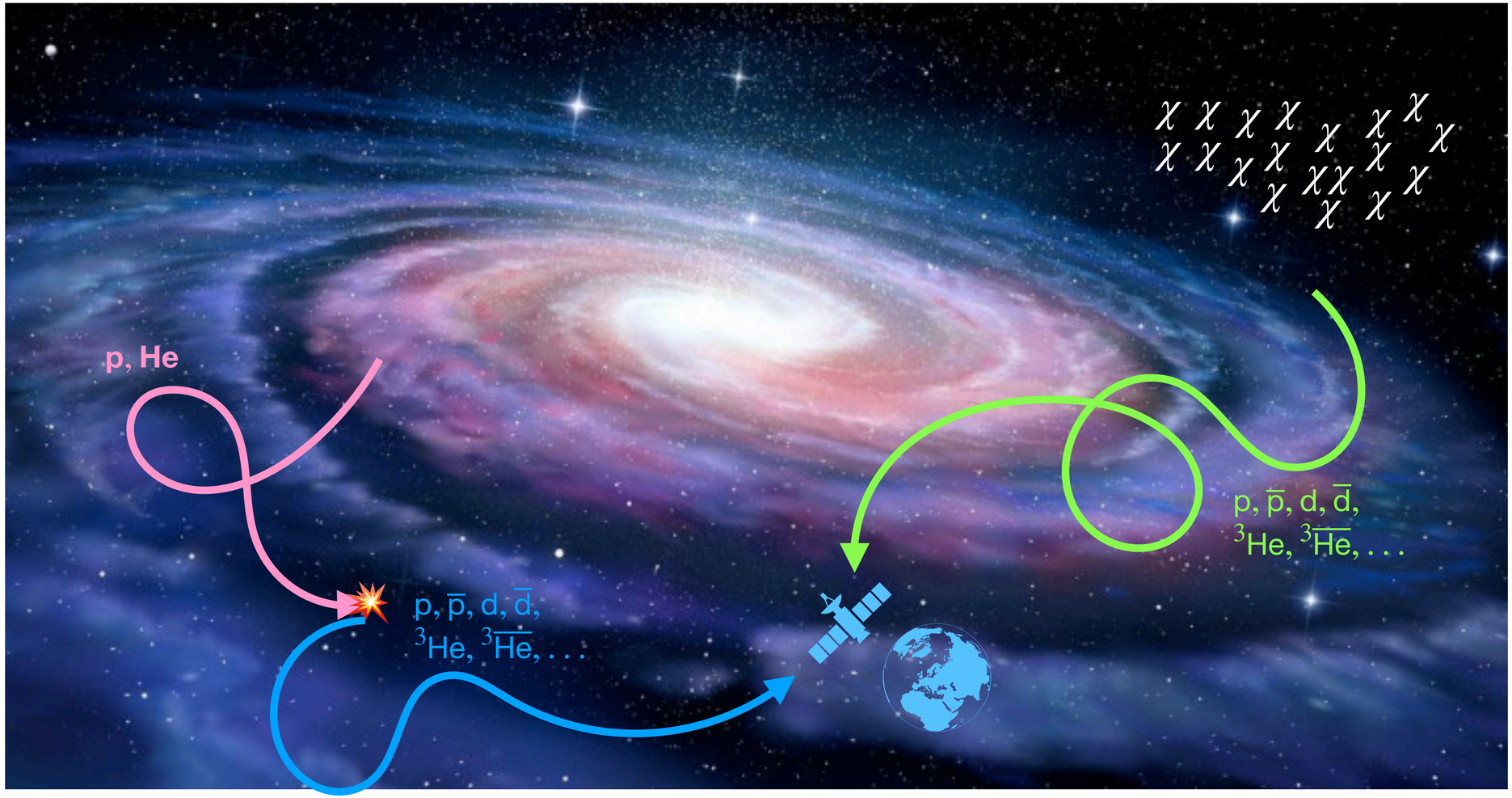
Measurement of the nuclear inelastic cross sections of antinuclei with ALICE and implications for indirect Dark Matter searches

Stephan Koenigstorfer
Technische Universität München
on behalf of the ALICE Collaboration

Introduction

Cosmic ray antinuclei - unique Dark Matter probe



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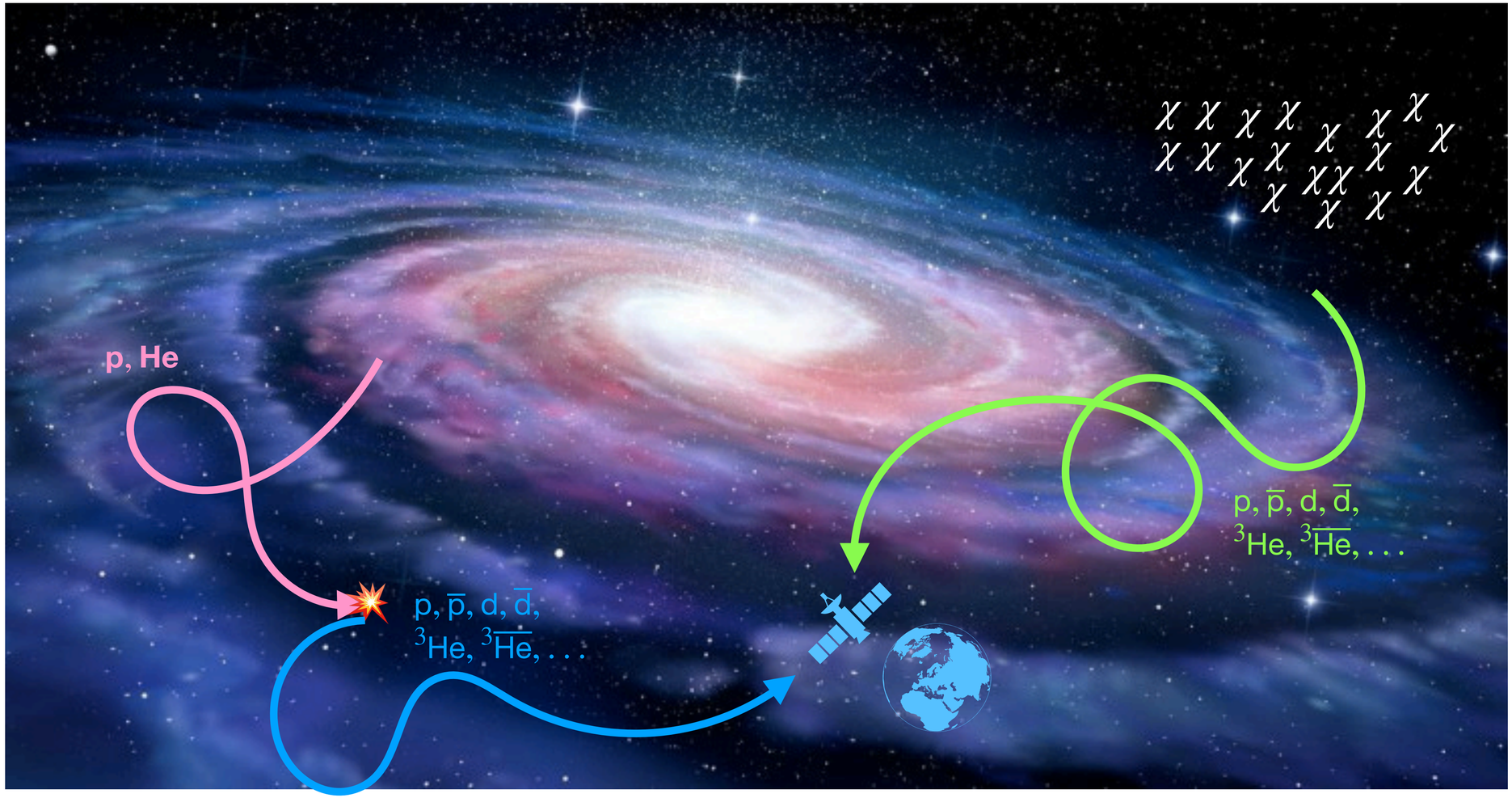
Cosmic ray antinuclei - unique Dark Matter probe

- Low background from secondary production is expected



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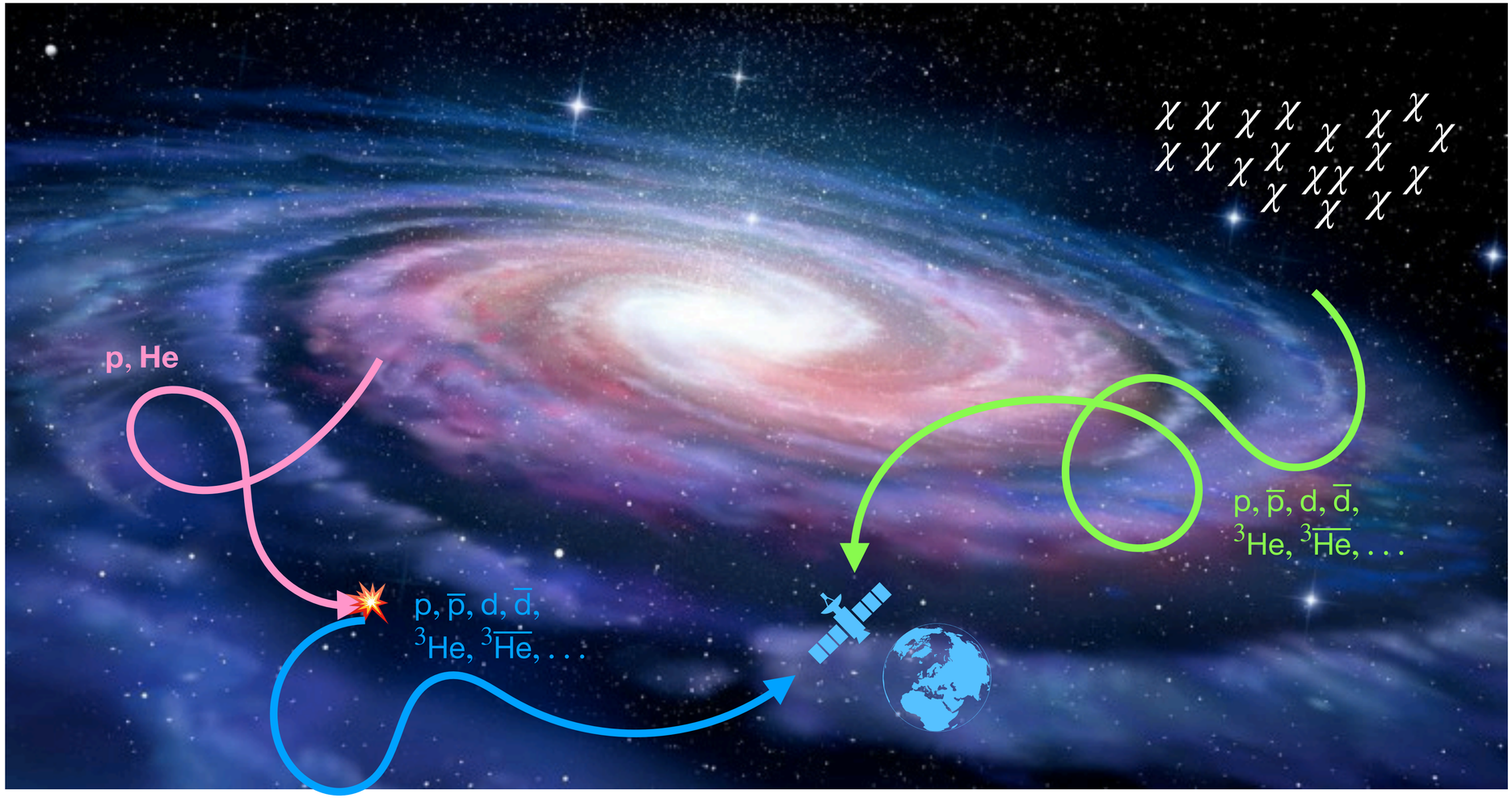
Cosmic ray antinuclei - unique Dark Matter probe

- Low background from secondary production is expected
- Need to determine exact primary and secondary fluxes!



Predicted antinuclei fluxes near earth

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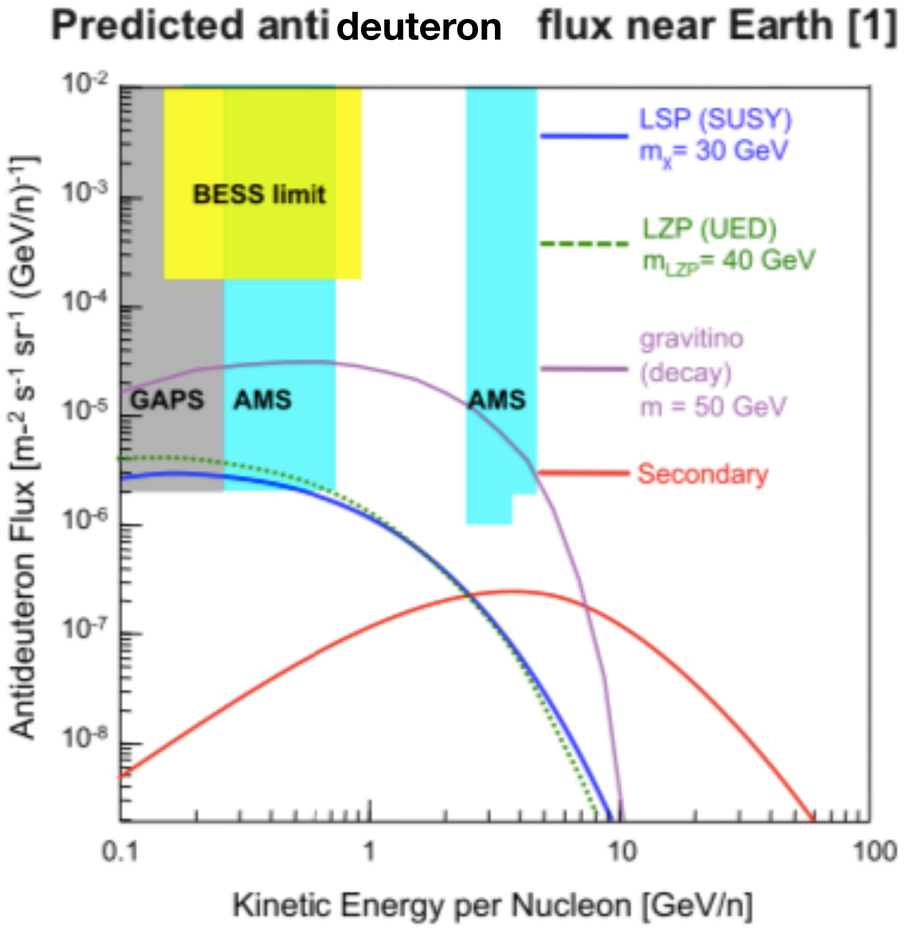

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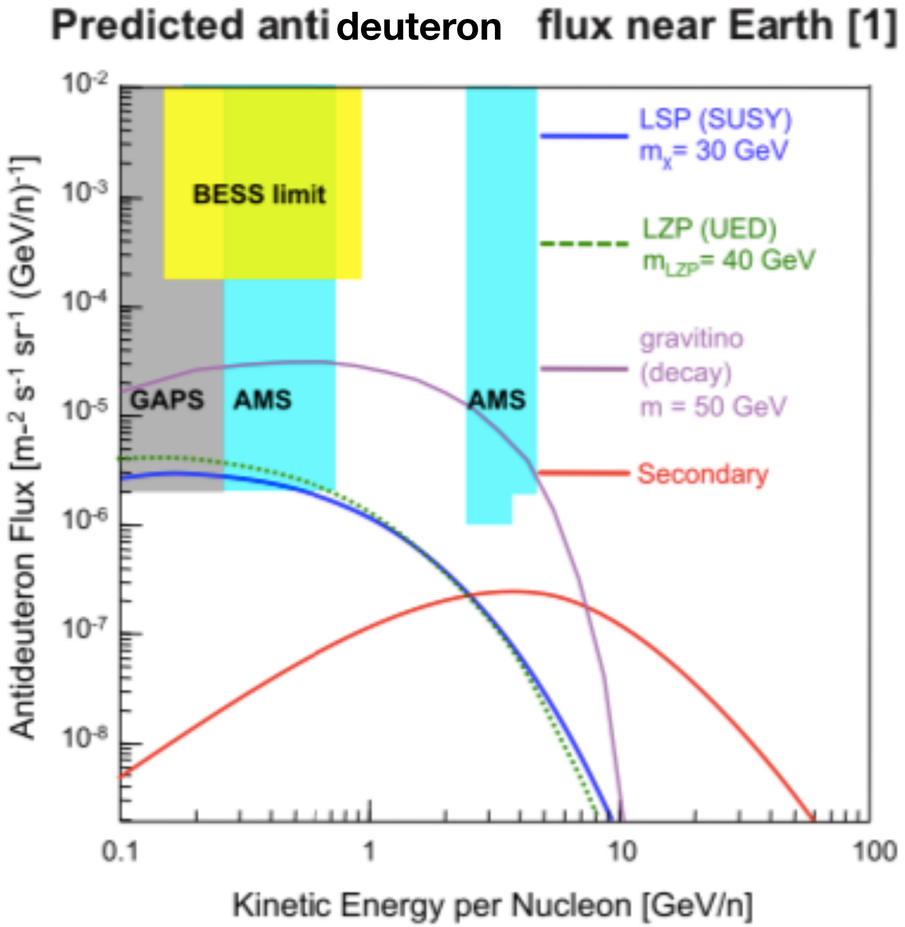

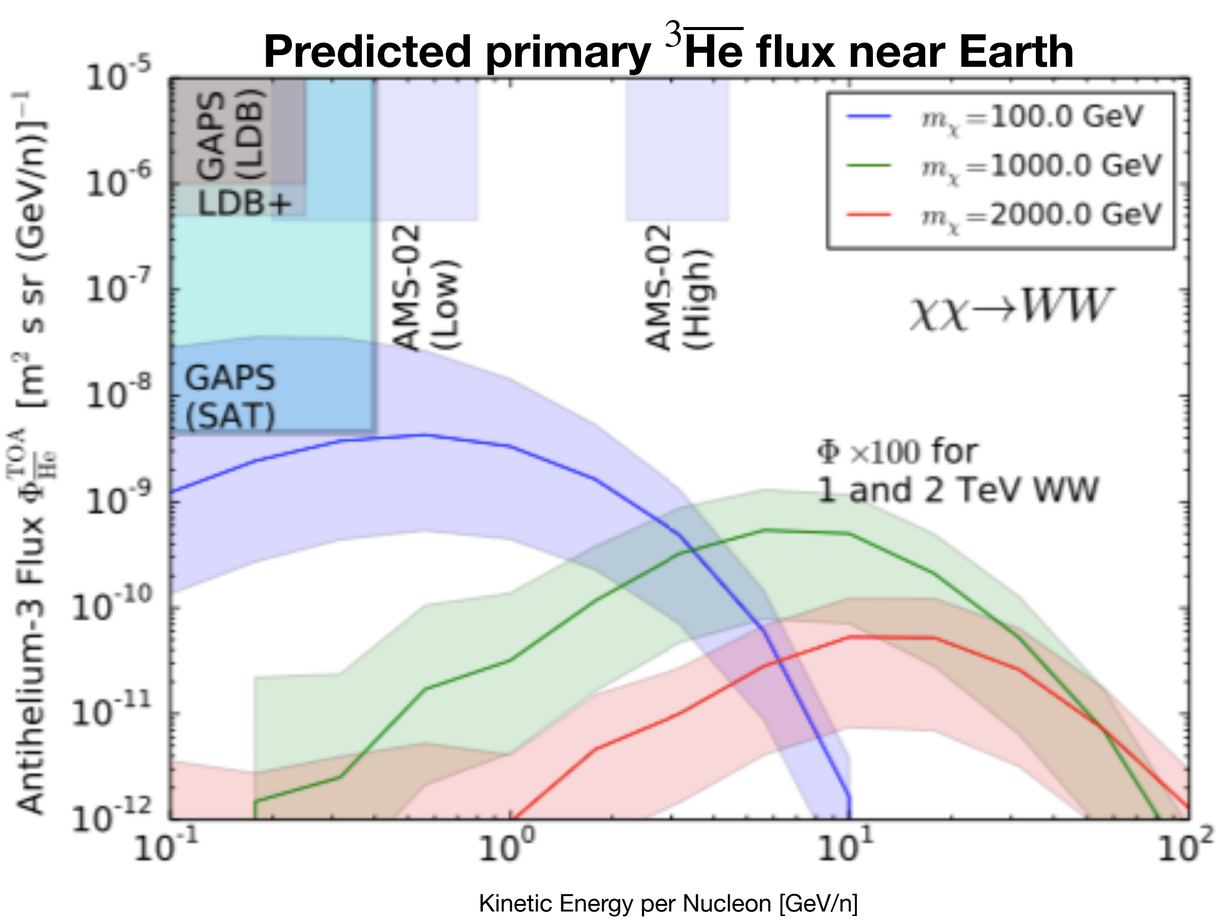

Content of this talk

- What is needed to calculate cosmic ray antinuclei fluxes
- Current status of antinuclei inelastic cross section measurements
- The ALICE experiment
- Method to determine antinuclei inelastic cross sections with ALICE
- Antiproton, antideuteron and $^{3}\overline{\mathrm{He}}$ inelastic cross section
- Possible implications for indirect Dark Matter searches

A long way to the detectors

A long way to the detectors

Interstellar Medium

- Injected primary cosmic ray (CR) spectra
- Production of secondary CR in interstellar medium
- Transport
- Absorption and (re-)acceleration

Local interstellar flux

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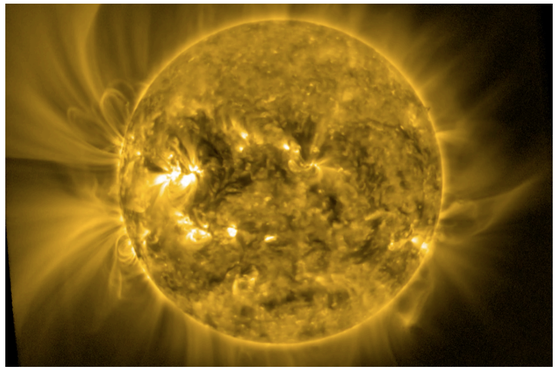

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- Most dominant effect at low momenta
- Time dependence of activity

Solar modulated flux

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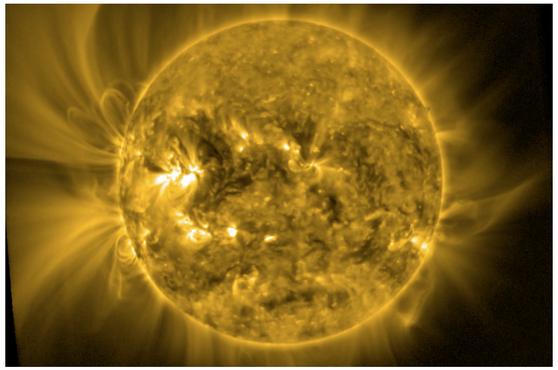

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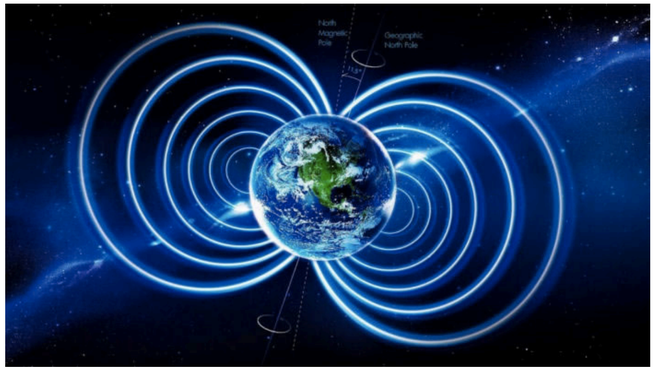
Near Earth environment



- Shielding/deflection by Earth's magnetic field
- Background production and absorption in Earth's atmosphere

Flux at experiment

A long way to the detectors

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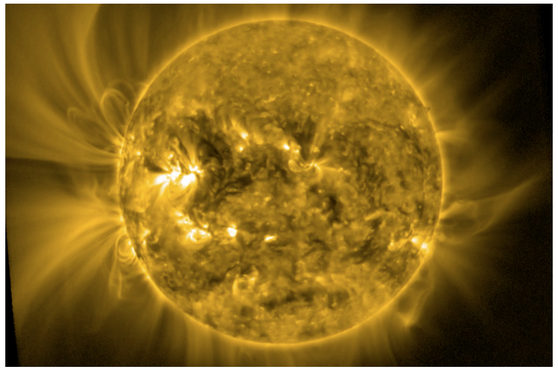

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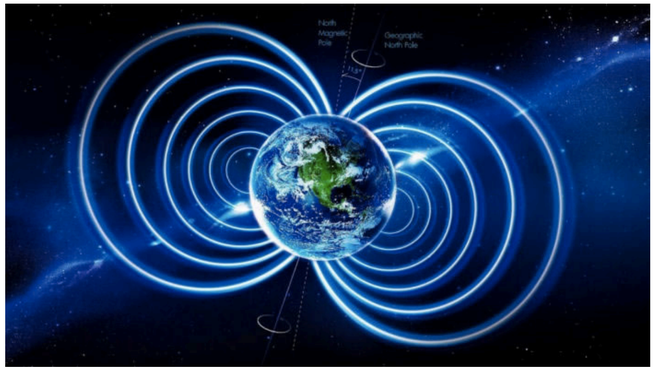

Steps in calculating antinuclei fluxes:

- Propagation: Common for all (anti)particles
- Annihilation in interstellar medium and Earth's atmosphere
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[1] CERN-SPSC-2019-022; SPSC-P-360

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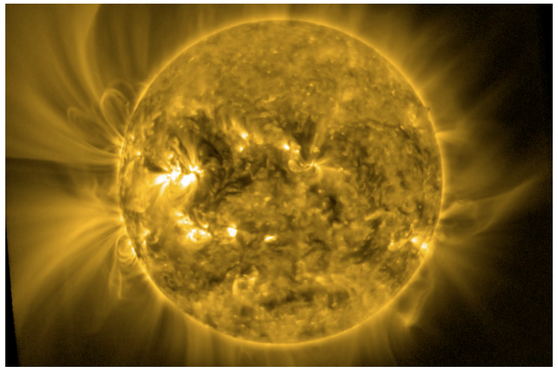

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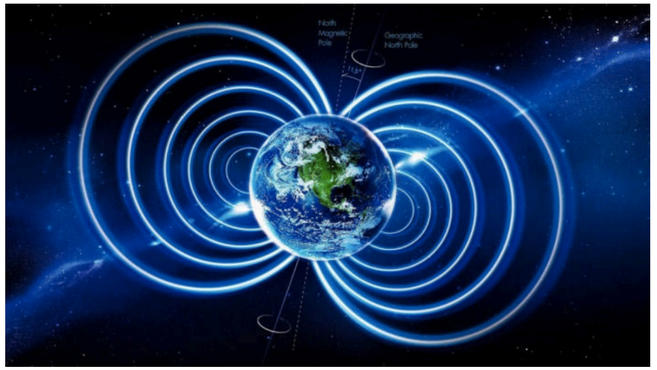

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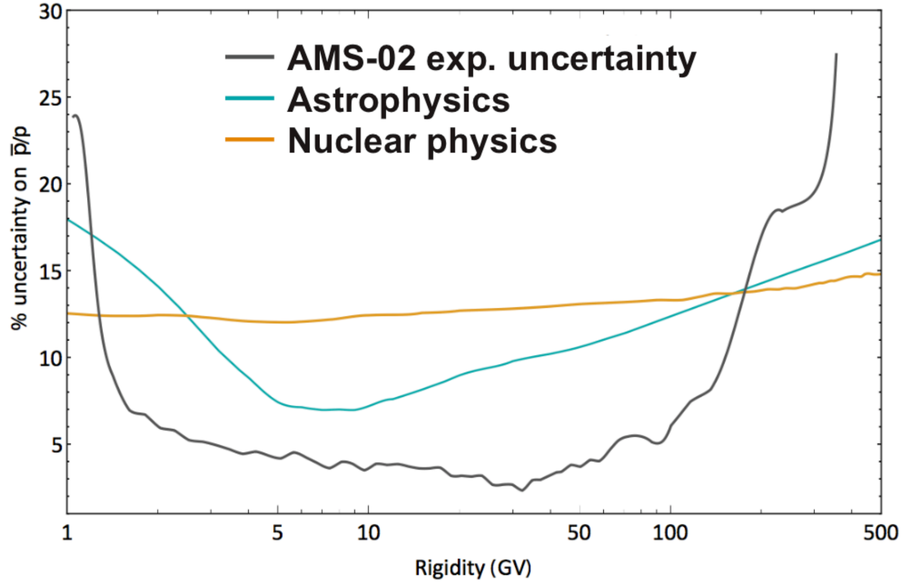

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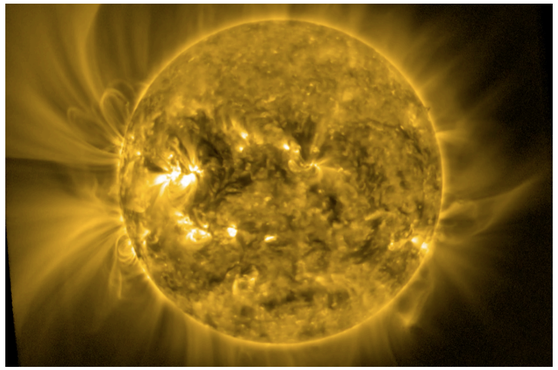

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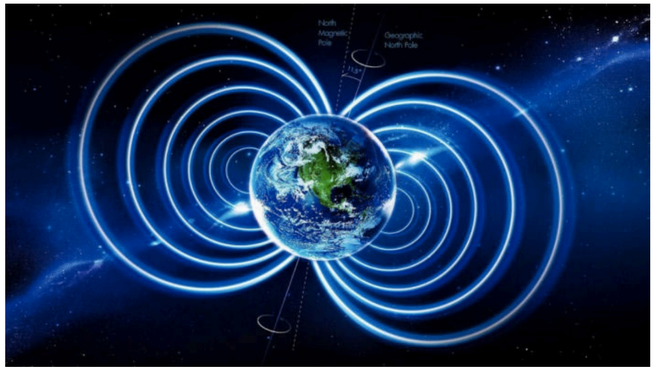

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Precise nuclear inelastic cross sections are needed to reduce large uncertainties from nuclear physics!

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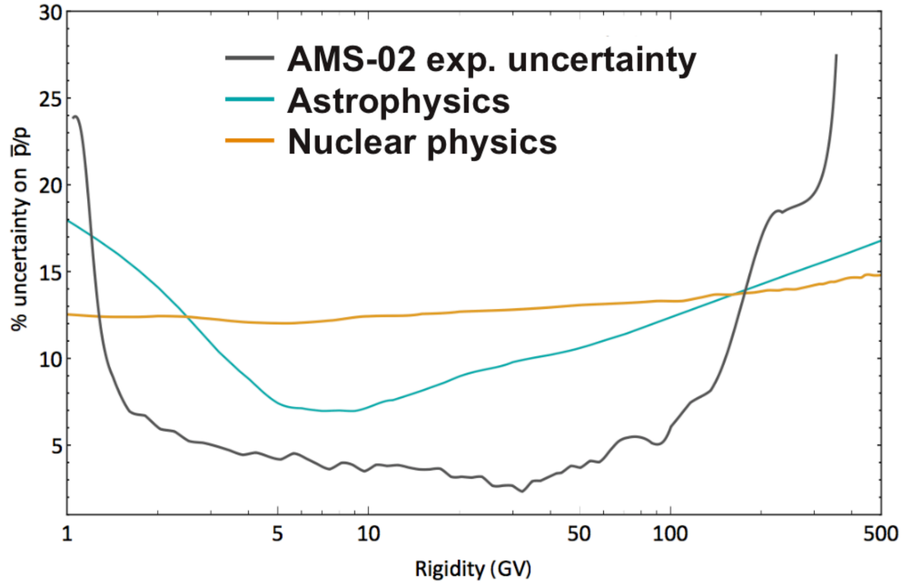

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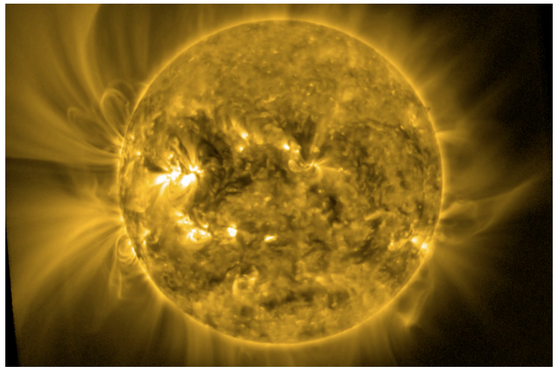

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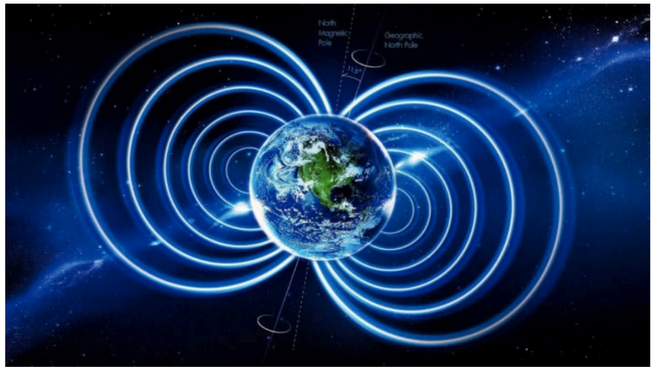

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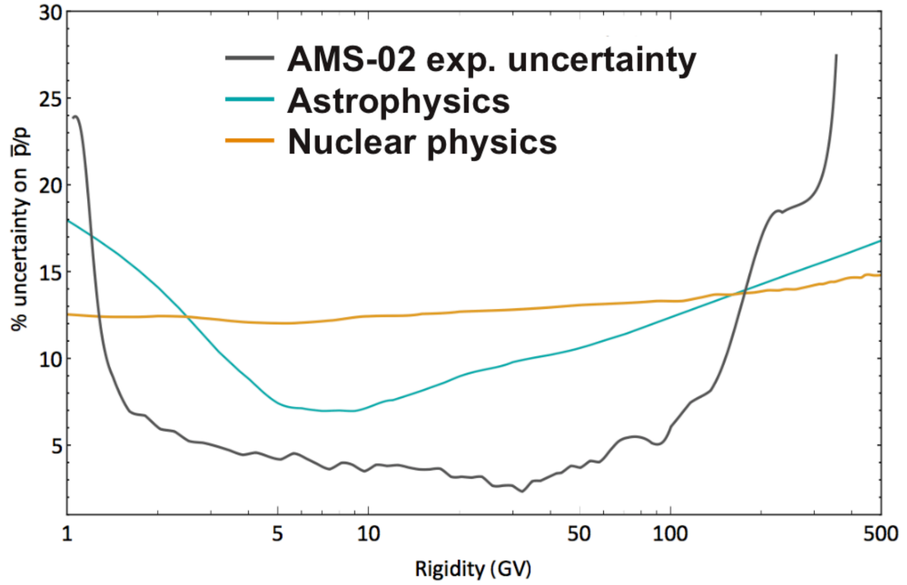

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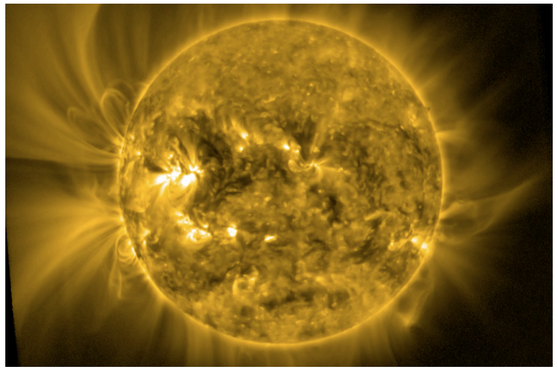

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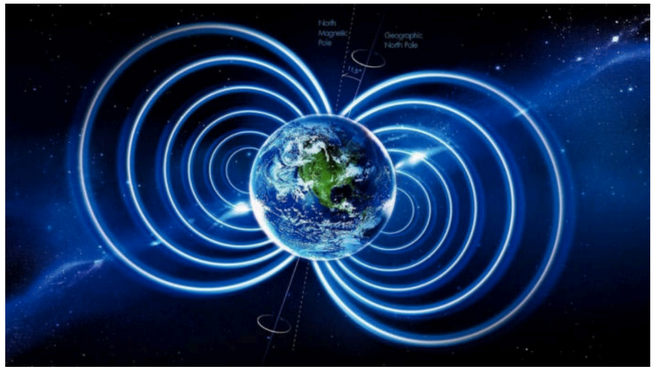

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Talks by S. Hornung and C. Pinto.

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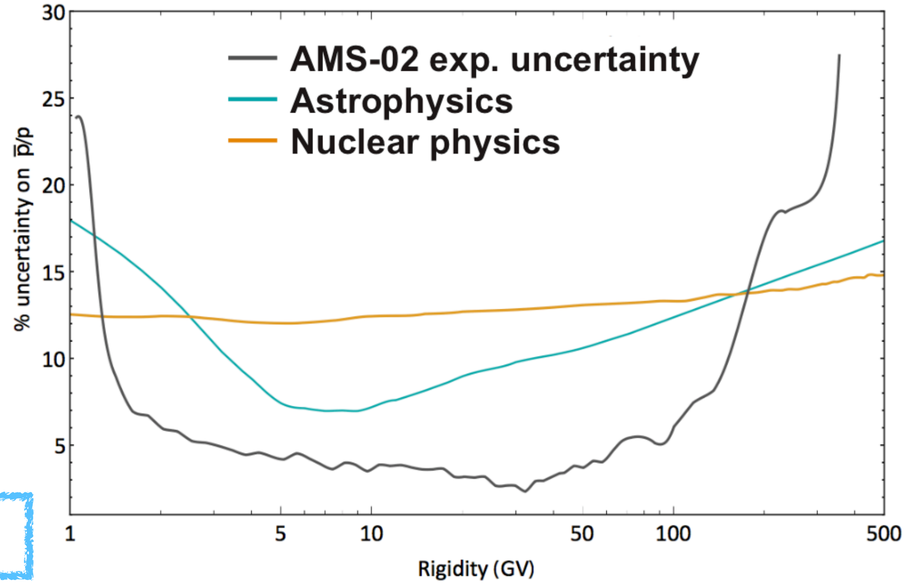

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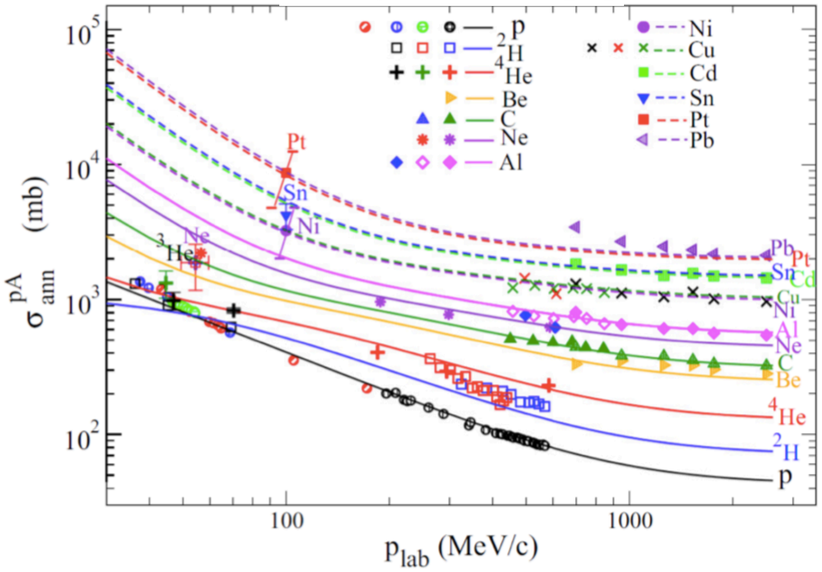

[1] Phys. Rev. C 89, 054601 (2014)

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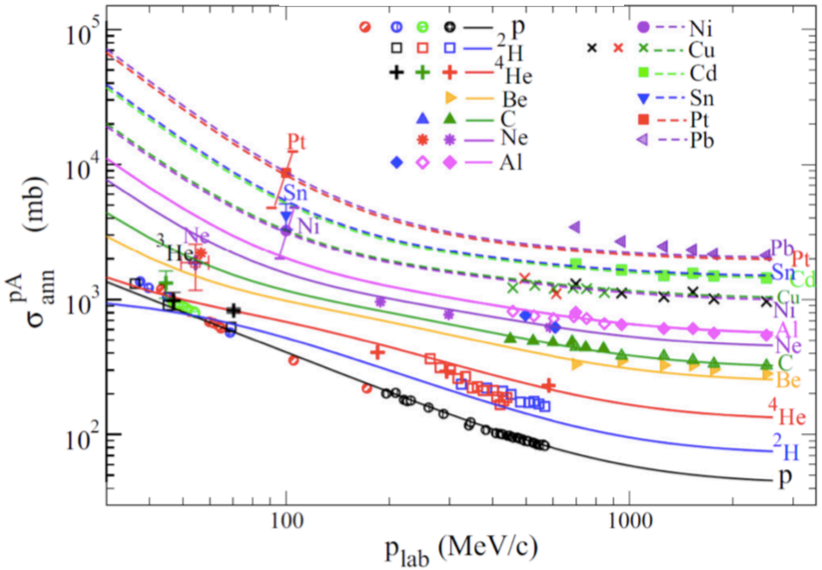
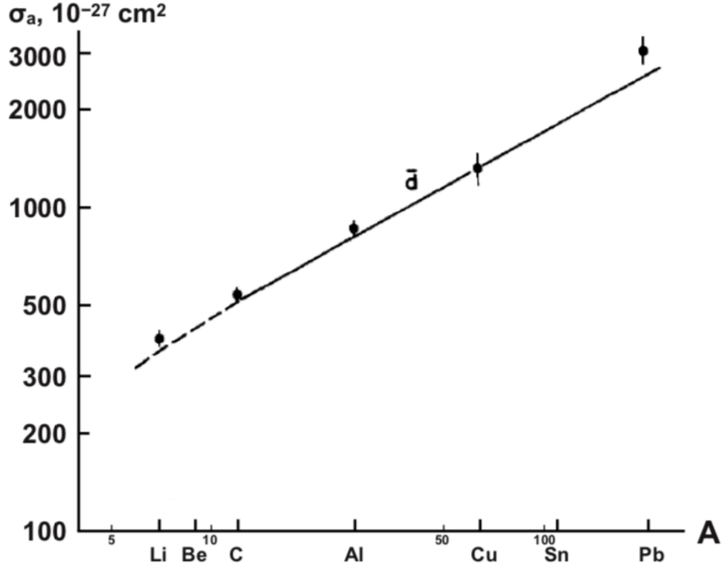


Antideuterons [2]



Current status of antinuclei inelastic cross sections

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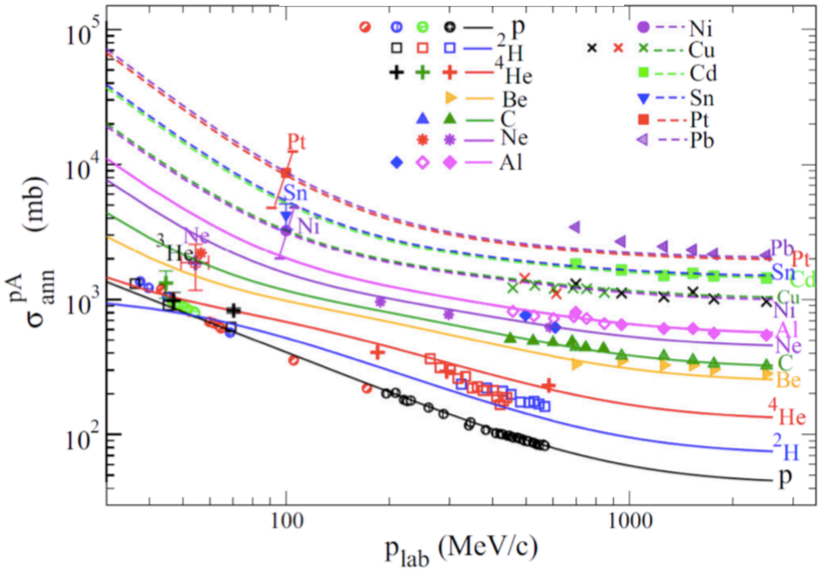

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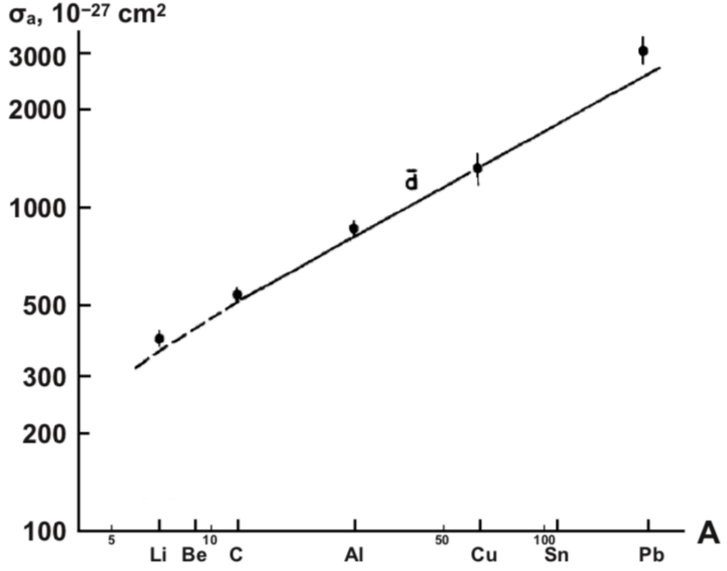
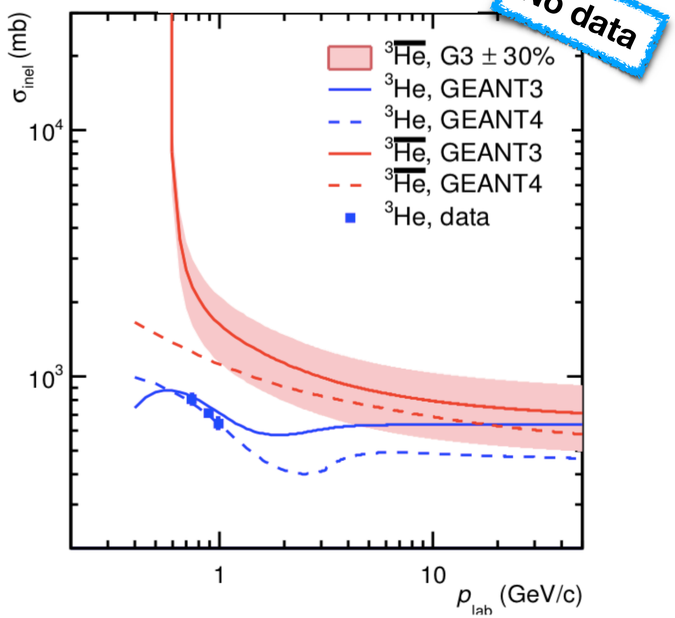


Anti-^{3}He on C

No data



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

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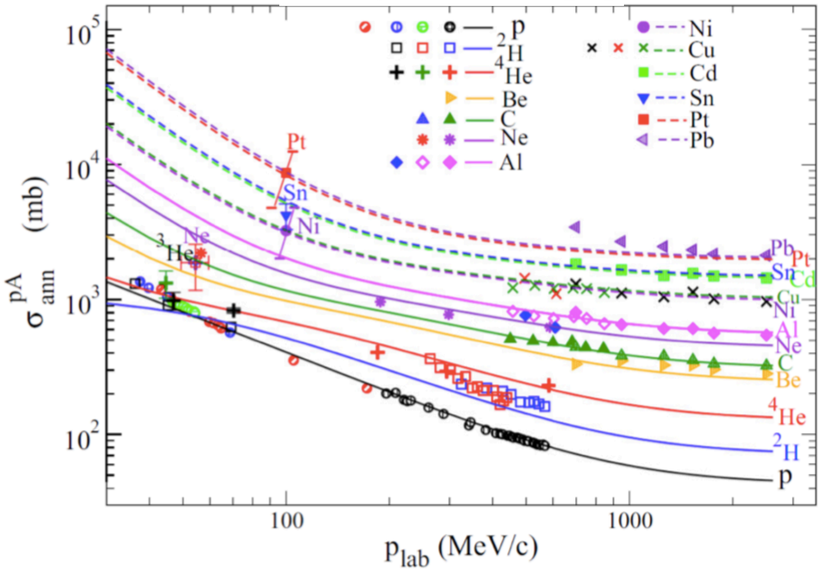

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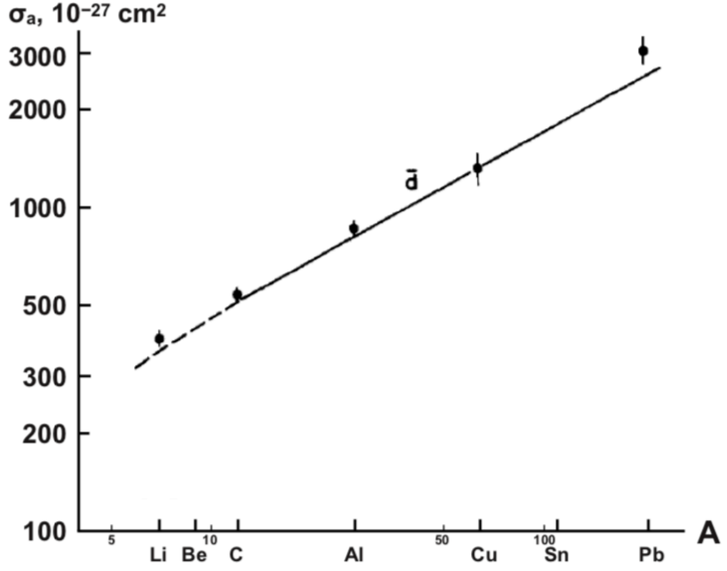

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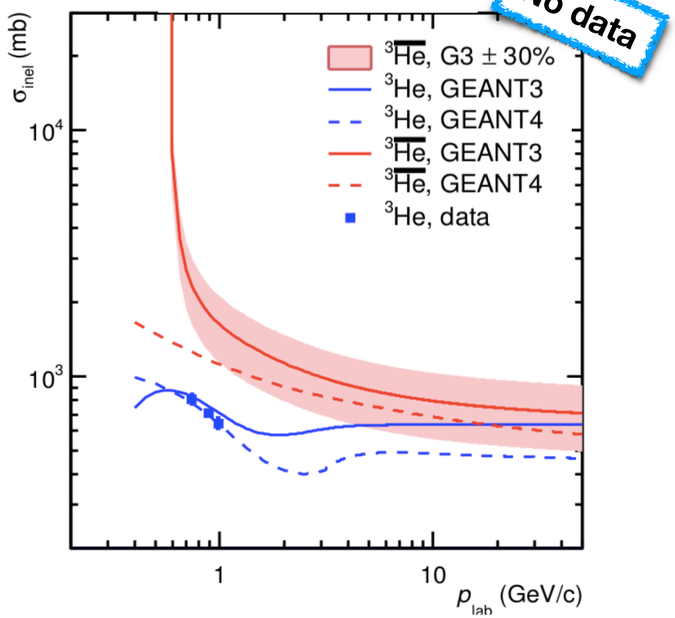
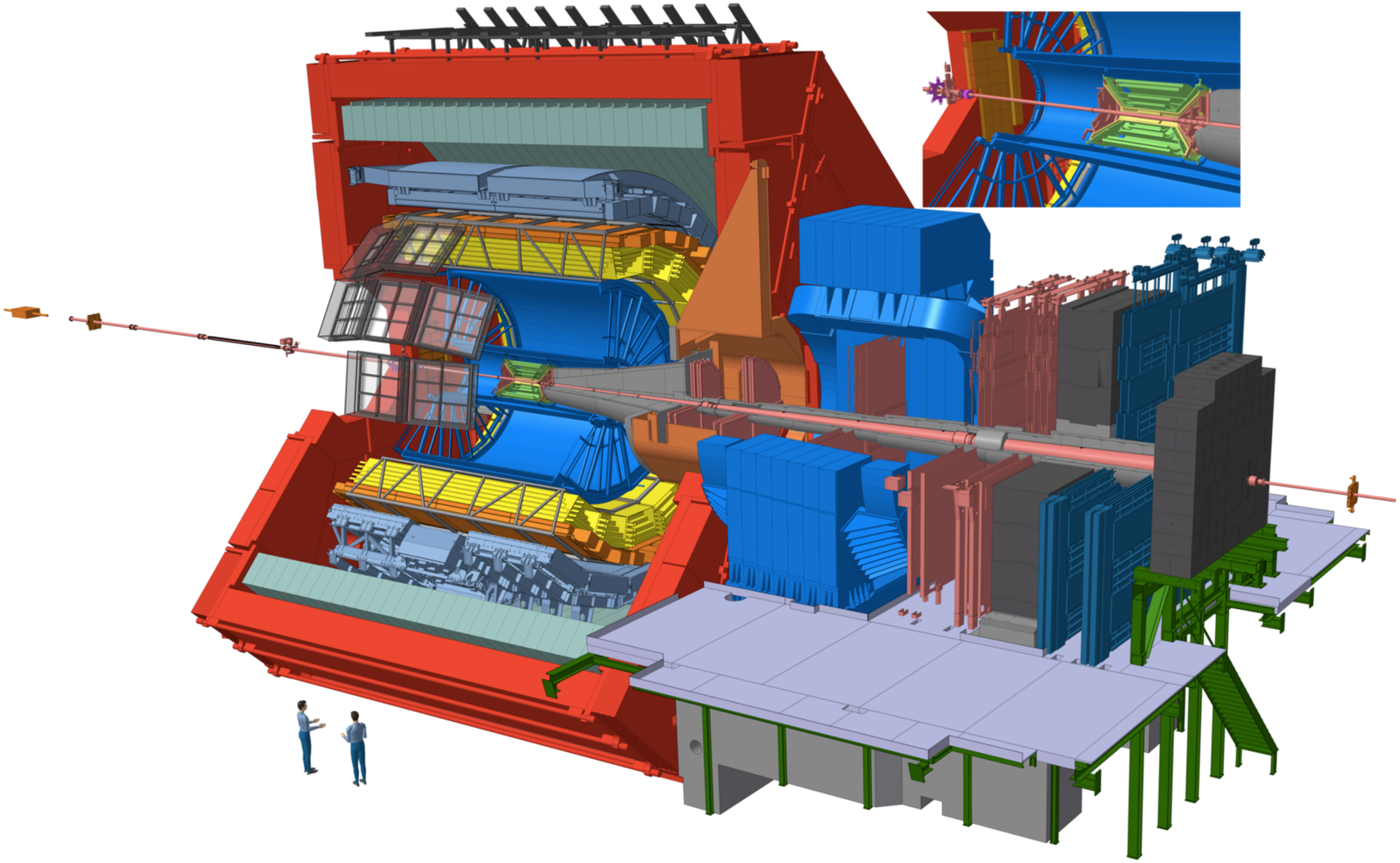


The ALICE experiment at CERN

General-purpose (heavy-ion) experiment at the Large Hadron Collider

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



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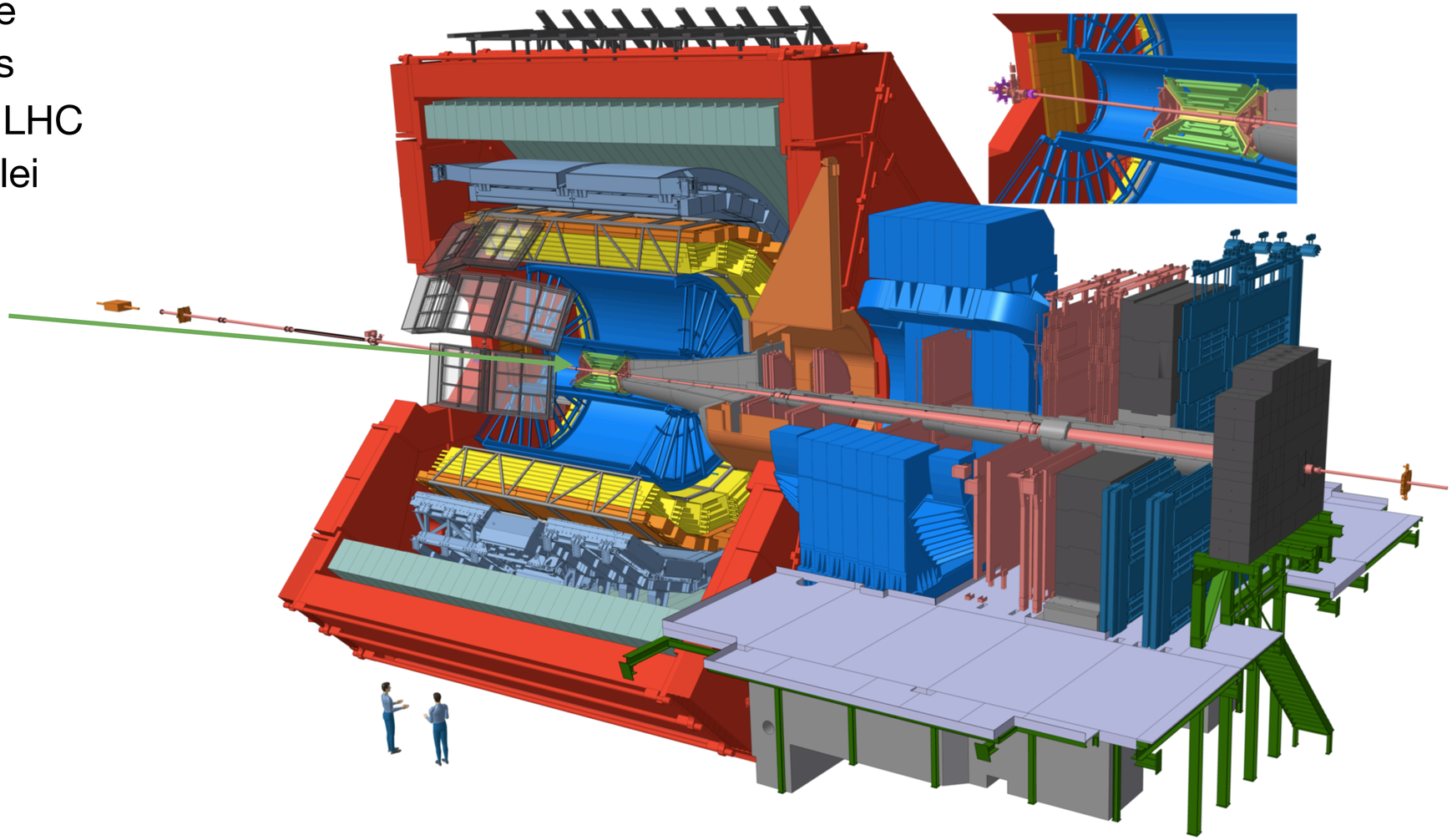

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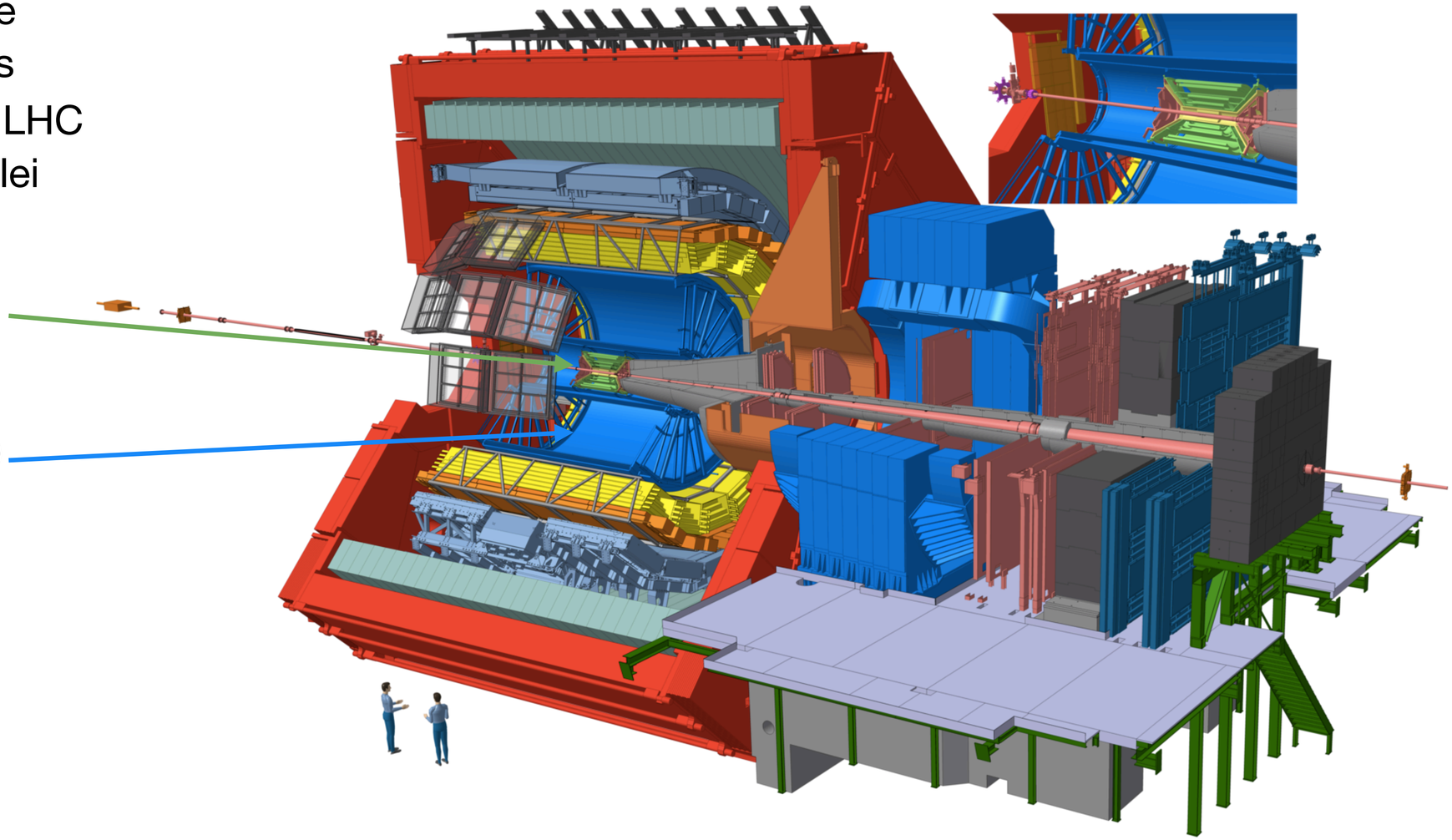

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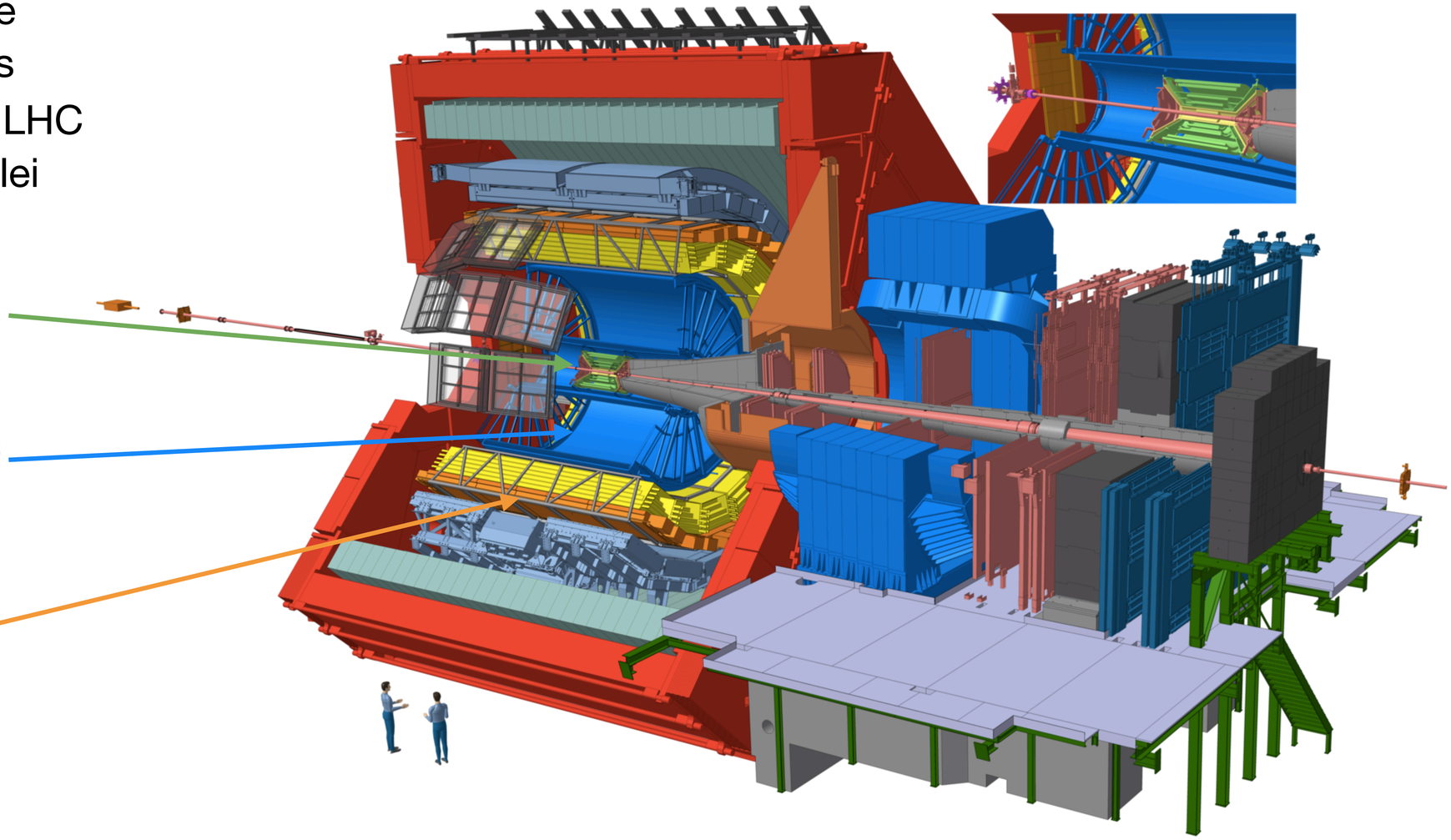
Time of Flight detector (TOF)

- PID (TOF measurement)



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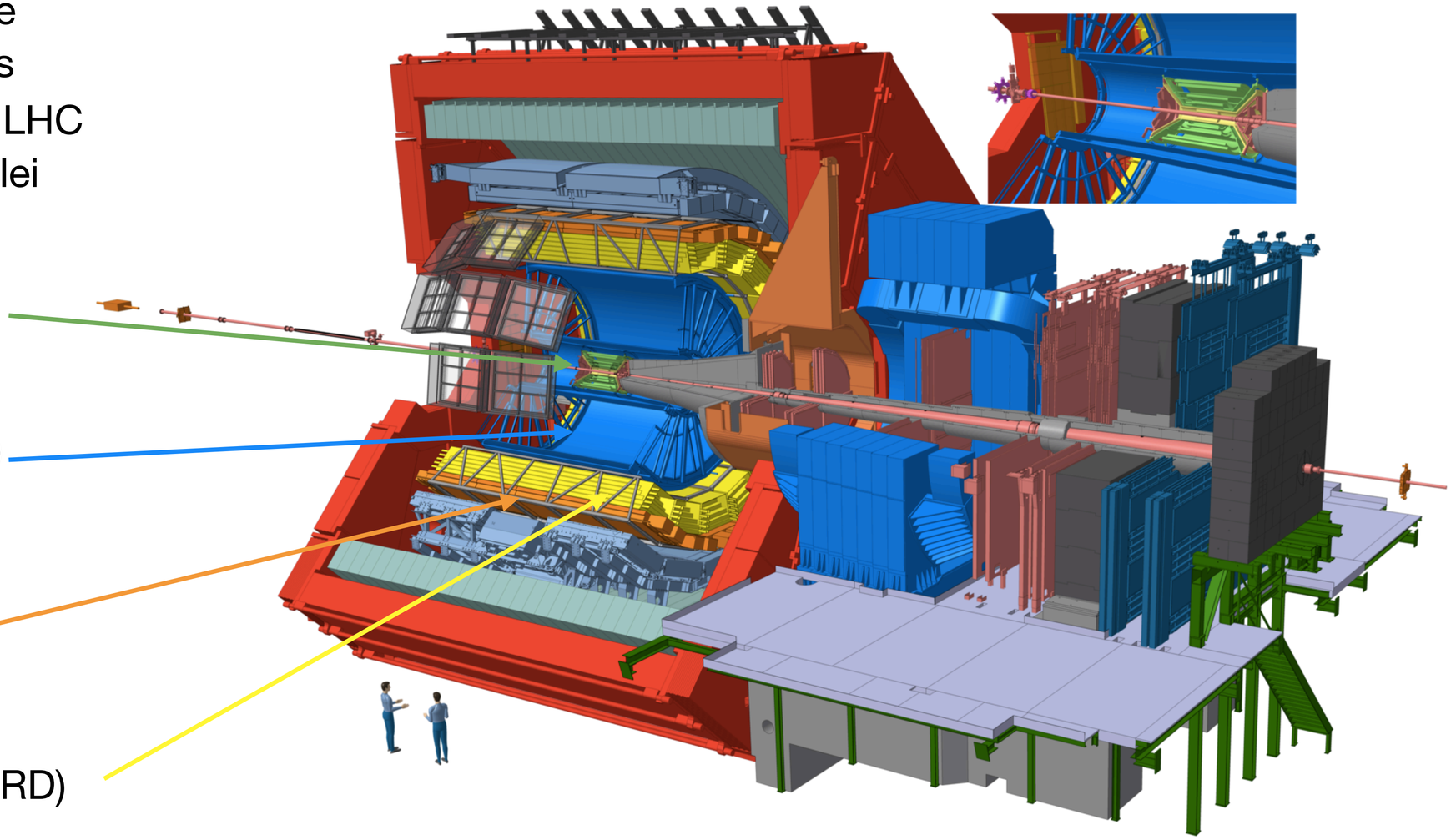


Use the LHC as an antimatter factory…

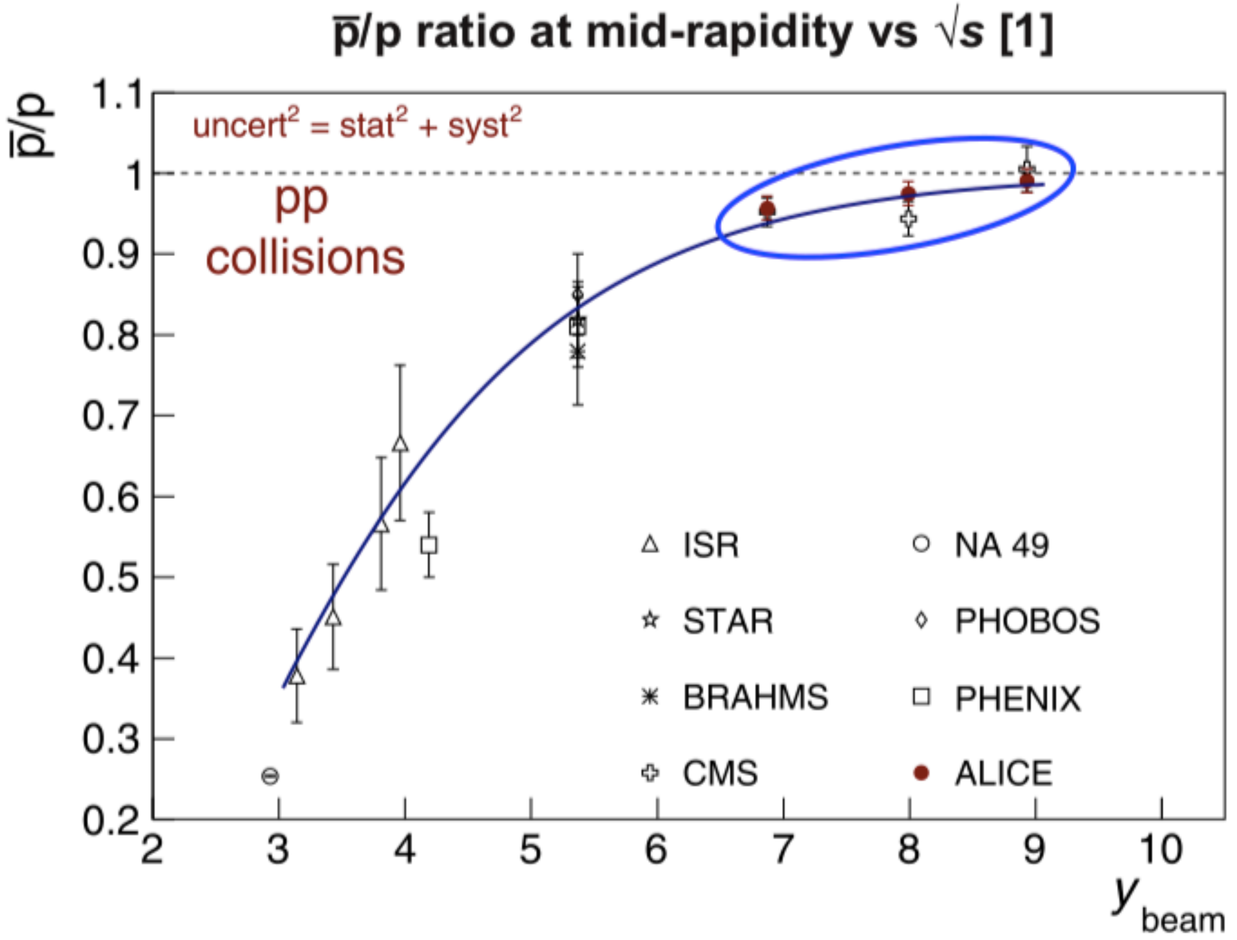
At LHC energies, particles and antiparticles are produced in almost equal amounts.

- Primordial antimatter-to-matter ratio approaches unity with increasing $\sqrt{s}$

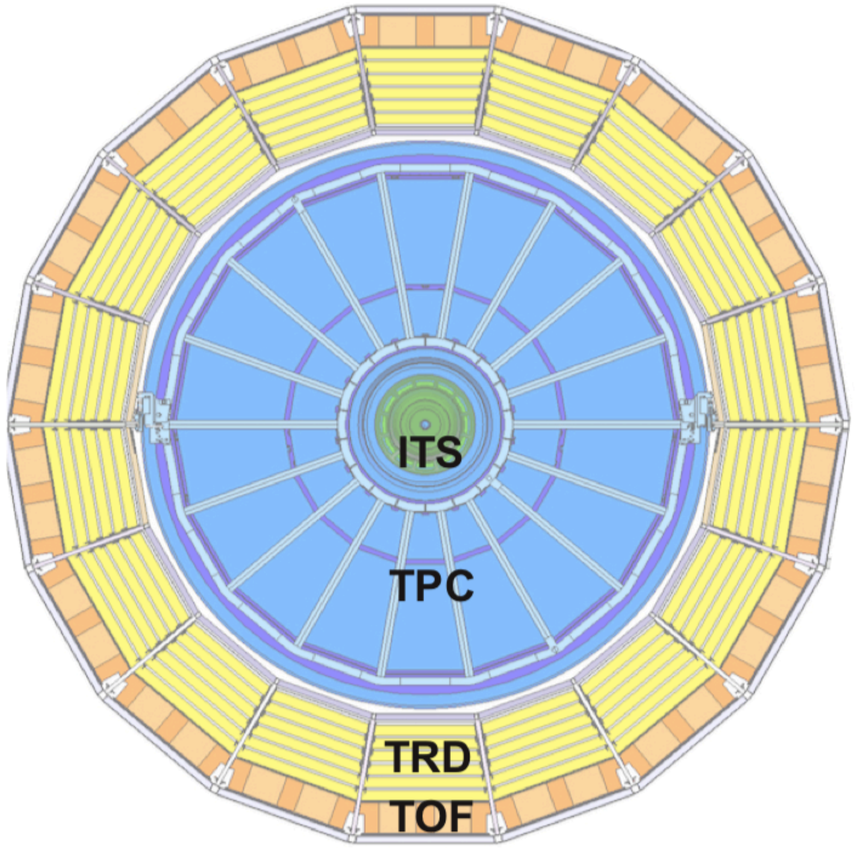
This talk:

- (Anti)-^{3}He results from high multiplicity pp collisions at $\sqrt{s} = 13$ TeV, ~10^9 events

- (Anti)proton and (anti)deuteron results from p-Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, ~300 M events.



… and the ALICE detector material as a target



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

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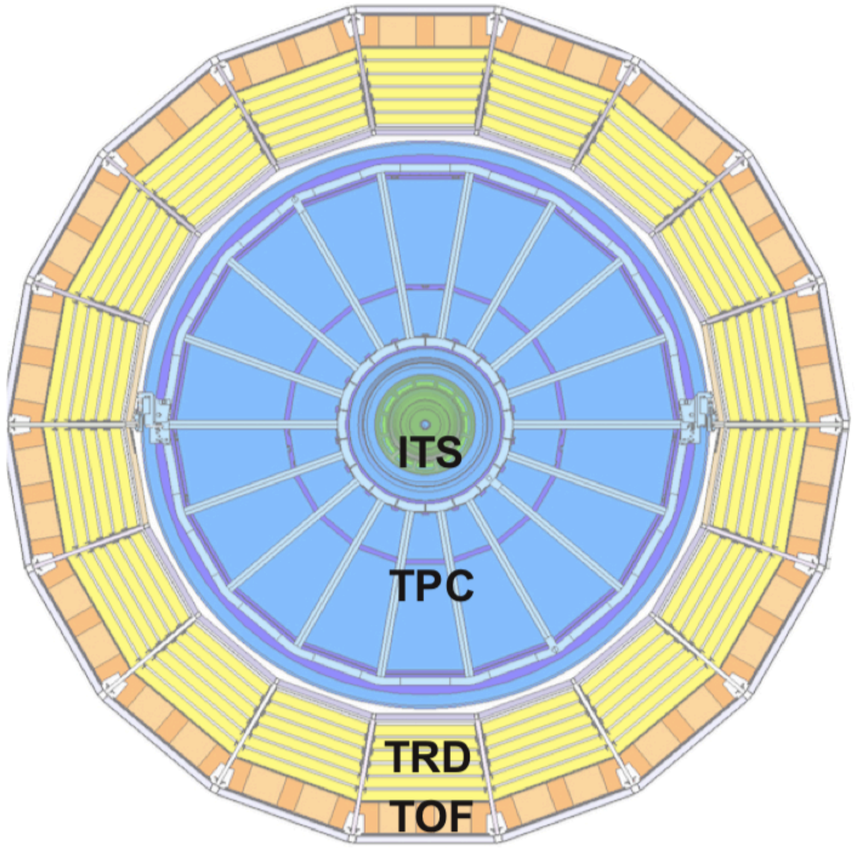
ALICE material budget at mid-rapidity [1]:



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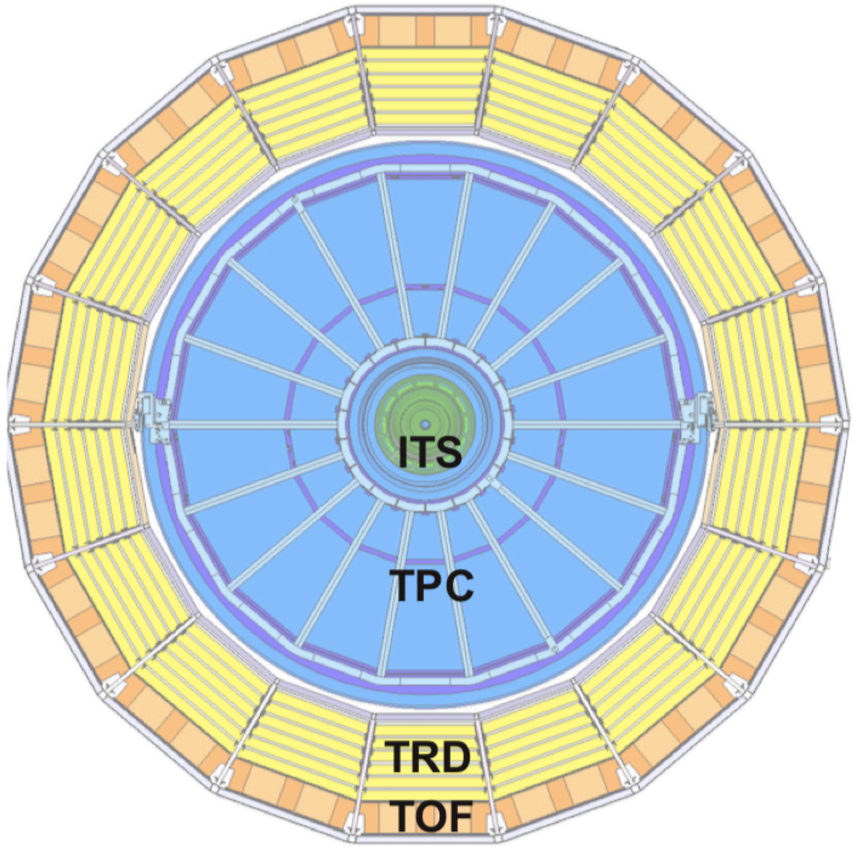

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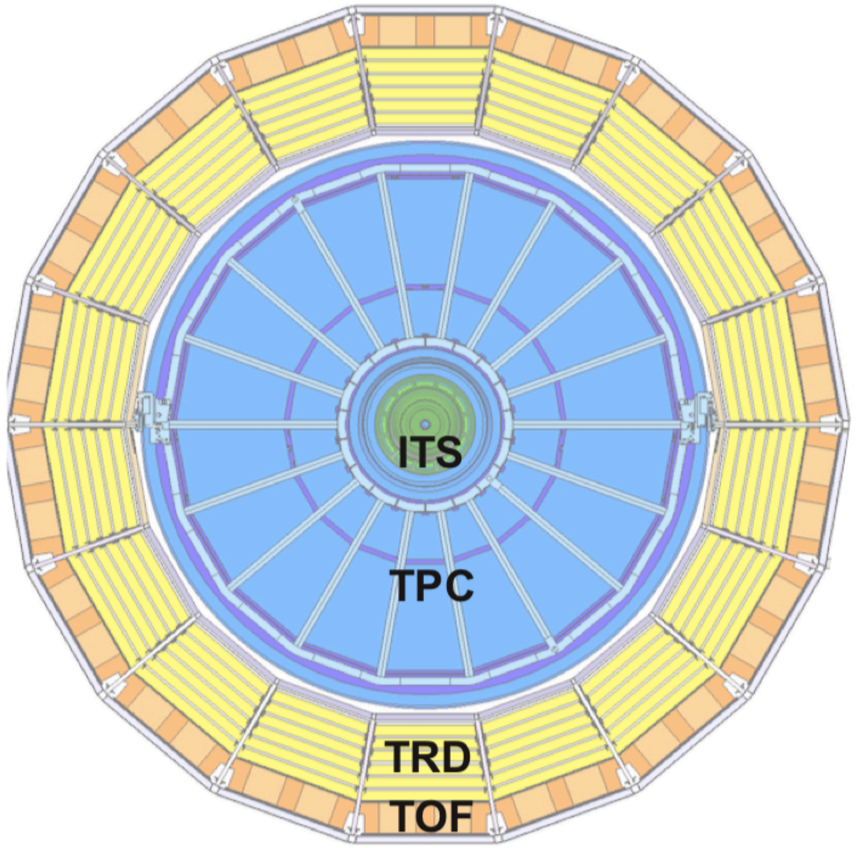

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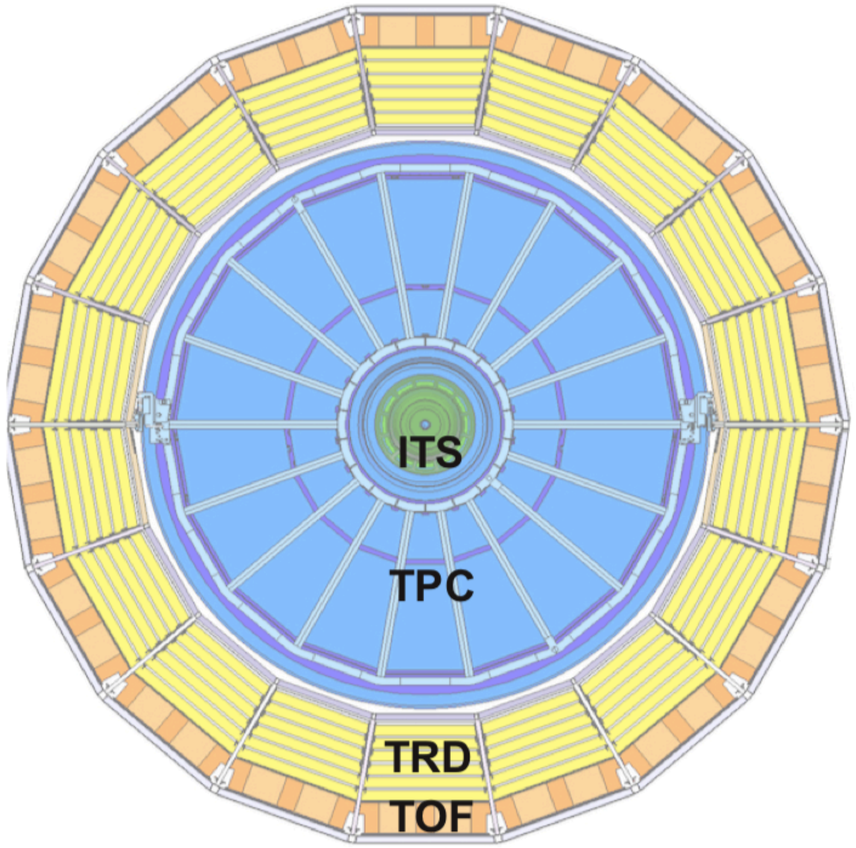

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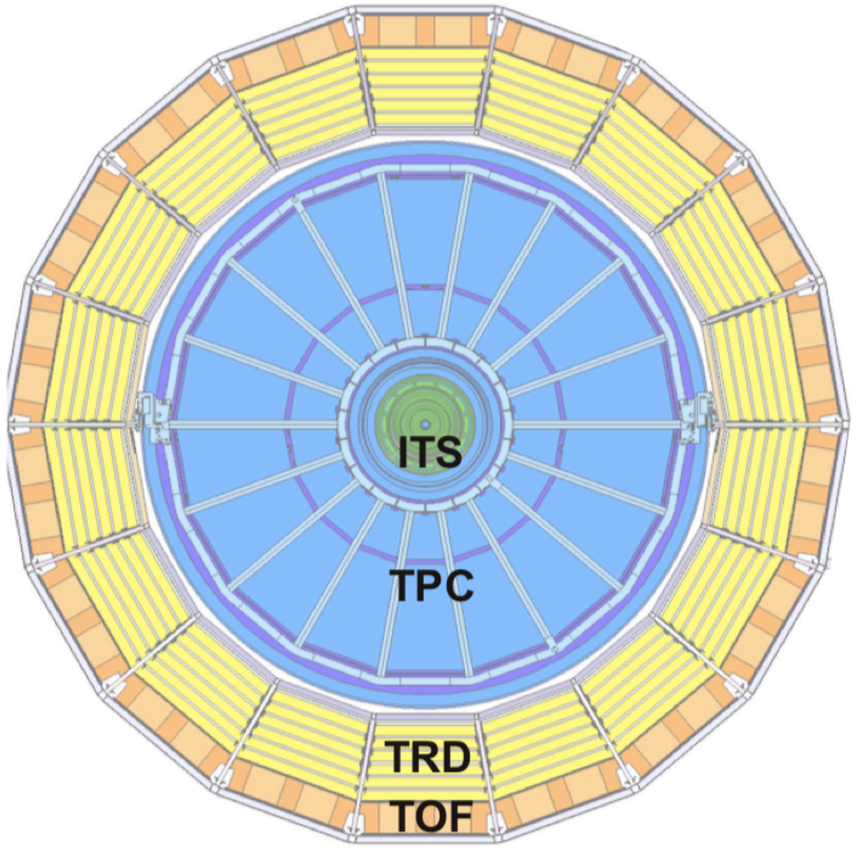
- **ITS (~8% X_0)**
- **TPC (~4% X_0)**
- **TRD (~25% X_0)**



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

… and the ALICE detector material as a target

ALICE material budget at mid-rapidity [1]:

- **Beryllium beam pipe (~0.3% X_0)**
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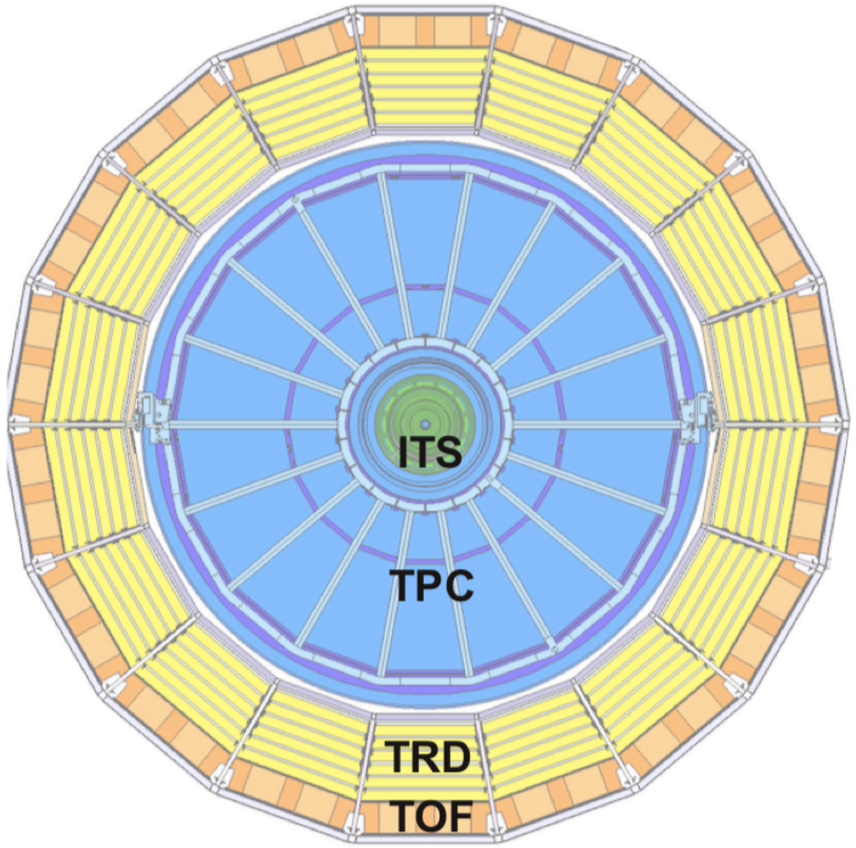

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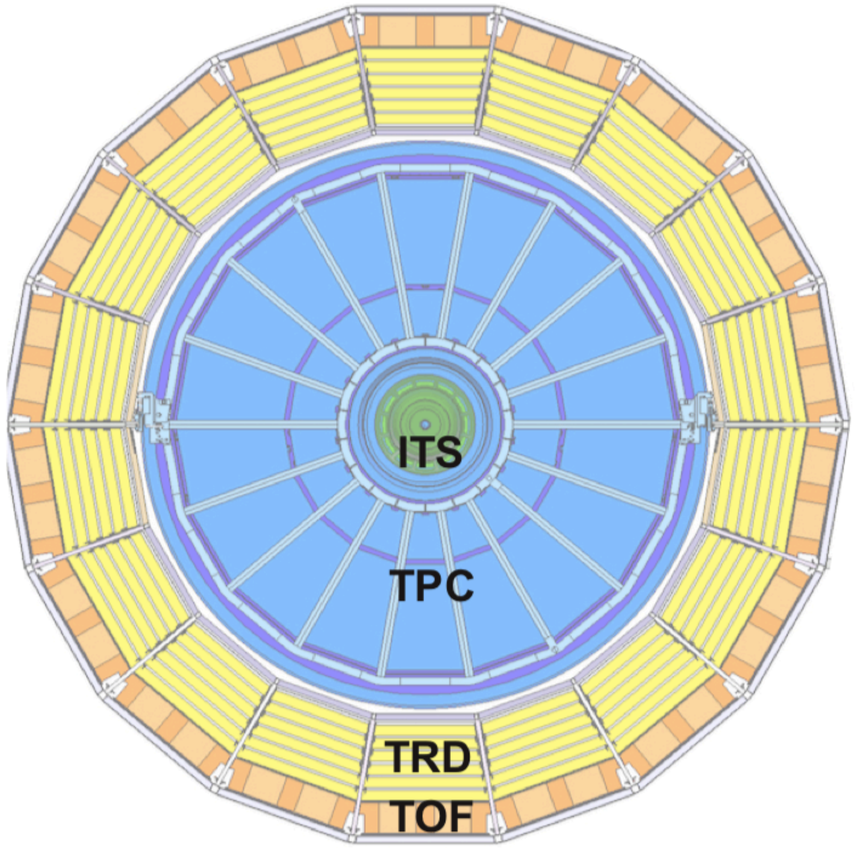

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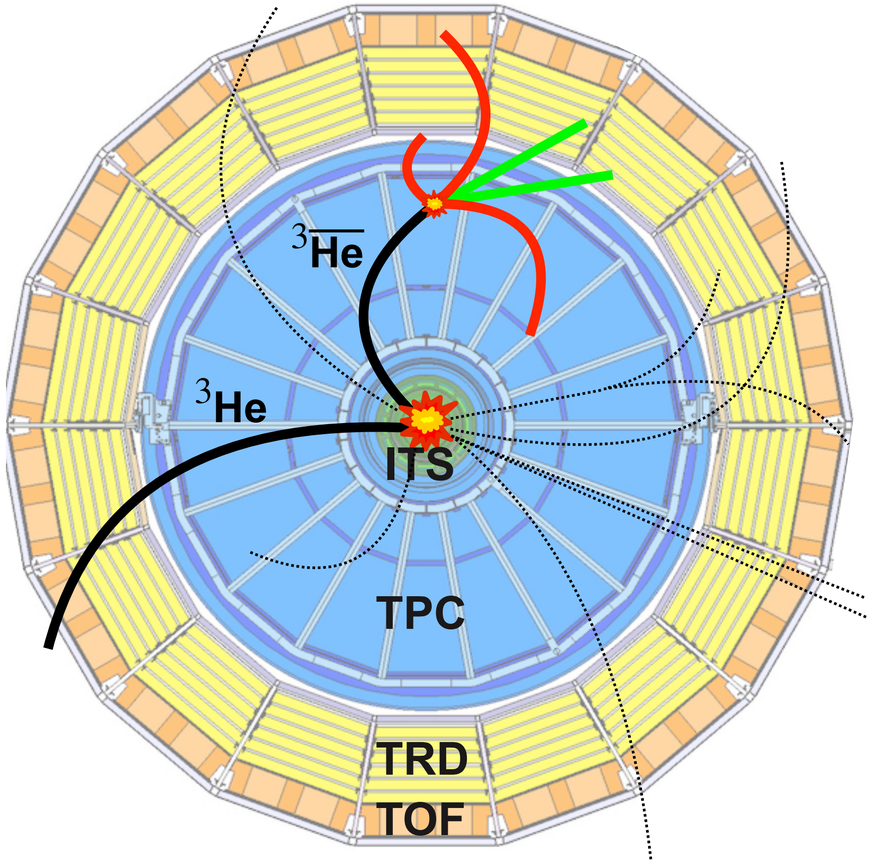

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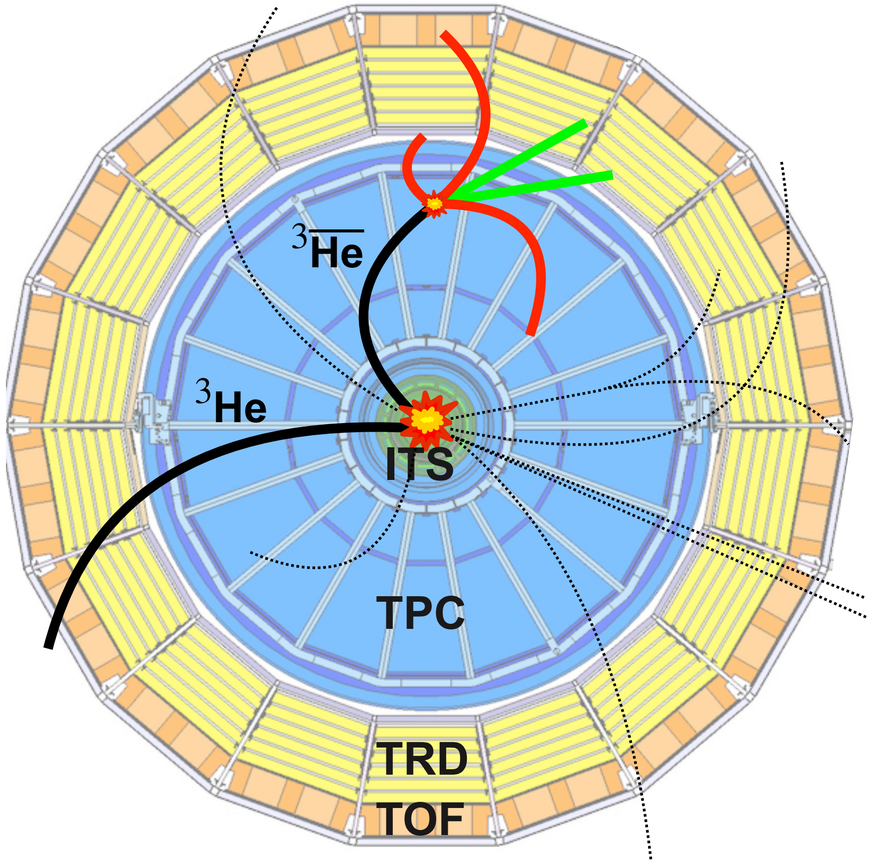

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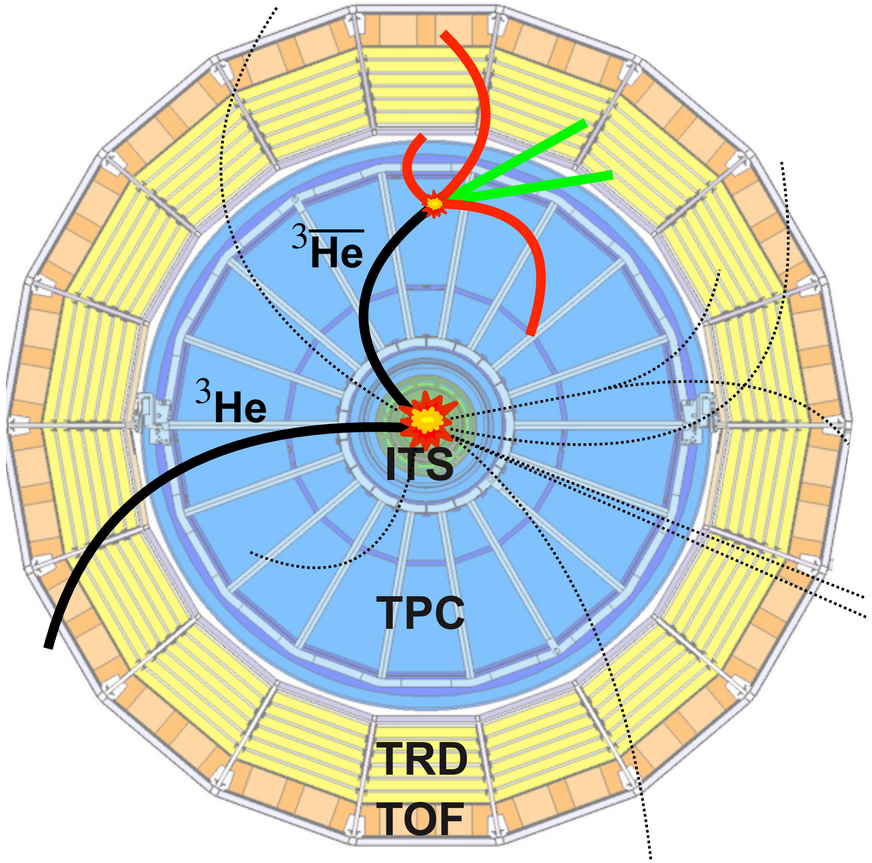

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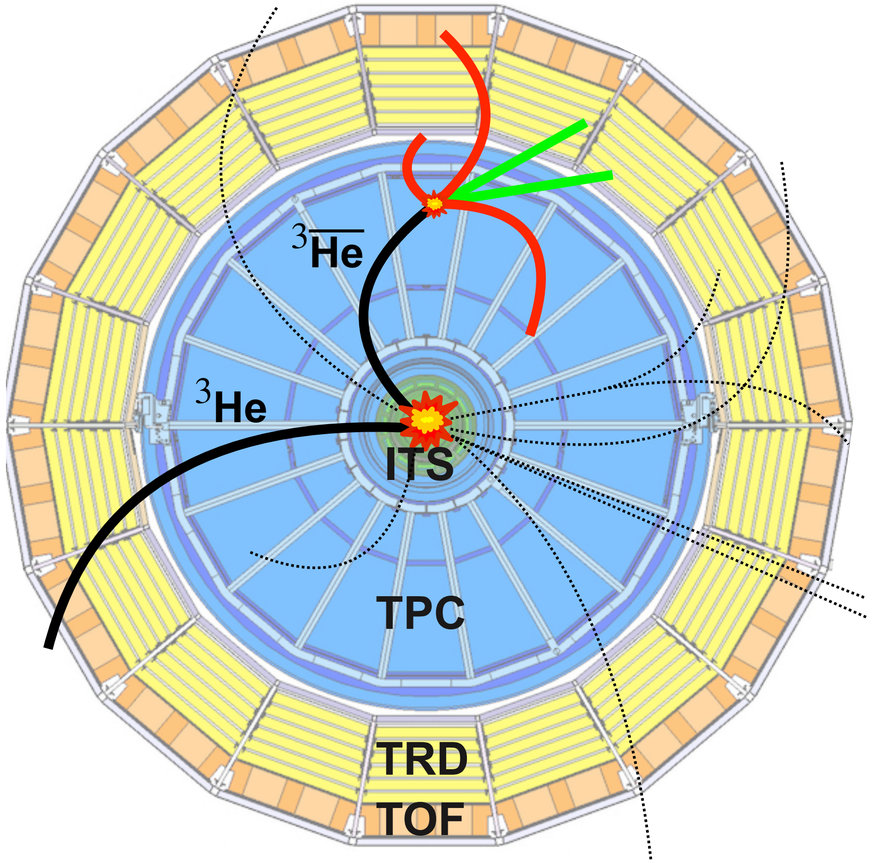
- Measure σ_{inel} via comparison with detailed Monte Carlo simulations using Geant4.



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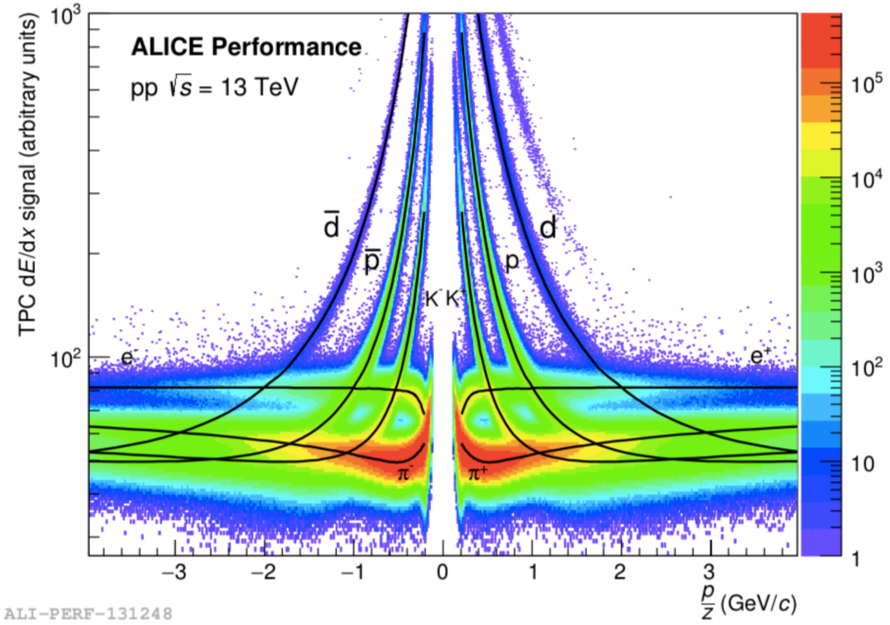

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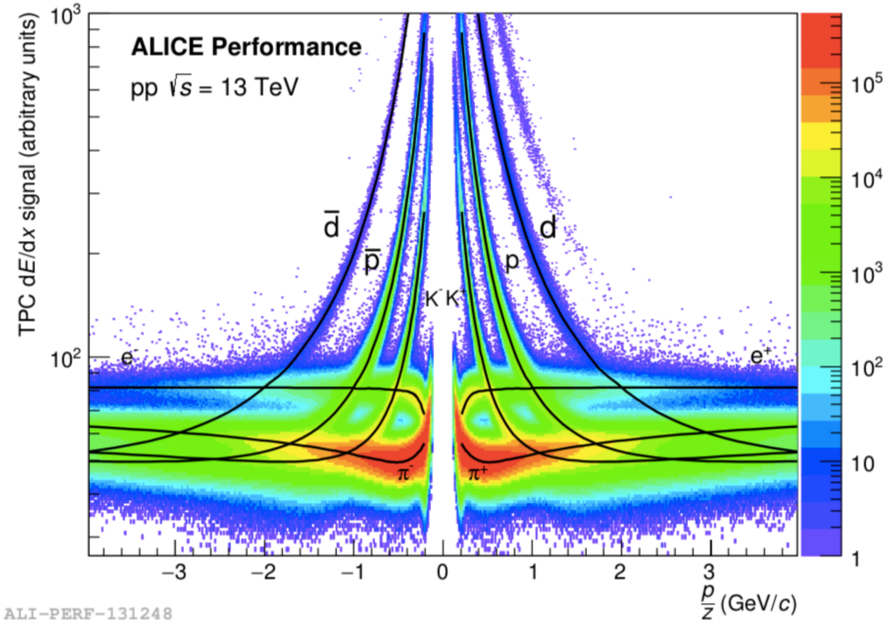

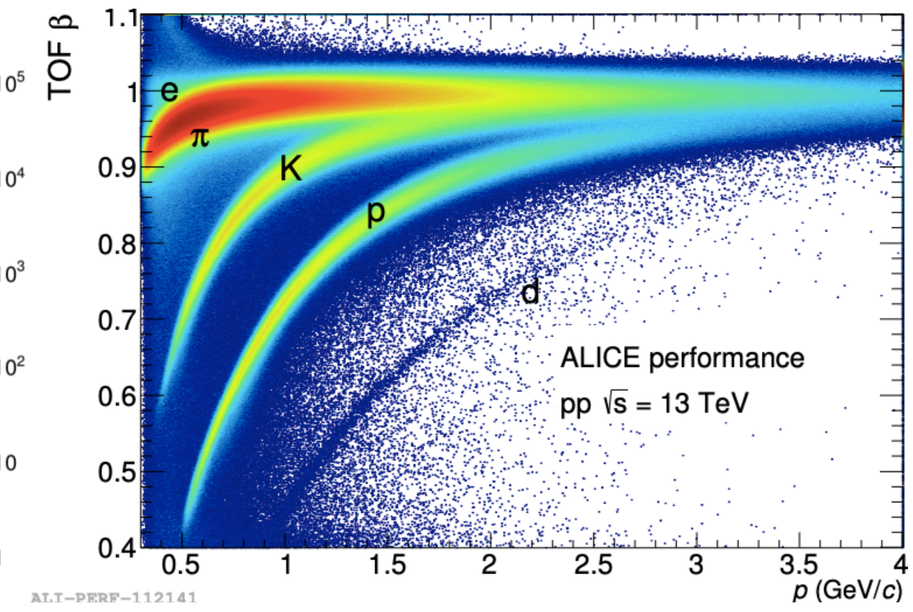

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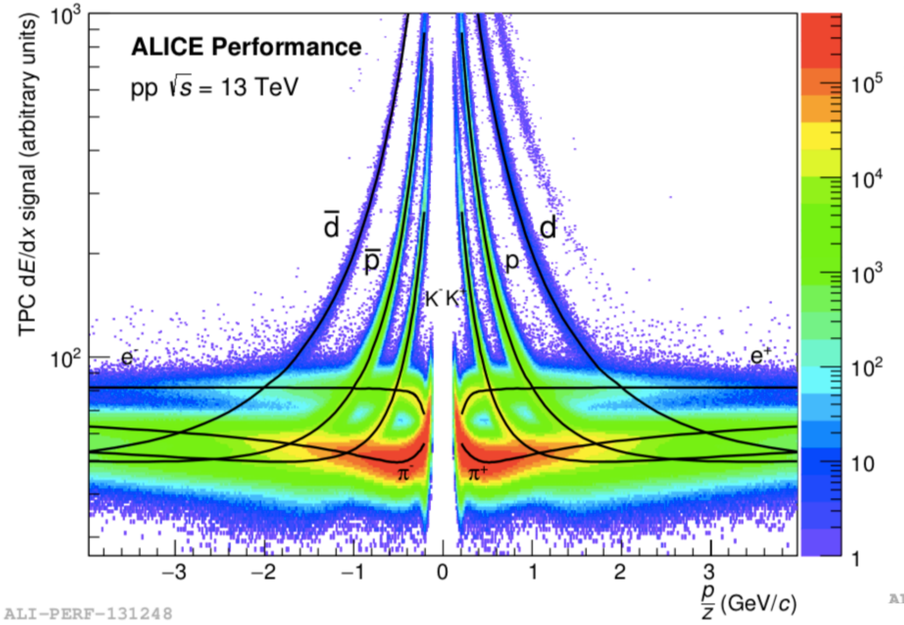

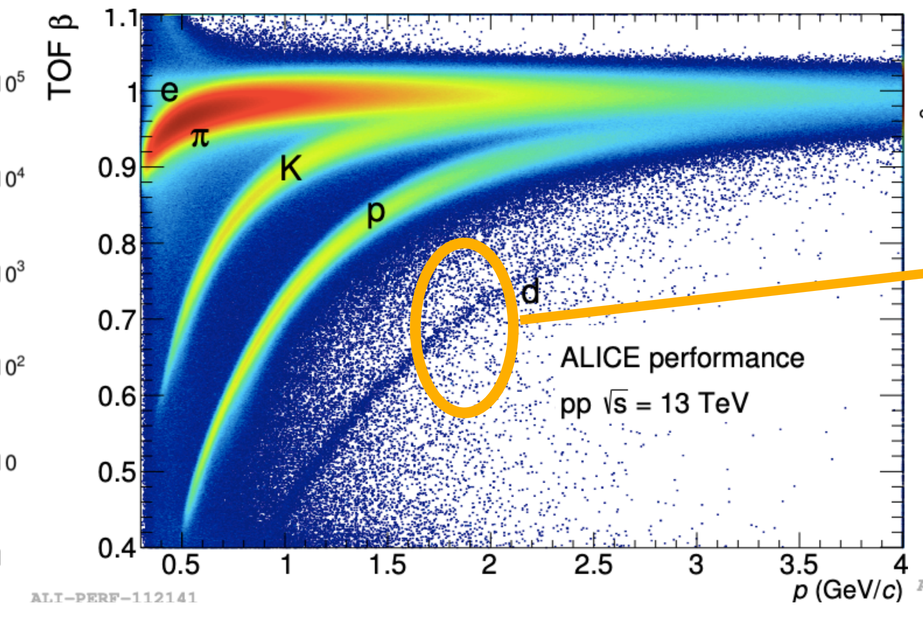

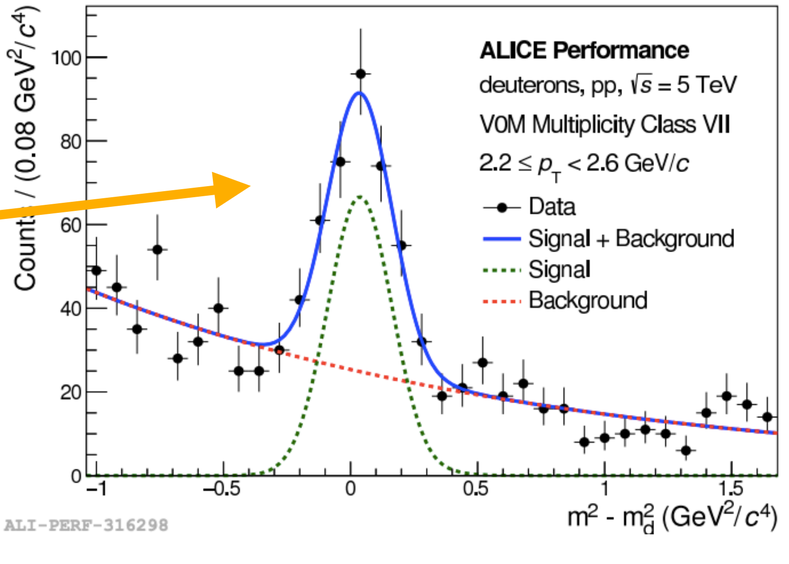

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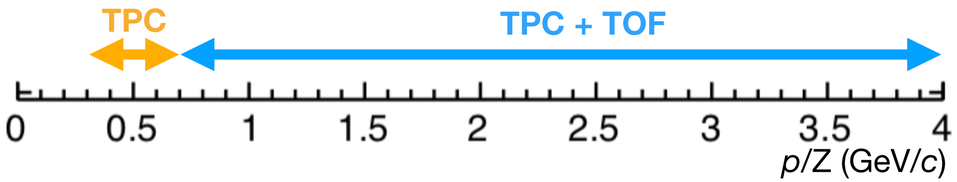
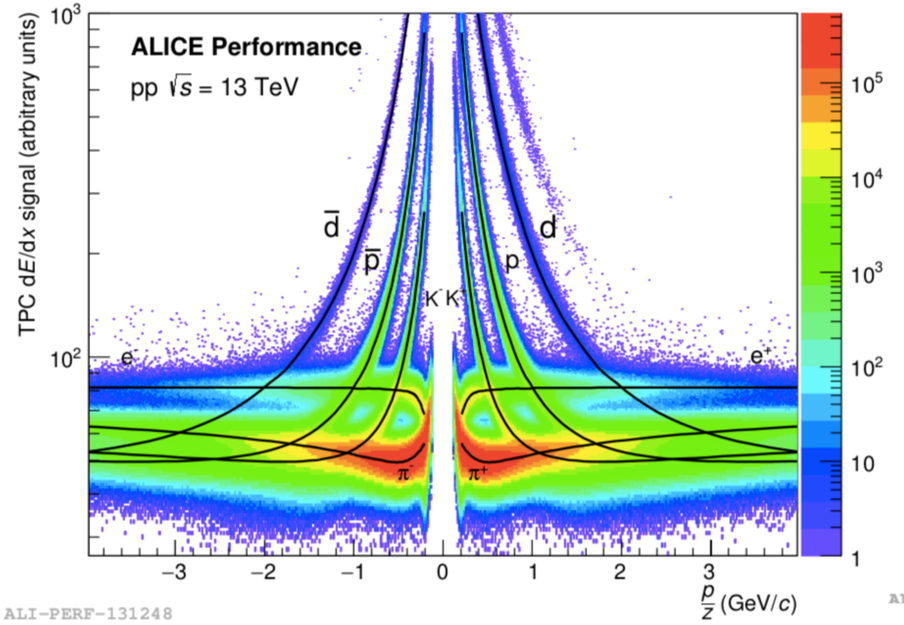
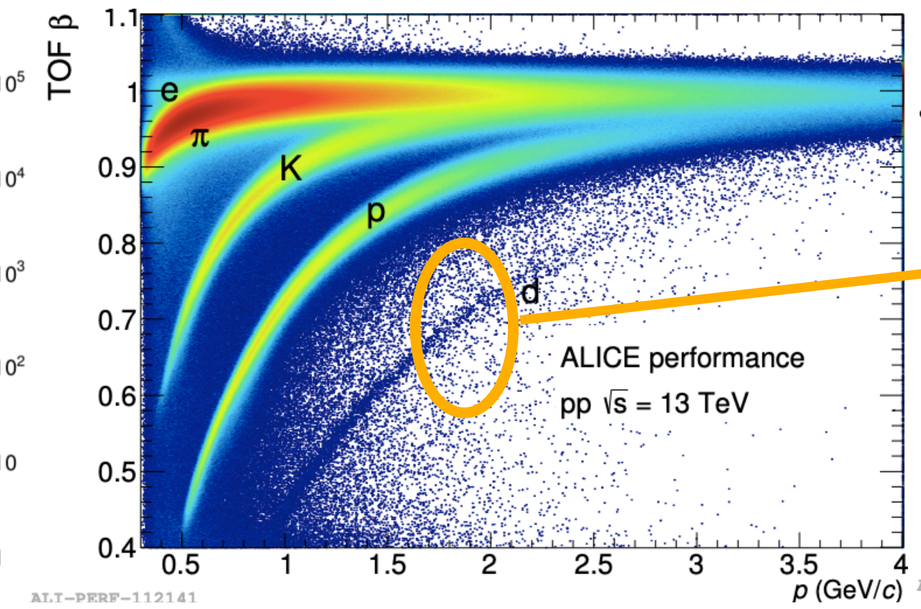
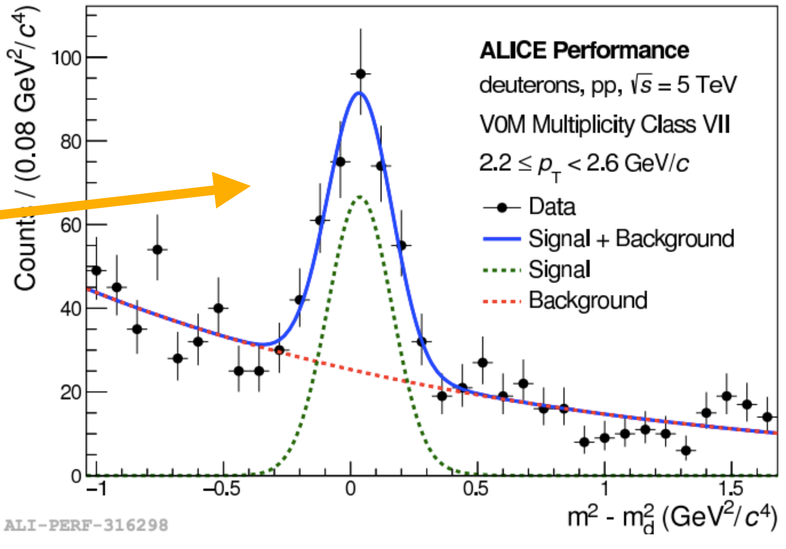
(Anti)protons









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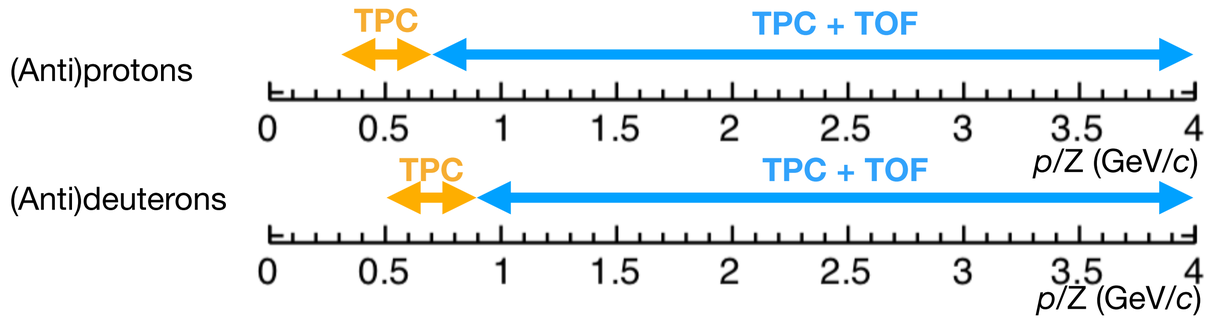

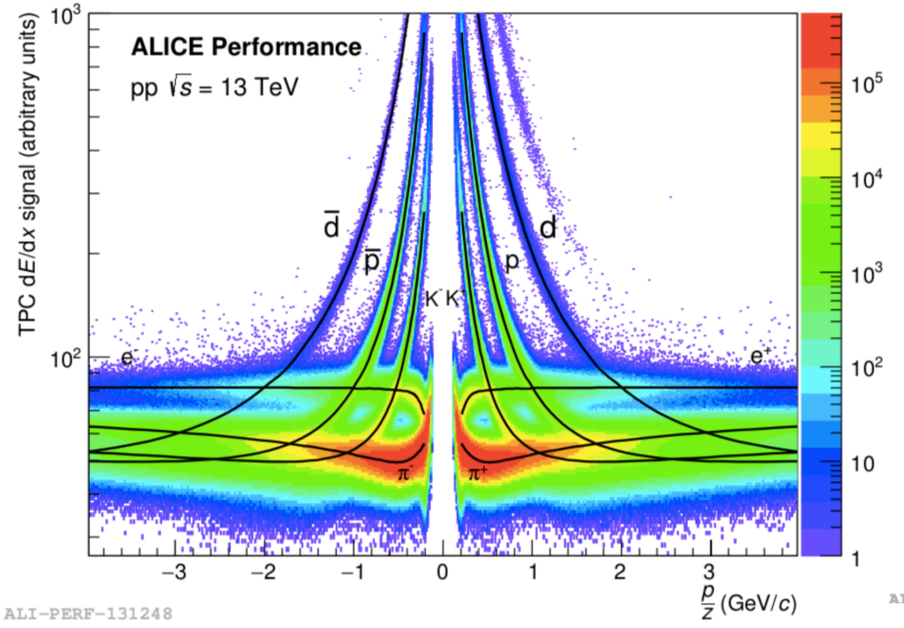

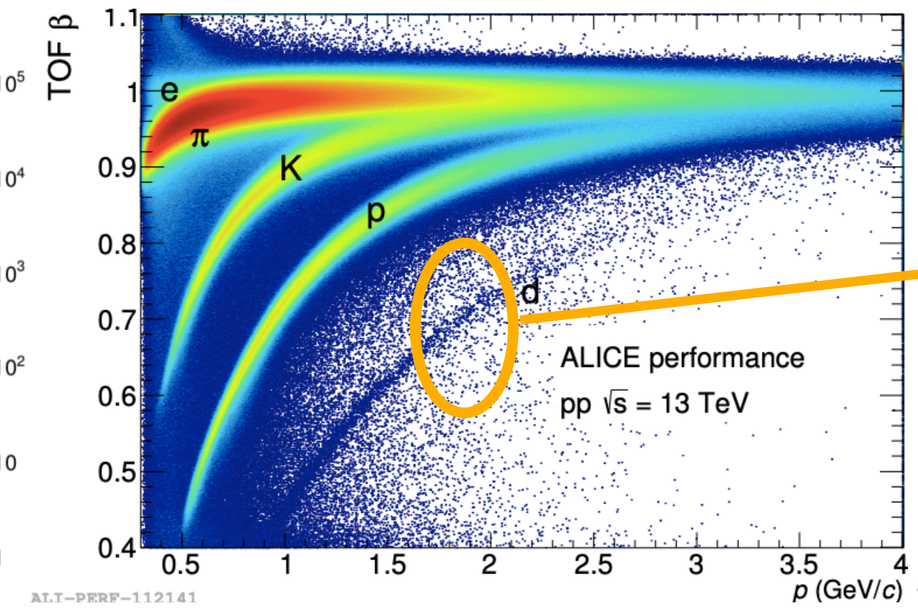

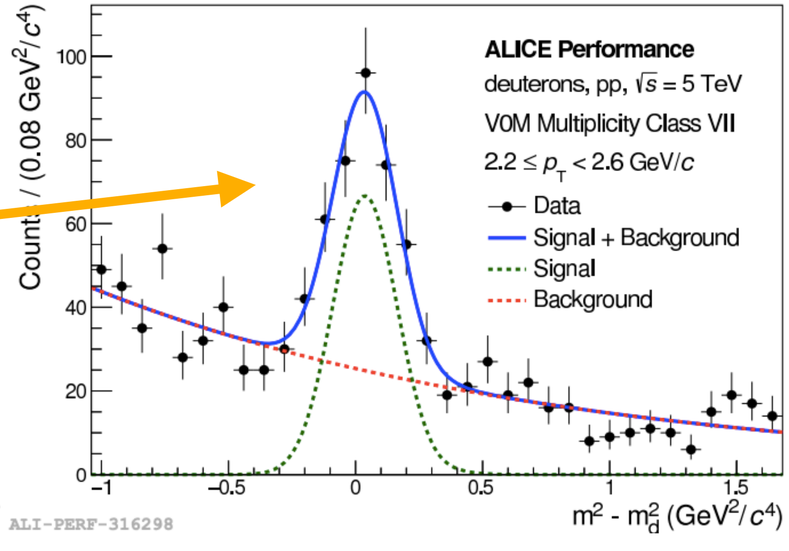

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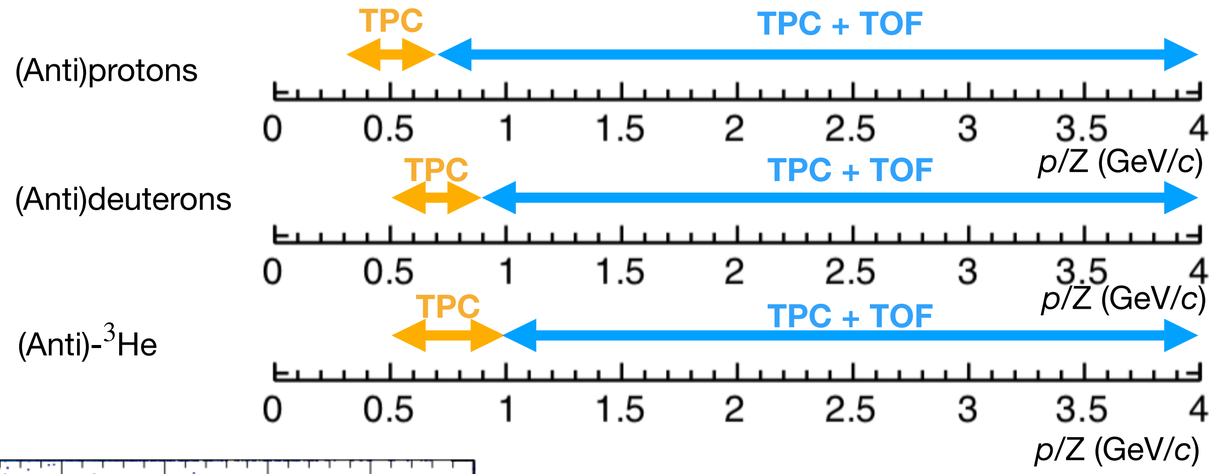

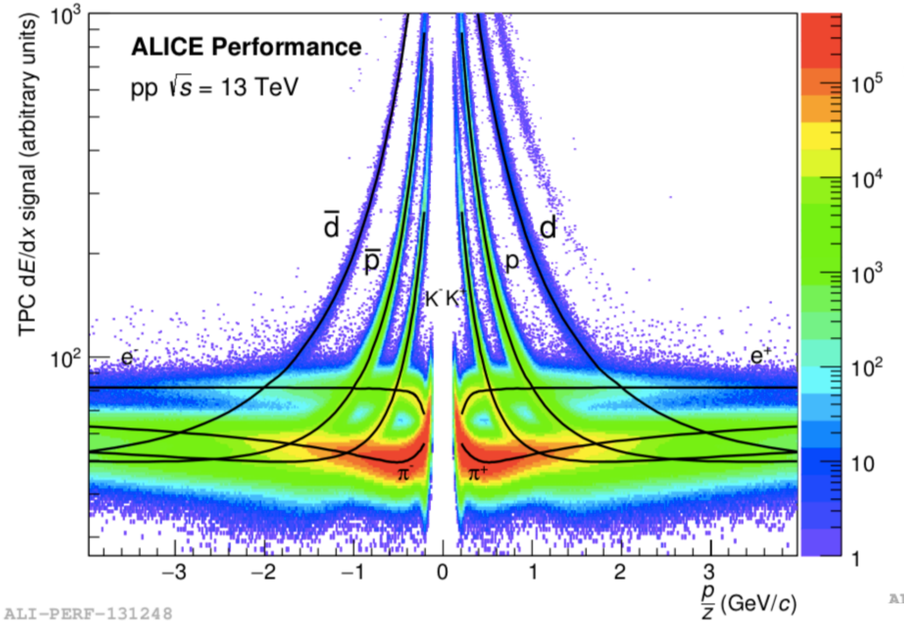

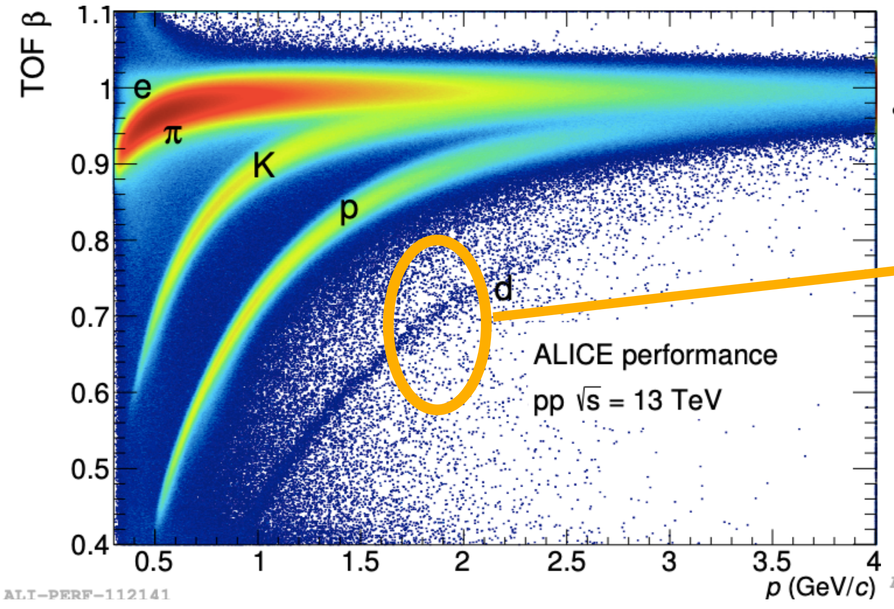

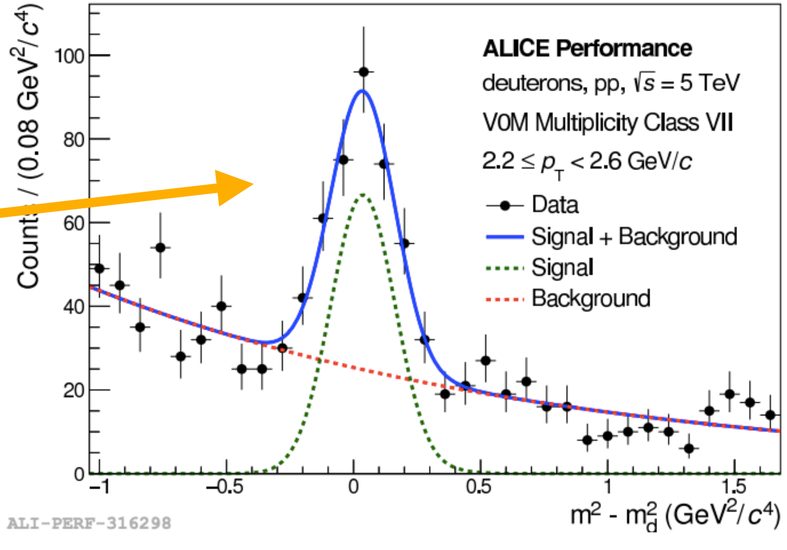

Raw primary antiproton-to-proton ratio

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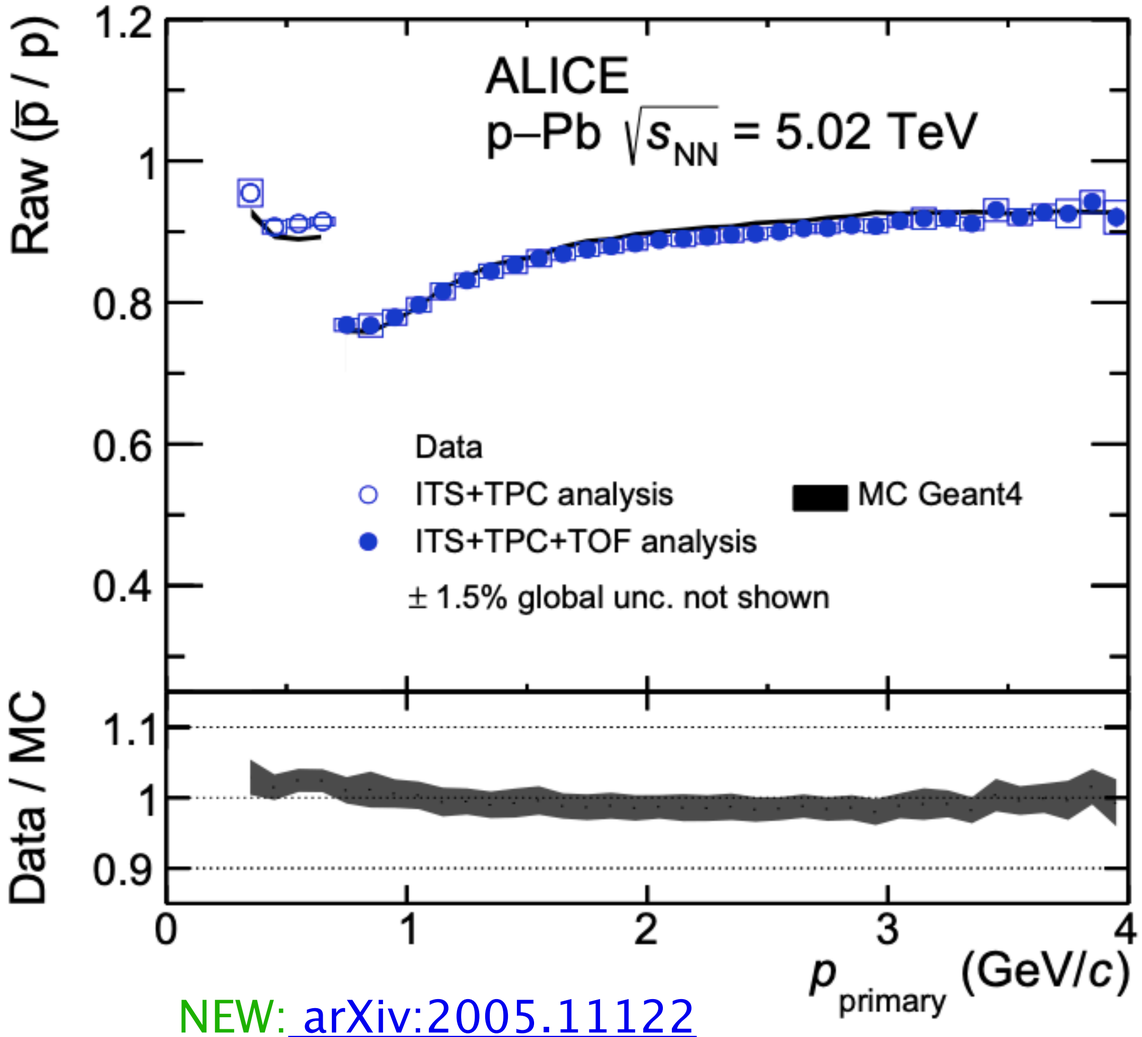

NEW: arXiv:2005.11122

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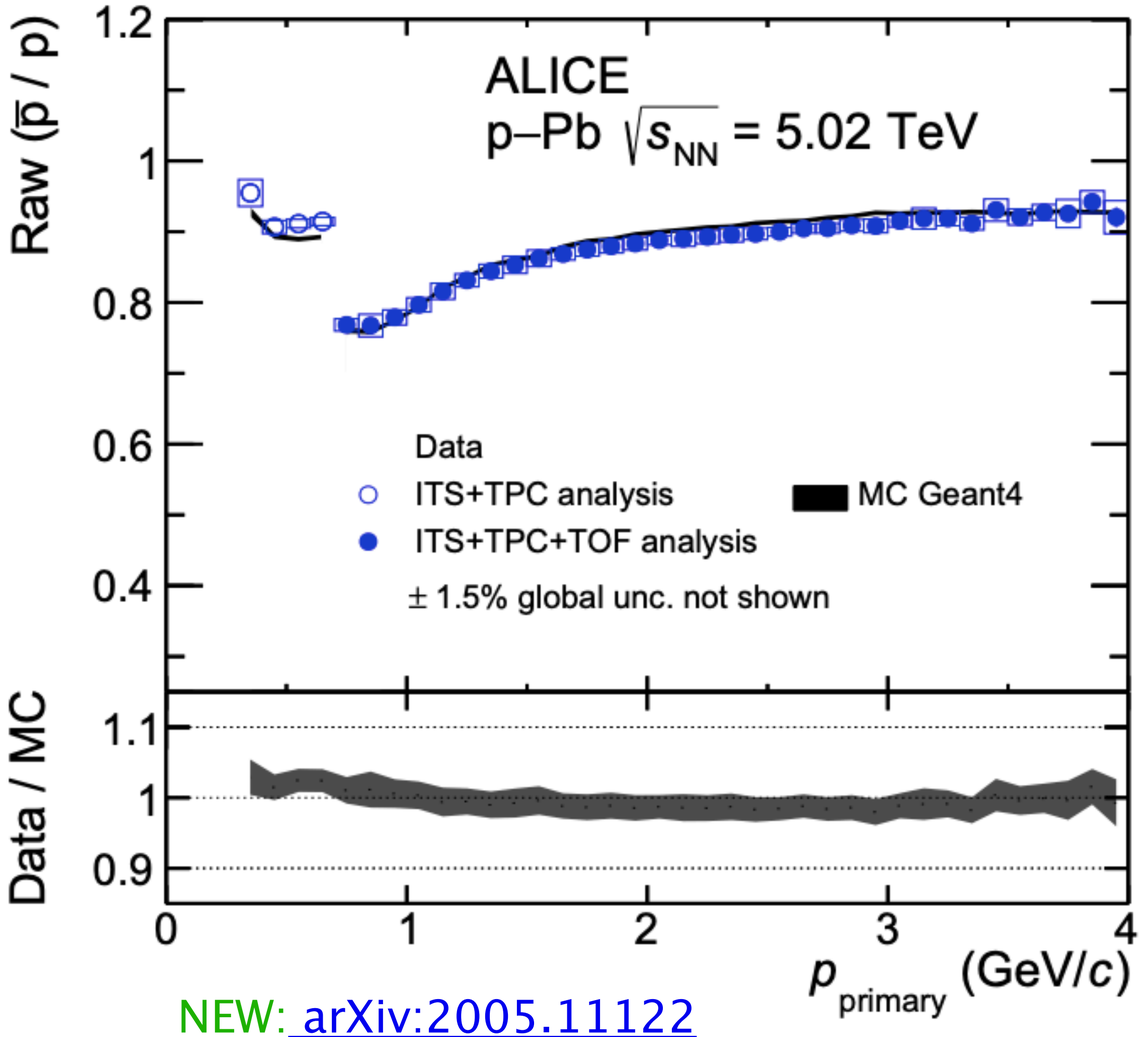

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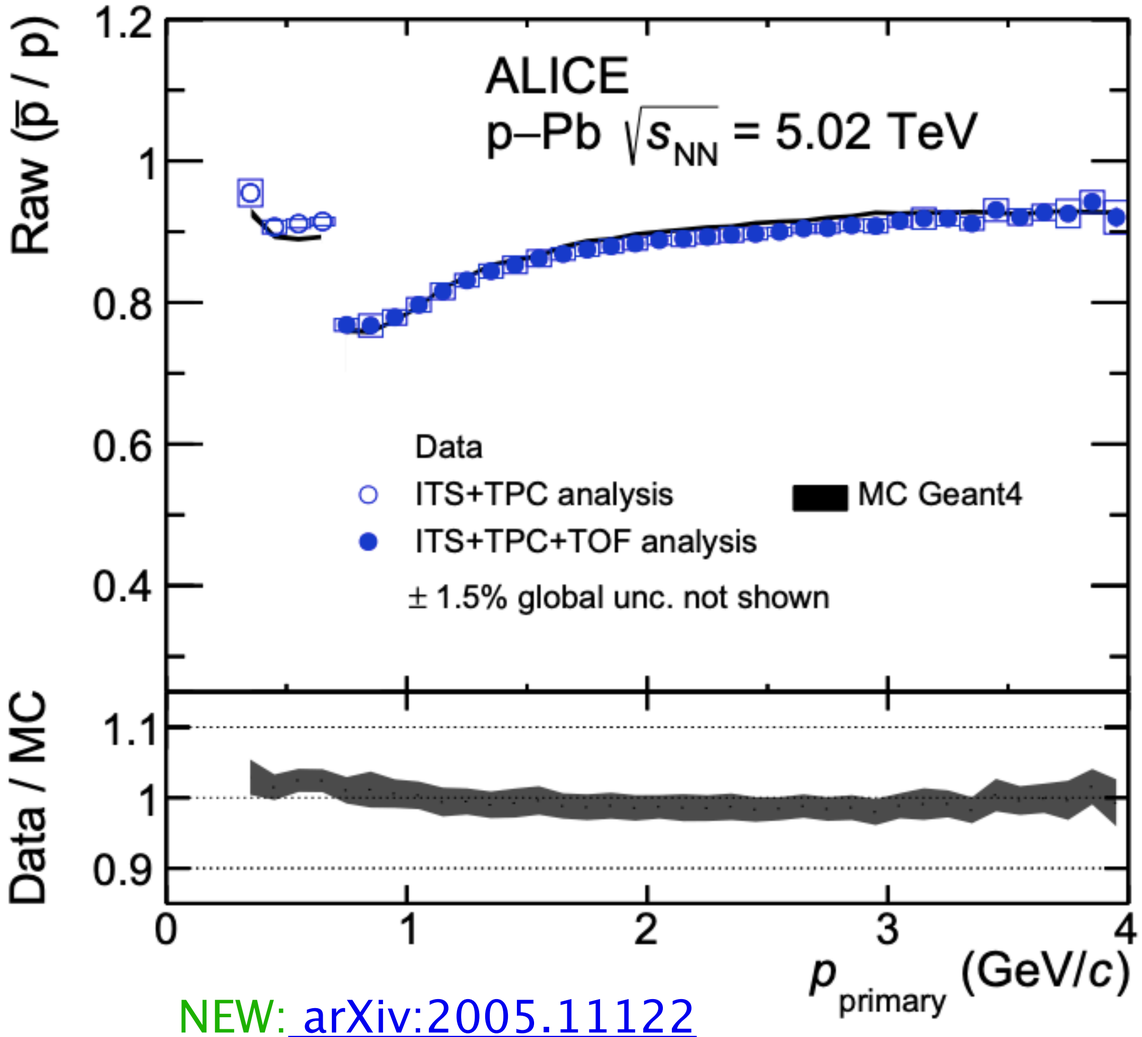

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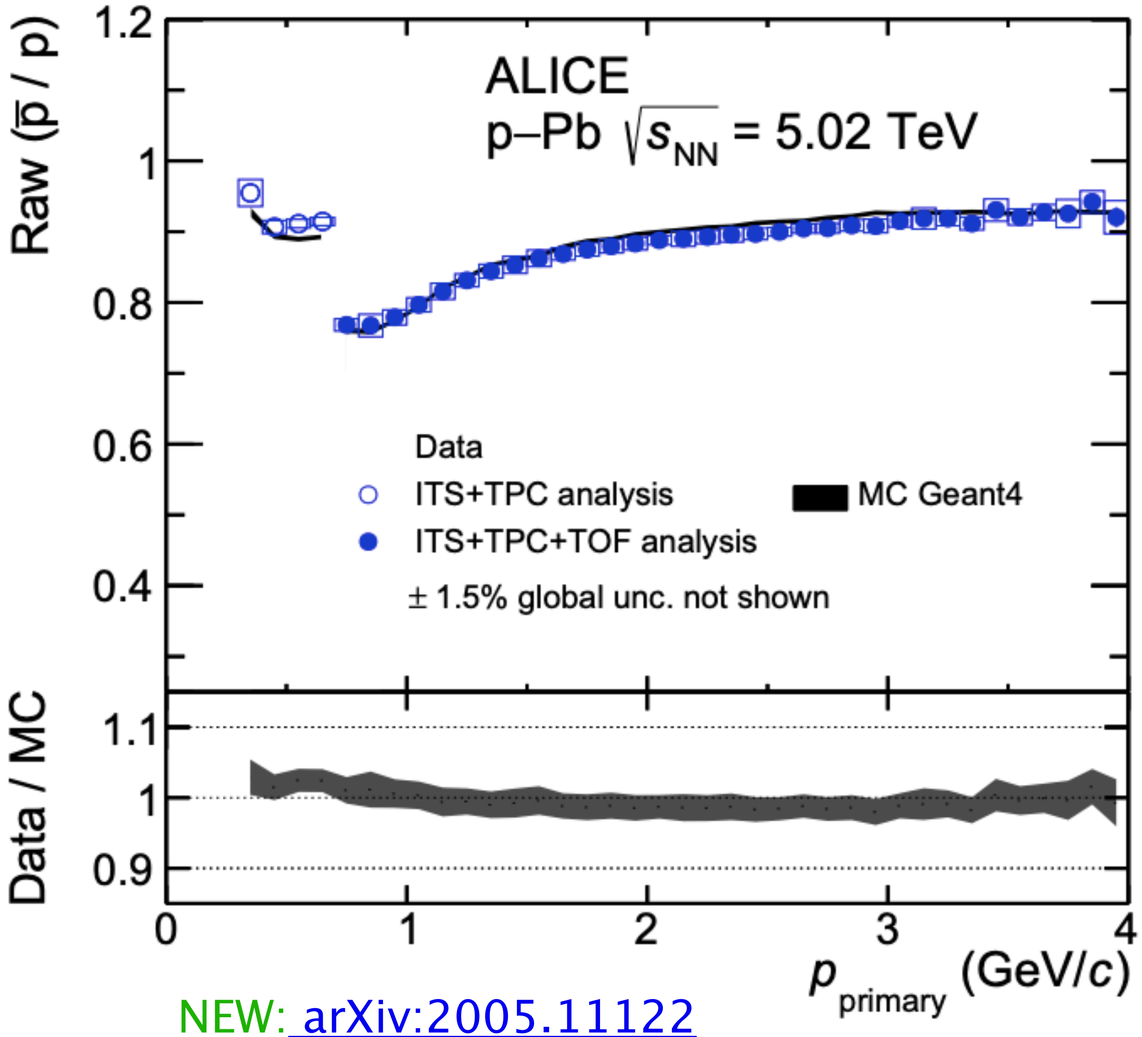

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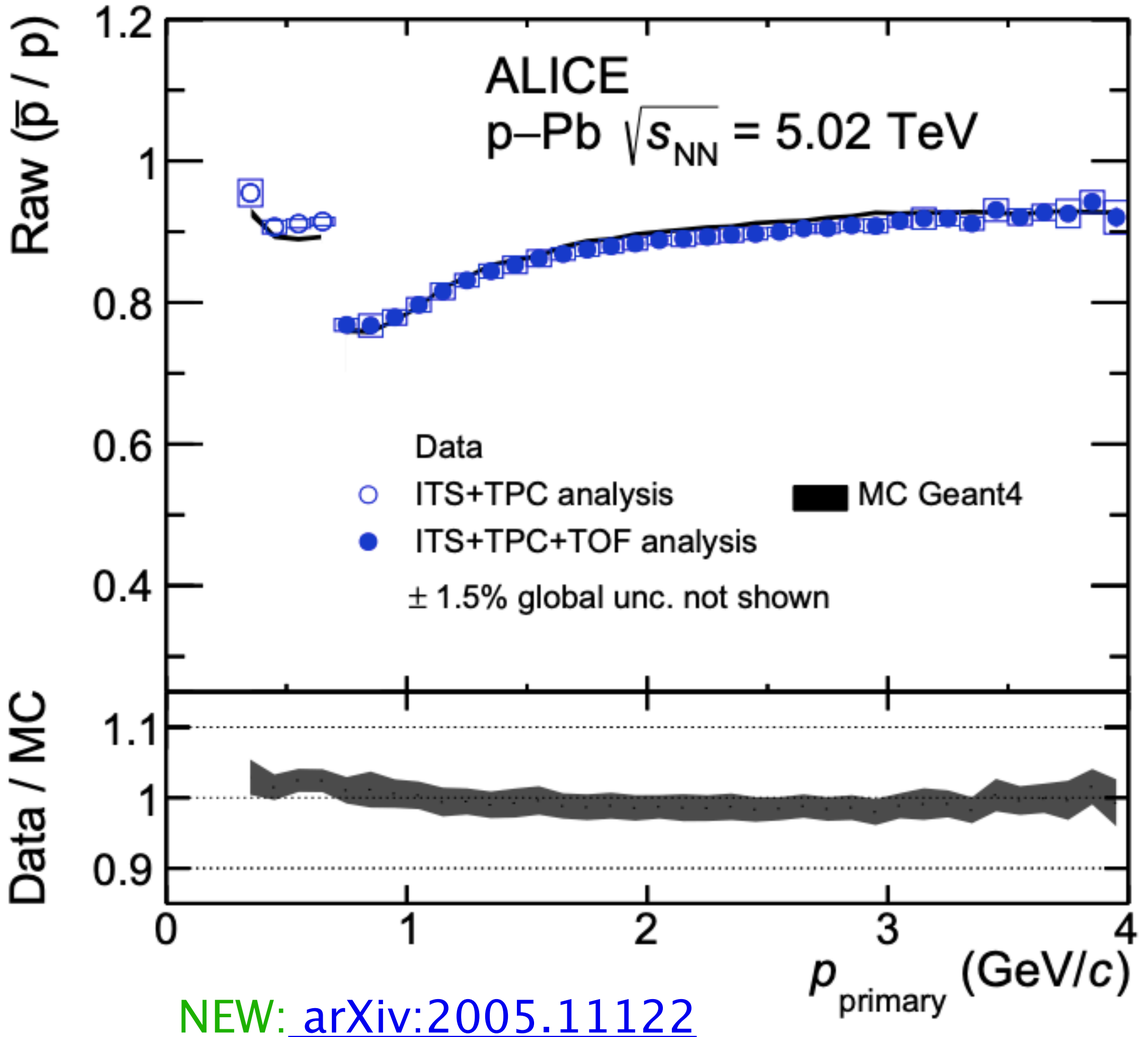

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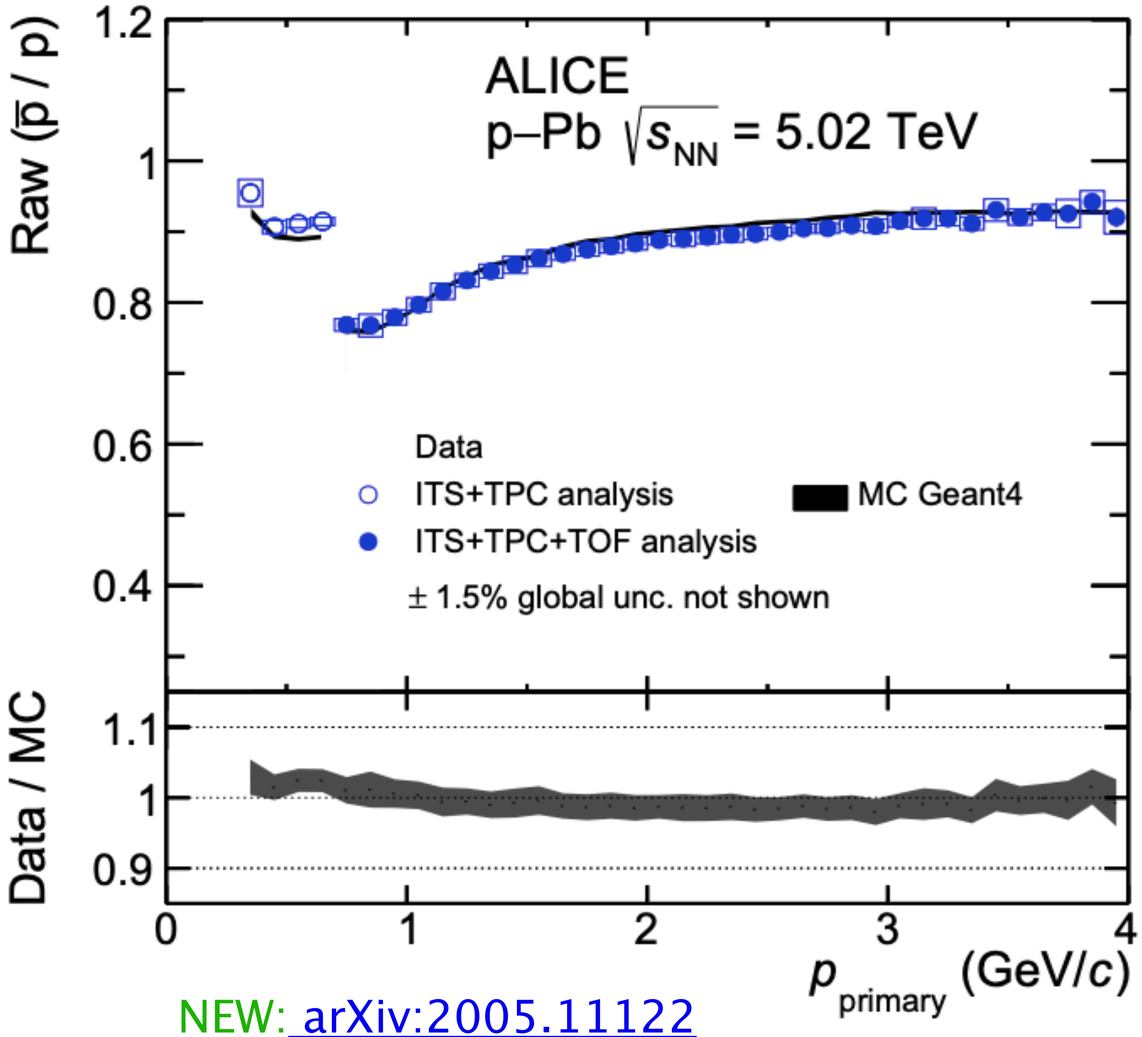

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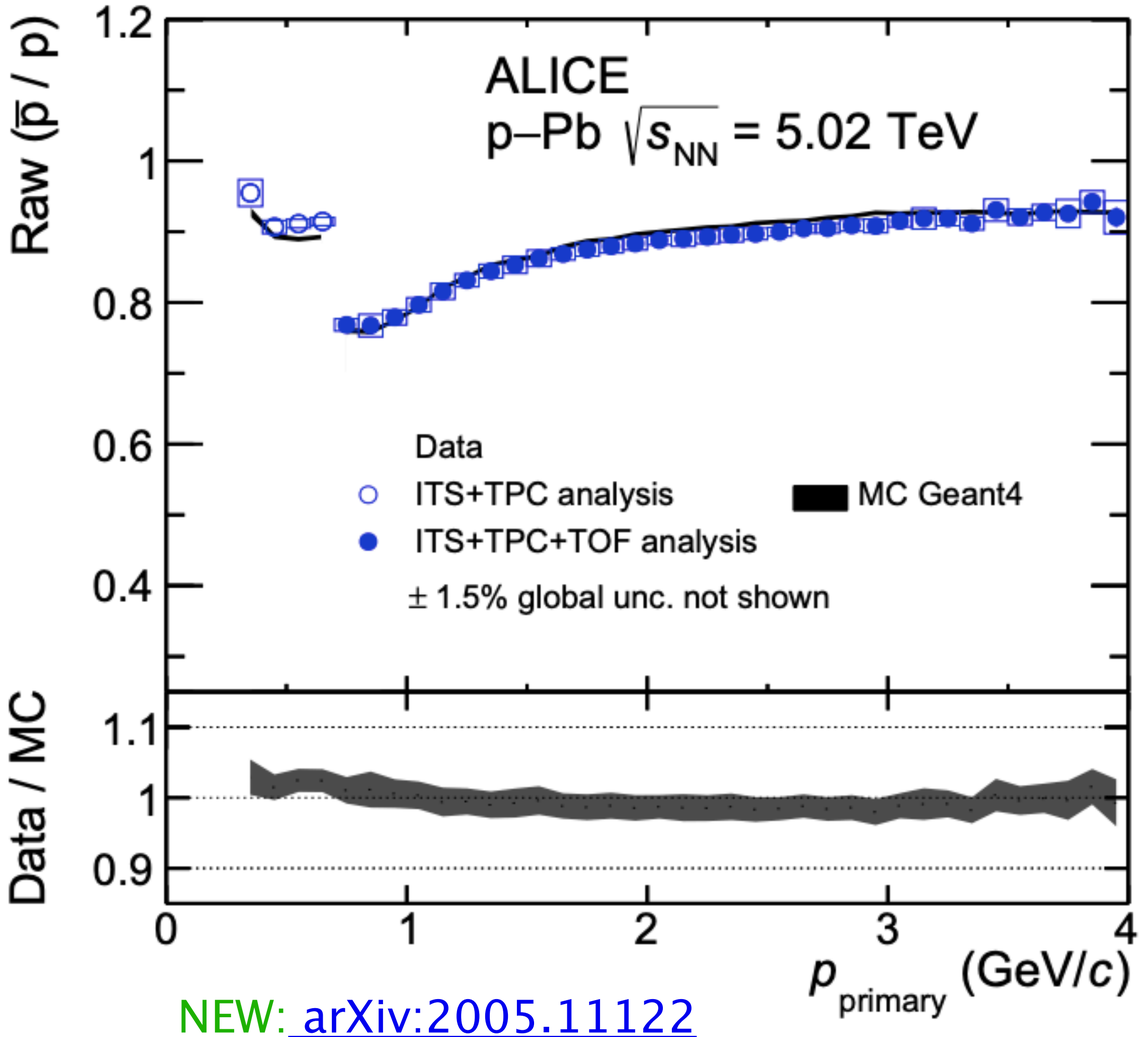

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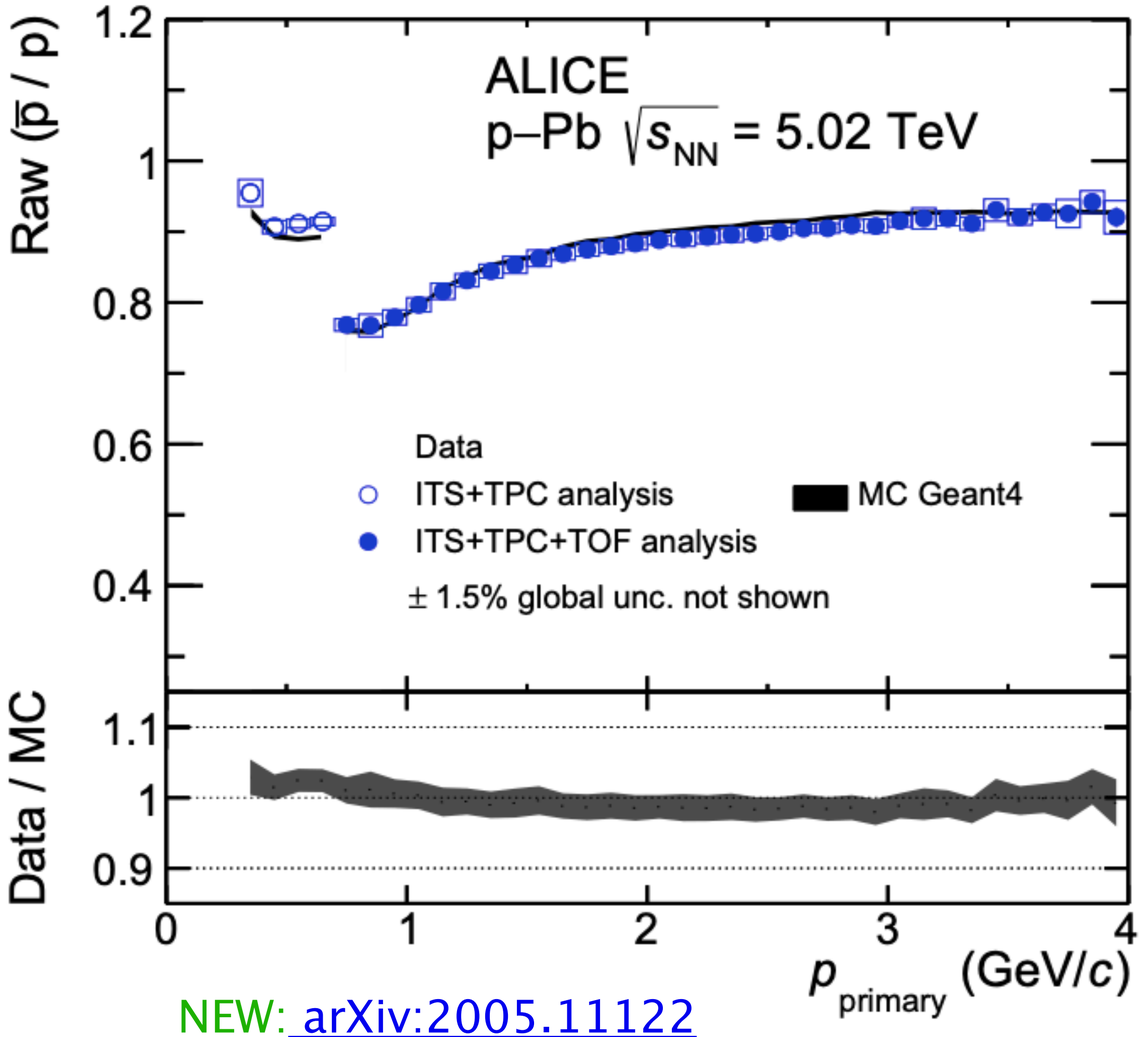

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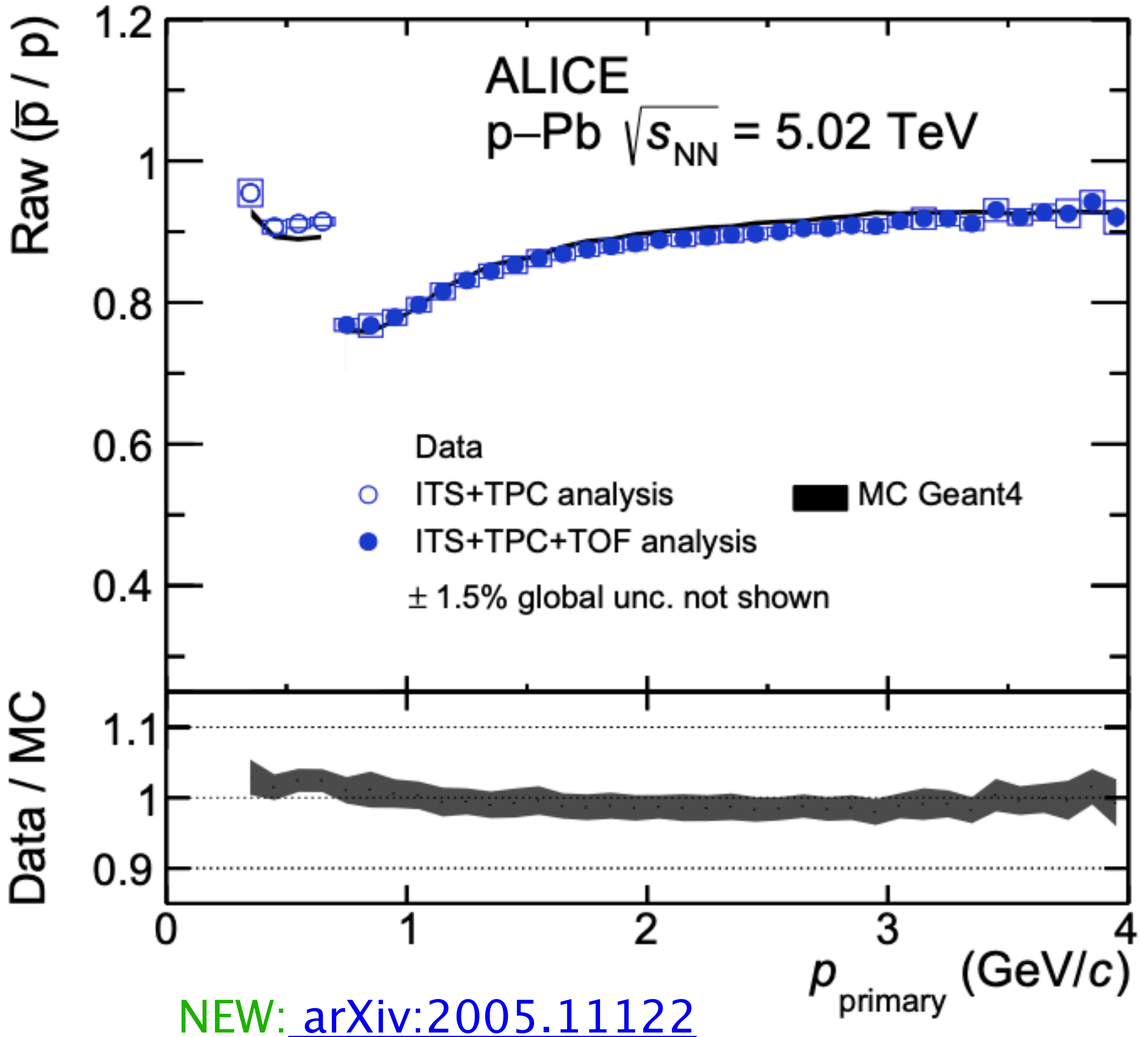

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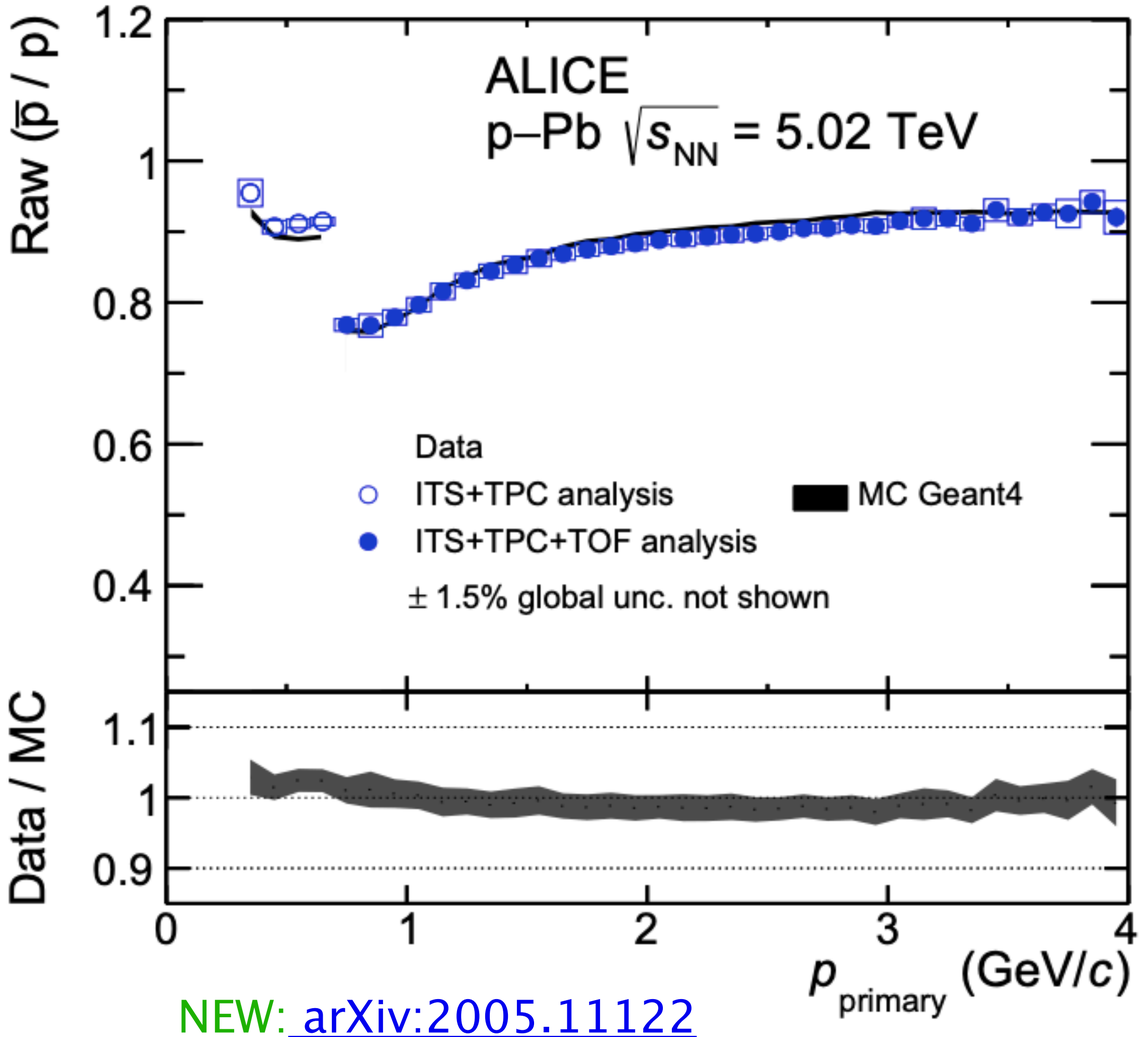

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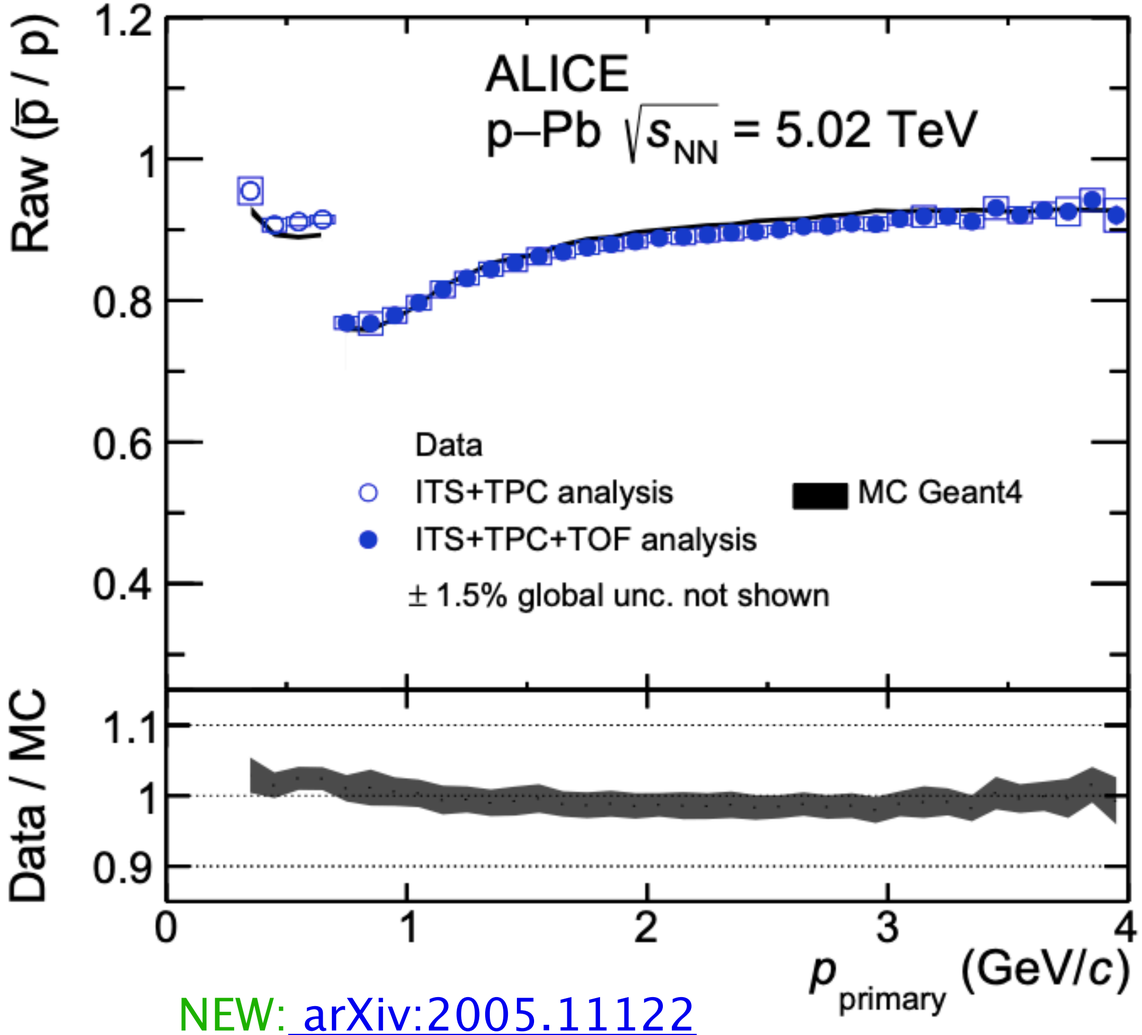

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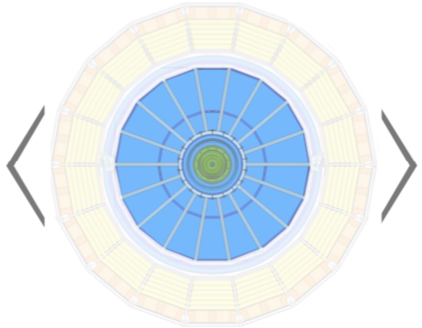
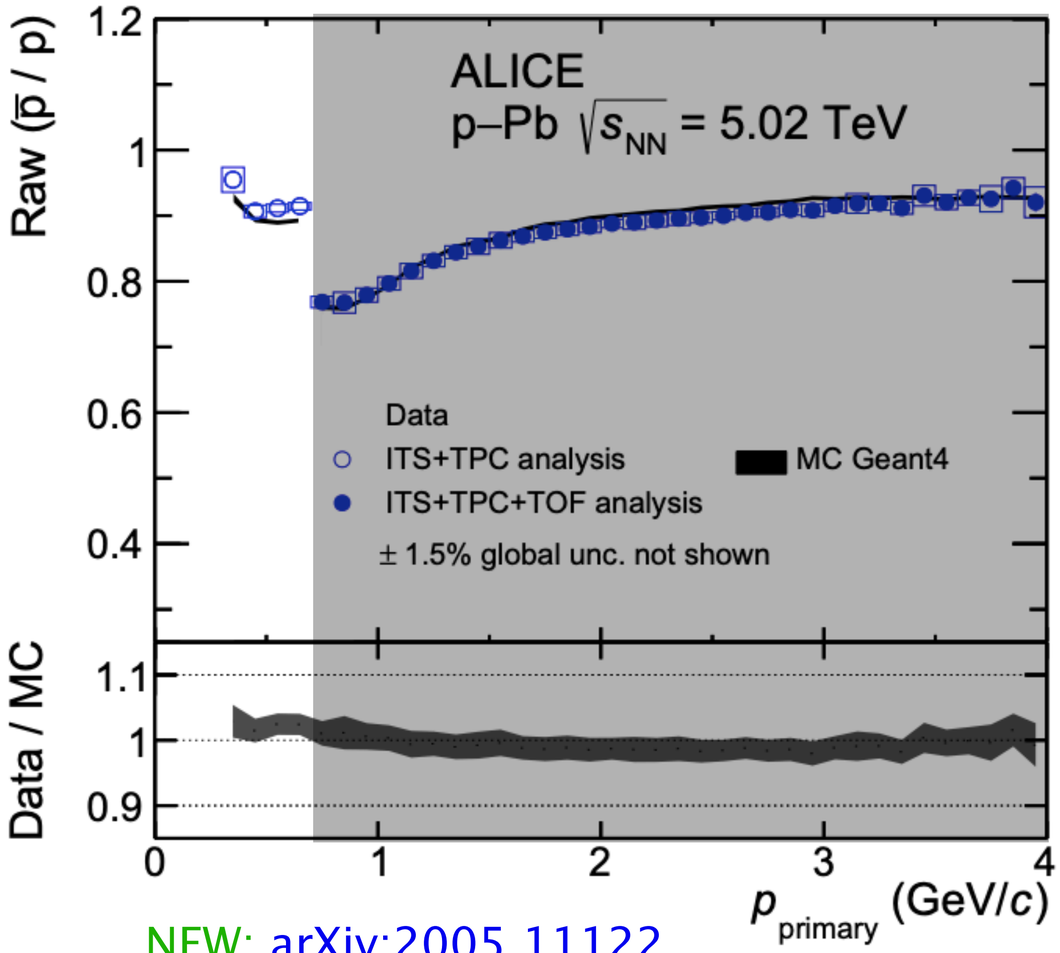
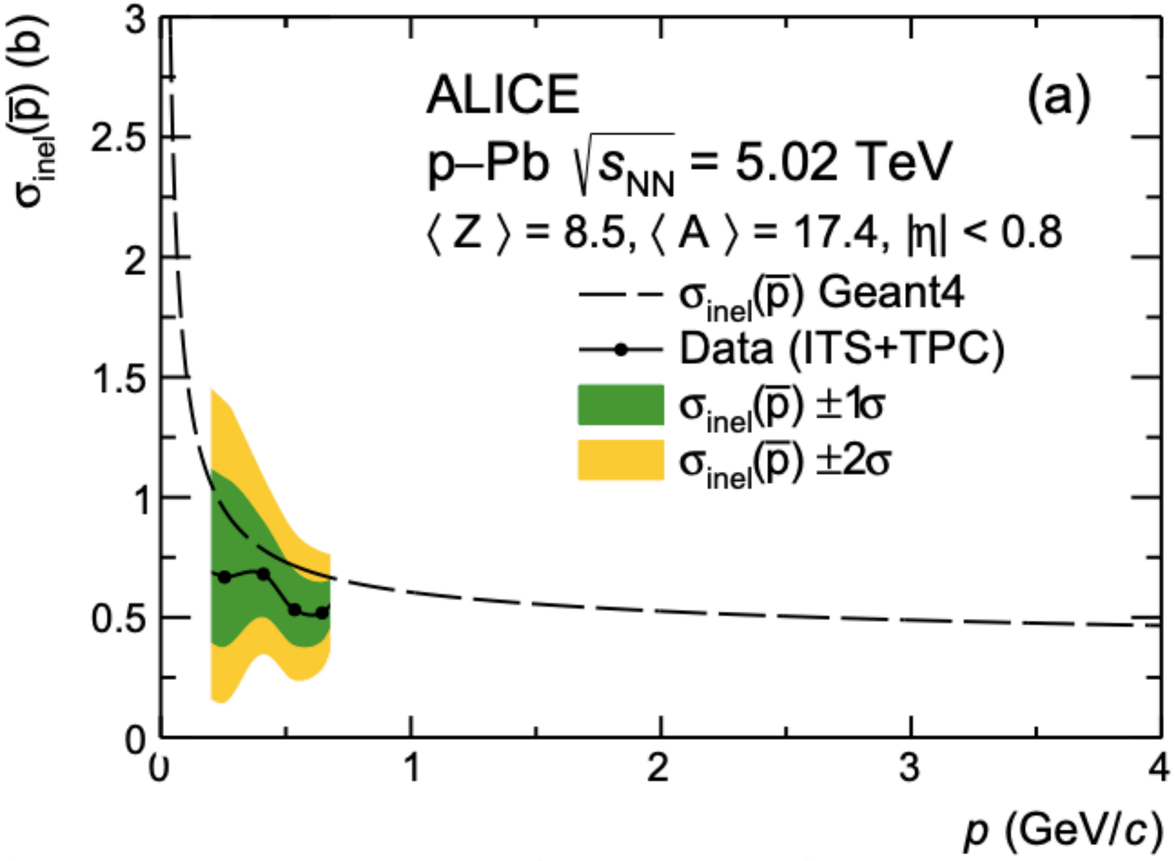
➡Agreement with of the antiproton cross section obtained confirms the correctness of the procedure.

Antiproton inelastic cross section

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







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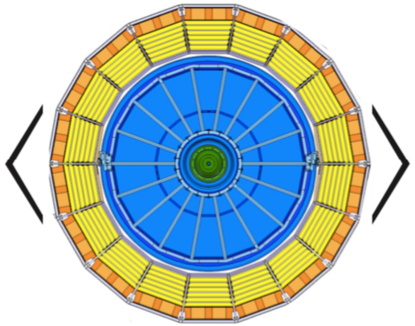
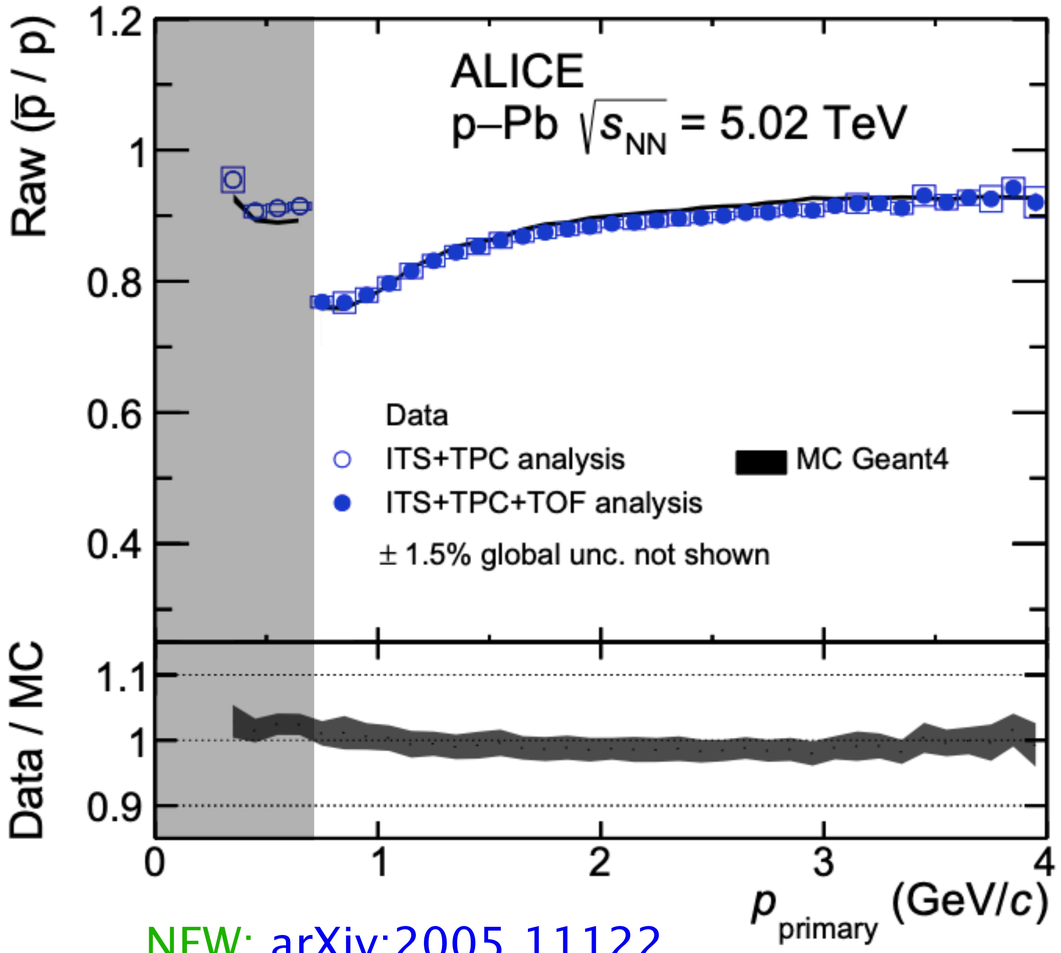
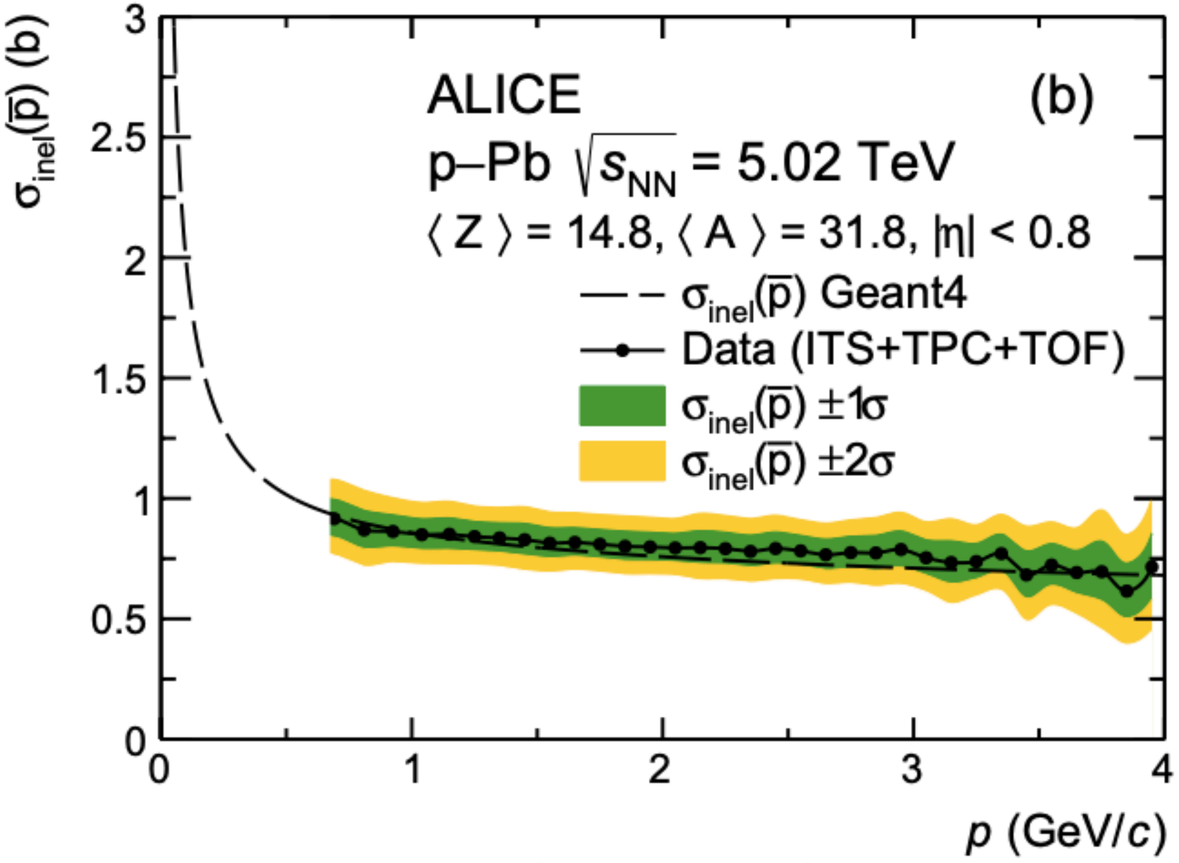


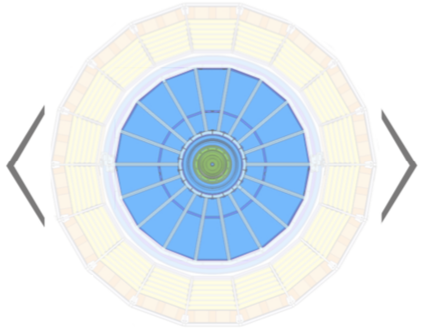


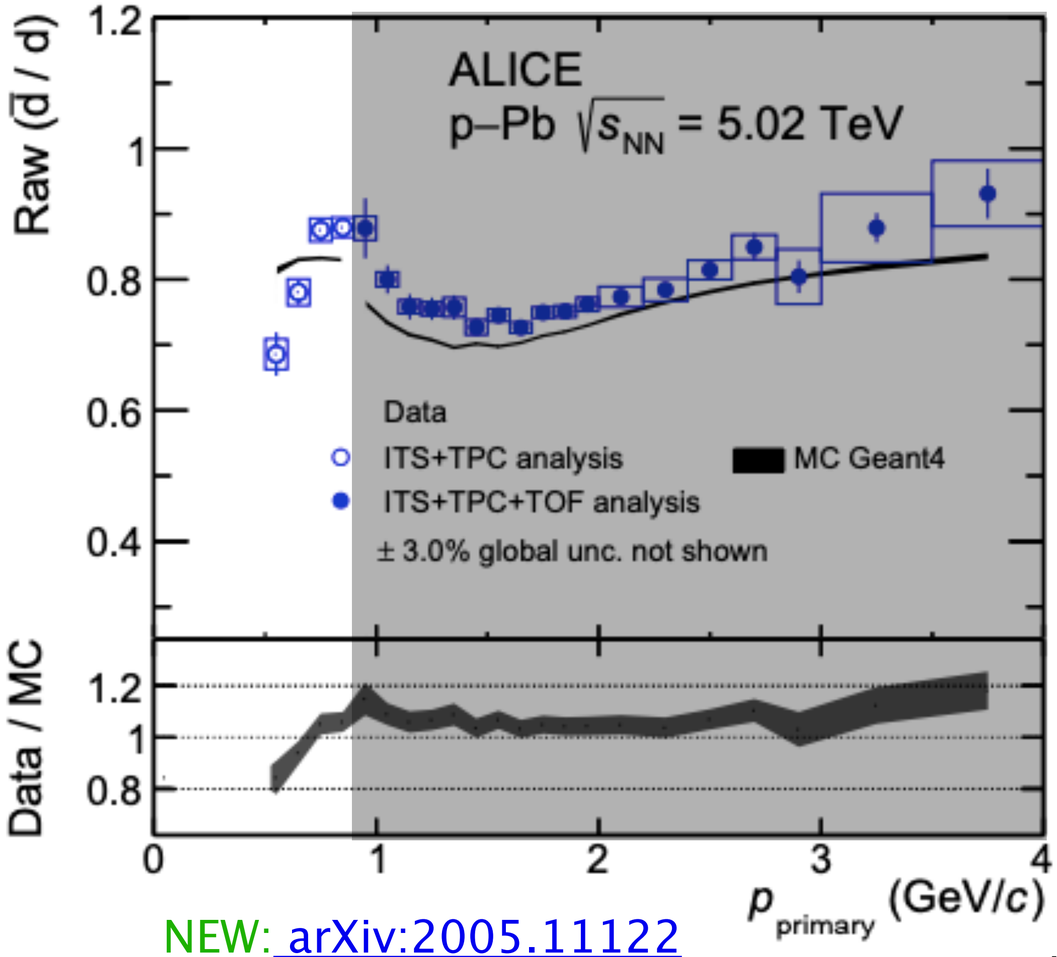


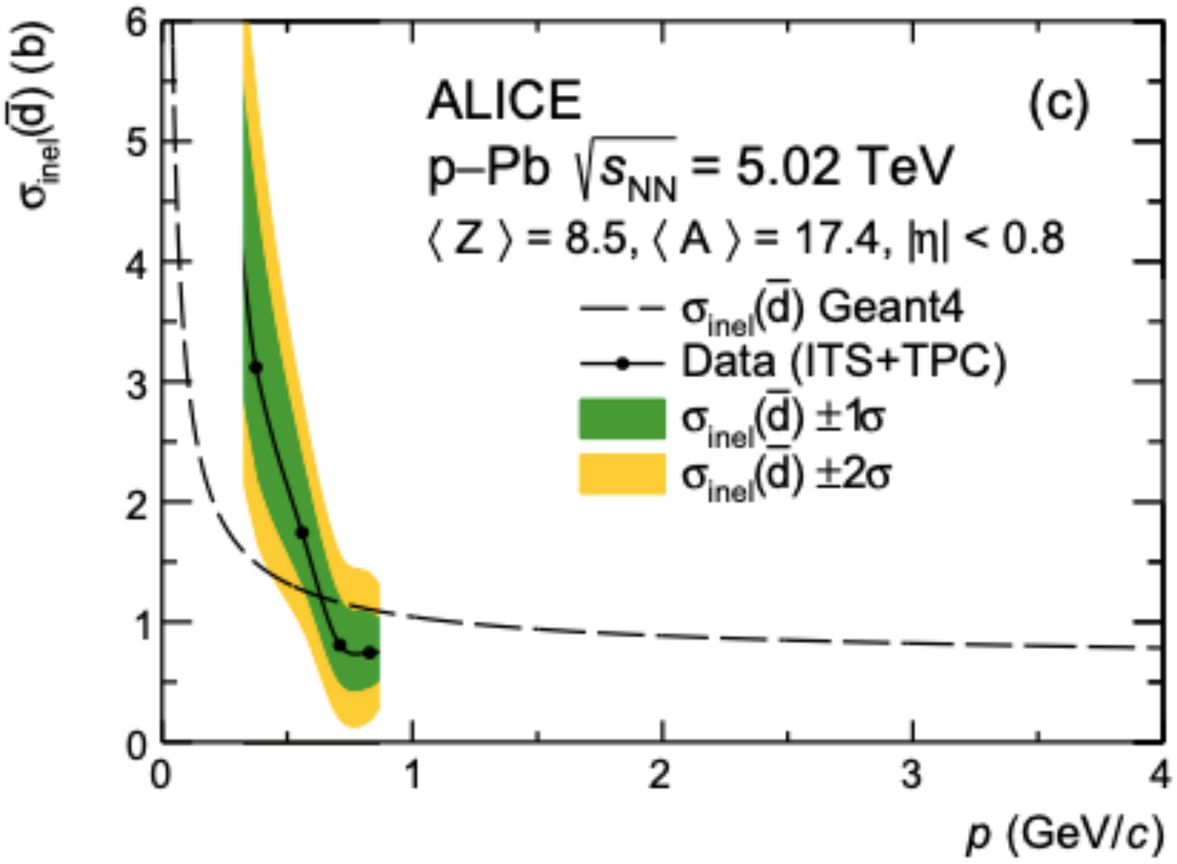
NEW: arXiv:2005.11122

Antideuteron inelastic cross section

$\sigma_{\text{inel}}(\bar{d})$ on average ALICE detector material.
Hint at steeper rise at low momentum.







NEW: arXiv:2005.11122

Antideuteron inelastic cross section

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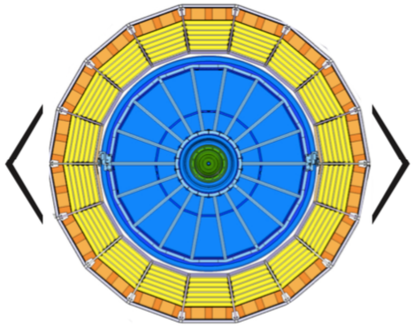

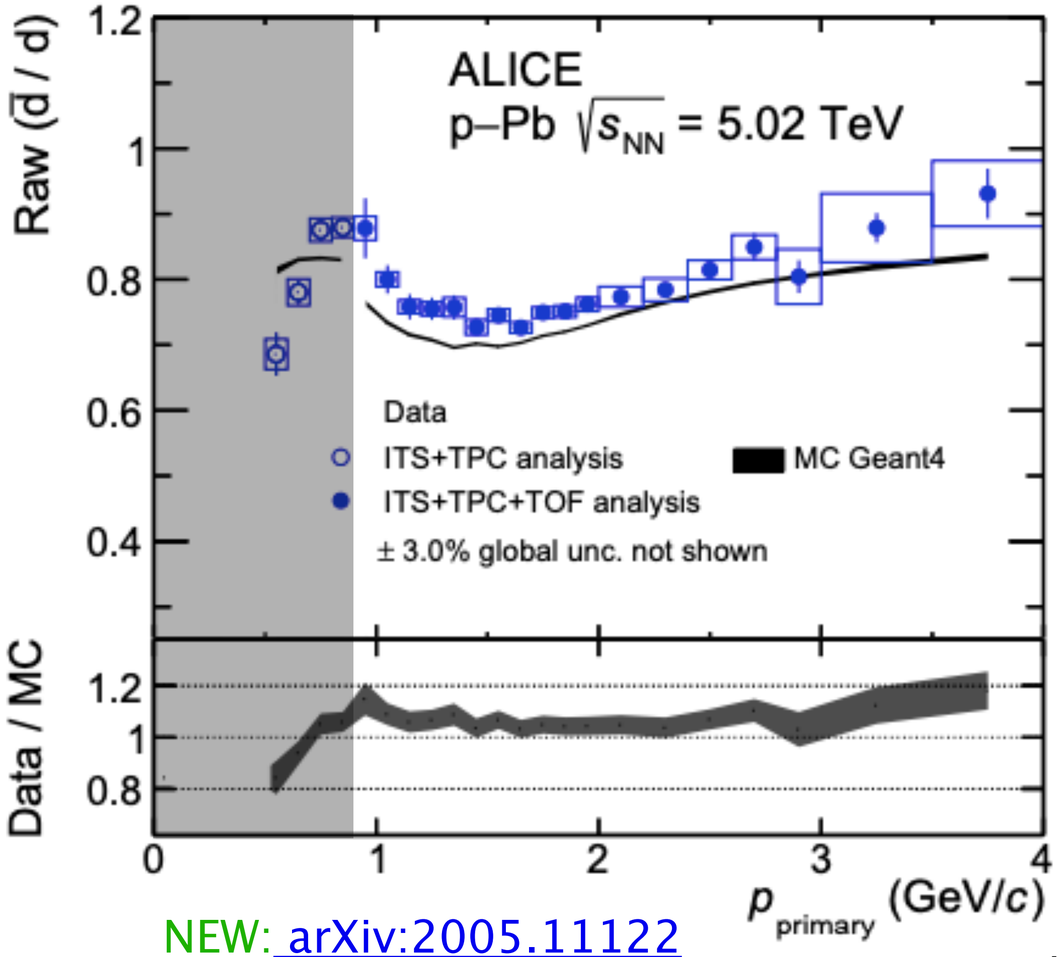

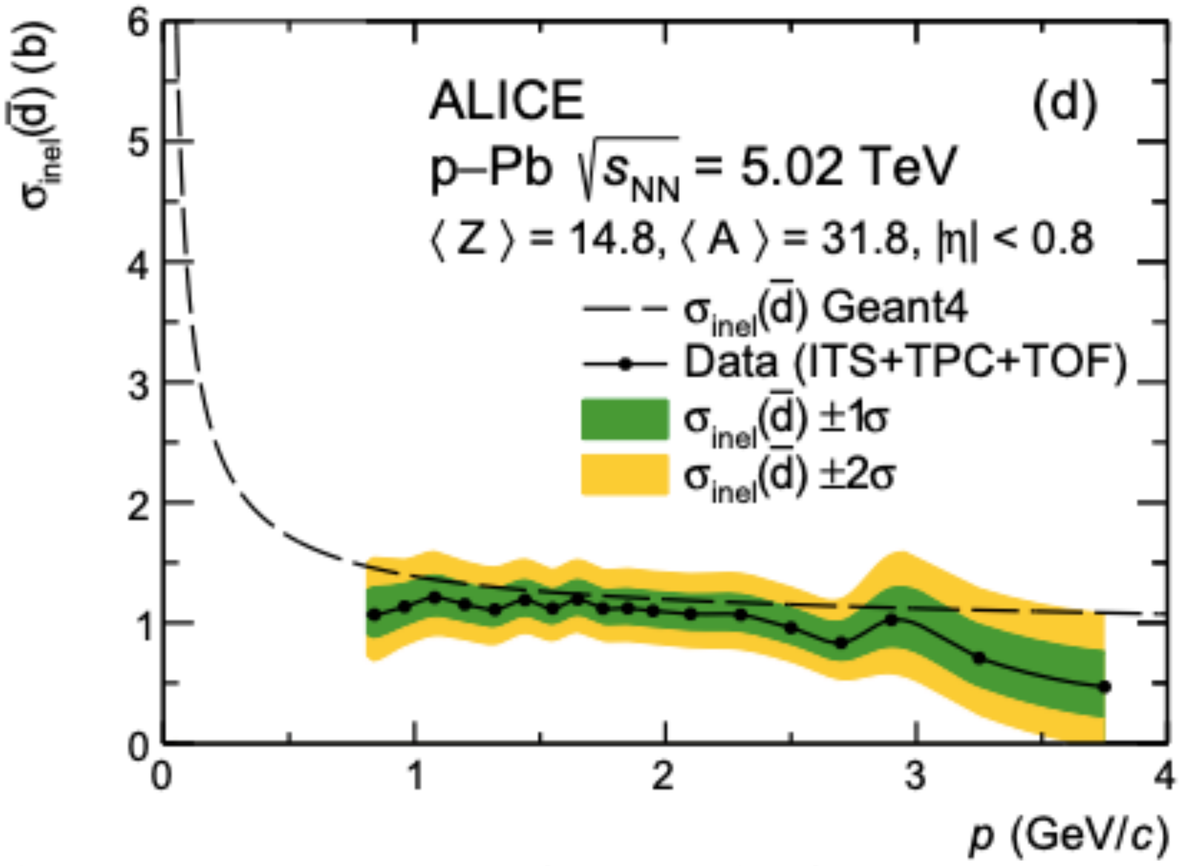

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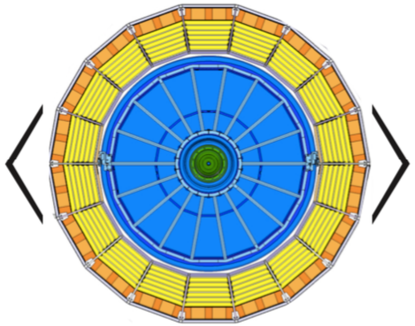

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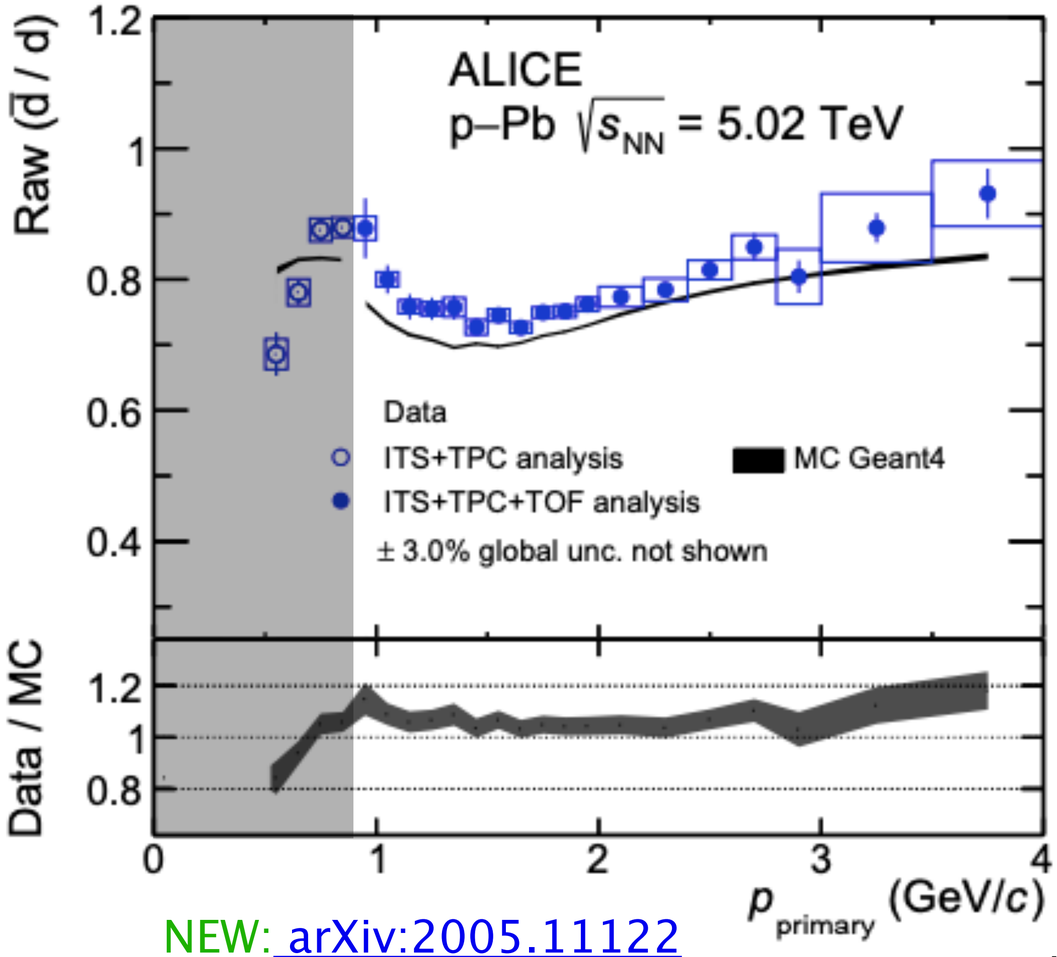
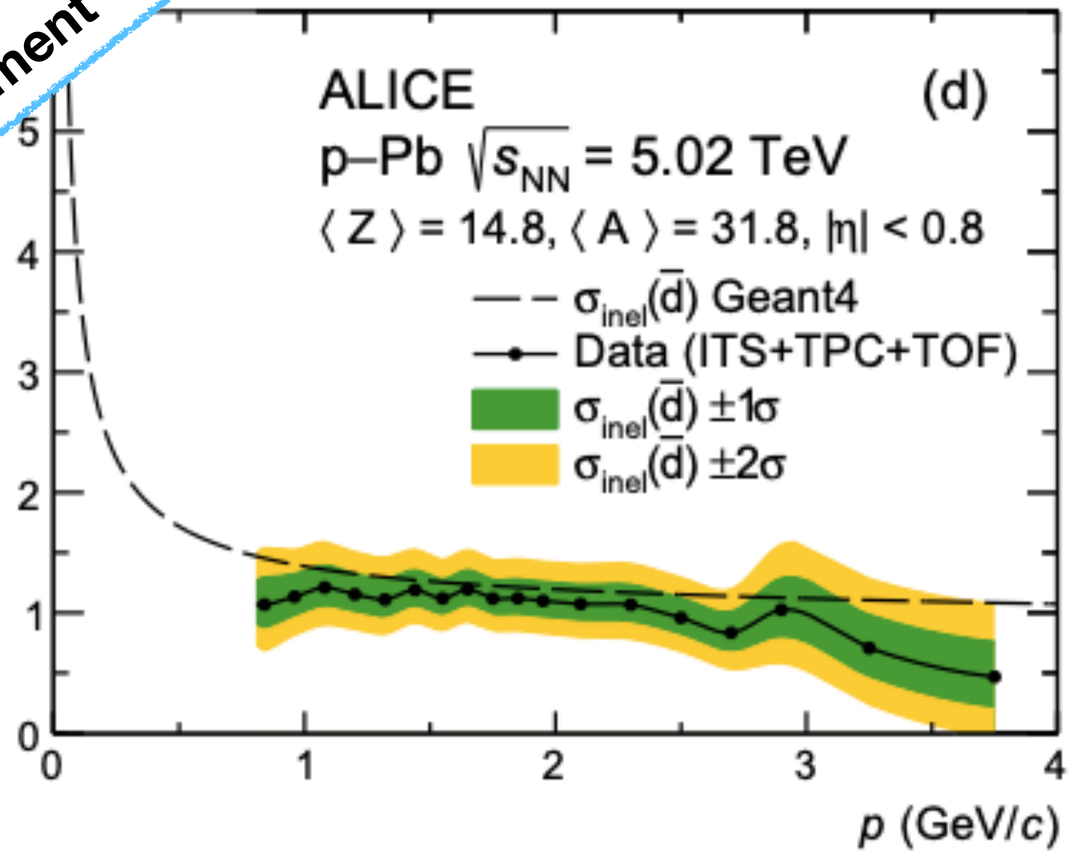


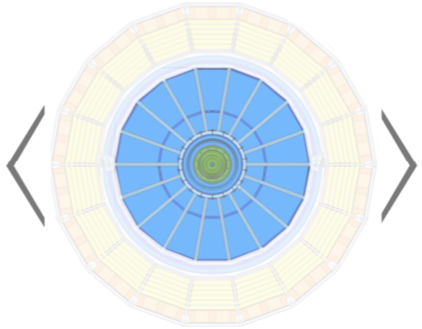


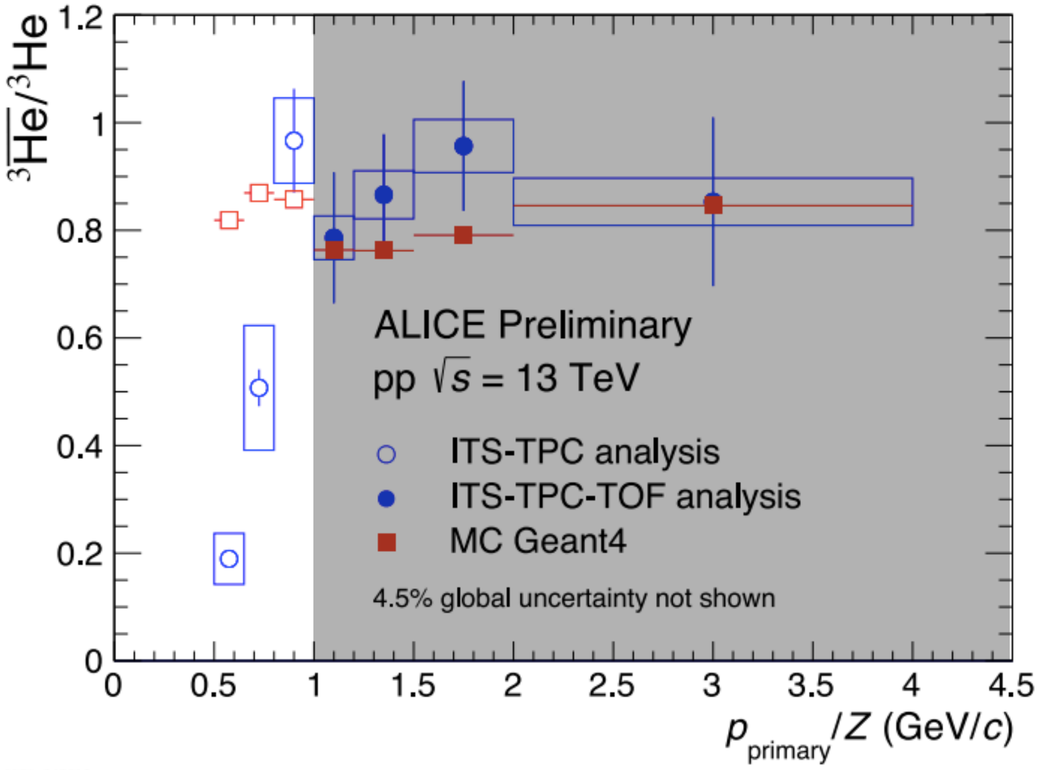
NEW: arXiv:2005.11122

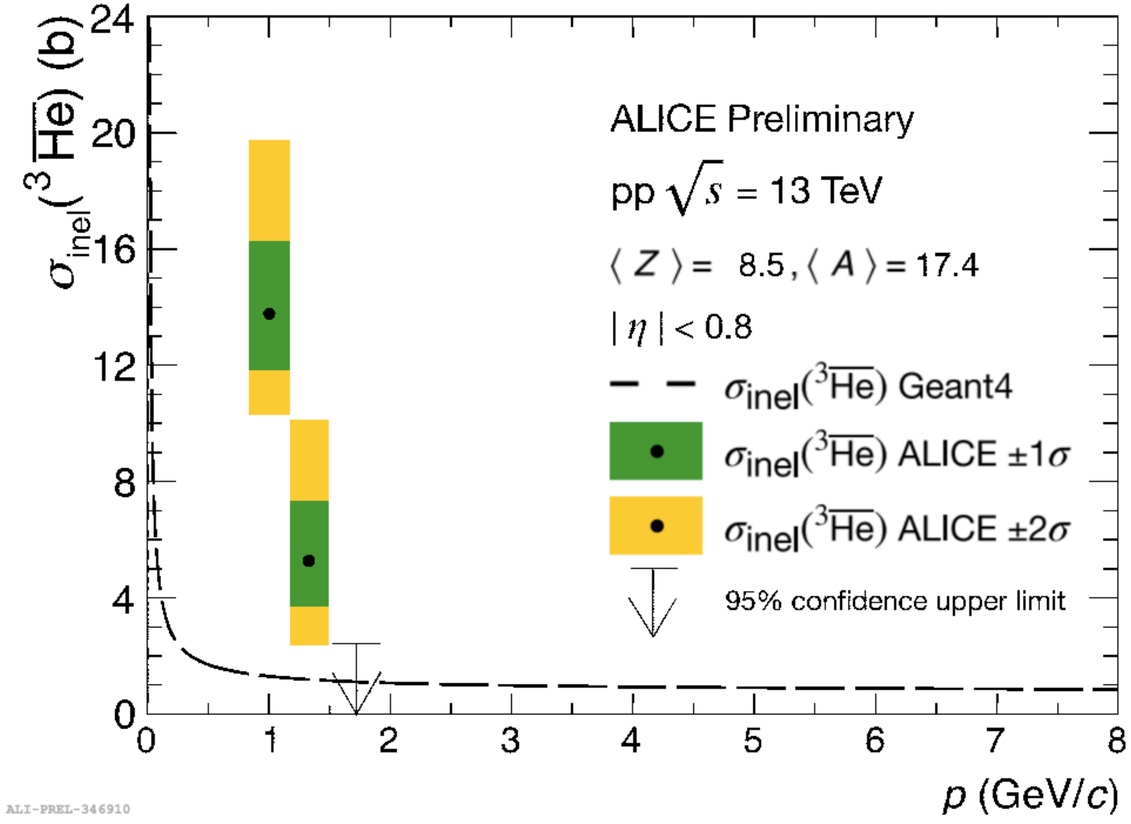
Anti-^{3}He inelastic cross section

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

- Much steeper rise at low momentum
- Good agreement for momenta > 1.5 GeV/c







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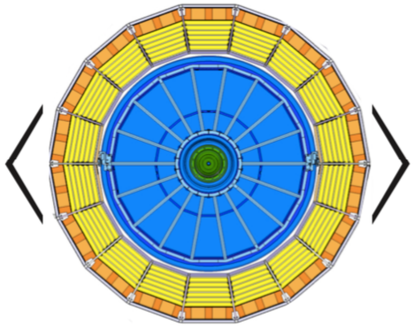

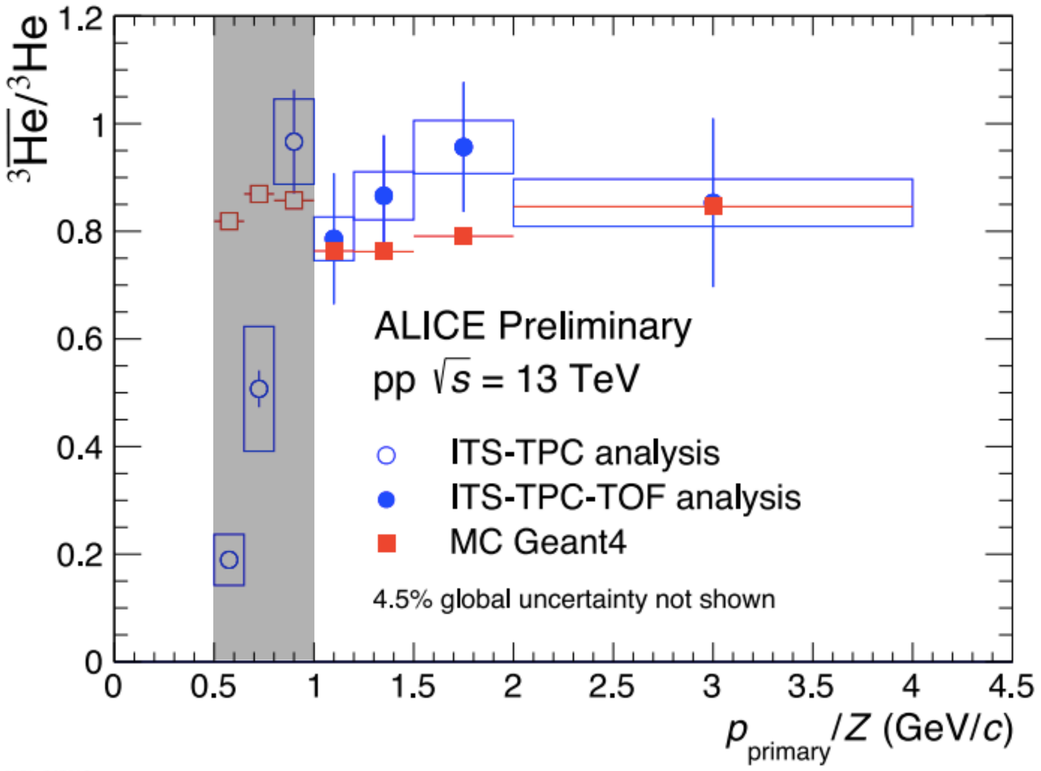

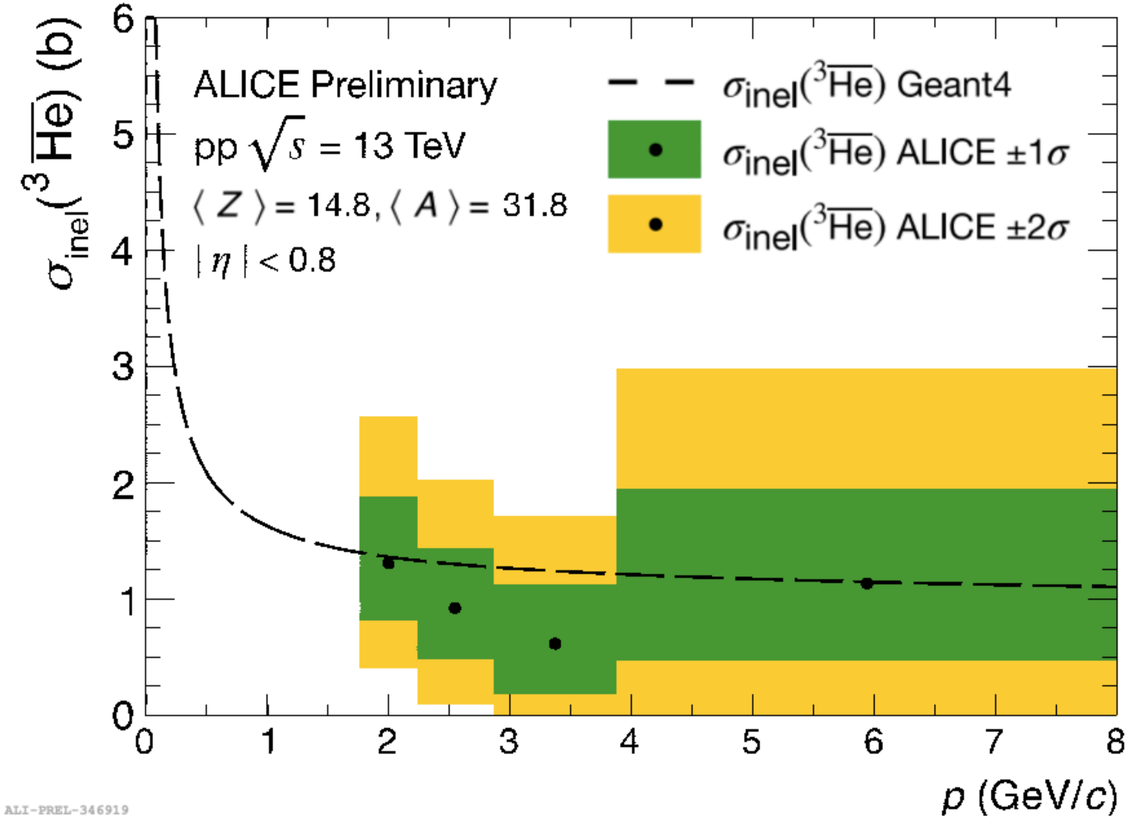

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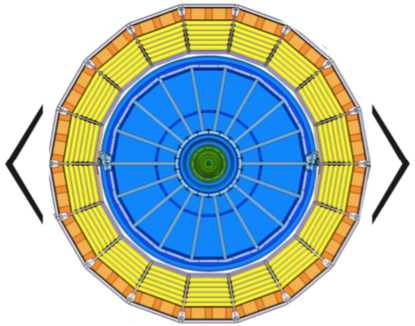
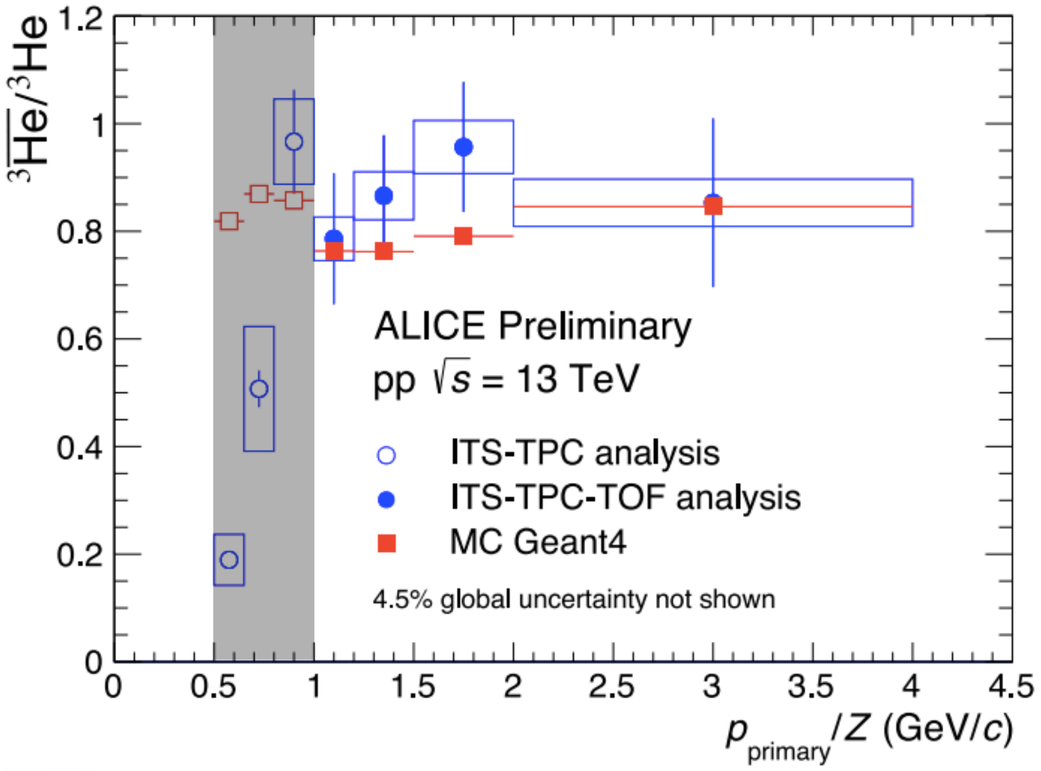
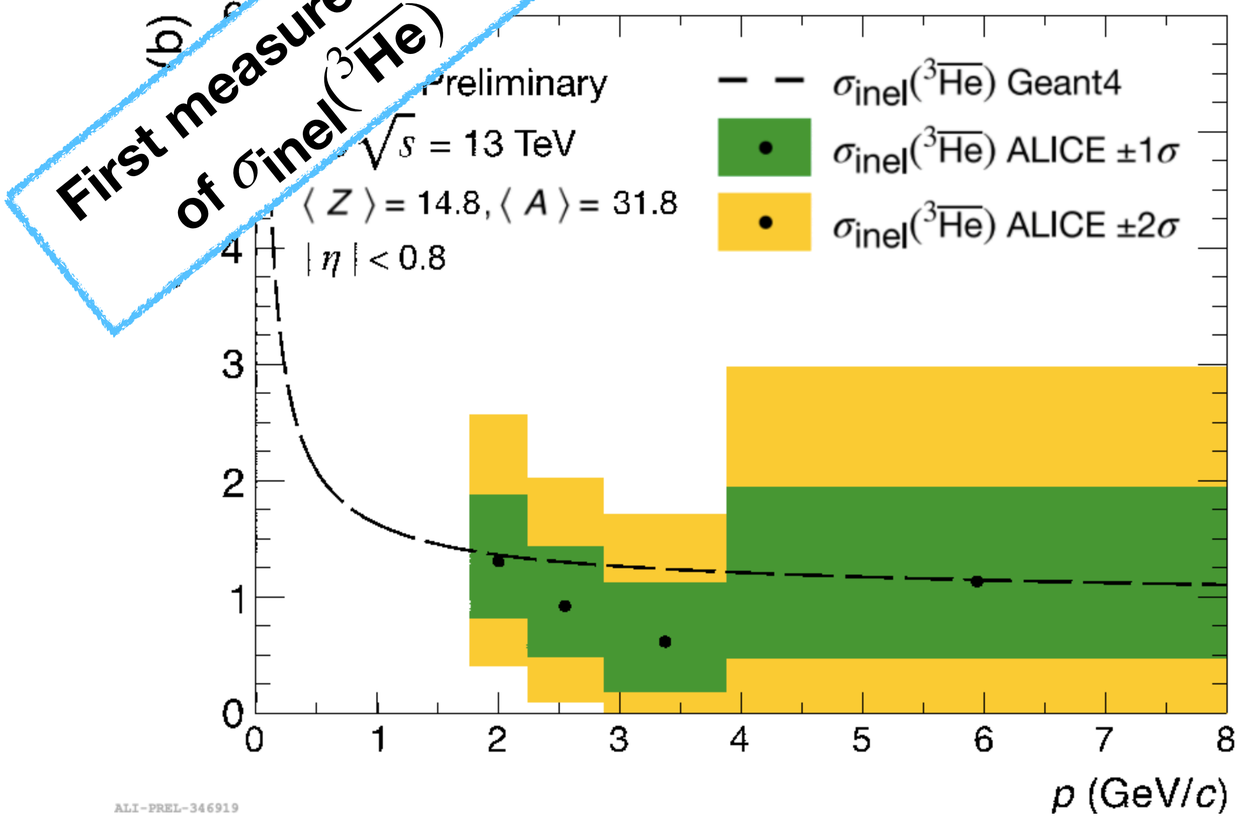




ALI-PREL-347219

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



ALI-PREL-346919

Effect on antinuclei in cosmic rays

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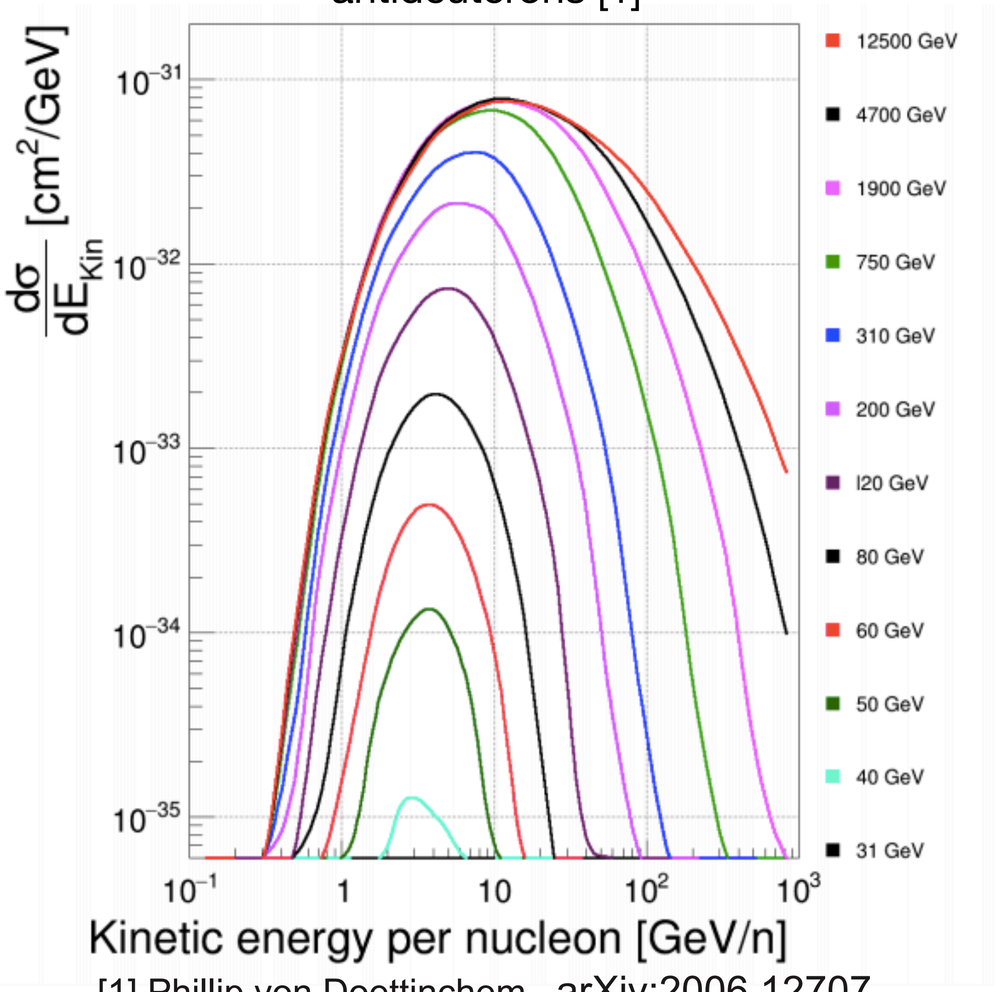
Production cross section for antideuterons [1]



[1] Phillip von Doettinchem, arXiv:2006.12707

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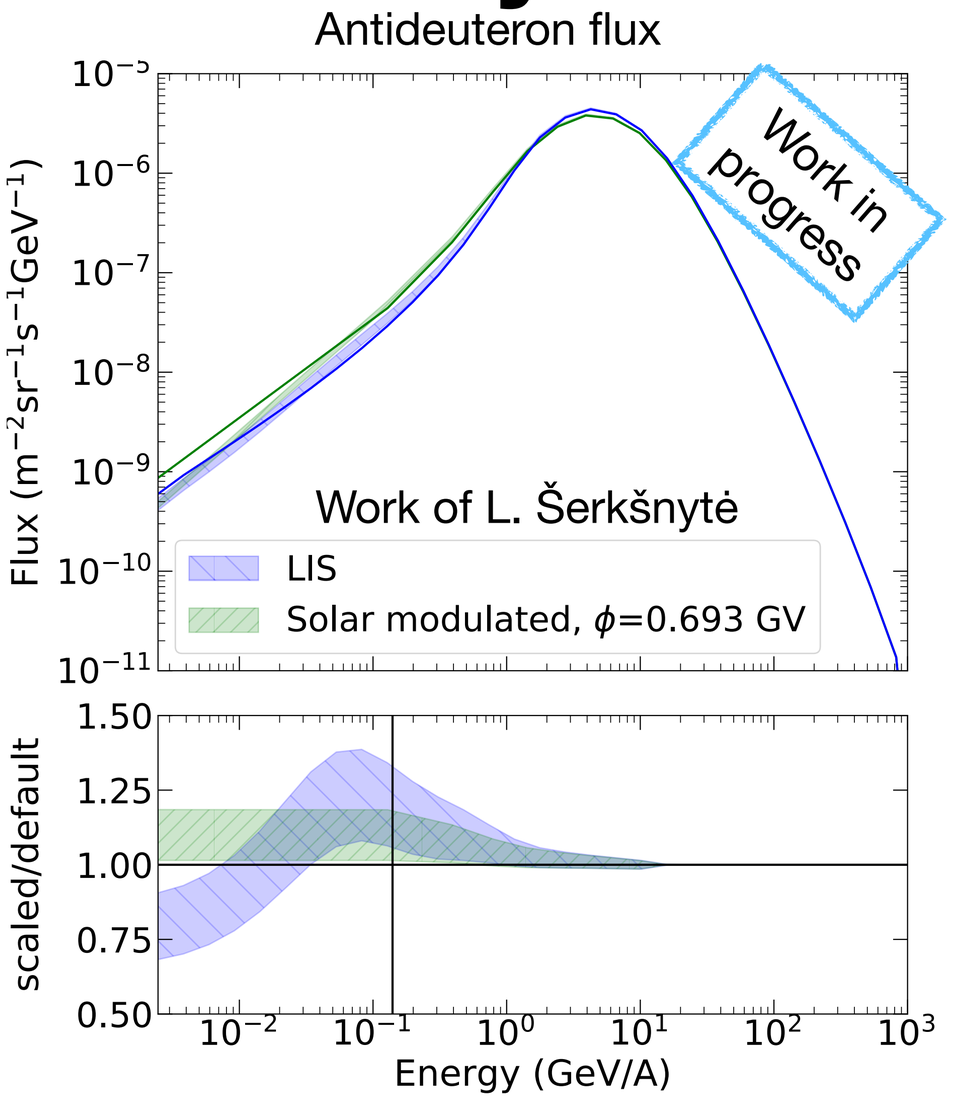
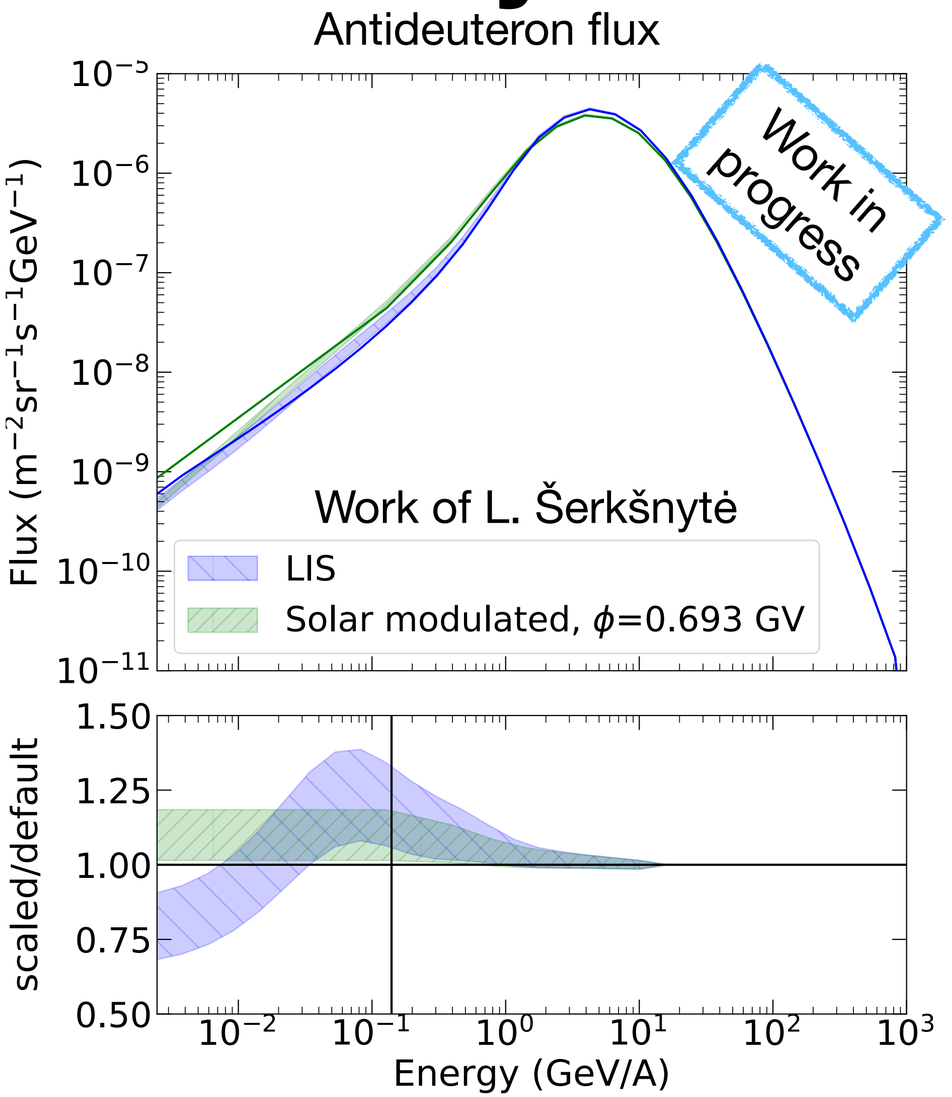


Effect on antinuclei in cosmic rays

- Particles can get reshuffled to lower momenta due to energy loss effects
- The flux is most sensitive to the cross section at the peak
- Since this measurement agrees with current parameterization at the momentum where the peak of the flux is, the effect on the secondary spectrum is small



Effect on antinuclei in cosmic rays (cont.)

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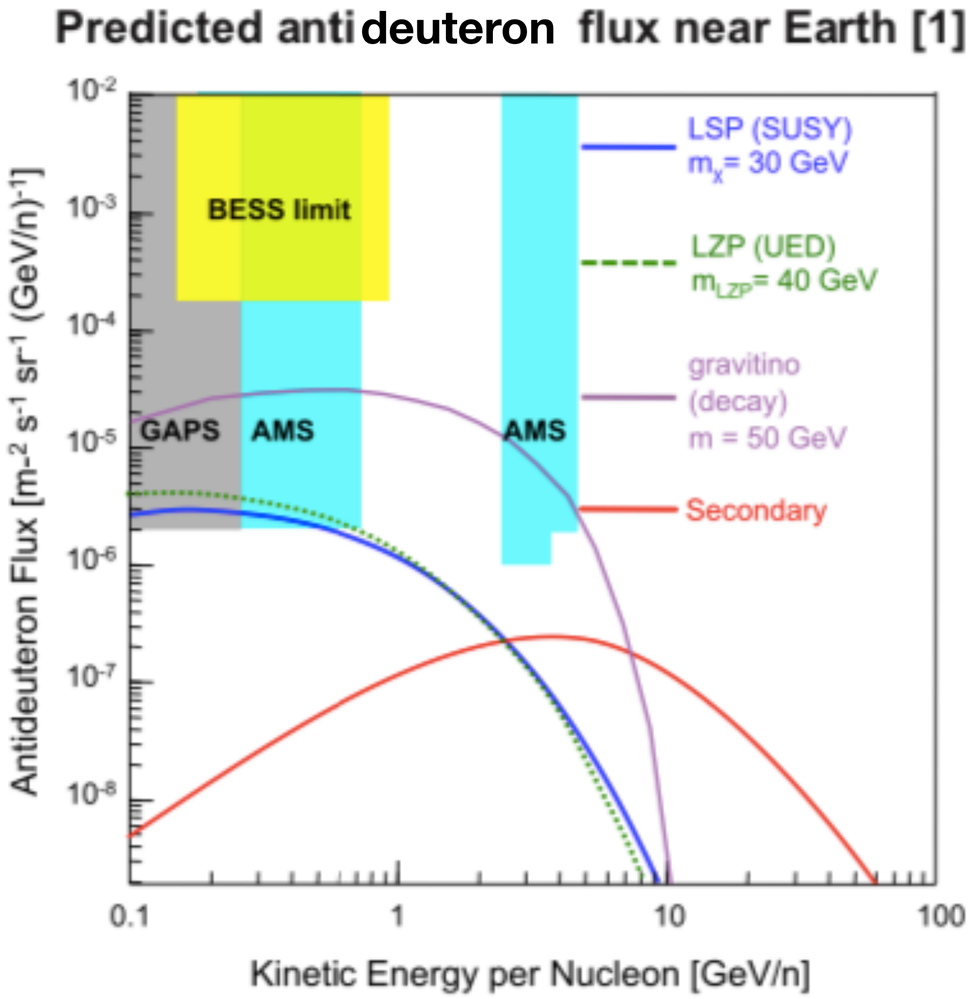

[1] Physics Report 618, 1

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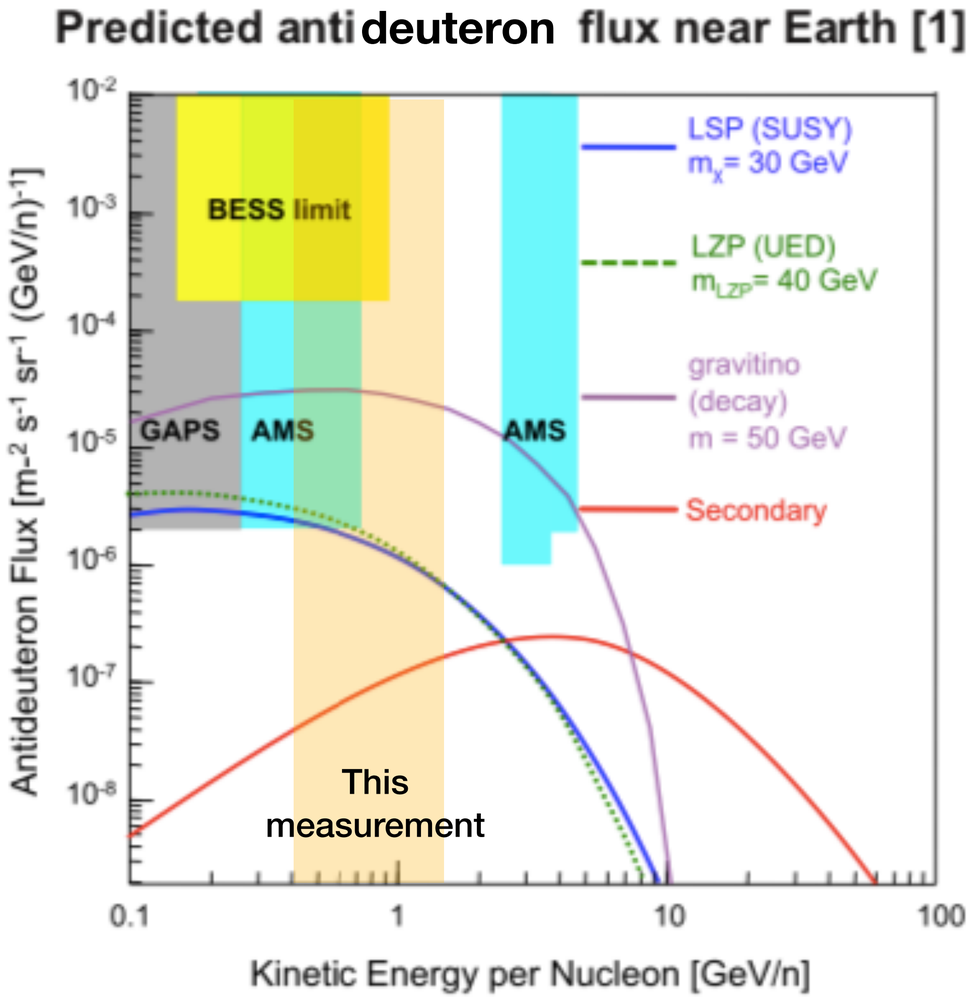

[1] Physics Report 618, 1

Effect on antinuclei in cosmic rays (cont.)

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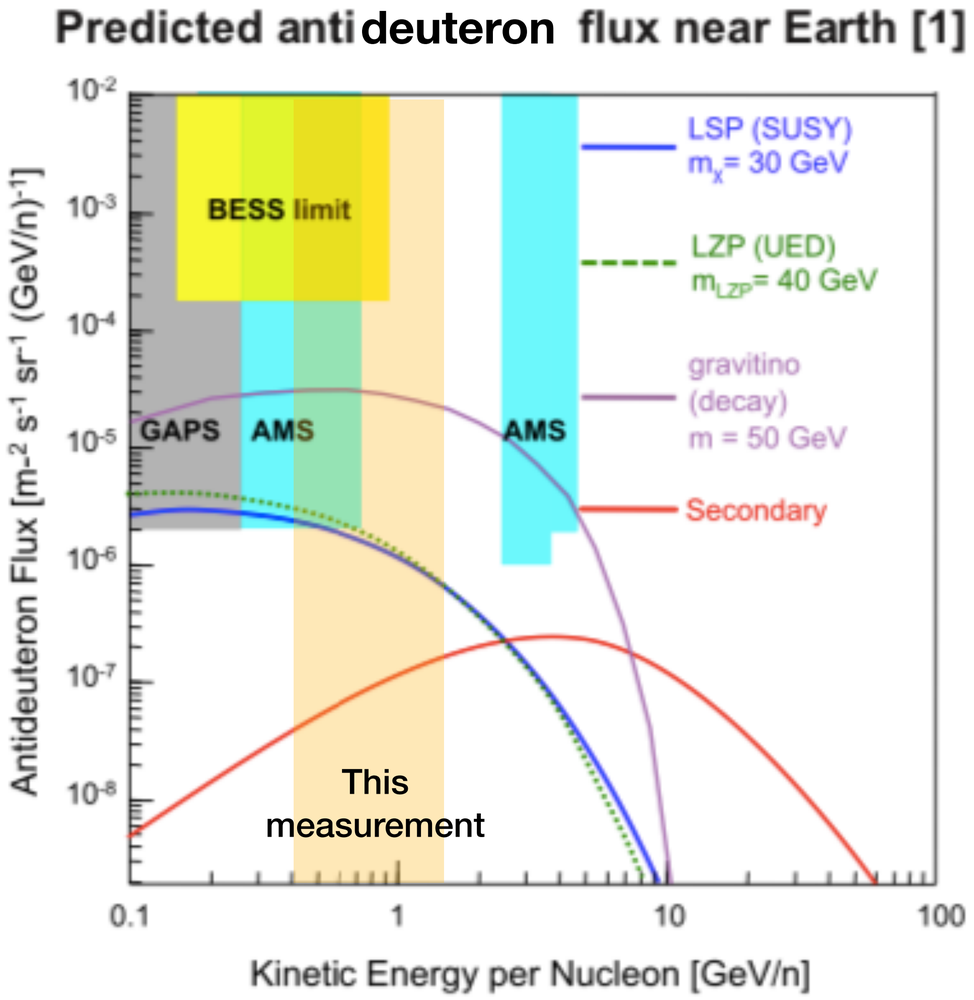

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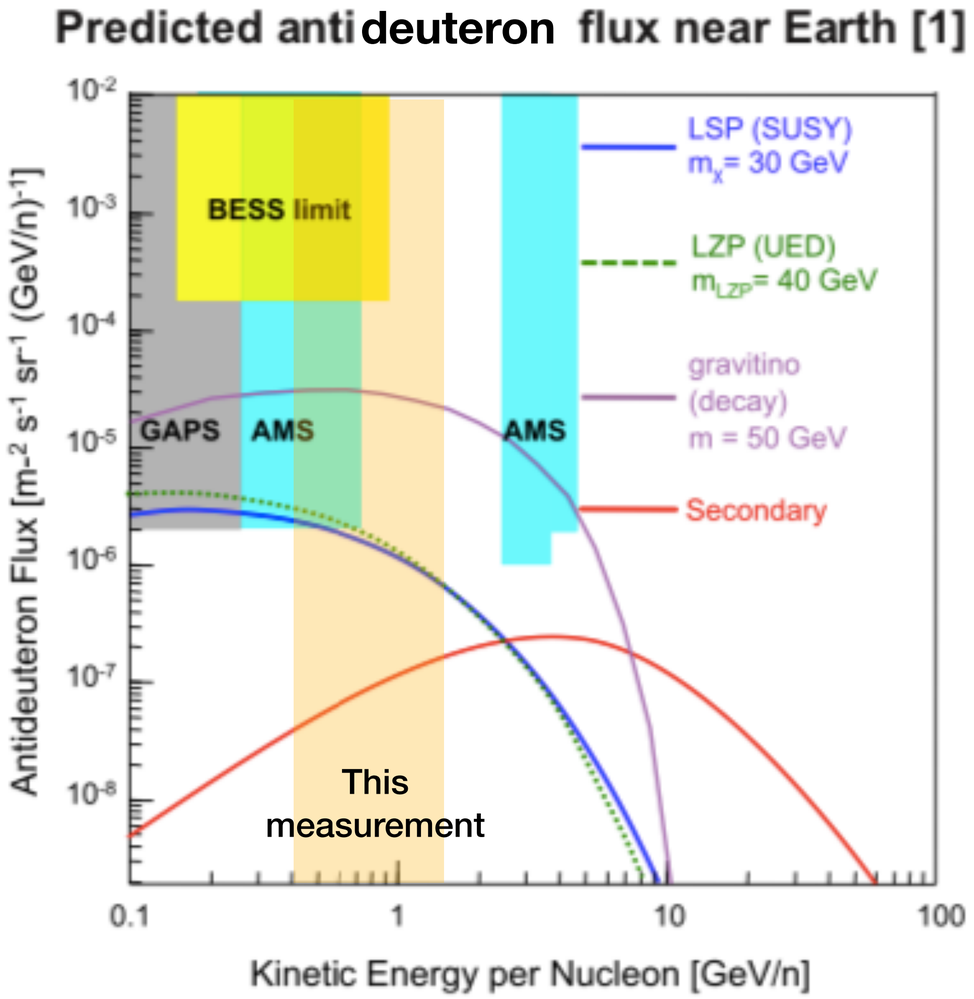

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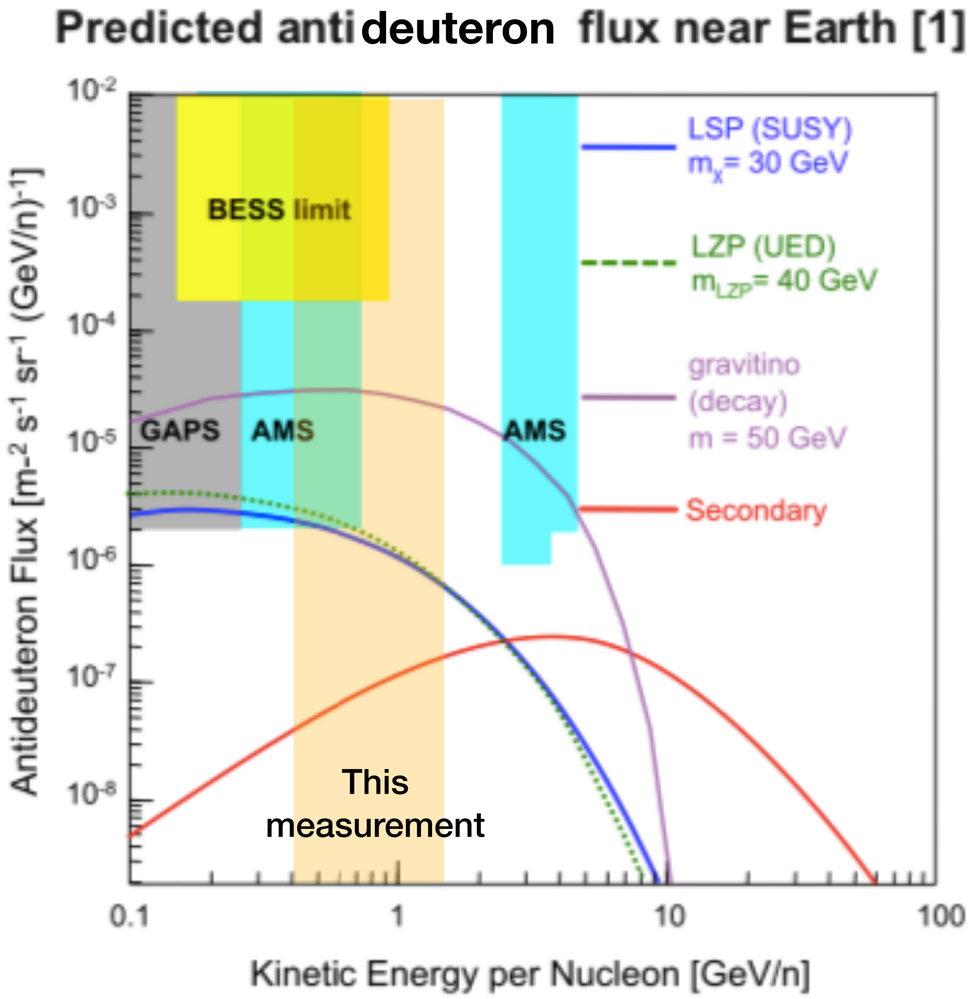

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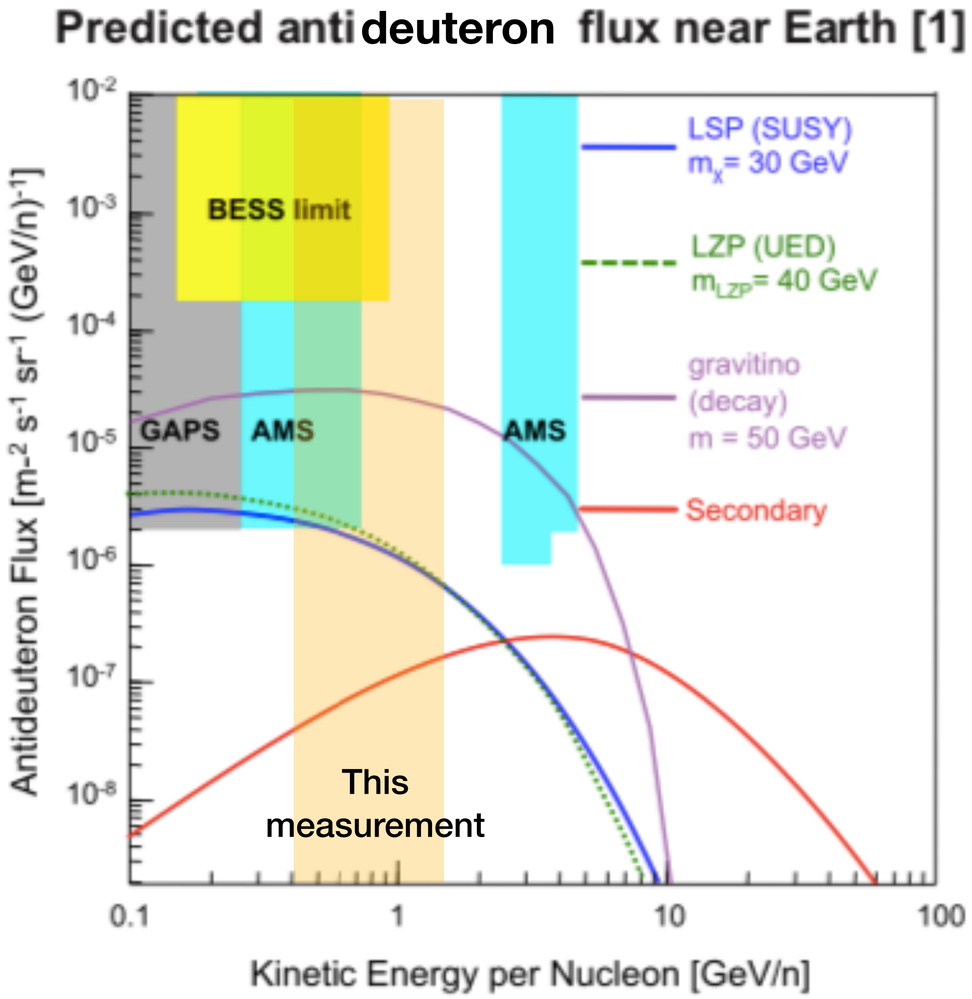
➡Potential lower antinuclei signals would be compatible with dark matter models!



[1] Physics Report 618, 1

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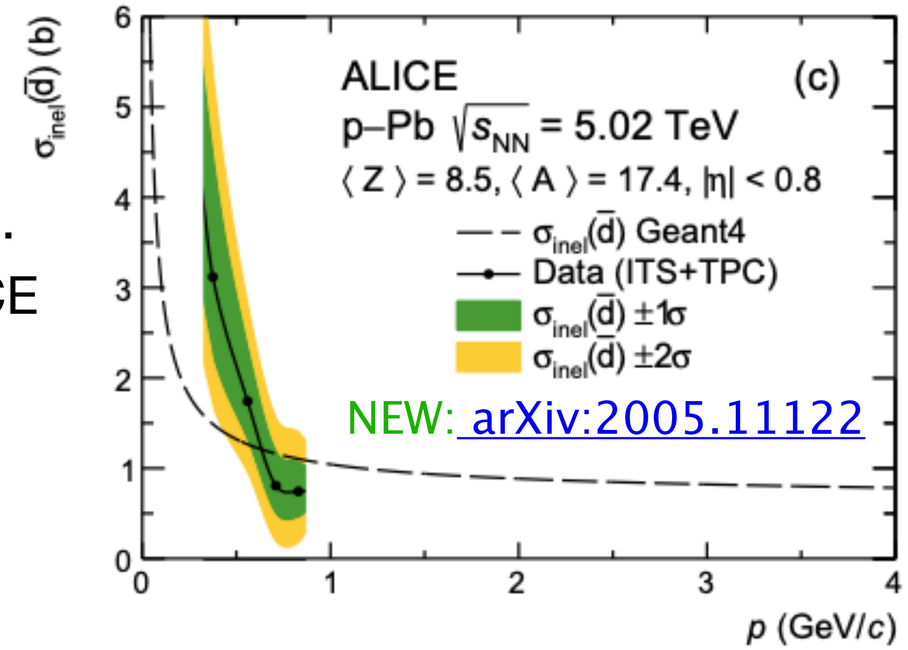

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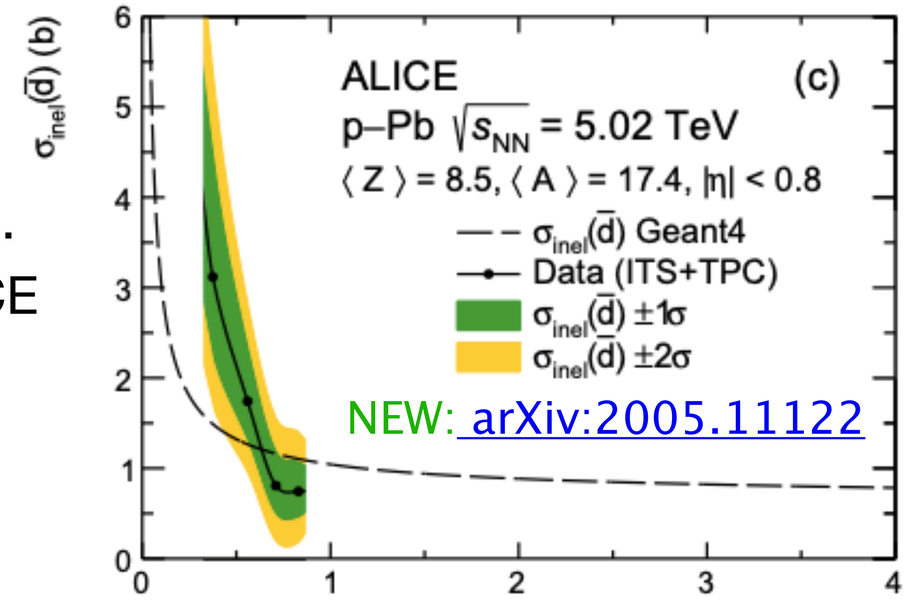

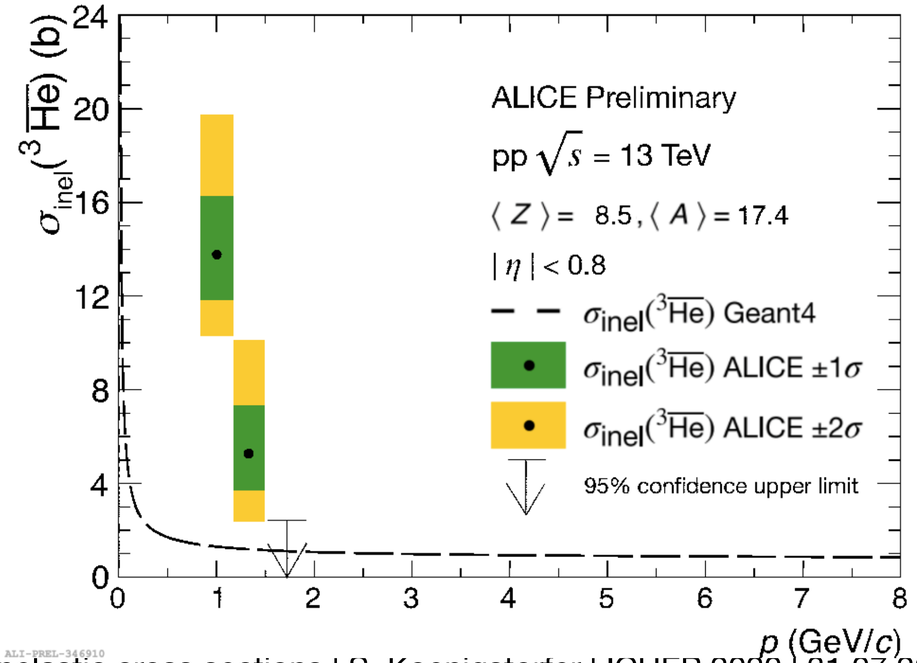

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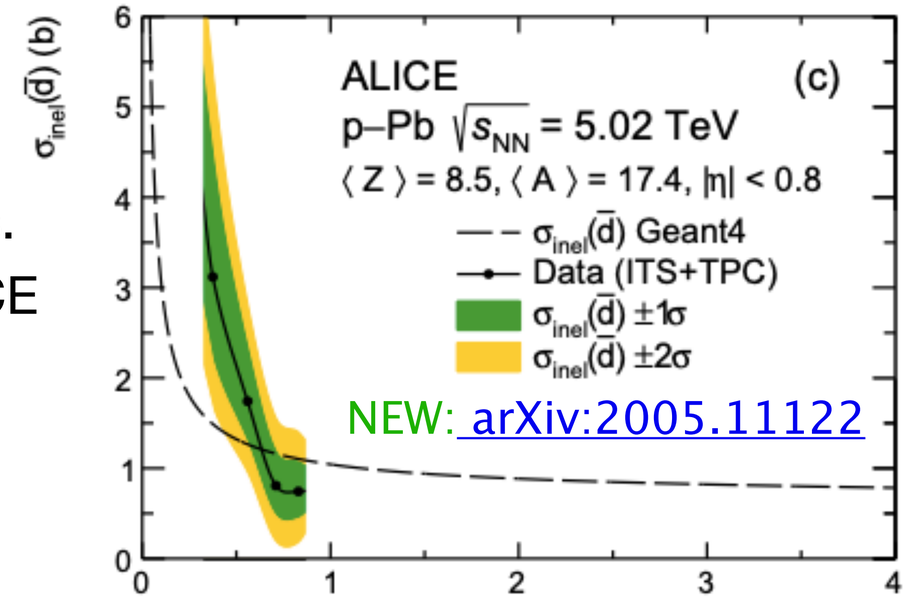

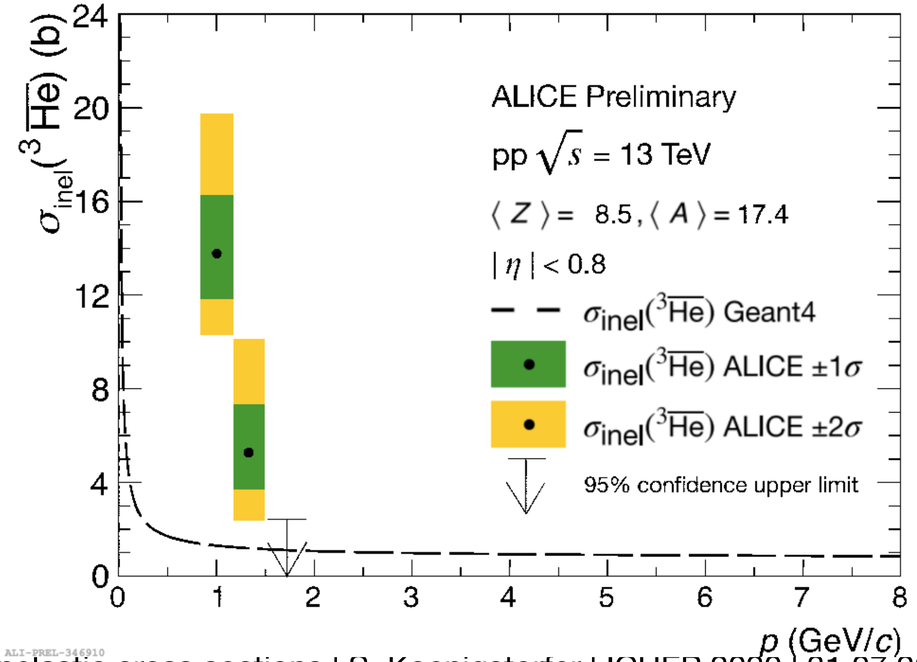

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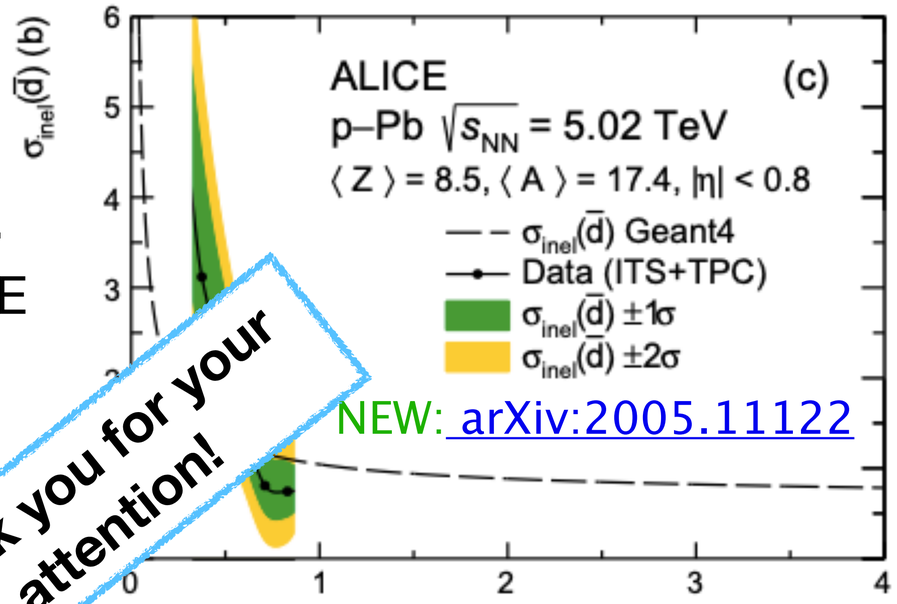
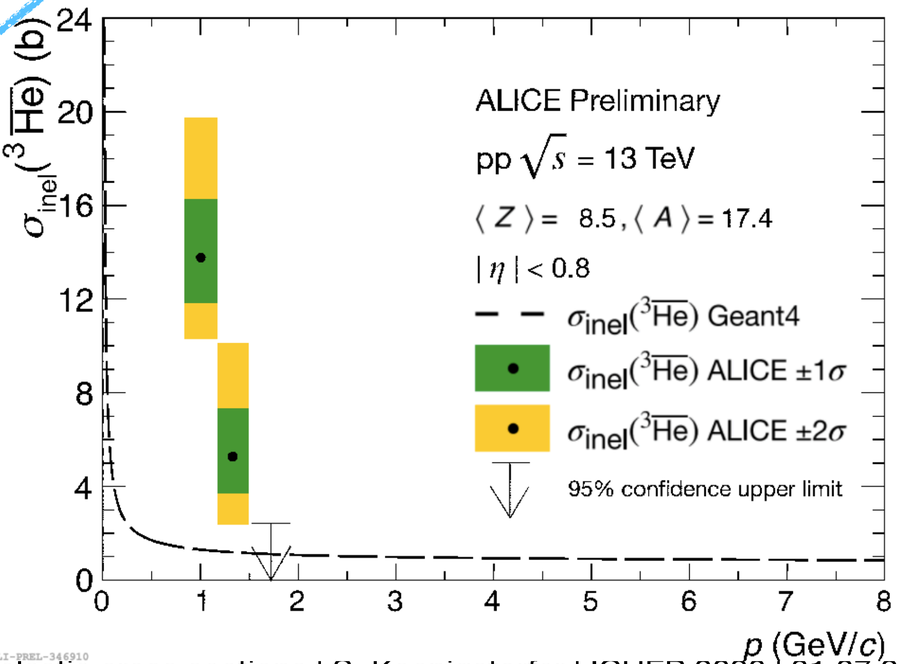


Thank you for your attention!

NEW: arXiv:2005.11122



Back-up slides

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:

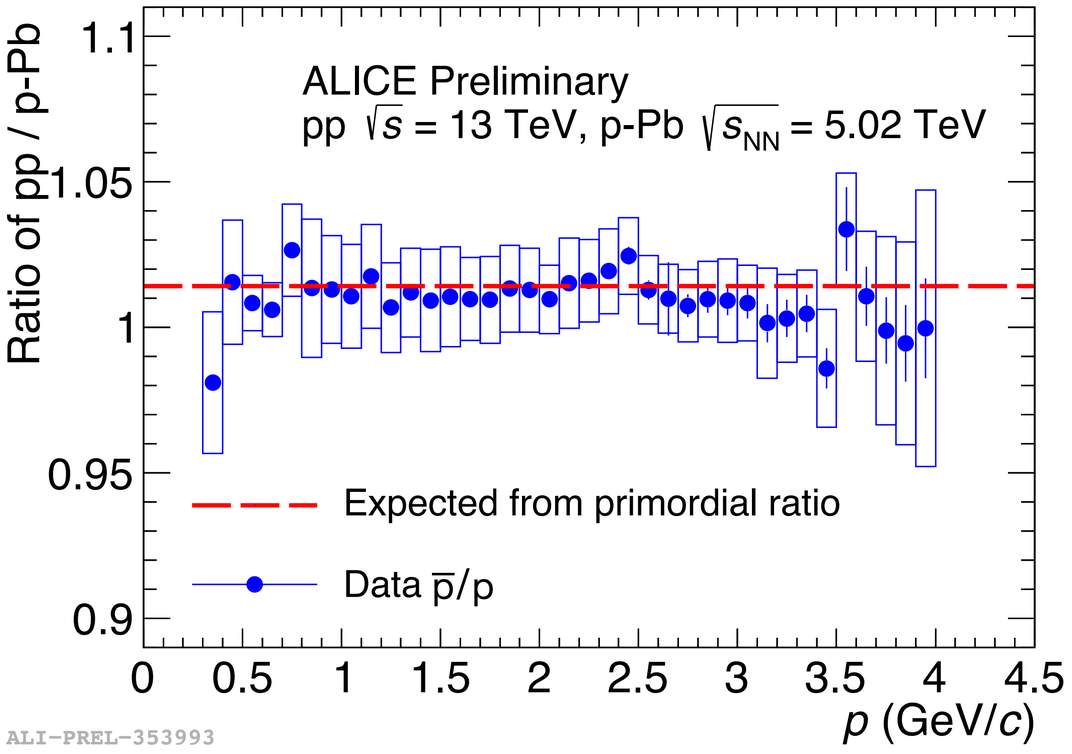
$$\bar{p}A\ R_A = 1.34A^{0.23} + 1.35/A^{1/3}\ (\text{fm}),$$
$$\bar{d}A\ R_A = 1.46A^{0.21} + 1.45/A^{1/3}\ (\text{fm}),$$
$$\bar{t}A\ R_A = 1.40A^{0.21} + 1.63/A^{1/3}\ (\text{fm}),$$
$$\bar{\alpha}A\ R_A = 1.35A^{0.21} + 1.10/A^{1/3}\ (\text{fm}).$$

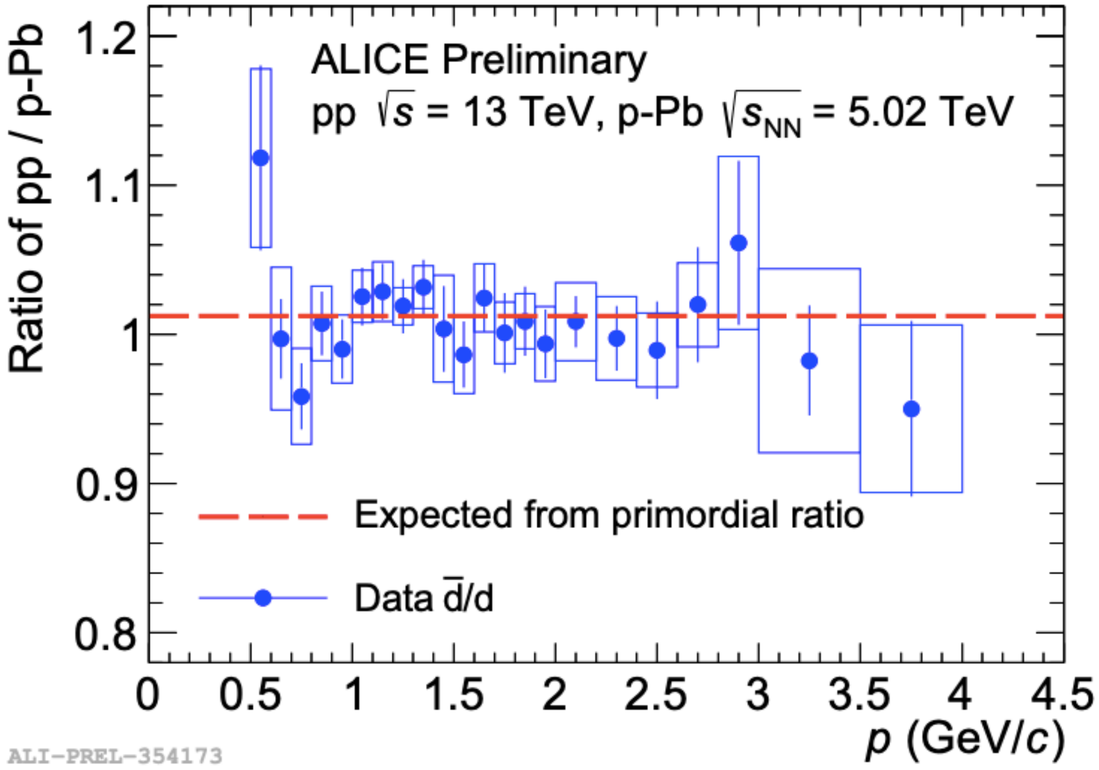
For inelastic cross-section:

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

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

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.

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

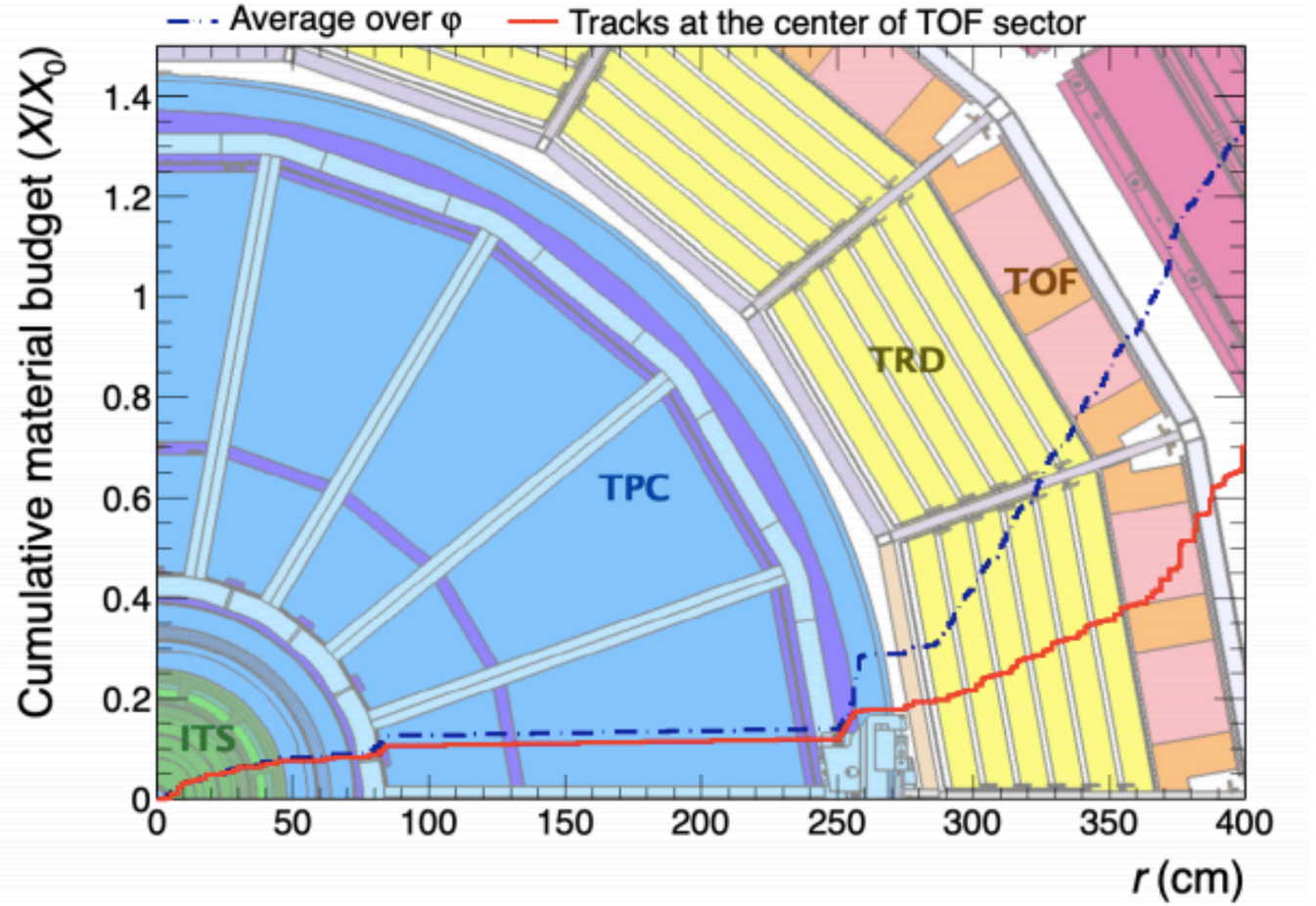
1. source function: PRIMARY OR SECONDARY
2. diffusion
3. convection
4. diffusive reacceleration
   momentum losses:
   5. via ionisation and bremsstrahlung
   6. adiabatic
7. annihilation

Work of L. Šerkšnytė.

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)



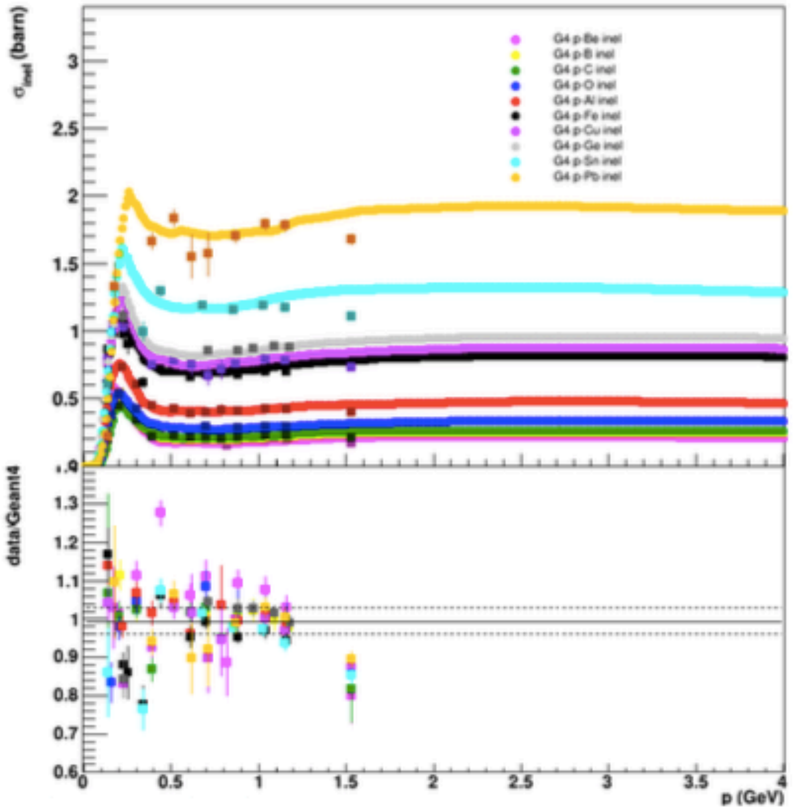
arXiv:2005.11122

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

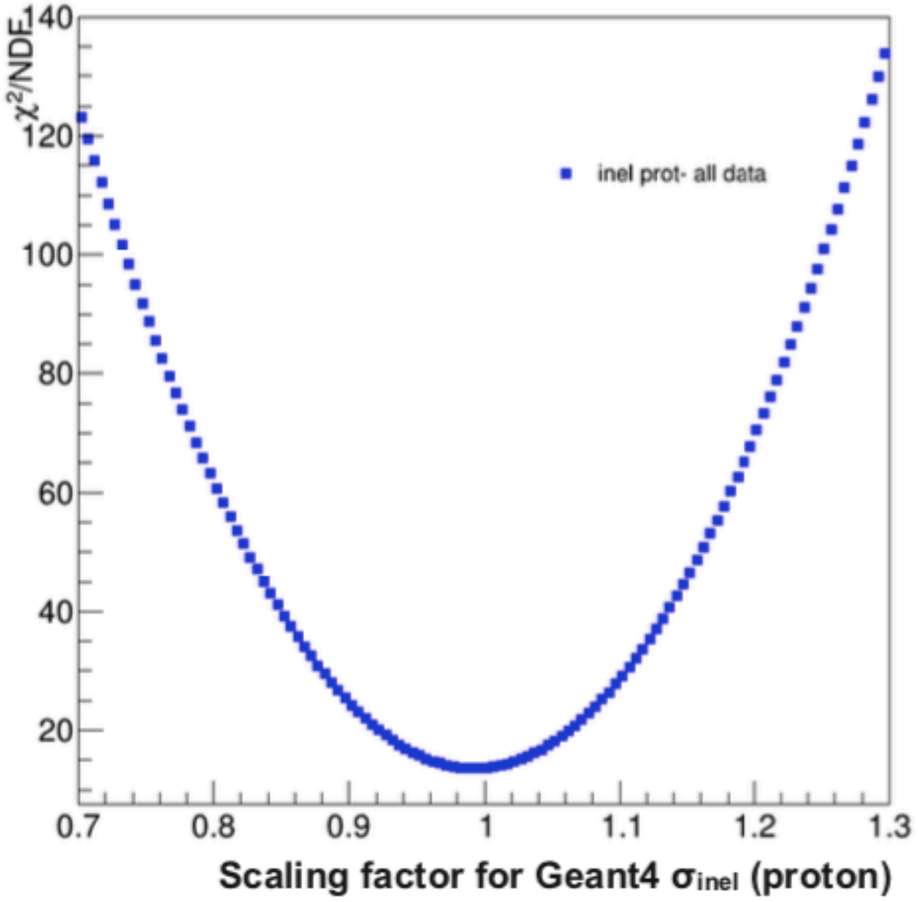
Uncertainty due to σ_{inel} (proton)

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 $\pm1\sigma$: **0.9925** $^{+0.0375}$ $_{-0.0325}$



+1σ
min. χ^2
-1σ



Variations of σ_{el} with simple Geant4 model

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

- σ_{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