3$He ratios and $^3\overline{He}_{TOF}/^3\overline{He}_{TPC}$ ratio

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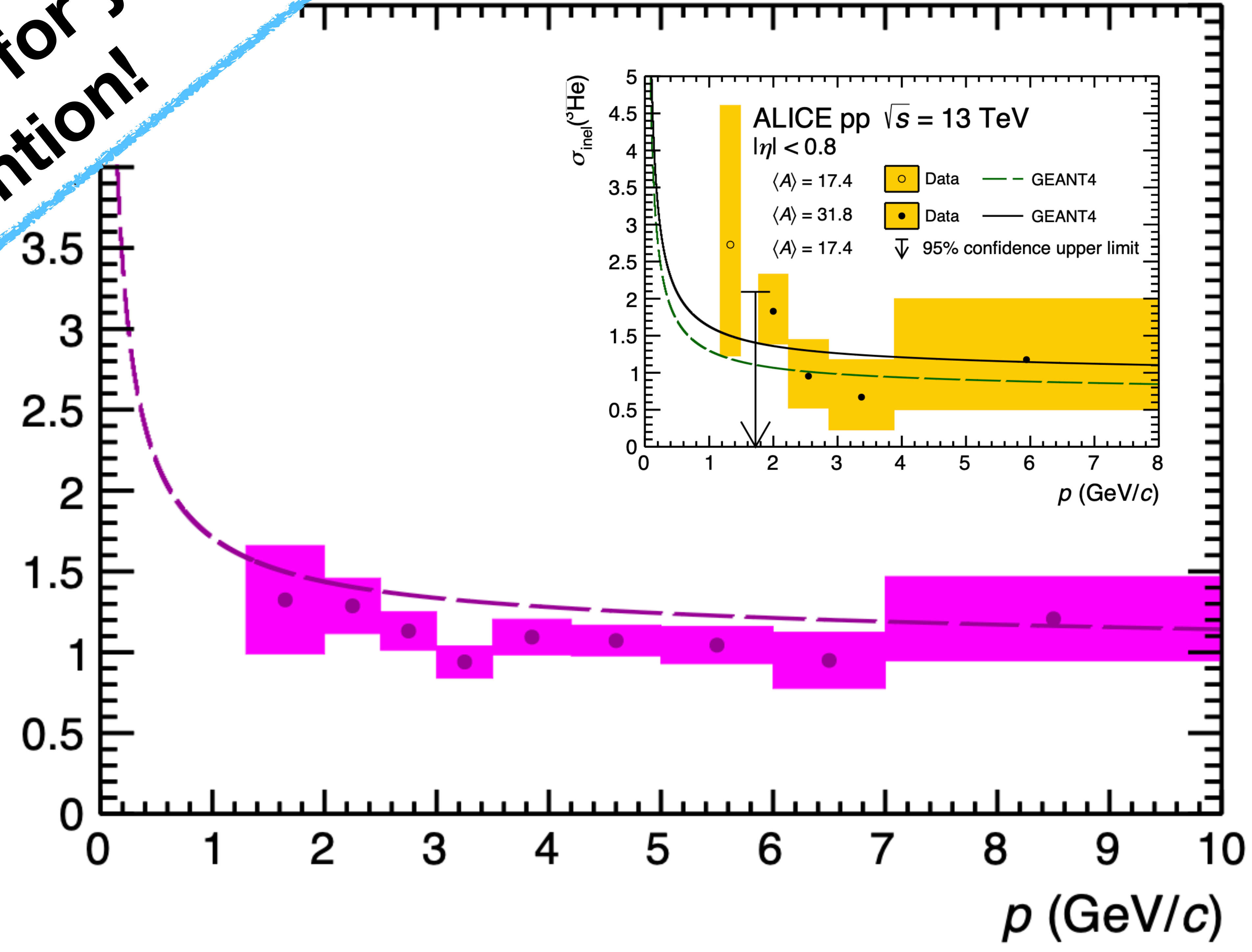
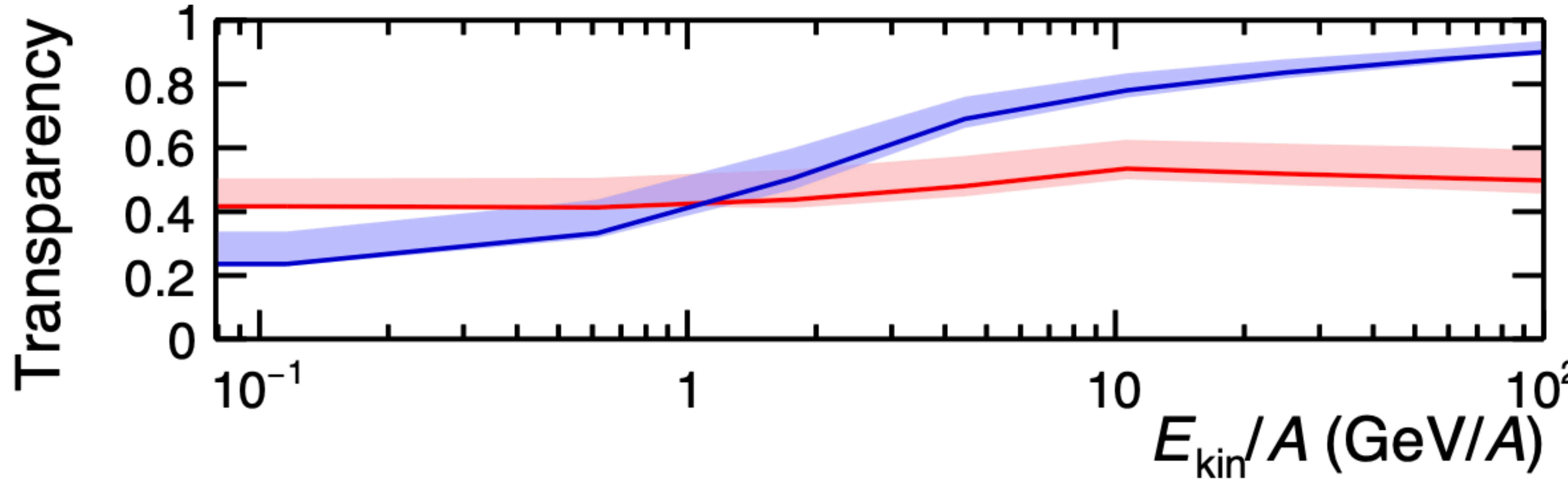
First measurement of the antitriton inelastic cross section

Effect of $\sigma_{inel}$ measurements:

- Transparency of the galaxy to $^3\overline{He}$ from different sources



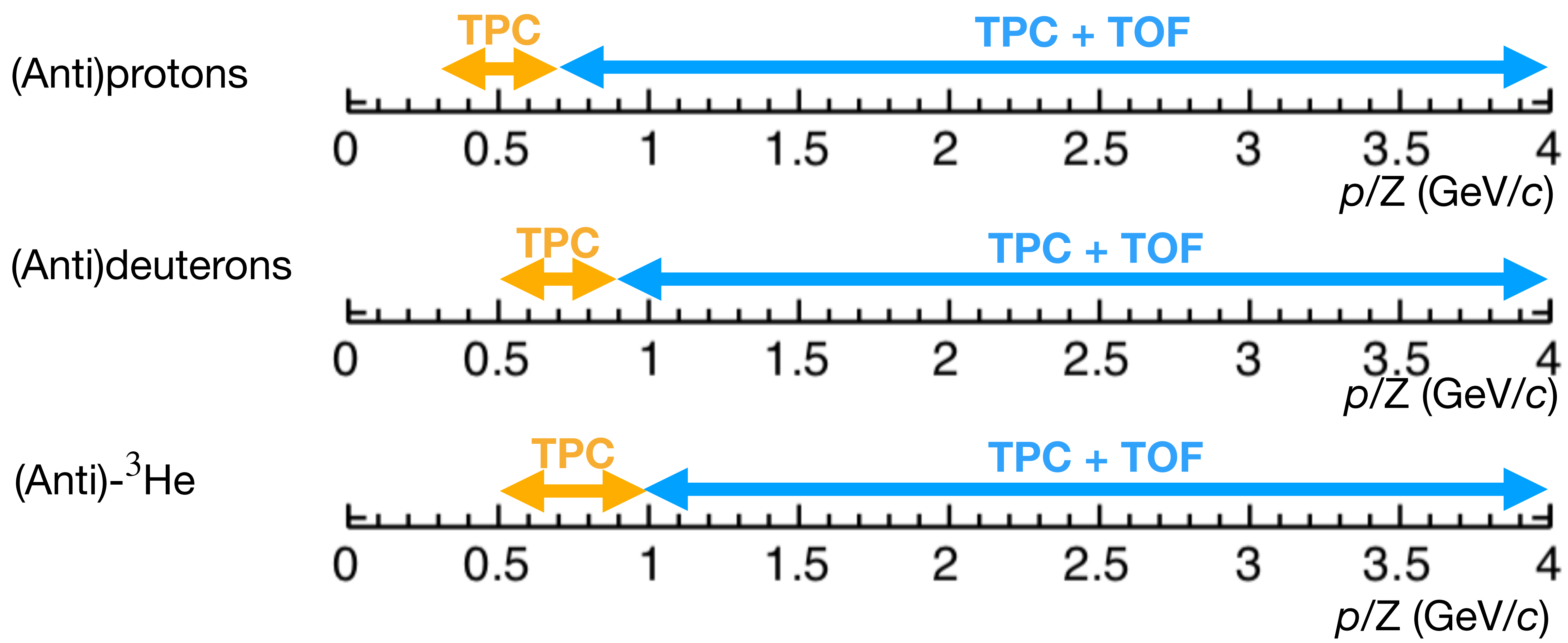



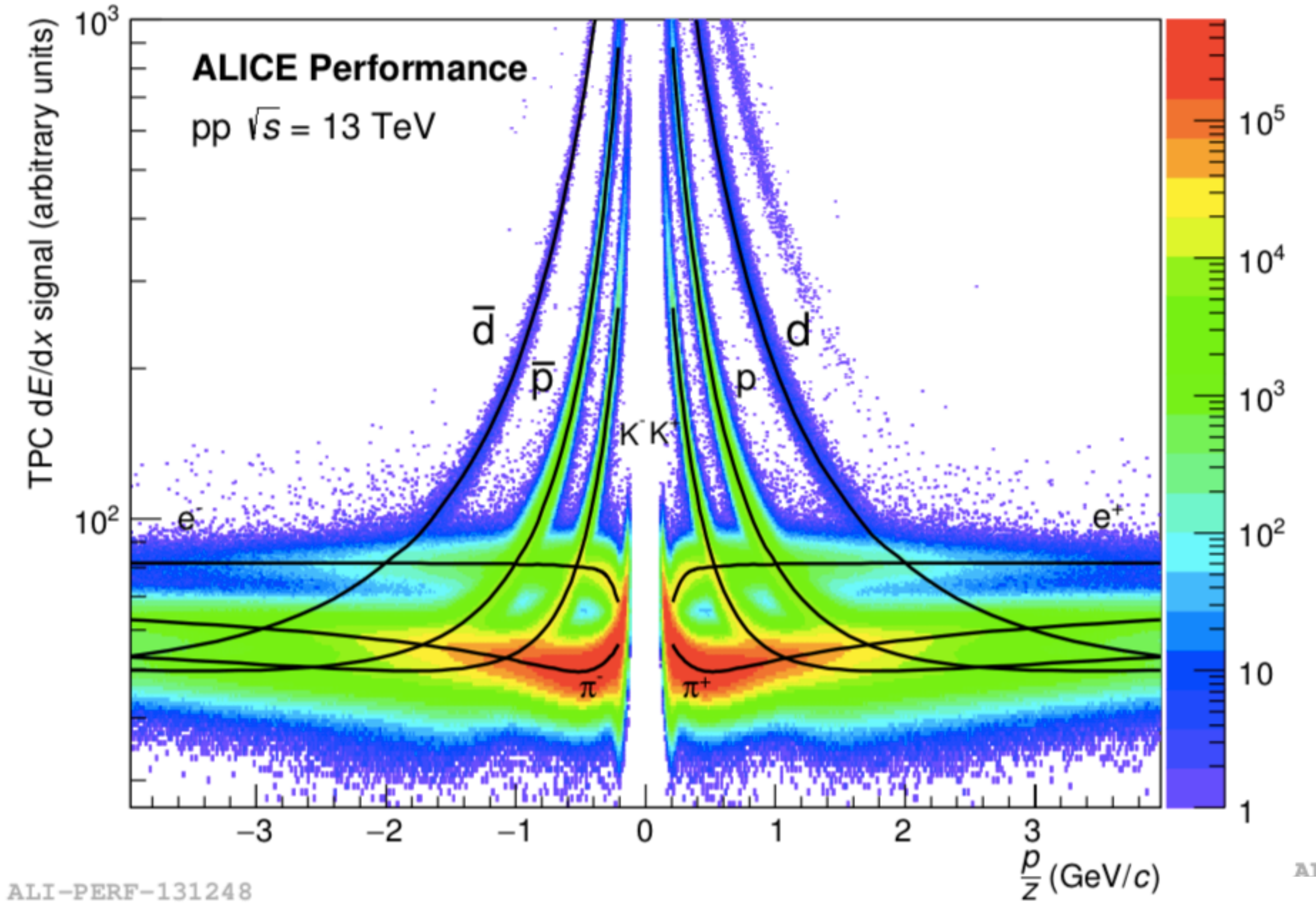
# Back-up slides

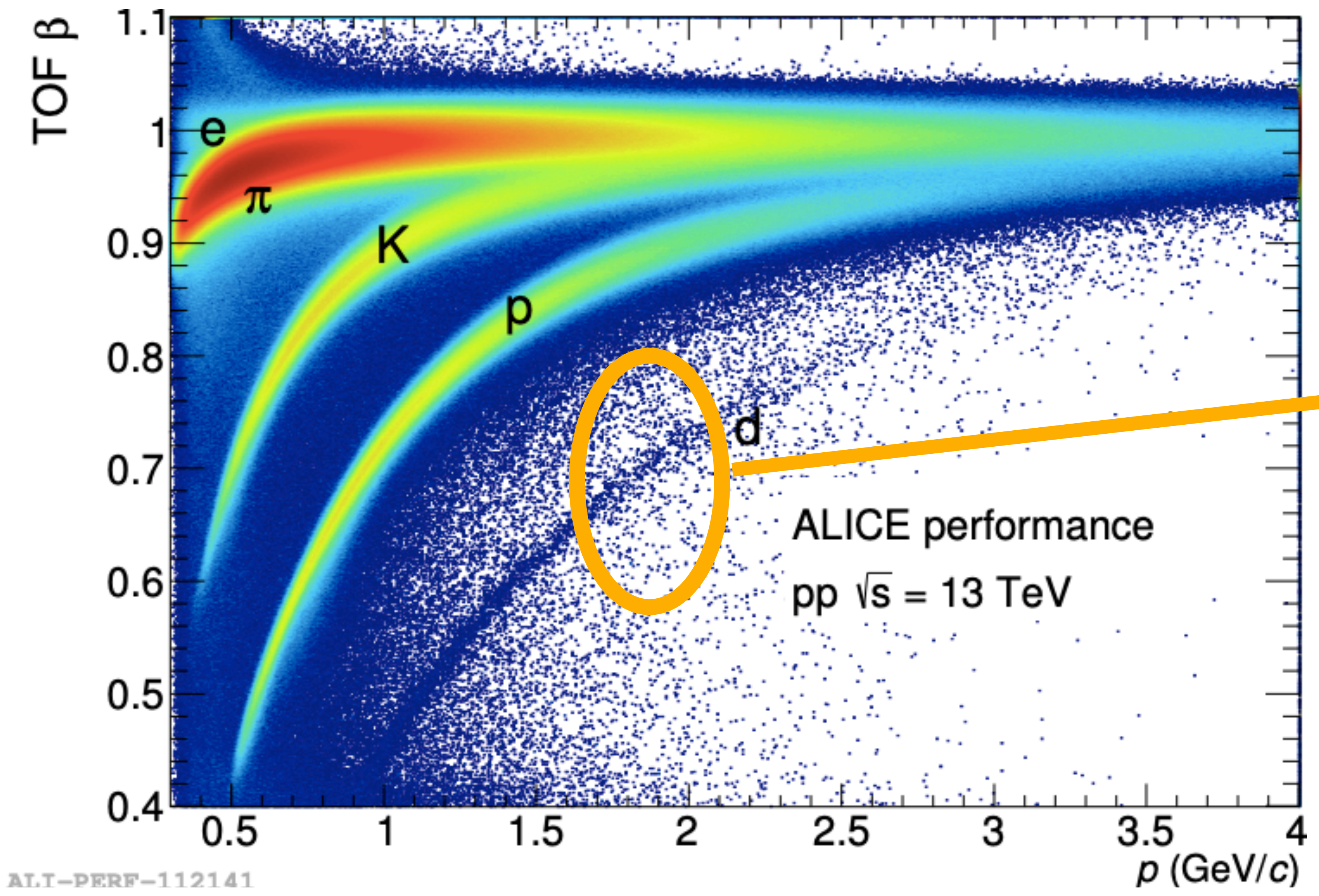
# Particle identification in TPC and TOF

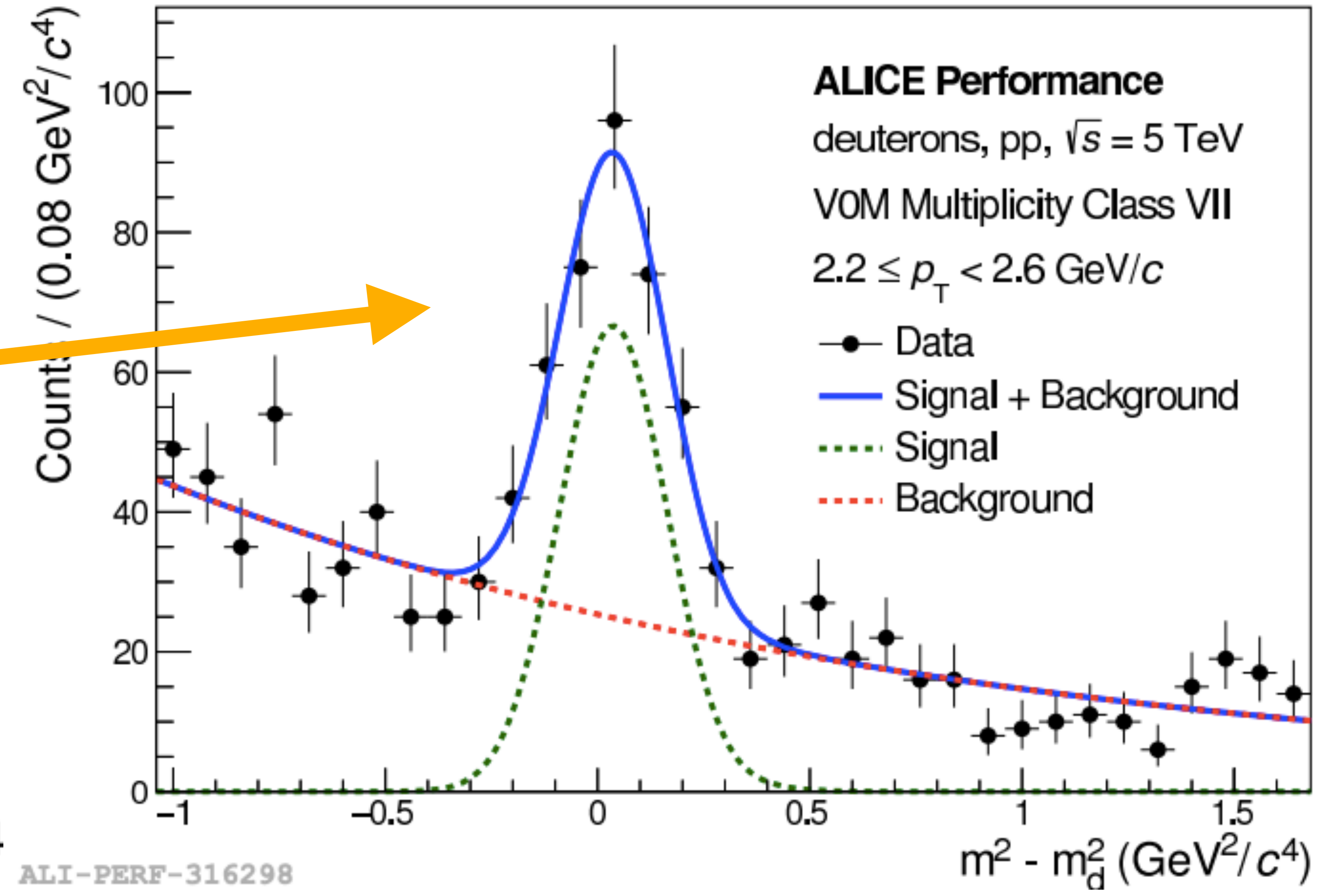
Complementary information from TPC and TOF detectors allows us to select high purity (anti)particles:

- TPC: dE/dx in gas
- TOF measurement $\beta = \frac{v}{c}$, $p = \gamma\beta mc$ -> mass



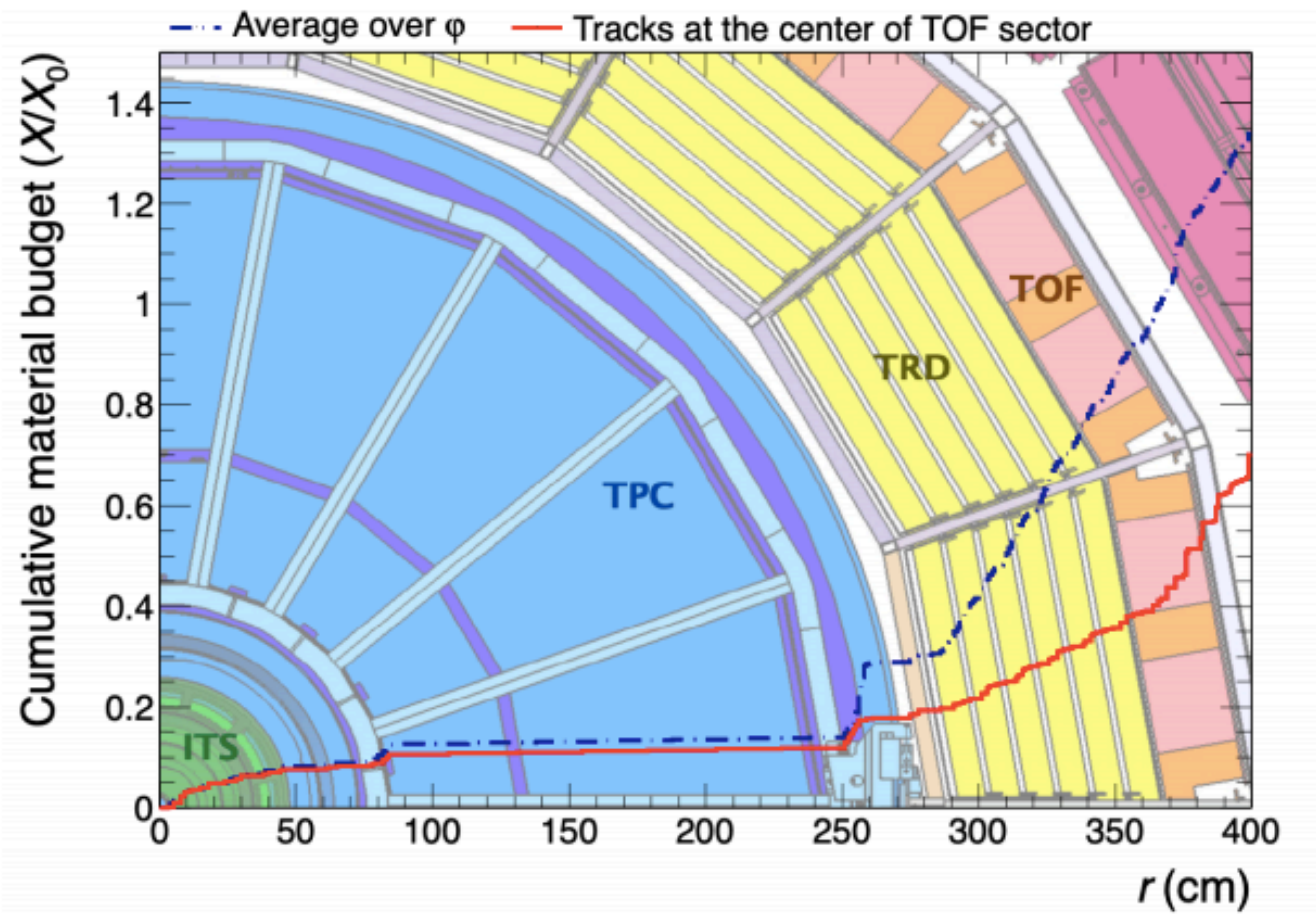



# ALICE material budget

ALICE material budget at mid-rapidity [1]:

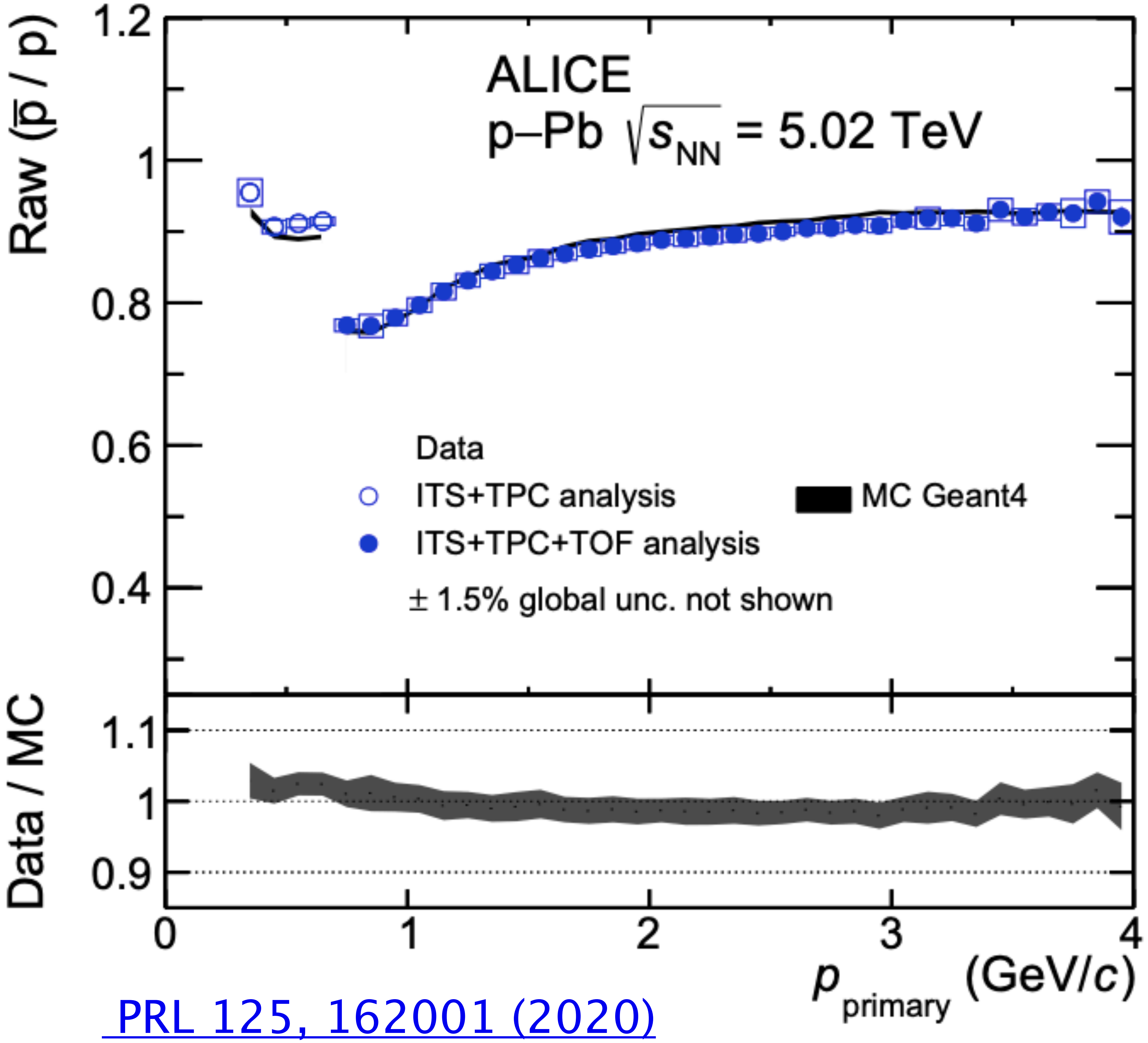
- **Beryllium beam pipe (~0.3% $X_0$)**
- **ITS (~8% $X_0$)**
- **TPC (~4% $X_0$)**
- **TRD (~25% $X_0$)**
- **Space frame (~20% $X_0$** between TPC and TOF)




PRL 125, 162001 (2020)

[1] Journal of Instrumentation 3, S08002 (2008)

# Raw primary antiproton-to-proton ratio




PRL 125, 162001 (2020)

Raw primary $\bar{p}/p$ ratio:

- Higher loss of antiprotons in detector material
- Step at 0.7 GeV/$c$ due to additional detector material

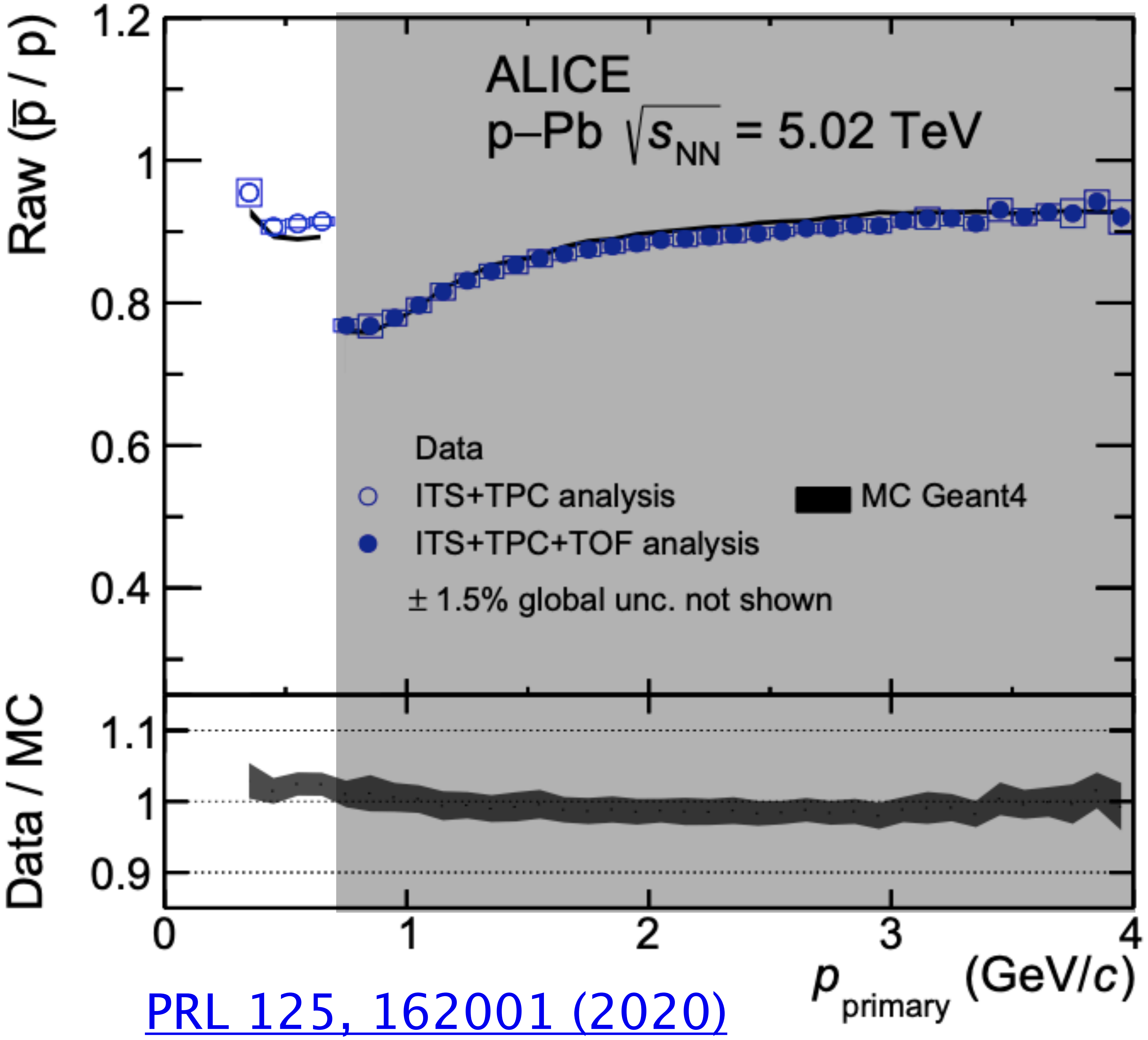
Monte Carlo simulation:

- Detailed simulations of the ALICE detector performance
- Propagation with Geant4

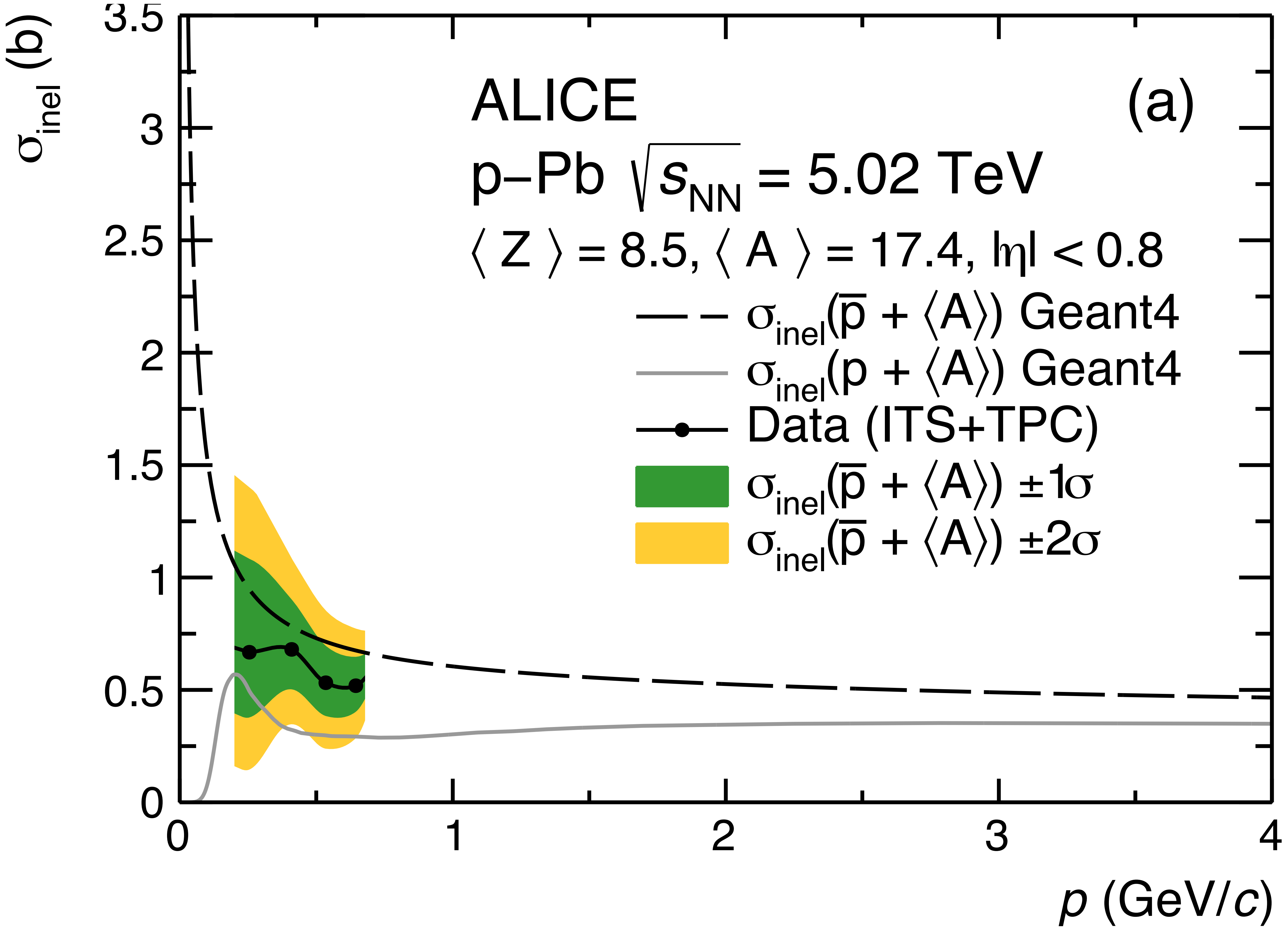
➡Agreement between data and MC confirms the correctness of the procedure.

# Antiproton inelastic cross section

$\sigma_{inel}(\overline{p})$ on average ALICE detector material.
Good agreement with Geant4 parameterization.




PRL 125, 162001 (2020)



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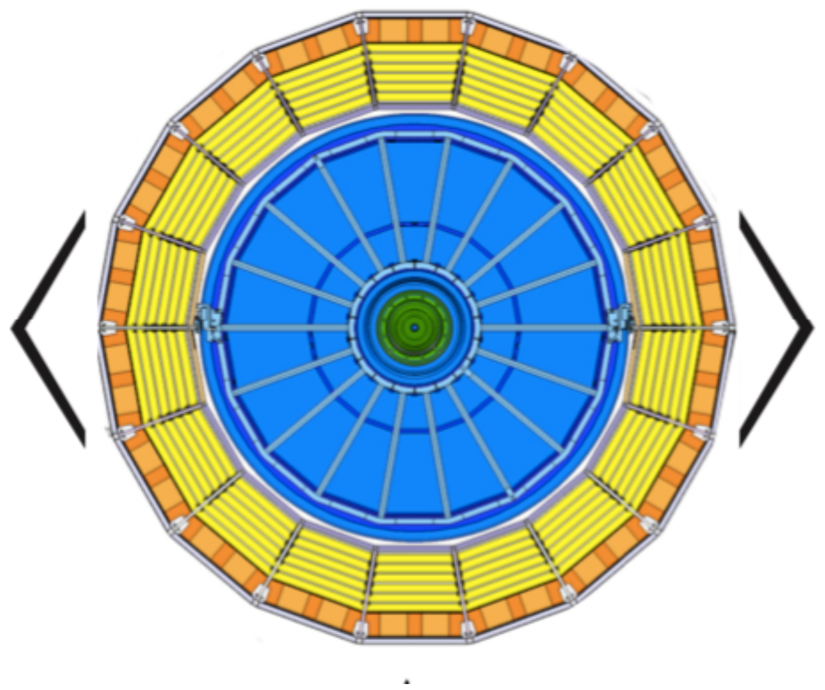
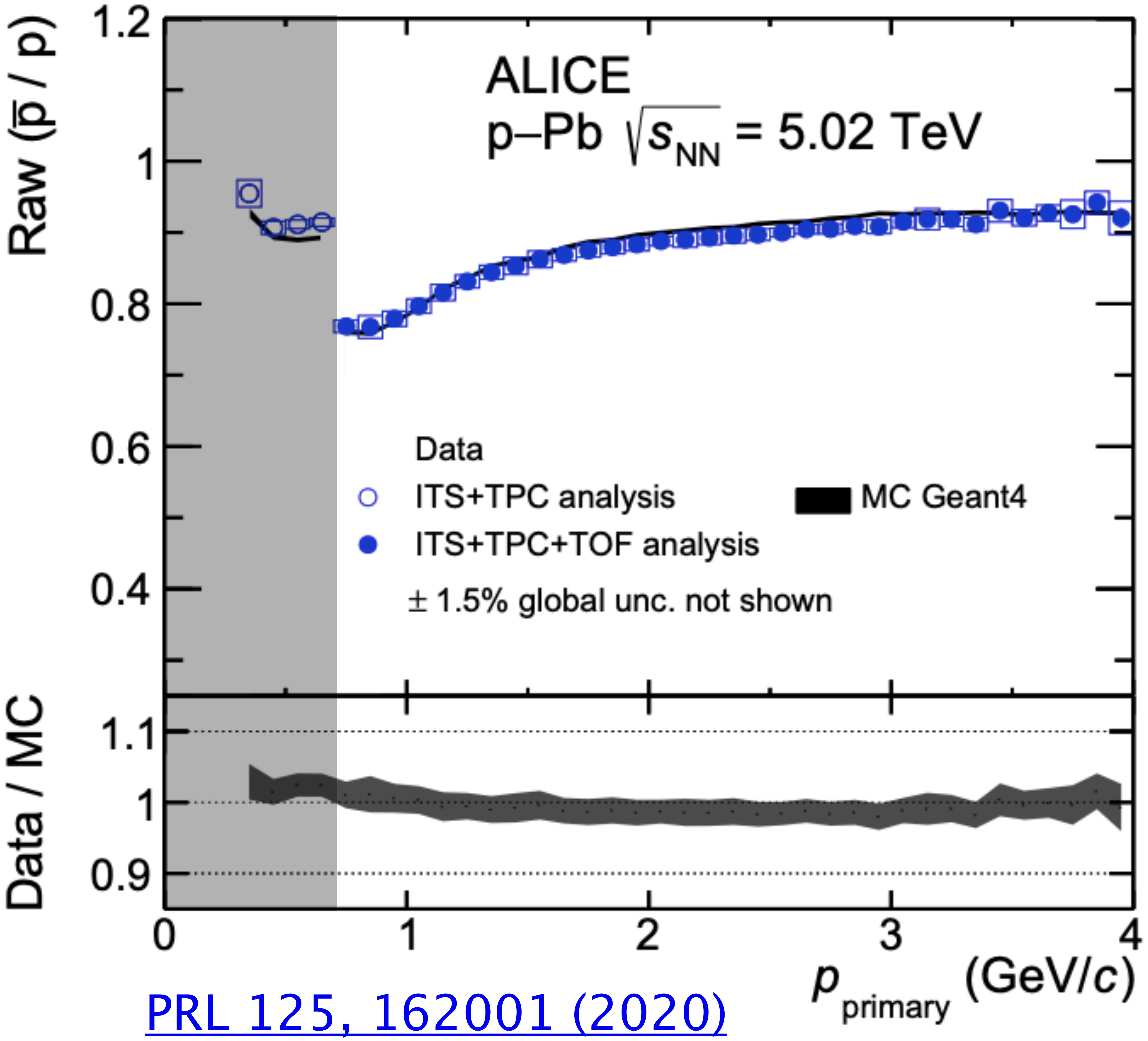
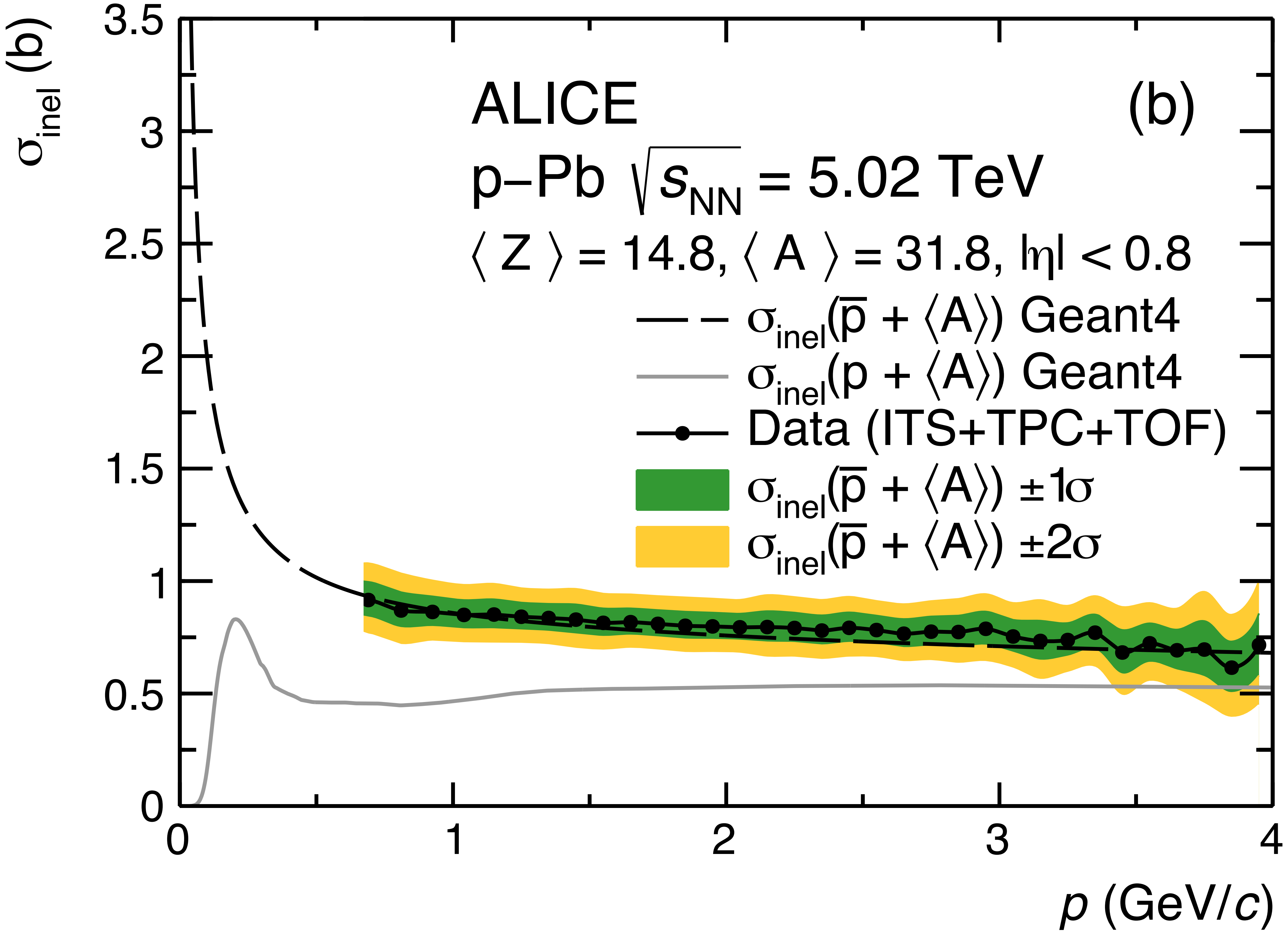




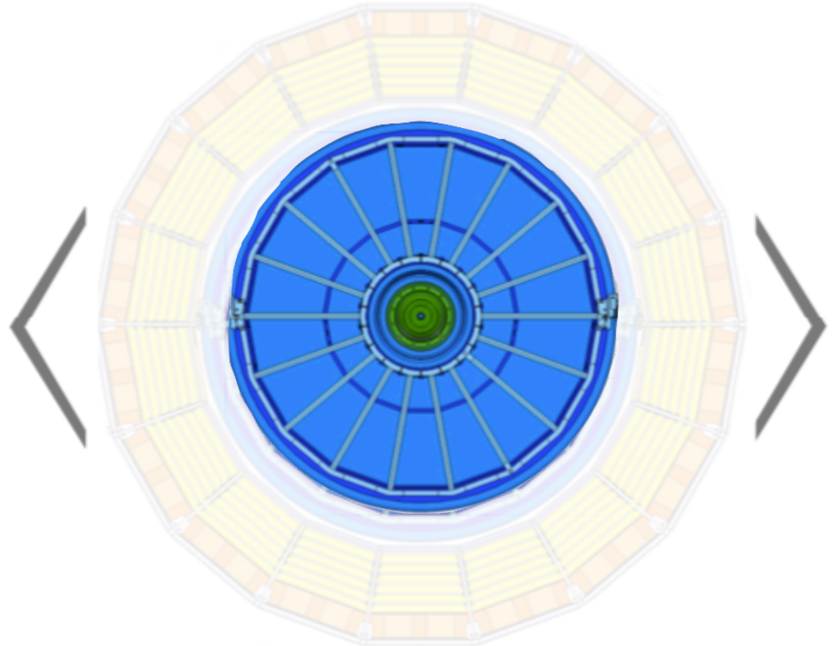

[PRL 125, 162001 (2020)](PRL 125, 162001 (2020))

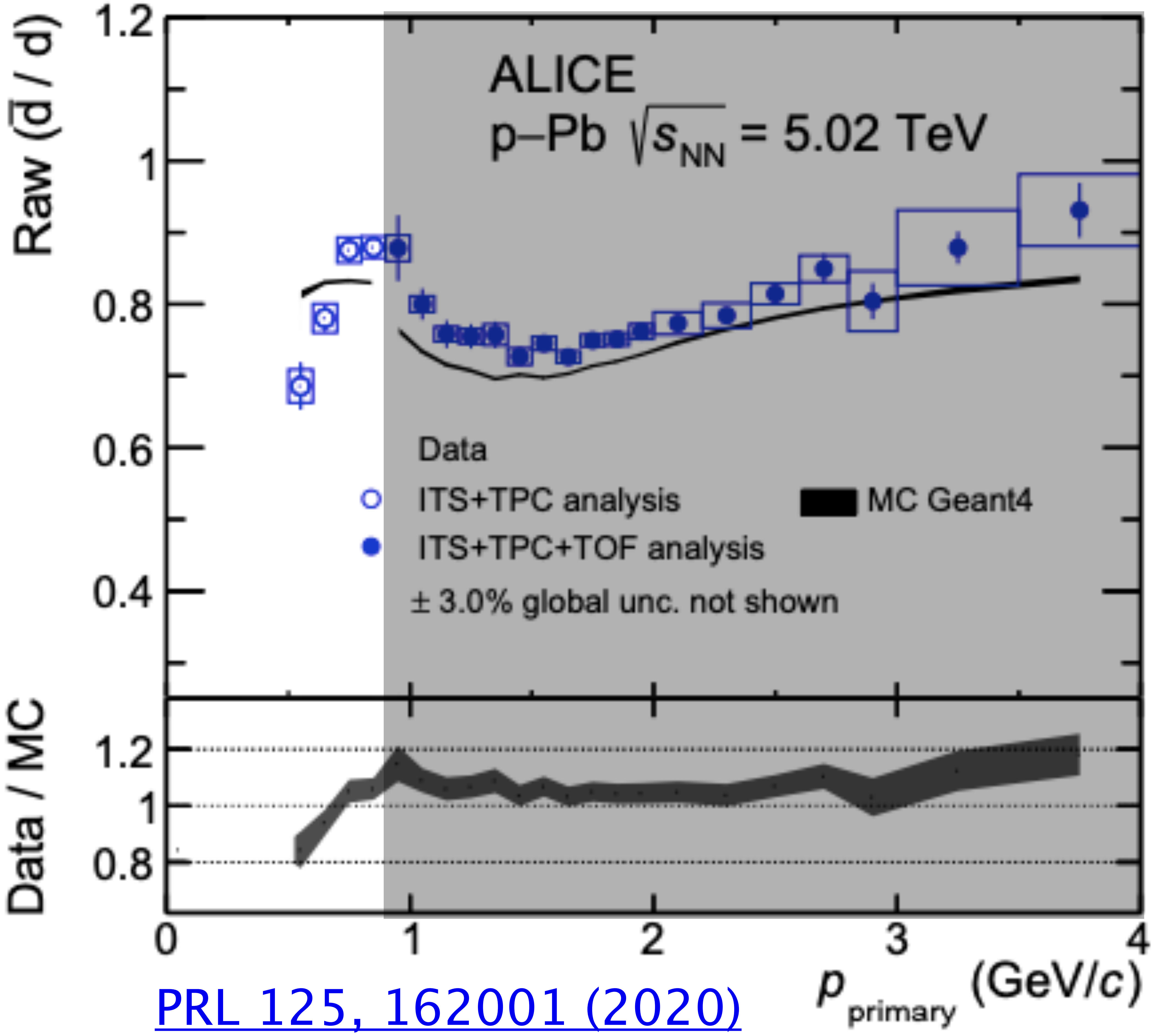


# Antideuteron inelastic cross section

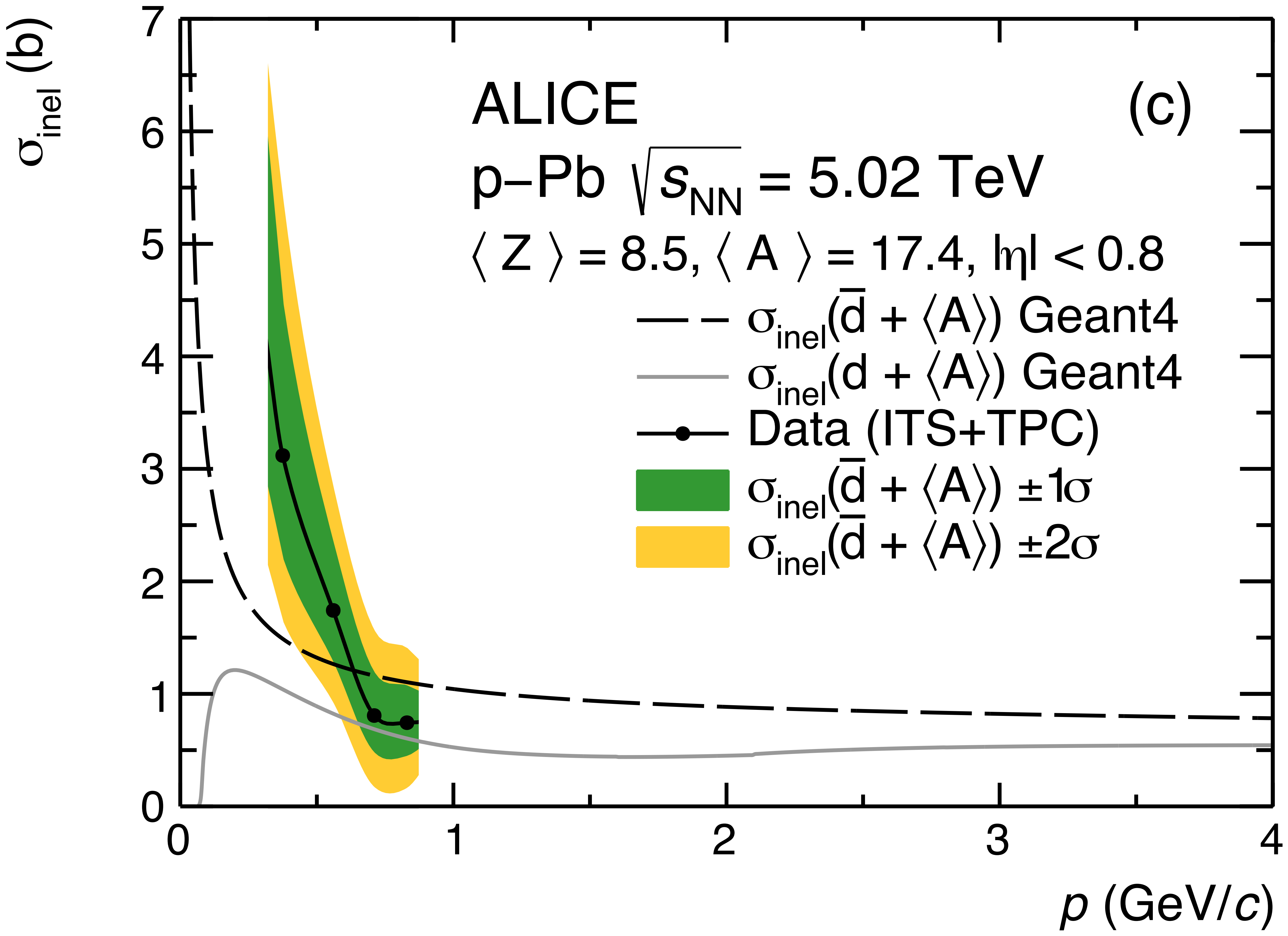
$\sigma_{inel}(\overline{d})$ on average ALICE detector material.

Hint of a steeper rise at low momentum.






[PRL 125, 162001 (2020)](#)

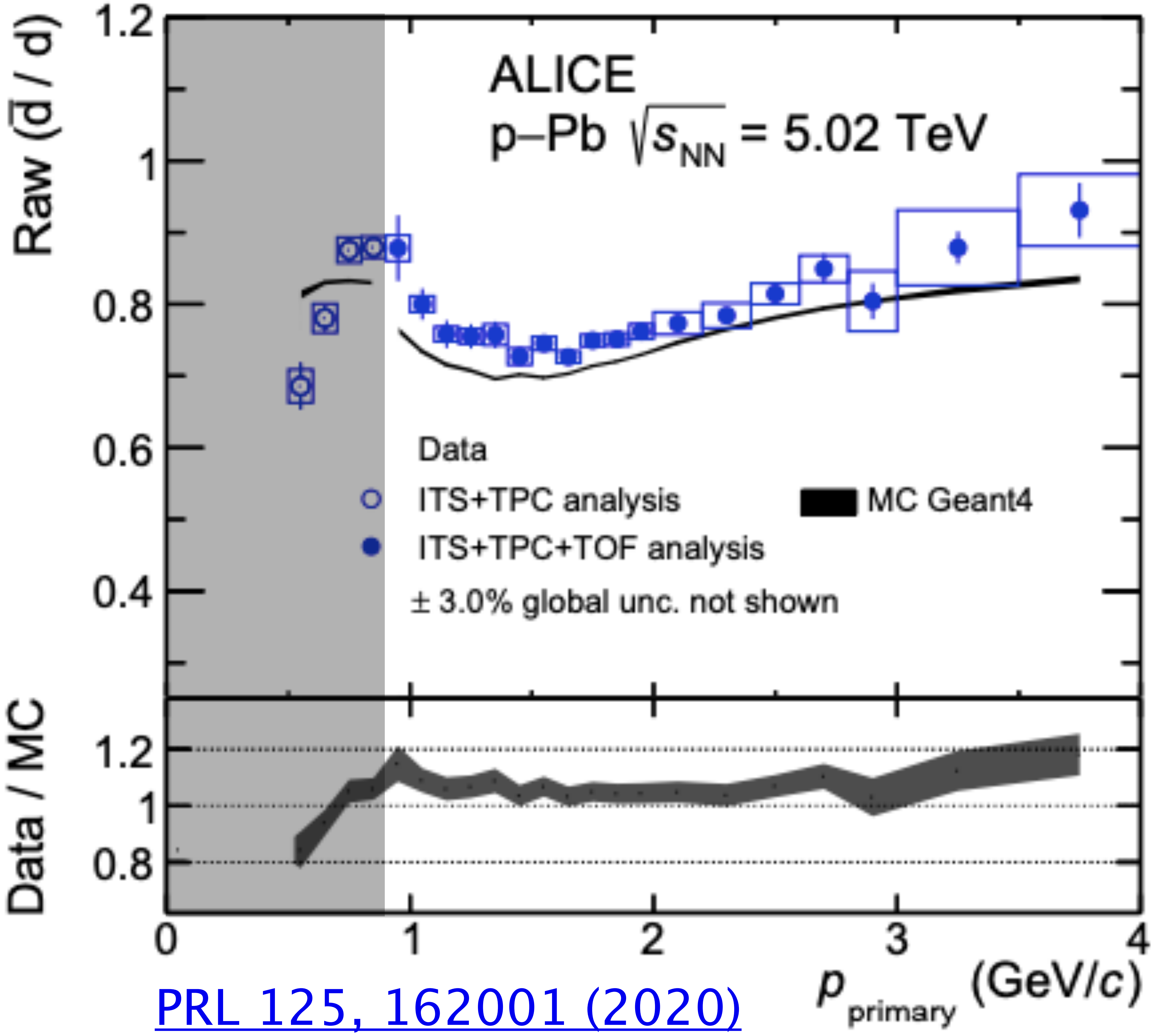


# Antideuteron inelastic cross section

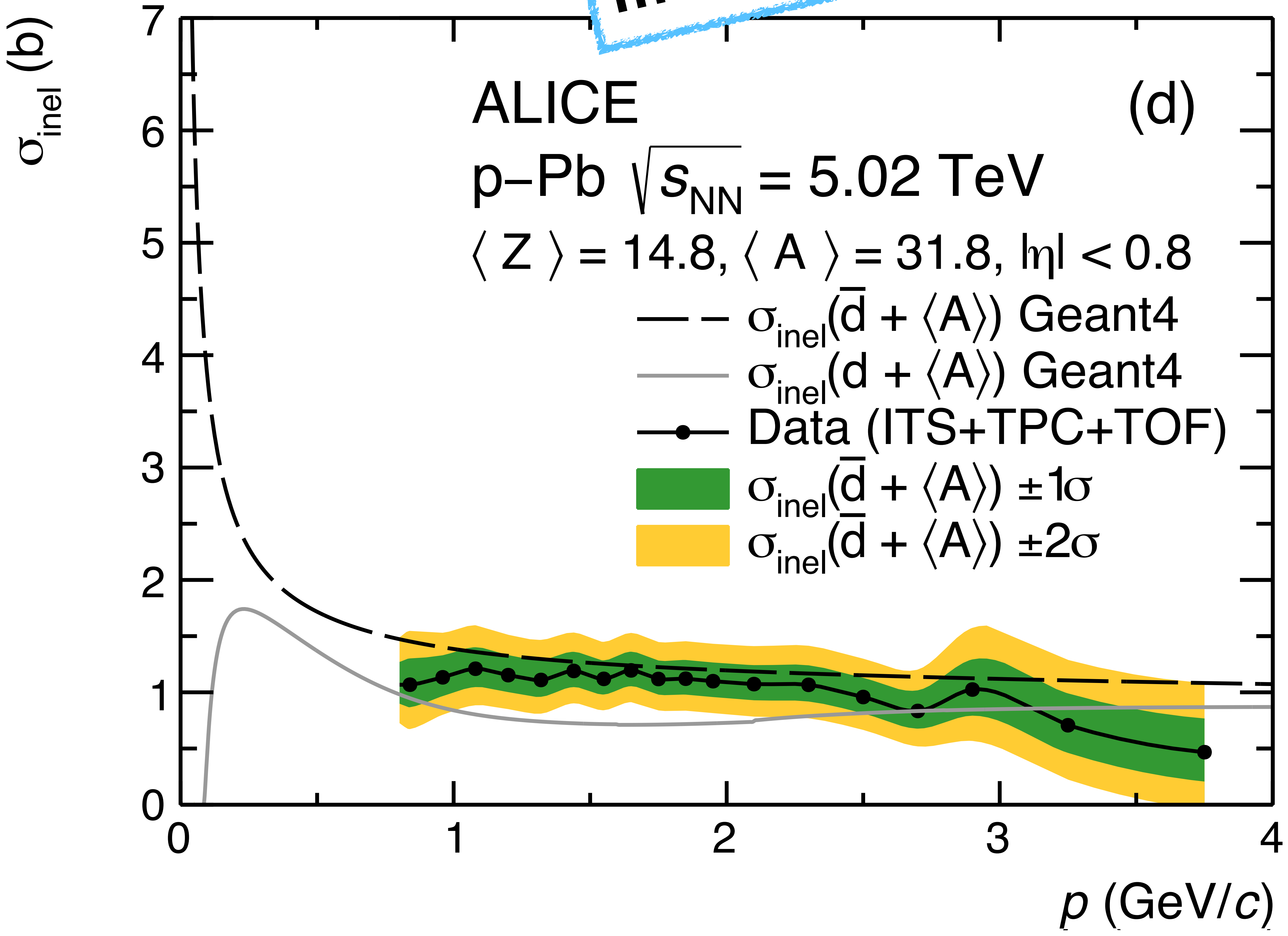
$\sigma_{inel}(\overline{d})$ on average ALICE detector material.

Hint of a steeper rise at low momentum.

**First low-energy measurement of $\sigma_{inel}(\overline{d})$**

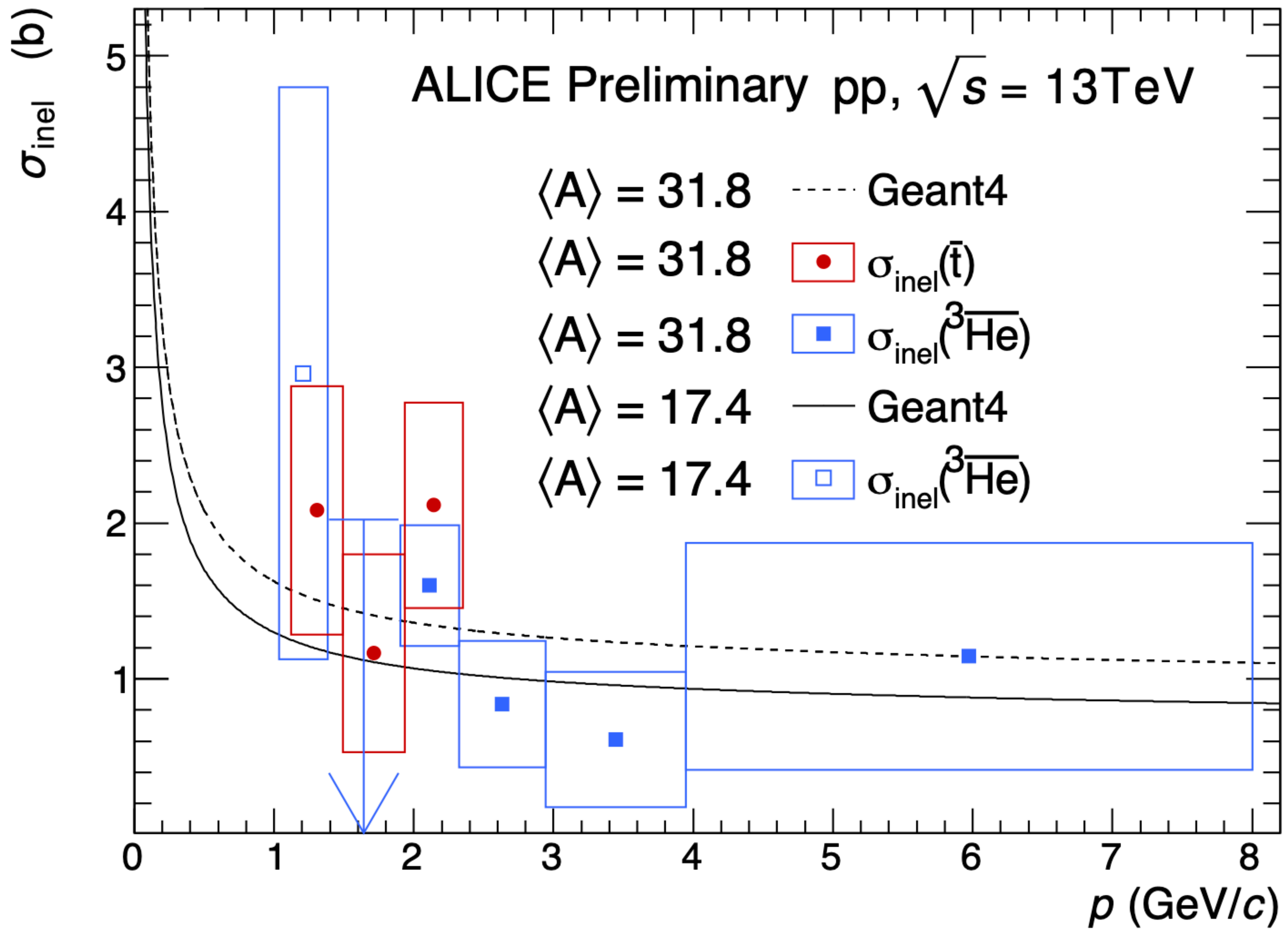



PRL 125, 162001 (2020)

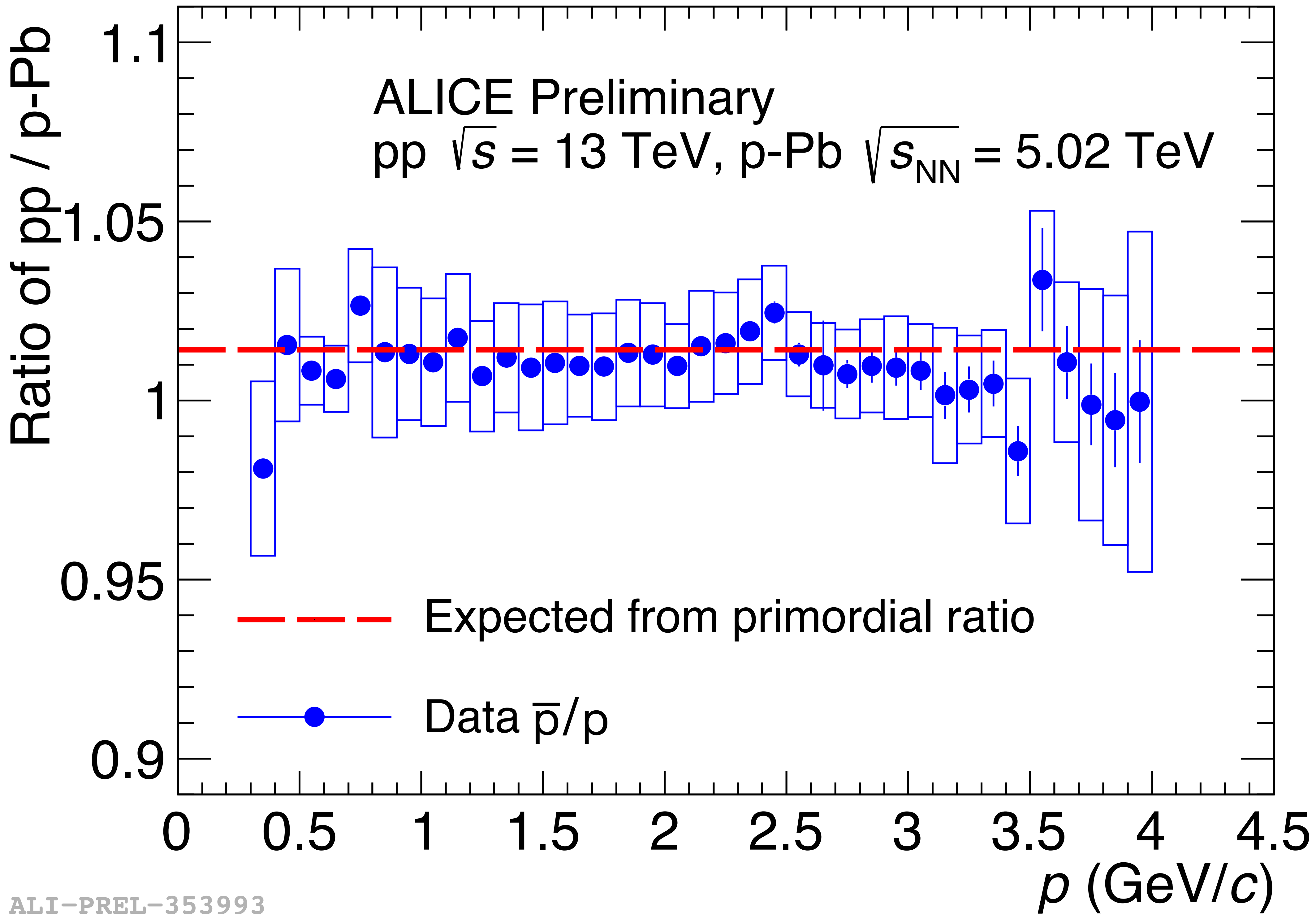


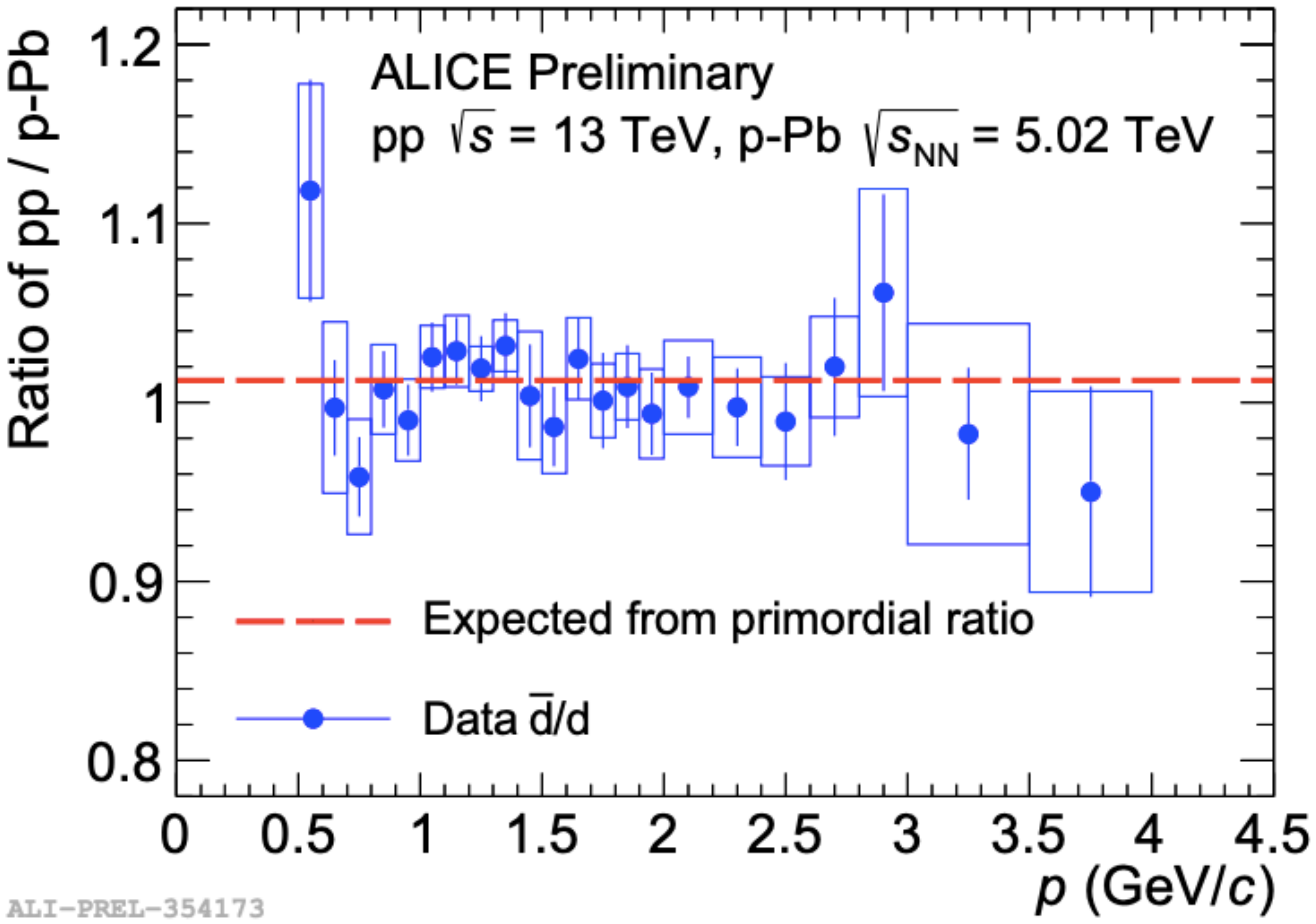
# Comparison of inelastic cross sections for A=3

Results are compatible within uncertainties.



# Comparison of pp and p-Pb systems



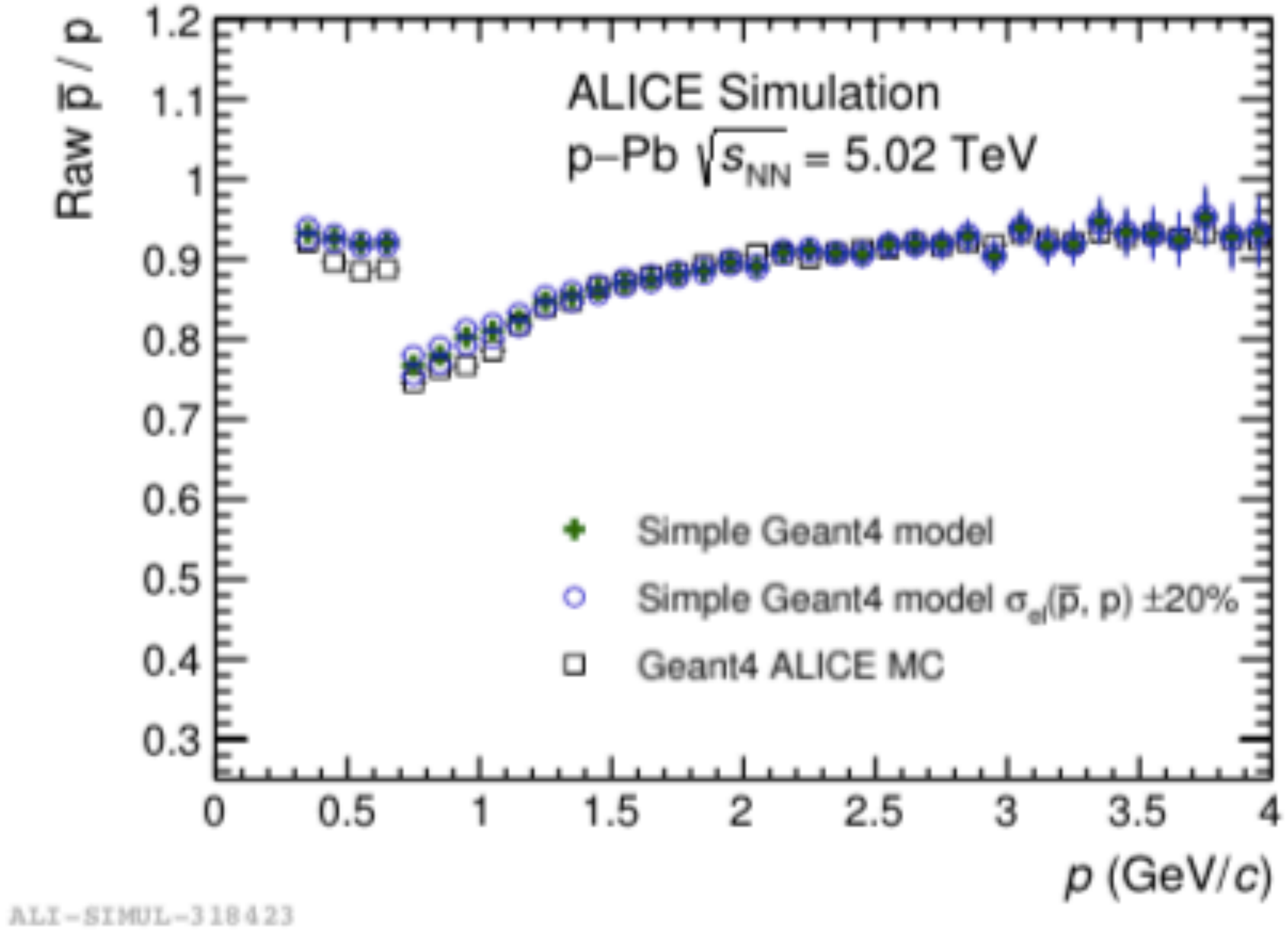

Comparison of raw primary antiparticle-to-particle ratio in p-Pb and pp collisions.
➡Consistent with the difference expected from primordial antimatter-to-matter ratio.
➡The cross section measurements are independent of the collisions system, as expected.
➡Analysis method is consistent.

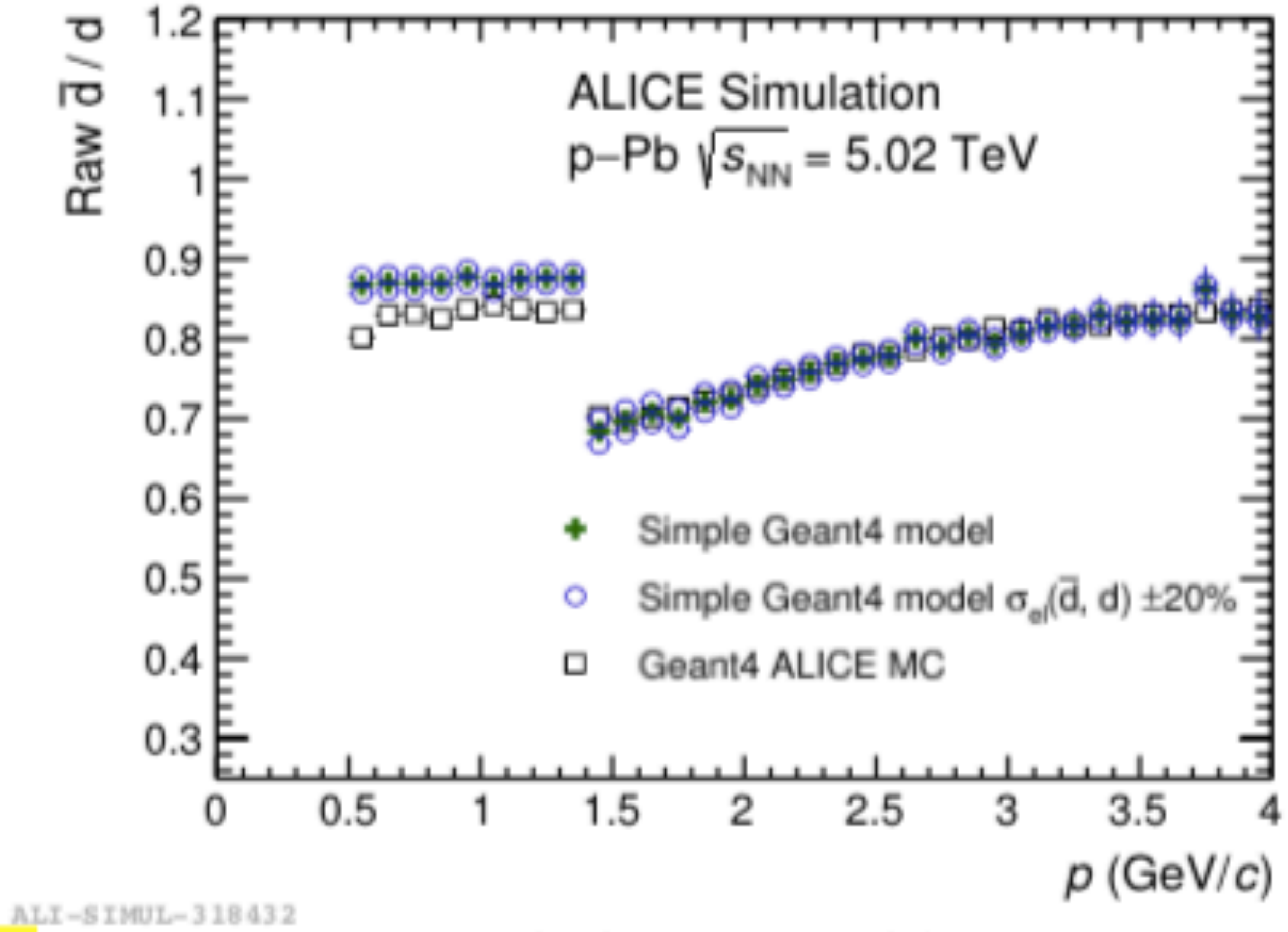
# Variations of $\sigma_{el}$ with simple Geant4 model

Vary each $\sigma_{el}$ by ±20% in all combinations and check the final ratio

- $\sigma_{el}$ contributes to scattering effects in ITS, TPC and TRD material
- Only a minor effect on the ratio (≲1% for $\bar{p}$ / p, ≲2% for $\bar{d}$ / d)

For final results: cross-check the variations with full ALICE MC simulations



# Parameterisations used in GEANT4

Direct Glauber calculations in GEANT4 in a run-time mode are too heavy
→ parametrise Glauber calculations with [1] :

$$\sigma_{hA}^{tot} = 2\pi R_A^2 \ln\left[1 + \frac{A\sigma_{hN}^{tot}}{2\pi R_A^2}\right] \qquad \sigma_{BA}^{tot} = 2\pi\left(R_B^2 + R_A^2\right)\ln\left[1 + \frac{BA\sigma_{NN}^{tot}}{2\pi(R_B^2 + R_A^2)}\right]$$

$$\sigma_{hA}^{in} = \pi R_A^2 \ln\left[1 + \frac{A\sigma_{hN}^{tot}}{\pi R_A^2}\right], \qquad \sigma_{BA}^{in} = \pi\left(R_B^2 + R_A^2\right)\ln\left[1 + \frac{BA\sigma_{hN}^{tot}}{\pi(R_B^2 + R_A^2)}\right],$$

$R_A$ cannot be directly connected with known values due to some simplifications
Use equations as a determination of $R_A$ having calculated $\sigma_{hA}$ and $\sigma_{BA}$ with Glauber

For total cross-section:

$$\bar{p}A\ R_A = 1.34A^{0.23} + 1.35/A^{1/3}\ \text{(fm)},$$
$$\bar{d}A\ R_A = 1.46A^{0.21} + 1.45/A^{1/3}\ \text{(fm)},$$
$$\bar{t}A\ R_A = 1.40A^{0.21} + 1.63/A^{1/3}\ \text{(fm)},$$
$$\bar{\alpha}A\ R_A = 1.35A^{0.21} + 1.10/A^{1/3}\ \text{(fm)}.$$

For inelastic cross-section:

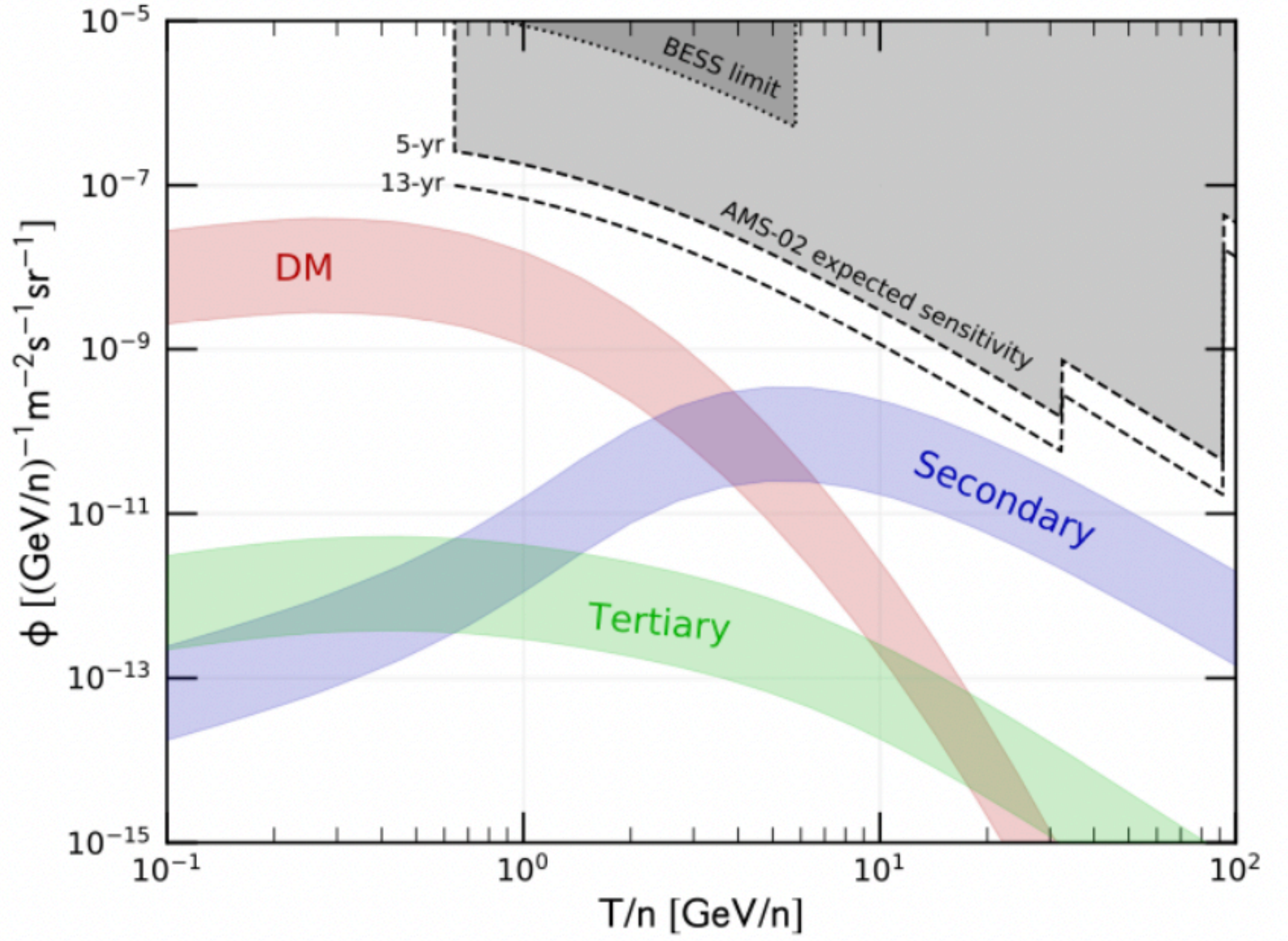
$$\bar{p}A\ R_A = 1.31A^{0.22} + 0.90/A^{1/3}\ \text{(fm)},$$
$$\bar{d}A\ R_A = 1.38A^{0.21} + 1.55/A^{1/3}\ \text{(fm)},$$
$$\bar{t}A\ R_A = 1.34A^{0.21} + 1.51/A^{1/3}\ \text{(fm)},$$
$$\bar{\alpha}A\ R_A = 1.30A^{0.21} + 1.05/A^{1/3}\ \text{(fm)}.$$

[1] V.M. Grichine, Eur. Phys. J. C 62 (2009) 399, Nucl. Instrum. Methods B 267 (2009) 2460

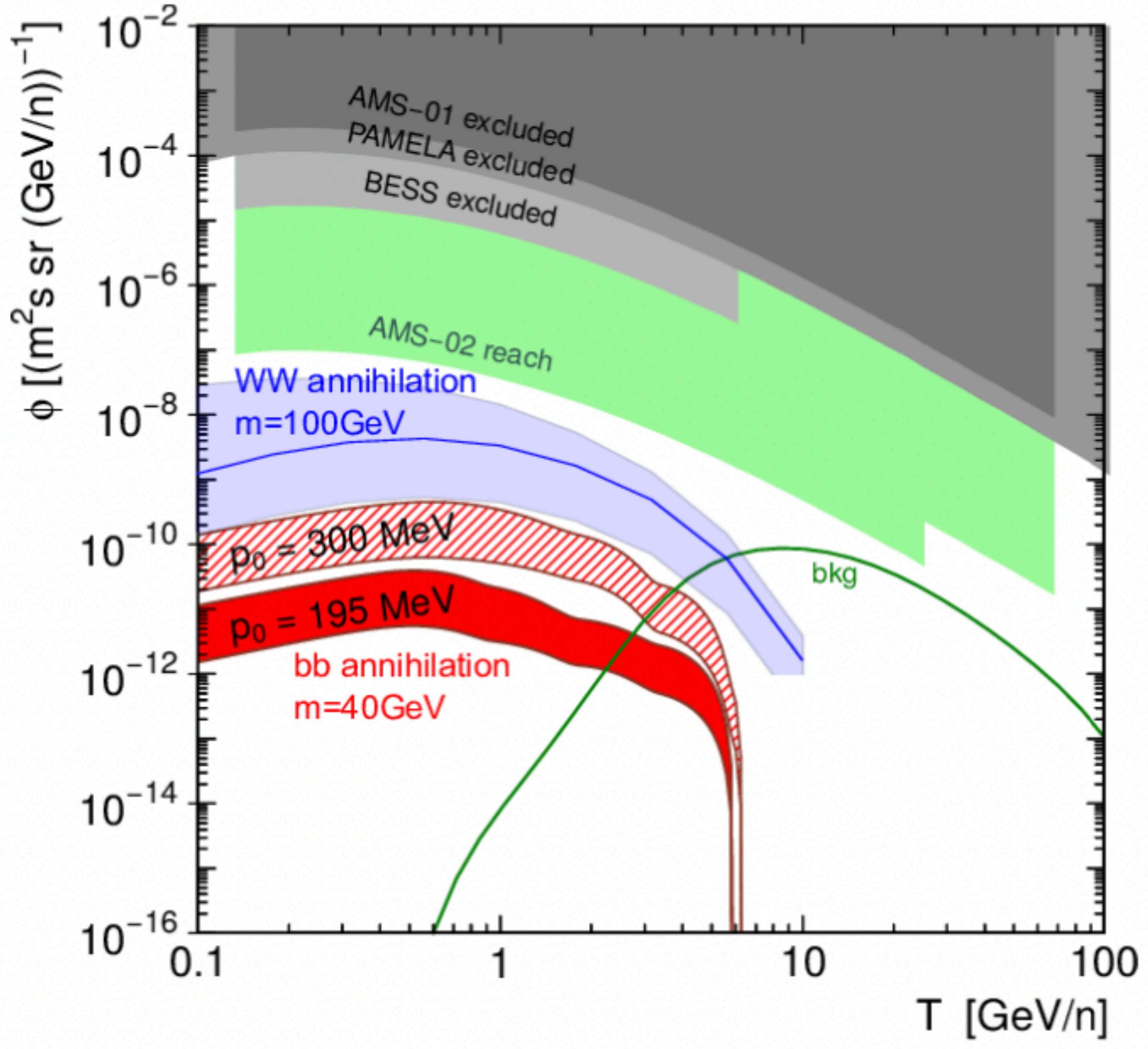
# Current predictions of antinuclei fluxes near earth

- Production: constrained using collider measurements - large uncertainty
- Propagation: constrained using cosmic ray measurements - large uncertainty
- Annihilation: no experimental data at low energies - **unknown uncertainty**

Uncertainty bands due to coalescence probability [1]




Uncertainty bands due to propagation model [2]




[1] Korsmeier et.al. Phys.R.D, 97 (2018)
[2] T.Aramaki et al, Physics Report 618, 1 (2016)

# Propagation in the galaxy

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

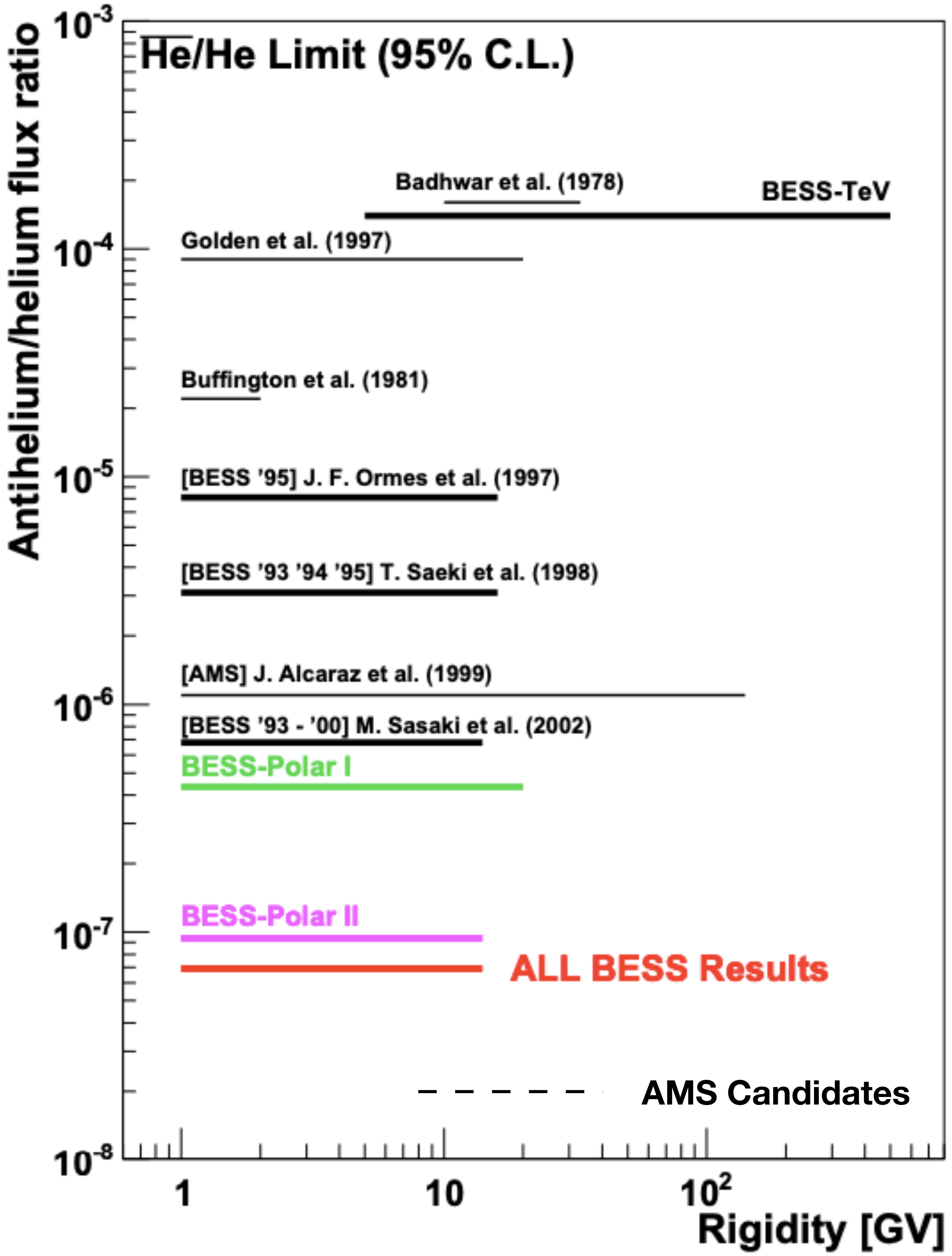
1 2 3 4 5 6 7

1 source function: PRIMARY OR SECONDARY
2 diffusion
3 convection
4 diffusive reacceleration
momentum losses:
- 5 via ionisation and bremsstrahlung
- 6 adiabatic

7 annihilation

Work of L. Šerkšnytė.

# $^{3}\overline{He}$ in cosmic rays?



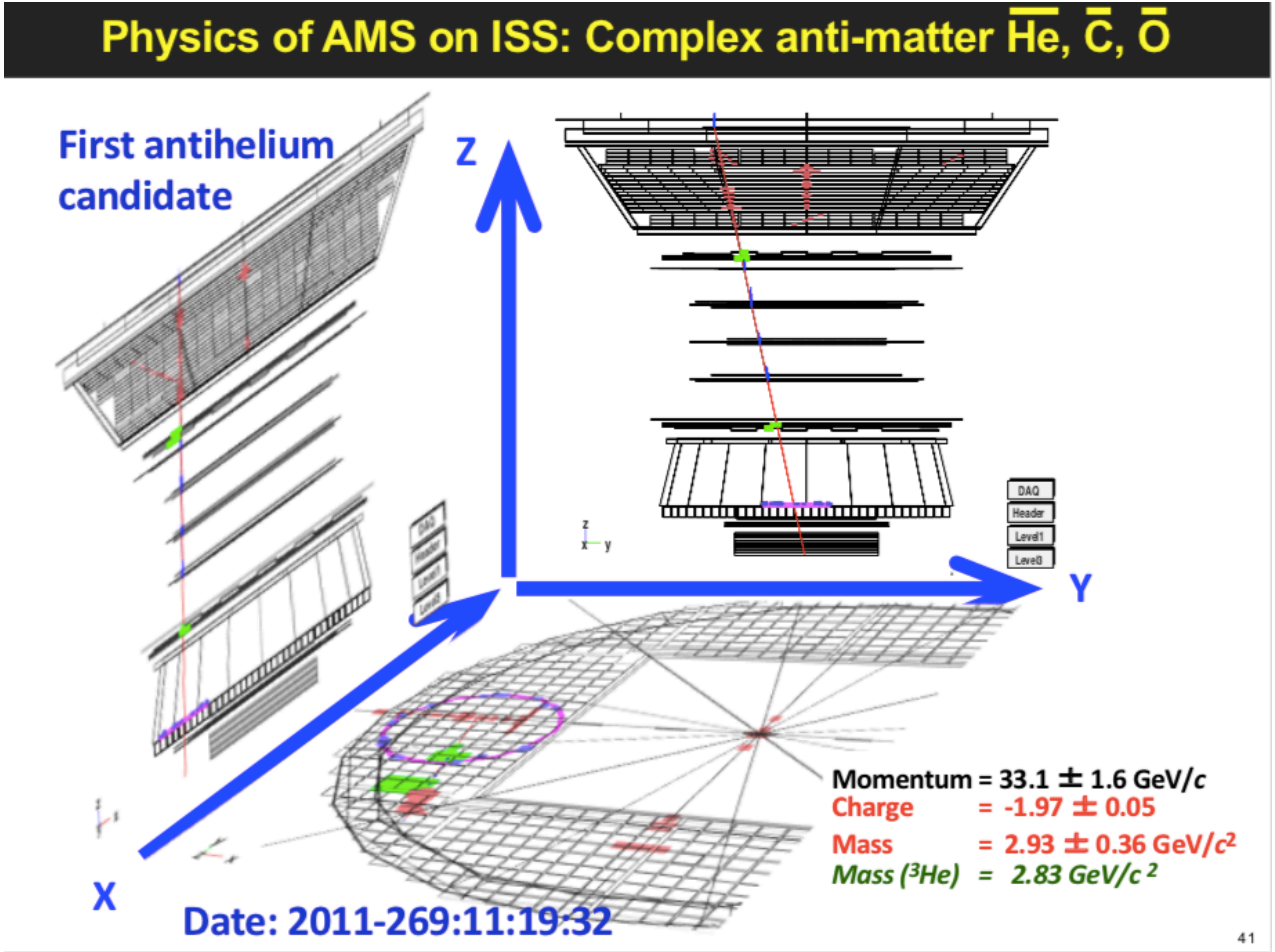

Bess Upper limit on $^{3}\overline{He}$ flux (latest published limit). [1]

$^{3}\overline{He}$ in cosmic rays is expected to be exceedingly rare, since the secondary flux expected from cosmic ray collisions is negligible.

- In ALICE, ca. 1 $^{3}\overline{He}$ per $10^{6}$ high multiplicity pp events at $\sqrt{s}$=13TeV.
- AMS has teased the observation of $^{3}\overline{He}$ candidates at conferences for the past few years, but the results have not been published yet.
- If published, even the observation of 1 event would signal new physics, because the flux cannot currently be explained by any considered production process (except an anti-star within 1 parsec).
- This is why it is vital to measure these cross sections.


[1] Abe et. al. , 2012, arXiv:1201.2967 [astro-ph.CO]
[2] Poulin et. al., 2018, arXiv:1808.08961 [astro-ph.HE]

# AMS $^{3}\overline{He}$ candidates




[1] A. Kounine and S. Ting, 2018, ICHEP Conference