# First measurement of anti-deuteron nuclear inelastic cross-section with ALICE

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**Technische Universität München**
**on behalf of the ALICE Collaboration**

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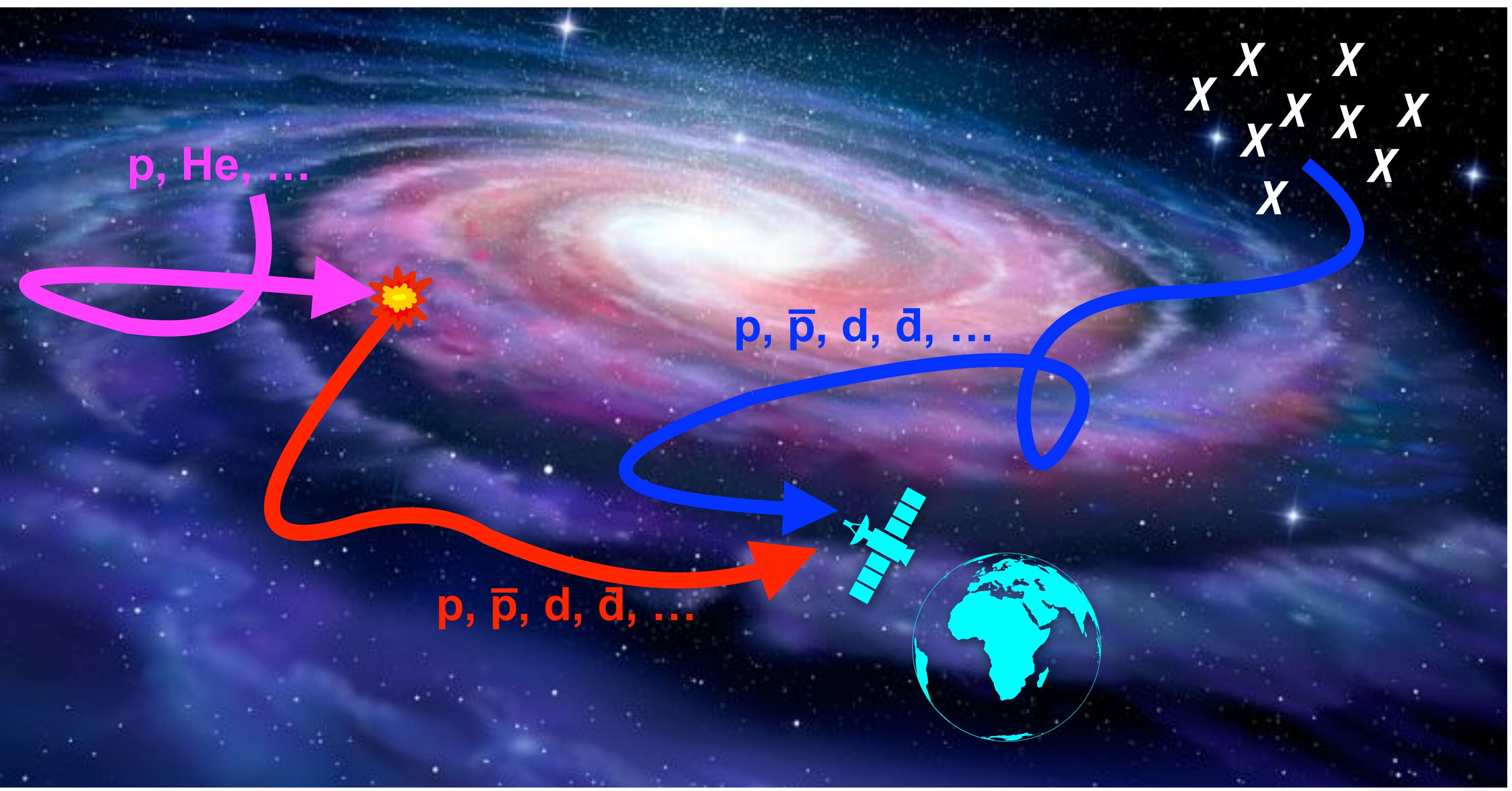
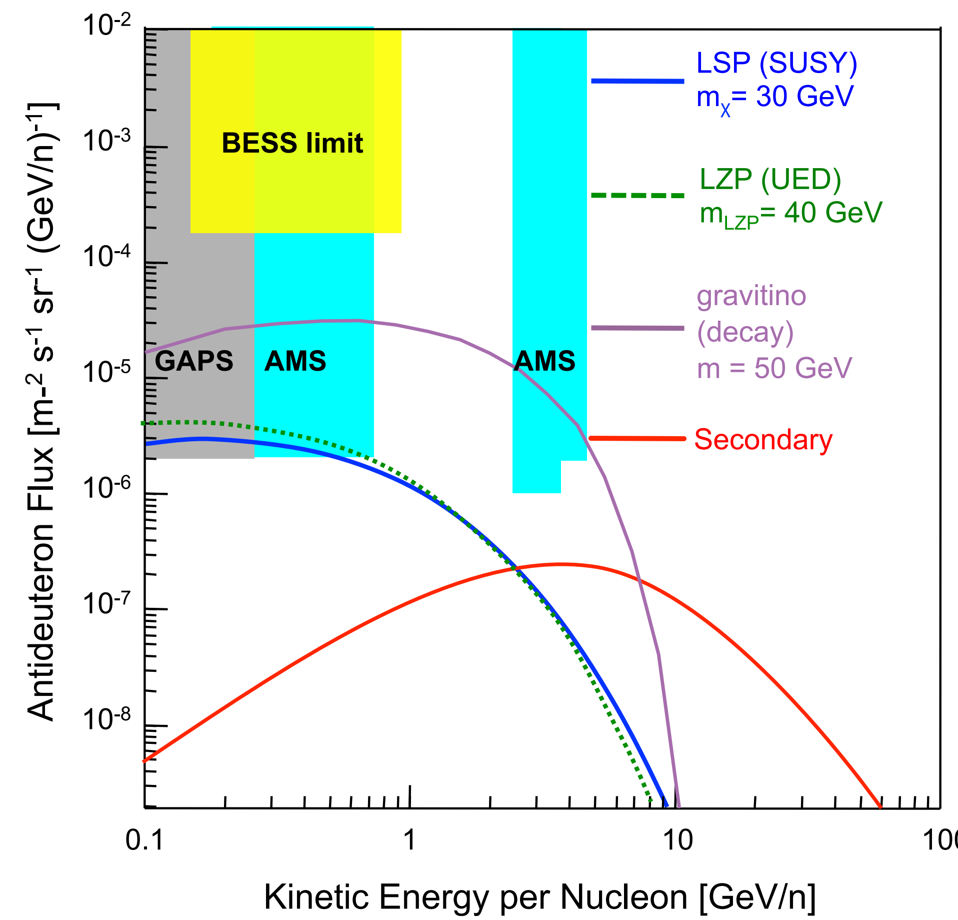
Bormio, Italy

# Indirect Dark Matter searches

Low-energy cosmic-ray anti-deuterons — unique probe for indirect DM searches
- Low background from secondary production is expected
- *Vital to determine precisely primary and secondary anti-deuteron flux!*




**Predicted anti-deuteron flux [1]**

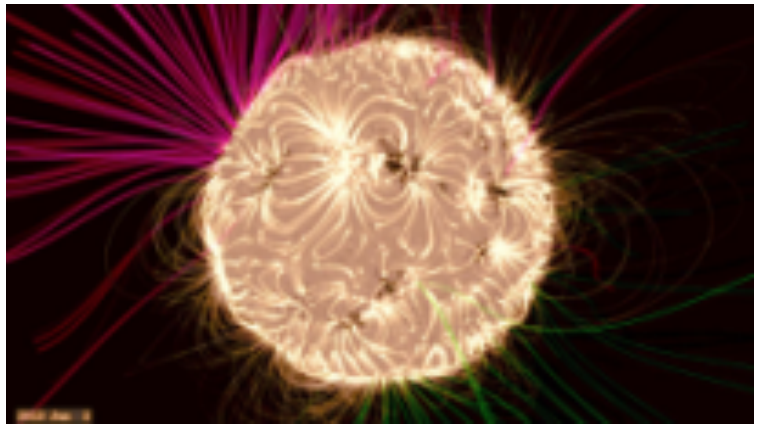



[1] Physics reports 618, 1 (2016)

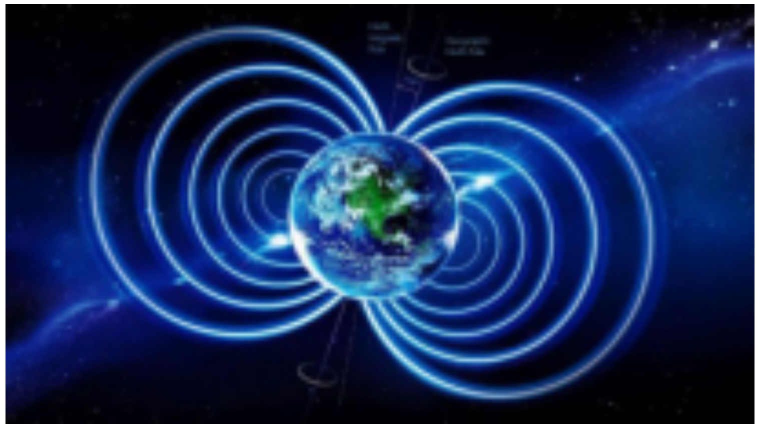
# A long way to the detectors

***Interstellar Space***

***Heliosphere***



***Near-Earth environment***



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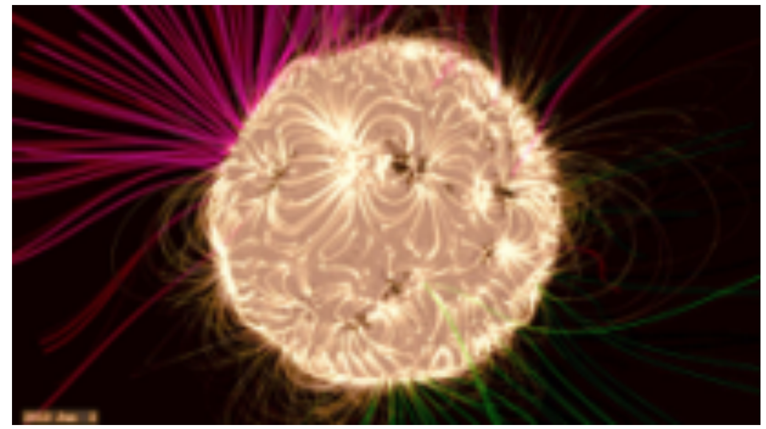

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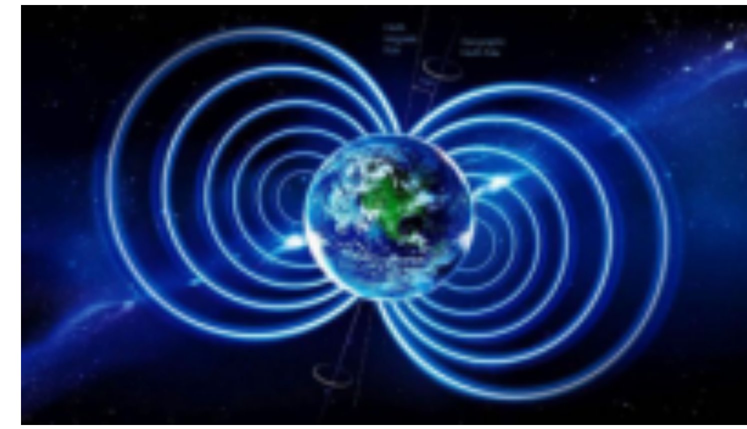


$$\nabla\left(-K\nabla N_{\bar{\mathrm{d}}}+V_c N_{\bar{\mathrm{d}}}\right)+\partial_T\left(b_{tot}N_{\bar{\mathrm{d}}}-K_{EE}\partial_T N_{\bar{\mathrm{d}}}\right)+\Gamma_{\mathrm{ann}}N_{\bar{\mathrm{d}}}=q_{\bar{\mathrm{d}}}+q_{\bar{\mathrm{d}}}^{\mathrm{ter}}$$

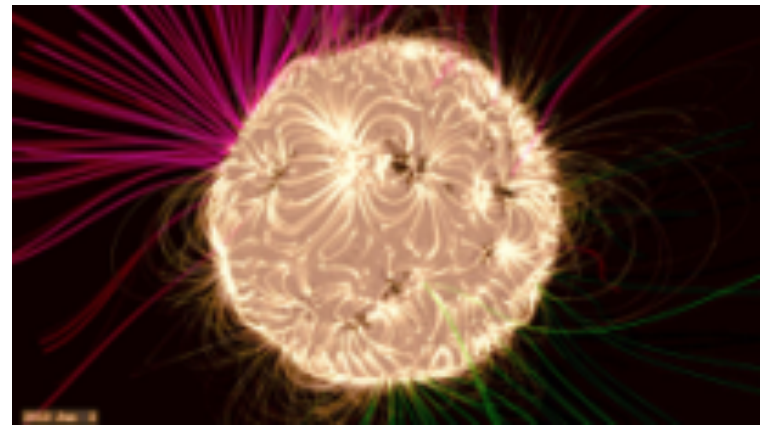
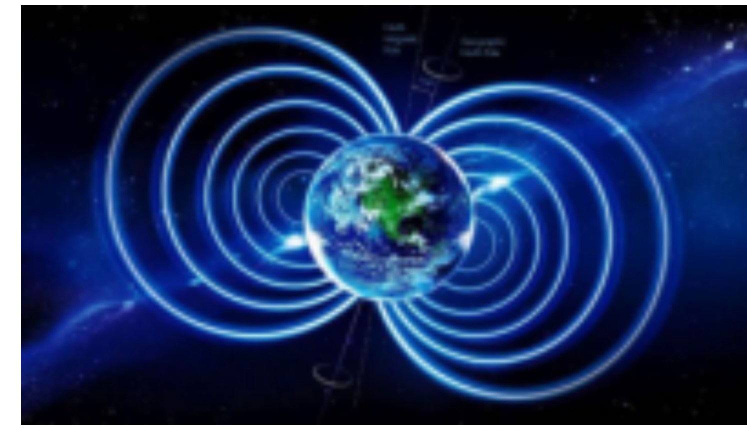
Basic ingredients for flux calculation:

**Propagation:** common for all (anti-)particles

**Annihilation** in interstellar medium, Earth's atmosphere, …

**Production** in pp, p$\bar{\mathrm{p}}$, p-A and $\bar{\mathrm{p}}$-A collisions

# A long way to the detectors

| *Interstellar Space* | *Heliosphere* | *Near-Earth environment* |
| --- | --- | --- |
|  |  |  |

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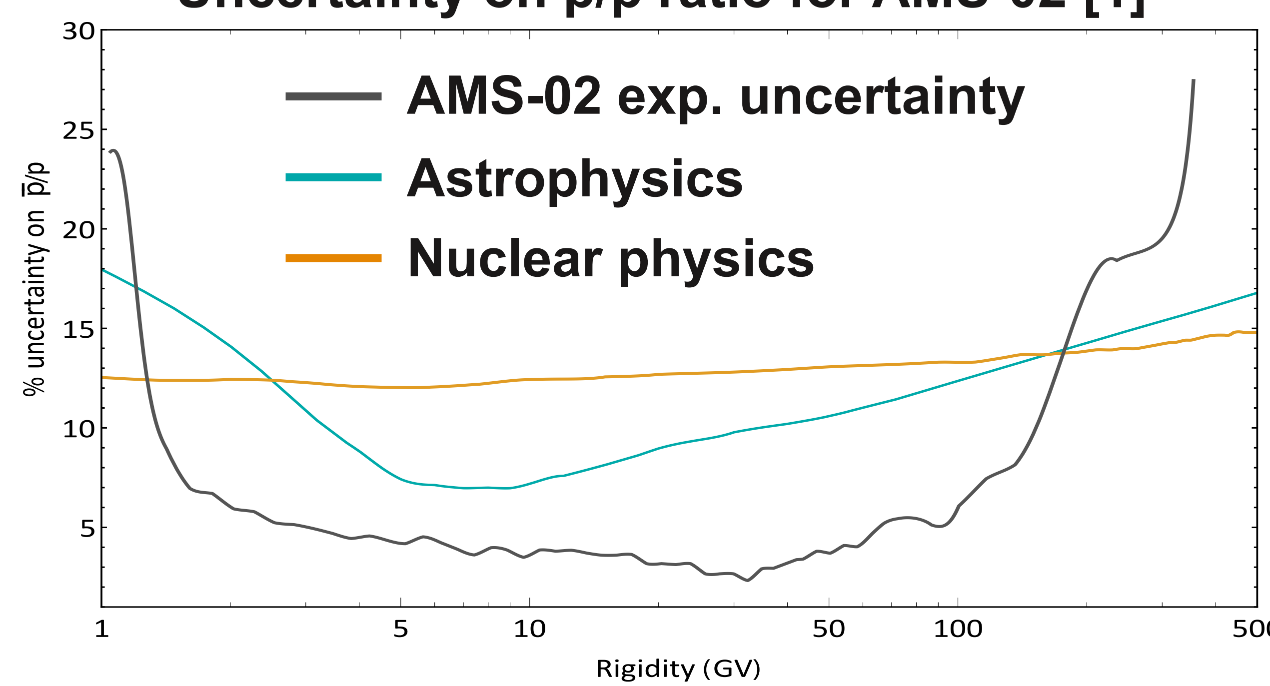
**Production** in pp, p$\bar{\mathrm{p}}$, p-A and $\bar{\mathrm{p}}$-A collisions

*(For anti-deuterons almost nothing is known in the relevant energy range)*

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

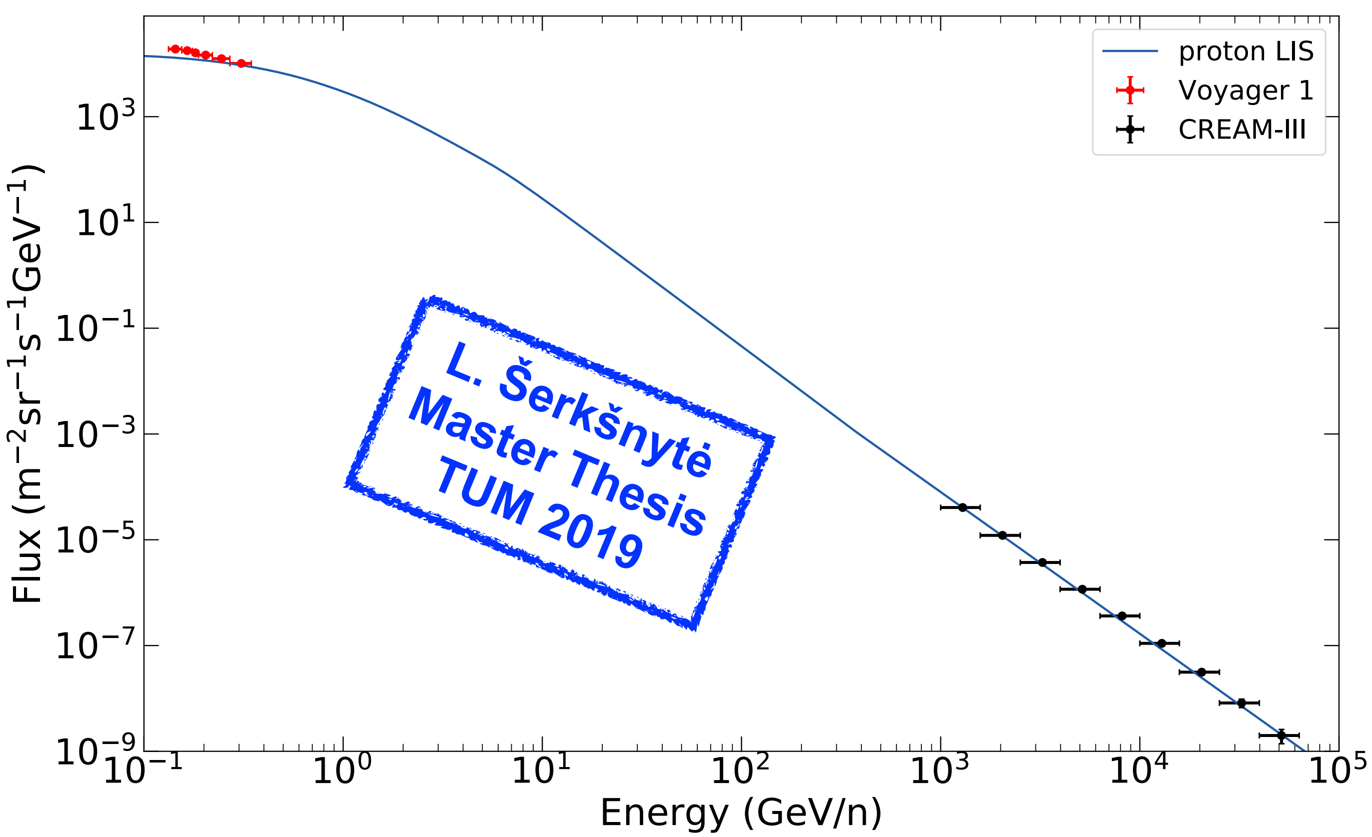



[1] CERN-SPSC-2019-022

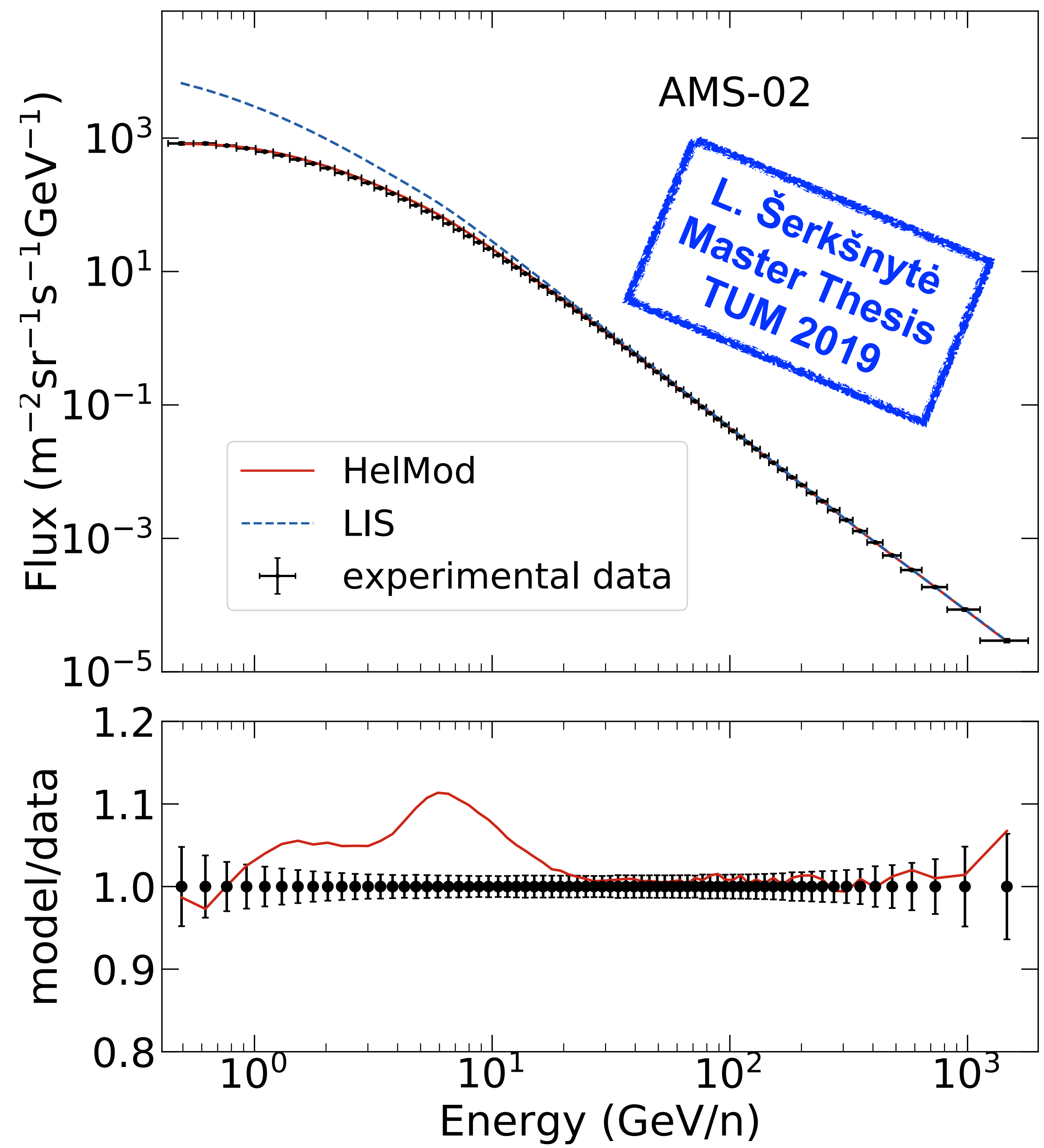
# Benchmark: simulation of cosmic ray protons

Modelling of propagation in interstellar medium and in solar magnetic field
- Chain of several MC-based frameworks
- Protons: mostly primaries from supernova remnants

**Local interstellar proton flux**




**Solar modulated proton flux**



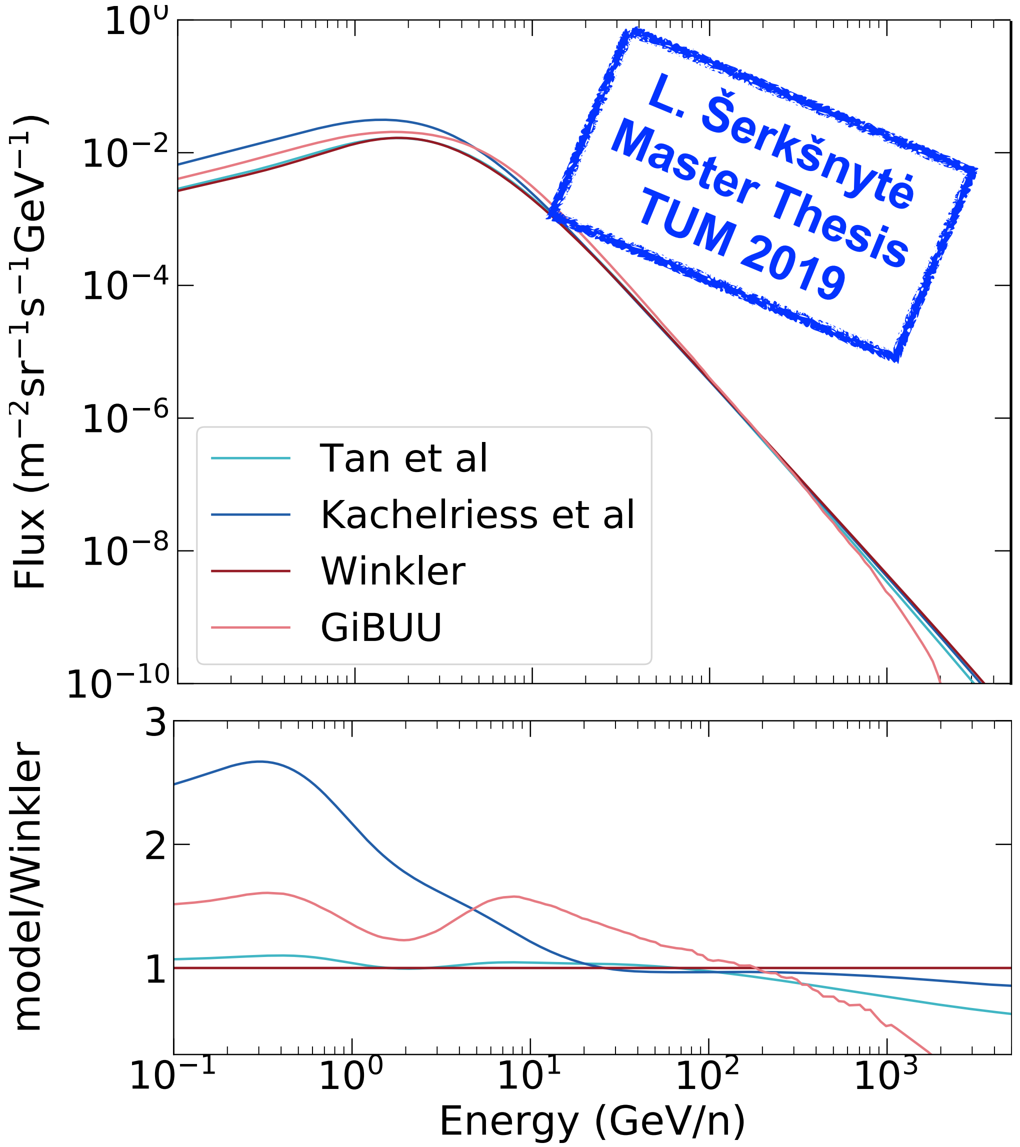

**Calculations can describe nicely the Voyager 1 and the AMS-02 data**

# Simulation of cosmic ray flux: anti-protons

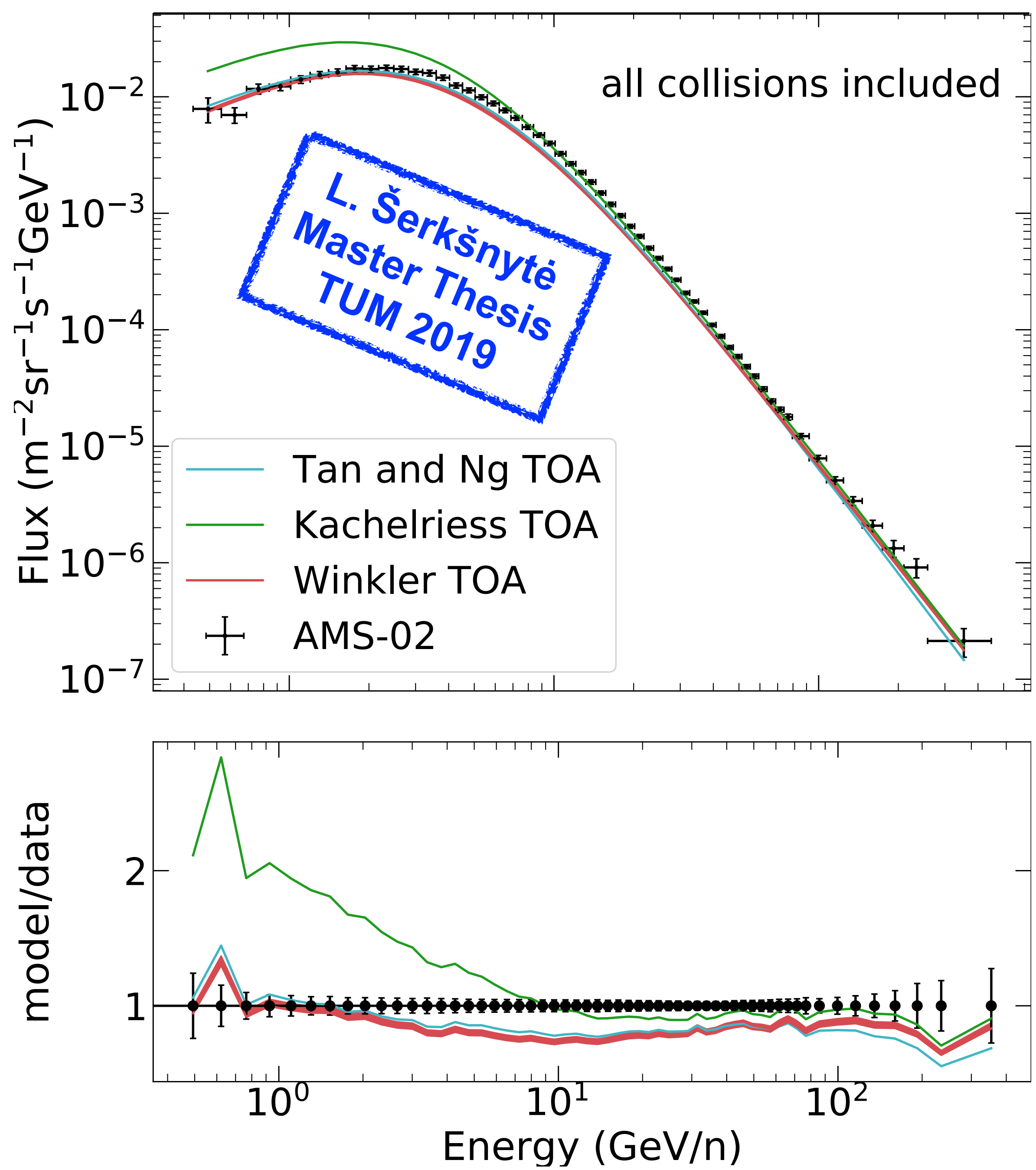
*Results are strongly model dependent!*

- Most relevant reactions for secondary anti-protons: pp, p-$^{4}$He, $^{4}$He-p, $^{4}$He-$^{4}$He

**Local interstellar anti-proton flux**




**Solar modulated anti-proton flux**



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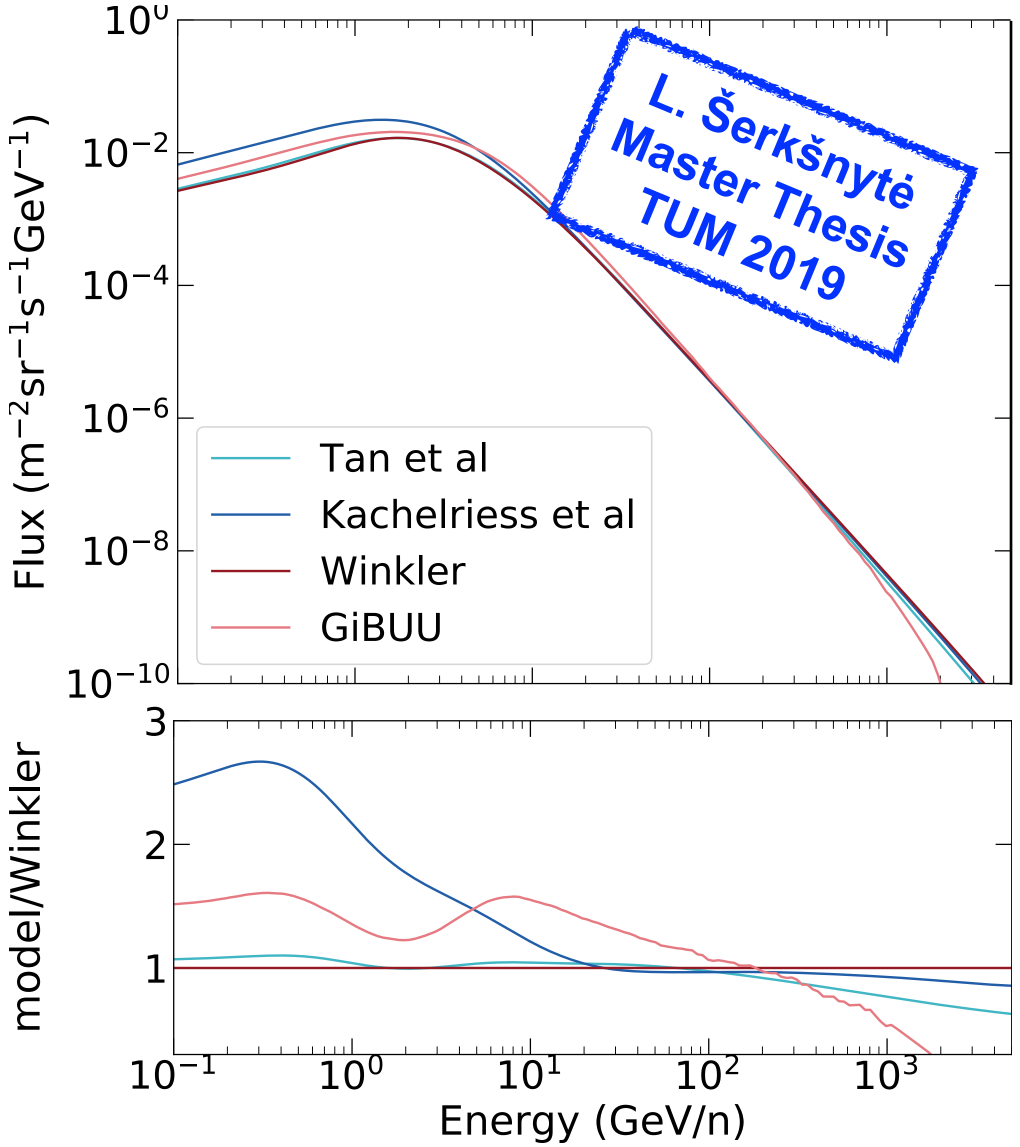


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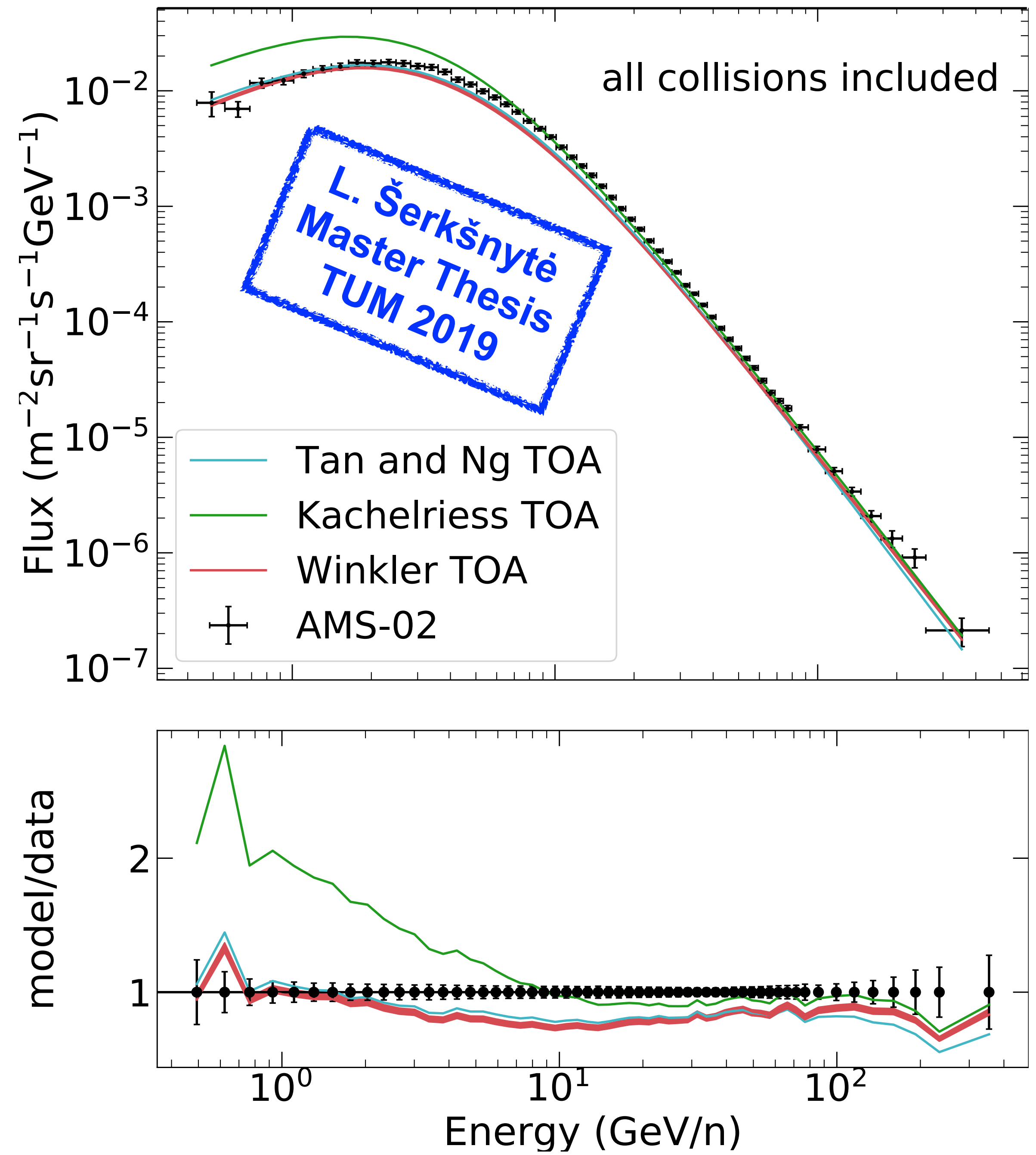


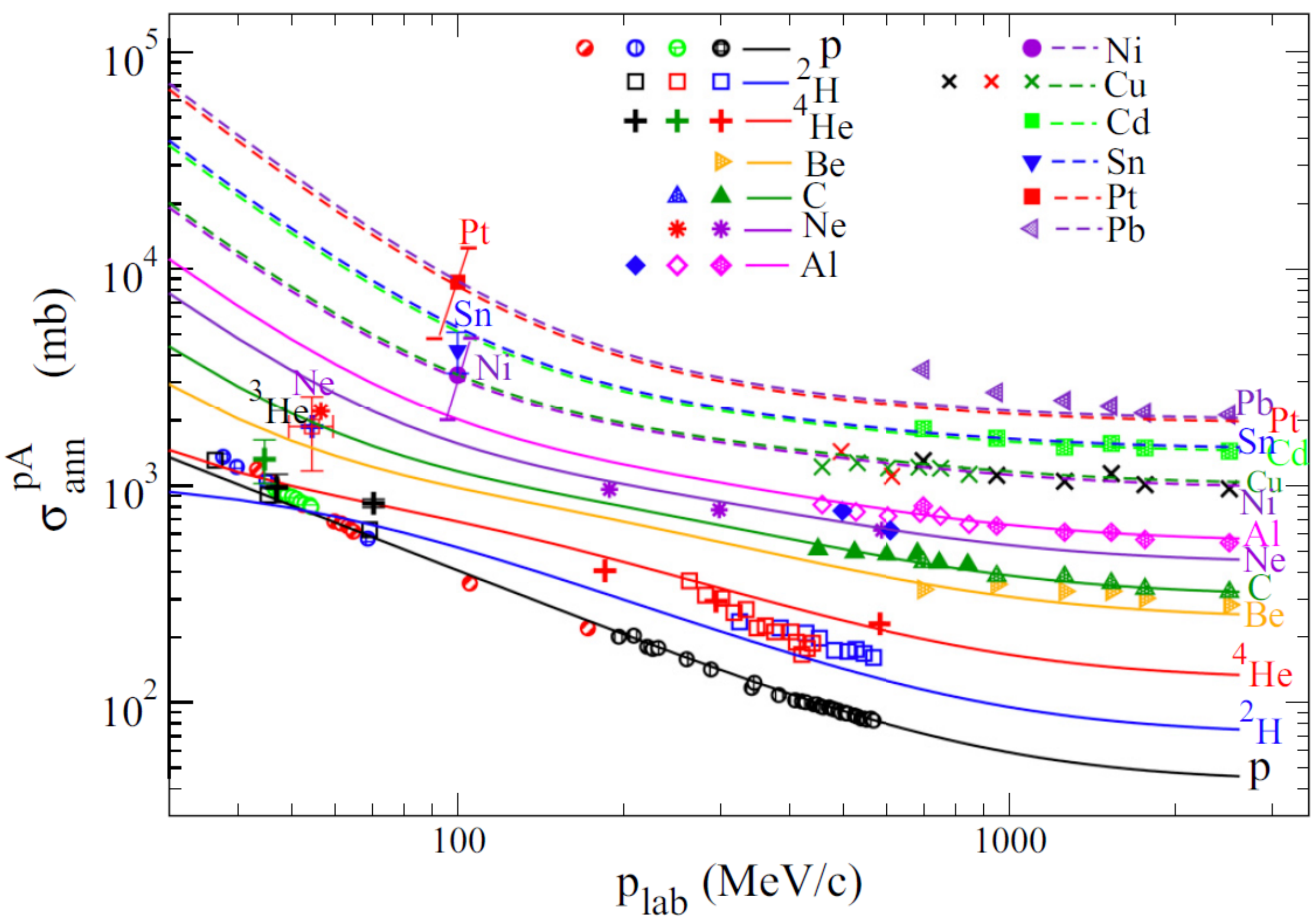

*Need to know the production and annihilation cross-sections as precisely as possible*

# Status of $\bar{p}$ and $\bar{d}$ annihilation c.s. measurements

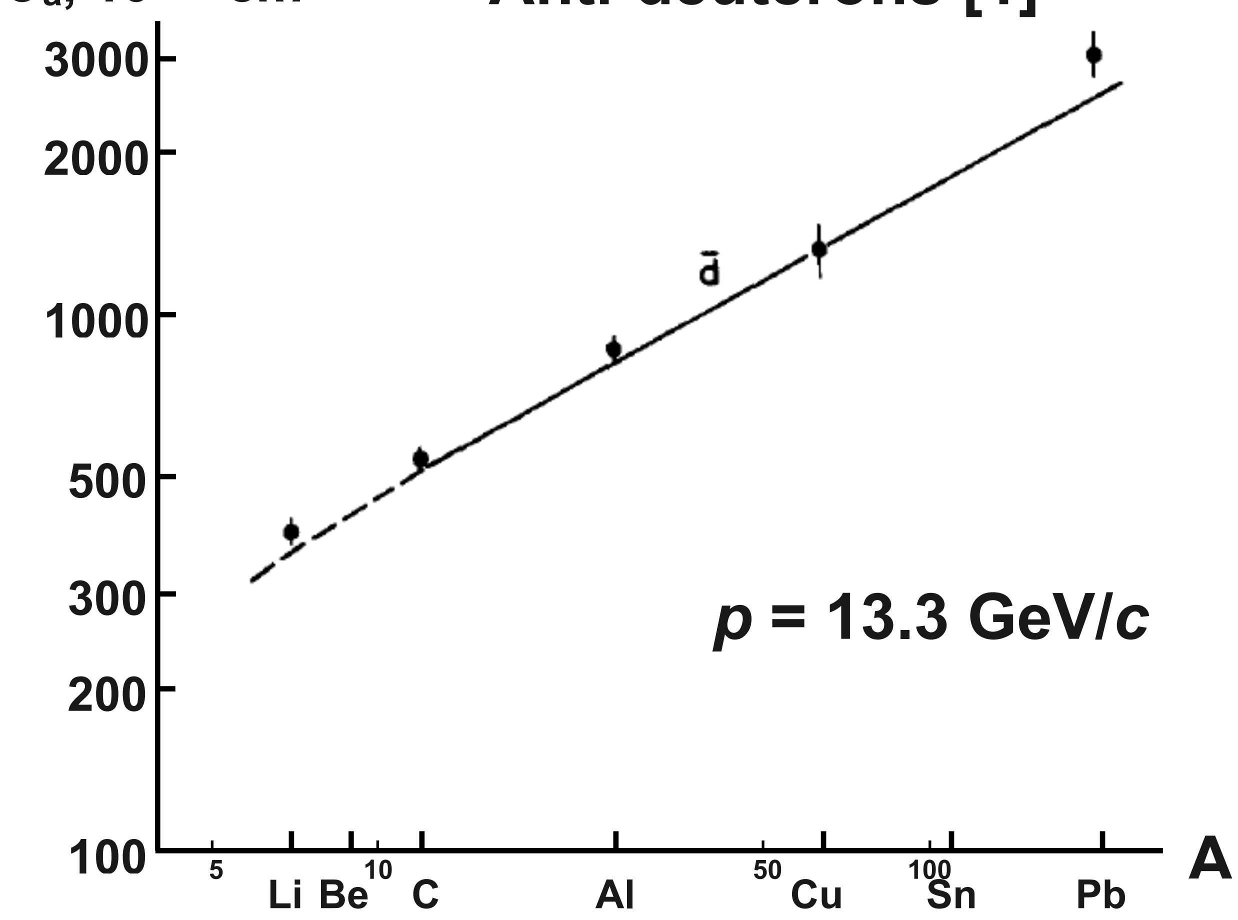
**Anti-deuteron inelastic cross-section is poorly known at low energies**

- No experimental data below $p_{lab}$ = 13.3 GeV/$c$ [1, 2]

**Anti-protons [3]**




**Anti-deuterons [1]**




[1] Nuclear Physics B 31(2), 253 (1971)
[2] Phys. Let. B 31(4), 230 (1970)
[3] Phys. Rev. C 89, 054601 (2014)

# Status of p̄ and d̄ annihilation c.s. measurements

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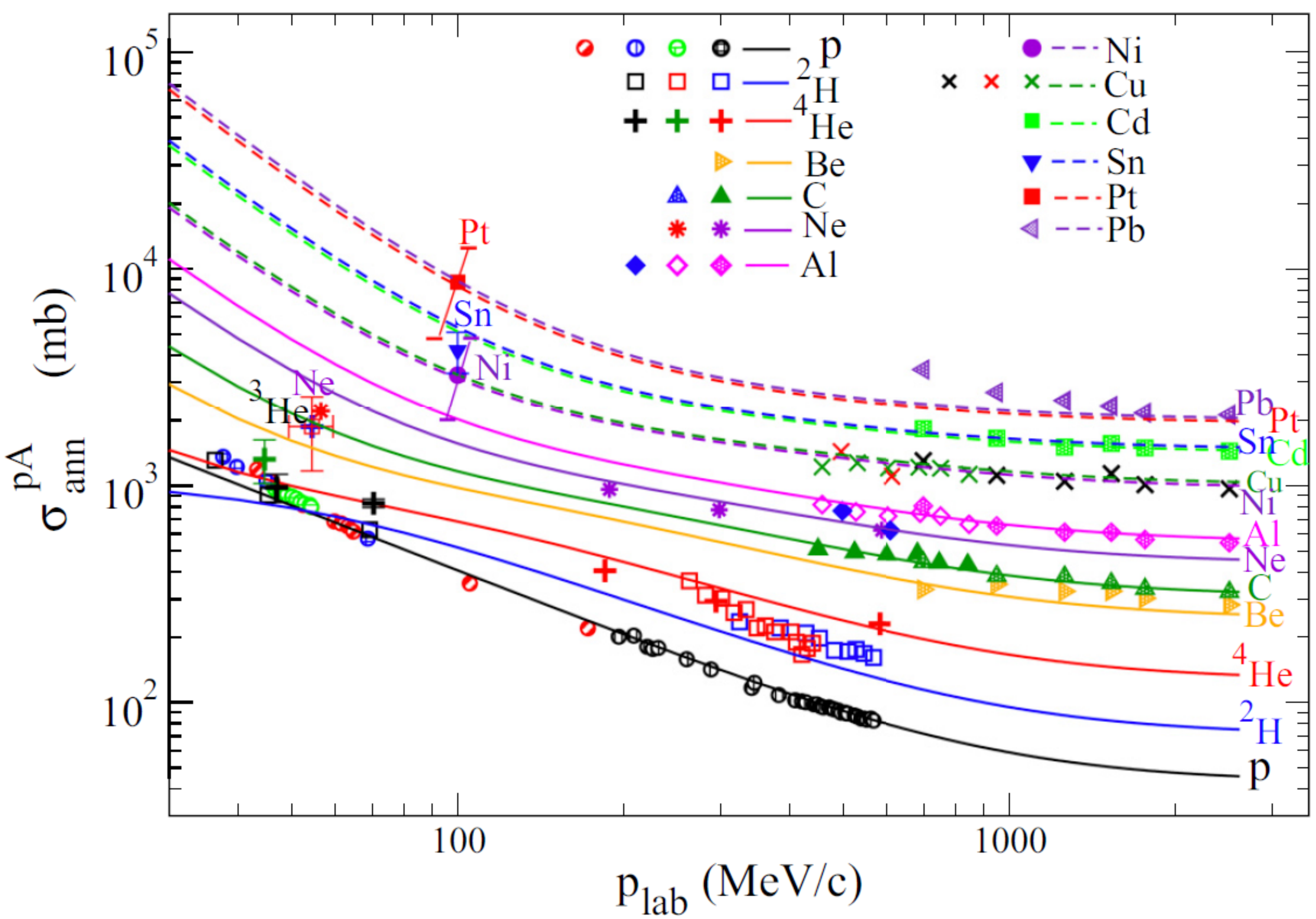
- No experimental data below $p_{lab}$ = 13.3 GeV/*c* [1, 2]

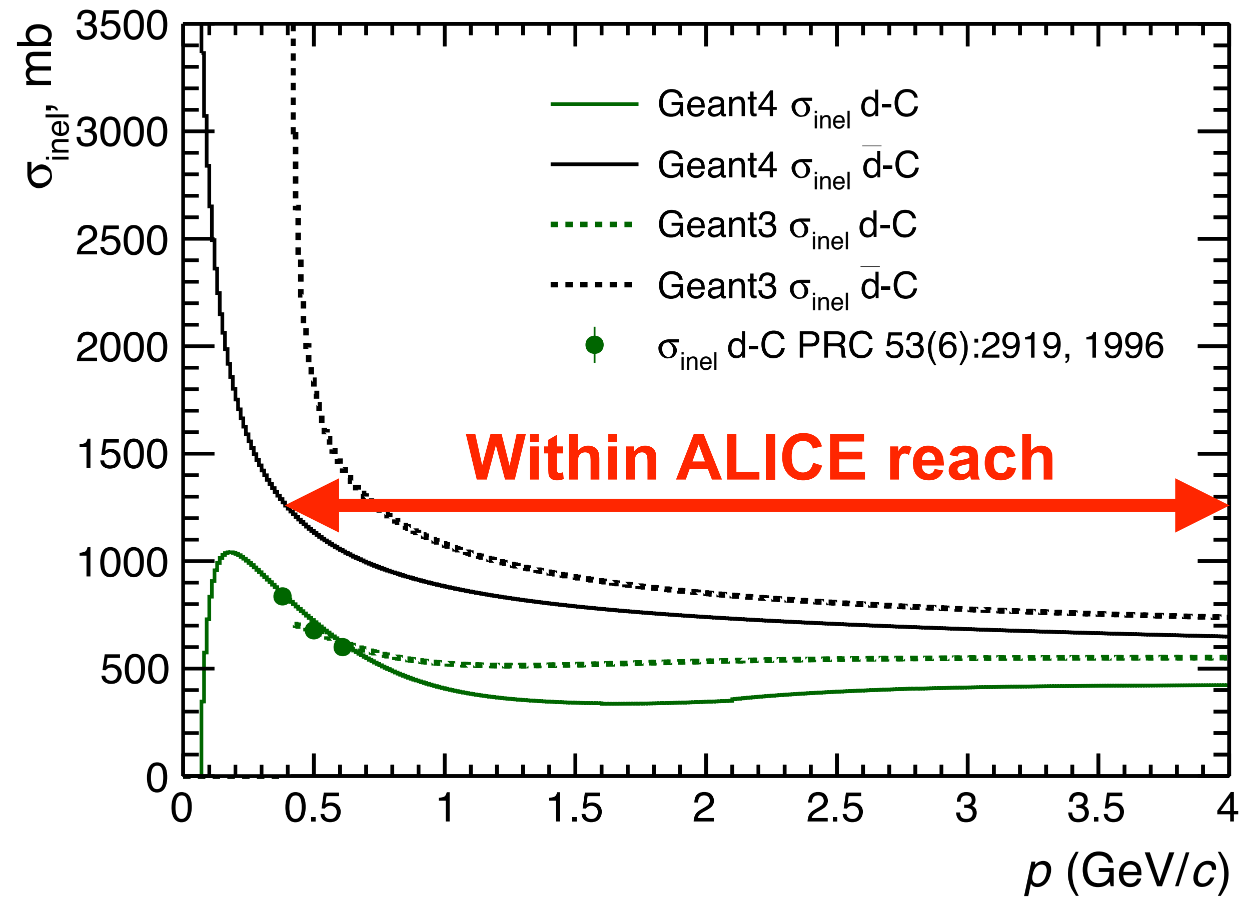
Deuteron inelastic cross-section is measured at low momentum

- *Use the ALICE experiment to study anti-deuteron absorption in detector material*

## Anti-protons [3]




## (Anti-)deuterons on carbon

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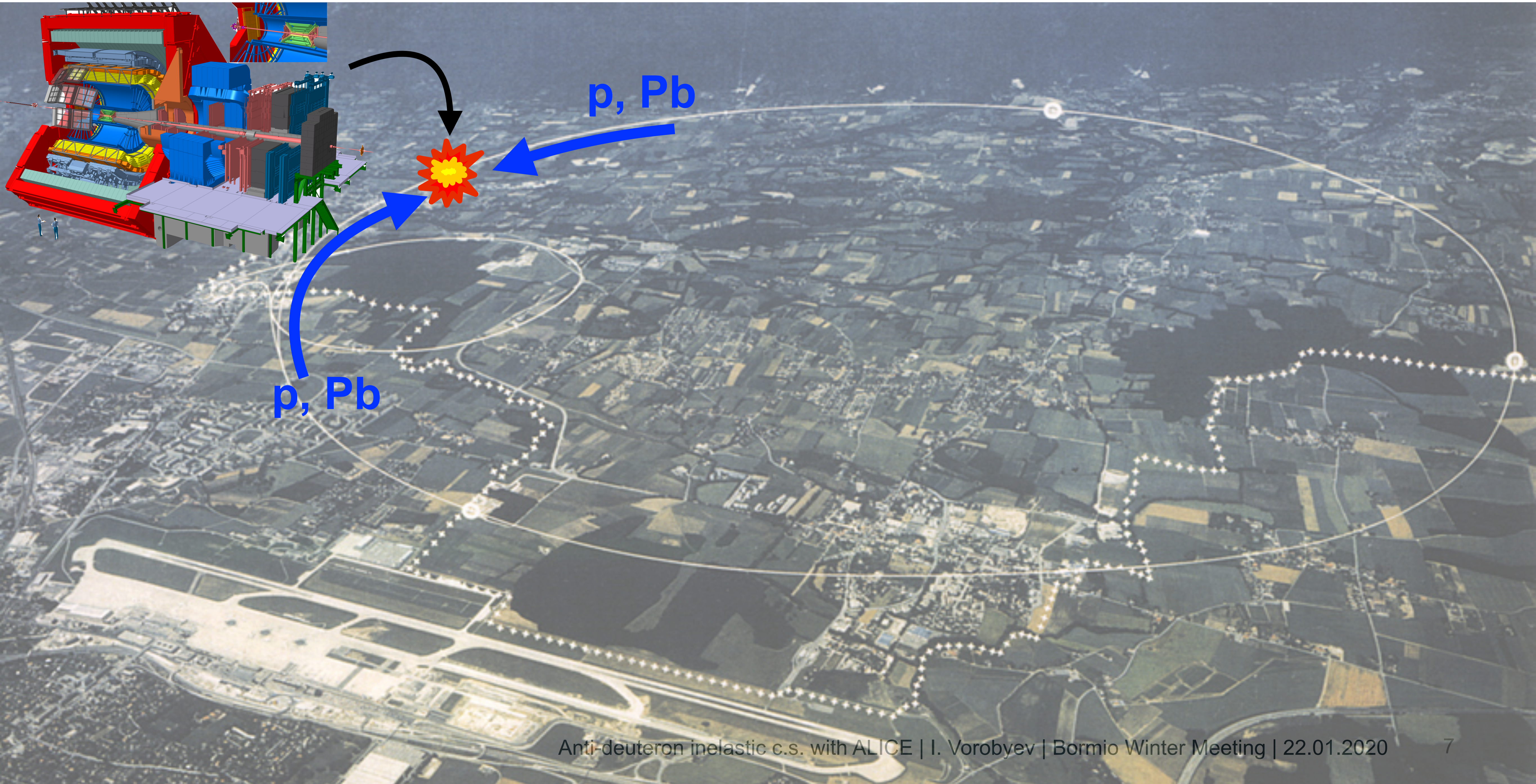
# Large Hadron Collider as an anti-matter factory

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



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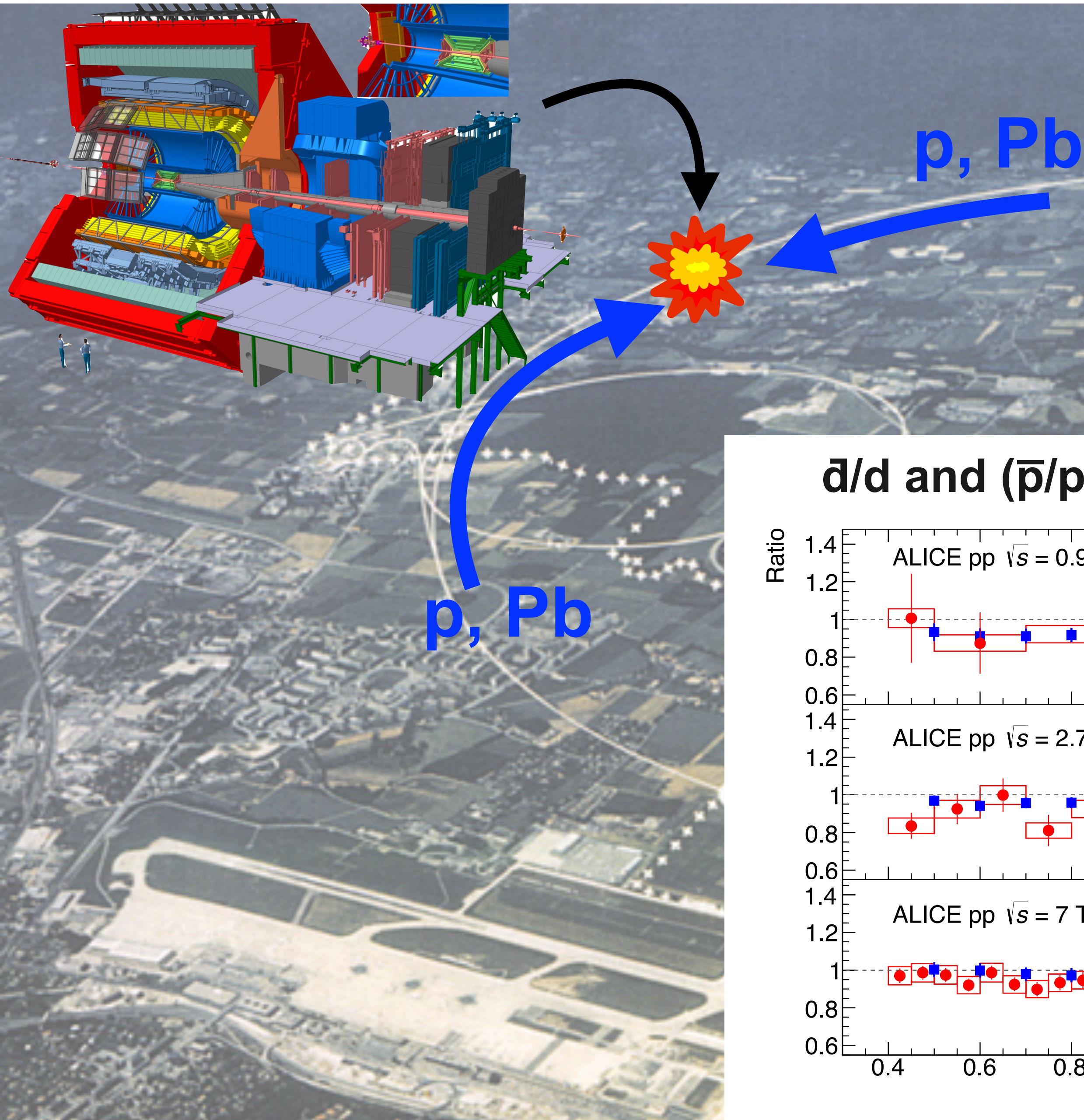
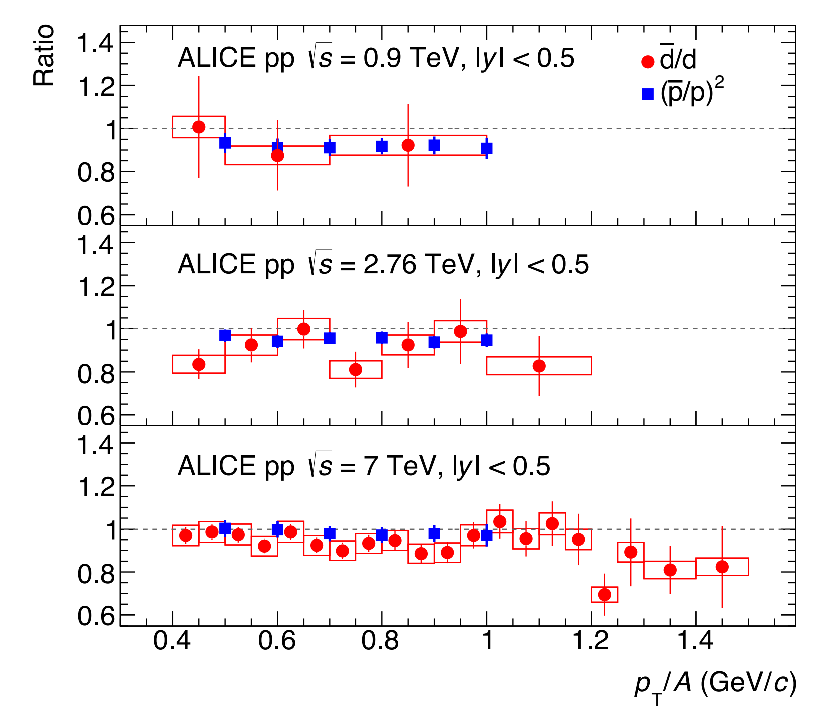
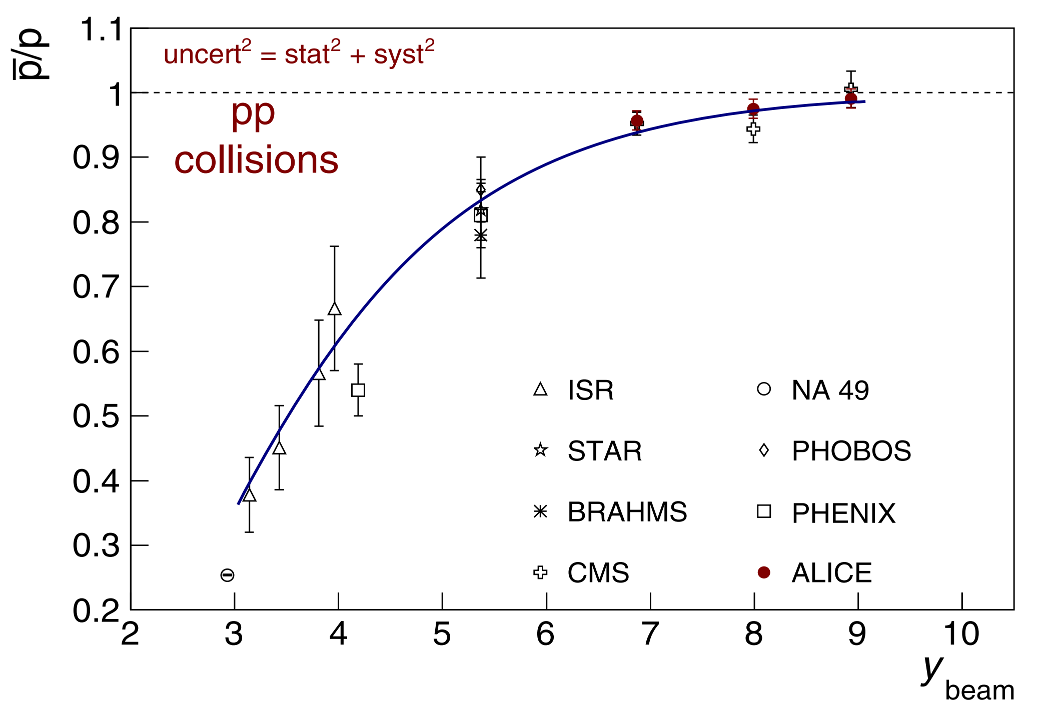



**d̄/d and (p̄/p)² ratios vs $p_T$ [1]**




**p̄/p ratio at mid-rapidity vs √s [1]**




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

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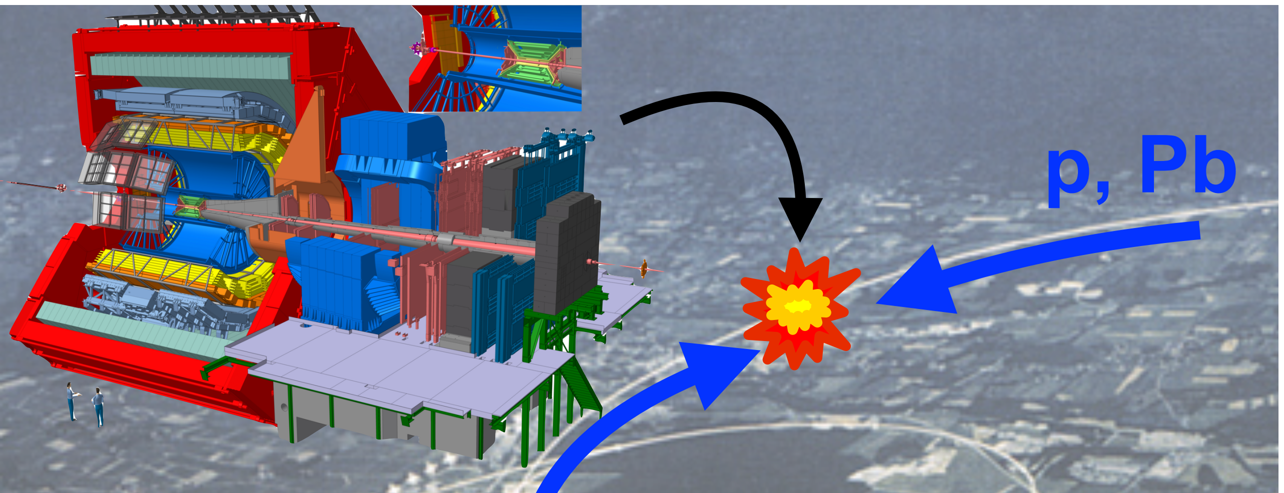
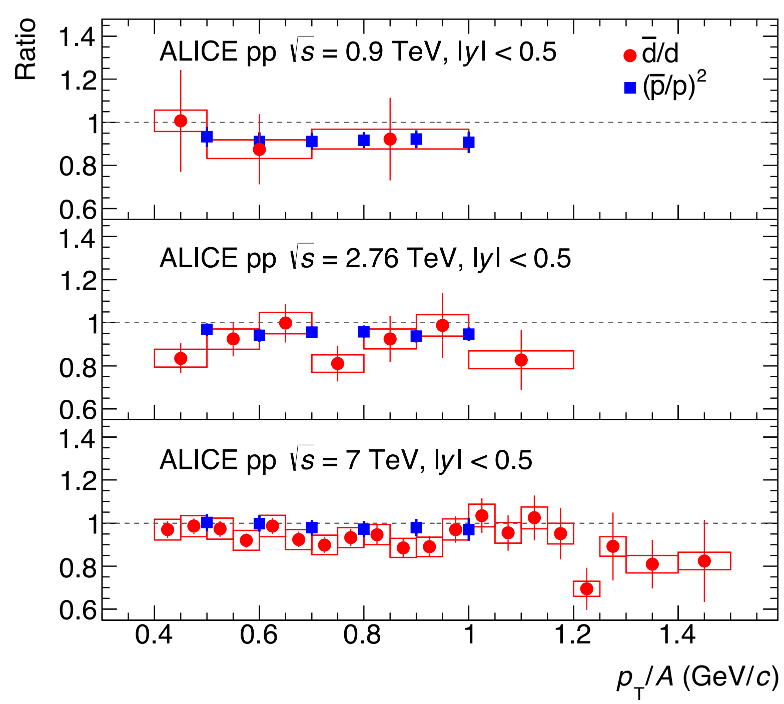



**This talk: results from p-Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV, ~300 M events**

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]**

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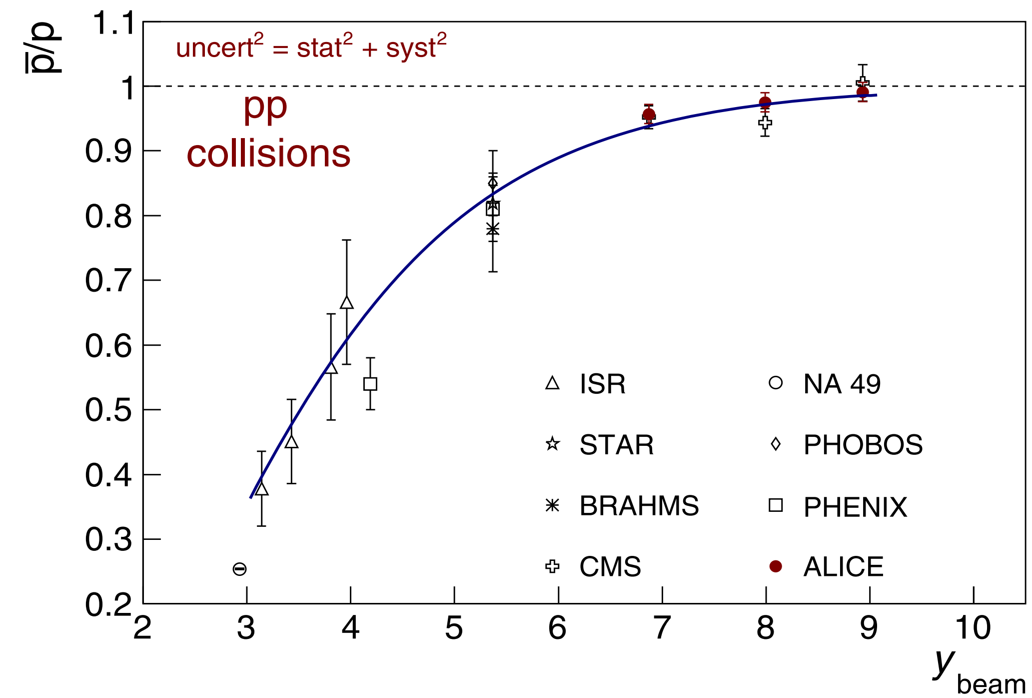


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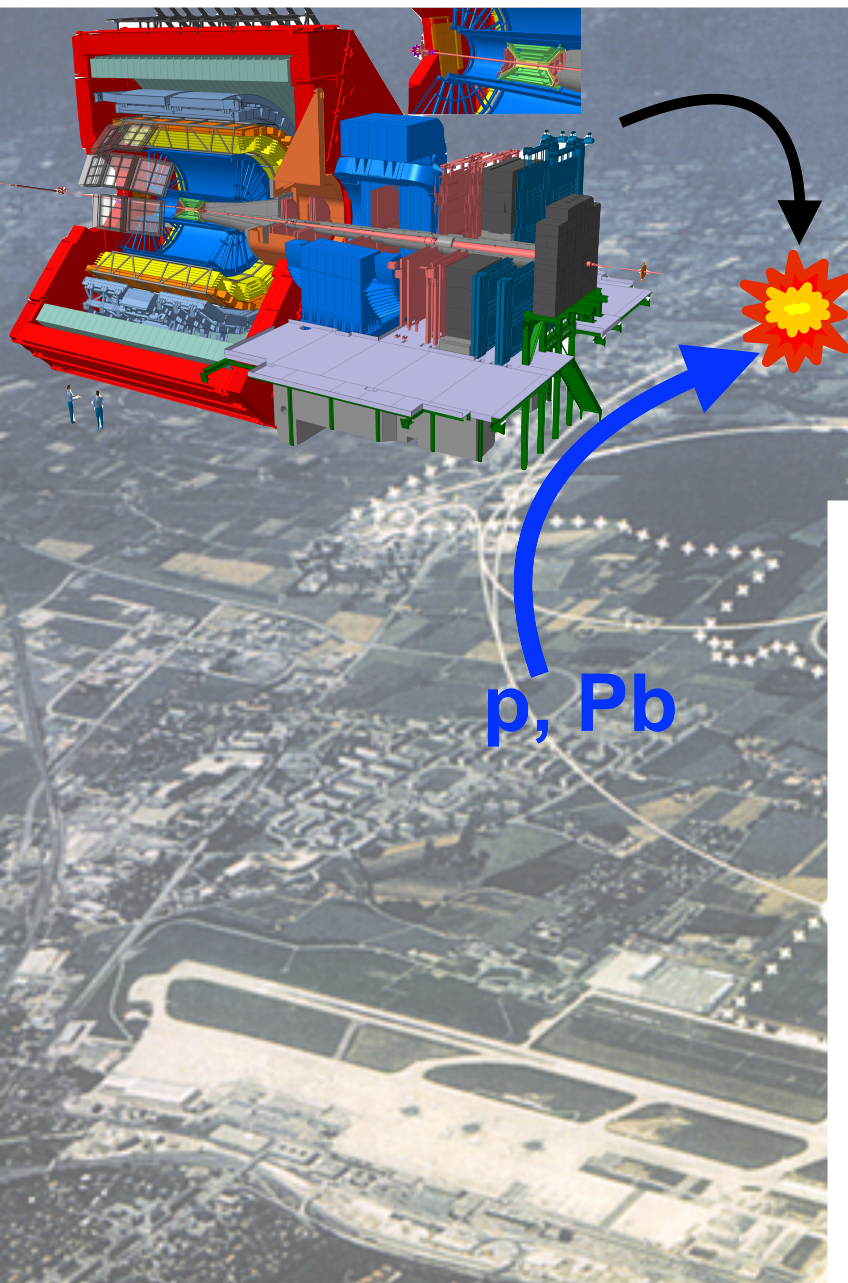
- (Anti-)deuterons interact inelastically with detector material - this can be quantified!

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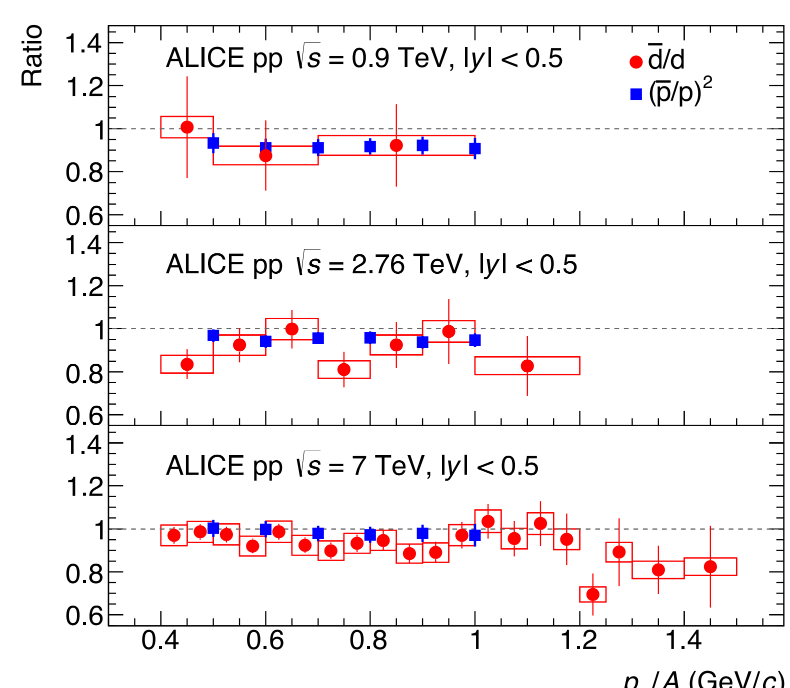


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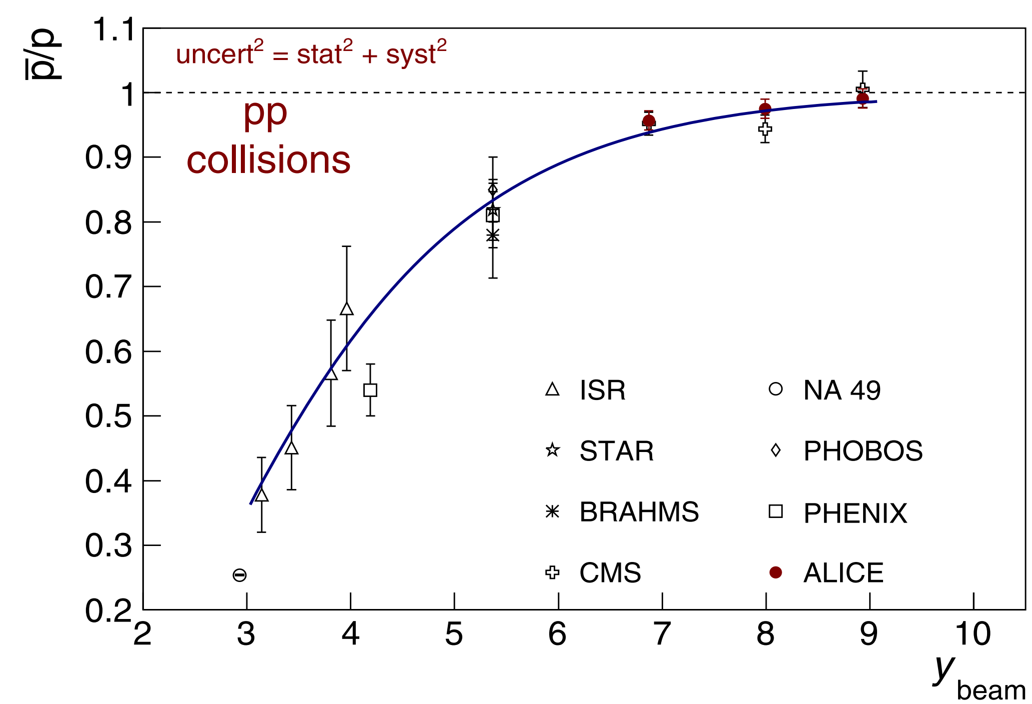


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# … and ALICE detector material as a target

Material budget at mid-rapidity [1]:
- Beam pipe (~0.3% $X_0$)
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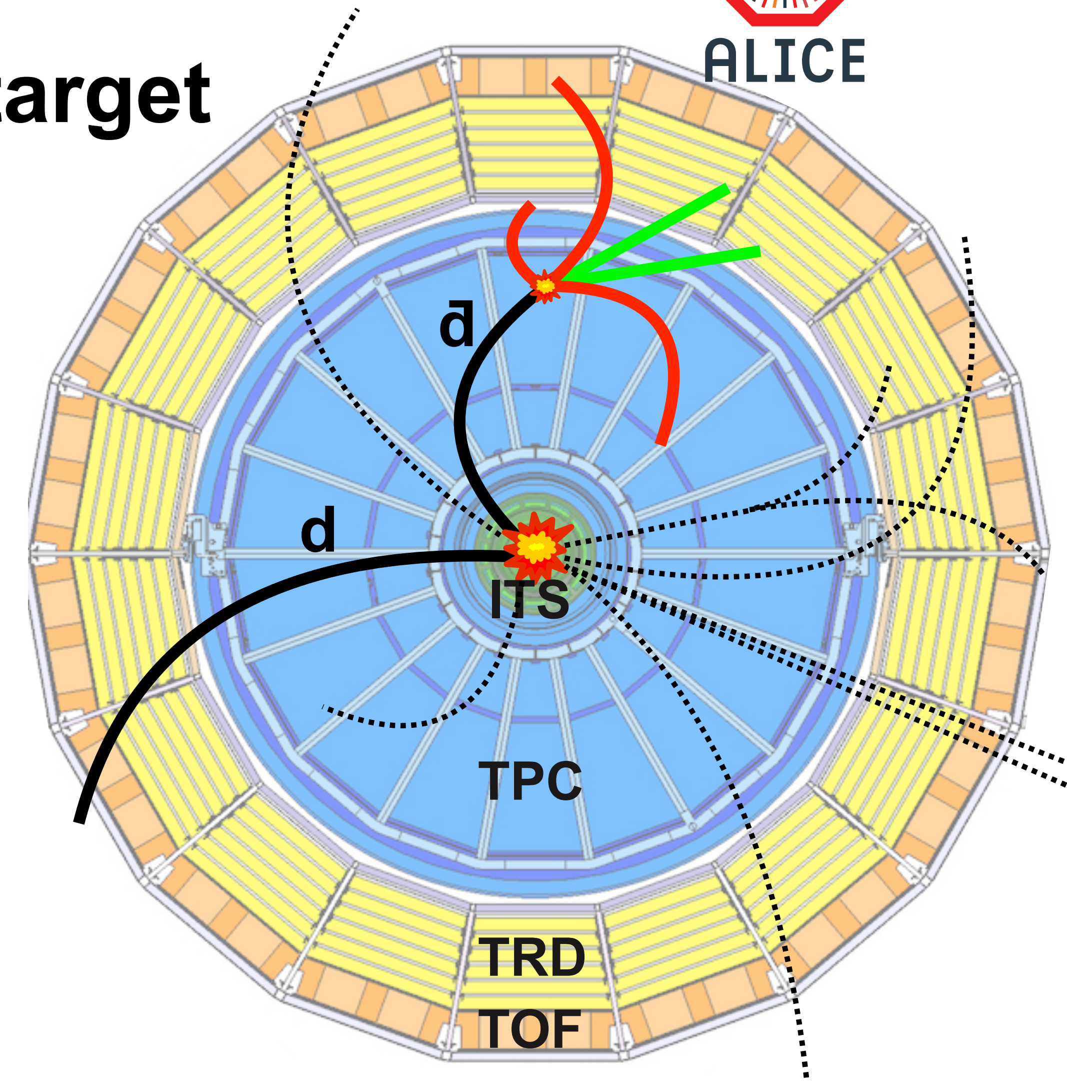
- Space frame (~20% $X_0$ between TPC and TOF)




**Idea: 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 $\sigma_{inel}(\bar{d})$

[1] JINST 3, S08002 (2008)

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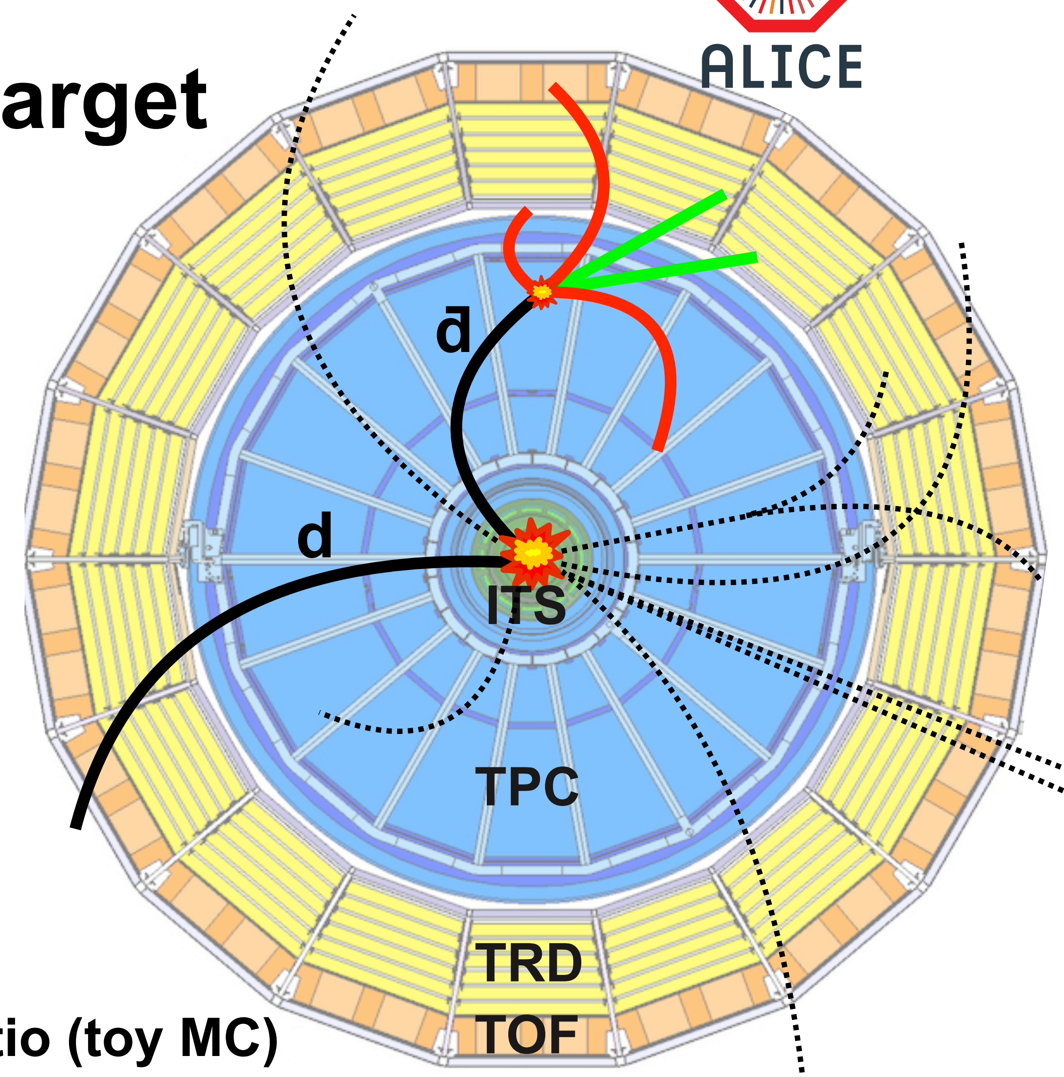


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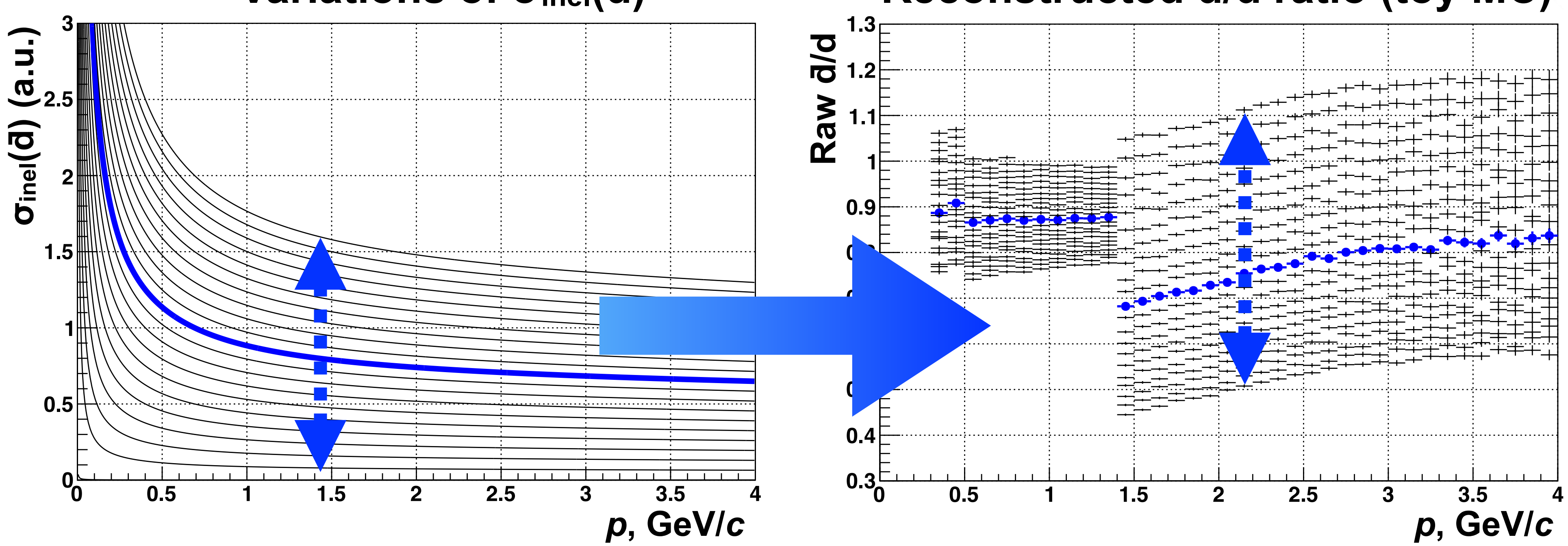
**Variations of $\sigma_{inel}$(d̄)** **Reconstructed d̄/d ratio (toy MC)**

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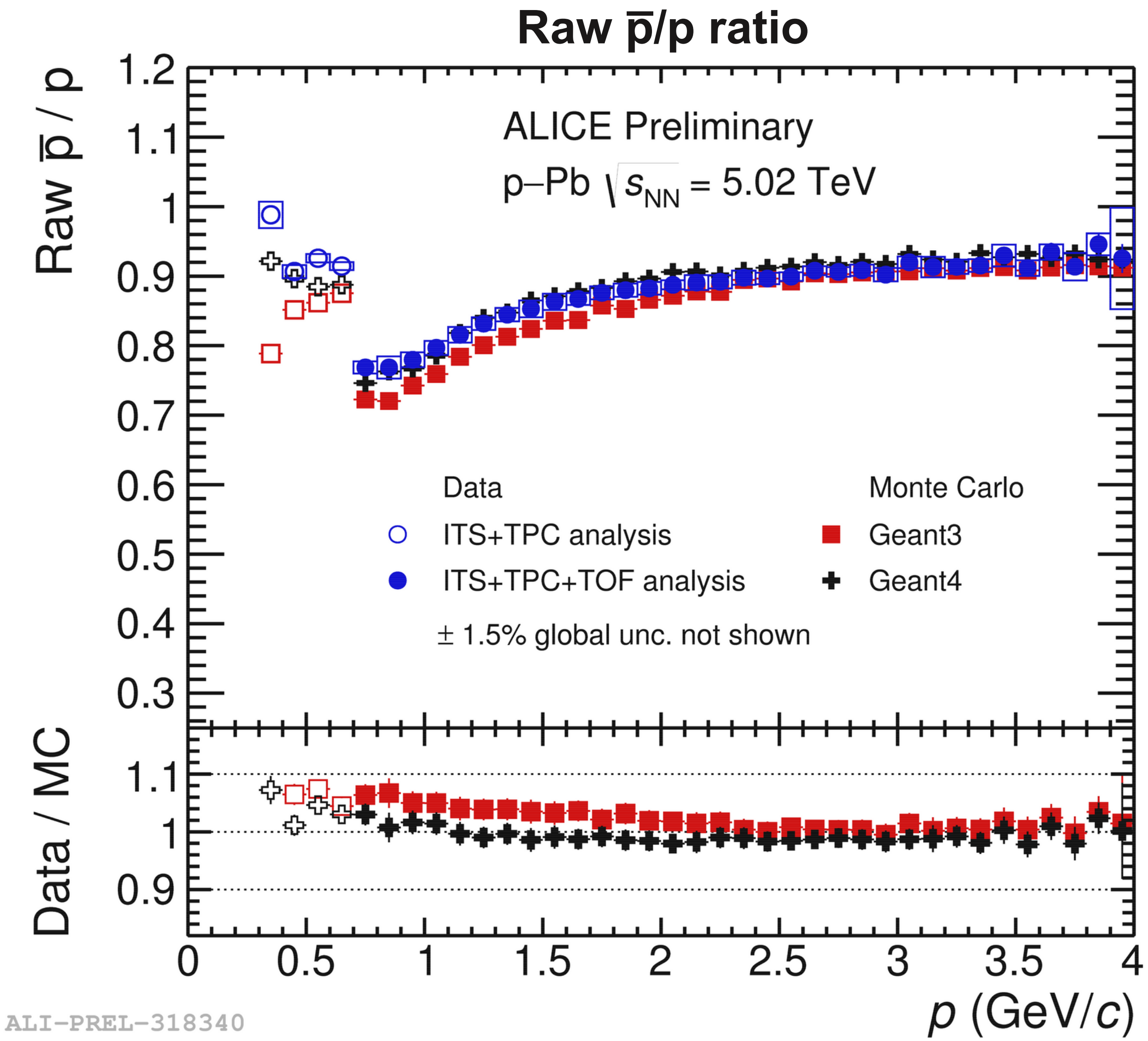
# Primary (anti-)protons as a benchmark analysis

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

- Higher loss of anti-protons in detector material as expected
- Step at $p$ = 0.7 GeV/$c$ due to additional detector material between TPC and TOF (TRD, space frame)

Monte Carlo data: detailed simulation of ALICE detector performance

- Propagation of (anti-)particles and interaction with matter with Geant



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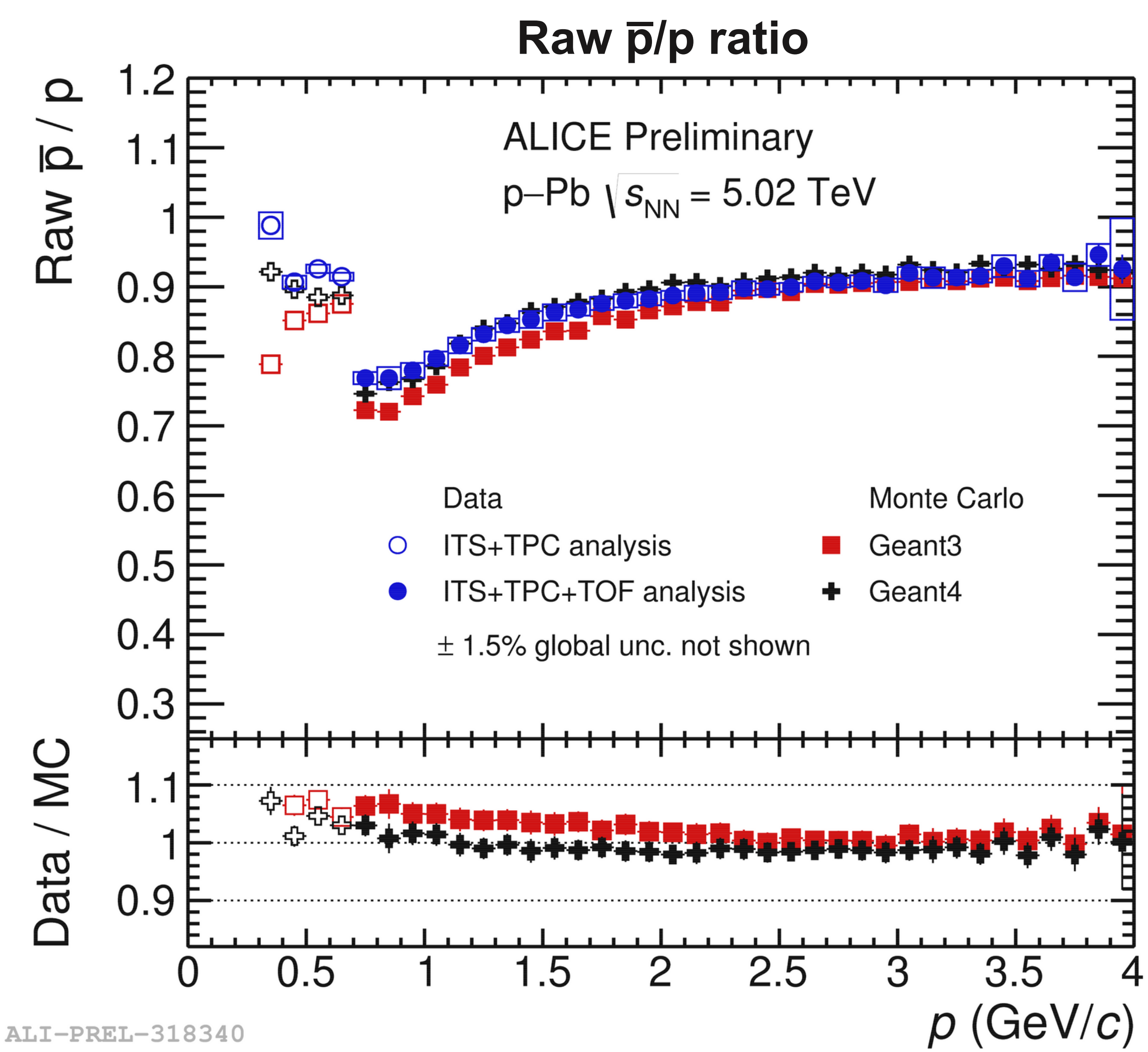
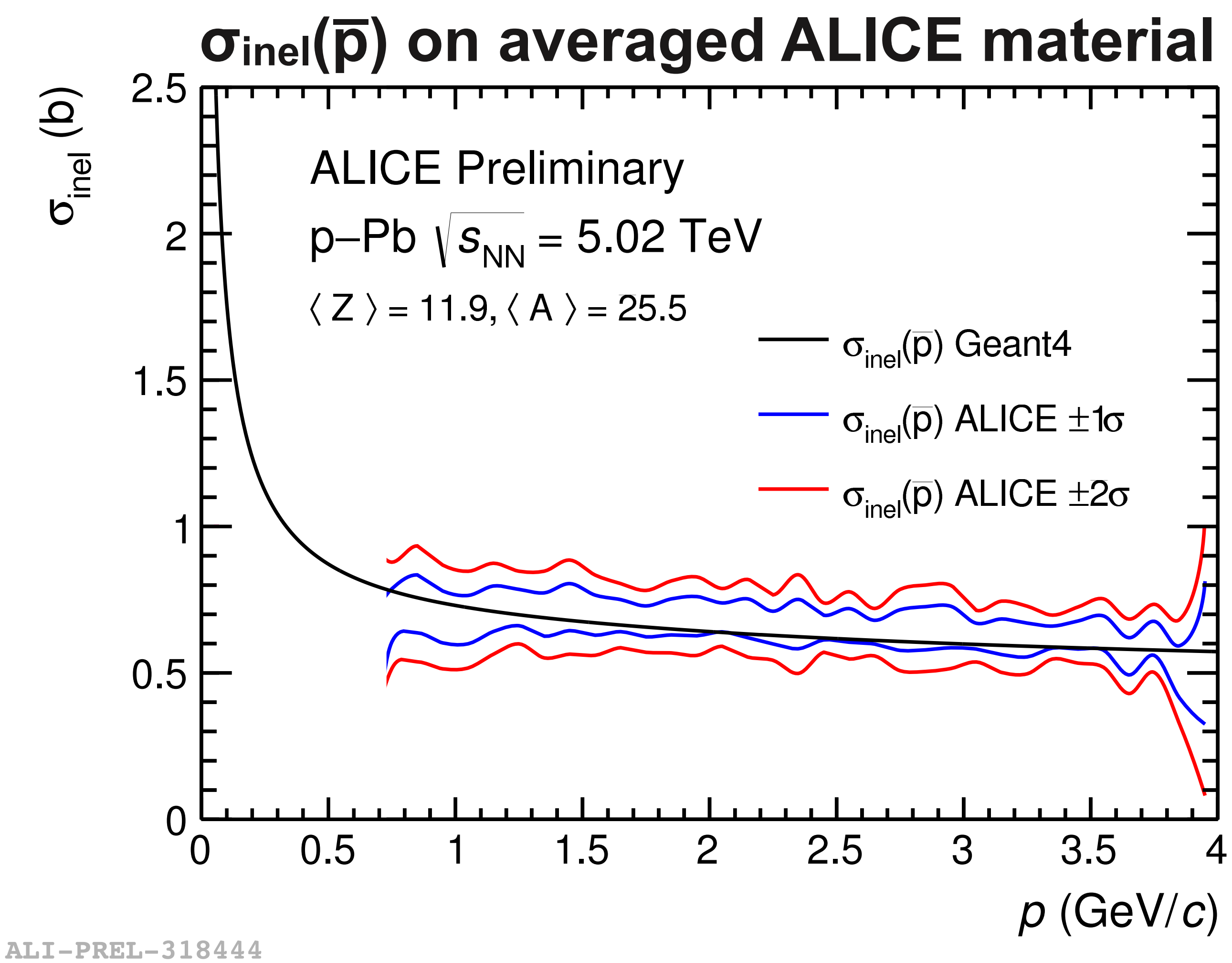



*Vary $\sigma_{inel}$ ($\bar{p}$) in Geant4-based simulations until MC ratio is ±1σ or ±2σ away from experimental ratio → constraints on $\sigma_{inel}$ ($\bar{p}$)*

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

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

- $\langle Z \rangle$ = 11.9, $\langle A \rangle$ = 25.5 (from primary collision vertex to the TOF detector)
- Good agreement with Geant4 parameterisations as expected



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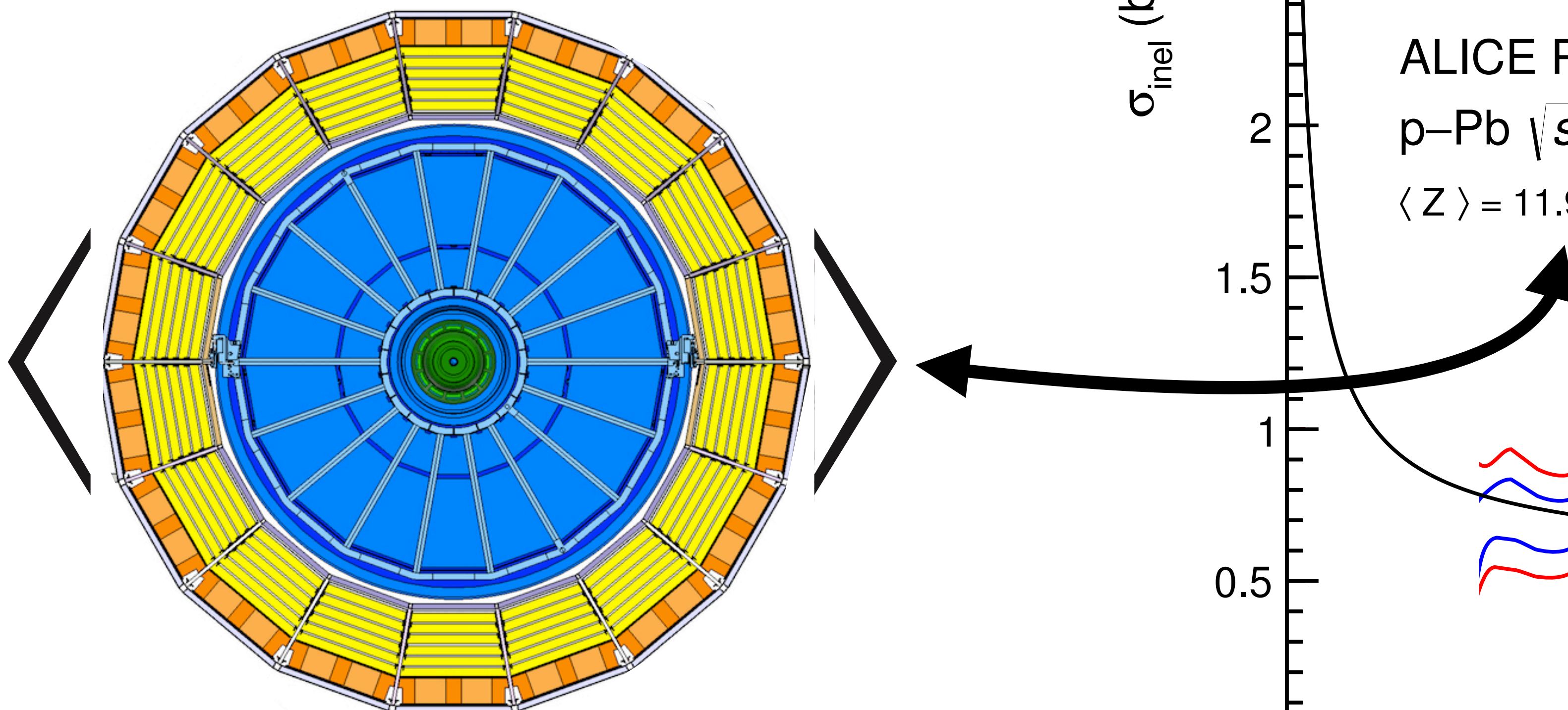

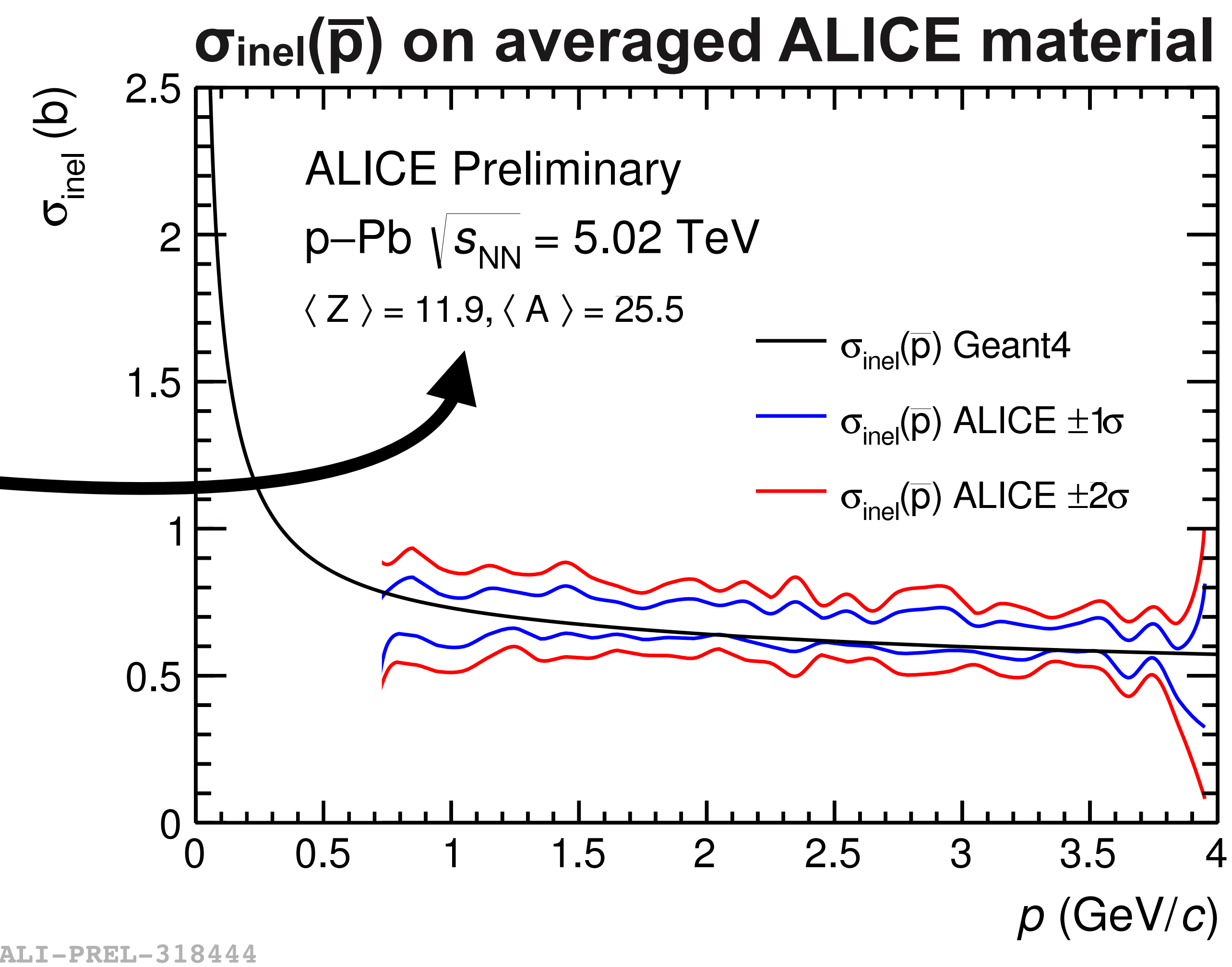

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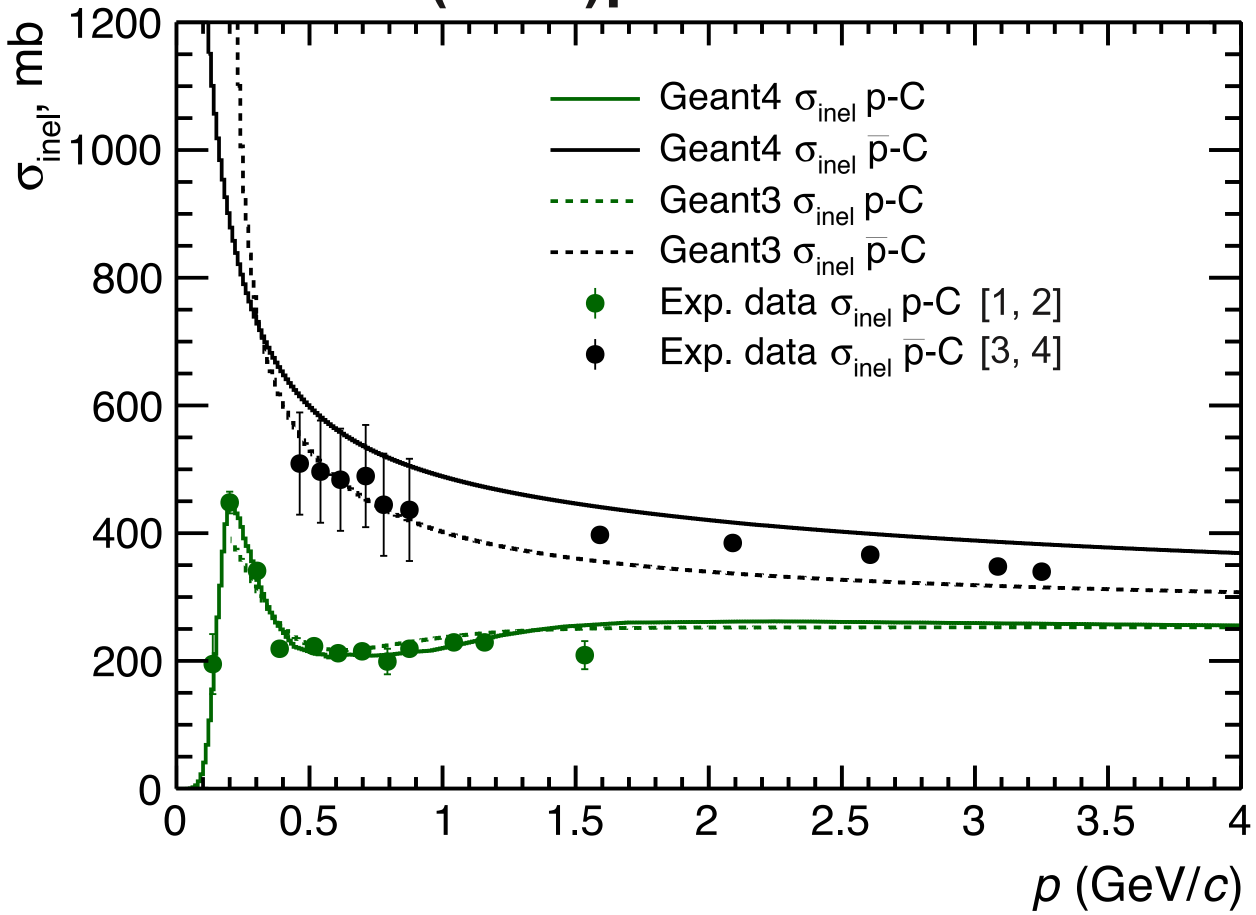
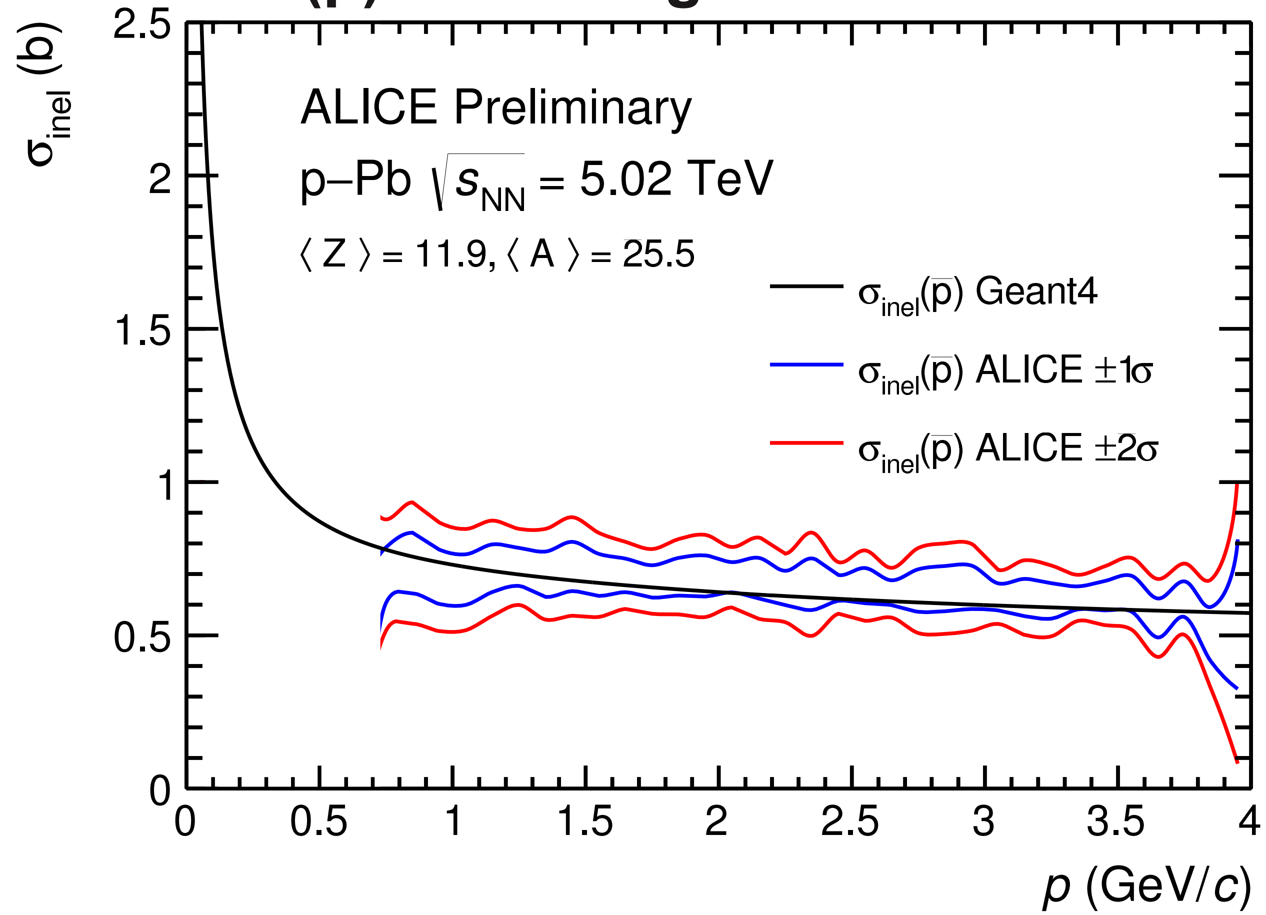
- Good agreement with Geant4 parameterisations as expected
- Several measurements available for $\sigma_{inel}(\bar{p})$ on different materials [3, 4]

**$\sigma_{inel}$ of (anti-)protons on carbon**




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

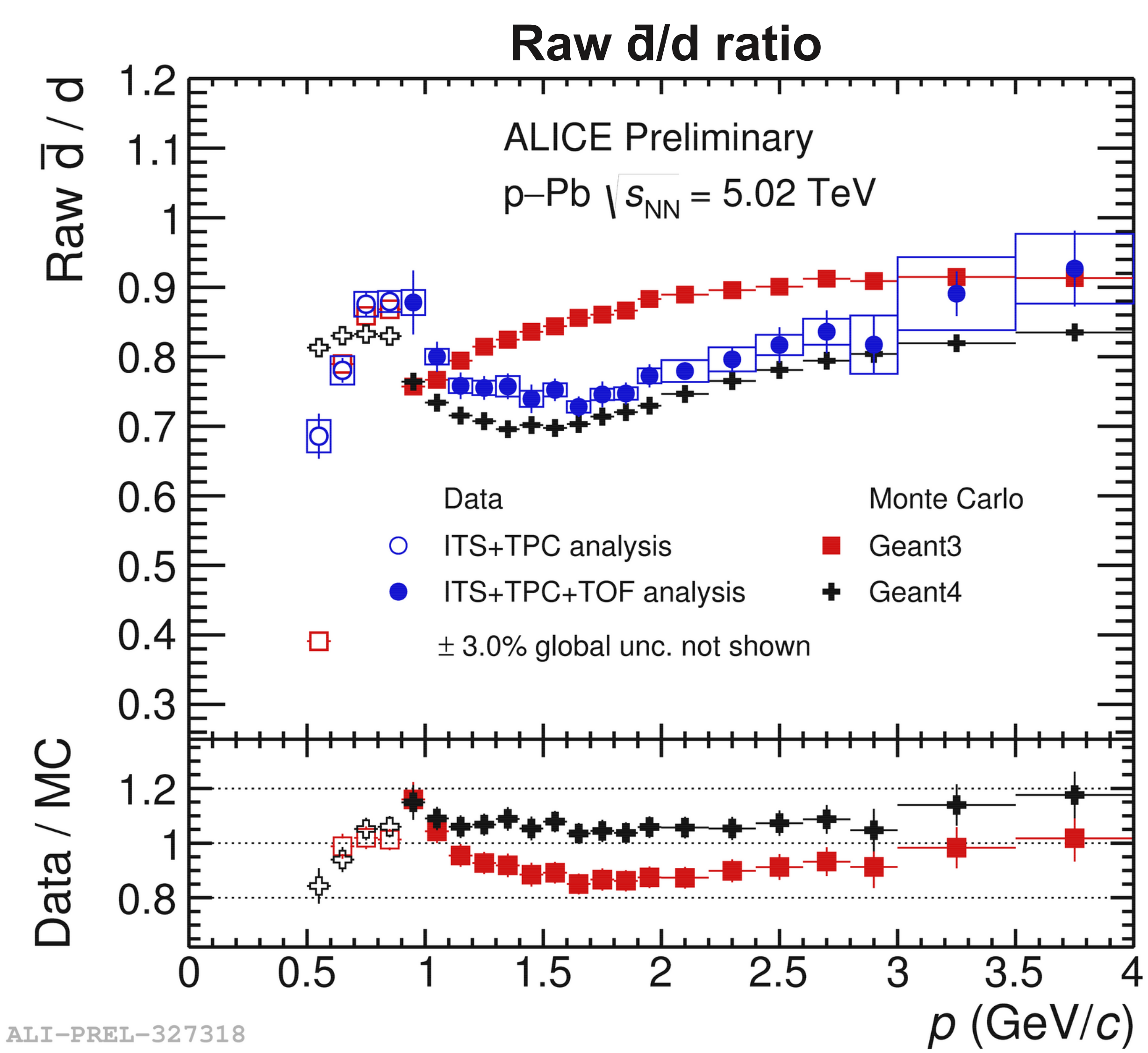



ALI-PREL-318444

[1] Phys. Rev. C 31 (1985) 1616, 18 (1978) 1436
[2] Nucl. Phys. A 319 (1979) 377, 97 (1967) 263
[3] Phys. Lett. B 704, 461 (2011)
[4] Nucl. Phys. A 576, 581 (1994)

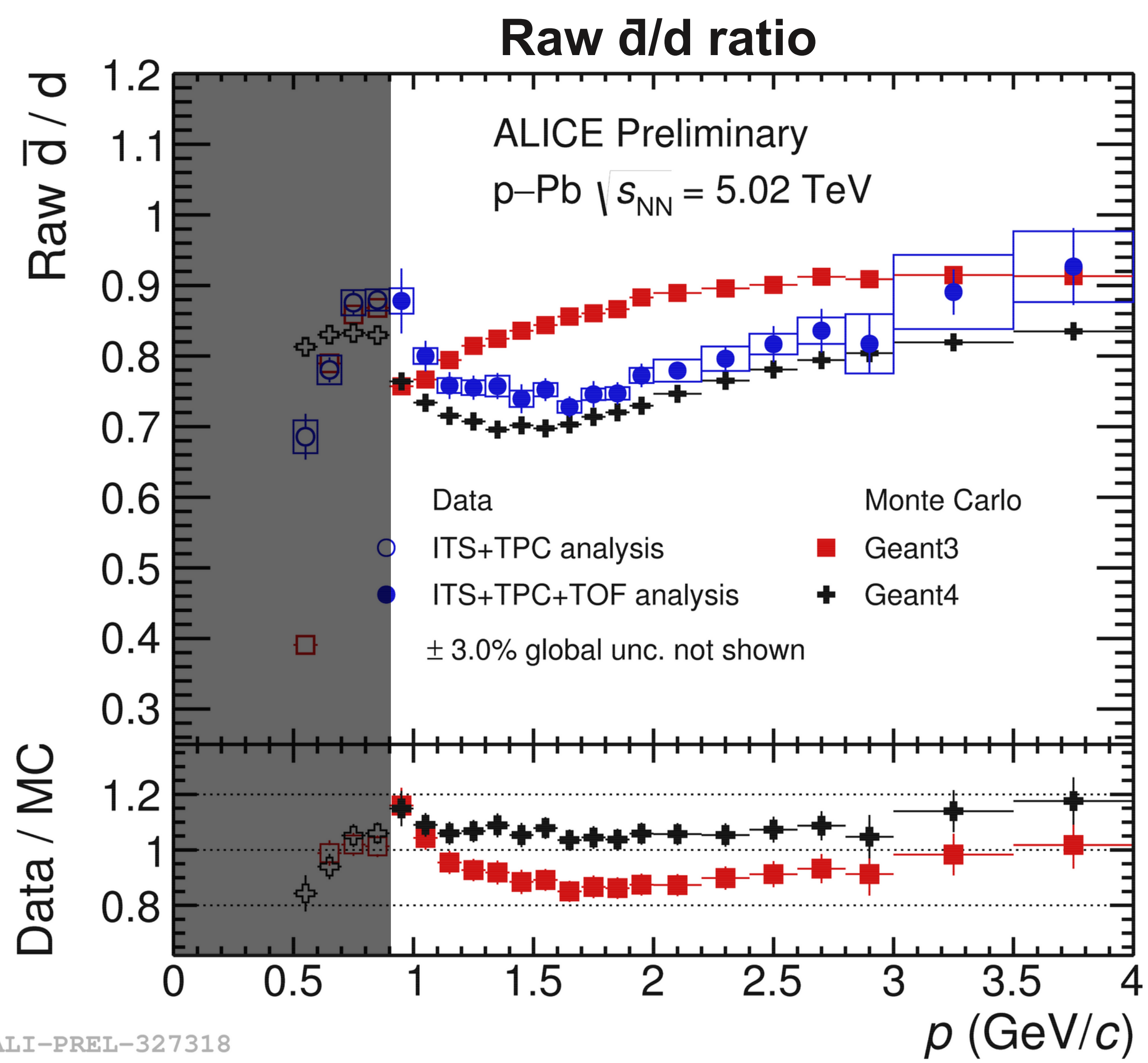
# Raw ratio of primary (anti-)deuterons

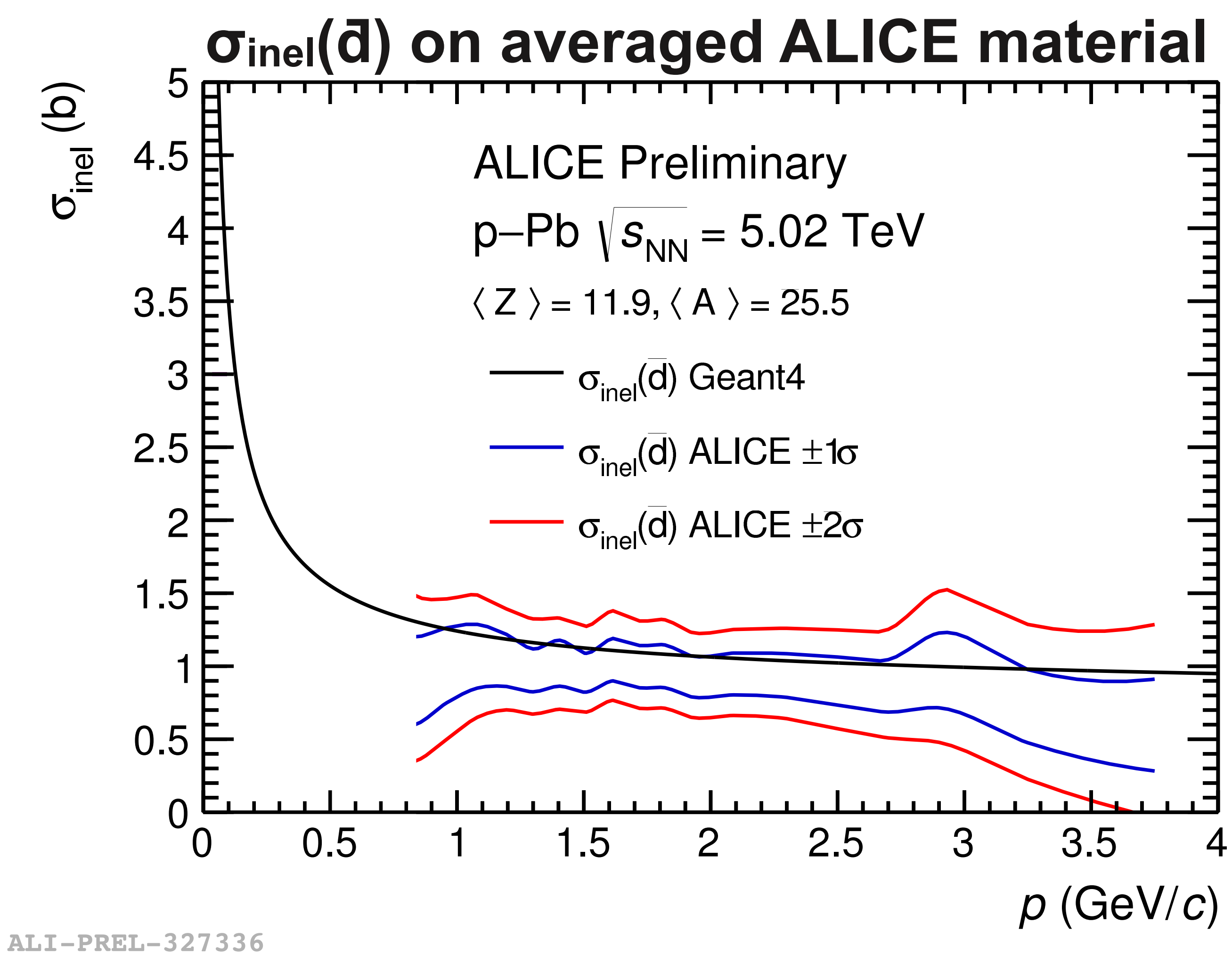
Raw d̄/d ratio compared to detailed ALICE Monte Carlo simulations
- *Geant4-based results in much better agreement with exp. data*



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

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

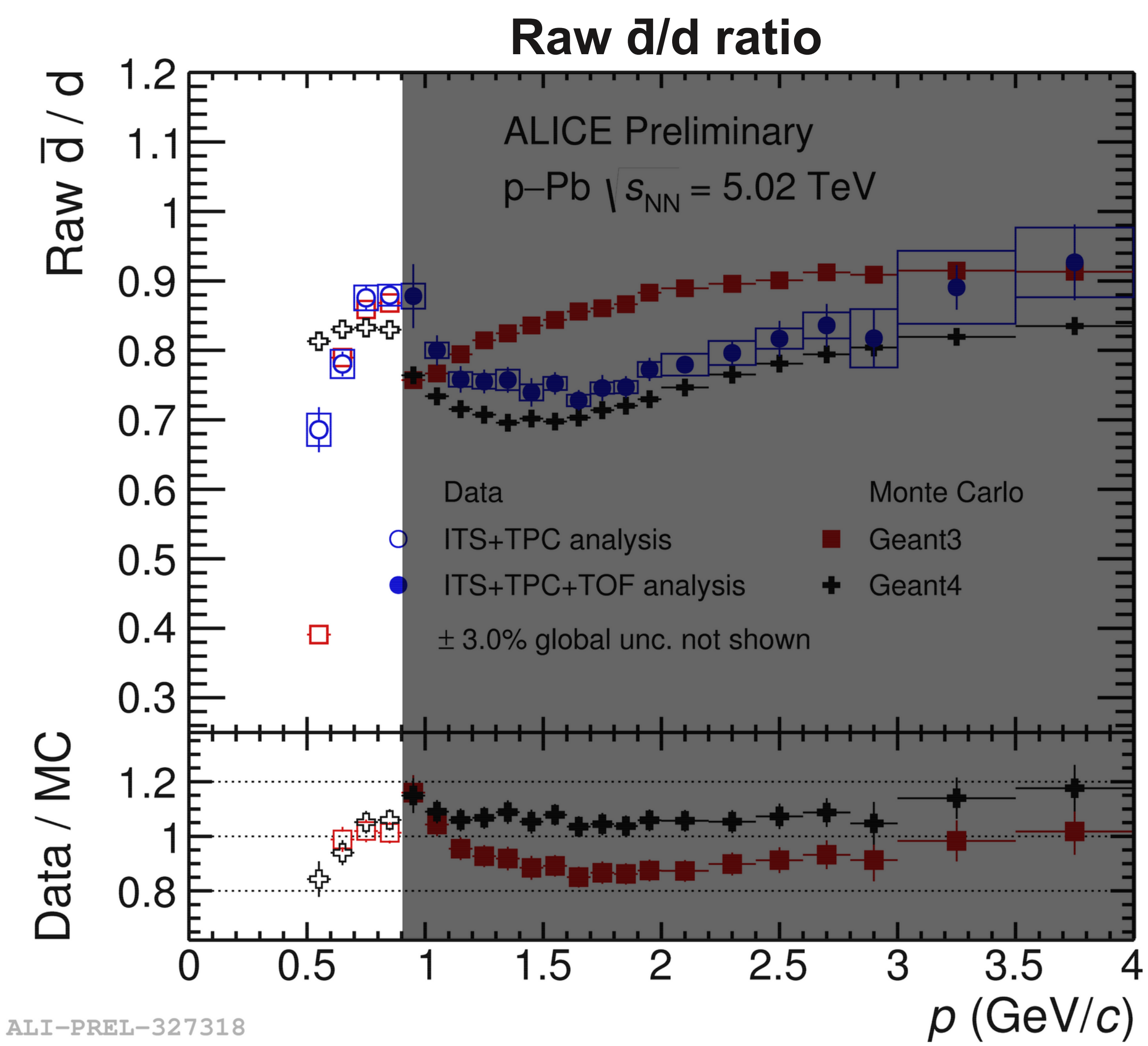


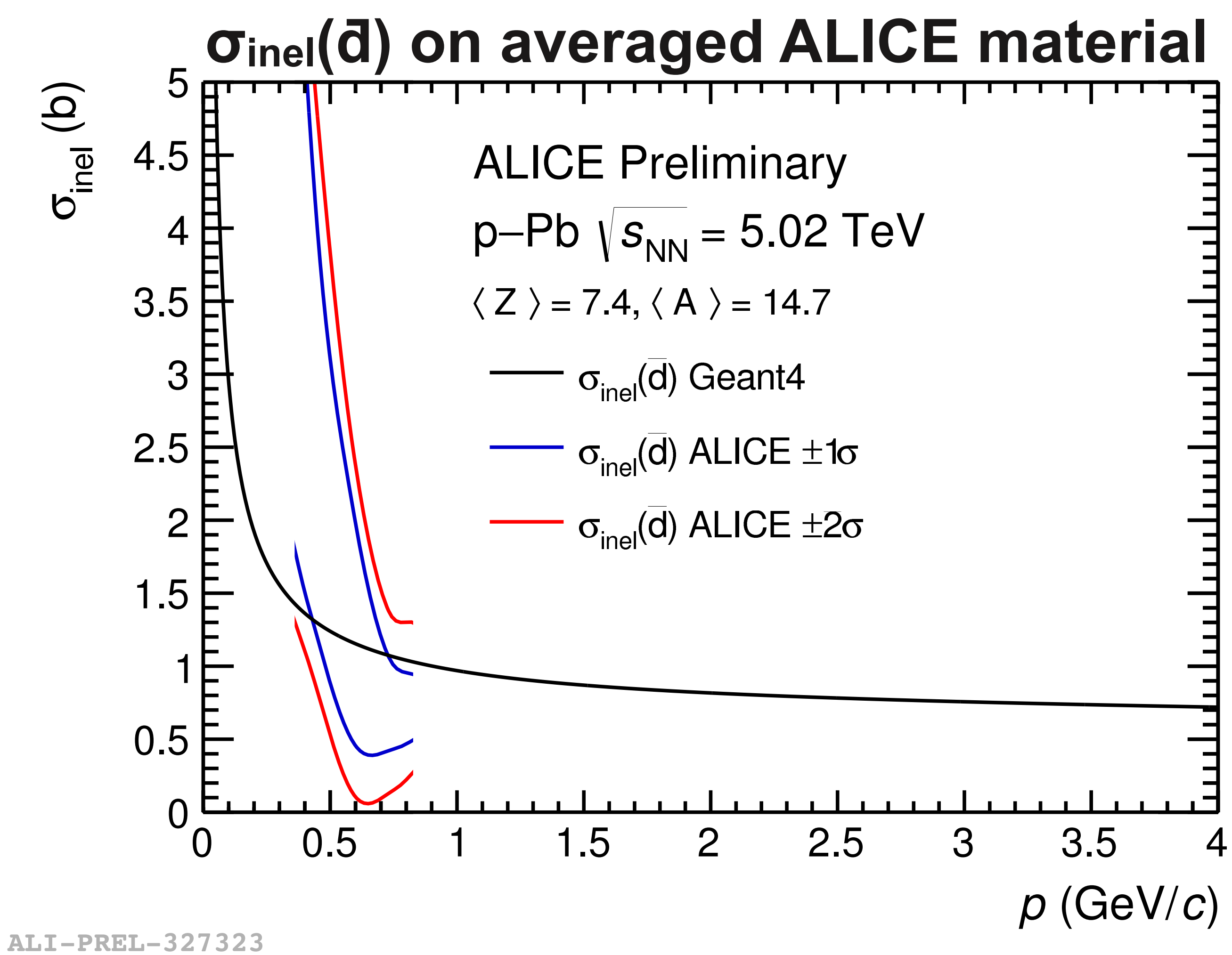



# Constraints for $\sigma_{inel}(\bar{d})$ with ALICE material

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

- Energy loss in detector material - inelastic interaction at $p$ < $p$ at primary vertex



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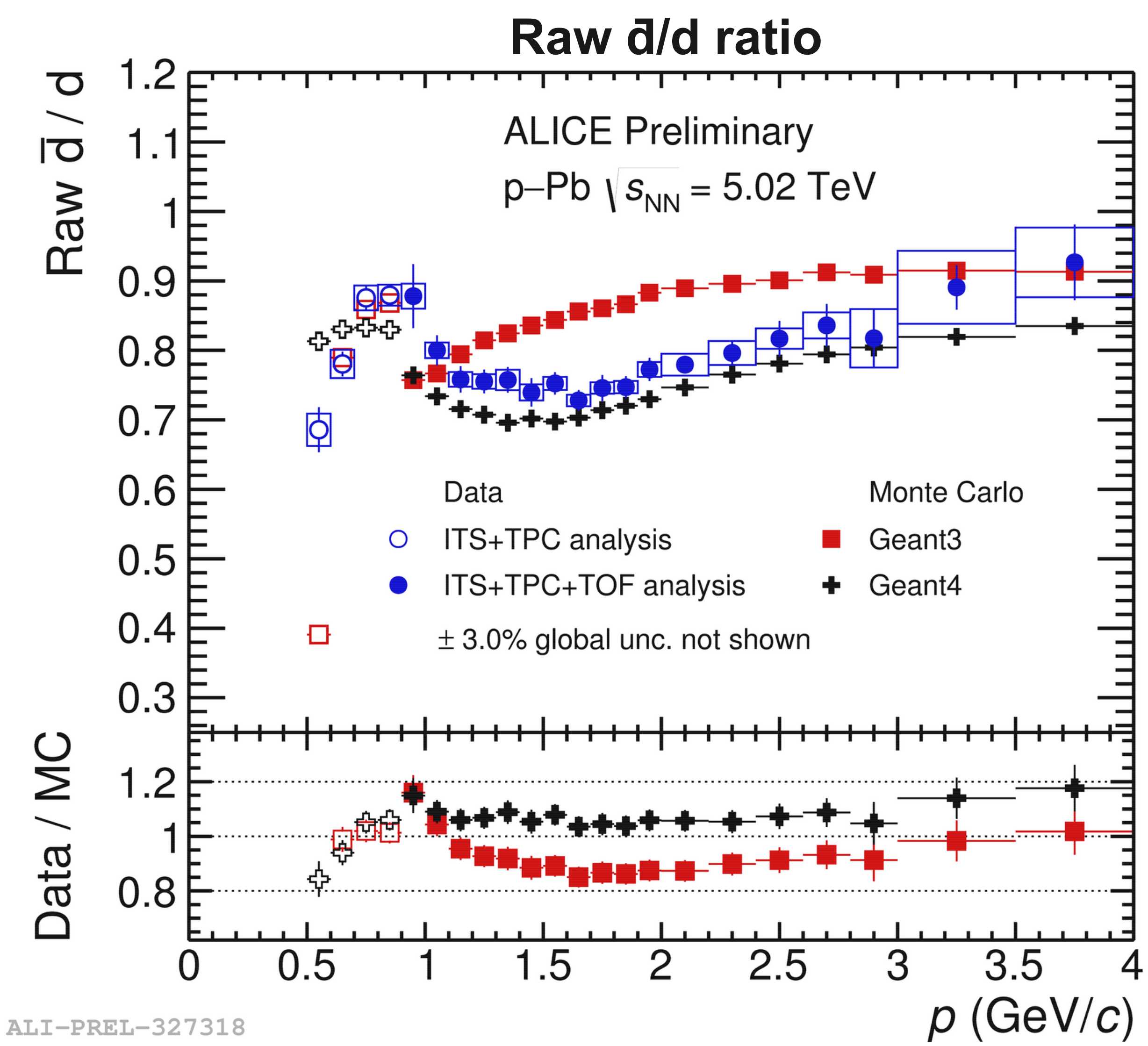
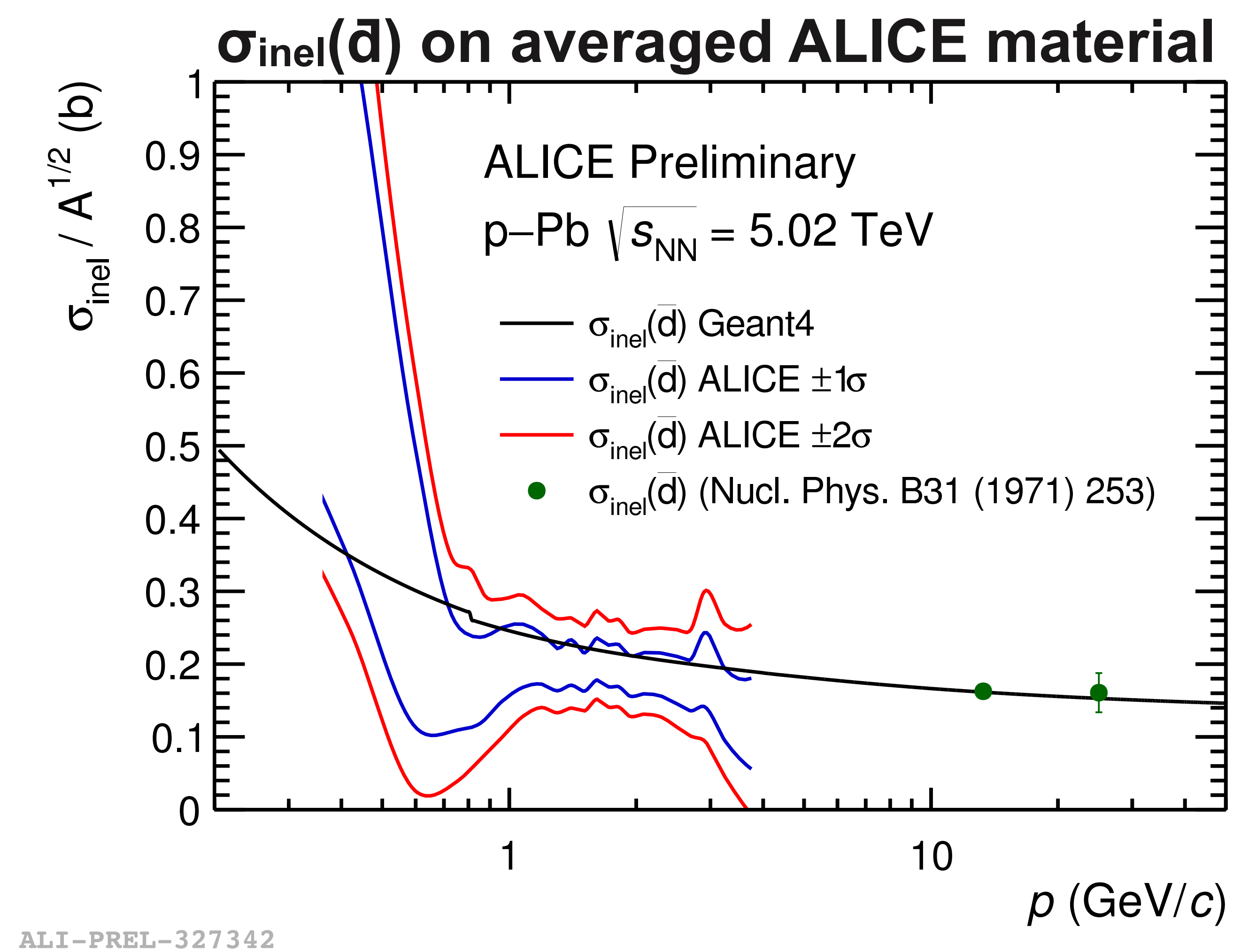
***<u>First experimental information on $\sigma_{inel}(\bar{d})$ at low momentum!</u>***



# Summary and outlook

ALICE Experiment at CERN LHC as a tool to study anti-deuteron absorption in detector material

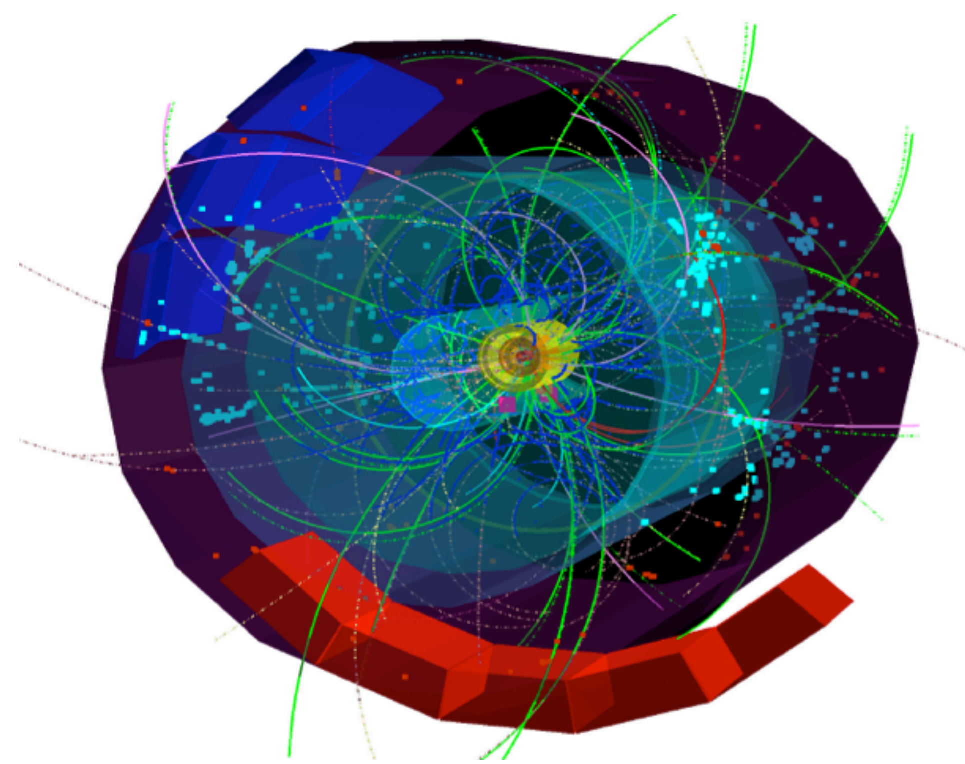
- Analysis of raw reconstructed $\bar{p}/p$ and $\bar{d}/d$ ratios
    - Better description of results with Geant4-based simulations
- Constrain $\sigma_{inel}(\bar{p})$ and $\sigma_{inel}(\bar{d})$ via comparison with Geant4-based Monte Carlo
    - Results for $\sigma_{inel}(\bar{p})$ in good agreement with existing data
    - First experimental constraints on $\sigma_{inel}(\bar{d})$ in momentum range below $p$ = 13 GeV/$c$

Work in progress towards the final results

- Paper in preparation

Extend the analysis to heavier anti-nuclei ($^{3}\overline{He}$, …)

*Use results as an input for cosmic ray propagation models!*



# Summary and outlook

ALICE Experiment at CERN LHC as a tool to study anti-deuteron absorption in detector material

- Analysis of raw reconstructed $\bar{p}/p$ and $\bar{d}/d$ ratios
  - Better 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
  - First experimental constraints on $\sigma_{inel}(\bar{d})$ in momentum range below $p$ = 13 GeV/$c$

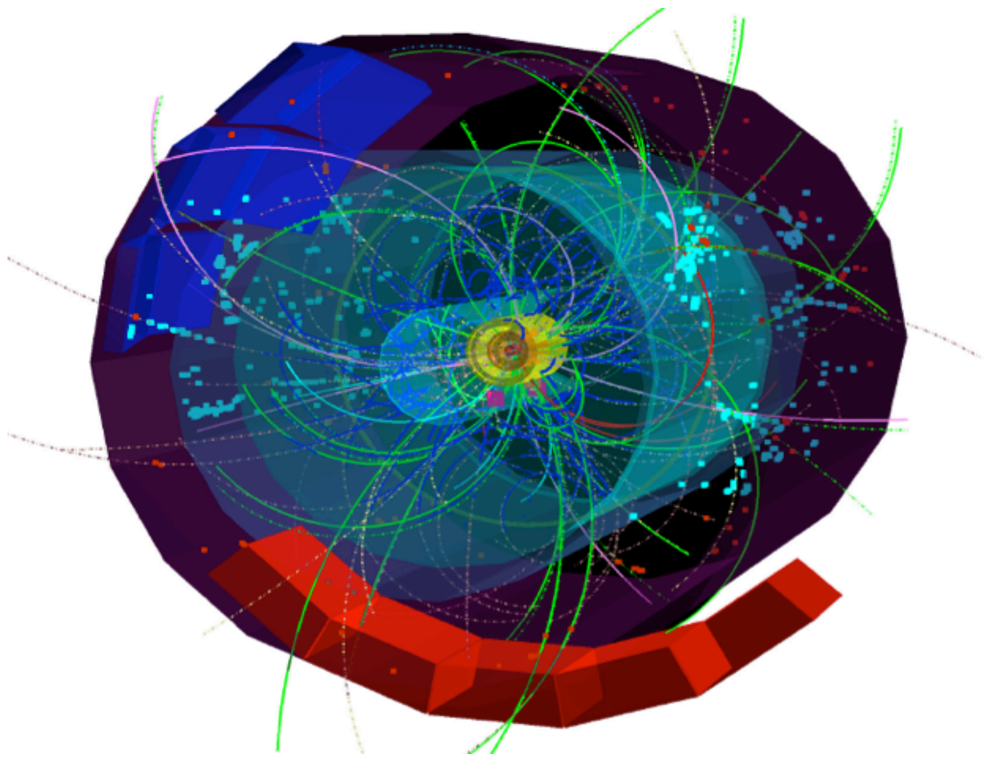
Work in progress towards the final results

- Paper in preparation

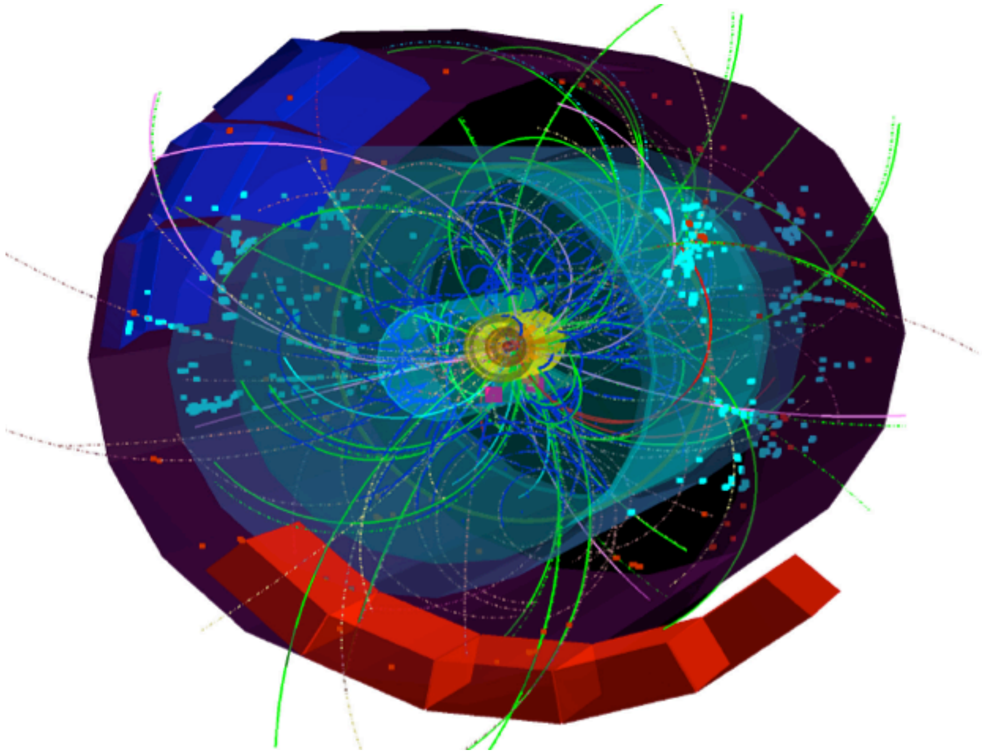
Extend the analysis to heavier anti-nuclei ($^3\overline{He}$, …)

*Use results as an input for cosmic ray propagation models!*

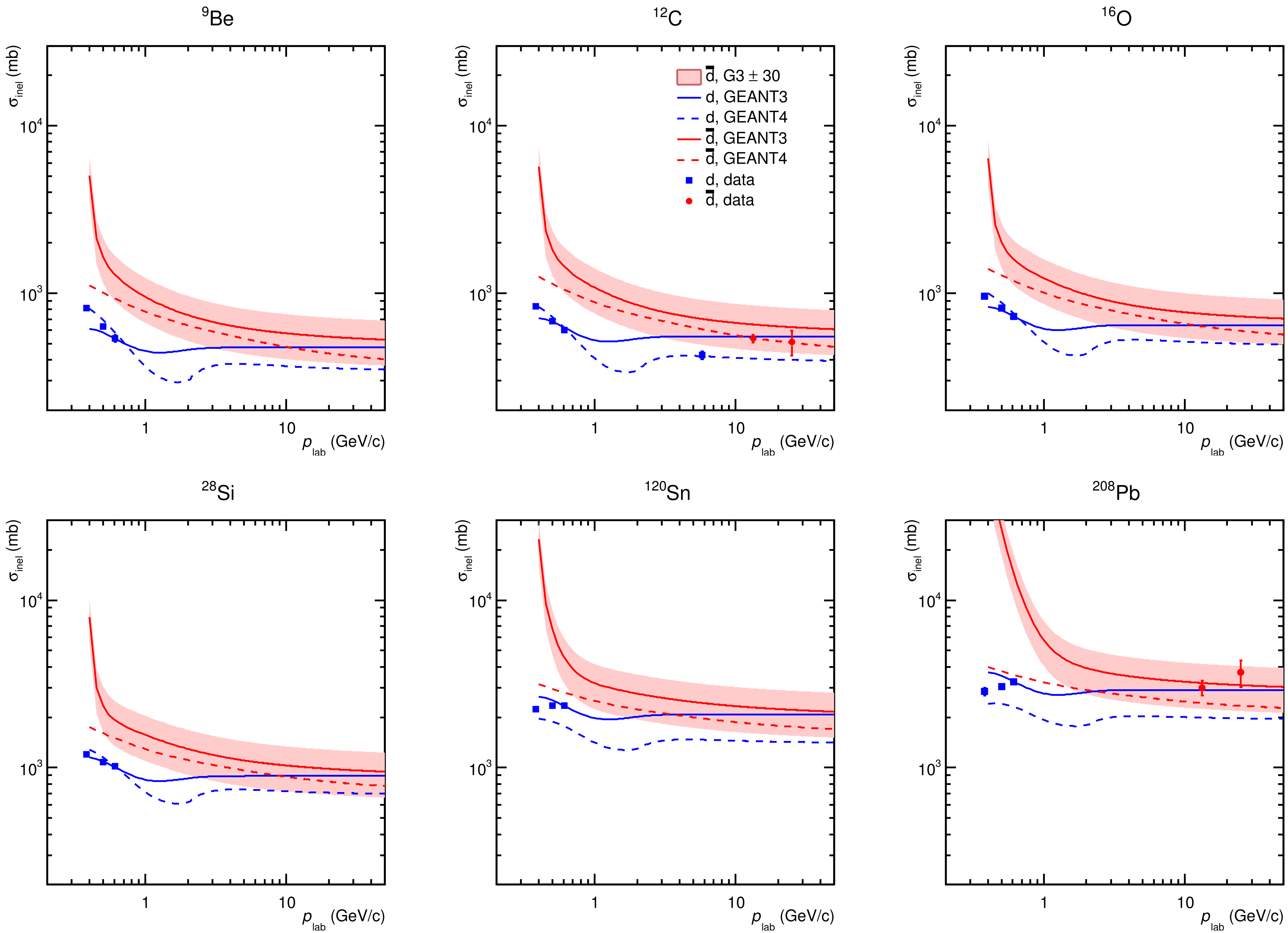
Thank you for your attention!



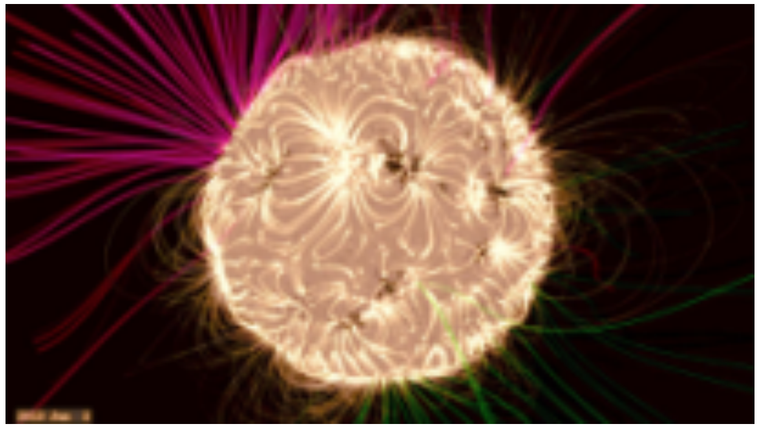
# Back-up slides

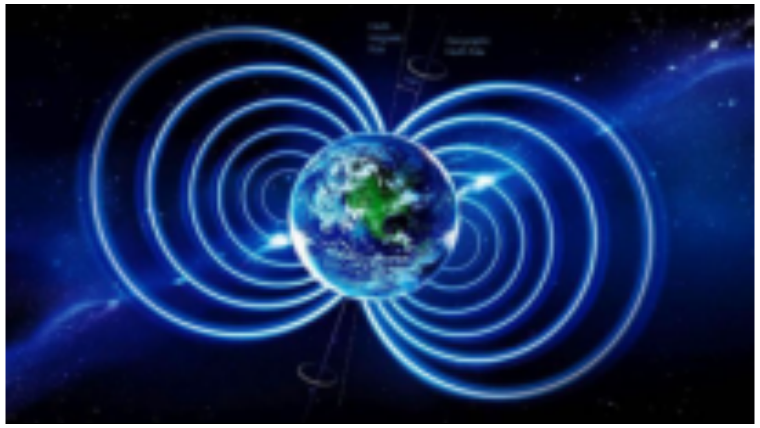


# GEANT3/4 cross-sections for (anti-)deuterons



# A long way to the detectors





**Interstellar Space**
- Injection of primary CR
- Production of secondary CR in interstellar matter
- Transport
  - Absorption and (re-)acceleration

**Heliosphere**
- Solar wind shielding
- Most dominant effects at low momenta
- Time dependency of solar activity

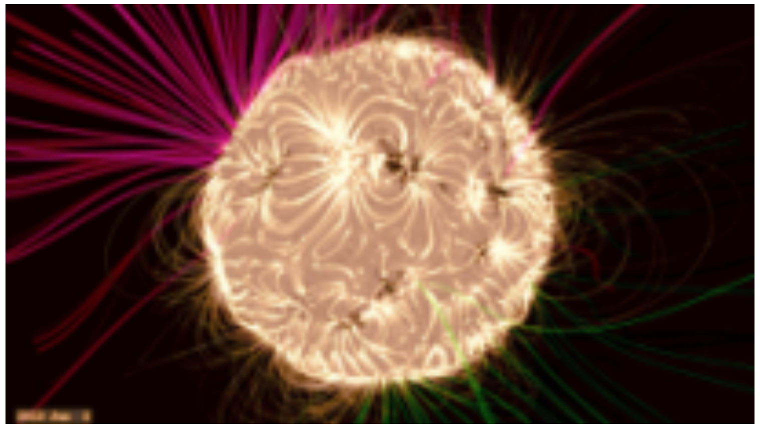
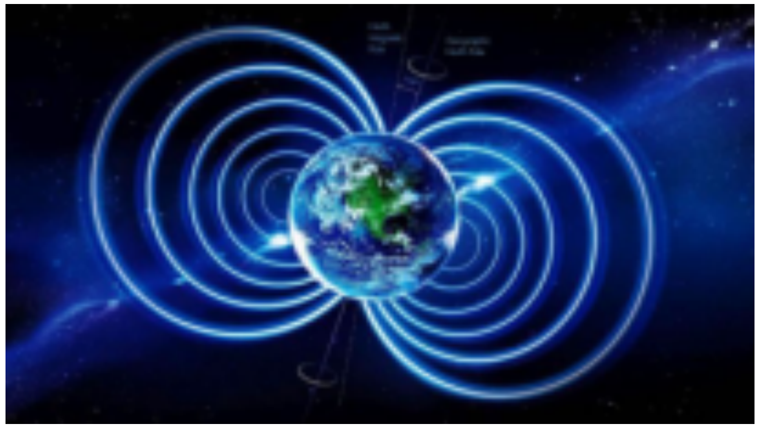
**Near-Earth environment**
- Shielding / deflection by Earth's magnetic field
- Background production and absorption in Earth's atmosphere

**Local interstellar flux**

**Solar-modulated flux**

**Flux at experiment**

# A long way to the detectors

**Injection spectra (particles)** → Propagation in the galaxy → Solar magnetic field → Earth's magnetic field and atmosphere → **Cosmic rays at Earth**

Galprop[1] Solarprop[2] Planetocosmics[3]

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

# A long way to the detectors

Galactic environment: magnetic fields, local plasma currents, ISM, annihilation…
Model cosmic transport by spatial diffusion and convection only

Cosmic-ray fluxes determined by transport equation:

$$\vec{\nabla}\cdot\left\{-K\,\vec{\nabla}N+\vec{V}_c\,N\right\}+\frac{\partial}{\partial E}\left\{f_0 N - s_0\frac{\partial N}{\partial E}\right\}=q_{\rm src}(\vec{r},E)-\Gamma_{\rm dst}N$$

diffusion convection 1st and 2nd order E transport terms source term destruction in ISM

- Diffusion coefficient $K(r, E)$ often assumed to depend only on $E$
- Low-E (< 10 GeV) anti-d can be swept by convection of local plasma and drift with $V_c$
- Conservation of cosmic ray currents in energy space → $f_0(r, E)$ and $s_0(r, E)$
- Production rate:

$$q_{\bar{d}}^{\rm pri}(\vec{r},E_{\bar{d}})=\frac{1}{2}\langle\sigma v\rangle\frac{{\rm d}N_{\bar{d}}}{{\rm d}E_{\bar{d}}}\left(\frac{\rho_{\rm DM}(\vec{r})}{m_{\rm DM}}\right)^2$$ for DM annihilation

$$q_{\bar{d}}^{\rm pri}(\vec{r},E_{\bar{d}})=\frac{1}{\tau_{\rm DM}}\frac{{\rm d}N_{\bar{d}}}{{\rm d}E_{\bar{d}}}\frac{\rho_{\rm DM}(\vec{r})}{m_{\rm DM}}$$ for DM decay

- Annihilation rate $\Gamma_{\rm dst}^{\bar{d}}=(n_{\rm H}+4^{2/3}n_{\rm He})\,v_{\bar{d}}\,\sigma_{\rm ine}(\bar{d}p\to X)$ , where $n_{\rm H}$ and $n_{\rm He}$ in ISM assumed to be homogeneous

# Prospects for the Dark Matter detection

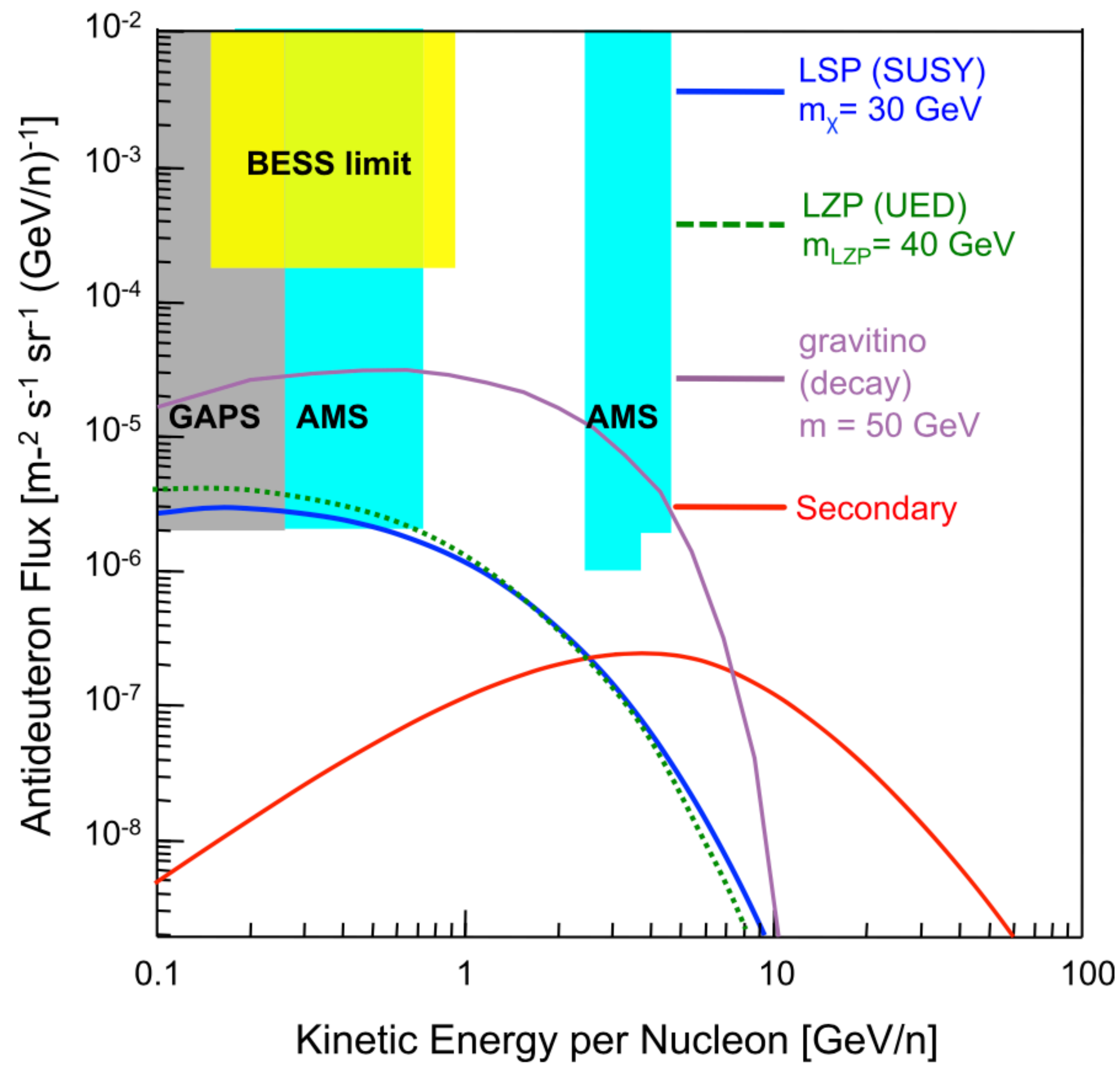



**Fig. 1.** Predicted antideuteron flux as a function of kinetic energy per nucleon for a 30 GeV neutralino, a 40 GeV extra-dimensional Kaluza–Klein neutrino, and a 50 GeV gravitino [45,46,50,49]. The antideuteron limits from BESS are shown [51], along with the projected sensitivities of AMS-02 for the superconducting-magnet configuration [52] after 5 years of operation and GAPS after three 35-day flights [53,54]. The MED Galactic propagation scenario is assumed (Section 4.1). These predictions use a coalescence momentum that is set to 195 MeV (Section 3) and the Einasto dark matter density profile (Section 4.1.4). For the solar modulation parameters see Section 4.2.

[1] Physics reports 618, 1 (2016)

# Prospects for the Dark Matter detection

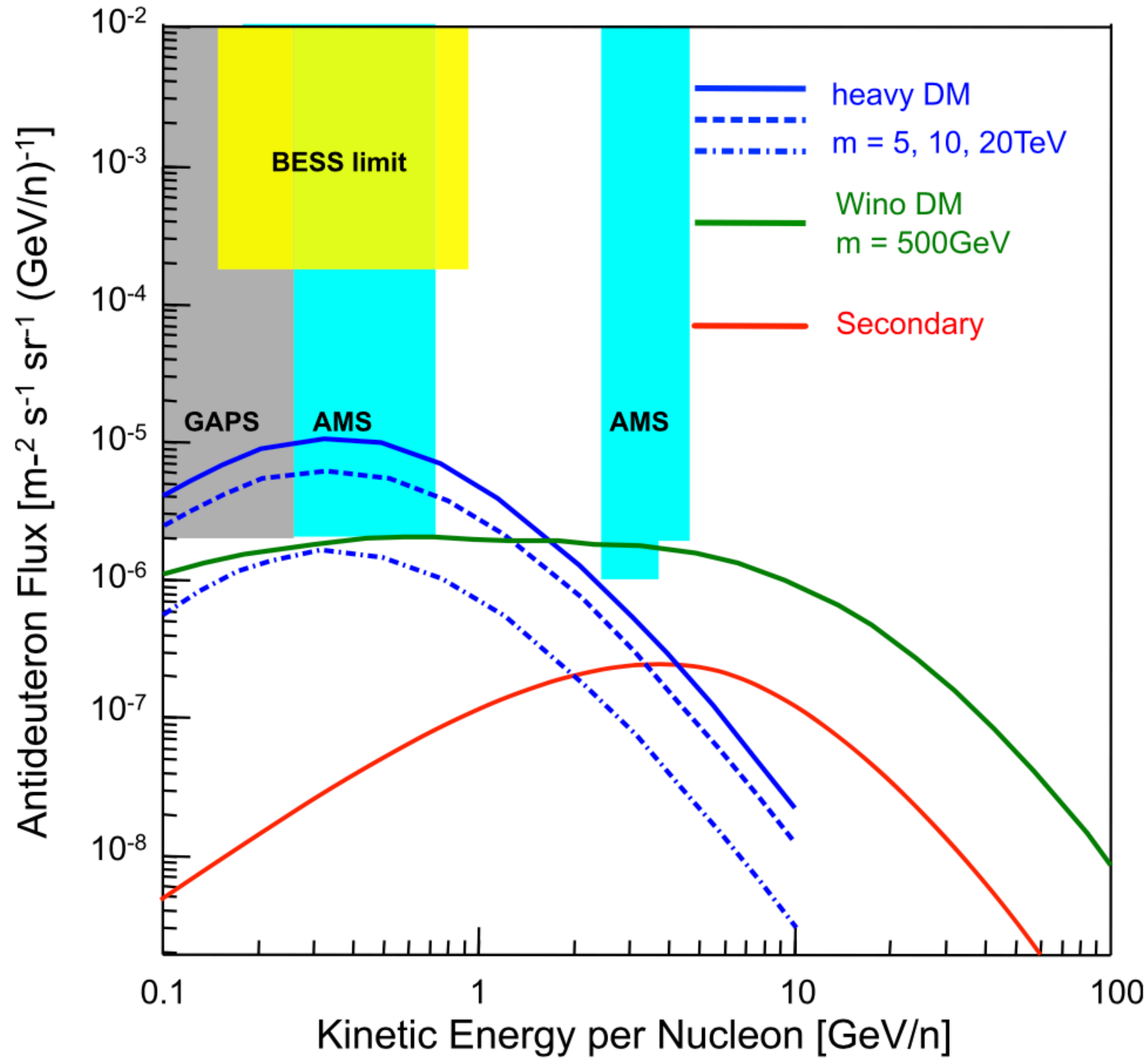



**Fig. 3.** Predicted antideuteron flux for annihilation of dark matter with $m_{\rm DM} = 5, 10, 20$ TeV [56] (blue lines, top to bottom) into $b\bar{b}$ with enhanced annihilation cross sections ($\langle\sigma v\rangle_{5\ \rm TeV} = 3\cdot10^{-22}$ cm$^3$/s, $\langle\sigma v\rangle_{10\ \rm TeV} = 7\cdot10^{-22}$ cm$^3$/s, $\langle\sigma v\rangle_{20\ \rm TeV} = 20\cdot10^{-22}$ cm$^3$/s). The predicted antideuteron flux from pure-Wino dark matter [90] (solid green line) with $m_{\rm DM} = 0.5$ TeV, $\langle\sigma v\rangle = 4.82\cdot10^{-25}$ cm$^3$/s with Sommerfeld enhanced annihilations into $W^+W^-$. The MAX propagation model is used for all predictions. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

[1] Physics reports 618, 1 (2016)

# AMS-02 uncertainties

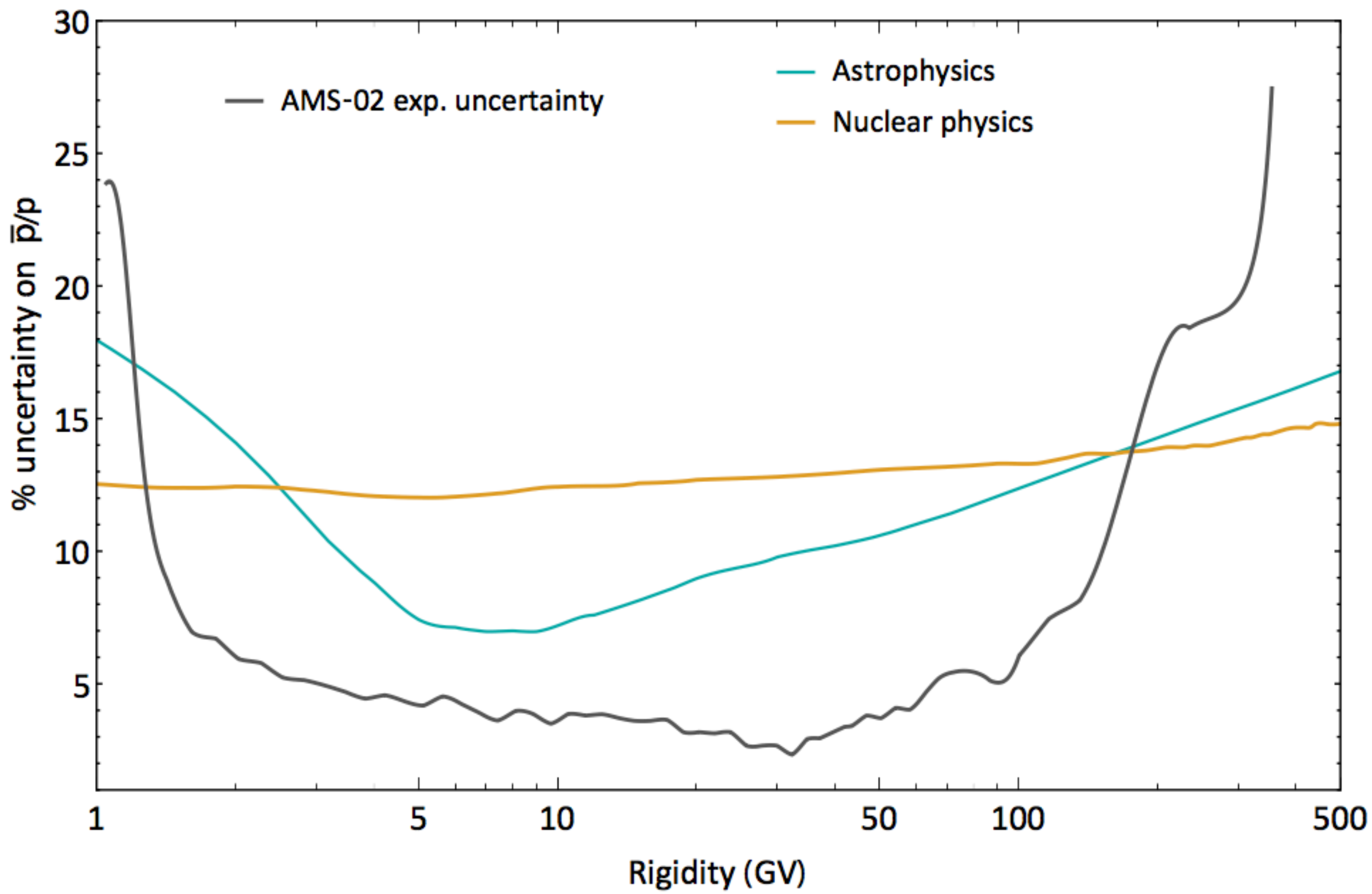



**Figure 32:** Relative uncertainty afflicting the prediction for the $\bar{p}$ / $p$ ratio, shown in dependence on the rigidity $p/Ze$ (expressed in GigaVolt): in light blue the up-to-date astrophysical uncertainty derived from [150–152] (based on AMS-02 data analysis), in dark yellow the mean of the nuclear physics uncertainties estimated in [159, 162]. In black for comparison the AMS-02 measurement uncertainties as reported in [140].

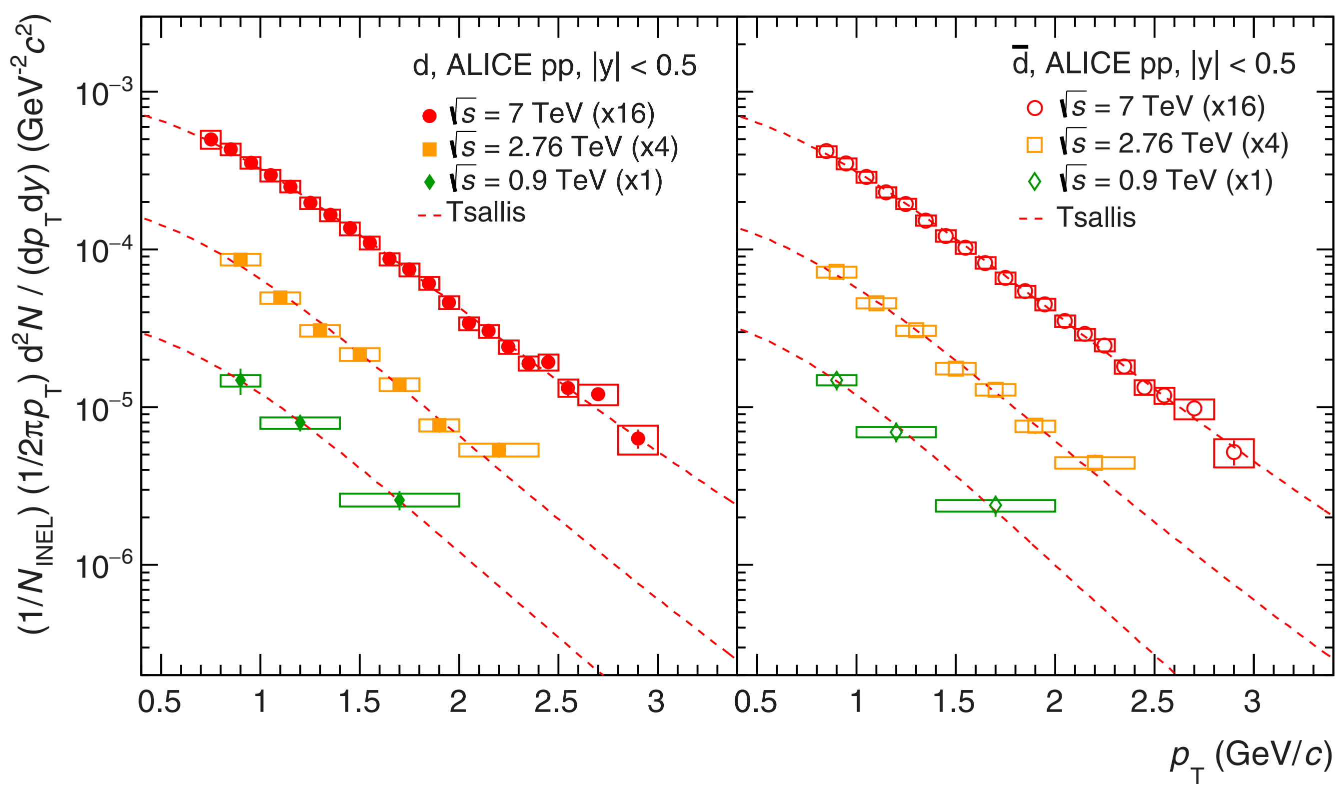
[1] CERN-SPSC-2019-022

# Large Hadron Collider as an anti-matter factory

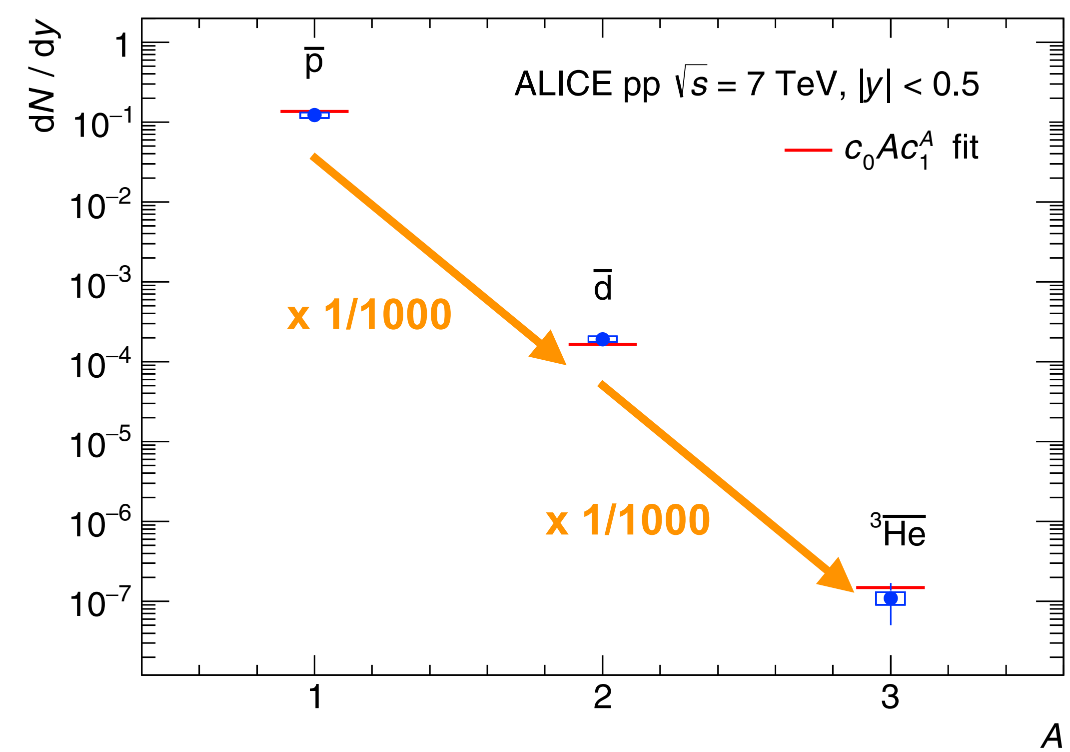
At LHC energies, particles and anti-particles are produced in almost equal amounts

- 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)

# The ALICE Experiment at the CERN LHC

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

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

**I**nner **T**racking **S**ystem

- Tracking, vertex, PID (d*E*/d*x*)

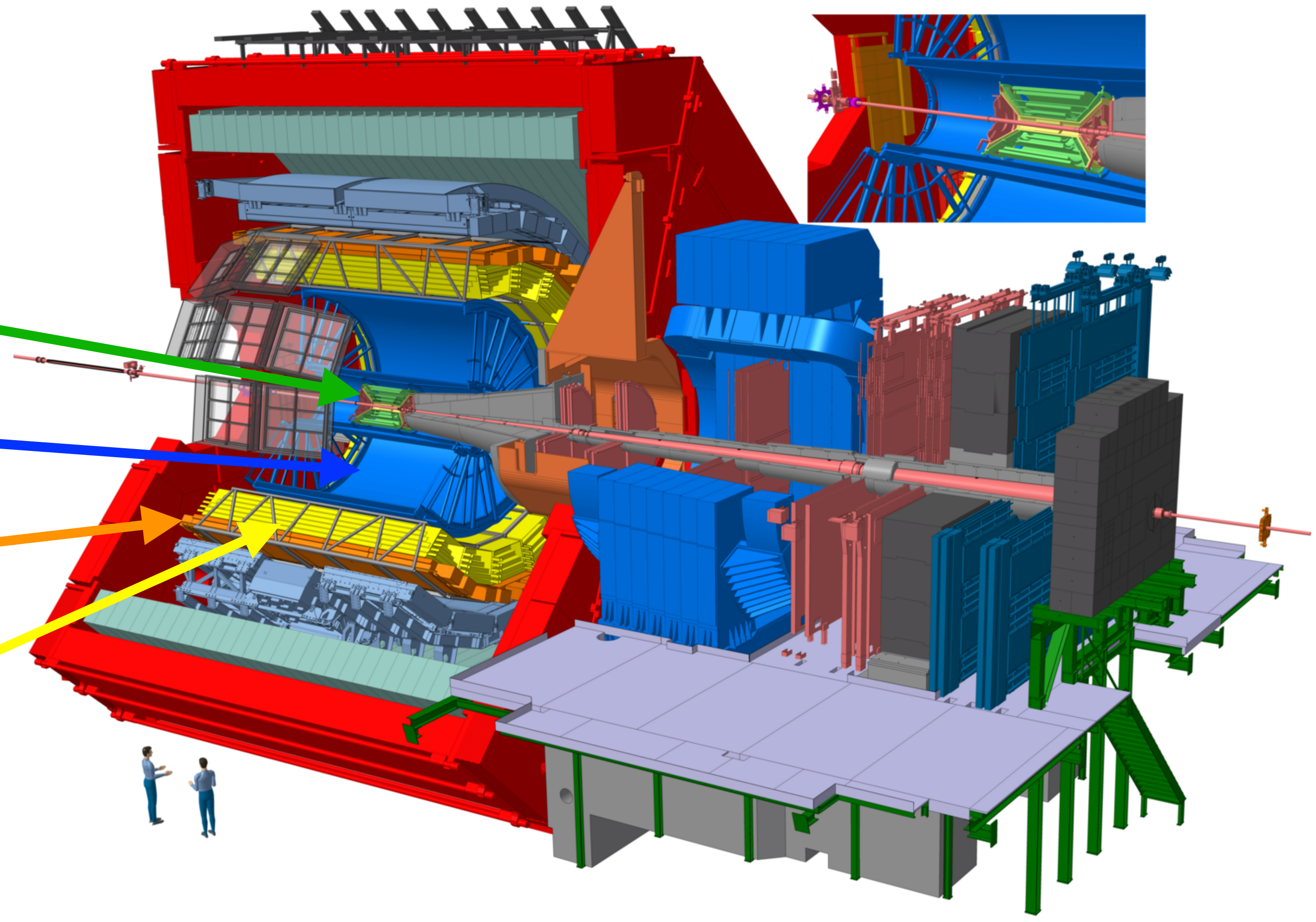
**T**ime **P**rojection **C**hamber

- Tracking, PID (d*E*/d*x*)

**T**ime **O**f **F**light detector

- PID (TOF measurement)

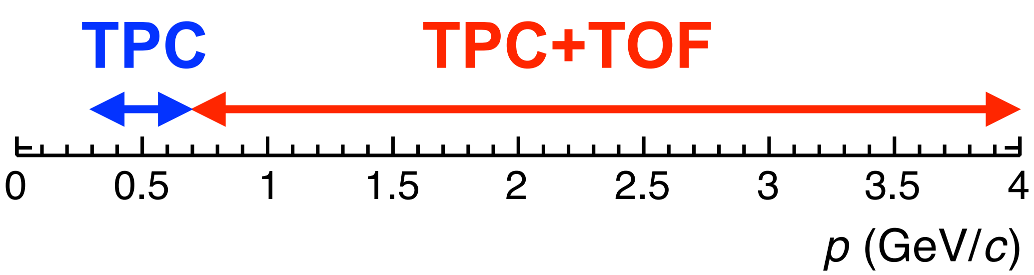
**T**ransition **R**adiation **D**etector



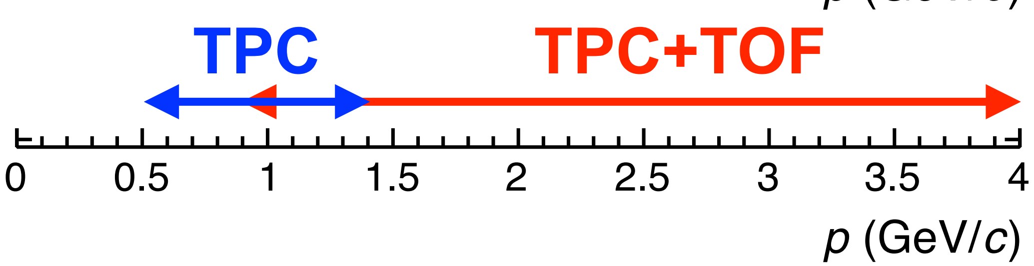
# Particle identification in TPC and TOF

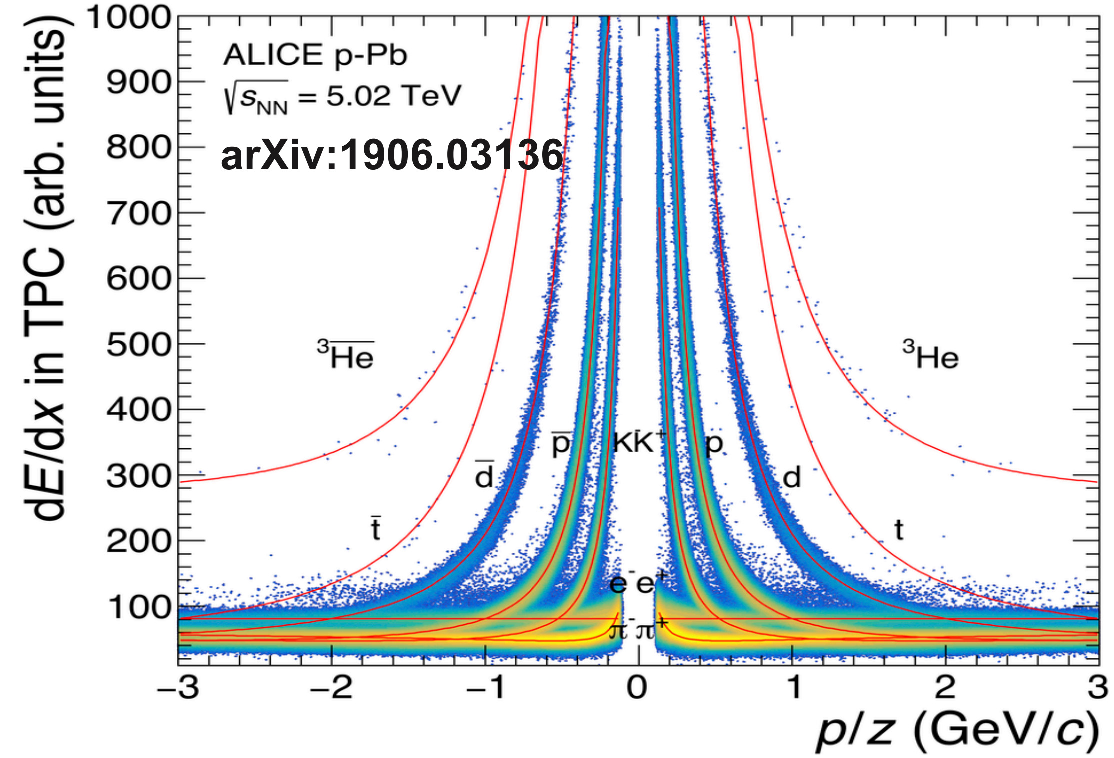
Complementary information from TPC and TOF detectors to select high-purity (anti-)protons and (anti-)deuterons

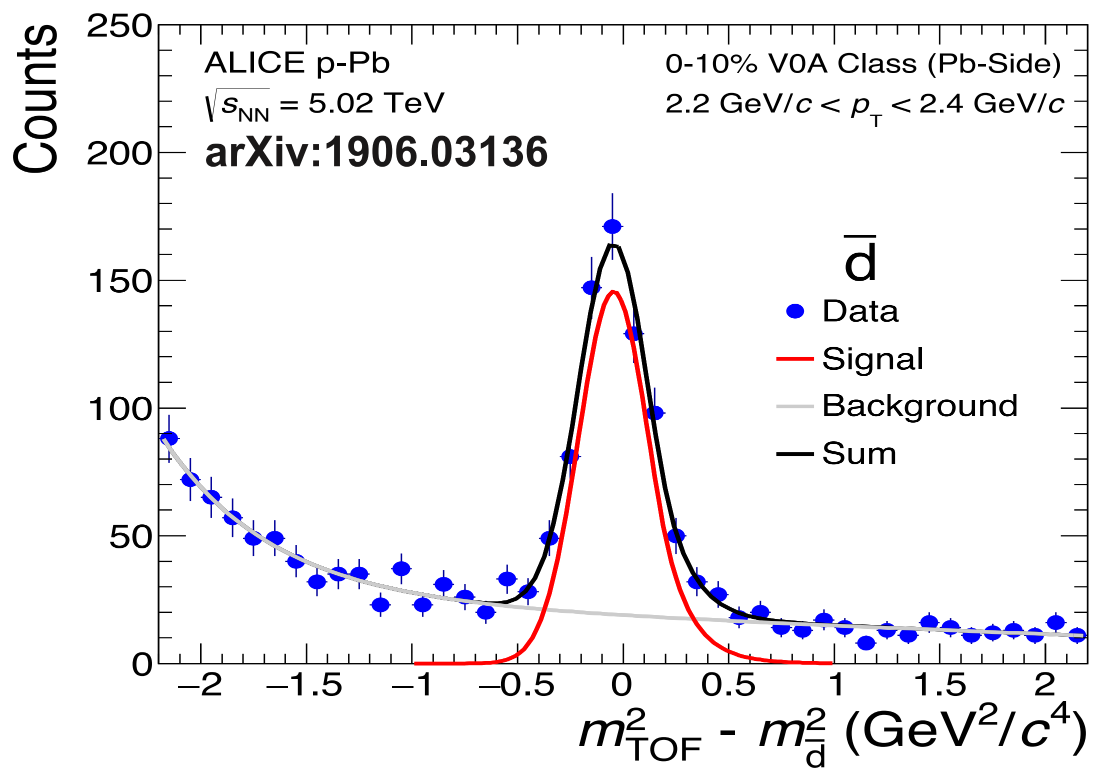
protons:

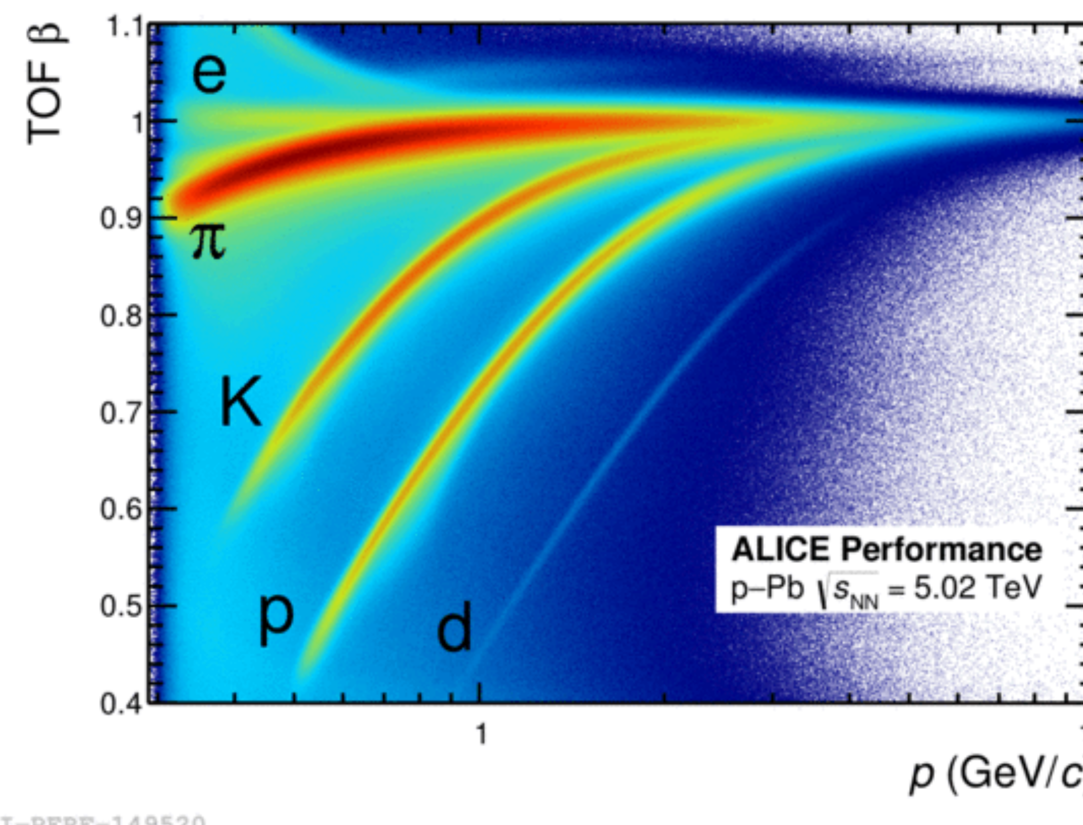



deuterons:



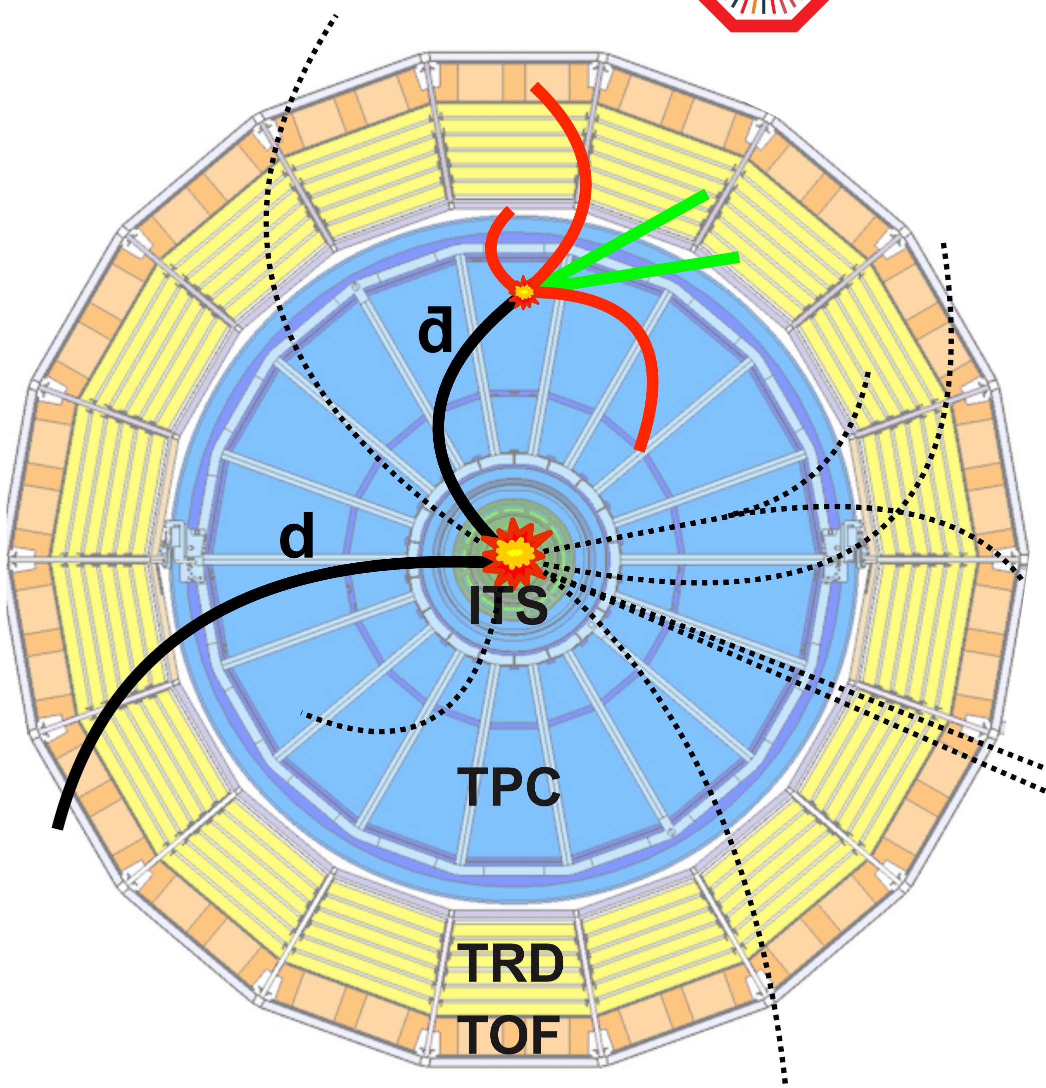



# ALICE detector material as a target

Material budget at mid-rapidity [1]:

- **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

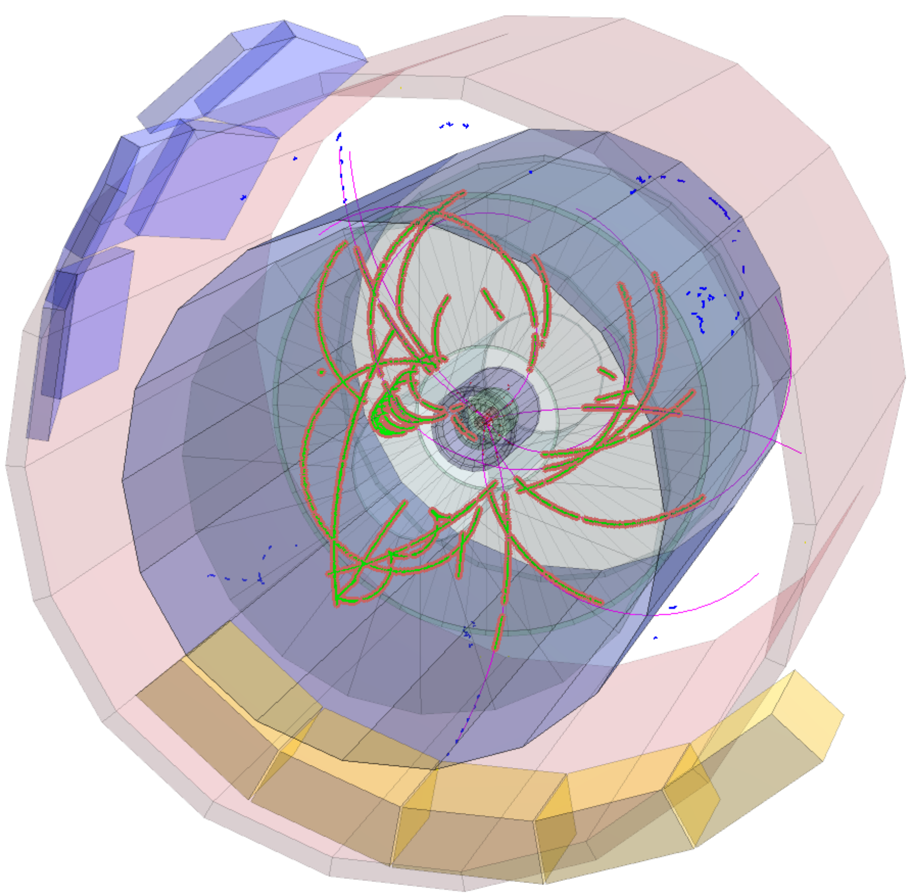


# Simple Geant4-based model

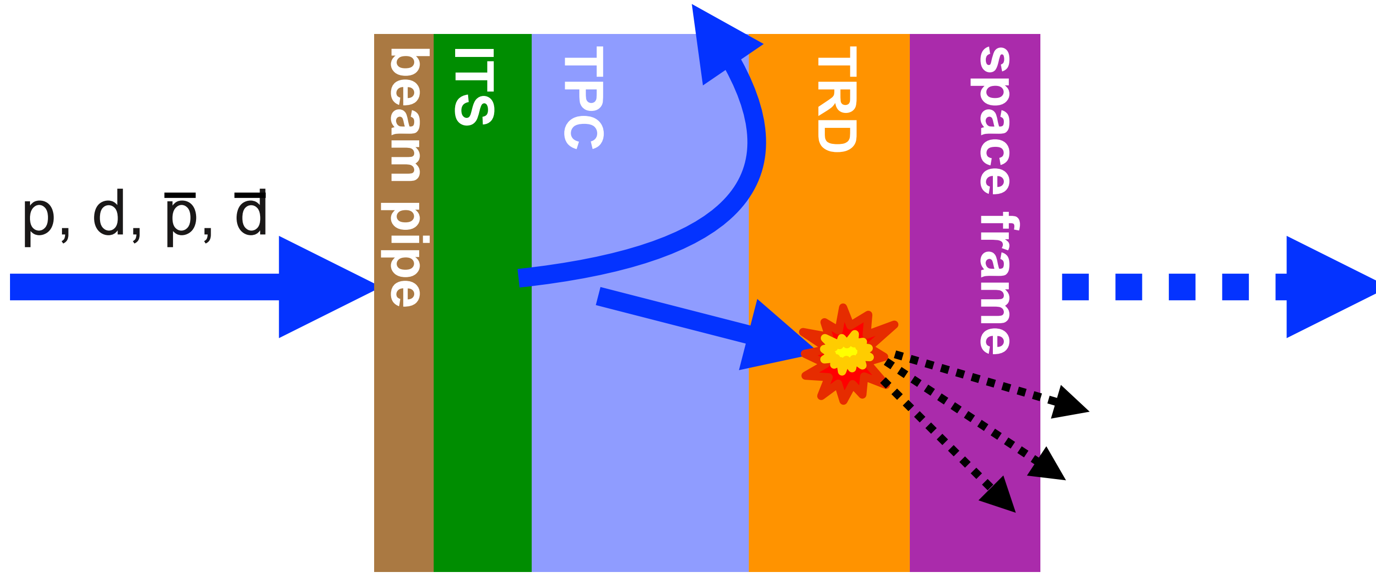
Standalone Geant4 simulation to understand ratios in more details

- (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> = 7.4, <A> = 14.8)
  - high *p*: beam pipe, ITS, TPC, TRD, SF (<Z> = 11.9, <A> = 25.5)
- 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 understand ratios in more details

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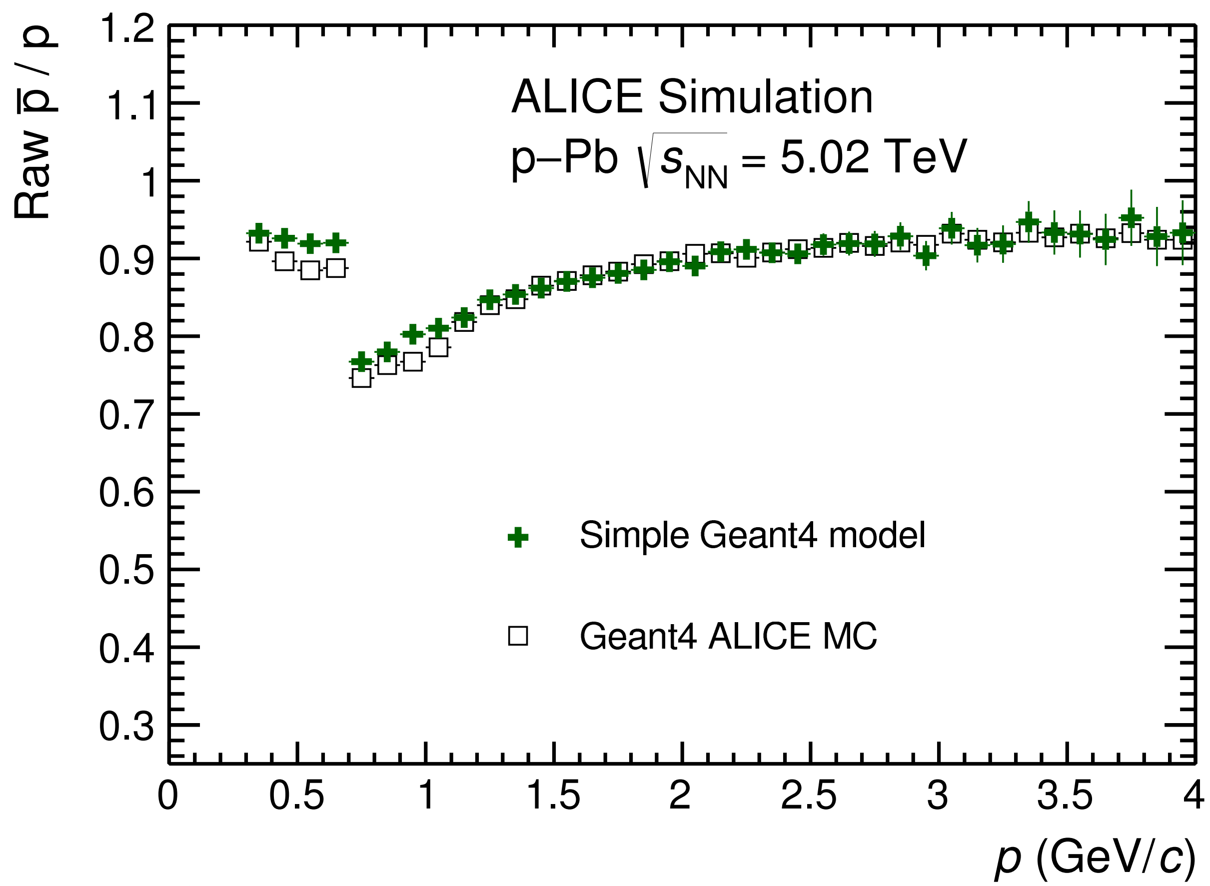
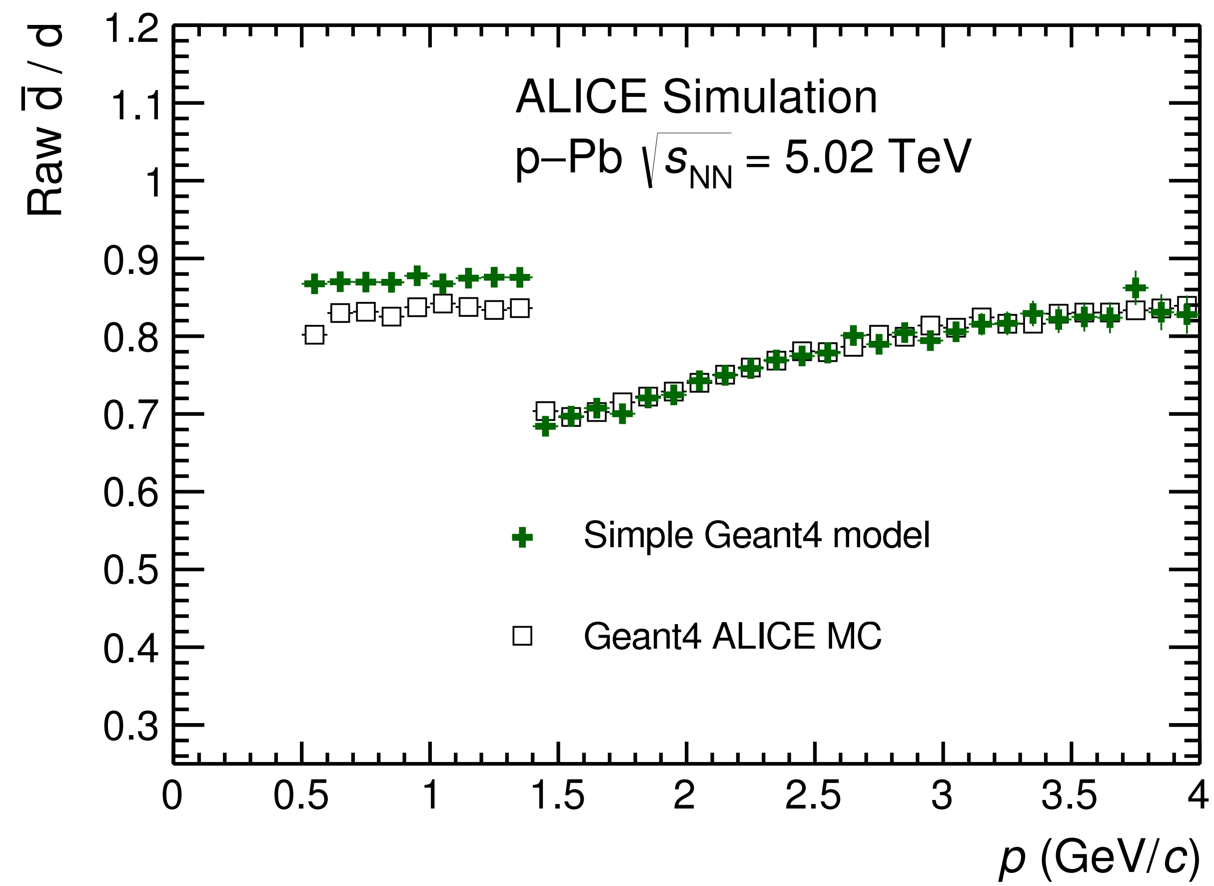



ALI-DER-324013




ALI-DER-324008

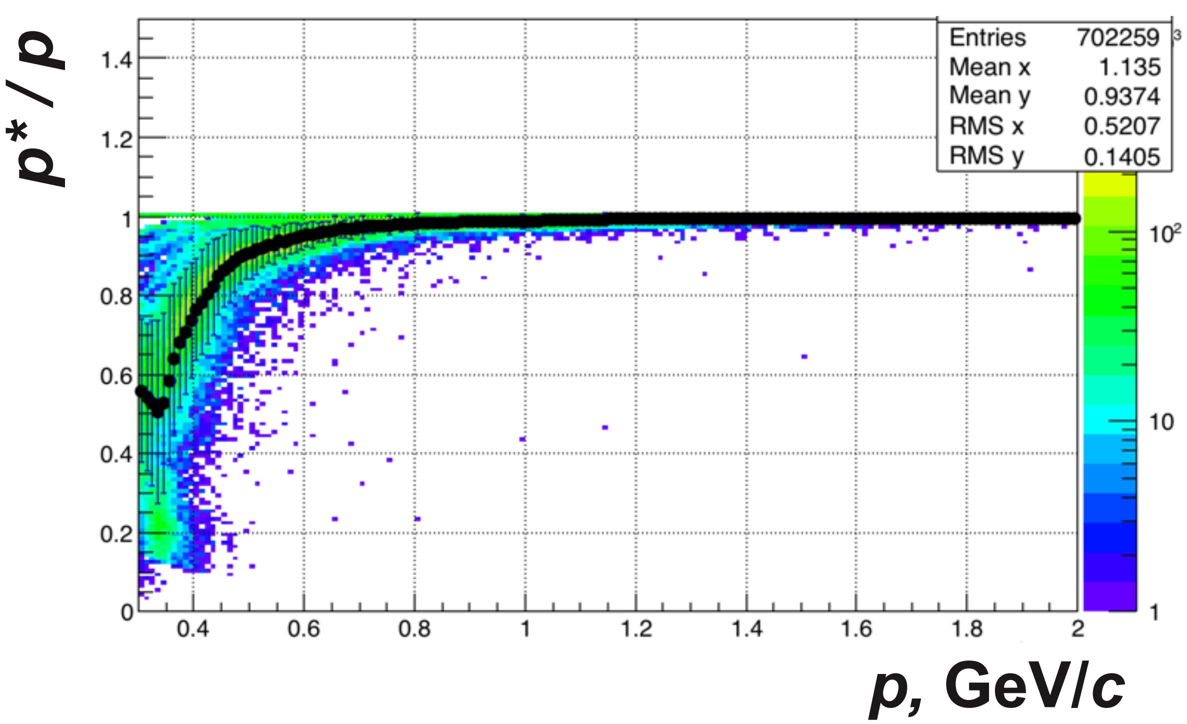
# Estimation of $p^*$ for anti-protons

Energy loss in detector material: inelastic interaction happens at momentum $p^*$ which is lower than $p$ at primary event vertex

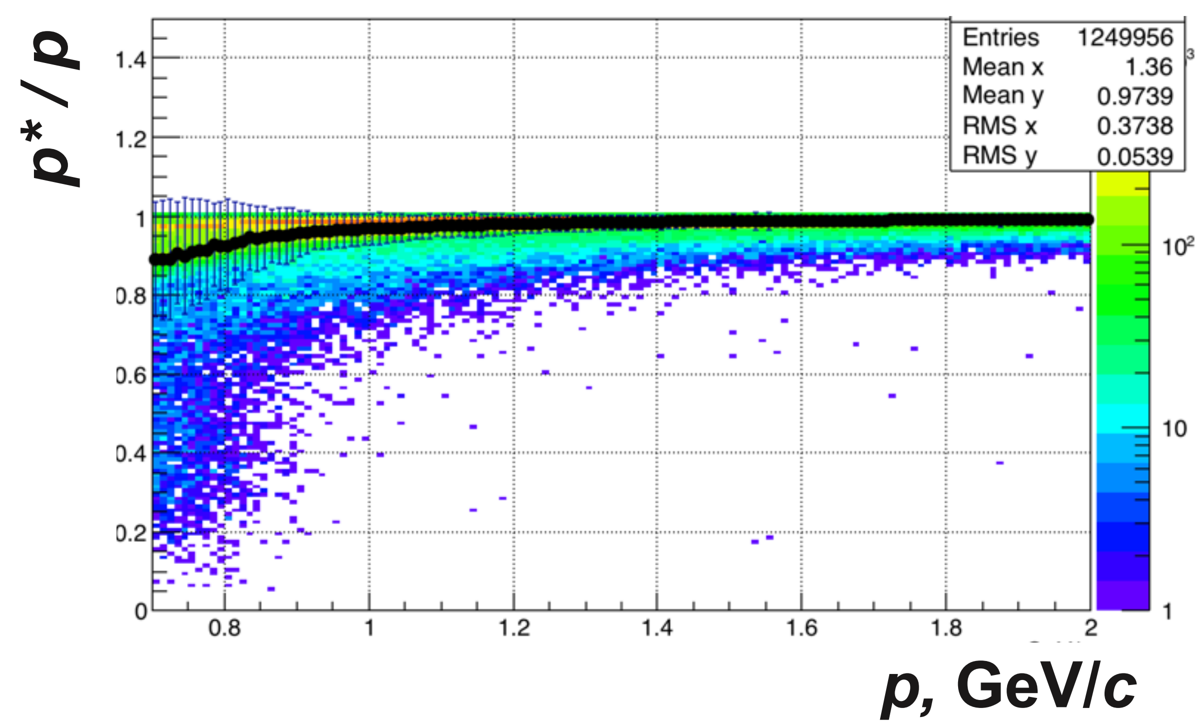
Momentum transformation matrices: $p^* / p$ vs $p$

- Black points/errors: profile of 2d map (mean ± RMS)

**ITS-TPC analysis**



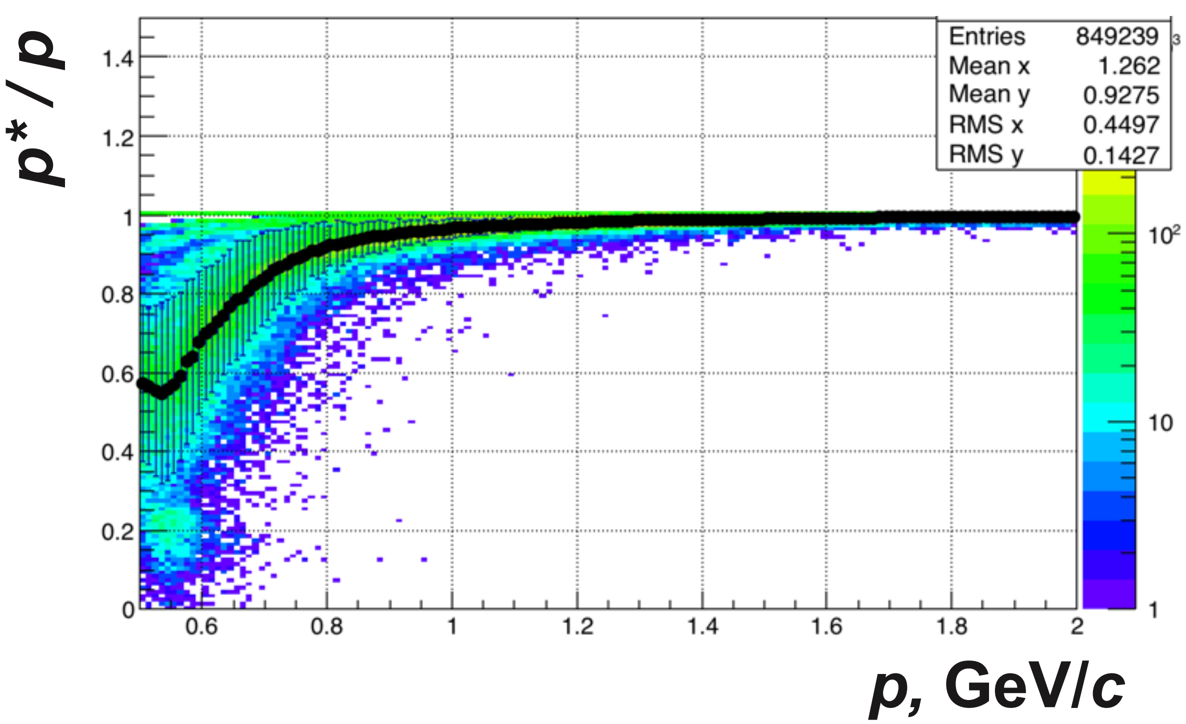

**TOF analysis**



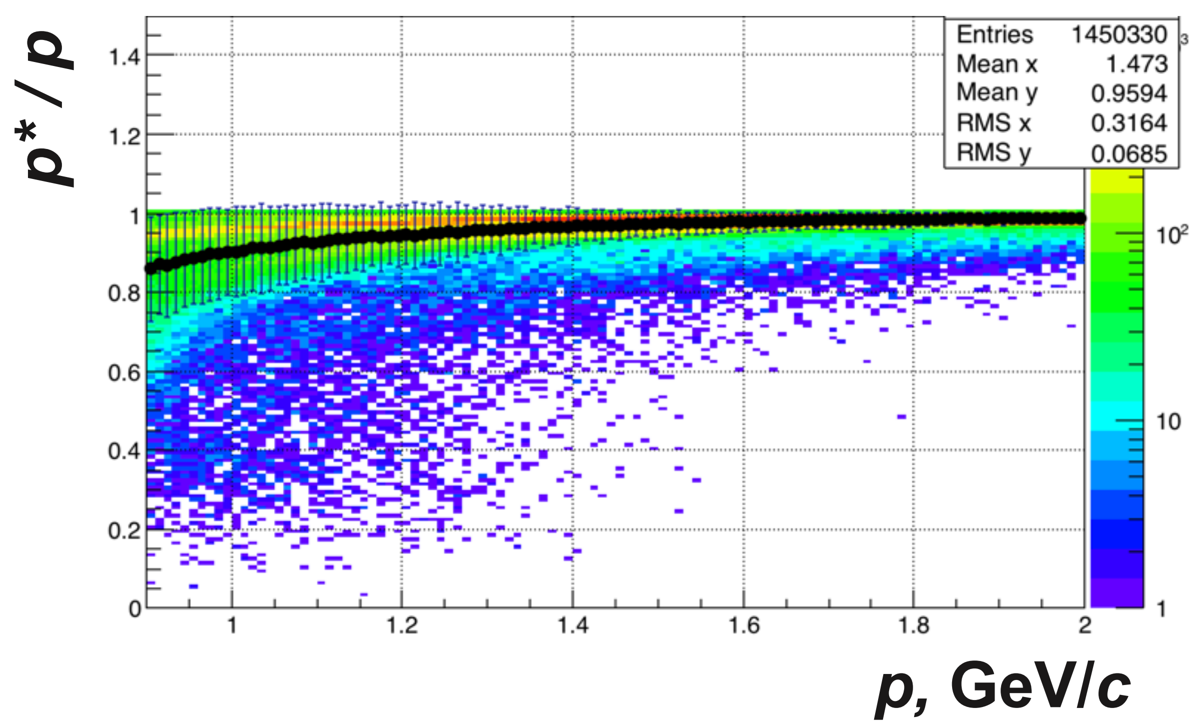
# Estimation of *p** for anti-deuterons

Energy loss in detector material: inelastic interaction happens at momentum *p** which is lower than *p* at primary event vertex
Momentum transformation matrices: *p** / *p* vs *p*
- Black points/errors: profile of 2d map (mean ± RMS)

## ITS-TPC analysis

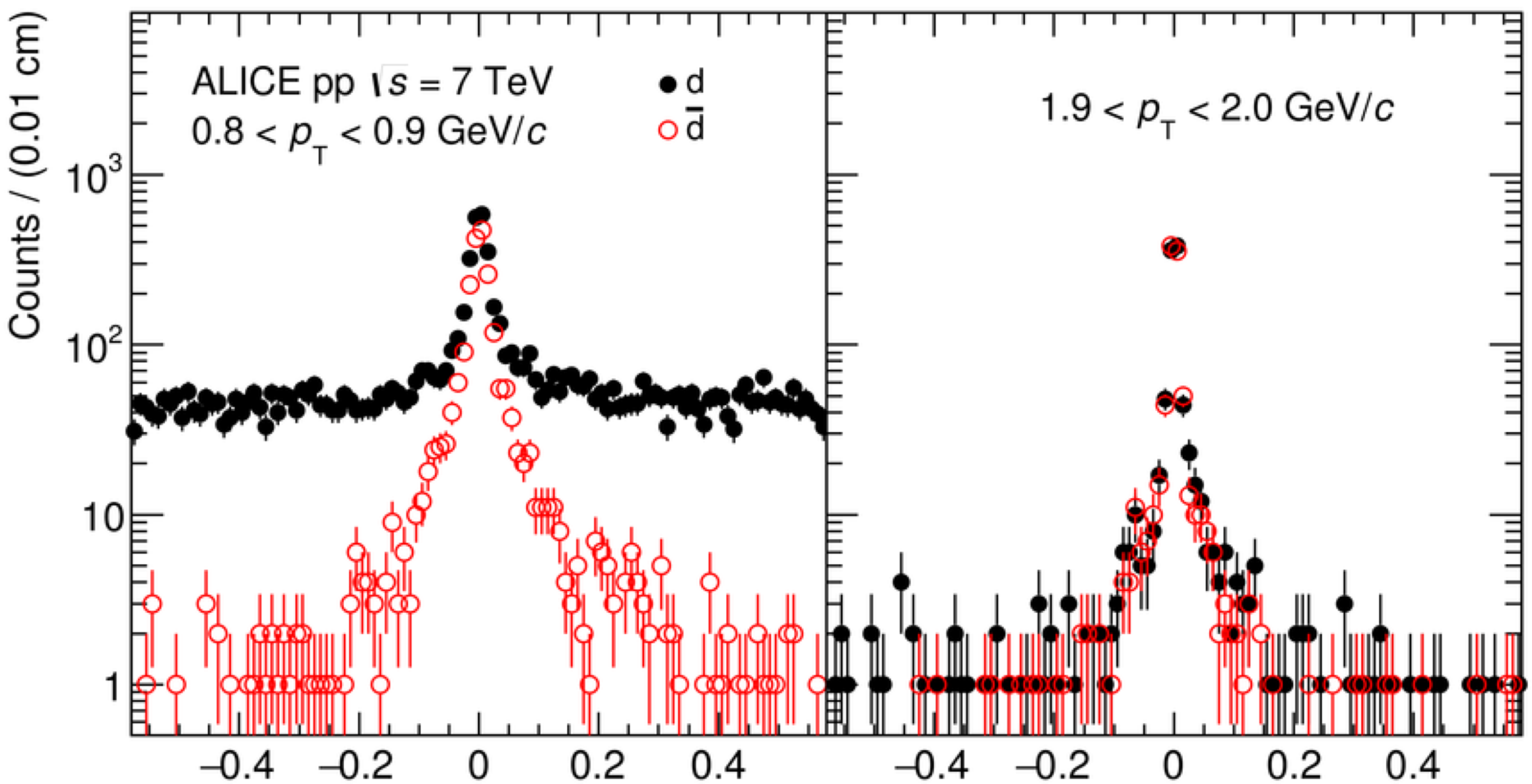



## TOF analysis



# Deuterons from spallation processes

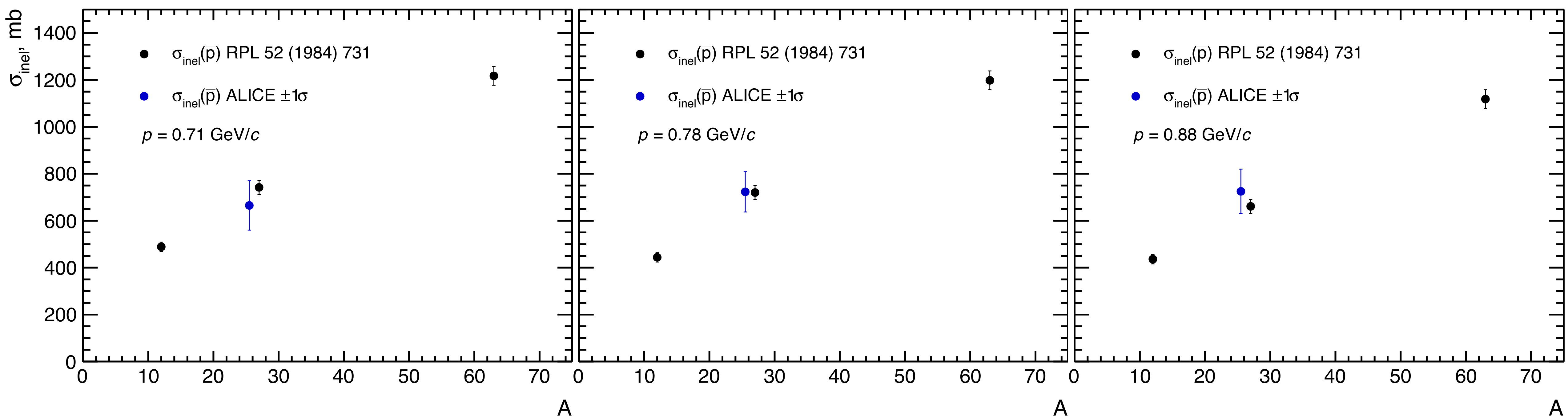
ALICE, Phys. Rev. C 97 (2018) 024615



# Comparison of ALICE results with existing data

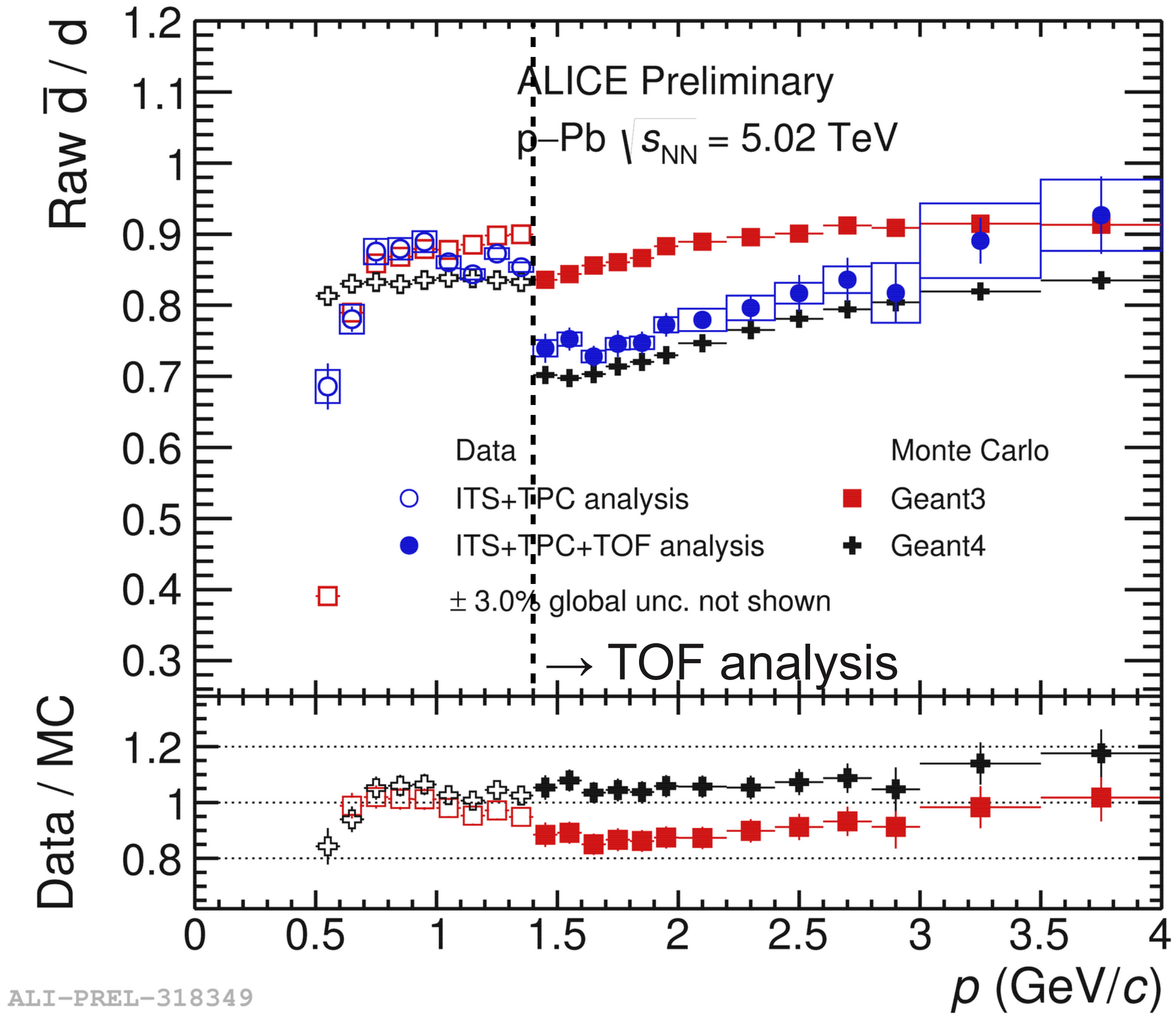
Anti-proton inelastic interaction cross-section as a function of A for fixed momentum

- ALICE results correspond to ±1σ limits (blue lines)

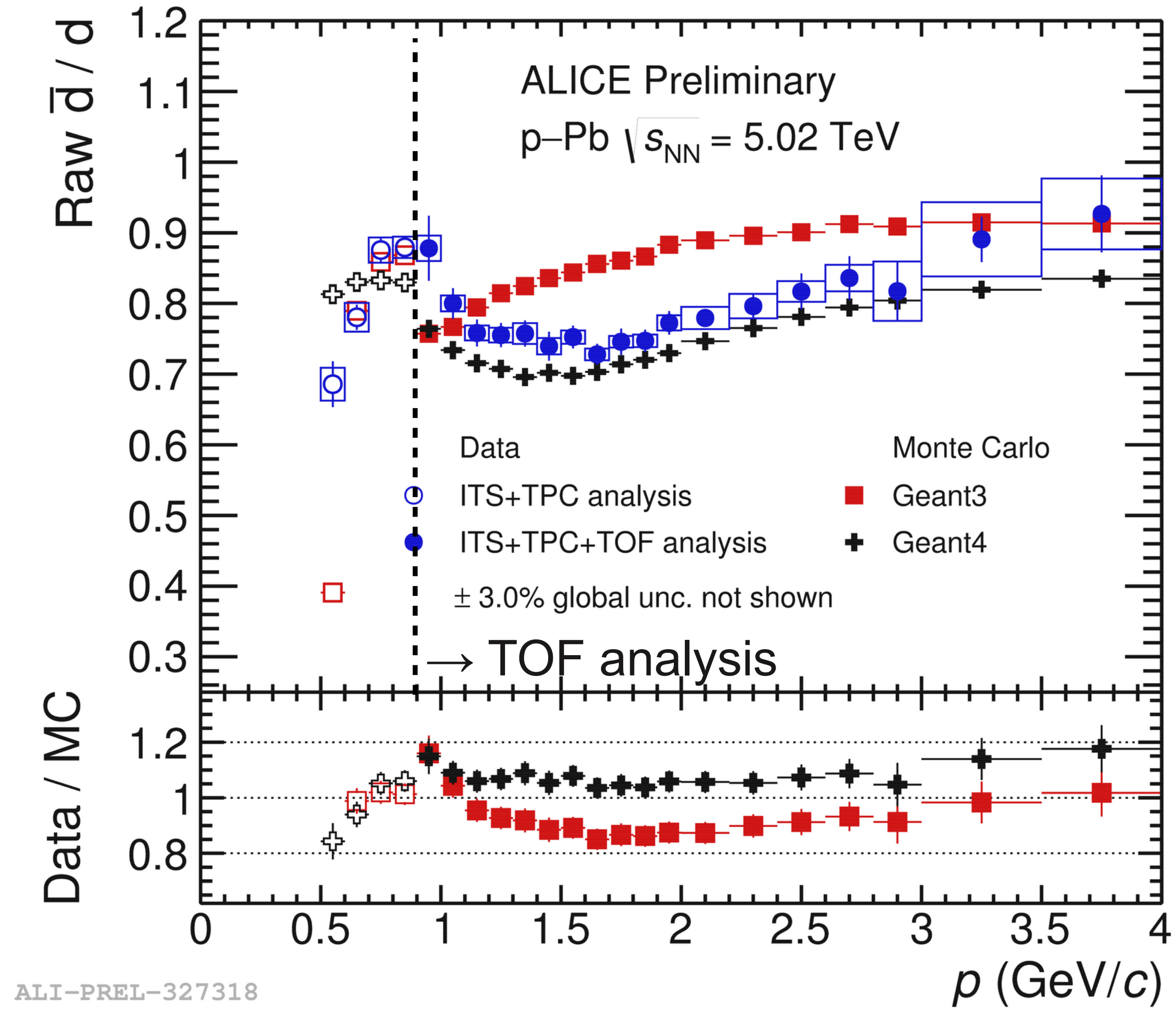


# Raw d̄ / d ratios

TOF analysis from $p$ = 1.4 GeV/$c$

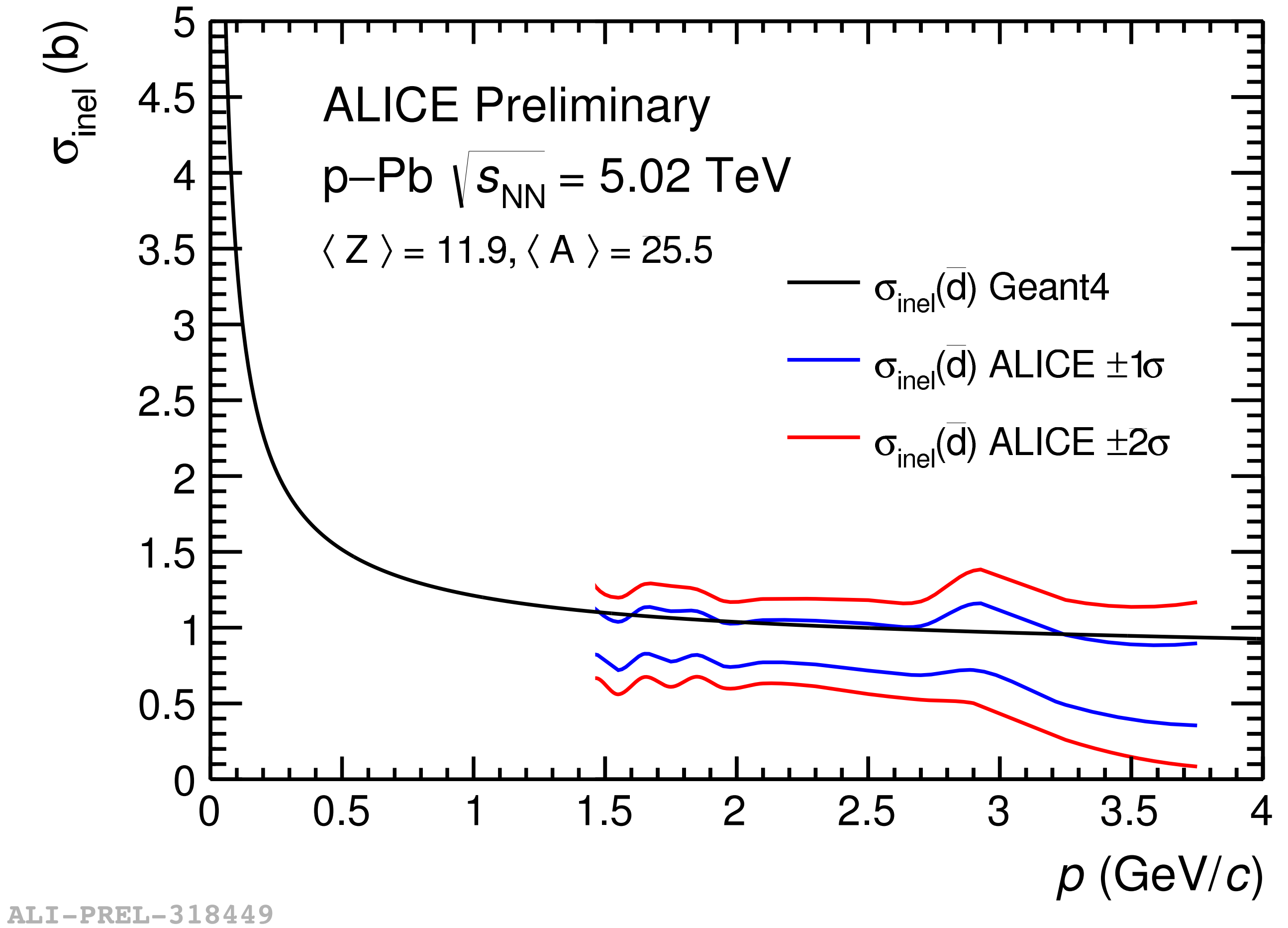



TOF analysis from $p$ = 0.9 GeV/$c$



# Constraints on $\sigma_{inel}(\bar{d})$

**TOF analysis from *p* = 1.4 GeV/*c***




**TOF analysis from *p* = 0.9 GeV/*c***