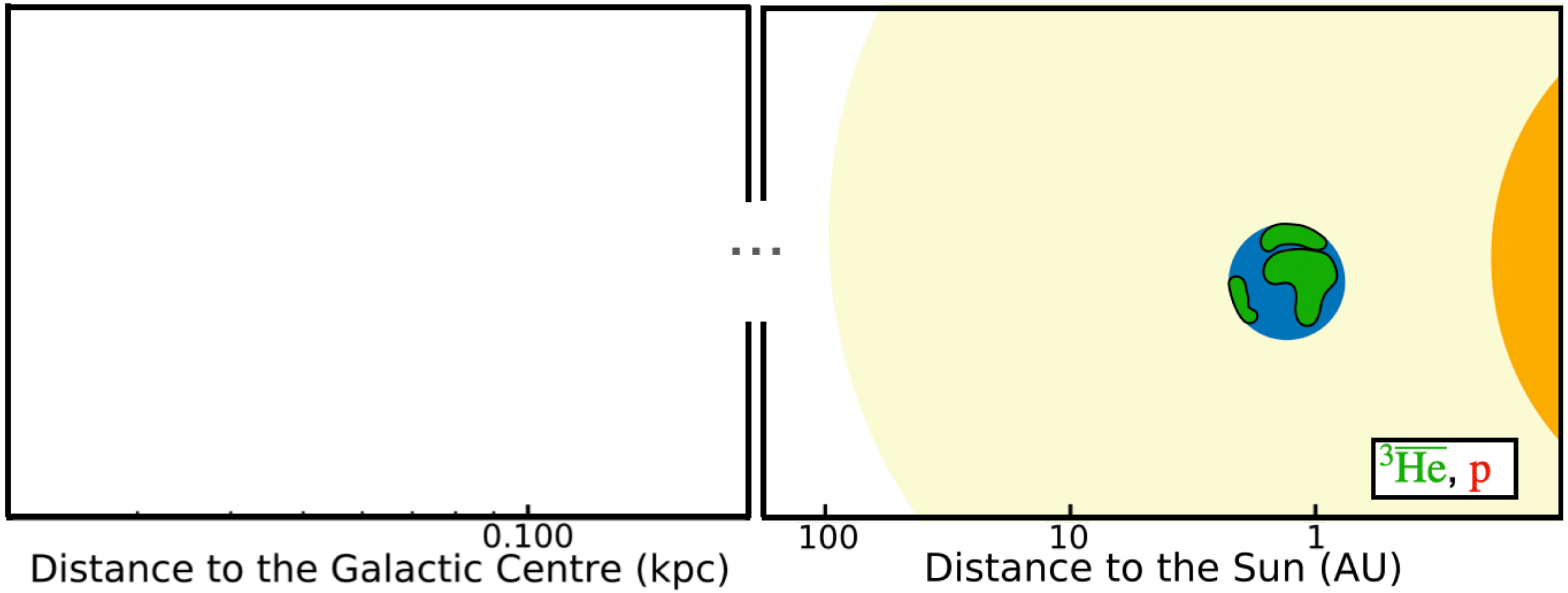
Antinuclei as messengers from the depths of our galaxy

Stephan Koenigstorfer on behalf of the ALICE Collaboration
Technische Universität München

59th International Winter Meeting on Nuclear Physics

Introduction



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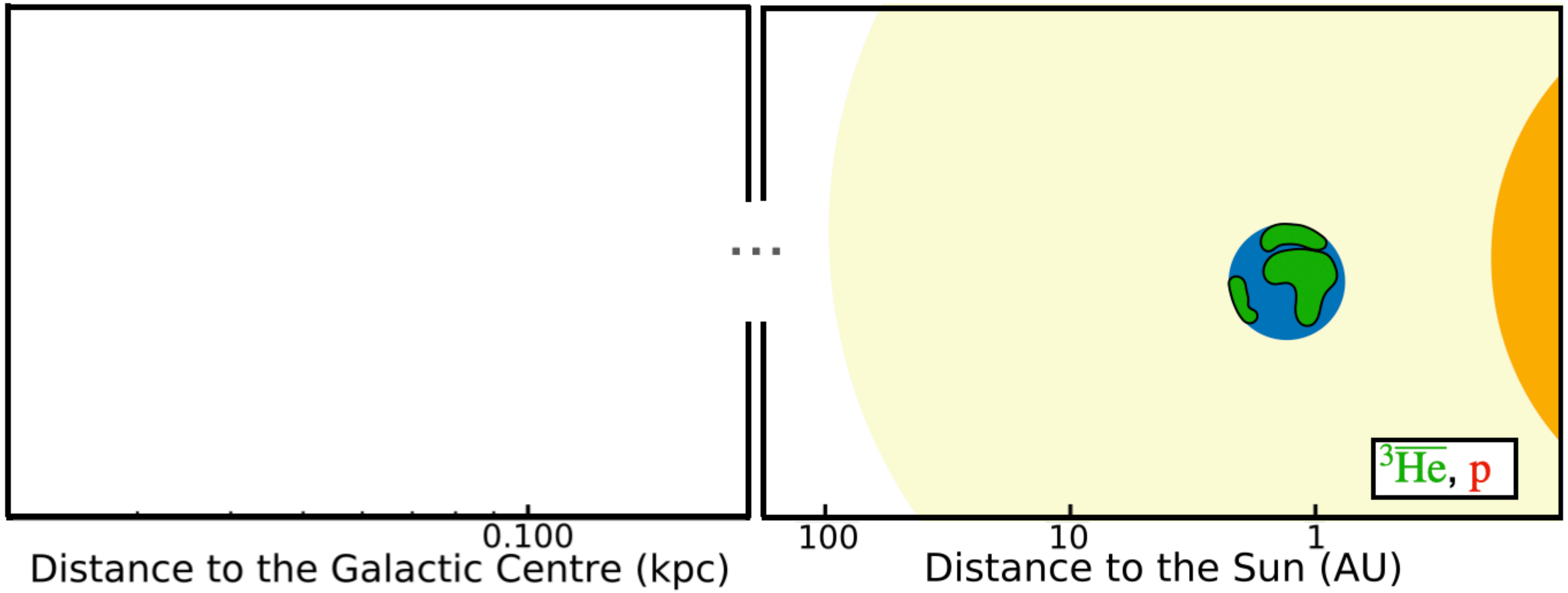
Cosmic ray antinuclei - unique probe into new physics such as dark matter



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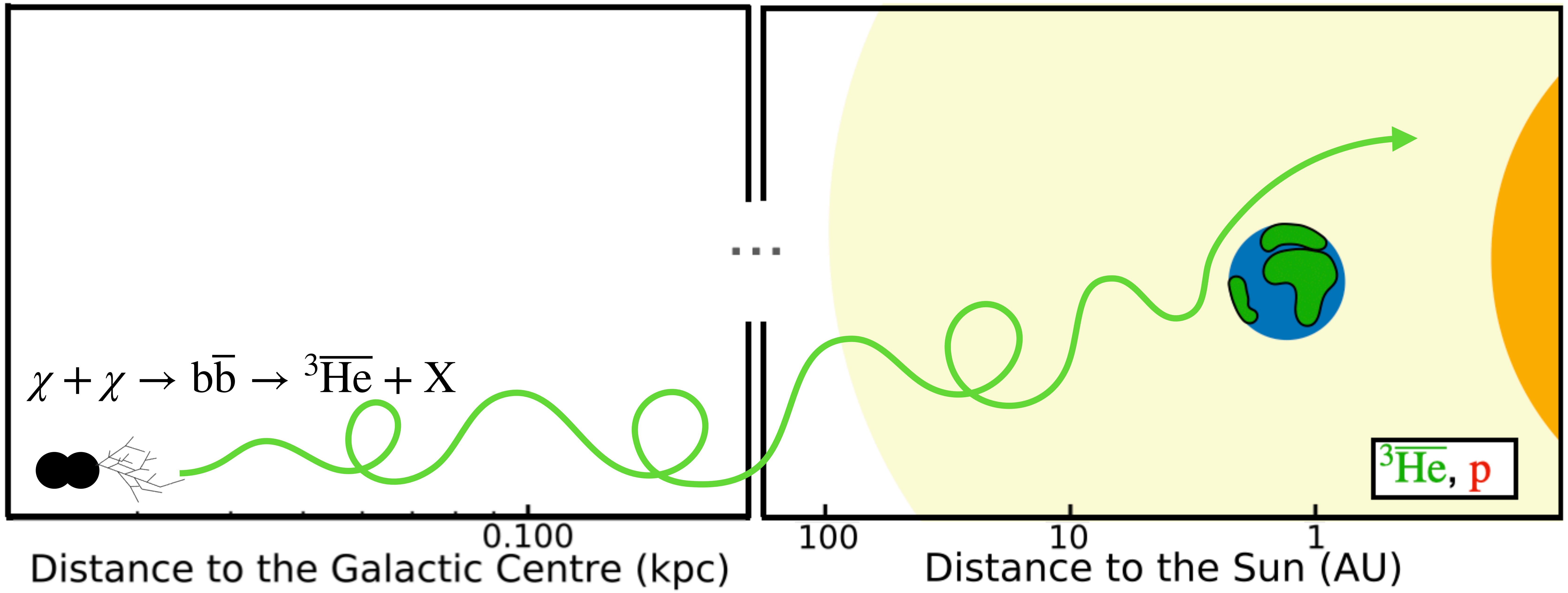

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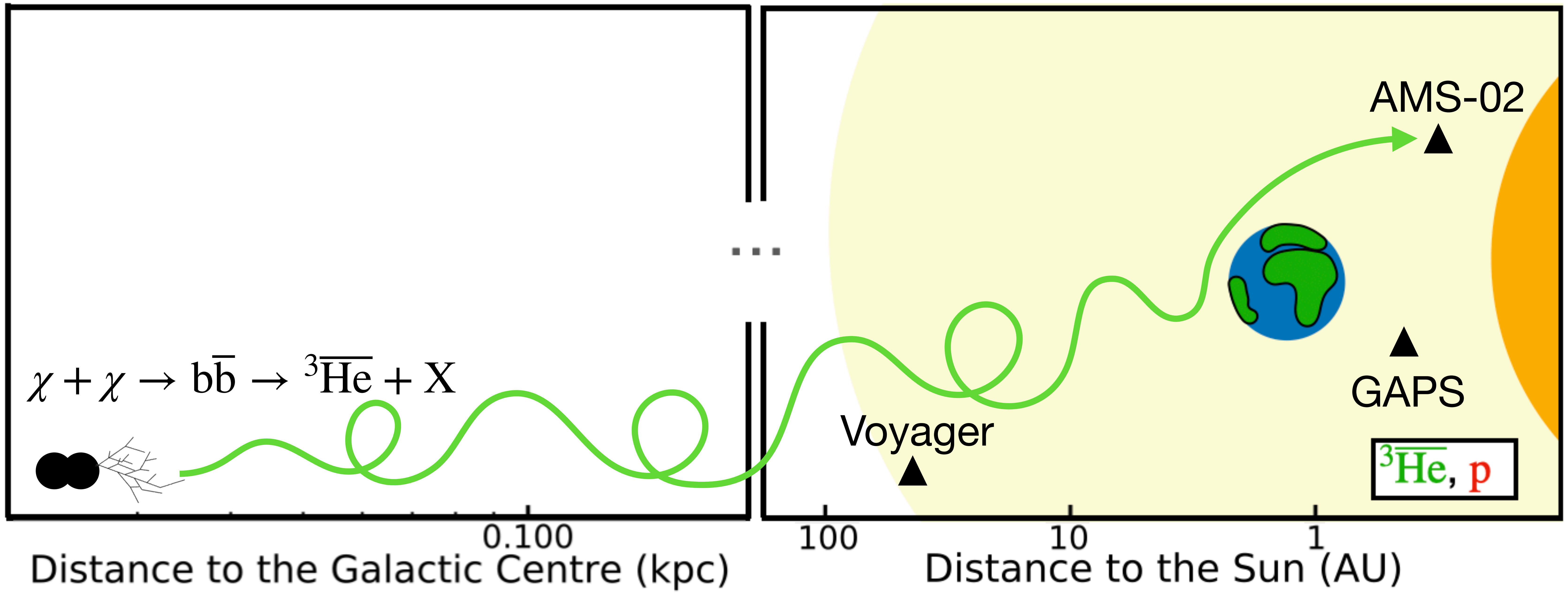

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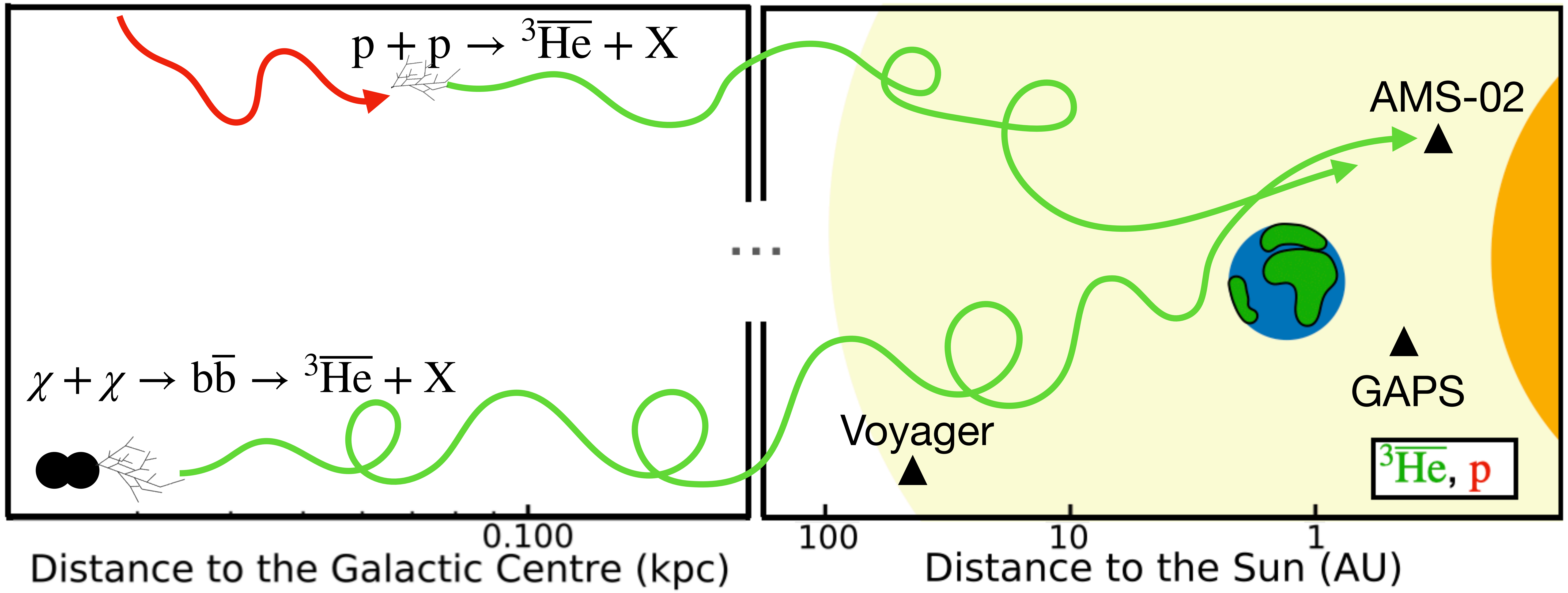

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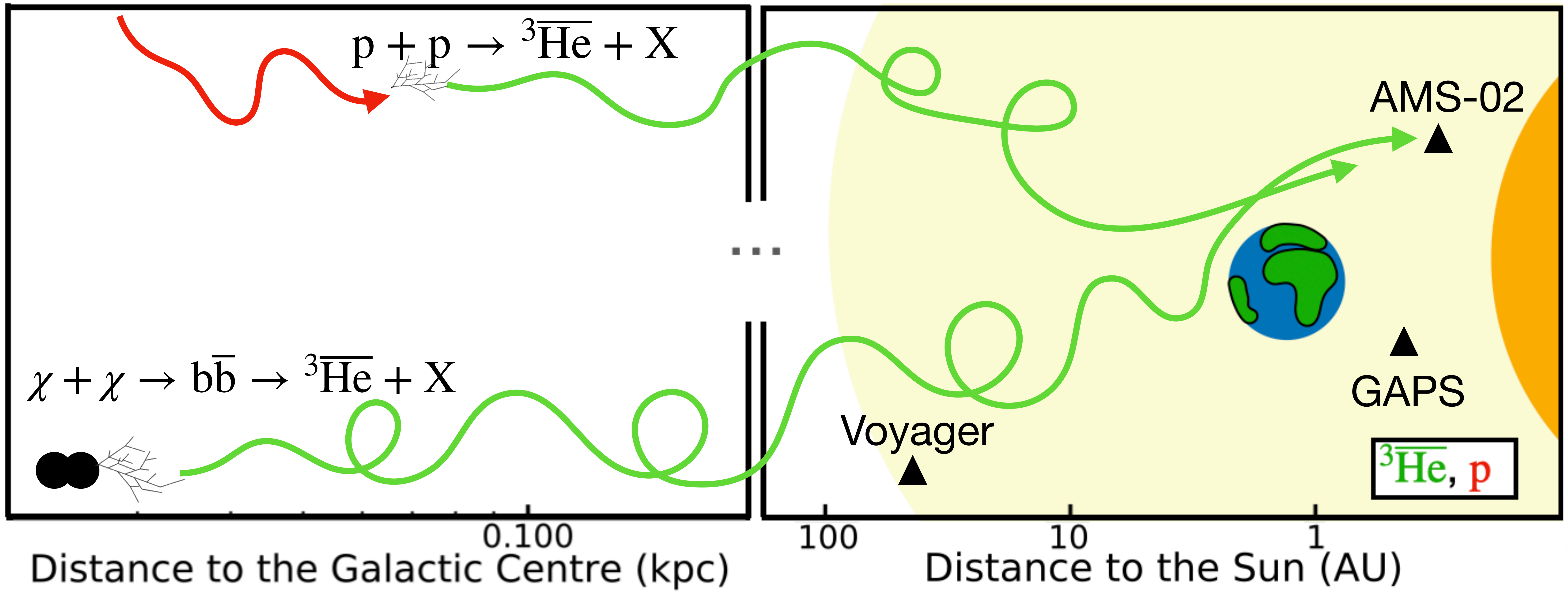

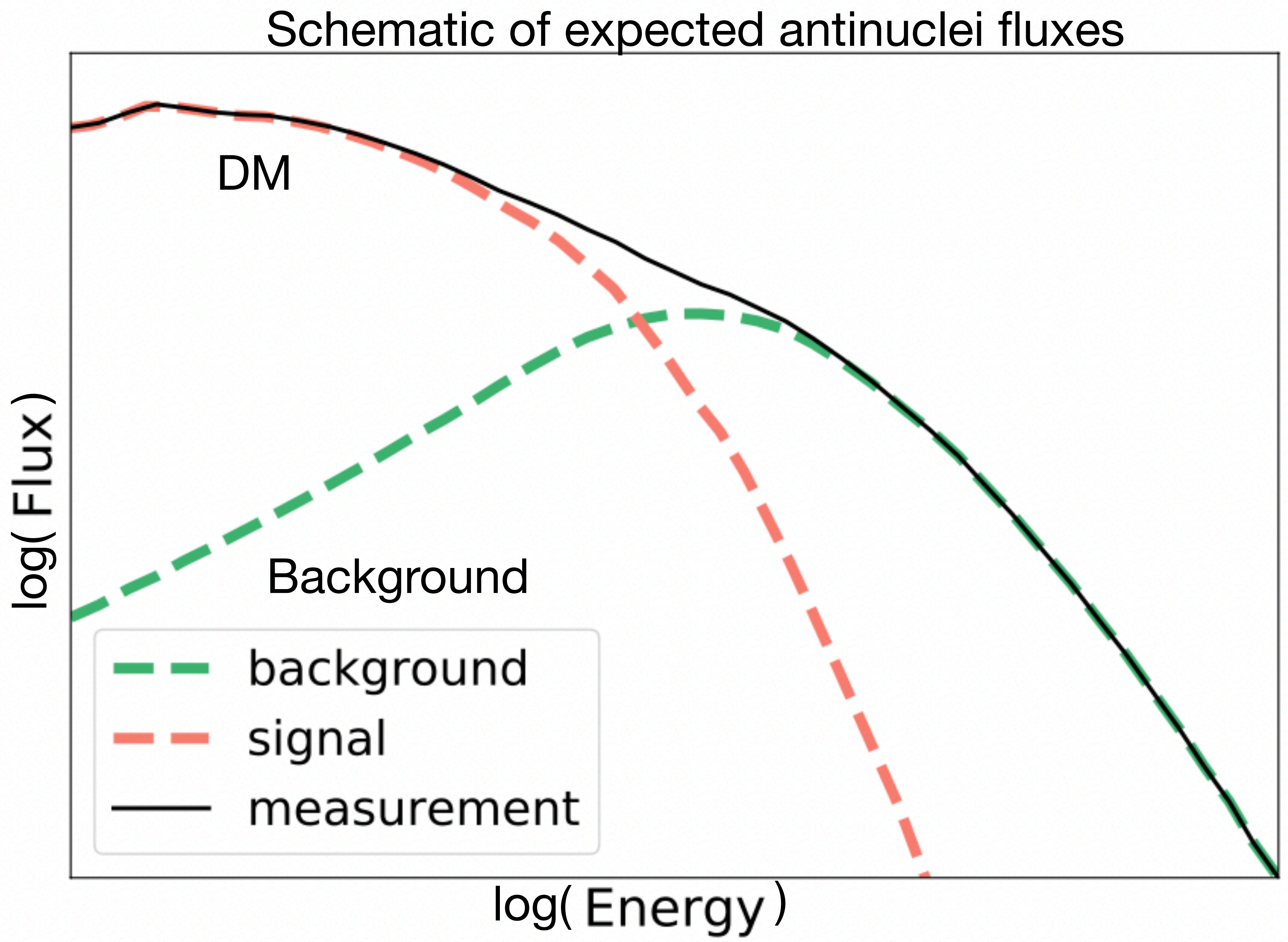

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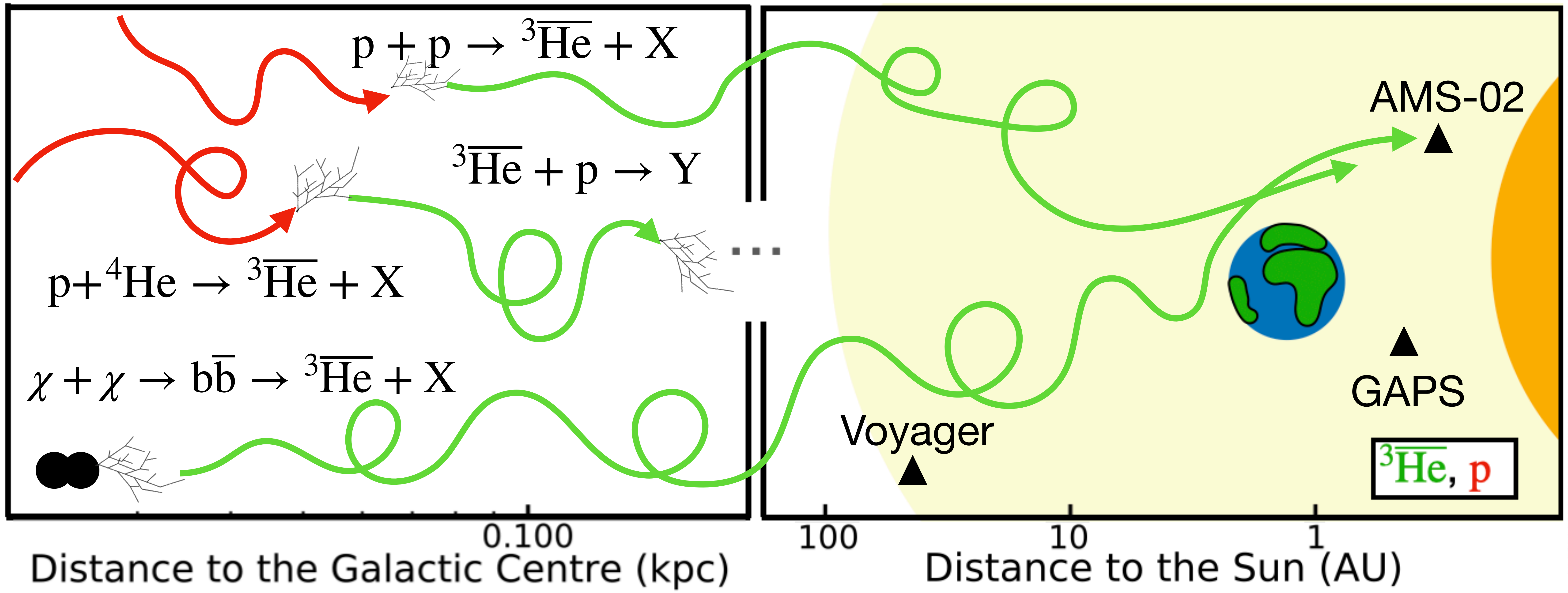

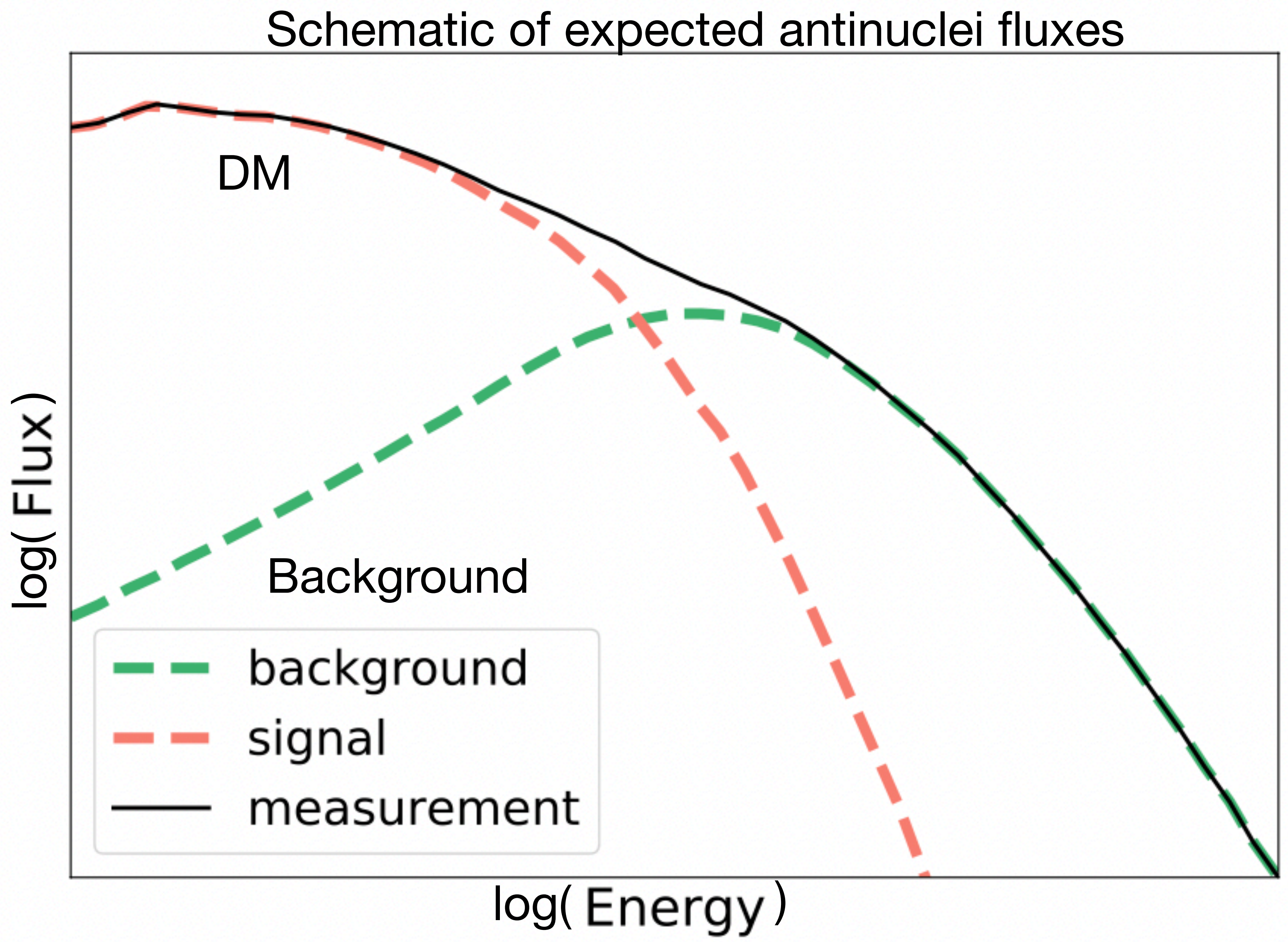

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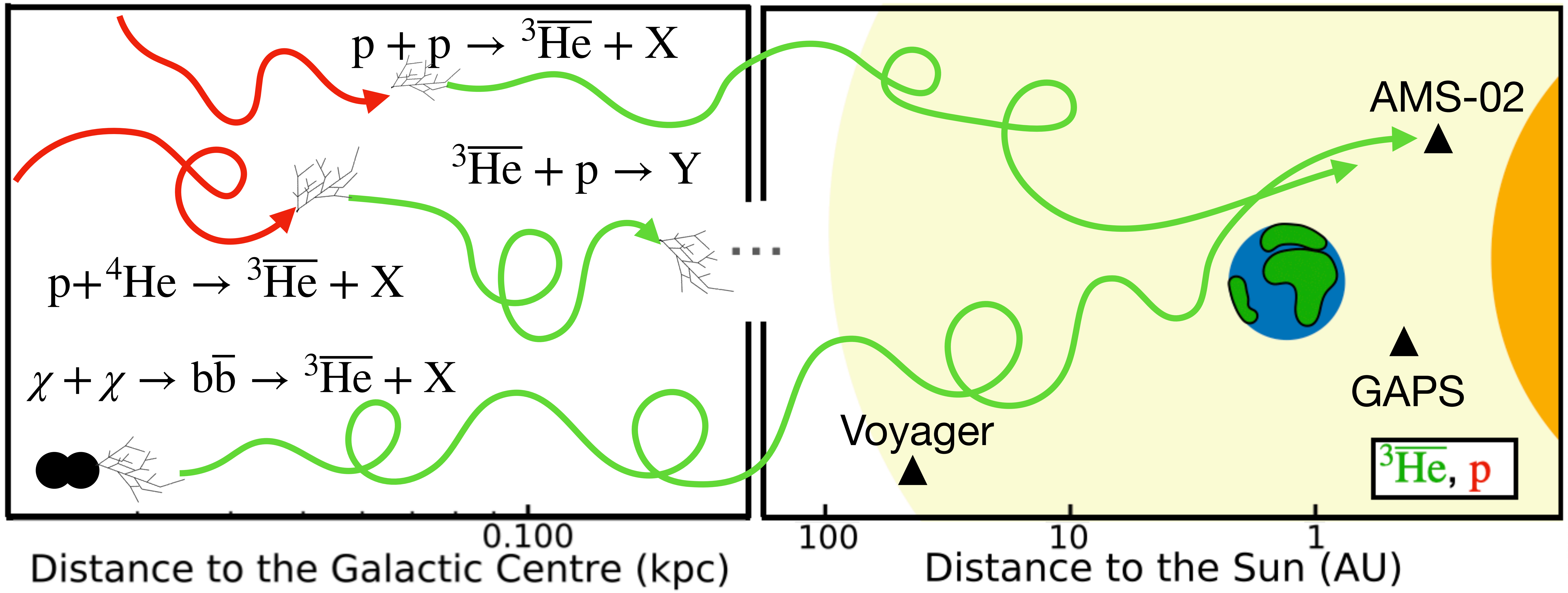
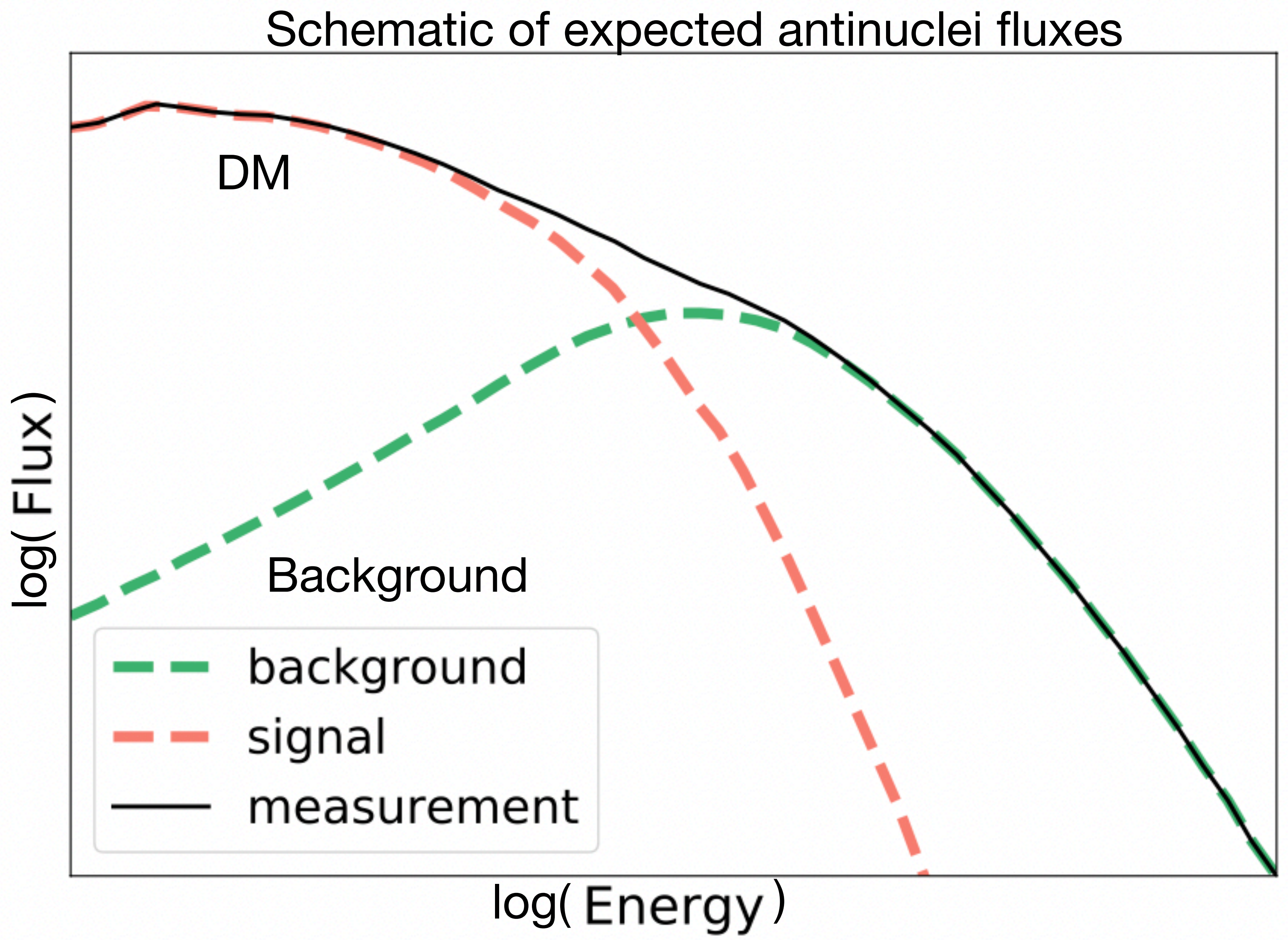
Cosmic ray antinuclei - unique probe into new physics such as dark matter

- 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





Space: the final frontier

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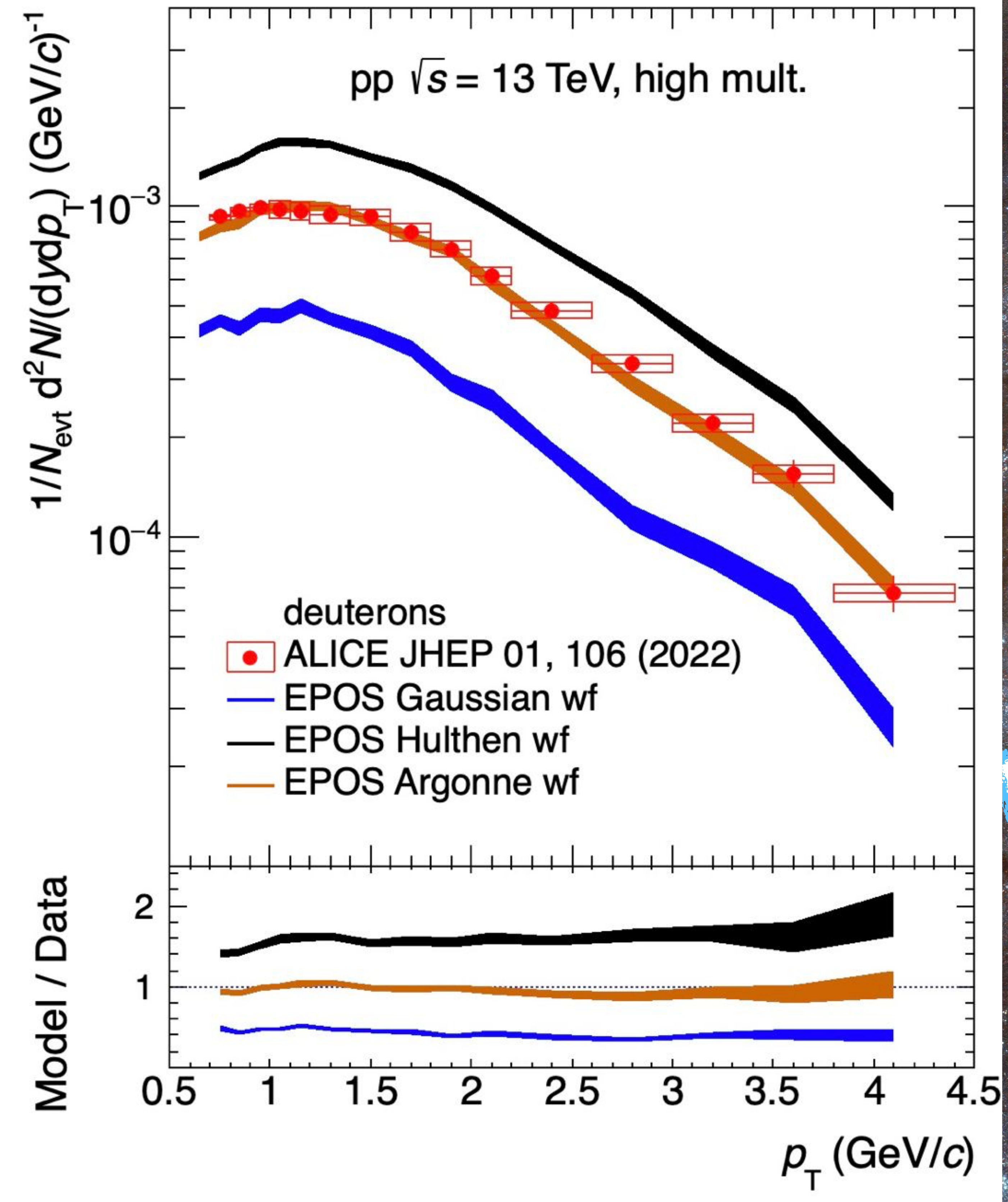

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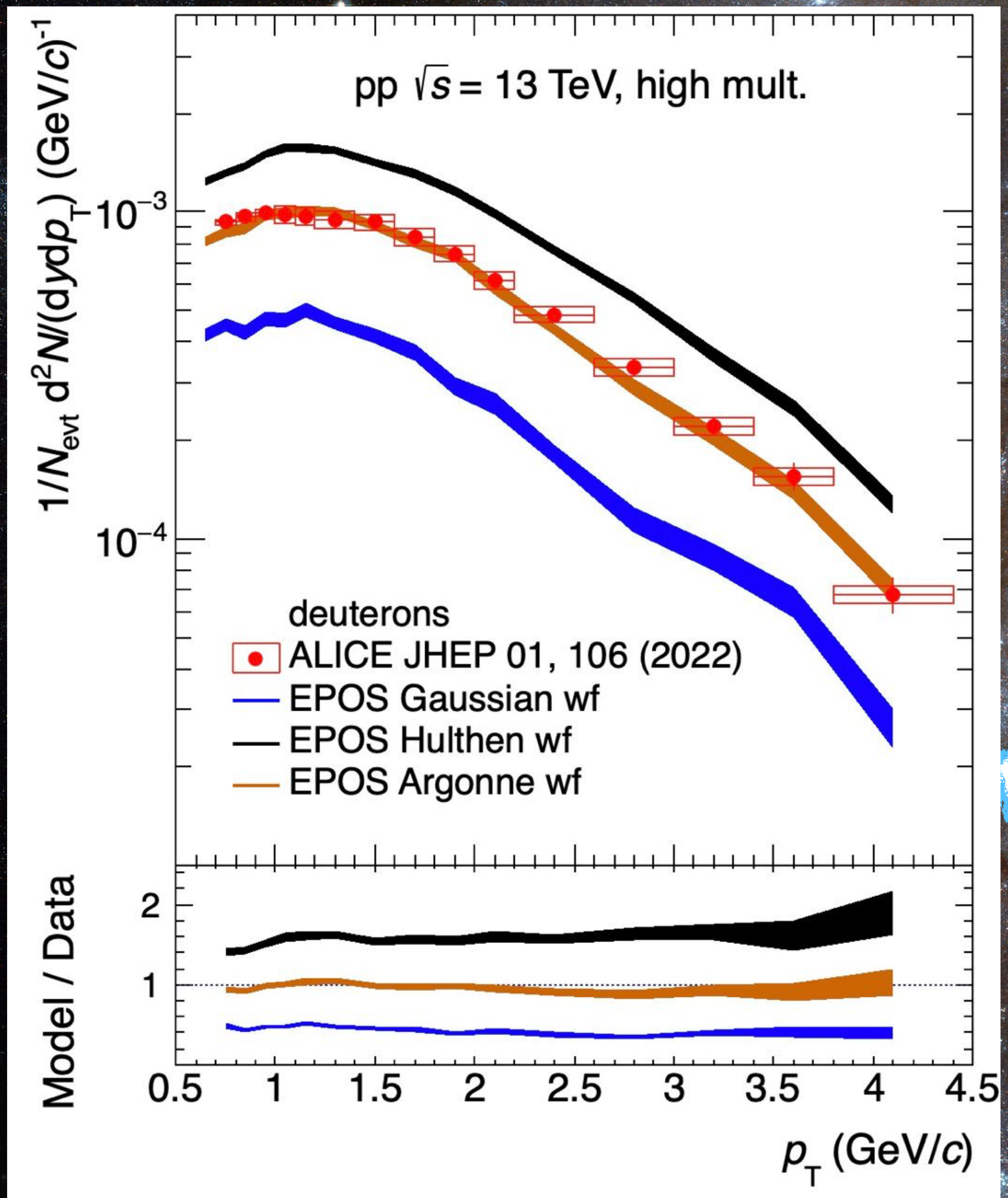

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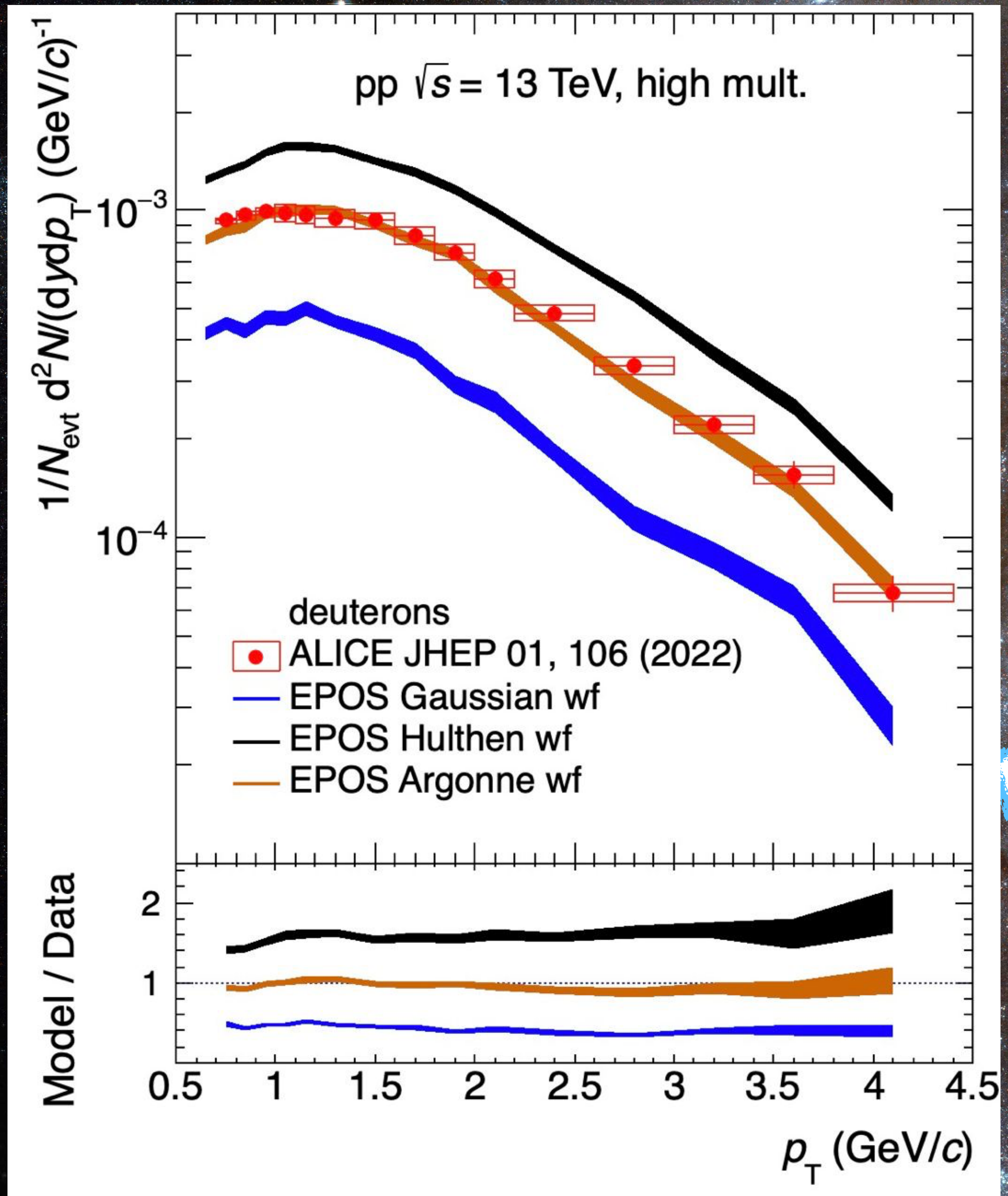

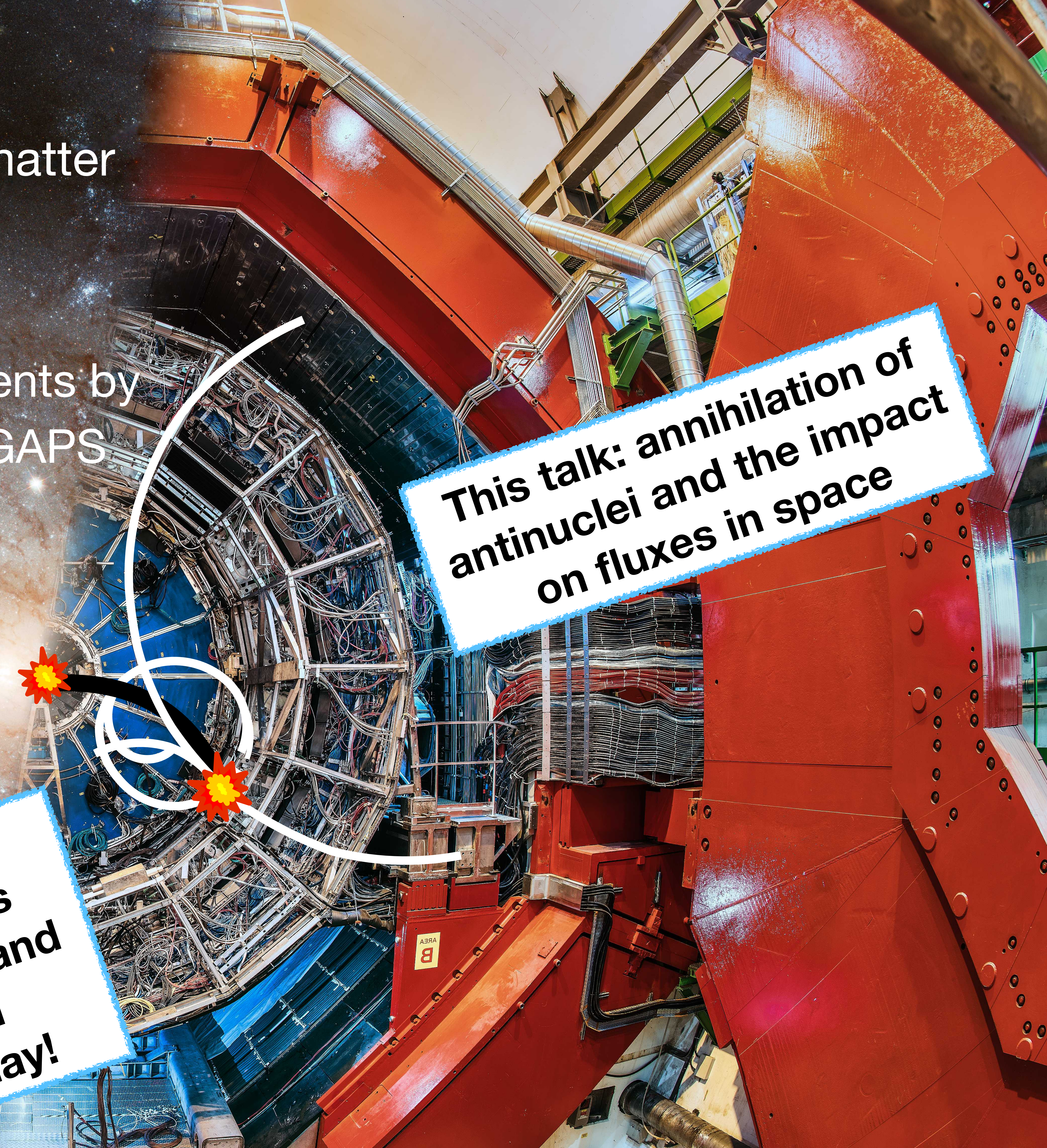

This talk: annihilation of antinuclei and the impact on fluxes in space

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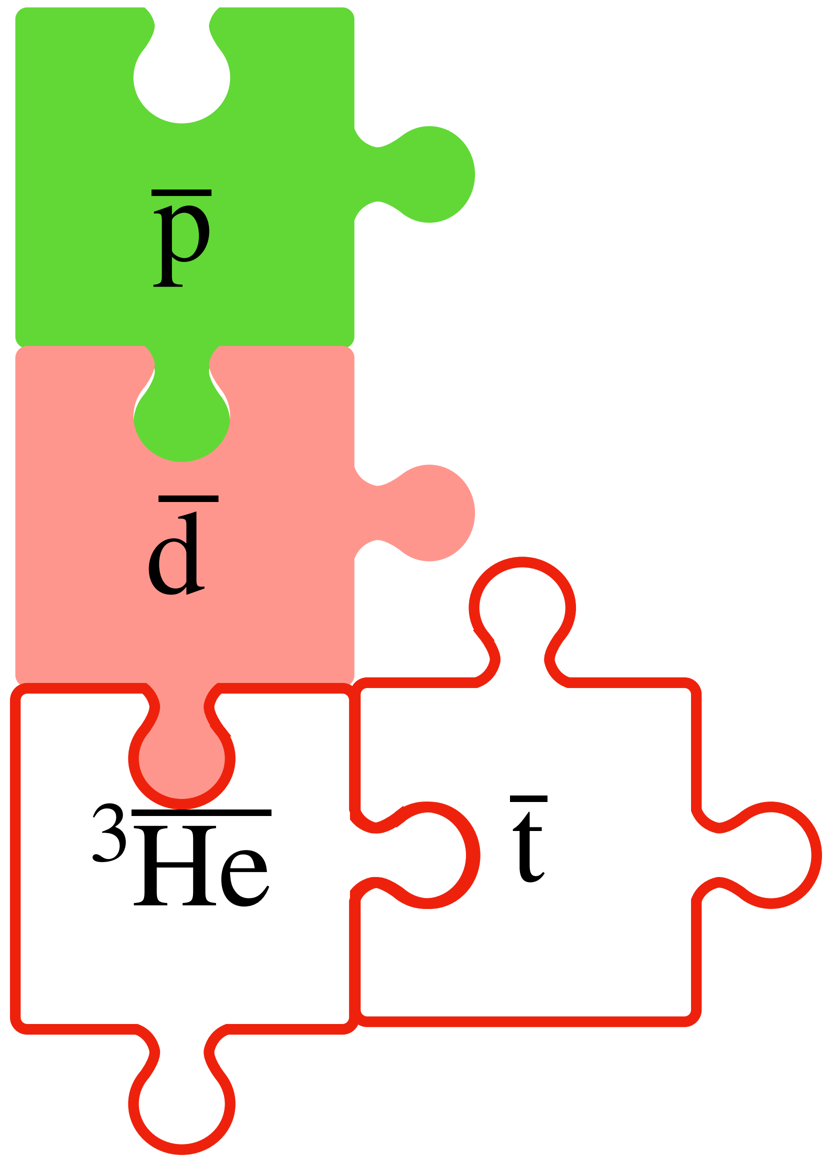
Annihilation: pieces of the puzzle

Previous



Annihilation: pieces of the puzzle

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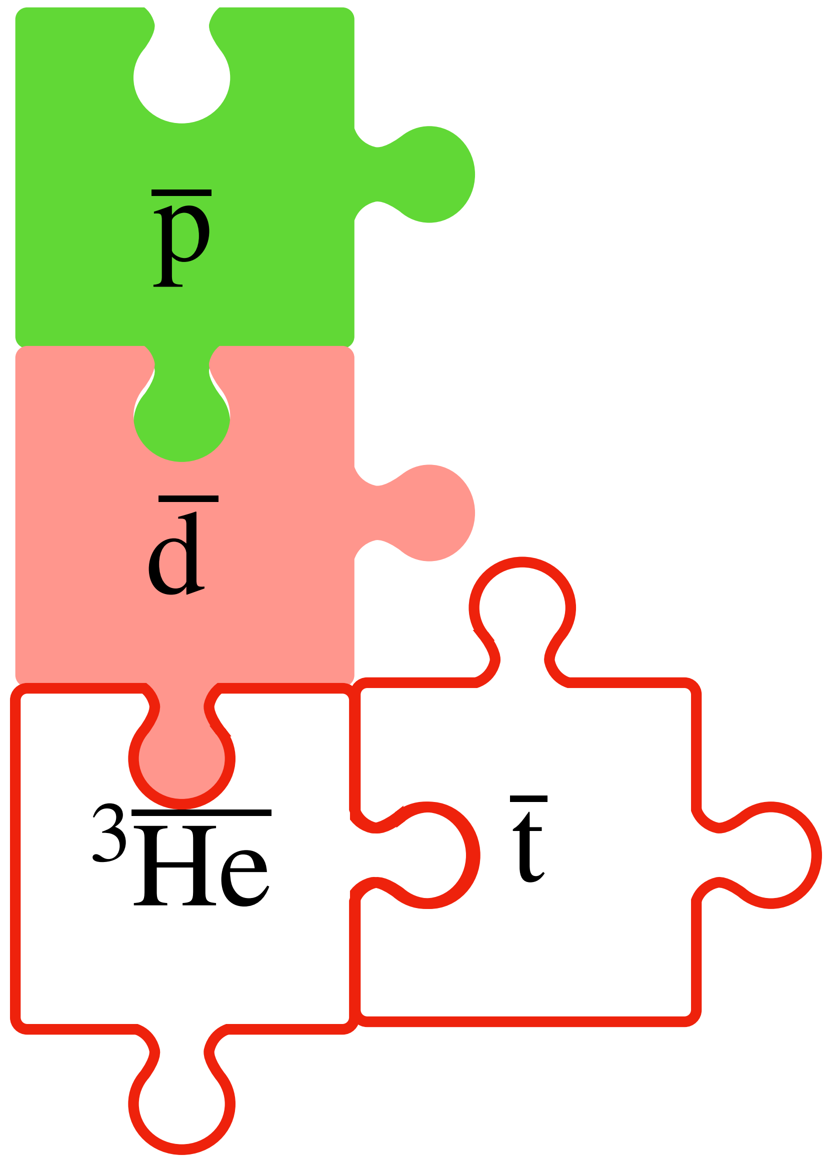

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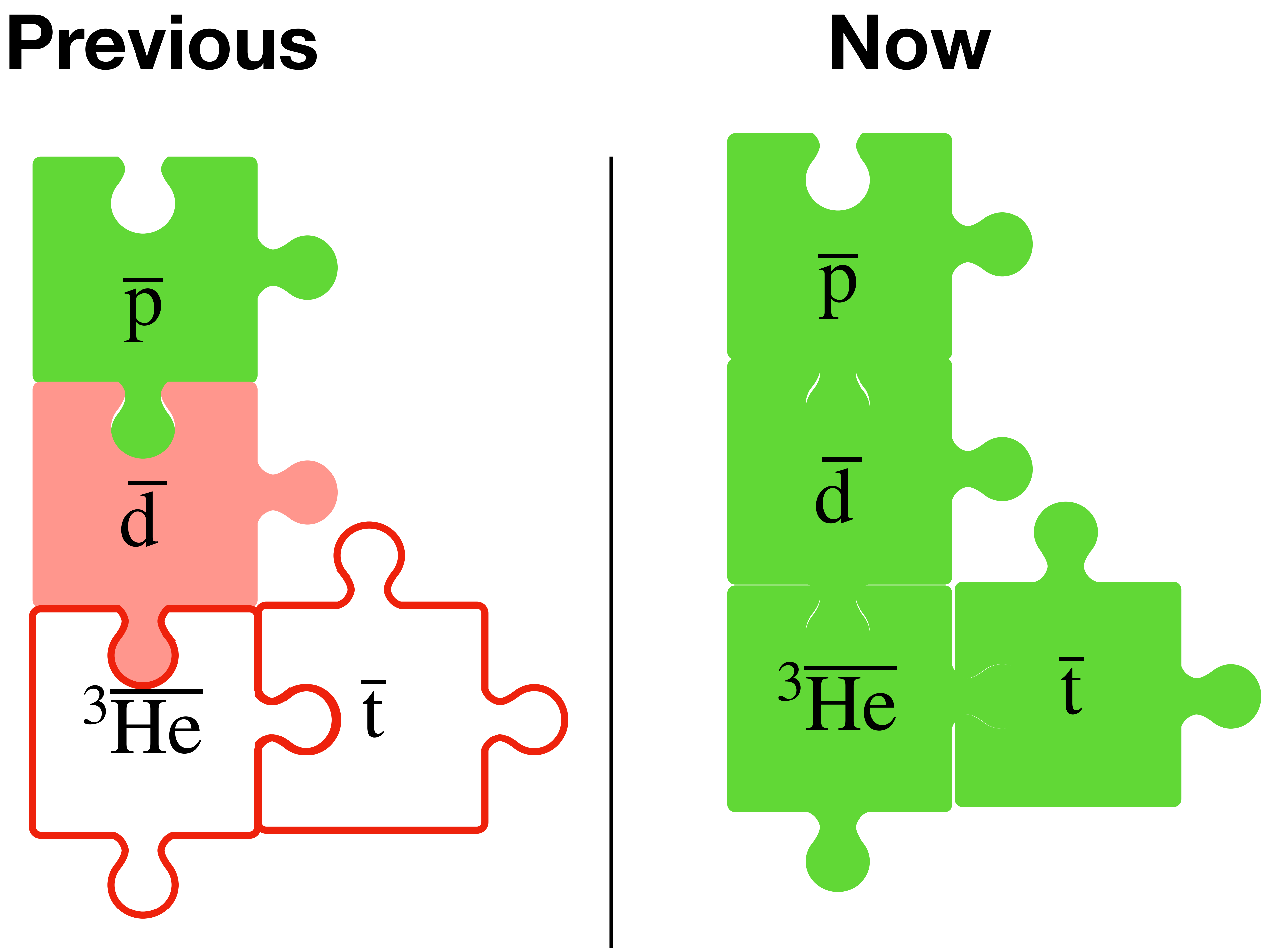

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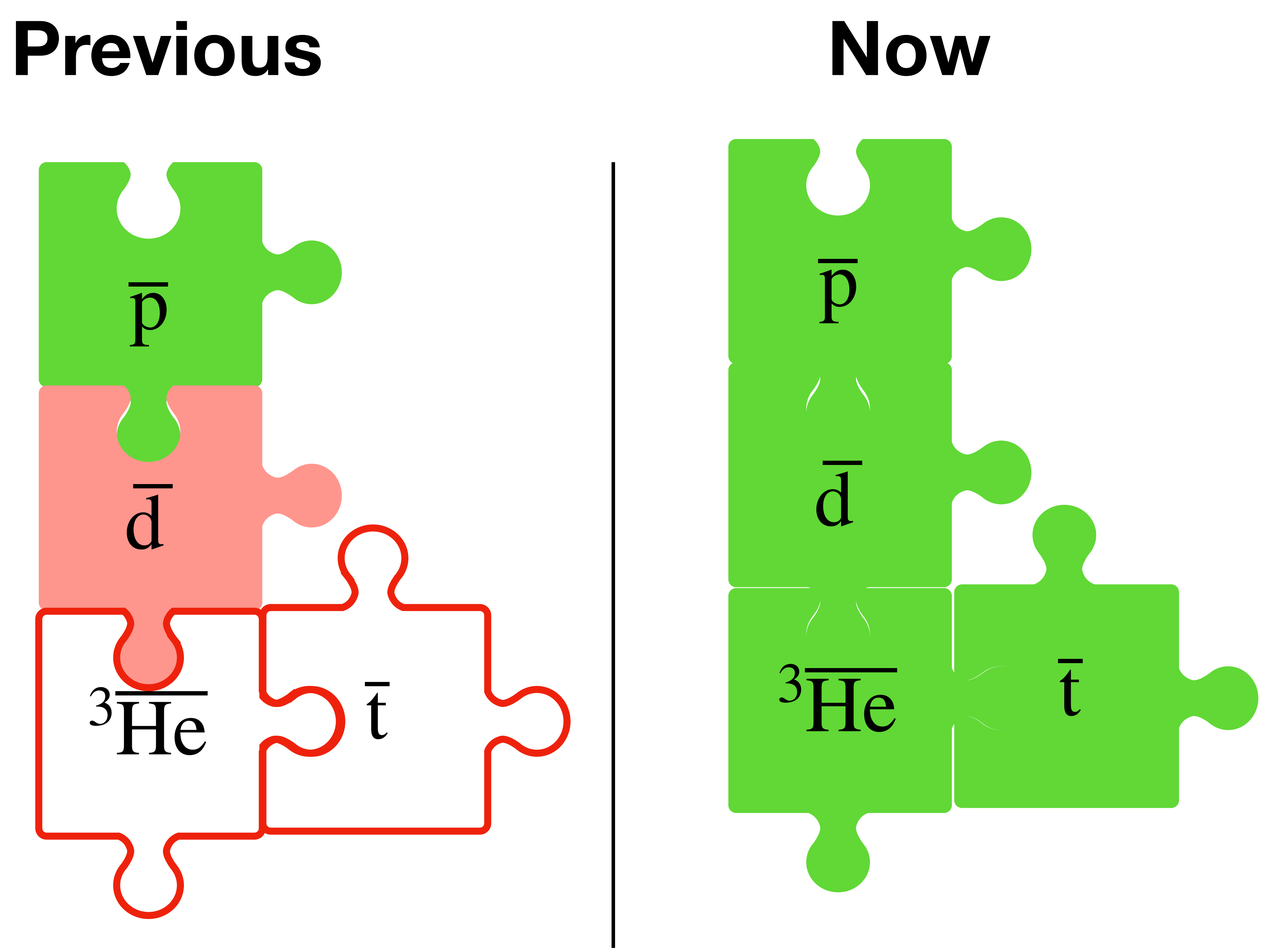

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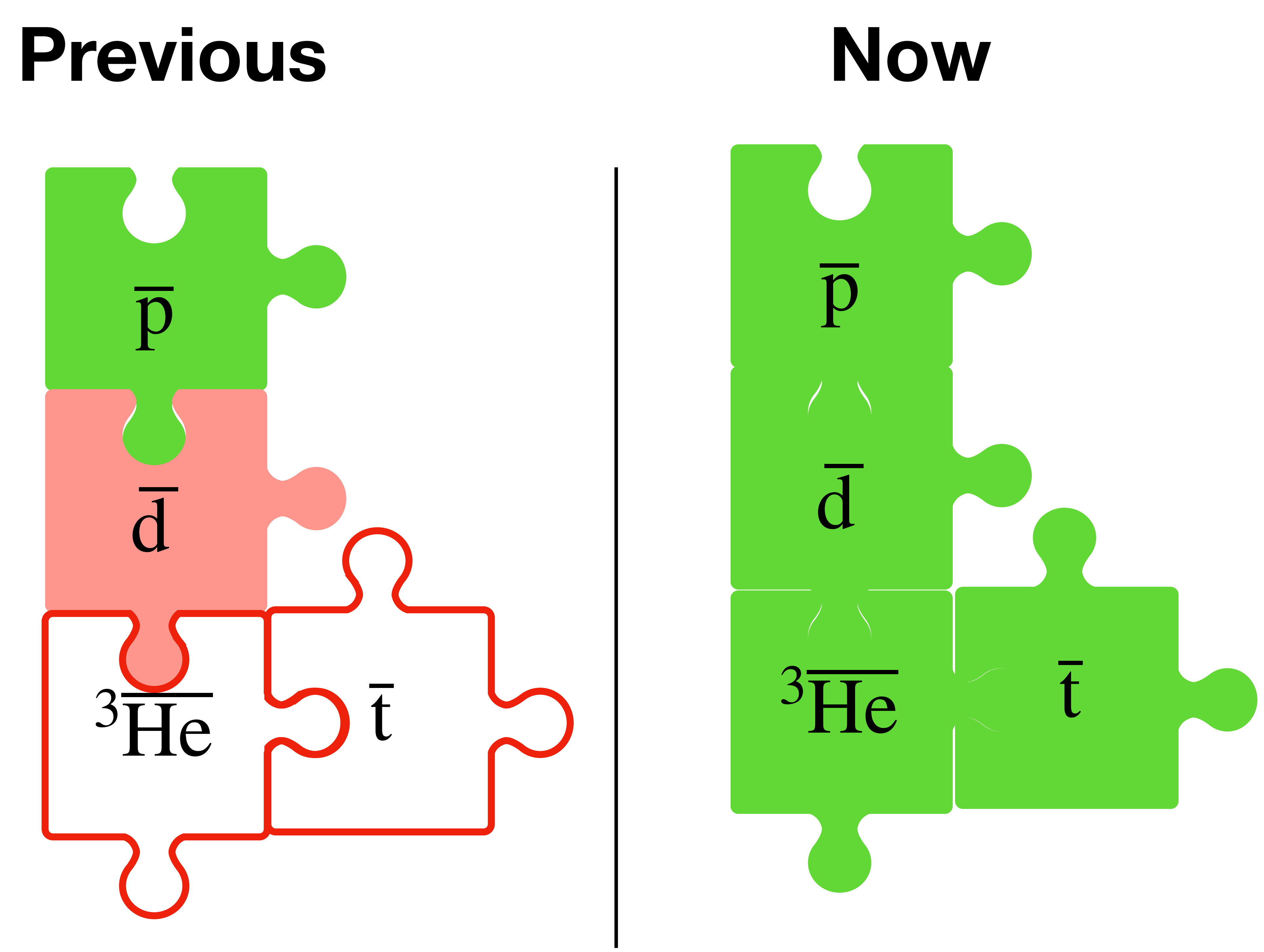
- This talk focuses mainly on A=3 results



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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

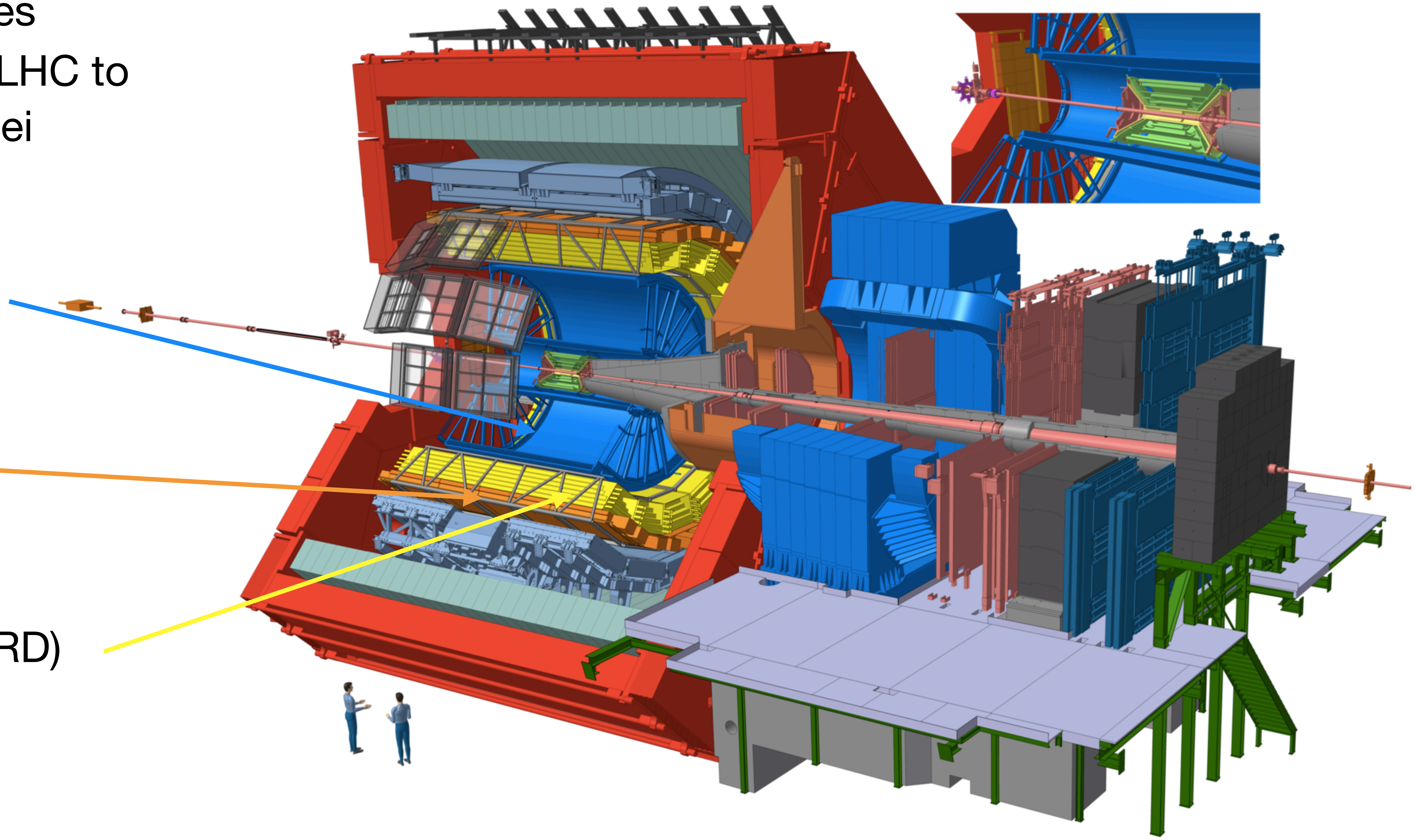
Time Projection Chamber (TPC)

- Tracking, PID (dE/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 $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV.
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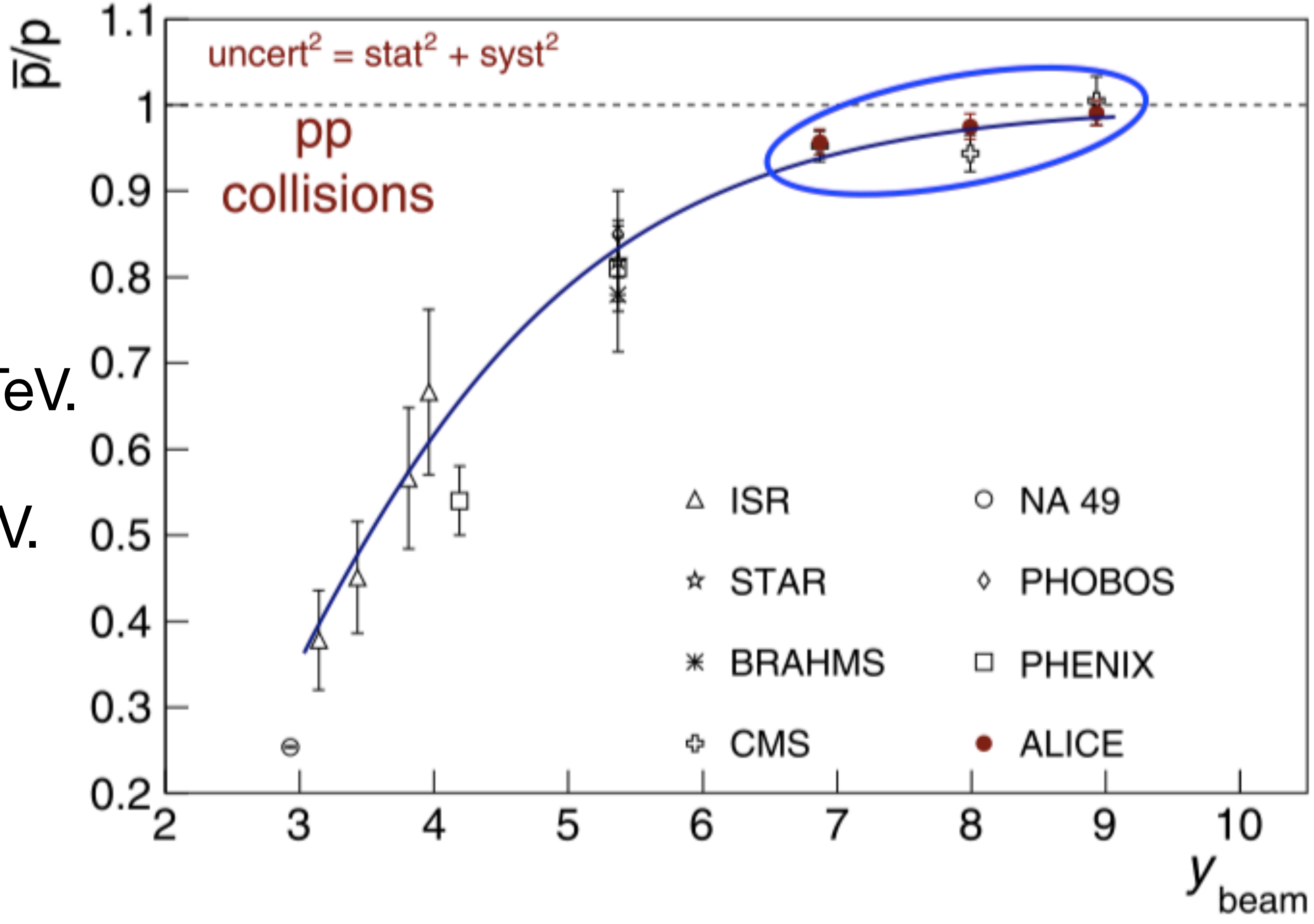
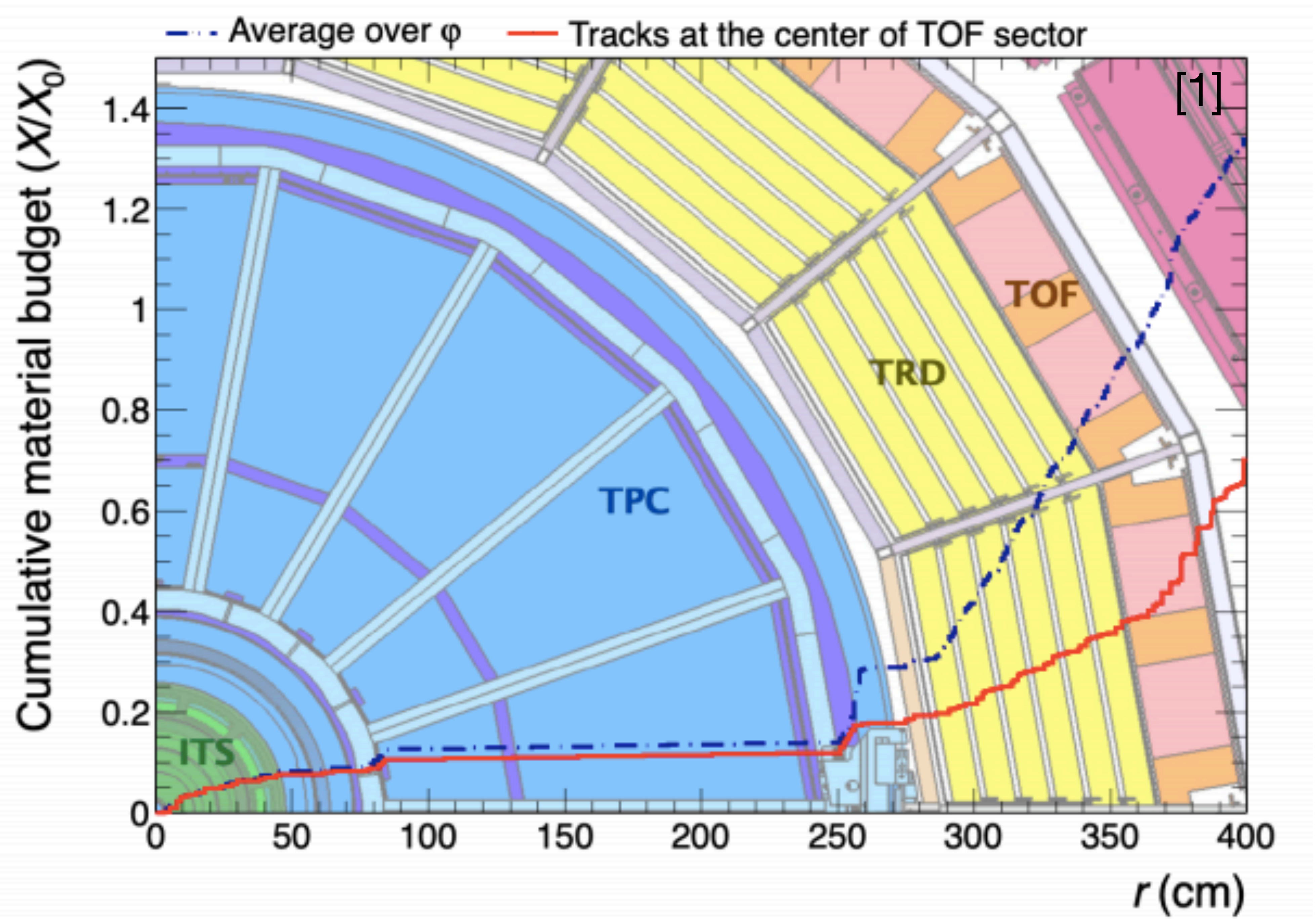
$\bar{\mathrm{p}}$/p ratio at mid-rapidity vs √s [1]



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

… and the ALICE detector material as a target



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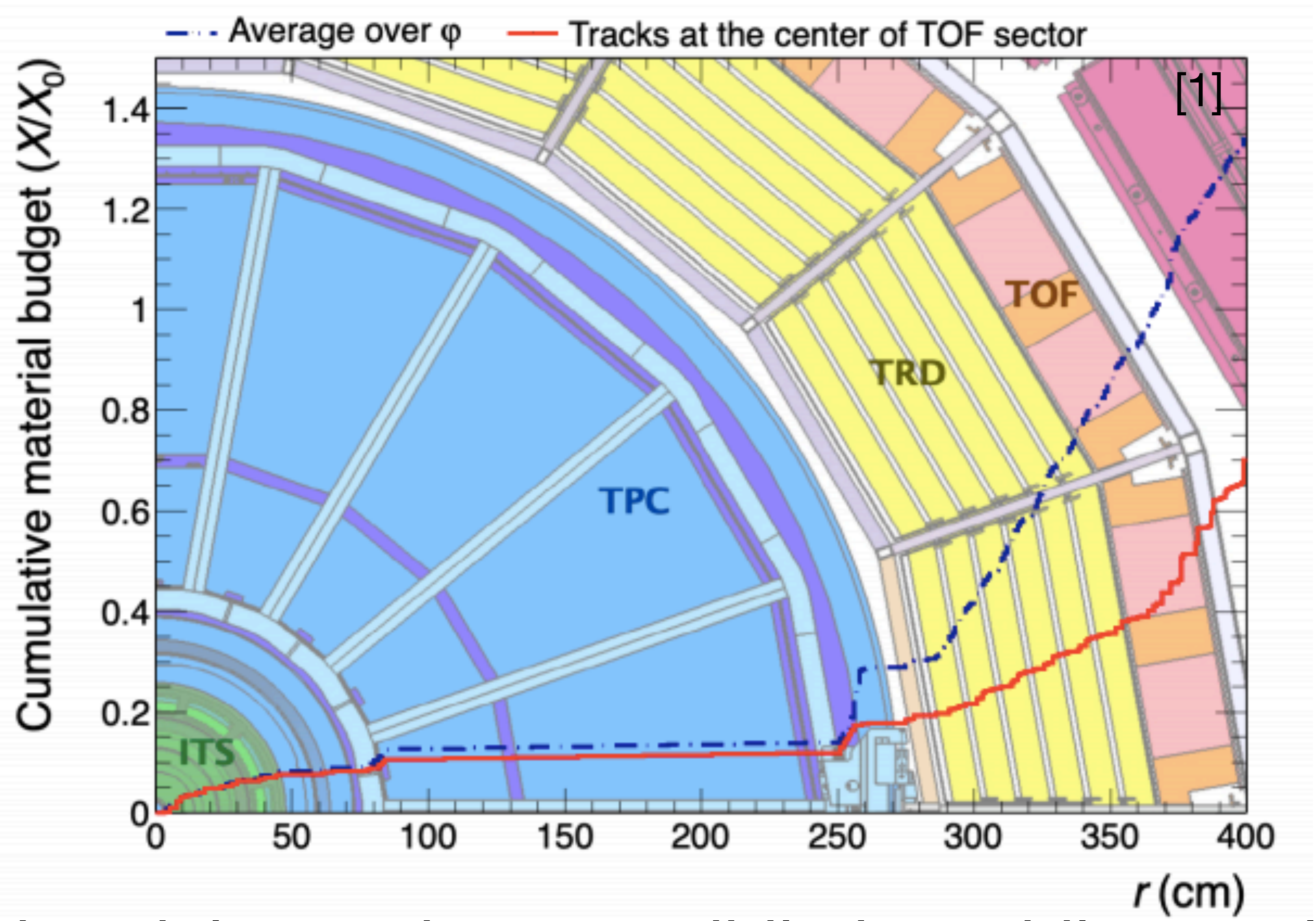

- Antiparticles undergo annihilation while traveling through the detector material
- By quantifying this loss, we can measure the inelastic cross section of antinuclei!

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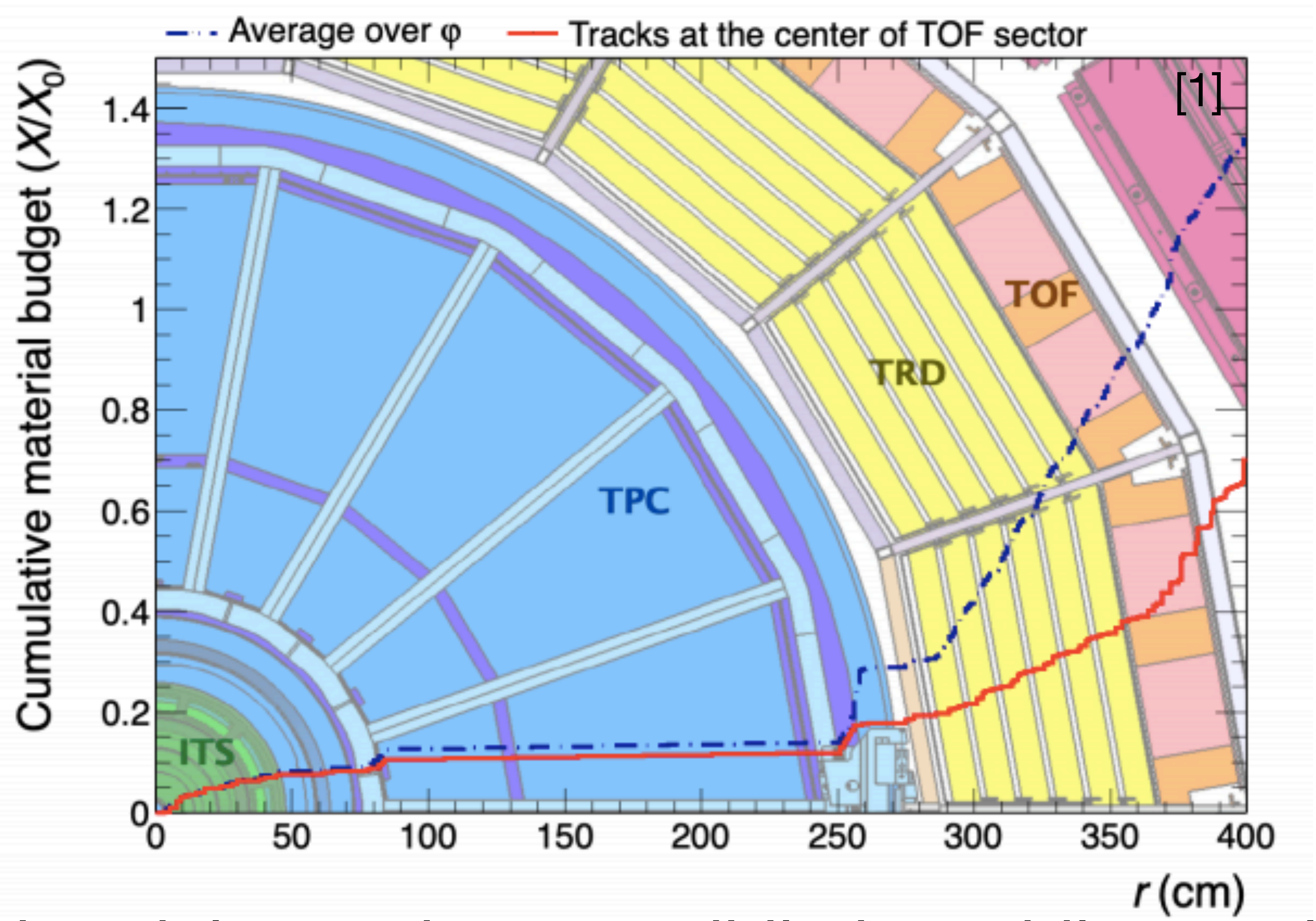

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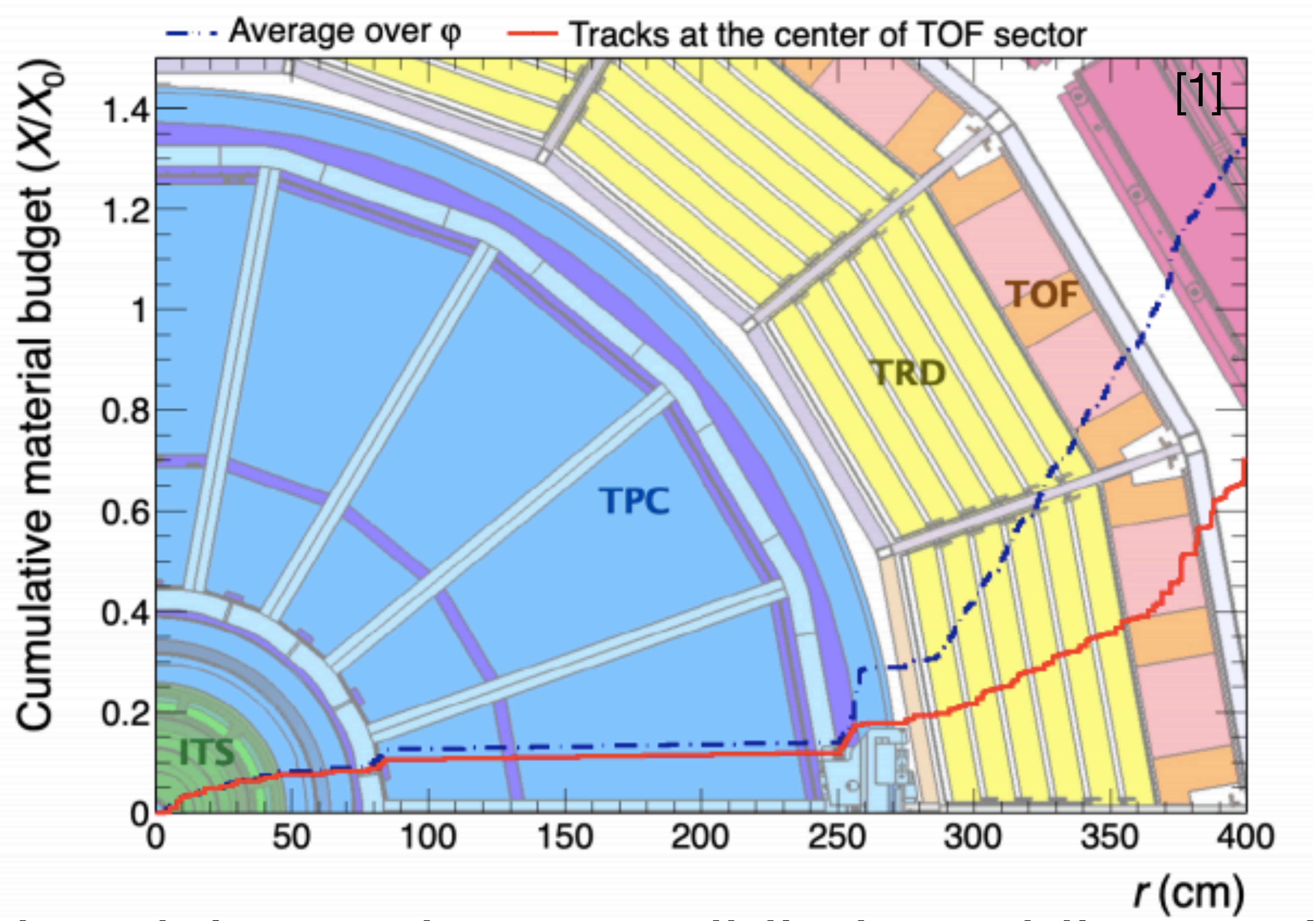

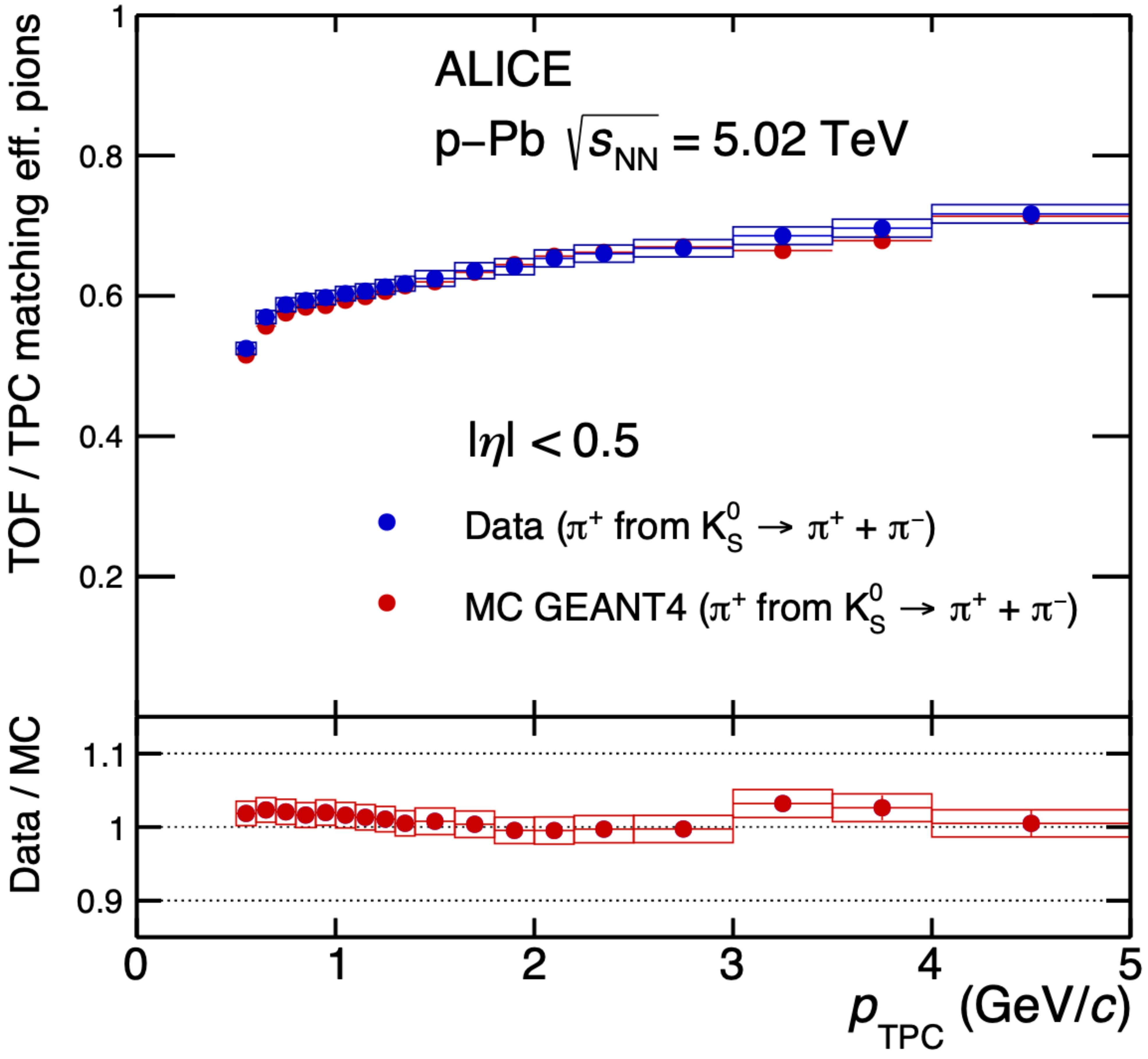

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Details in CERN public note

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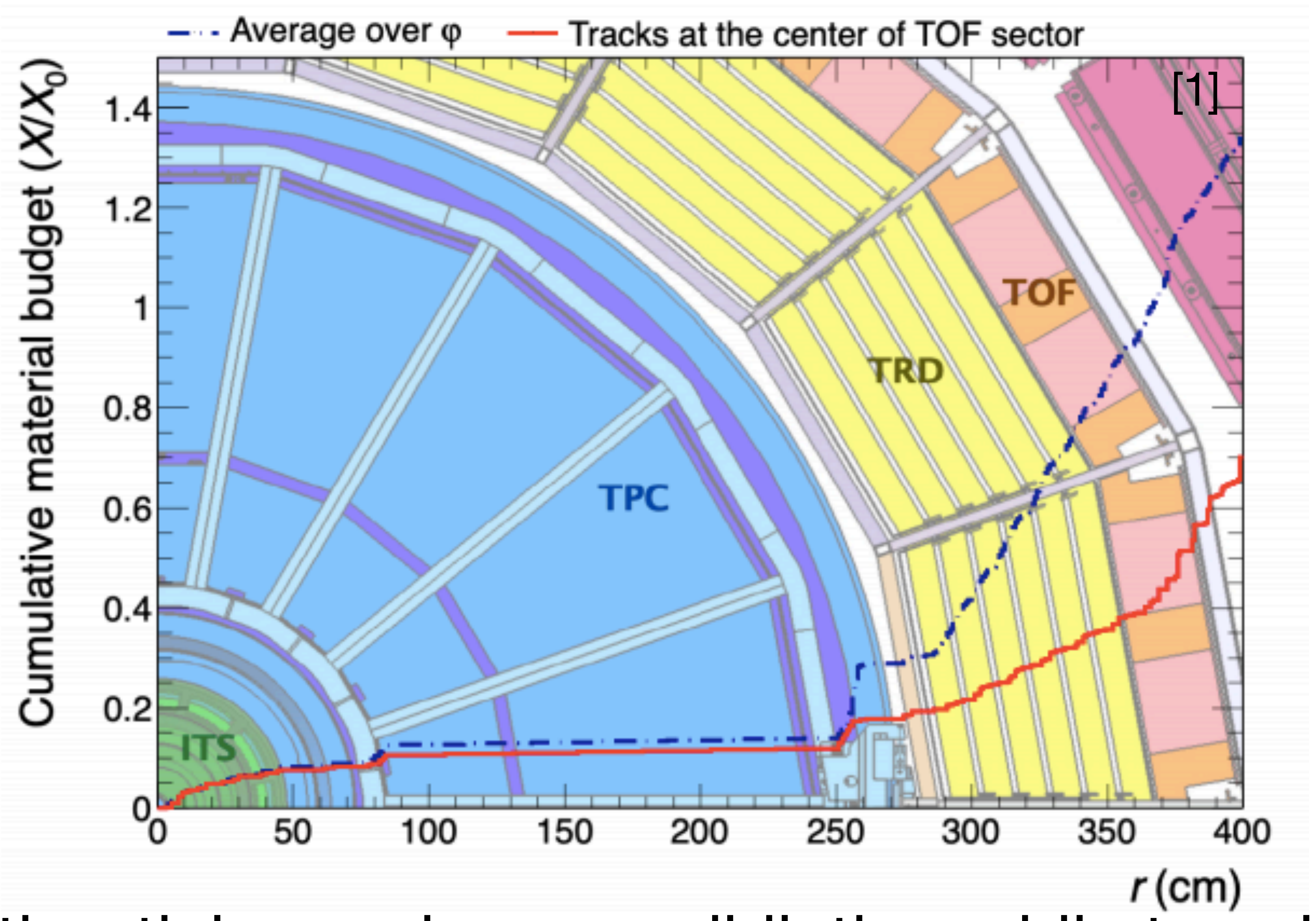

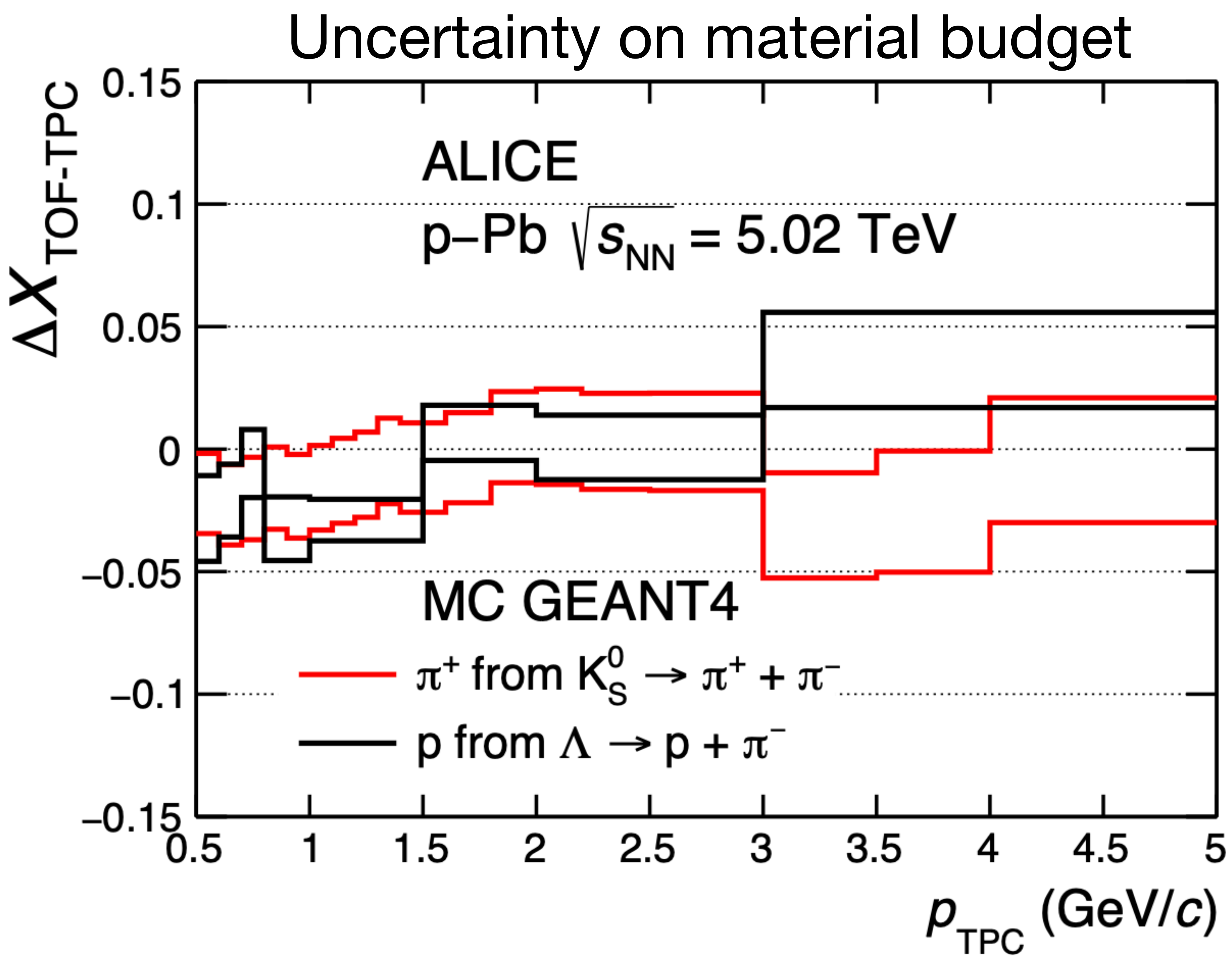

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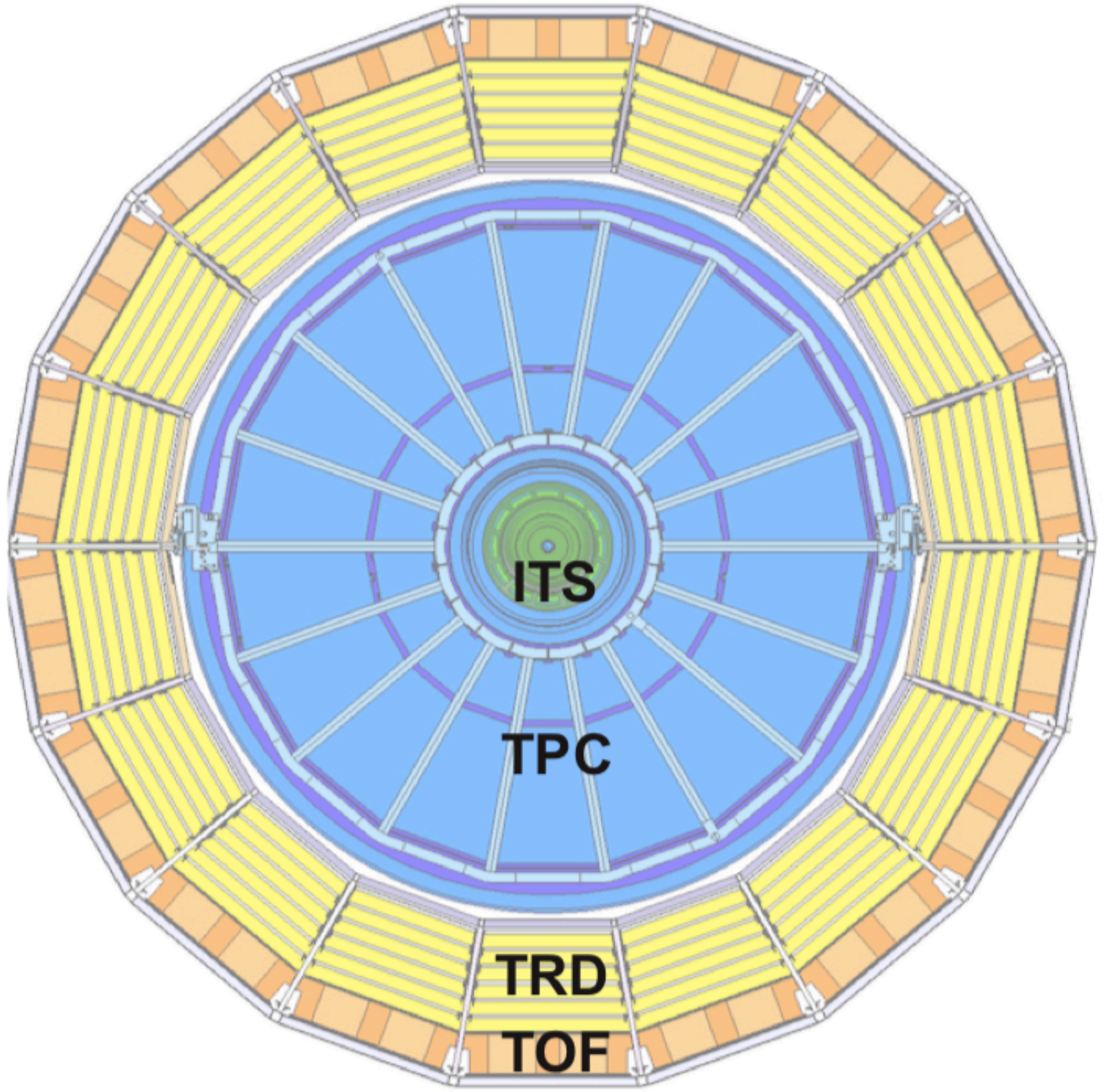
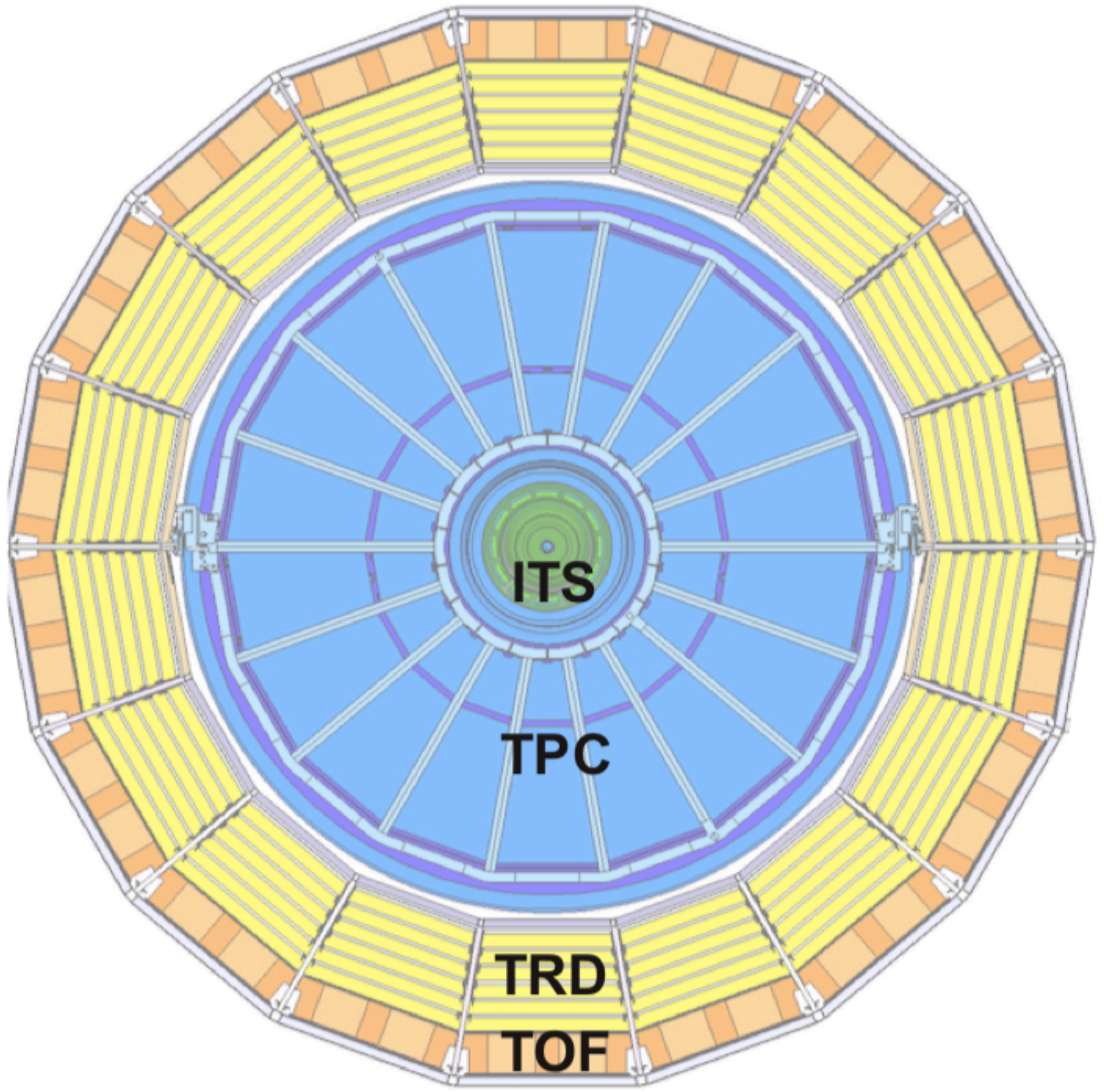
The observables: antimatter-to-matter and TOF/TPC ratio





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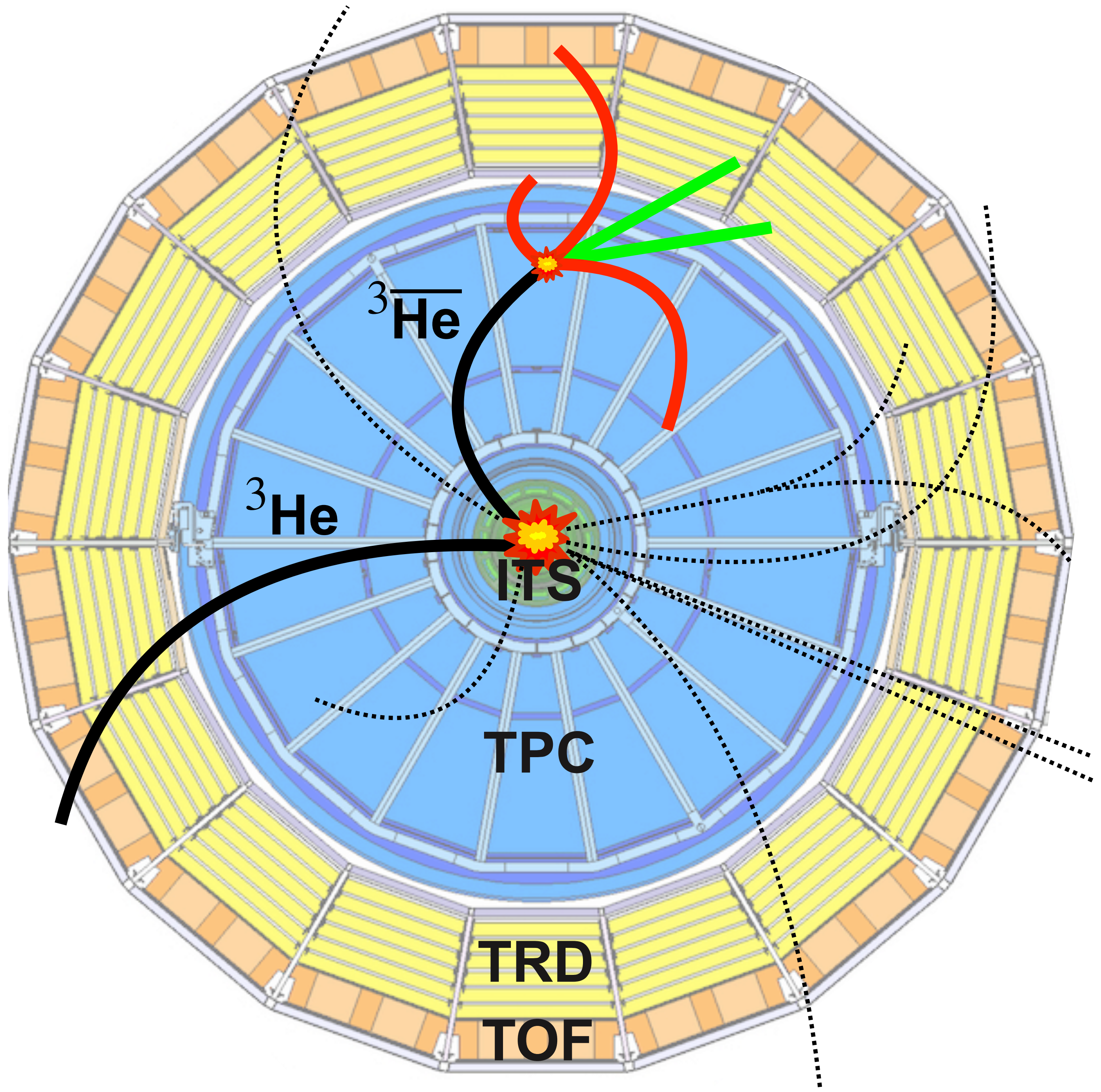
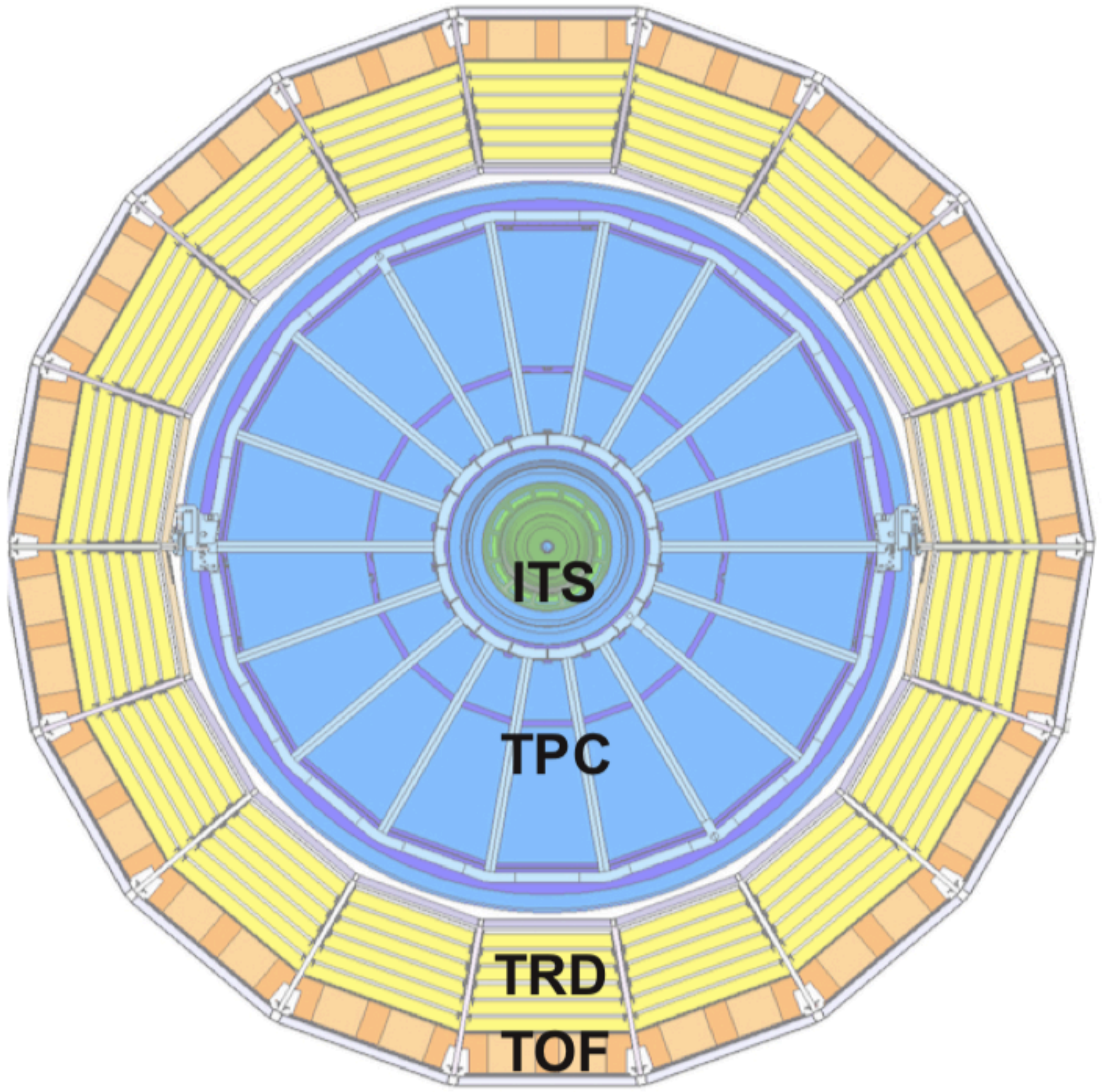
Antimatter-to-matter ratio

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





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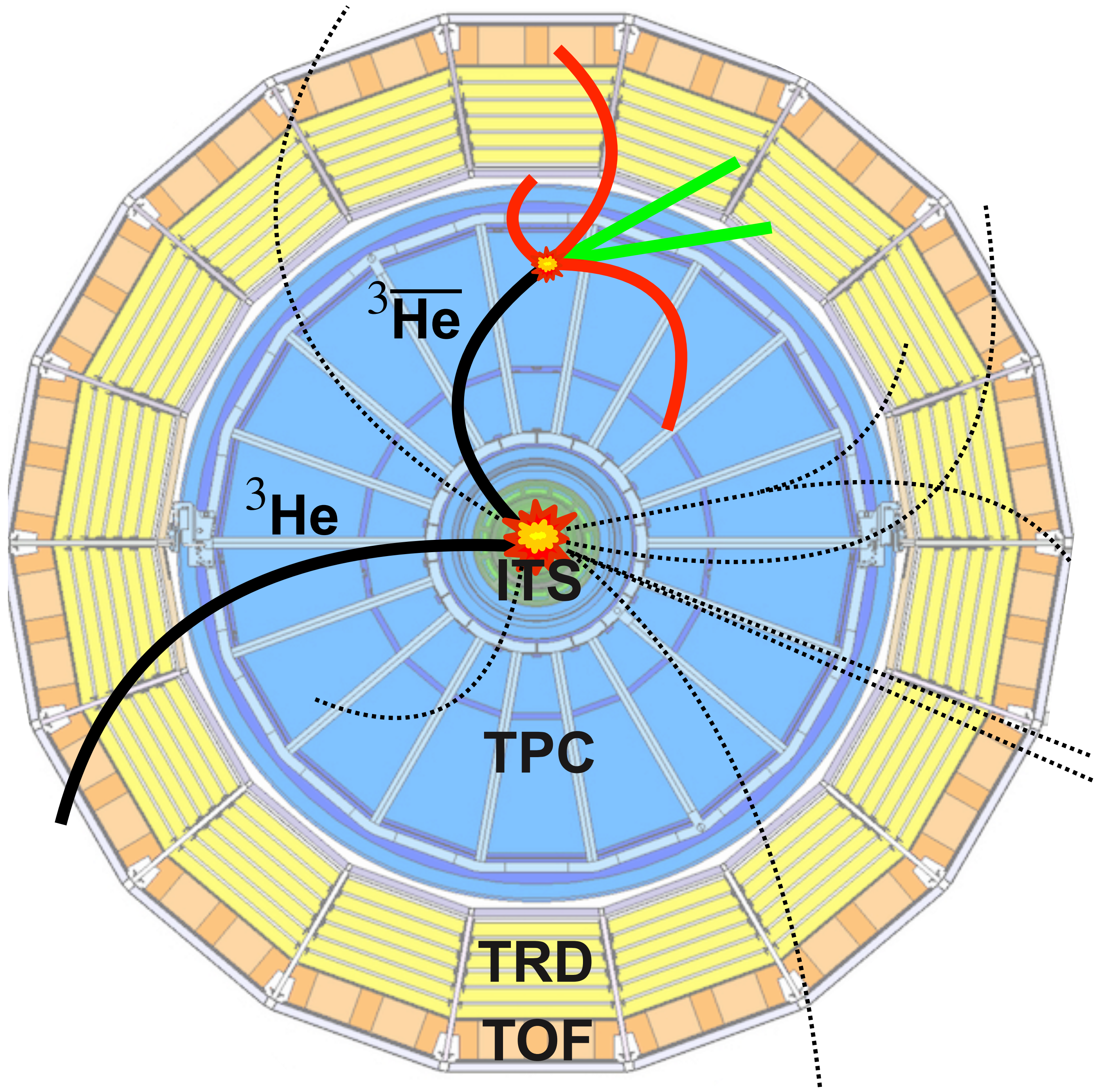
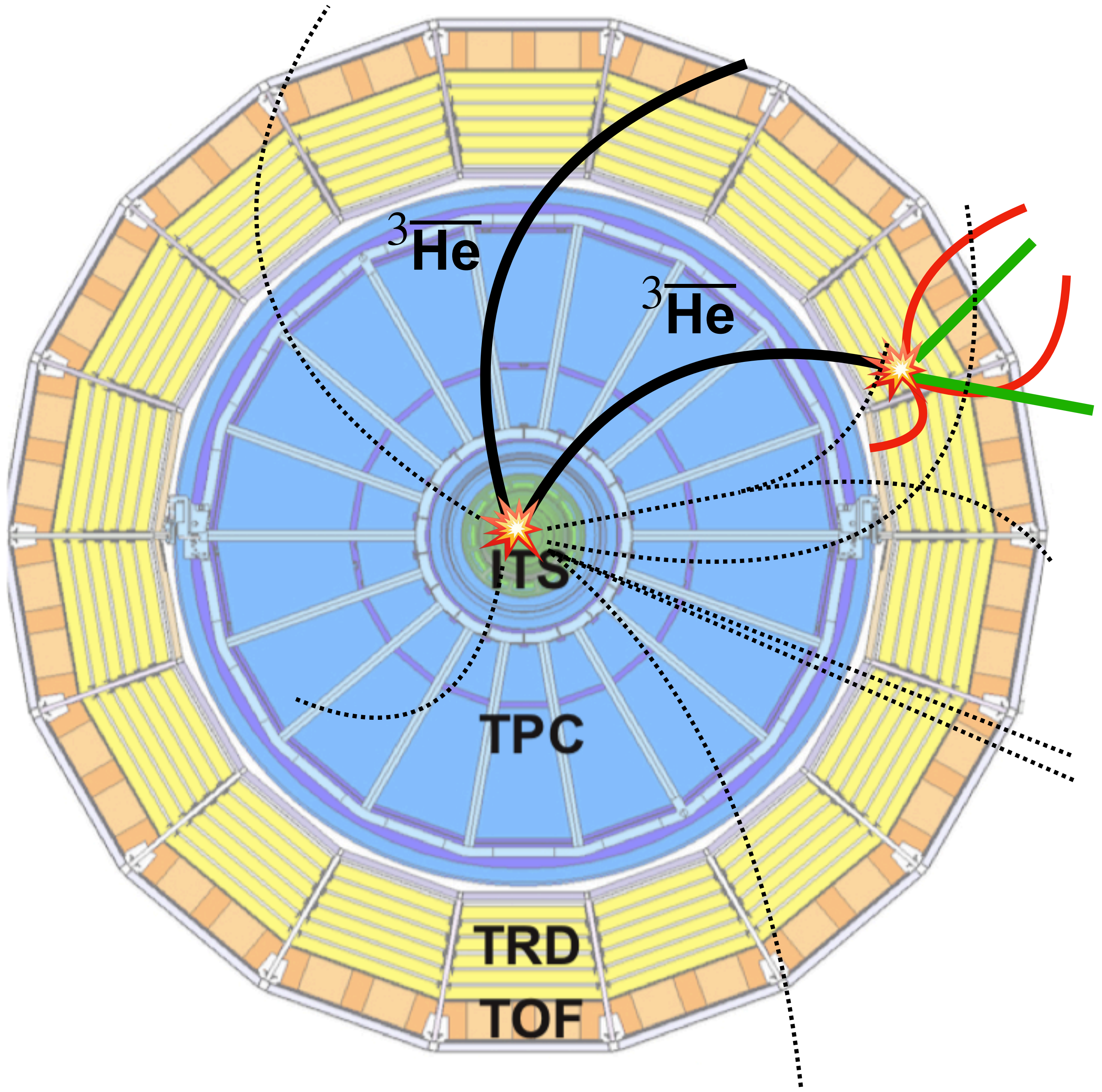
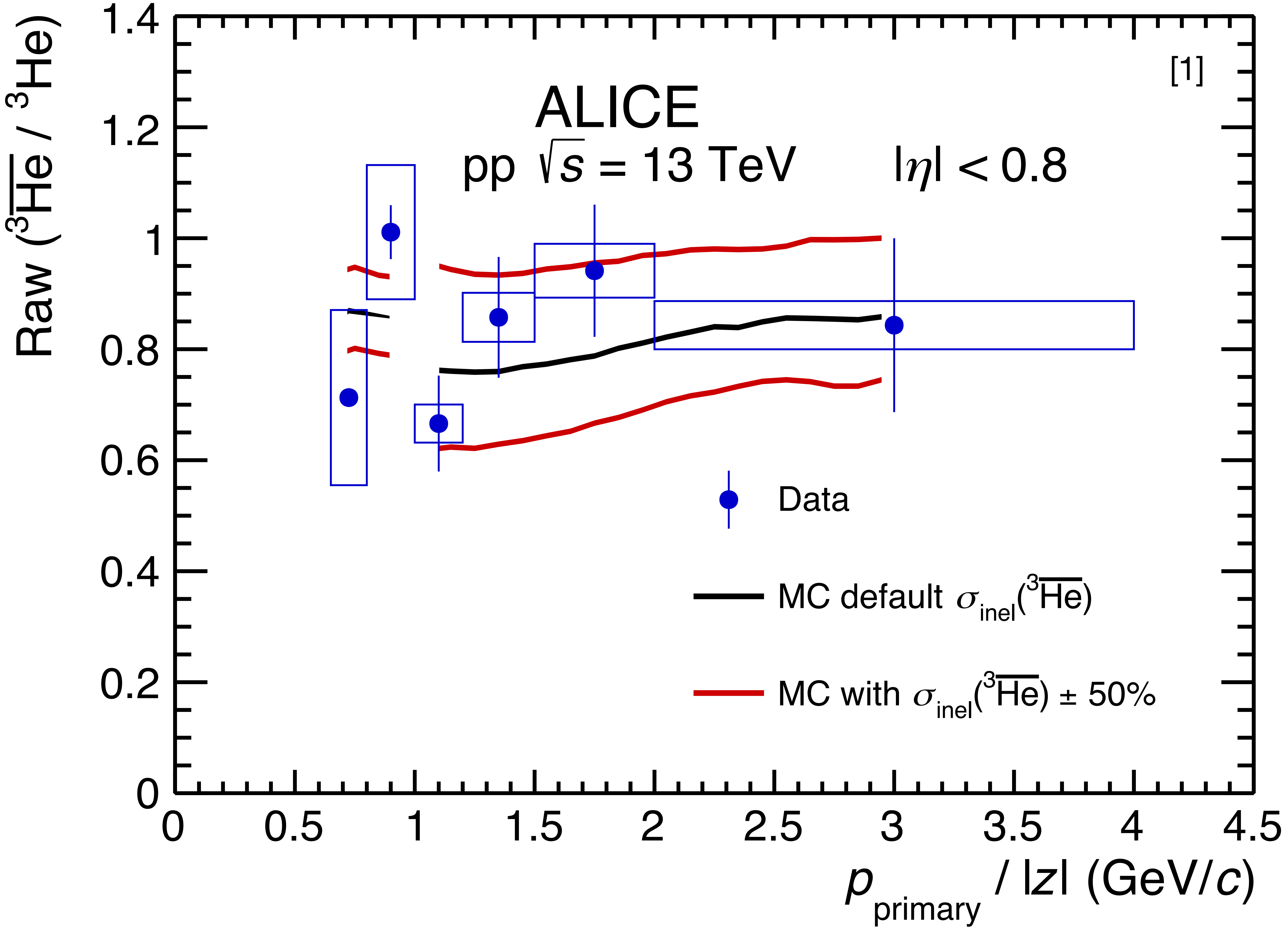


TOF-TPC-matching

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



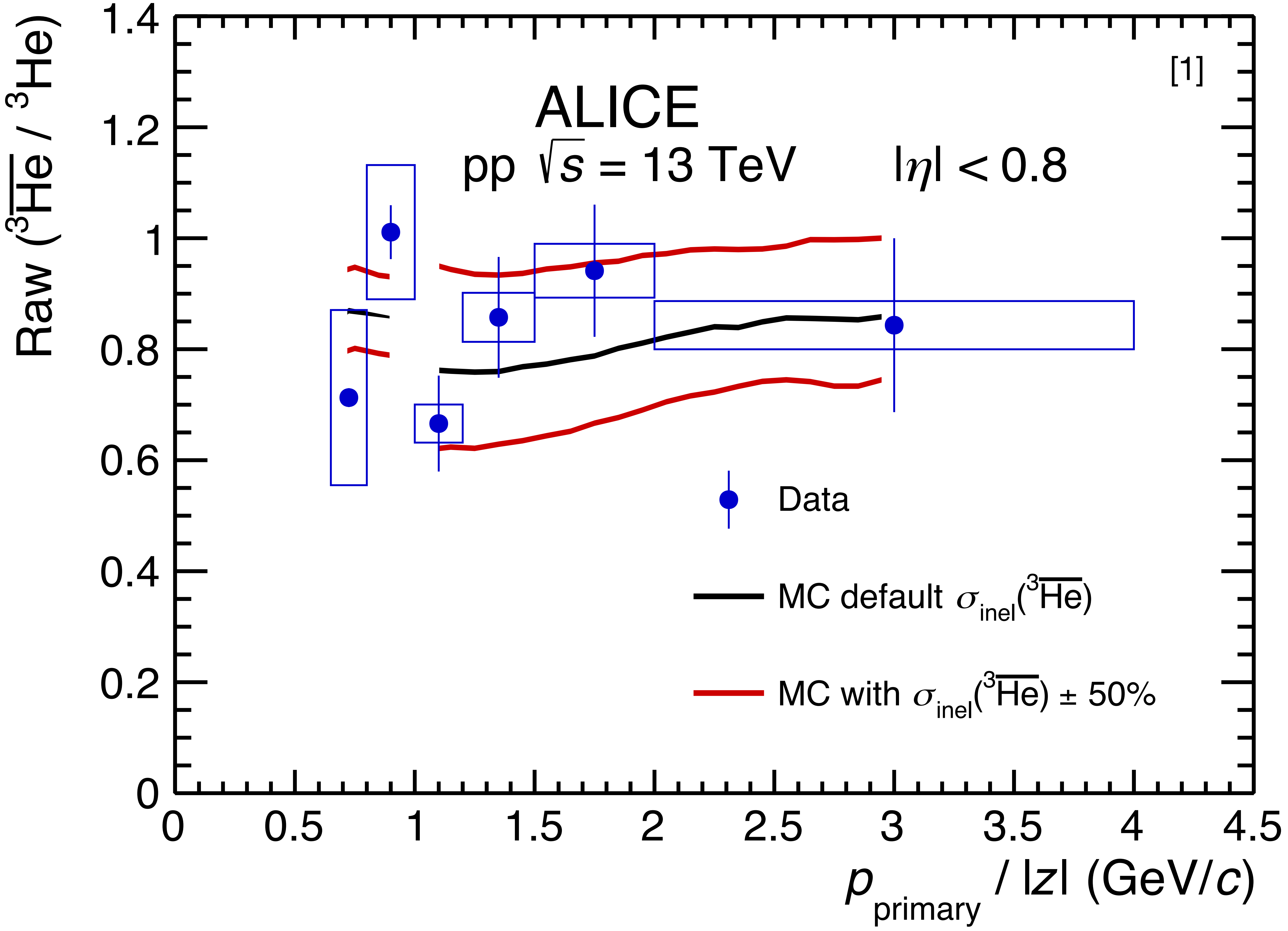
Extracting σ_{inel} from data and Monte Carlo



[1] arxiv.org/2202.01549

Extracting σ_{inel} from data and Monte Carlo

- Monte Carlo (MC) simulations with varied σ_{inel}



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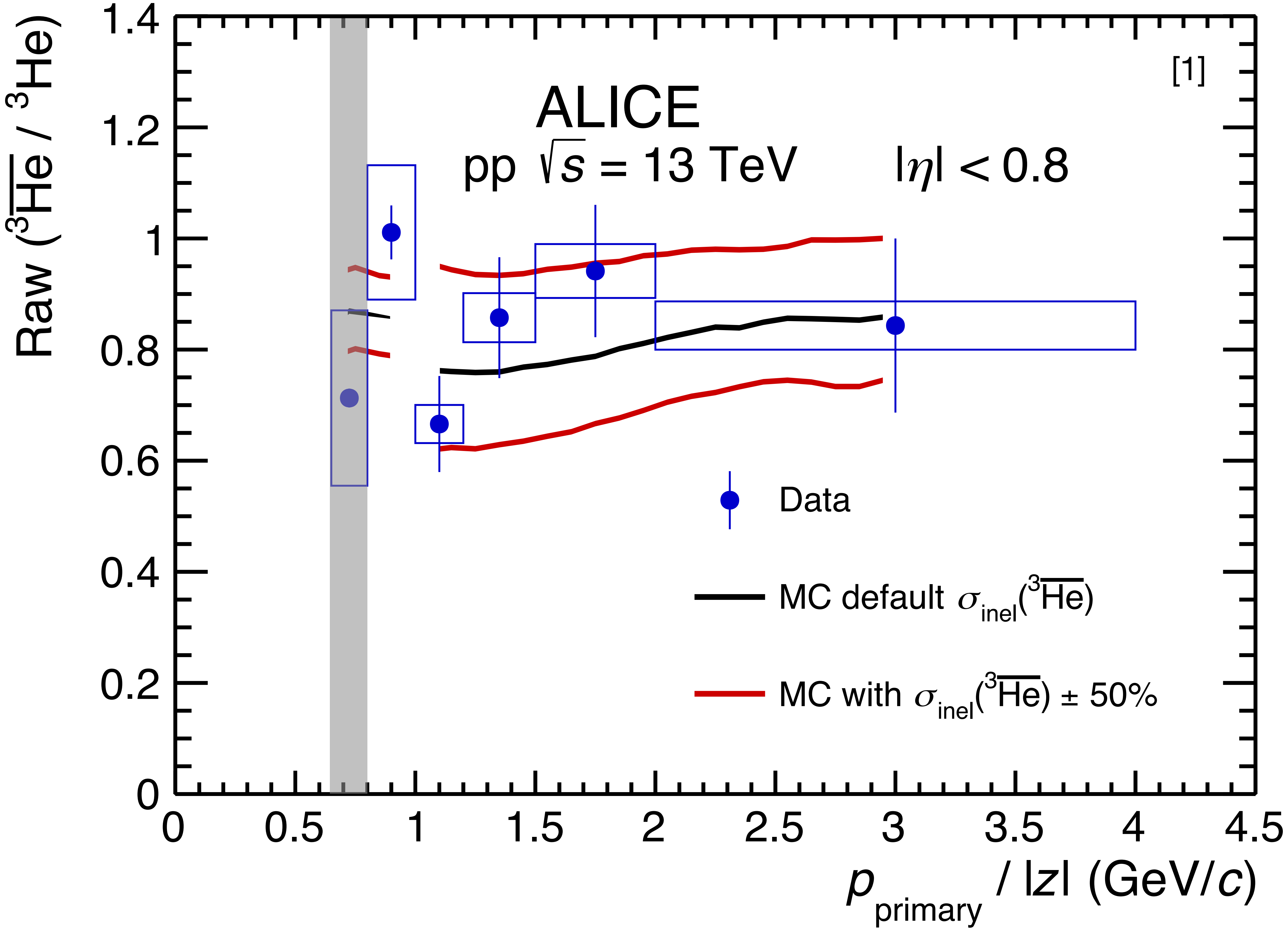
- Monte Carlo (MC) simulations with varied σ_{inel}
- In each momentum bin, compare the antiparticle-to-particle ratio in MC to the one in data
- MC points are fit with an exponential, according to the Lambert-Beer law:

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



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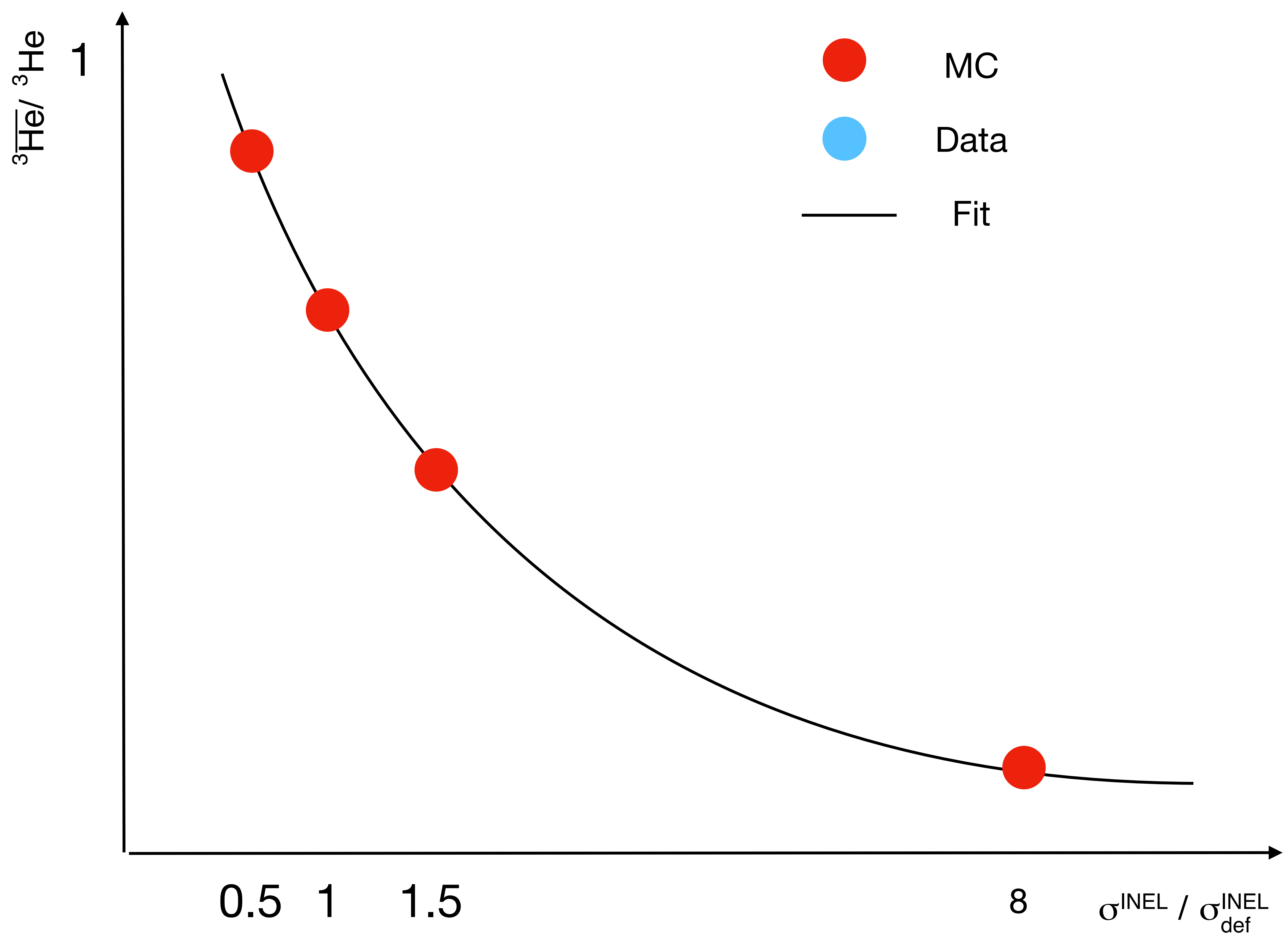

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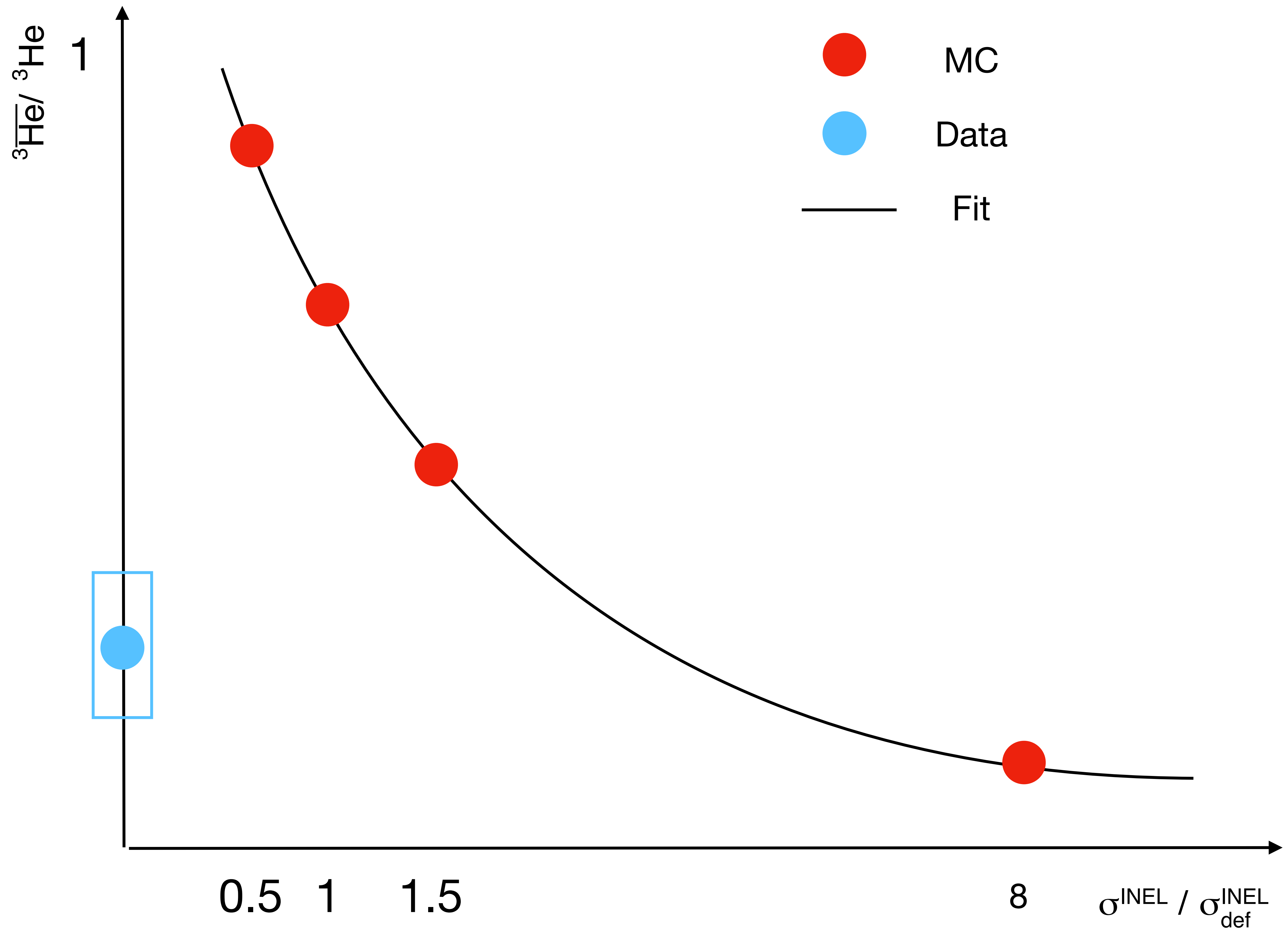

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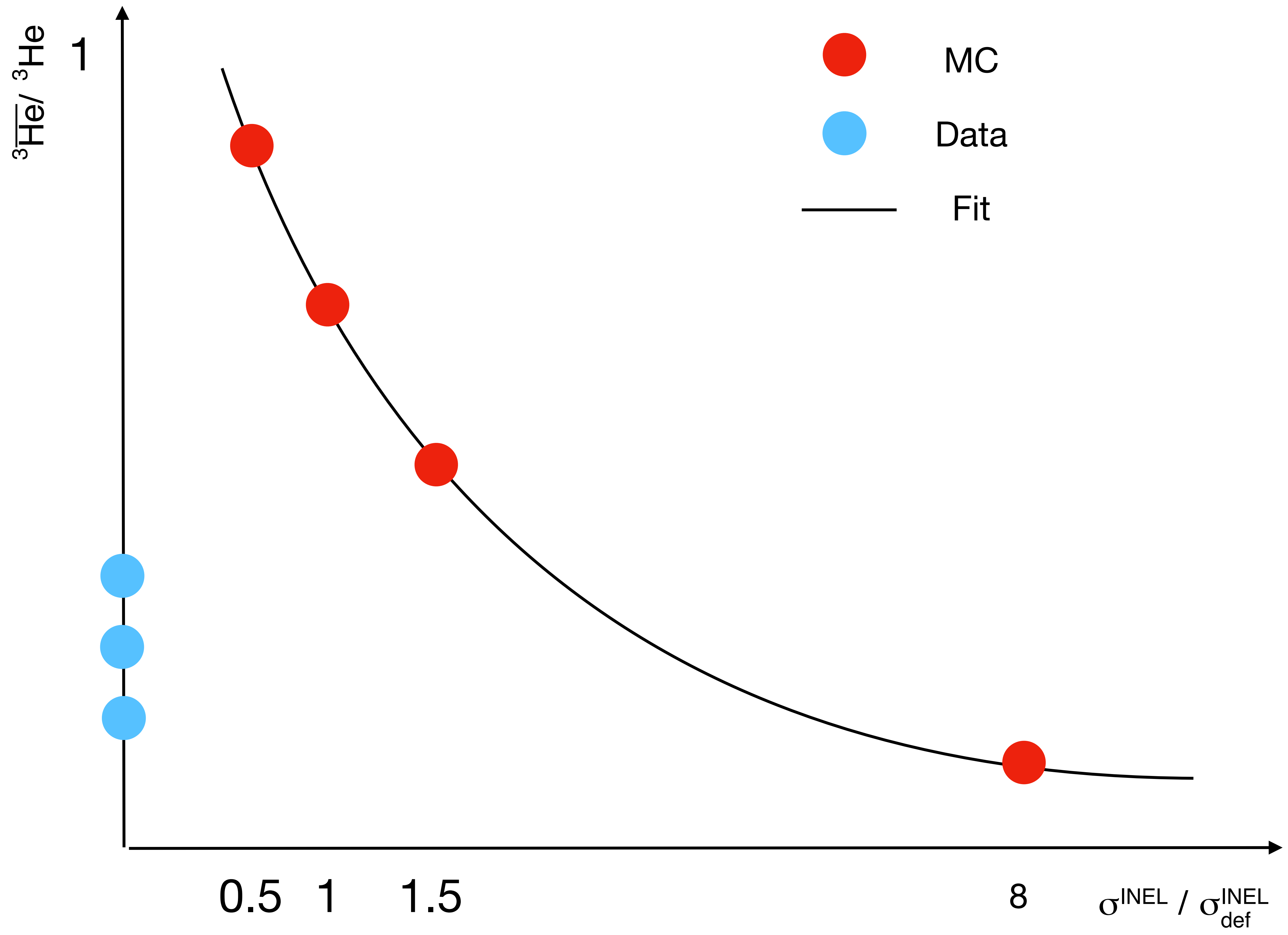

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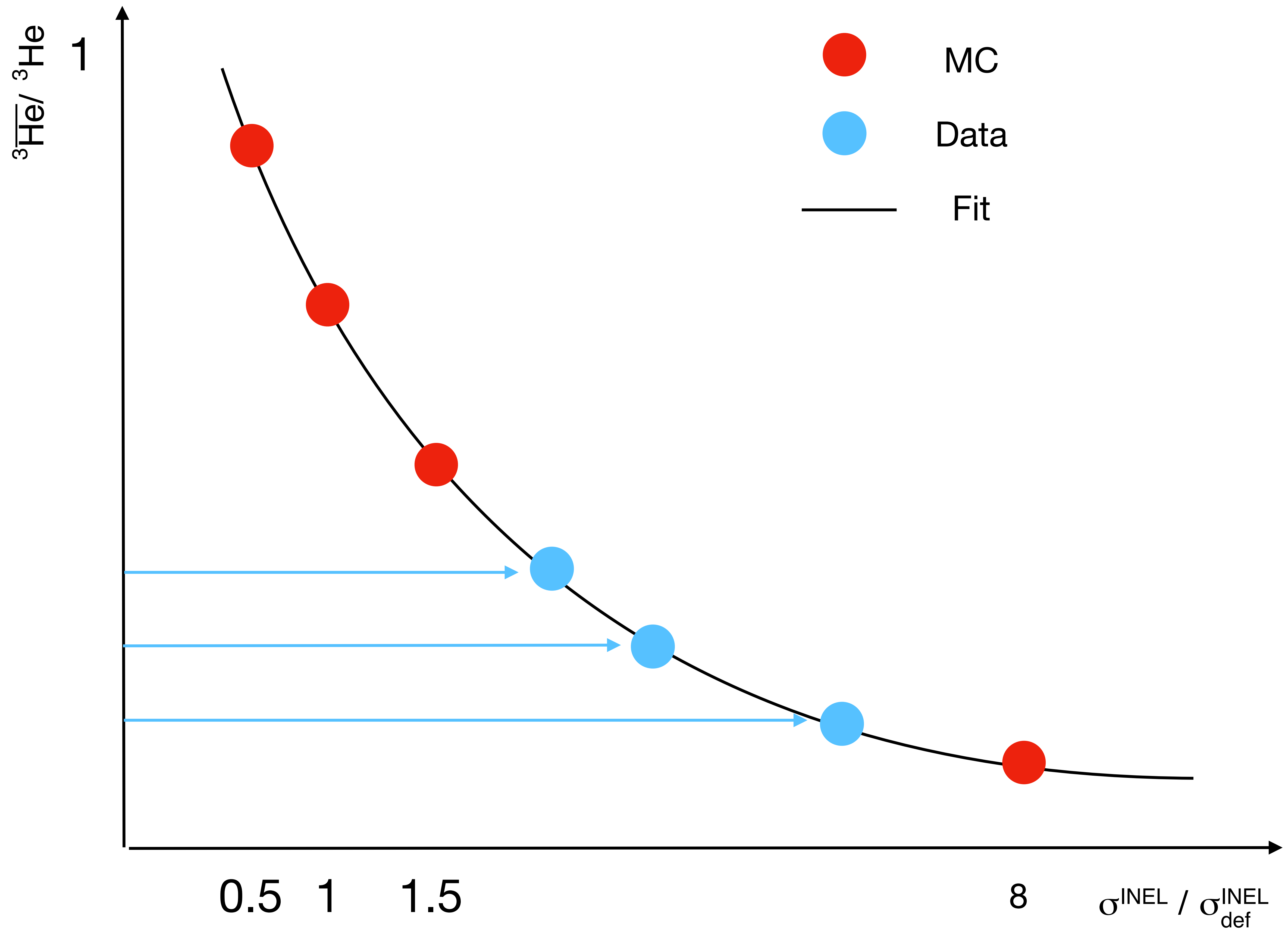

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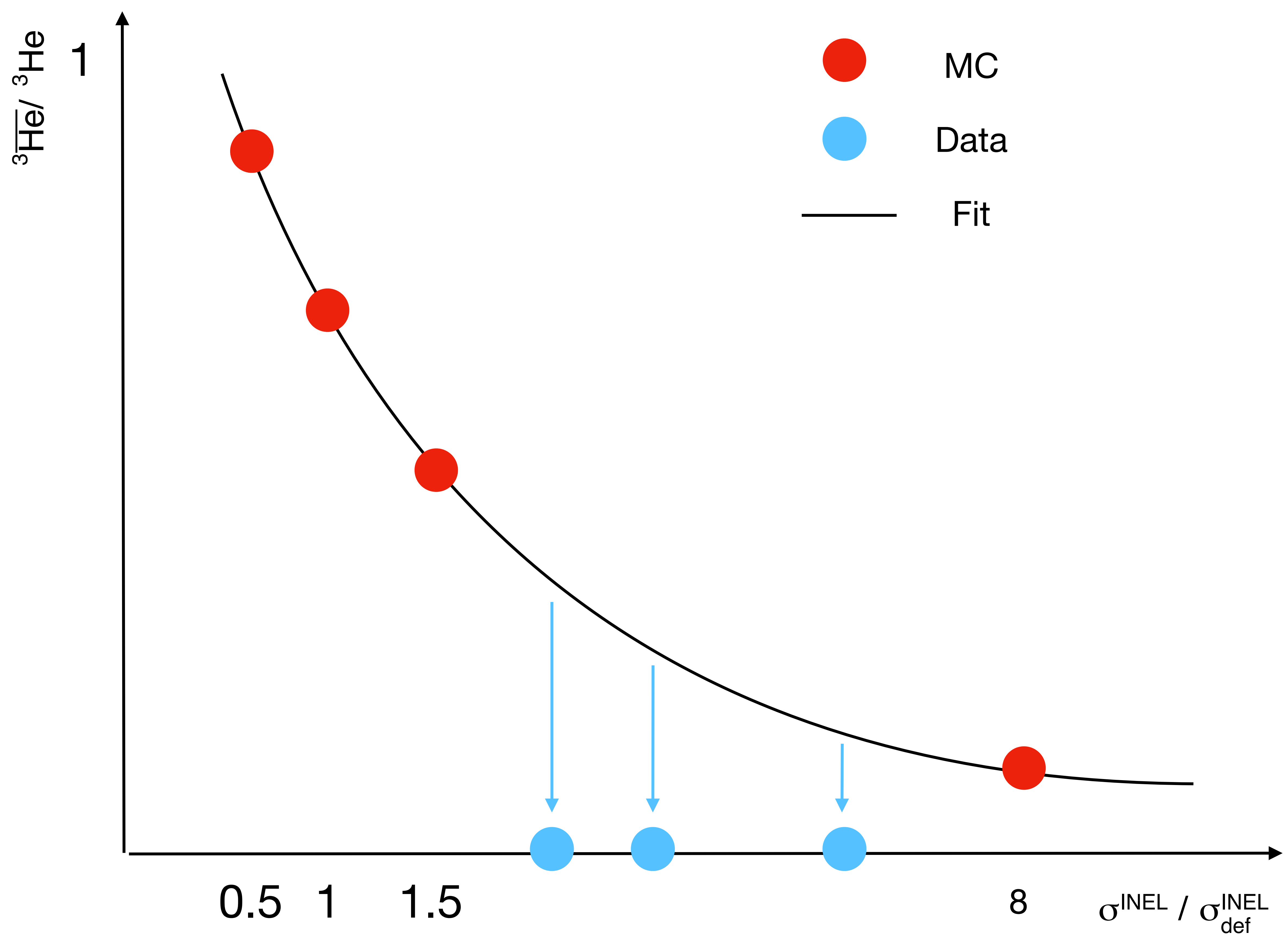

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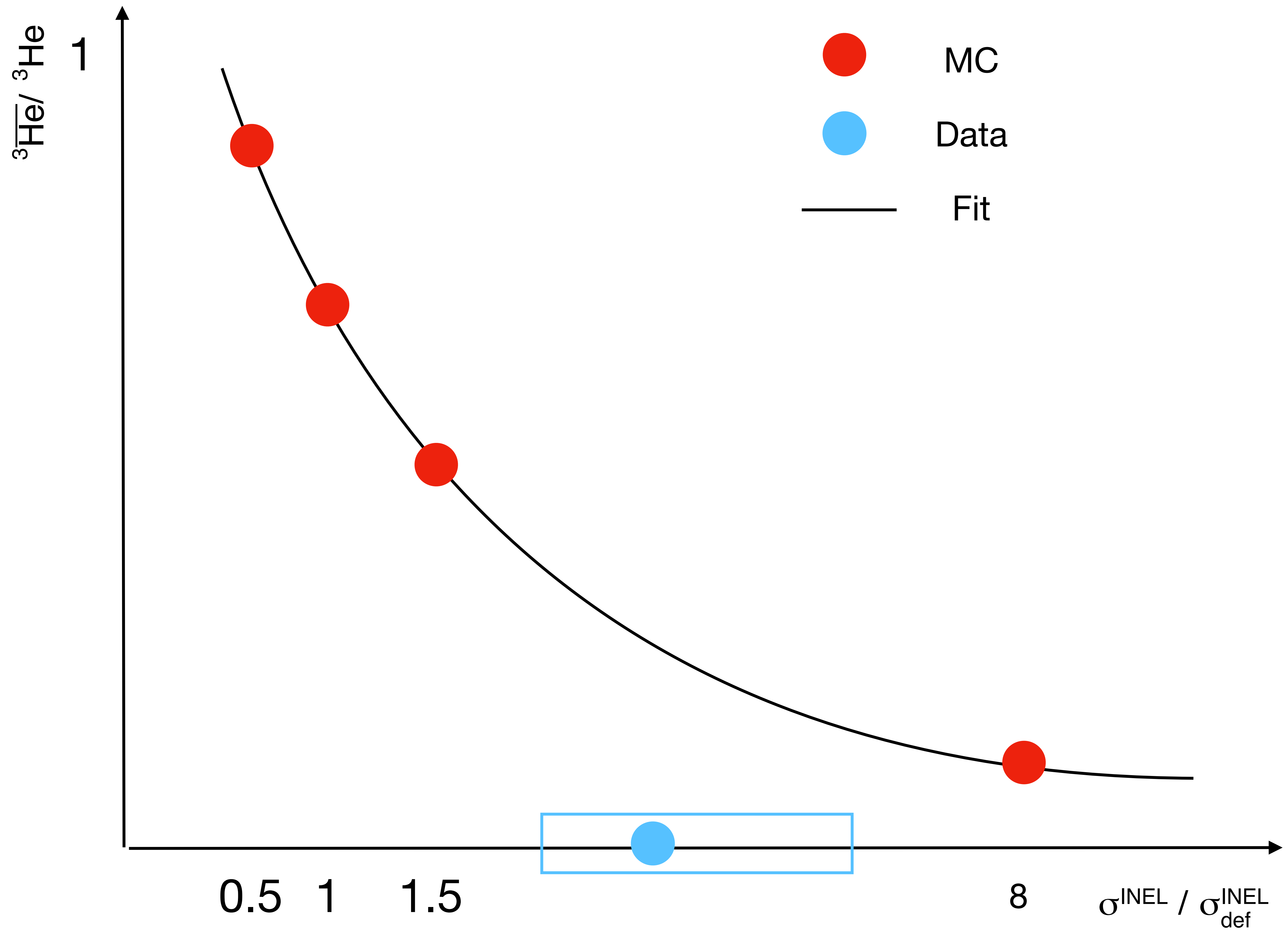

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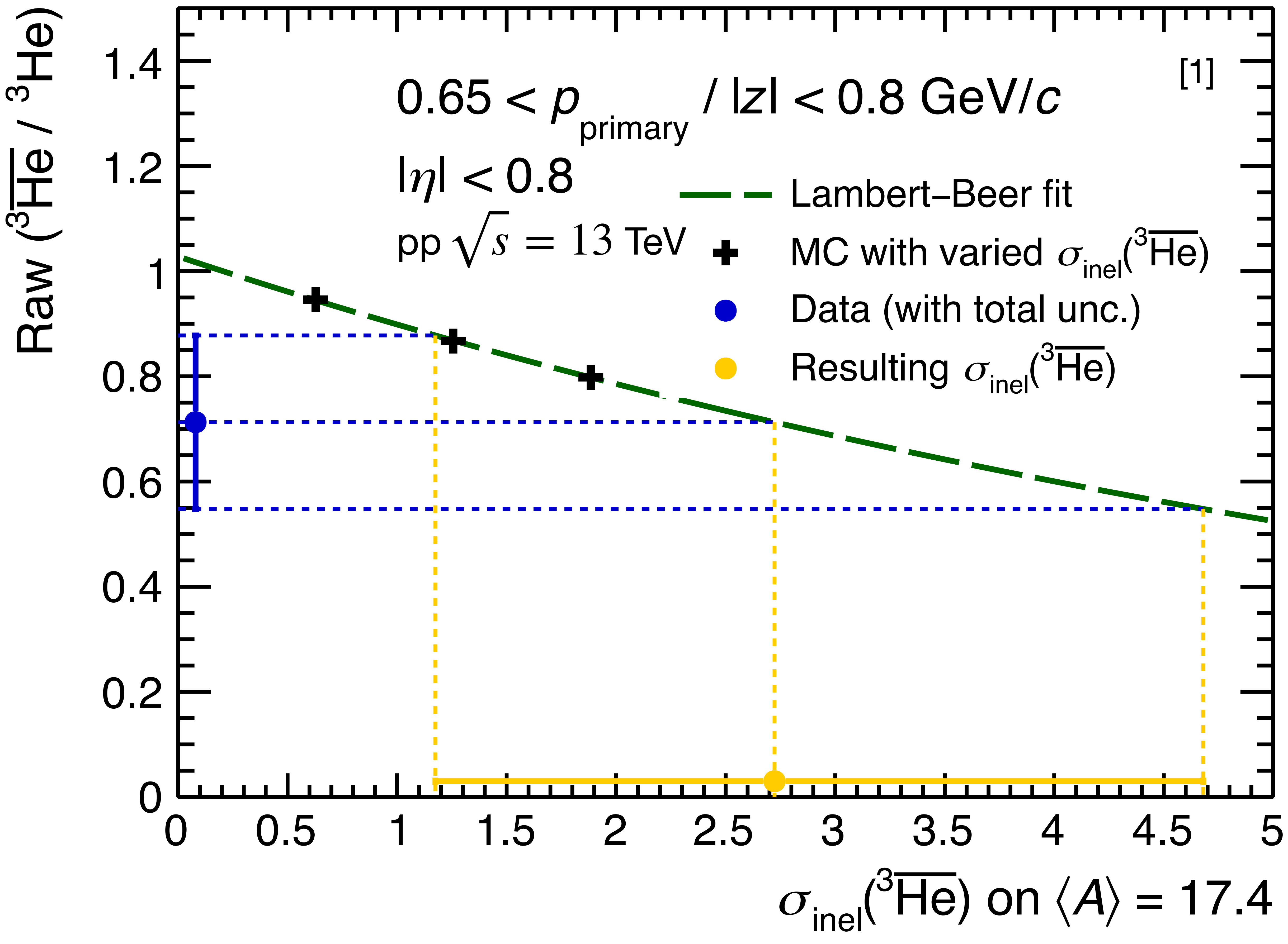

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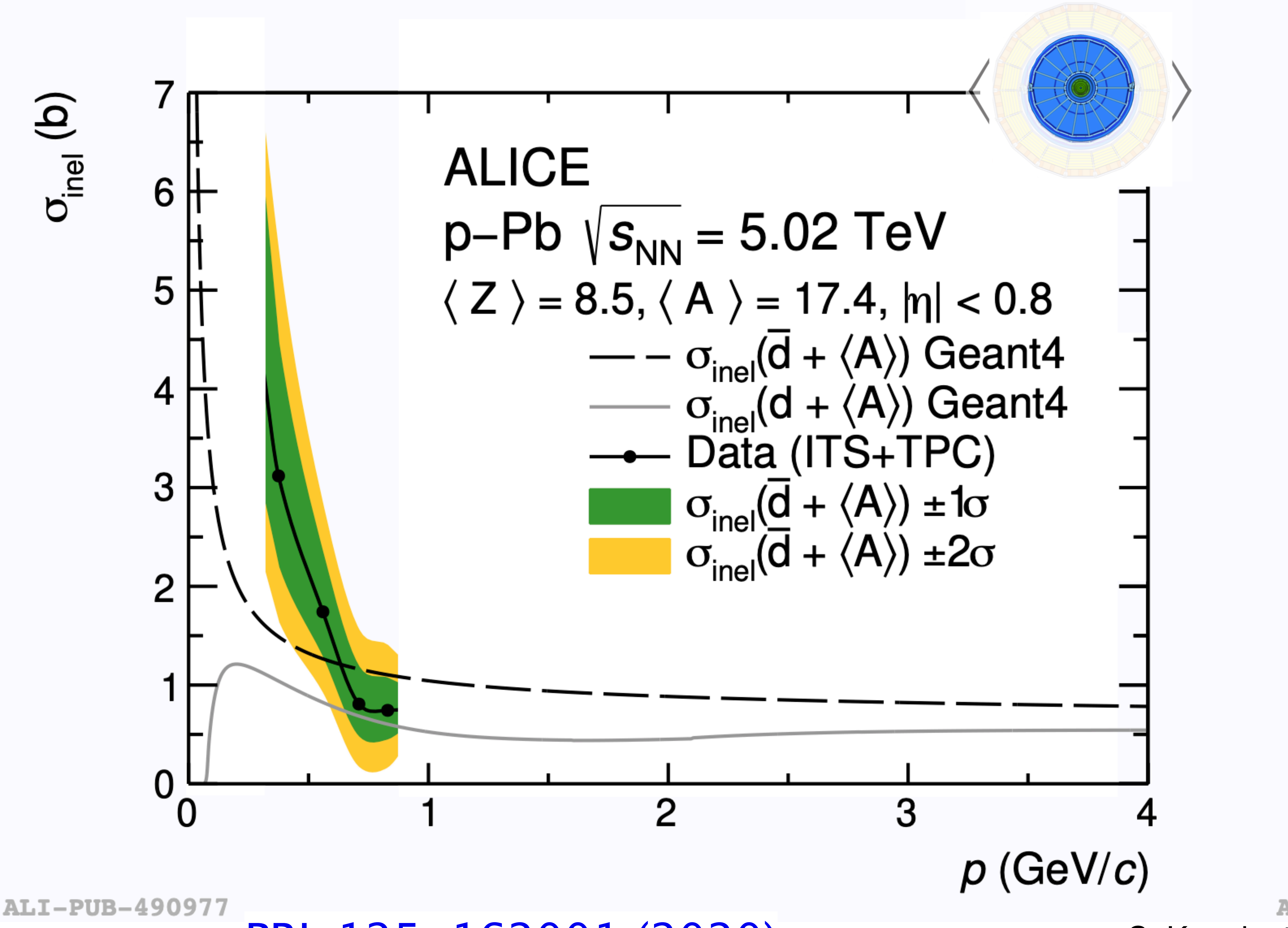
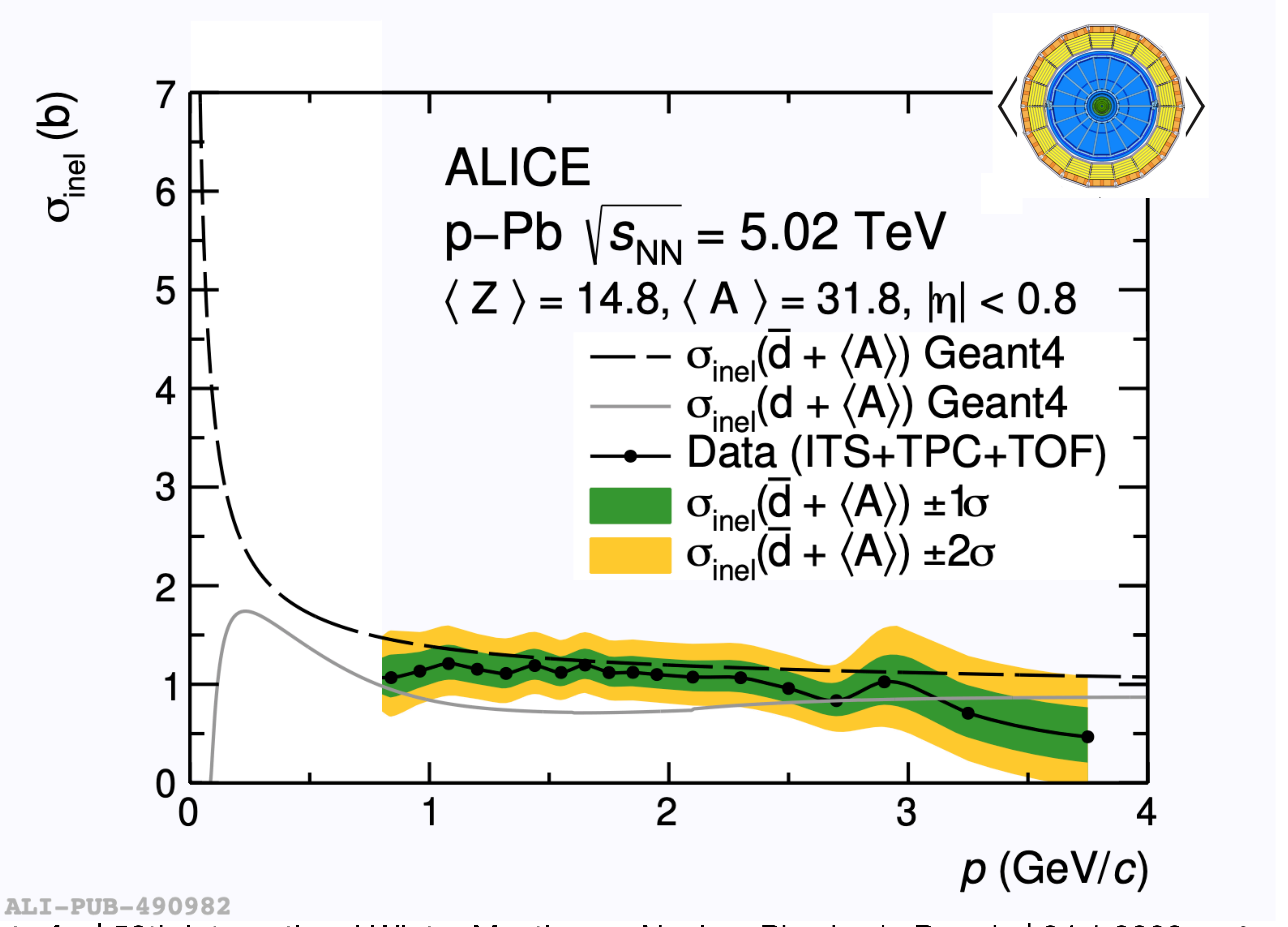
Antideuteron inelastic cross section

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

Hint of a steeper rise at low momentum





PRL 125, 162001 (2020)

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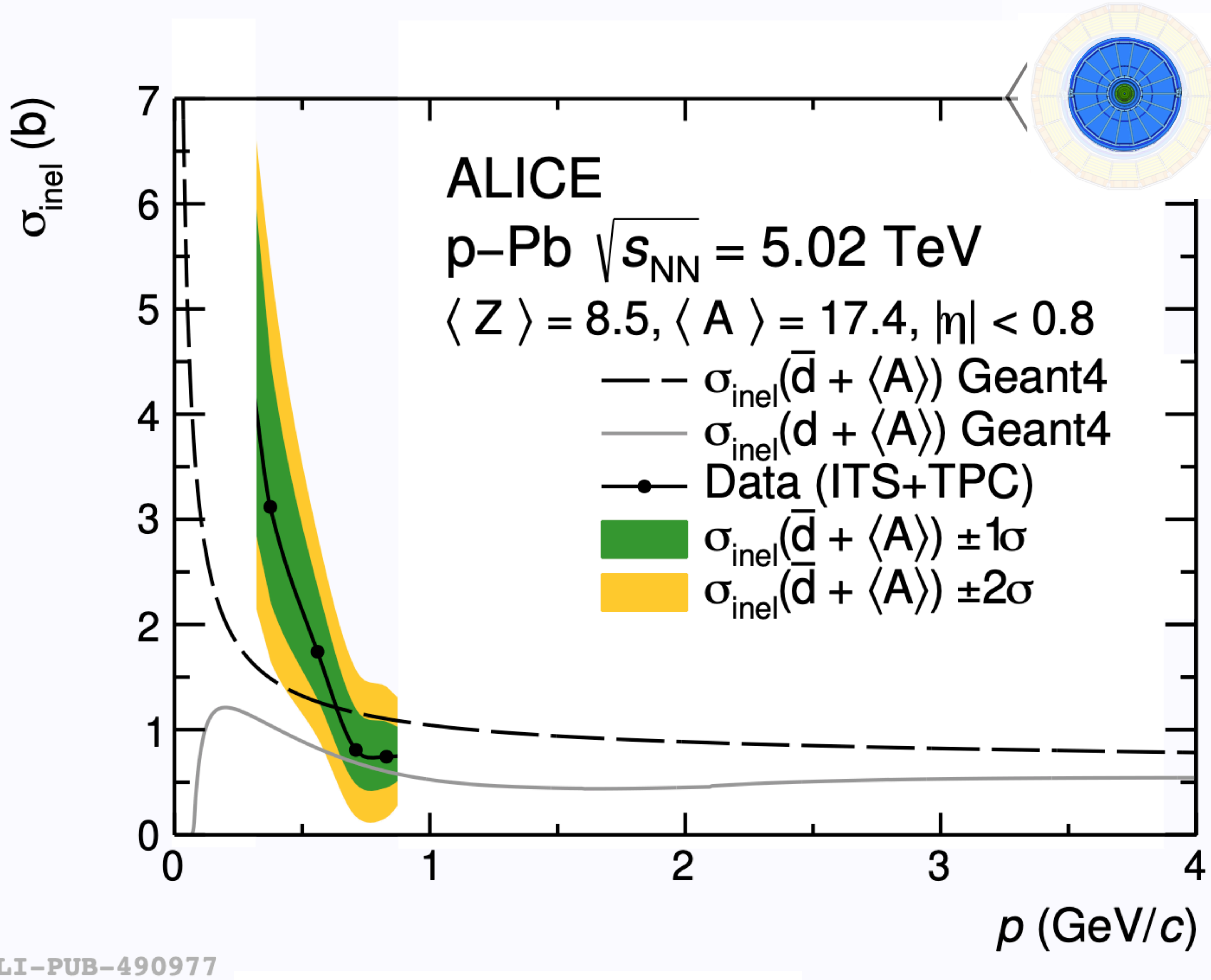
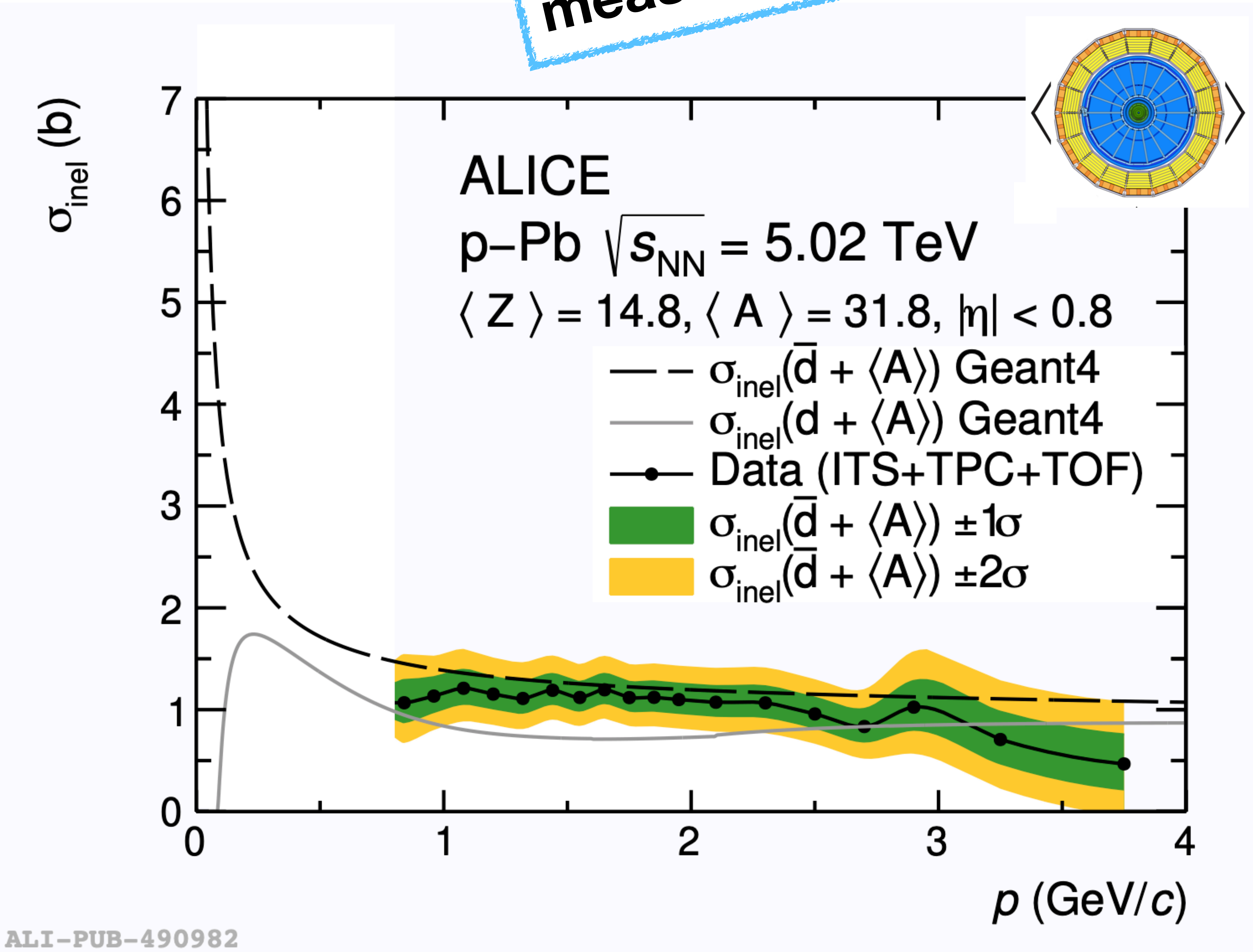
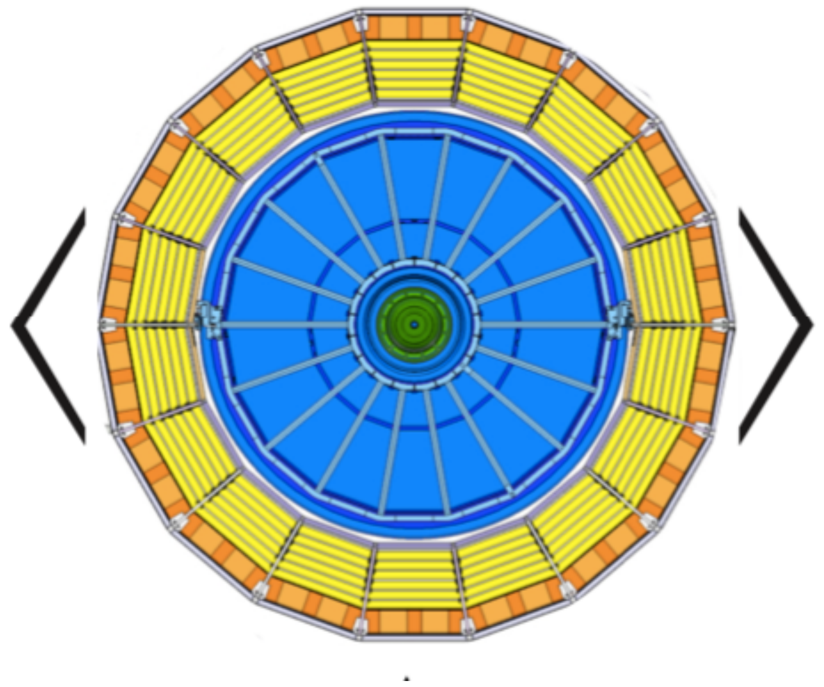
First low-energy measurement of $\sigma_{\text{inel}}(\overline{\text{d}})$





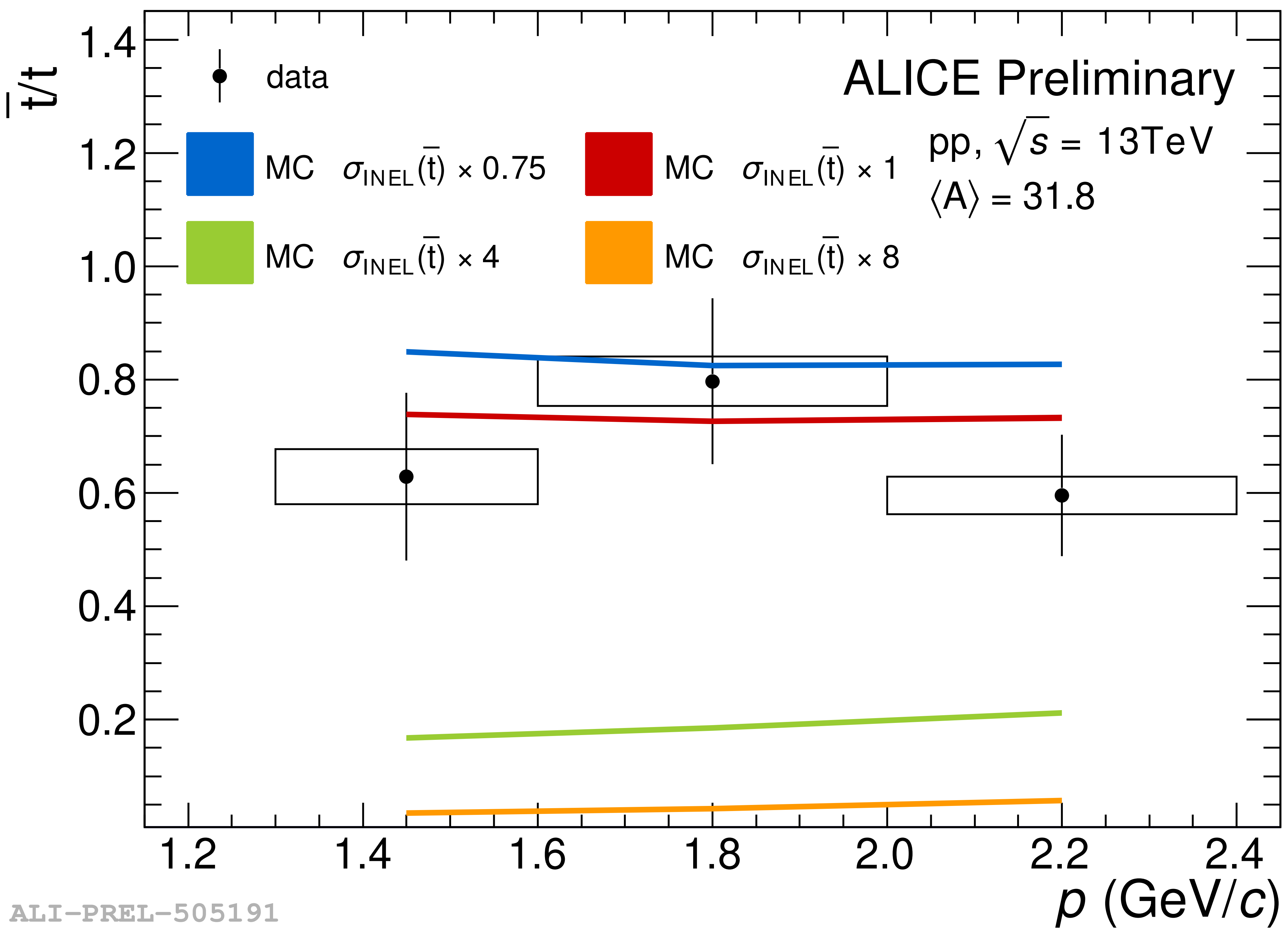
PRL 125, 162001 (2020)

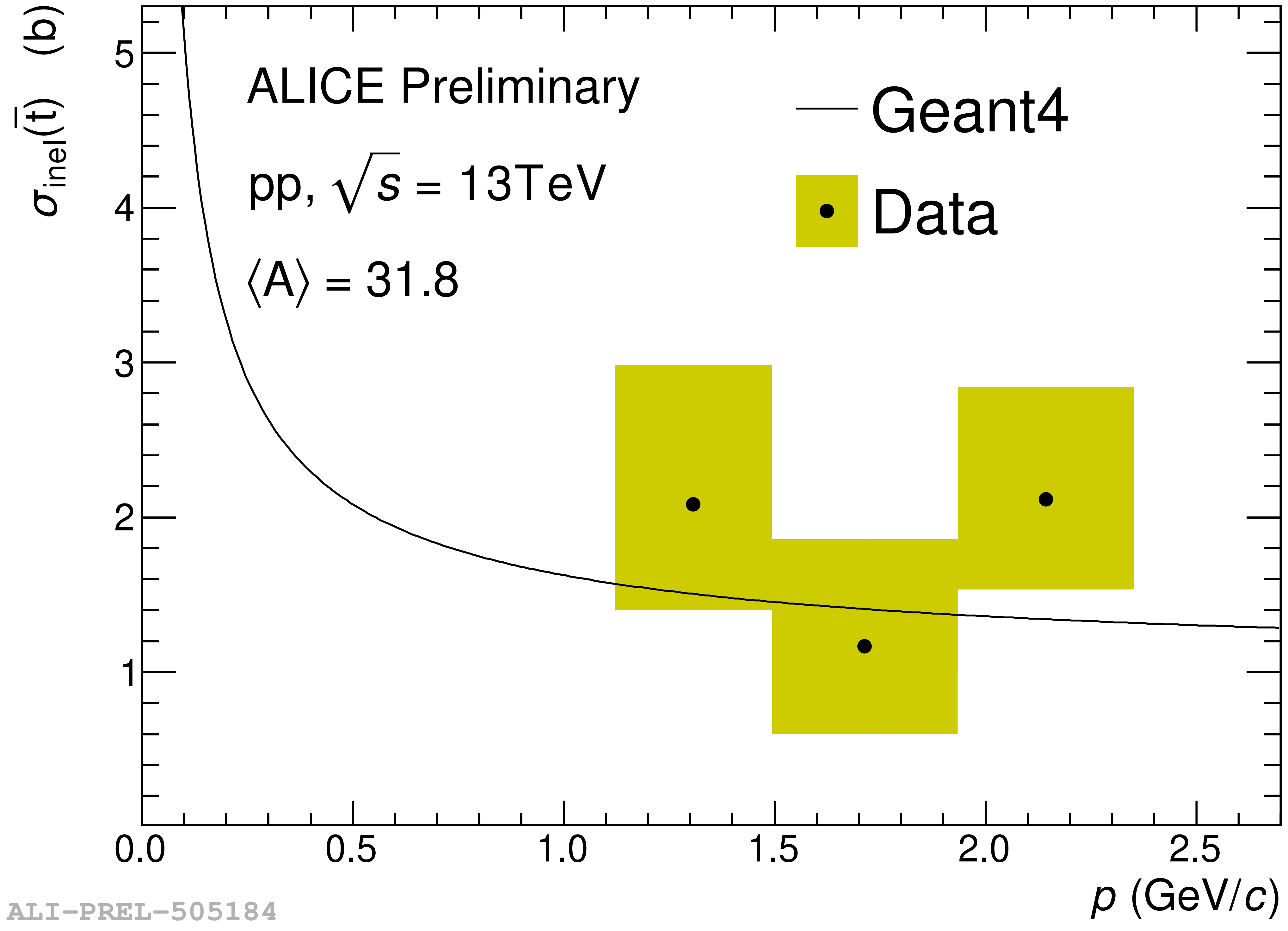
Antitriton inelastic cross section



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

Good agreement with Geant4, but with significant uncertainties





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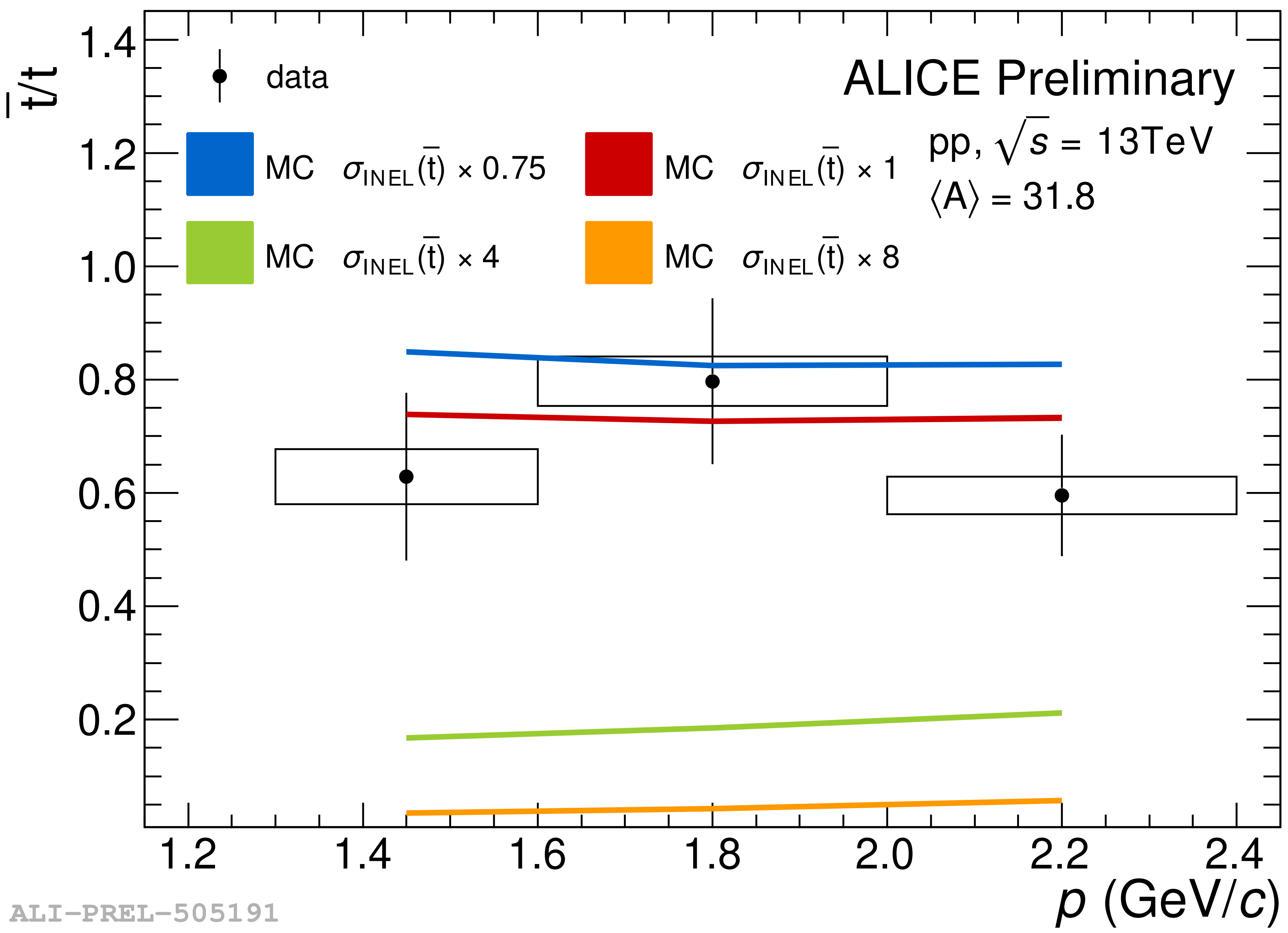
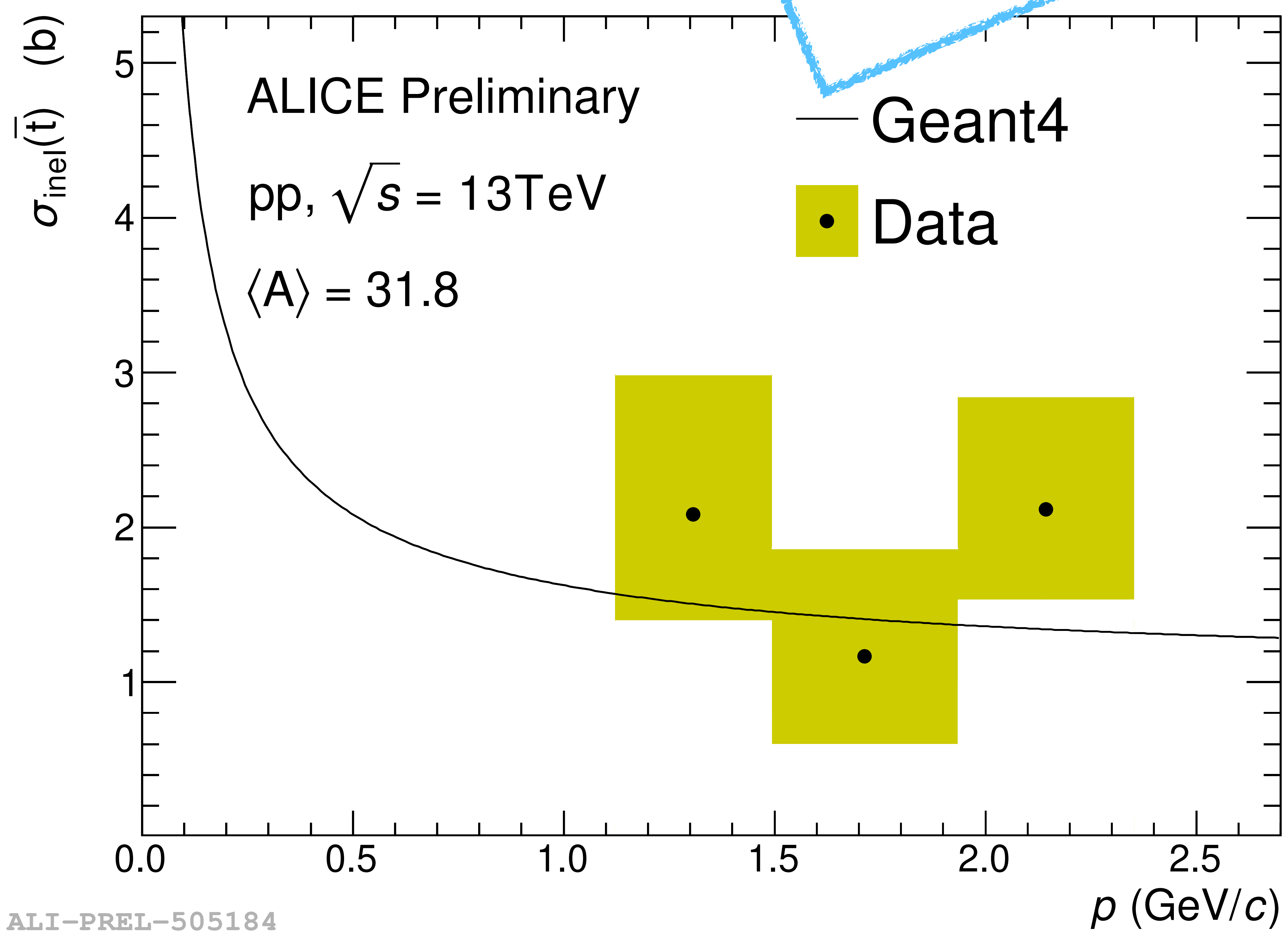
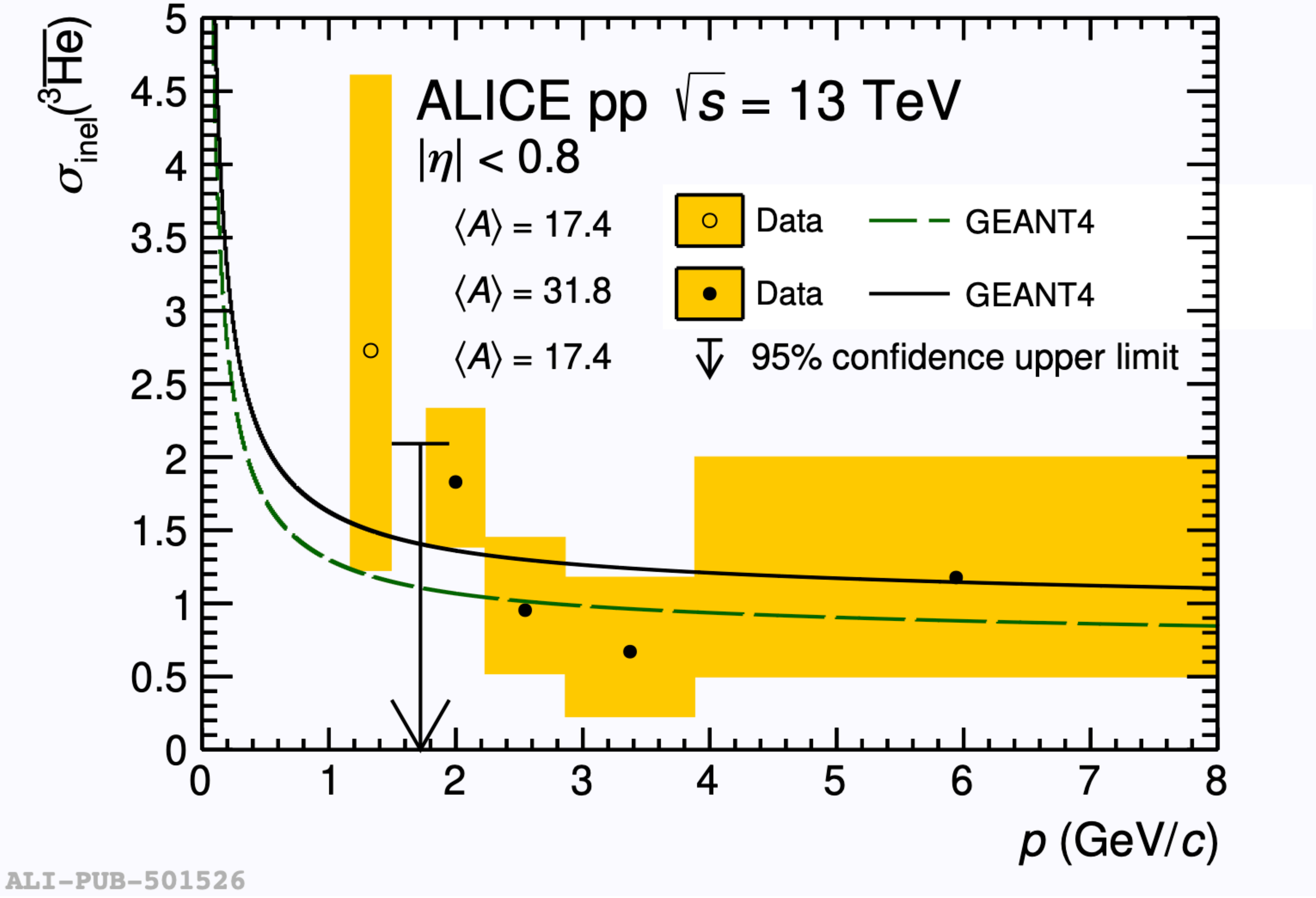


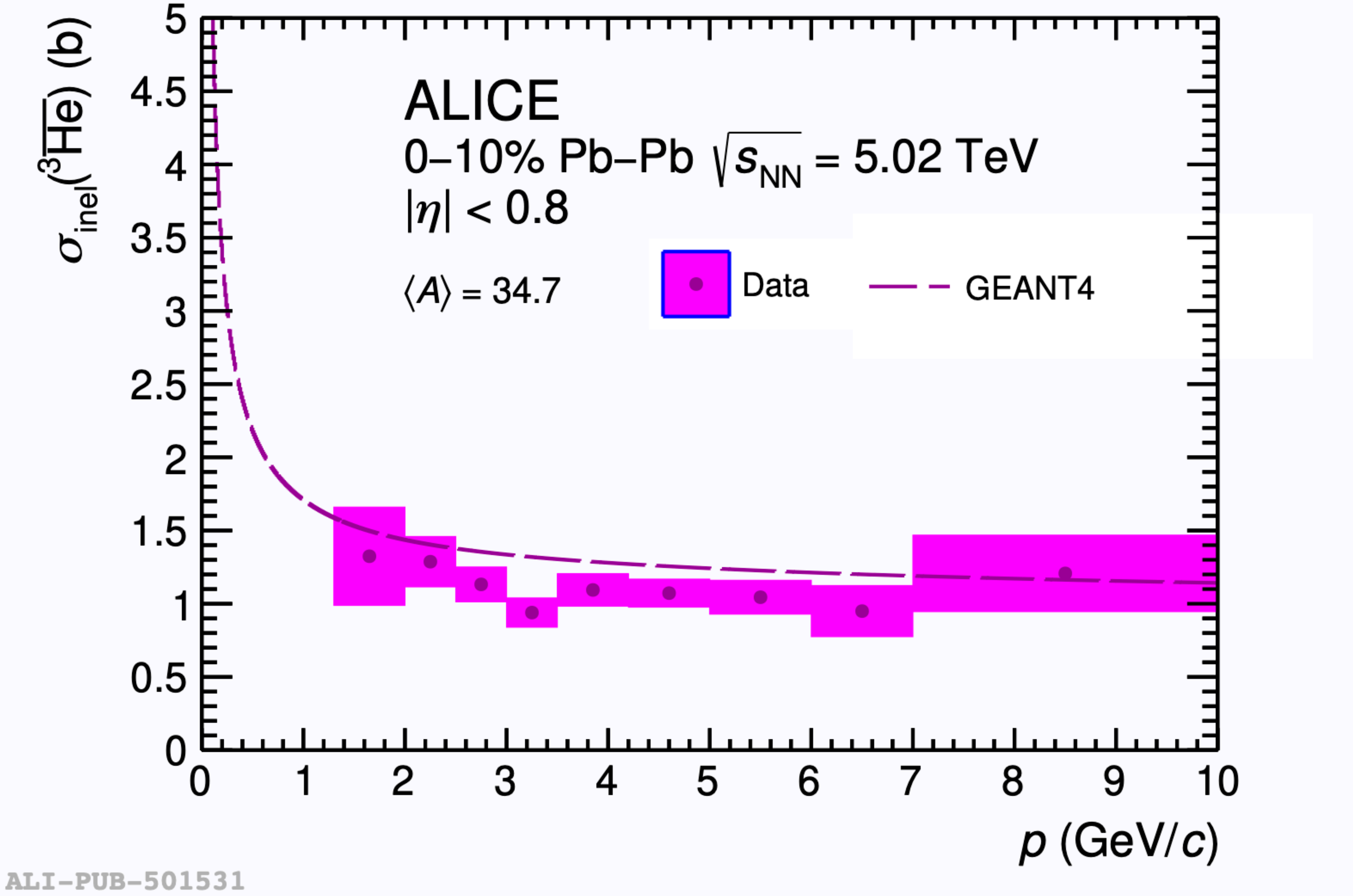


$^3\overline{\mathrm{He}}$ inelastic cross section

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

- Good agreement between the measurements and the Geant4 parameterizations





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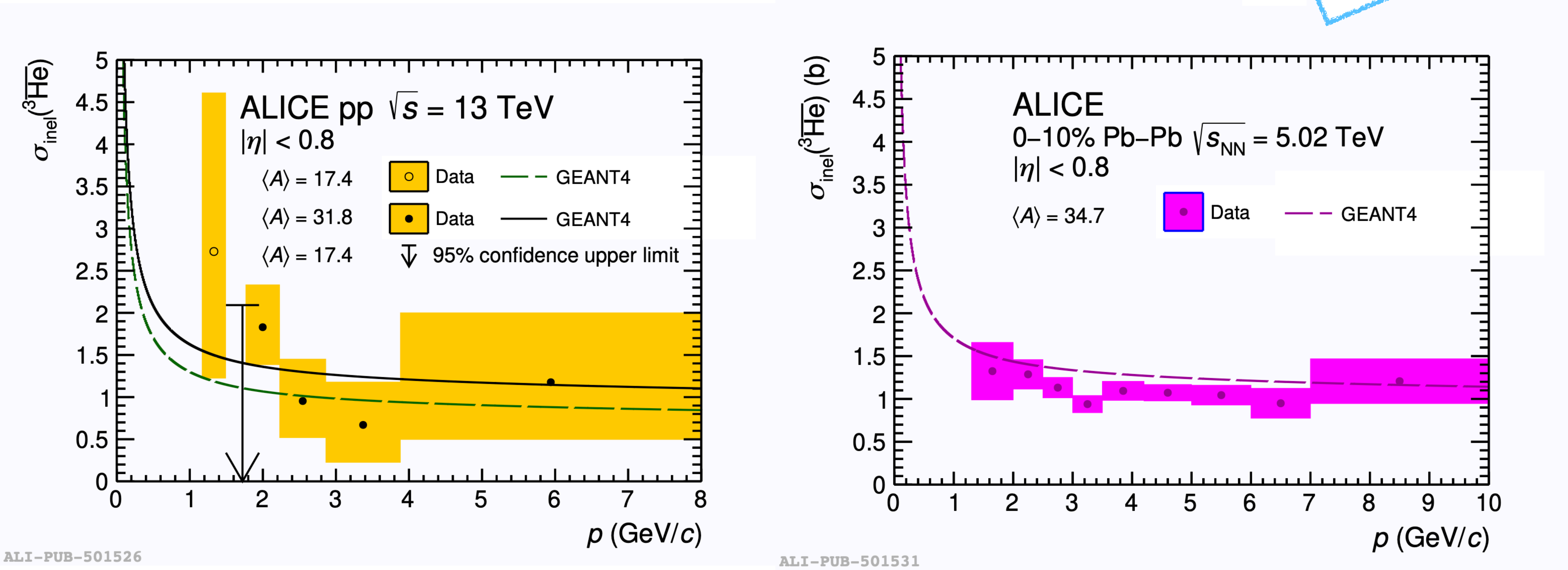

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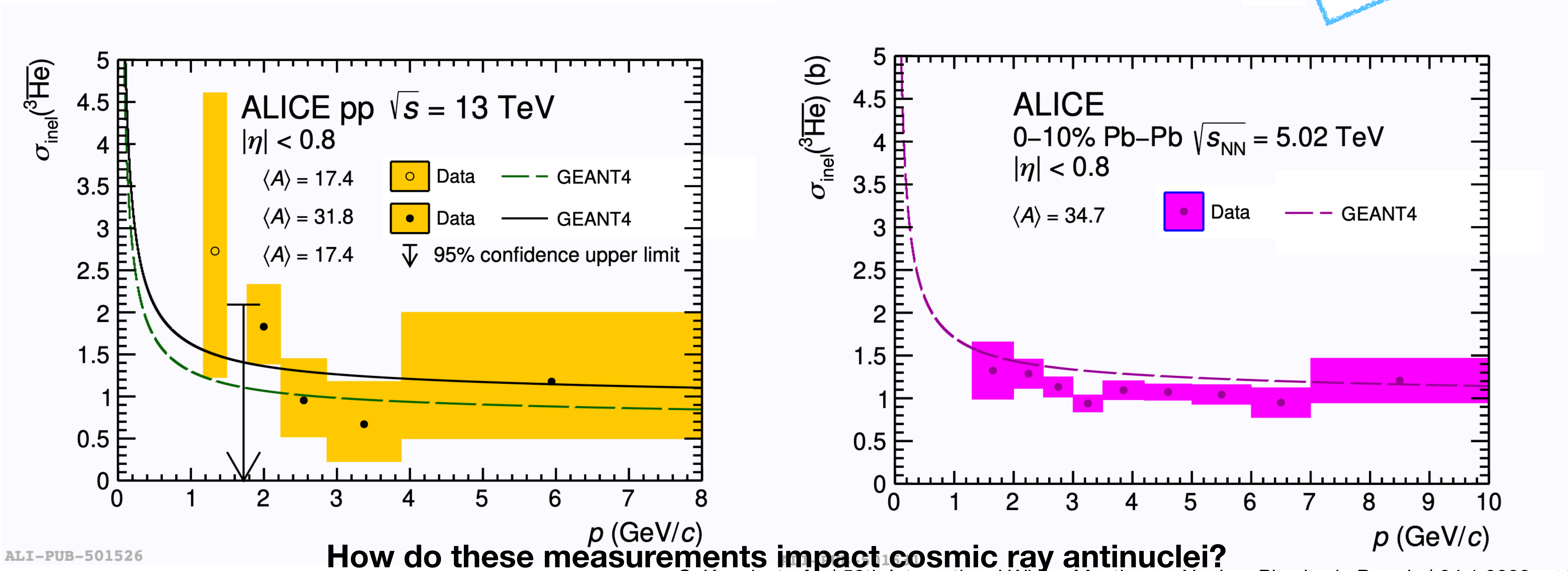

How do these measurements impact cosmic ray antinuclei?

Recipe to cook antinuclei fluxes

Galprop

Transport equation

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

Source Function

Propagation: diffusion, convection…

Fragmentation, annihilation

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Antinuclei source terms: dark matter

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

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

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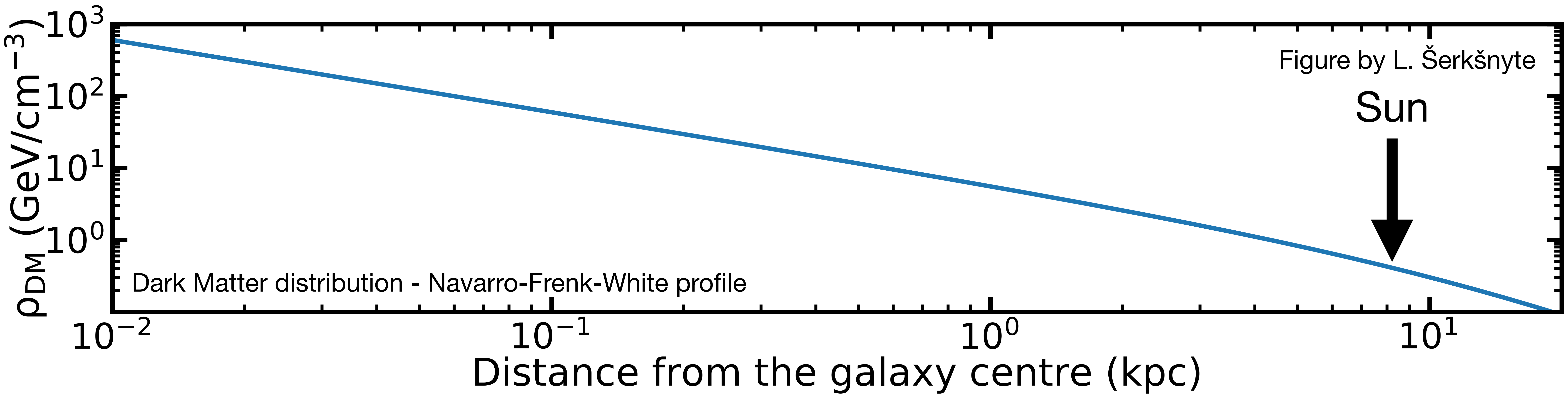

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This is the thermally averaged annihilation cross section.

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

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

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

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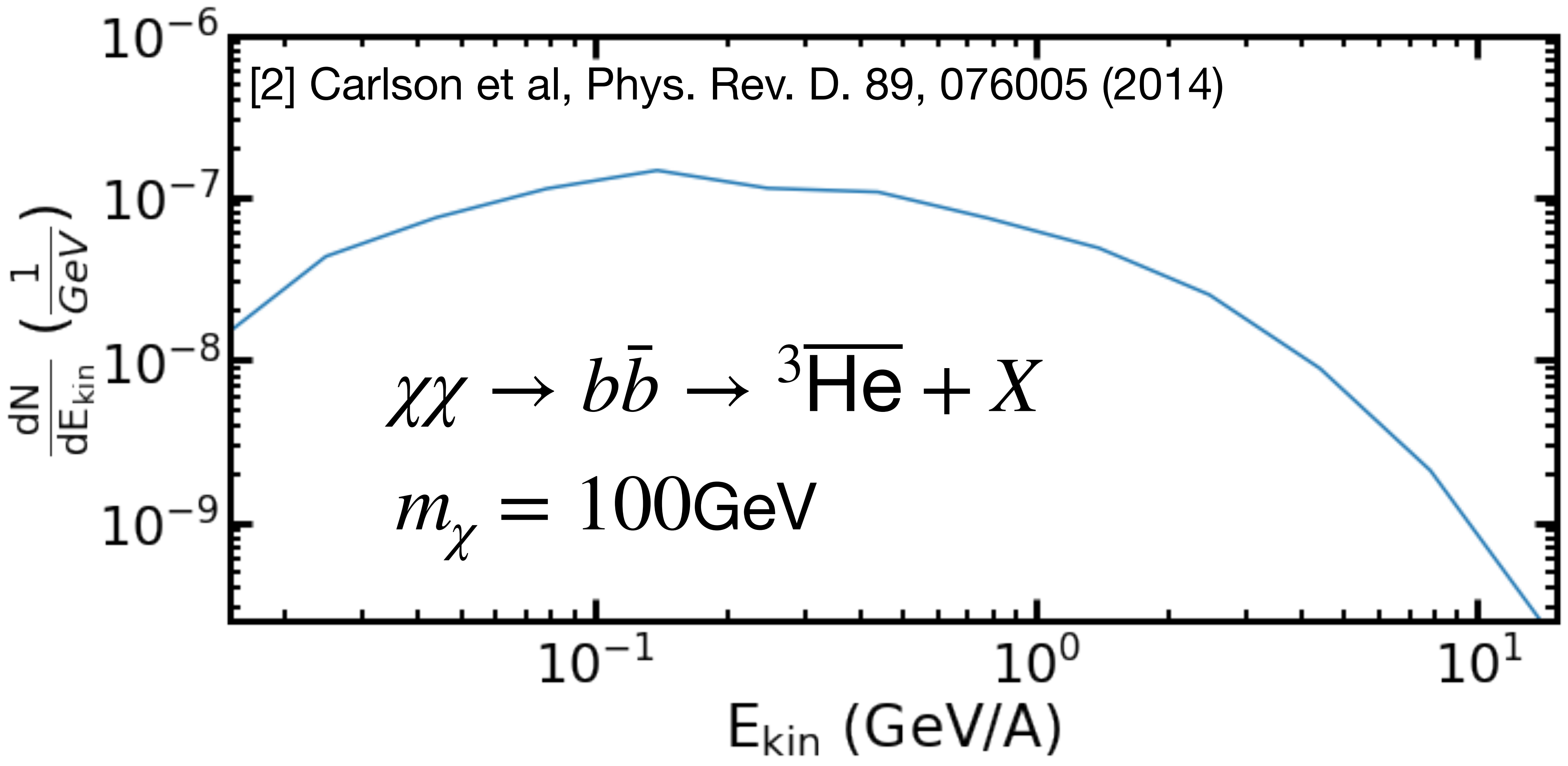

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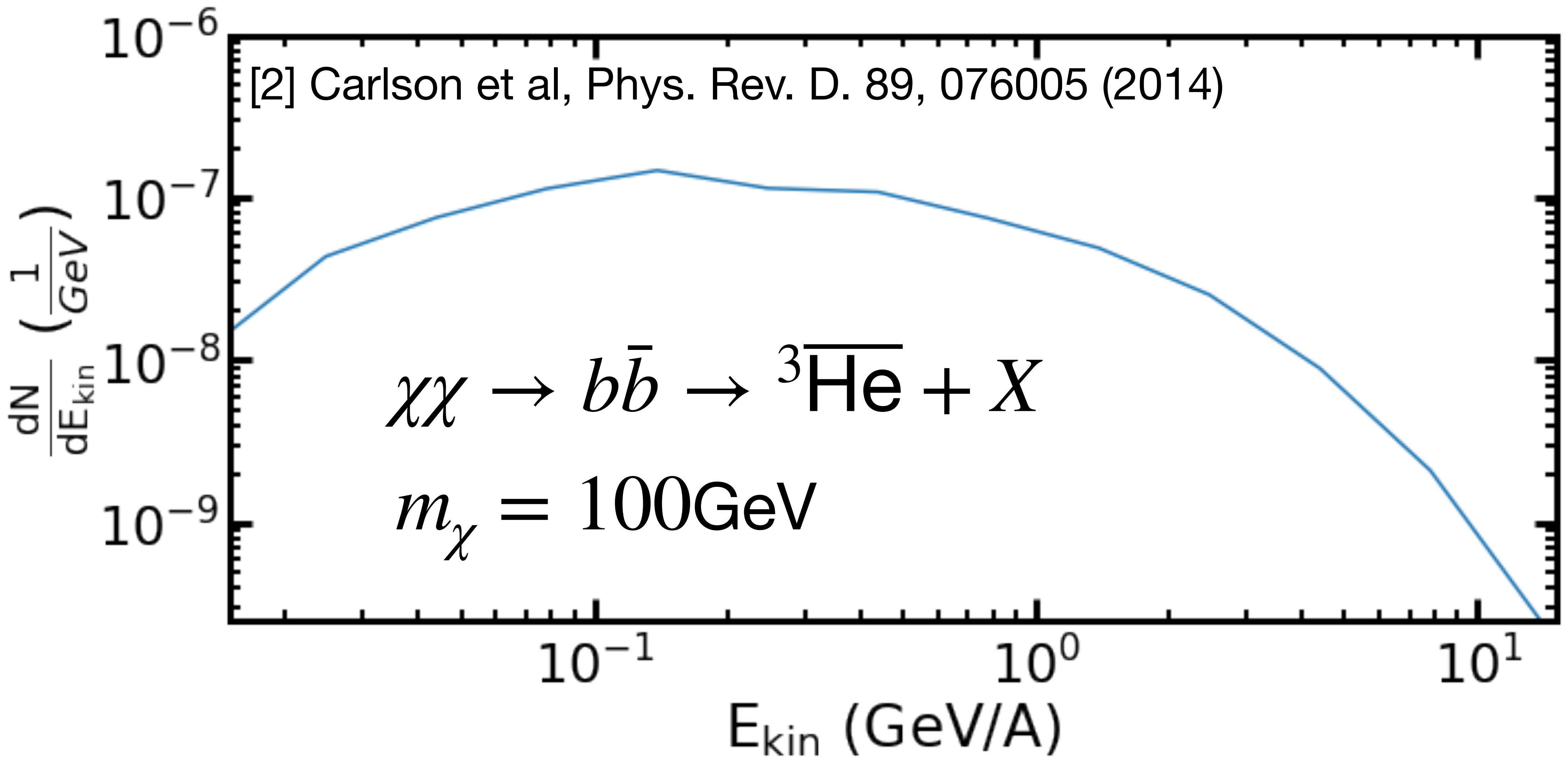
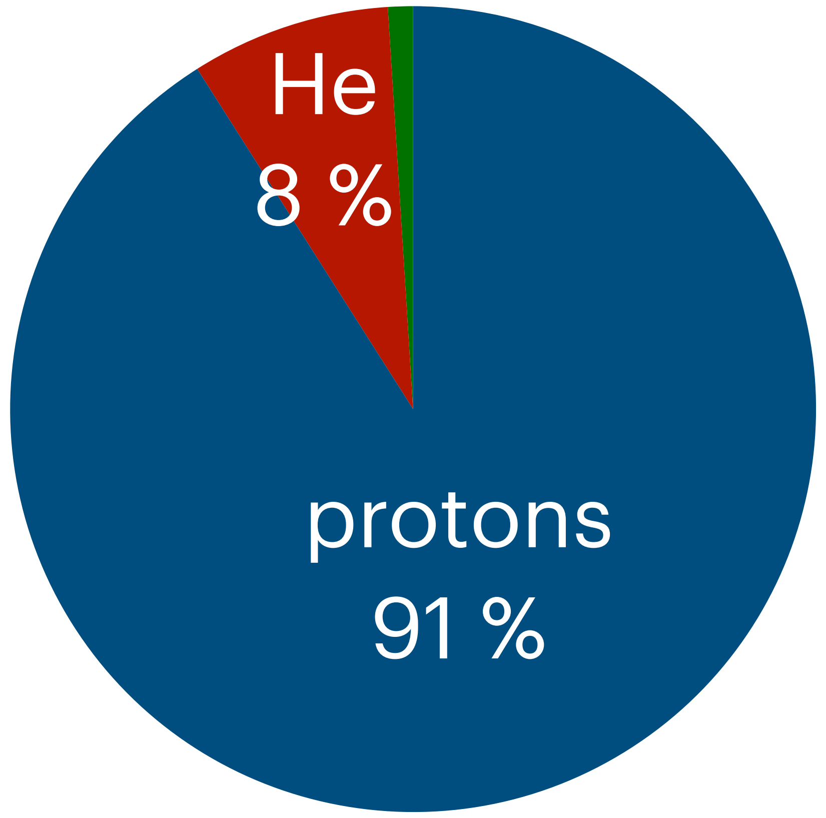
- This can be calculated using a coalescence model. [3]



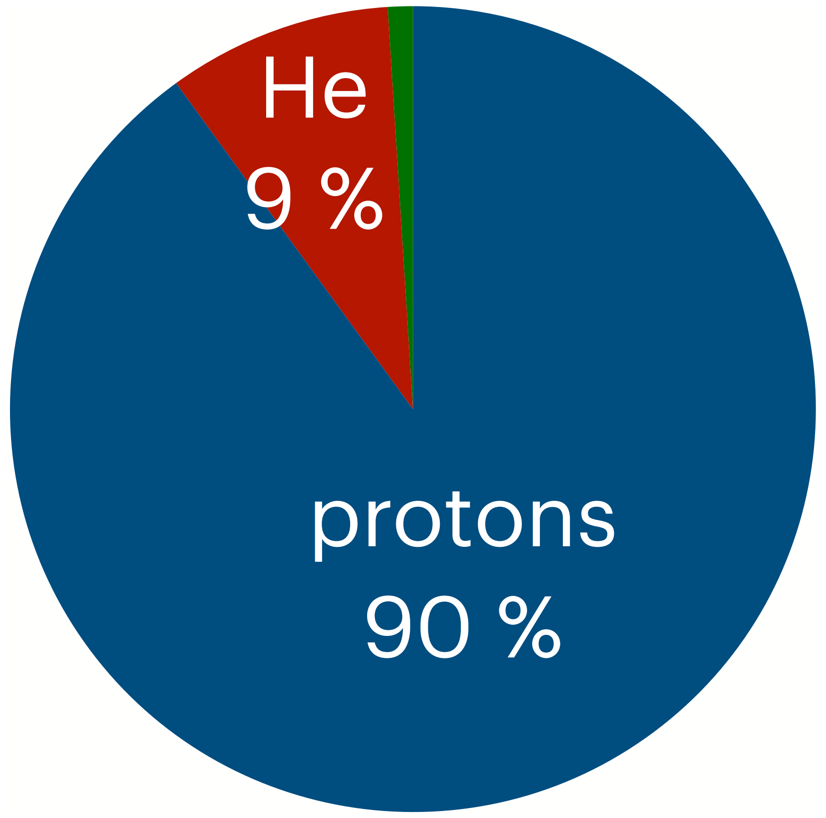
[3] F. Bellini, A. Kelweit, Phys.Rev.C pp (2019)

Antinuclei source terms: CR collisions with the ISM

Cosmic rays



ISM



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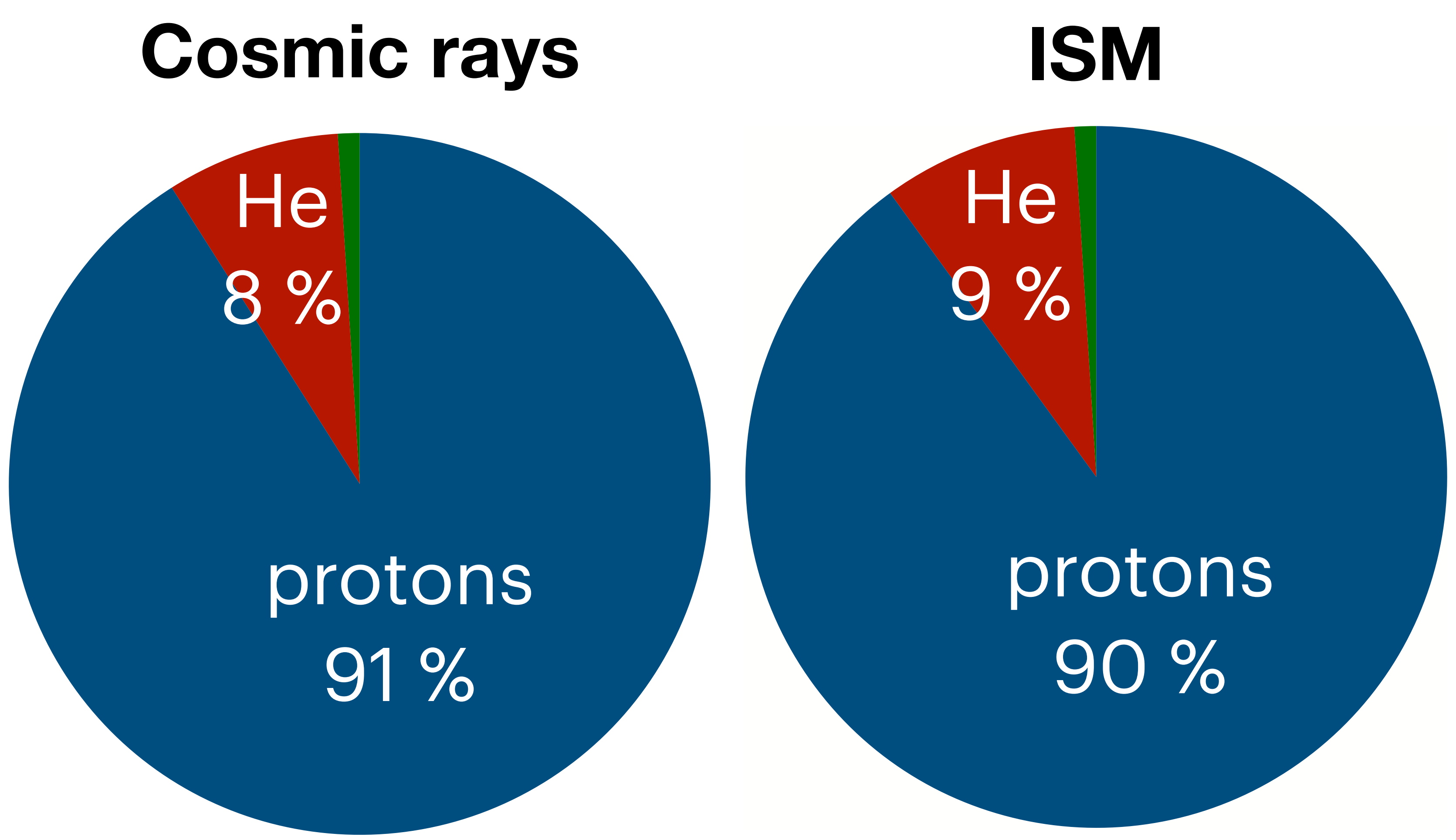
Relevant collision systems: pp, p-He, He-p, He-He



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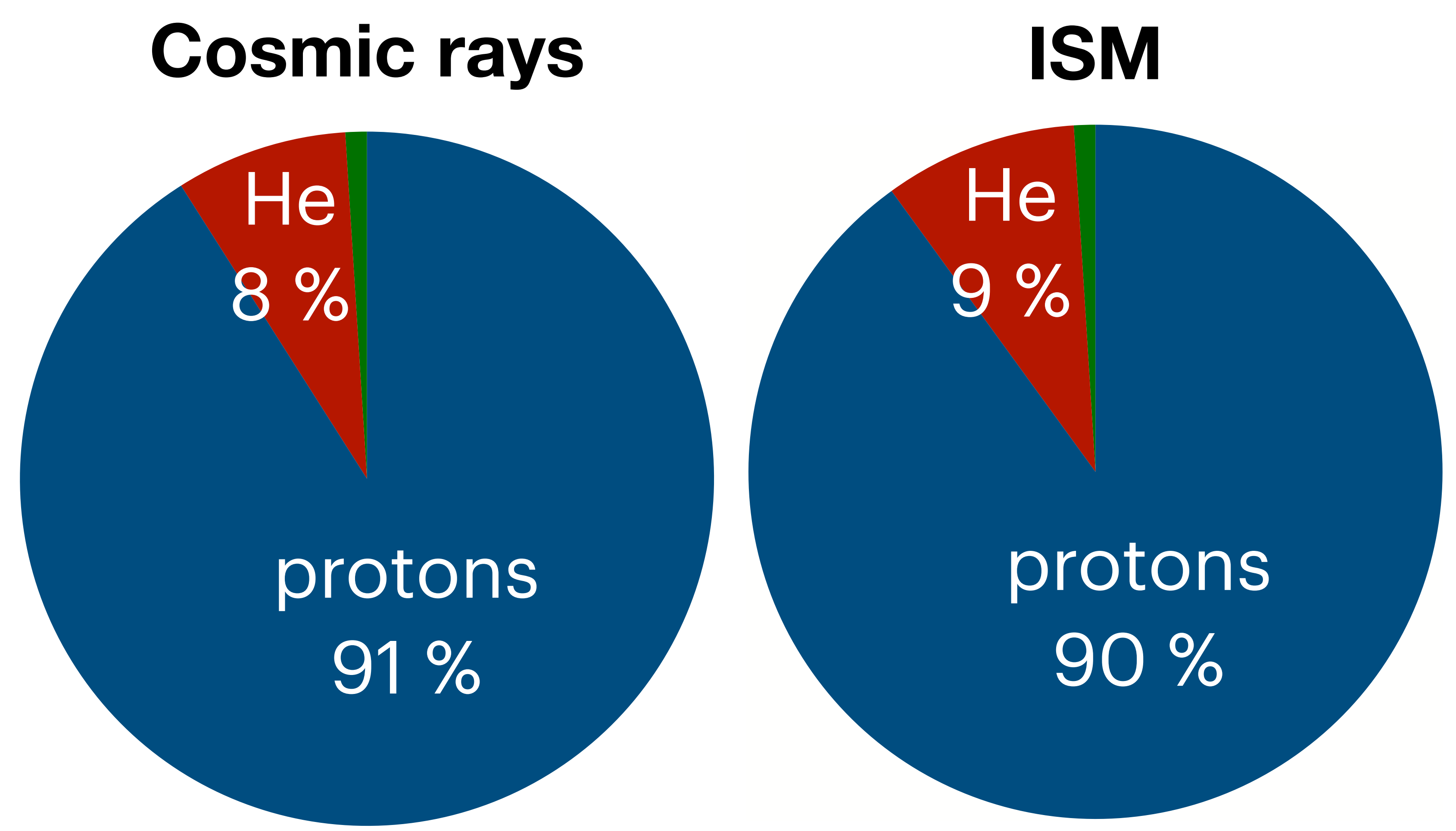
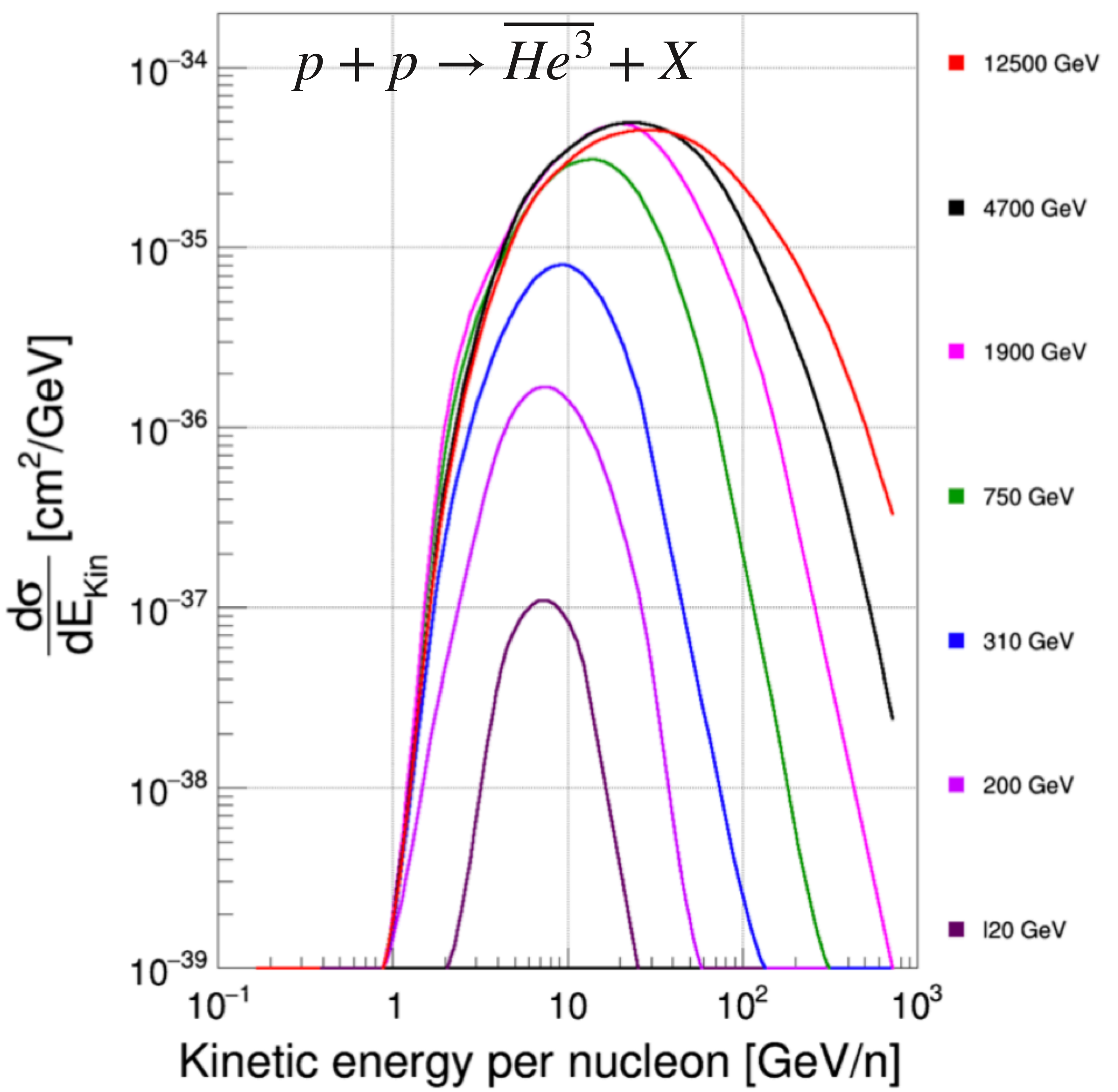


$^3\overline{He}$ **production in pp**



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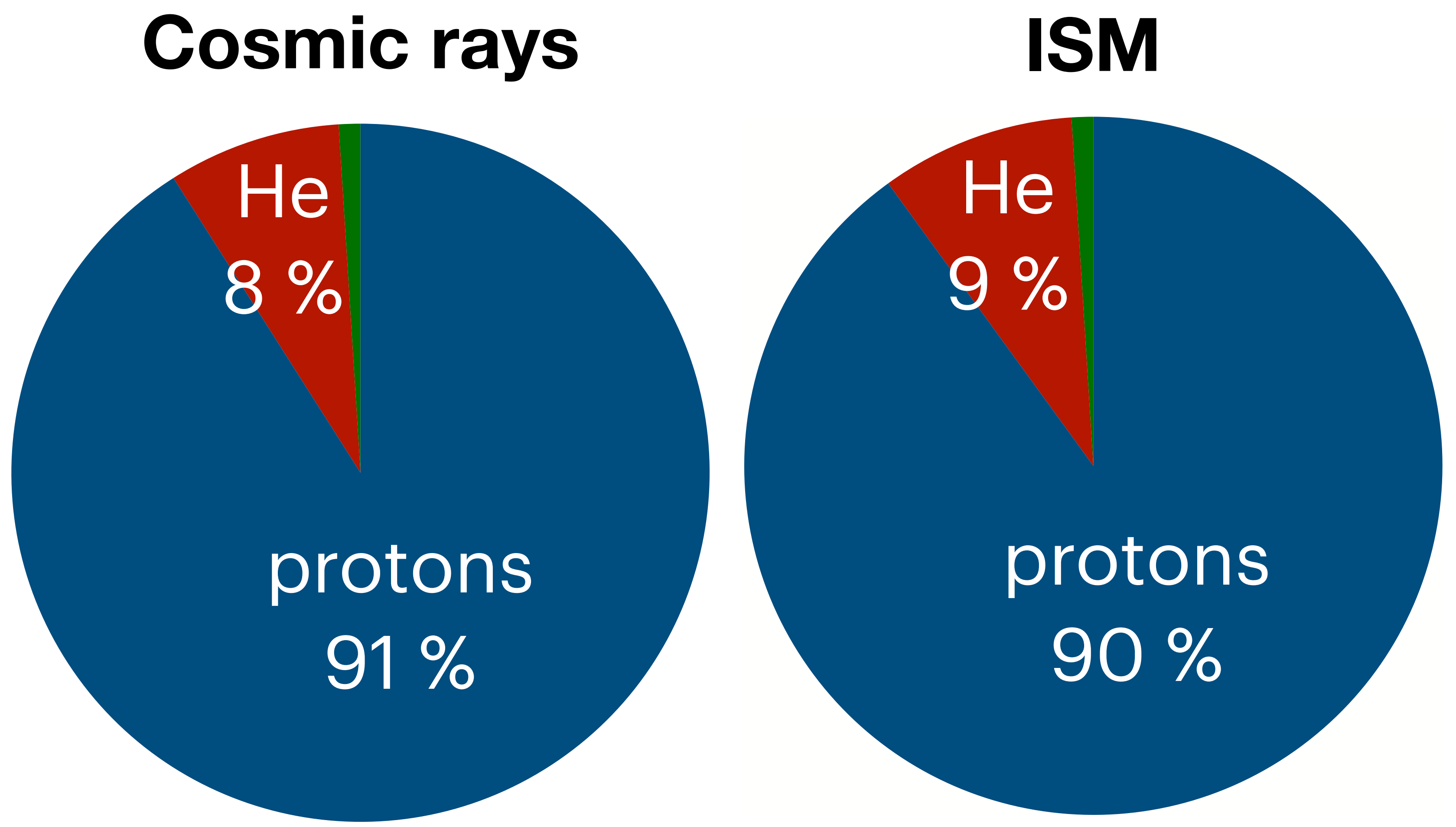

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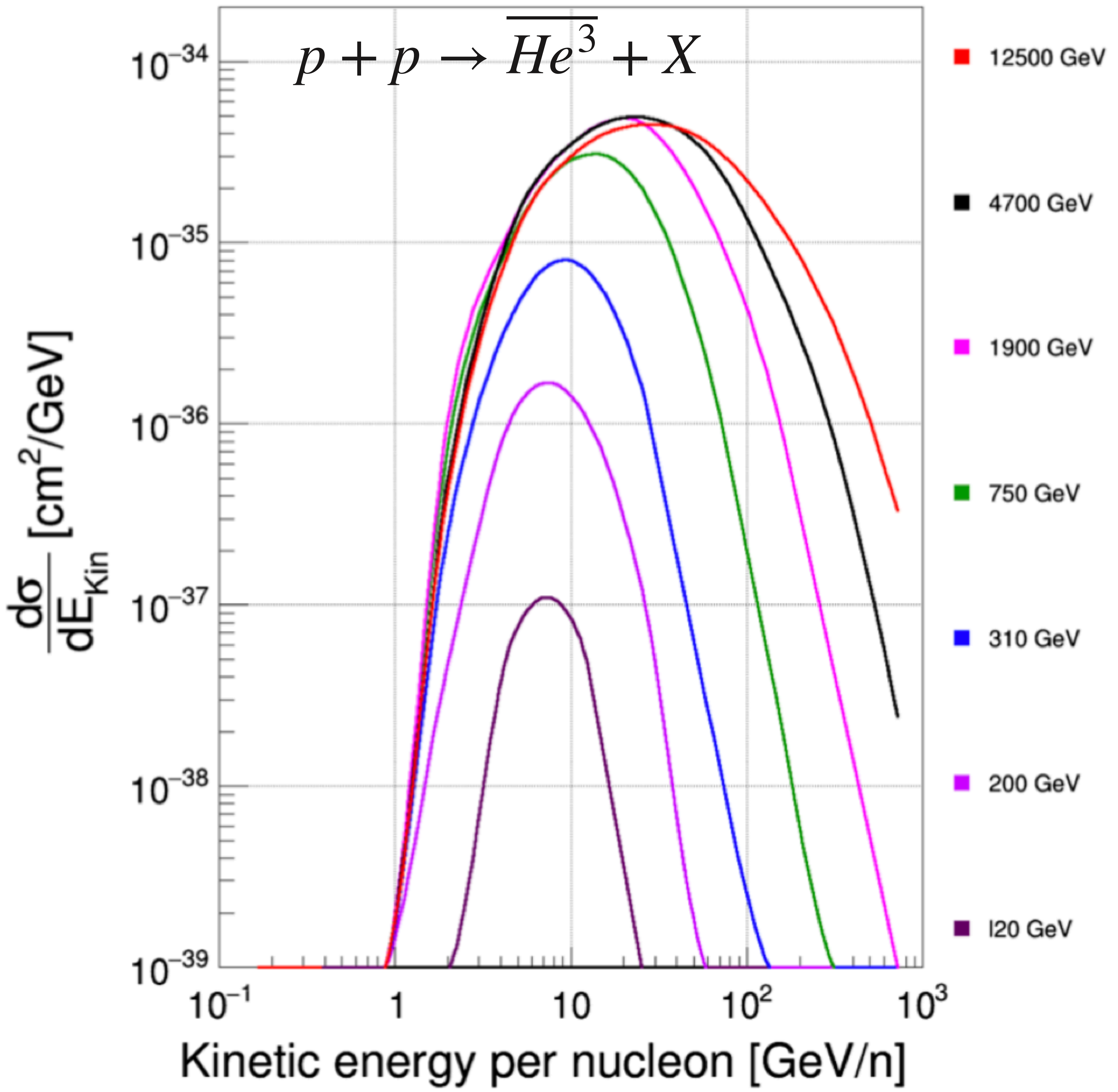

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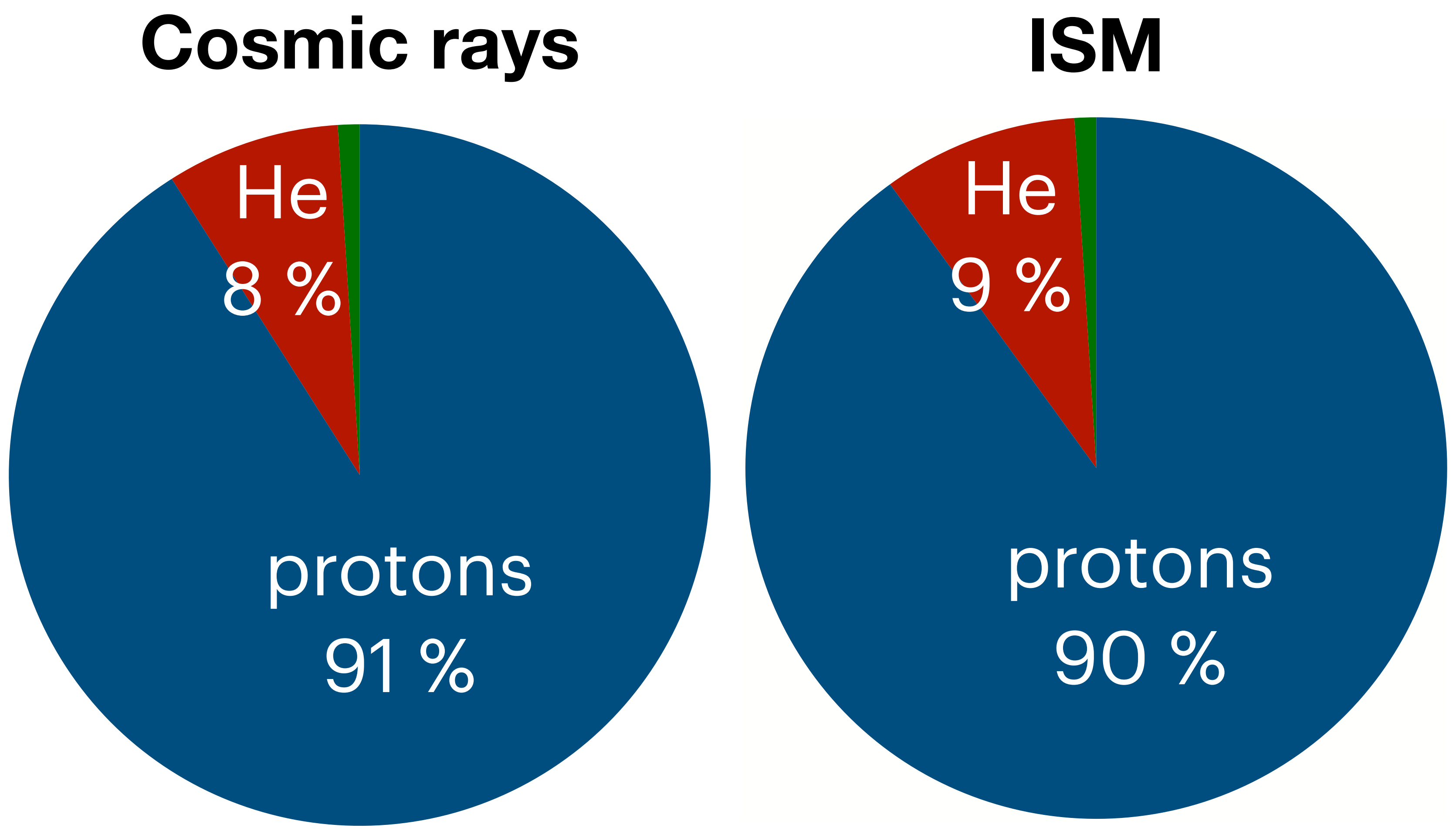

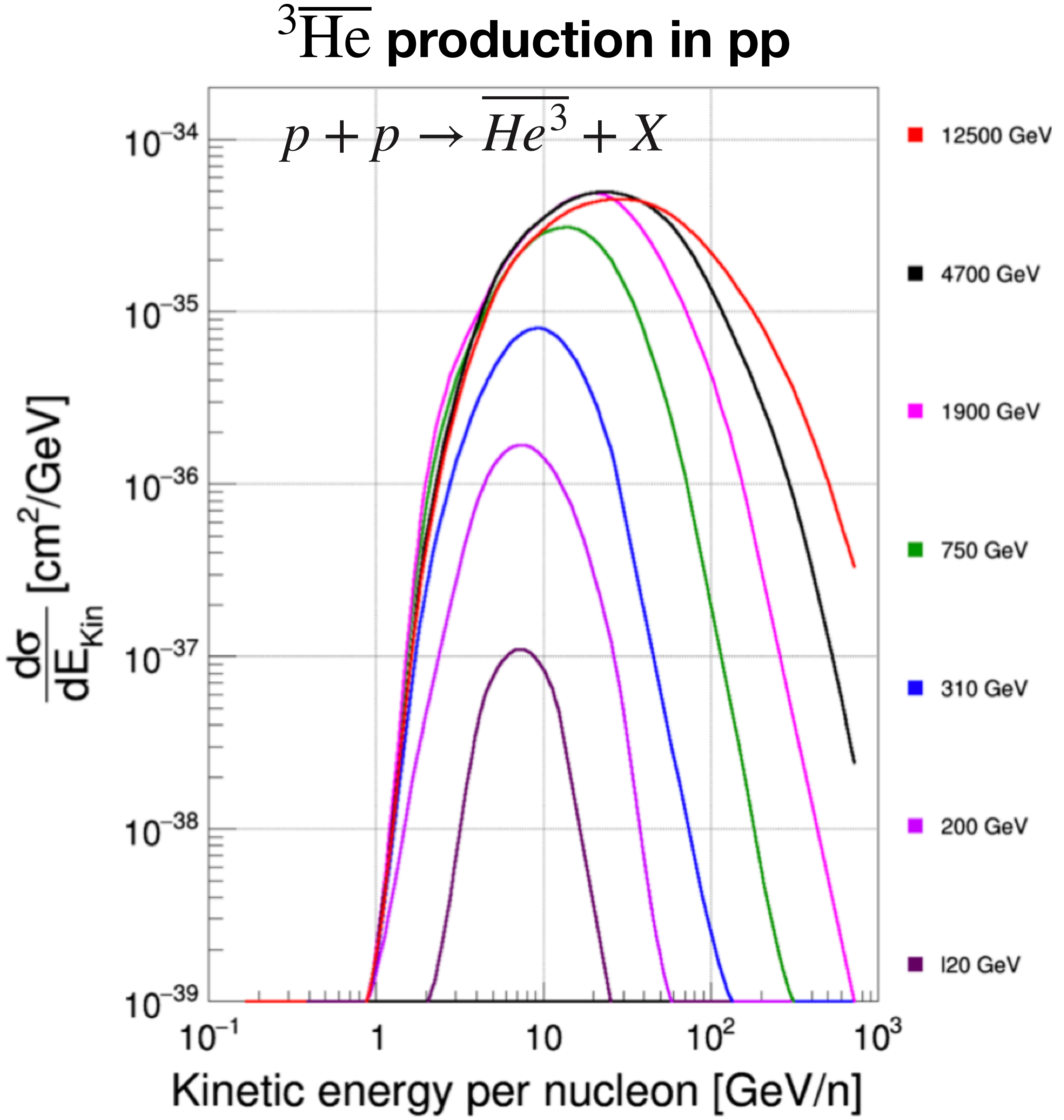

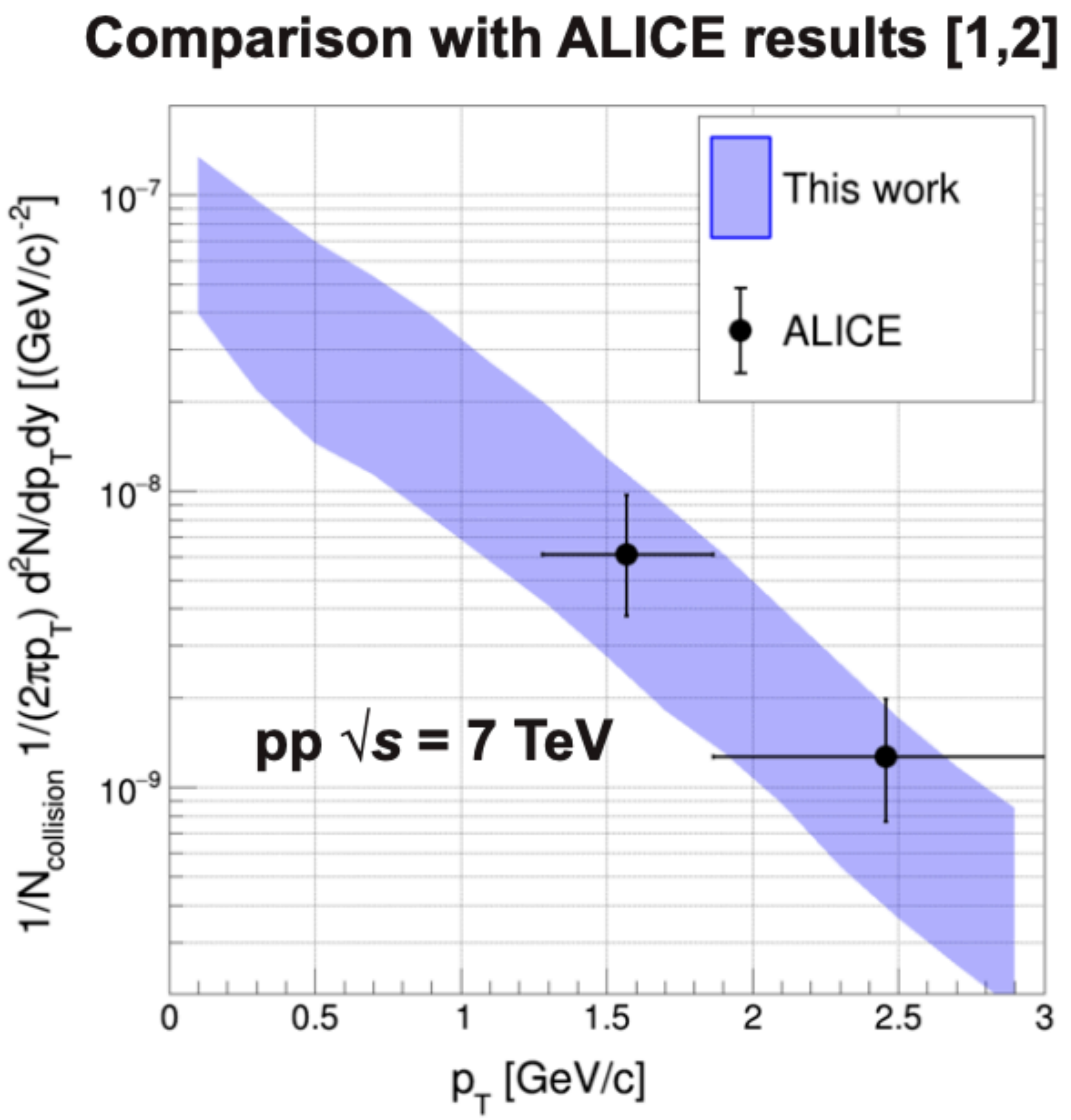

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[2] ALICE, Phys. Rev. C 97, 024615 (2018)

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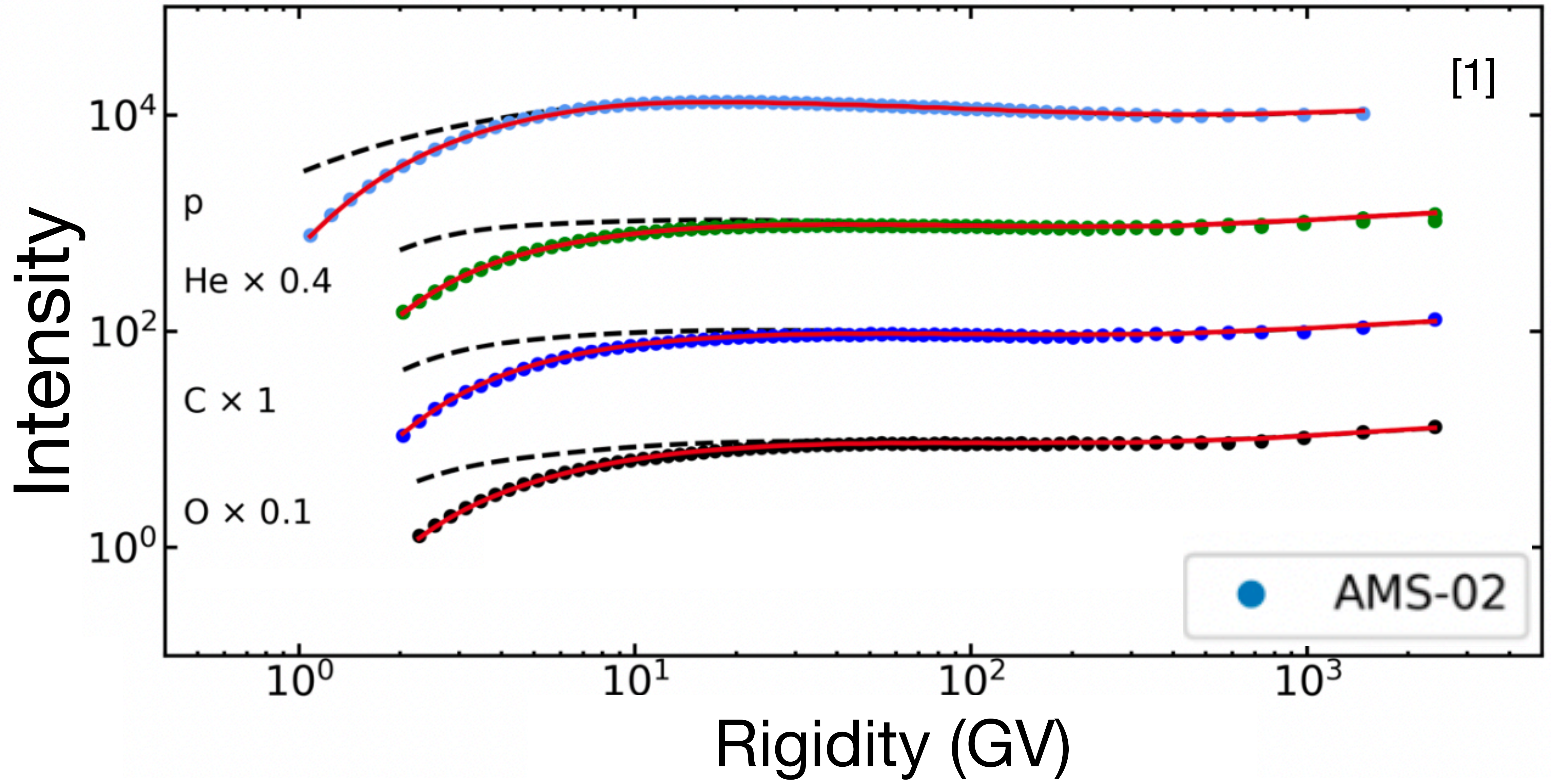

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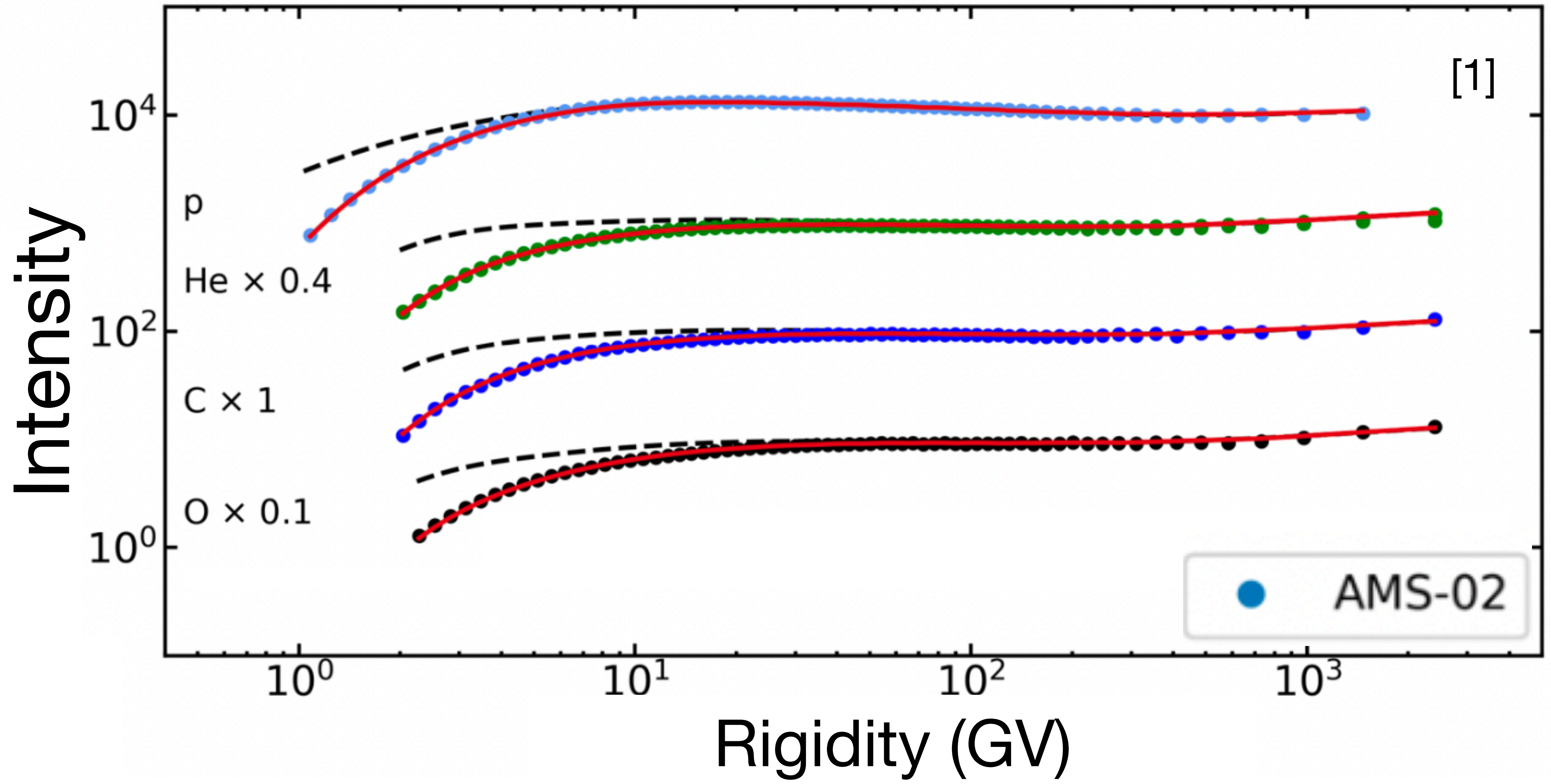

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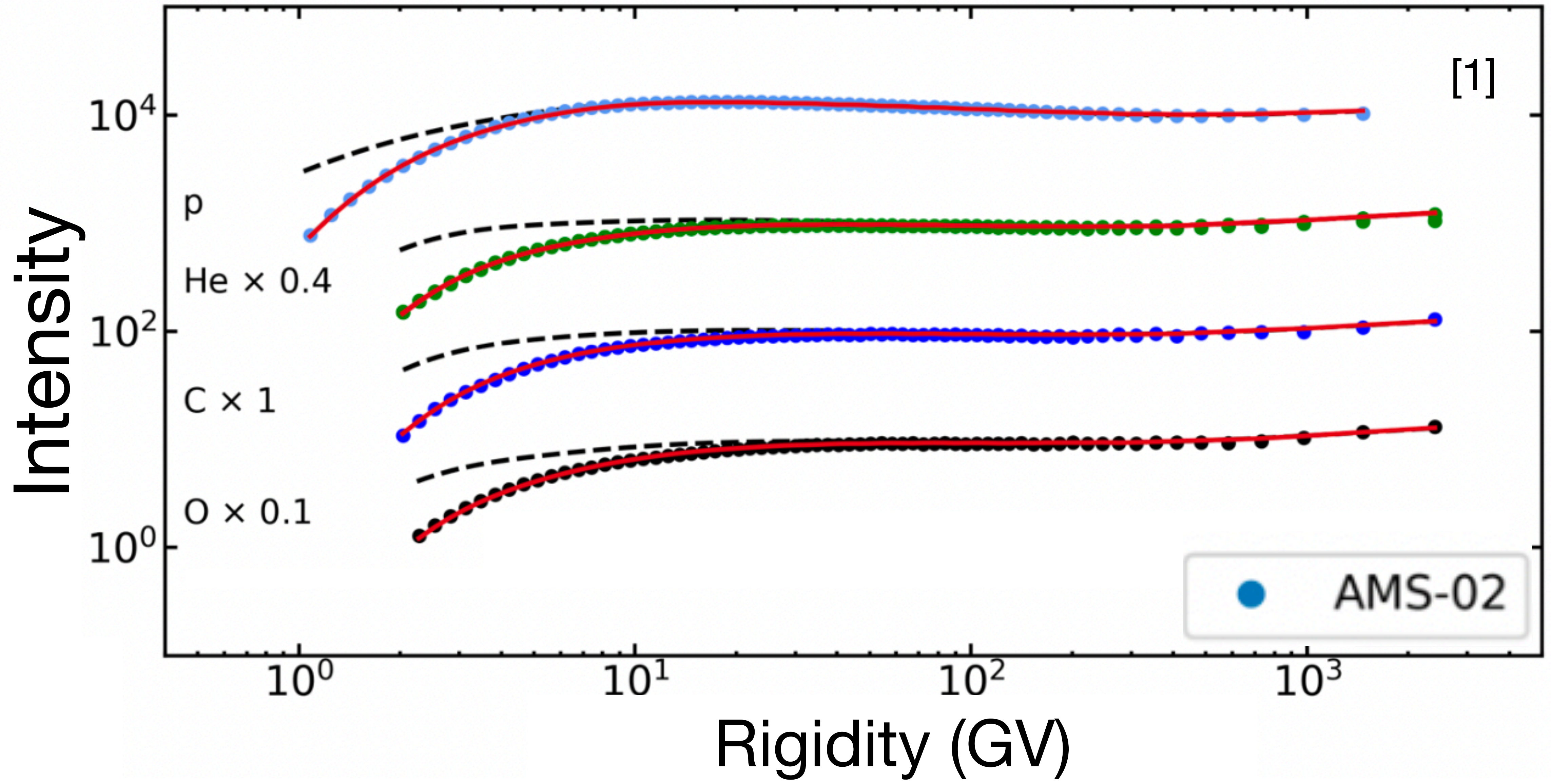


Propagation studied in detail in
Šerkšnytė et. al. PRD 105 (2022)

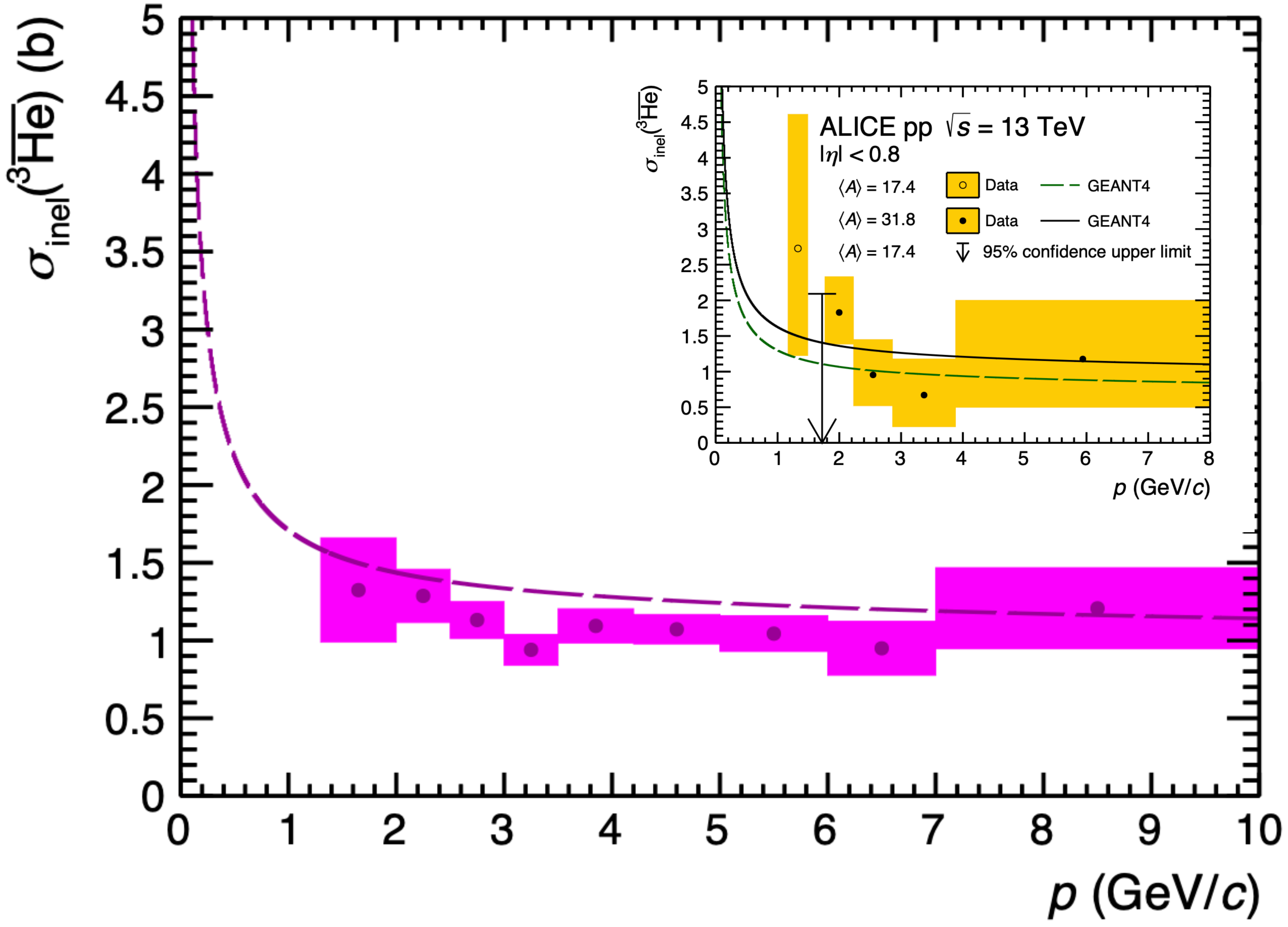
[1] Boschini et al. ApJS 250 27 (2020)
[2] Galprop modifications
[3] A. Strong, et. al. Nuclear and Particle Physics Proceedings, 297-299, 2018

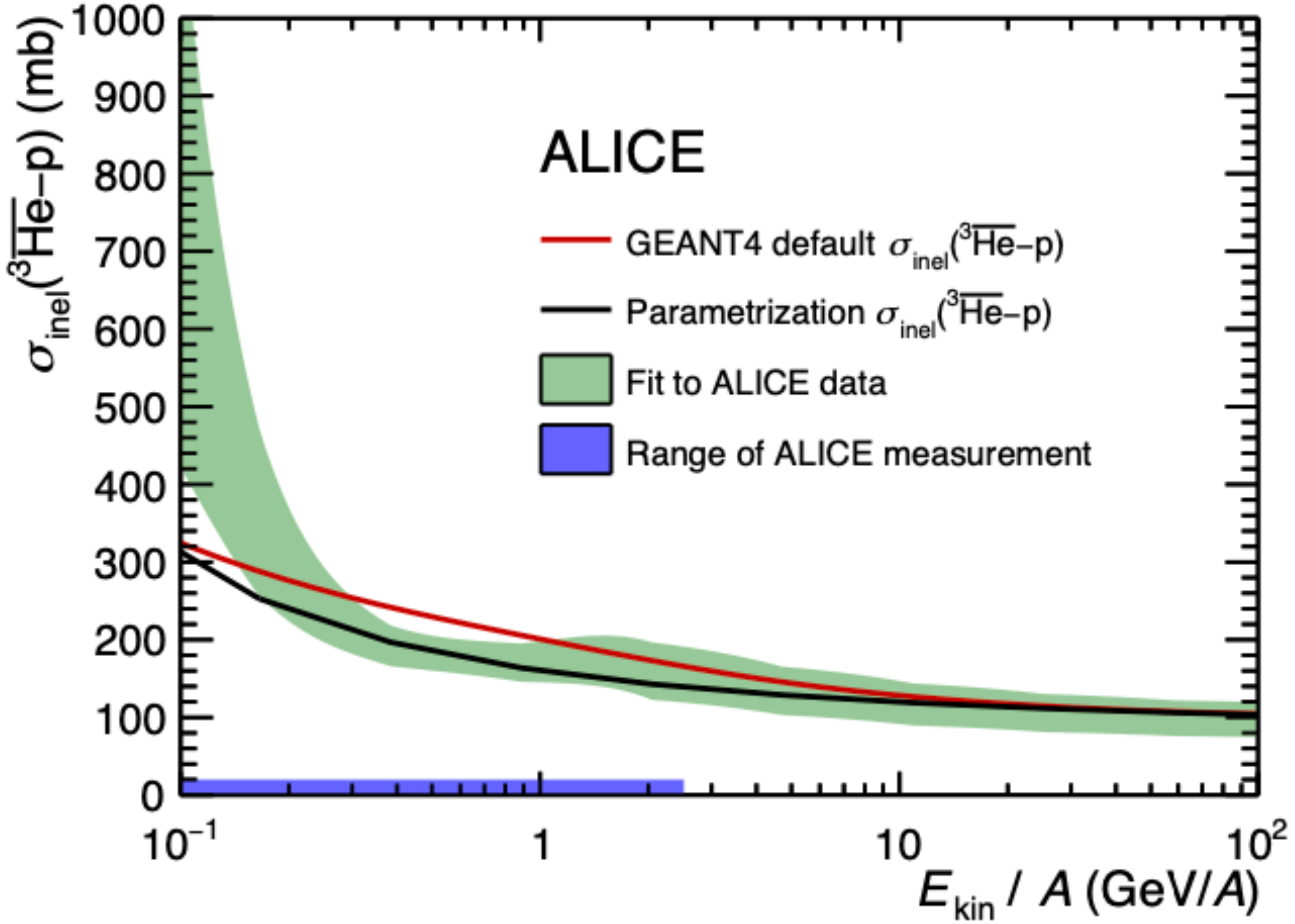
Inelastic interactions

ALICE measurements of σ_{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 A scaling [1]





[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 σ_{inel}

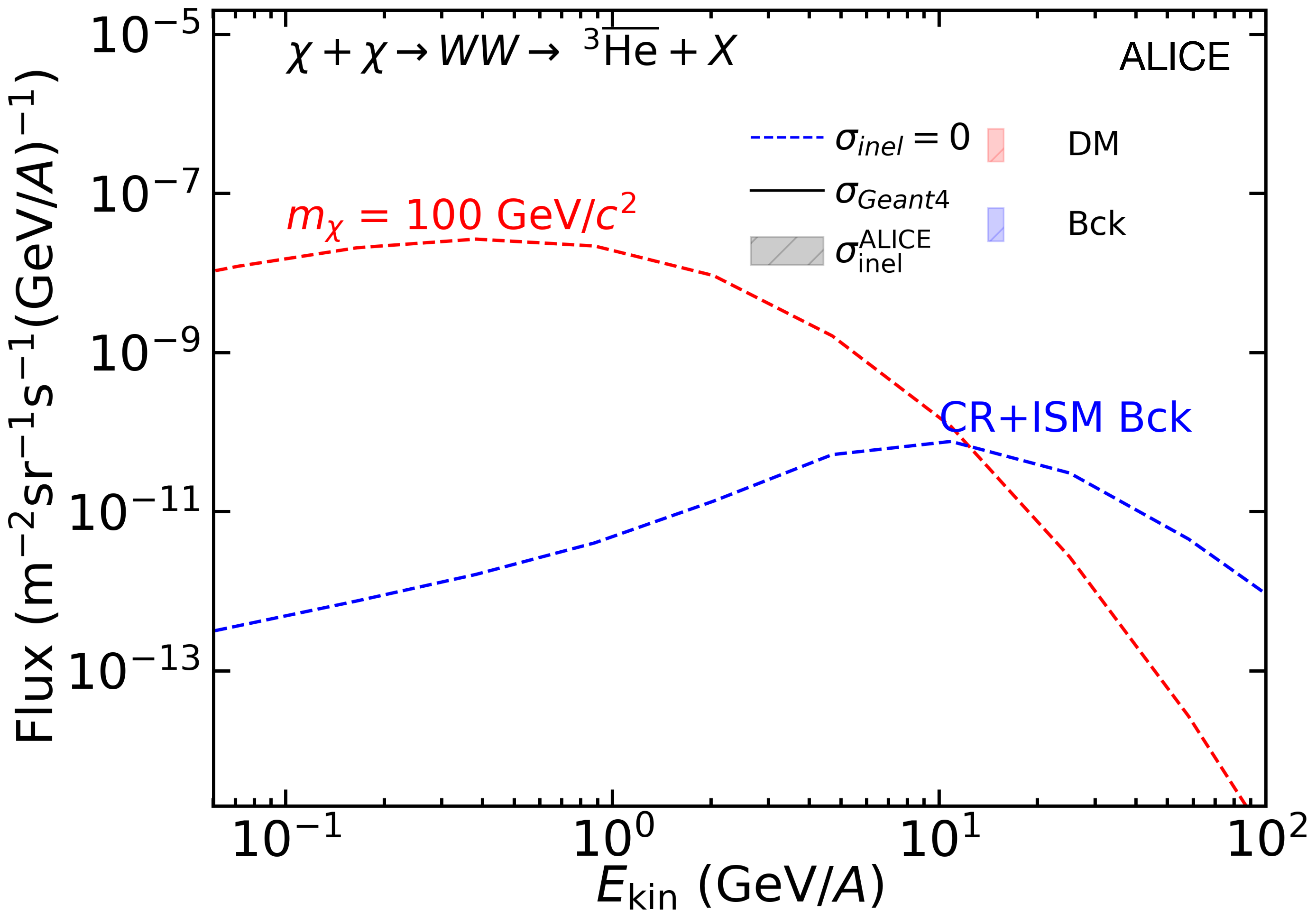
- **Small compared to other uncertainties in the field!**

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

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

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

Outside heliosphere



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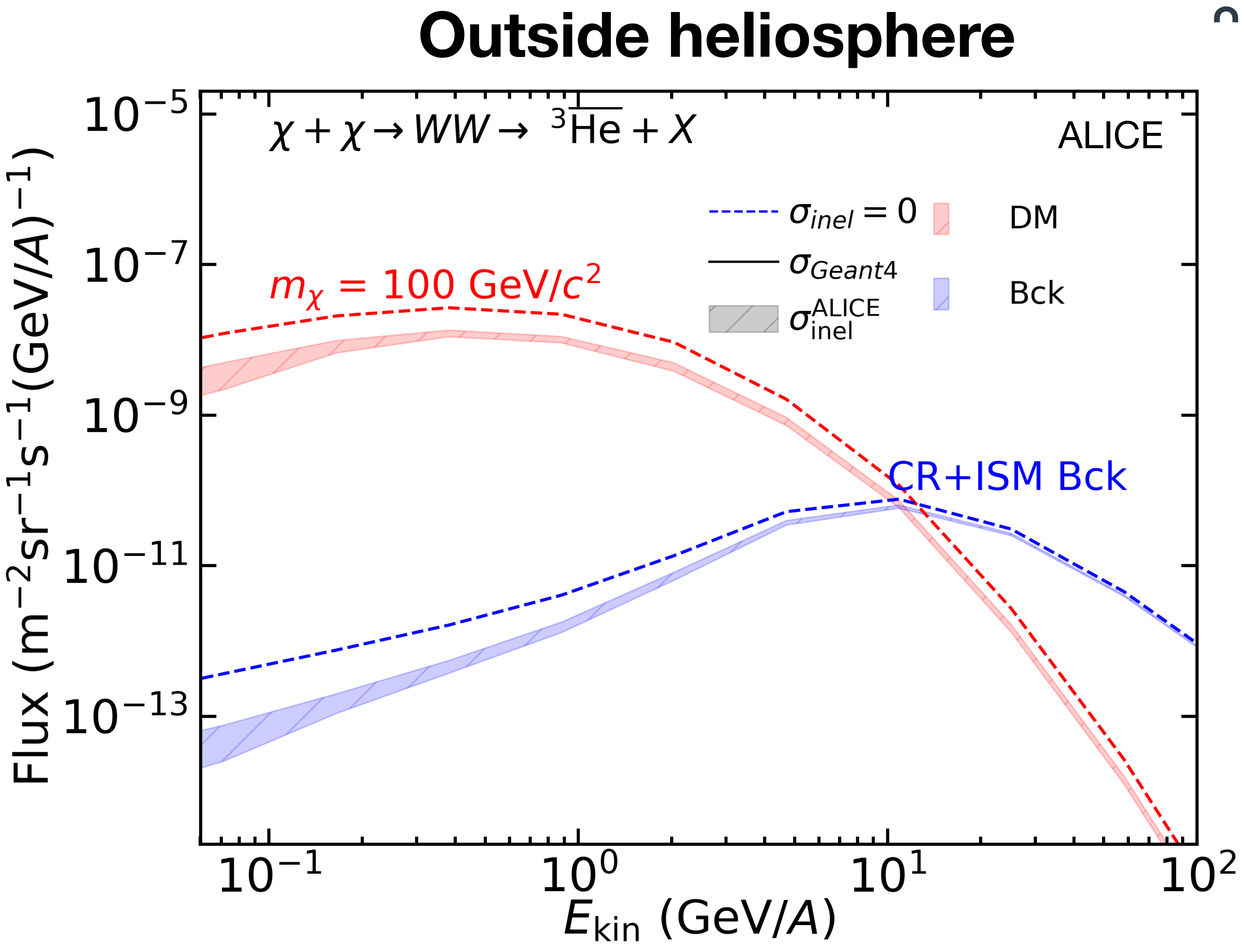

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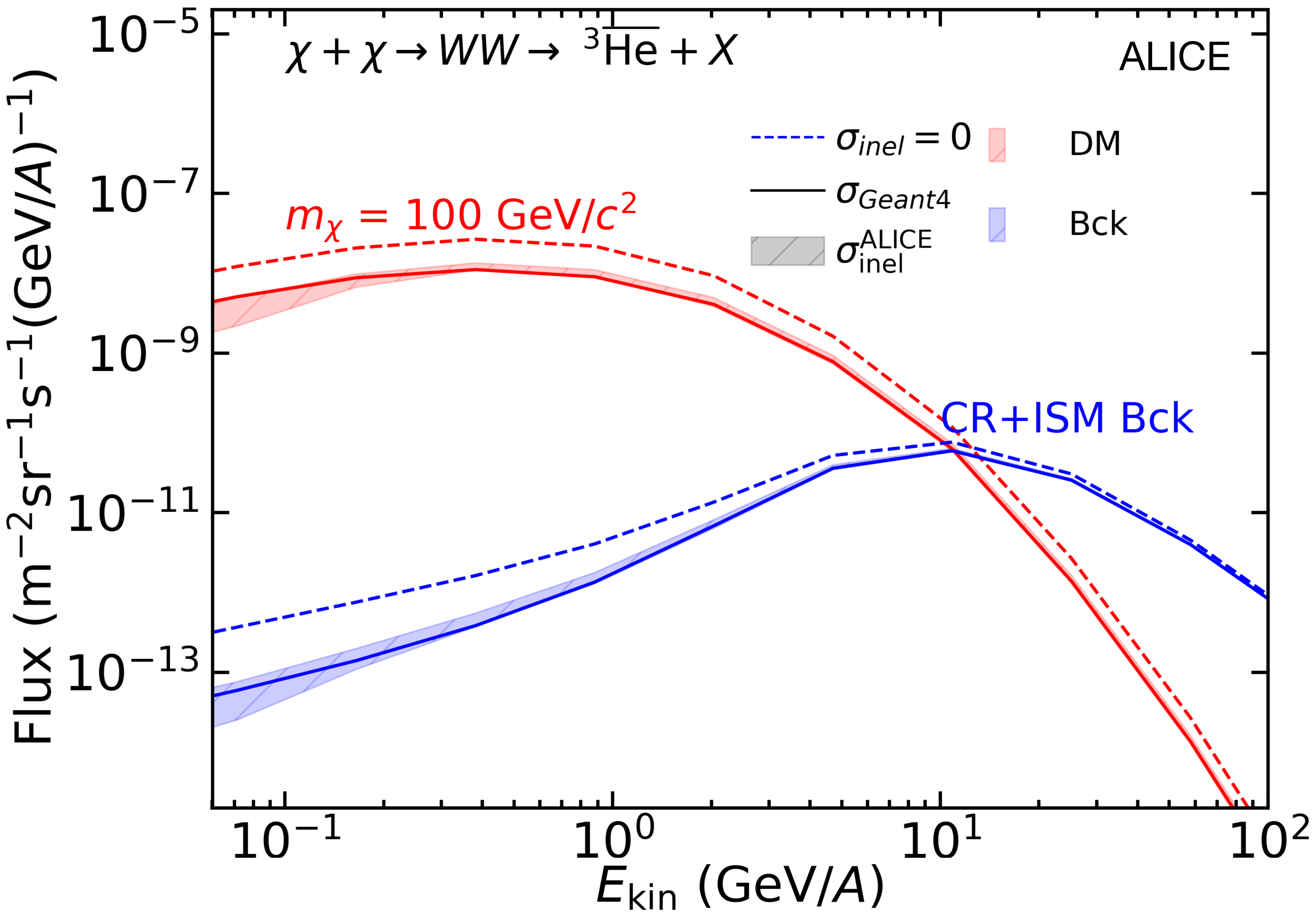

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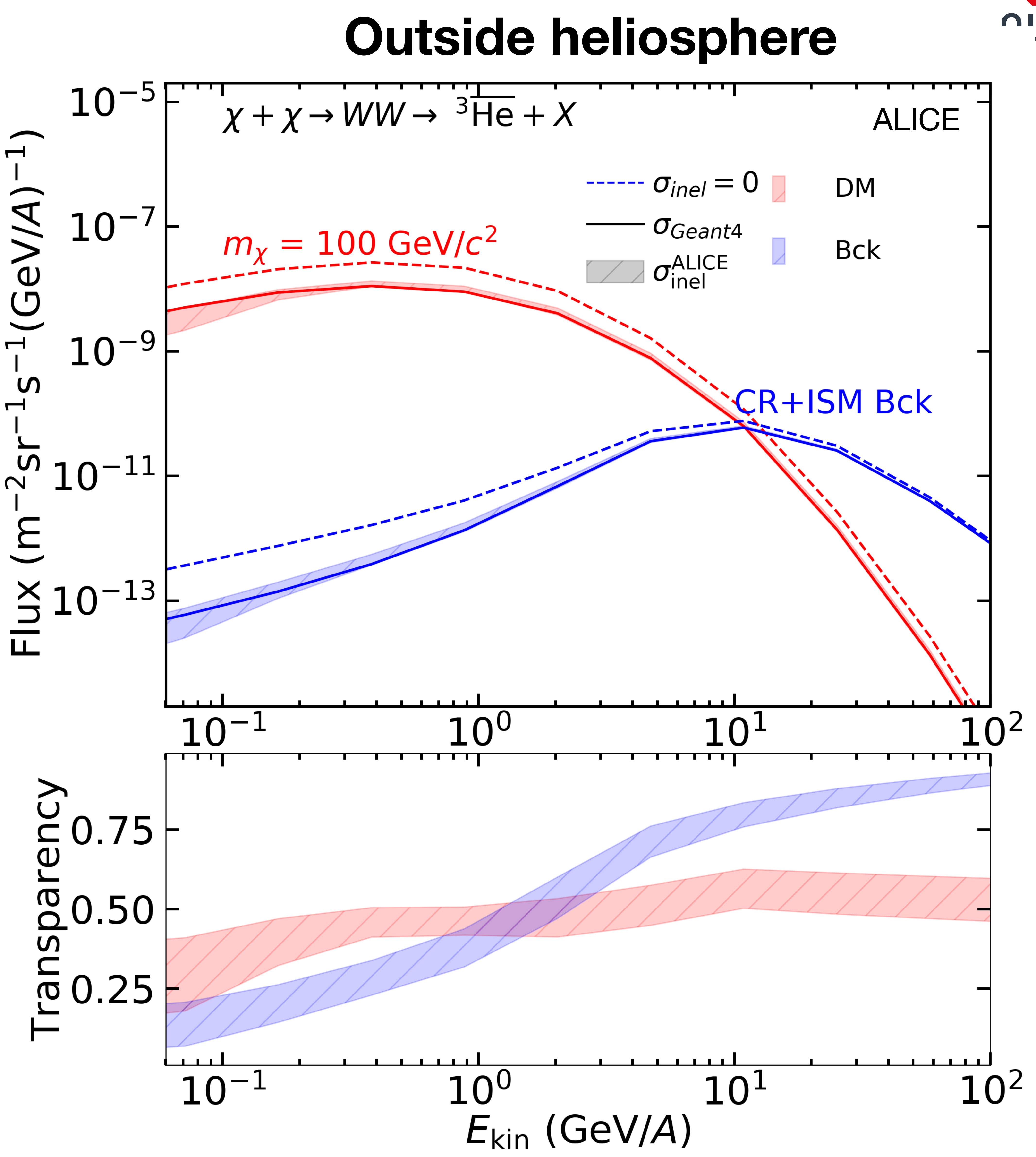

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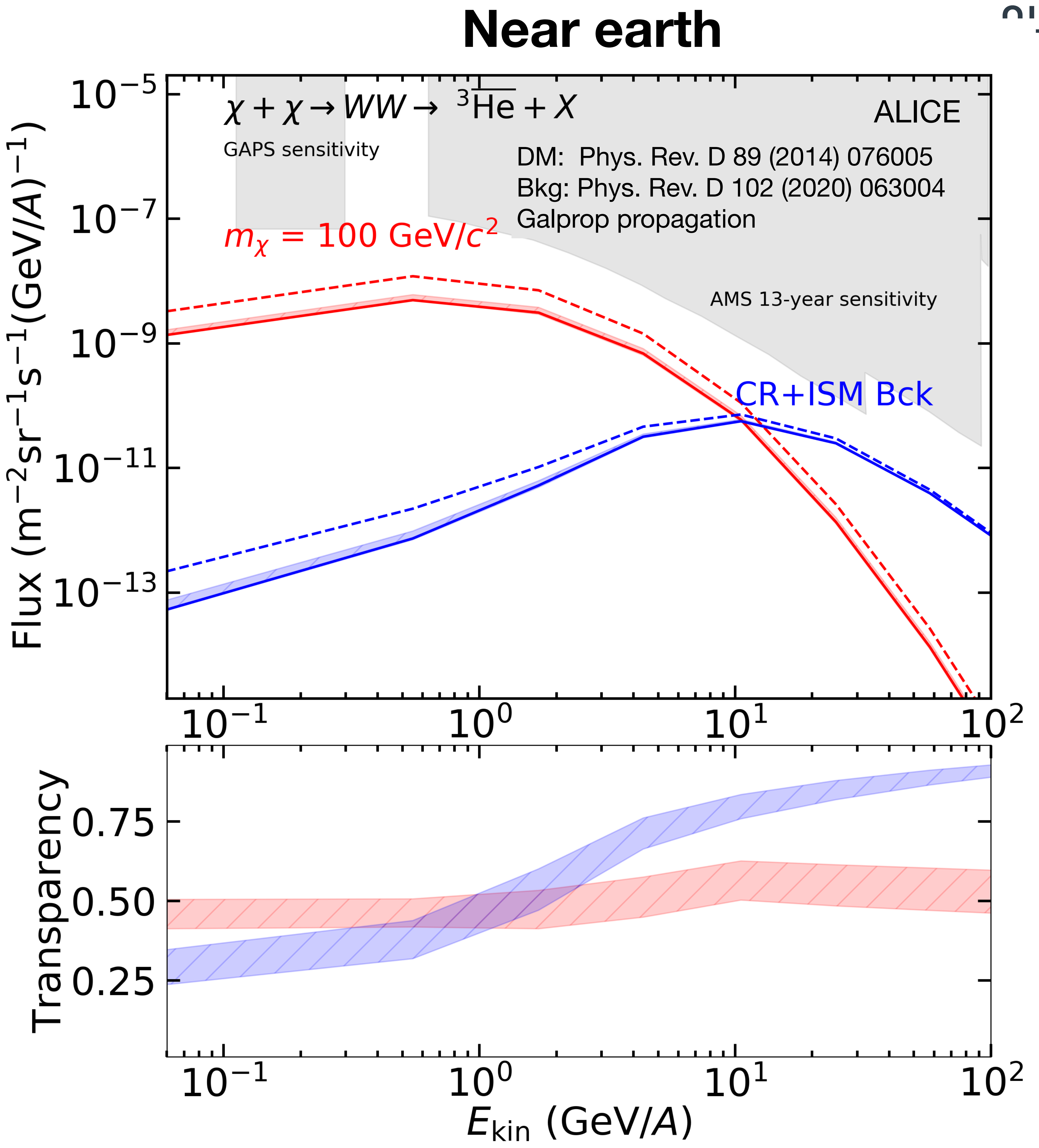

Summary and outlook

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Measurement of σ_{inel} via comparison with detailed ALICE Monte Carlo simulations using Geant4

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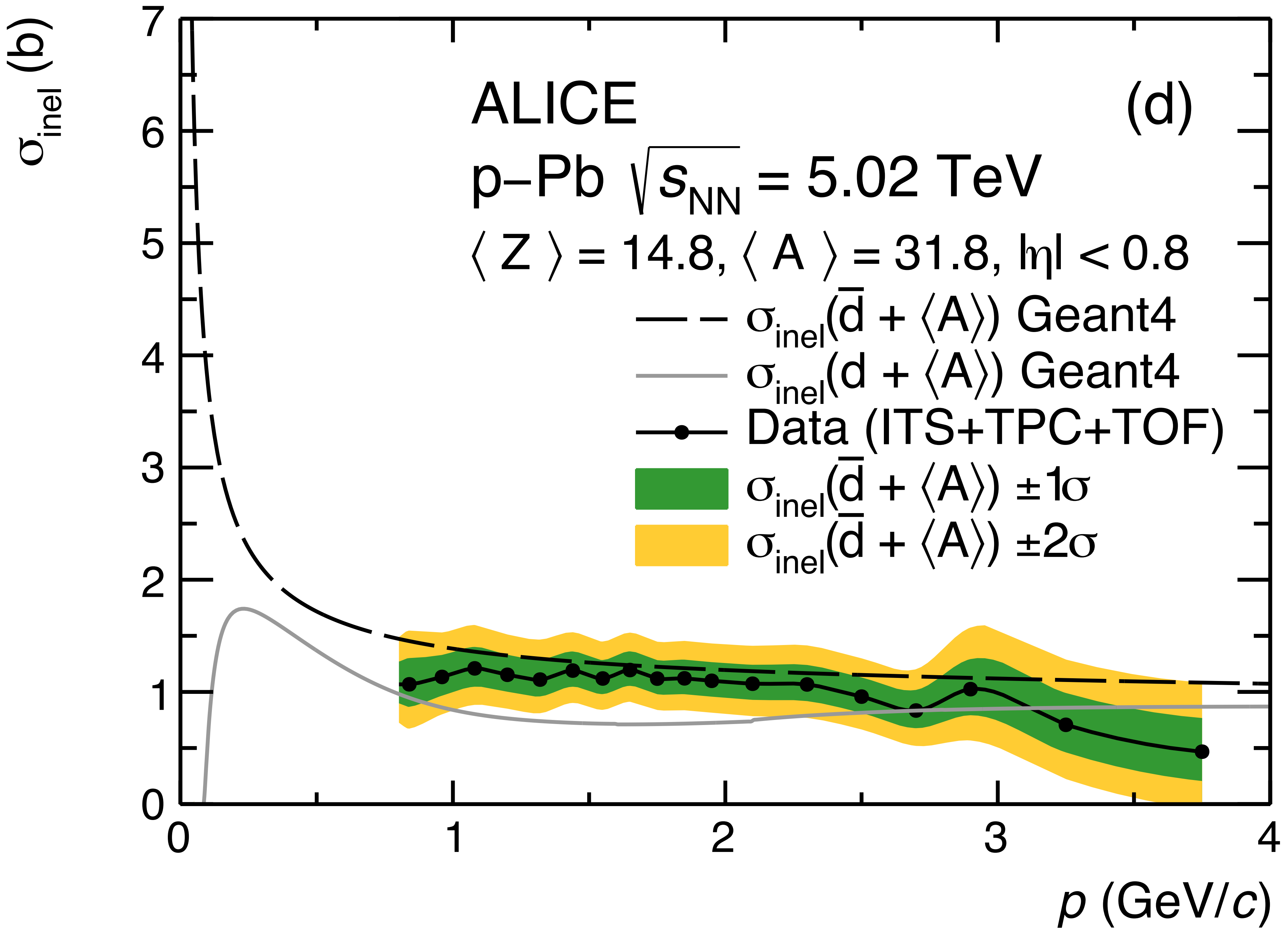

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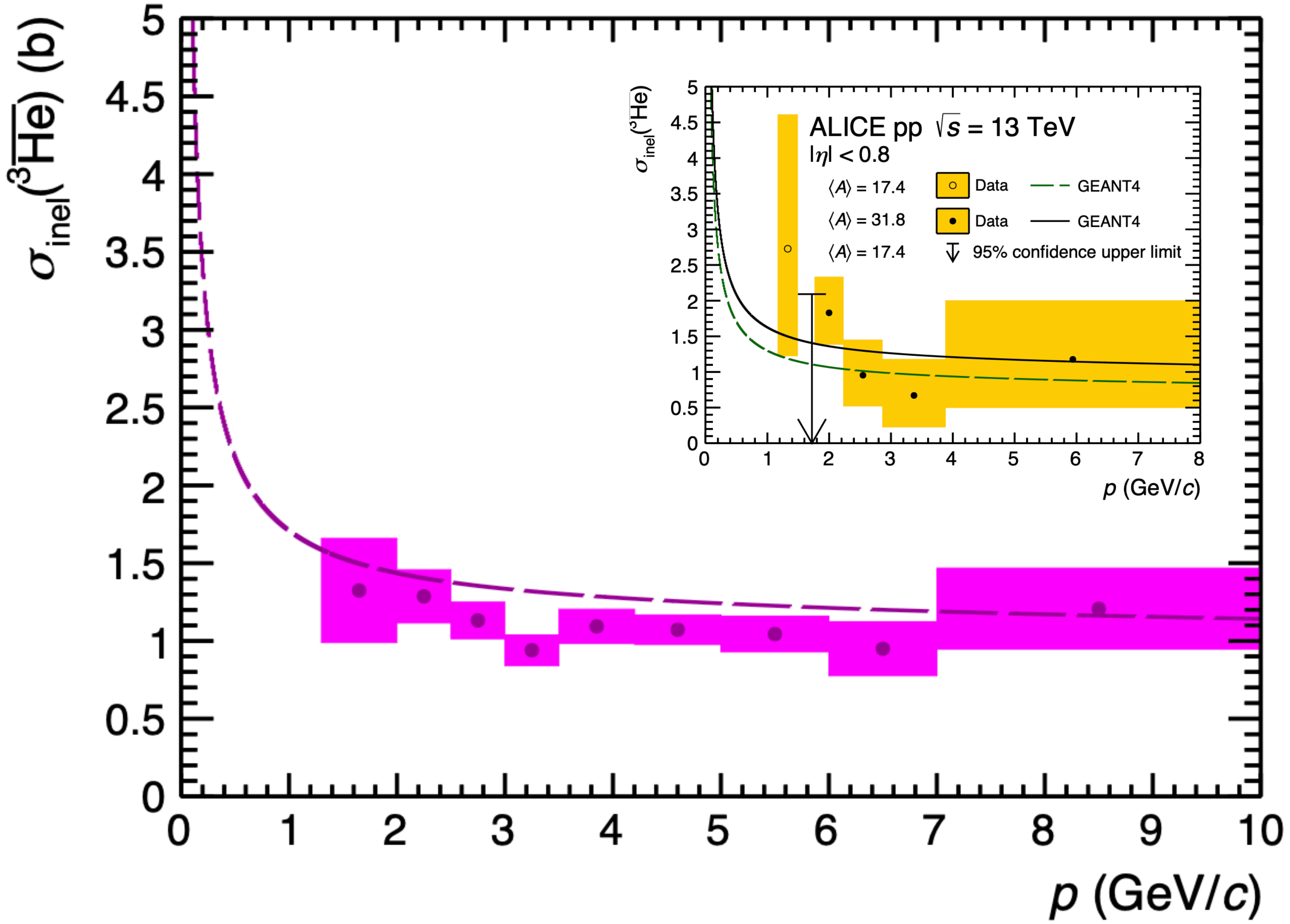

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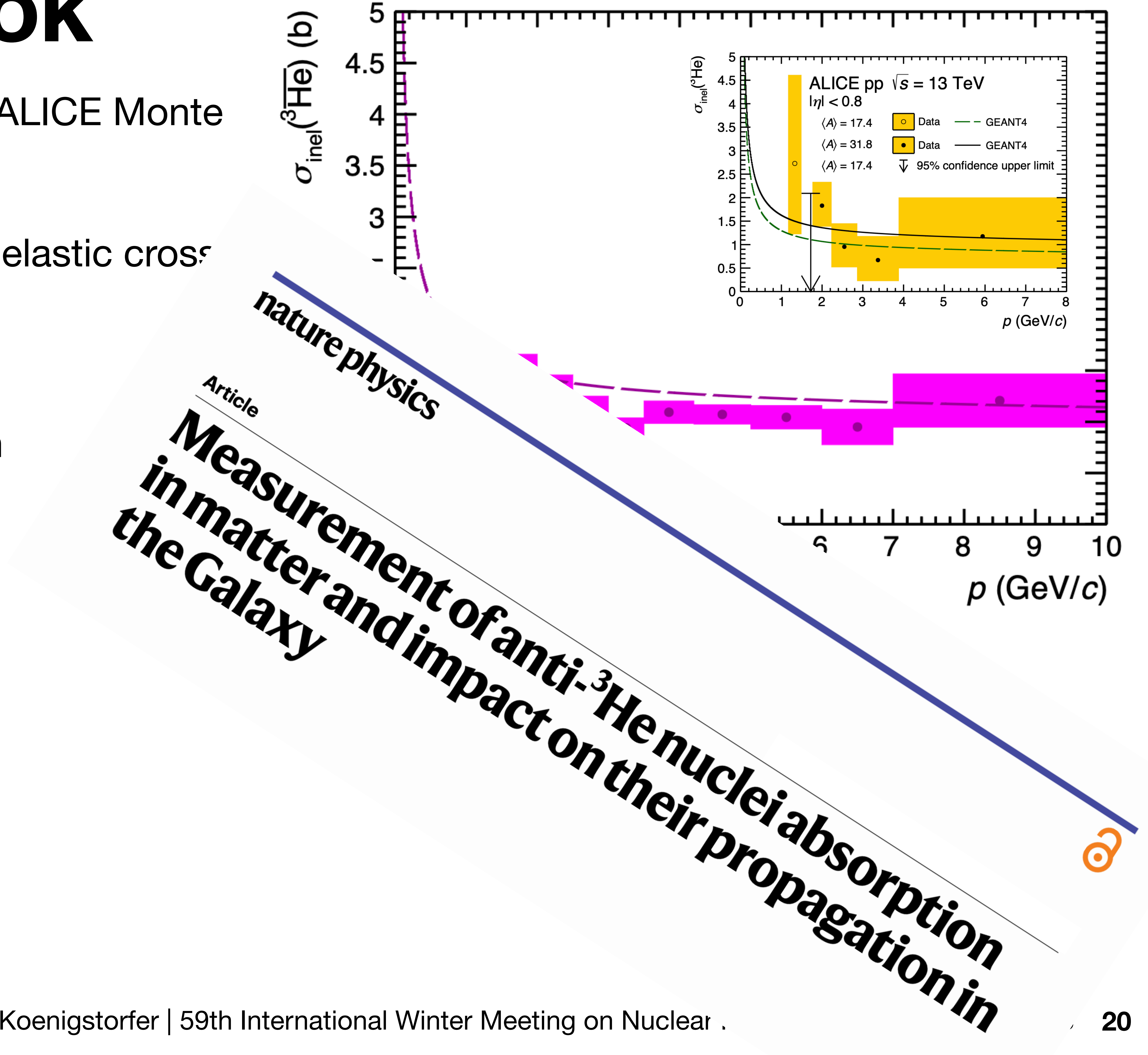
- Paper published in Nature Physics



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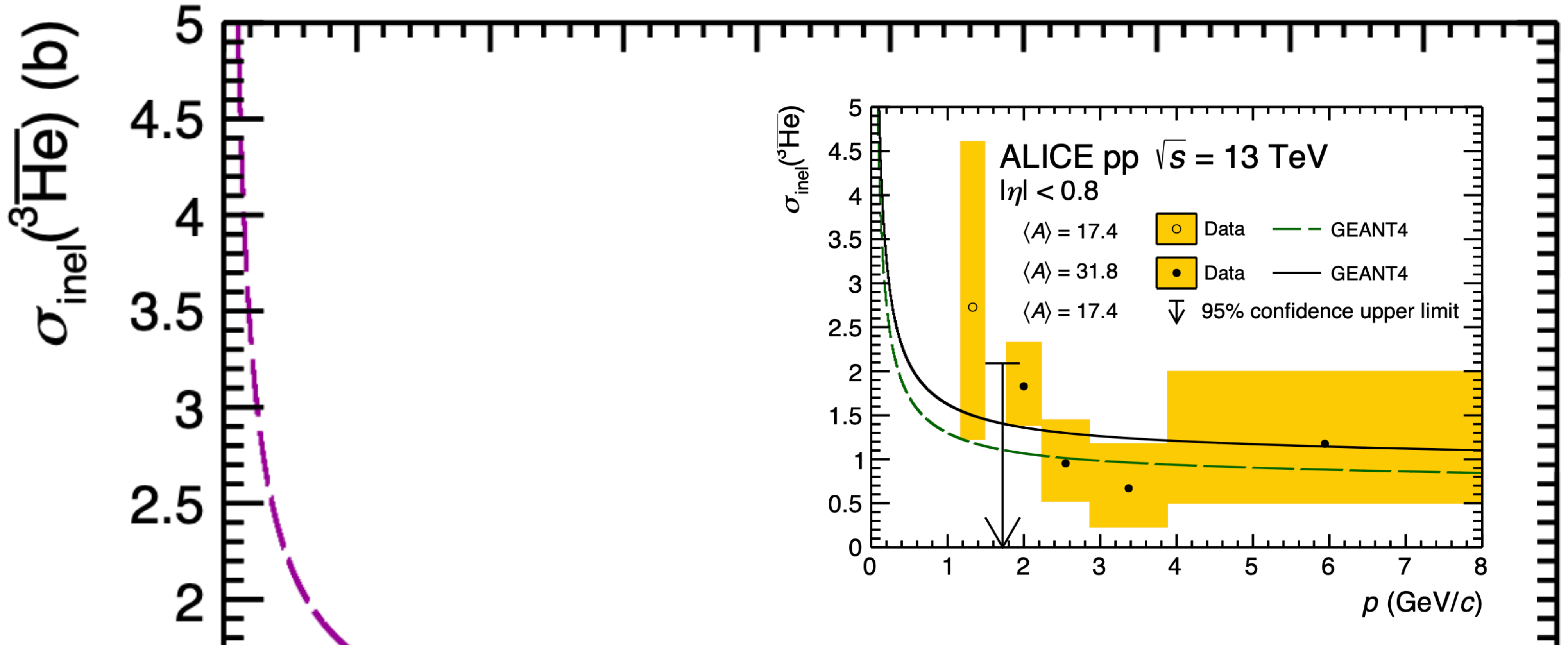

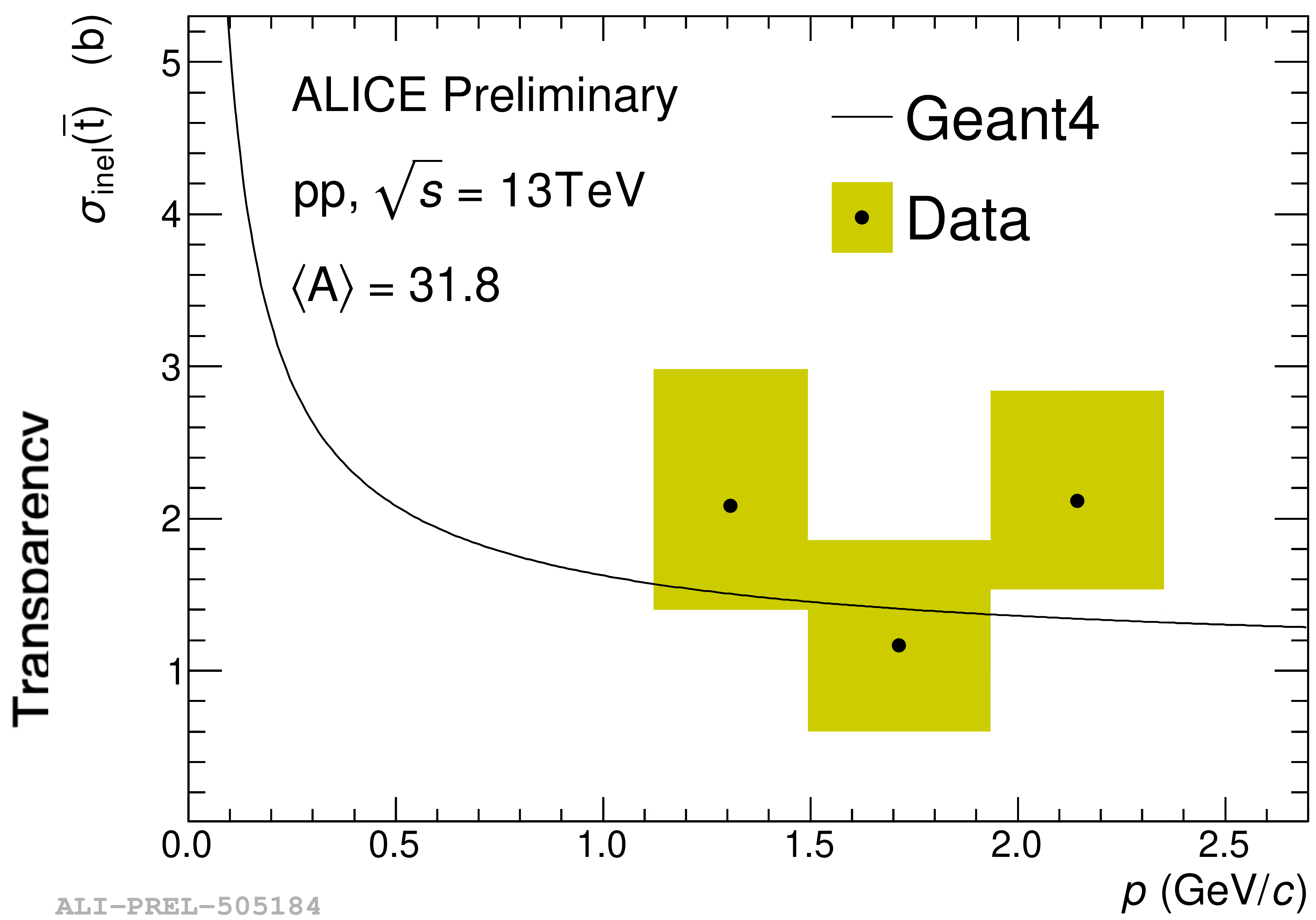

Summary and outlook

Measurement of σ_{inel} via comparison with detailed ALICE Monte Carlo simulations using Geant4

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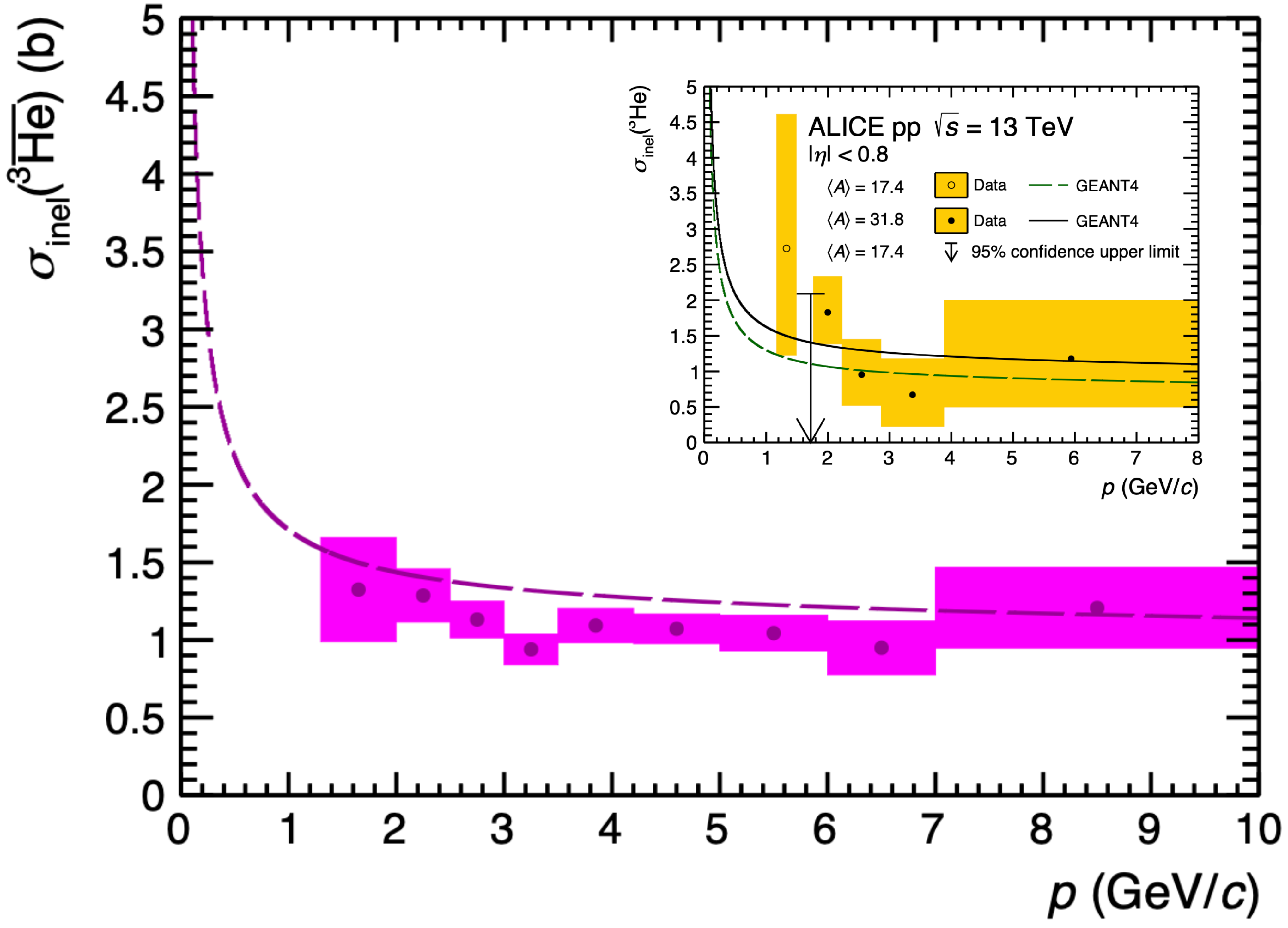

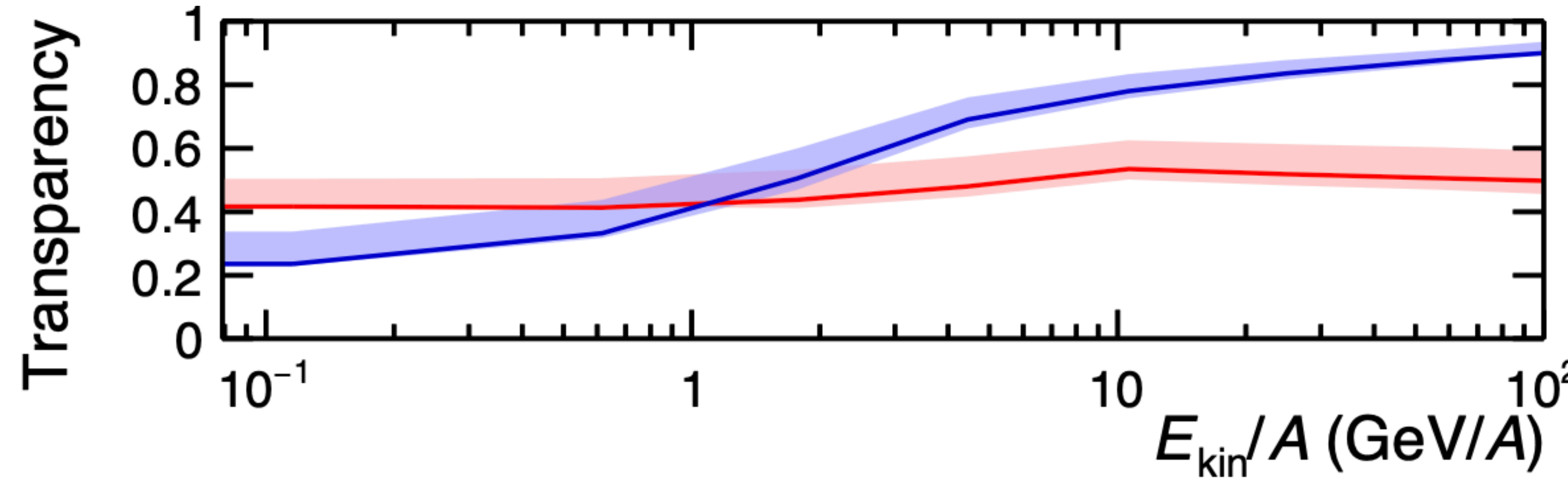

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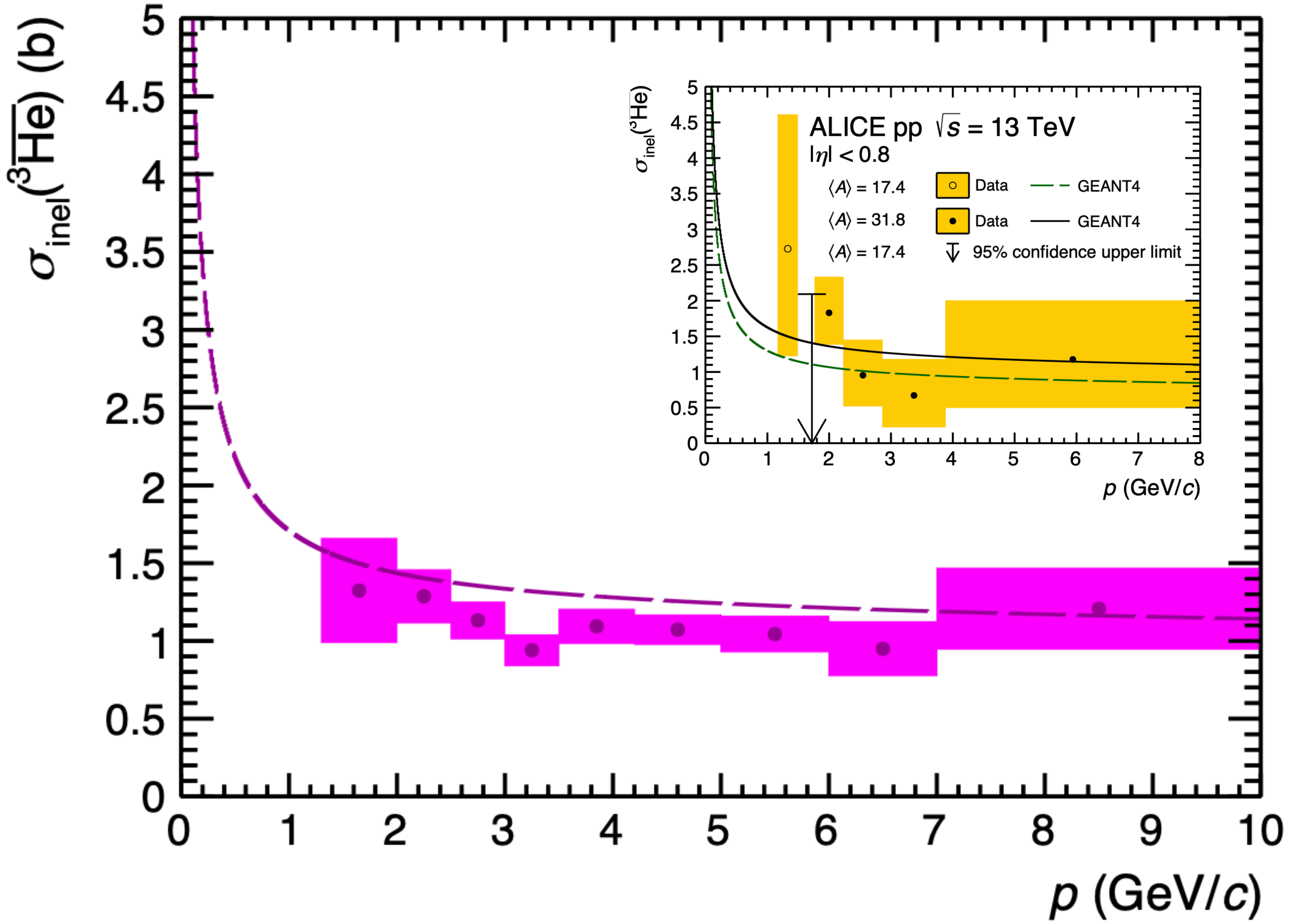

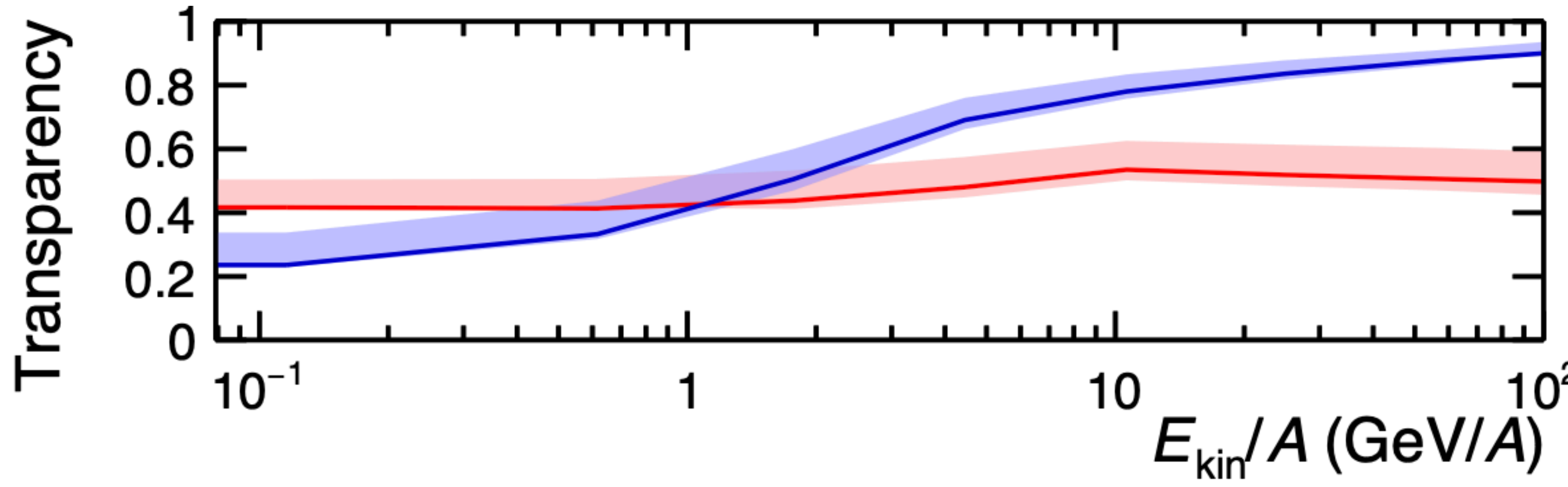

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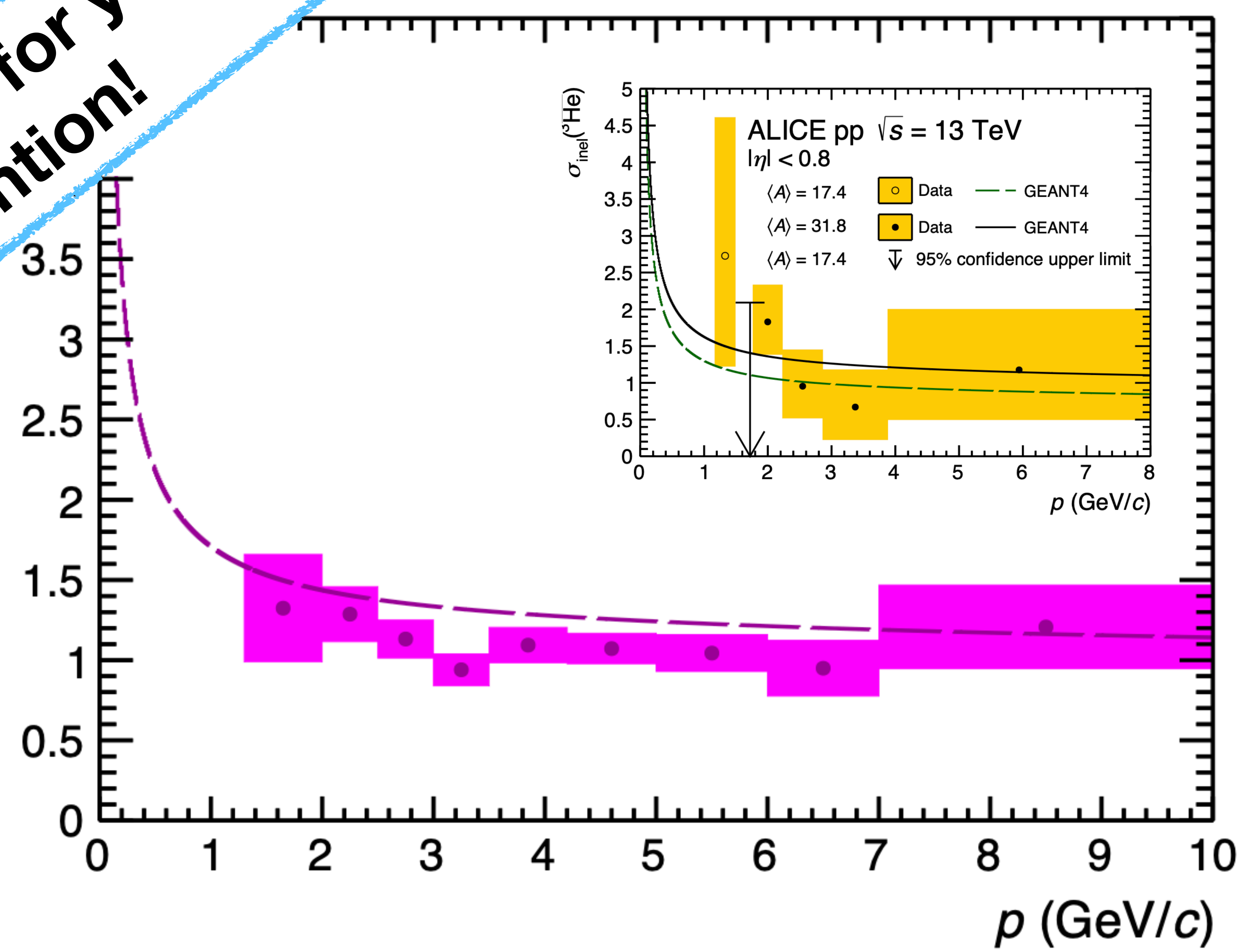

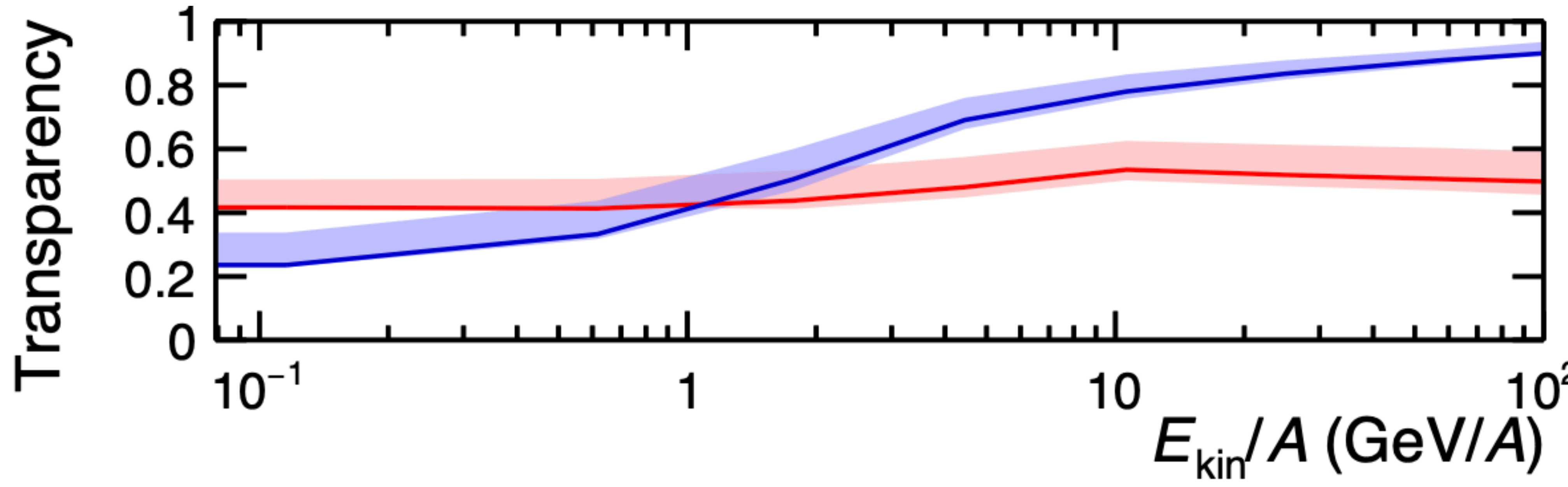

Back-up slides

Particle identification in TPC and TOF

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

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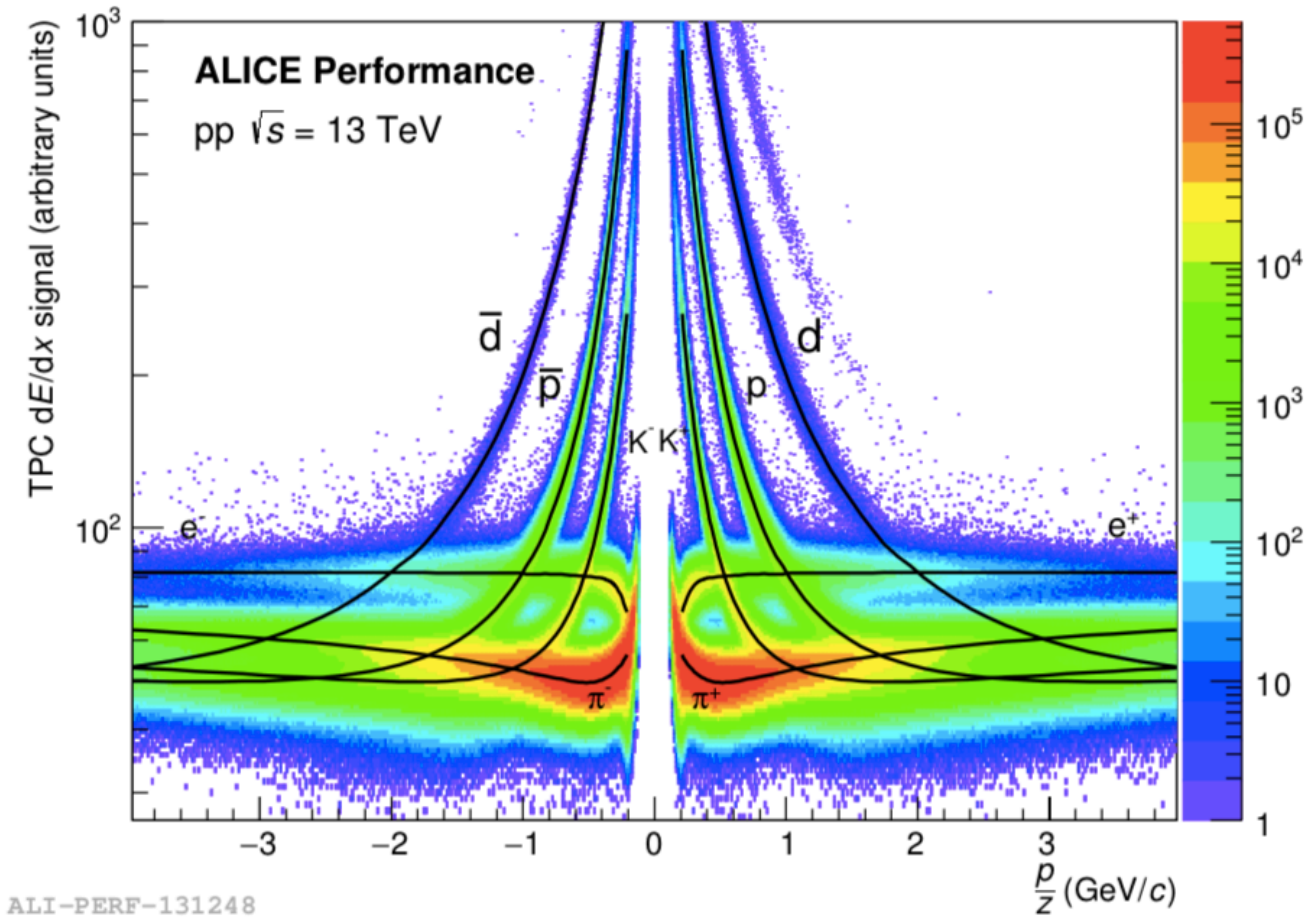

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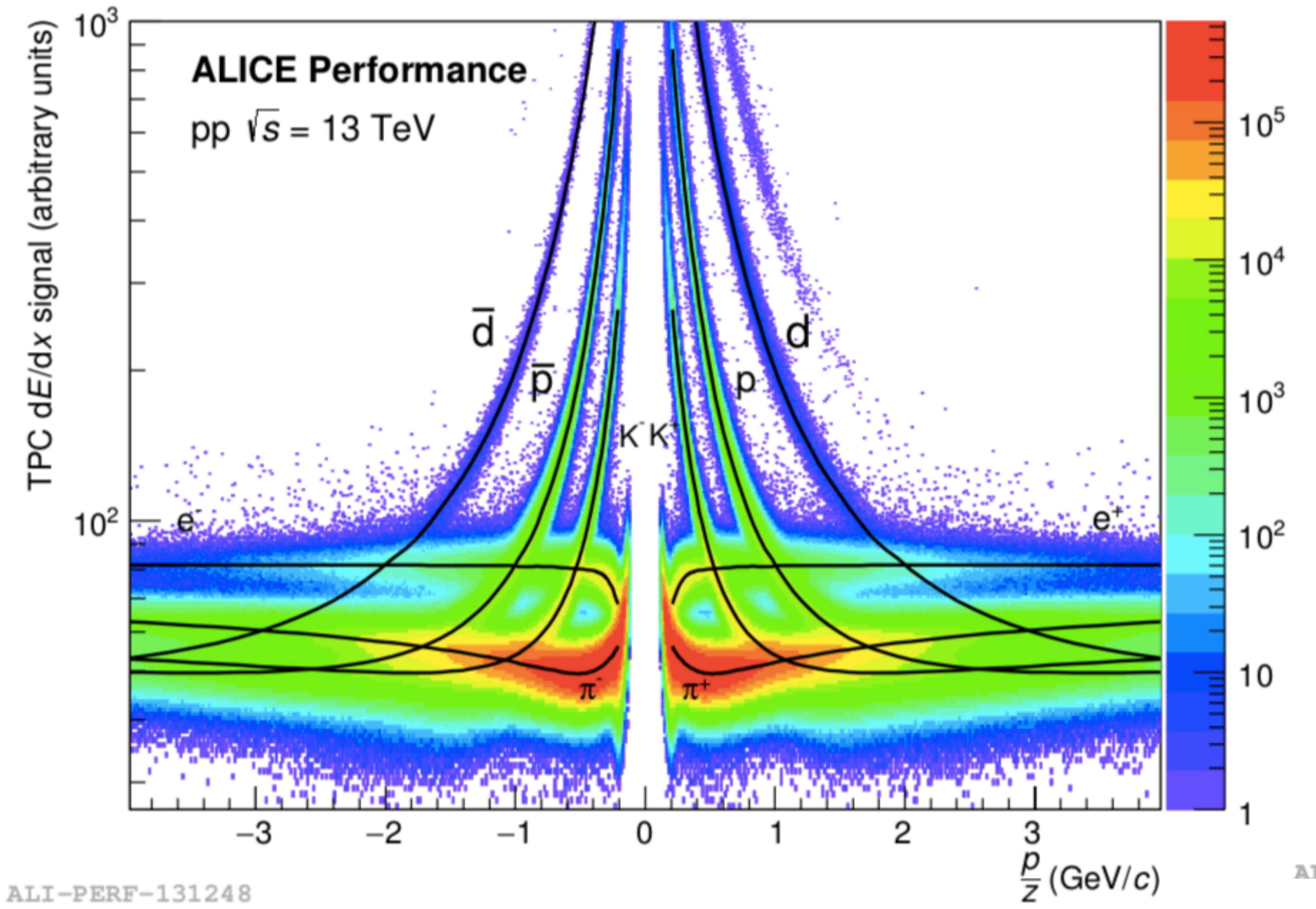

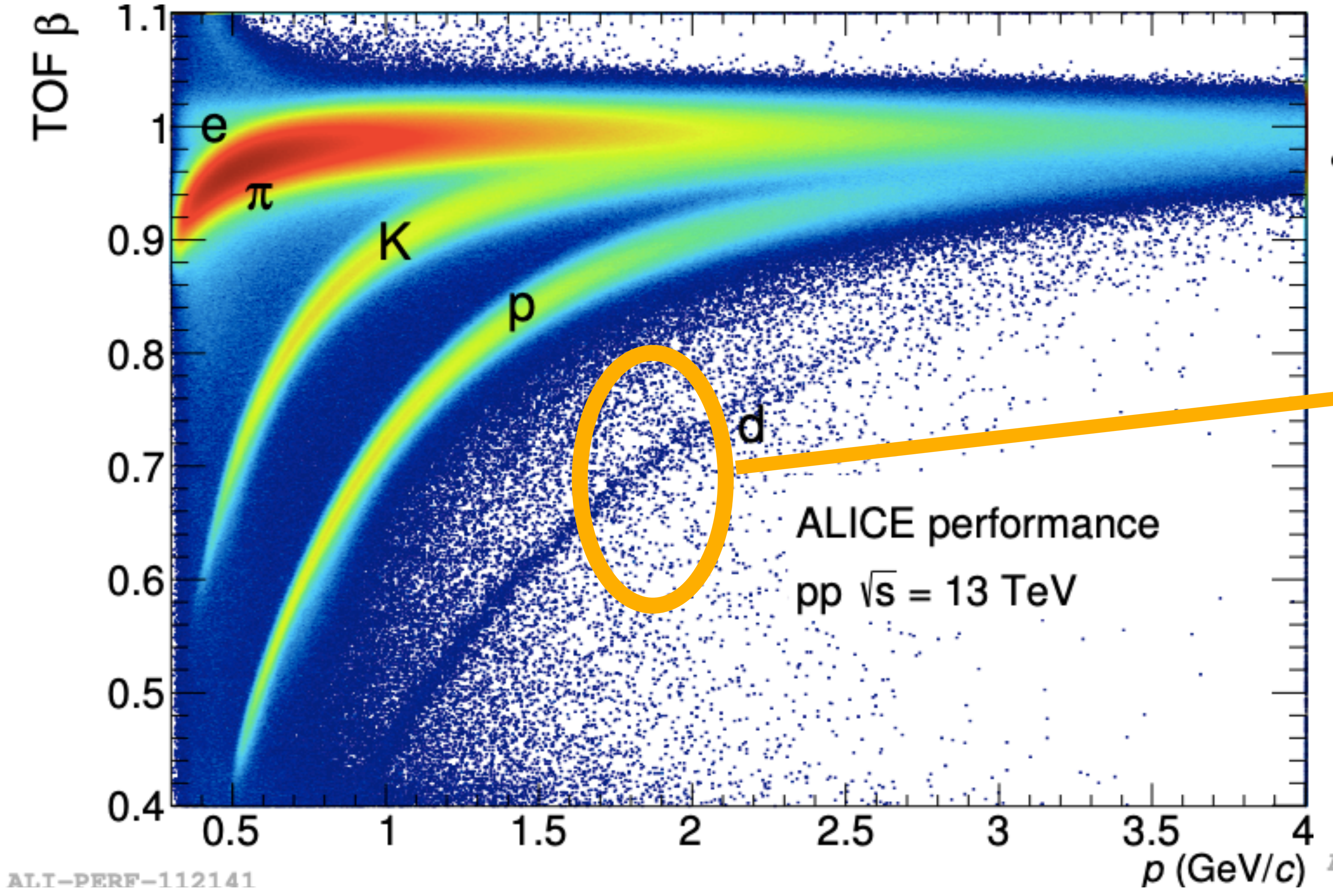

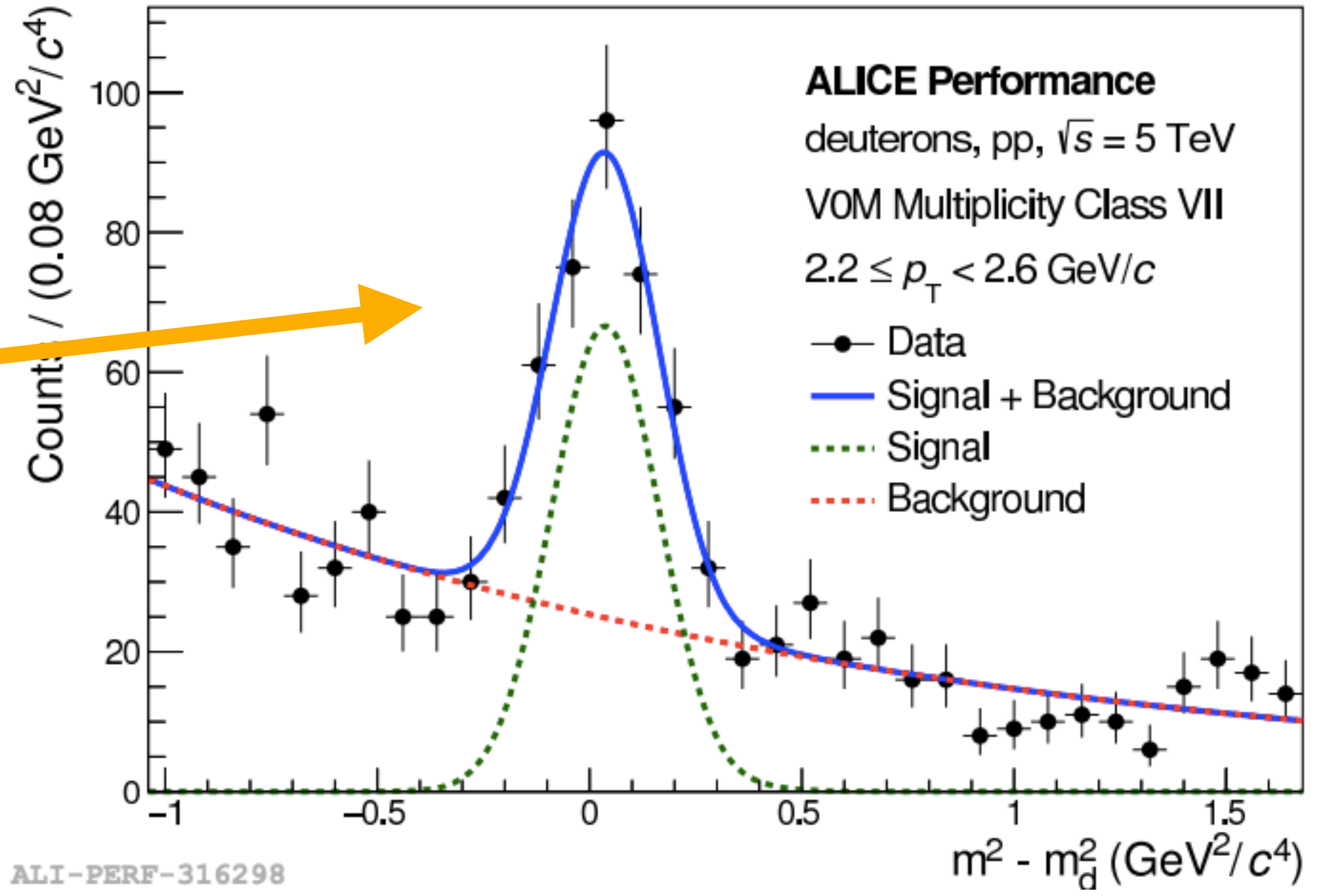

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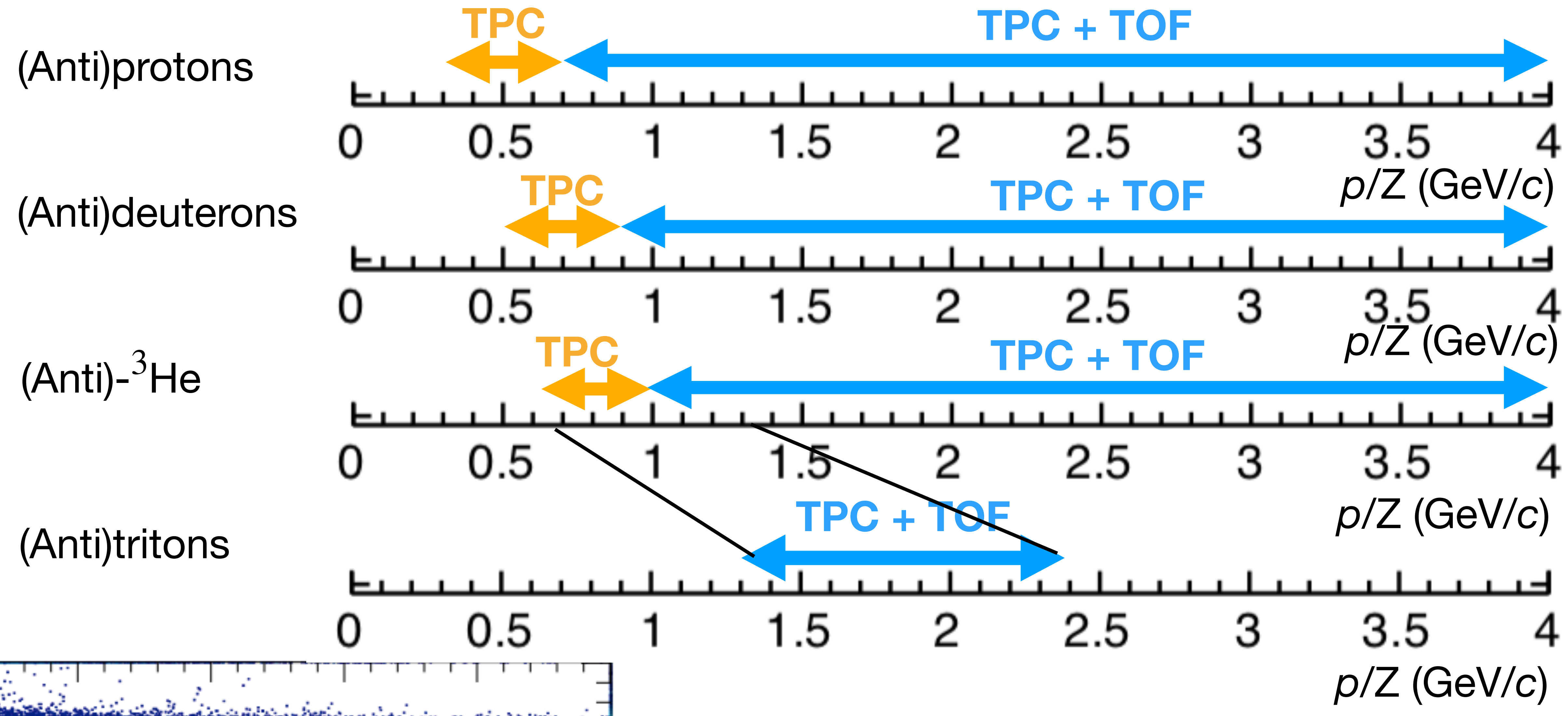
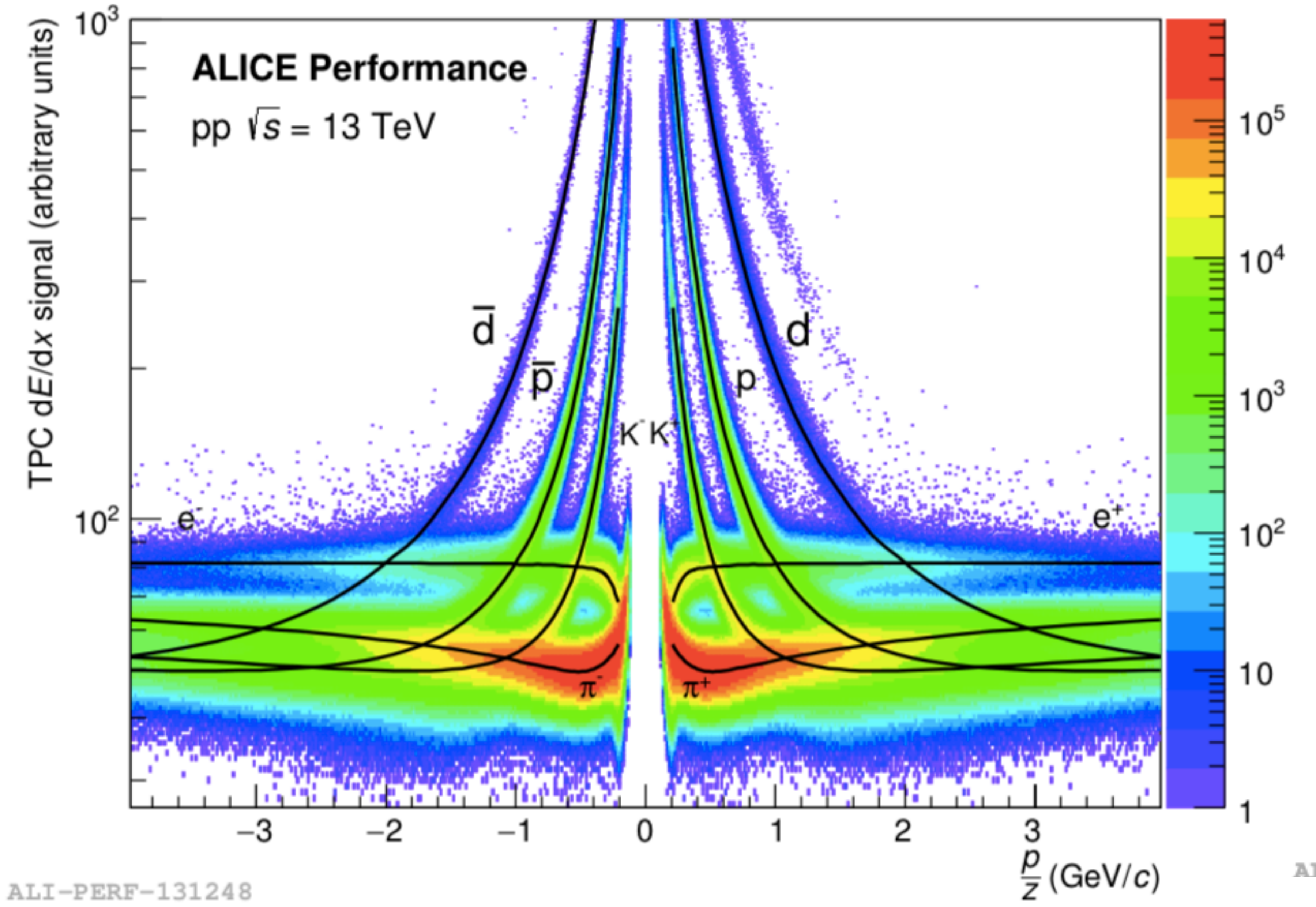
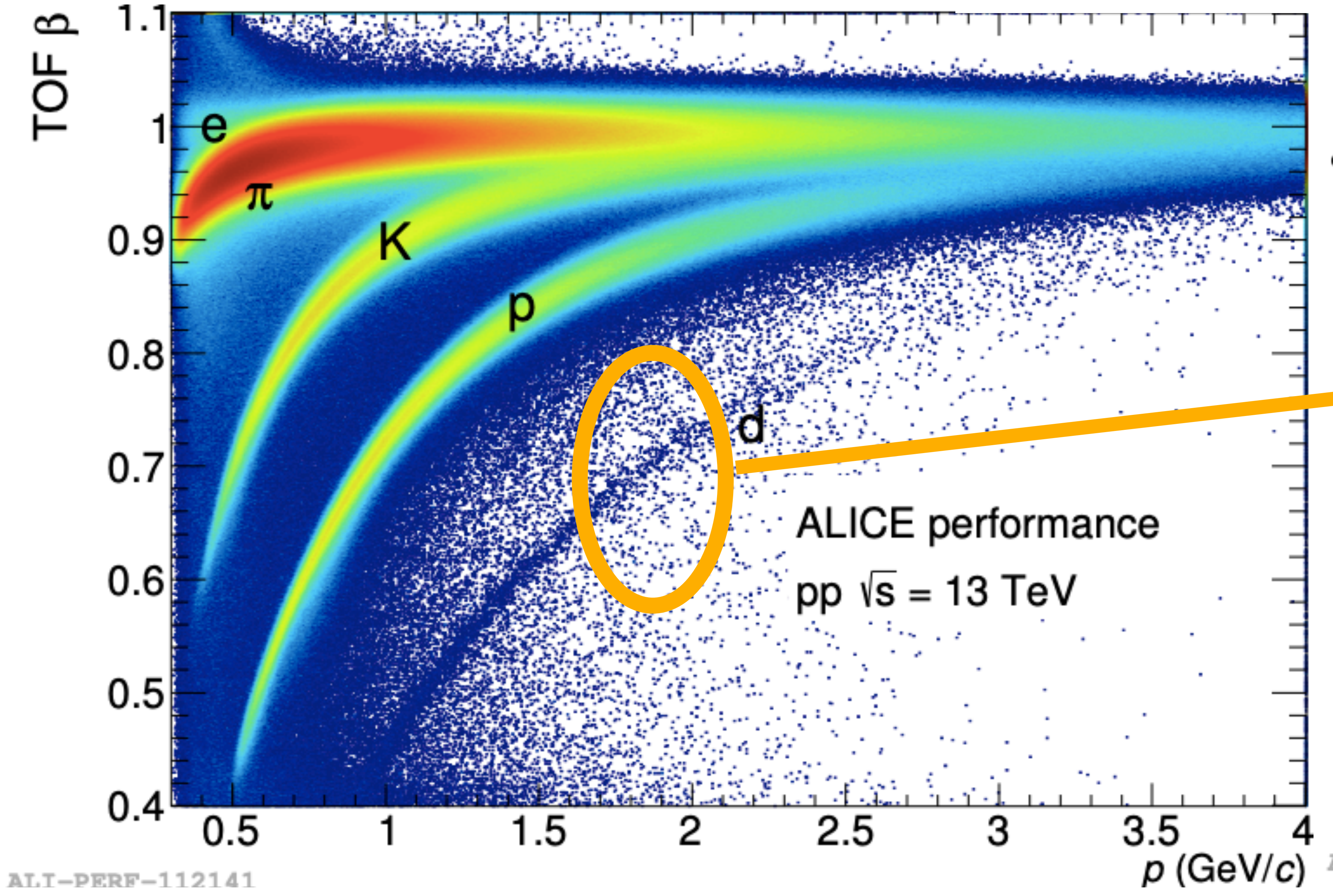
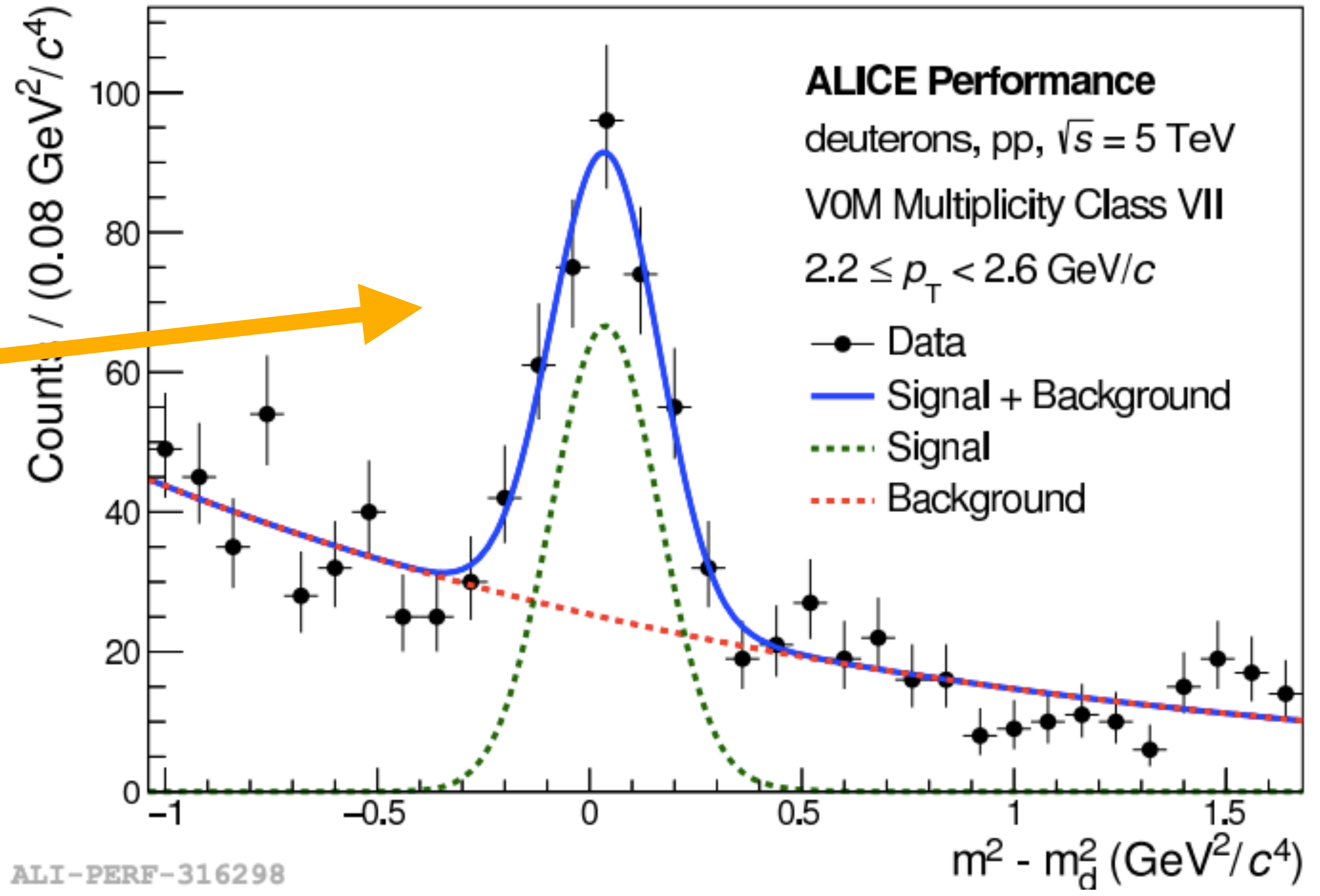




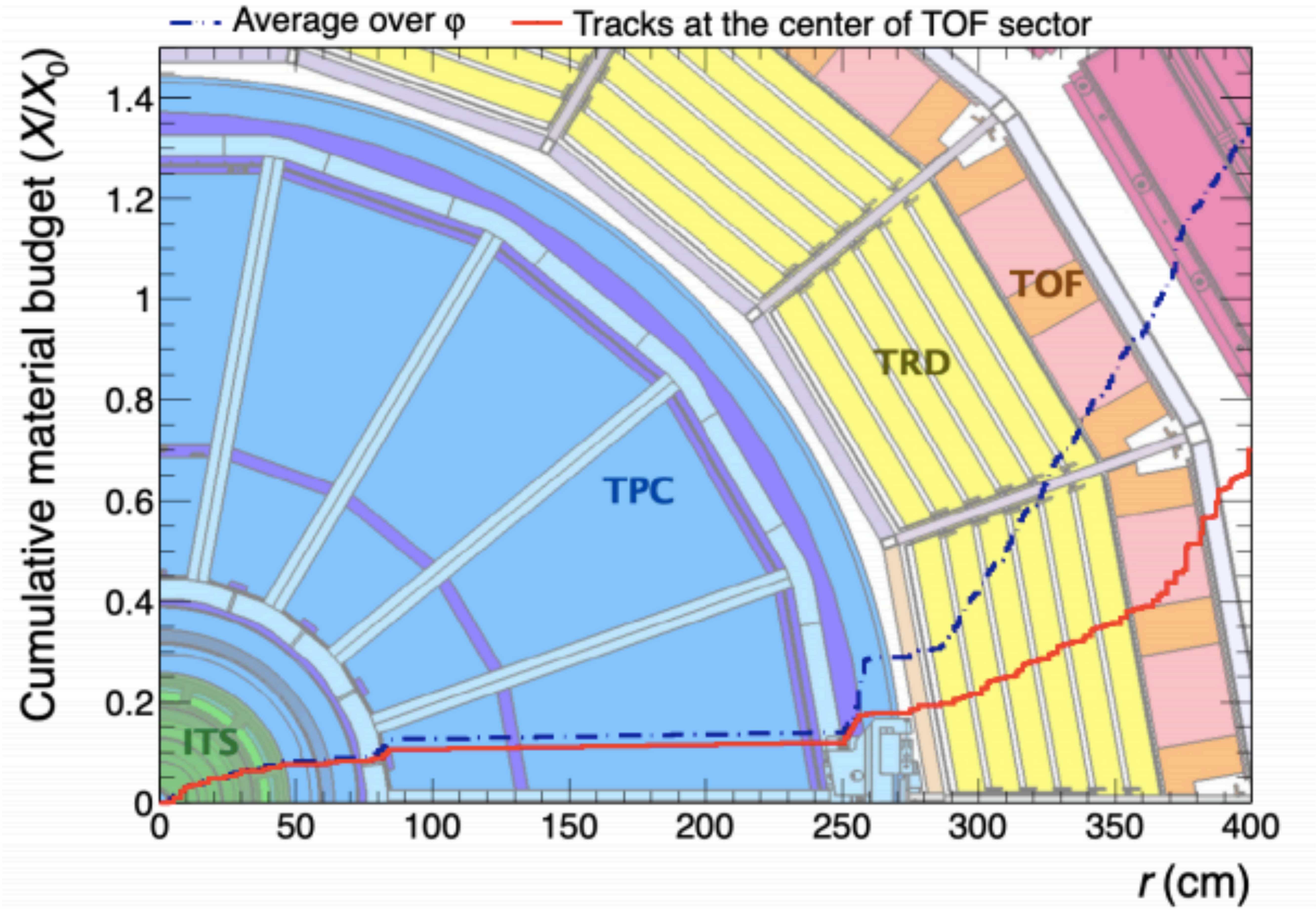




ALICE material budget

ALICE material budget at mid-rapidity [1]:

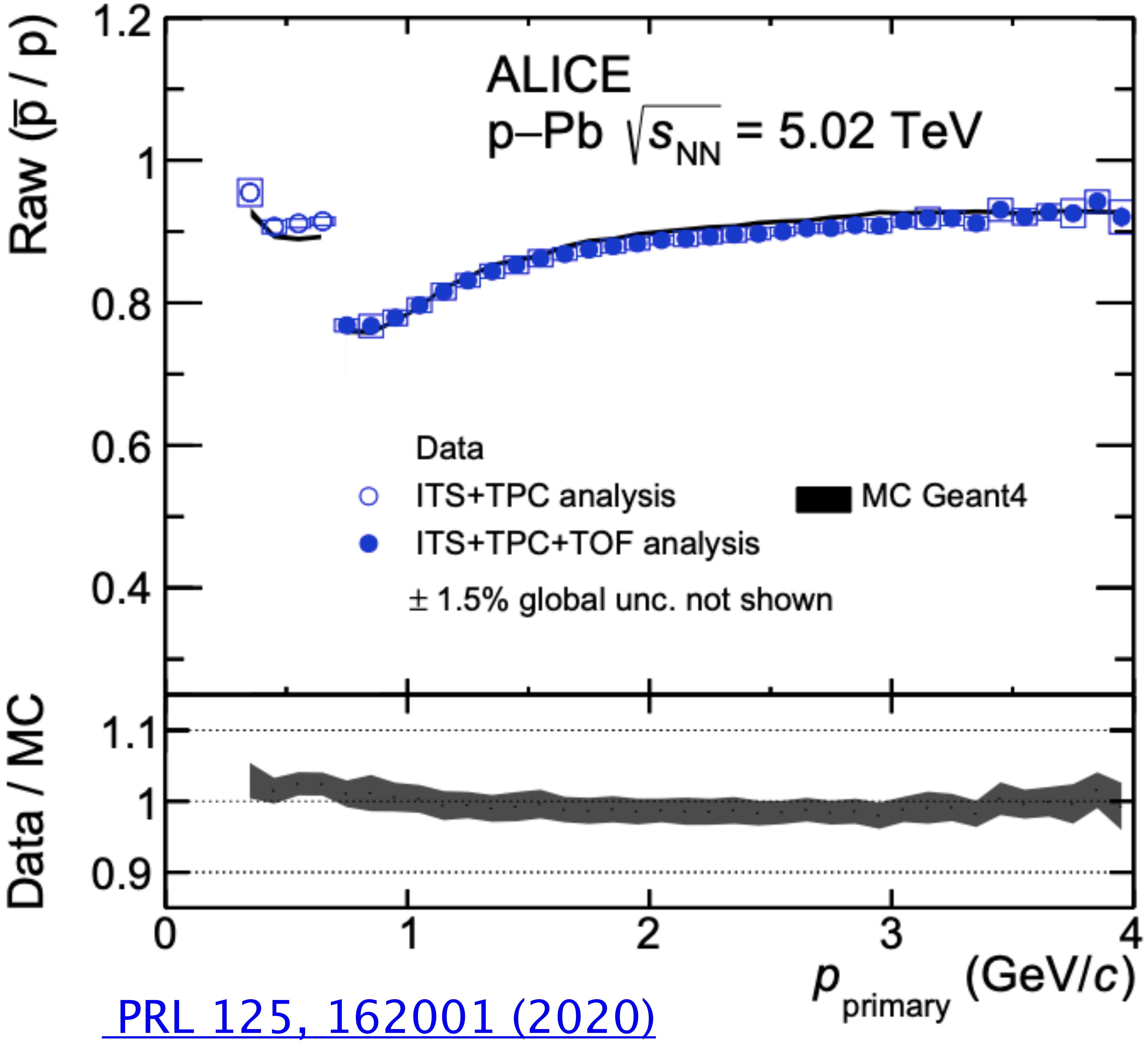
- **Beryllium beam pipe (~0.3% X_0)**
- **ITS (~8% X_0)**
- **TPC (~4% X_0)**
- **TRD (~25% X_0)**
- **Space frame (~20% X_0** between TPC and TOF)



PRL 125, 162001 (2020)

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

Raw primary antiproton-to-proton ratio



PRL 125, 162001 (2020)

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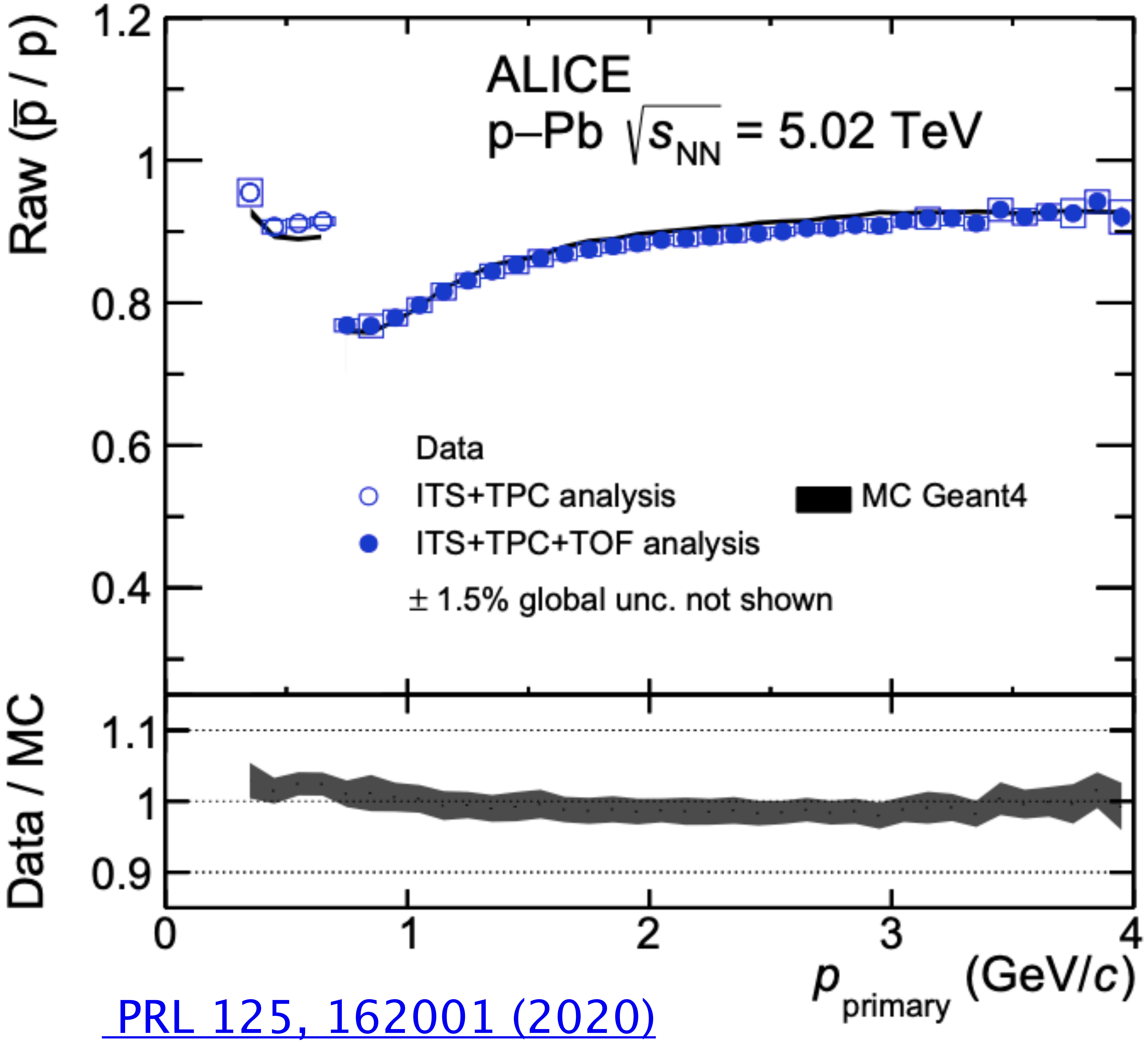

PRL 125, 162001 (2020)

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

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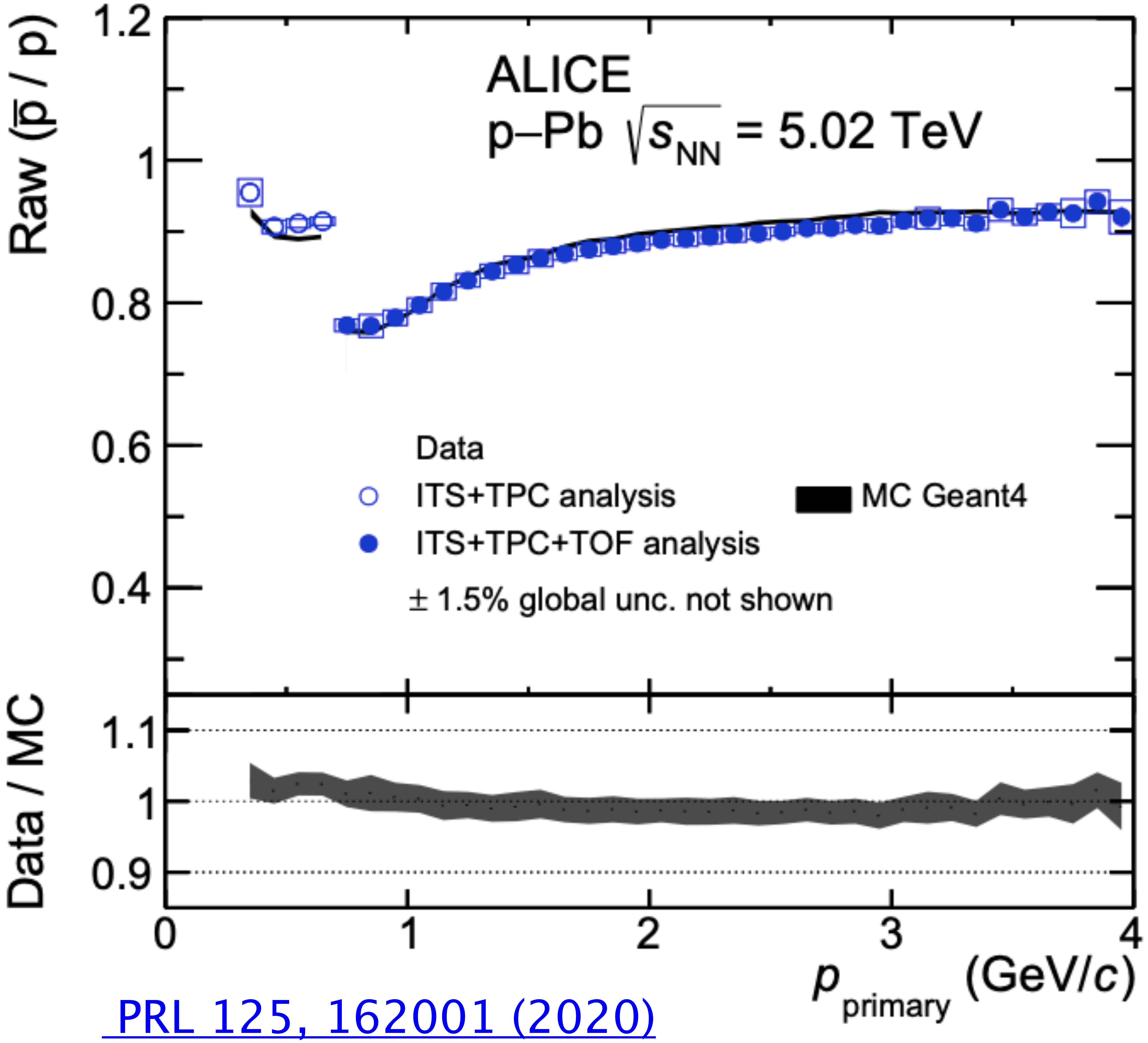

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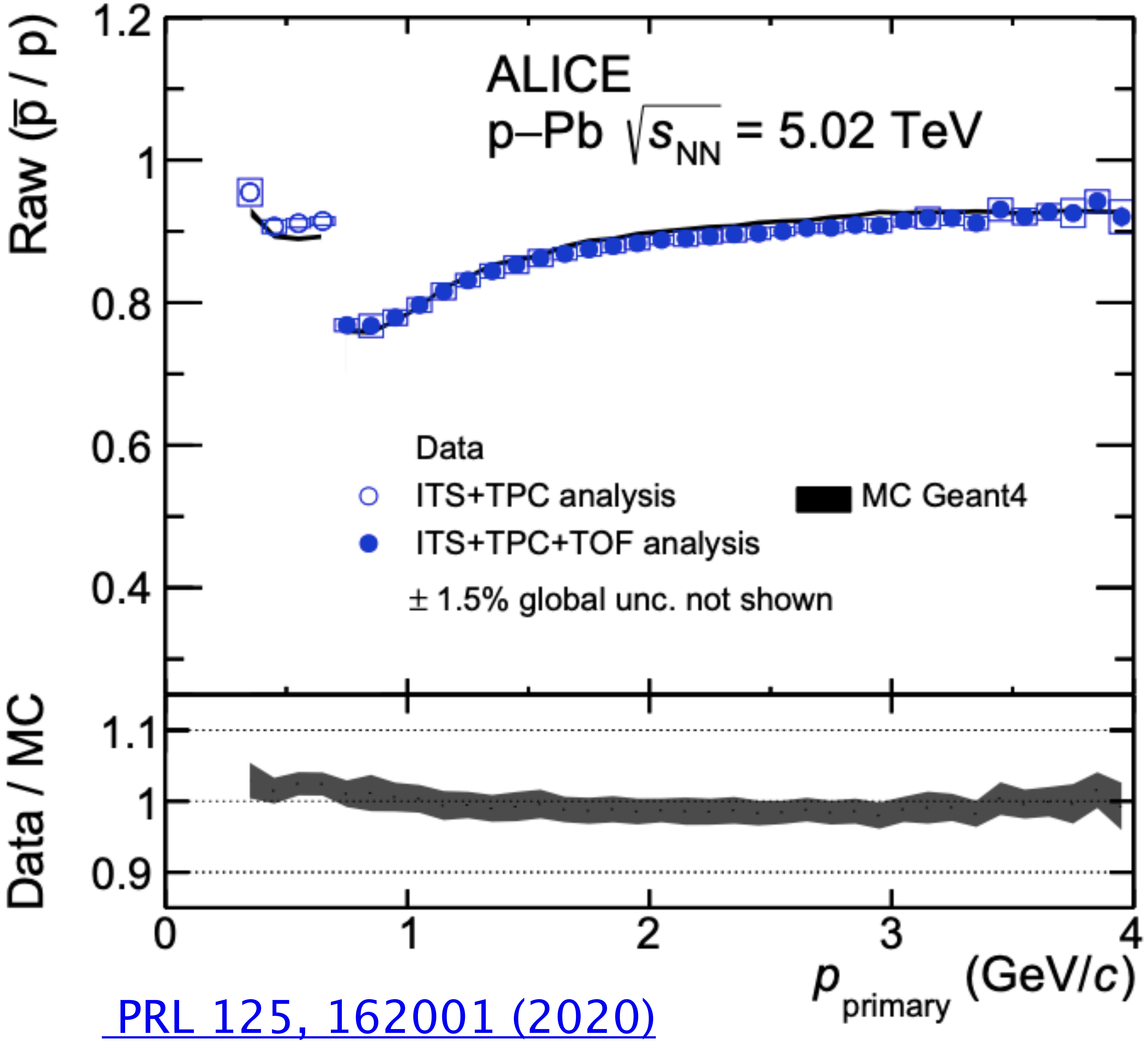

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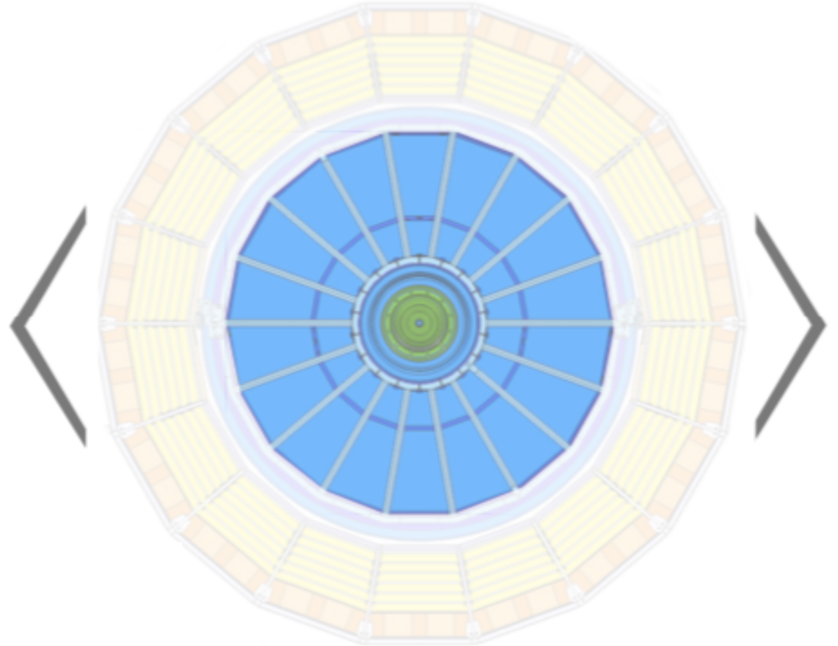
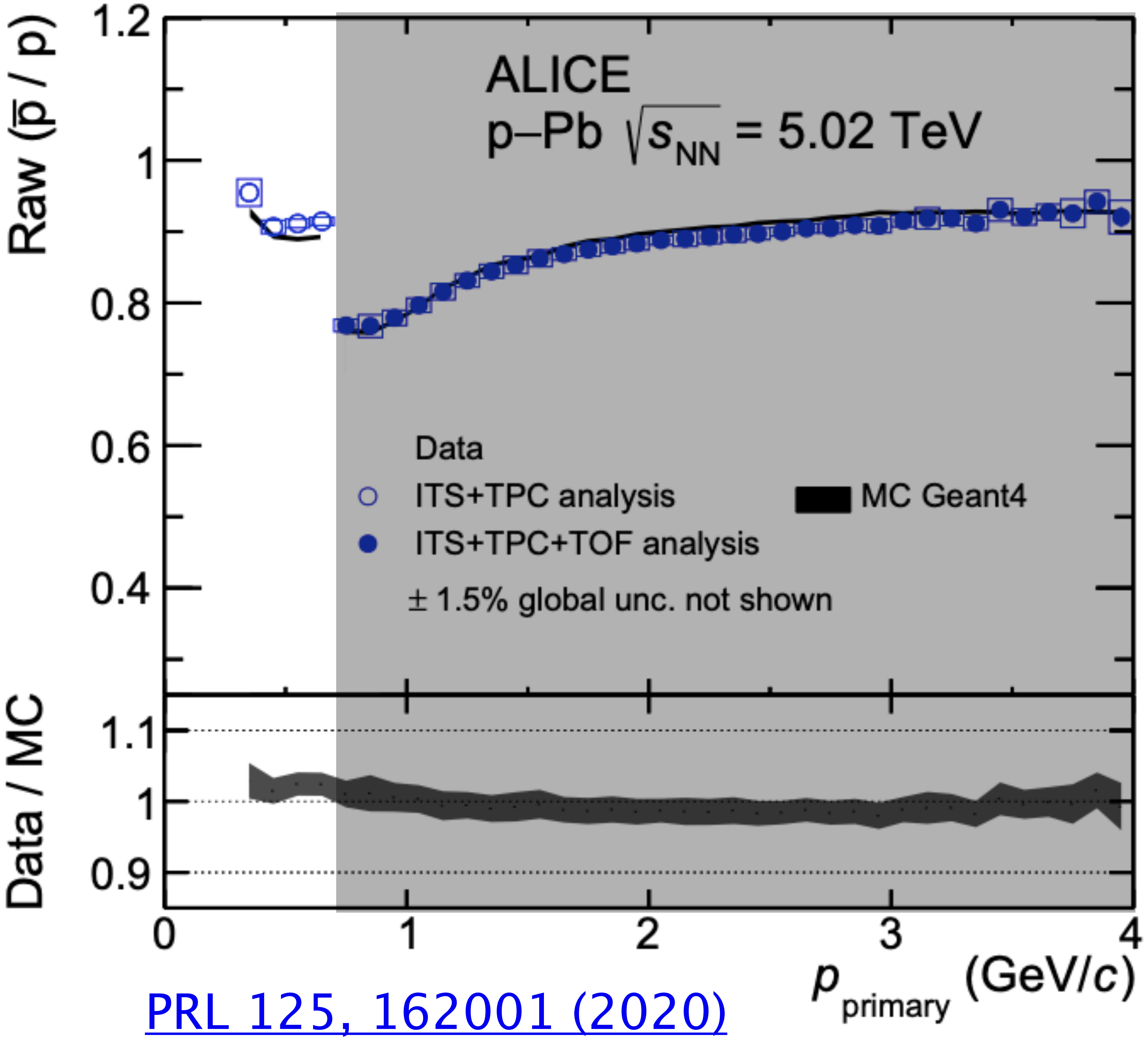
➡Agreement between data and MC confirms the correctness of the procedure.

Antiproton inelastic cross section

$\sigma_{\mathrm{inel}}(\bar{\mathrm{p}})$ on average ALICE detector material.

Good agreement with Geant4 parameterization.





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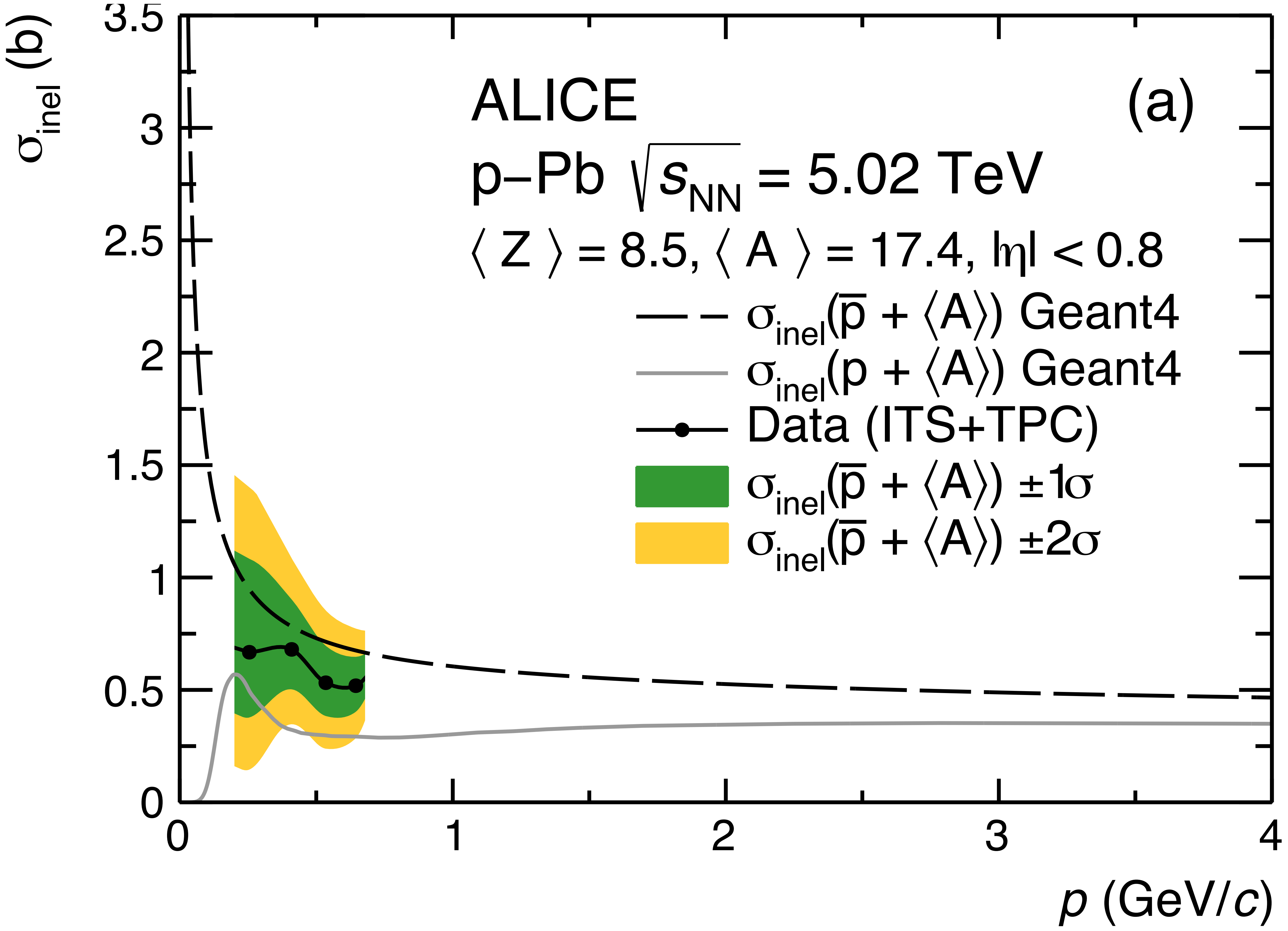

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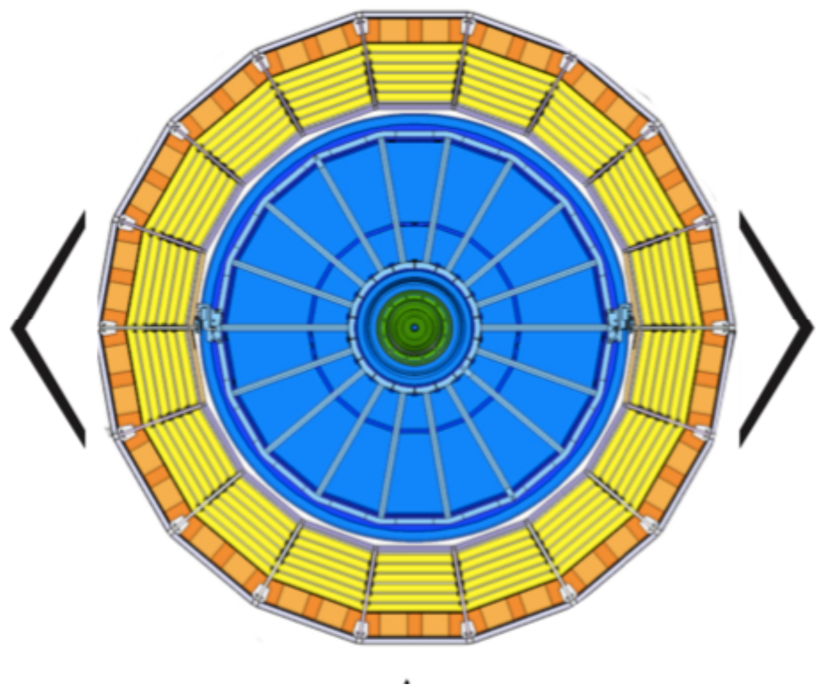

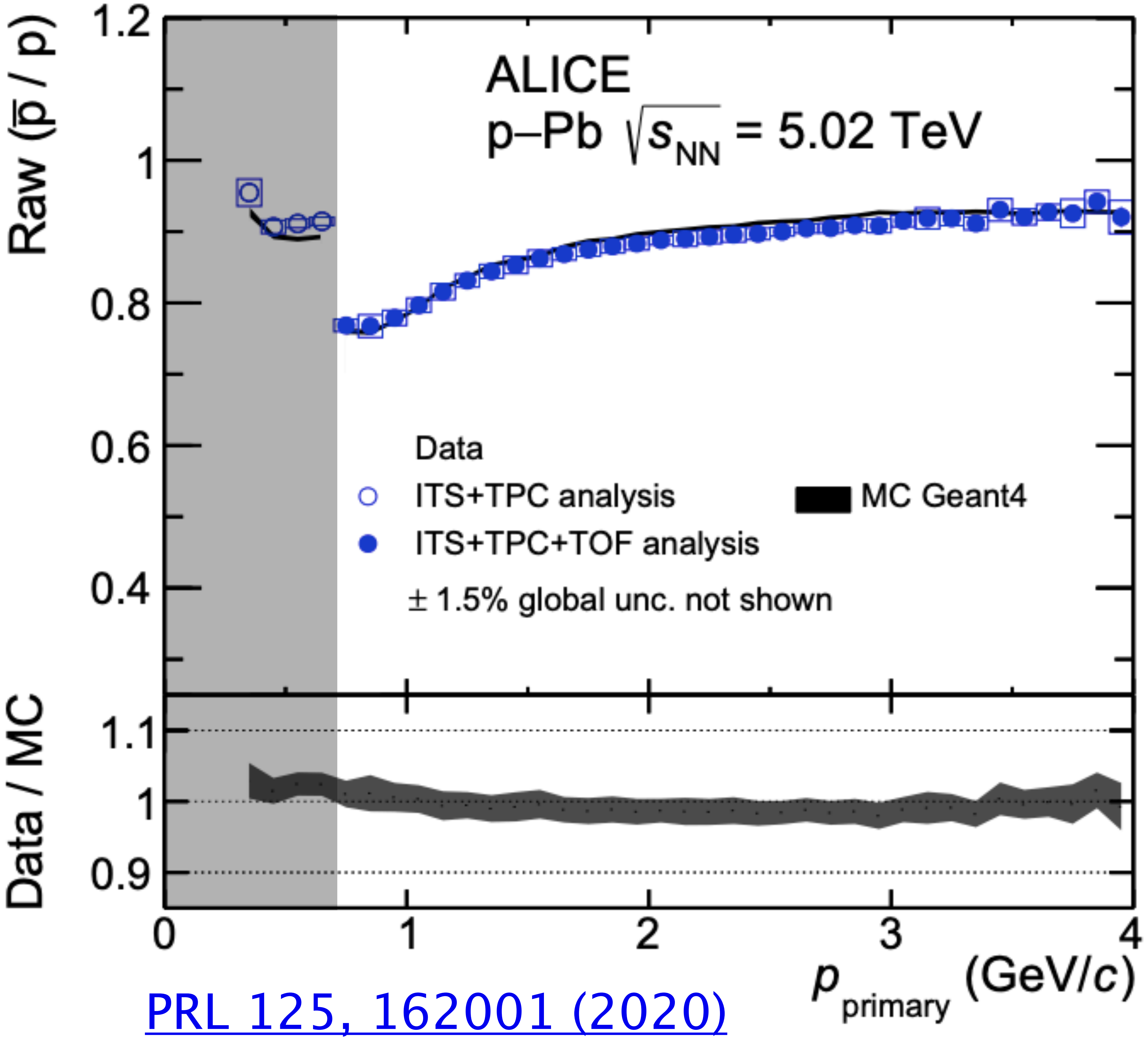

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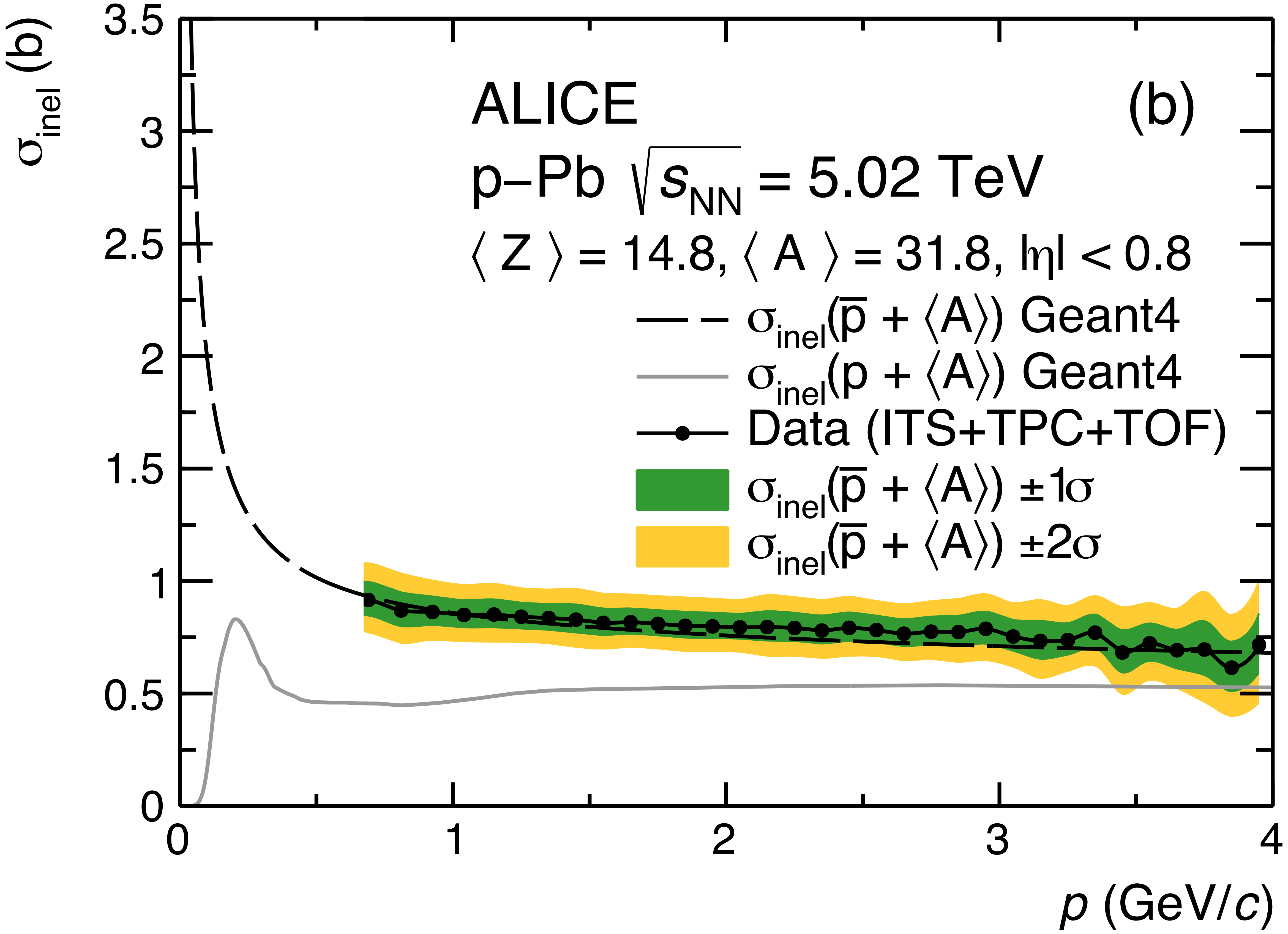
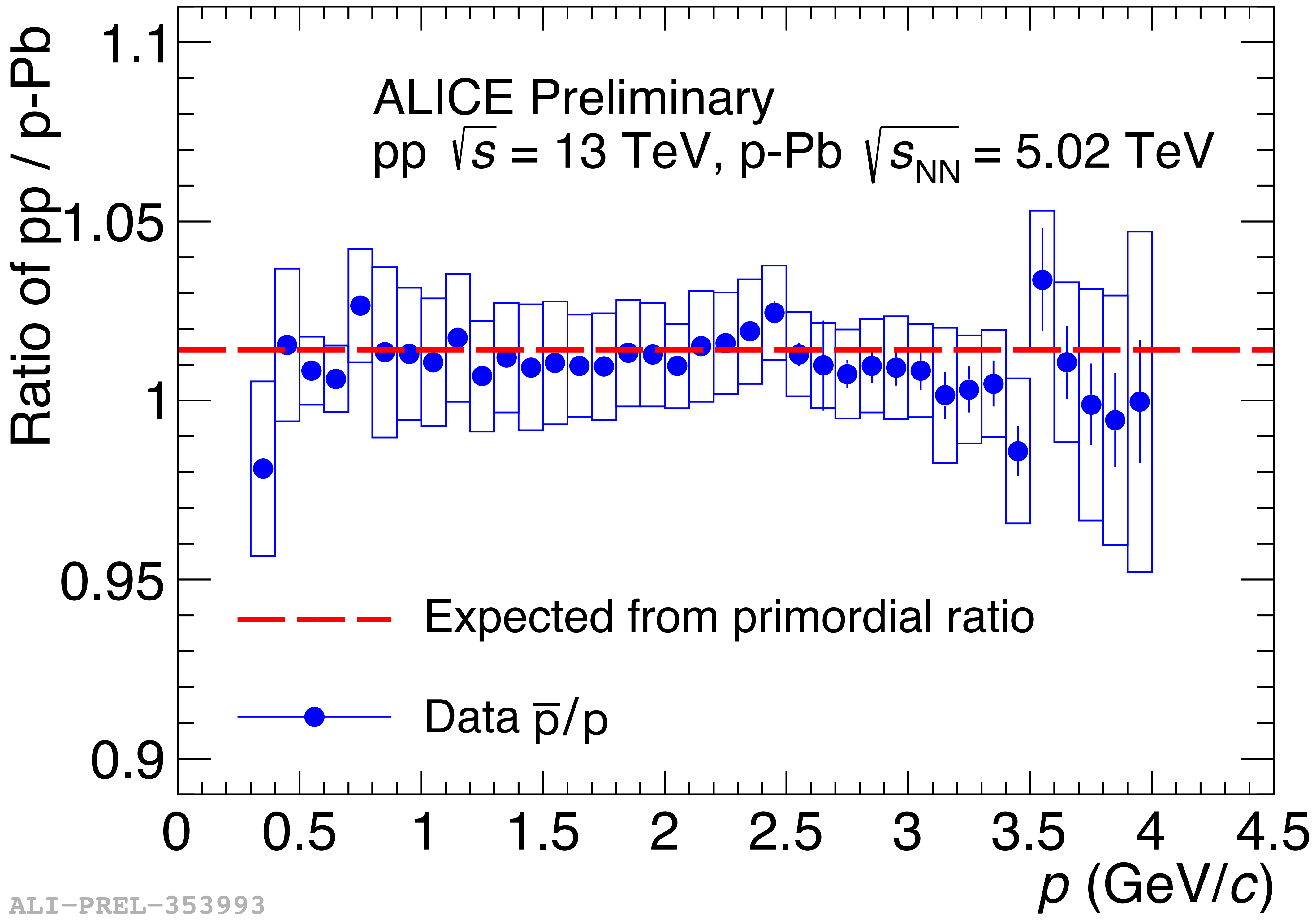
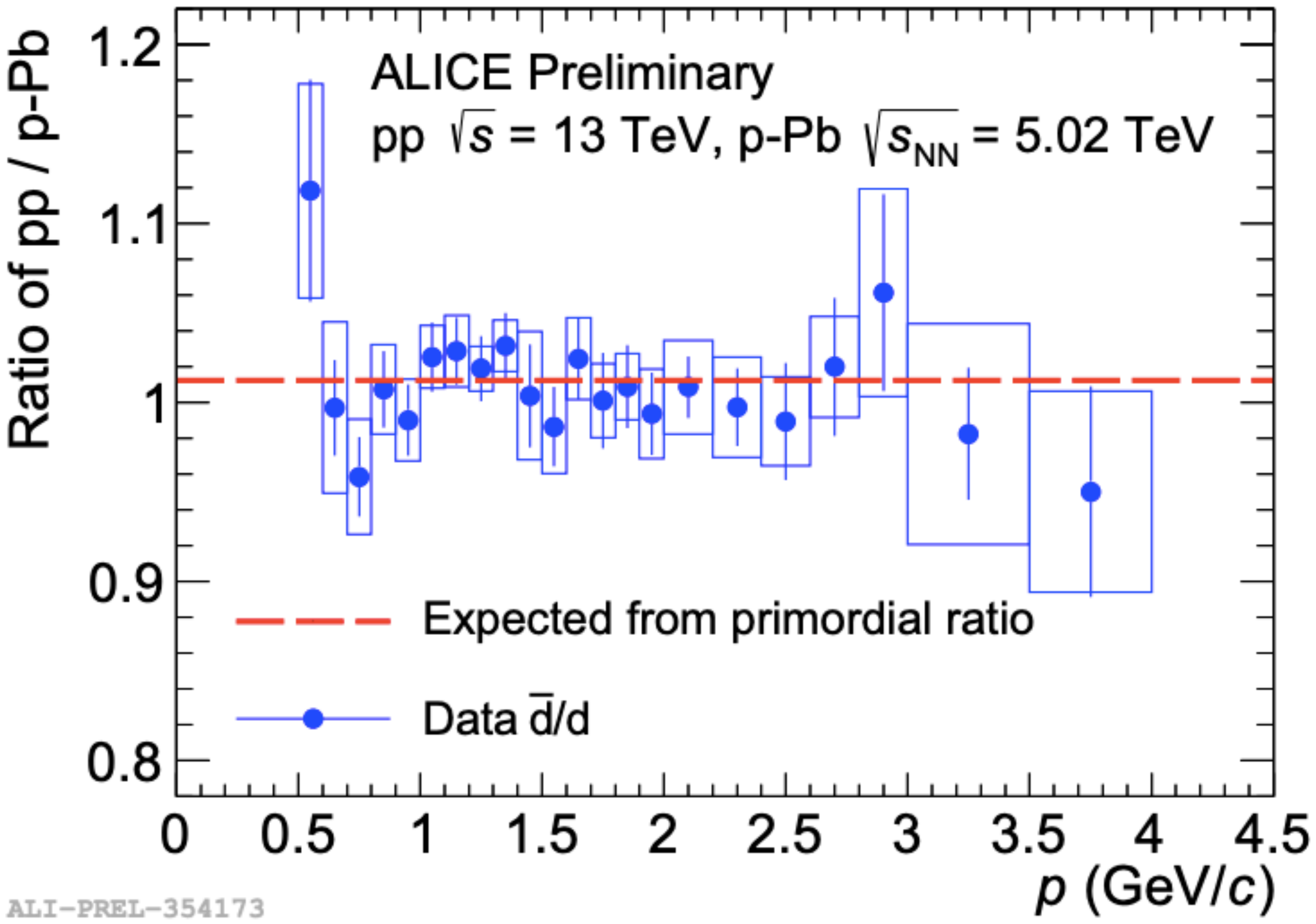


Comparison of pp and p-Pb systems





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.

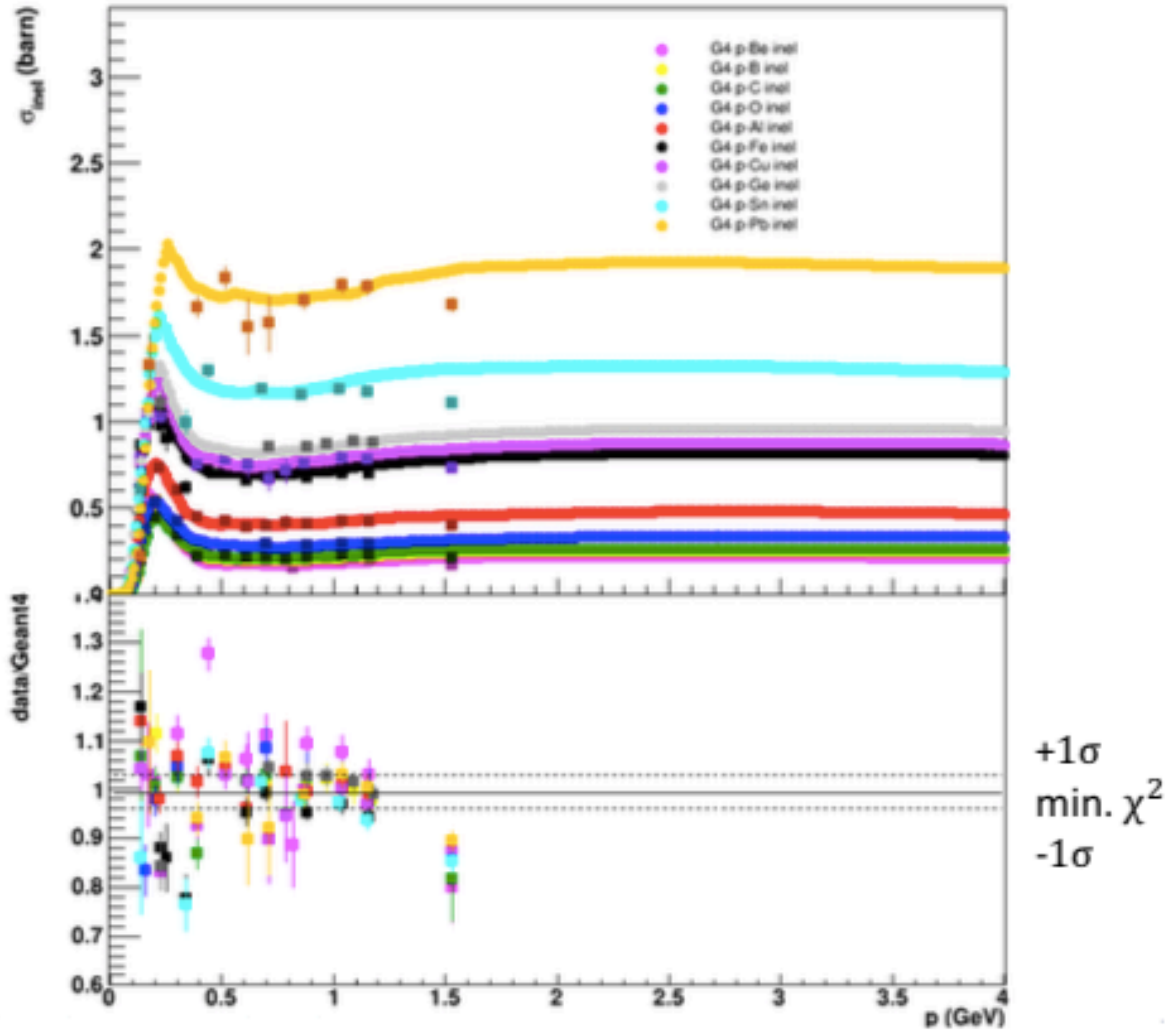
➡The cross section measurements are independent of the collisions system, as expected.

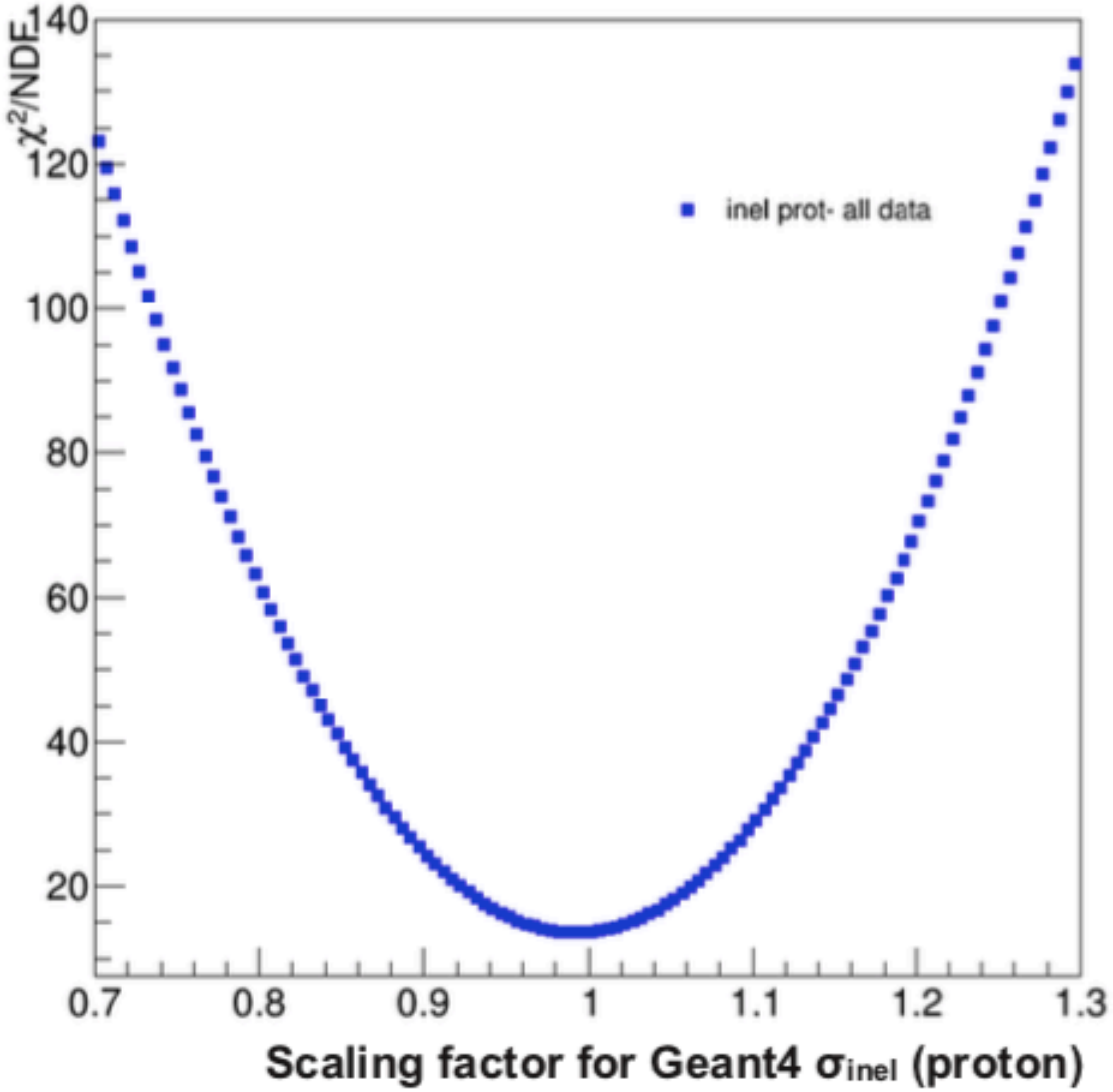
➡Analysis method is consistent.

Uncertainty due to σ_{inel} (proton)

How precise σ_{inel} (proton) is described by Geant4?

- Check available experimental data (Be,B,C,O,Al,Fe,Cu,Ge,Sn,Pb)
- Vary Geant4 parametrisation, calculate χ^2 for all data points
- Minimum χ^2 and ±1σ : **0.9925** $^{+0.0375}_{-0.0325}$





Parameterisations used in GEANT4

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

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

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

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

For total cross-section:

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

For inelastic cross-section:

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

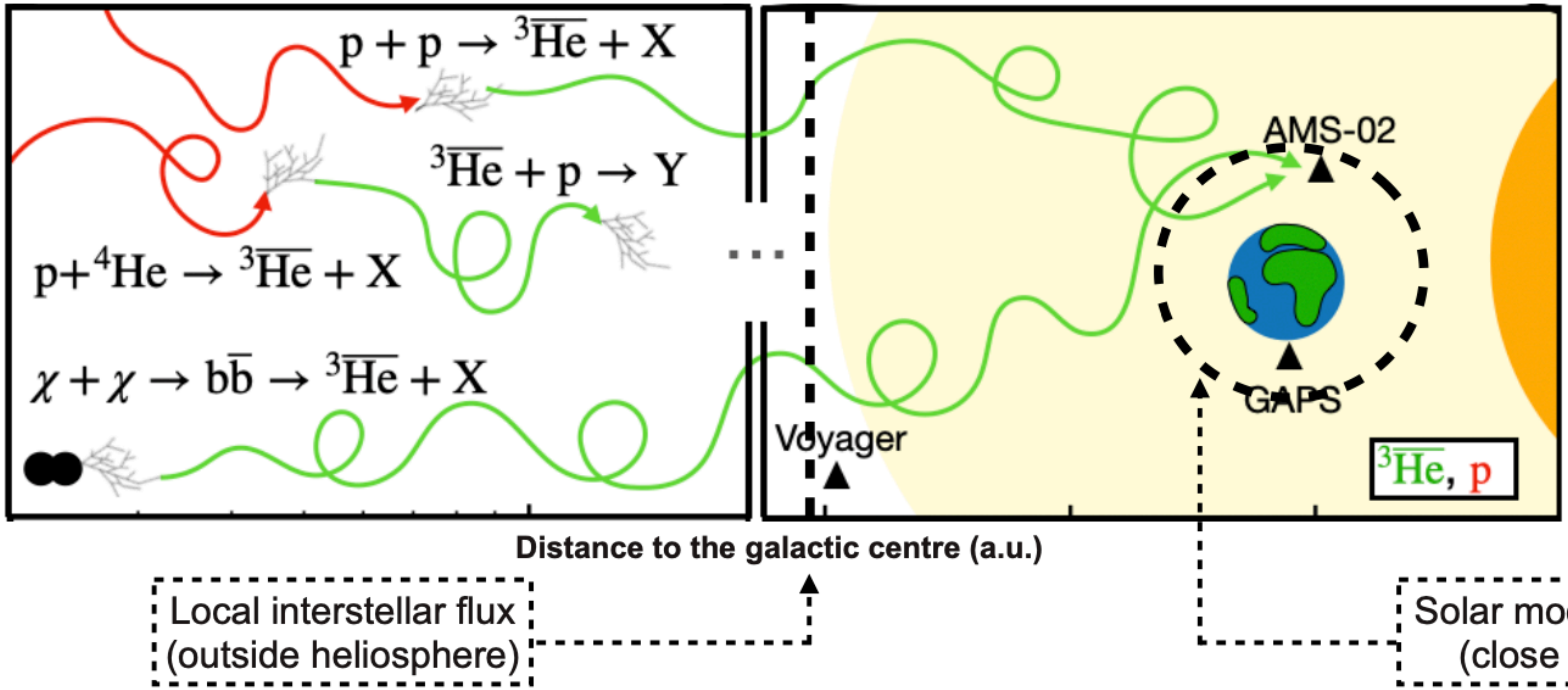
[1] V.M. Grichine, Eur. Phys. J. C 62 (2009) 399, Nucl. Instrum. Methods B 267 (2009) 2460

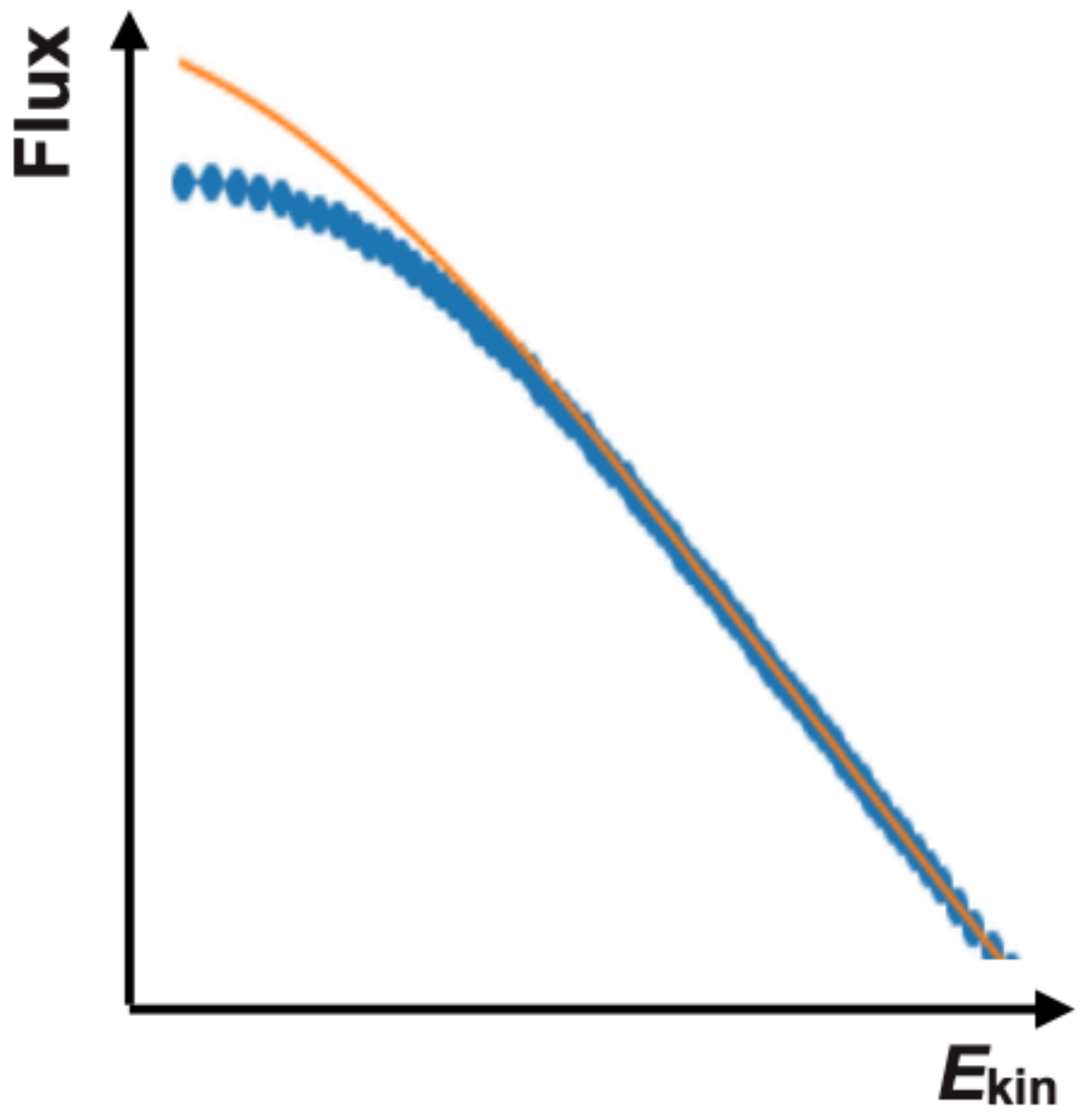
Solar environment effects

Solar magnetic field forms heliosphere which shields cosmic rays.

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

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

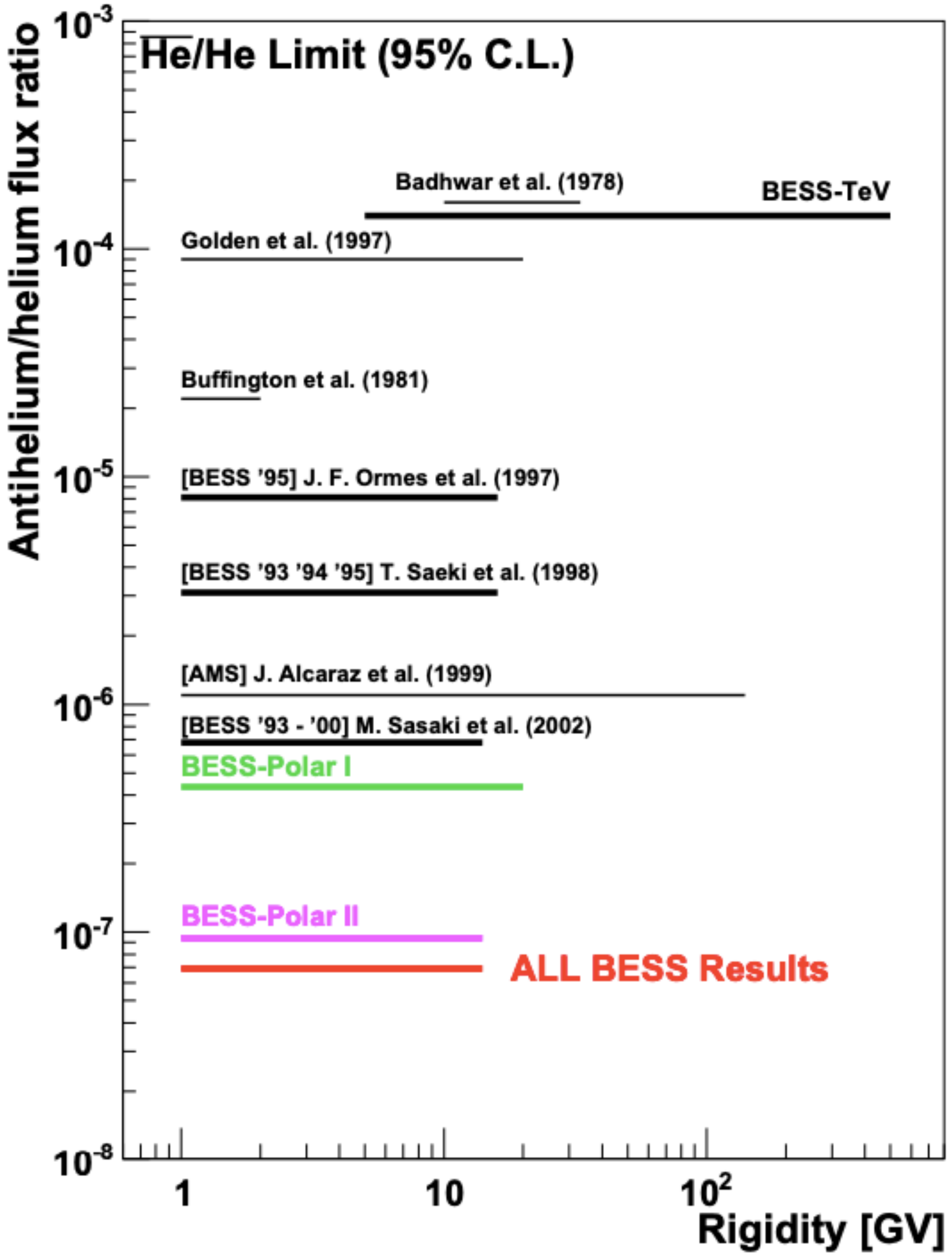




[1] Gleeson, Axford, Astrophys. J. 154 (1968) 1011

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

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



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

[1] Abe et. al. , 2012, arXiv:1201.2967 [astro-ph.CO]
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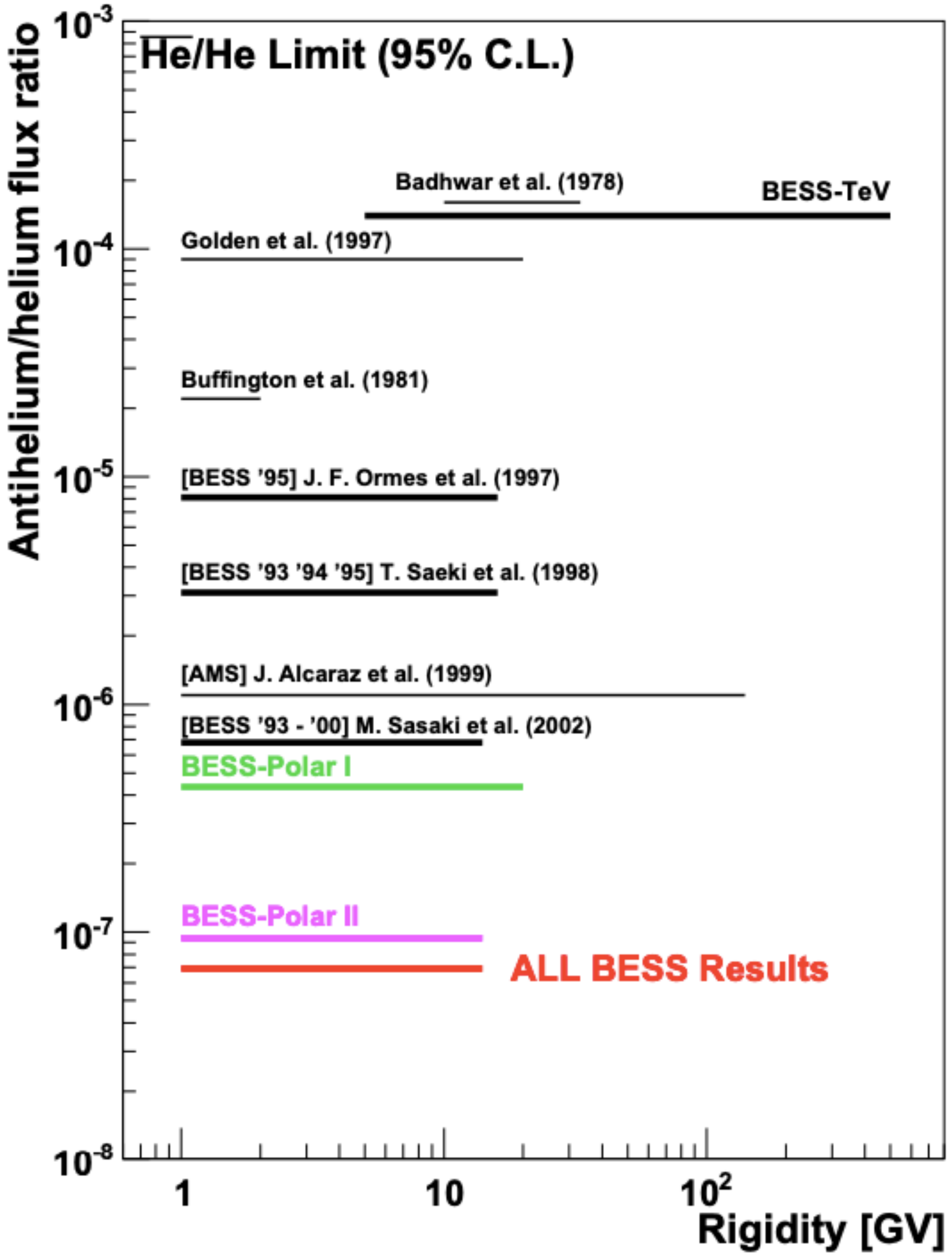

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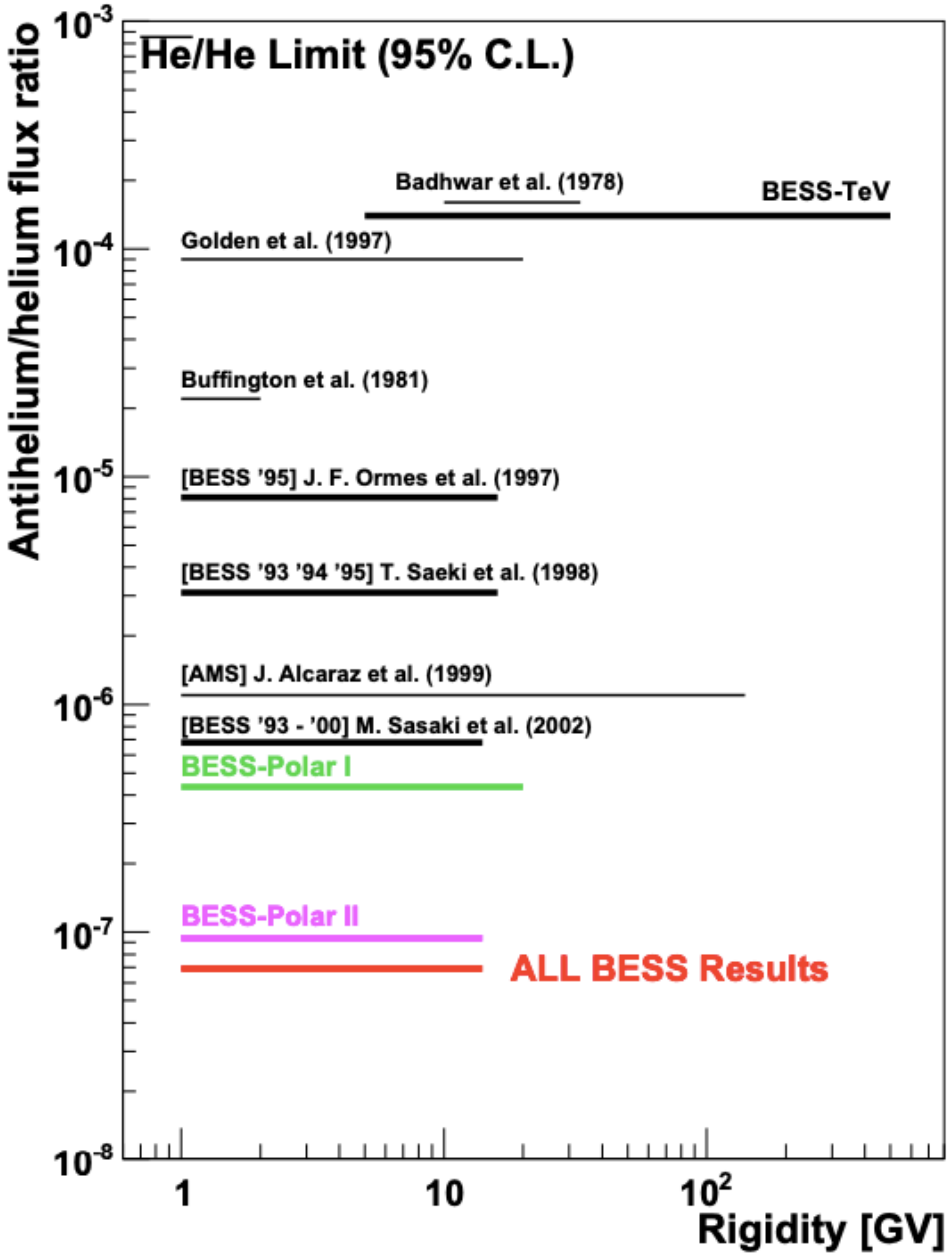

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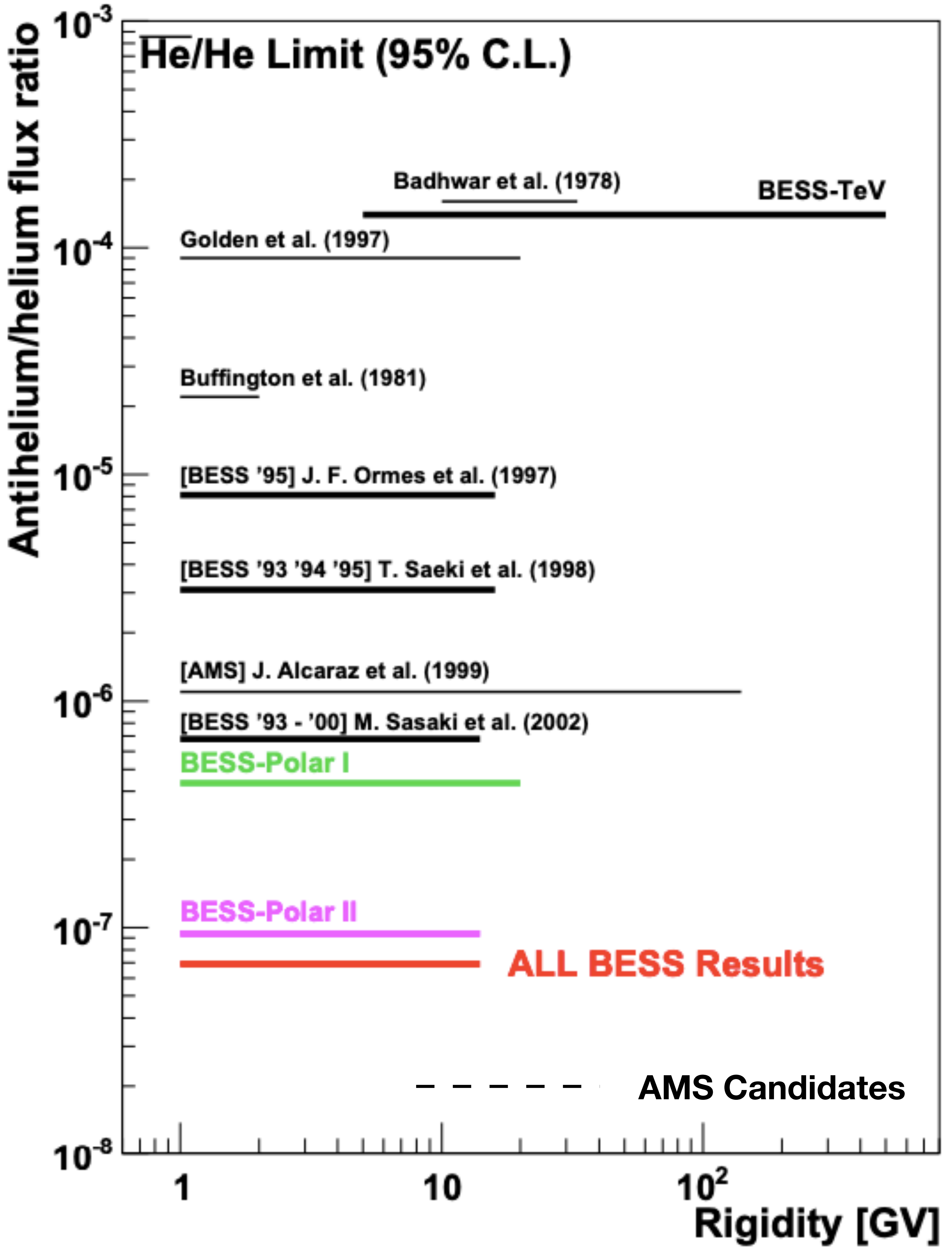

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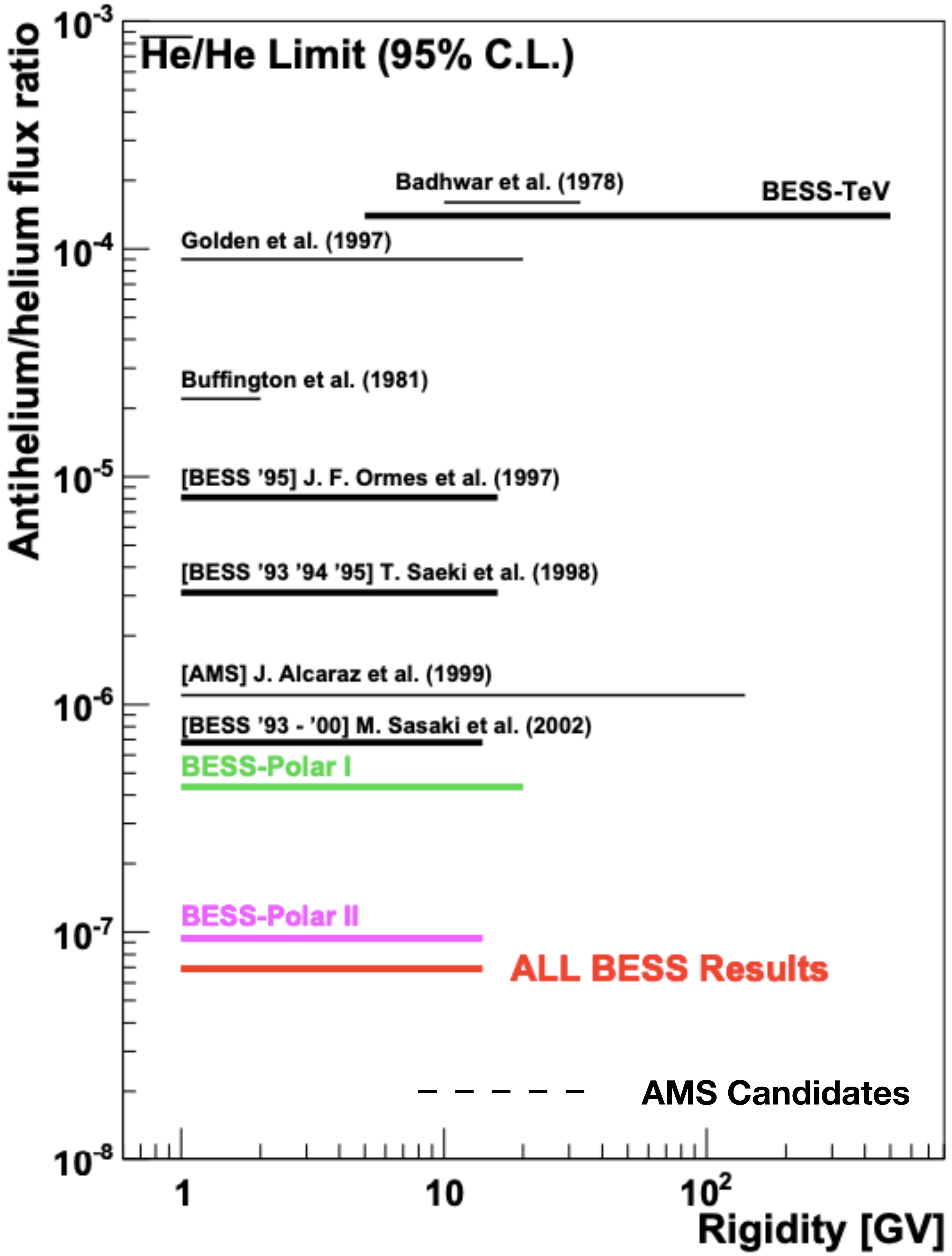

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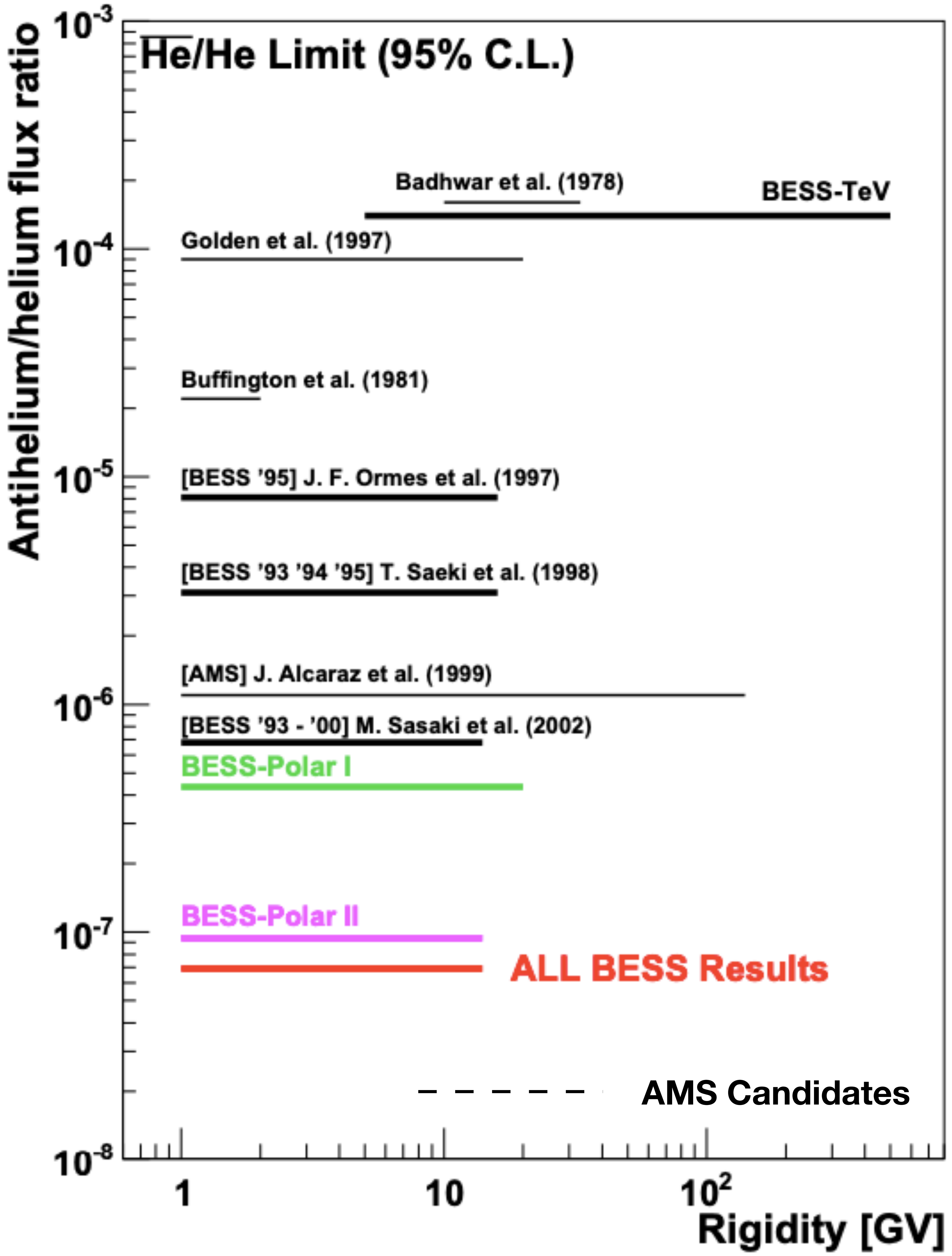

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- This is why it is vital to measure these cross sections.

[1] Abe et. al. , 2012, arXiv:1201.2967 [astro-ph.CO]
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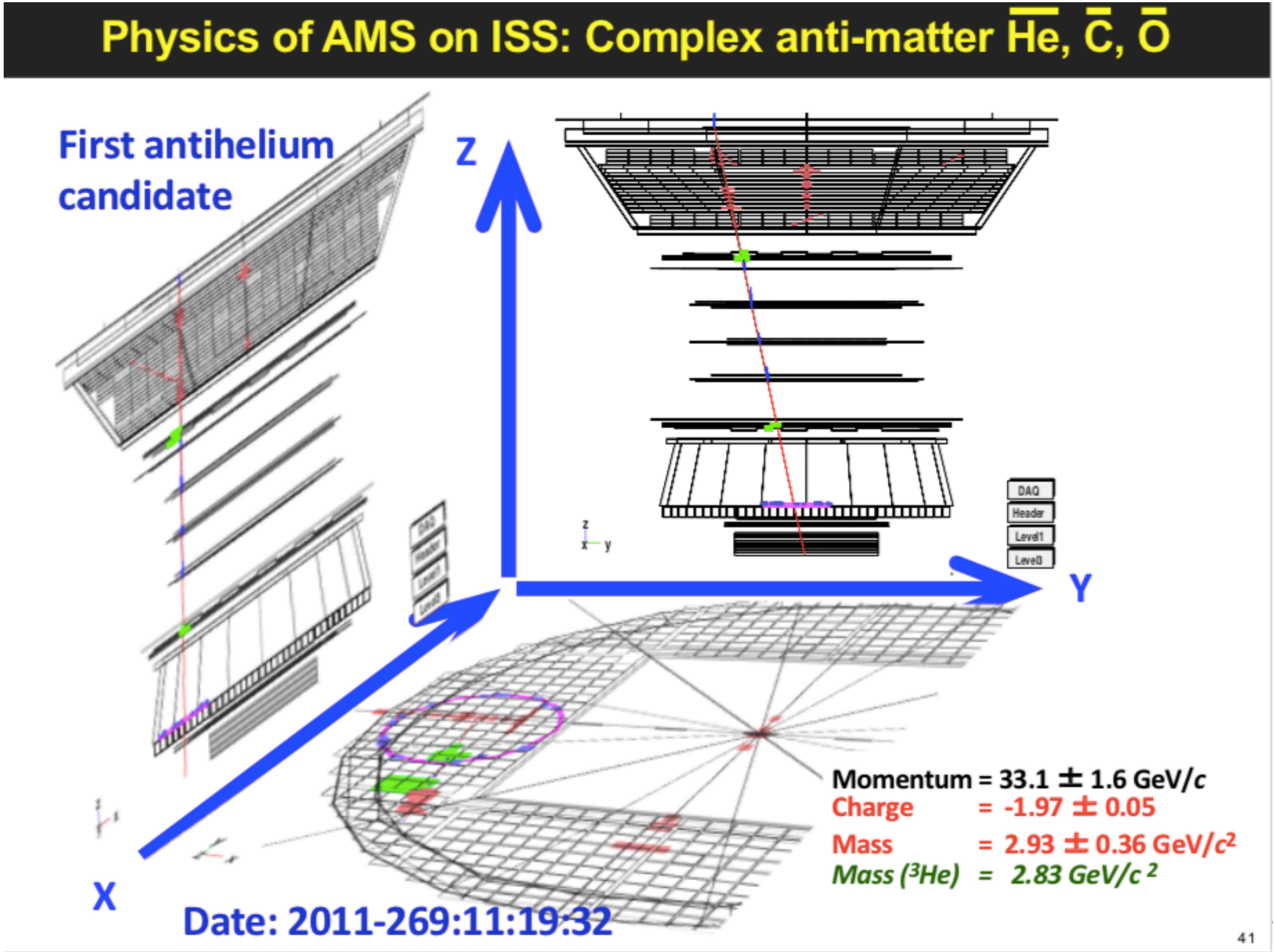
AMS $^{3}\overline{He}$ candidates



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