Constraining the antideuteron nuclear inelastic cross section with ALICE

Phys. Rev. Let. 125, 162001 (2020)

I. Vorobyev on behalf of the ALICE Collaboration

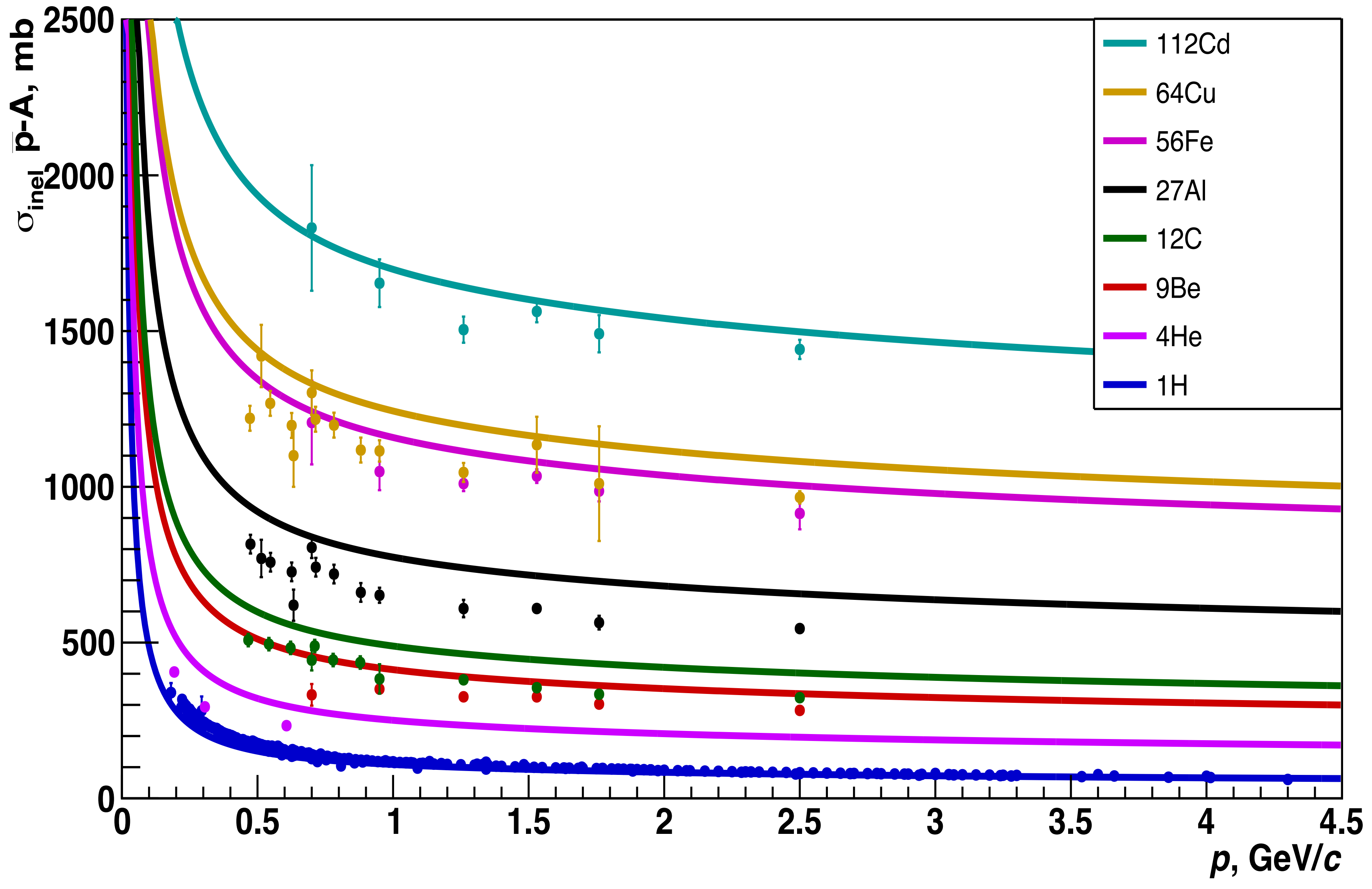
4th Workshop on LHC detector simulations
2-3 November 2020, CERN

Antinuclei inelastic cross sections

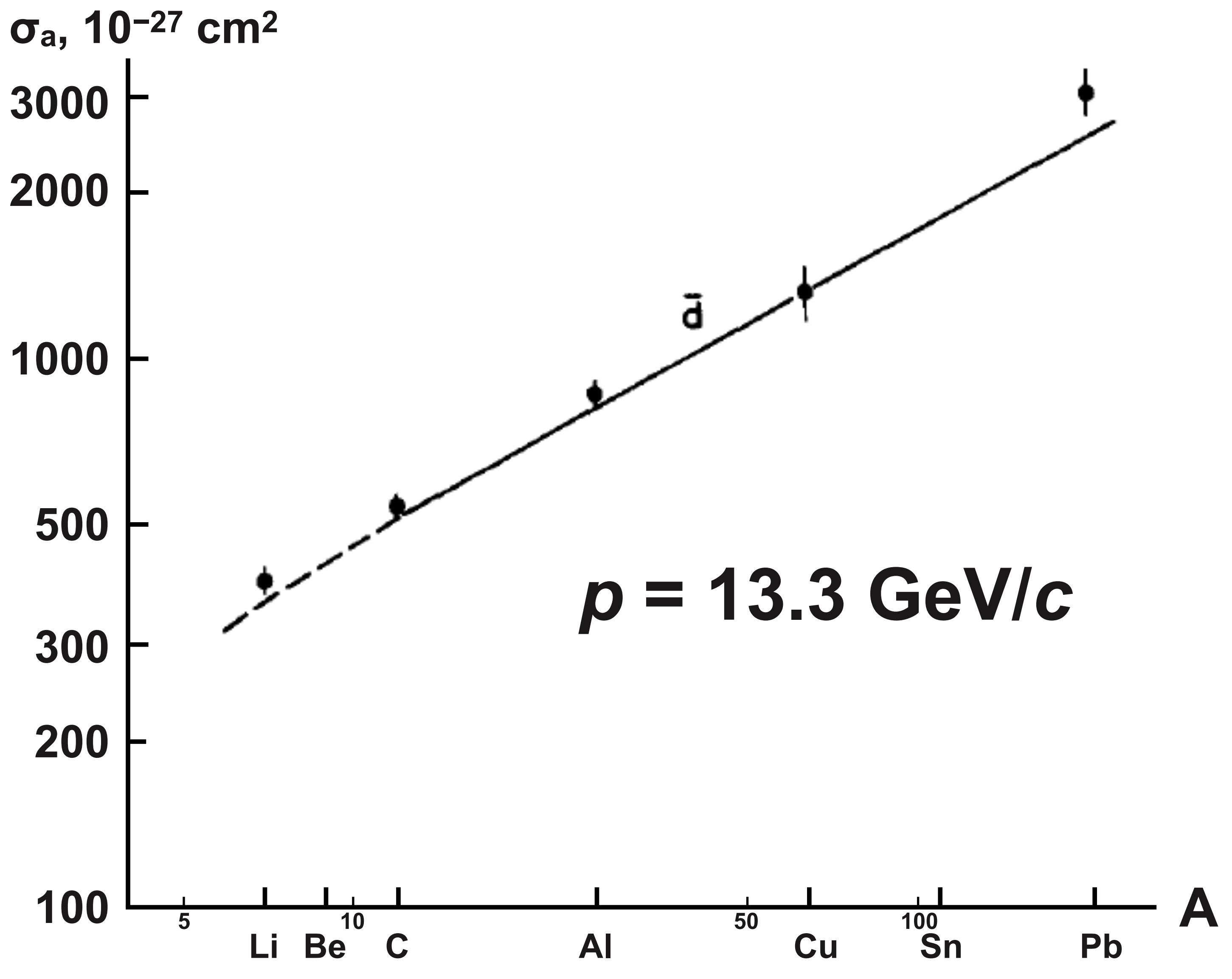
Antinuclei inelastic cross sections are very poorly known for A ≥ 2

- Antideuterons: experimental data at *p* = 13.3 GeV/*c* [1] and at *p* = 25 GeV/*c* [2] (from 1970s!)
- Highly demanded in physics community right now! (Indirect DM searches with antinuclei in space)

Antiprotons



Antideuterons [1]

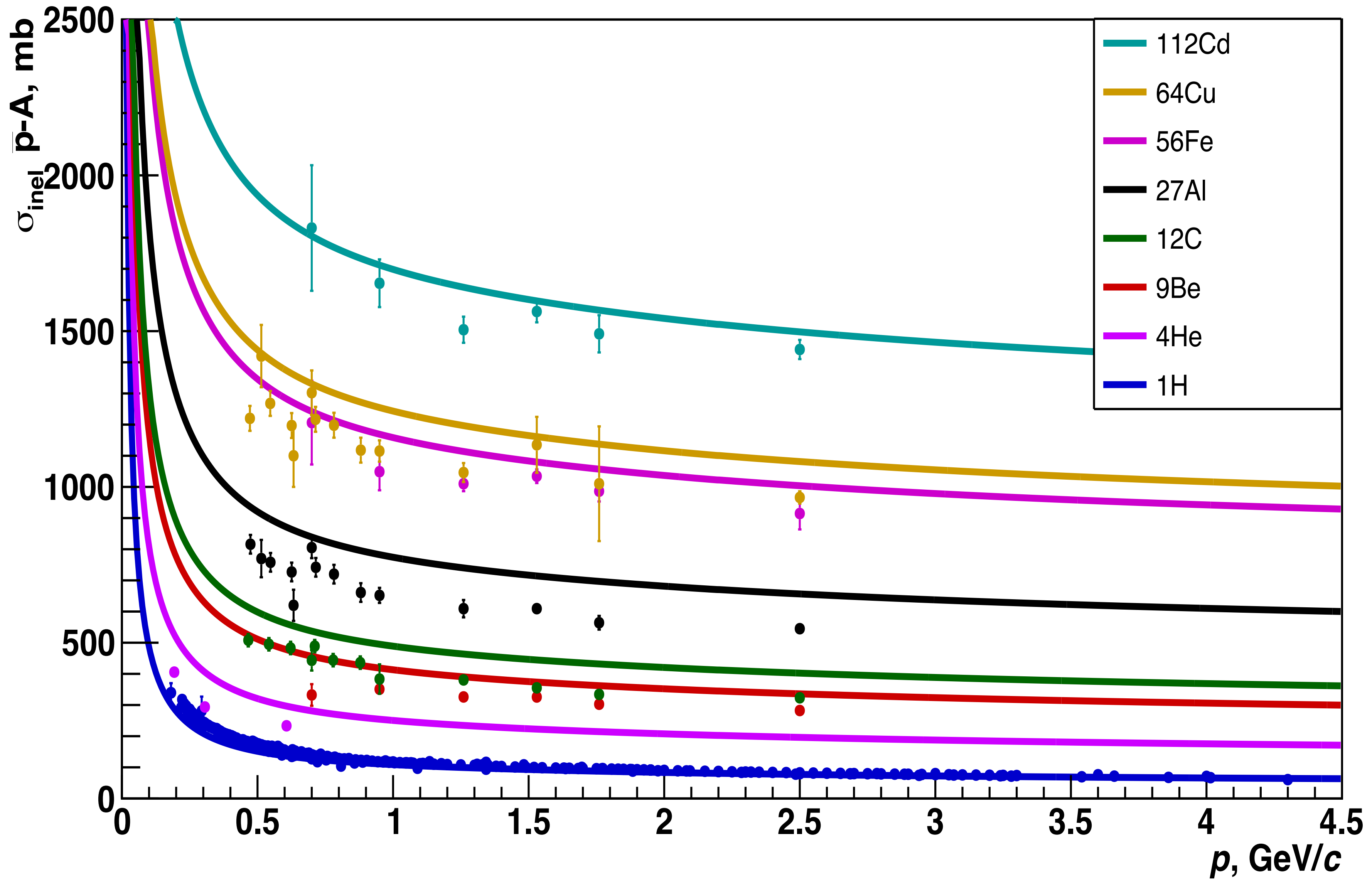


[1] Nuclear Physics B 31(2), 253 (1971)
[2] Phys. Lett. B 31 (1970) 230

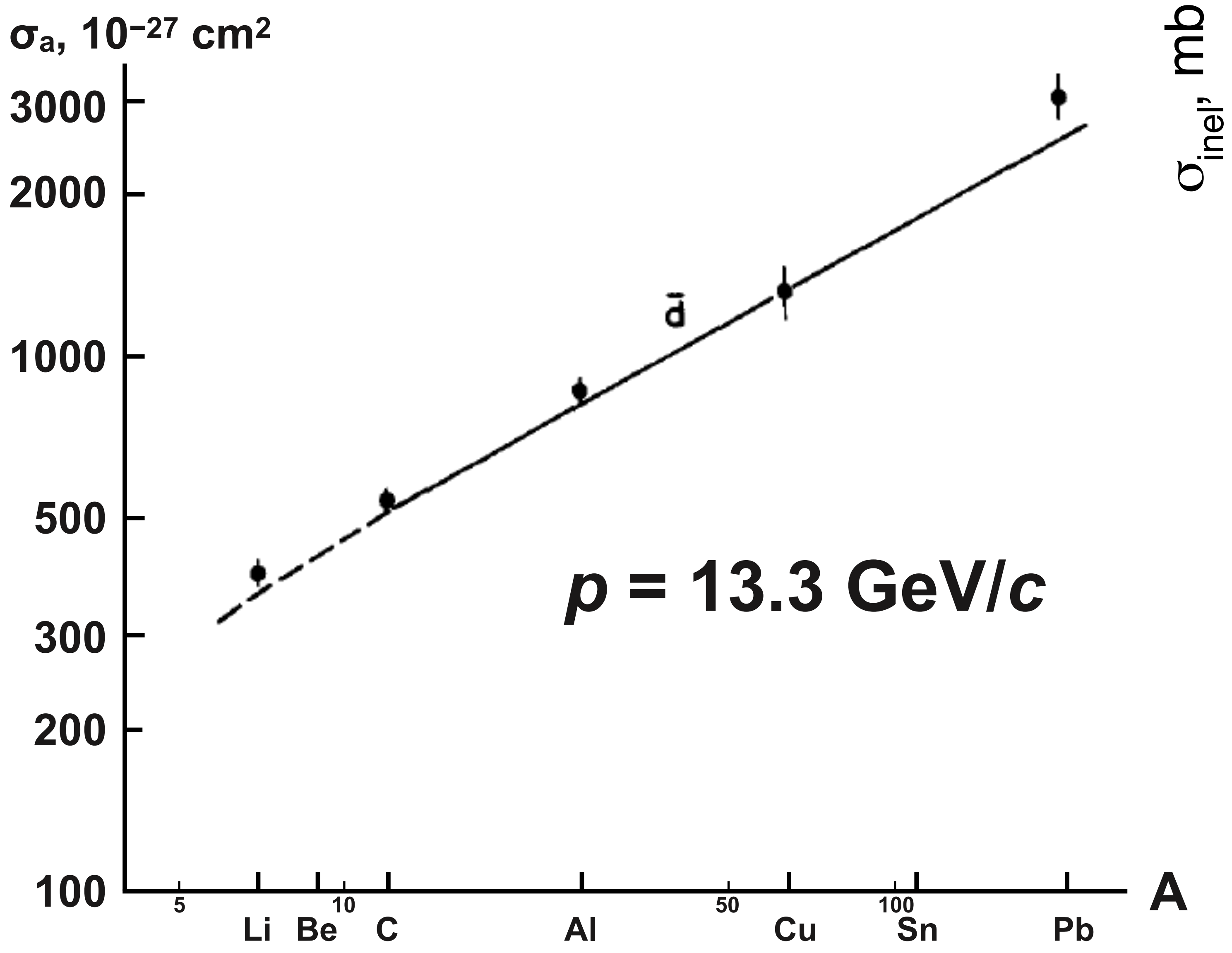
Antinuclei inelastic cross sections

Antinuclei inelastic cross sections are very poorly known for A ≥ 2
- Antideuterons: experimental data at *p* = 13.3 GeV/*c* [1] and at *p* = 25 GeV/*c* [2] (from 1970s!)
- Highly demanded in physics community right now! (Indirect DM searches with antinuclei in space)

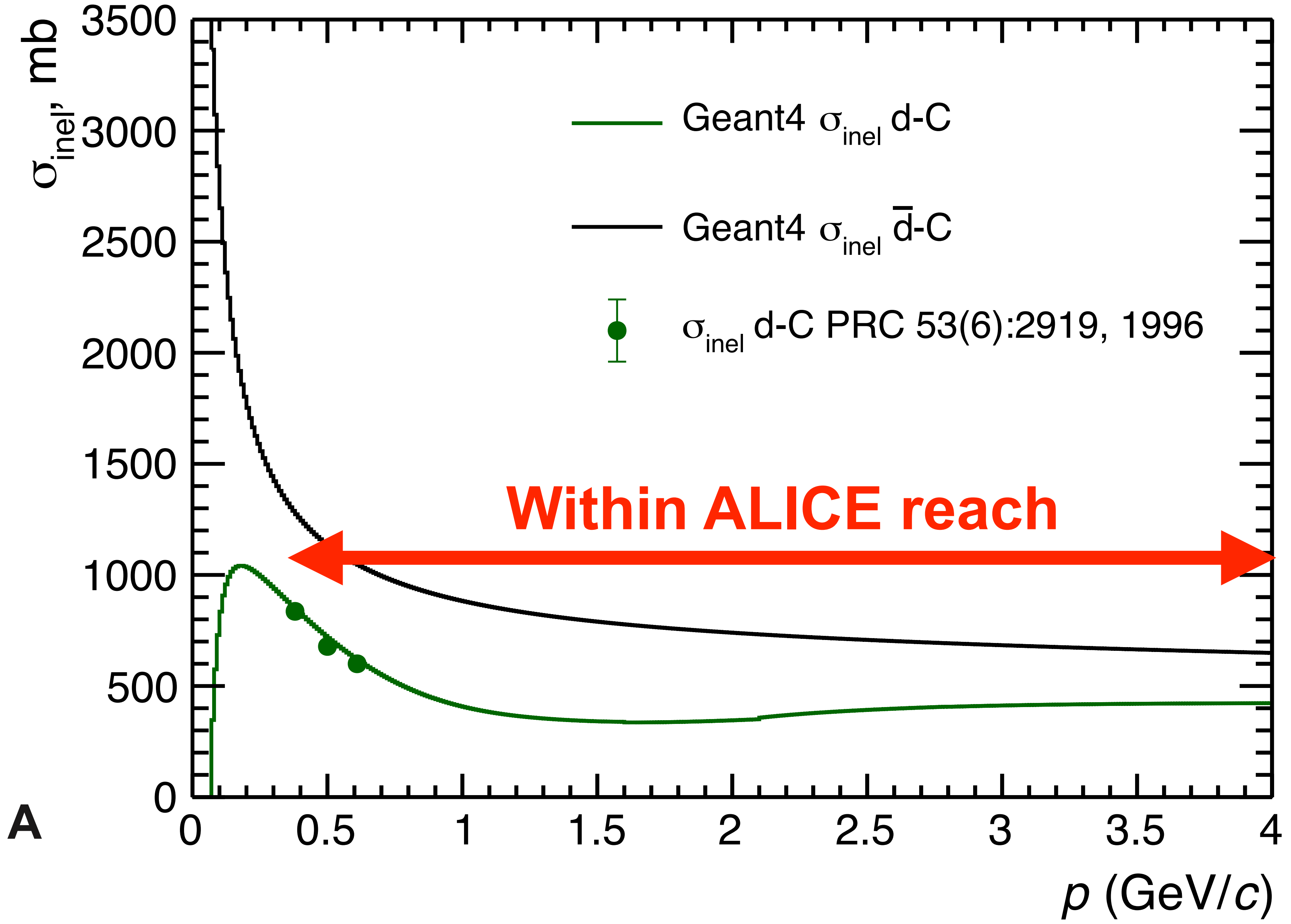
Antiprotons



Antideuterons [1]



(Anti)deuterons on carbon



High-energy collisions at LHC produce a lot of antinuclei
- *Setup a "fixed-target experiment": source (collisions at LHC) + target (ALICE detector material)*

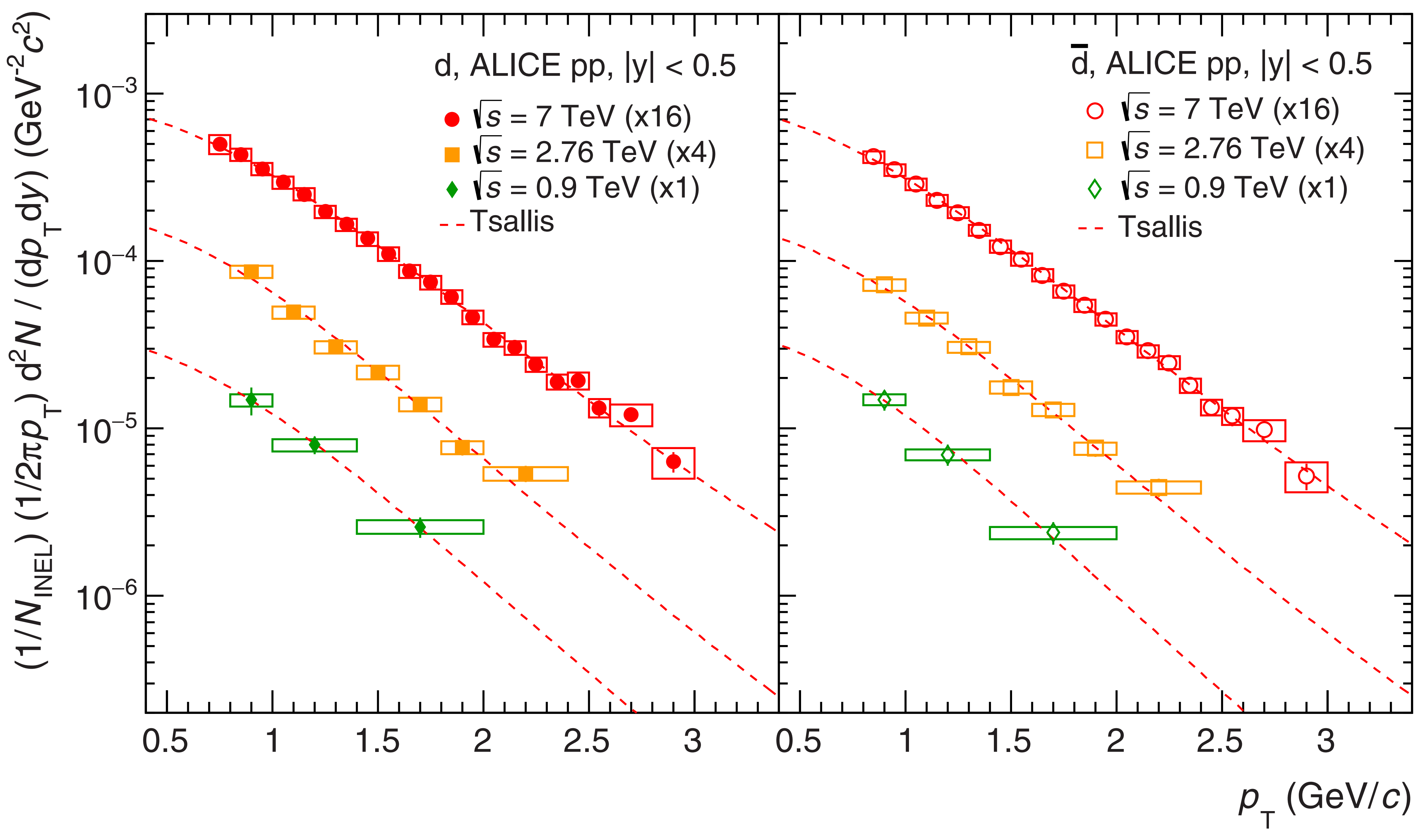
[1] Nuclear Physics B 31(2), 253 (1971)
[2] Phys. Lett. B 31 (1970) 230

LHC as an antimatter factory

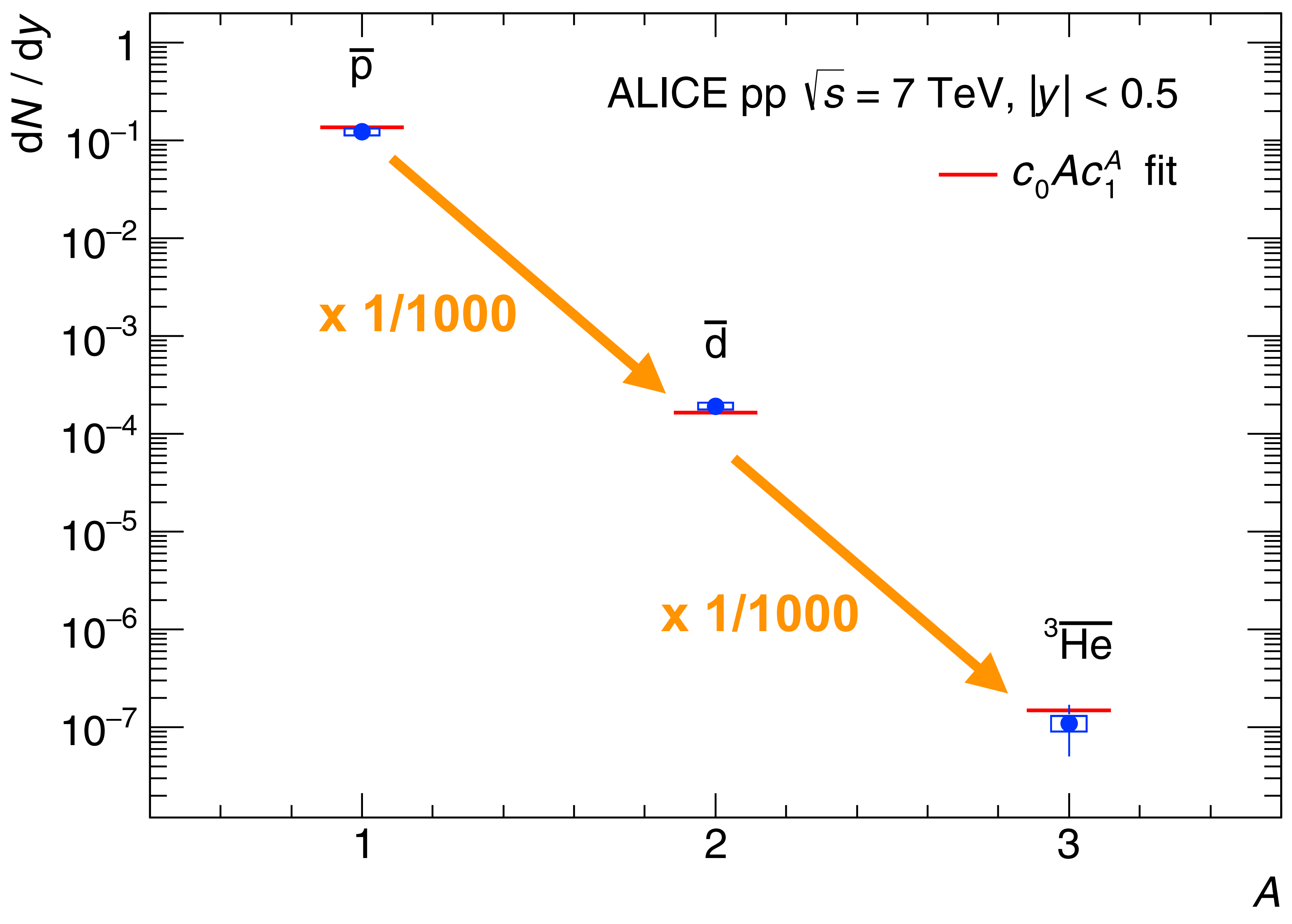
At LHC energies, particles and antiparticles are produced in almost equal amounts

- Protons and deuterons: about ~5% and ~0.005% of all charged particles
  - Penalty factor of ~1000 to produce one additional nucleon (in pp collisions)

(Anti-)deuteron momentum spectra in pp collisions [1]



Integrated yield at mid-rapidity [1]



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 $\sqrt{s}$

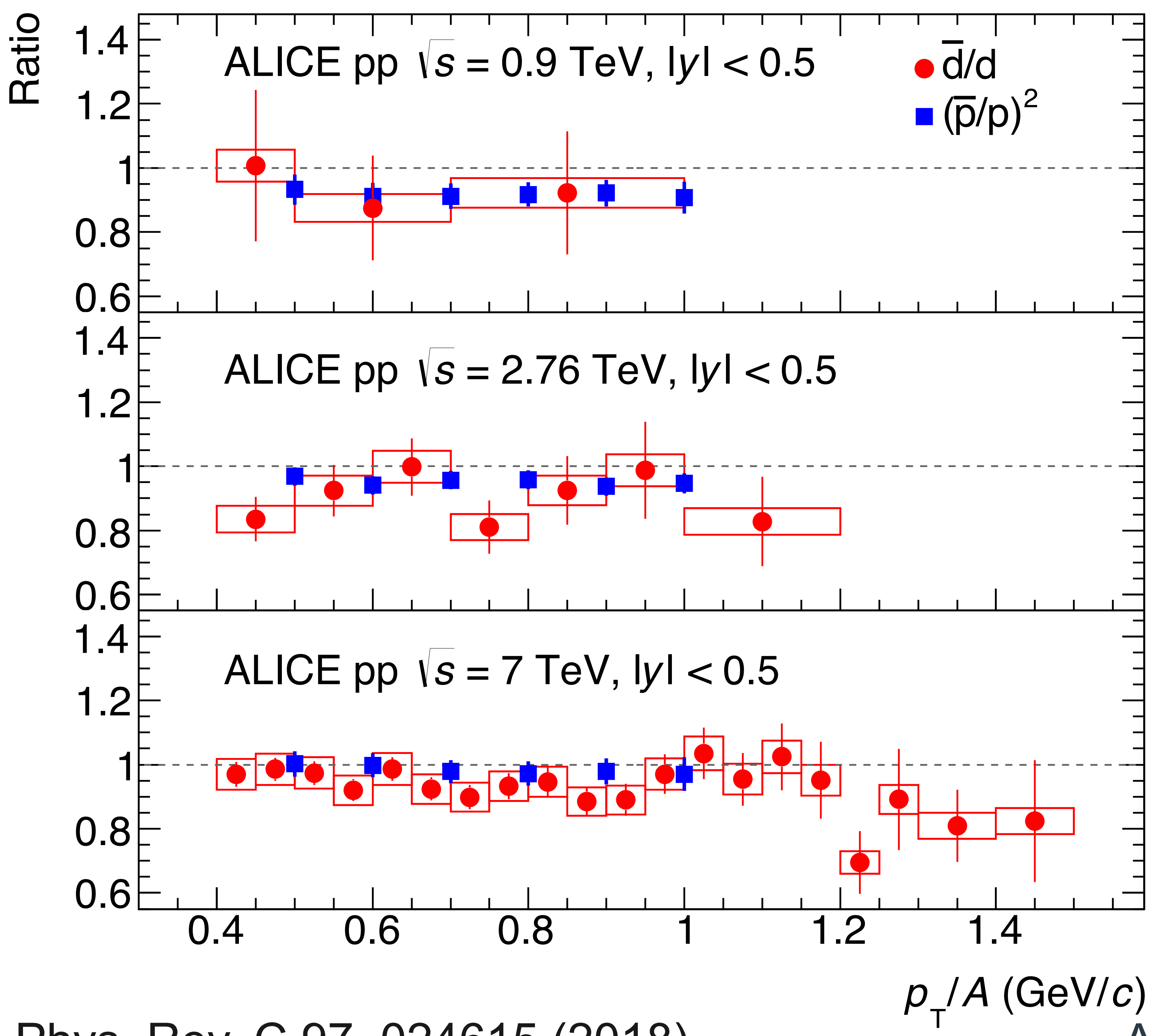
Today's talk: results on $\sigma_{\text{inel}}(\bar{d})$ in pPb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV

Extrapolation for $\sqrt{s}$ = 5.02 TeV:

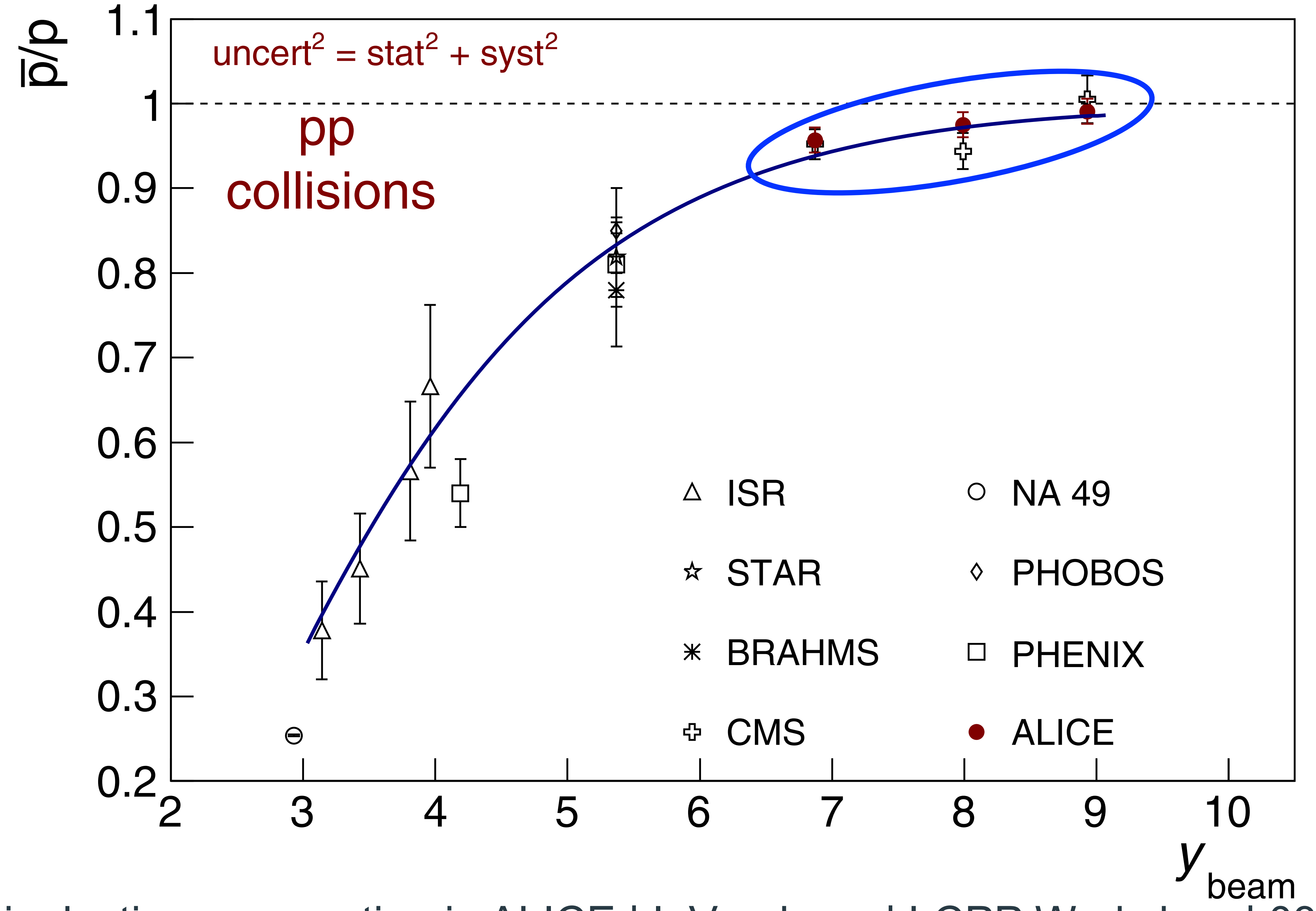
- Primordial $\bar{p}$ / p ratio: **R = 0.984 ± 0.015** → primordial $\bar{d}$ / d: **R = 0.968 ± 0.030**

Coalescence model: d yield ~ (p yield)²

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



$\bar{p}$/p ratio at mid-rapidity vs $\sqrt{s}$ [1]



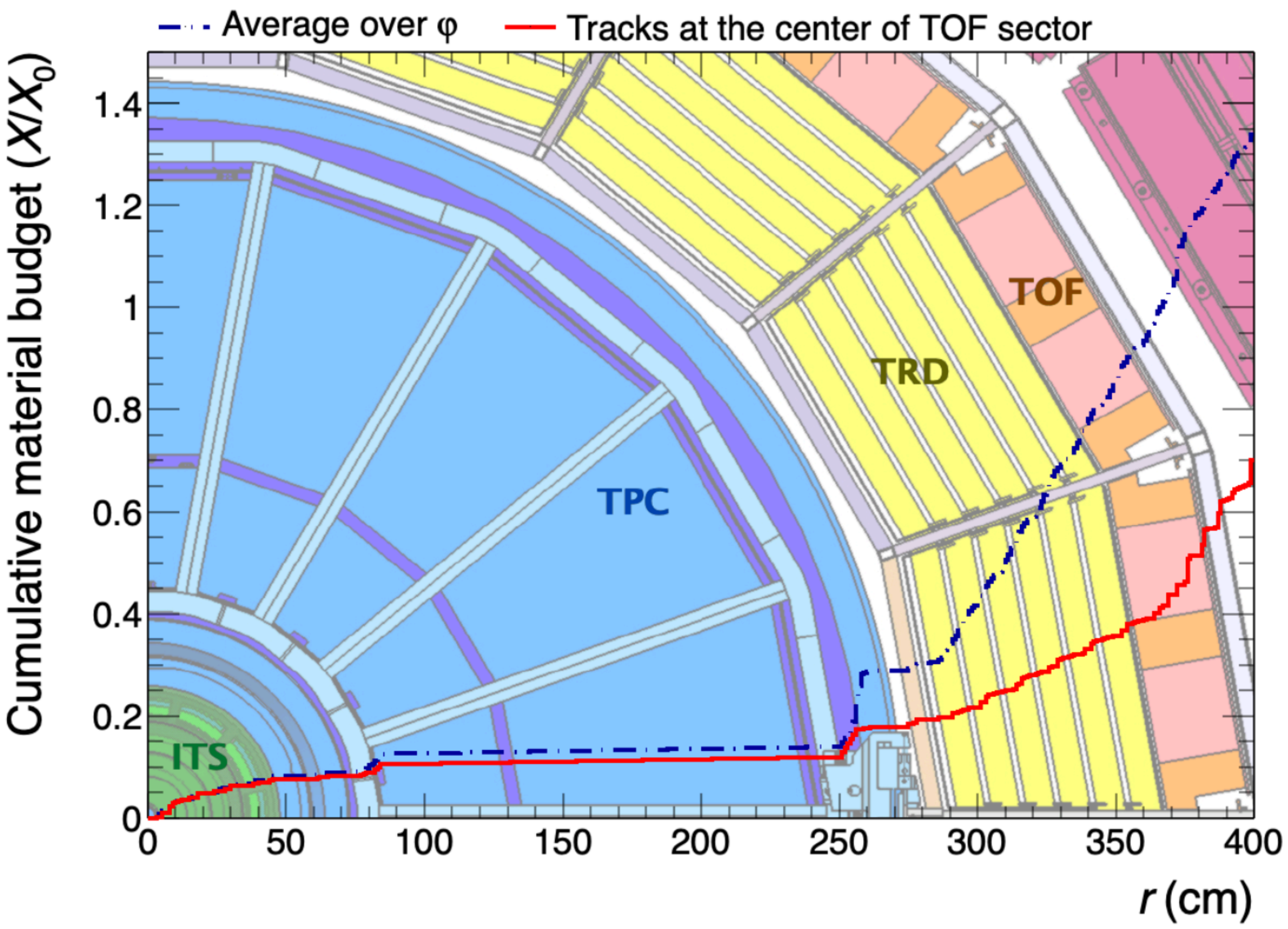
[1] Phys. Rev. C 97, 024615 (2018)

… and ALICE detector material as a target

Material budget at mid-rapidity at the centre of ALICE sector [1]:

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

Additionally, space frame between TPC and TOF can contribute to ~20-30% X_0



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

… and ALICE detector material as a target

Material budget at mid-rapidity at the centre of ALICE sector [1]:

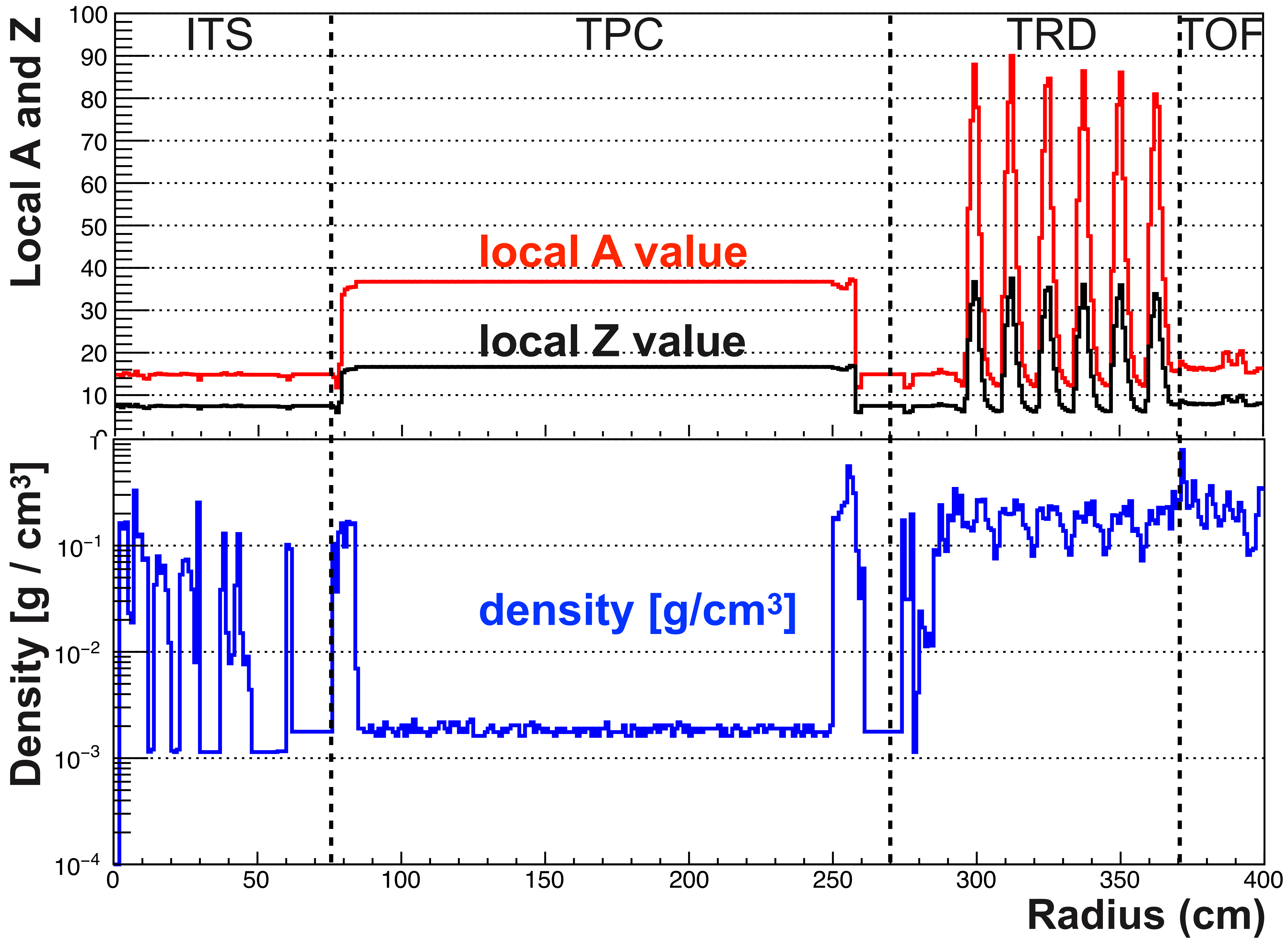
- **ITS (~8% X_0)**
- **TPC (~4% X_0)**
- **TRD (~25% X_0)**

Additionally, space frame between TPC and TOF can contribute to ~20-30% X_0

Our "target" is very non-uniform!

Average <A> and <Z> values of the materials weighted with density:

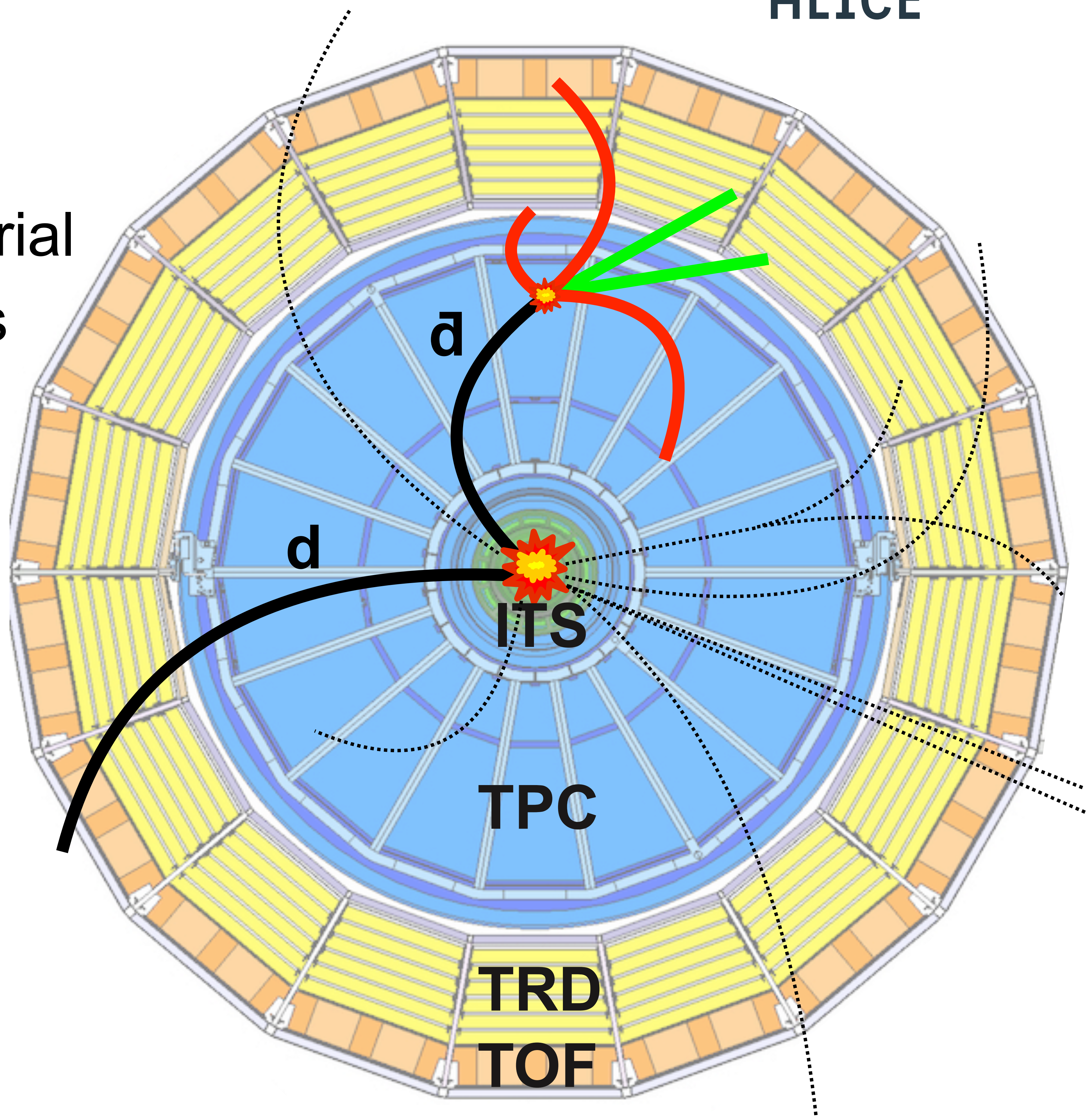
	<Z>	<A>
ITS+TPC	8.5	17.4
From IP to TOF	14.8	31.8



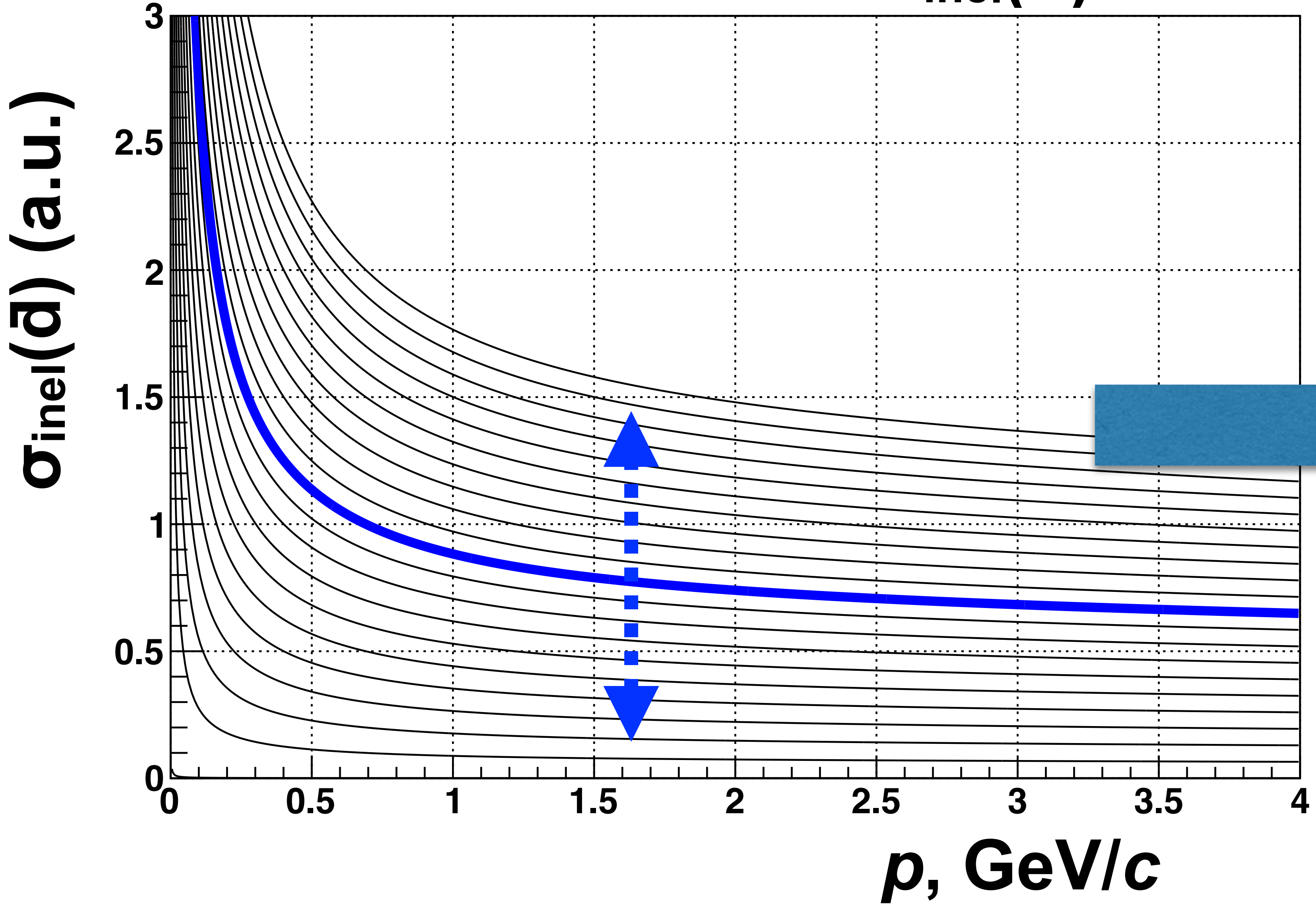
Idea of the analysis

Analyse *raw reconstructed* antideuteron-to-deuteron ratio

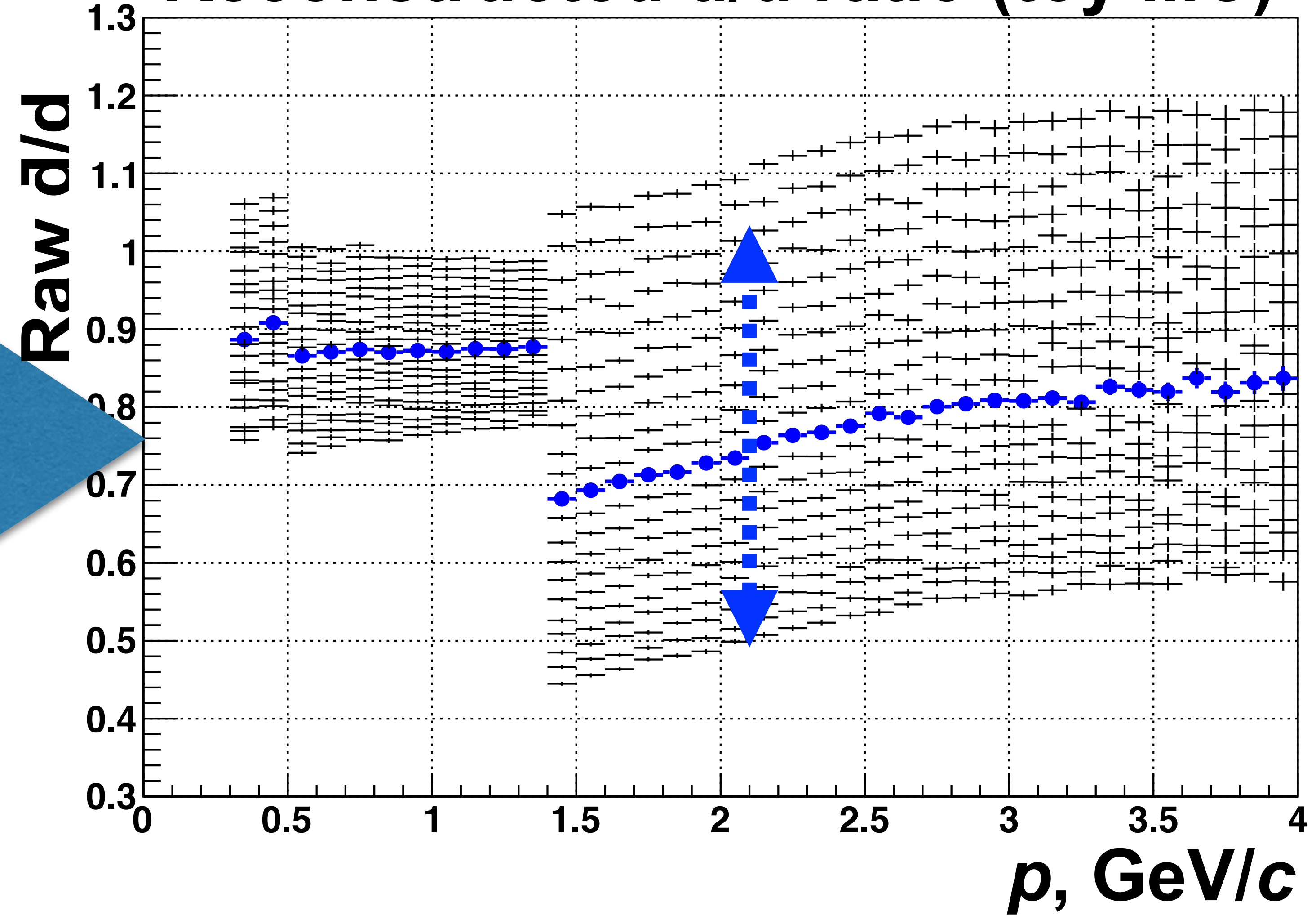
- No correction due to detector efficiency or absorption in detector material
- Correct for secondary (anti)deuterons from weak decays or spallations
- Constrain $\sigma_{inel}(\bar{d})$ via comparison with detailed Monte Carlo simulations based on Geant4
  - Vary $\sigma_{inel}(\bar{d})$ in MC simulations, $\sigma_{inel}(d)$ is fixed to the one used in Geant4 (describes well the experimental data)
- (Anti)proton analysis as a benchmark



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



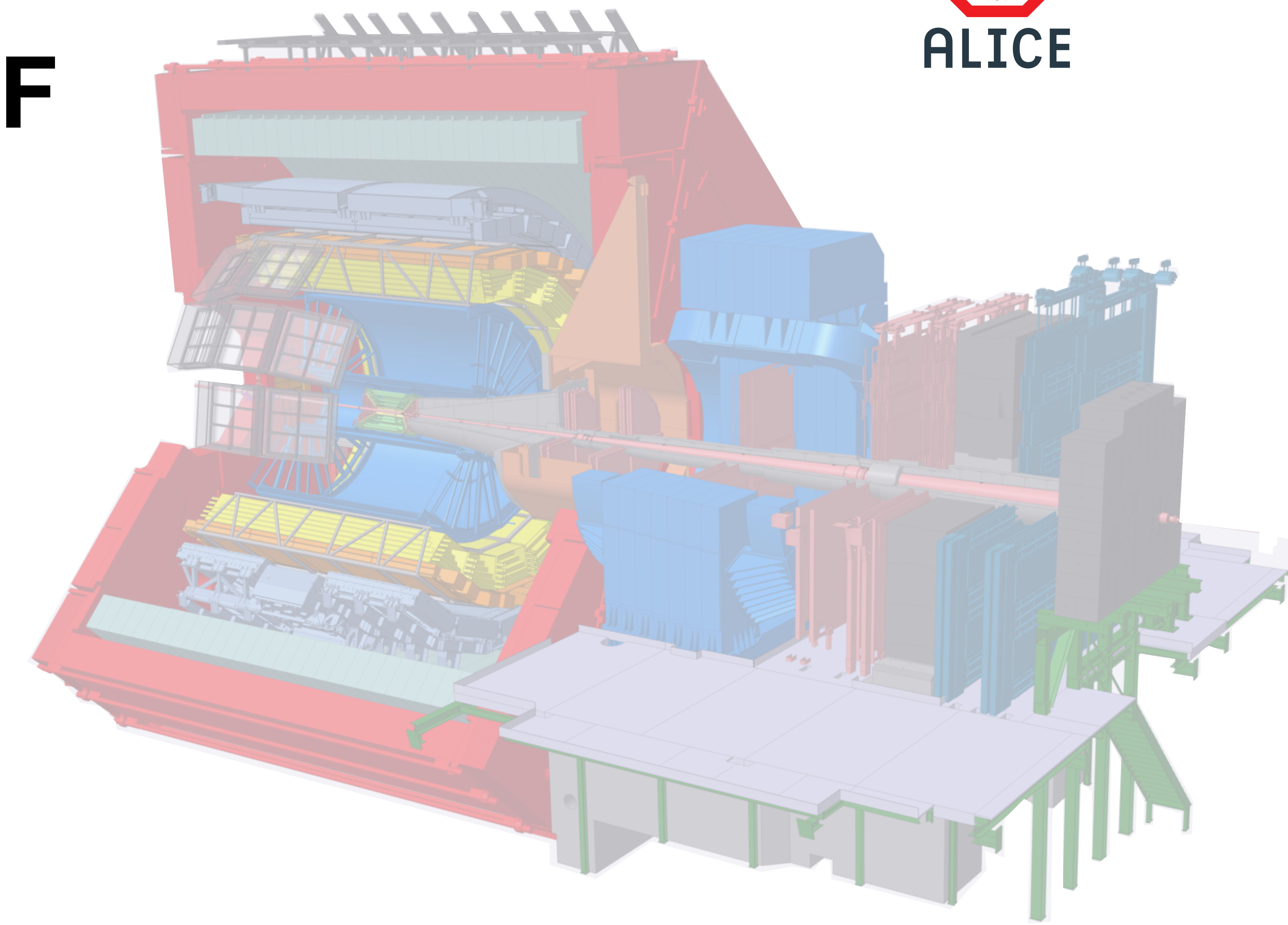
Reconstructed d̄/d ratio (toy MC)



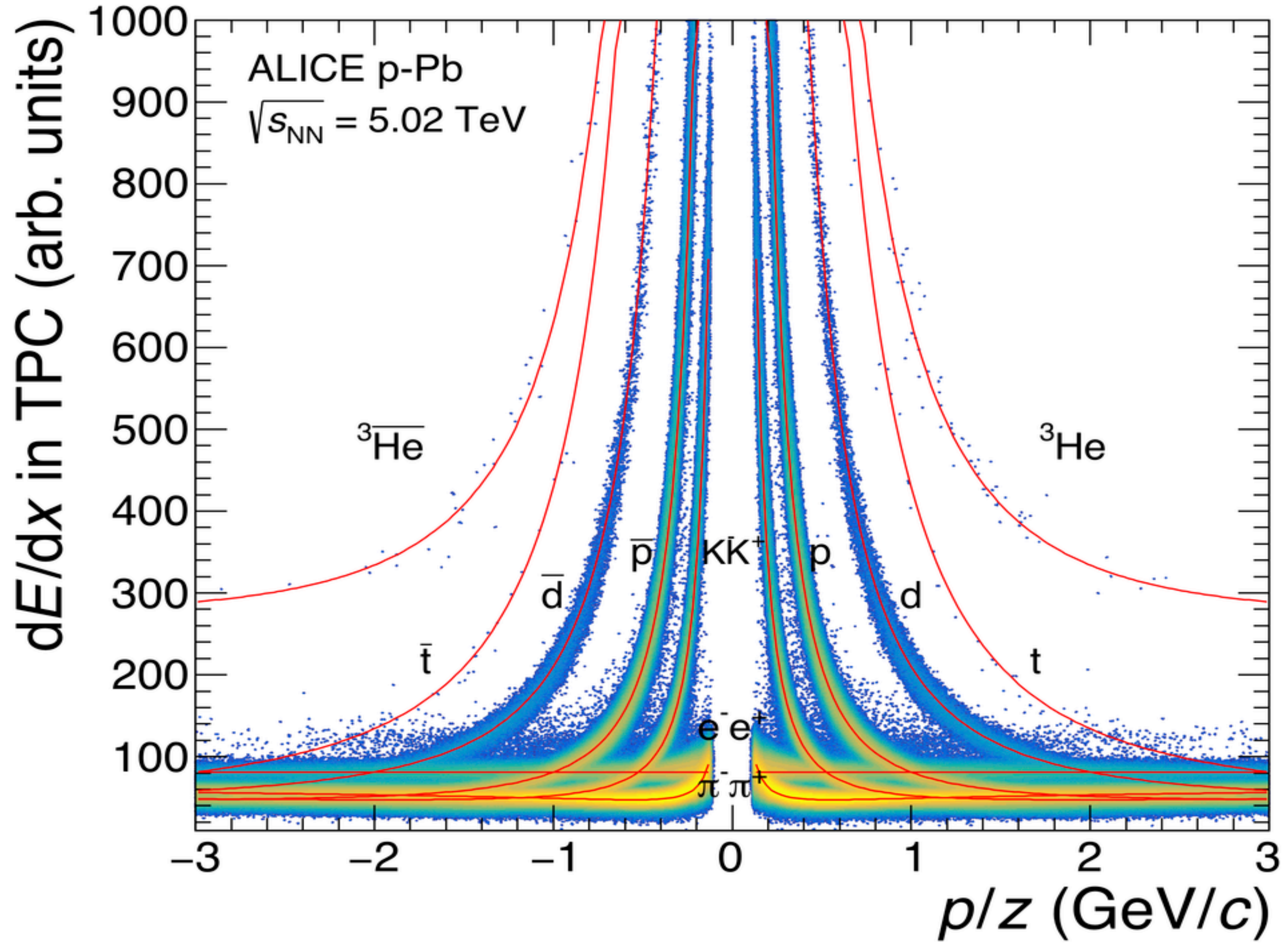
Particle identification in TPC and TOF

Complementary information from TPC and TOF detectors allows to select high-purity (anti)nuclei

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



dE/dx in ALICE TPC [1]



[1] PLB 800 (2019) 135043

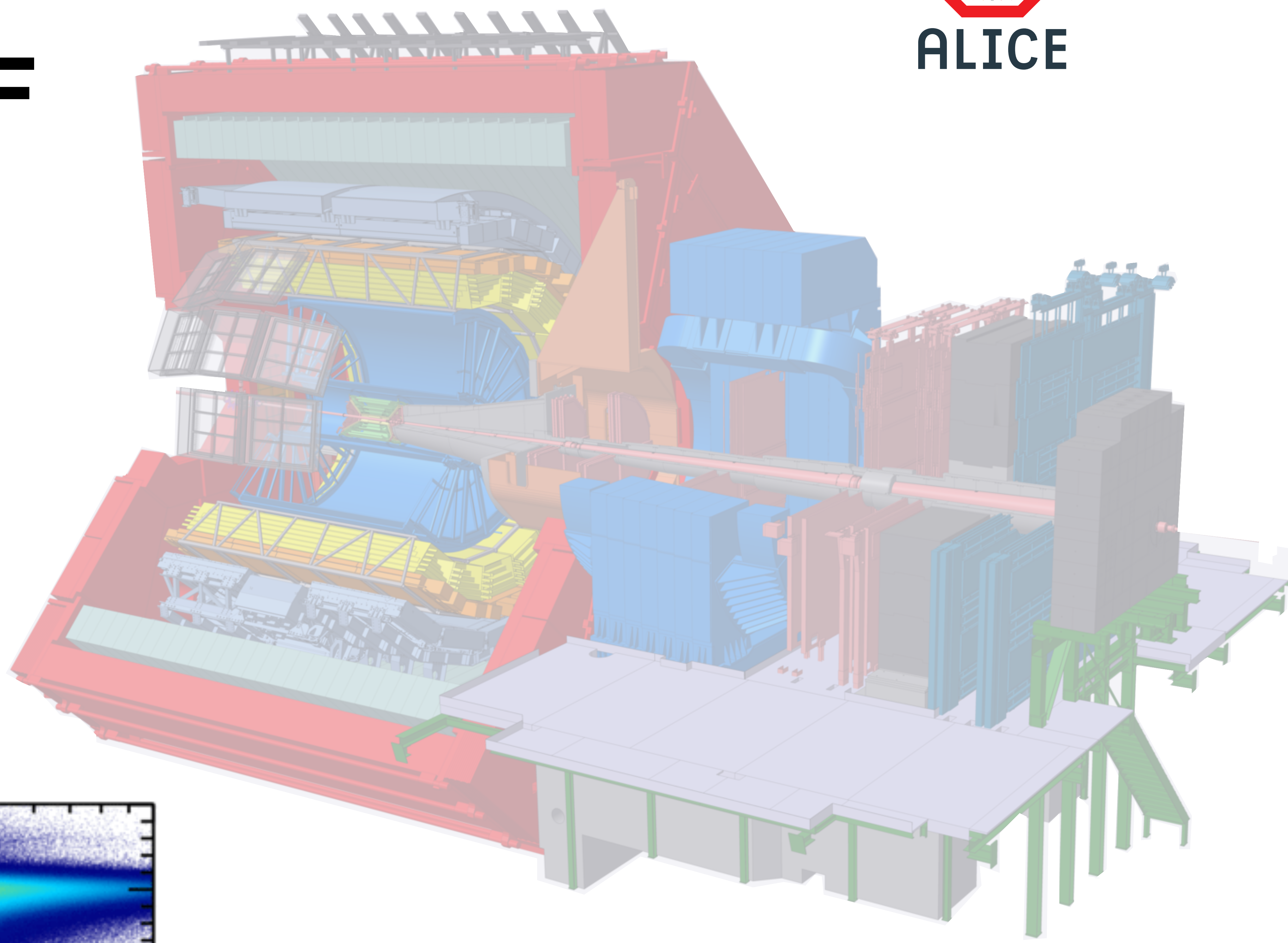
Particle identification in TPC and TOF

Complementary information from TPC and TOF detectors allows to select high-purity (anti)nuclei

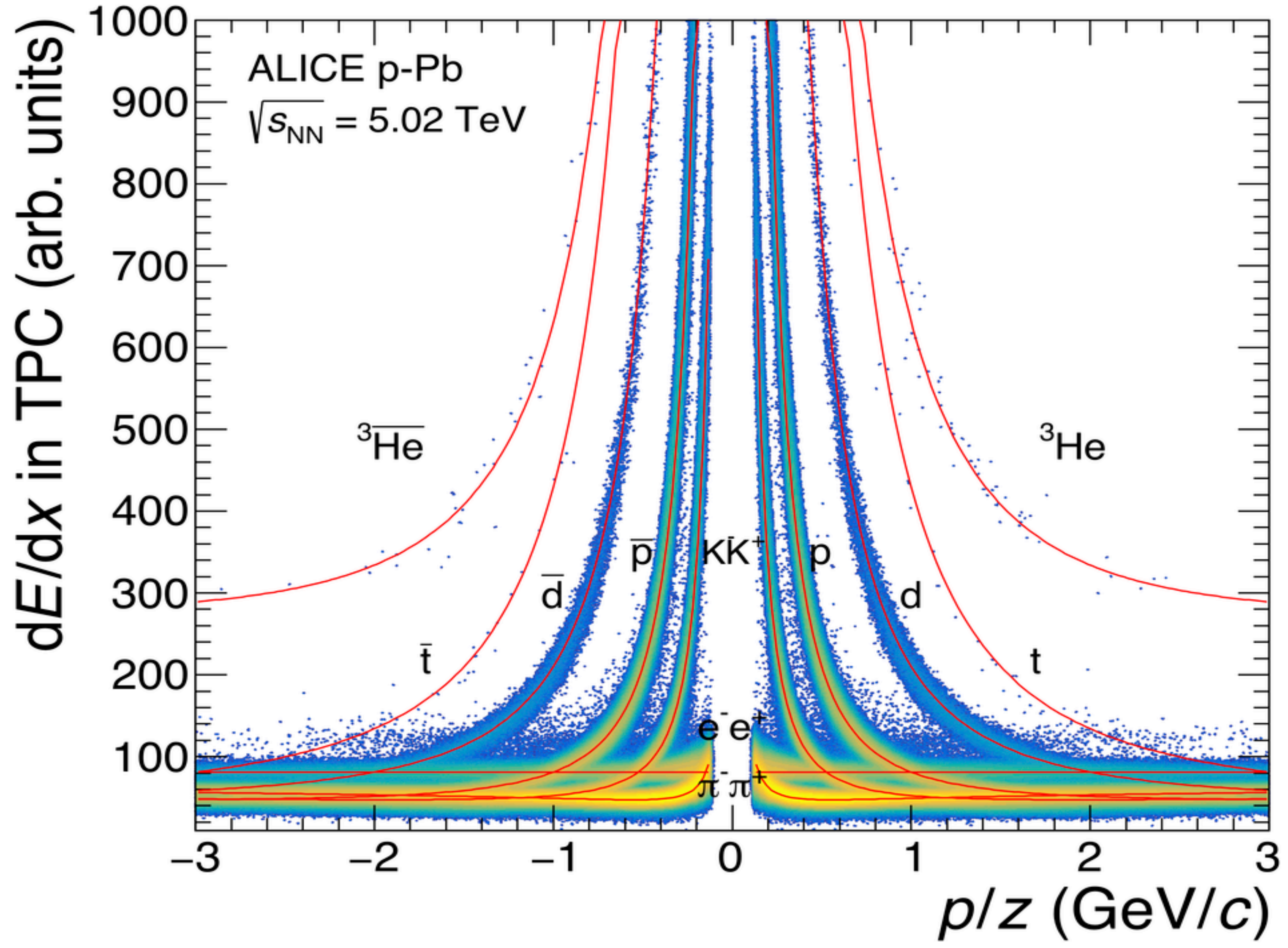
TPC: dE/dx in gas (Ar/CO_2)

TOF measurements: $\beta = v/c$

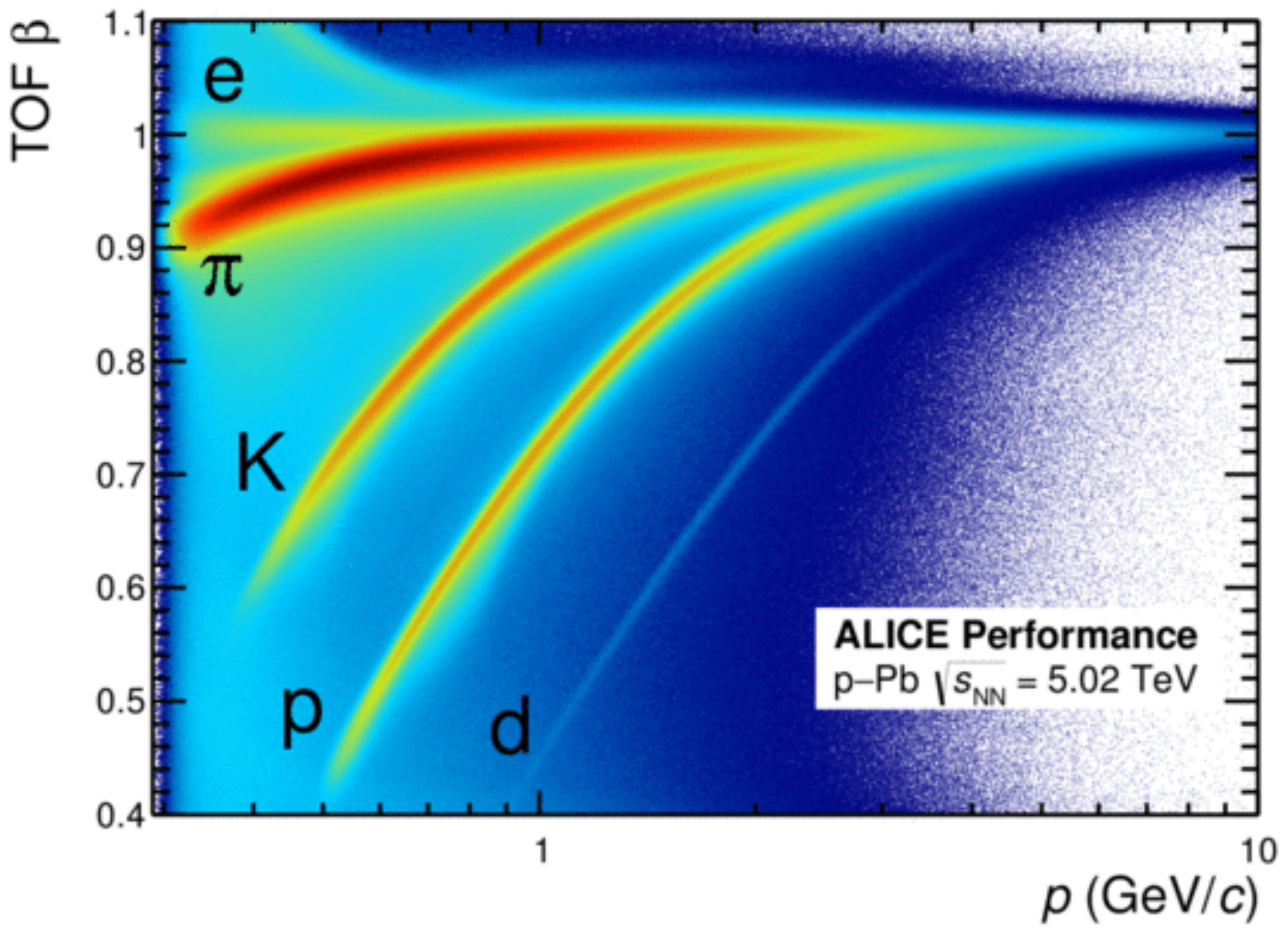
- $p = \gamma\beta m \rightarrow$ mass



d*E*/dx in ALICE TPC [1]



TOF β



[1] PLB 800 (2019) 135043

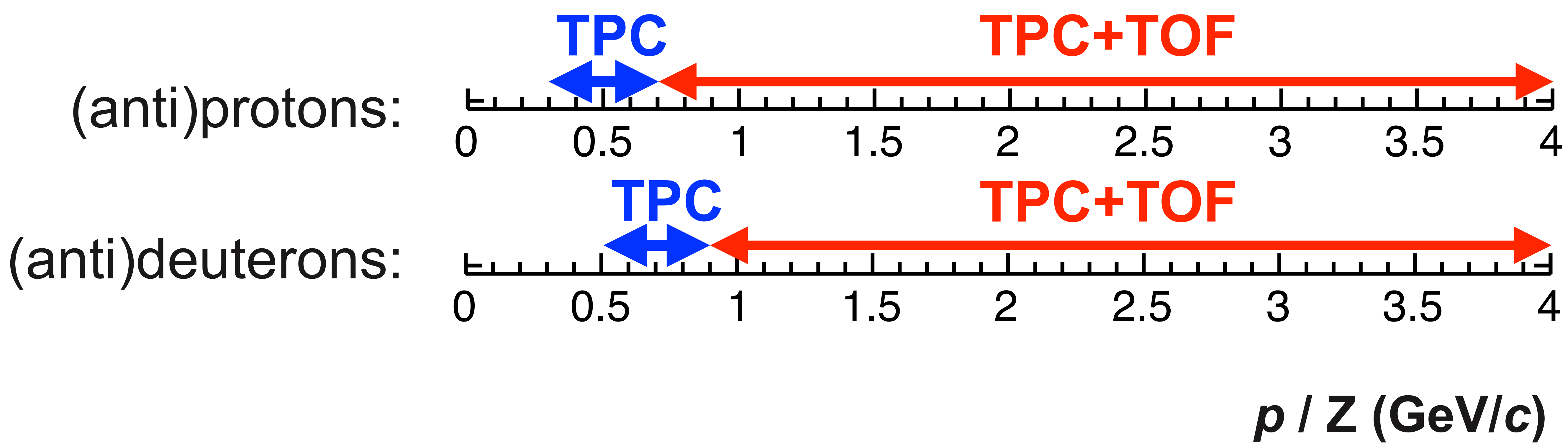
Particle identification in TPC and TOF

Complementary information from TPC and TOF detectors allows to select high-purity (anti)nuclei

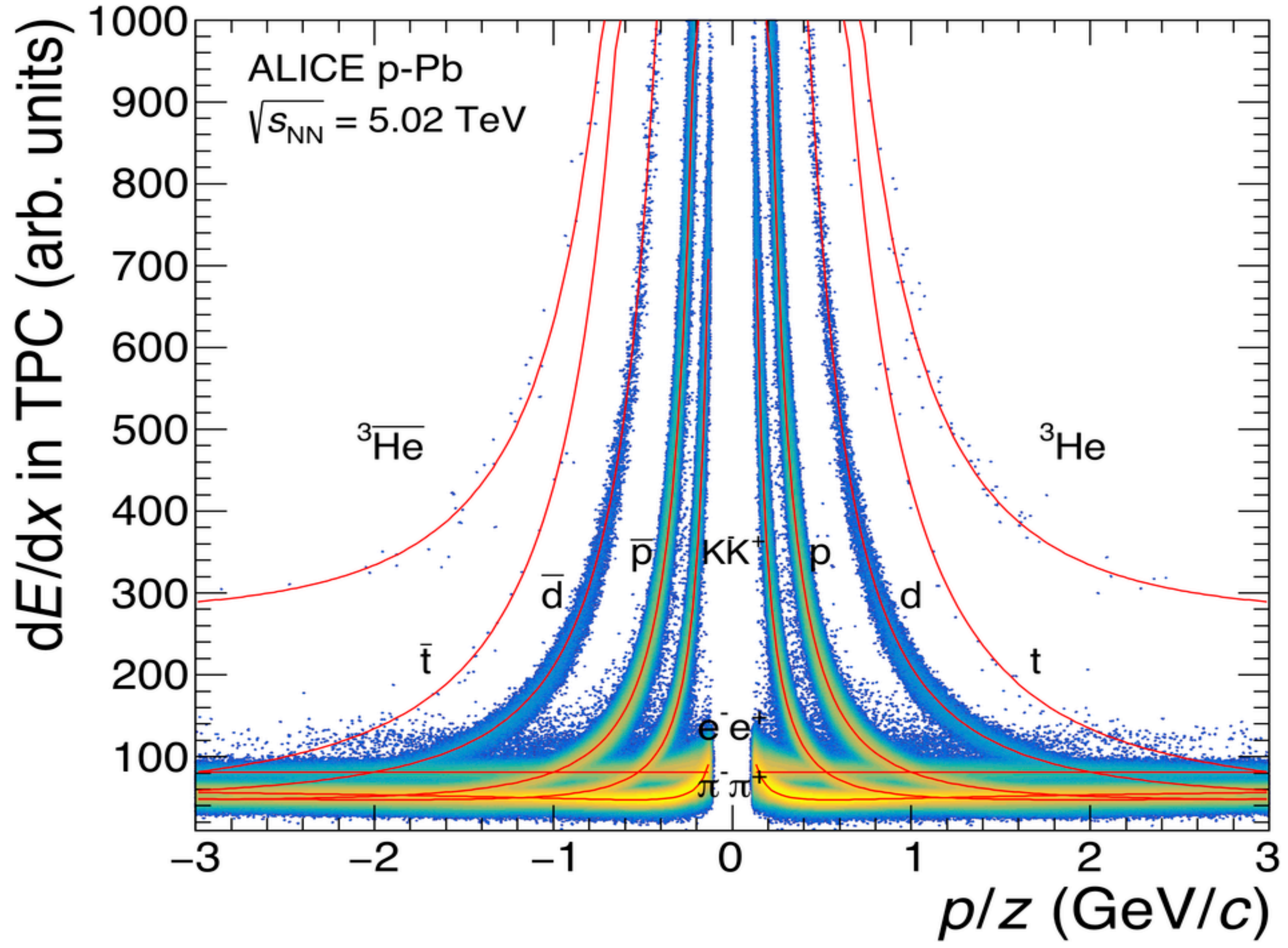
TPC: d*E*/dx in gas (Ar/CO_2)

TOF measurements: $\beta = v/c$

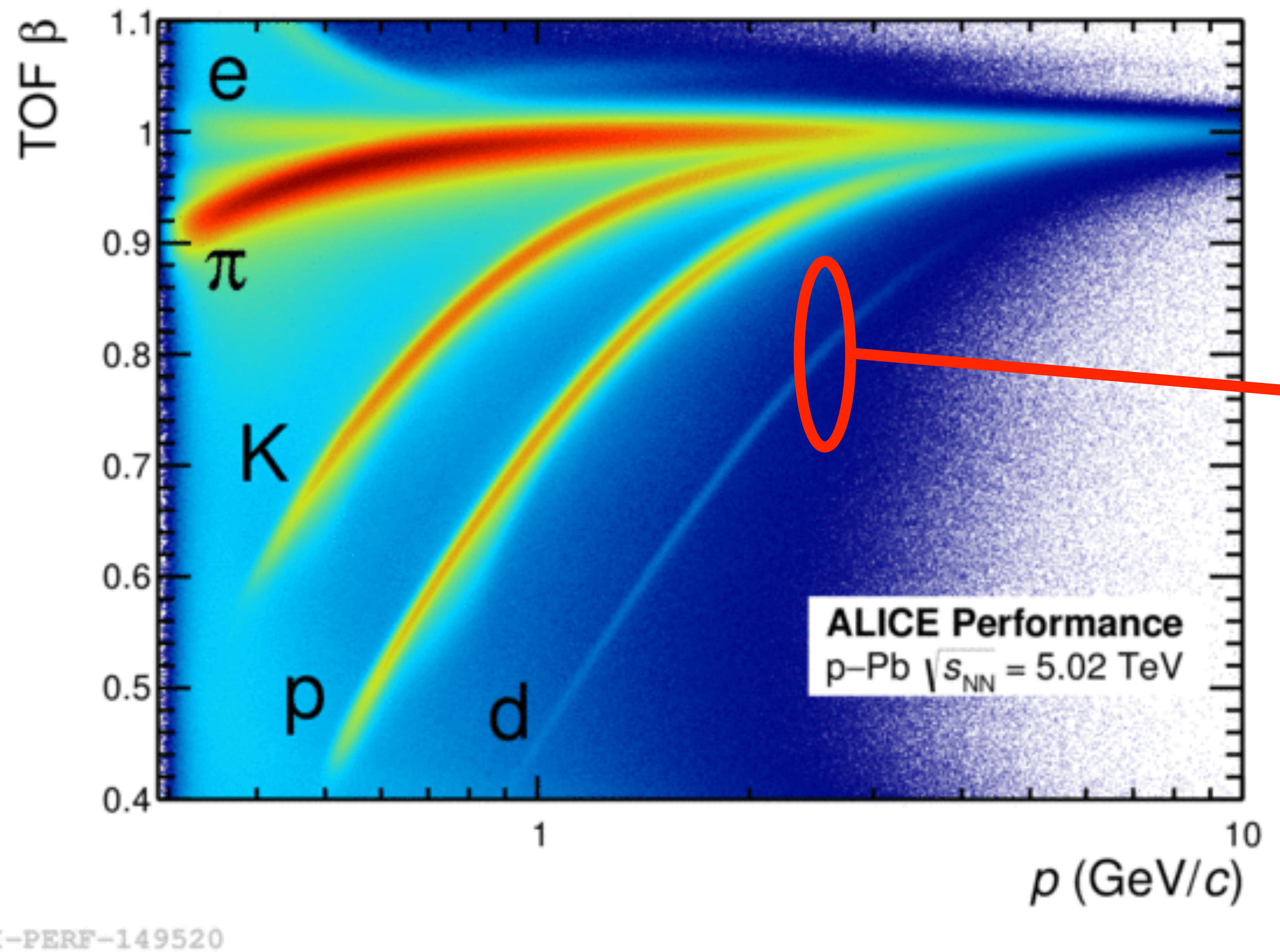
- $p = \gamma\beta m \rightarrow$ mass
- Extract yields using fits to TOF m^2

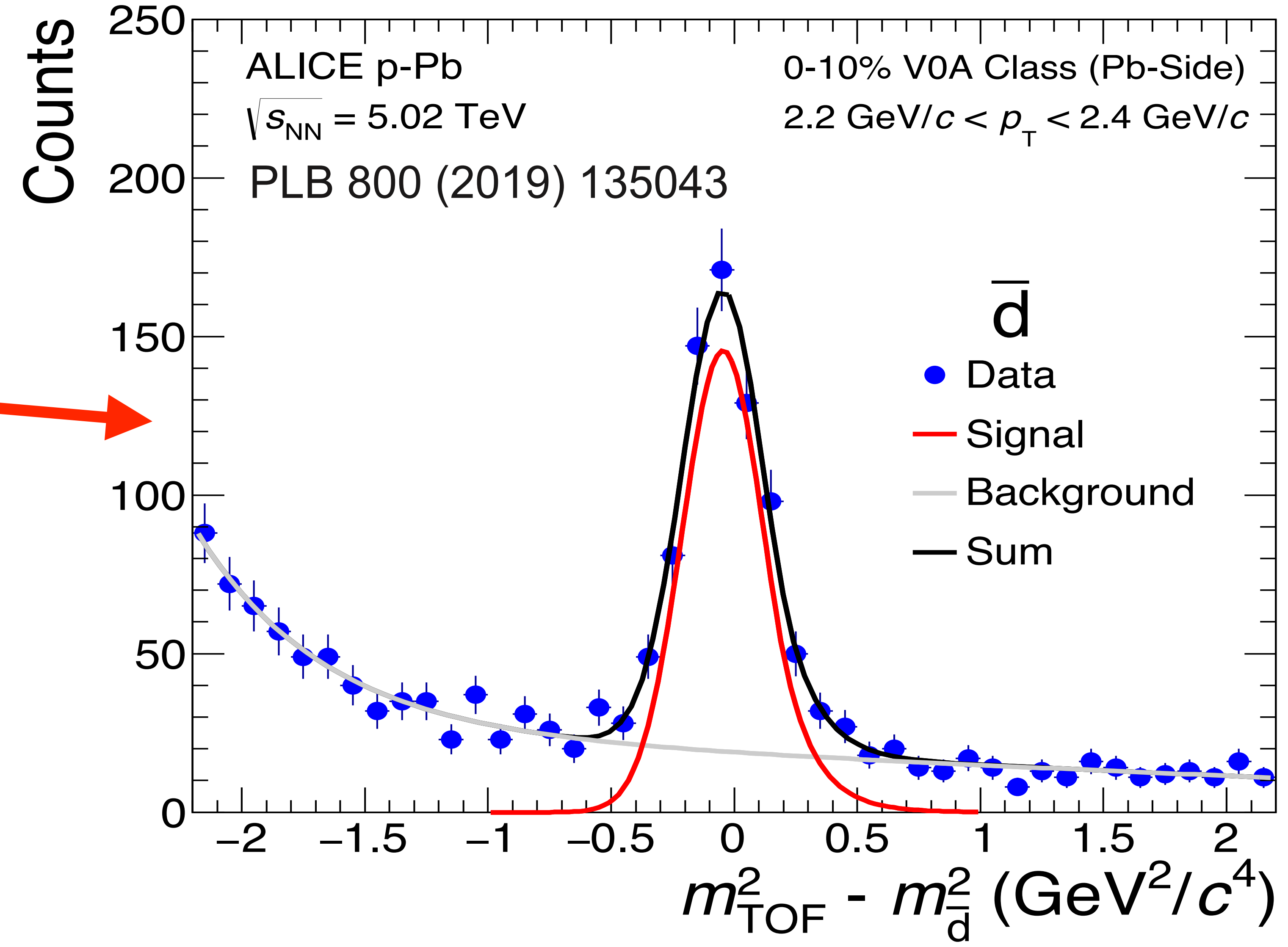


d*E*/dx in ALICE TPC [1]



TOF β





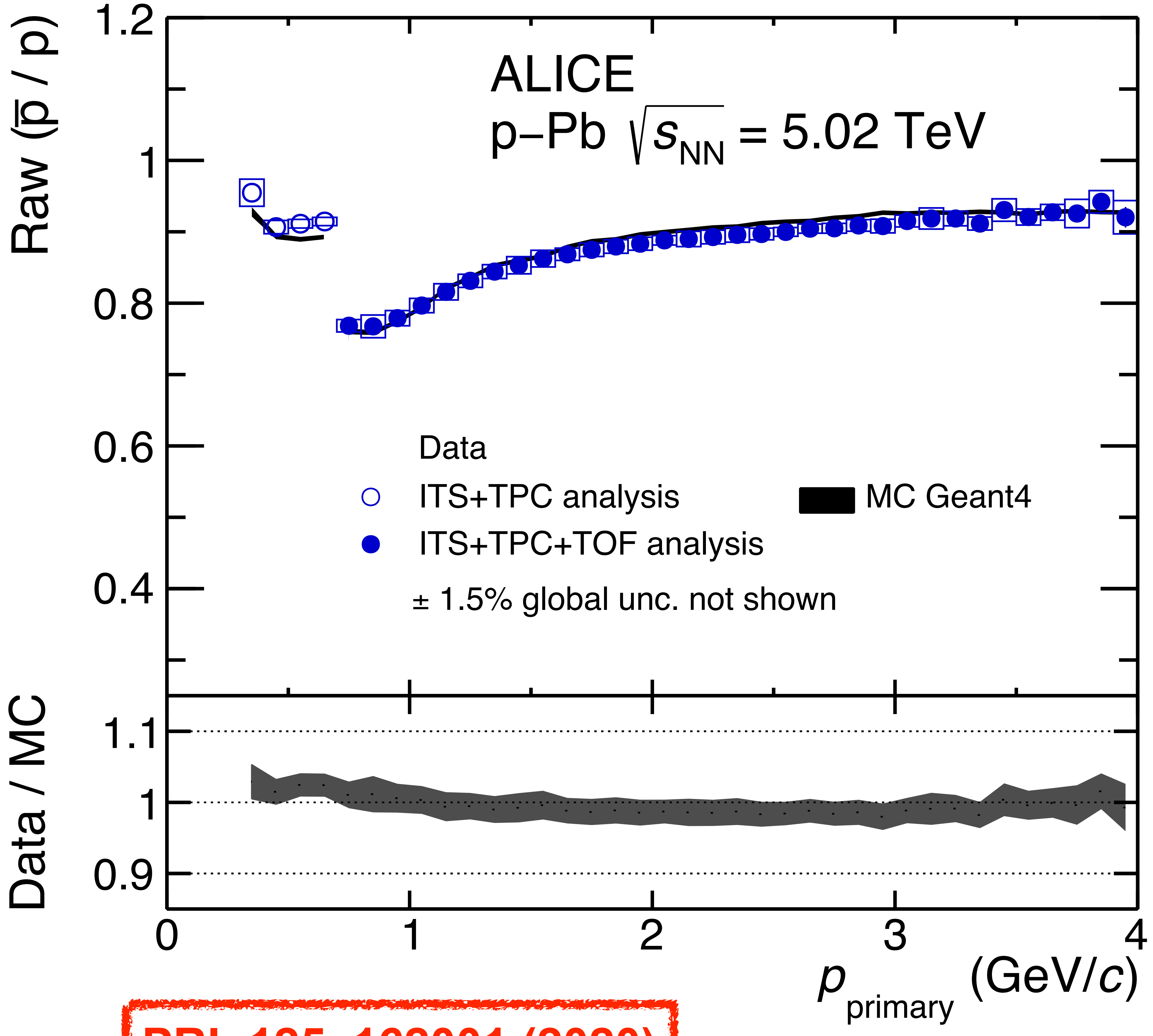
[1] PLB 800 (2019) 135043

Raw ratio of primary (anti)protons

Raw $\bar{p}$ / p ratio compared to detailed ALICE MC simulations based on Geant4

- Geant4: version 10.4.2, FTFP_INCLXX_EMV physics list

Raw $\bar{p}$ / p ratio



PRL 125, 162001 (2020)

- Higher loss of antiprotons in detector material as expected

Monte Carlo data: detailed simulation of ALICE detector performance

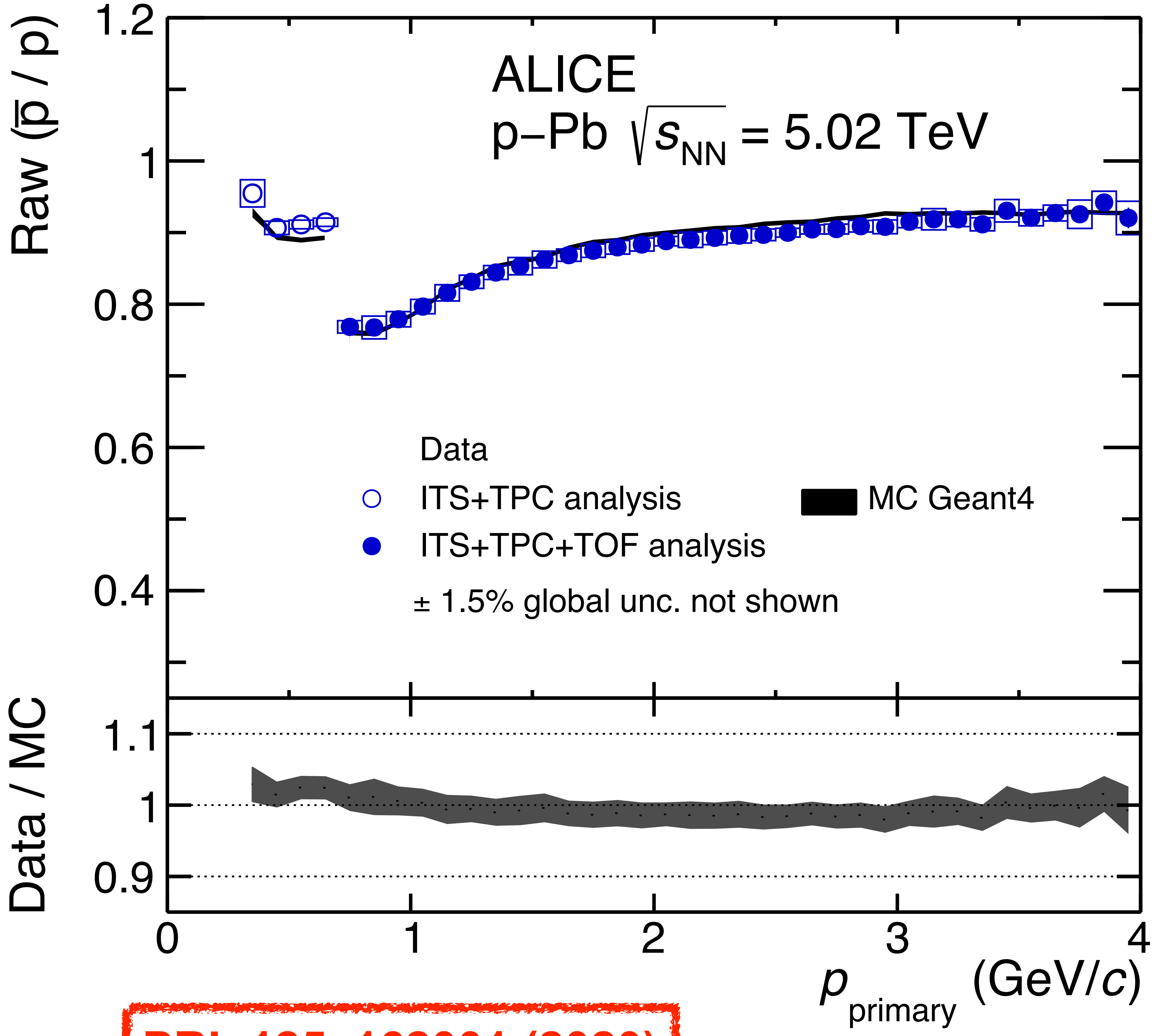
- Propagation of (anti)particles and interaction with matter with Geant4
- Very good description of raw reconstructed $\bar{p}$ / p ratio

Raw ratio of primary (anti)protons

Raw $\bar{p}$ / p ratio compared to detailed ALICE MC simulations based on Geant4

- Geant4: version 10.4.2, FTFP_INCLXX_EMV physics list

Raw $\bar{p}$ / p ratio



PRL 125, 162001 (2020)

- Higher loss of antiprotons in detector material as expected

Monte Carlo data: detailed simulation of ALICE detector performance

- Propagation of (anti)particles and interaction with matter with Geant4
- Very good description of raw reconstructed $\bar{p}$ / p ratio

Vary σ_{inel} ($\bar{p}$) in simulations until MC ratio is ±1σ or ±2σ away from experimental ratio → constraints on σ_{inel} ($\bar{p}$)

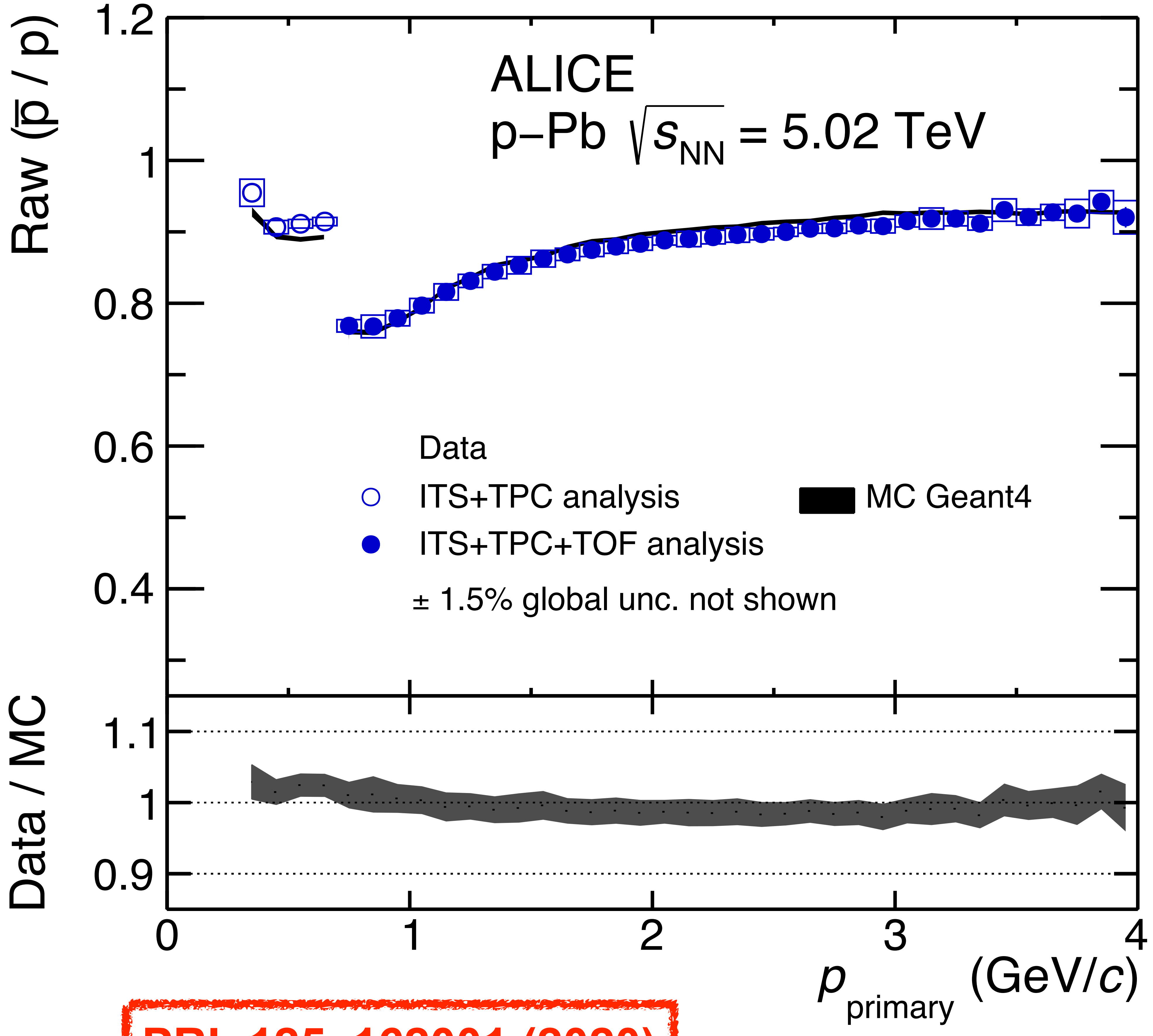
- σ_{inel}(p) is fixed to the Geant4 parameterisations (describe well exp. data on σ_{inel}(p))

Raw ratio of primary (anti)protons

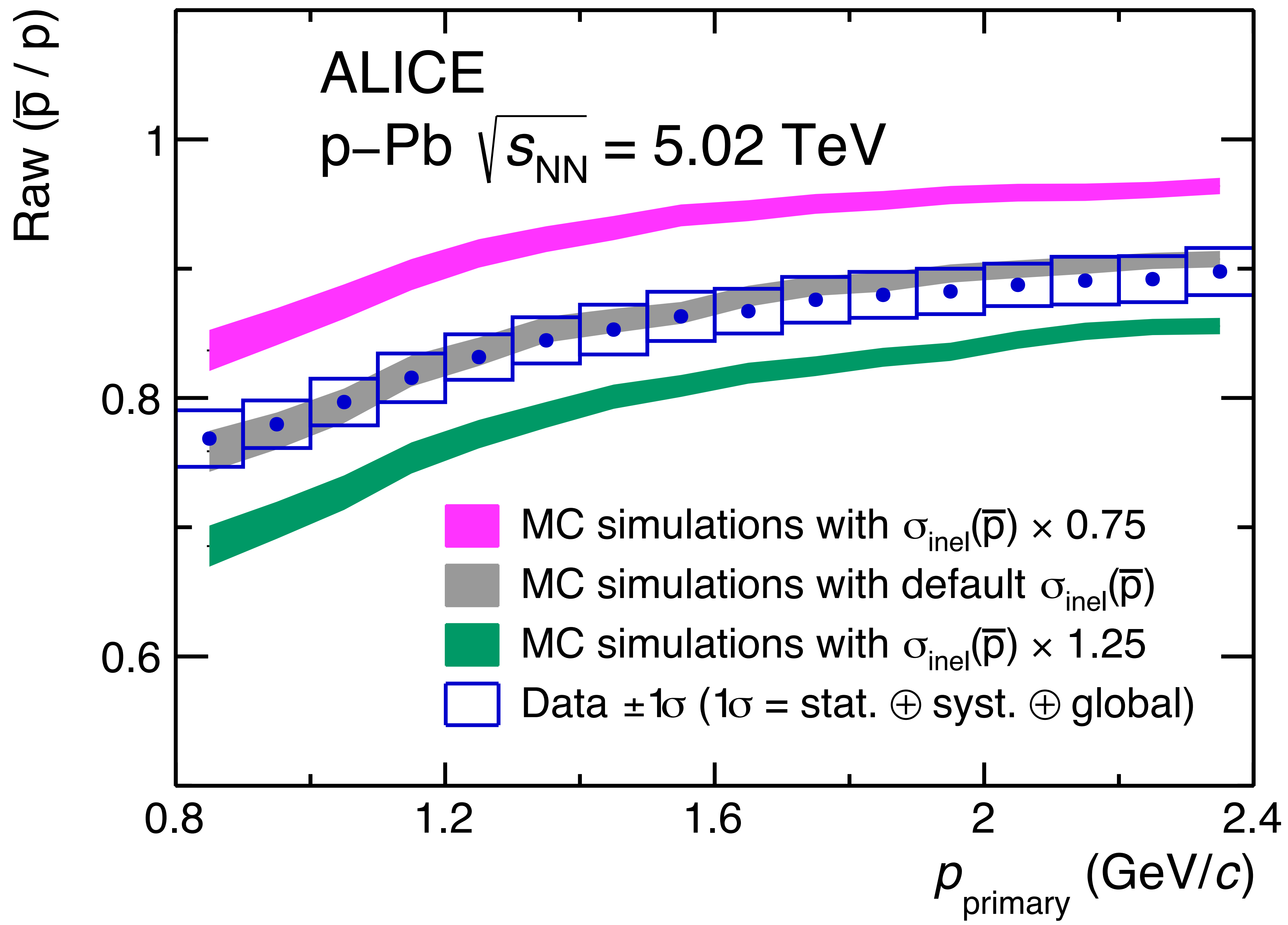
Raw $\bar{p}$ / p ratio compared to detailed ALICE MC simulations based on Geant4

- Geant4: version 10.4.2, FTFP_INCLXX_EMV physics list

Raw $\bar{p}$ / p ratio



Variations of σ_{inel} ($\bar{p}$) in MC simulations



Uncertainties on data: stat., syst. and global unc. from primordial ratio

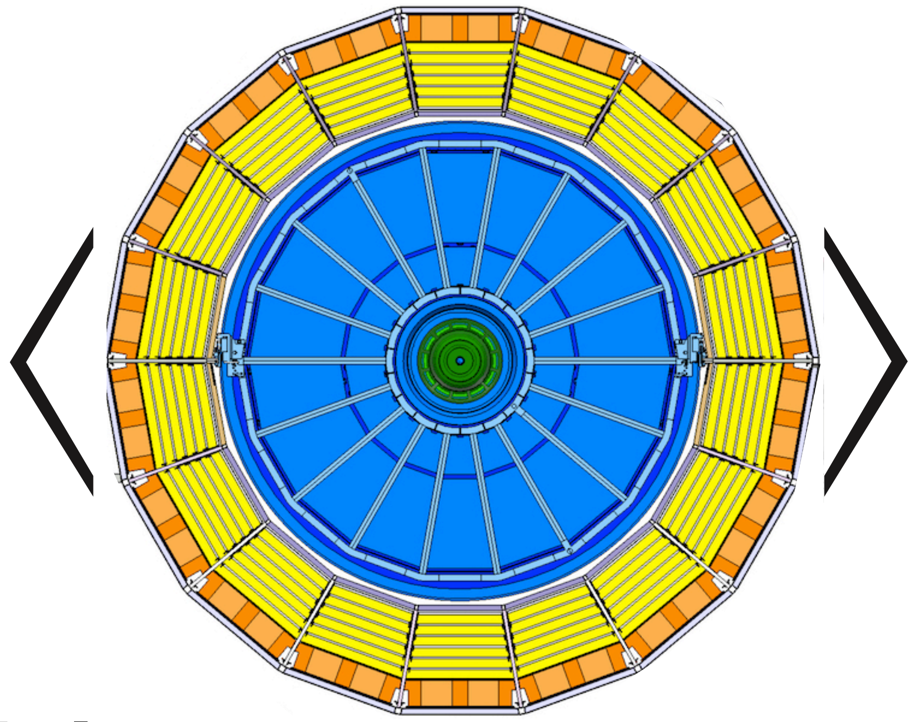
Uncertainties on MC results: variations of σ_{inel}(p) and σ_{el}

PRL 125, 162001 (2020)

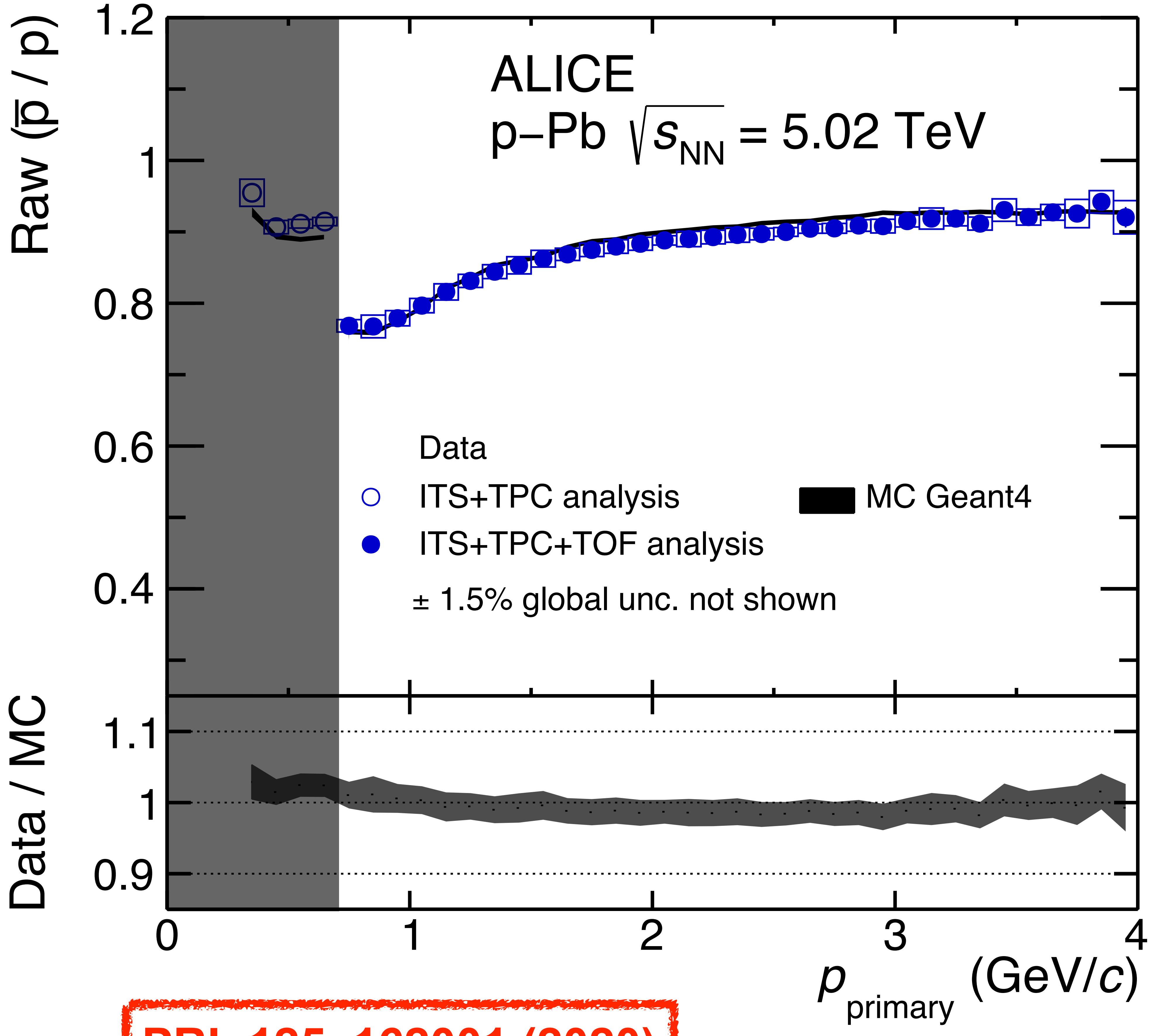
Results for $\sigma_{inel}(\bar{p})$

$\sigma_{inel}(\bar{p})$ is estimated on an averaged material element of the ALICE detector

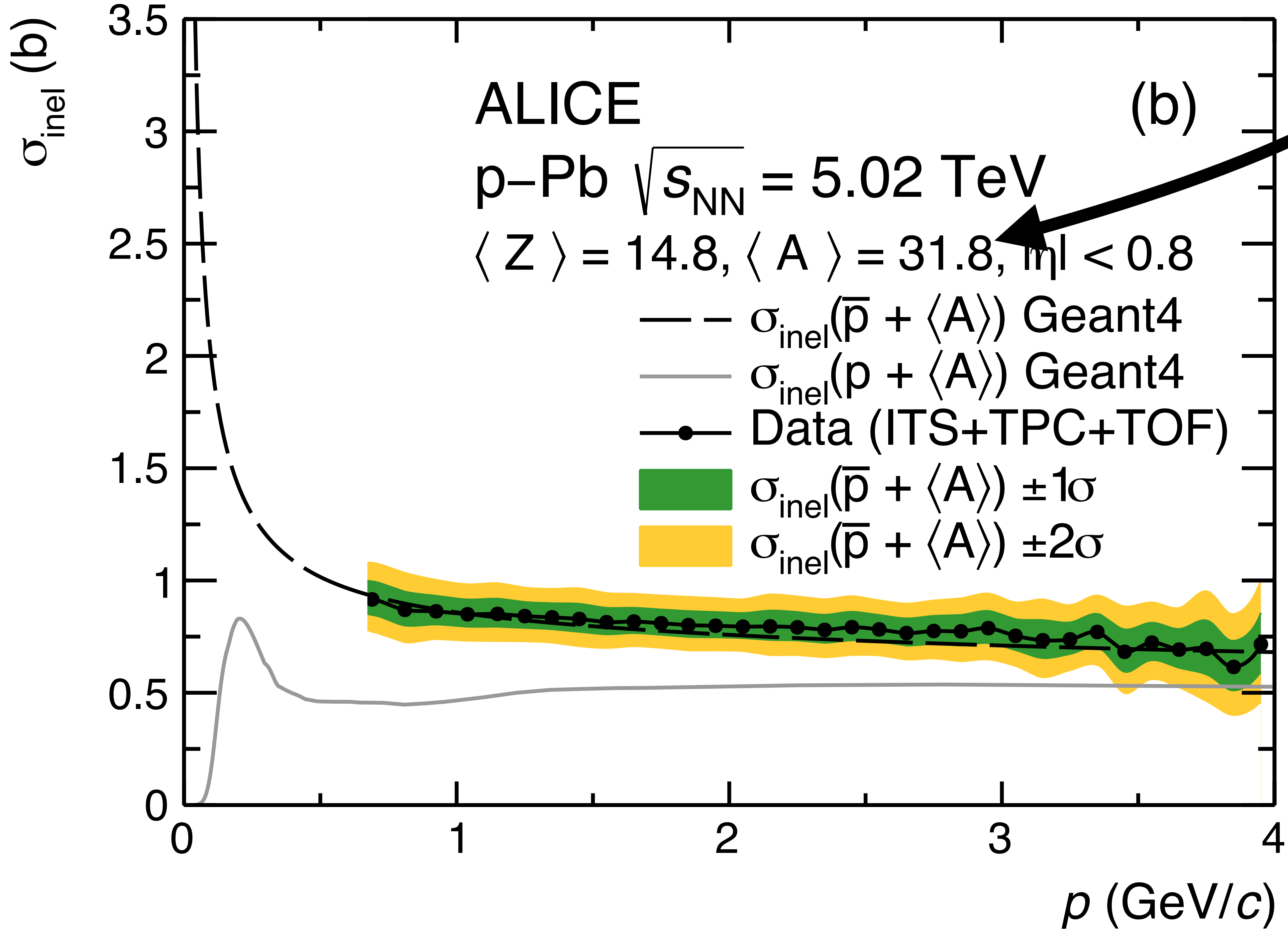
Good agreement with Geant4 parameterisations in whole investigated momentum range



Raw $\bar{p}$ / p ratio



$\sigma_{inel}(\bar{p})$ on averaged ALICE material



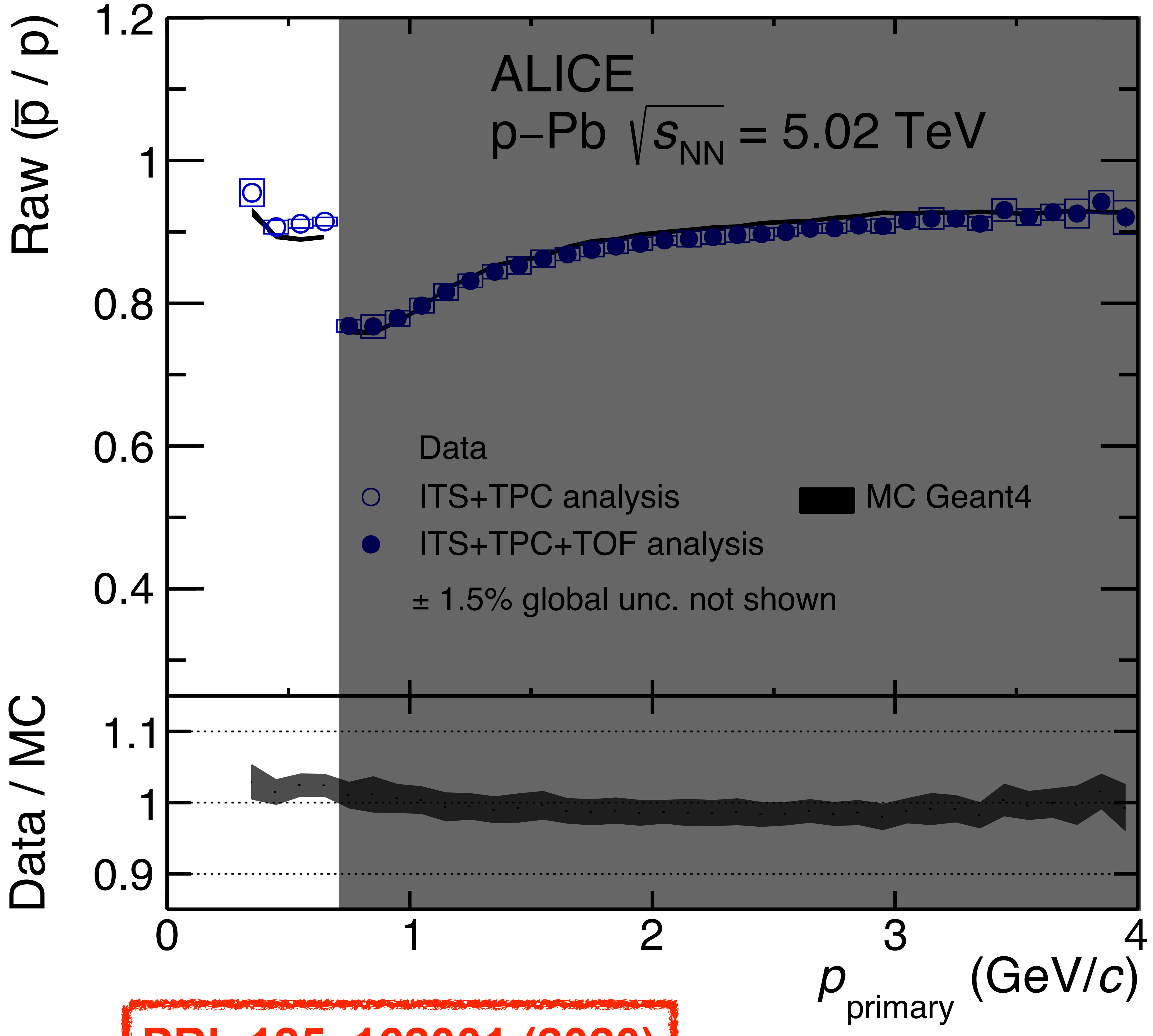
PRL 125, 162001 (2020)

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

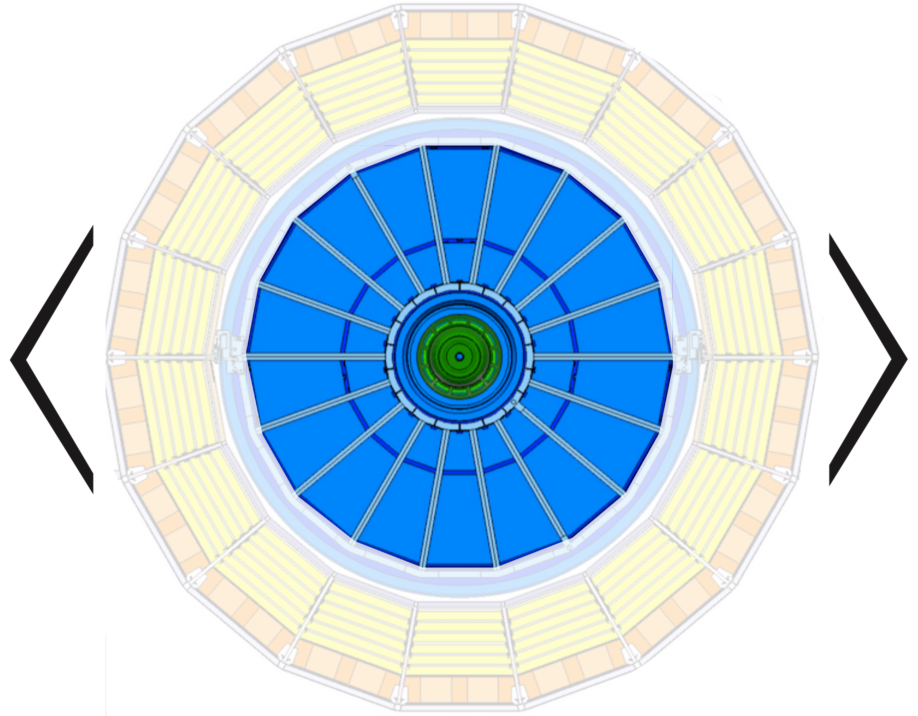
$\sigma_{inel}(\bar{p})$ is estimated on an averaged material element of the ALICE detector

Good agreement with Geant4 parameterisations in whole investigated momentum range

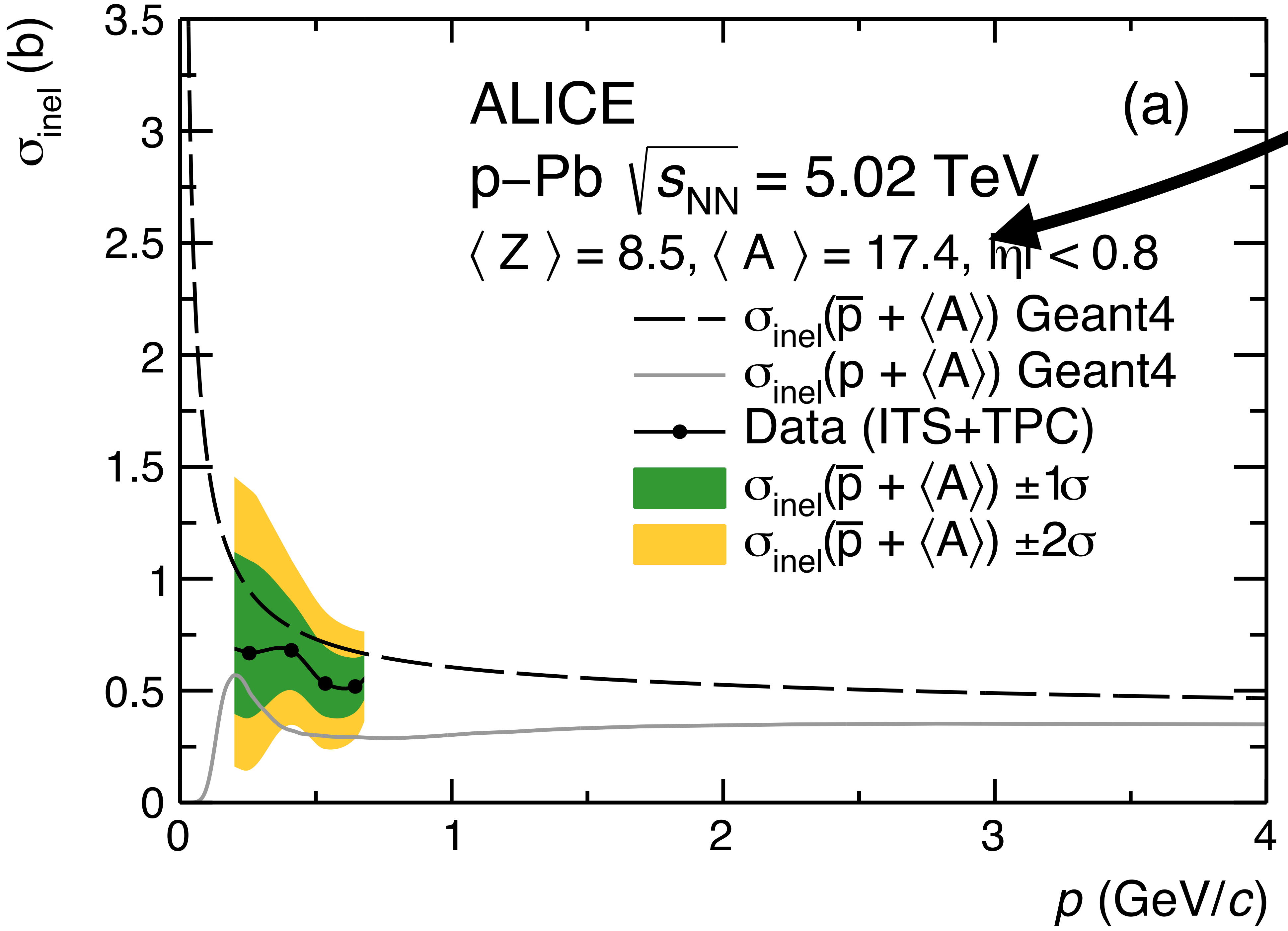
Raw $\bar{p}$ / p ratio



Energy loss effects: annihilation happens at momentum $p < p_{primary}$



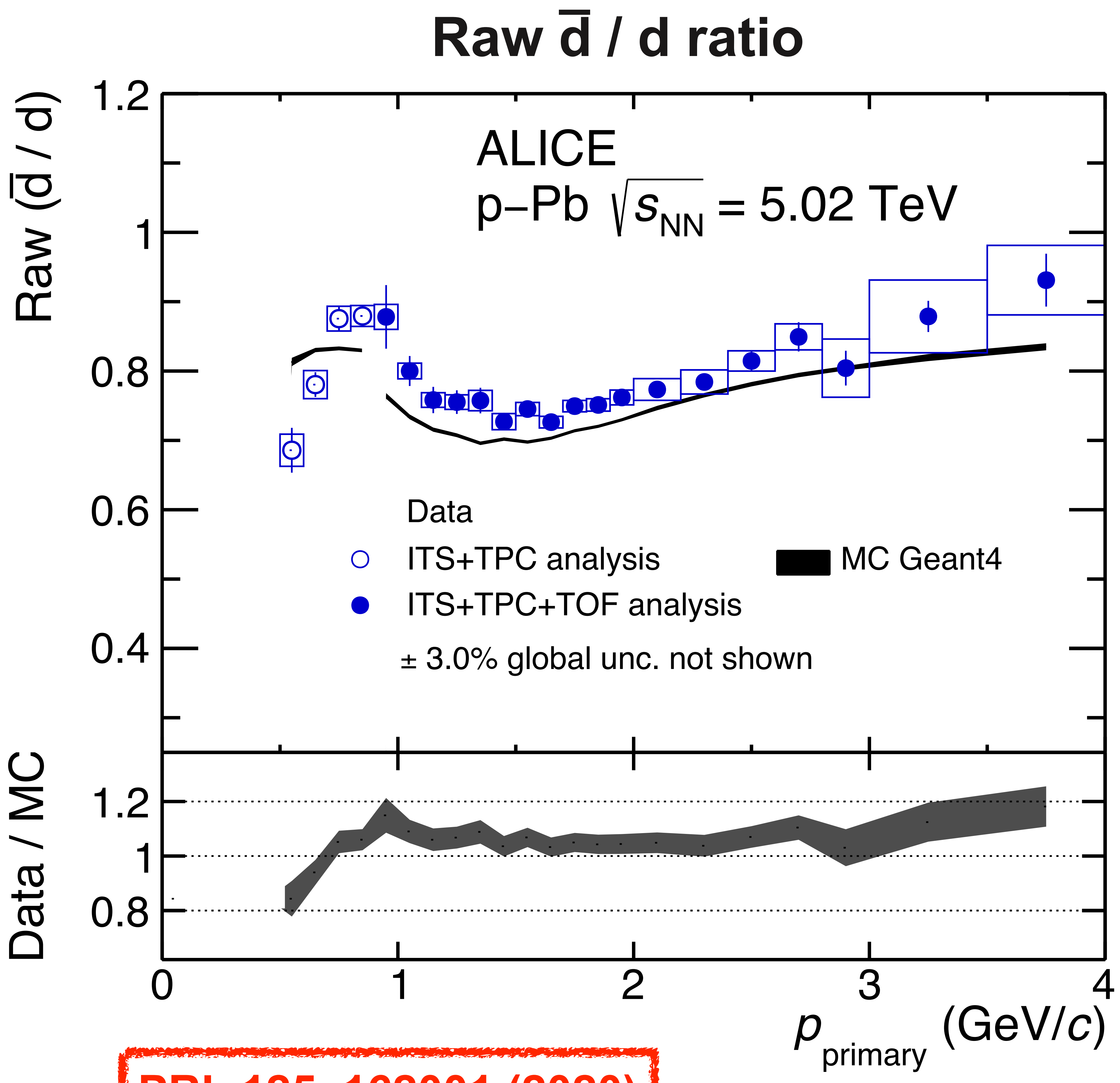
$\sigma_{inel}(\bar{p})$ on averaged ALICE material



PRL 125, 162001 (2020)

Raw ratio of primary (anti)deuterons

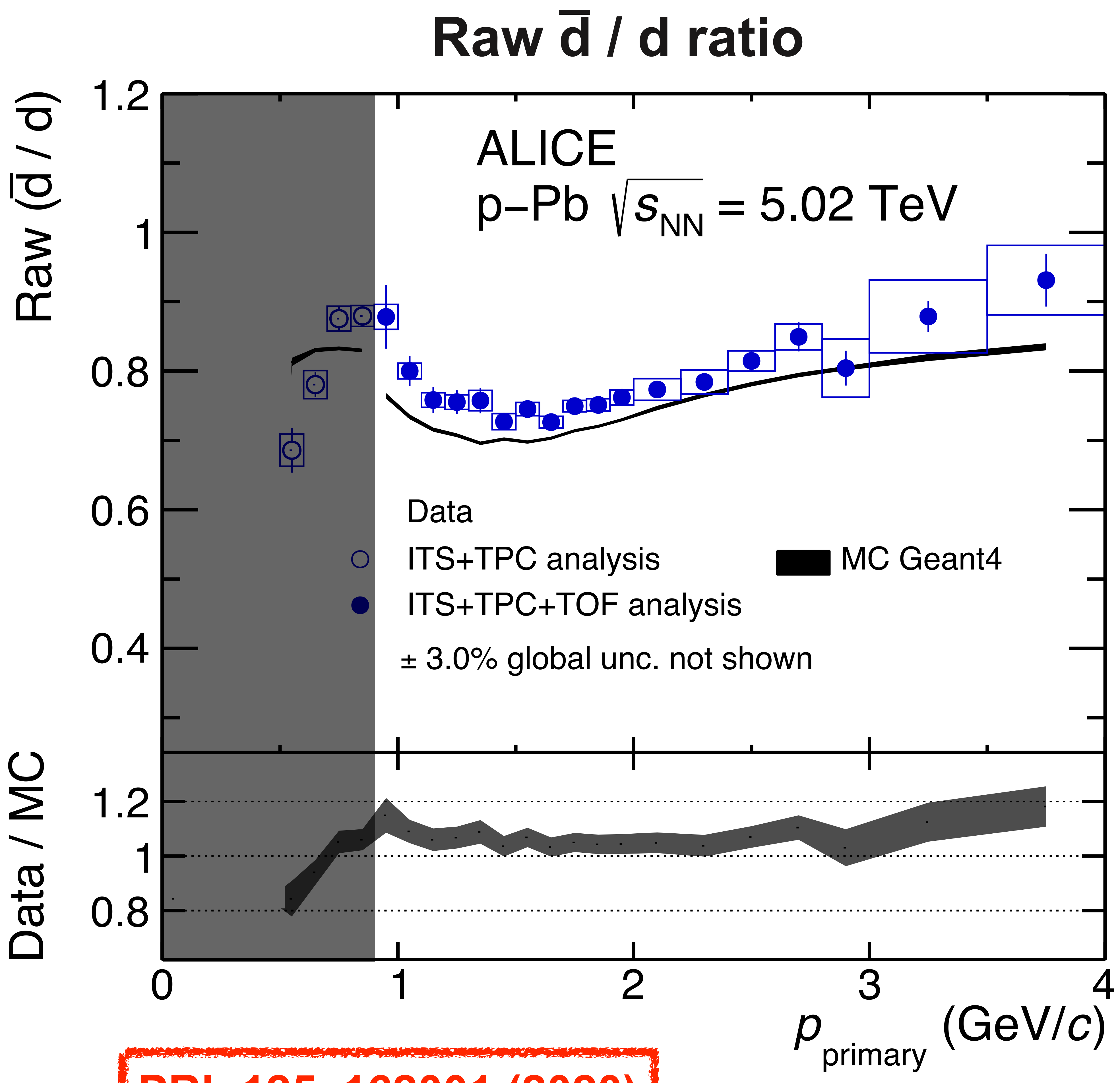
Raw d̄ / d ratio compared to detailed ALICE MC simulations based on Geant4



PRL 125, 162001 (2020)

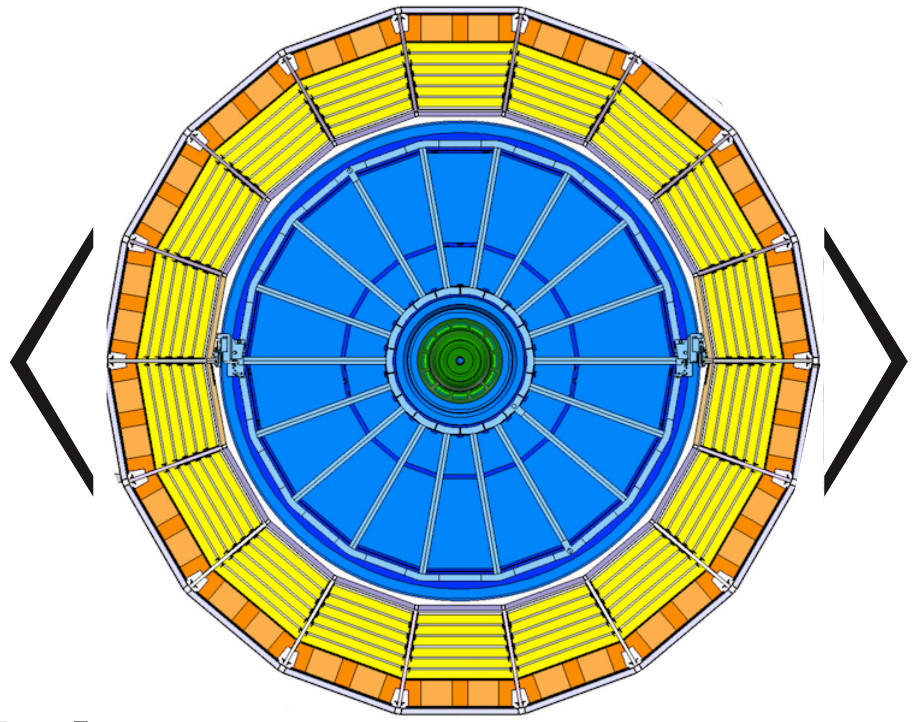
Results for $\sigma_{inel}(\bar{d})$

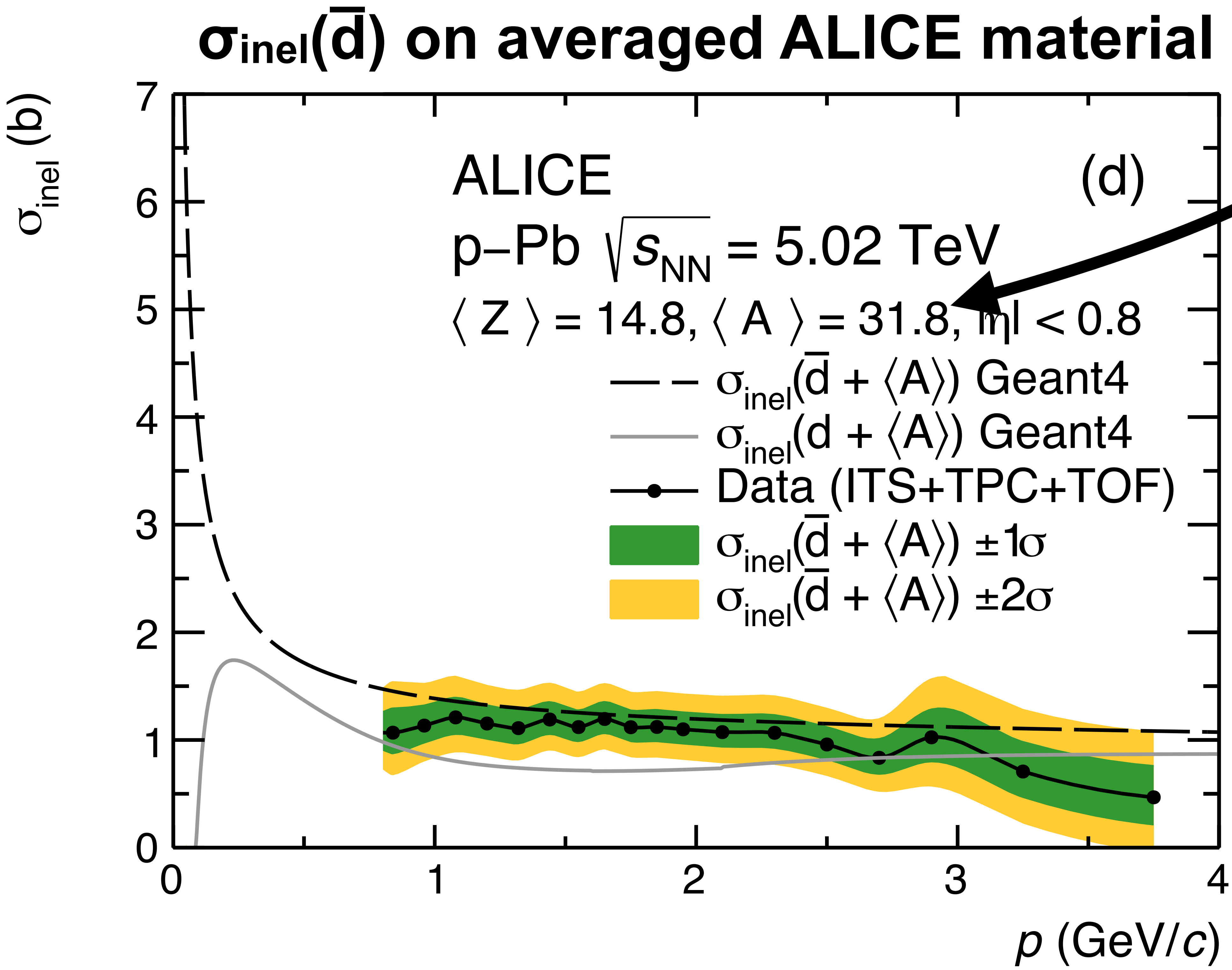
High p region (TOF analysis): good agreement with Geant4 parameterisations



PRL 125, 162001 (2020)

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



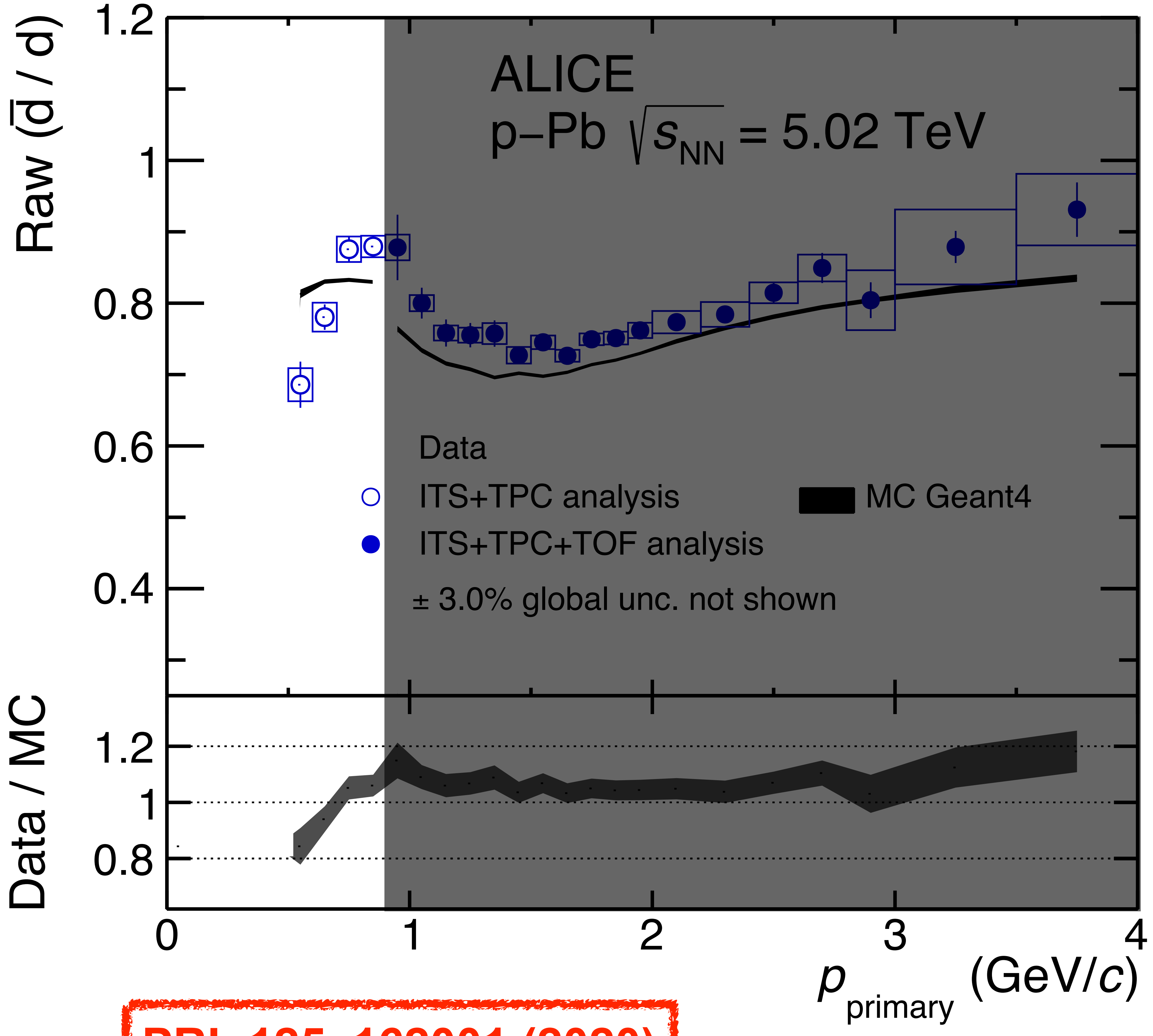


Results for $\sigma_{inel}(\bar{d})$

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

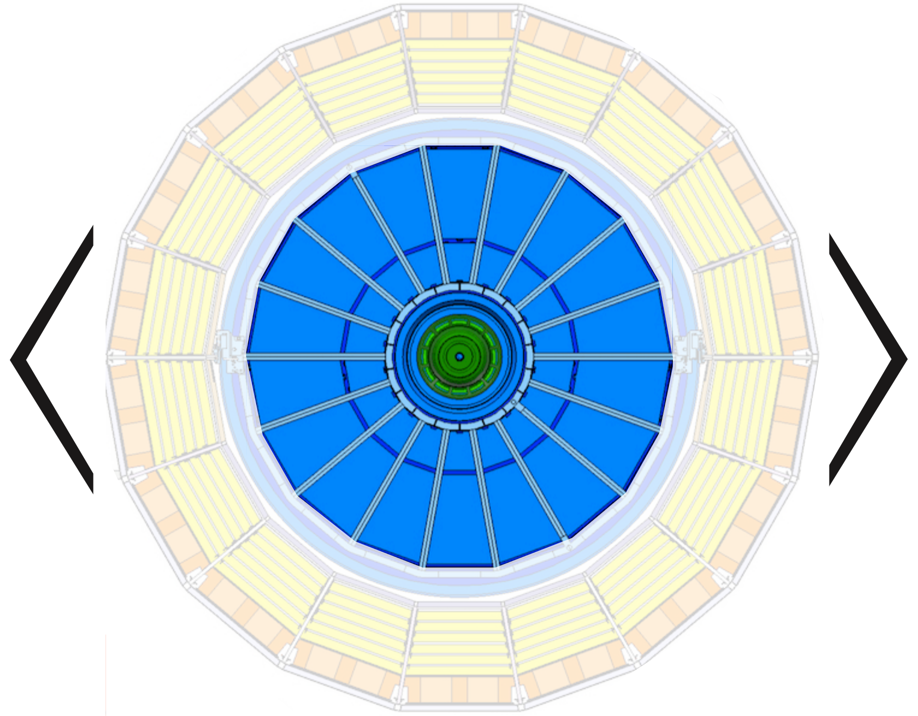
Low p region (ITS-TPC analysis): hint for steeper rise of $\sigma_{inel}(\bar{d})$ than in Geant4!

Raw $\bar{d}$ / d ratio

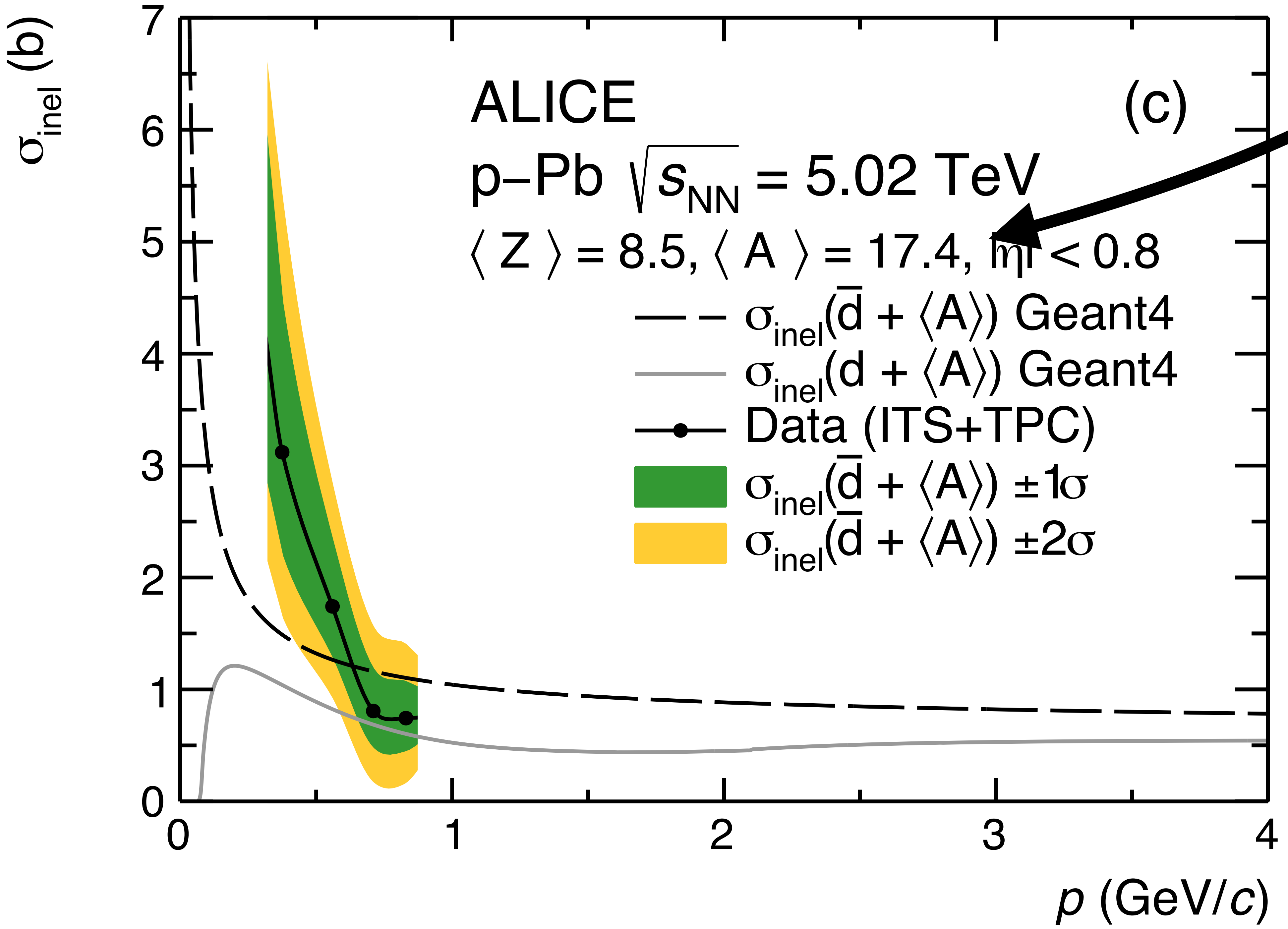


PRL 125, 162001 (2020)

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



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



Antinuclei inelastic cross sections in Geant4 [1]

Cross sections of antinuclei ($\bar{p}$, $\bar{d}$, $\bar{t}$, $\bar{\alpha}$) interactions with A are first calculated in the Glauber approximation

Direct Glauber calculations in Geant4 in a run-time mode are too heavy

→ parametrise Glauber calculations with [2, 3] :

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

These equations are then used as a determination of R_A (having calculated σ_{hA} and σ_{BA} with Glauber)

For inelastic cross-section:

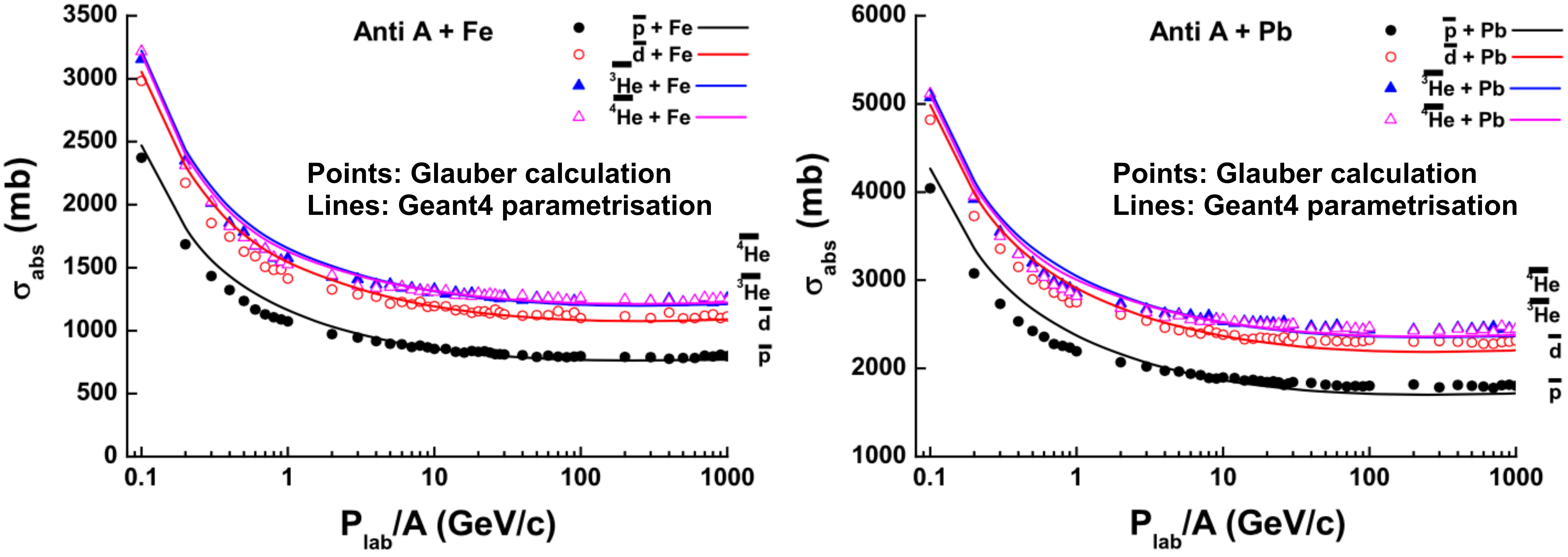
$$\bar{p}A\ R_A = 1.31A^{0.22} + 0.90/A^{1/3}\ \text{(fm)},$$
$$\bar{d}A\ R_A = 1.38A^{0.21} + 1.55/A^{1/3}\ \text{(fm)},$$
$$\bar{t}A\ R_A = 1.34A^{0.21} + 1.51/A^{1/3}\ \text{(fm)},$$
$$\bar{\alpha}A\ R_A = 1.30A^{0.21} + 1.05/A^{1/3}\ \text{(fm)}.$$

[1] Phys. Lett. B705, 235 (2011)
[2] Eur. Phys. J. C 62 (2009) 399
[3] Nucl. Instrum. Methods B 267 (2009) 2460

Antinuclei inelastic cross sections in Geant4 [1]

Good description of Glauber calculations with parameterisations

The parameterisations are used in Geant4 in 100 MeV/*c* < *p*/A < 1000 GeV/*c* momentum range

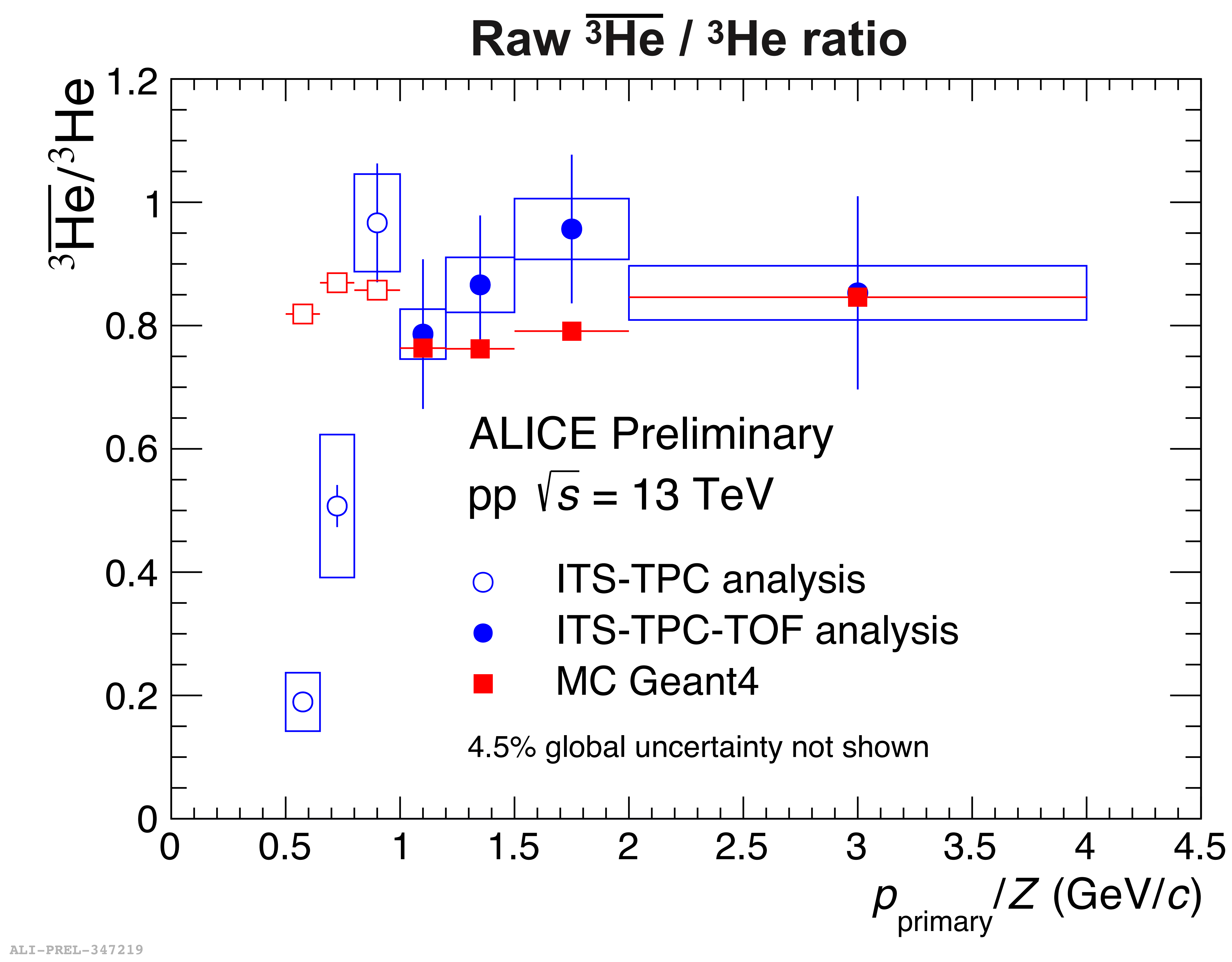


New ALICE results: steeper rise of inelastic c.s. at very low momentum!

[1] Phys. Lett. B705, 235 (2011)

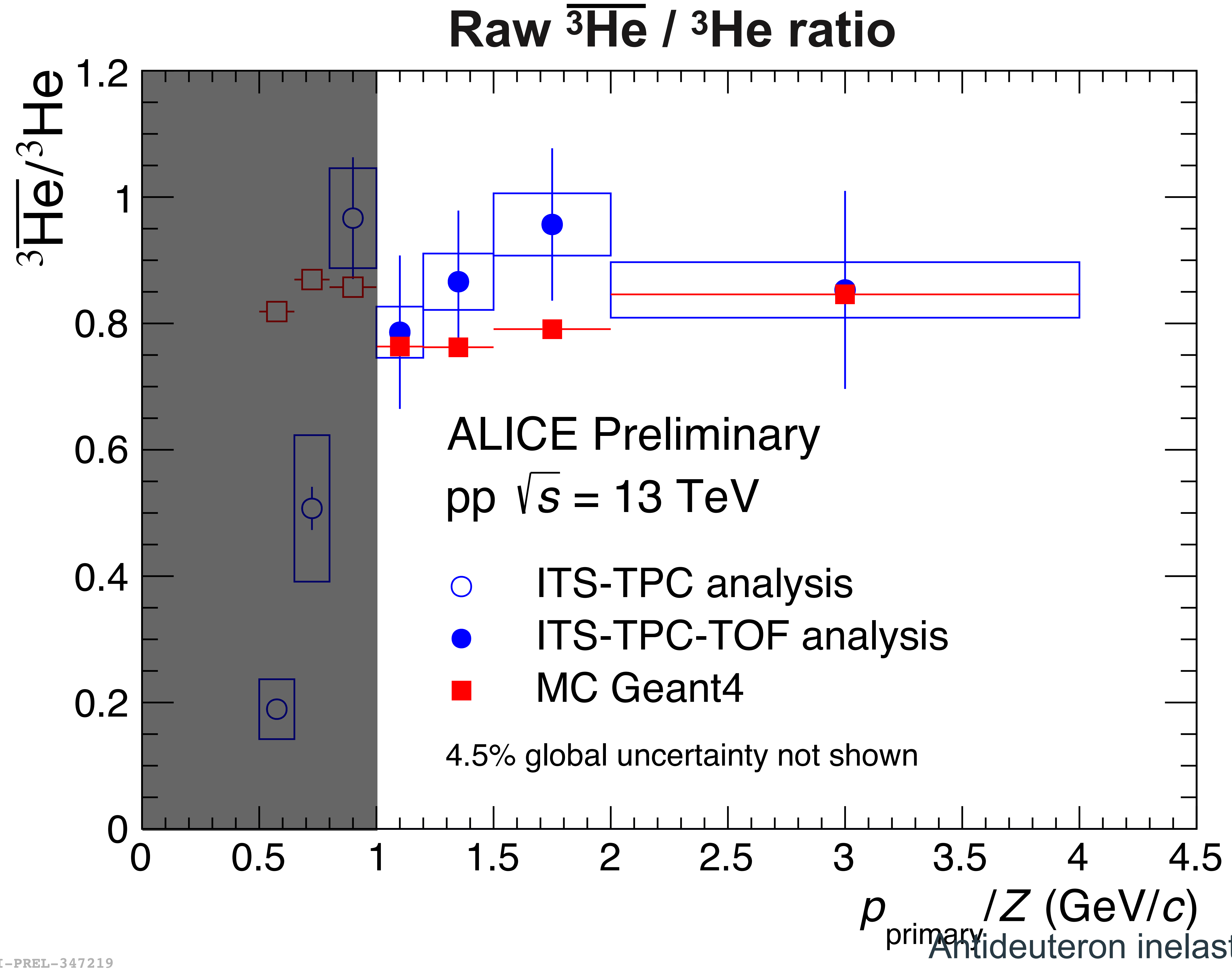
Preliminary results for (anti)^{3}He

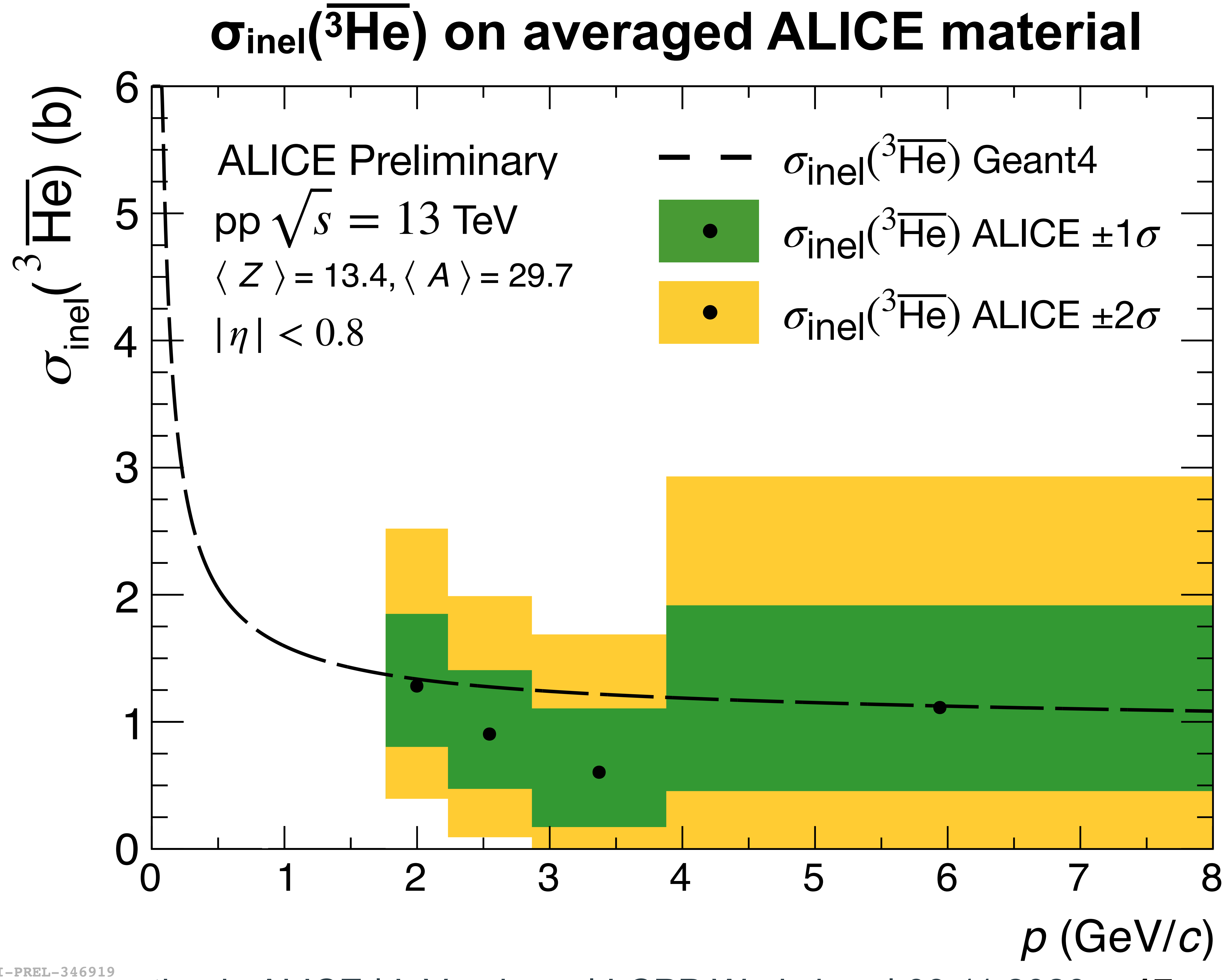
Raw $\overline{^3He}$ / ^{3}He ratio compared to detailed ALICE MC simulations based on Geant4



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

High *p* region (TOF analysis): in agreement with Geant4

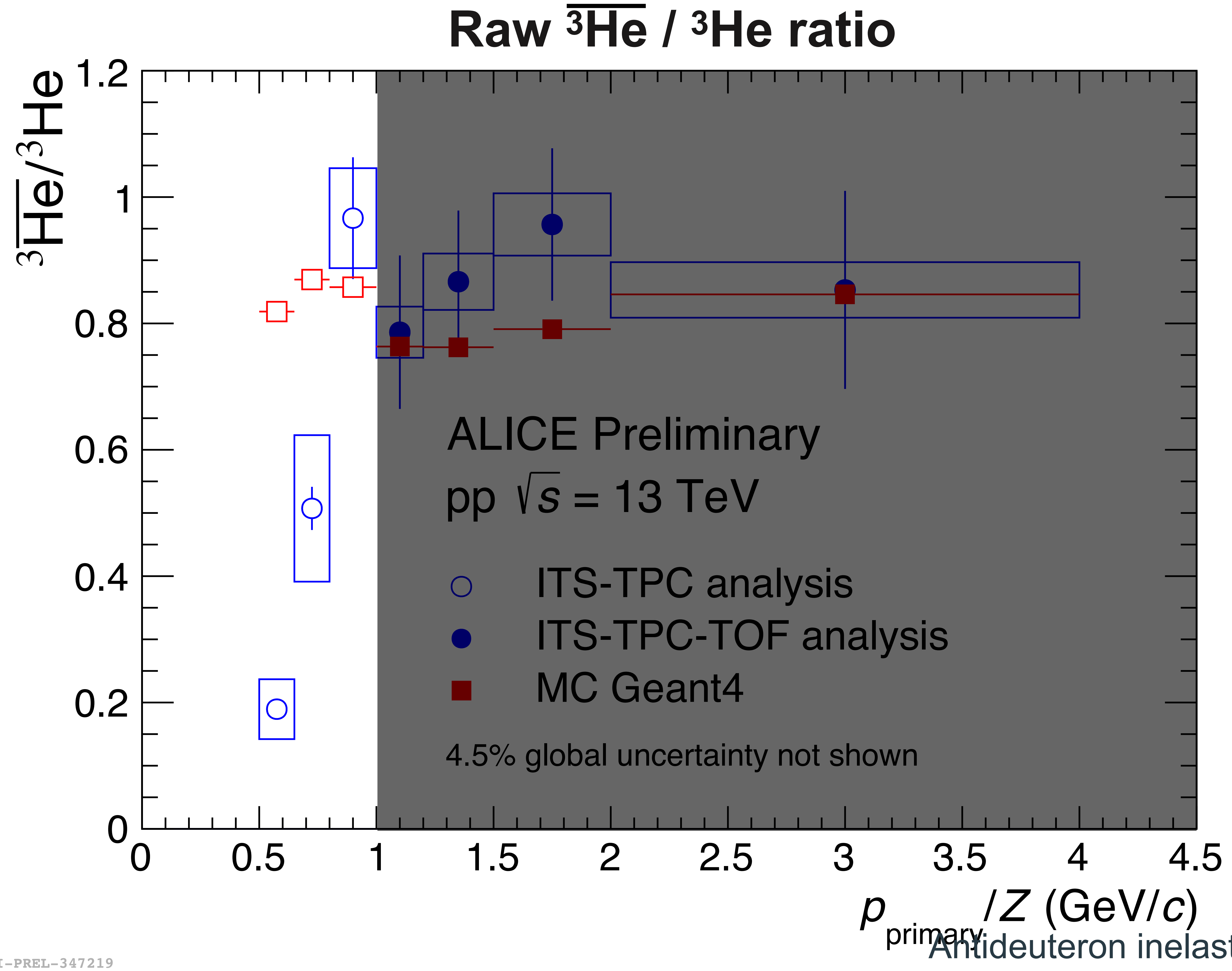


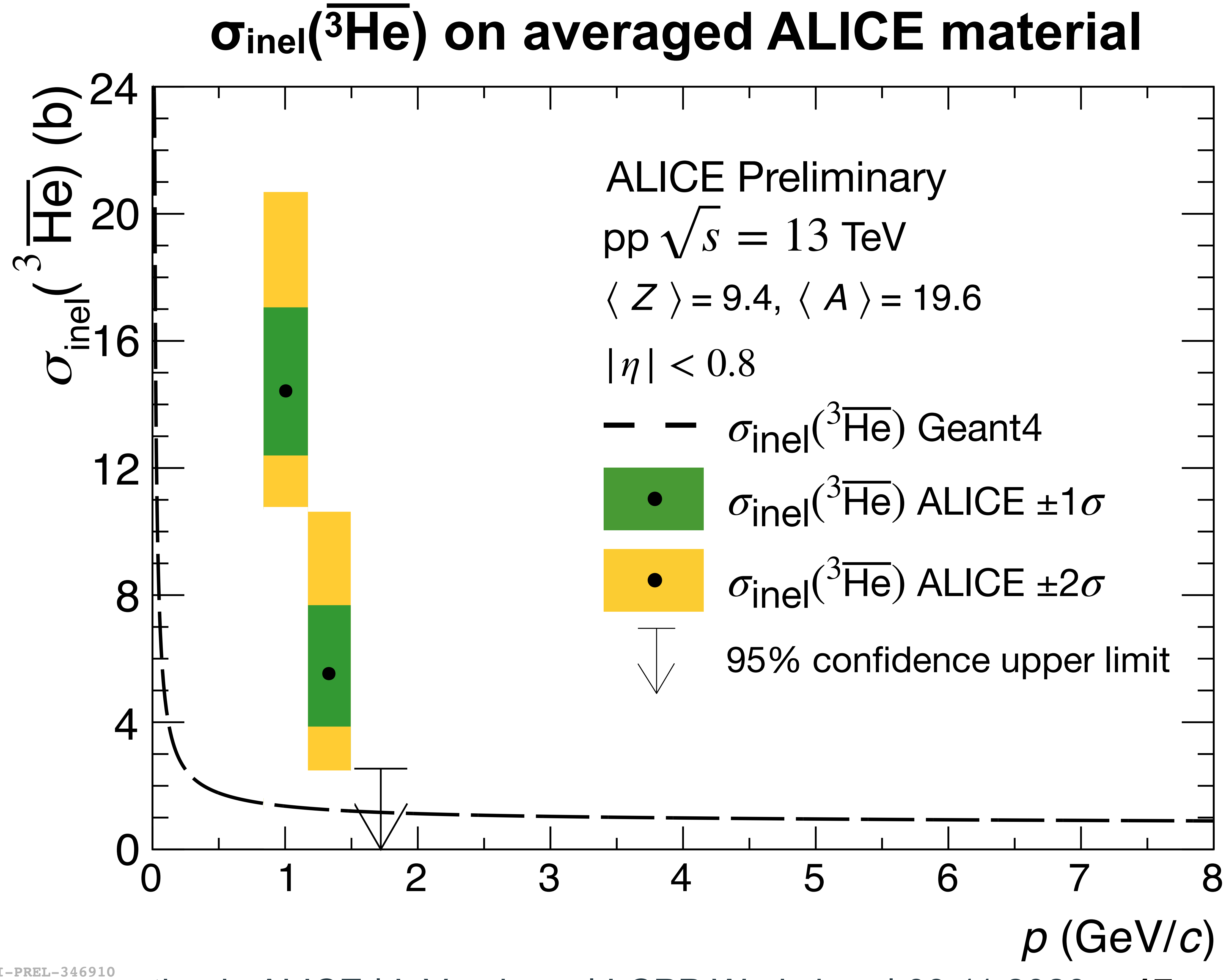


Preliminary results for $\sigma_{inel}(^3\overline{He})$

High *p* region (TOF analysis): in agreement with Geant4

Low *p* region (ITS-TPC analysis): *much steeper rise of $\sigma_{inel}(^3\overline{He})$ than in Geant4!*





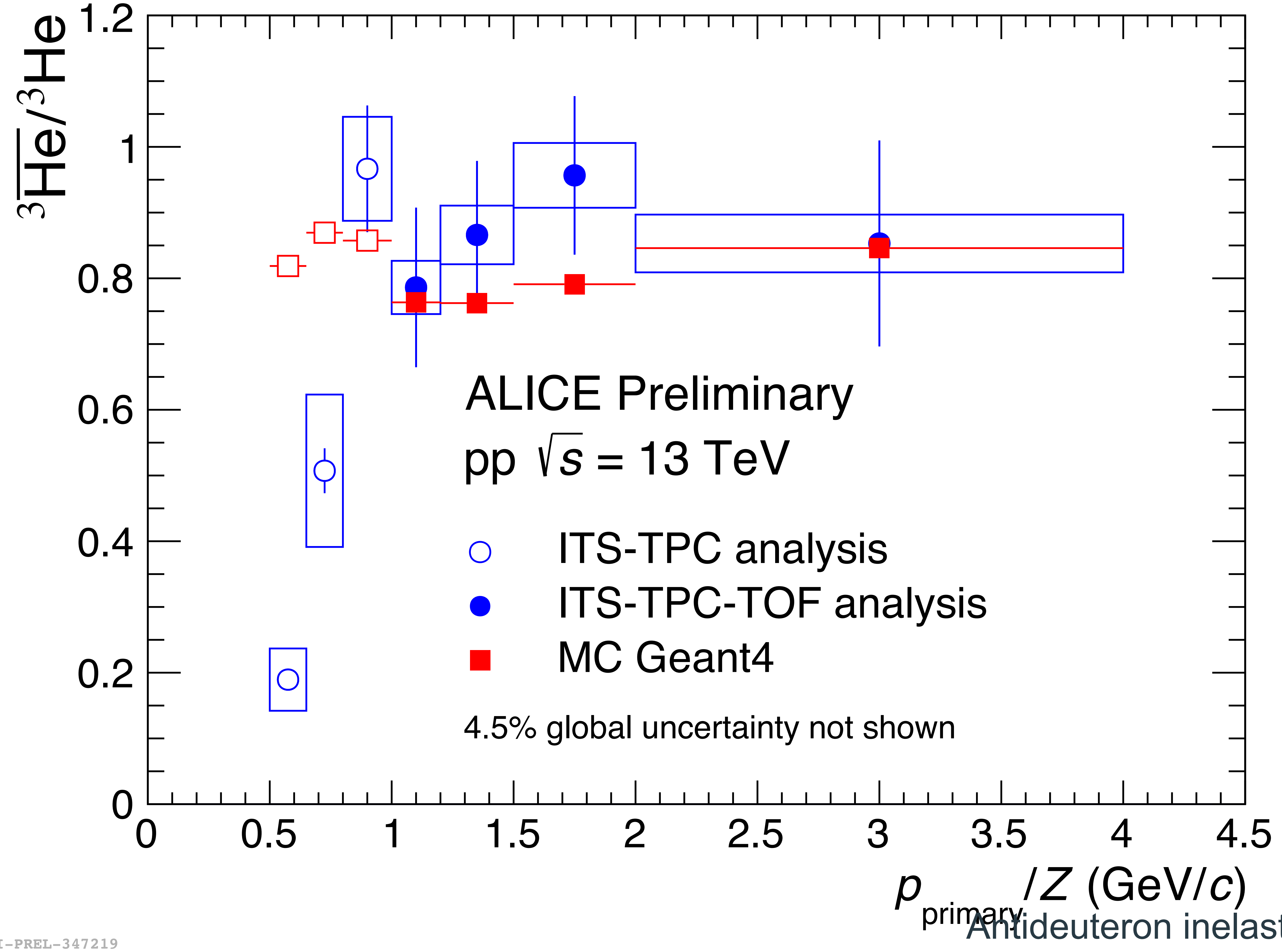
Preliminary results for $\sigma_{inel}(^3\overline{He})$

High *p* region (TOF analysis): in agreement with Geant4

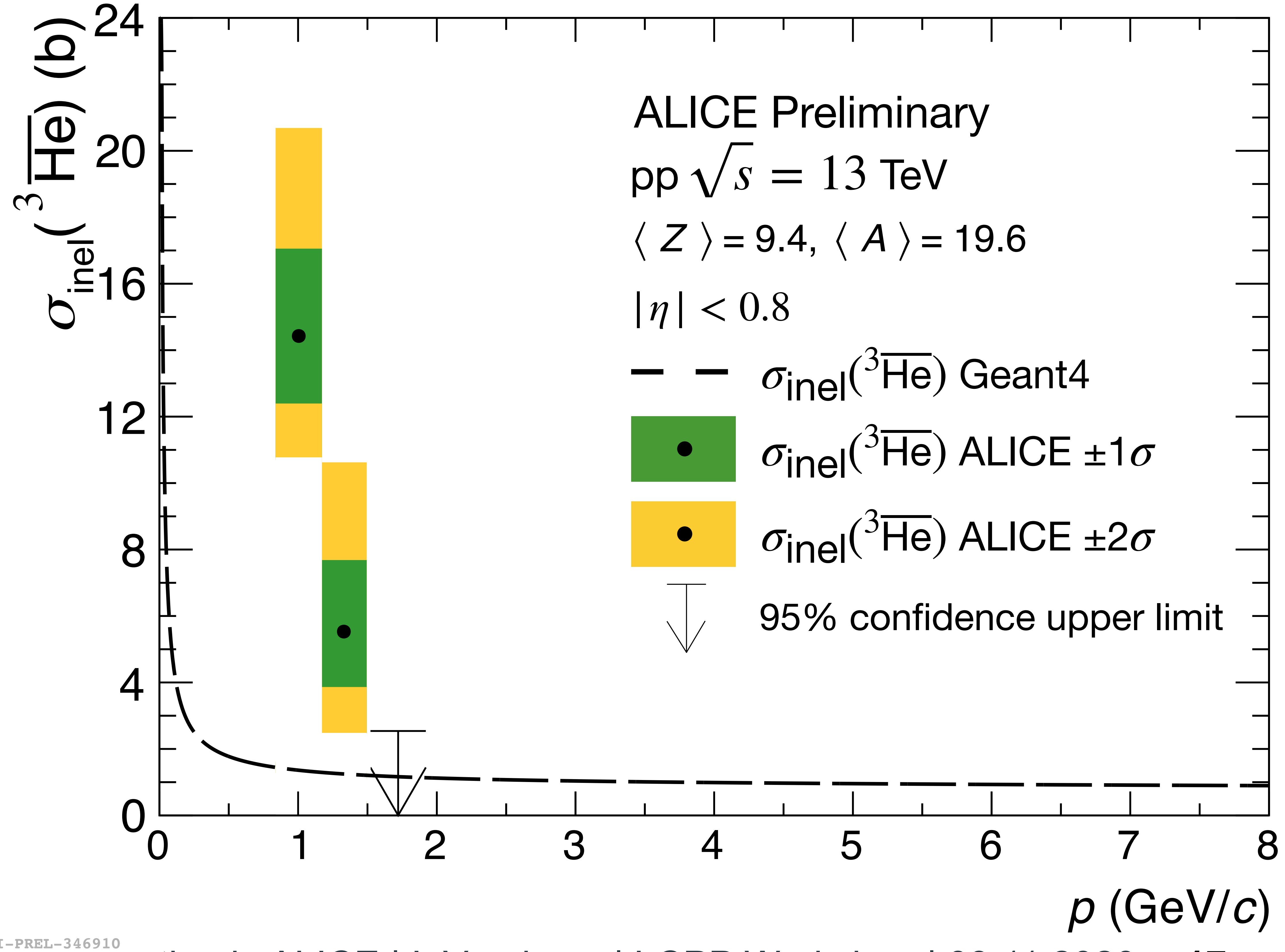
Low *p* region (ITS-TPC analysis): *much steeper rise of $\sigma_{inel}(^3\overline{He})$ than in Geant4!*

First experimental data on $\sigma_{inel}(^3\overline{He})$ ever!

Raw $^3\overline{He}$ / ^3He ratio



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



Summary and outlook

ALICE Experiment at CERN LHC as a tool to study antinuclei absorption in detector material

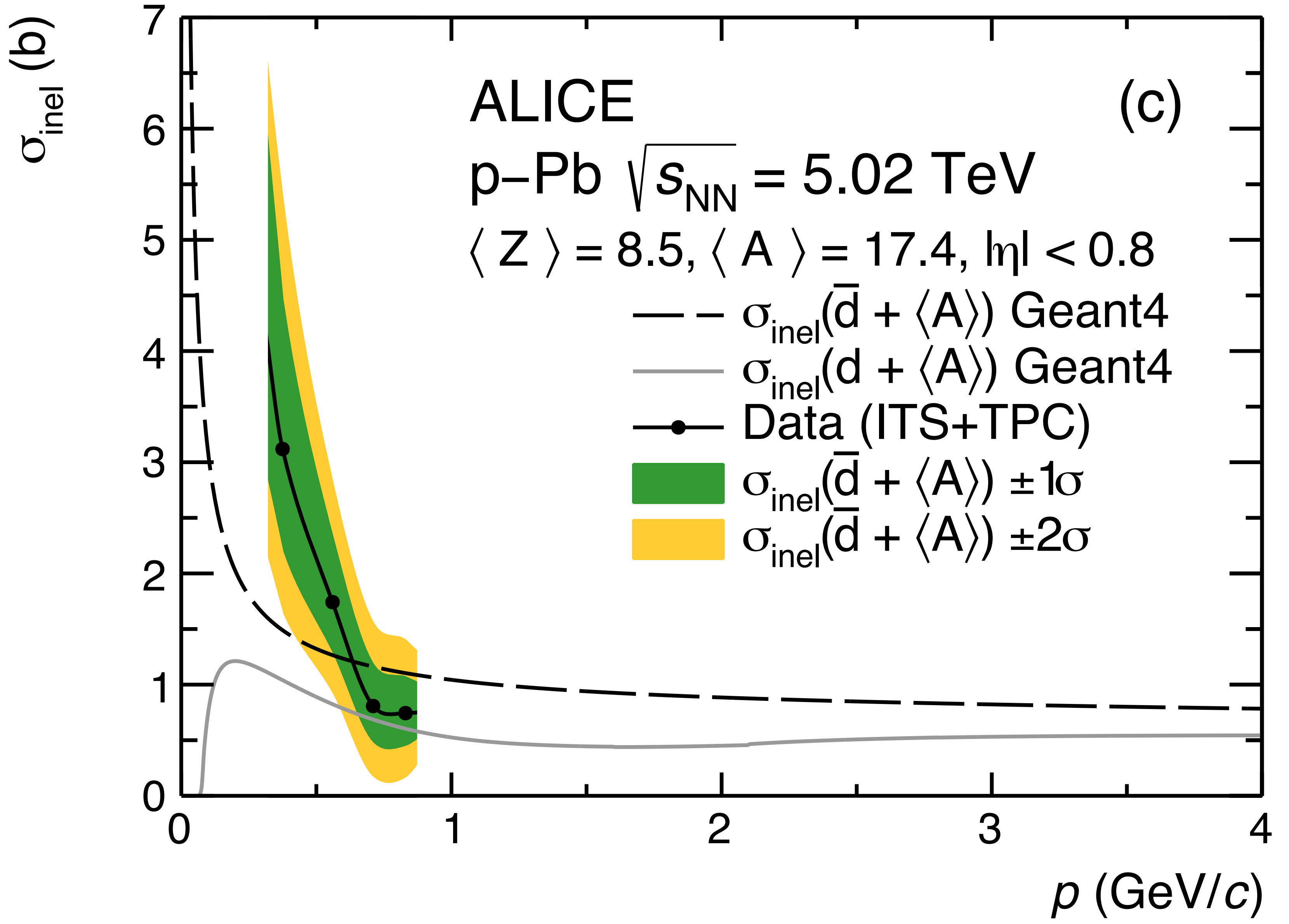
- Analysis of raw reconstructed antinuclei/nuclei ratios
- Constrain $\sigma_{inel}(\overline{d})$ via comparison with Geant4-based simulations
  - Benchmark on $\sigma_{inel}(\overline{p})$ - in good agreement with existing data
  - First experimental information on $\sigma_{inel}(\overline{d})$ (and $\sigma_{inel}(^{3}\overline{He})$) at low *p*!

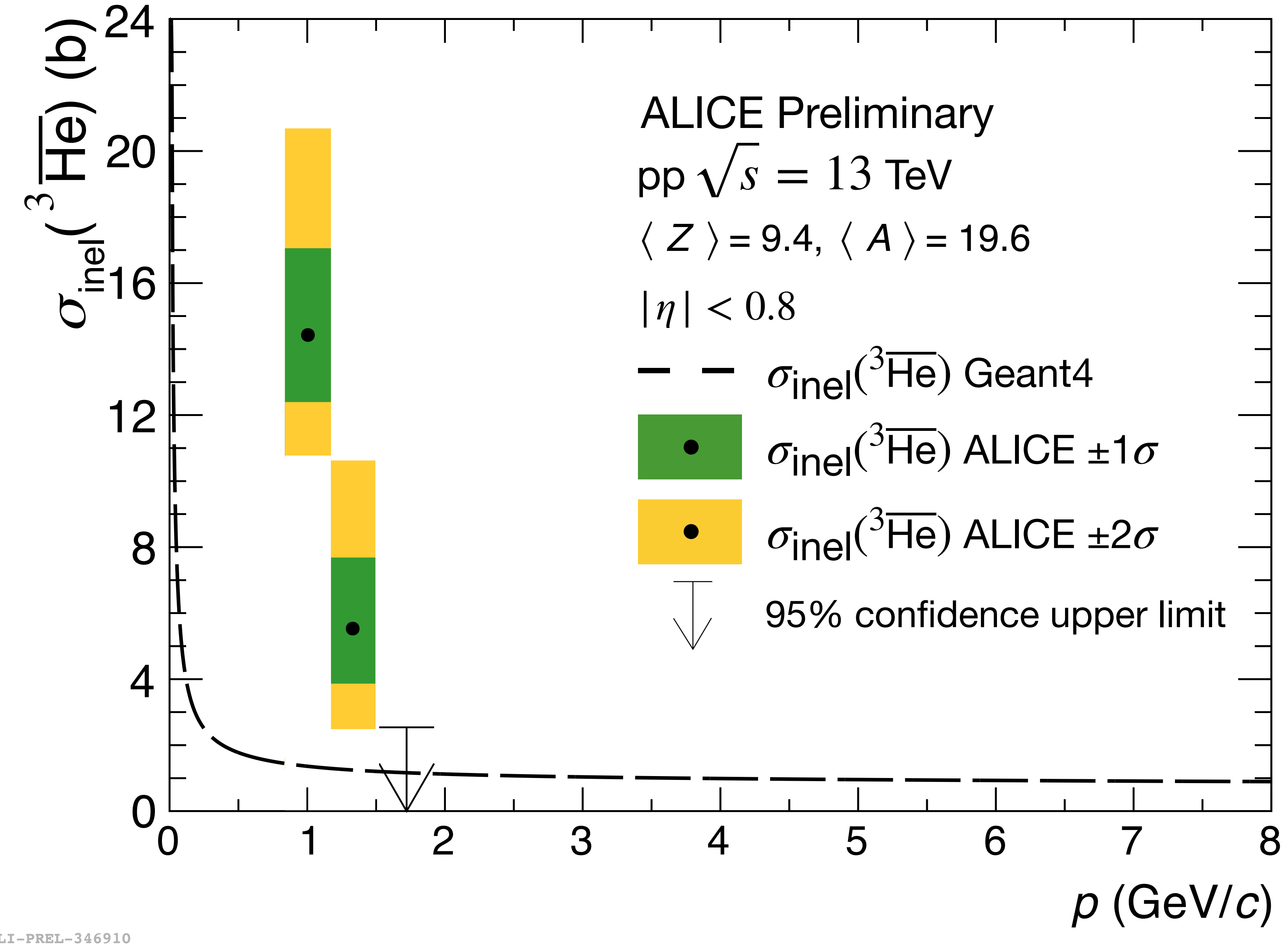
Stronger rise at very low momentum than predicted by Geant4!

- Adjust the antinuclei inelastic c.s. in Geant4 at very low *p*?

Work in progress towards further results

- Understand the origin of steep rise at low momentum
- Analyse more data with higher statistics for (anti)^{3}He
- Try to extend the analysis to (anti)^{4}He

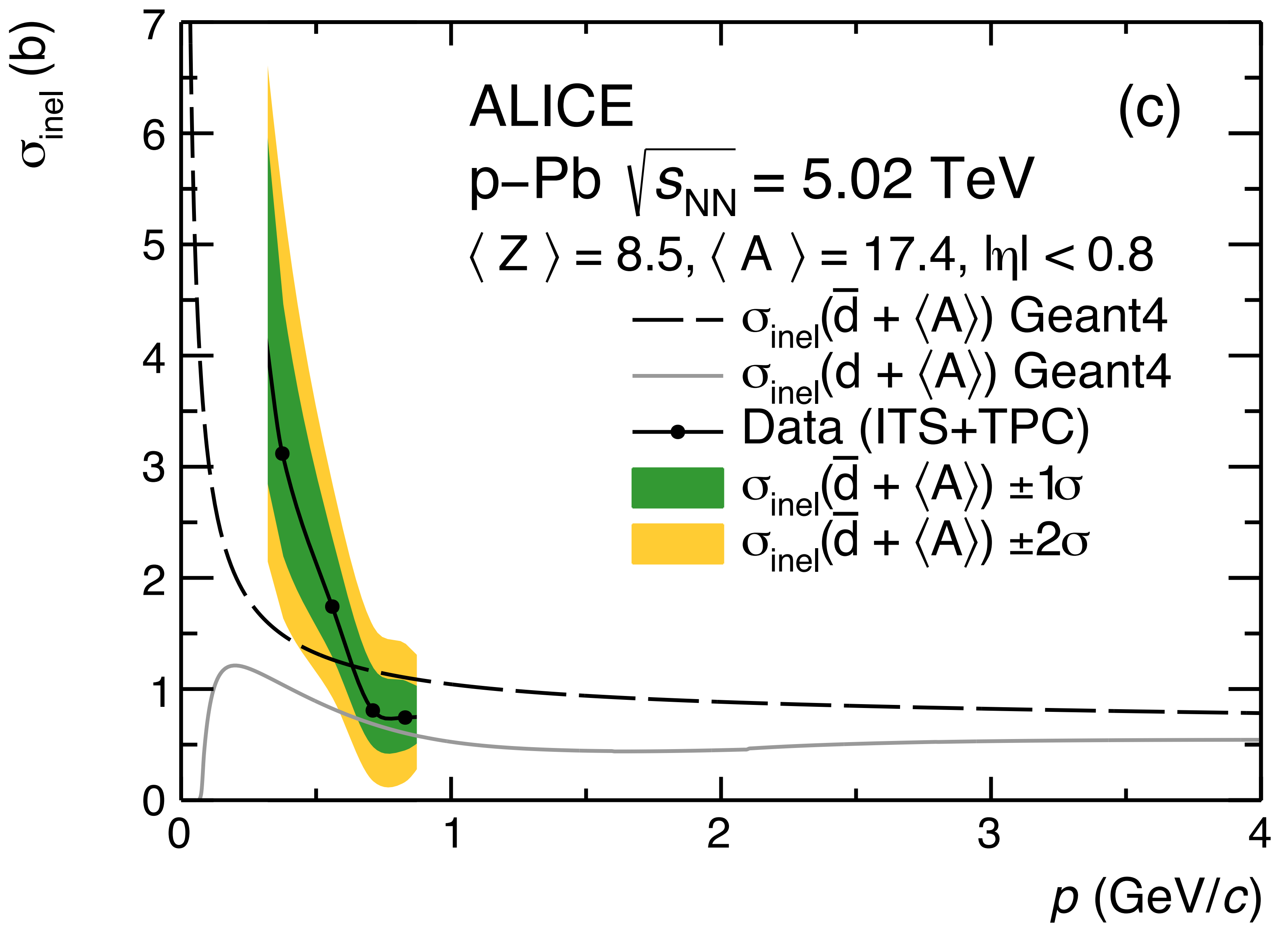




Summary and outlook

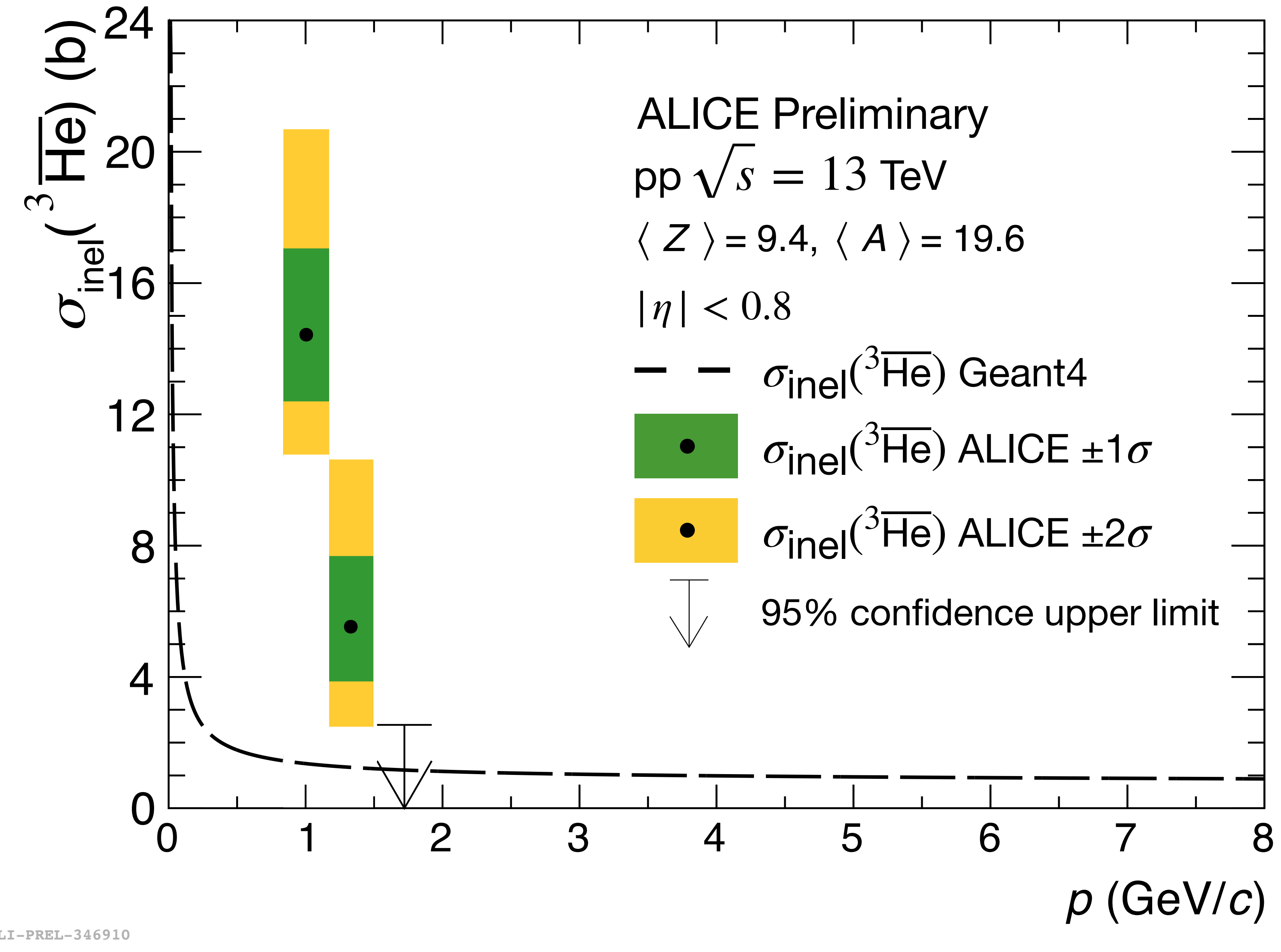
ALICE Experiment at CERN LHC as a tool to study antinuclei absorption in detector material

- Analysis of raw reconstructed antinuclei/nuclei ratios
- Constrain $\sigma_{inel}(\bar{d})$ via comparison with Geant4-based simulations
  - Benchmark on $\sigma_{inel}(\bar{p})$ - in good agreement with existing data
  - First experimental information on $\sigma_{inel}(\bar{d})$ (and $\sigma_{inel}(\overline{^3He})$) at low *p*!



Stronger rise at very low momentum than predicted by Geant4!

- Adjust the antinuclei inelastic c.s. in Geant4 at very low *p*?

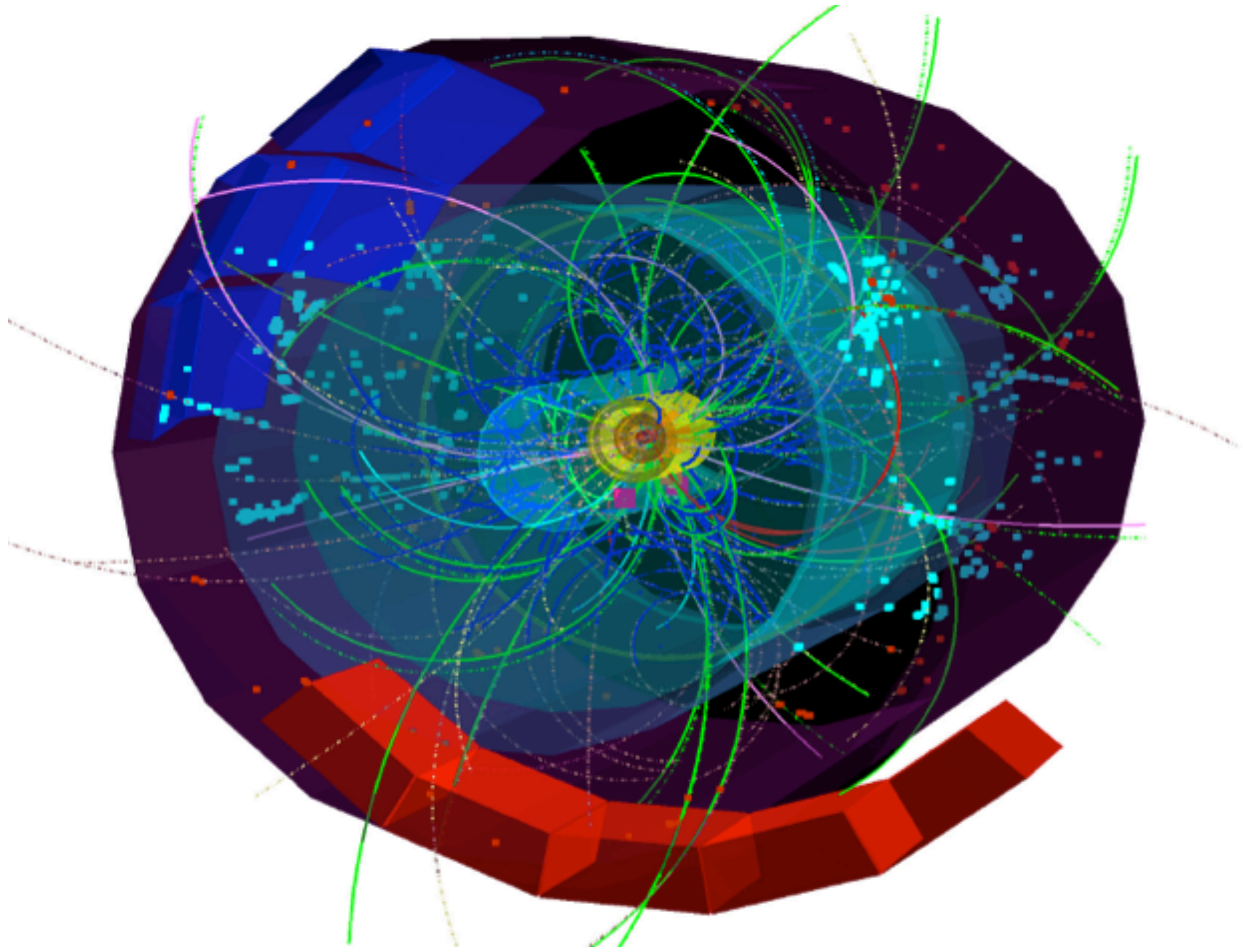


Work in progress towards further results

- Understand the origin of steep rise at low momentum
- Analyse more data with higher statistics for (anti)^{3}He
- Try to extend the analysis to (anti)^{4}He

Thank you for your attention!

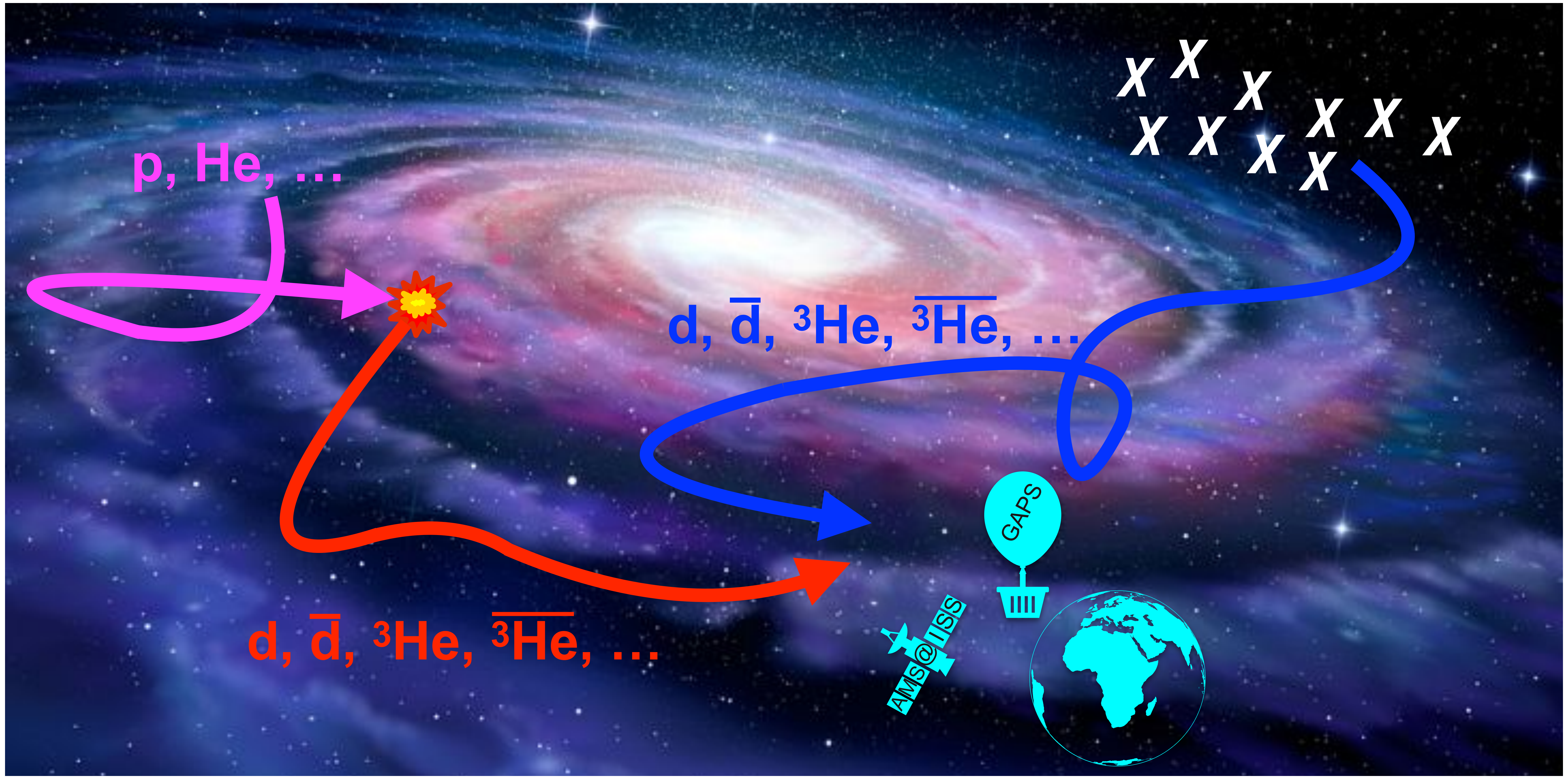
Back-up slides



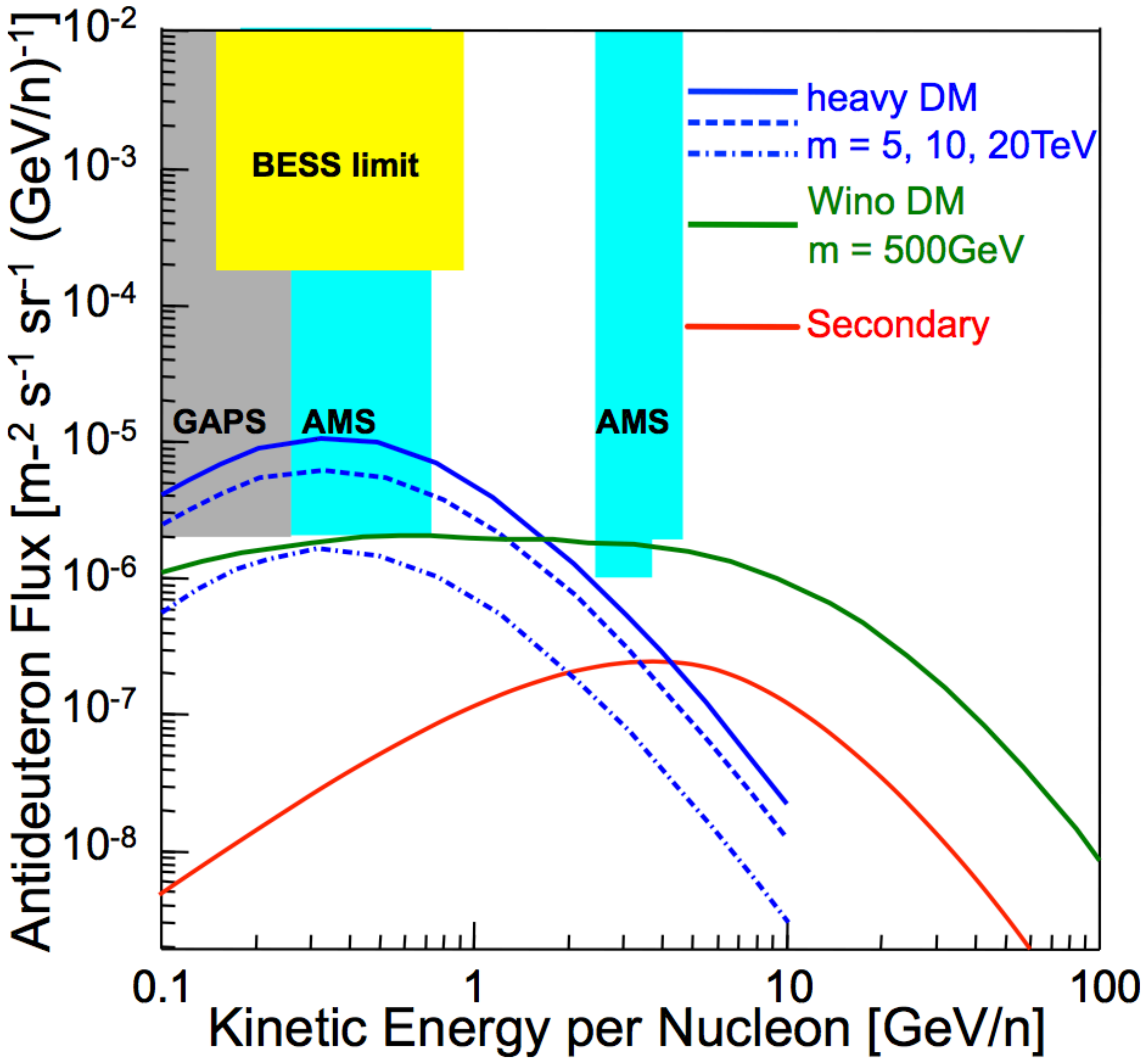
Indirect Dark Matter searches

Low-energy cosmic-ray antinuclei ($\bar{d}$, $^{3}\overline{He}$, $^{4}\overline{He}$) - unique probe for indirect Dark Matter searches

- Low background from secondary production is expected
- *Vital to determine primary and secondary antinuclei fluxes as precise as possible!*



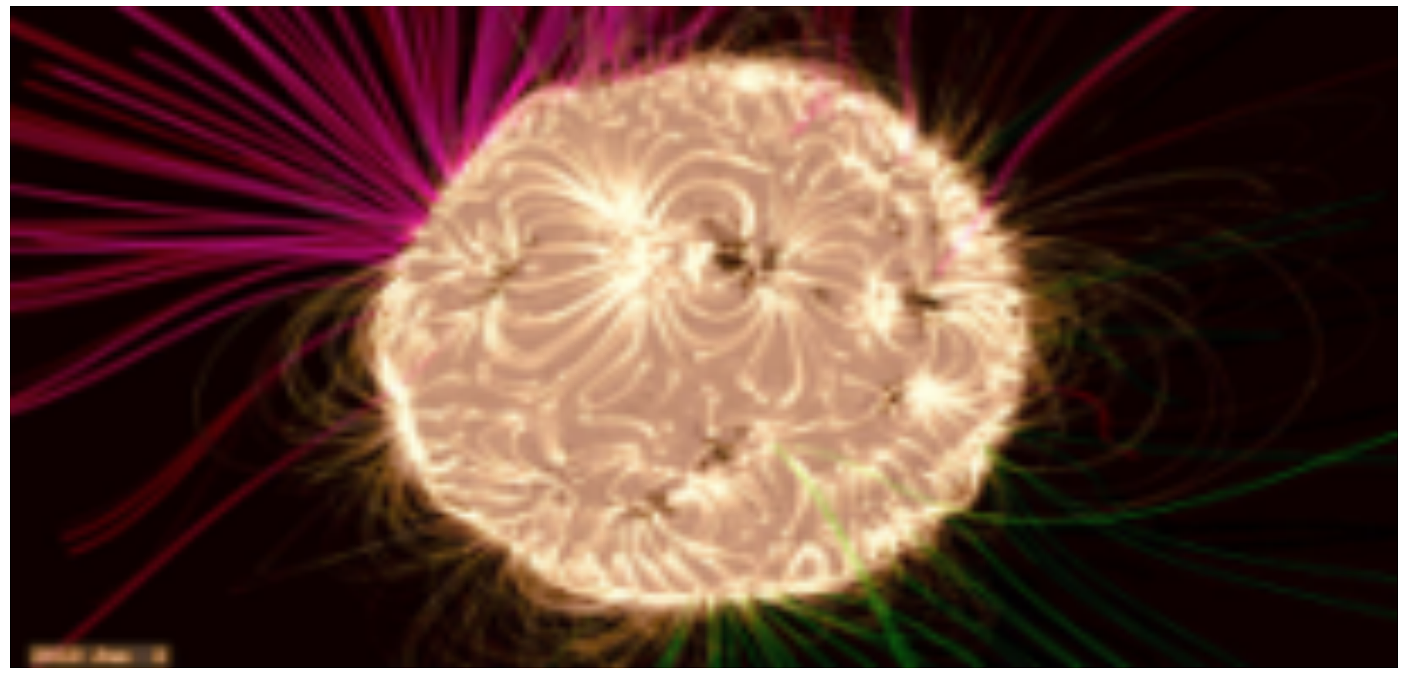
Predicted antideuteron flux near Earth [1]



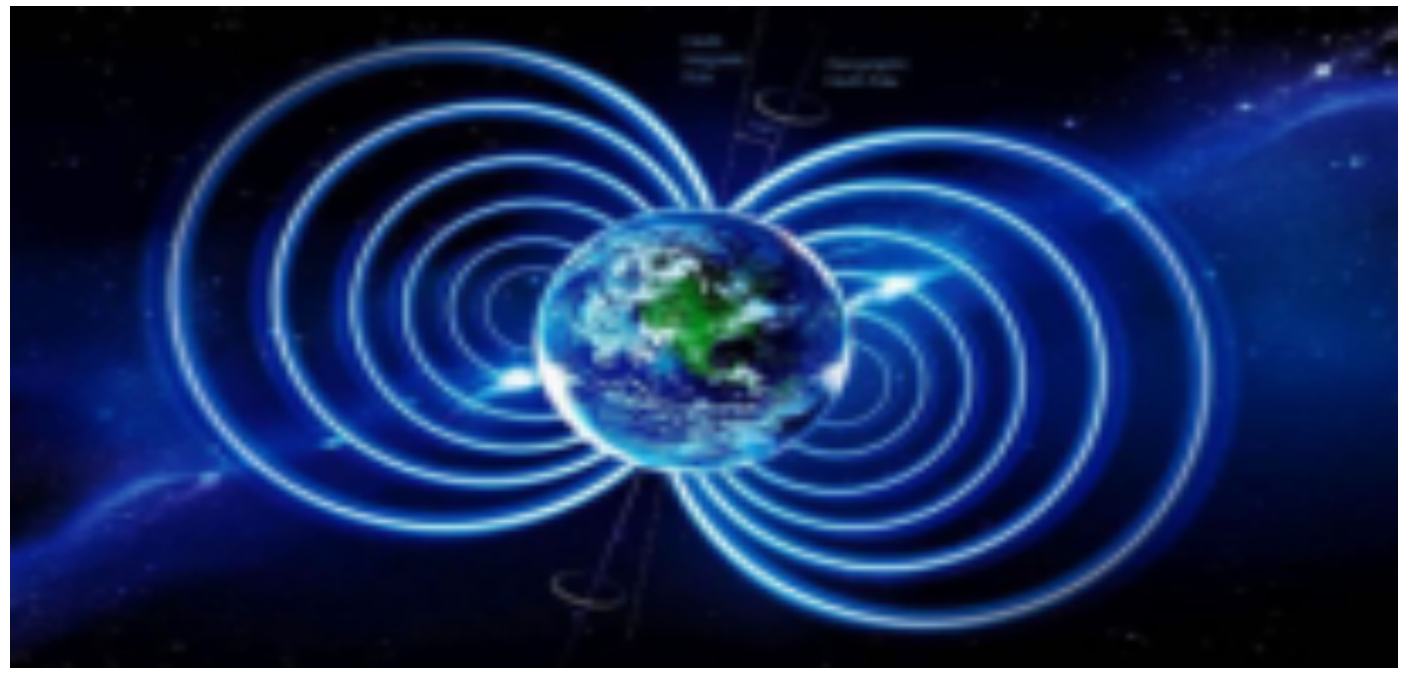
A long way to the detectors

Interstellar Medium

Heliosphere



Near-Earth Environment

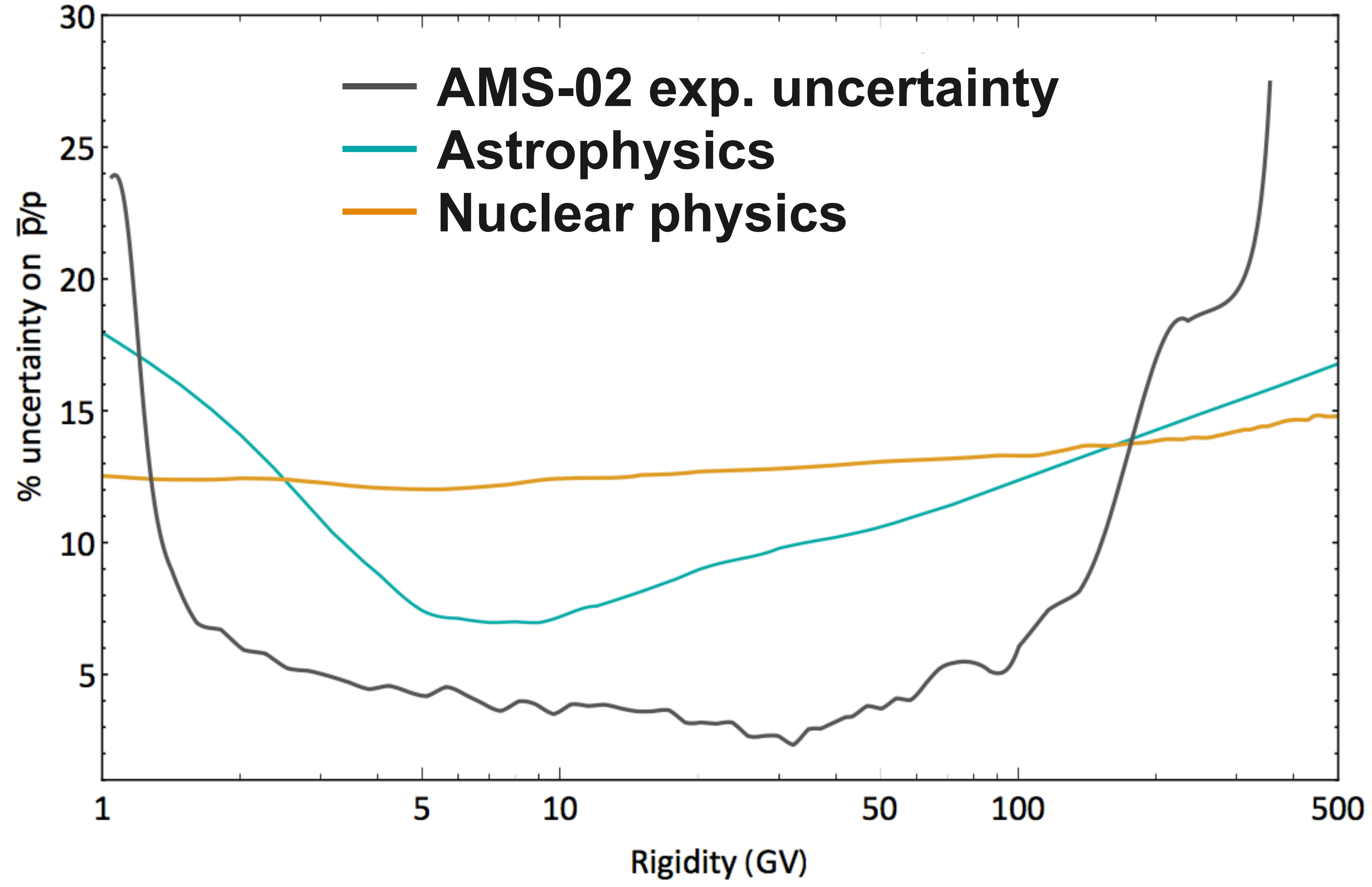


Basic ingredients for antinuclei flux calculation:

- Propagation: common for all (anti)particles
- Annihilation in interstellar medium, Earth's atmosphere, …
- Production of antinuclei in pp, p$\bar{p}$, p-He, $\bar{p}$-He…

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

Uncertainty on $\bar{p}$/p ratio for AMS-02 [1]

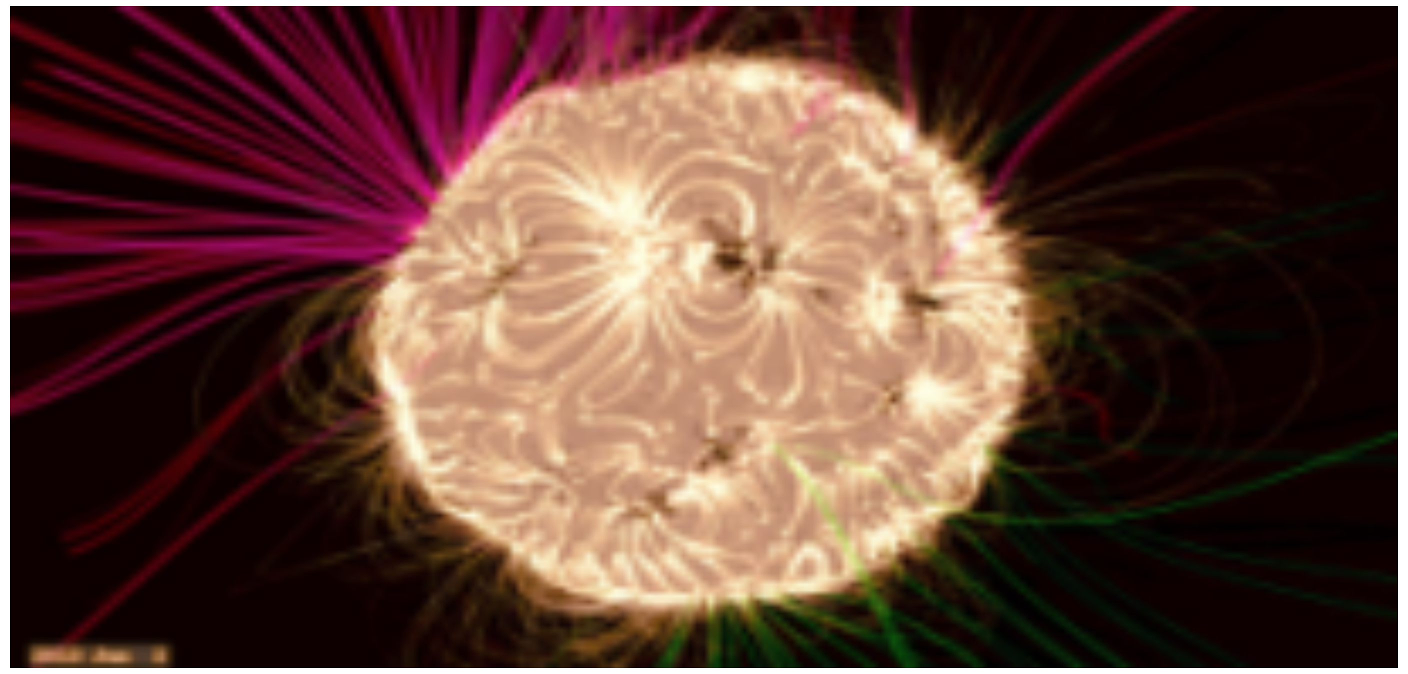


[1] CERN-SPSC-2019-022; SPSC-P-360

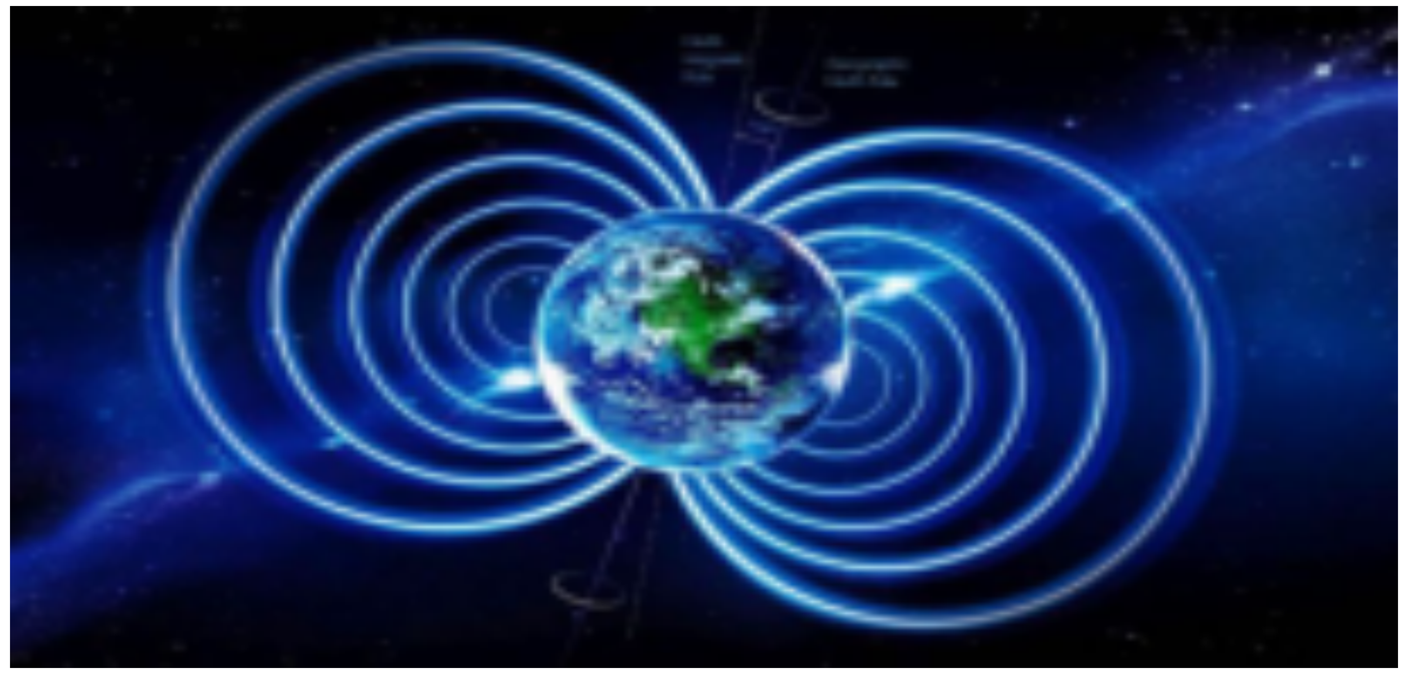
Modelling of cosmic rays propagation

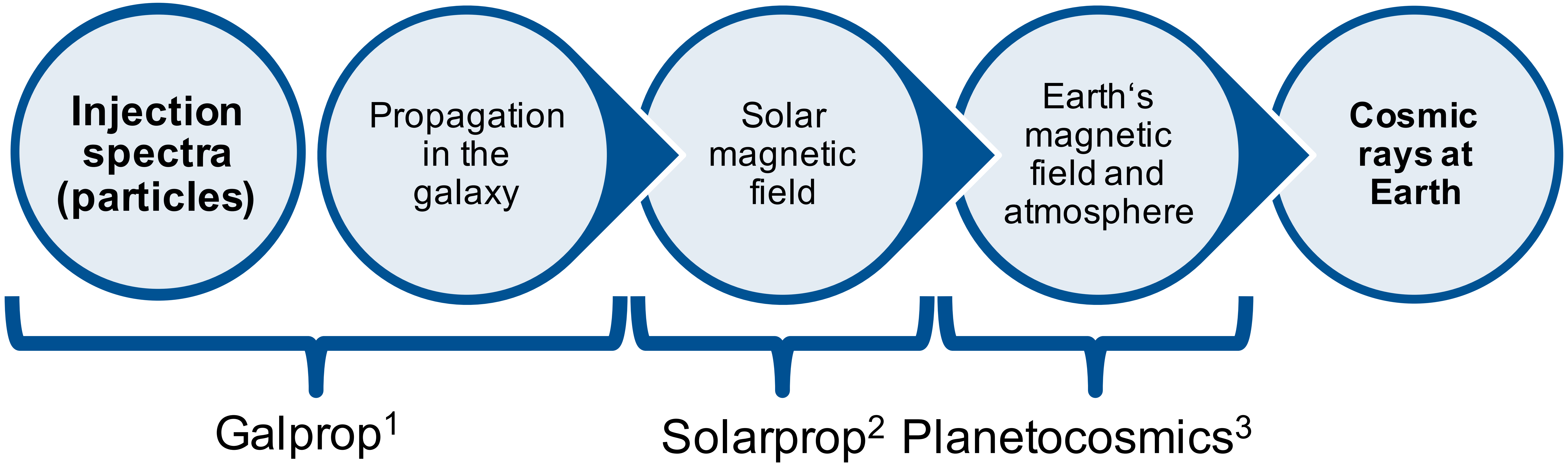
Interstellar Medium

Heliosphere



Near-Earth Environment





[1] https://galprop.stanford.edu
[2] http://www.th.physik.uni-bonn.de/nilles/people/kappl
[3] http://cosray.unibe.ch/~laurent/planetocosmics

Antideuteron diffusion equation

$$\nabla(-K\nabla N_{\bar{d}} + \boldsymbol{V}_c N_{\bar{d}}) + \partial_T(b_{\text{tot}} N_{\bar{d}} - K_{EE}\partial_T N_{\bar{d}}) + \Gamma_{\text{ann}} N_{\bar{d}} = q_{\bar{d}} + q_{\bar{d}}^{\text{ter}}$$

Propagation term

- Common for all (anti-)particle species

Annihilation term

- Annihilation of anti-deuterons (interstellar medium, Earth's atmosphere…)

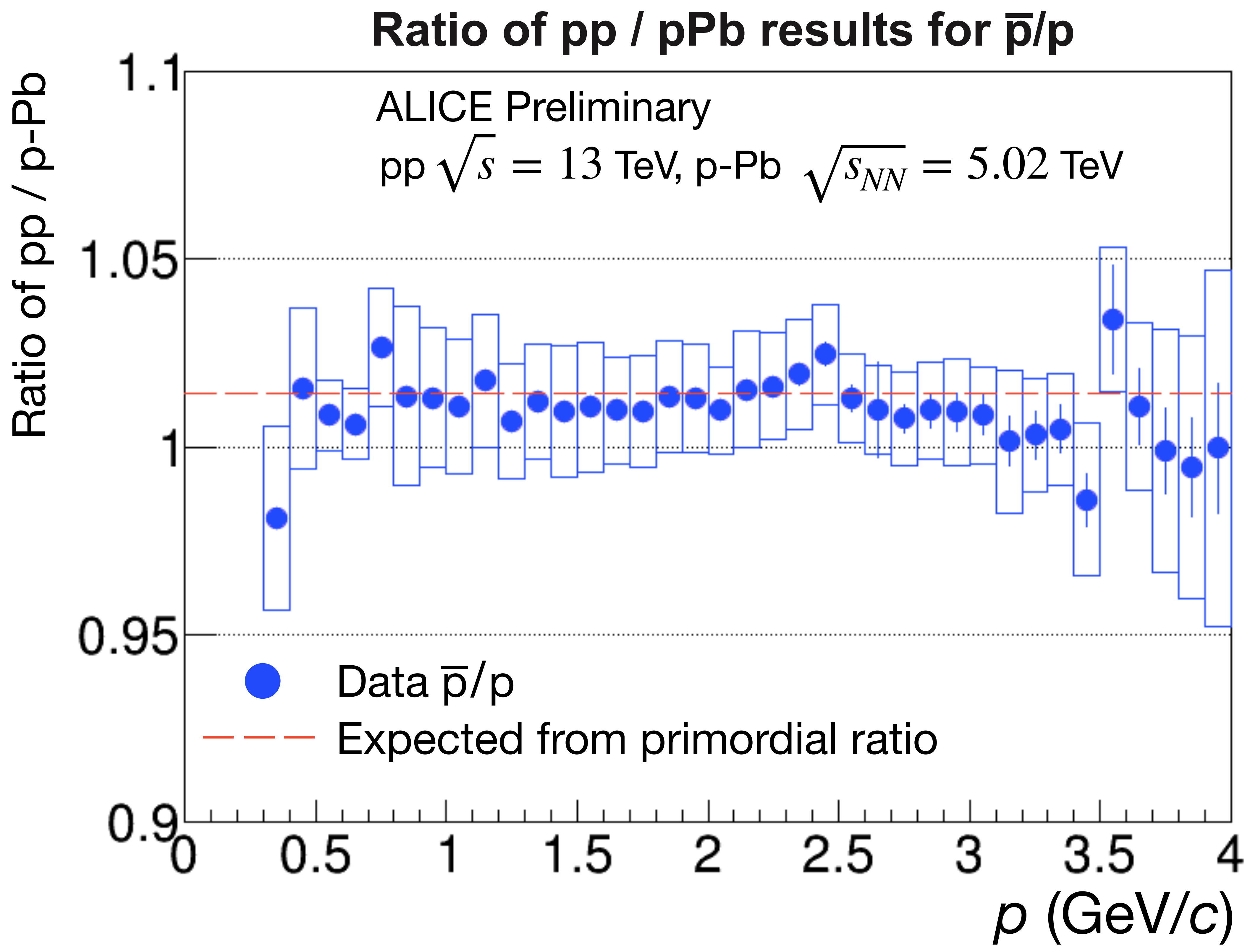
Source term

- Production of anti-deuterons in collisions of pp, p$\bar{\text{p}}$, p-He, $\bar{\text{p}}$-He…

Consistency of results between pp and pPb data

Are raw $\bar{p}$/p and $\bar{d}$/d ratios compatible in different collision systems?

Yes, modulo the change of primary antimatter/matter ratio, so analysis is robust!

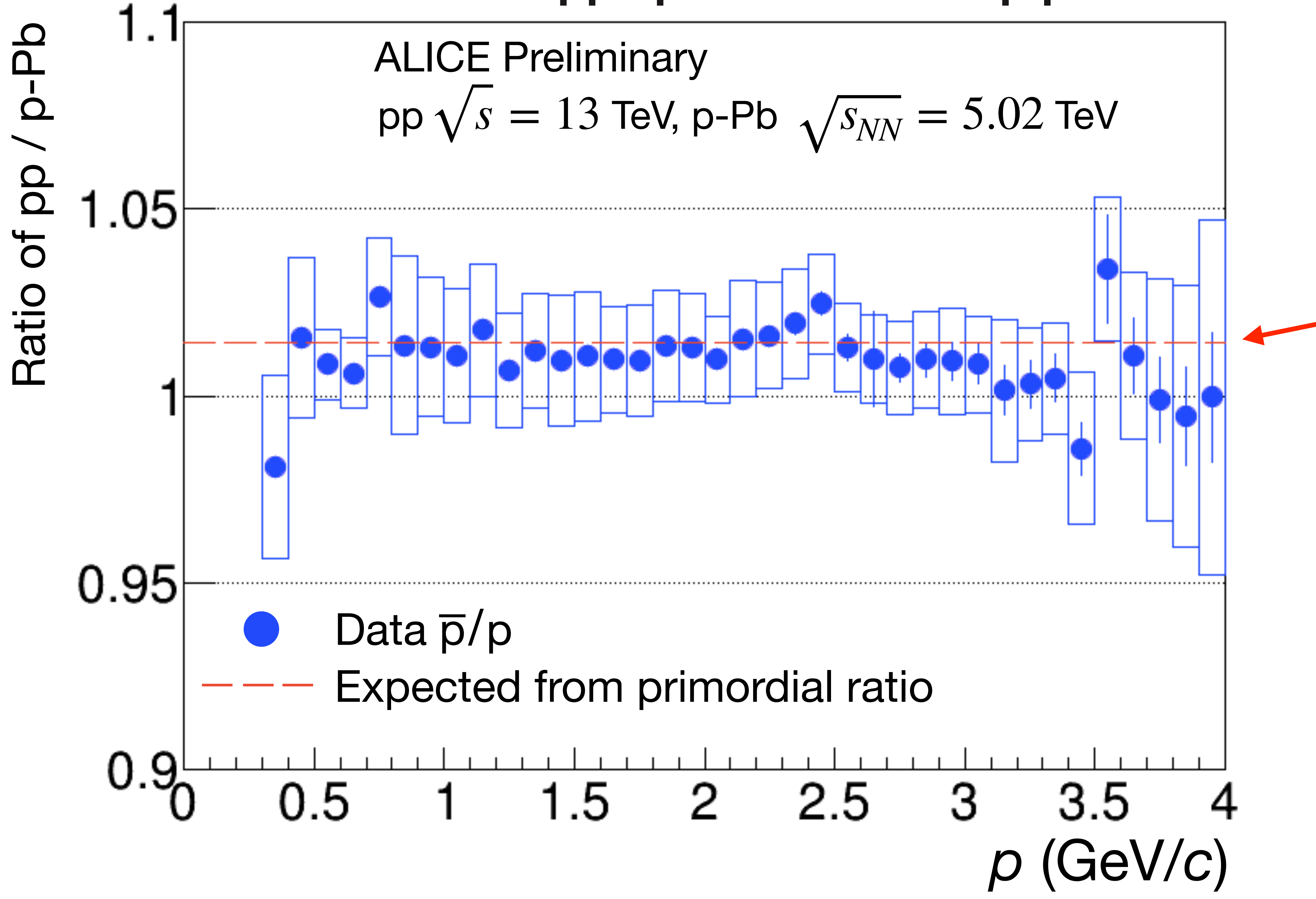


Consistency of results between pp and pPb data

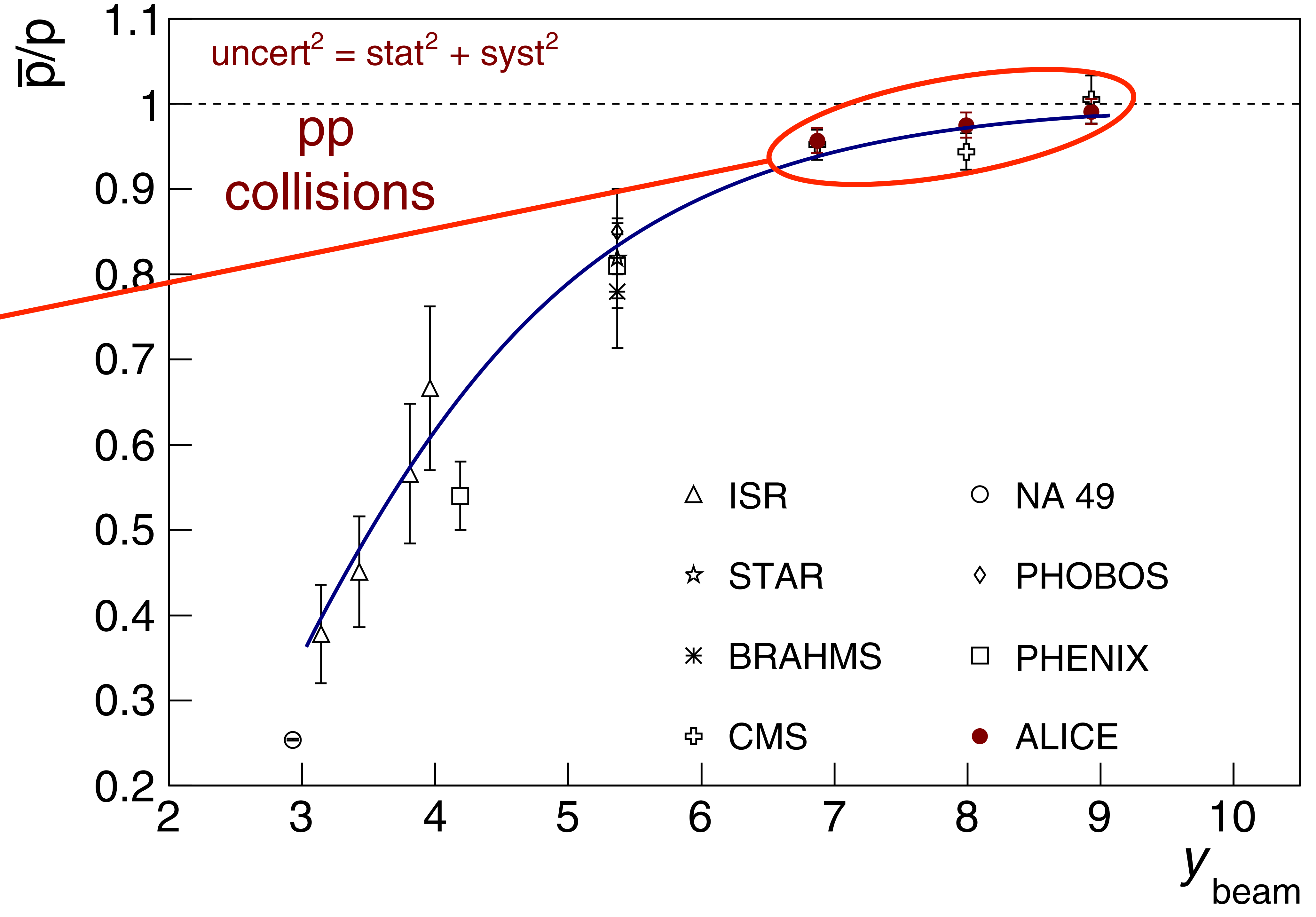
Are raw $\bar{p}$/p and $\bar{d}$/d ratios compatible in different collision systems?

Yes, modulo the change of primary antimatter/matter ratio, so analysis is robust!

Ratio of pp / pPb results for $\bar{p}$/p



$\bar{p}$/p ratio at mid-rapidity vs $\sqrt{s}$ [1]

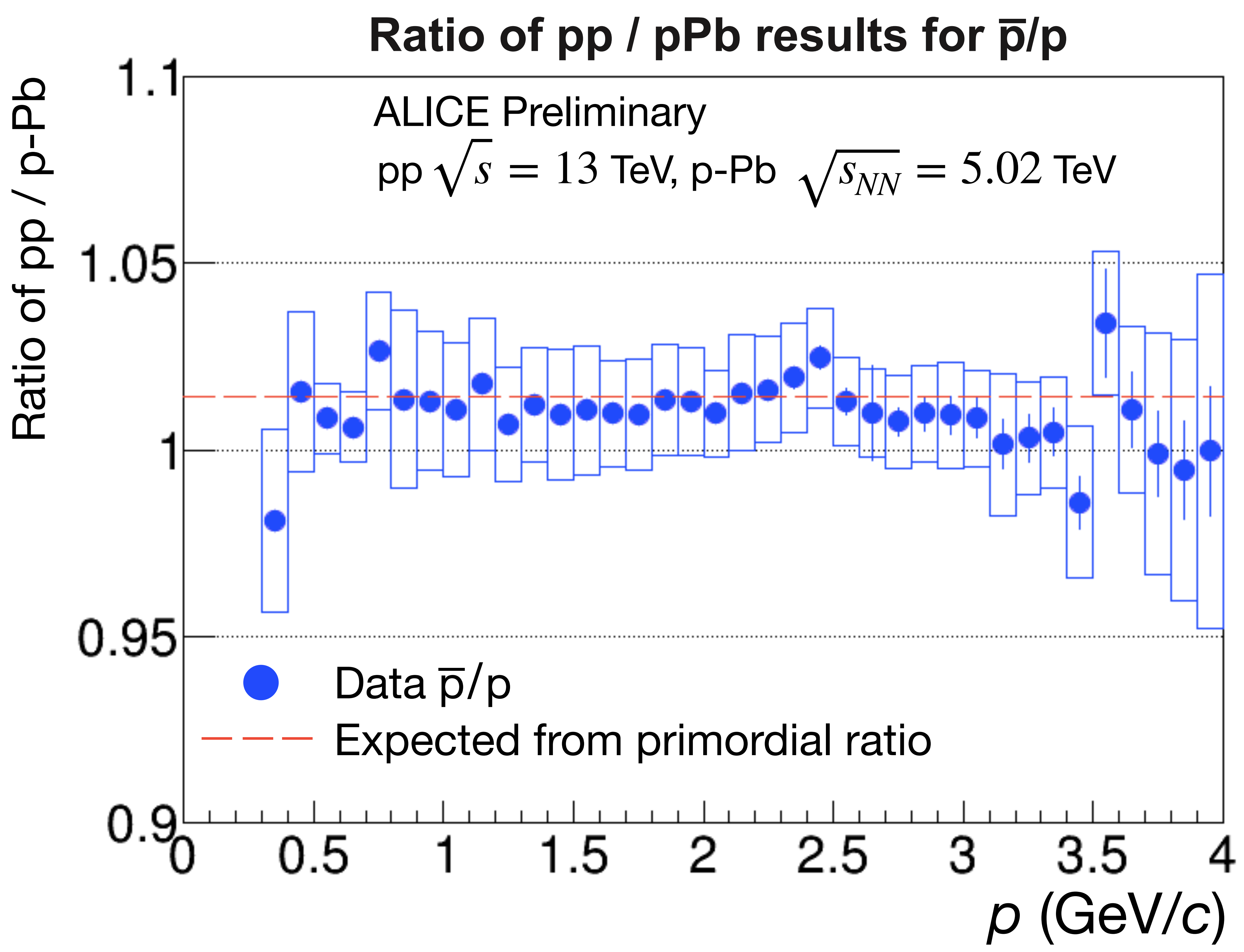


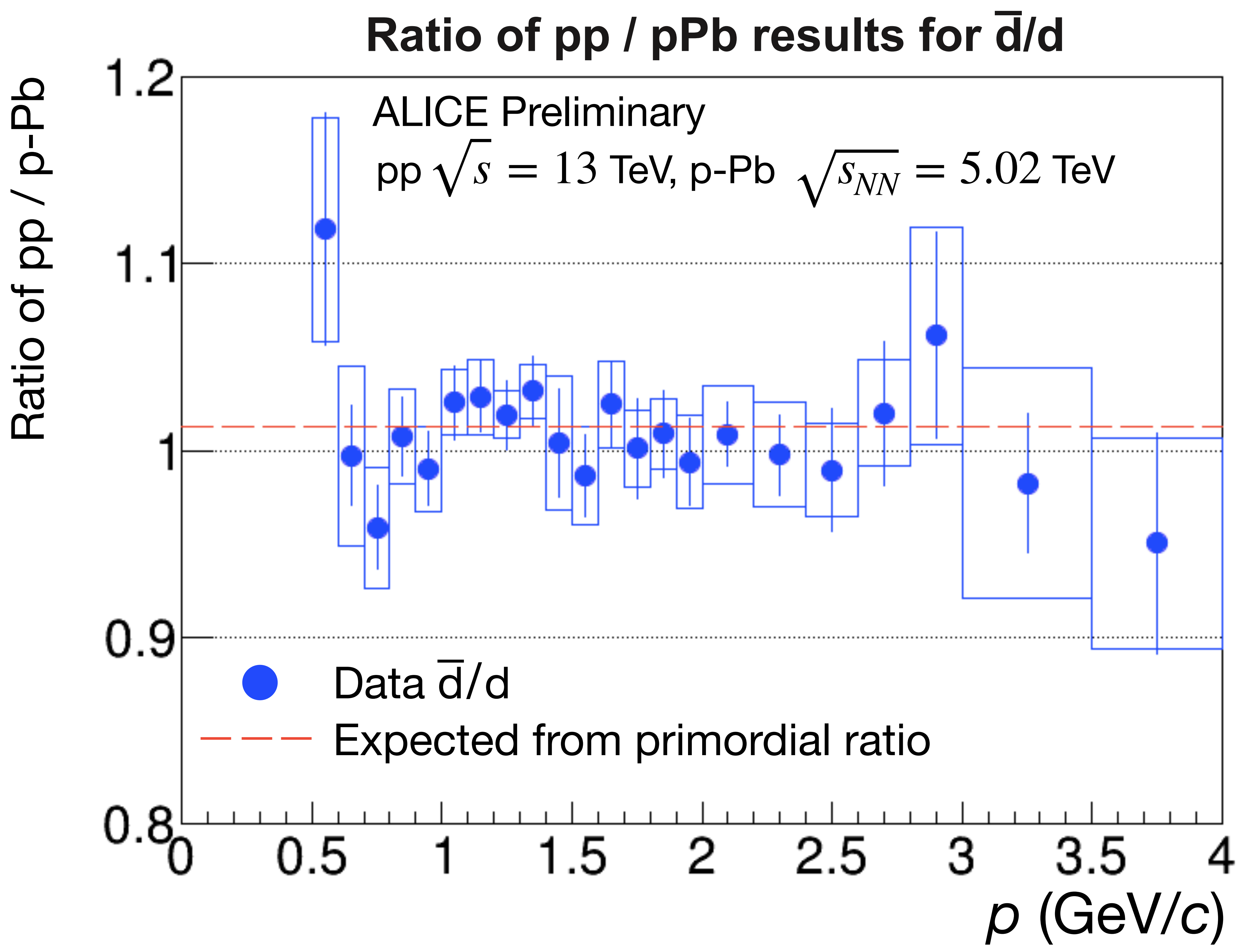
[1] Phys. Rev. C 97, 024615 (2018)

Consistency of results between pp and pPb data

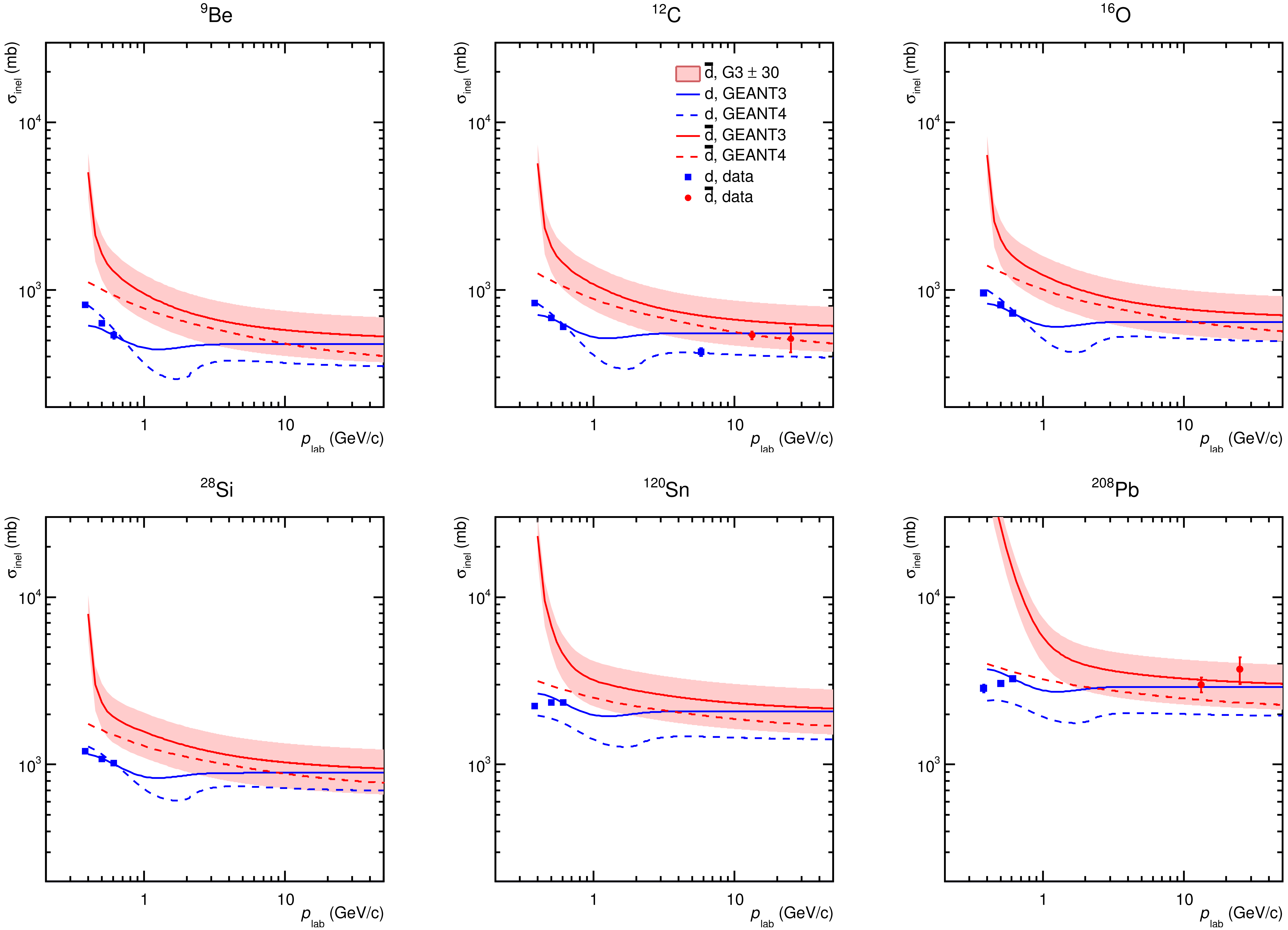
Are raw $\bar{p}/p$ and $\bar{d}/d$ ratios compatible in different collision systems?

Yes, modulo the change of primary antimatter/matter ratio, so analysis is robust!

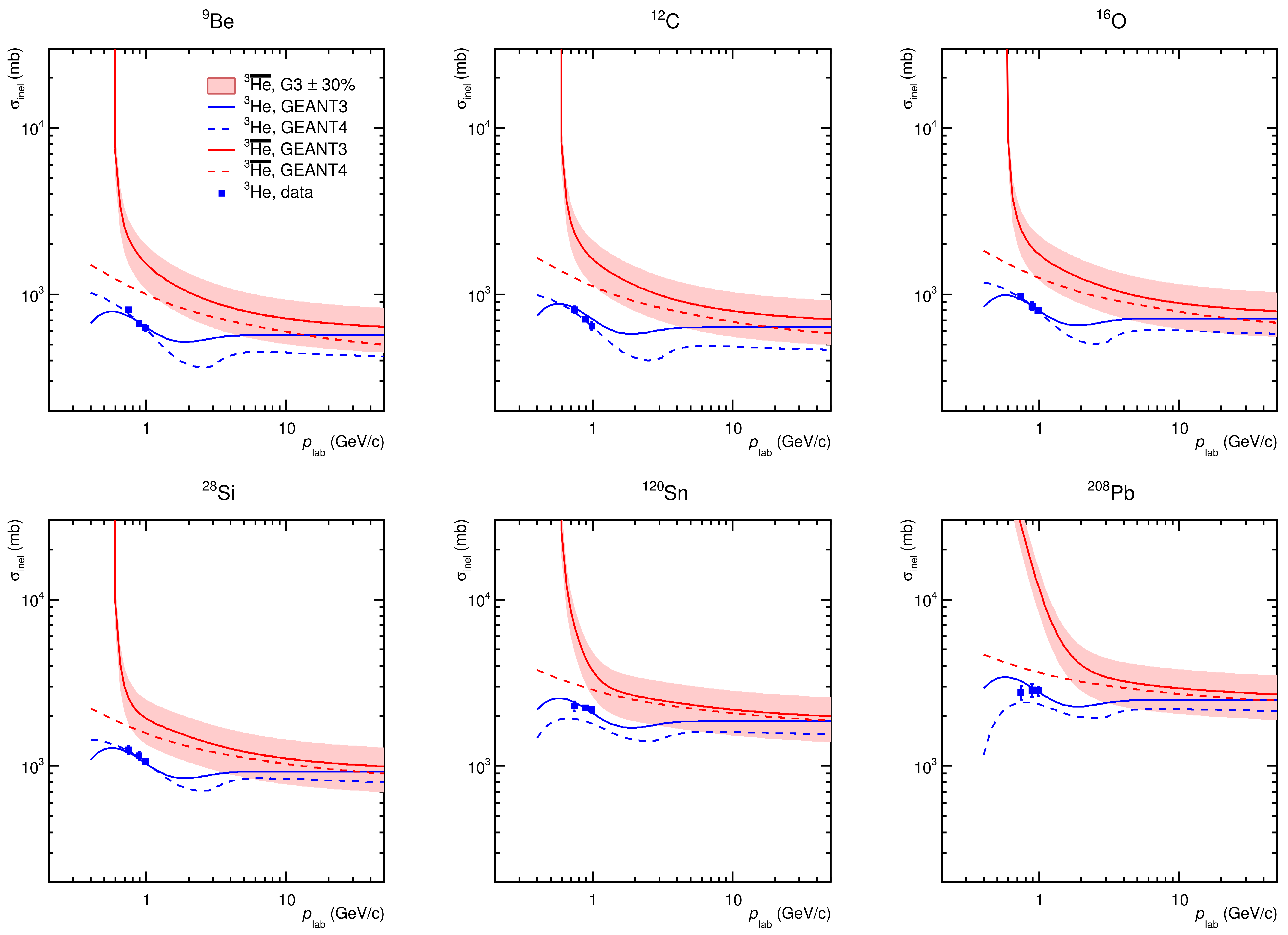




GEANT3/4 cross-sections for (anti)deuterons



GEANT3/4 cross-sections for (anti)^{3}He



GEANT3 inelastic cross-sections

Empirical parameterisation based on Moiseev' formula [1]:

$$\sigma_R = \left(Z_P \sigma_{pA}^{3/2} + N_P \sigma_{nA}^{3/2}\right)^{2/3} K(A_T)$$

$$K(A_T) = C_0 \log(A_T + 2)^{-C_1}$$

$$\sigma_{pA} = 45 A_T^{0.7} \left(1 + 0.016 \sin(5.3 - 2.63 \ln A_T)\right) \left(1 - 0.62 e^{-5E} \sin(1.58 E^{-0.28})\right)$$

$$\sigma_{nA} = 43.2 A_T^{0.719}$$

$$\sigma_{\bar{p}A} = \left(a_0 + a_1 Z_T + a_2 Z_T^2\right) A_T^{2/3}$$

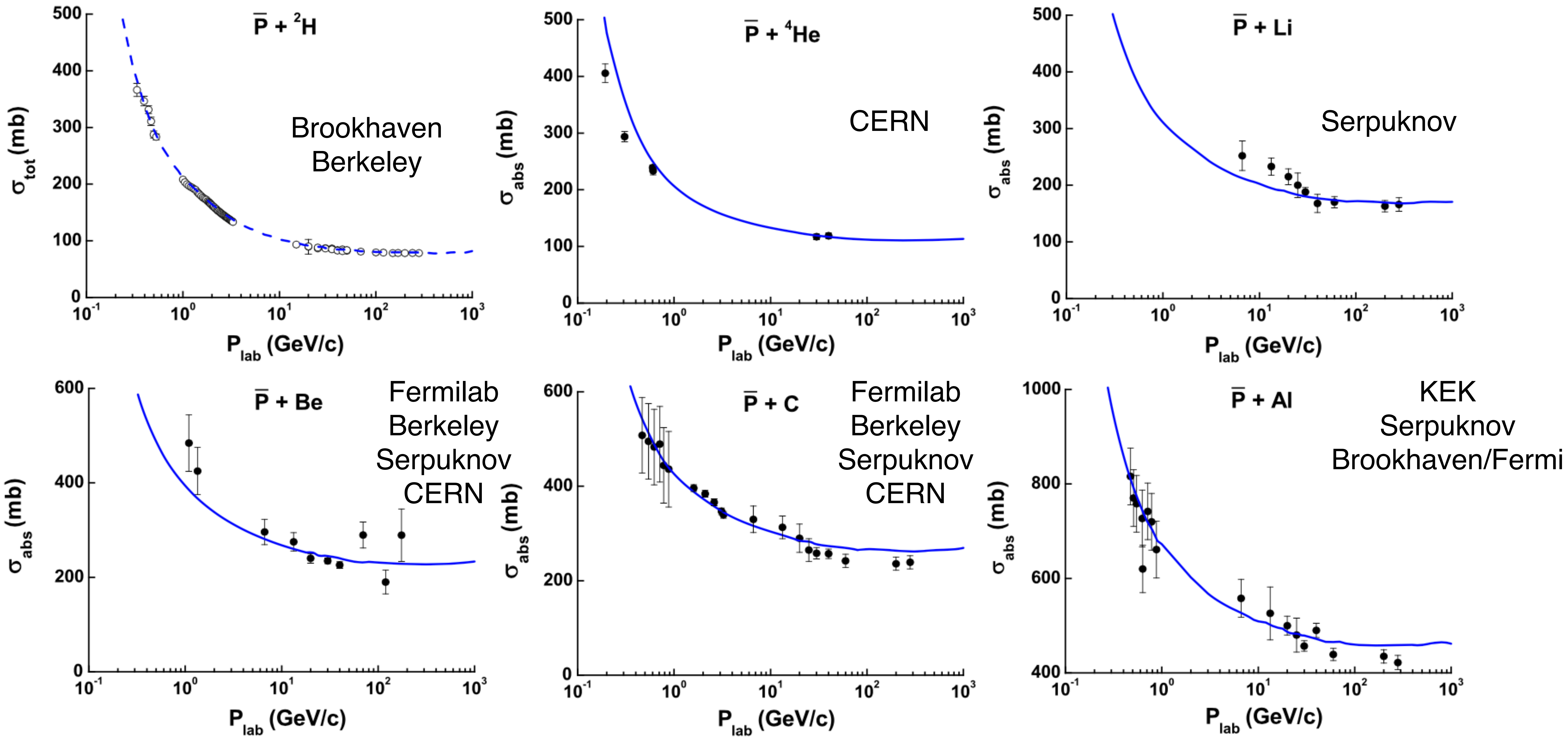
where $a_0 = 48.2 + 19(E - 0.02)^{-0.55}$, $a_1 = 0.1 - 0.18 E^{-1.2}$ and $a_2 = 0.0012 E^{-1.5}$

$$\sigma_{\bar{n}A} = (51 + 16 E^{-0.4}) A_T^{2/3}$$

[1] A. A. Moiseev, J. F. Ormes, Astroparticle Physics, 6(34):379-386, 1997

Geant4: Glauber calculations vs data

Lines are Glauber calculations, points are various exp. data [1]



[1] Phys. Lett. B705, 235 (2011)

Parameterisations used in GEANT4

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

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

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

R_A cannot be directly connected with known values due to some simplifications
Use equations as a determination of R_A having calculated 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:

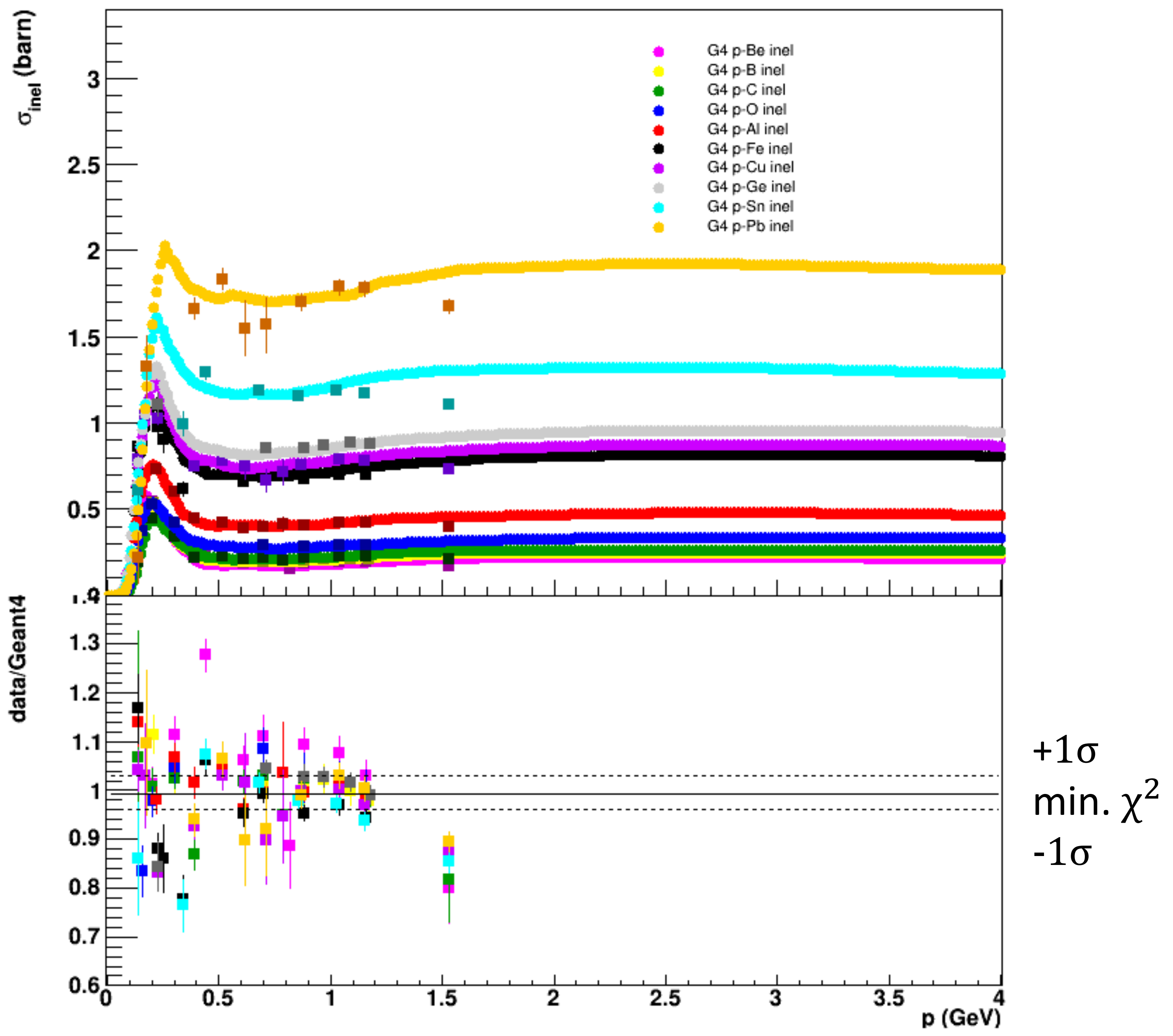
$$\bar{p}A\ R_A = 1.31A^{0.22} + 0.90/A^{1/3}\ (\text{fm}),$$
$$\bar{d}A\ R_A = 1.38A^{0.21} + 1.55/A^{1/3}\ (\text{fm}),$$
$$\bar{t}A\ R_A = 1.34A^{0.21} + 1.51/A^{1/3}\ (\text{fm}),$$
$$\bar{\alpha}A\ R_A = 1.30A^{0.21} + 1.05/A^{1/3}\ (\text{fm}).$$

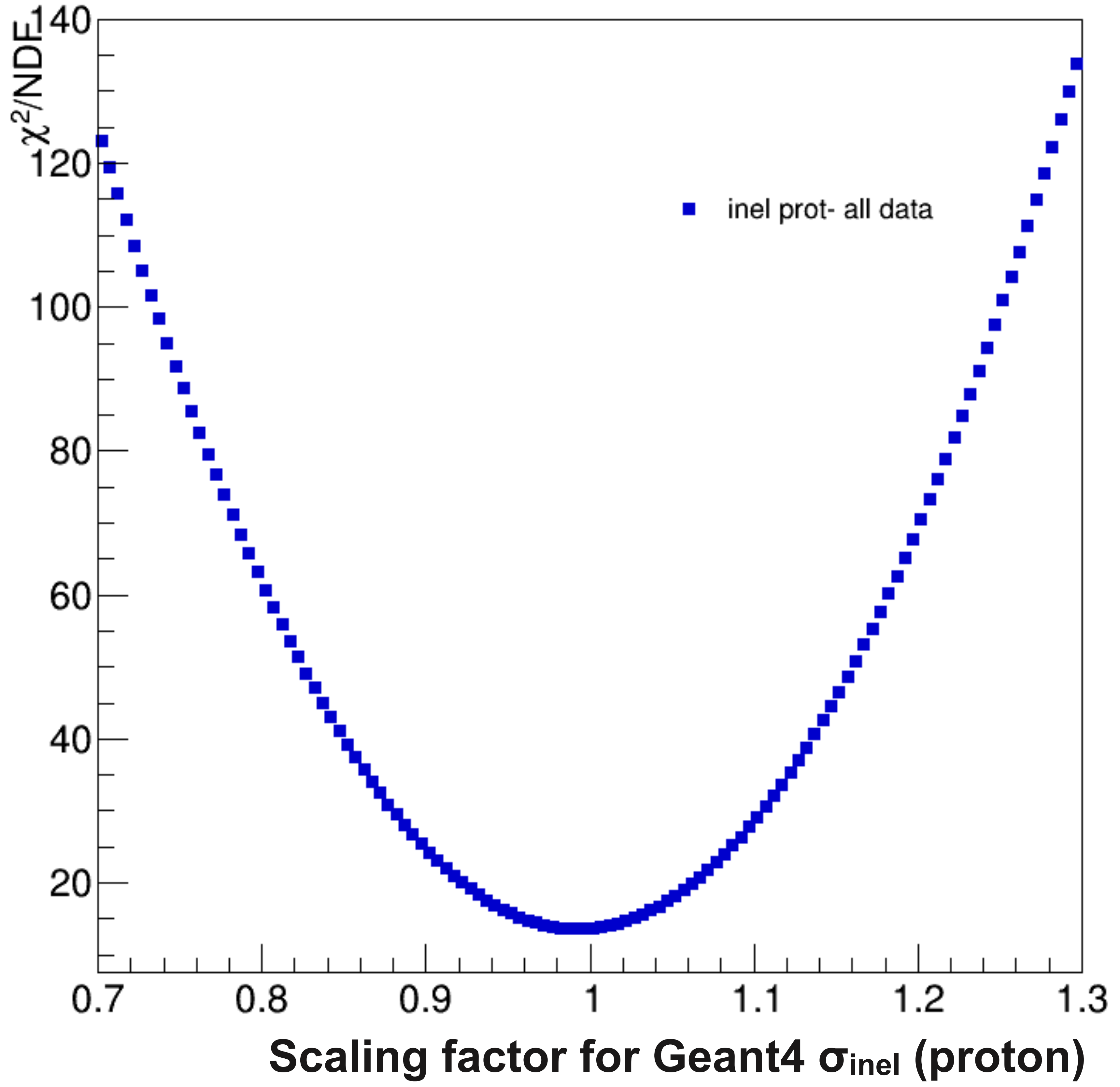
[1] V.M. Grichine, Eur. Phys. J. C 62 (2009) 399, Nucl. Instrum. Methods B 267 (2009) 2460

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** $^{+0.0375}_{-0.0325}$

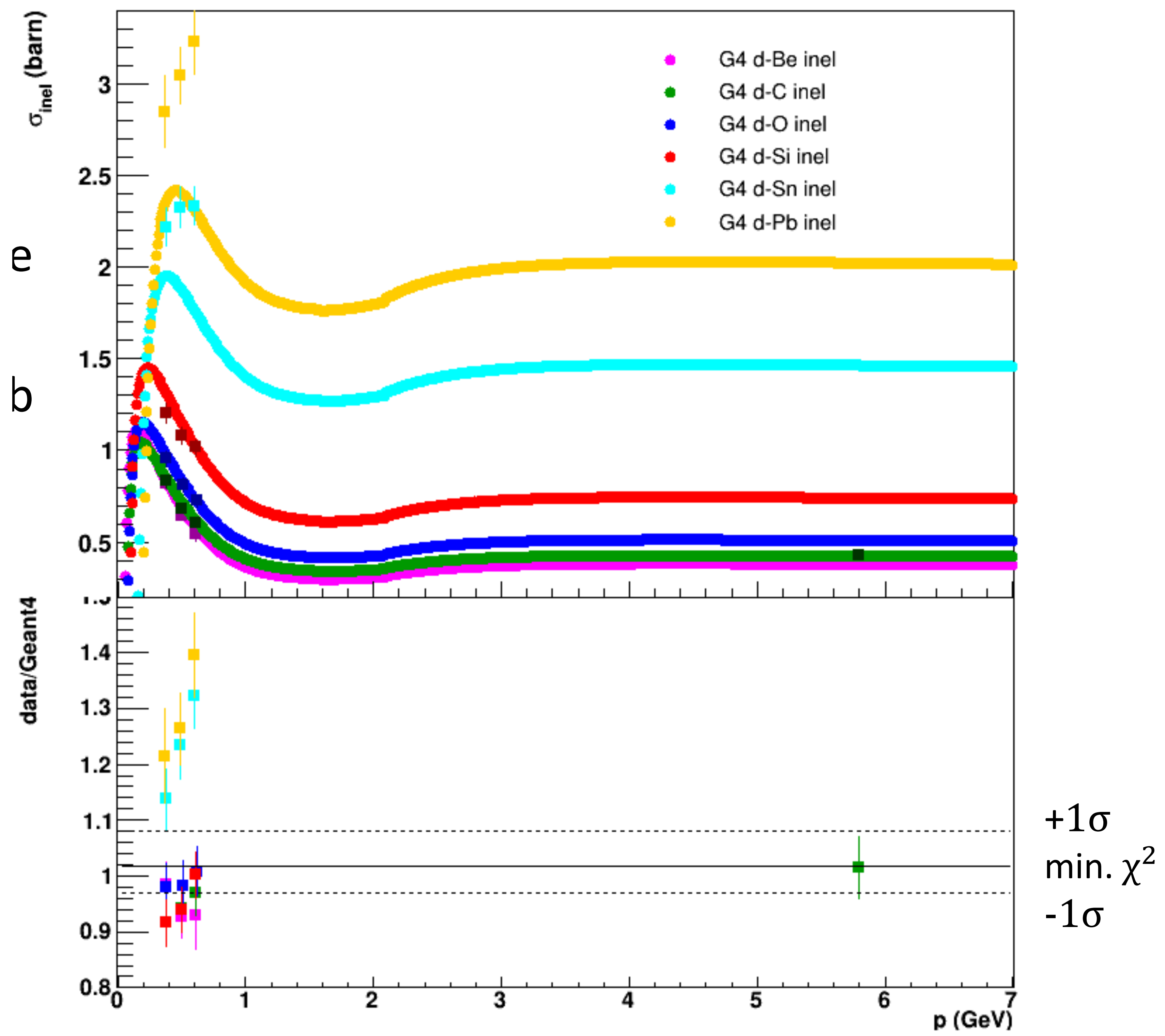


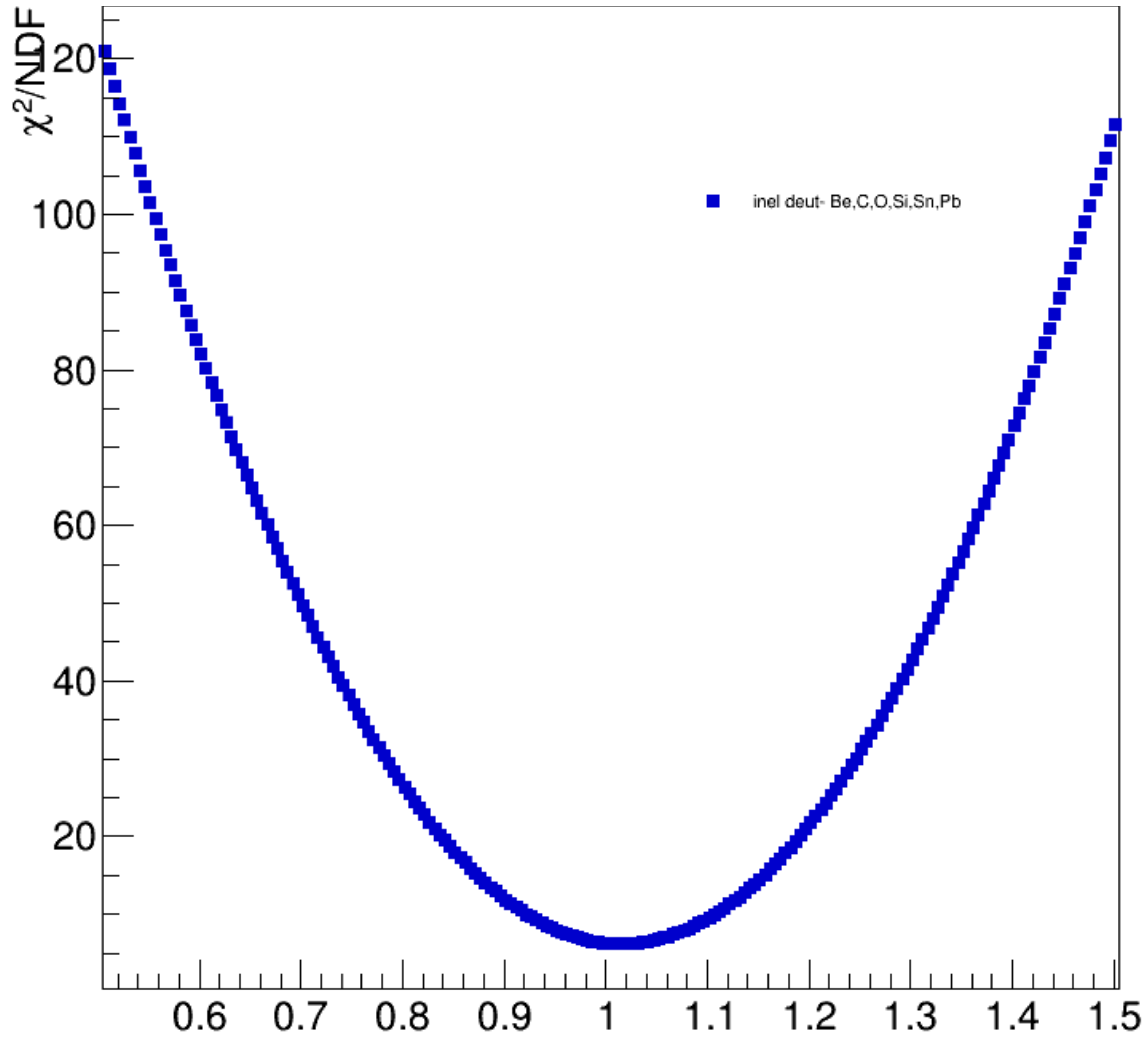


Uncertainty due to σ_{inel} (deuteron)

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

- Check available experimental data (Be, C, O,Si, Sn, Pb)
- Vary Geant4 parametrisation, calculate χ^2 for all data points
- Minimum χ^2 and ±1σ : **1.0175 $^{+0.0625}_{-0.0475}$**



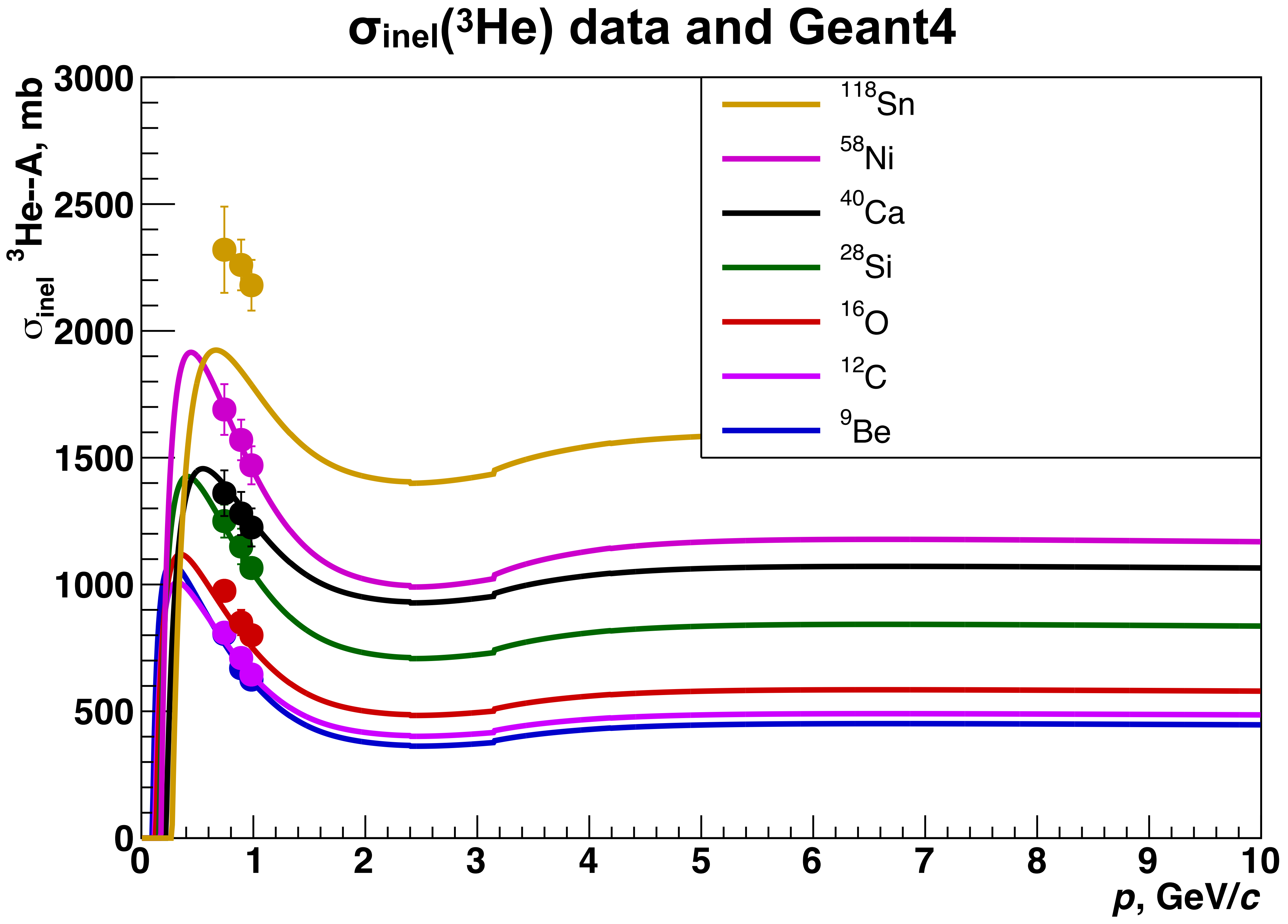


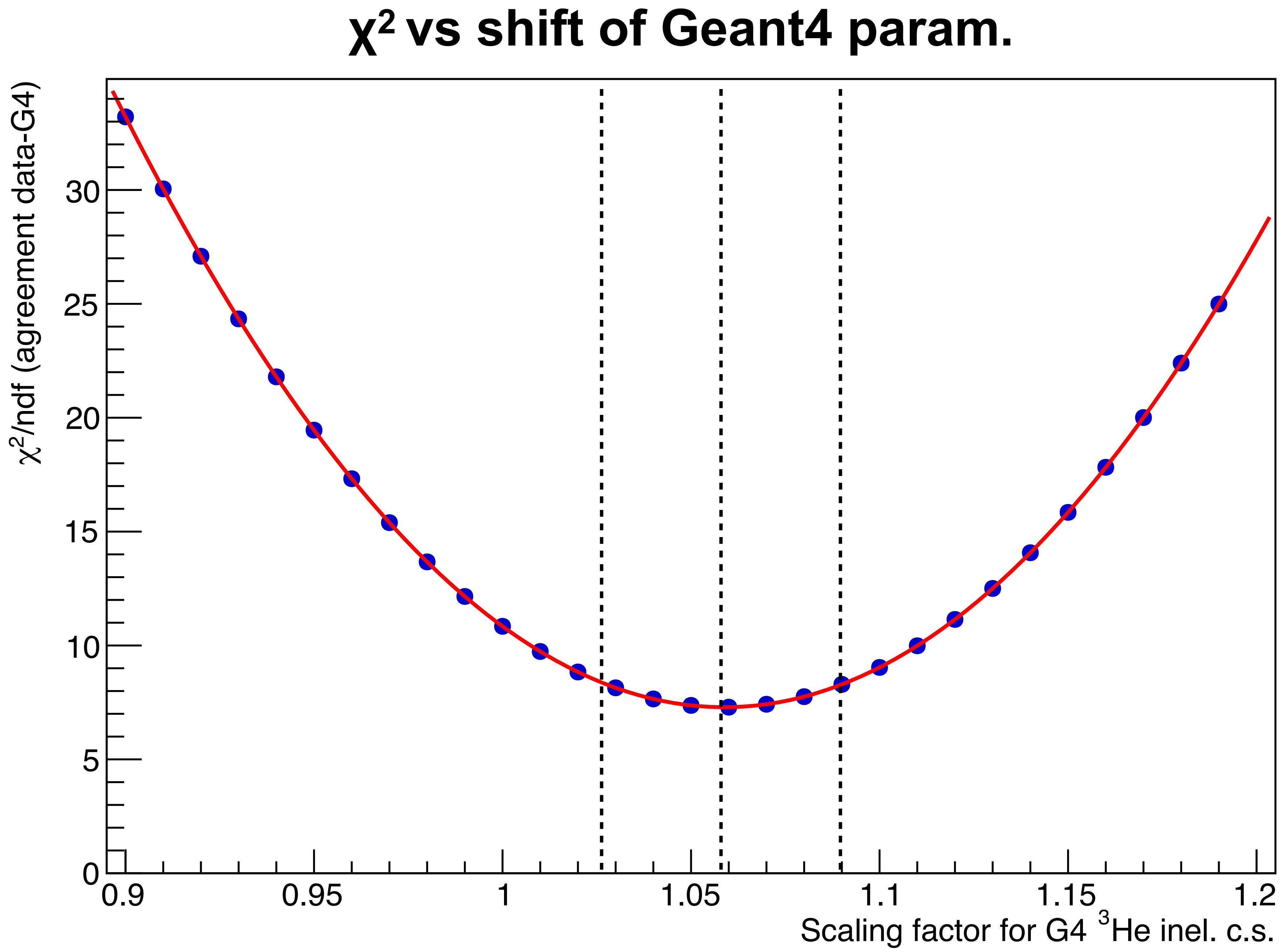
Scaling factor for Geant4 σ_{inel} (proton)

Uncertainty due to σ_{inel} (^{3}He)

How precise σ_{inel} (^{3}He) is described by Geant4?

- Check available experimental data [1]
- Vary Geant4 parametrisation, calculate χ^2 for all data points
- Minimum χ^2 and ±1σ : **$1.058^{+0.031}_{-0.031}$**

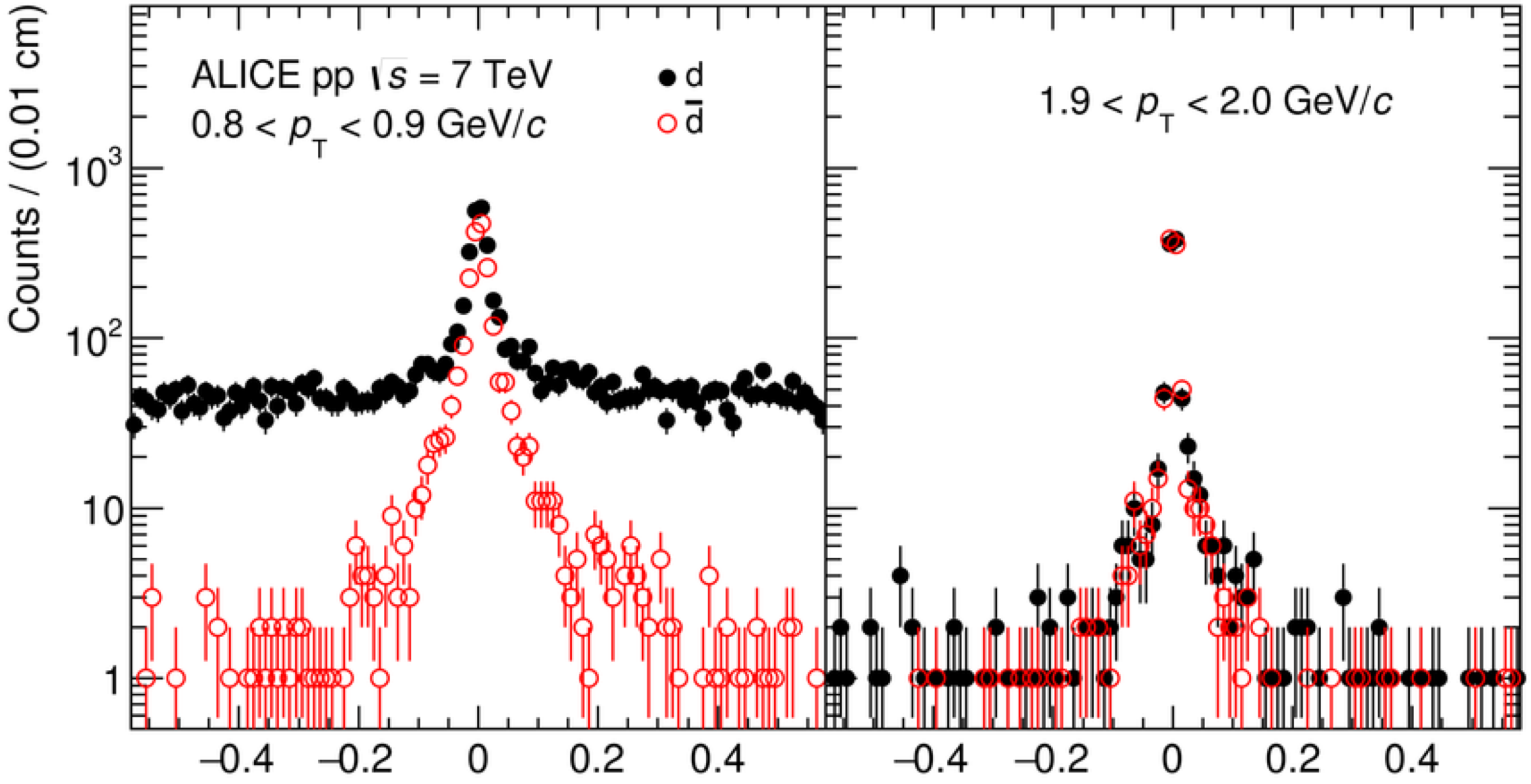




[1] Nuclear Physics A 696 (2001) 3–30

Deuterons from spallation processes

ALICE, Phys. Rev. C 97 (2018) 024615

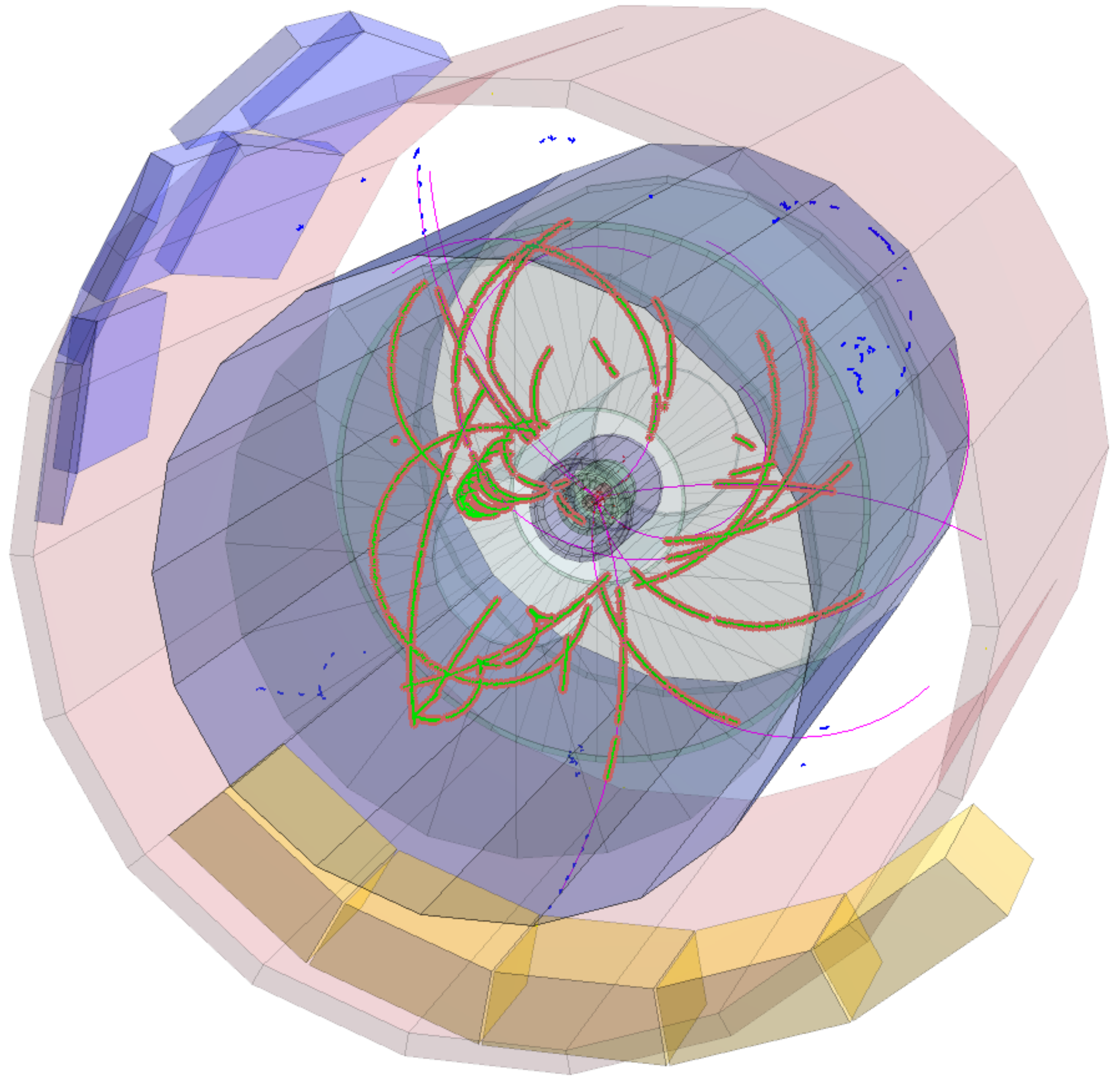


Simple Geant4-based model

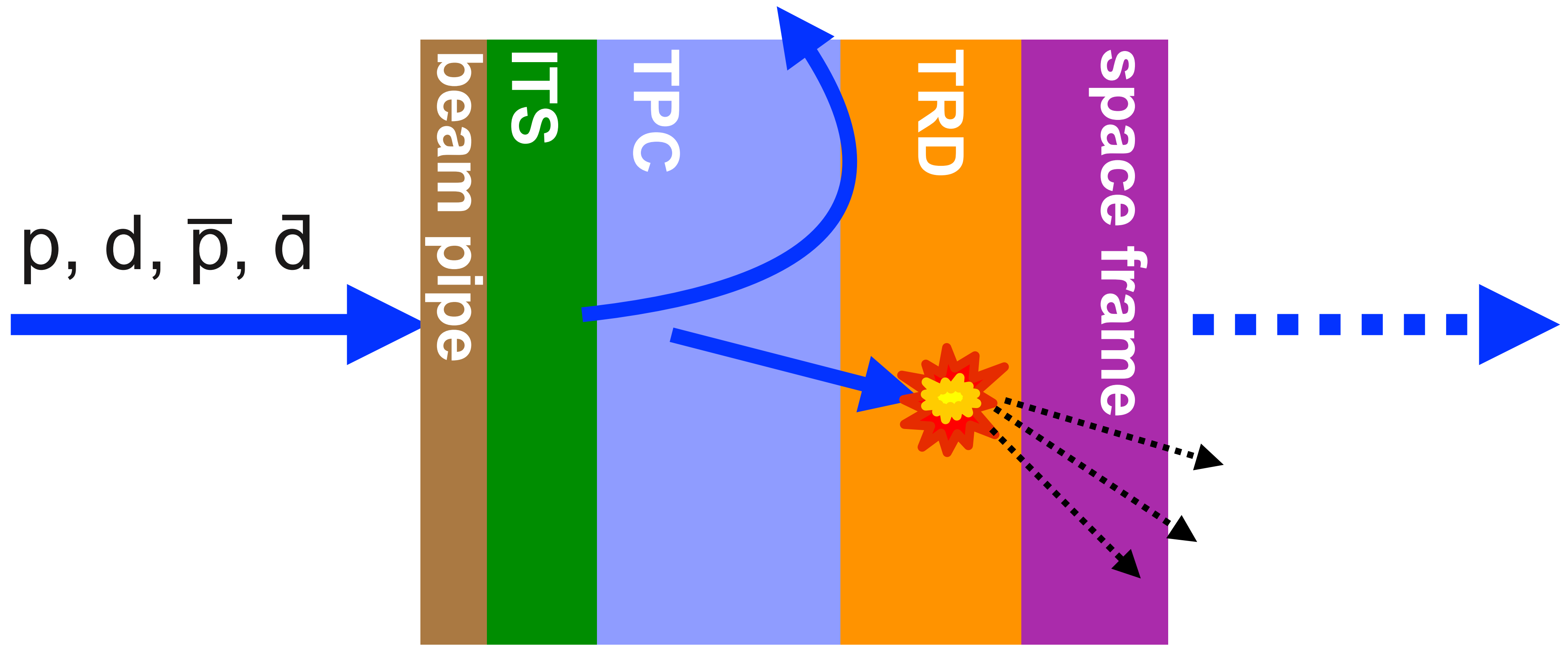
Standalone Geant4 simulation to investigate ratios in more details

- (Anti-)proton and (anti-)deuteron source + a target made of ALICE detector materials
- Loss of (anti-)particles due to inelastic processes in detector material
  - low *p*: beam pipe, ITS, TPC (<Z> = 8.5, <A> = 17.4)
  - high *p*: beam pipe, ITS, TPC, TRD, SF (<Z> = 14.8, <A> = 31.8)
- Loss of (anti-)particles due to scattering effects in ITS, TPC and TRD material
  - Multiple coulomb and hadron elastic scattering

Detailed ALICE simulation



Simple Geant4 setup

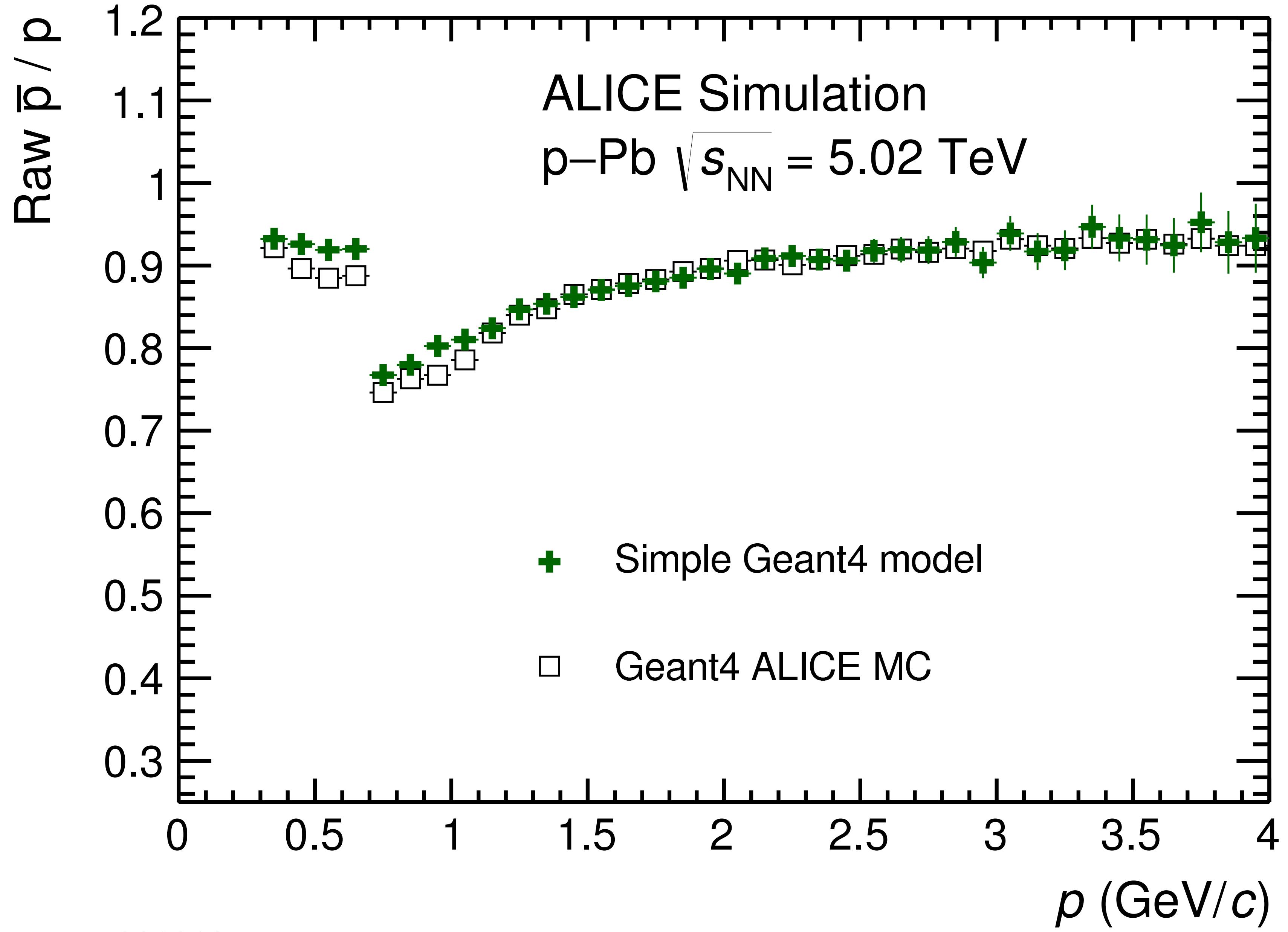


Same materials as for the full ALICE simulation

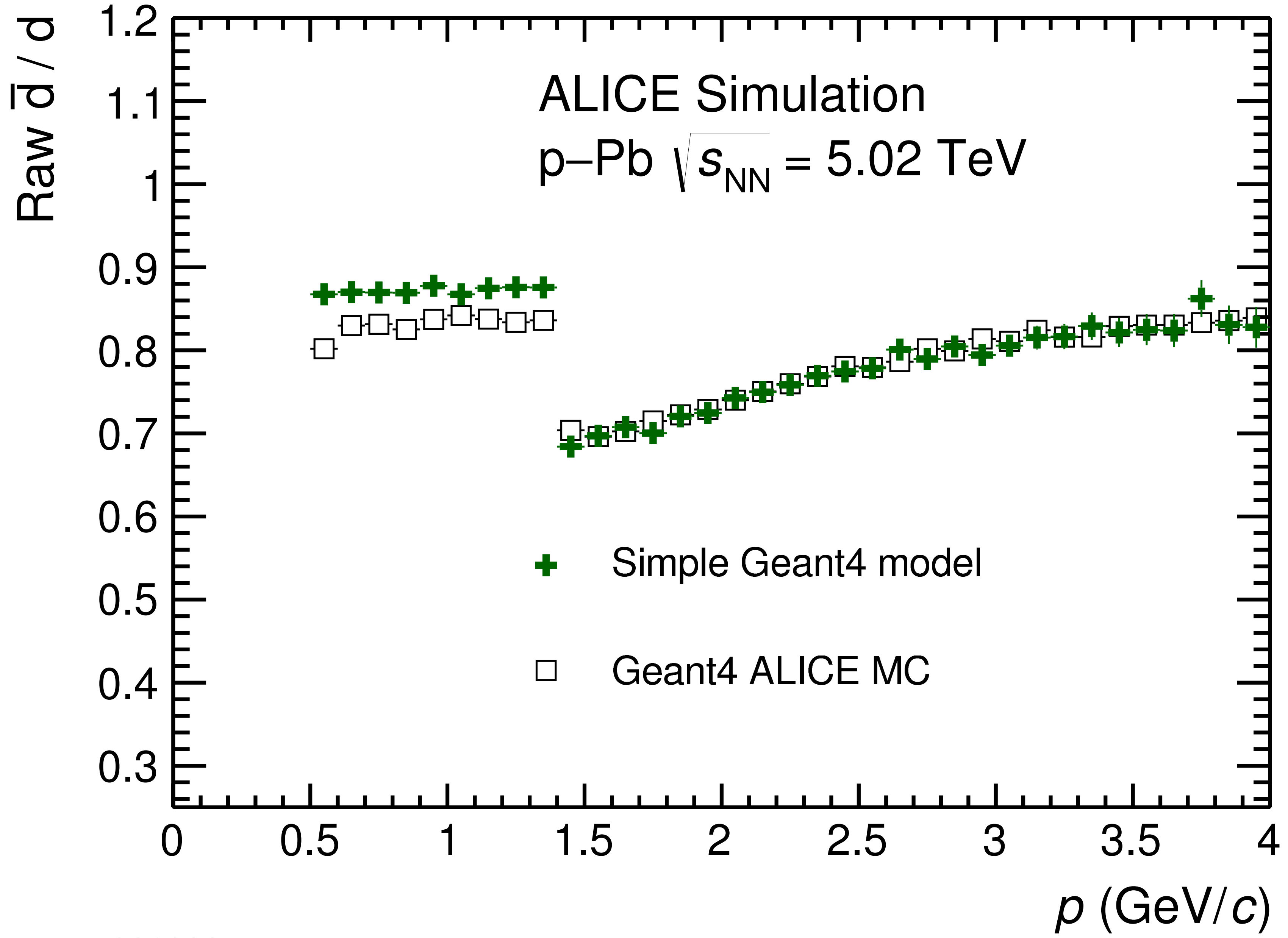
Simple Geant4-based model

Standalone Geant4 simulation to investigate ratios in more details

- (Anti-)proton and (anti-)deuteron source + a target made of ALICE detector materials
- Loss of (anti-)particles due to inelastic processes in detector material
  - low *p*: beam pipe, ITS, TPC (<Z> = 8.5, <A> = 17.4)
  - high *p*: beam pipe, ITS, TPC, TRD, SF (<Z> = 14.8, <A> = 31.8)
- Loss of (anti-)particles due to scattering effects in ITS, TPC and TRD material
  - Multiple coulomb and hadron elastic scattering



ALI-DER-324013



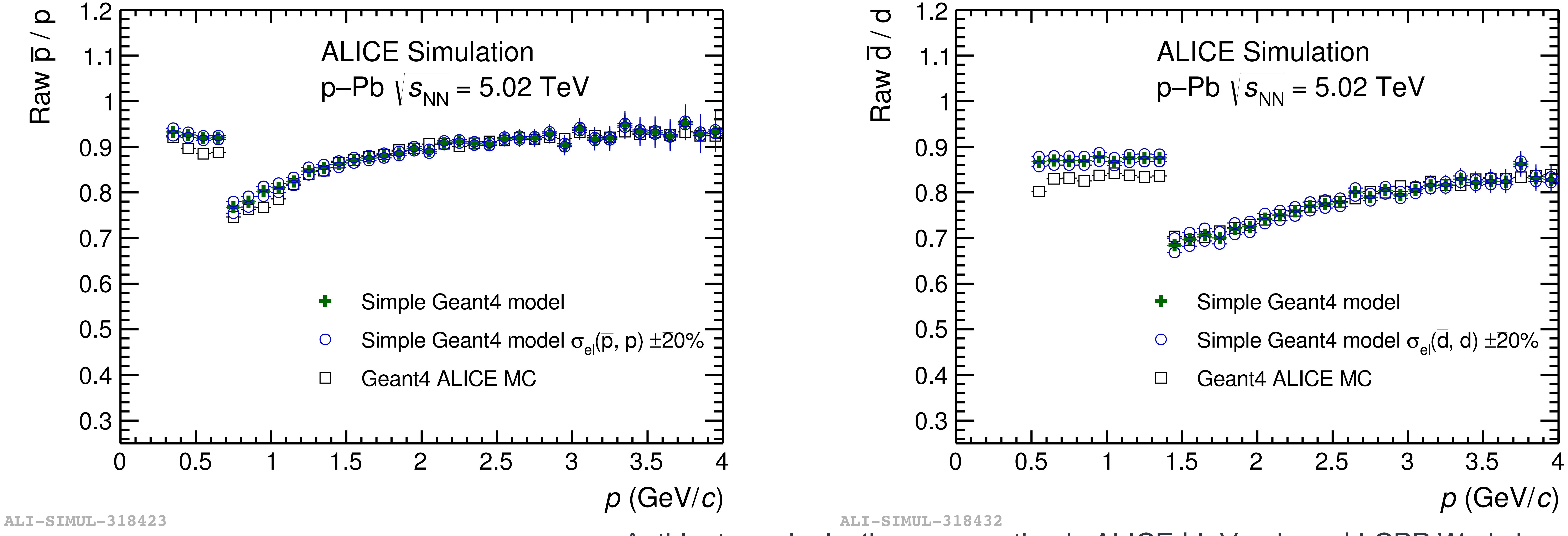
ALI-DER-324008

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



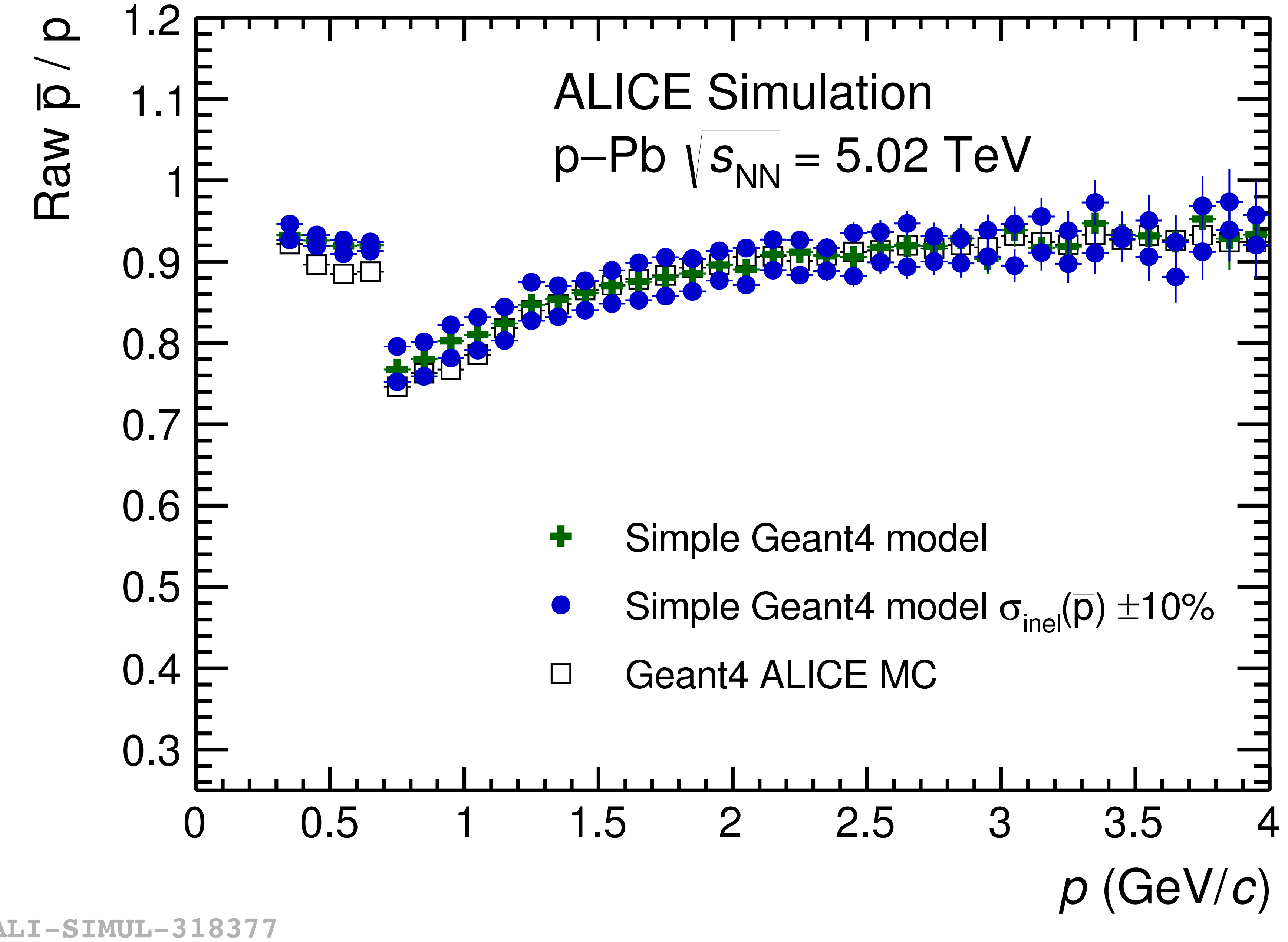
Variations of σ_{inel} with simple Geant4 model

Ratios are sensitive to the variations of $\sigma_{inel}(\bar{p})$ and $\sigma_{inel}(\bar{d})$

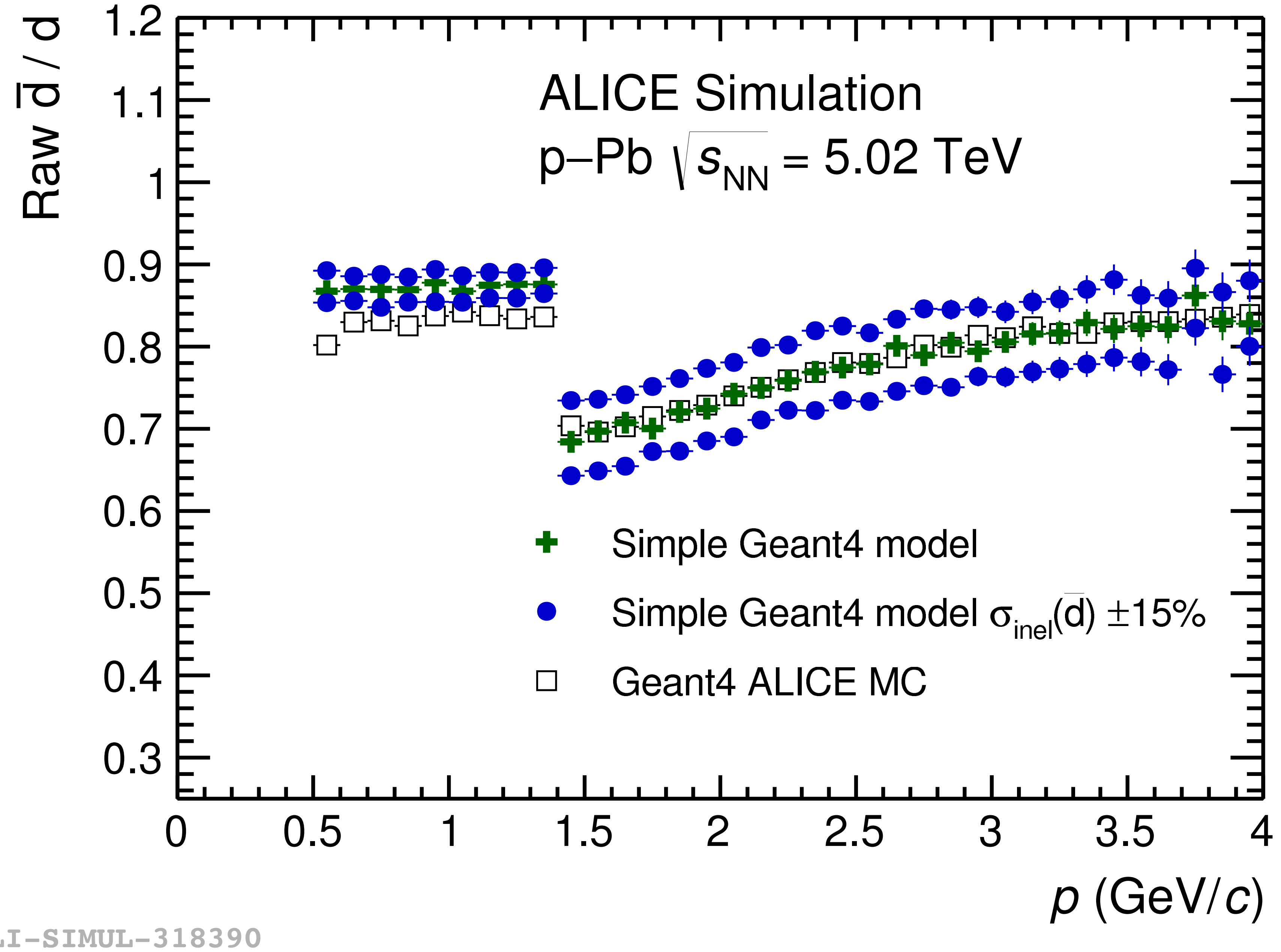
Re-scale $\sigma_{inel}(\bar{p})$ and $\sigma_{inel}(\bar{d})$ to be ±1σ/±2σ away from experimentally measured ratio

1σ = uncertainties added in quadrature:

- Stat. and syst. uncertainties of the data
- Uncertainty from primordial ratio (1.5% for $\bar{p}$/p, 3% for $\bar{d}$/d)
- Unc. from variations of $\sigma_{inel}(p)$ and $\sigma_{inel}(d)$ within precision of Geant4 parameterisations
- Uncertainty from variations of elastic cross-sections



ALI-SIMUL-318377



ALI-SIMUL-318390