Constraining the anti-deuteron nuclear inelastic cross-section with ALICE

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Geant4 technical forum
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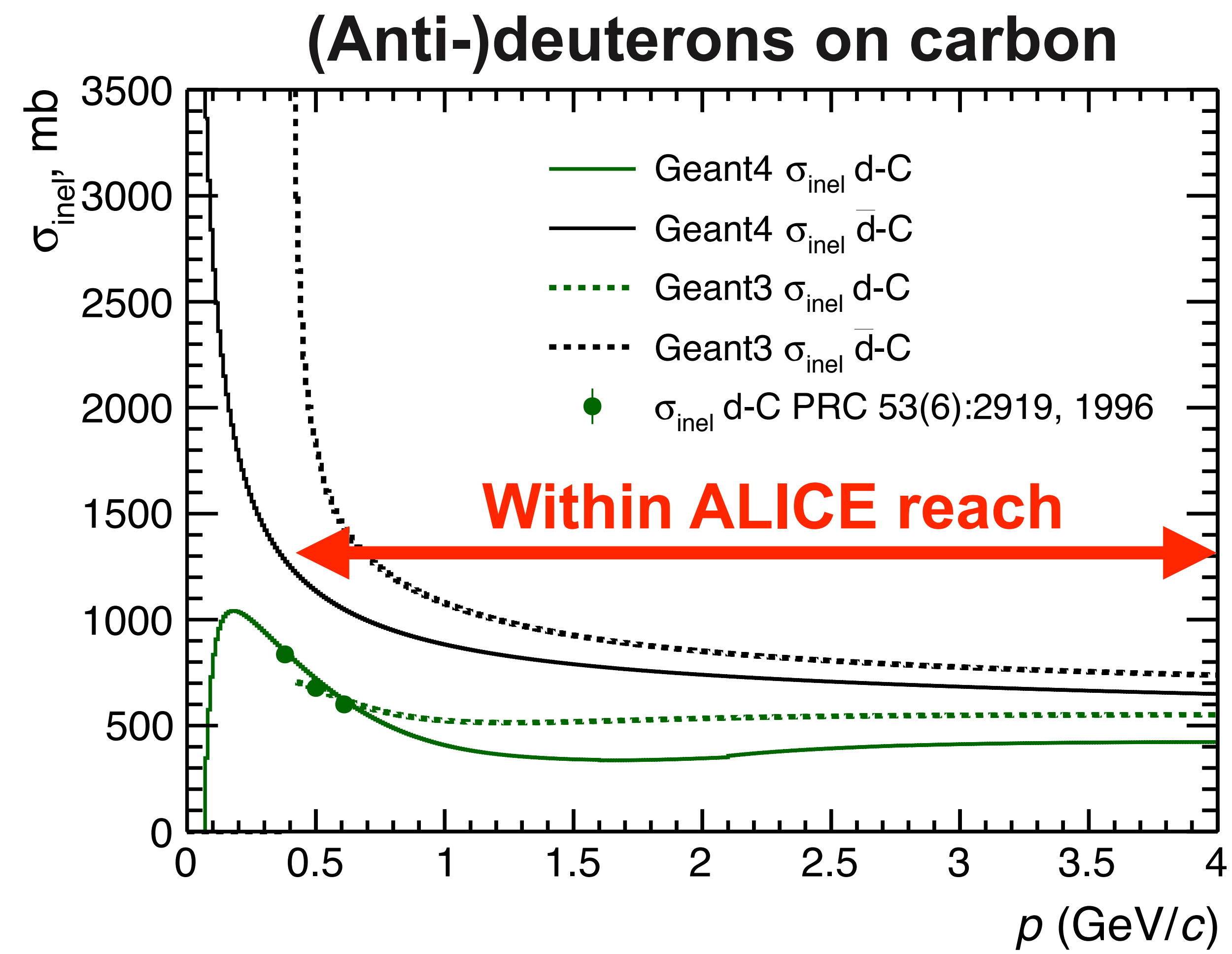
Introduction

Anti-deuteron inelastic cross-section is poorly known at low energies

- Only two measurements available, for $p_{\bar{d}}$ = 13.3. and 25 GeV/*c* [1, 2]
- Important input for various physics, e.g. indirect Dark Matter searches
- Deuteron inelastic c.s. has been measured at low momentum [3]



At the LHC, matter and anti-matter are produced in equal (and large) amounts

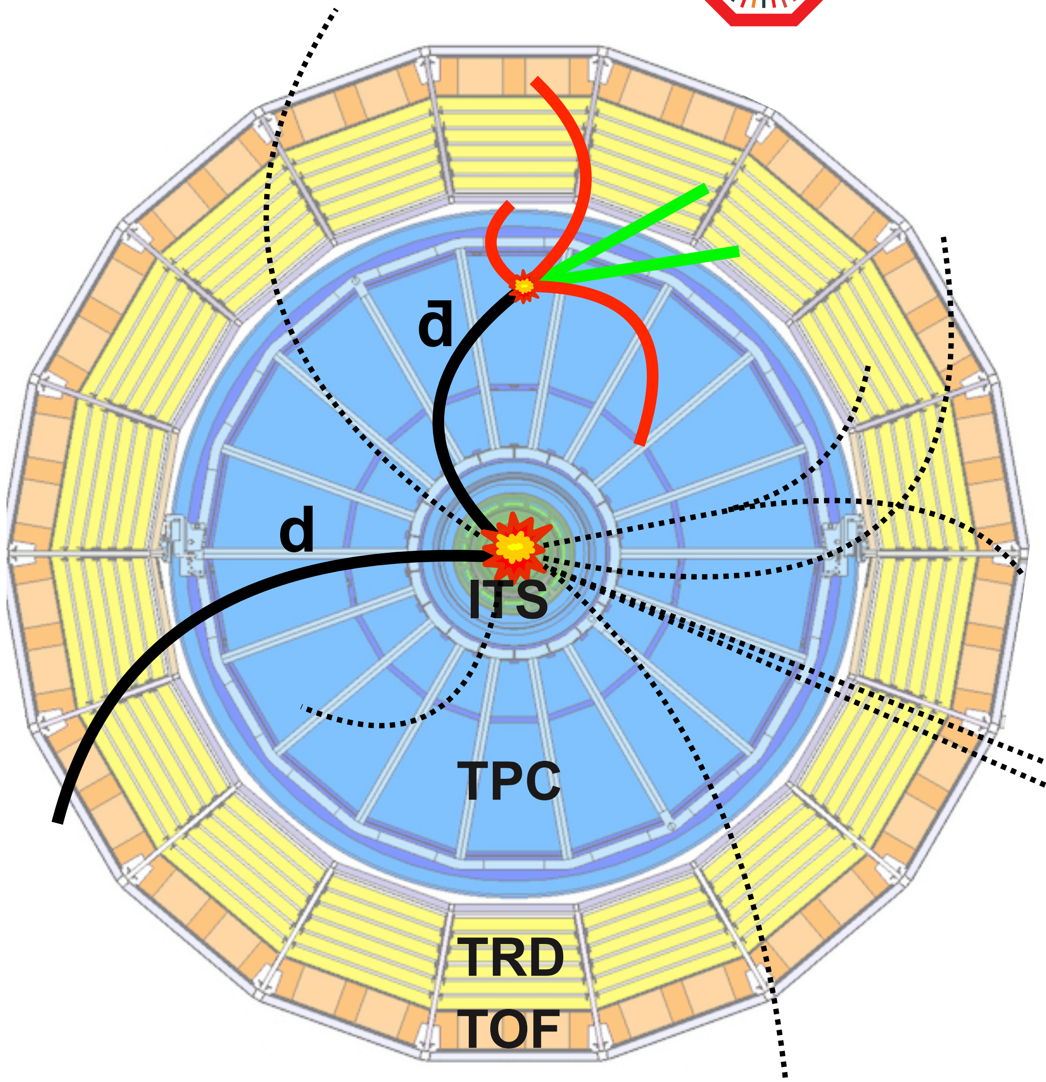
- Use pp/p-Pb/Pb-Pb collisions as a source of (anti-)deuterons and ALICE detector material as a target
- ALICE can reconstruct (anti-)deuterons in $0.5 < p < 4.0$ GeV/*c* momentum range

[1] Nuclear Physics B 31(2), 253 (1971)
[2] Phys. Let. B 31(4), 230 (1970)
[3] Phys. Rev. C 53(6):2919 (1996)

Idea of the current analysis*

Analyse *raw reconstructed* anti-deuteron to deuteron ratios

- No correction due to detector efficiency or absorption in detector material
- Raw reconstructed d̄/d ratio is sensitive to σ_{inel}(d̄)
- Benchmark with (anti-)protons since their cross-sections are known much better



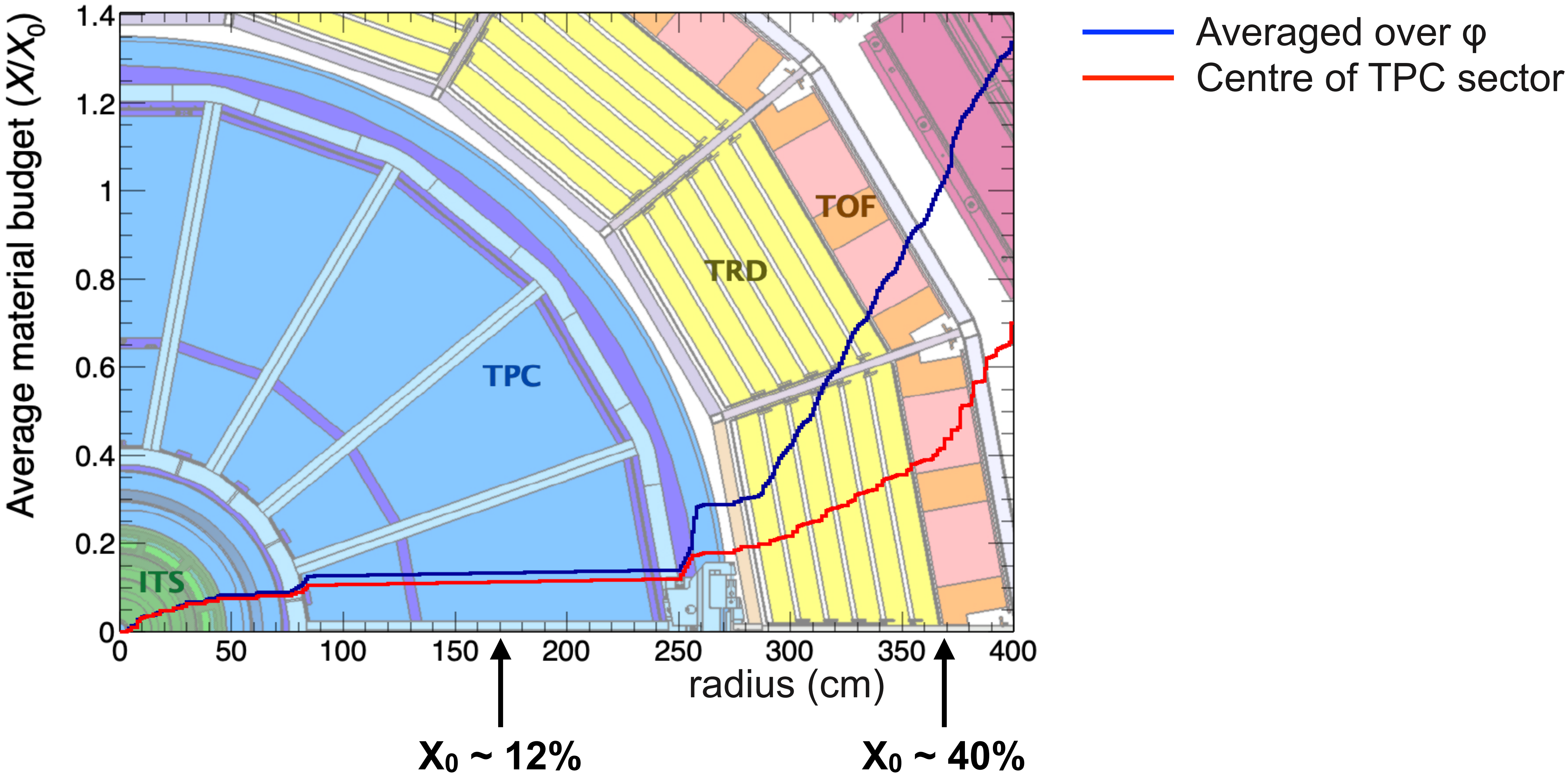
Compare the obtained d̄/d ratio to detailed MC simulations

- Geant4 for the propagation of (anti-)particles through the detector material
- *By how much one should adjust the σ_{inel}(d̄) in Geant4 in order to describe experimental d̄/d ratio?*

** Other ideas are also being explored, e.g. reconstruct the annihilation directly, compare d̄ yields in TPC and in TOF, extend the analysis to anti-^{3}He, …*

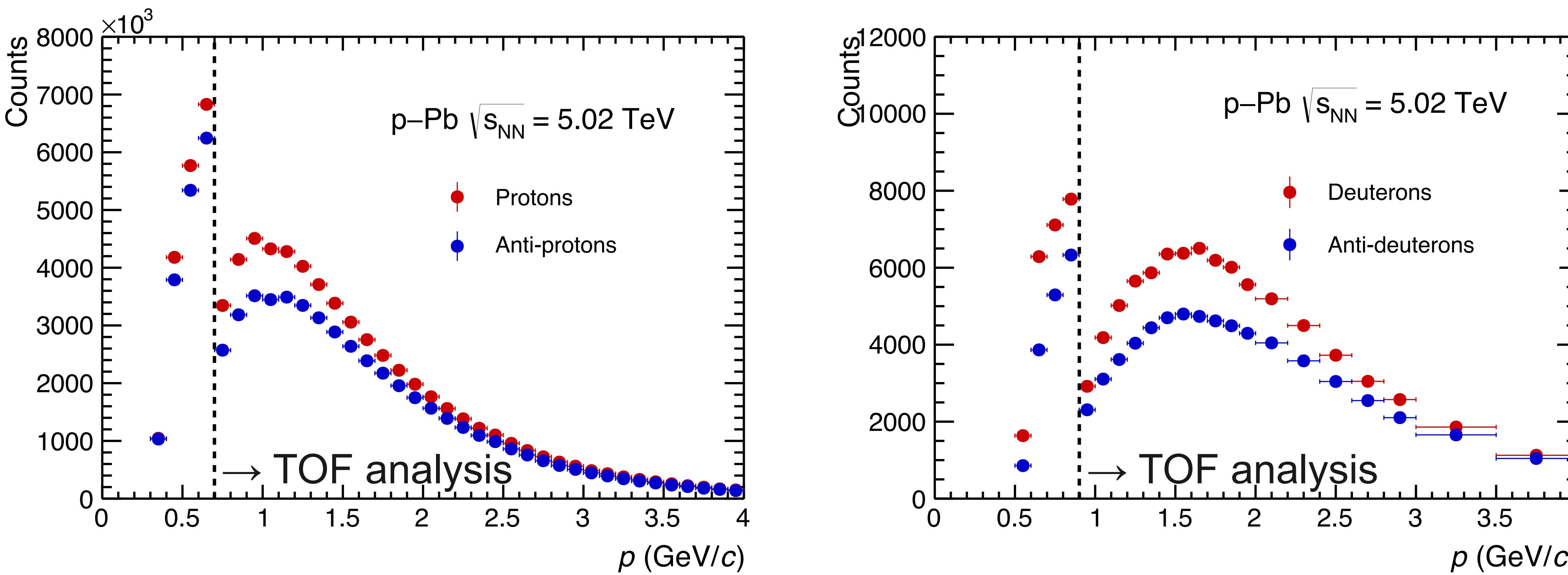
ALICE material budget at mid-rapidity

Material at mid-rapidity for straight perpendicular tracks



Raw primary spectra

Results from p-Pb collisions at 5.02 TeV, ~600 M events
- (Anti-)particles are reconstructed either with ITS+TPC or with ITS+TPC+TOF
- Drop in raw spectra for TOF analysis: efficiency + loss in additional detector material



Use these spectra to construct $\bar{p}$/p and $\bar{d}$/d ratios and compare the results with MC
- Reconstruction efficiencies cancel in ratio
- (Anti-)protons as a benchmark, since their inelastic c.s. are known much better

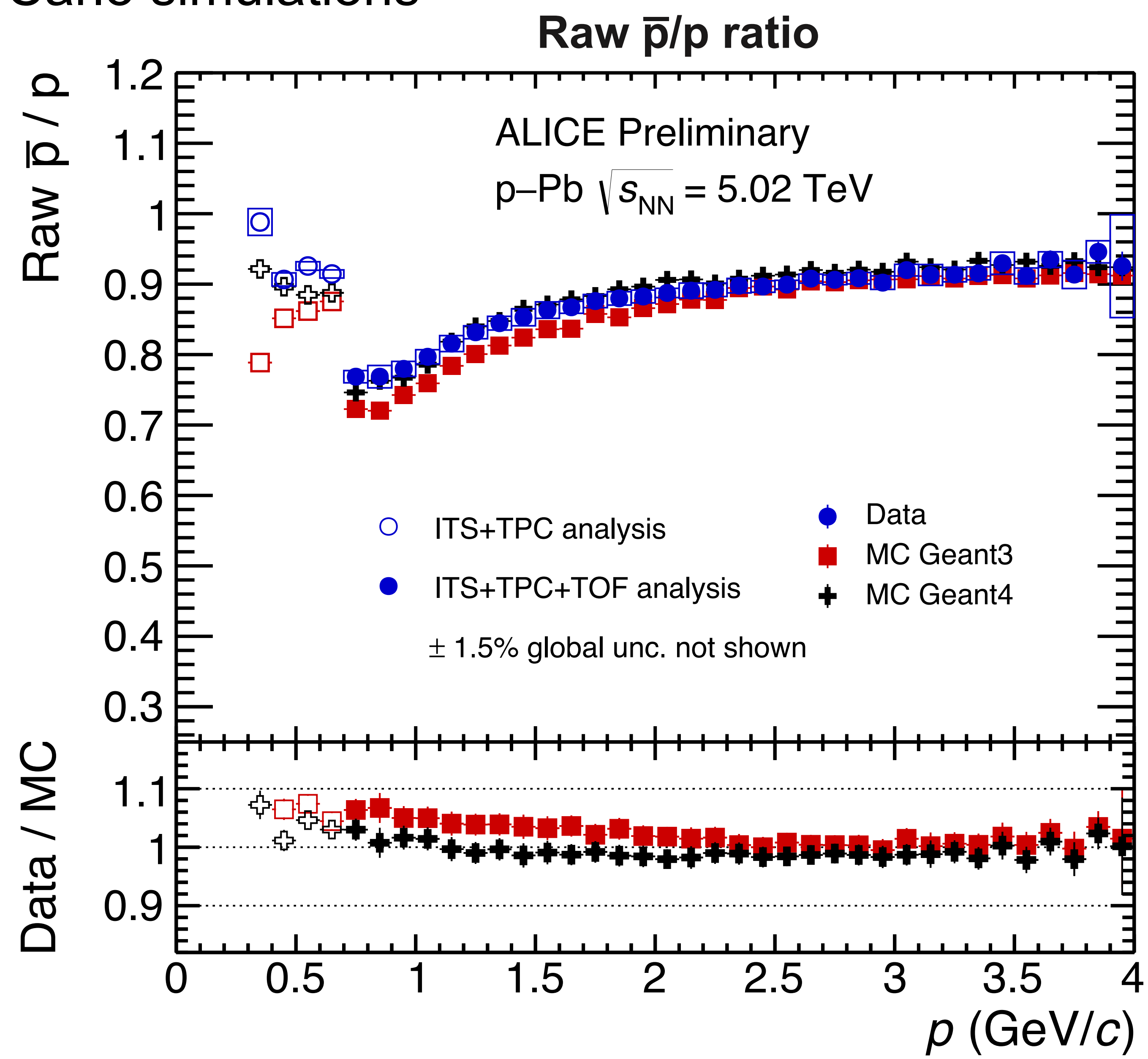
$\bar{p}$/p ratio compared to MC simulations

Raw $\bar{p}$/p ratio compared to ALICE Monte Carlo simulations

- Higher loss of anti-protons in detector material as expected

Monte Carlo data: detailed simulation of ALICE detector performance

- Same reconstruction algorithms as for experimental data
- Propagation of (anti-)protons and interaction with matter with Geant4
- **Geant4 version used: 10.4.2, FTFP_INCLXX_EMV physics list**



Geant4 in good agreement with experimental data in whole investigated momentum range

d̄/d ratio compared to MC simulations

Raw d̄/d ratio compared to ALICE Monte Carlo simulations

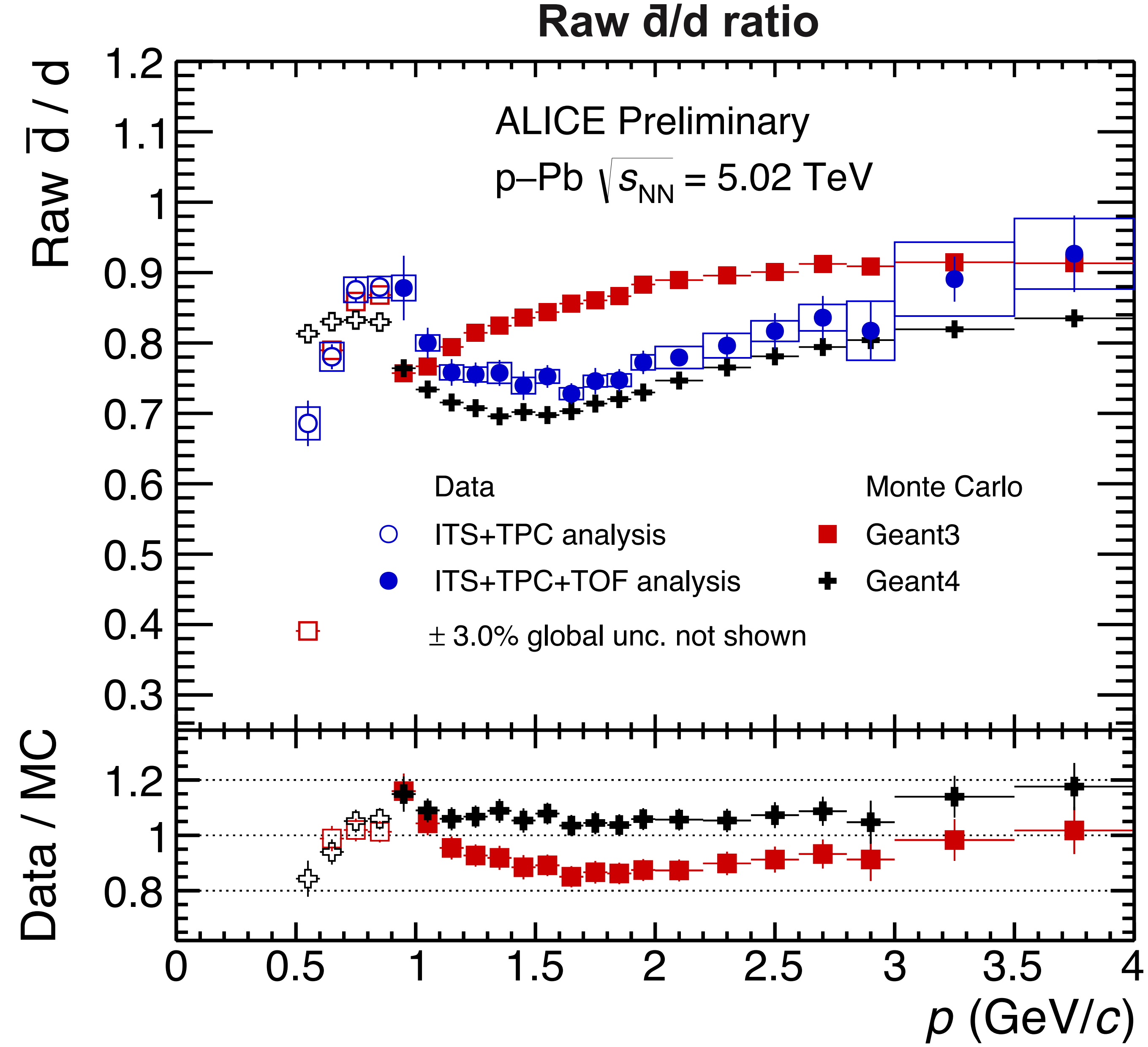
- Higher loss of anti-deuterons in detector material as expected

Monte Carlo data: detailed simulation of ALICE detector performance

- Same reconstruction algorithms as for experimental data
- Propagation of (anti-)deuterons and interaction with matter with Geant4
- **Geant4 version used: 10.4.2, FTFP_INCLXX_EMV physics list**

Good description of experimental results with Geant4-based simulations

- *Vary σ_{inel} (d̄) in Geant4-based simulations until MC ratio is ±1σ or ±2σ away from experimental ratio → constraints on σ_{inel}(d̄)*



Geant4 inelastic c.s. for anti-nuclei

Parameterisations are based on Glauber calculation as described in [1]

- Direct Glauber calculations in GEANT4 in a run-time mode are too heavy
  → parametrise Glauber calculations with [2, 3] :

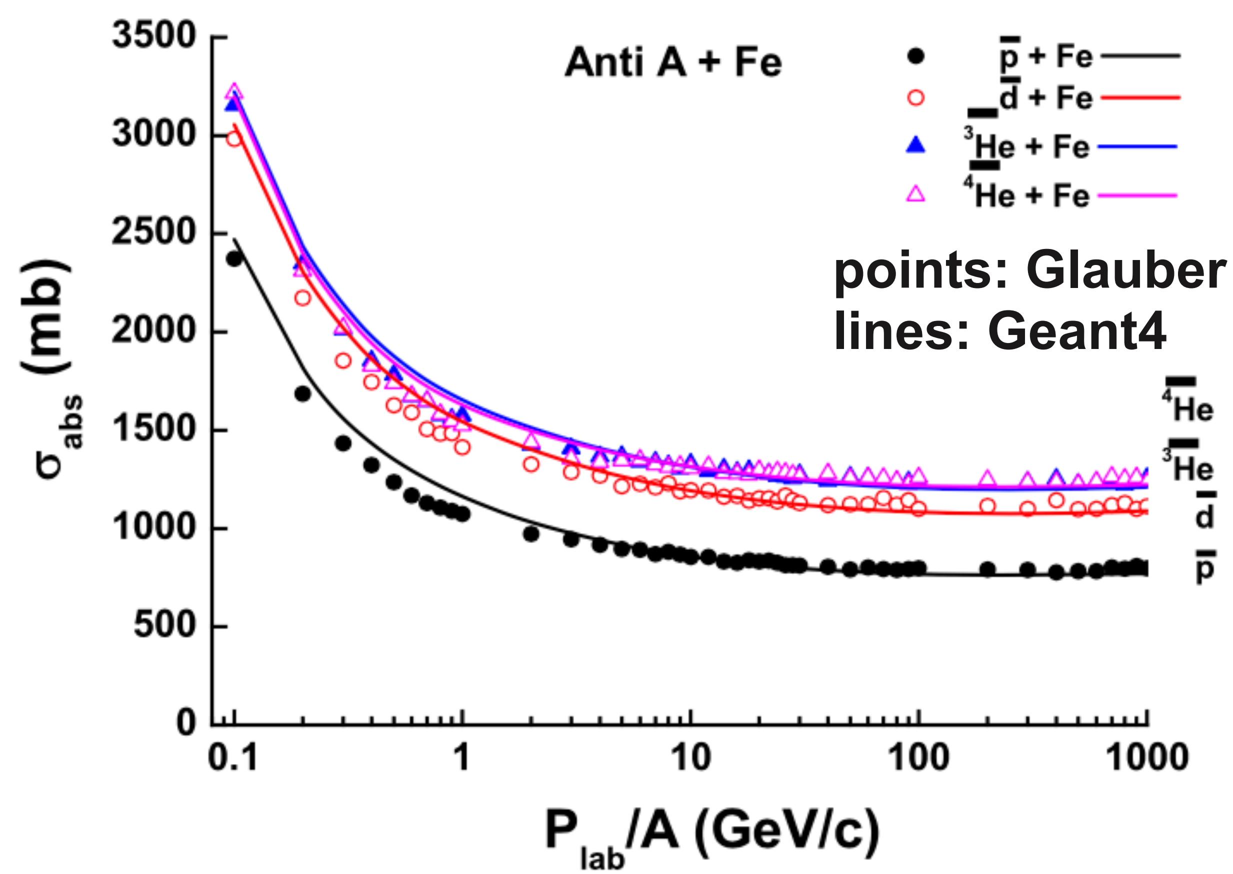
$$\sigma_{hA}^{tot} = 2\pi R_A^2 \ln\left[1 + \frac{A\sigma_{hN}^{tot}}{2\pi R_A^2}\right]$$

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

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

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

Phys. Lett. B705, 235 (2011)



Implemented in G4ComponentAntiNuclNuclearXS::GetInelasticElementCrossSection()

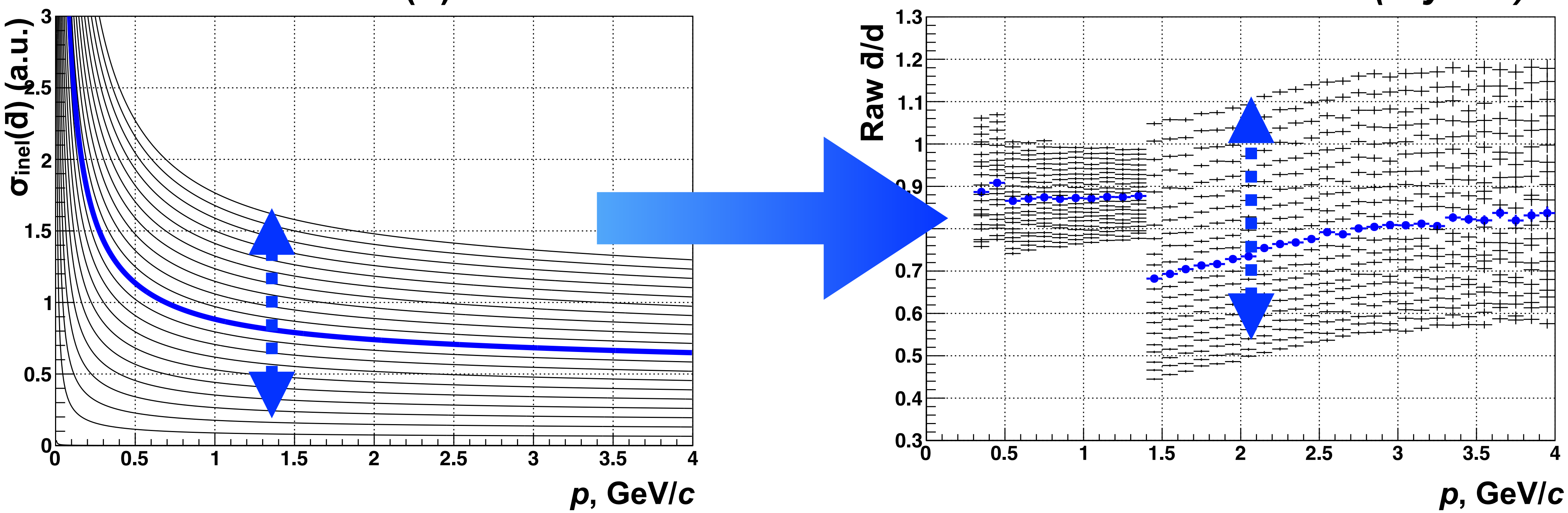
[1] Phys. Lett. B705, 235 (2011)
[2] Eur. Phys. J. C 62 (2009) 399
[3] Nucl. Instrum. Methods B 267 (2009) 2460

Variations of σ_{inel} in MC simulations

Vary the σ_{inel} in Geant4 to see the effect on raw ratios

- Almost linear dependence between σ_{inel} and raw ratio has been found

Variations of $\sigma_{inel}(\bar{d})$ in Geant4 **Reconstructed $\bar{d}$/d ratio *(toy MC)***



Vary σ_{inel} until MC ratio is ±1σ/±2σ away from experimental data

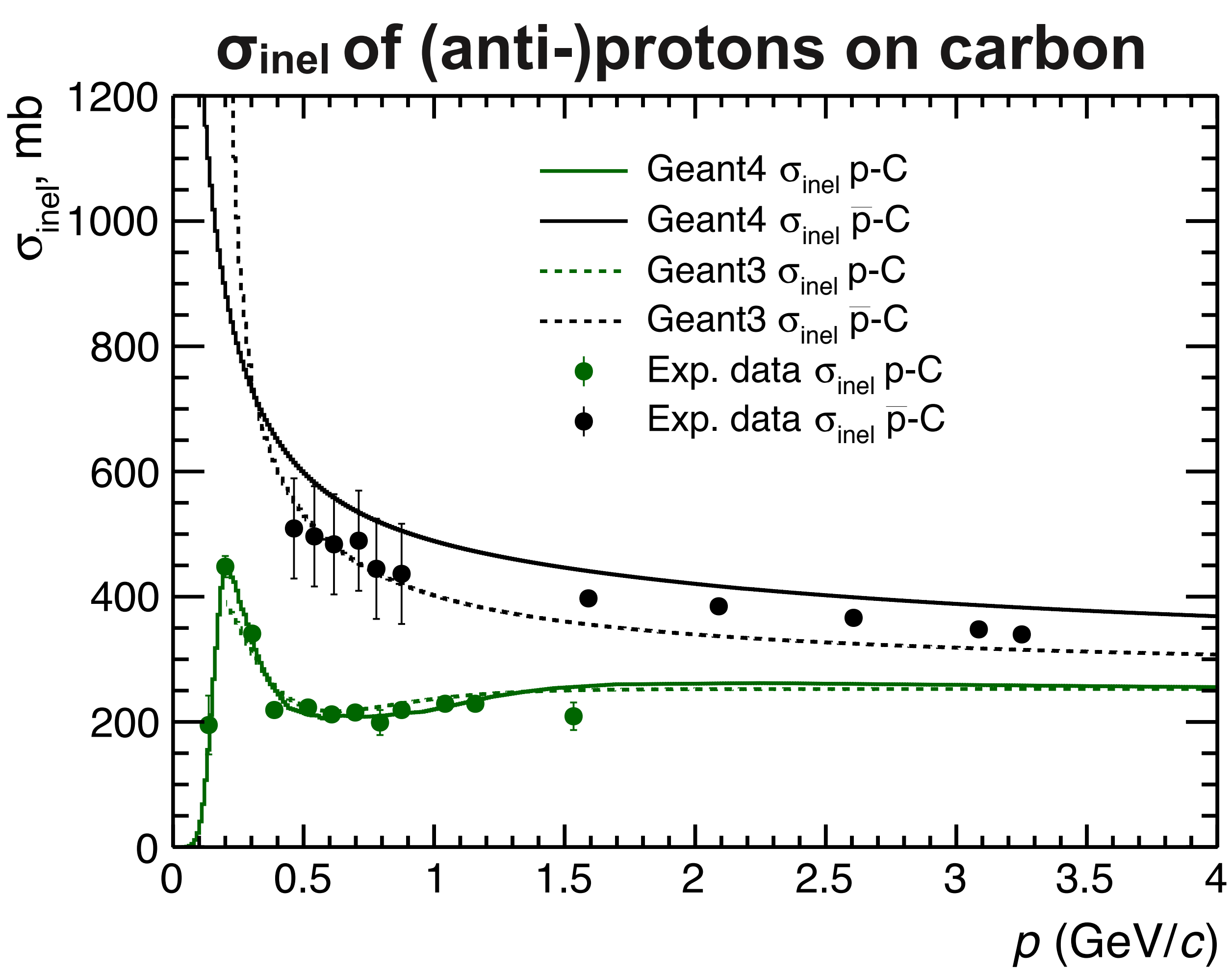
1σ: all uncertainties on ratio added in quadrature

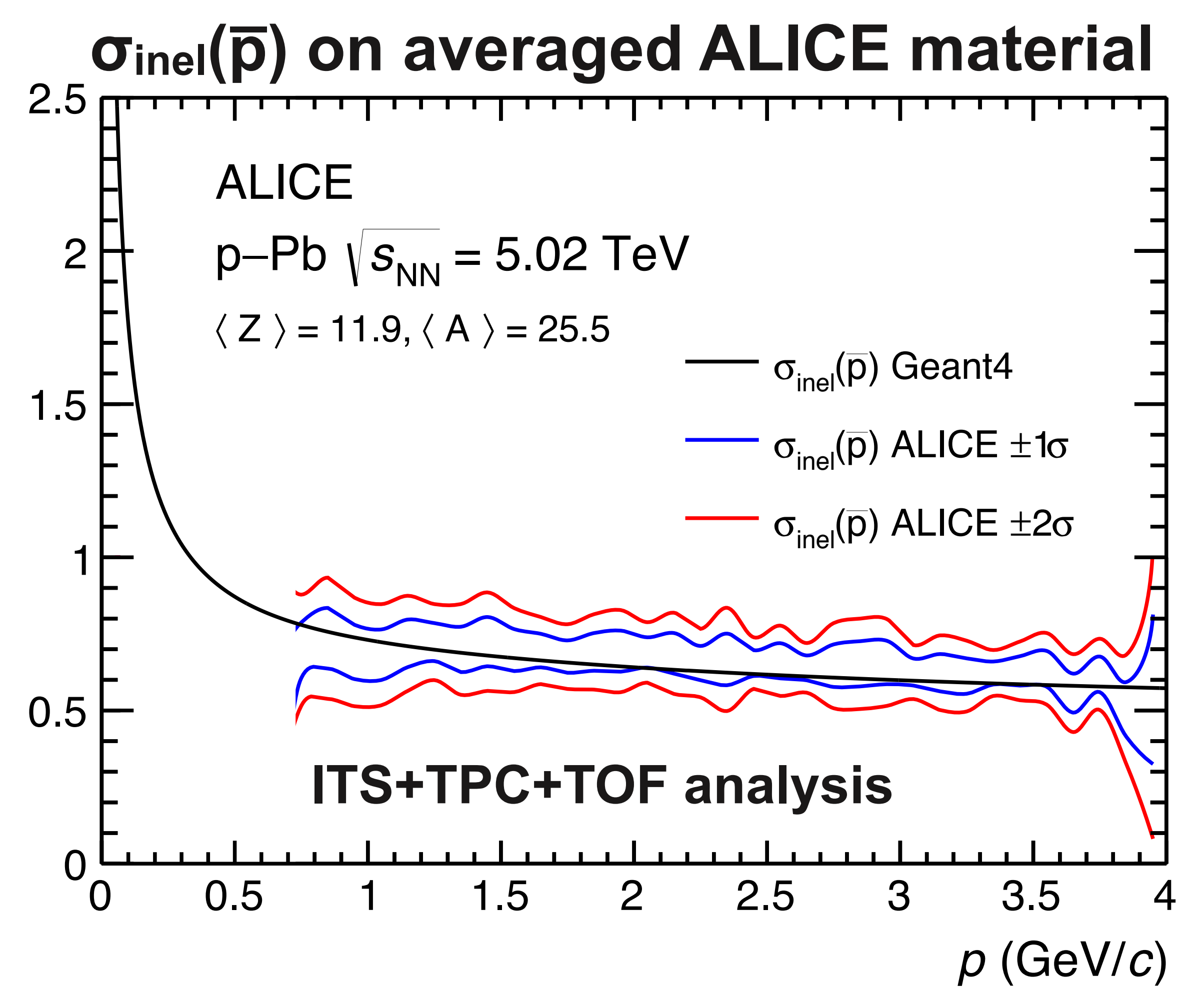
- Stat. and syst. uncertainties of experimental data
- Primordial anti-matter/matter ratio produced at the primary collision vertex
  - $\bar{p}/p = 0.984 \pm 0.015$, $\bar{d}/d = 0.968 \pm 0.030$
- Variations of σ_{inel}(p) and σ_{inel}(d) within the precision of Geant4 description (in back-up)
- Variations of all elastic cross-sections by ±20%

Constraints for $\sigma_{inel}(\bar{p})$ with ALICE material

$\sigma_{inel}(\bar{p})$ has been estimated for an “averaged element” of ALICE detector material

- Good agreement with Geant4 parameterisations as expected
- Several measurements available for $\sigma_{inel}(\bar{p})$ on different materials, good description with Geant4 parameterisations



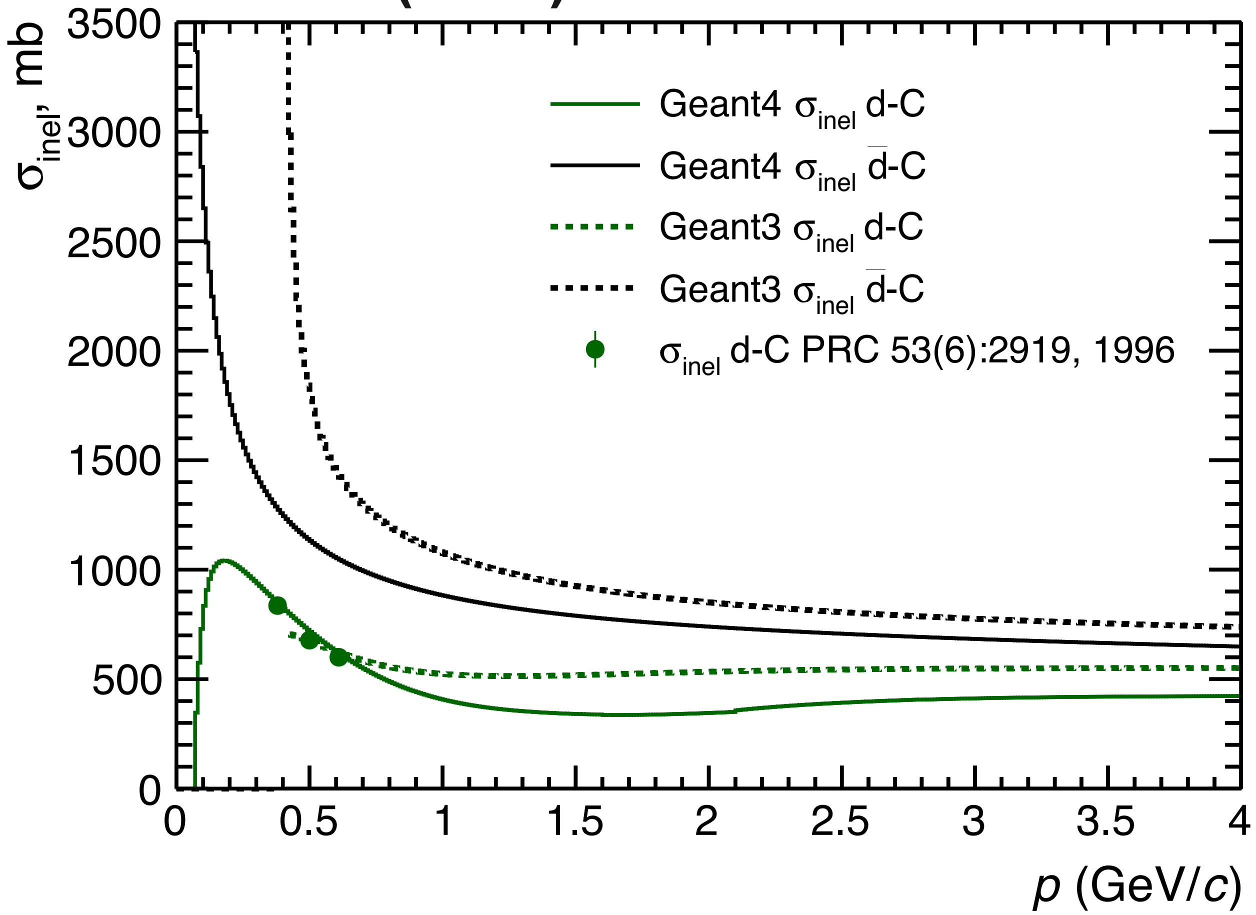


Constraints for $\sigma_{inel}(\bar{d})$ with ALICE material

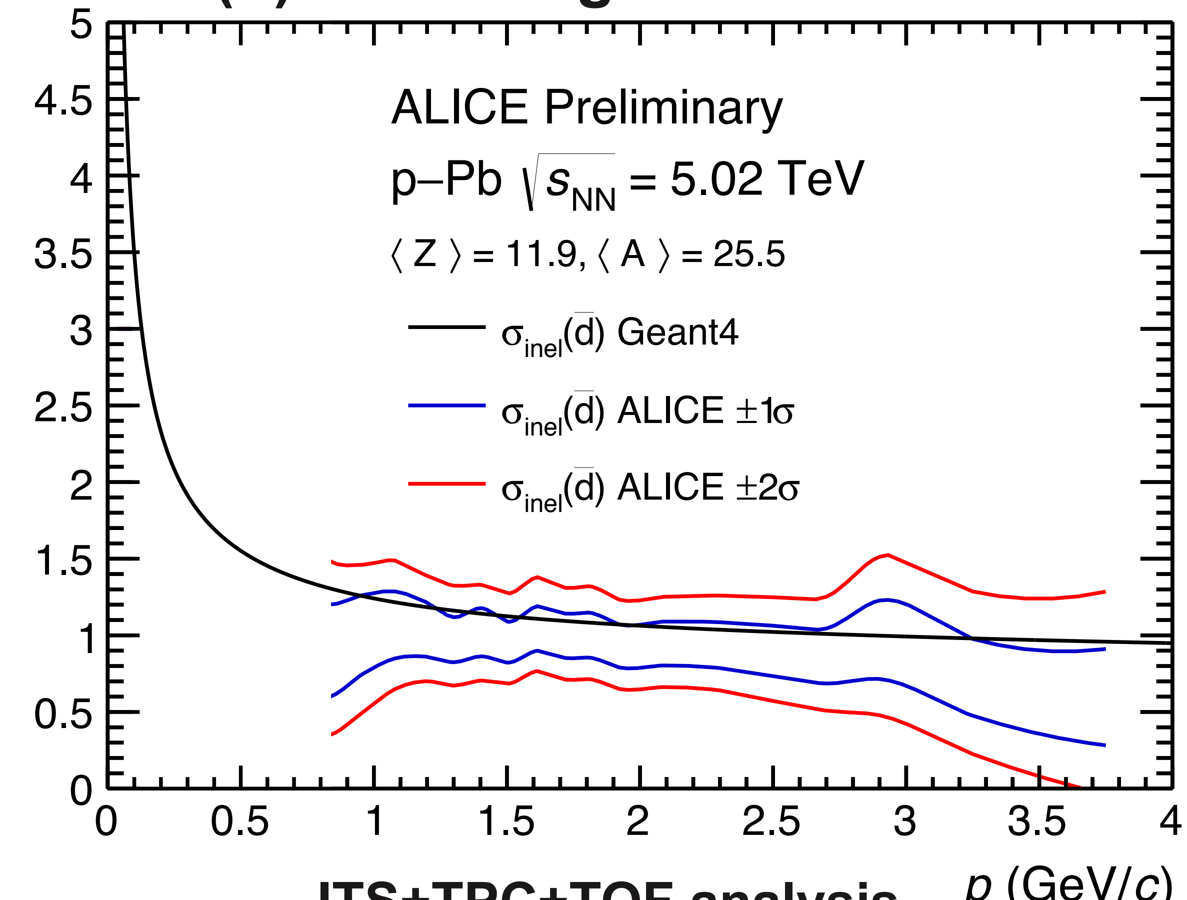
$\sigma_{inel}(\bar{d})$ has been estimated for an “averaged element” of ALICE detector material

- Good agreement with Geant4 parameterisations for ITS+TPC+TOF analysis ($0.9 < p_{\bar{d}} < 4.0$ GeV/c)

σ_{inel} of (anti-)deuterons on carbon



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



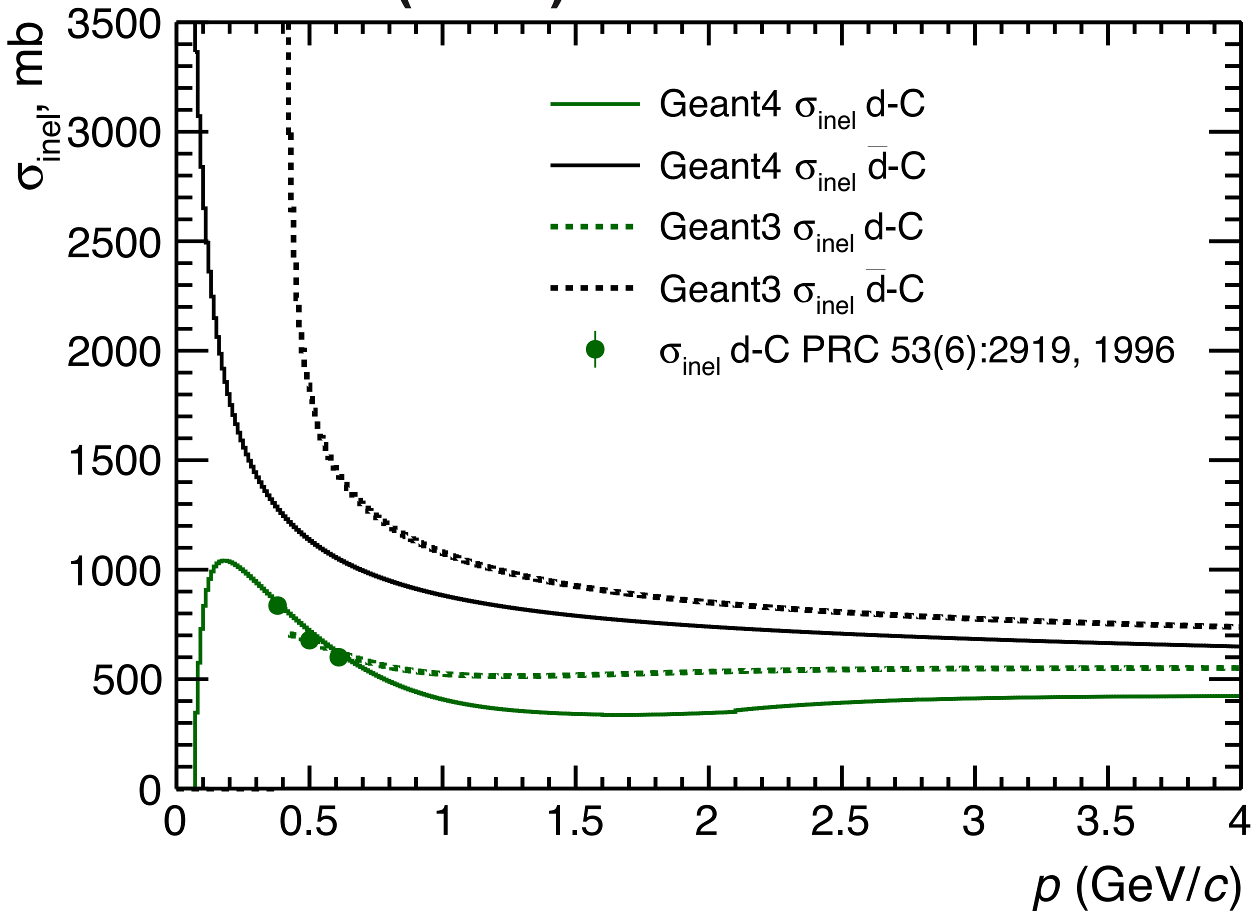
ITS+TPC+TOF analysis

Constraints for $\sigma_{inel}(\bar{d})$ with ALICE material

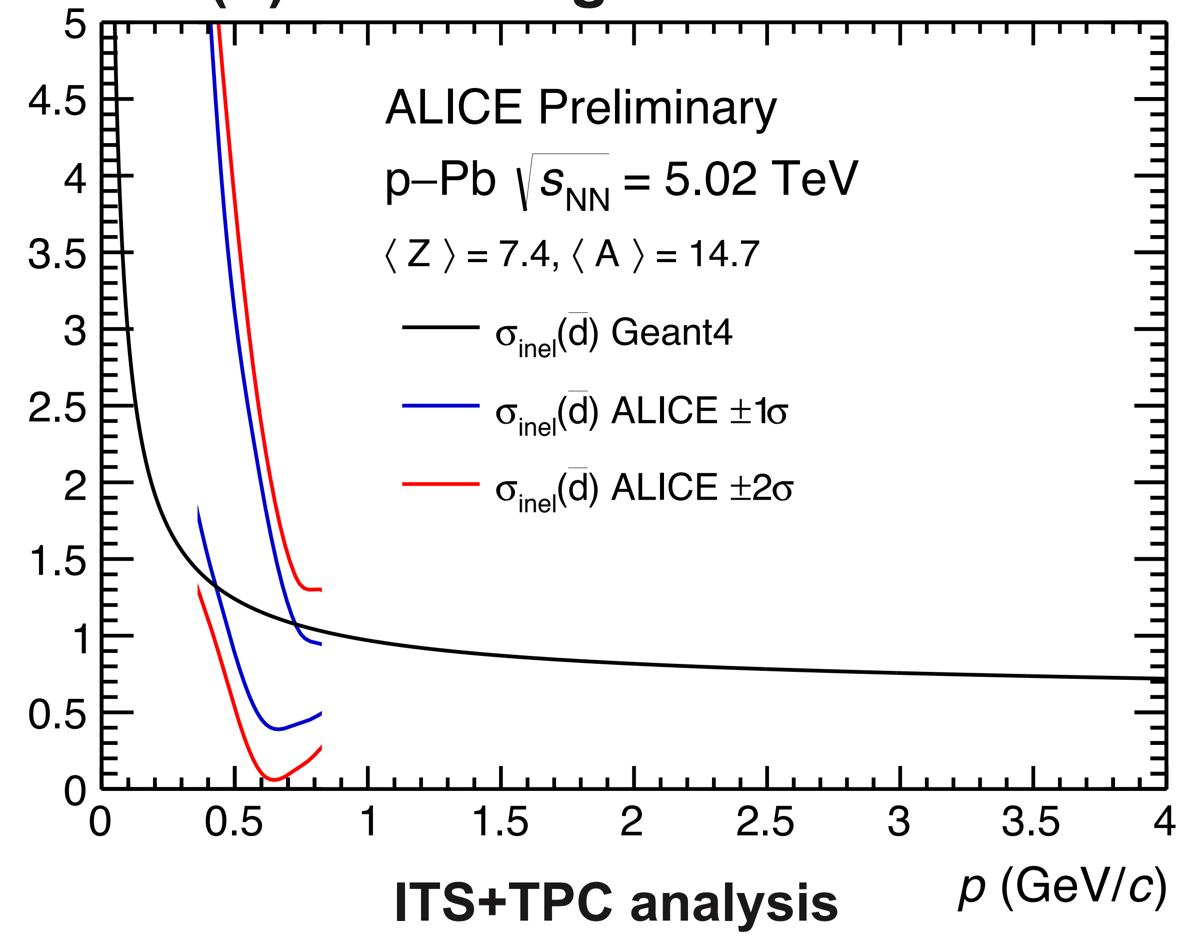
$\sigma_{inel}(\bar{d})$ has been estimated for an “averaged element” of ALICE detector material

- Good agreement with Geant4 parameterisations for ITS+TPC+TOF analysis ($0.9 < p_{\bar{d}} < 4.0$ GeV/c)
- *Hint for steeper rise of $\sigma_{inel}(\bar{d})$ at low momentum!*

σ_{inel} of (anti-)deuterons on carbon



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



Conclusions and remarks

ALICE experiment at CERN LHC as a tool to study anti-deuteron inelastic c.s.

Analysis of raw reconstructed $\bar{p}/p$ and $\bar{d}/d$ ratios

- Good description of results with Geant4-based simulations

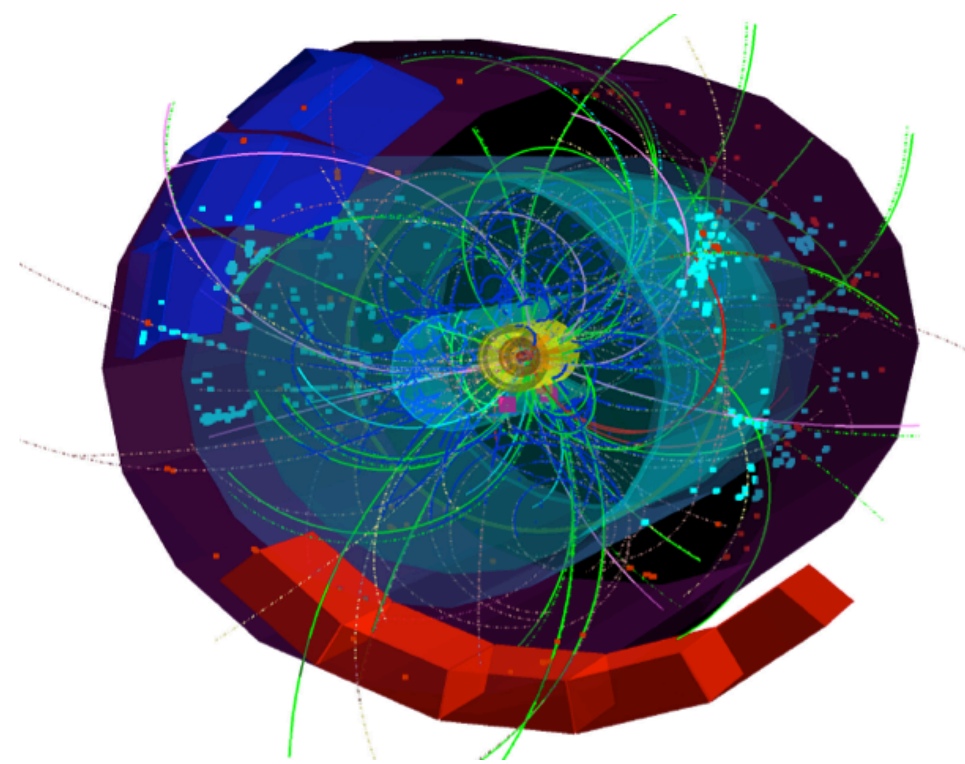
- Constrain $\sigma_{inel}(\bar{p})$ and $\sigma_{inel}(\bar{d})$ via comparison with Geant4-based Monte Carlo
    - Results for $\sigma_{inel}(\bar{p})$ in good agreement with existing data
    - ***Constraints on $\sigma_{inel}(\bar{d})$ point at steeper rise at low momentum***

Work in progress towards the final results

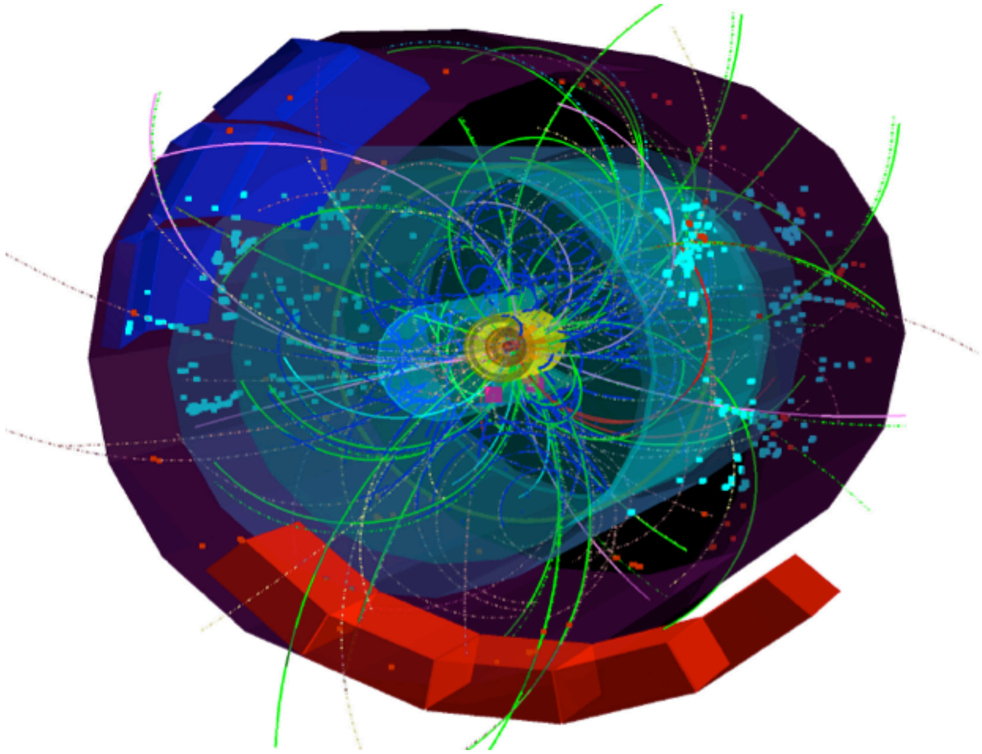
- Paper in preparation (currently under internal ALICE review)

Another request from ALICE: ***proper treatment of hypertriton in the propagation***

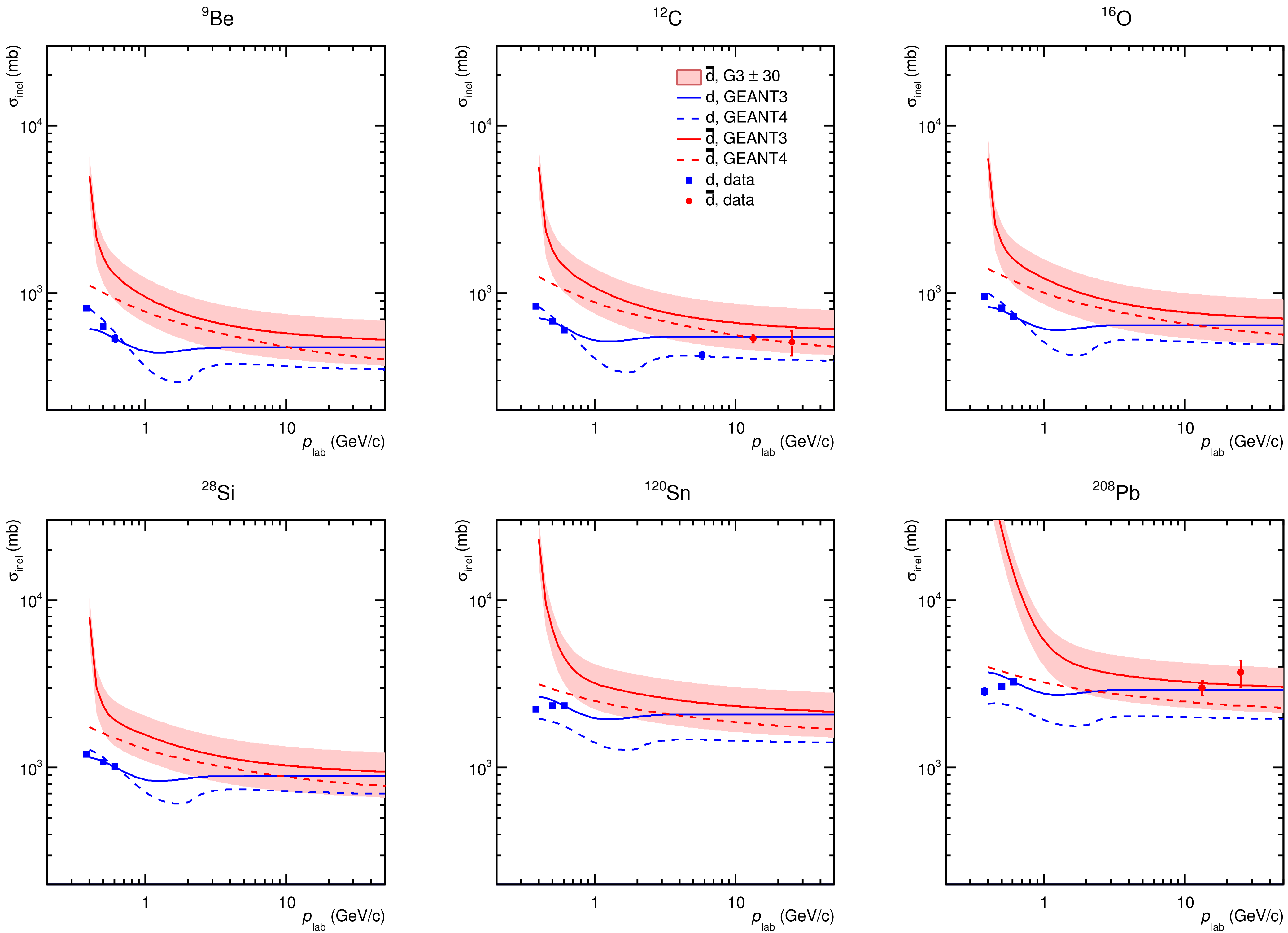
- Currently treated as a normal nucleus, but from its structure is more like a halo-nucleus (→ enhanced energy loss)
- If available, similar study as presented today will be possible for hypertriton in the future



Back-up slides



GEANT3/4 cross-sections for (anti-)deuterons



GEANT3 inelastic cross-sections

- Empirical parametrization based on Moiseev‘s formula:

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

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

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

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

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

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

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

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

Geant4: total antip-p cross-section

Total antip-p cross-section parametrised as [1-3]:

$$\sigma_{\bar{p}p}^{tot} = \sigma_{asmpt}^{tot}\left[1 + \frac{C}{\sqrt{s-4m_N^2}}\frac{1}{R_0^3}\left(1+\frac{d_1}{s^{0.5}}+\frac{d_2}{s^1}+\frac{d_3}{s^{1.5}}\right)\right]$$

$$\sigma_{asmpt}^{tot} = 36.04 + 0.304\ \ (log(s/33.0625))^2$$

, where m_N is the nucleon mass (GeV), $s = E_{cm}^2$ (GeV^2), and

$$R_0^2 = 0.40874044\sigma_{asymp}^{tot} - B(s)\ \mathrm{GeV}^{-2}$$

$$B(s) = b_0 + b_1\left[\ln(\sqrt{s}/20.74)\right]^2\ \mathrm{GeV}^{-2}$$

$$b_0 = 11.92 \pm 0.15\ \mathrm{GeV}^{-2},$$

$$b_2 = 0.3036 \pm 0.0185\ \mathrm{GeV}^{-2}$$

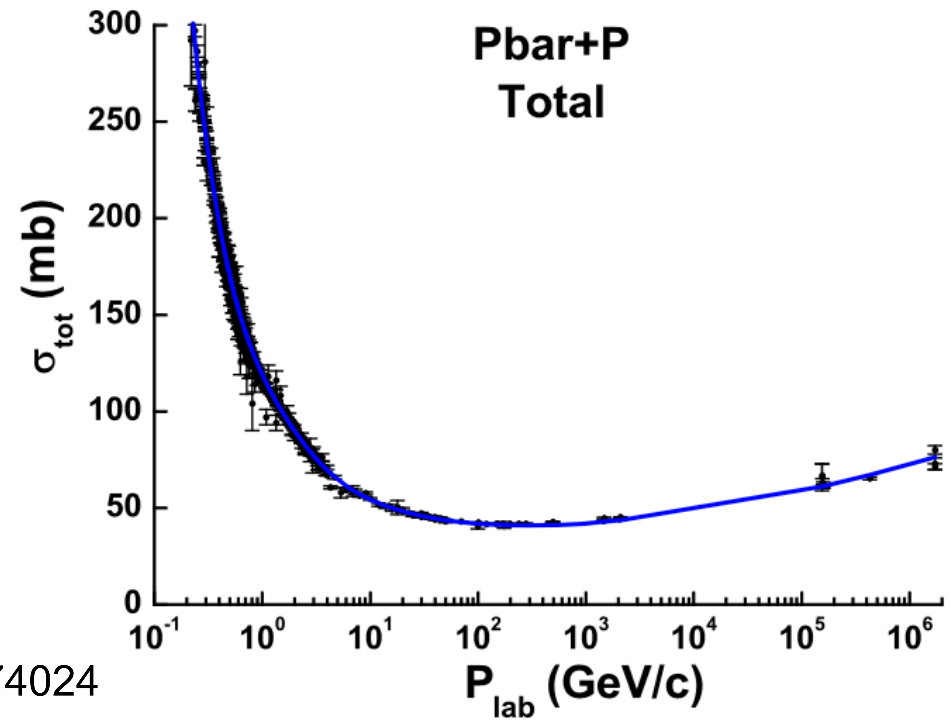
Parameters C, d_1, d_2 and d_3 are determined from fit to exp. data [PDG]

$$C = 13.55 \pm 0.09\ \mathrm{GeV}^{-2},$$

$$d_1 = -4.47 \pm 0.02\ \mathrm{GeV},$$

$$d_2 = 12.38 \pm 0.05\ \mathrm{GeV}^2,$$

$$d_3 = -12.43 \pm 0.05\ \mathrm{GeV}^3.$$



1. J.R. Cudell, et al., COMPLETE Collaboration, Phys. Rev. D 65 (2002) 074024
2. M. Ishida, K. Igi, Phys. Rev. D 79 (2009) 096003.
3. A.A. Arkhipov, hep-ph/9909531, hep-ph/9911533, 1999

Geant4: elastic antip-p cross-section

Parametrisation for elastic antip-p cross-section [1-3]:

$$\sigma_{\bar{p}p}^{el} = \sigma_{asmpt}^{el} \left[1 + \frac{C}{\sqrt{s - 4m_N^2}} \frac{1}{R_0^3} \left(1 + \frac{d_1}{s^{0.5}} + \frac{d_2}{s^1} + \frac{d_3}{s^{1.5}}\right)\right]$$

Same formula, but with different parameters σ_{asymp} and C, d_1, d_2, d_3

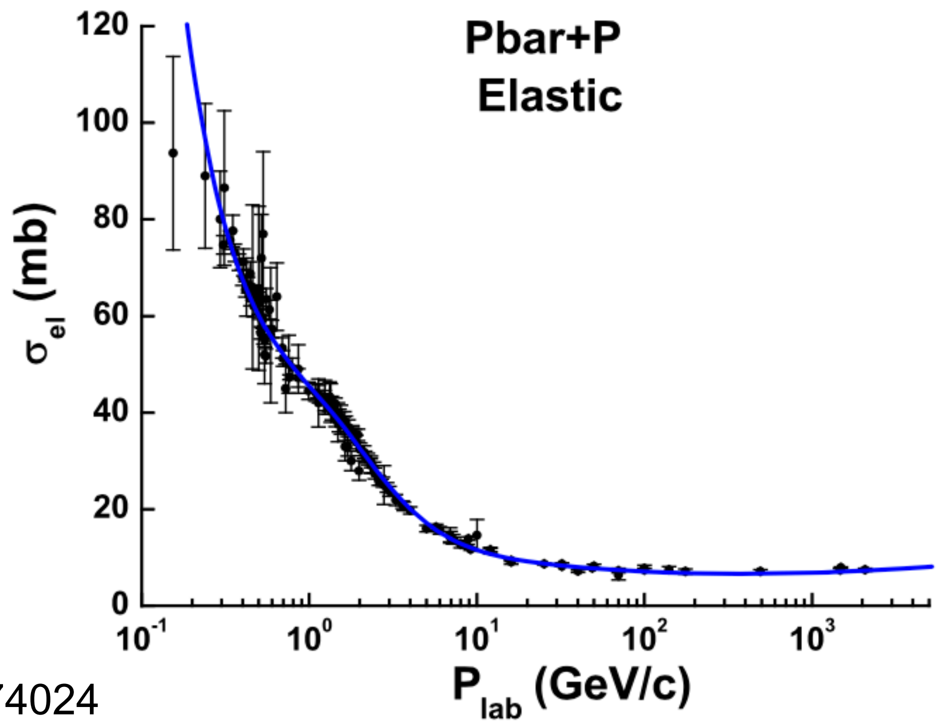
$$\sigma_{asmpt}^{el} = 4.5 + 0.101 \ (log(s/33.0625))^2$$

$C = 59.3 \pm 2.0 \text{ GeV}^{-2}$,

$d_1 = -6.95 \pm 0.09 \text{ GeV}$,

$d_2 = 23.54 \pm 0.29 \text{ GeV}^2$,

$d_3 = -25.34 \pm 0.36 \text{ GeV}^3$.

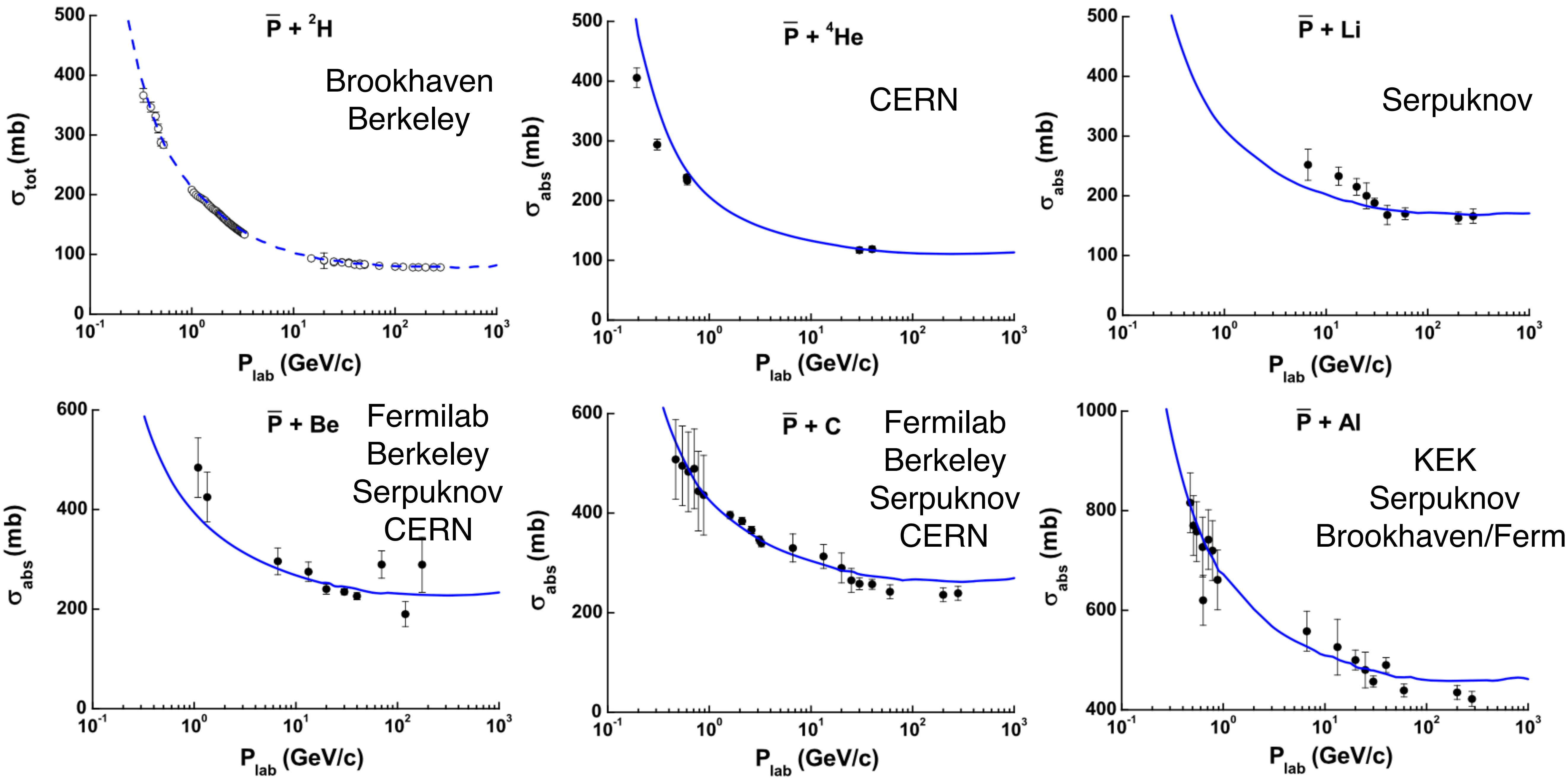


1. J.R. Cudell, et al., COMPLETE Collaboration, Phys. Rev. D 65 (2002) 074024
2. M. Ishida, K. Igi, Phys. Rev. D 79 (2009) 096003.
3. A.A. Arkhipov, hep-ph/9909531, hep-ph/9911533, 1999

Phys. Lett. B705, 235 (2011)

Geant4: Glauber calculations vs data

Lines are Glauber calculations, points are various exp. data



Parametrisation used in GEANT4

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

$$\sigma_{hA}^{tot} = 2\pi R_A^2 \ln\left[1 + \frac{A\sigma_{hN}^{tot}}{2\pi R_A^2}\right]$$

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

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

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

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

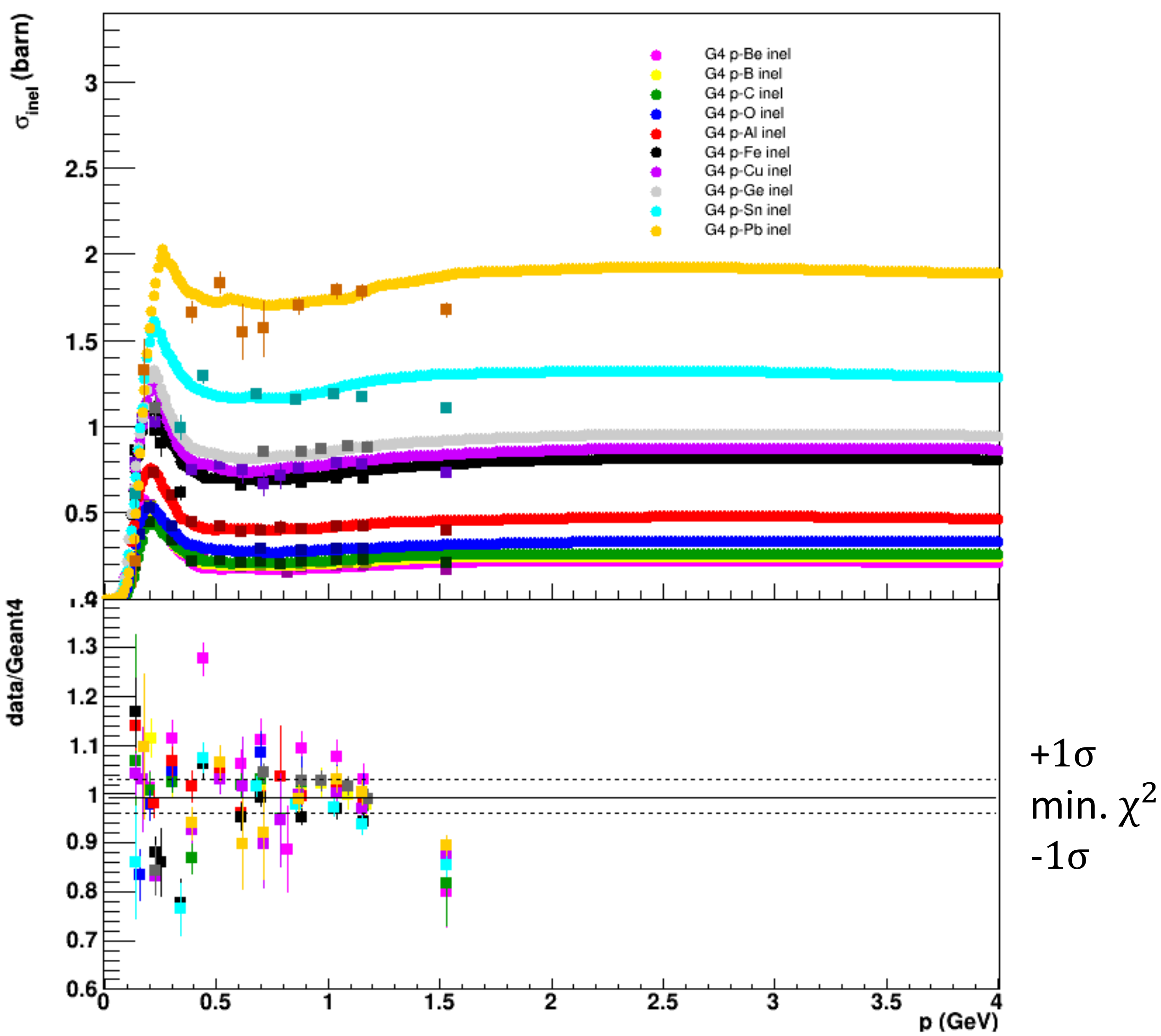
$$\bar{p}A\ R_A = 1.31A^{0.22} + 0.90/A^{1/3}\ (\text{fm}),$$
$$\bar{d}A\ R_A = 1.38A^{0.21} + 1.55/A^{1/3}\ (\text{fm}),$$
$$\bar{t}A\ R_A = 1.34A^{0.21} + 1.51/A^{1/3}\ (\text{fm}),$$
$$\bar{\alpha}A\ R_A = 1.30A^{0.21} + 1.05/A^{1/3}\ (\text{fm}).$$

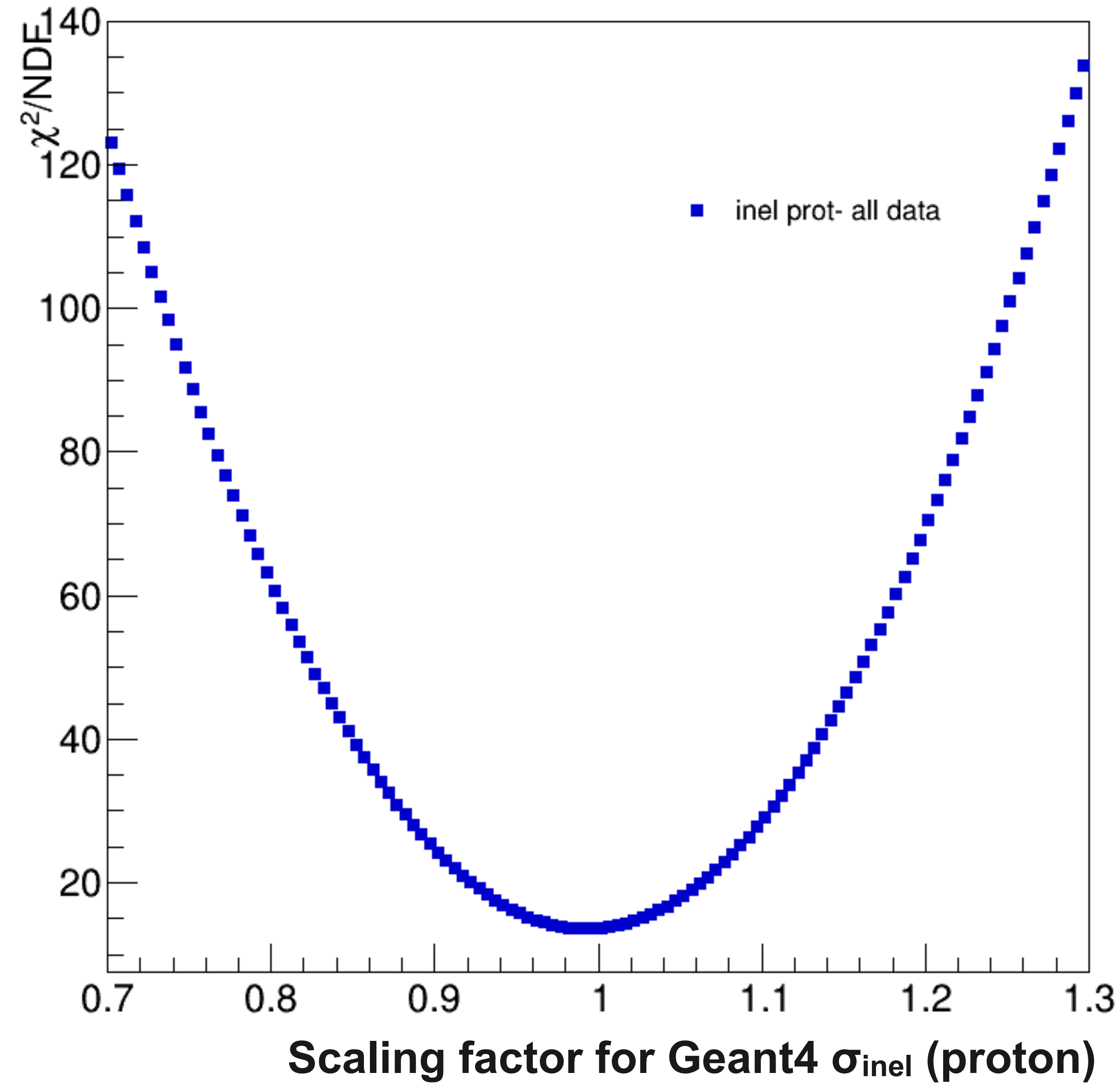
1. V.M. Grichine, Eur. Phys. J. C 62 (2009) 399, Nucl. Instrum. Methods B 267 (2009) 2460

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 : $\mathbf{0.9925^{+0.0375}_{-0.0325}}$

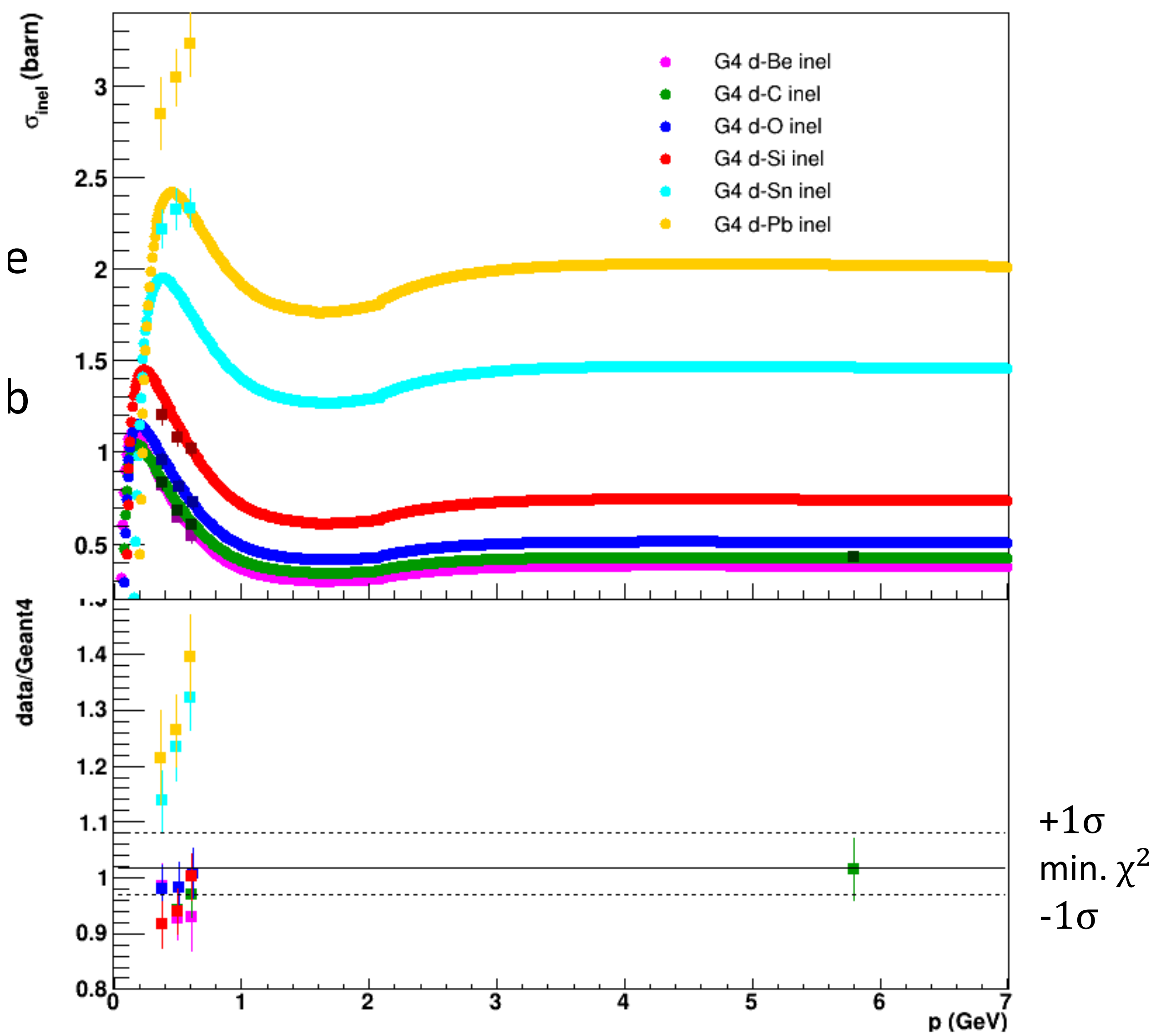


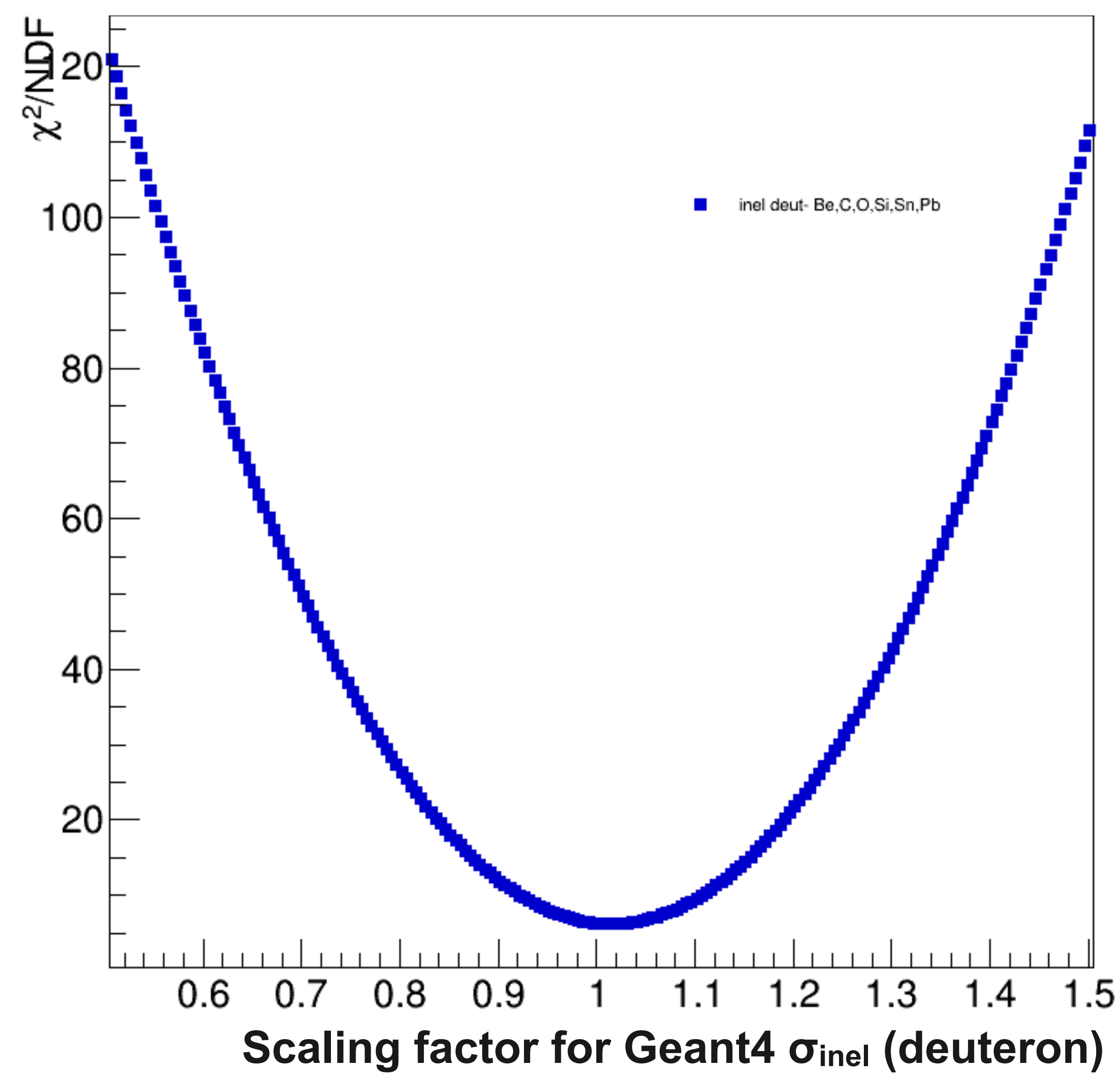


Uncertainty due to σ_{inel} (deuteron)

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 $\pm1\sigma$: **1.0175 $^{+0.0625}_{-0.0475}$**
  - Agreement is worse for Sn and Pb





Total uncertainties on raw ratios

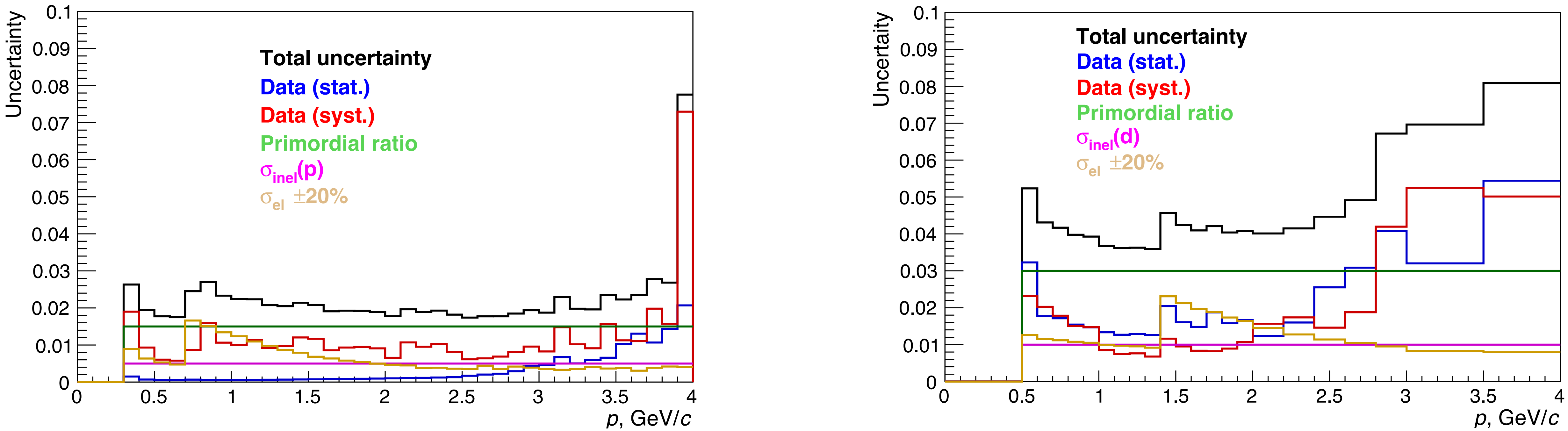
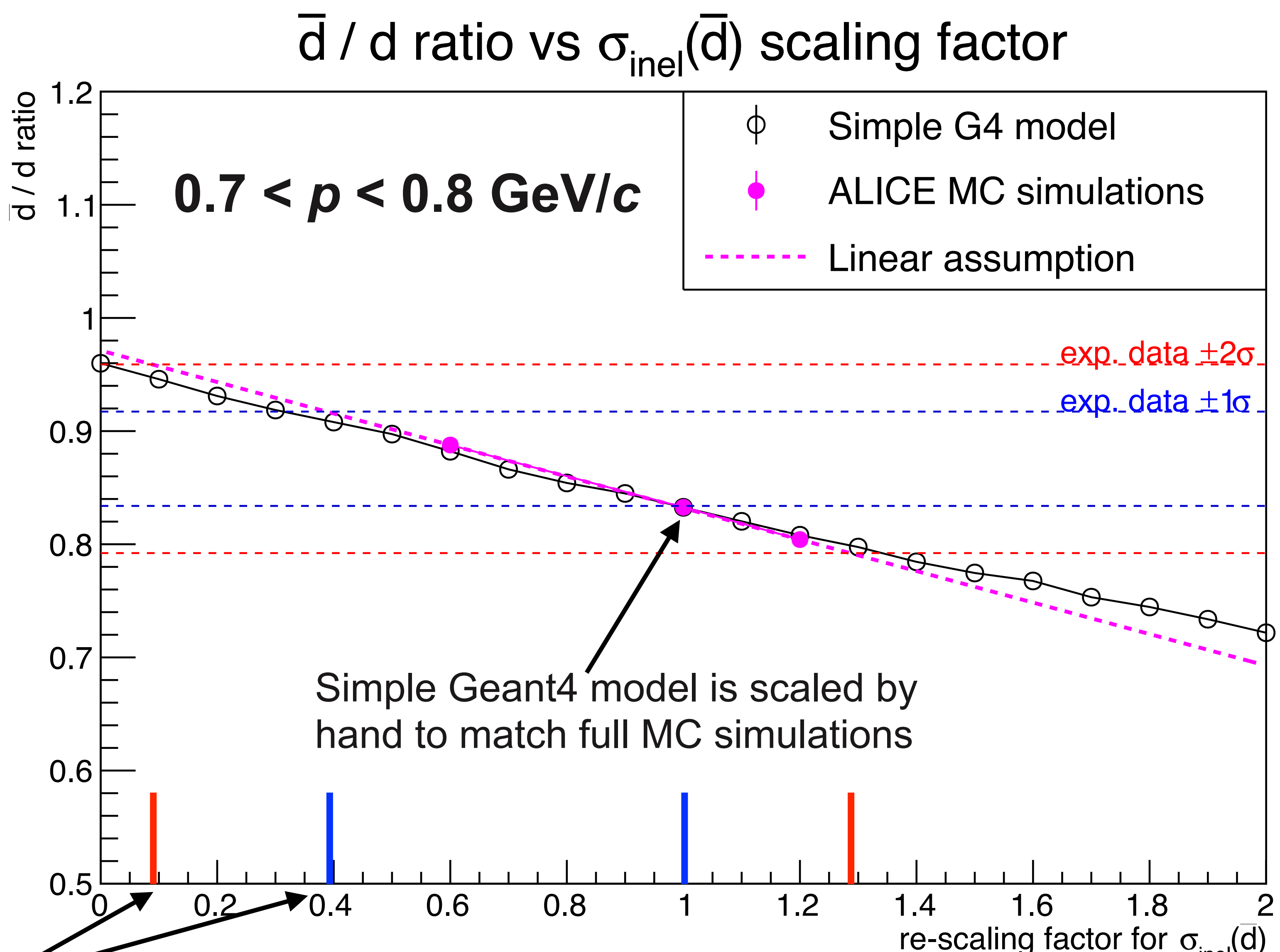


Fig. 62: Summary of all uncertainties used for the constraints on $\sigma_{inel}(\bar{\mathrm{p}})$ (left) and on $\sigma_{inel}(\bar{\mathrm{d}})$ (right). For the total uncertainty, individual sources are added in quadrature.

(Linear) dependence between d̄ / d and σ_{inel}(d̄)

- Vary σ_{inel}(d̄) in simple Geant4 model from 0 to 200%
  - Central value is scaled by hand to match full MC simulations
  - Relative change of d̄ / d is in good agreement with full MC
- Almost no deviation from linear dependence in whole σ_{inel}(d̄) range
- Constraints on σ_{inel}(d̄) are extracted from full MC simulations (magenta line)



Resulting constrains on σ_{inel}(d̄)

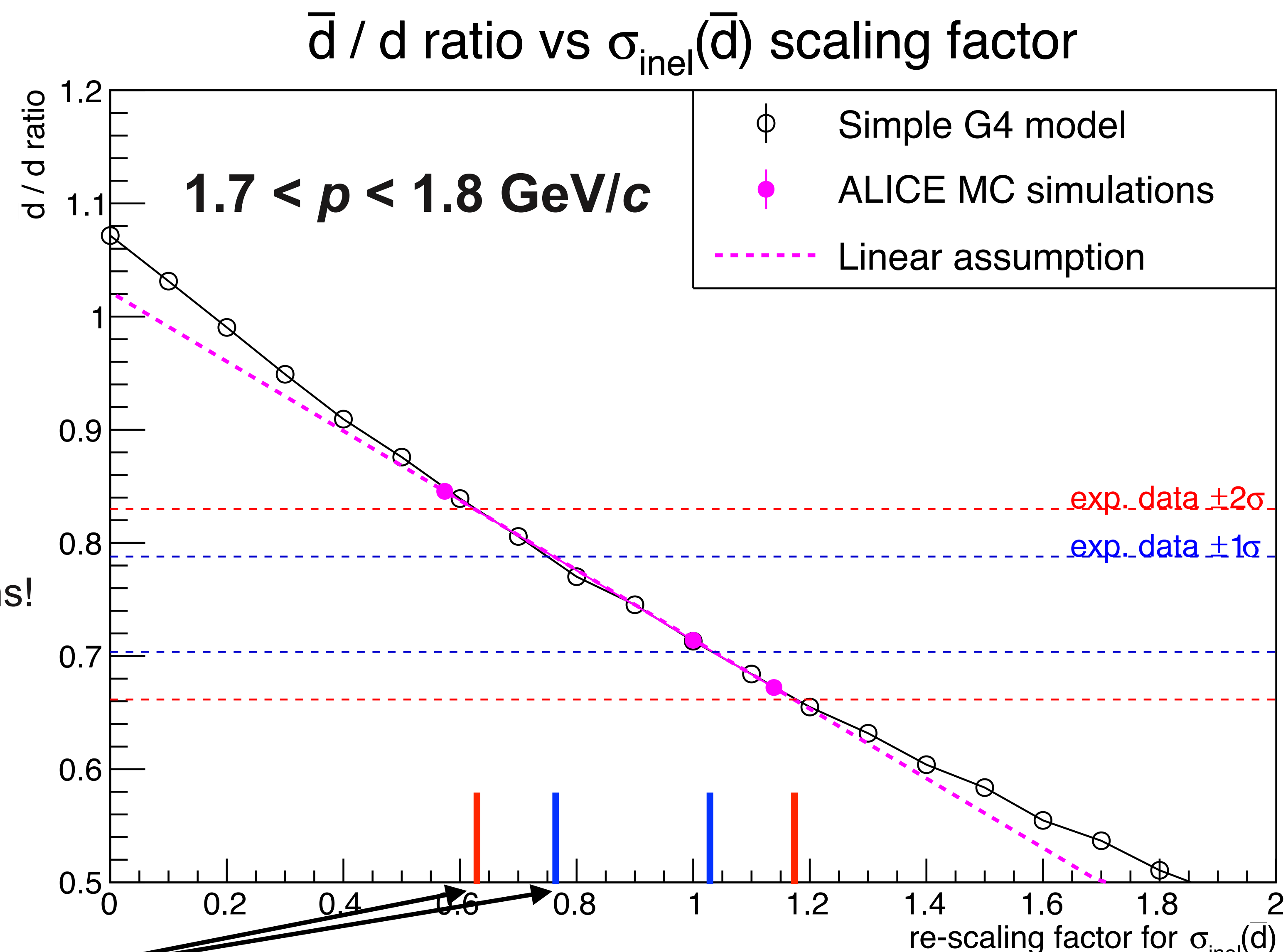
ALICE

(Linear) dependence between d̄ / d and σ_{inel}(d̄)

- Vary σ_{inel}(d̄) in simple Geant4 model from 0 to 200%
- Some deviation from linear dependence, but very close to linear inside ±2σ limits
- Constraints on σ_{inel}(d̄) are extracted from full MC simulations (magenta line)

Ratio is much more sensitive to σ_{inel}(d̄) variations than at low *p*! (much steeper slope)

- **Motivation for the TOF (anti-)deuteron analysis starting from lower *p***



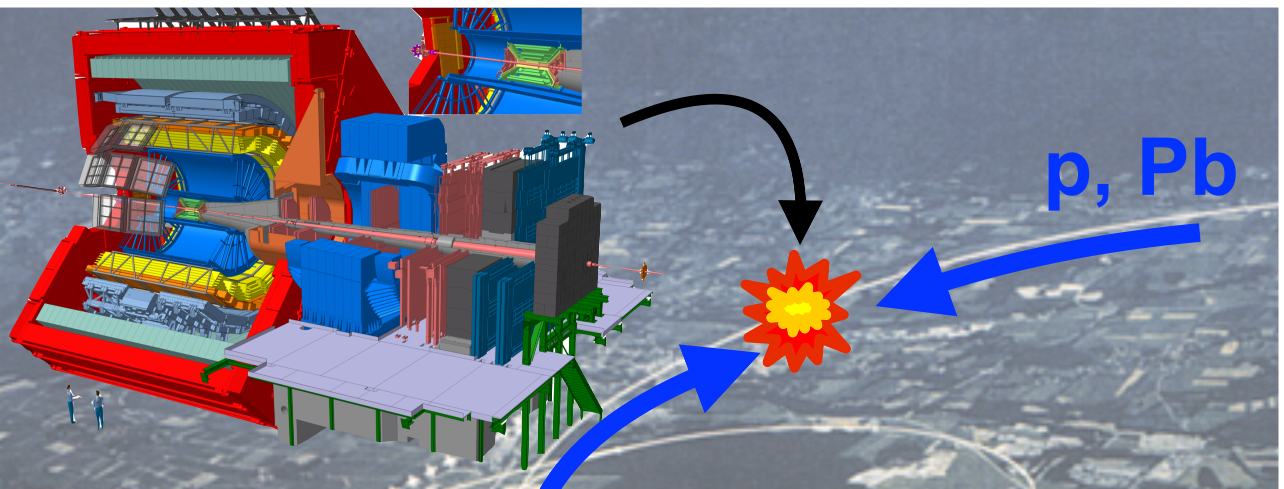
Simple Geant4 model is **NOT** scaled by hand to match full MC simulations!

Resulting constrains on σ_{inel}(d̄)

Large Hadron Collider as an anti-matter factory

At LHC energies, *matter and anti-matter are produced in almost equal amounts*

- (Anti-)deuterons interact inelastically with detector material - this can be quantified!

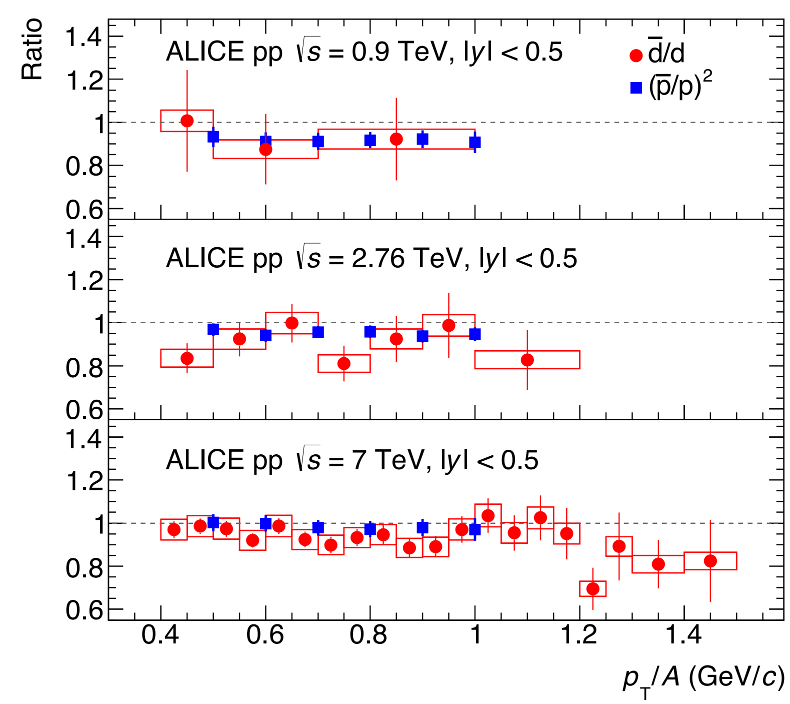


This talk: results from p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, ~300 M events

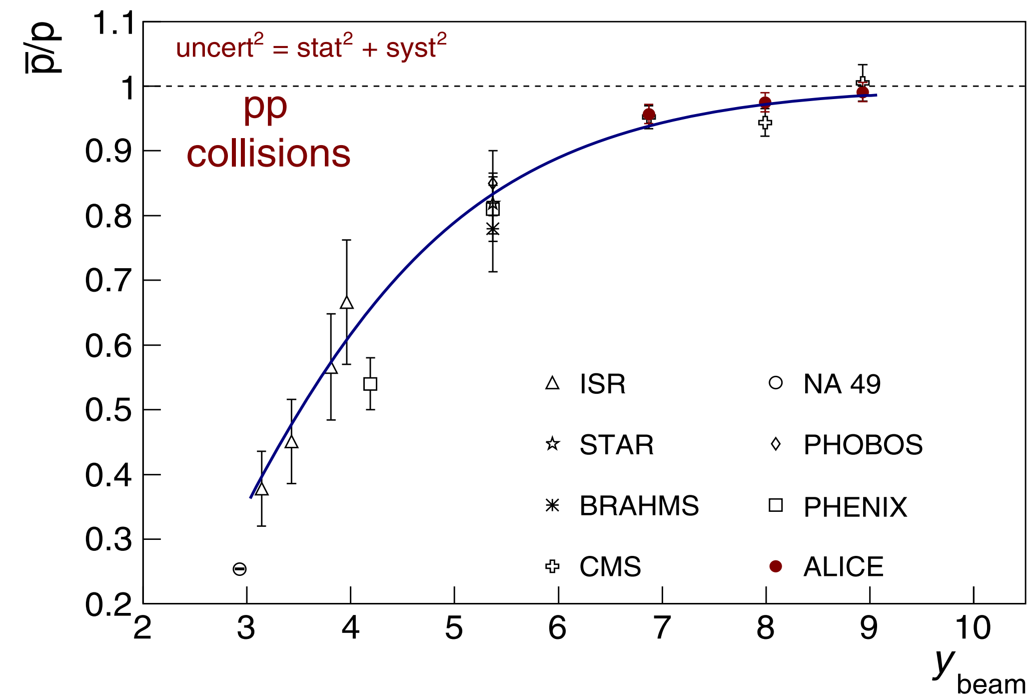
Extrapolations for $\sqrt{s_{NN}}$ = 5.02 TeV:

- $\bar{p}/p$: **R = 0.984 ± 0.015**
- → $\bar{d}/d$: **R = 0.968 ± 0.030** ($\bar{d}/d \sim (\bar{p}/p)^2$)

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



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

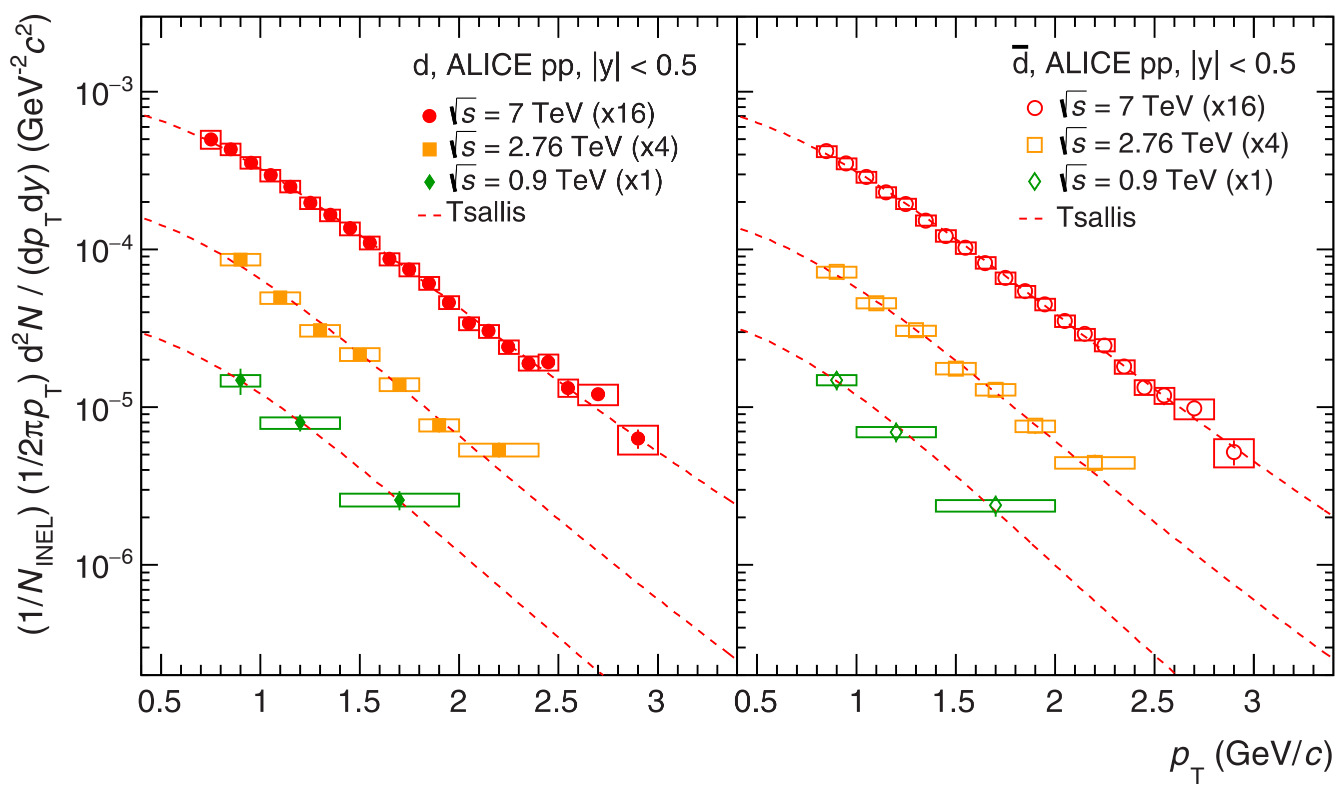


[1] Phys. Rev. C 97, 024615 (2018)

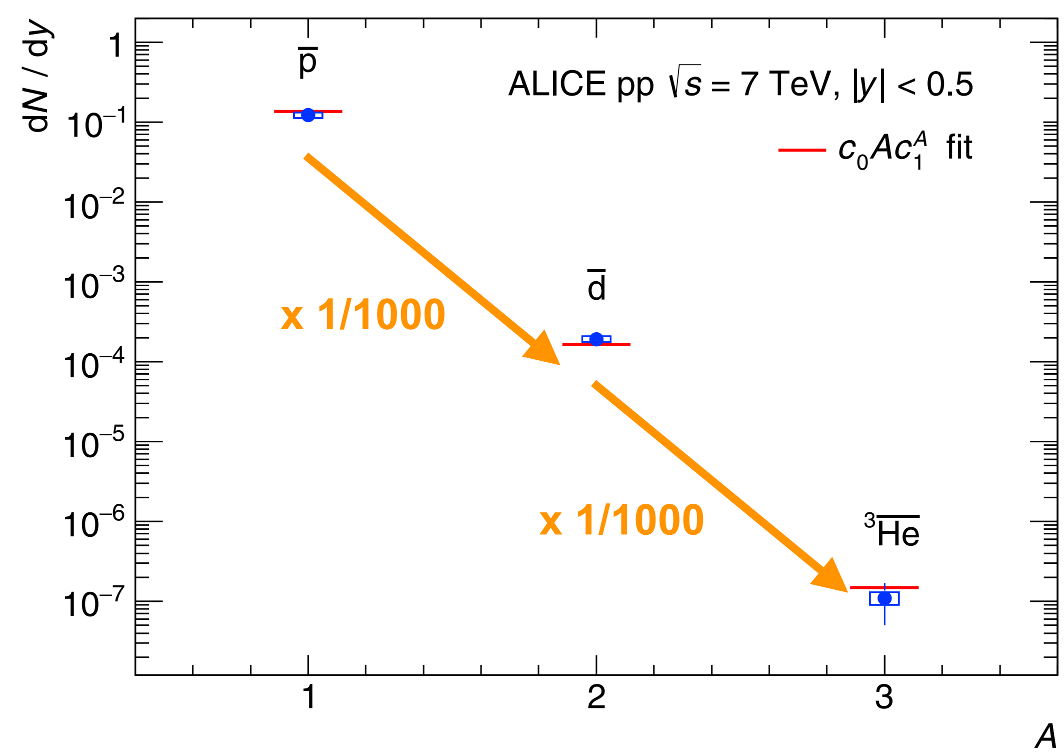
Large Hadron Collider as an anti-matter factory

At LHC energies, particles and anti-particles are produced in almost equal amounts
- Protons and deuterons: only ~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]

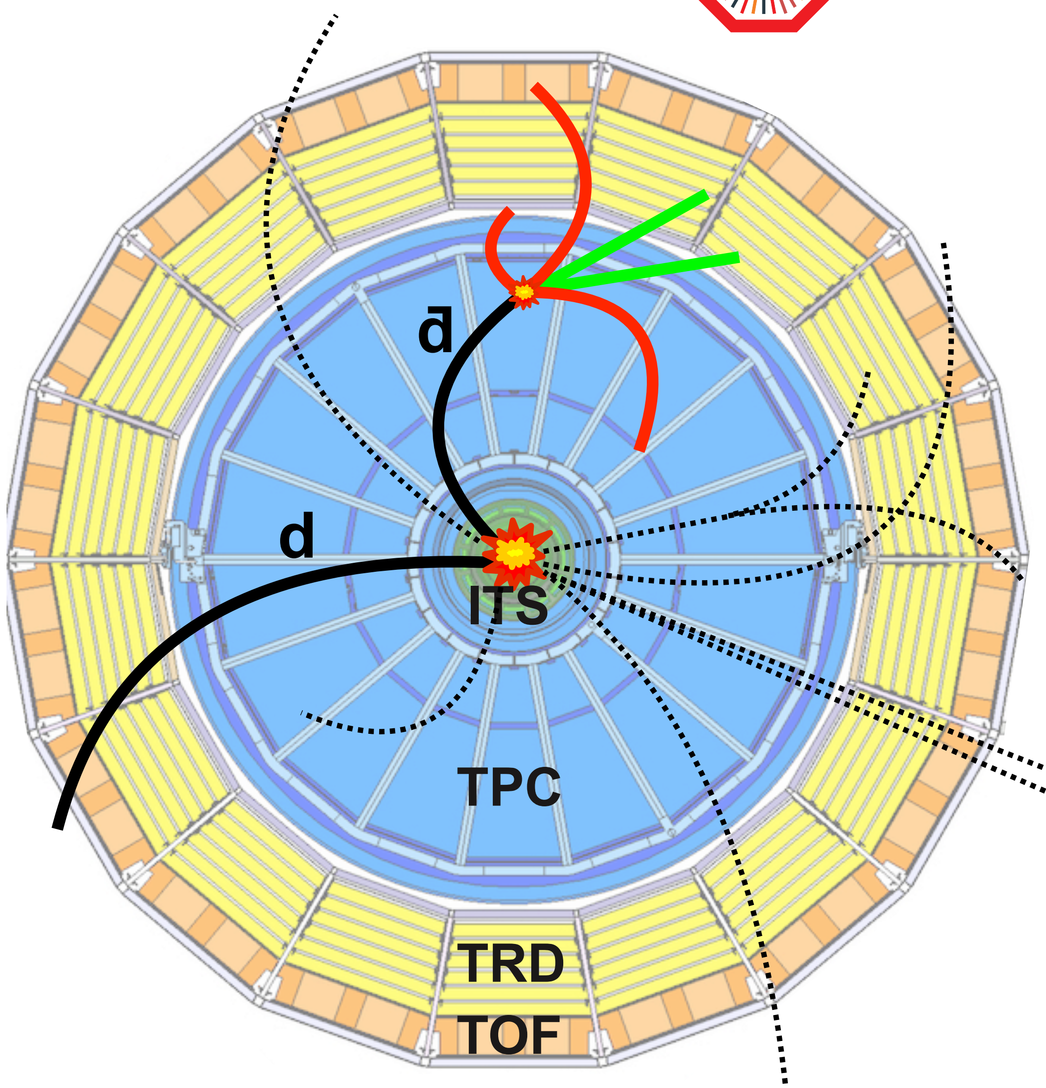


1) Phys. Rev. C 97, 024615 (2018)

ALICE detector material as a target

Material budget at mid-rapidity:

- **Beam pipe (~0.3% X_0):** beryllium
- **ITS (~8% X_0):** silicon detectors, carbon supporting structures
- **TPC (~4% X_0):** Ar/CO_2 gas (88/12), nomex field cage
- **TRD (~25% X_0):** carbon/polypropylene fibre radiator, Xe/CO_2 gas, carbon supporting structures
- **Space frame (~20% X_0** between TPC and TOF detectors): stainless steel



Tables of detector materials

Table D.1: List of ITS materials

Material	Thickness, mm
SPD C (M55J)	0,9955
SPD Bus	0,6484
SPD C shield	1,336
SPD Kapton	0,1522
SPD Si chip	0,4348
SSD C (M55J)	1,2834
SDD C (M55J)	0,513
SDD X7R Weld	0,0153
SDD Kapton	1,187
SDD Si insensitive	0,1168
SDD Si	1,811
SDD Si chip	0,0773
SDD C Al (M55J)	0,678
SDD X7R capacitor	0,0032
SDD ruby	0,0244
Air	502,1
Water	0,3122
Rohacell	15,401
RYTON	0,0775
Nickel	0,0102
ITS Sn	0,0017
Copper	0,0248
STD Glass	0,0066
GEN C	0,344
Al	0,396
KaptonH (POLYCH2)	0,139
Ceramics	0,0305
G10Fr4	0,04135
NiSn	0,0107
Inox	0,0966
Freon	0,290
EPOXY	0,2134

Material	Description	Thickness [cm]	Density [g/cm^3]	X/X_0 [%]
Mylar	Mylar layer on radiator	0.0015	1.39	0.005
Carbon	Carbon fiber mats	0.0055	1.75	0.023
Araldite	Glue on the fiber mats	0.0065	1.12	0.018
Rohacell	Sandwich structure	0.8	0.075	0.149
PP	Fiber mats inside radiator	3.186	0.068	0.490
Xe/CO_2	The drift region	3.0	0.00495	0.167
Xe/CO_2	The amplification region	0.7	0.00495	0.039
Copper	Wire planes	0.00011	8.96	0.008
Copper	Copper of pad plane	0.0025	8.96	0.174
G10	PCB of pad plane	0.0356	2.0	0.239
Araldite	Glue on pad plane	0.0923	1.12	0.249
Araldite	+ additional glue (leaks)	0.0505	1.12	0.107
Carbon	Carbon fiber mats	0.019	1.75	0.078
Aramide	Honeycomb structure	2.0299	0.032	0.169
G10	PCB of readout boards	0.0486	2.0	0.326
Copper	Copper of readout boards	0.0057	8.96	0.404
Copper	Electronics and cables	0.0029	8.96	0.202

Fig. D.1: List of materials of a single TRD readout chamber [1]

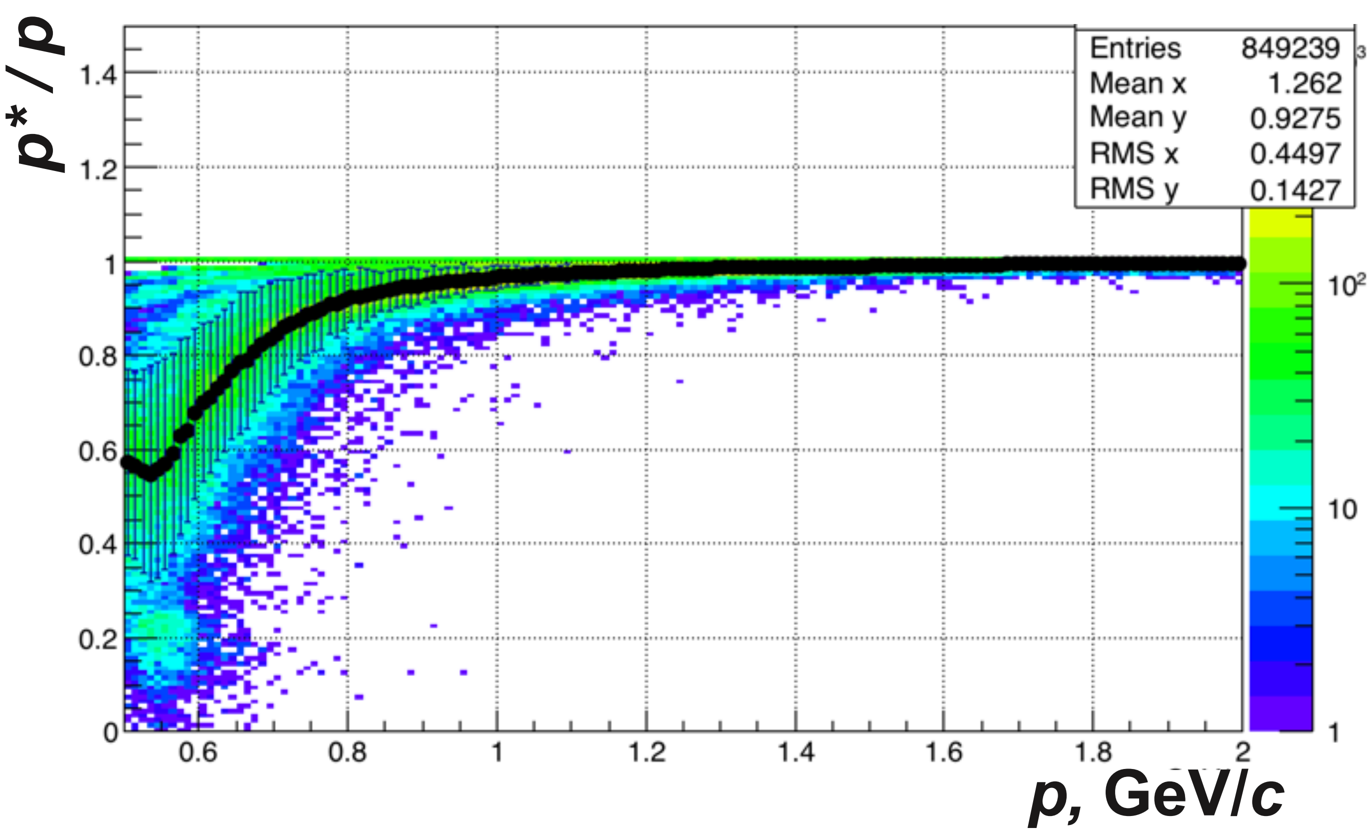
Table D.2: List of TPC materials [12, 13]

Material	Thickness, mm
Aluminium	0,2
Tedlar	0,4
Prepreg	2,4
Nomex	90
CO2	300
Macrolon rods	2,32
Ar/CO2 (90/10)	1700

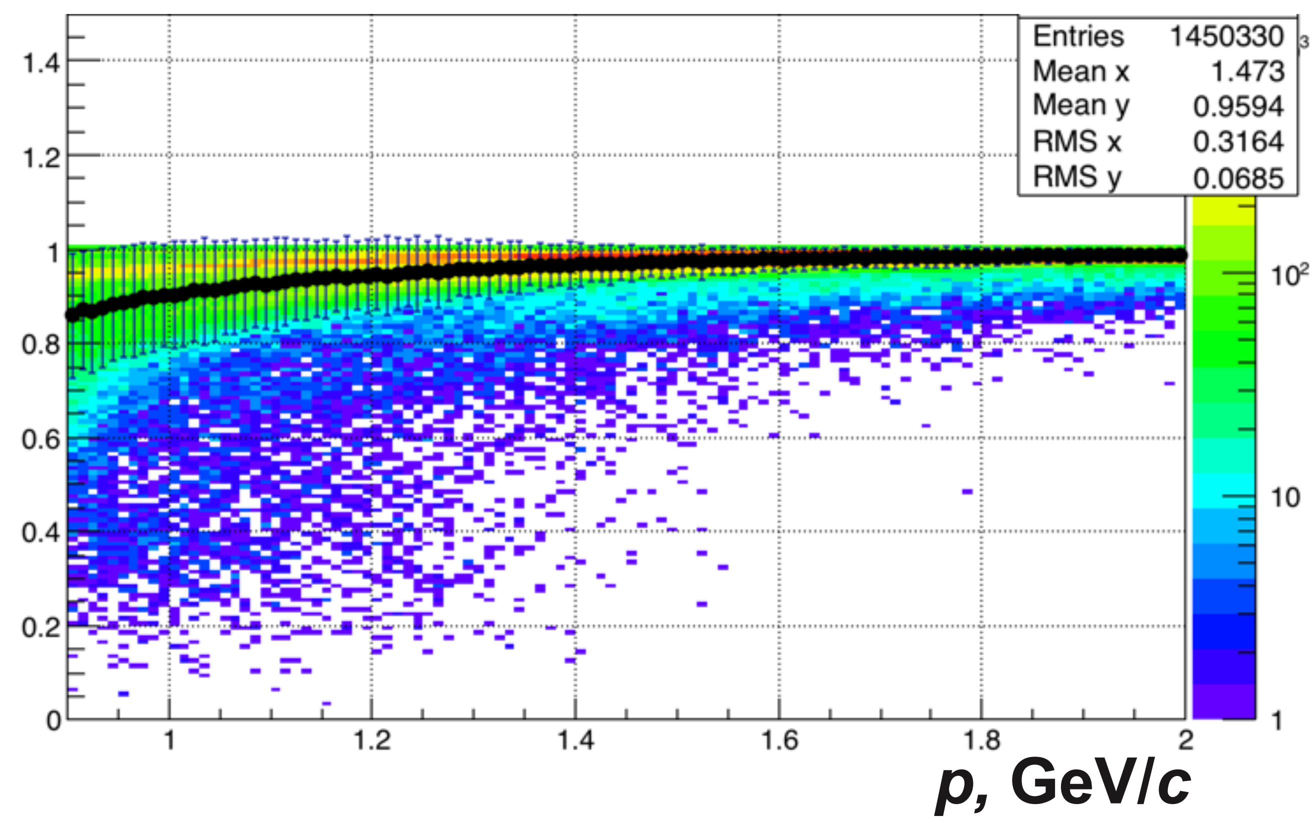
Estimation of *p** for anti-deuterons

- As estimation for *p**: use *last available momentum* in Track Refs
  - ITS-TPC analysis: if particle didn't reach TRD, store p_{VTX} or p_{ITS} or p_{TPC}
  - TOF analysis: if particle didn't reach TOF, store p_{VTX} or p_{ITS} or p_{TPC} or p_{TRD}
- Black points/errors: profile of 2d map (mean ± RMS)

ITS-TPC analysis



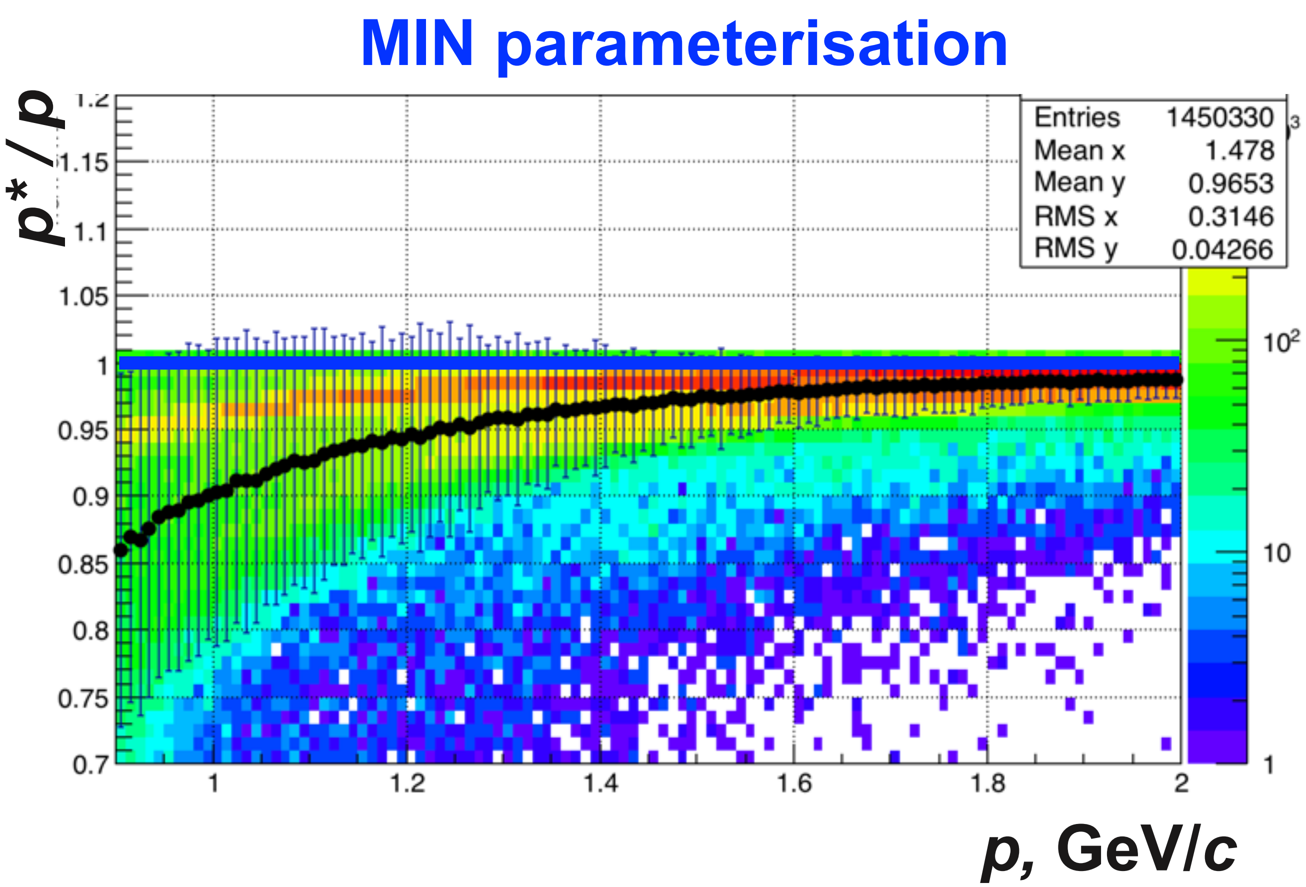
TOF analysis

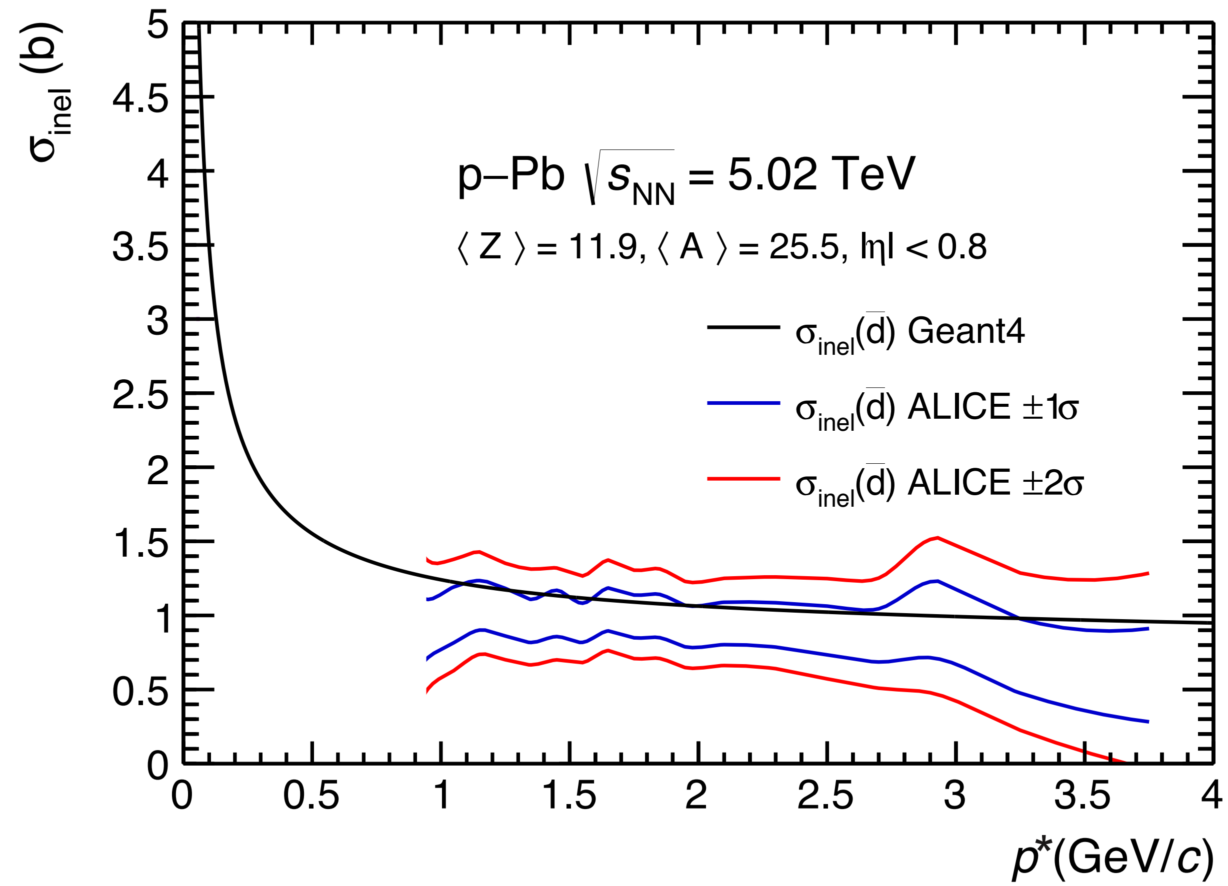


- These maps are used for transformation $p \rightarrow p^*$
- Significant uncertainties, inelastic interaction happens at various momenta $p^* < p$

Transformation $p \rightarrow p^*$ for $\sigma_{inel}(\bar{d})$ (TOF analysis)

- No correction for $p \rightarrow p^*$ (consistent with upper uncertainties on the left)
  - "MIN" parameterisation (minimal effect for $p \rightarrow p^*$)

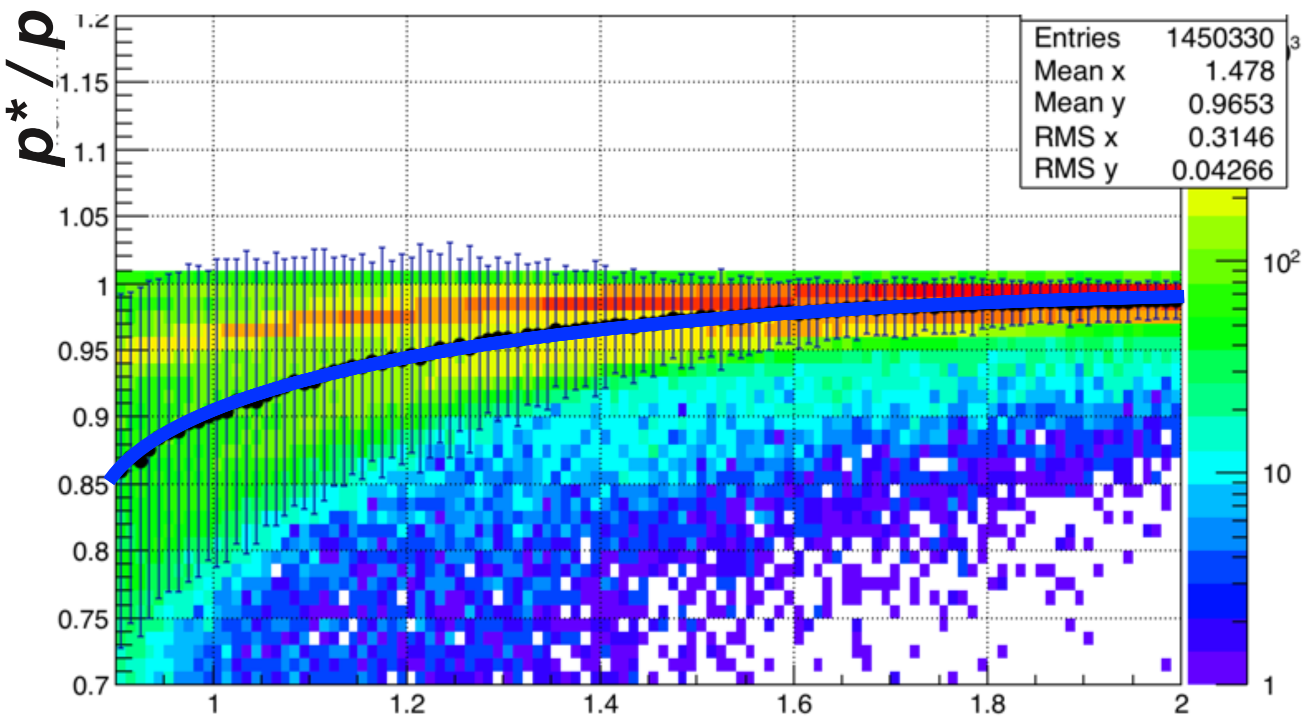


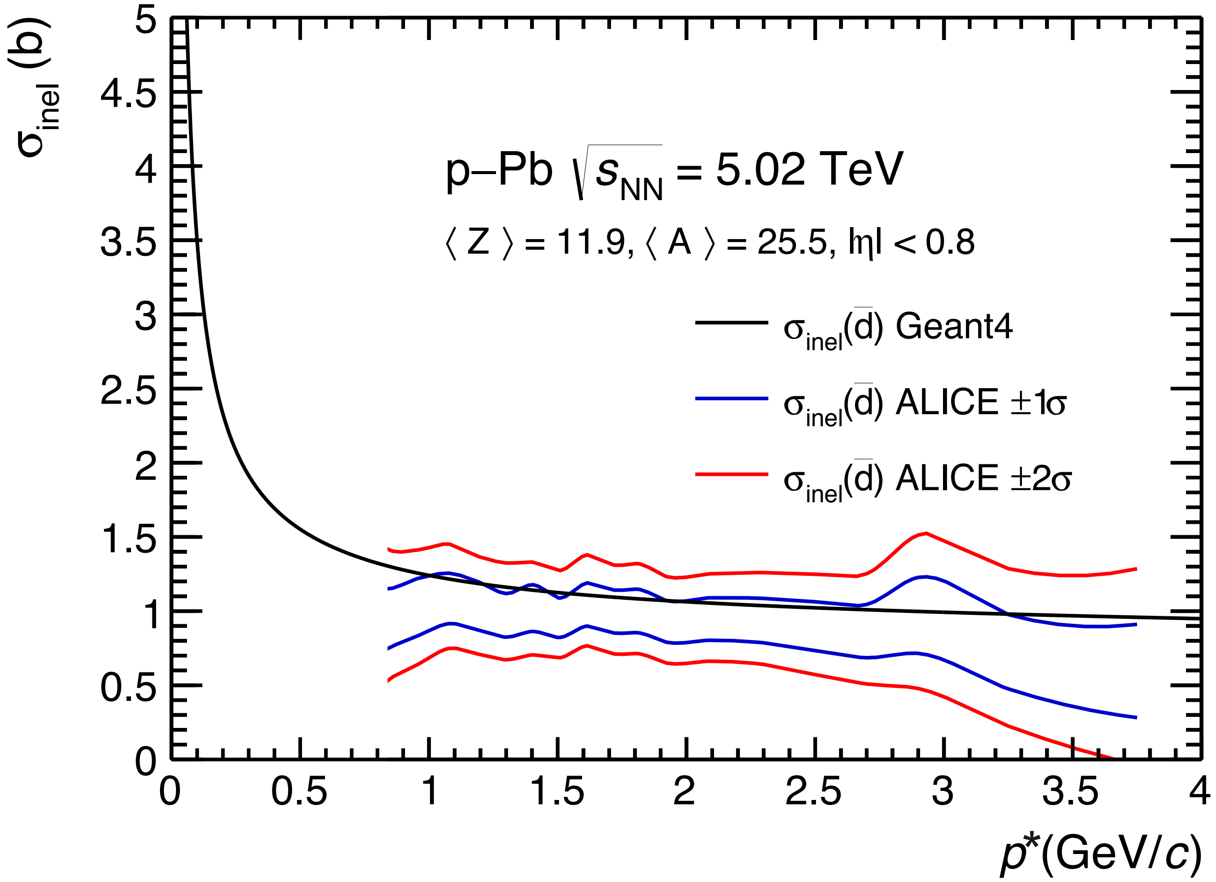


Transformation $p \rightarrow p^*$ for $\sigma_{inel}(\bar{d})$ (TOF analysis)

- Using mean values for $p \rightarrow p^*$ (black points on the left)
  - "MEAN" parameterisation (average effect for $p \rightarrow p^*$)

MEAN parameterisation

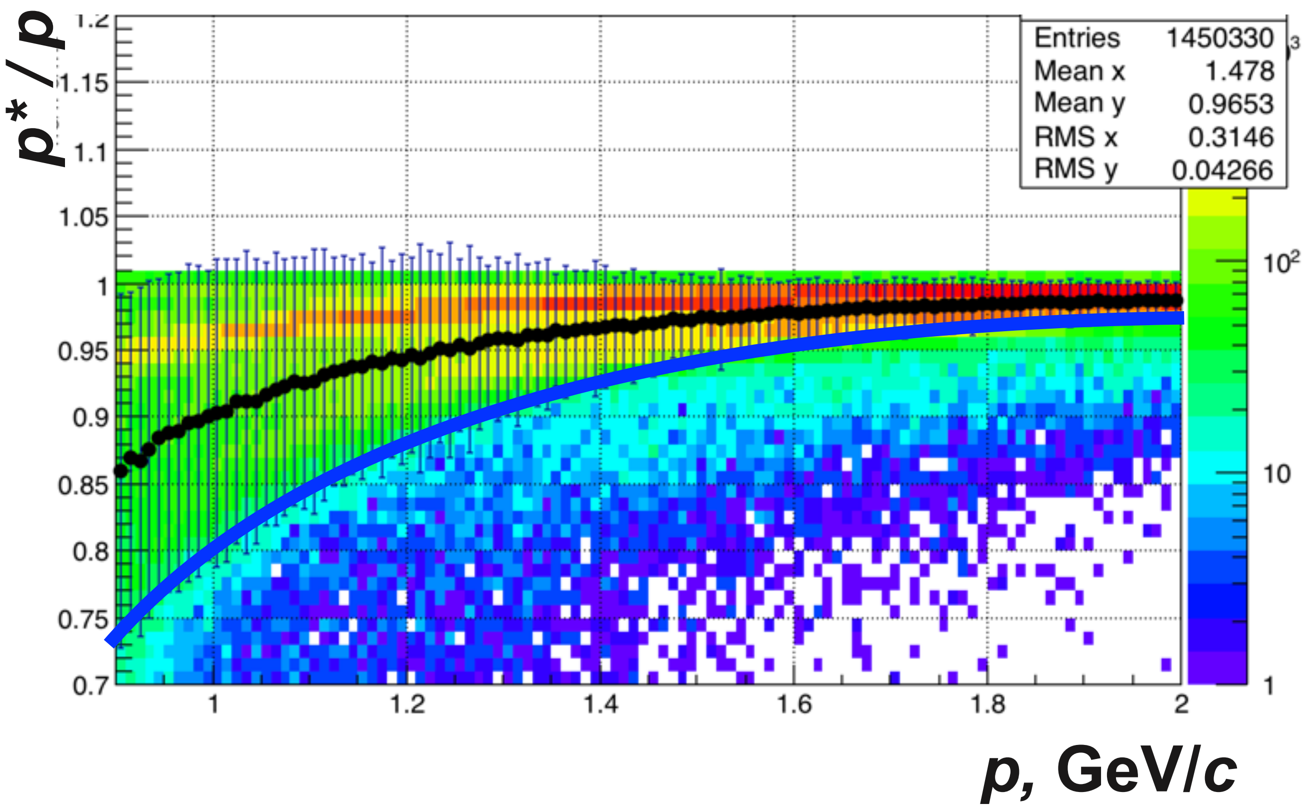


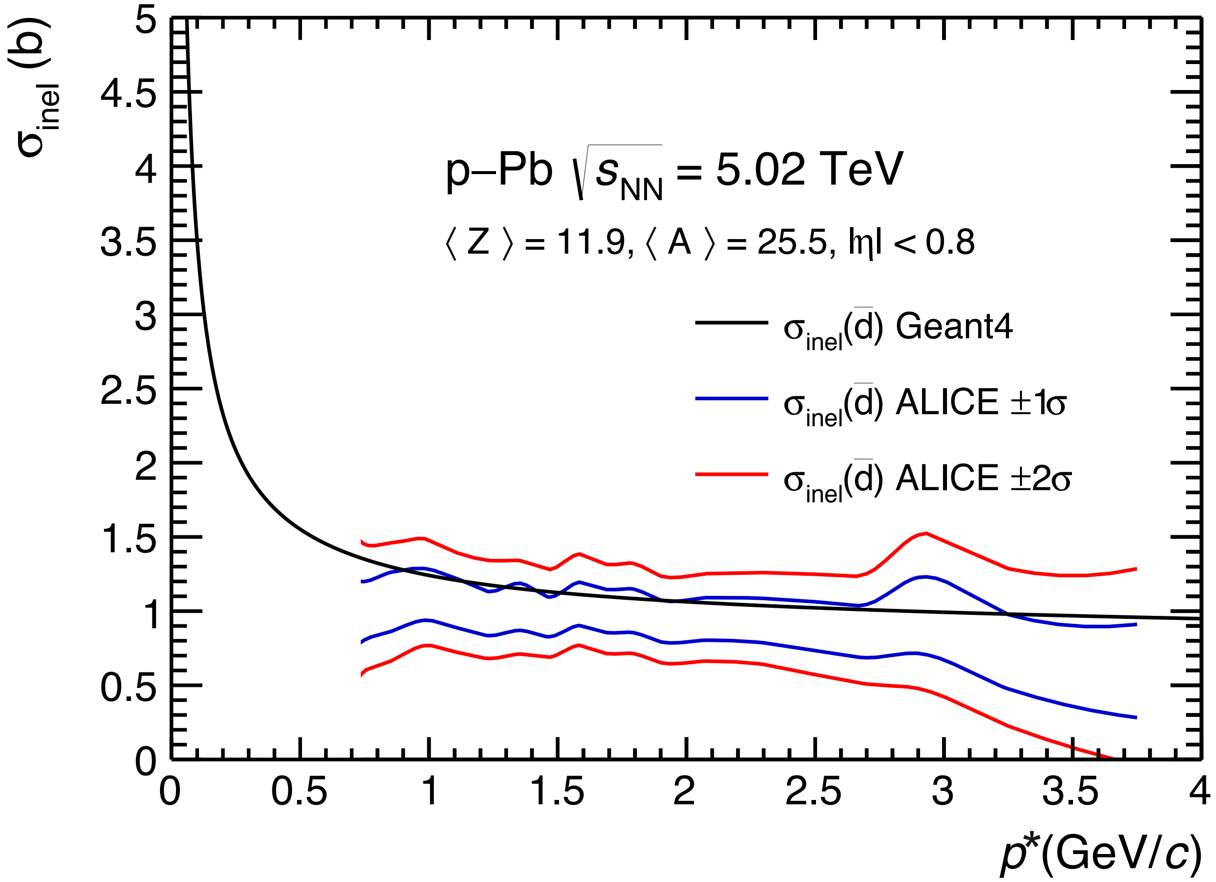


Transformation $p \rightarrow p^*$ for $\sigma_{inel}(\bar{d})$ (TOF analysis)

- Using lower uncertainties for $p \rightarrow p^*$
  - "MAX" parameterisation (maximal effect for $p \rightarrow p^*$)

MAX parameterisation



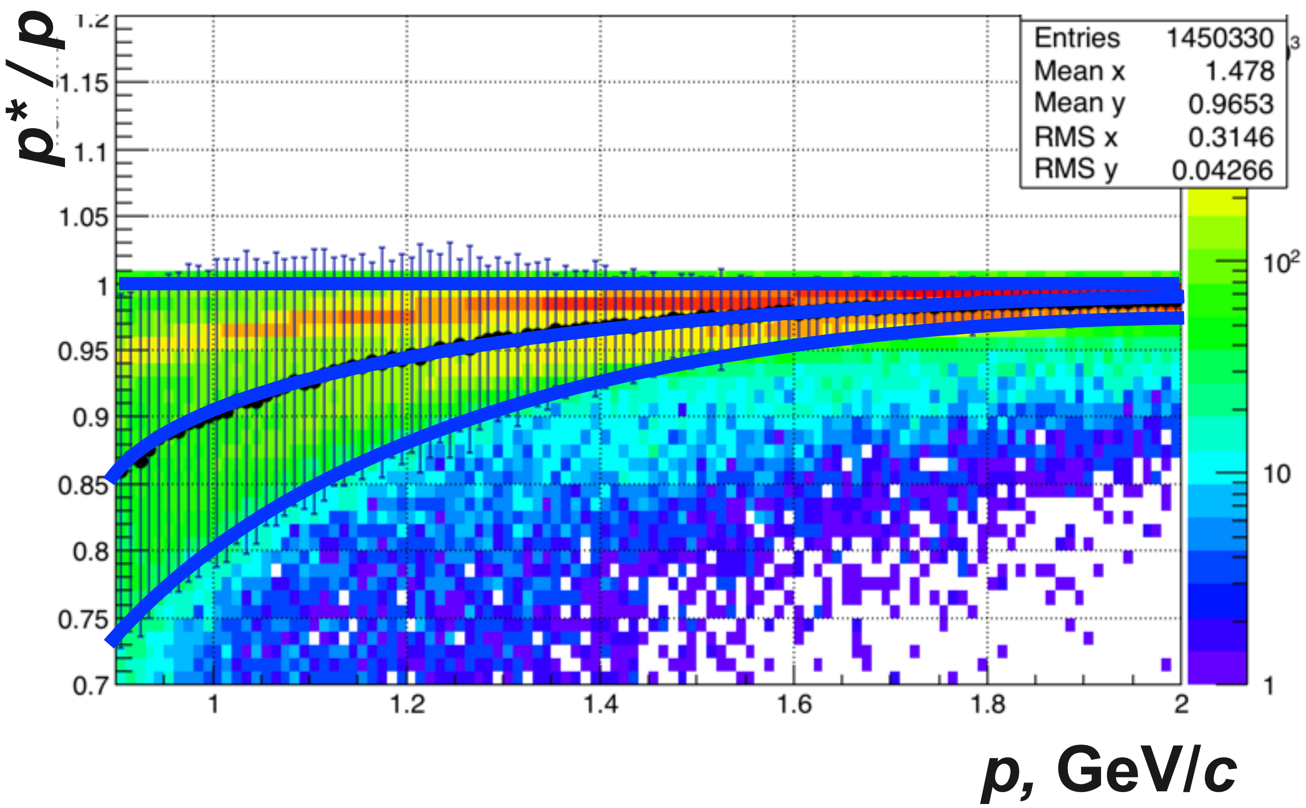


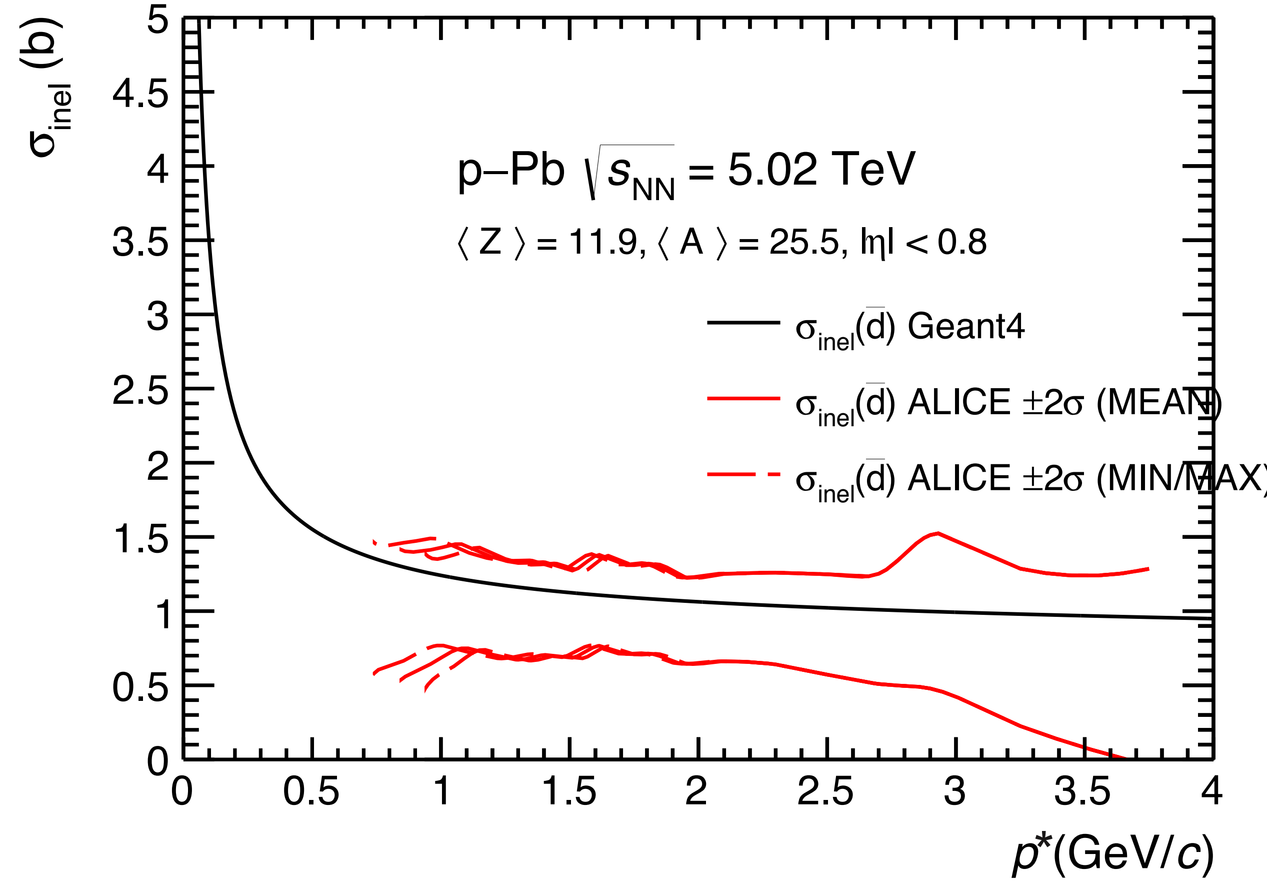
ALICE

Transformation $p \rightarrow p^*$ for $\sigma_{inel}(\bar{d})$ (TOF analysis)

- Different parameterisations should be taken into account as uncertainty
  - In principle uncertainty along x axis

All 3 parameterisations





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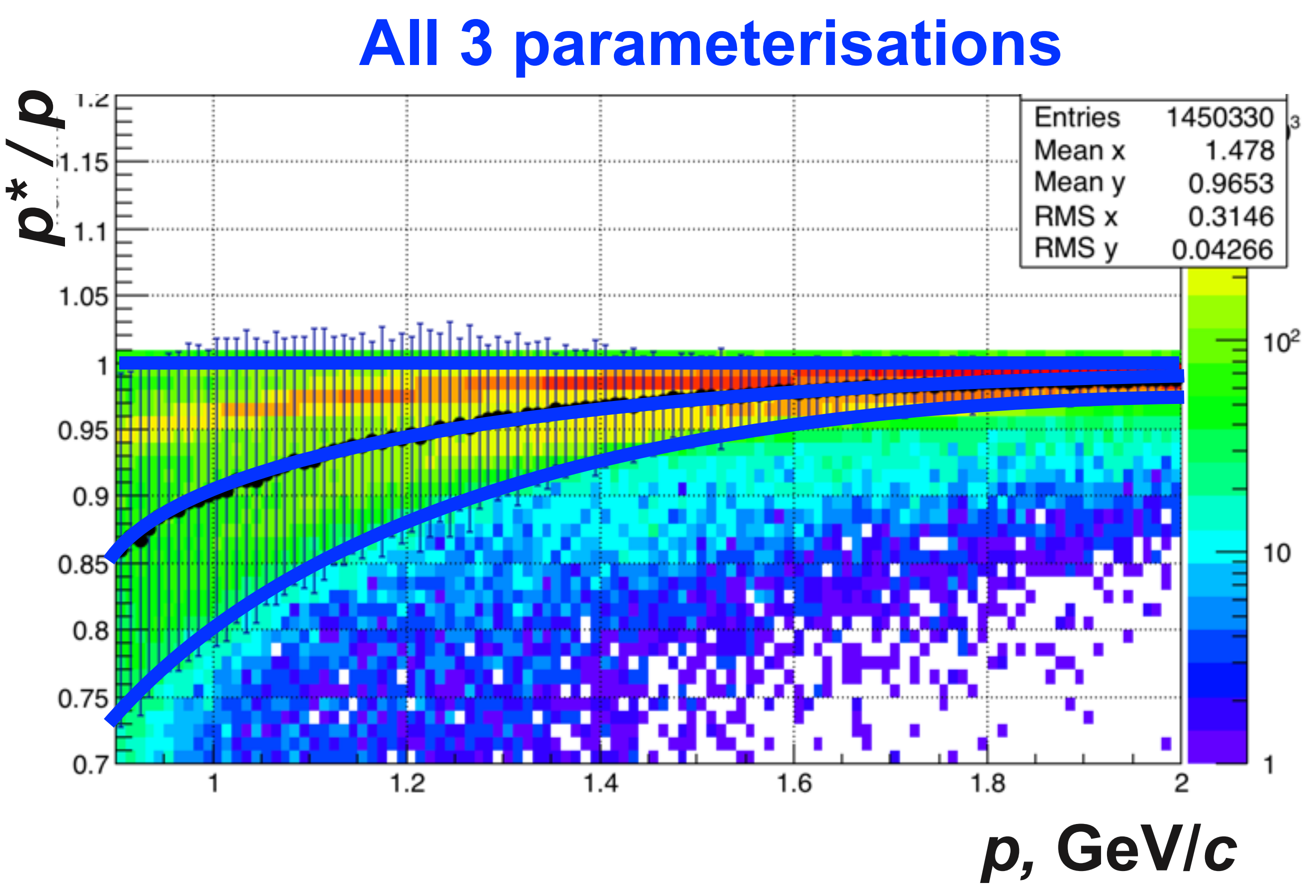
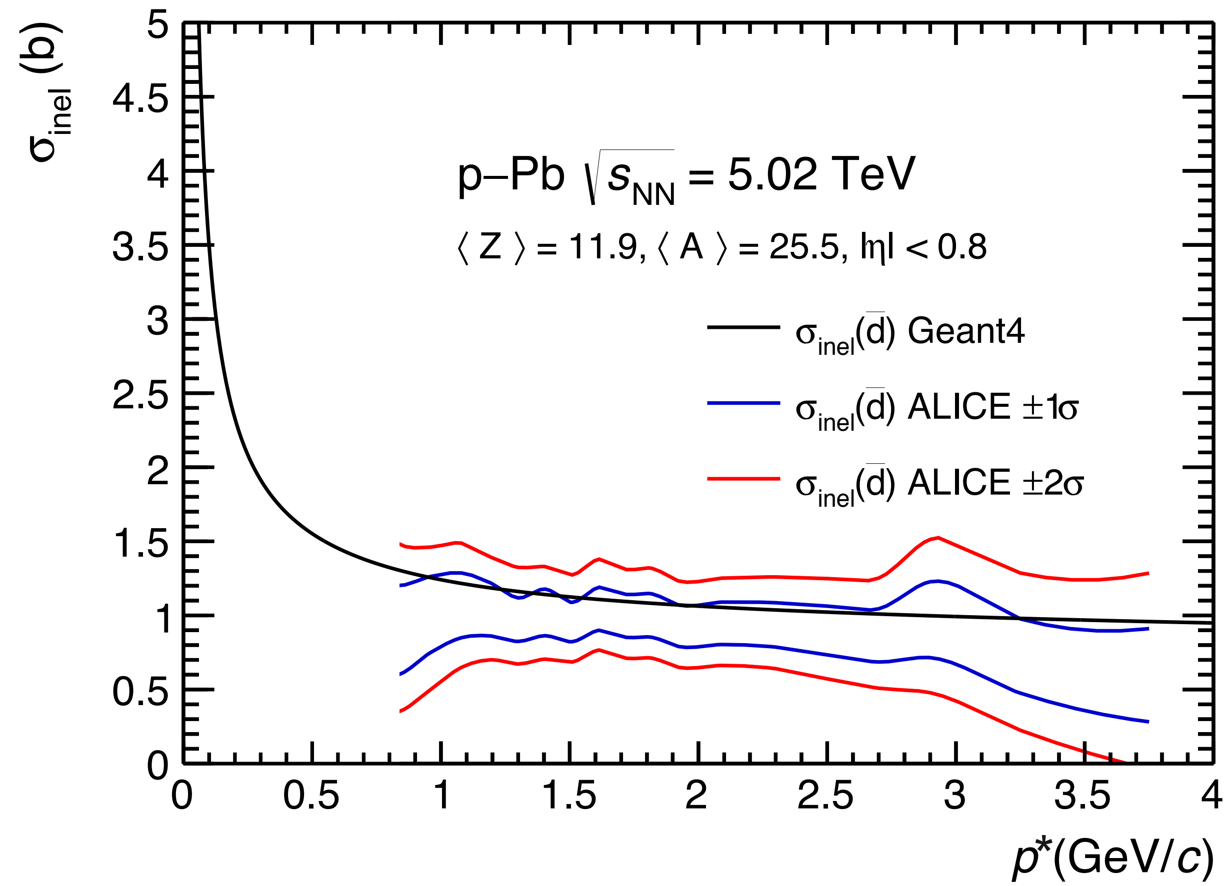




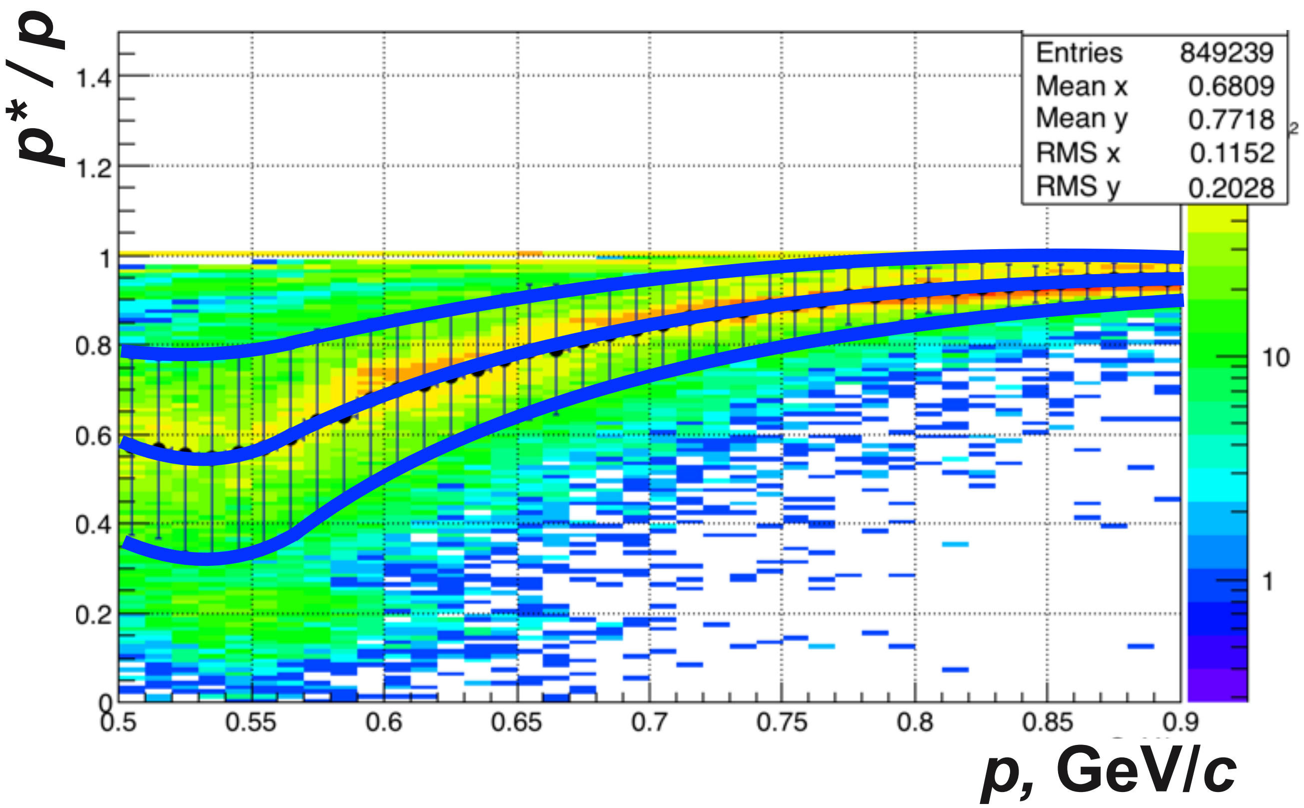
Draw constraints on $\sigma_{inel}(\bar{d})$ so that the results include possible uncertainty from $p \rightarrow p^*$

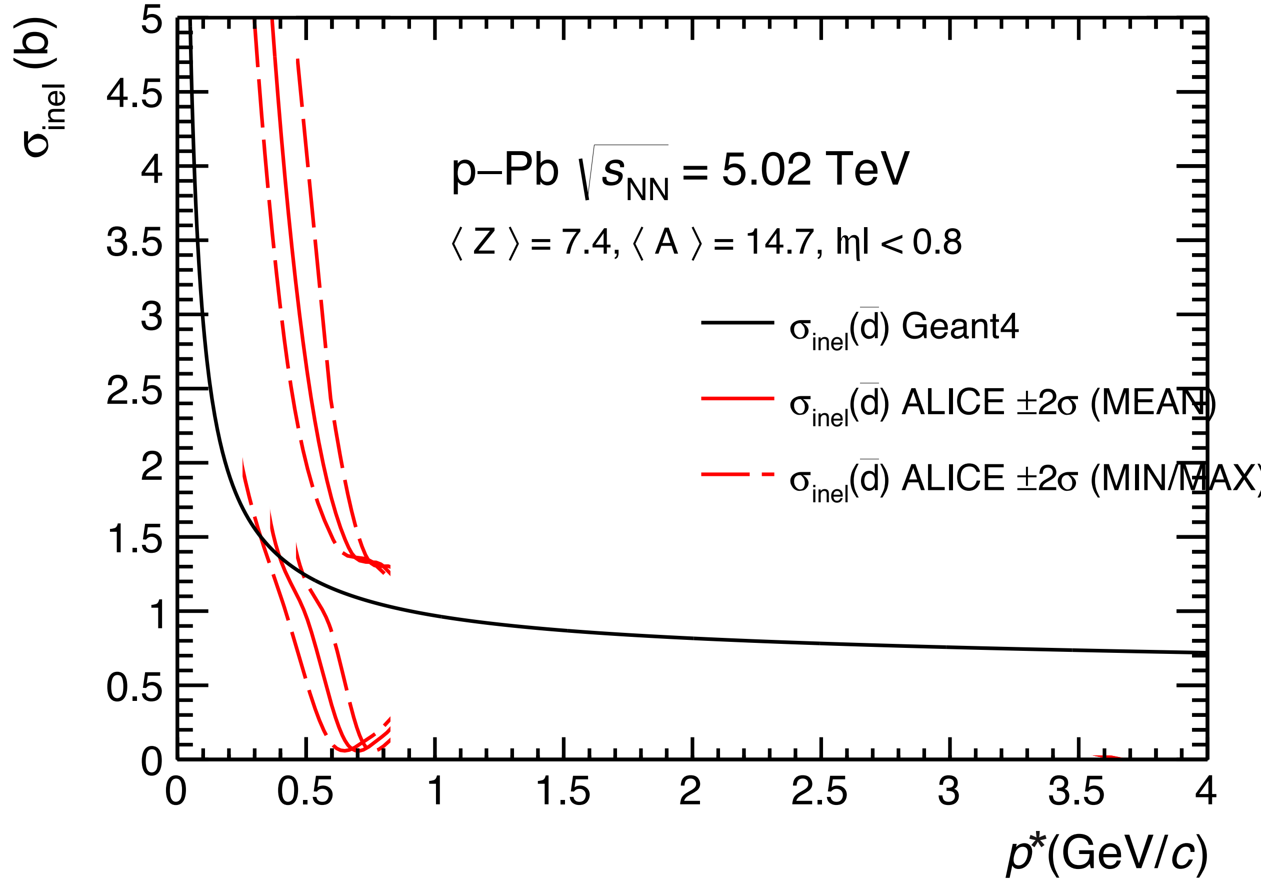
- Momentum range: according to MEAN transformation
- For constraints on $\sigma_{inel}(\bar{d})$: take the widest band from 3 parameterisations

Transformation $p \rightarrow p^*$ for $\sigma_{inel}(\bar{d})$ (ITS-TPC analysis)

- Different parameterisations should be taken into account as uncertainty
  - In principle uncertainty along x axis

All 3 parameterisations





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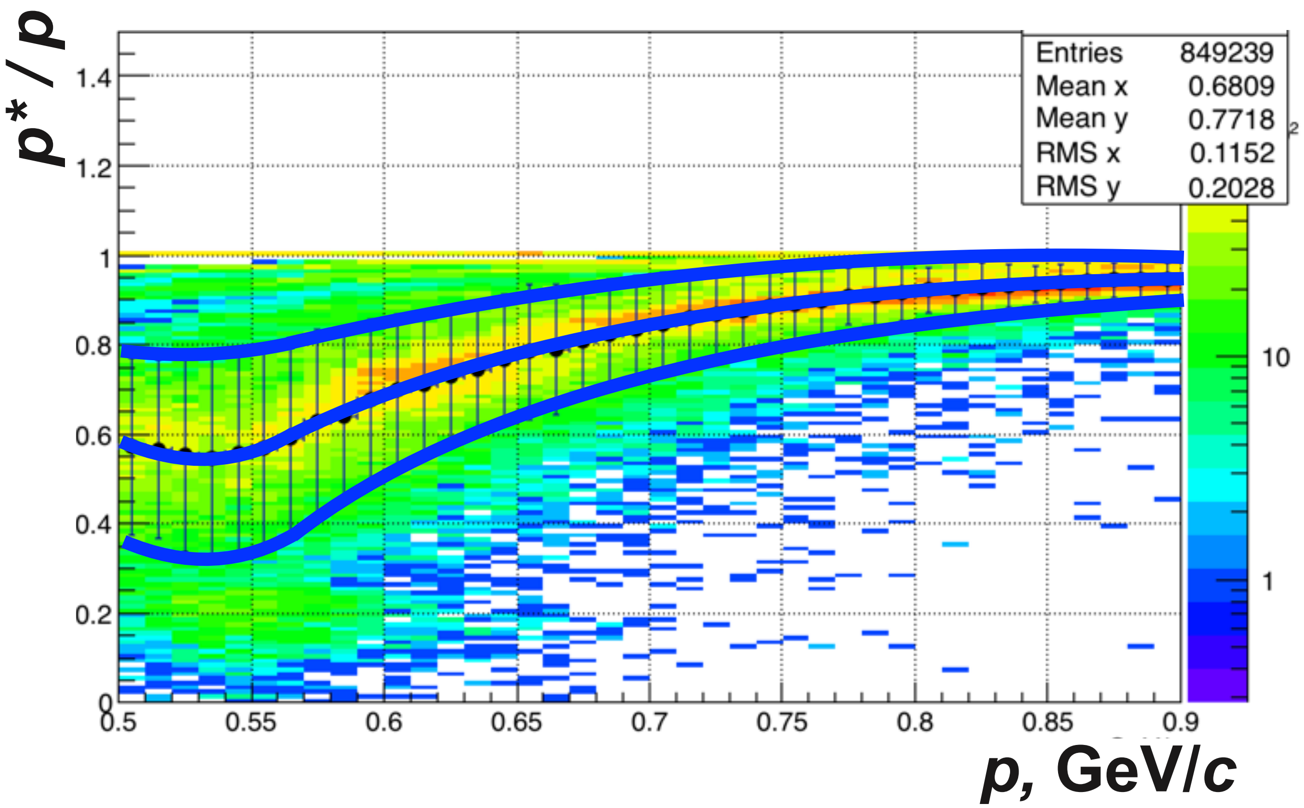
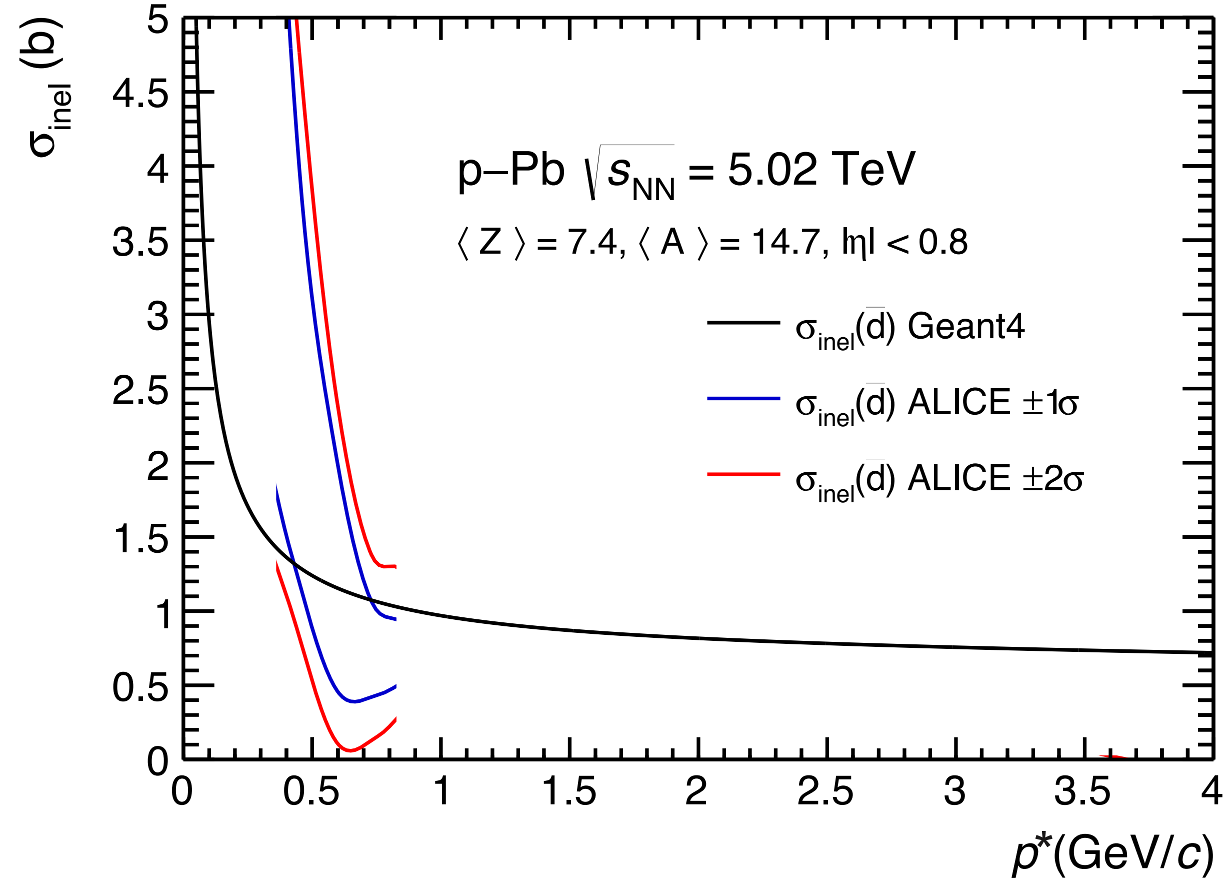
All 3 parameterisations





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- For constraints on $\sigma_{inel}(\bar{d})$: take the widest band from 3 parameterisations