Constraining the anti-deuteron inelastic interaction cross-section with the ALICE at CERN LHC

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On behalf of the ALICE Collaboration

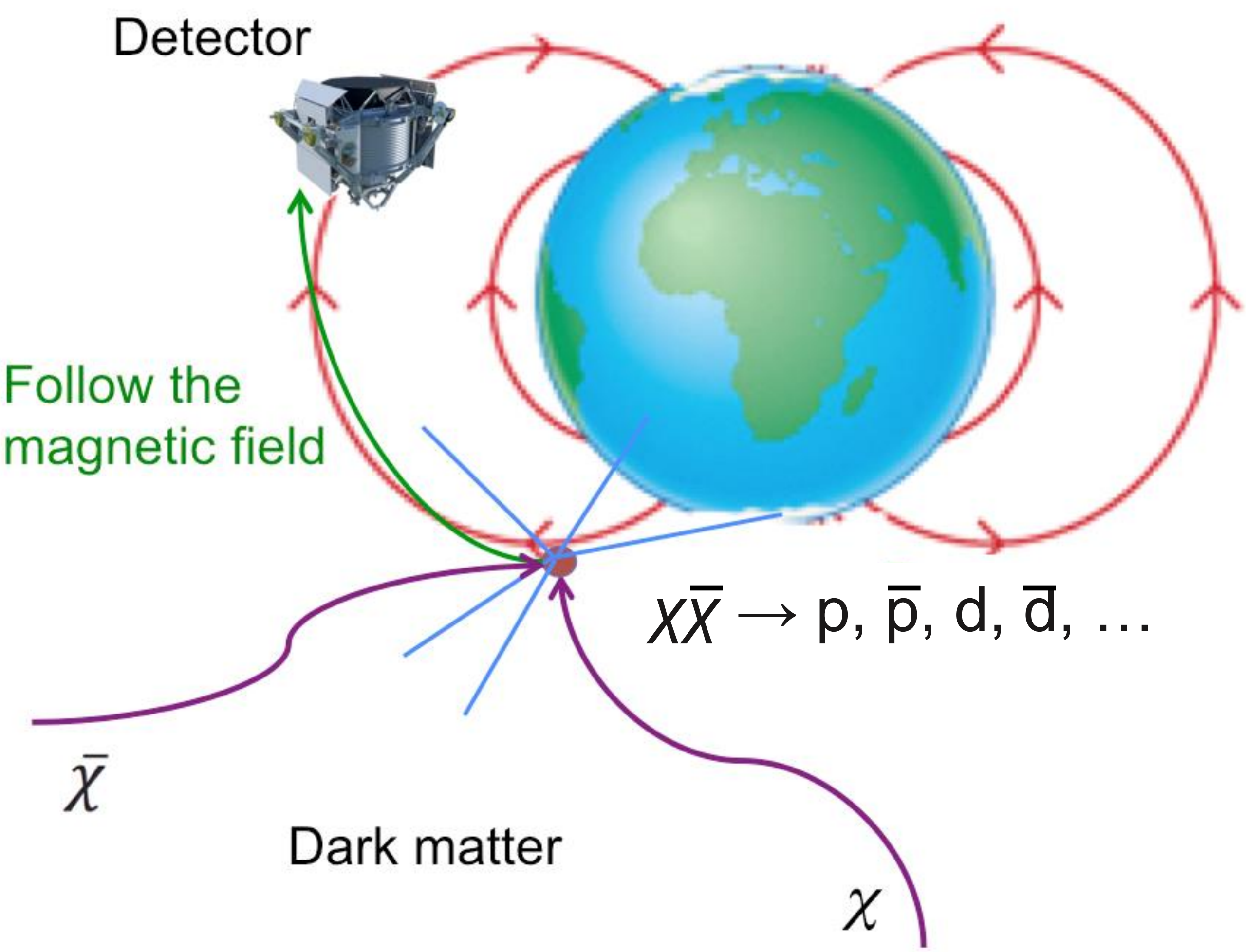
Antiproton-nucleus interactions and related phenomena
Trento, 19.06.2019

Introduction

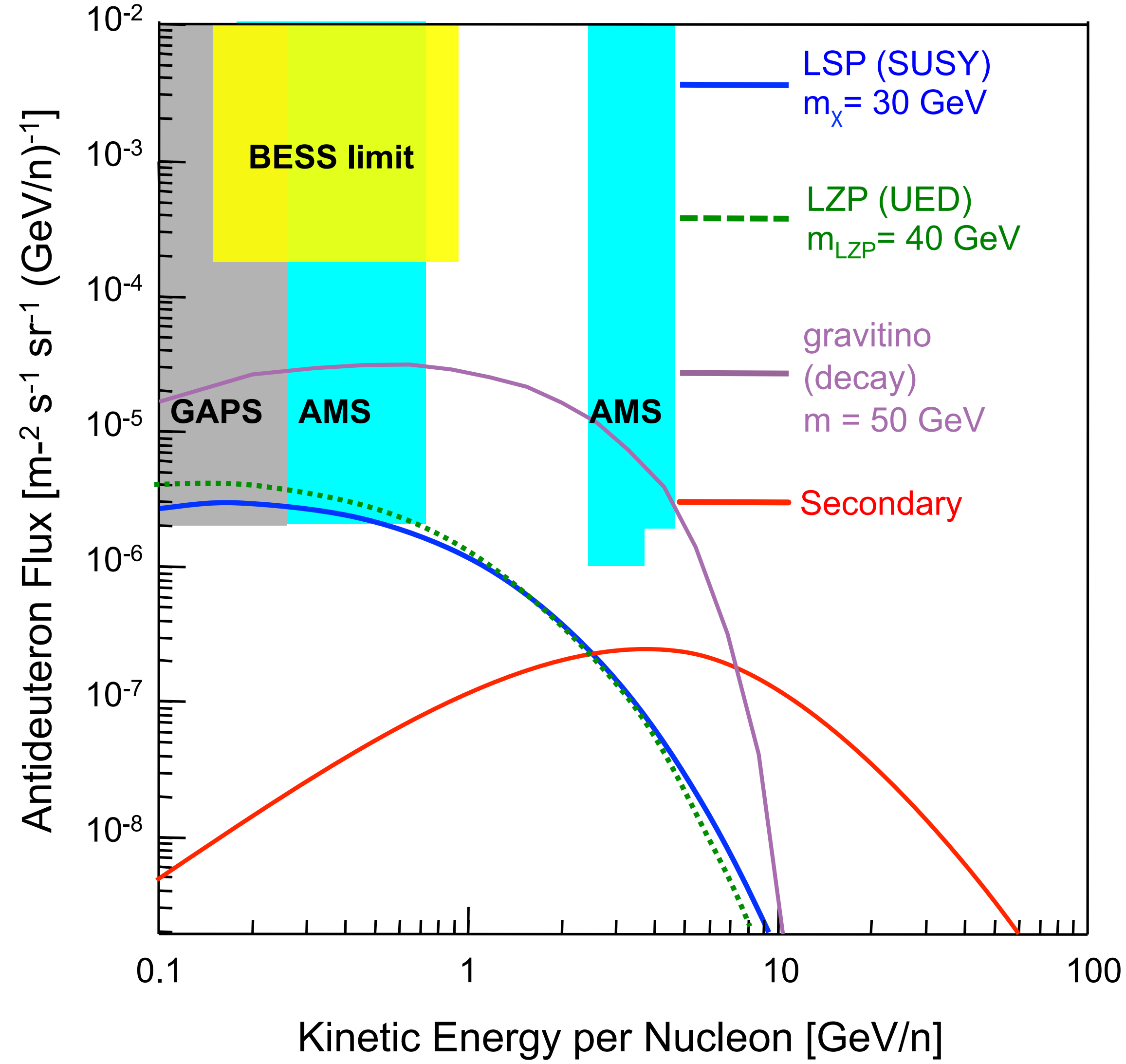
Low-energy cosmic anti-deuterons - unique probe for indirect Dark Matter searches

Vital to determine primary and secondary anti-deuteron flux!

- Need to know precisely the production and absorption cross-sections at low energies

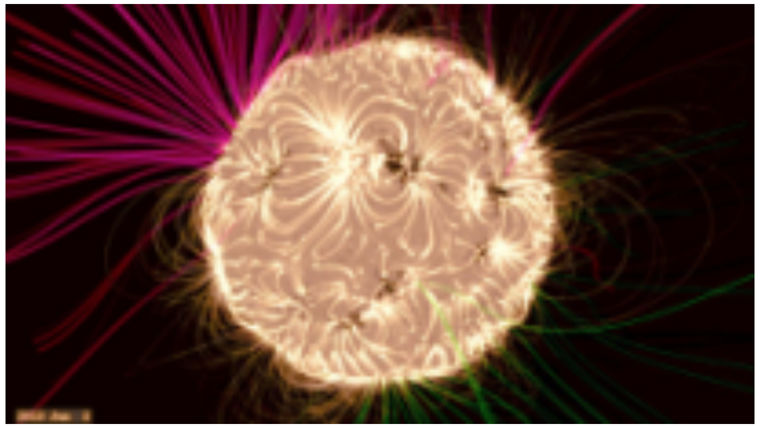


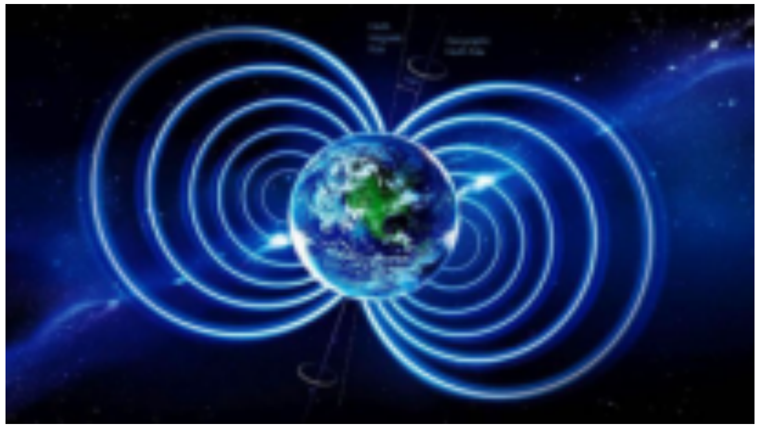
Predicted anti-deuteron flux [1]



1) Physics reports 618, 1 (2016)

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

Calculation of secondary anti-deuteron flux

Anti-deuteron diffusion equation:

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

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, pp̄, pHe, p̄He…

Calculation of secondary anti-deuteron flux

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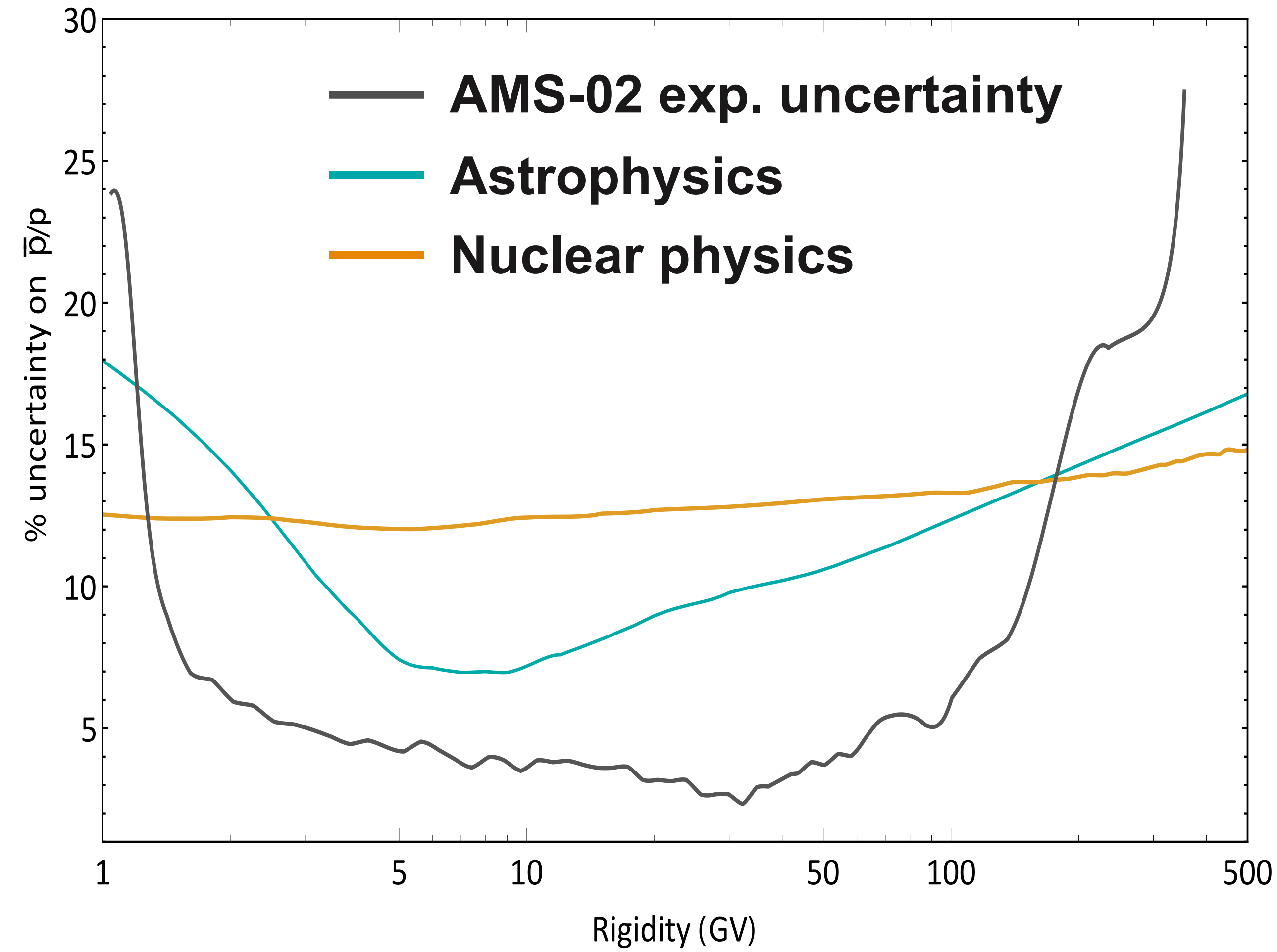
- Production of anti-deuterons in collisions of pp, pp̄, pHe, p̄He…

Uncertainty on p̄/p ratio for AMS-02 [1]



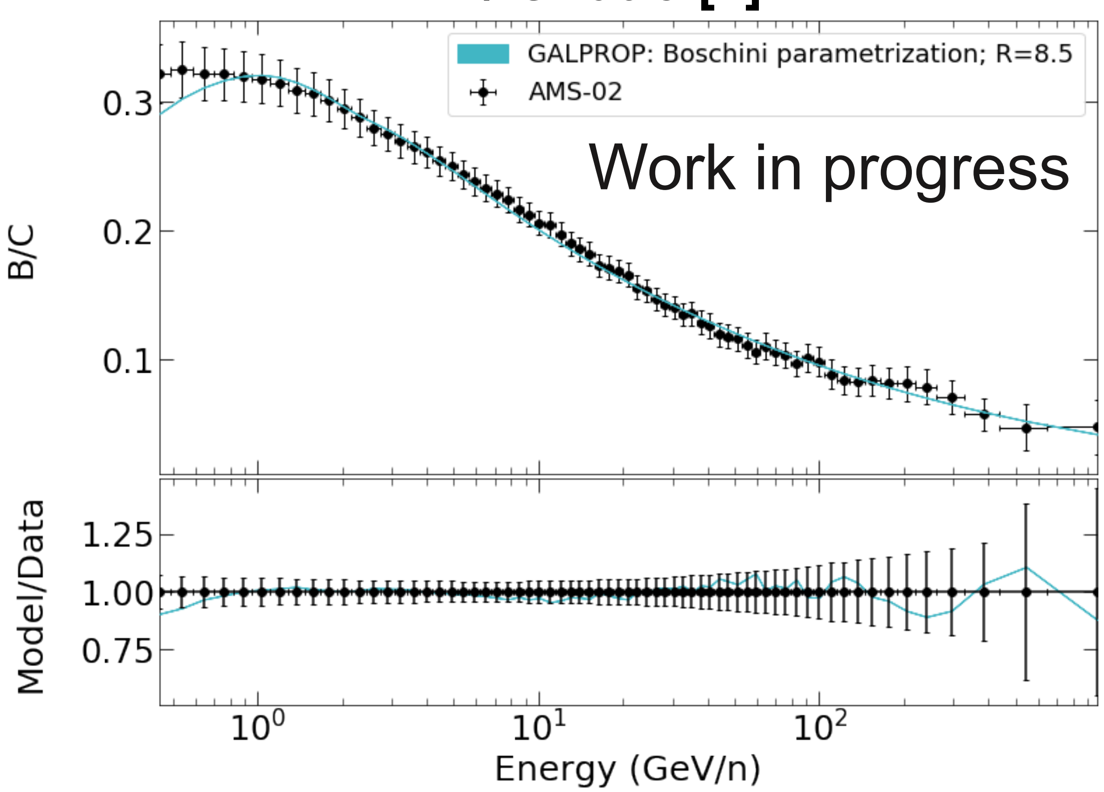
1) CERN-SPSC-2019-022; SPSC-P-360

Simulation of cosmic ray flux: protons

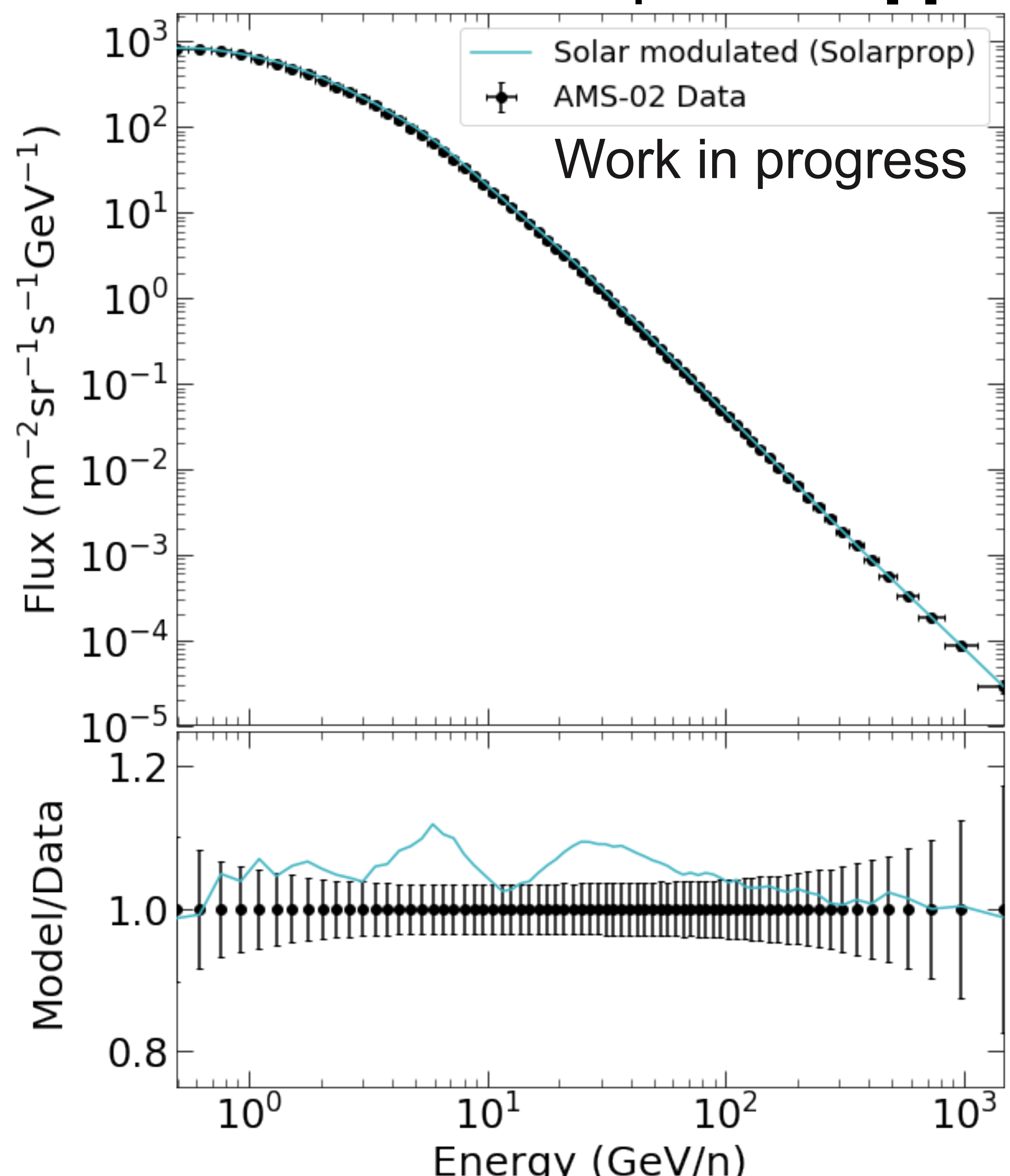
Modelling of propagation in interstellar medium and in solar magnetic field

- Chain of several MC-based frameworks
- Protons: mostly primaries from supernova remnants
- Boron / carbon ratio to constrain propagation of primary and secondary particles

B / C ratio [1]



Solar modulated proton flux [1]



Calculations can describe nicely the AMS-02 data

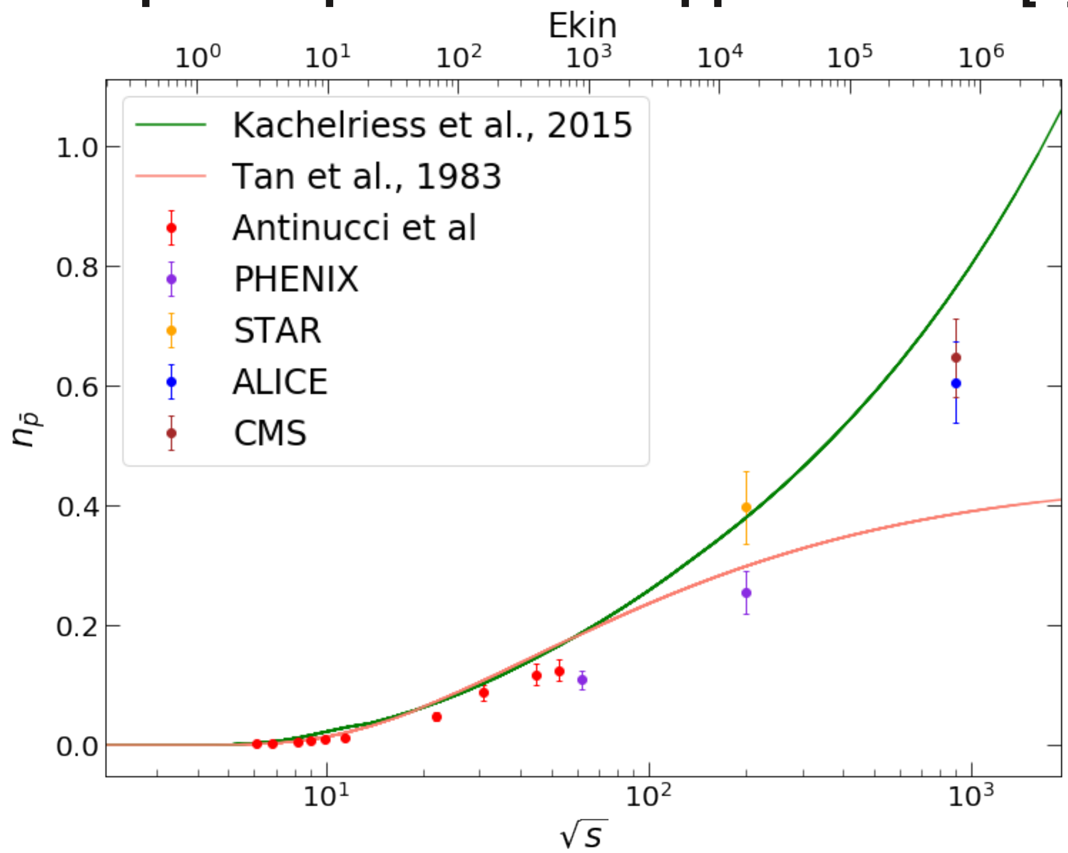
1) L. Šerkšnytė, T. Pöschl, private communication

Simulation of cosmic ray flux: anti-protons

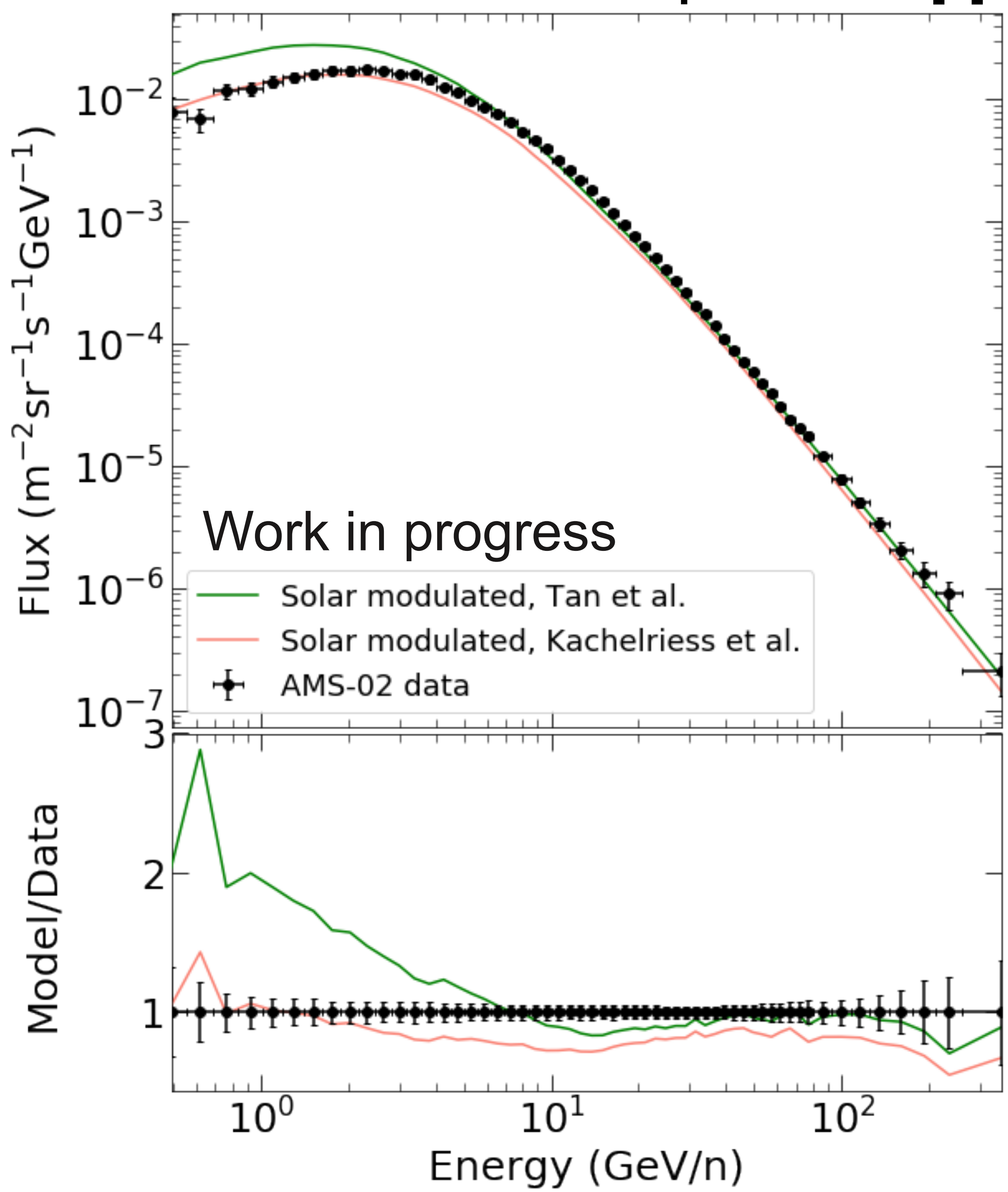
Modelling of propagation in interstellar medium and in solar magnetic field

- Chain of several MC-based frameworks
- Most relevant reactions for secondary anti-protons: pp, p-^{4}He, ^{4}He-p, ^{4}He-^{4}He
- *No conclusive model which describes AMS-02 data in whole energy range*

Anti-proton production in pp collisions [1]



Solar modulated anti-proton flux [1]



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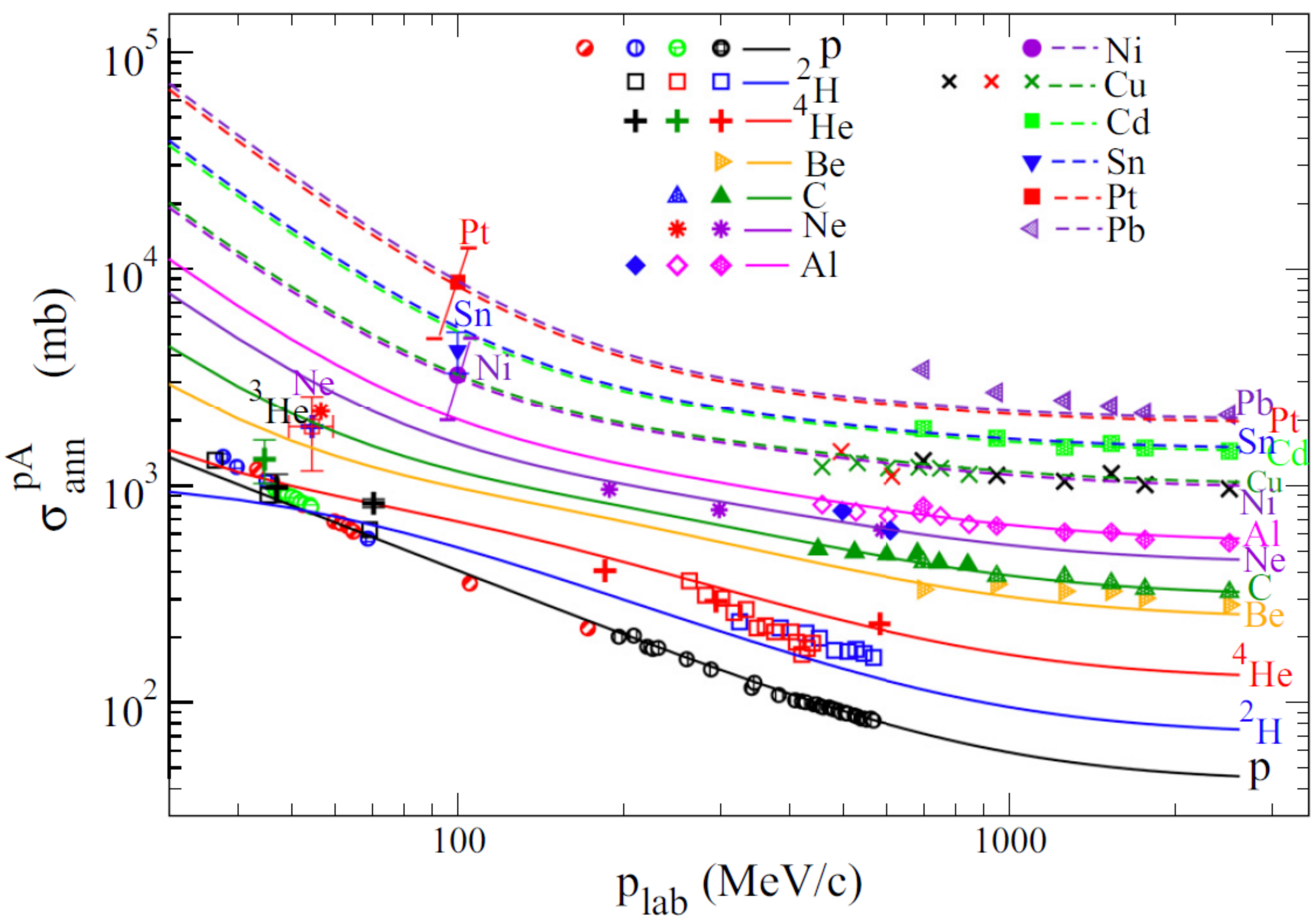
Status of $\bar{p}$ and $\bar{d}$ annihilation cross-section

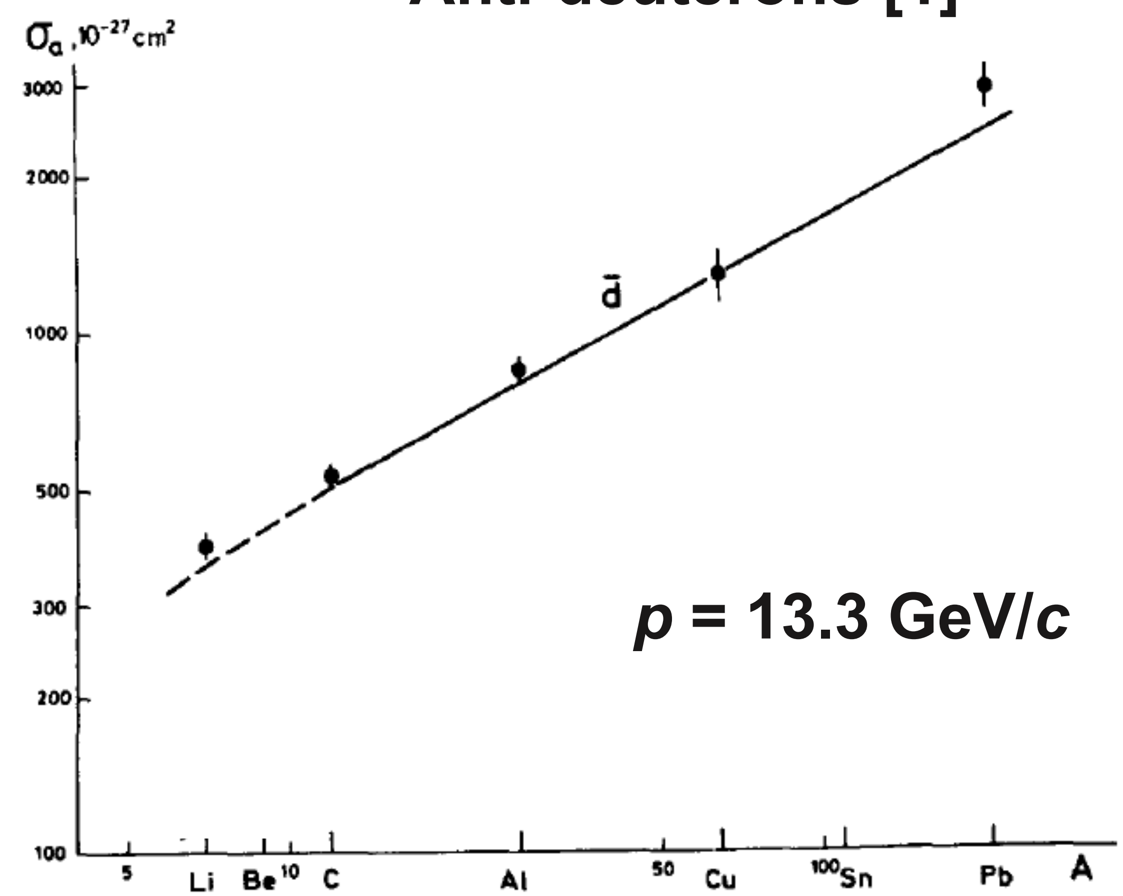
Anti-deuteron annihilation cross-section is poorly known at low energies

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

Anti-protons [3]



Anti-deuterons [1]



p* = 13.3 GeV/*c

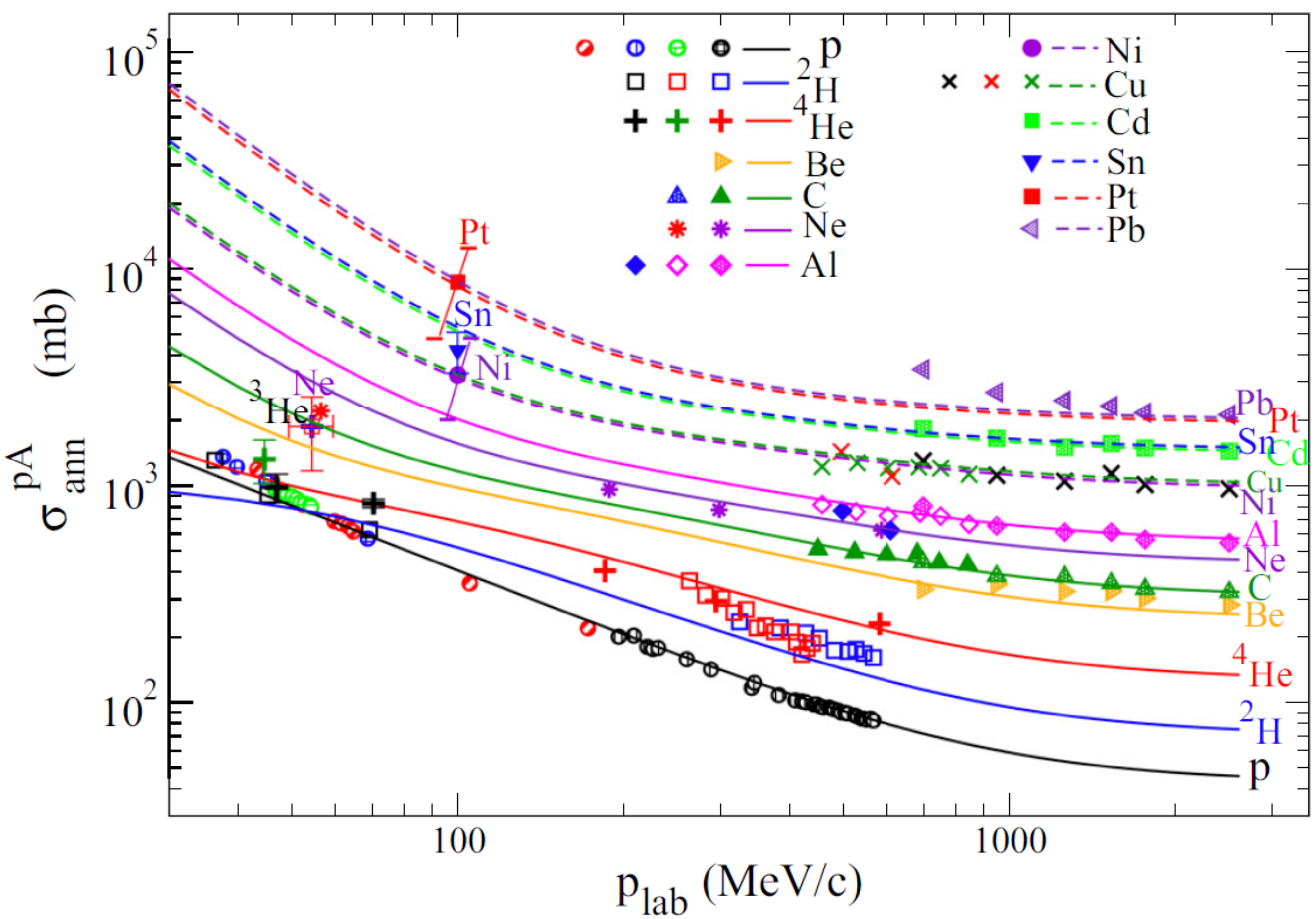
1) Nuclear Physics B 31(2), 253 (1971)
2) Phys. Let. B 31(4), 230 (1970)
3) Phys. Rev. C 89, 054601 (2014)

Status of p̄ and d̄ annihilation cross-section

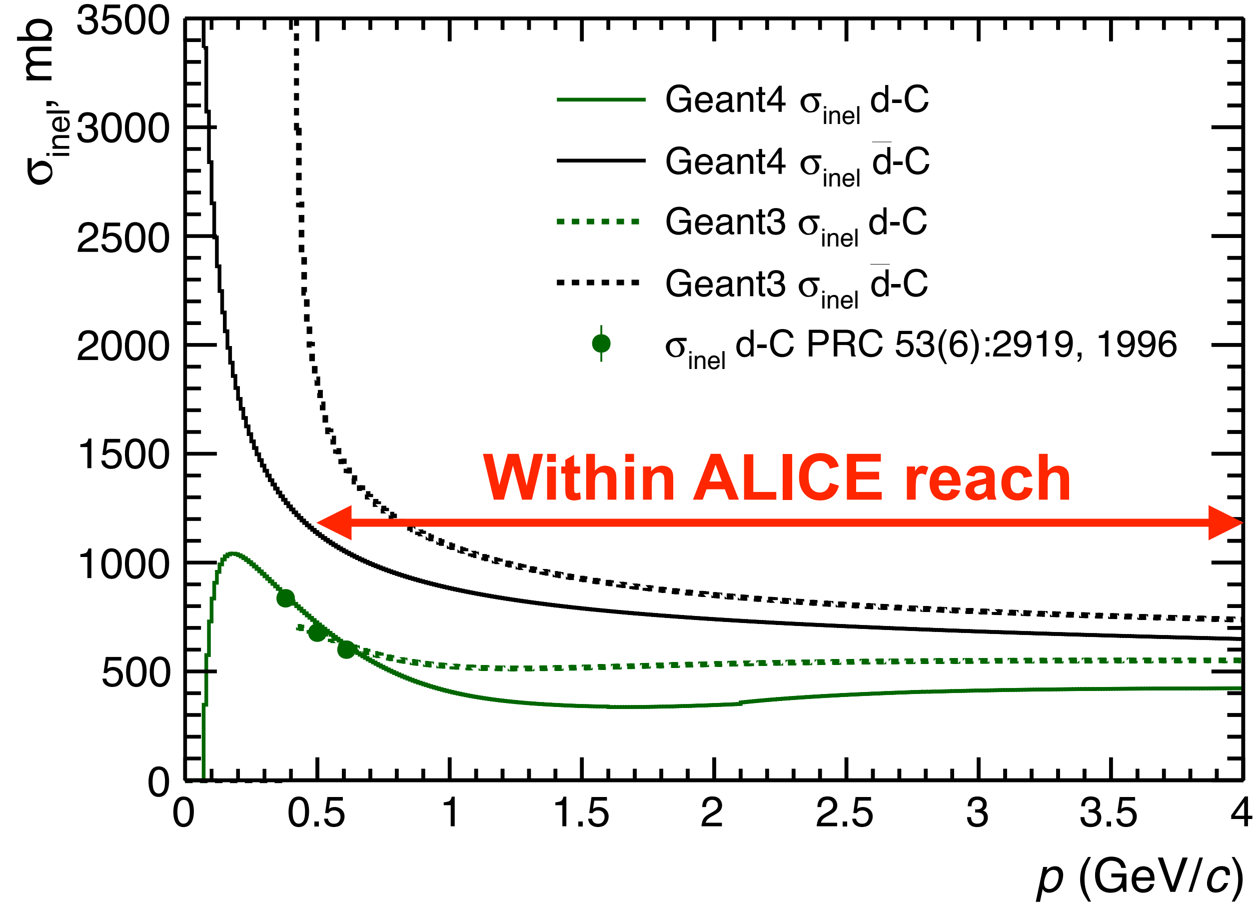
Anti-deuteron annihilation cross-section is poorly known at low energies

- No experimental data below p_{lab} = 13.3 GeV/c [1, 2]
- *Can the ALICE Experiment at CERN LHC be used to study anti-deuteron absorption in detector material?*

Anti-protons [3]



Anti-deuterons



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The ALICE Experiment at the CERN LHC

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

Inner **T**racking **S**ystem

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

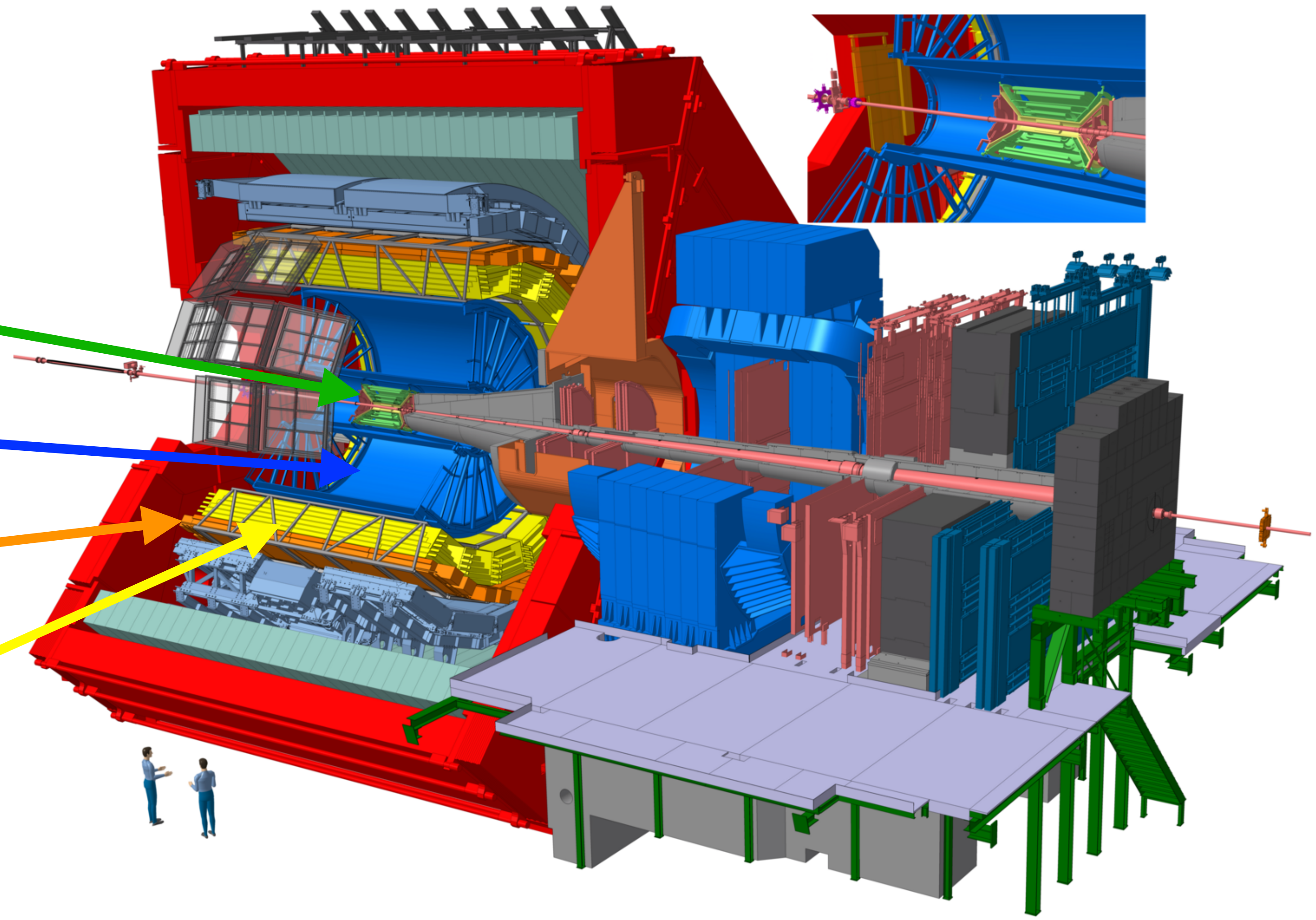
Time **P**rojection **C**hamber

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

Time **O**f **F**light detector

- PID (TOF measurement)

Transition **R**adiation **D**etector



Large samples of pp, p-Pb and Pb-Pb data at various collision energies

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

Particle identification in TPC and TOF

dE/dx in material: Bethe-Bloch

- TPC gas: Ar/CO_2 (88/12)

$$-\left\langle \frac{dE}{dx} \right\rangle = K z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[\frac{1}{2} \ln \frac{2 m_e c^2 \beta^2 \gamma^2 T_{\max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

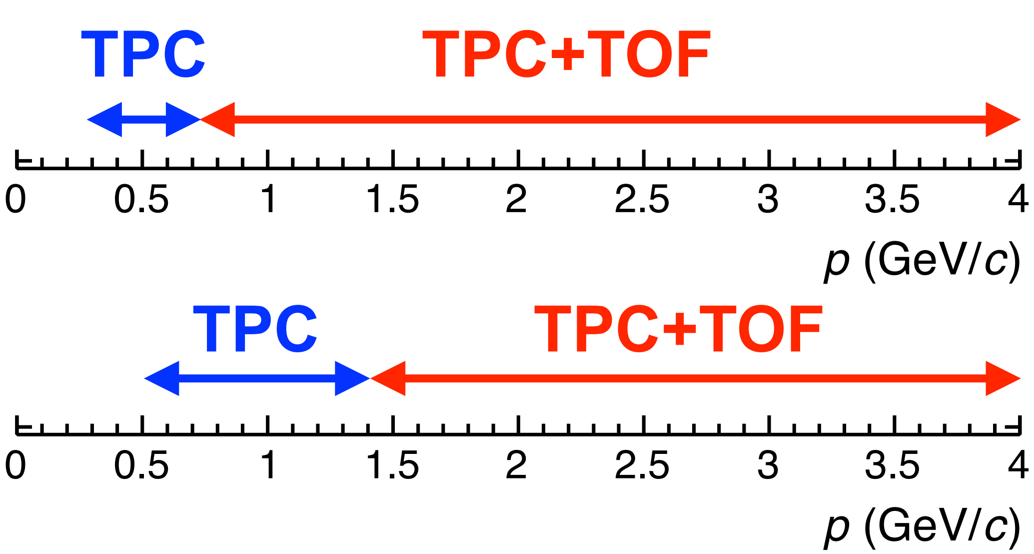
Time of Flight: $\beta = v/c$

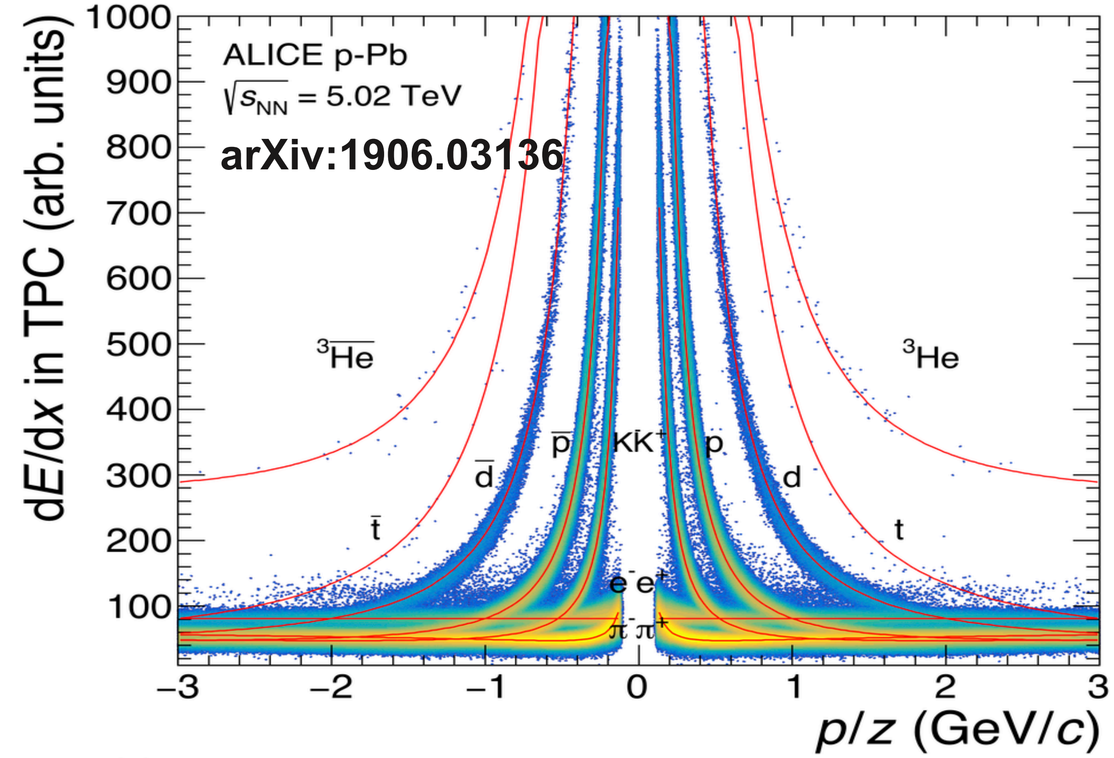
- $p = \gamma\beta m \rightarrow$ mass

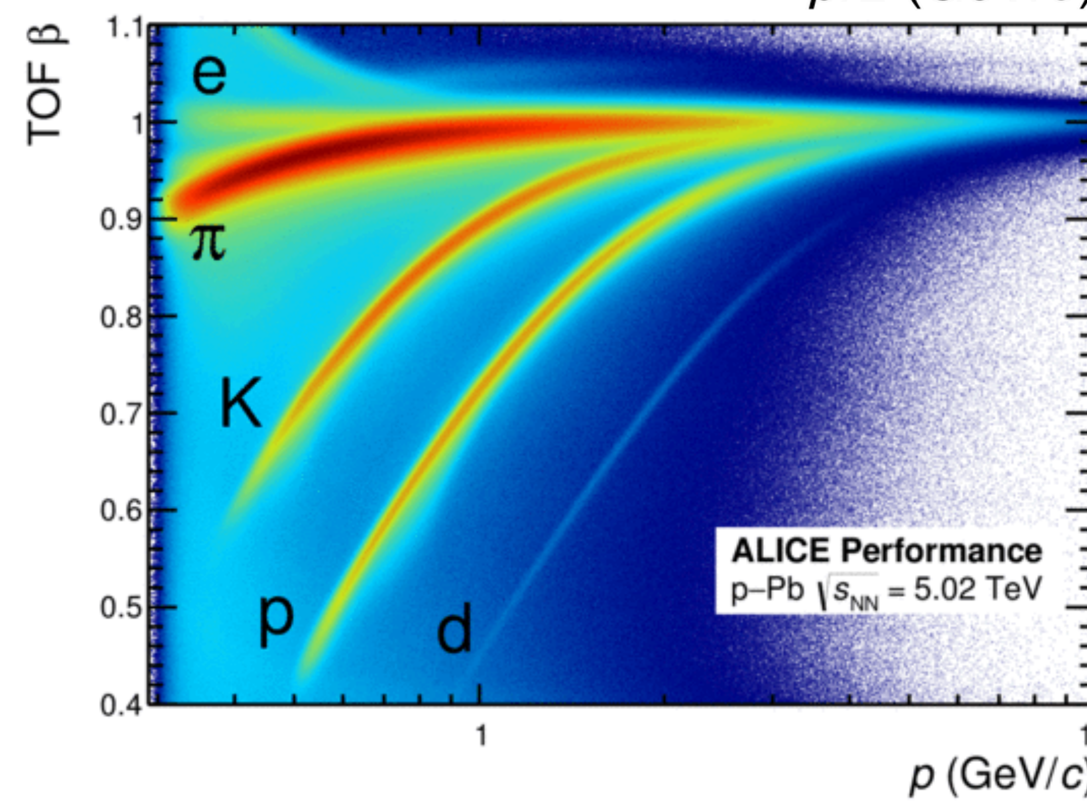
Complementary information from TPC and TOF detectors allows to select high-purity (anti-)protons and (anti-)deuterons

protons:

deuterons:







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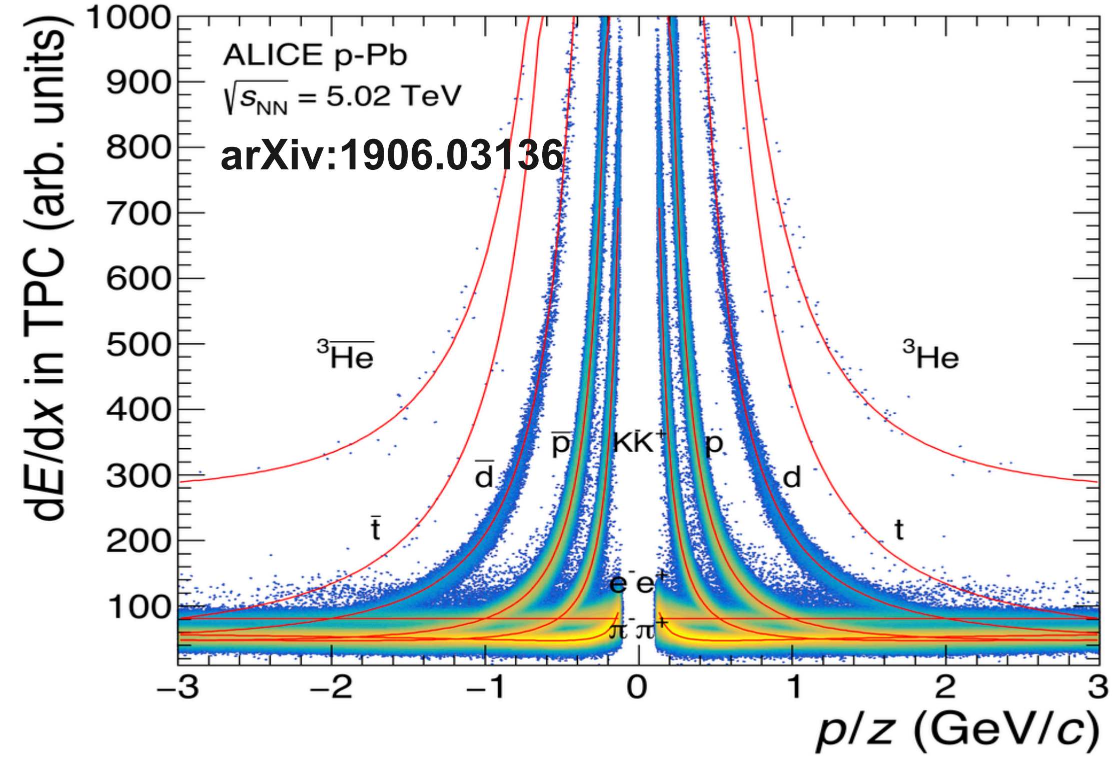
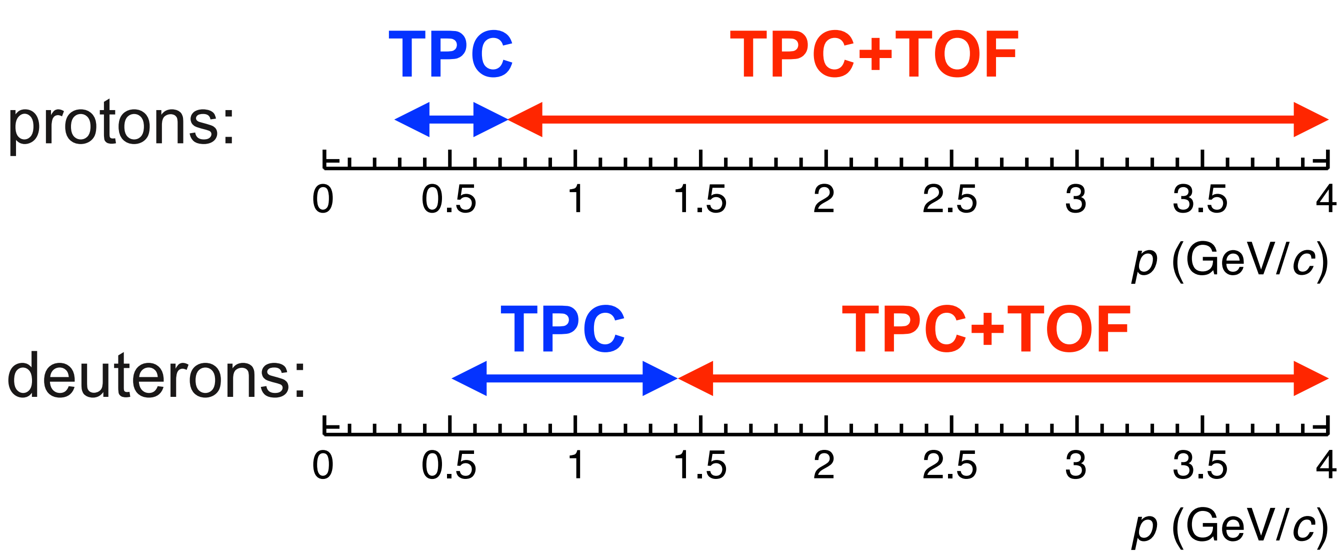
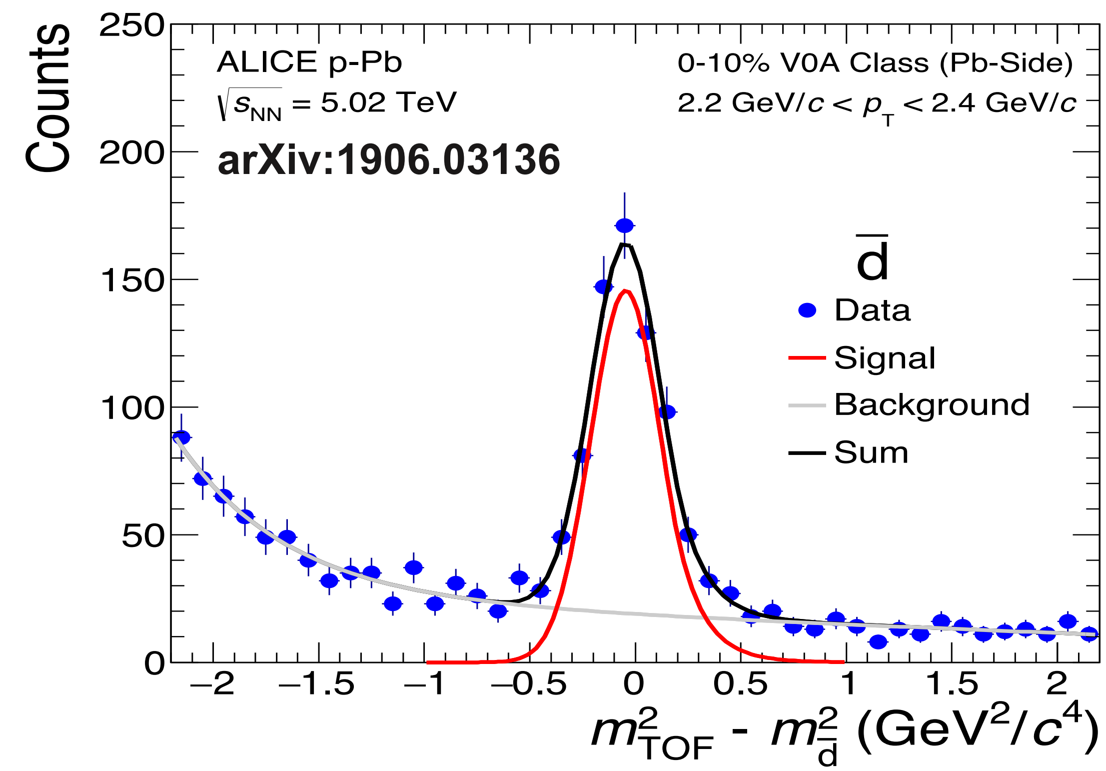


Complementary information from TPC and TOF detectors allows to select high-purity (anti-)protons and (anti-)deuterons



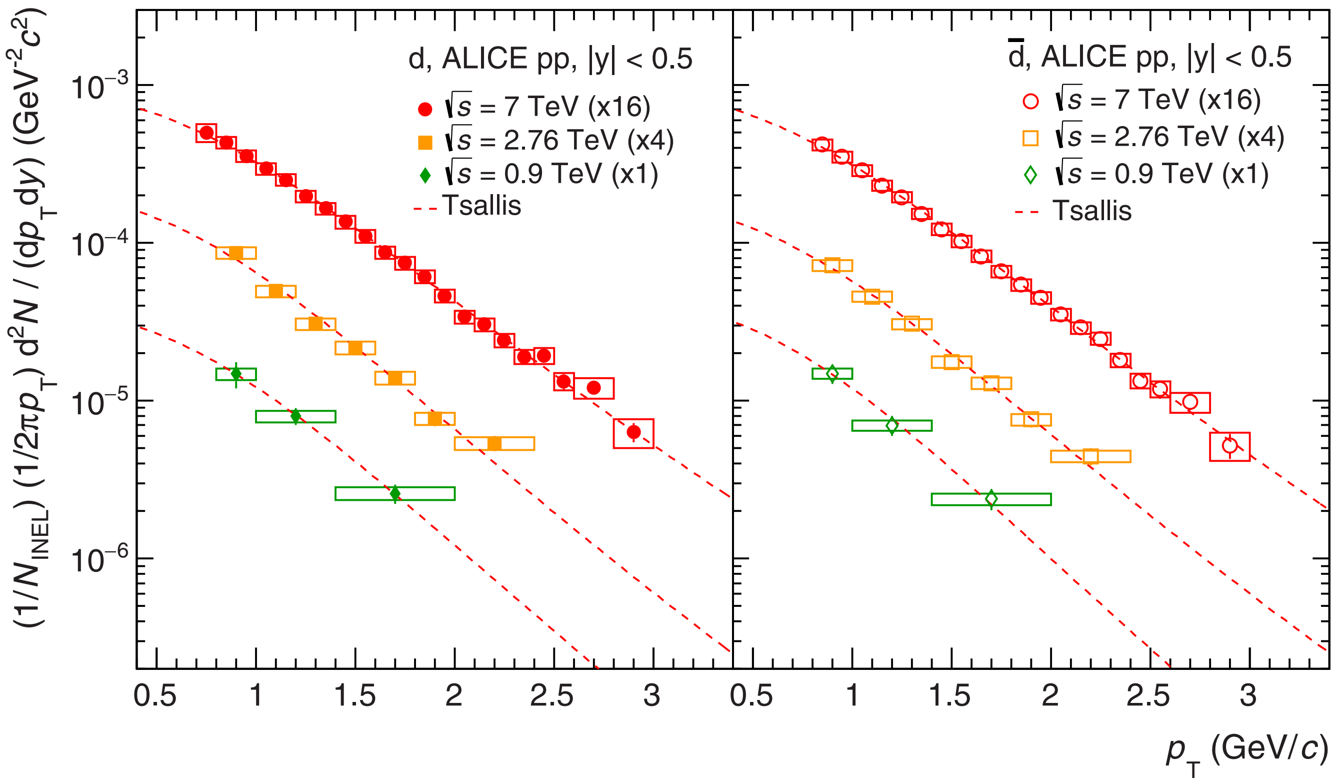


LHC as an anti-matter factory

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

- Protons and deuterons: only ~5% and ~0.005% of all charged particles

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



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

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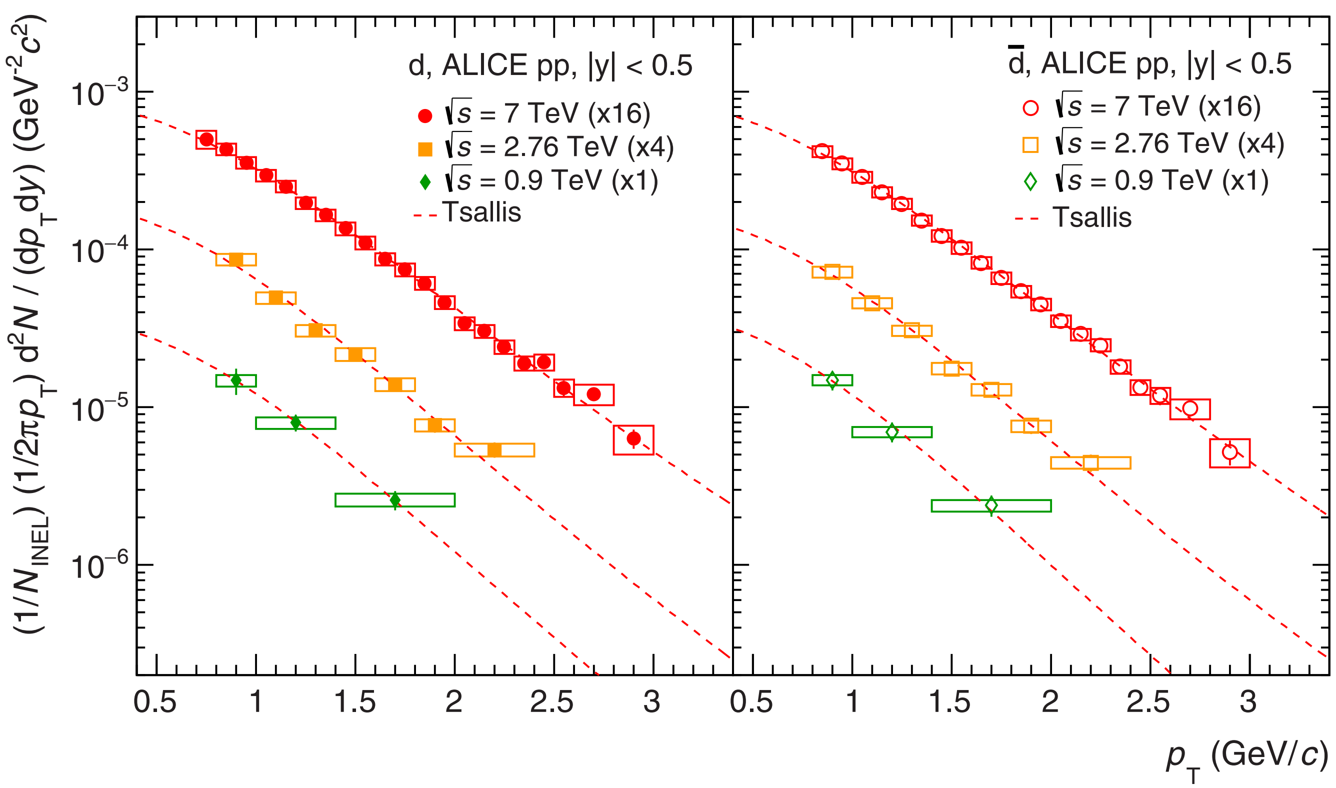
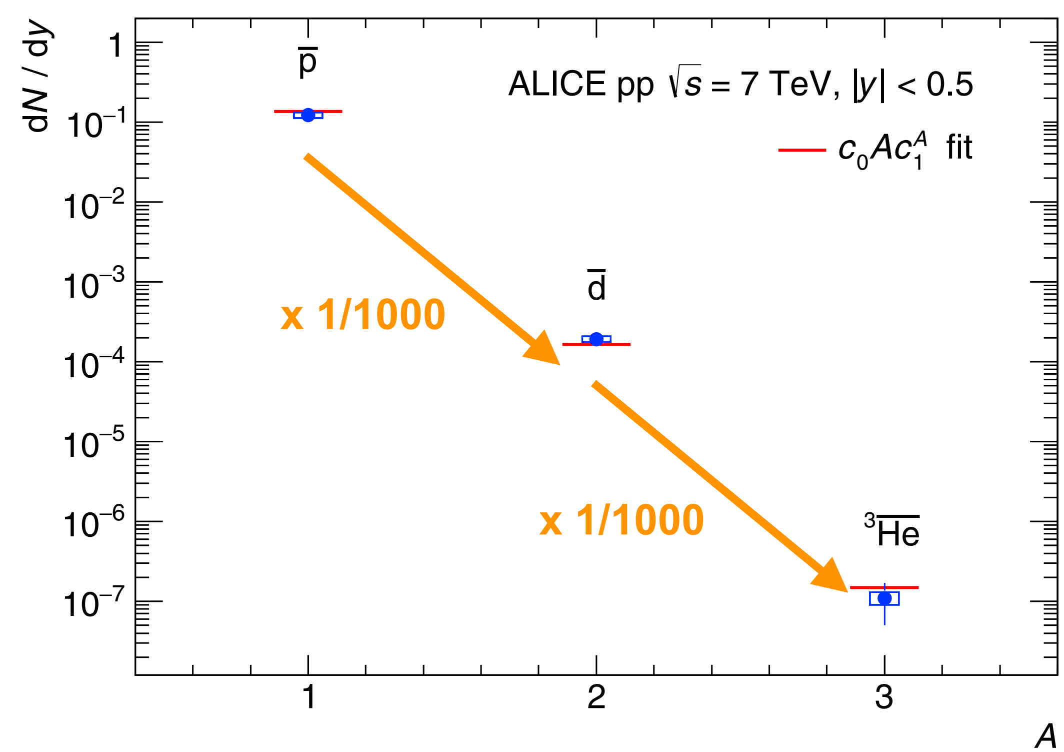


Integrated yield at mid-rapidity [1]



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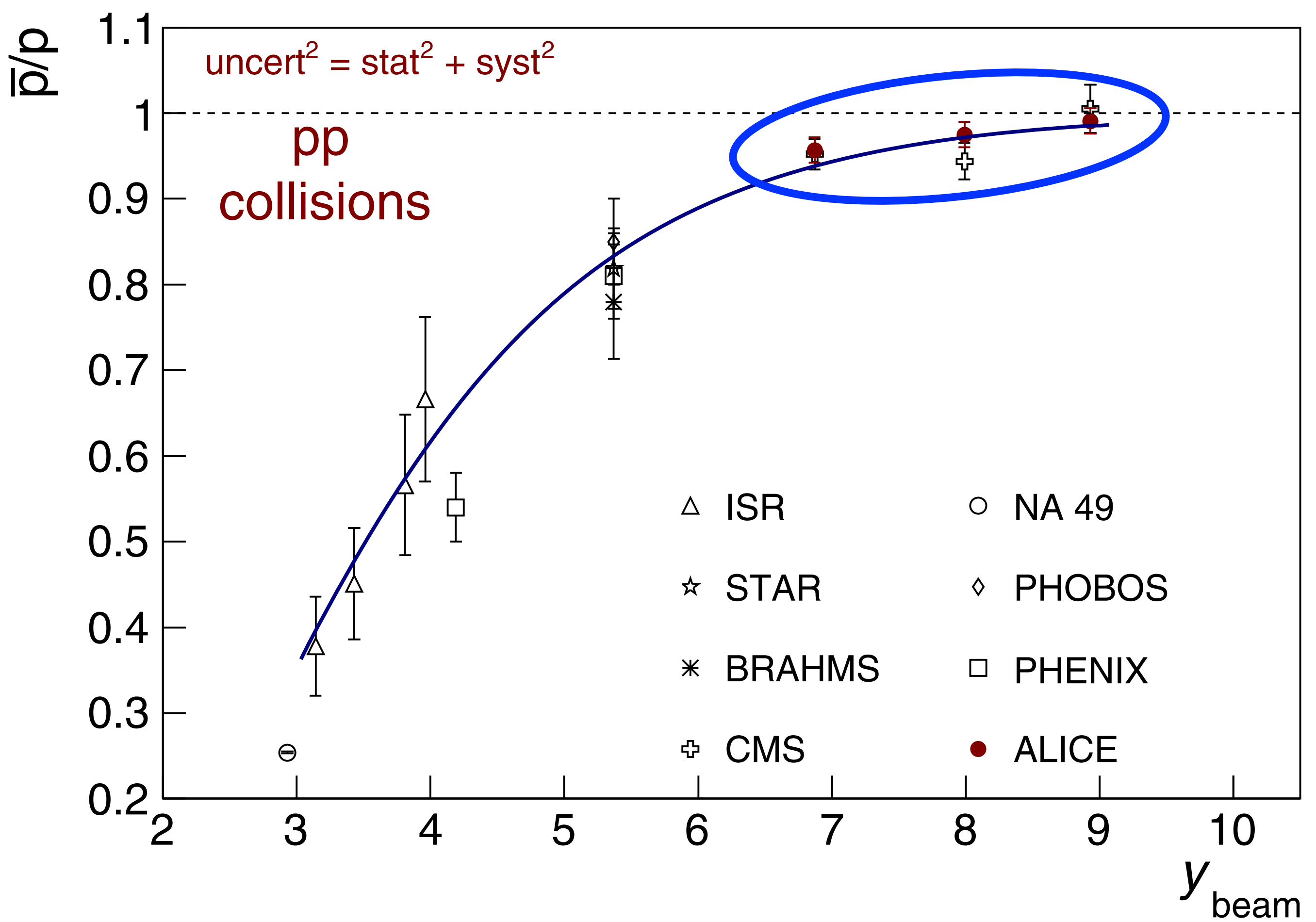
Primordial ratio extrapolated to $\sqrt{s}$ = 5.02 TeV collision energy:

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

Primordial $\bar{p}$/p ratio at mid-rapidity [1]

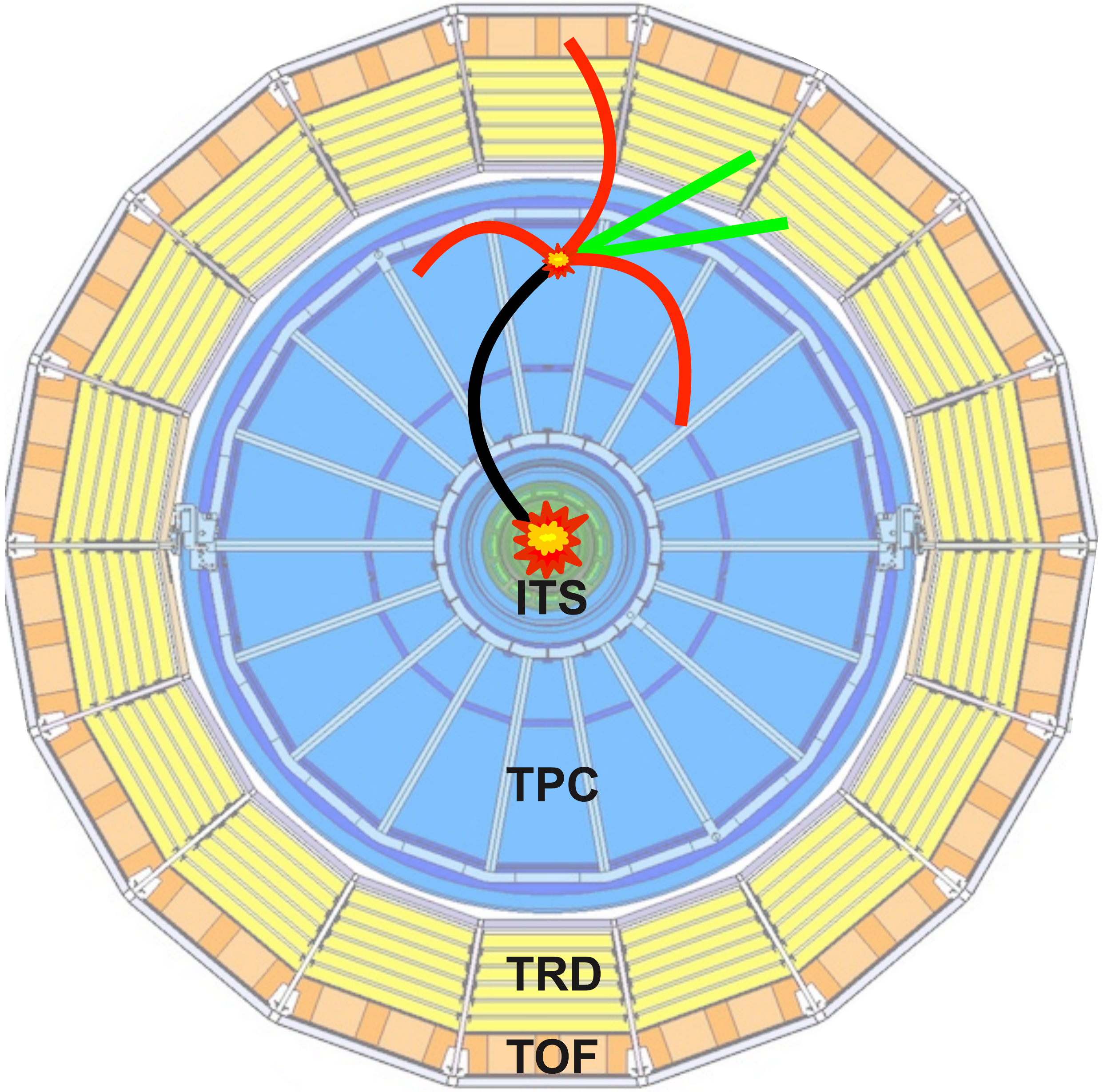


1) Phys. Rev. C 97, 024615 (2018)

… and 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



1) Journal of Instrumentation 3, S08002 (2008)

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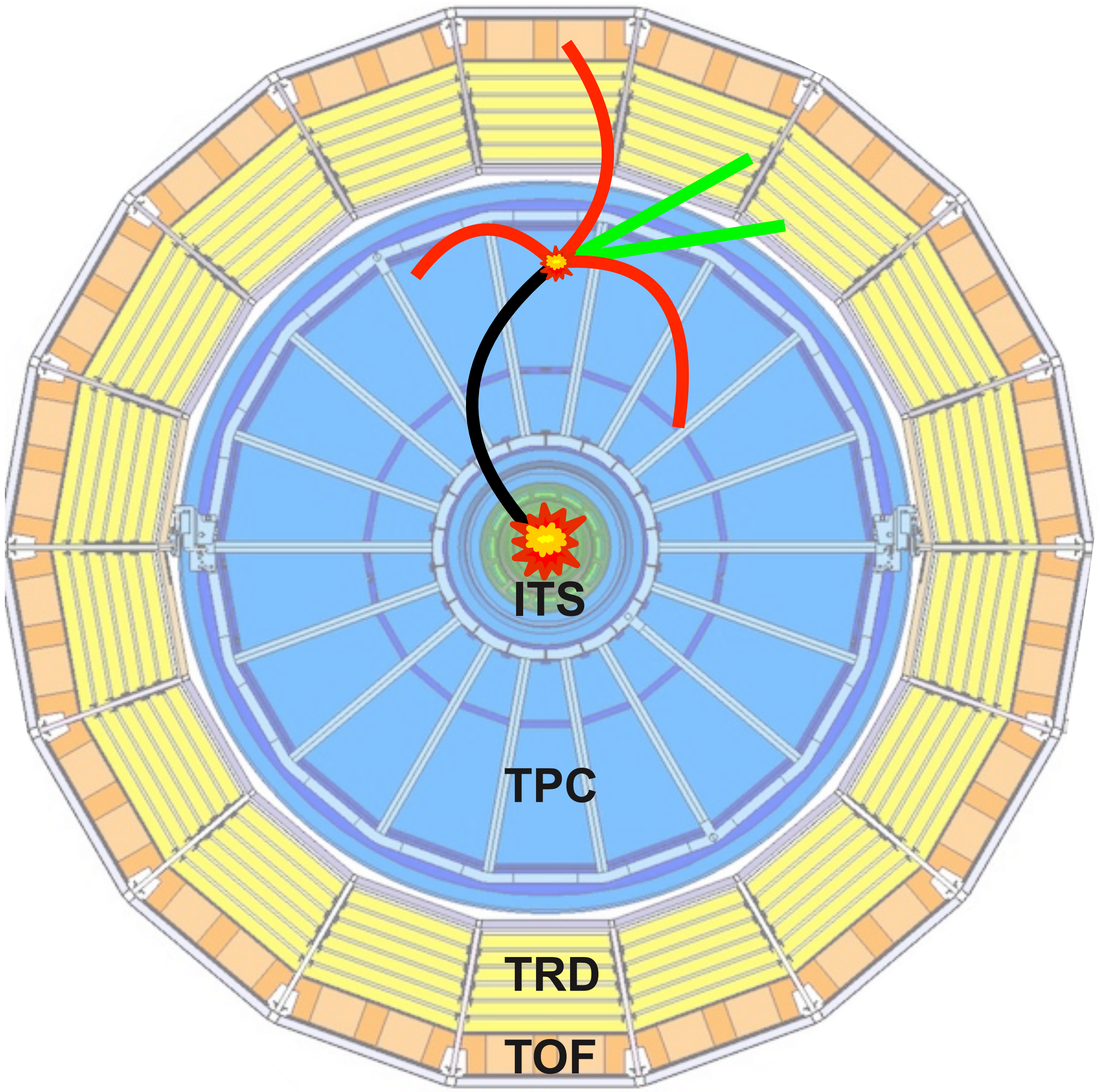


Idea: analyse "*raw" reconstructed* anti-particle to particle ratios

- No correction due to detector efficiency or absorption in detector material
- Correction for secondary (anti-)particles (weak decays or spallation processes)
- Higher loss of anti-particles in detector material due to higher σ_{inel}
  - Constrain $\sigma_{inel}(\bar{d})$ via comparison with Monte Carlo simulations based on Geant

1) Journal of Instrumentation 3, S08002 (2008)

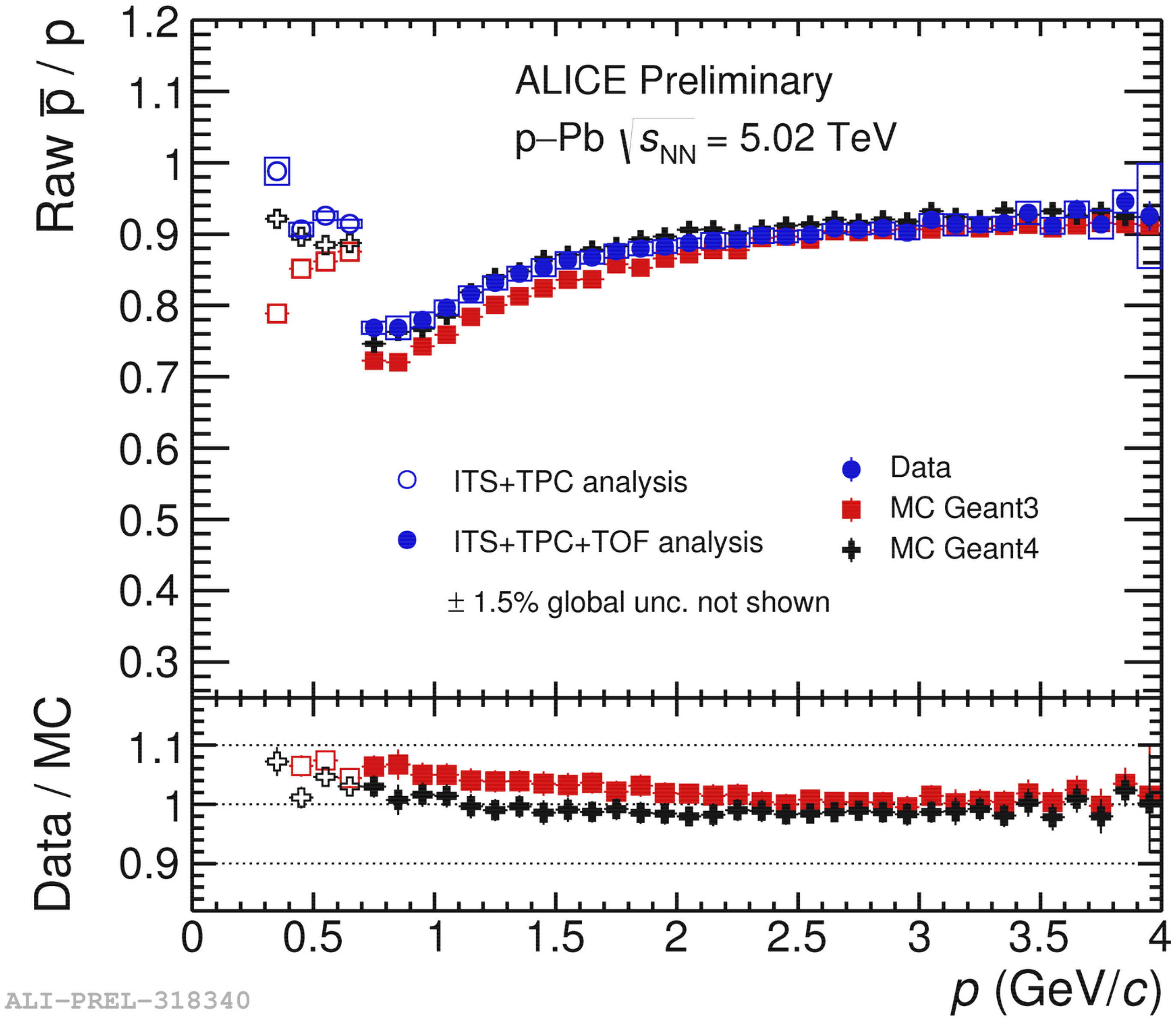
Ratio of raw primary (anti-)protons

Raw primary p̄ / p ratio compared to full-scale ALICE Monte Carlo simulations

- Higher loss of anti-protons in detector material
- 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

- Reconstruction of tracks starting from raw hits as for real experimental data
- Propagation of (anti-)particles and interaction with matter with Geant



Geant4-based simulations are in better agreement with experimental data

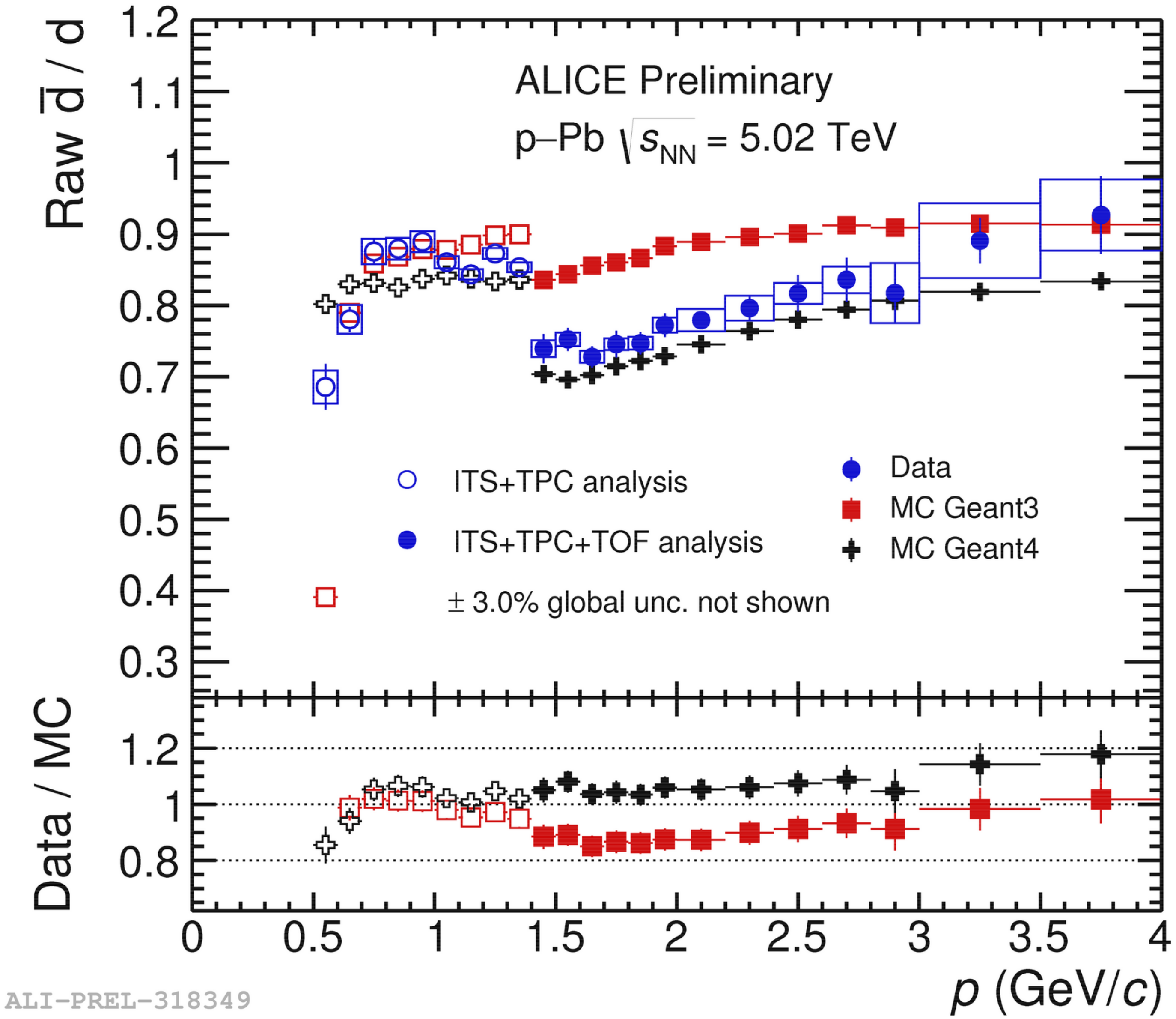
Ratio of raw primary (anti-)deuterons

Raw primary d̄ / d ratio compared to full-scale ALICE Monte Carlo simulations

- Higher loss of anti-deuterons in detector material
- Step at p = 1.4 GeV/c due to additional detector material between TPC and TOF (TRD, space frame)

Monte Carlo data: detailed simulation of ALICE detector

- Reconstruction of tracks starting from raw hits as for real experimental data
- Propagation of (anti-)particles and interaction with matter with Geant



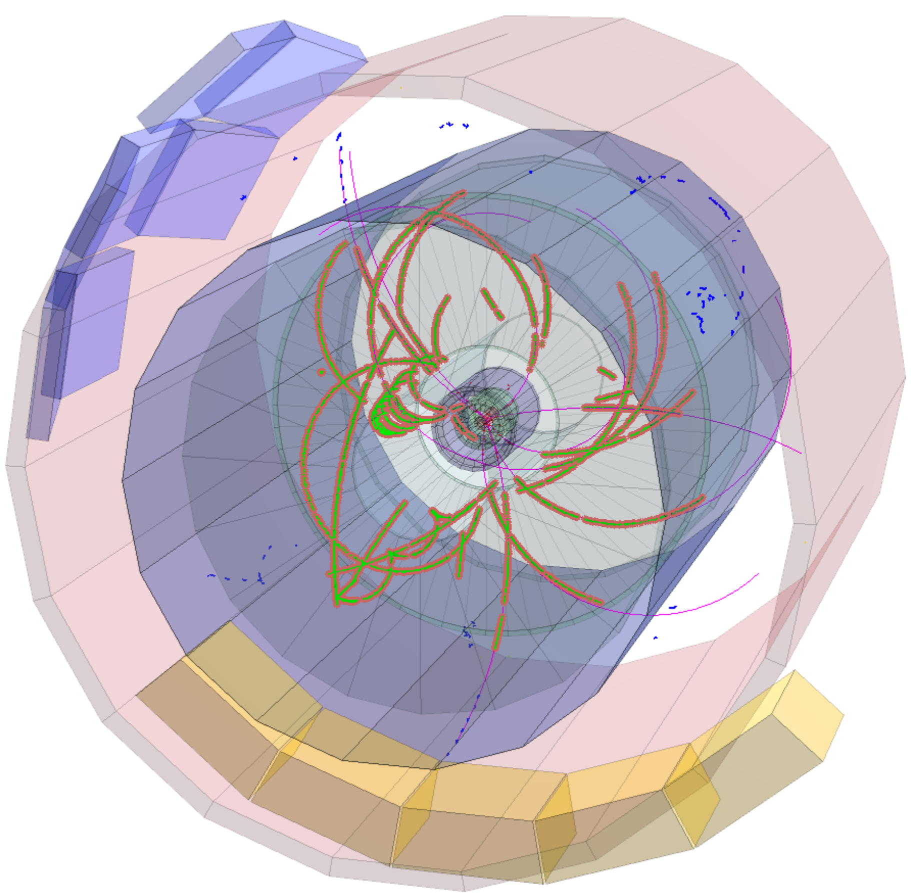
Geant4-based simulations are in much better agreement with experimental data

Simple Geant4-based model

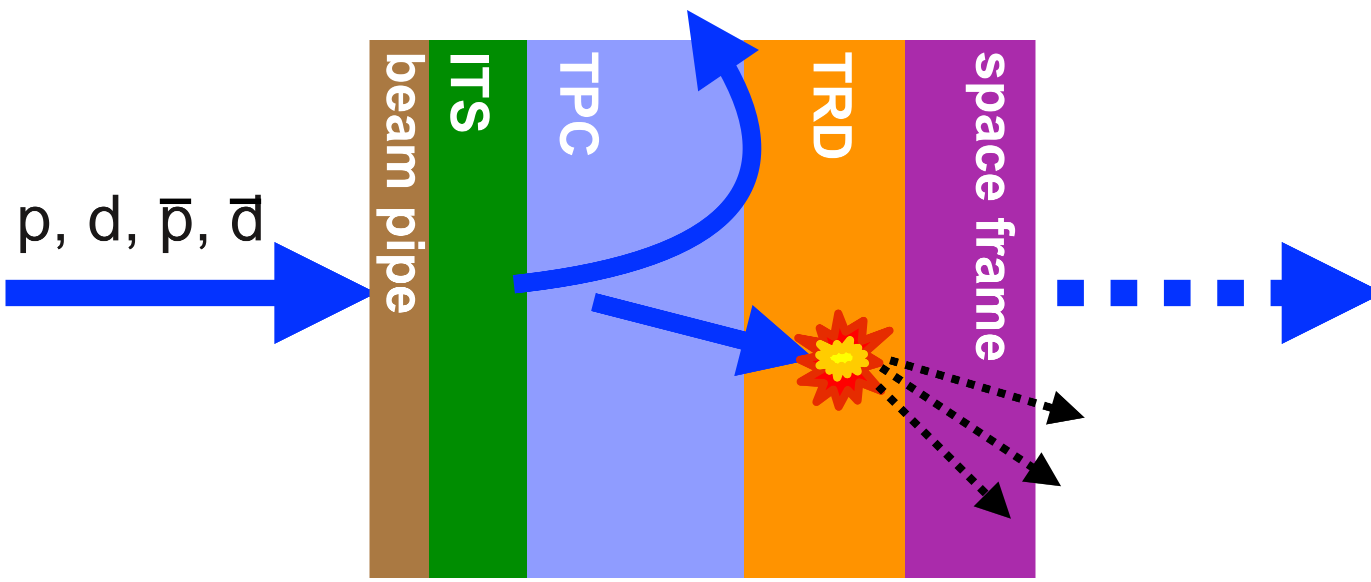
Standalone Geant4 simulation to understand ratios in more details

- (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 ($\langle Z \rangle = 7.4$, $\langle A \rangle = 14.8$)
  - high p: beam pipe, ITS, TPC, TRD, SF ($\langle Z \rangle = 11.9$, $\langle A \rangle = 25.5$)
- 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

- (Anti-)proton and (anti-)deuteron source + a target made of ALICE detector materials
- Loss of (anti-)particles due to inelastic processes in detector material
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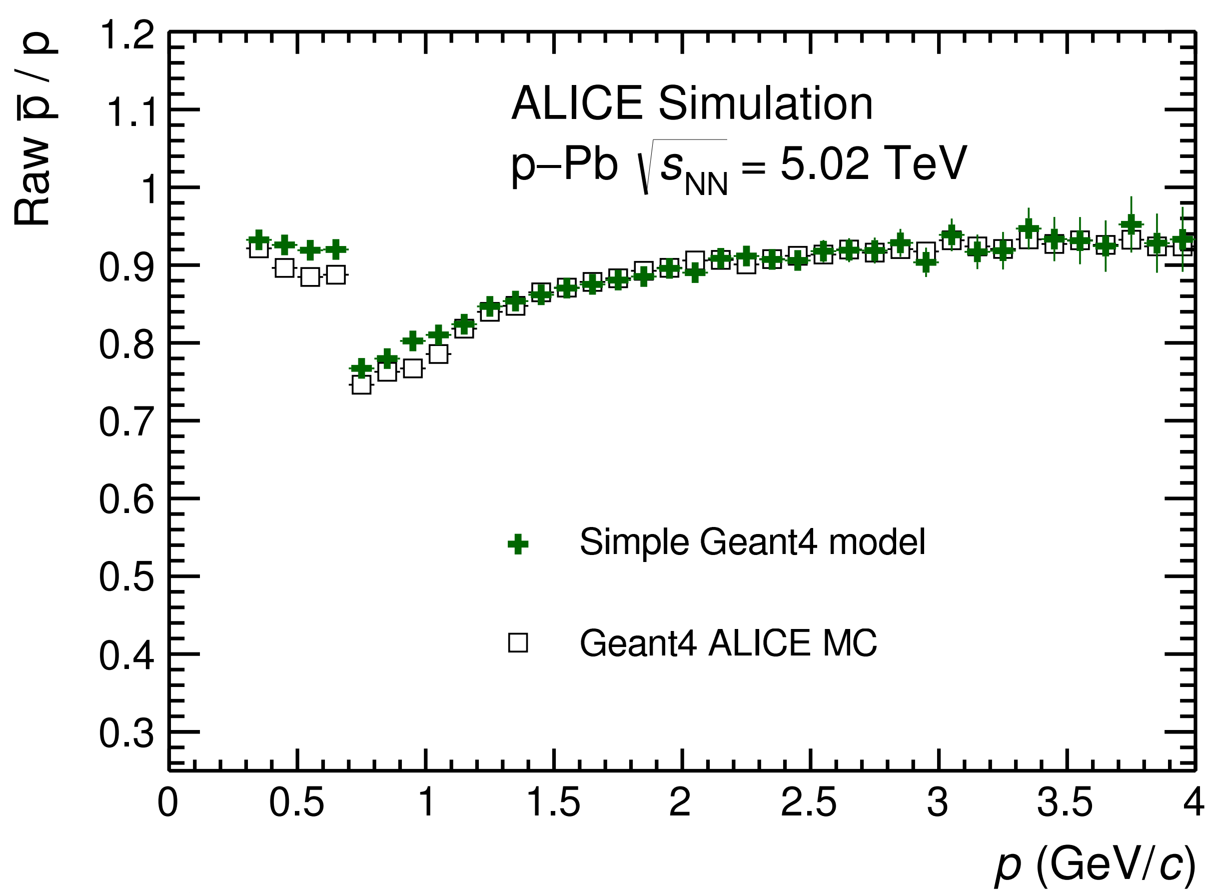
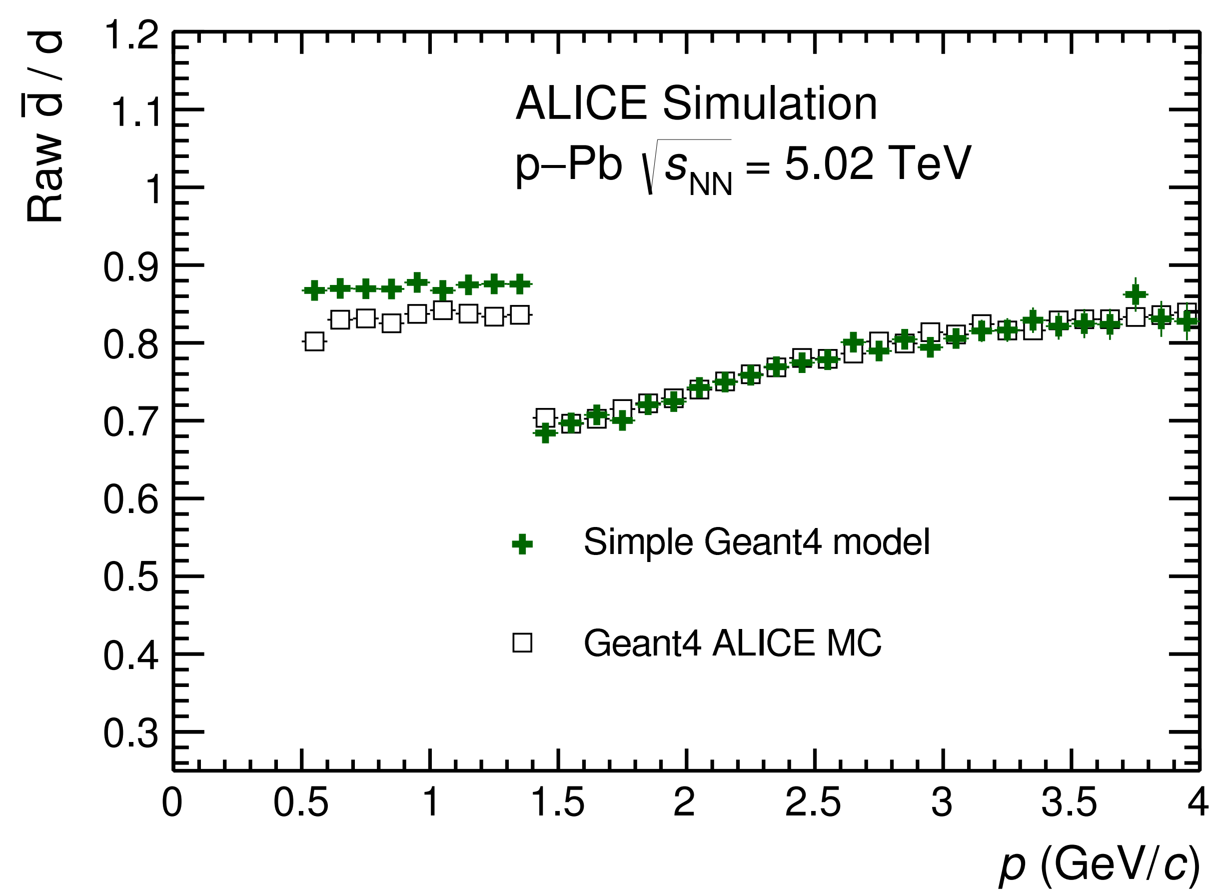


ALI-DER-324013



ALI-DER-324008

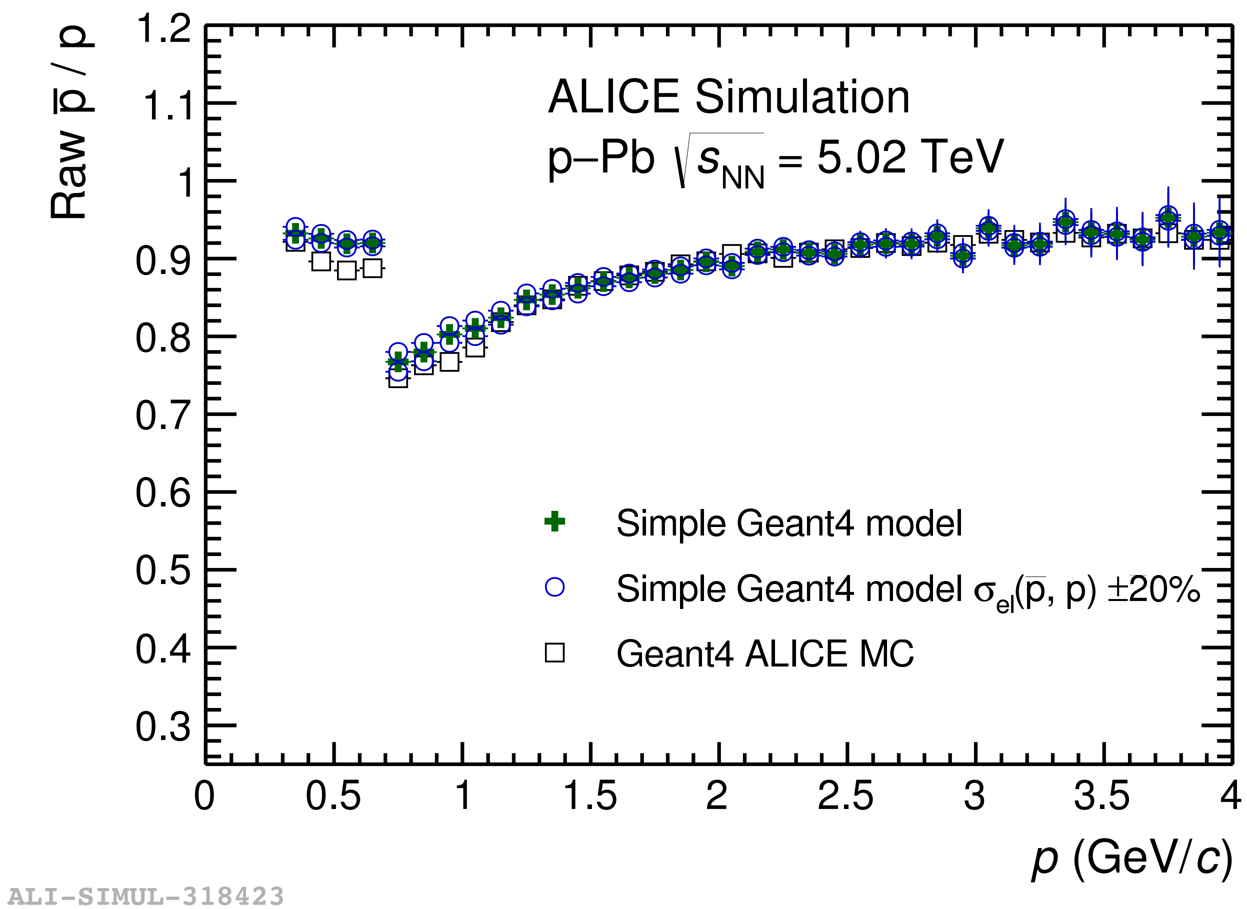
Variations of σ_{el} with simple Geant4 model

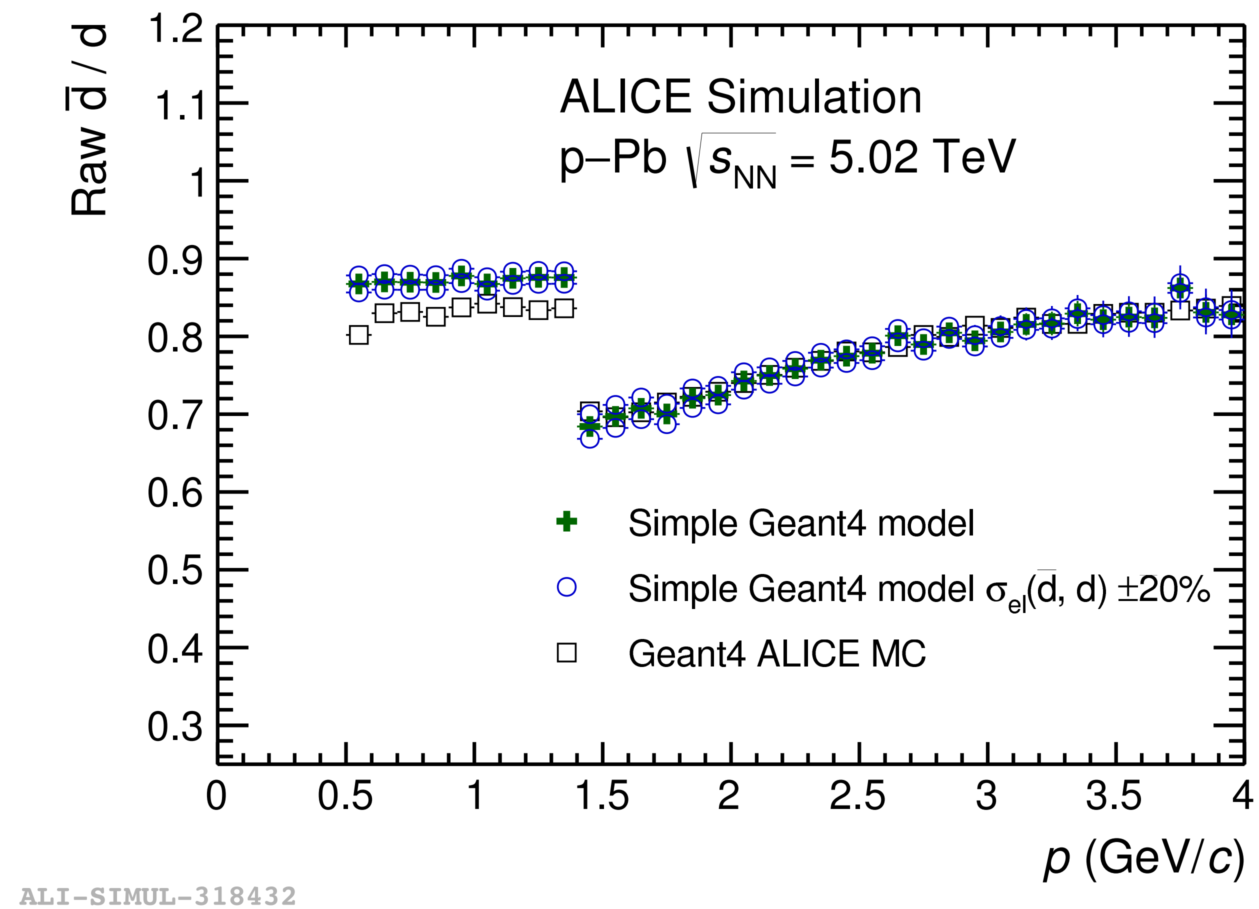
Vary each σ_{el} by ±20% in all combinations and check the final ratio

- 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)

Some disagreement between model and full-scale MC simulations at low *p*

- ***Constraints on $\sigma_{inel}(\bar{p})$ and $\sigma_{inel}(\bar{d})$ are extracted only for high p part***

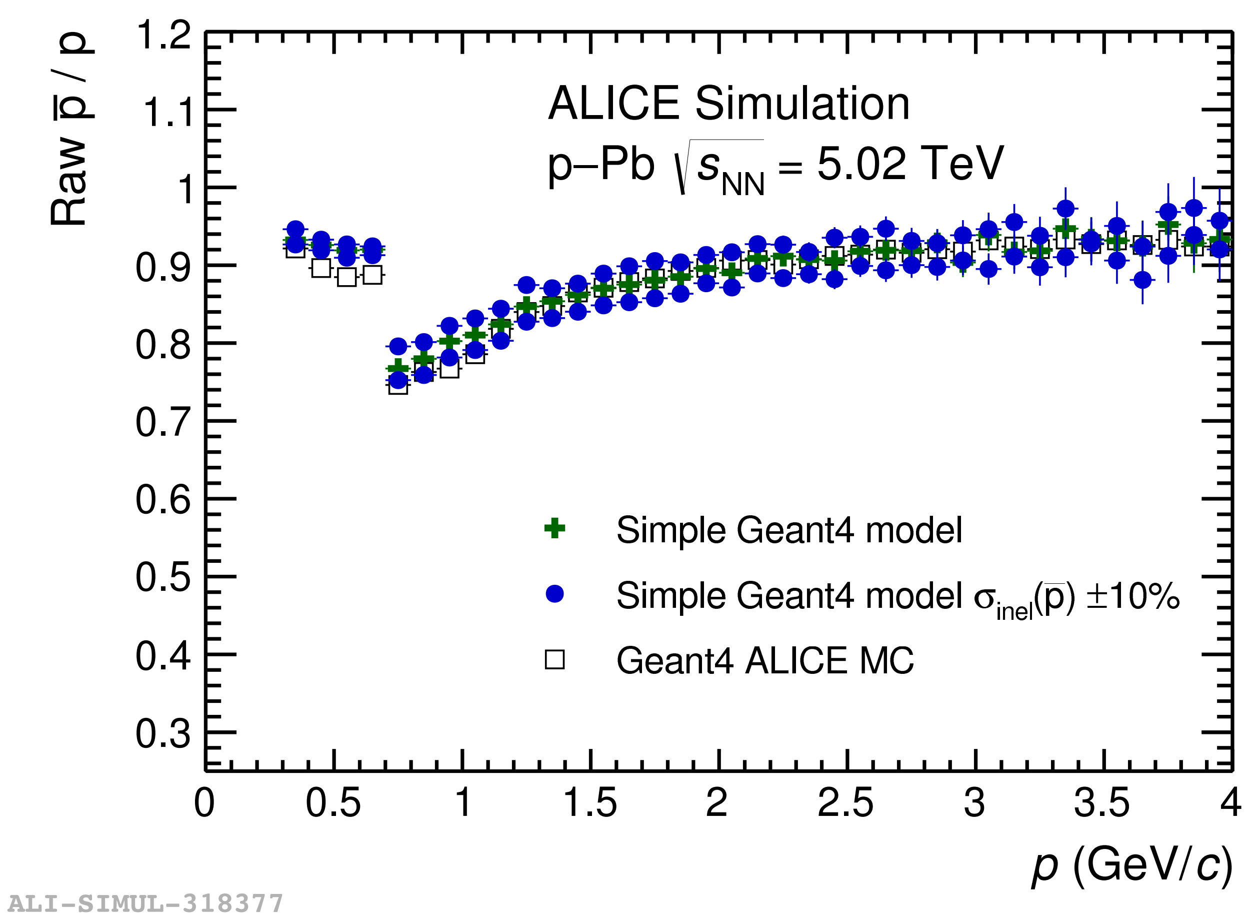


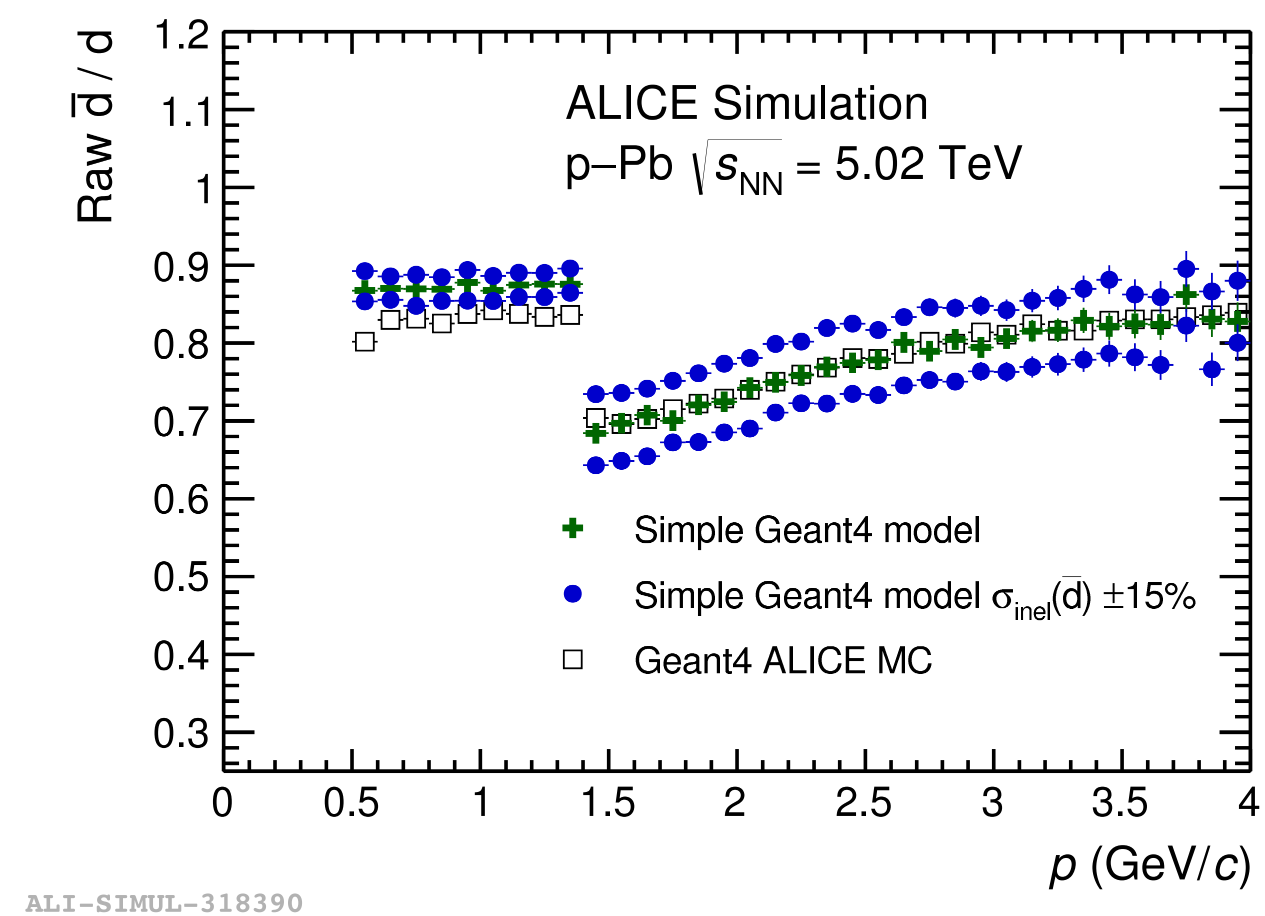


Variations of σ_{inel} with simple Geant4 model

Ratios are quite 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



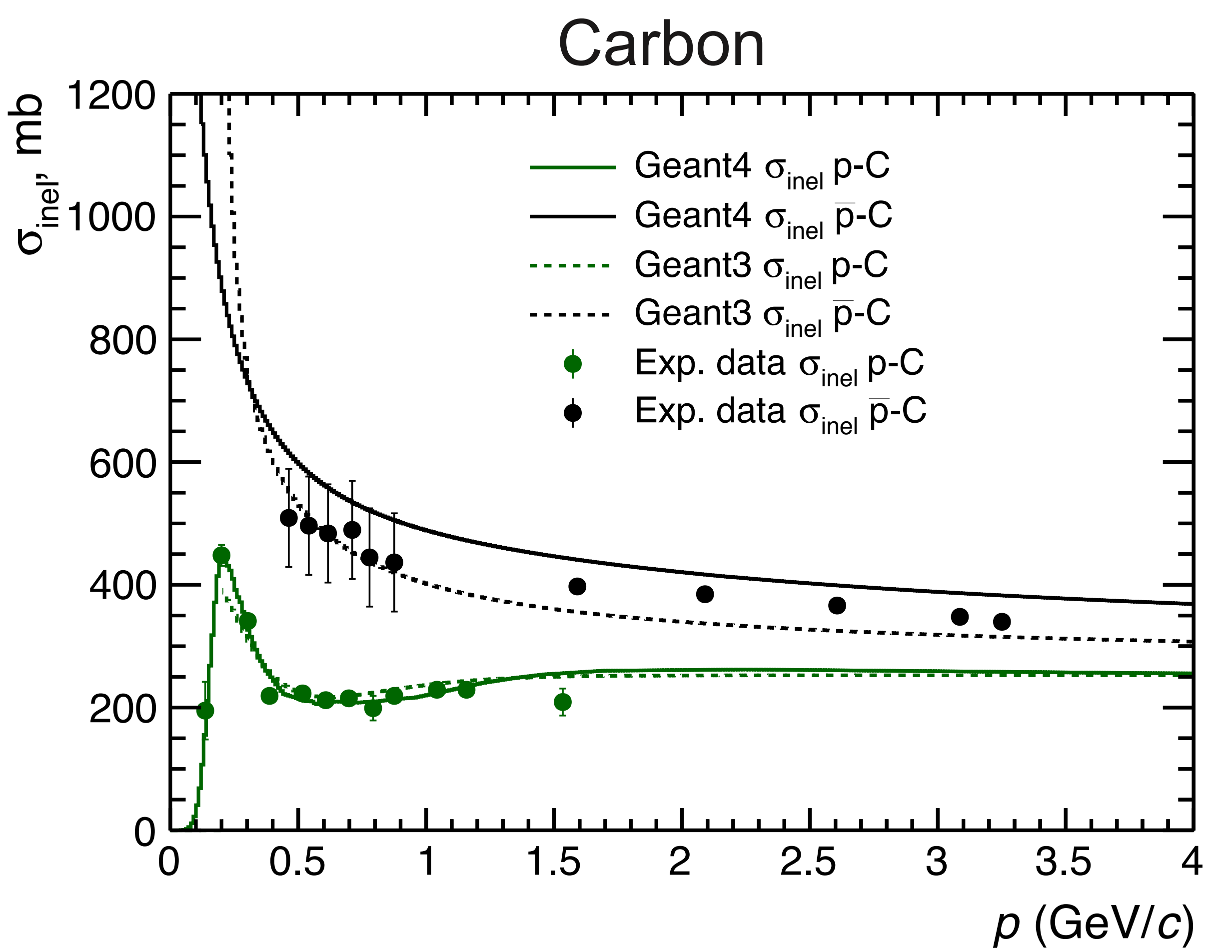


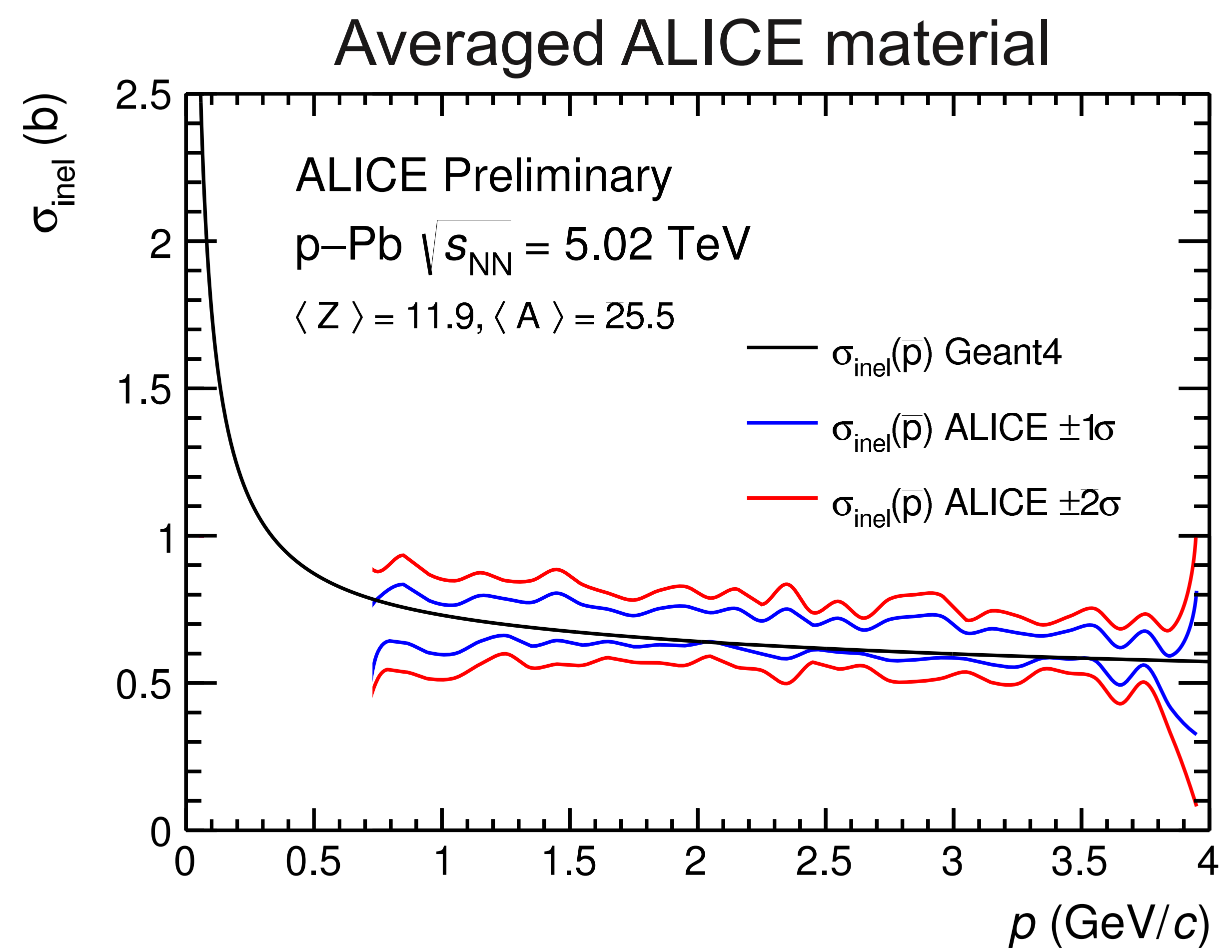
Constraints for σ_{inel} ($\bar{p}$) with ALICE material

Several measurements available for $\sigma_{inel}(\bar{p})$ on different materials

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

- <Z> = 11.9, <A> = 25.5 (from primary collision vertex to the TOF detector)
- Good agreement with Geant4 parameterisations





ALI-PREL-318444

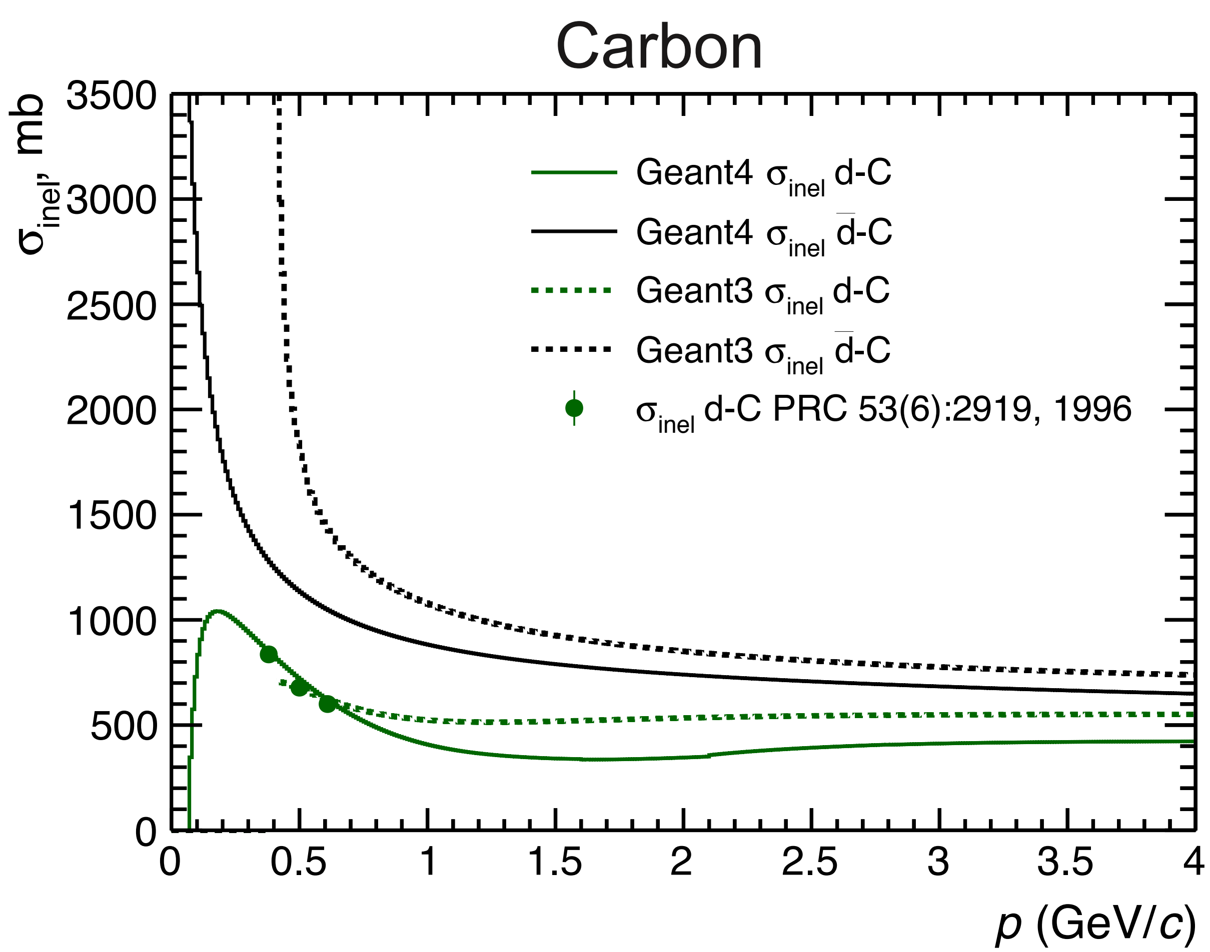
Constraints for σ_{inel} ($\bar{d}$) with ALICE material

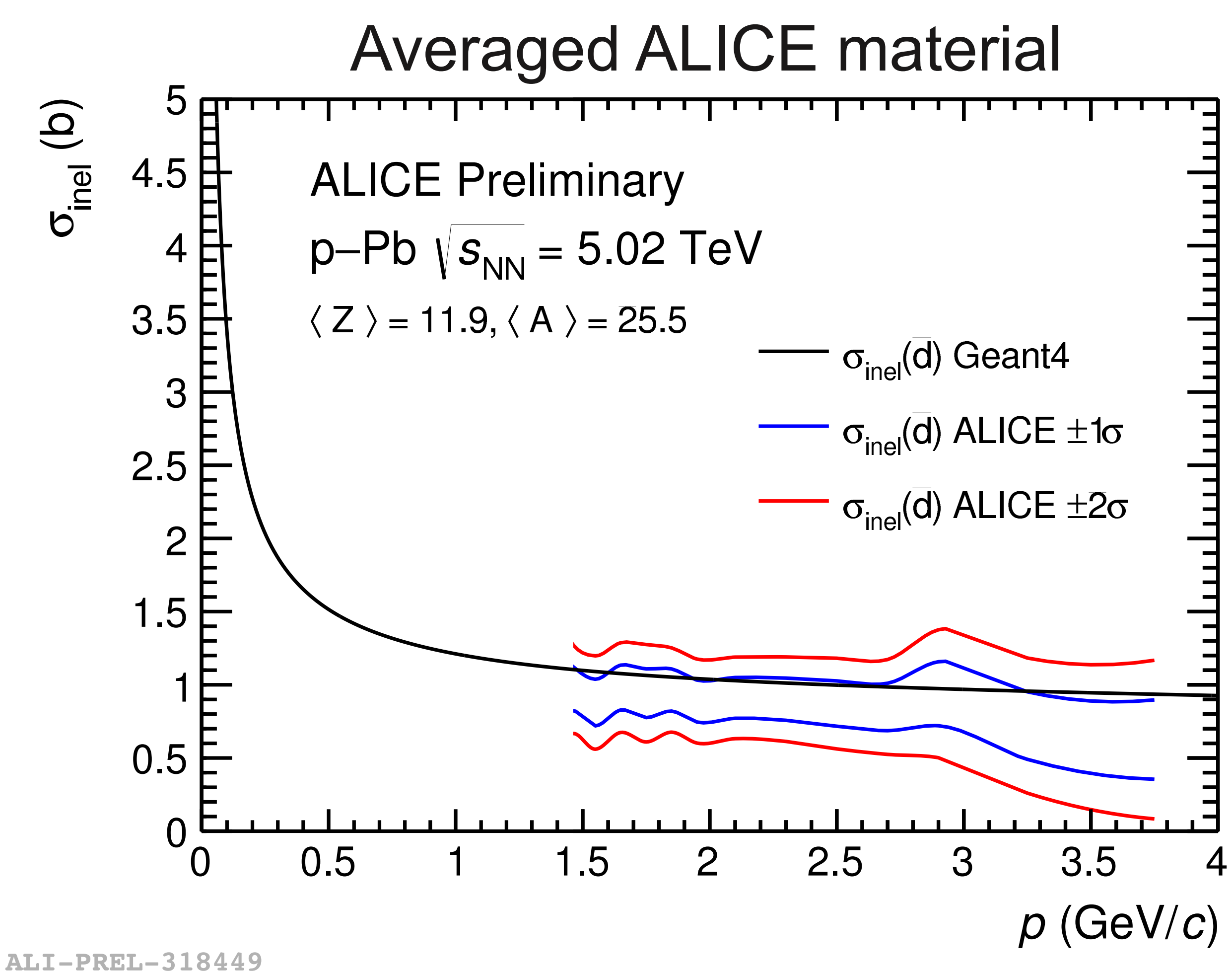
No experimental data for $\sigma_{inel}(\bar{d})$ for p < 13 GeV/c [1, 2]

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

- <Z> = 11.9, <A> = 25.5 (from primary collision vertex to the TOF detector)

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





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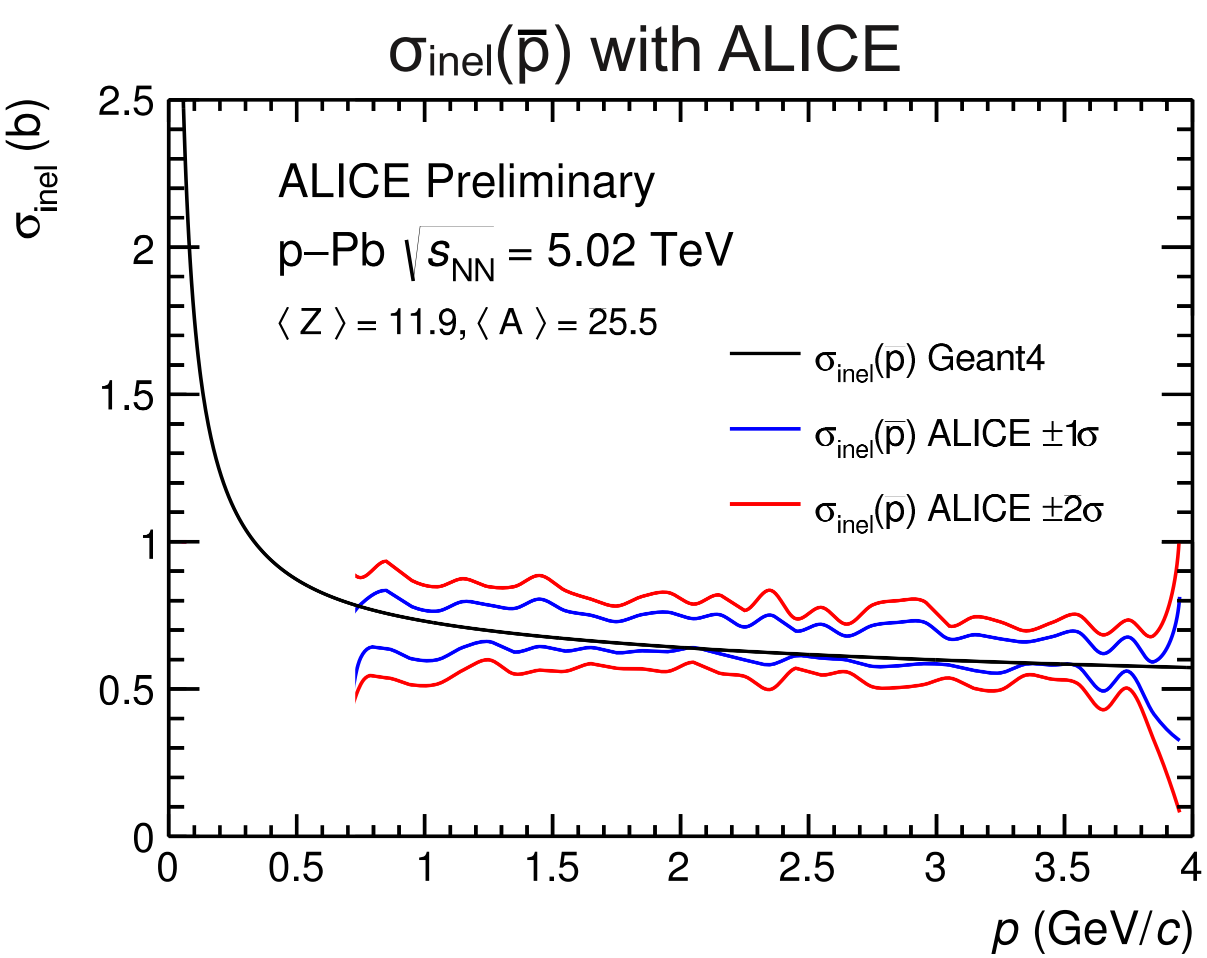
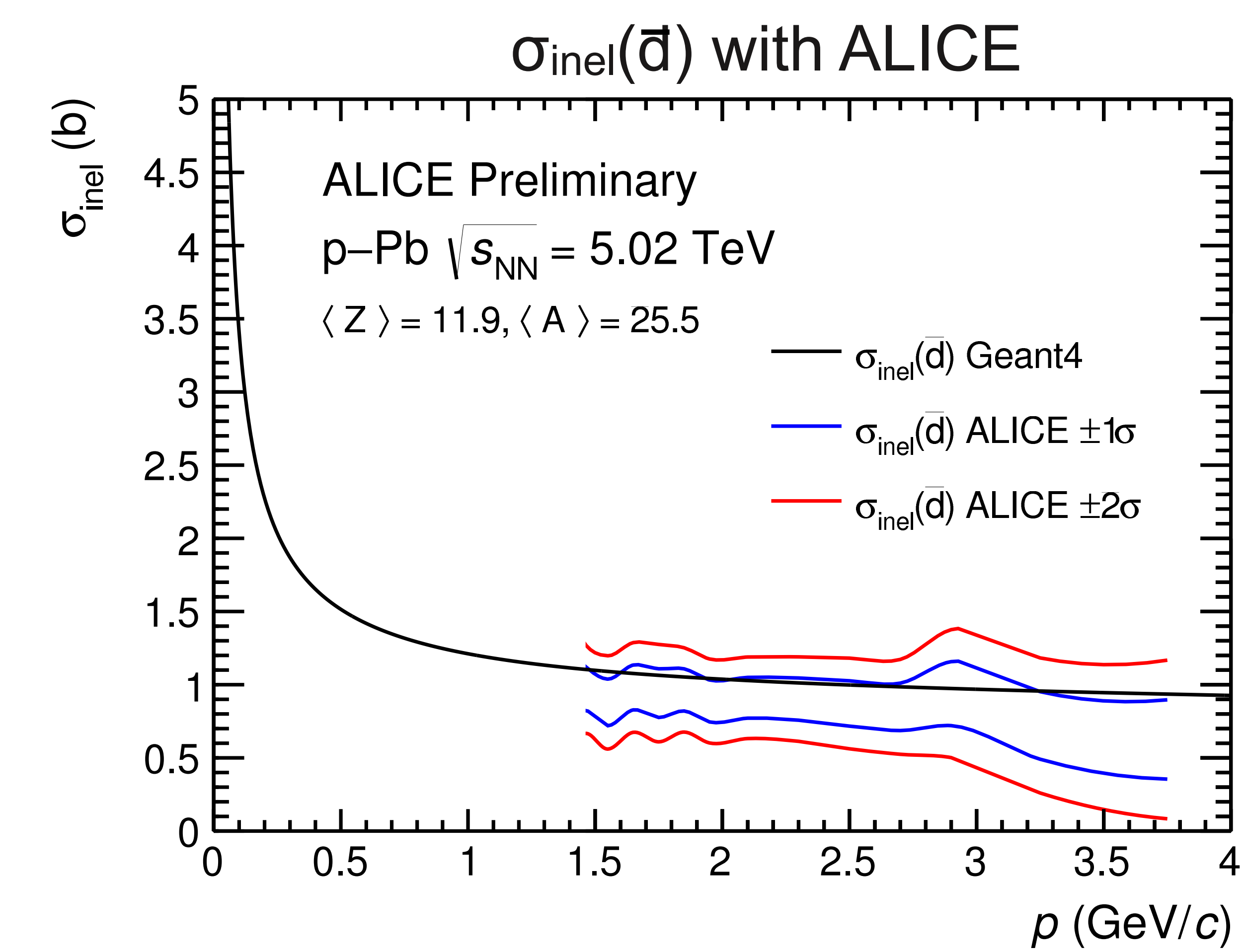
2) Phys. Let. B 31(4), 230 (1970)

Outlook for future analysis

- Improve statistical and systematic uncertainties on data for tighter constraints
- Push anti-deuteron analysis towards lower momentum
- Constrain $\sigma_{inel}(\bar{d})$ with full-scale ALICE Monte Carlo simulations
  - Input for cosmic ray propagation models!

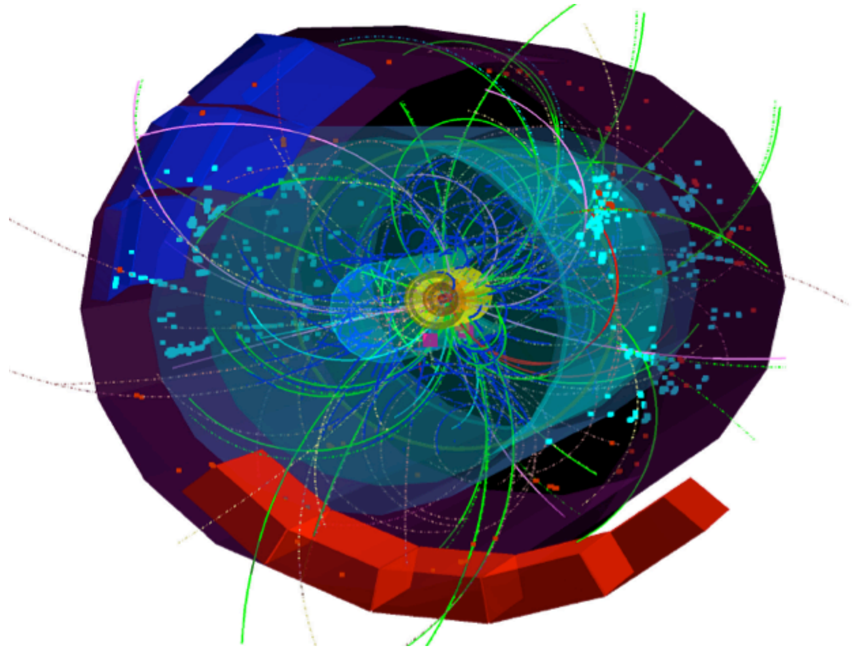




Summary and conclusion

Simulation of Galactic cosmic rays propagation with a chain of MC-based tools
- Good description of experimental proton flux near Earth
- Lack of precise anti-proton and anti-deuteron data (production, absorption)

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 simulations
  - Limits for $\sigma_{inel}(\bar{p})$ in good agreement with existing data
  - First experimental constraints on $\sigma_{inel}(\bar{d})$ in momentum range $1.4 < p < 4.0$ GeV/c



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Simulation of Galactic cosmic rays propagation with a chain of MC-based tools

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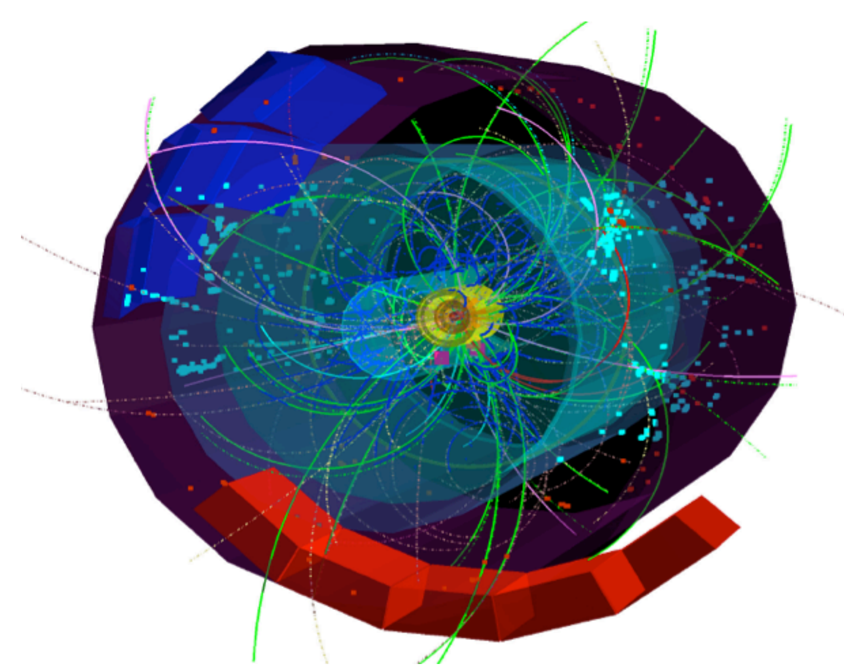
Thank you for your attention!

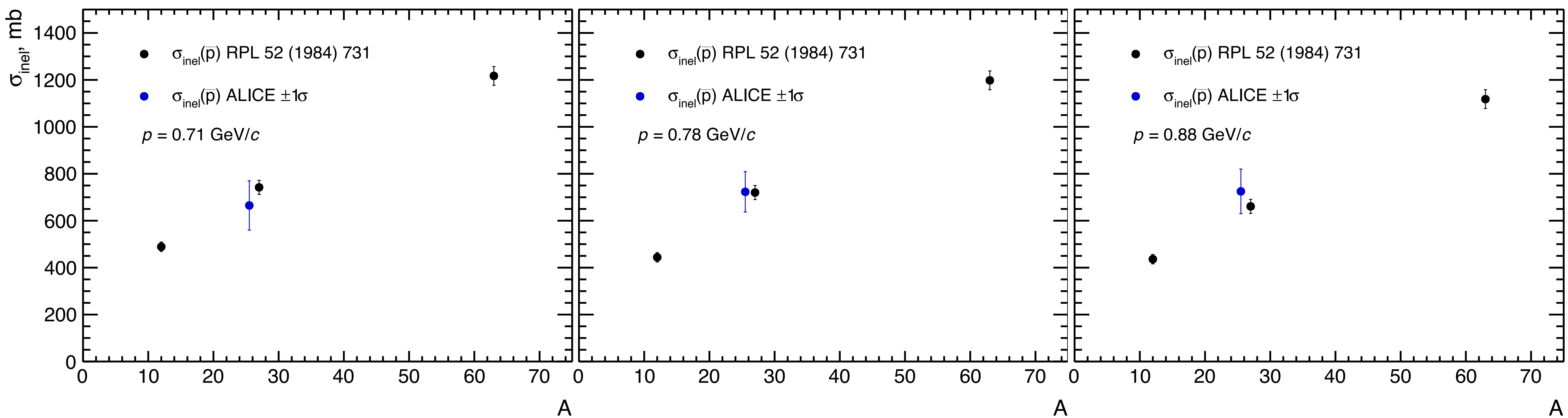


Back-up slides

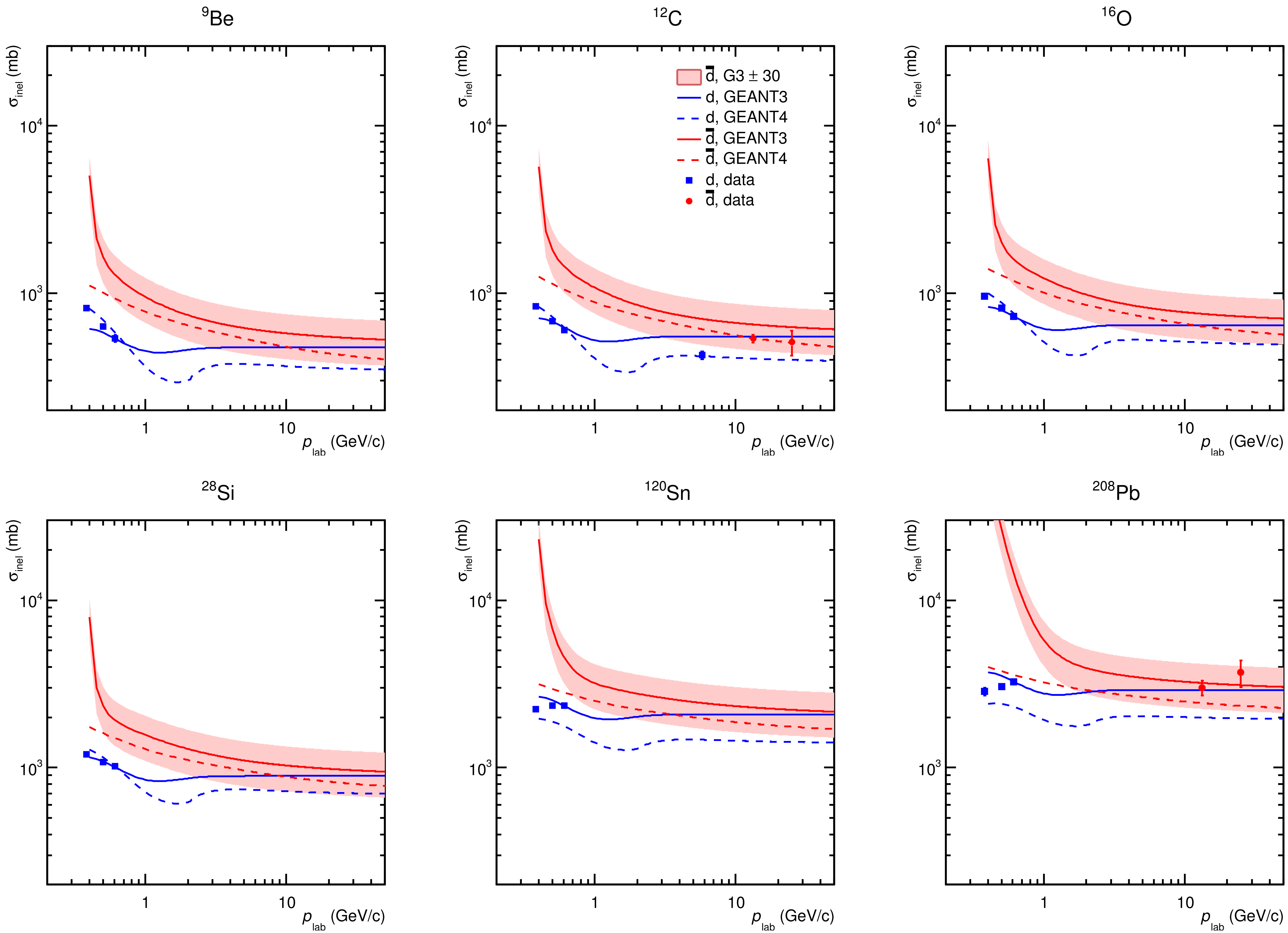
Comparison of ALICE results with existing data

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

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



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



GEANT3 inelastic cross-sections

- Empirical parametrization based on Moiseev's formula:

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

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

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

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

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

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

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

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

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

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

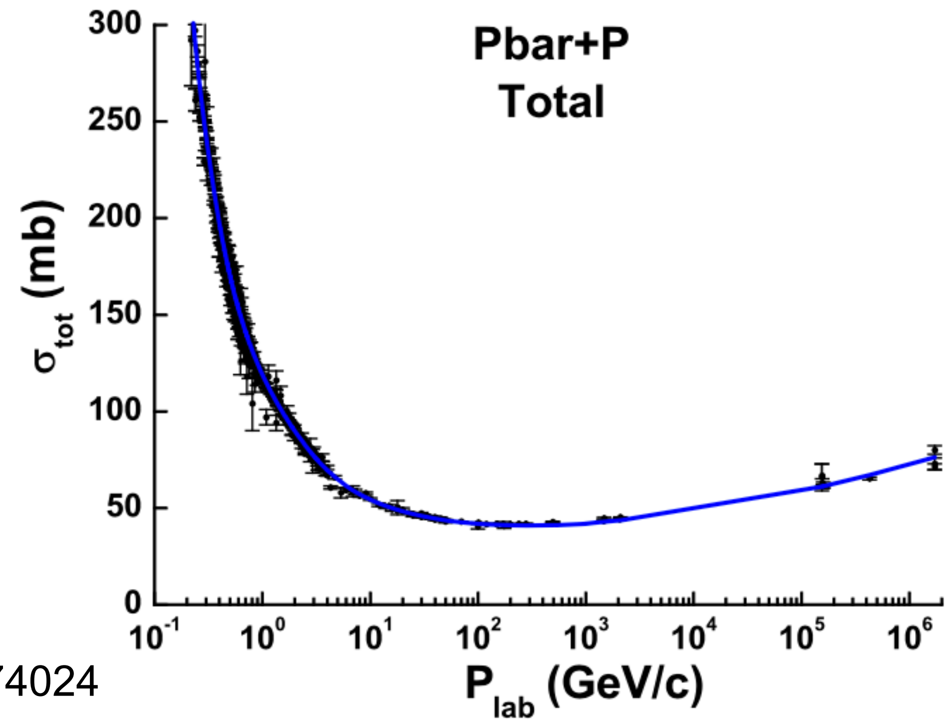
Parameters C, d_1, d_2 and d_3 are determined from fit to exp. data [PDG]

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

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

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

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



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

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

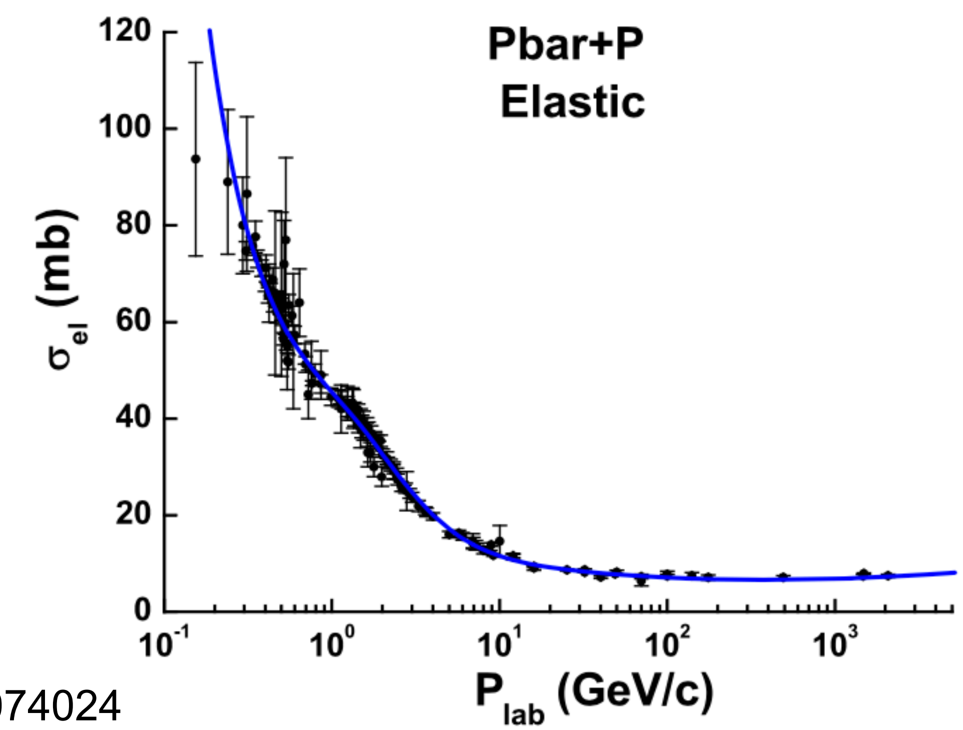
$$\sigma_{asmpt}^{el} = 4.5 + 0.101 \ \left(log(s/33.0625)\right)^2$$

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

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

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

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



1. J.R. Cudell, et al., COMPLETE Collaboration, Phys. Rev. D 65 (2002) 074024
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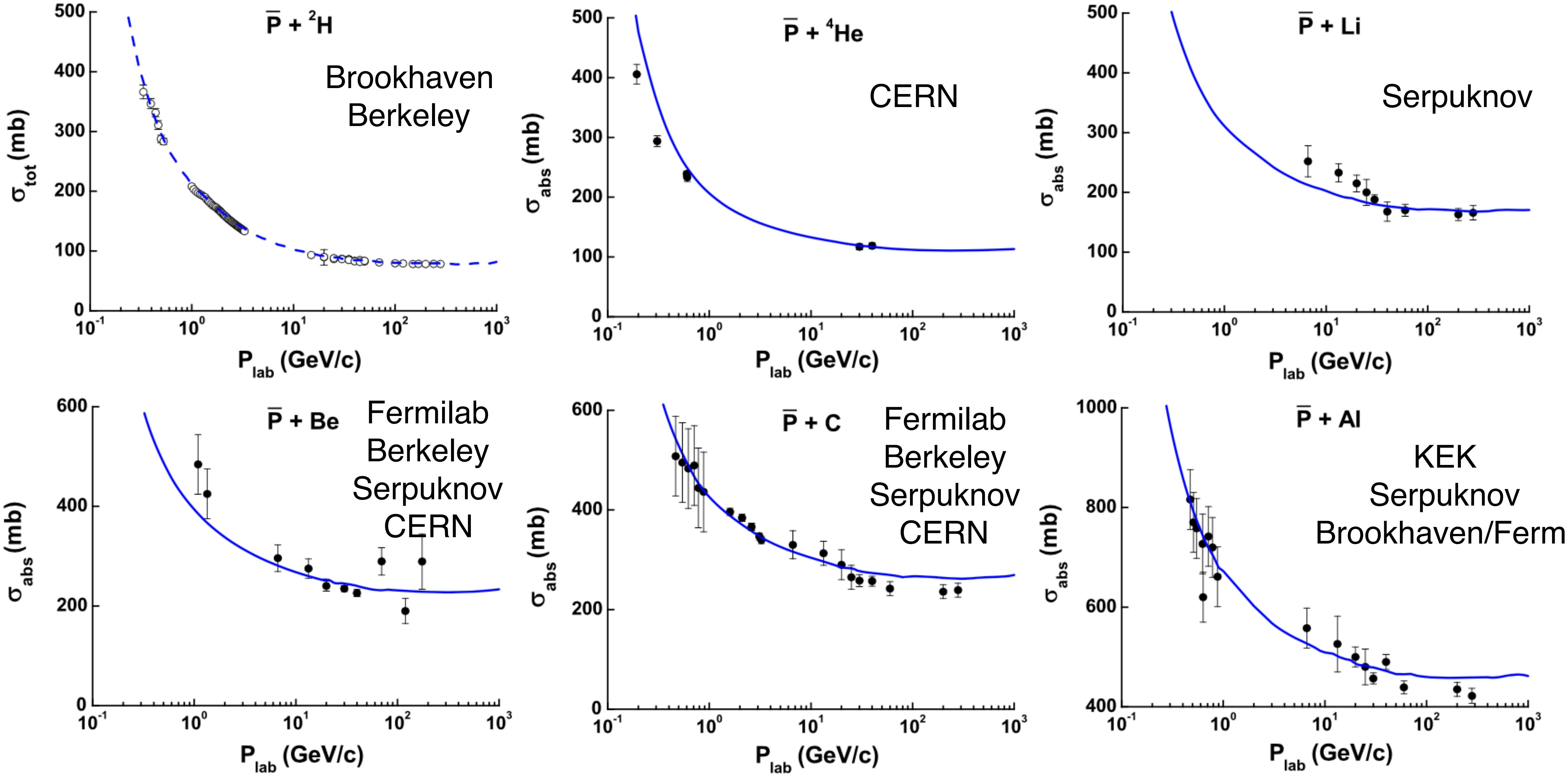
3. A.A. Arkhipov, hep-ph/9909531, hep-ph/9911533, 1999

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] :

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

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

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:

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

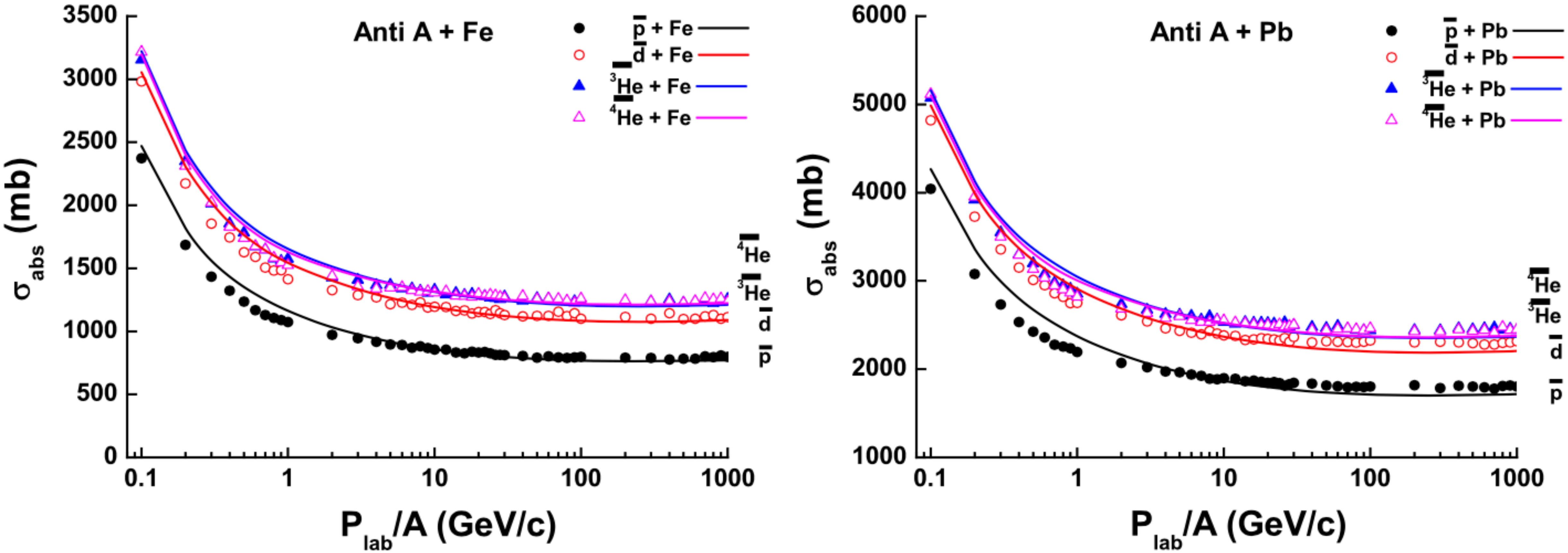
For inelastic cross-section:

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

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

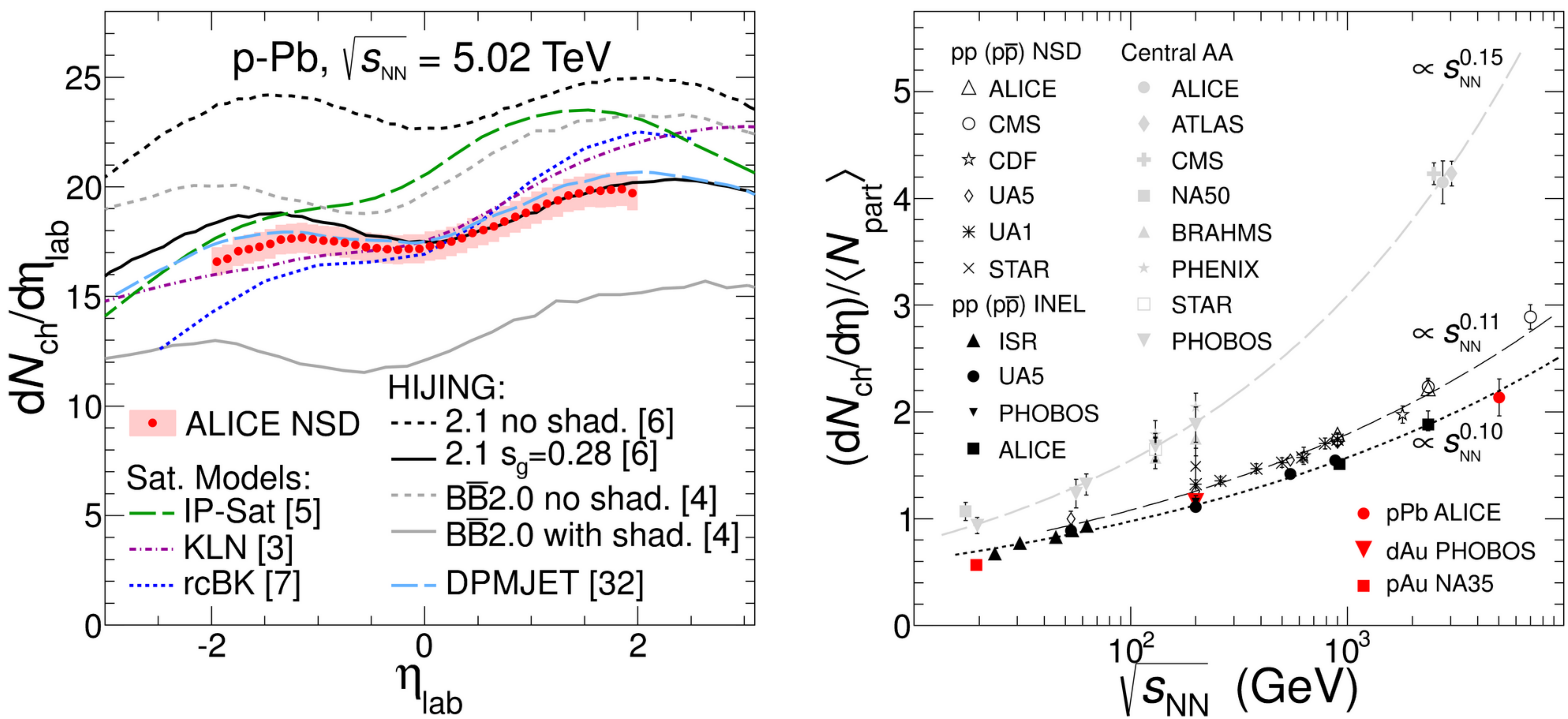
Geant4: antih-A and antiB-A cross-sections

Points are Glauber calculation, lines are GEANT4 parametrisation



Particle production at LHC energies

ALICE, Phys. Rev. Lett. 110 (2013) 032301

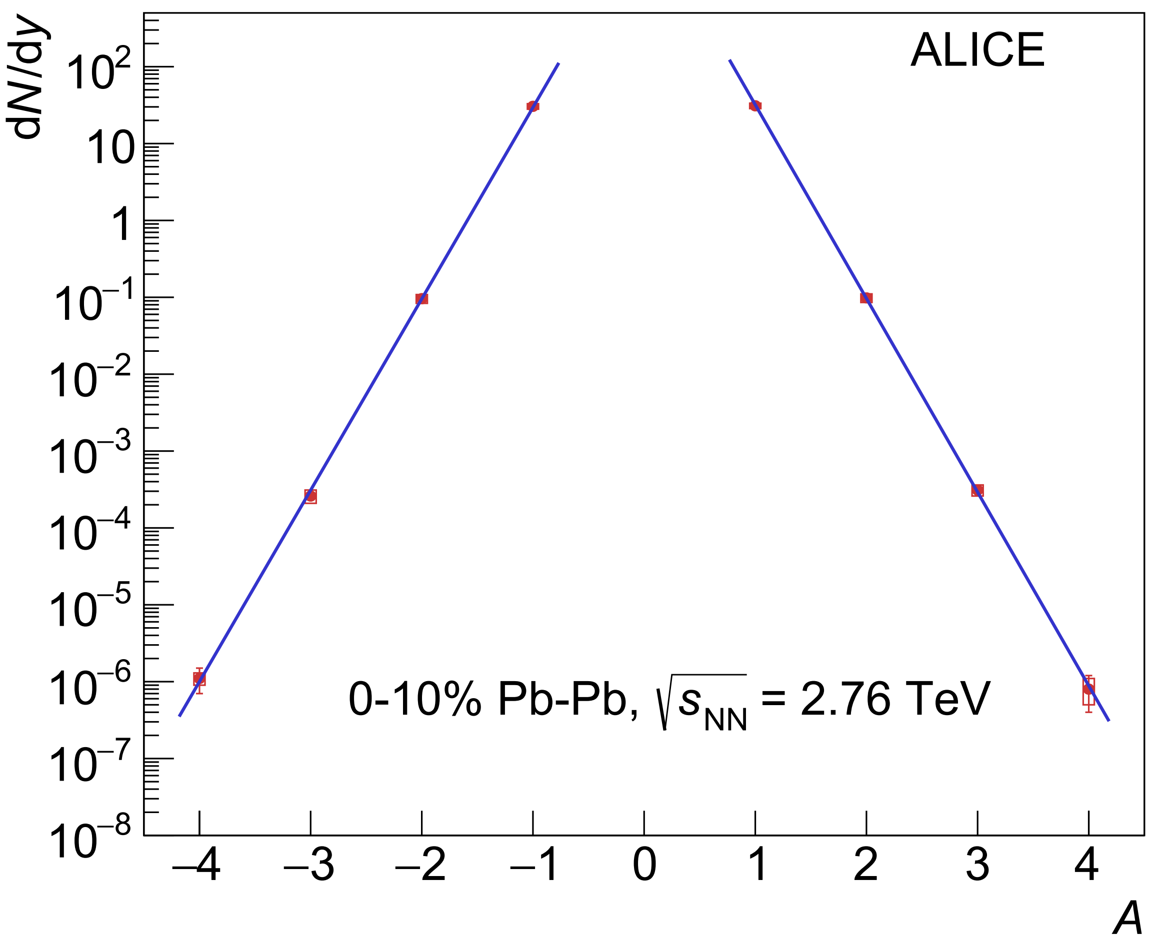


Light (anti-)nuclei at LHC

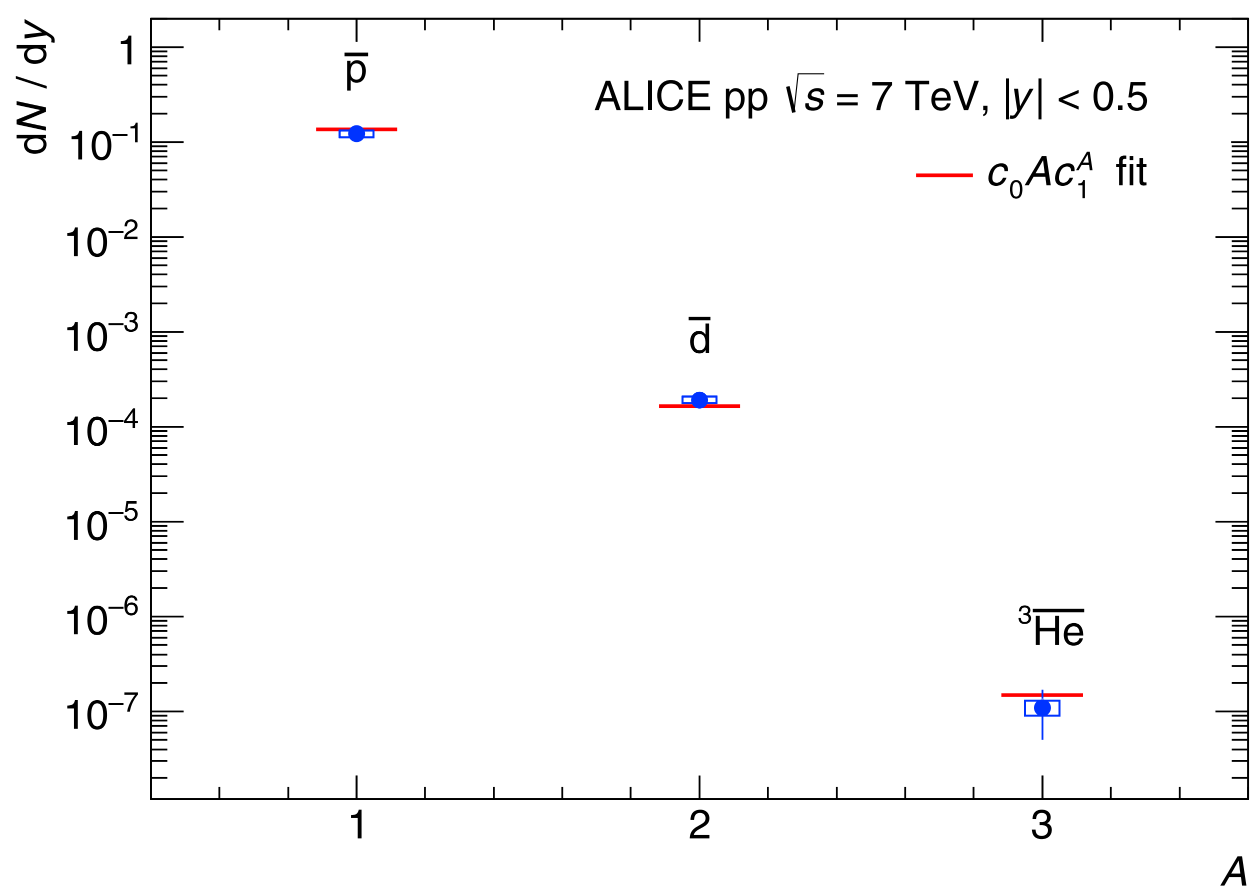
Light (anti-) nuclei up to A =4 are reachable with the currently available statistics
Penalty factor to produce one additional nucleon:

- ~ 350 in central PbPb collisions
- ~ 1000 in pp collisions

ALICE, Nuclear Physics A 971 (2018) 1

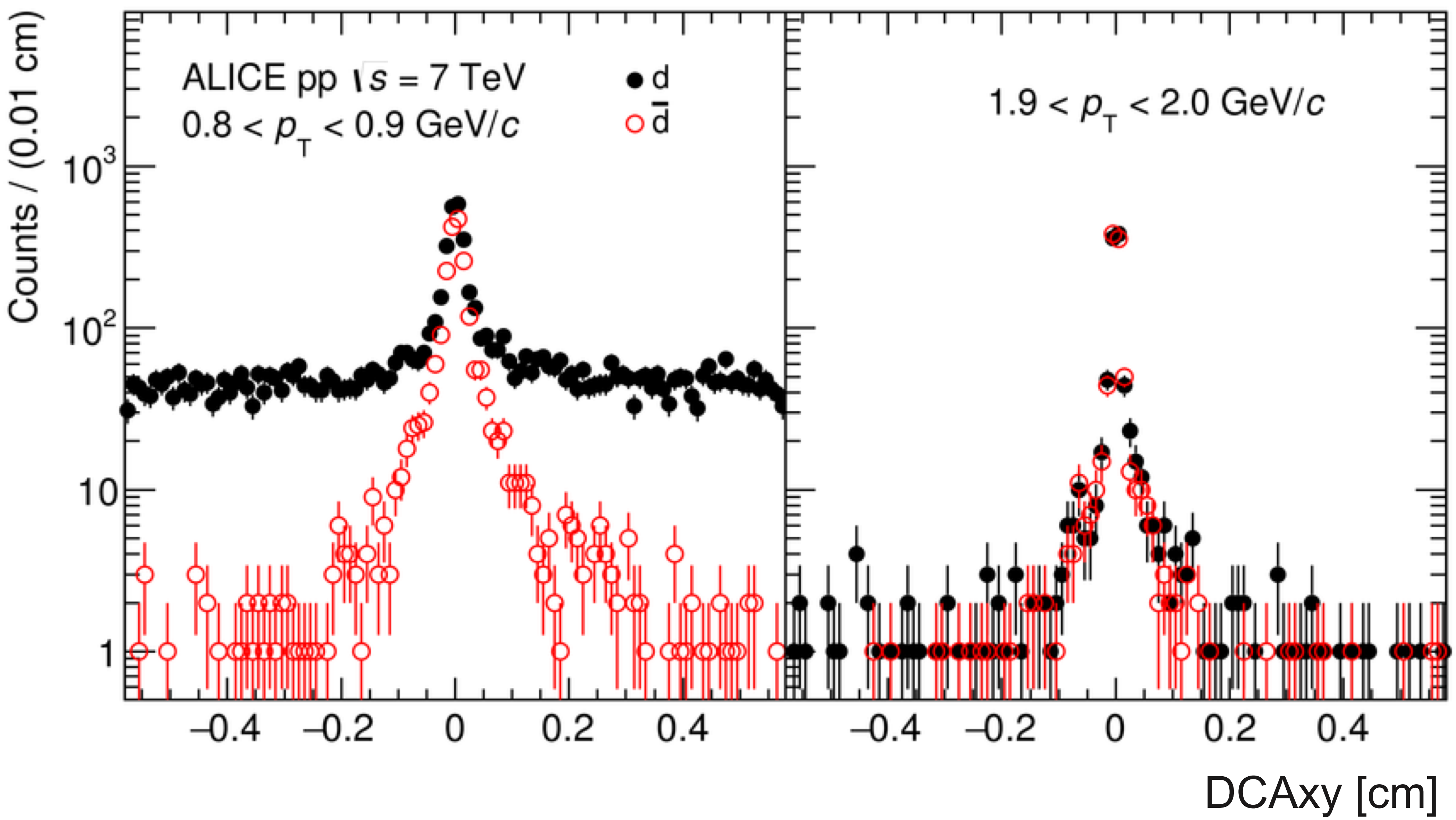


ALICE, PRC 97 (2018) 024615



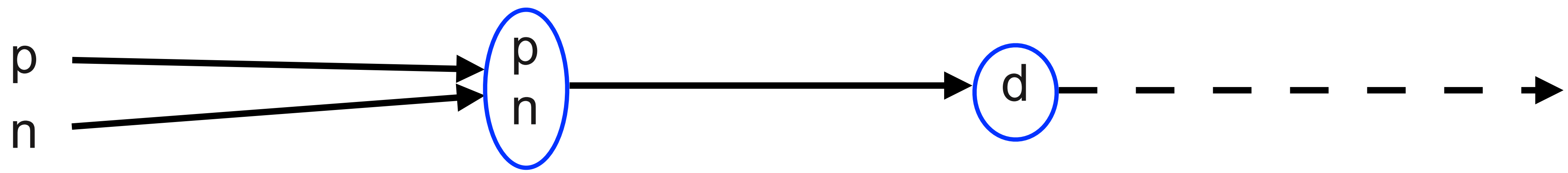
Deuterons from spallation processes

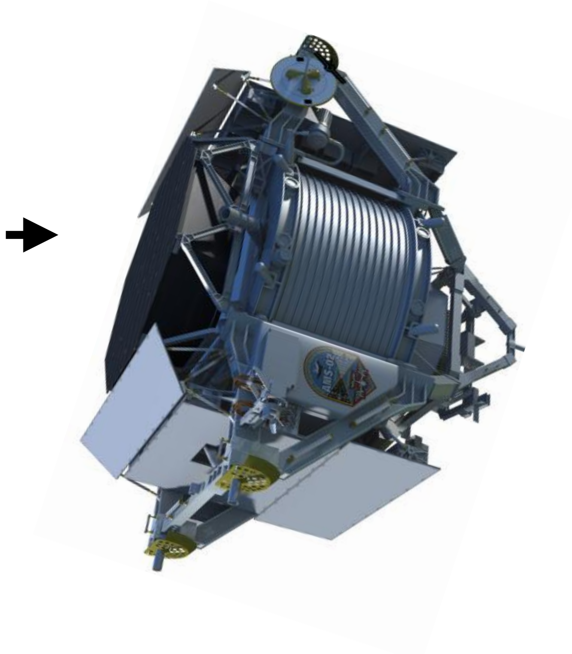
ALICE, Phys. Rev. C 97 (2018) 024615



Coalescence model for (anti-)deuteron production

- Basic idea: if $\Delta p < p_0$, (anti)proton and (anti)neutron will coalesce to form (anti)d
- p_0 is the only free parameter of this phenomenological model





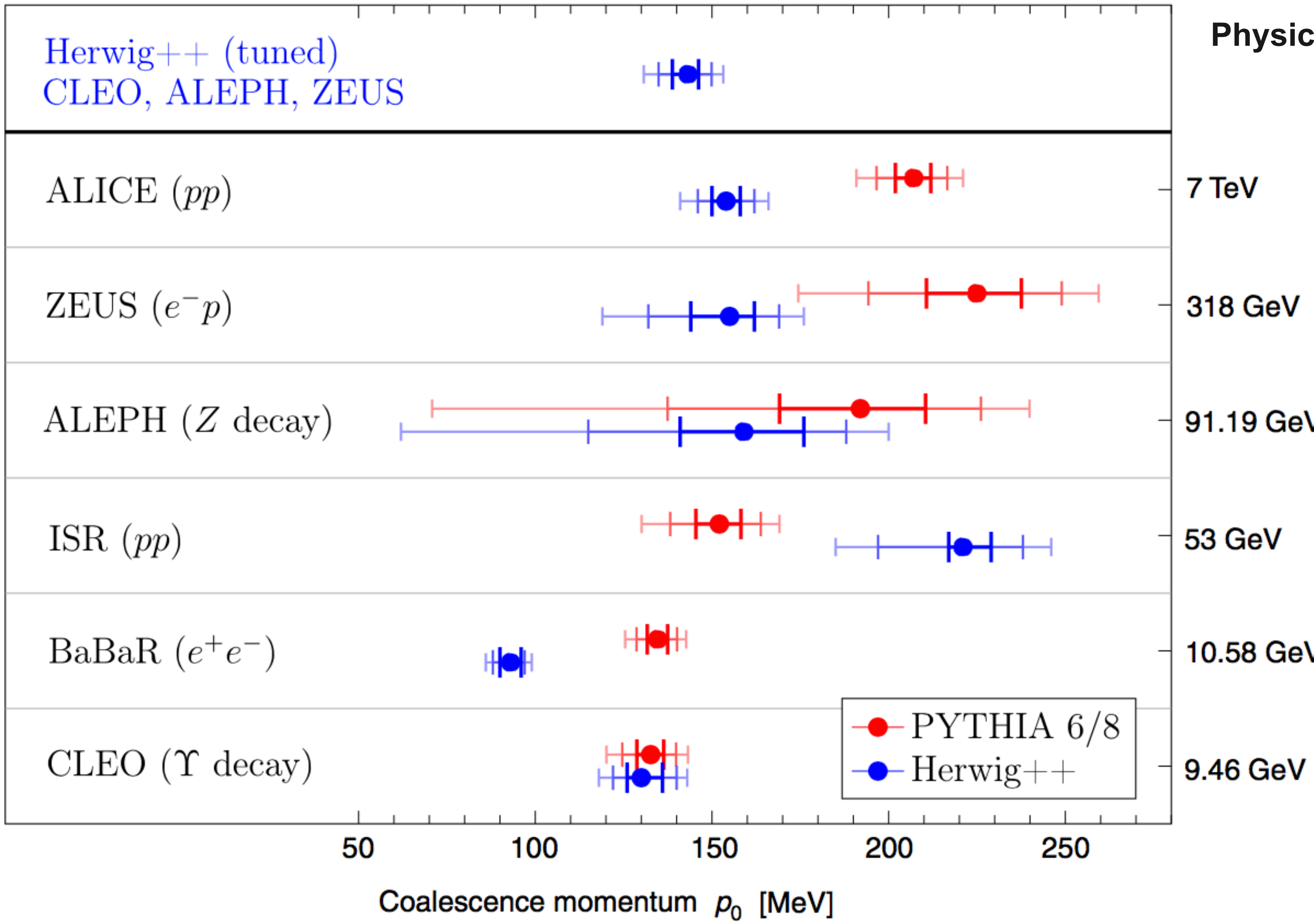
Simplest assumption: isotropic and uncorrelated nucleon spectra

- deuteron ~ proton x neutron => deuteron ~ proton^2
- Maximum momentum difference (p_0) is approx. 100 MeV (5.3 MeV kinetic energy of a nucleon in the rest frame of the other)

$$E_{\mathrm{d}} \frac{\mathrm{d}^3 N_{\mathrm{d}}}{\mathrm{d}p_{\mathrm{d}}^3} = B_2 \left(E_{\mathrm{p}} \frac{\mathrm{d}^3 N_{\mathrm{p}}}{\mathrm{d}p_{\mathrm{p}}^3} \right)^2$$

Can be implemented as an afterburner in event generators

Determination of p_0 from fits to data

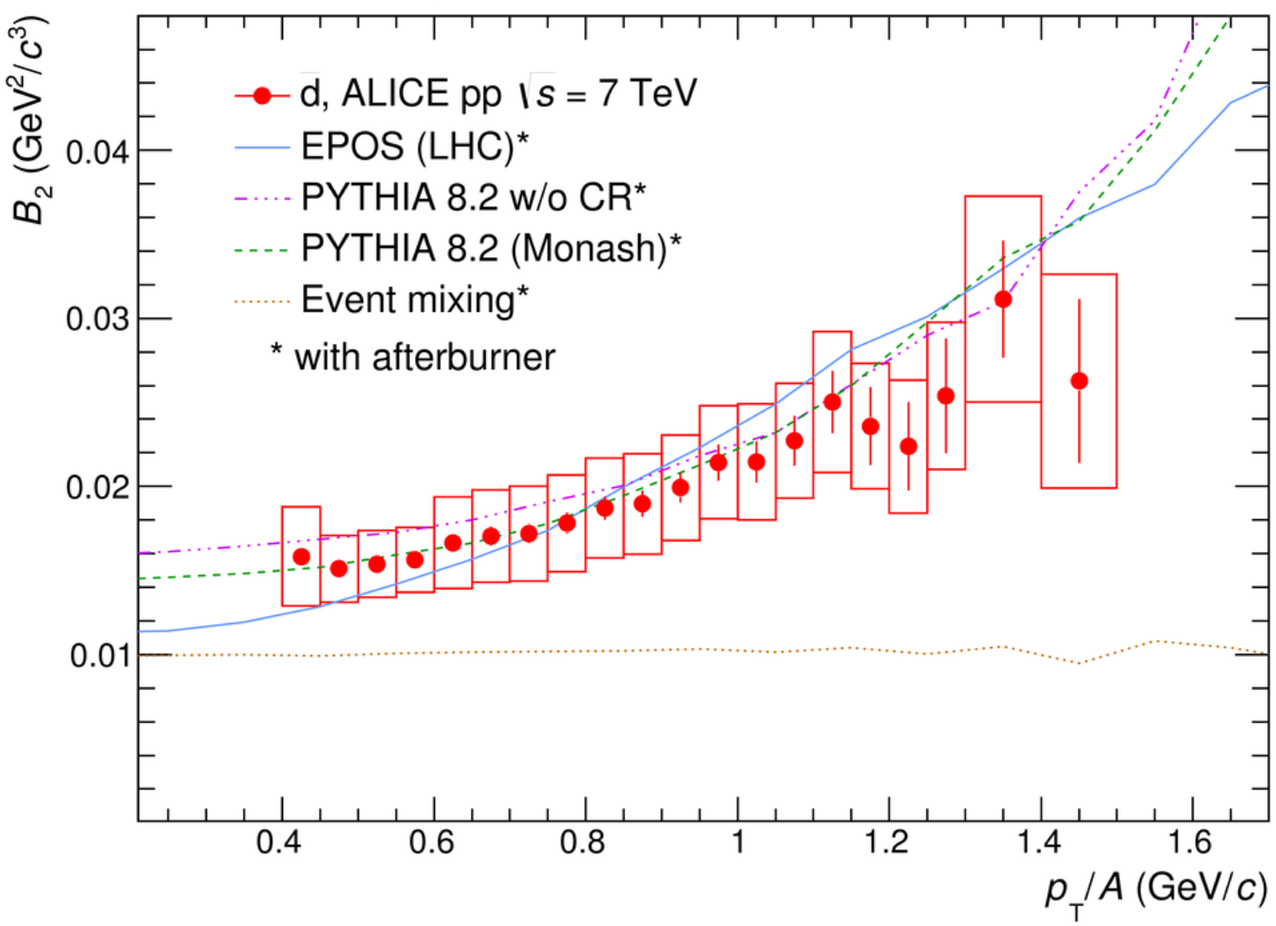


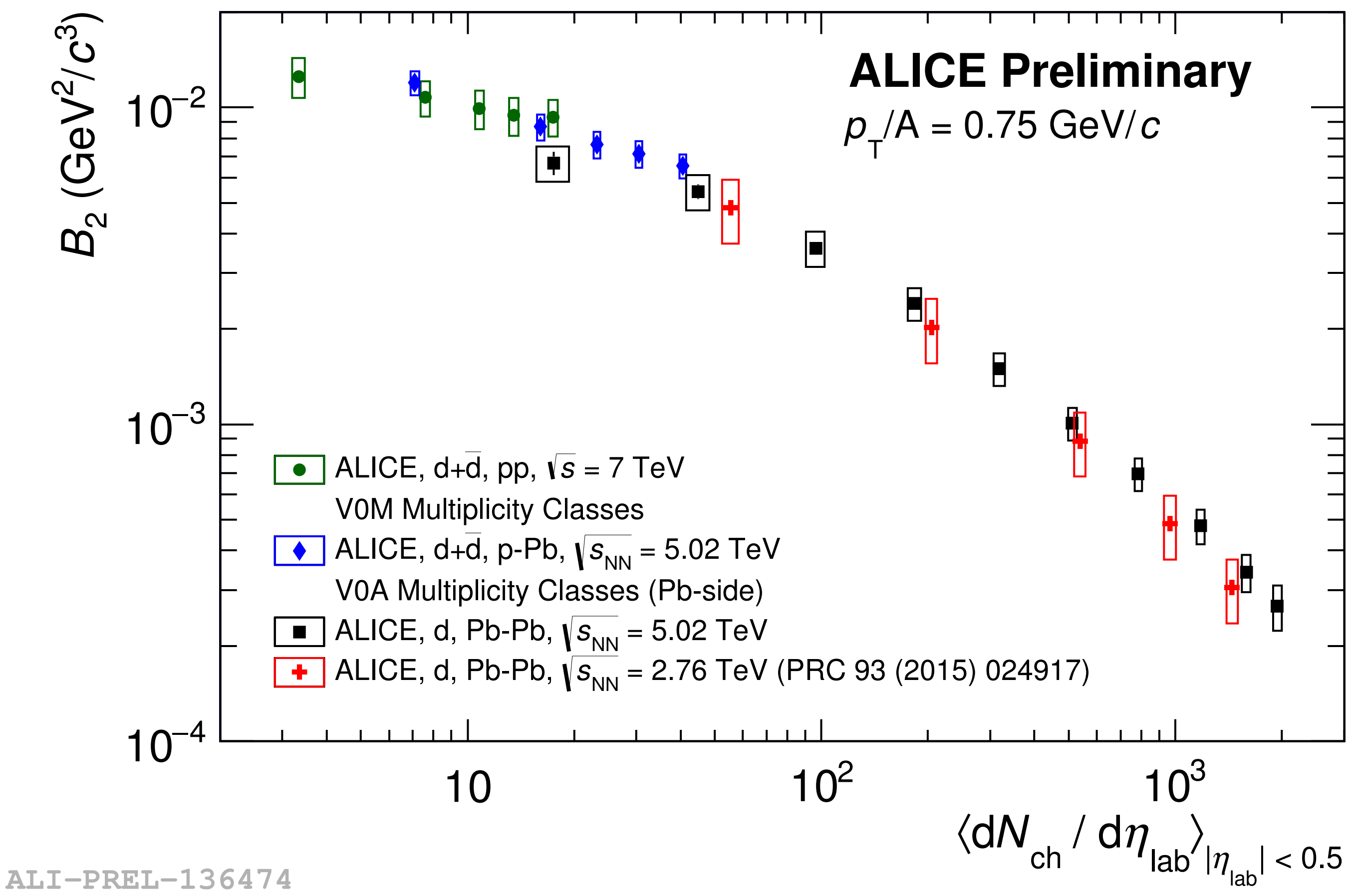
Physics reports 618, 1 (2016)

- Which p_0 value should be used in calculations of anti-d flux from DM?…
- Does anti-d production depend on √s and/or underlying process or MC needs further refinements?…
- Dramatic effect on final uncertainty, $N_d \sim p_0^3$! (also holds well for per-event MC)

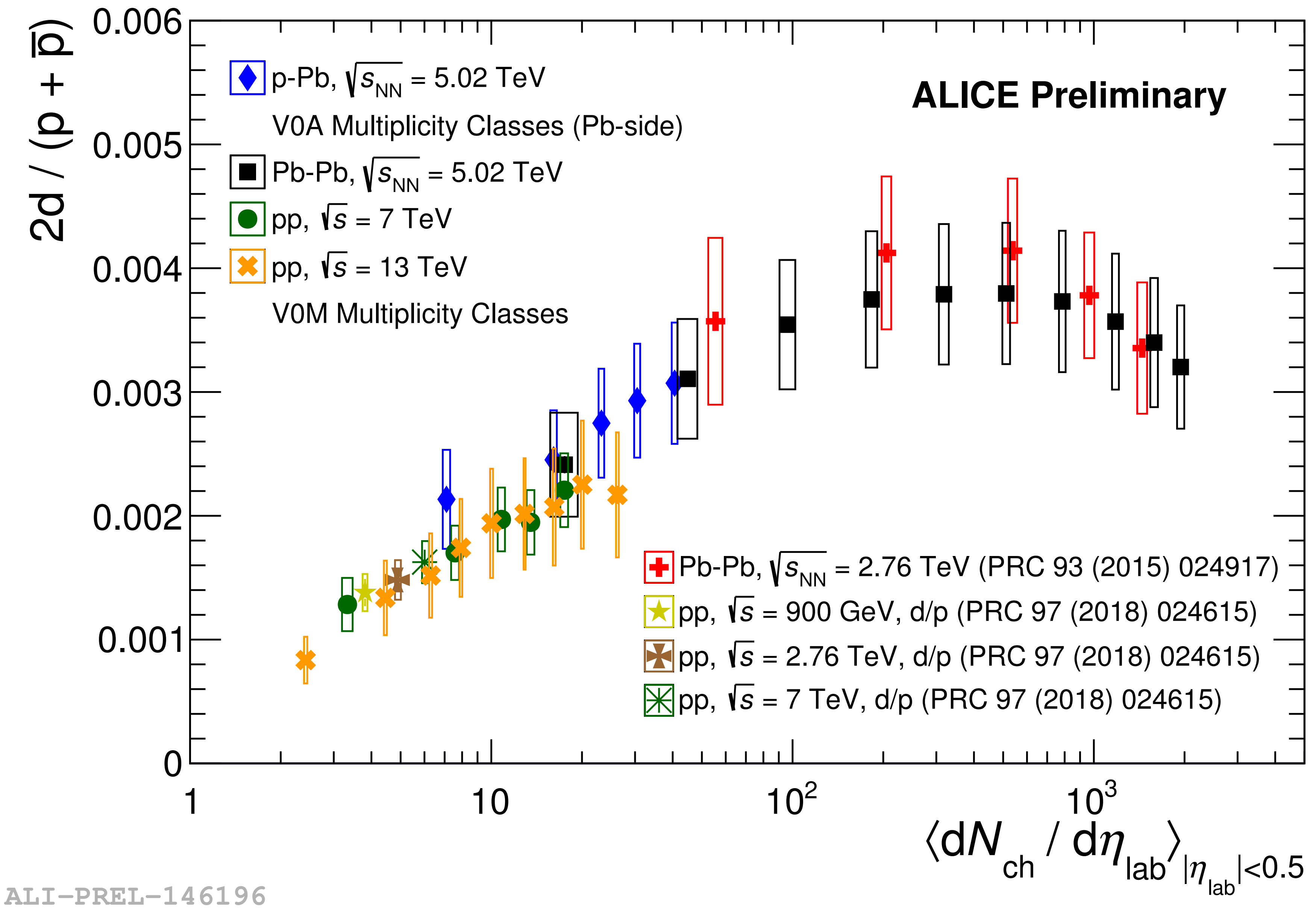
Coalescence parameter B_2

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





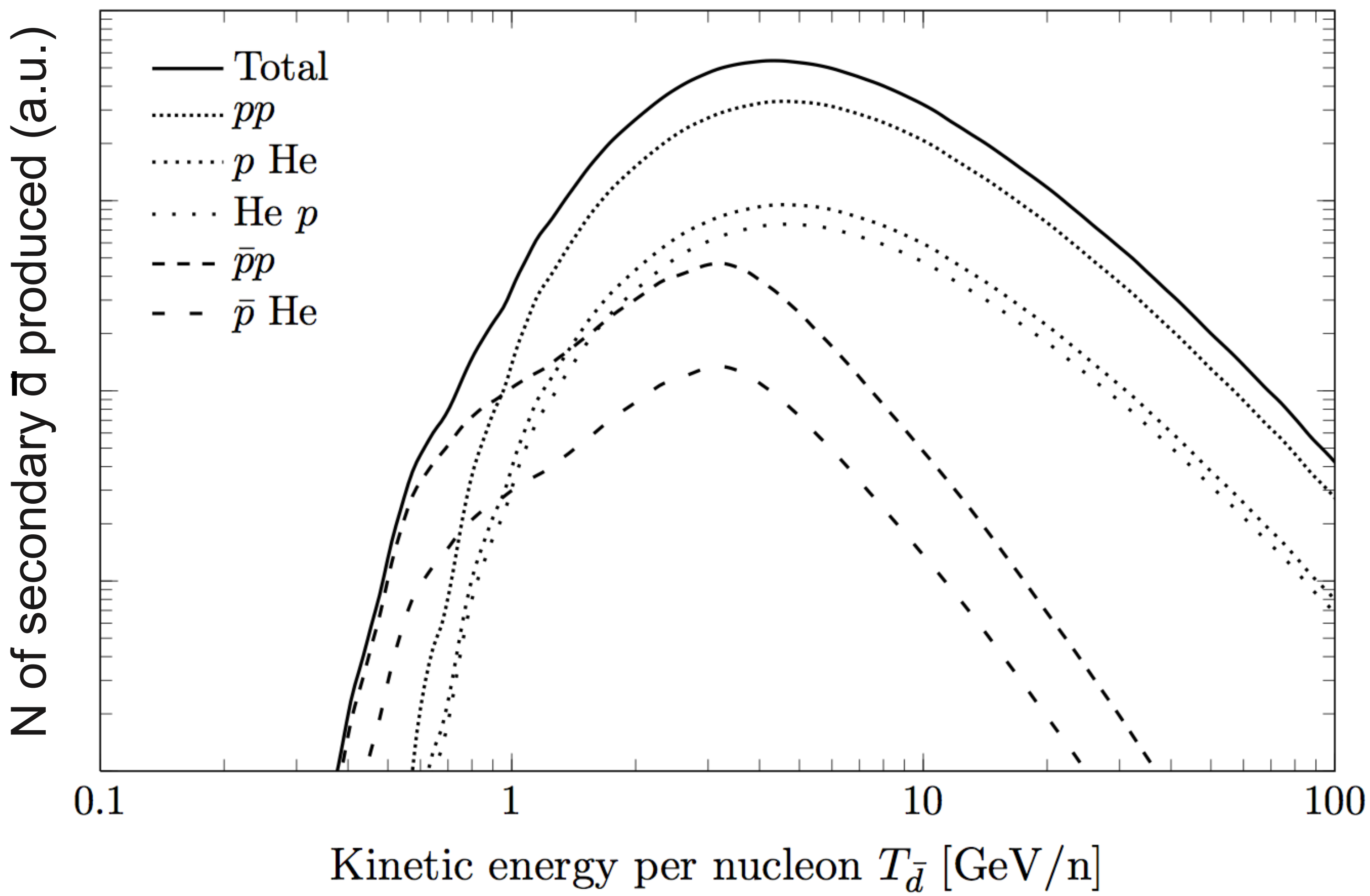
Deuteron to proton ratio



- d/p increases with multiplicity from pp to peripheral Pb-Pb: consistent with simple coalescence
- No significant centrality dependence in Pb-Pb: consistent with thermal model (yield fixed by T_{chem} as ~exp(-m/T_{chem}))

Background sources for d̄

Dominant source: cosmic-ray particles interacting with interstellar medium



Physics reports 618, 1 (2016)

At low energies the background is highly suppressed

- High threshold E for d̄ production (e.g. for pp→d̄X it's E_{thr} = 16 m_N)
- Steep energy spectrum of cosmic rays

For d̄ flux at TOA at T_d ~ 0.1 to 1 GeV/n different DM models give **S/B ~ 10^2 to 10**

- Despite large S/B still a rare event search!

$\bar{d}$ propagation through the Universe

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:

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

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:

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

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

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

Prospects for DM detection

Left: DM annihilation/decay from 3 benchmark models

- MED propagation, coalescence model with p_0 = 195 MeV

Right: annihilation of heavy ($m_{DM} \gtrsim 0.5$ TeV) DM

- MAX propagation, annihilation into bb or W^+W^- (Wino DM)

Sensitivities: 5 years of operation for AMS-02, three 35-days flights for GAPS

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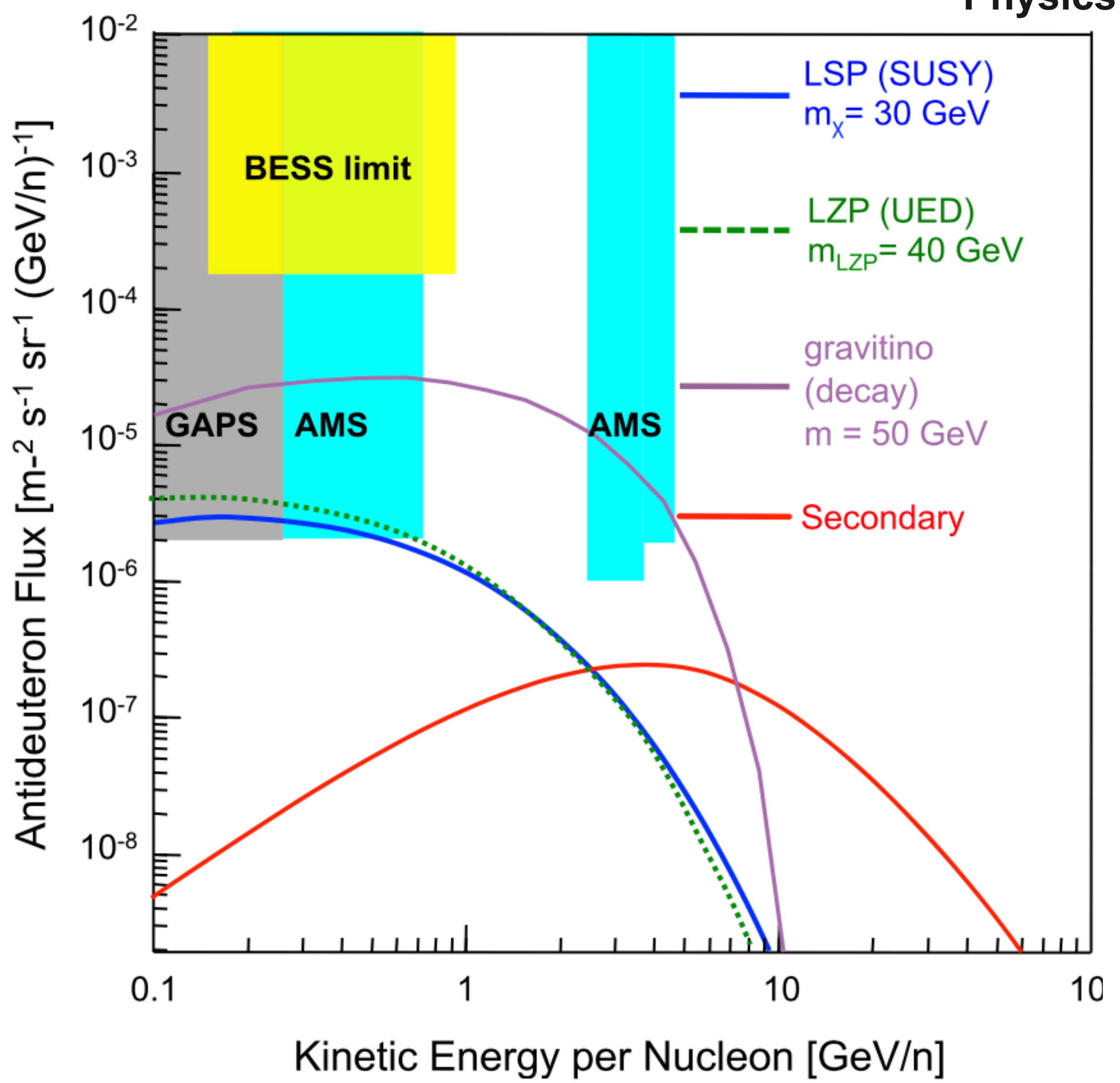

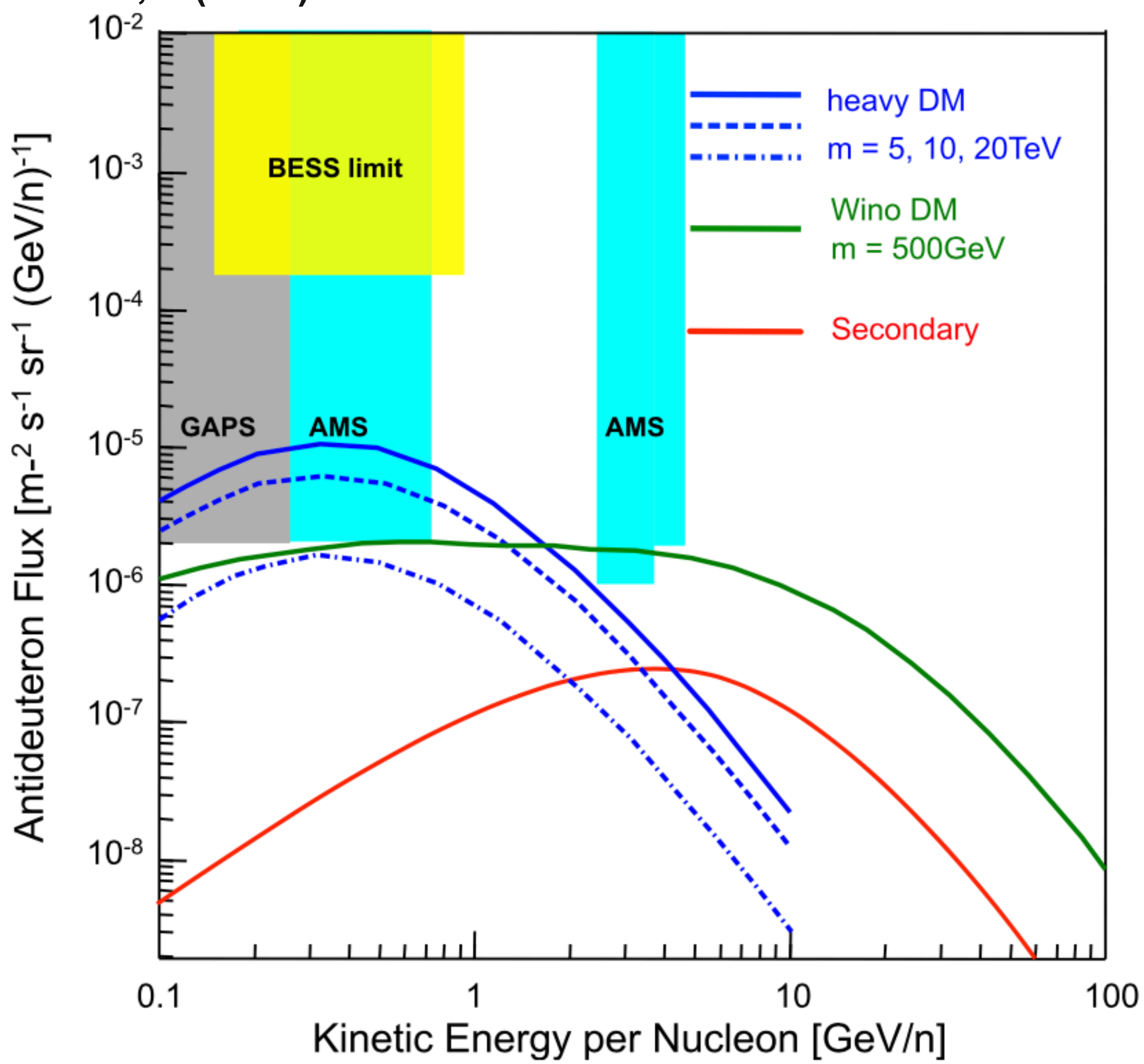

Primary/secondary cosmic rays

A. Kounine and S. Ting, ICHEP 2018, Seoul

Traditionally, there are two prominent classes of cosmic rays:

Primary Cosmic Rays (p, He, C, O, …)

Secondary Cosmic Rays (Li, Be, B, …)
are produced in the collisions of primary cosmic rays. They carry information on the history of the travel and on the properties of the interstellar matter.

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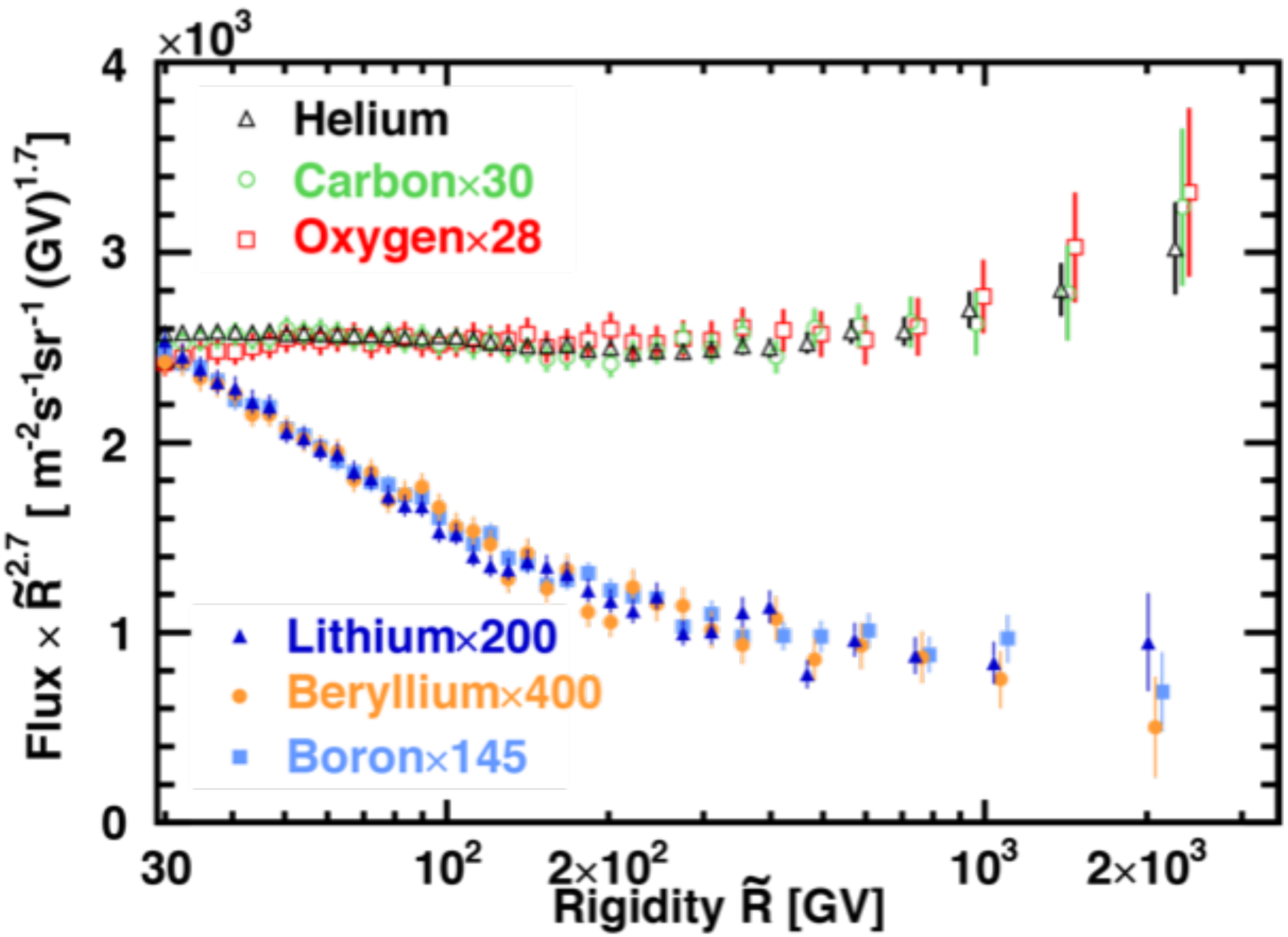
Primary/secondary cosmic rays

A. Kounine and S. Ting, ICHEP 2018, Seoul

Rigidity dependence of Primary and Secondary Cosmic Rays

Both deviate from a traditional single power law above 200 GeV.
But their rigidity dependences are distinctly different.



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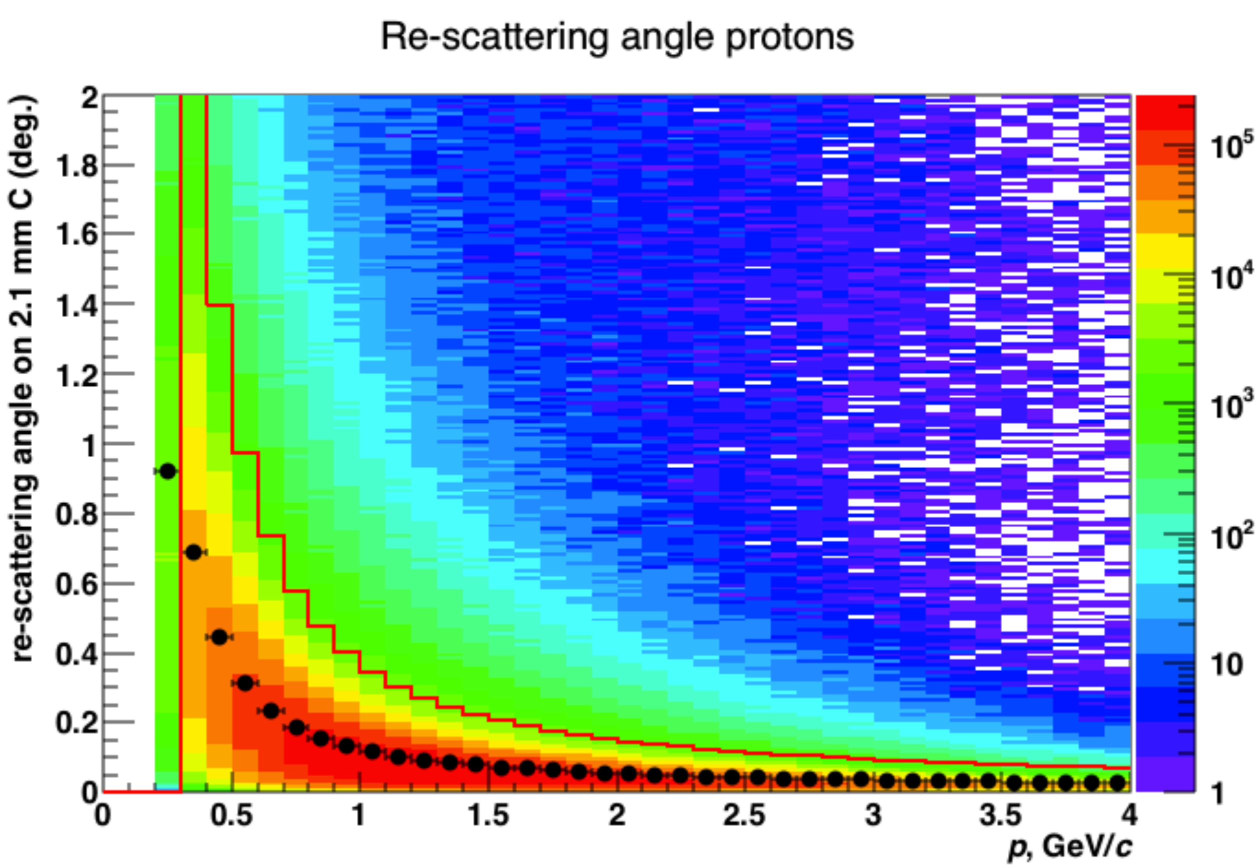
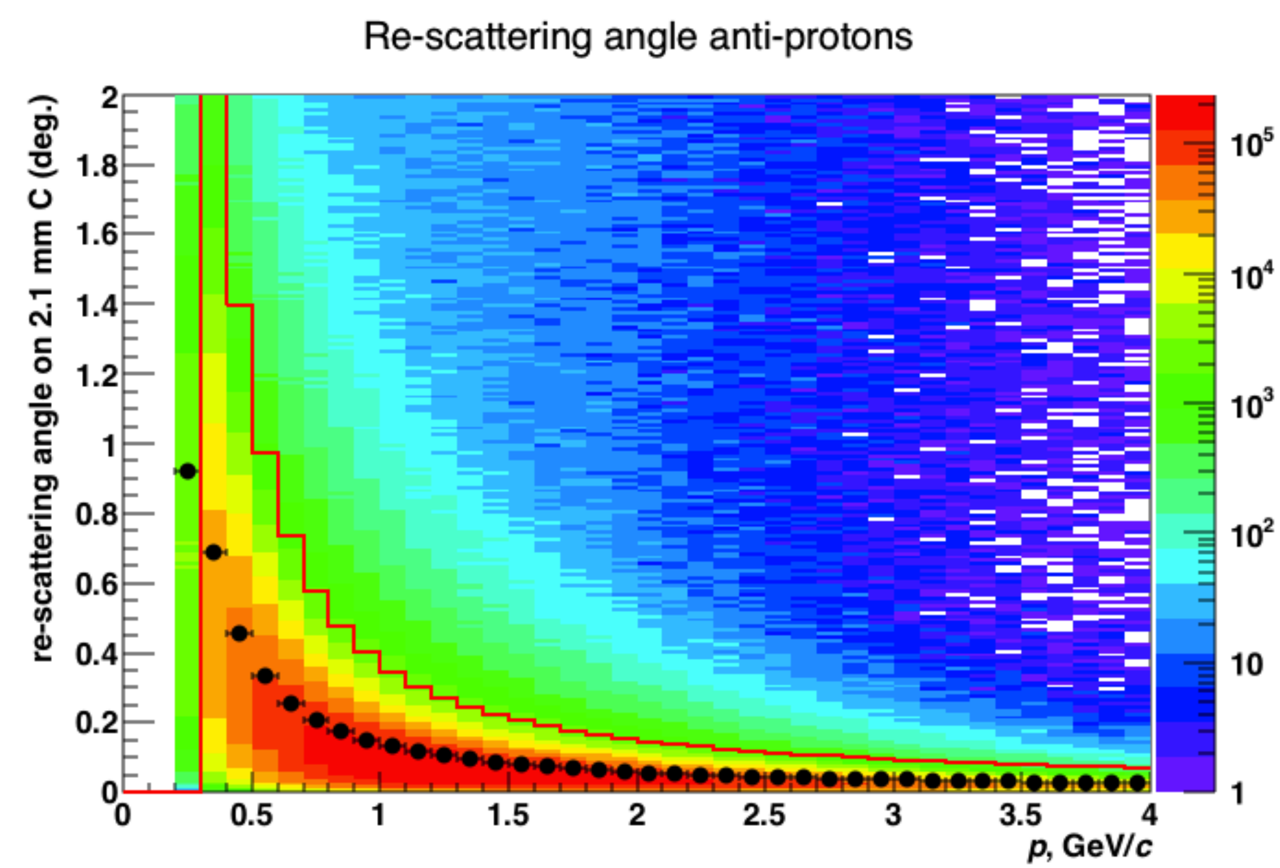
Re-scattering angle vs momentum: (anti-)protons

Total re-scattering angle after passing 2.1mm of carbon (1% X/X_0)
ALICE tracking: multiple coulomb scattering (MCS) is taken into account for ITS/TPC tracking and track-cluster association
Red line: "cut" on $3\sqrt{4/\pi} \cdot \sigma_{MCS}$, where $\sigma_{MCS} = 57.3 \cdot 0.014 \cdot \sqrt{X/X_0}/(\beta p)$





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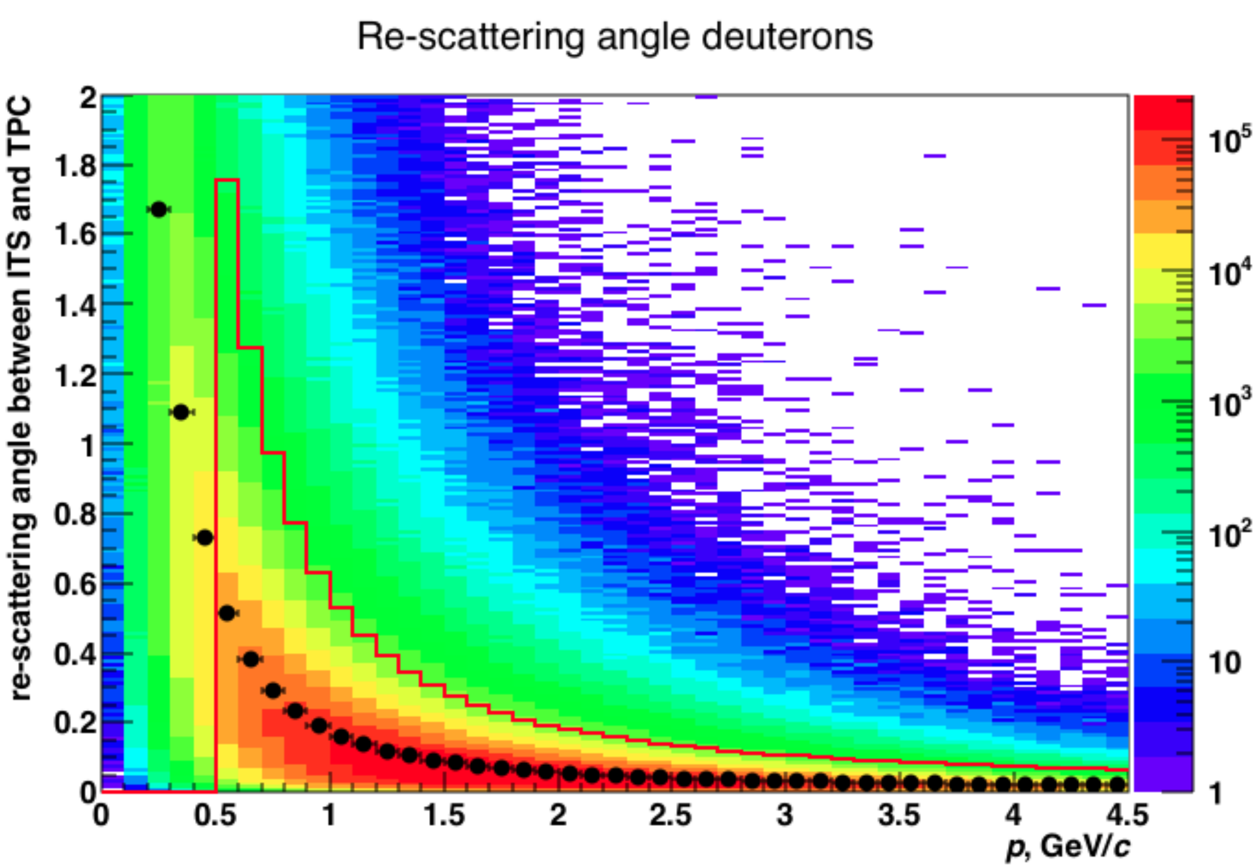
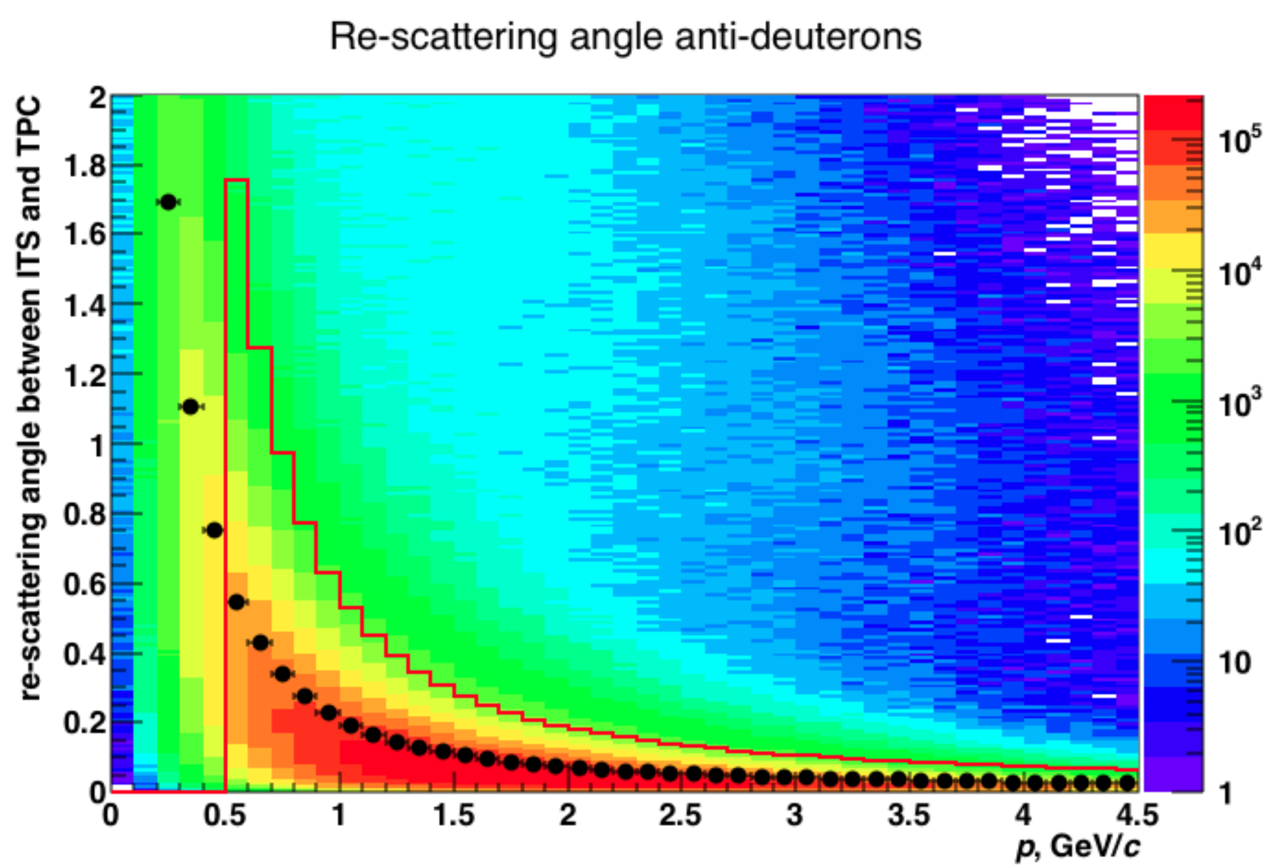


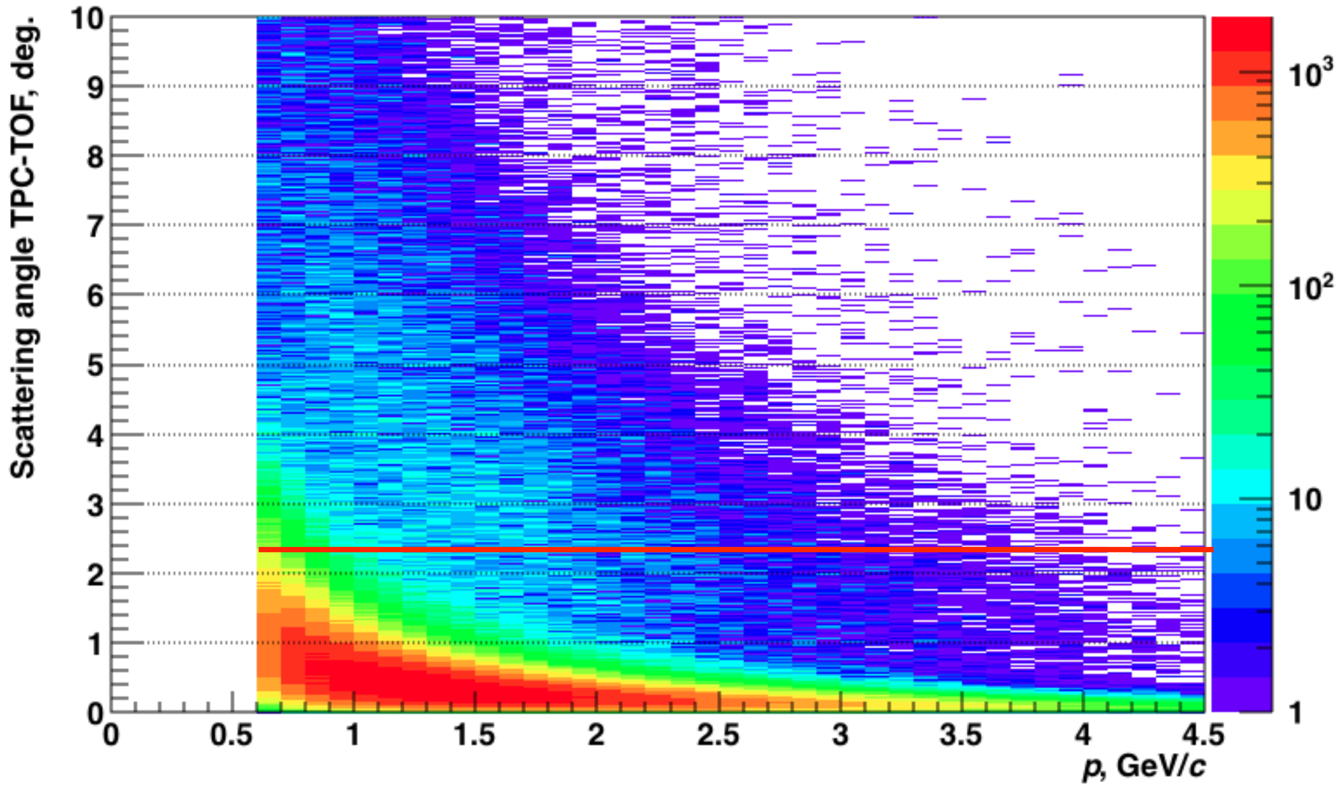


Geant4 model: TPC-TOF matching

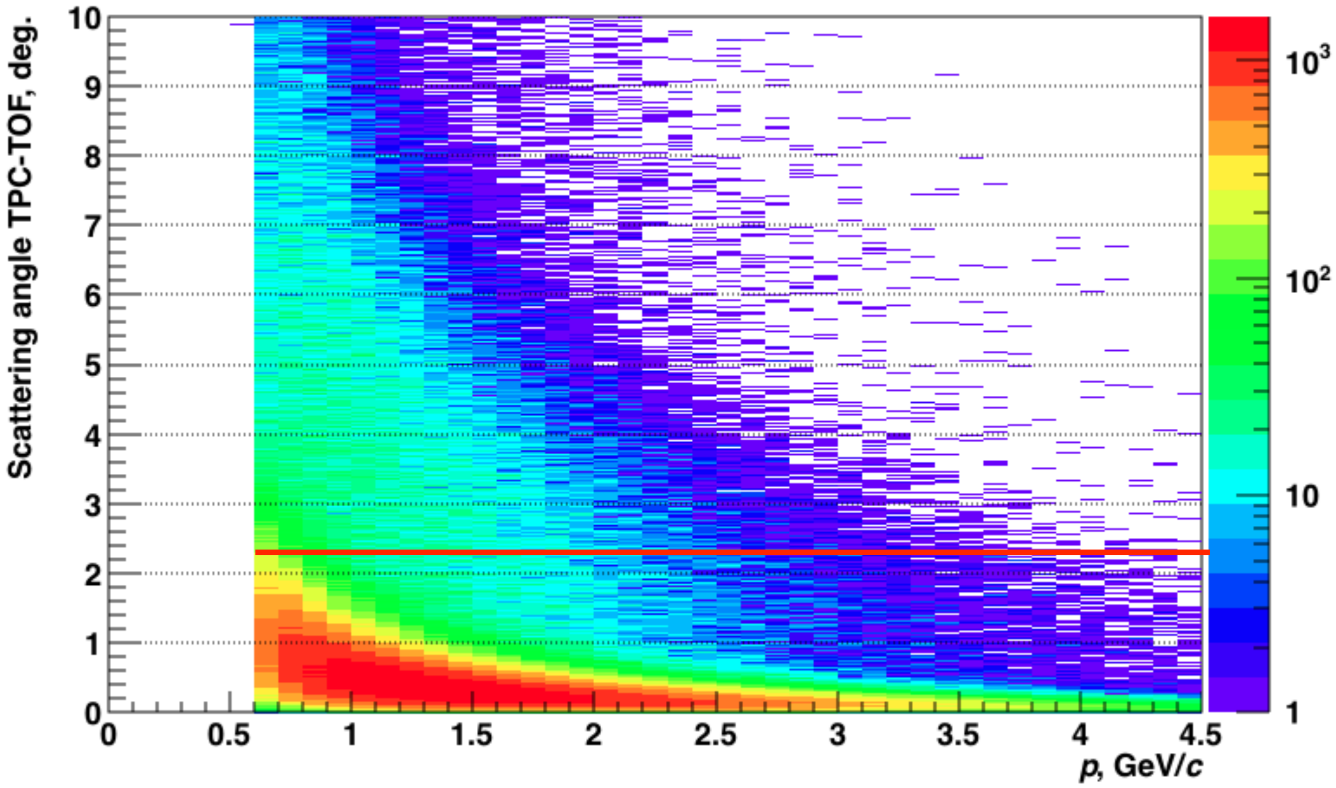
Tracking in pp and pPb collisions: a window of 10x10 cm is open for track at the TOF radius

- Big difference whether track is a passive scatterer or its parameters are updated in TRD layers
- Approximate window with a circle of r = 5 cm
  - → cut on 2.32º angle between TPC and TOF

Scattering angle TPC-TOF (protons)



Scattering angle TPC-TOF (anti-protons)



Geant4 model: TPC-TOF matching

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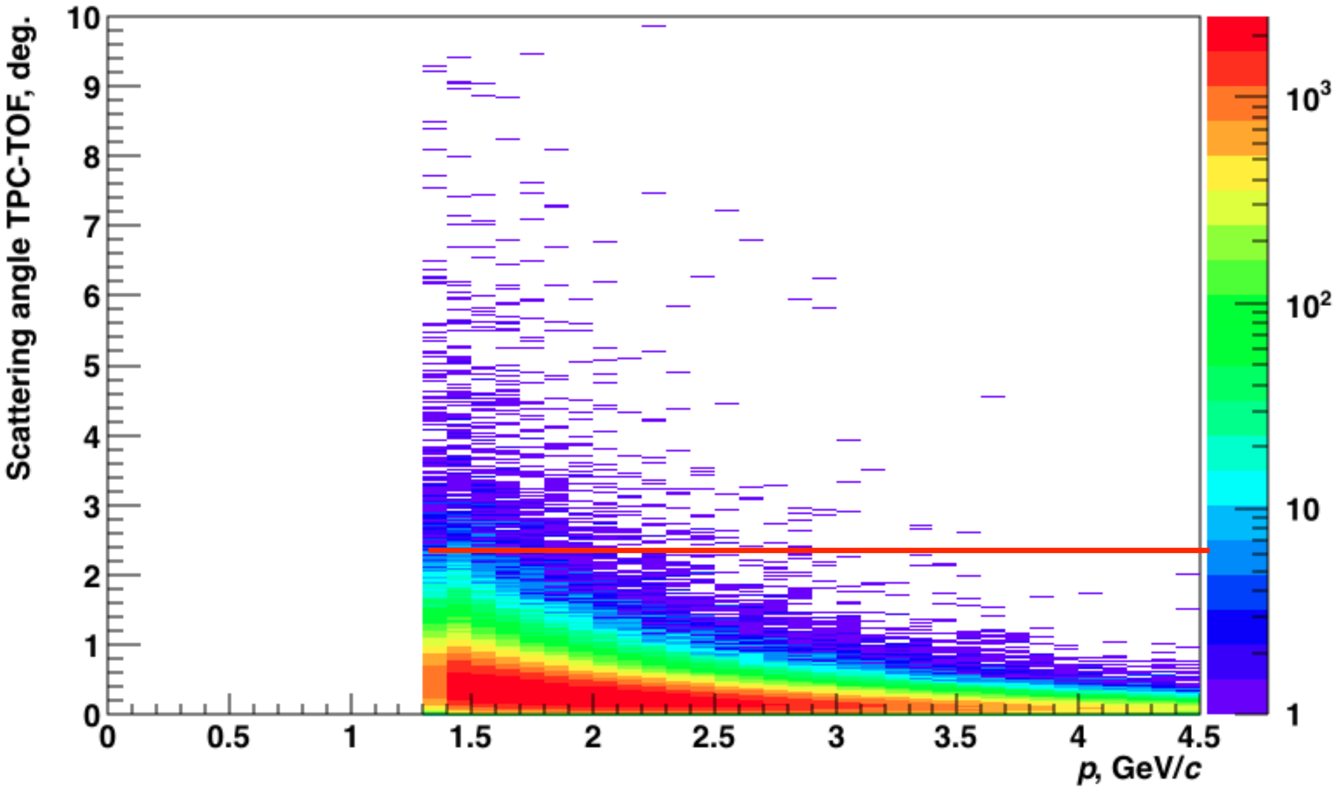
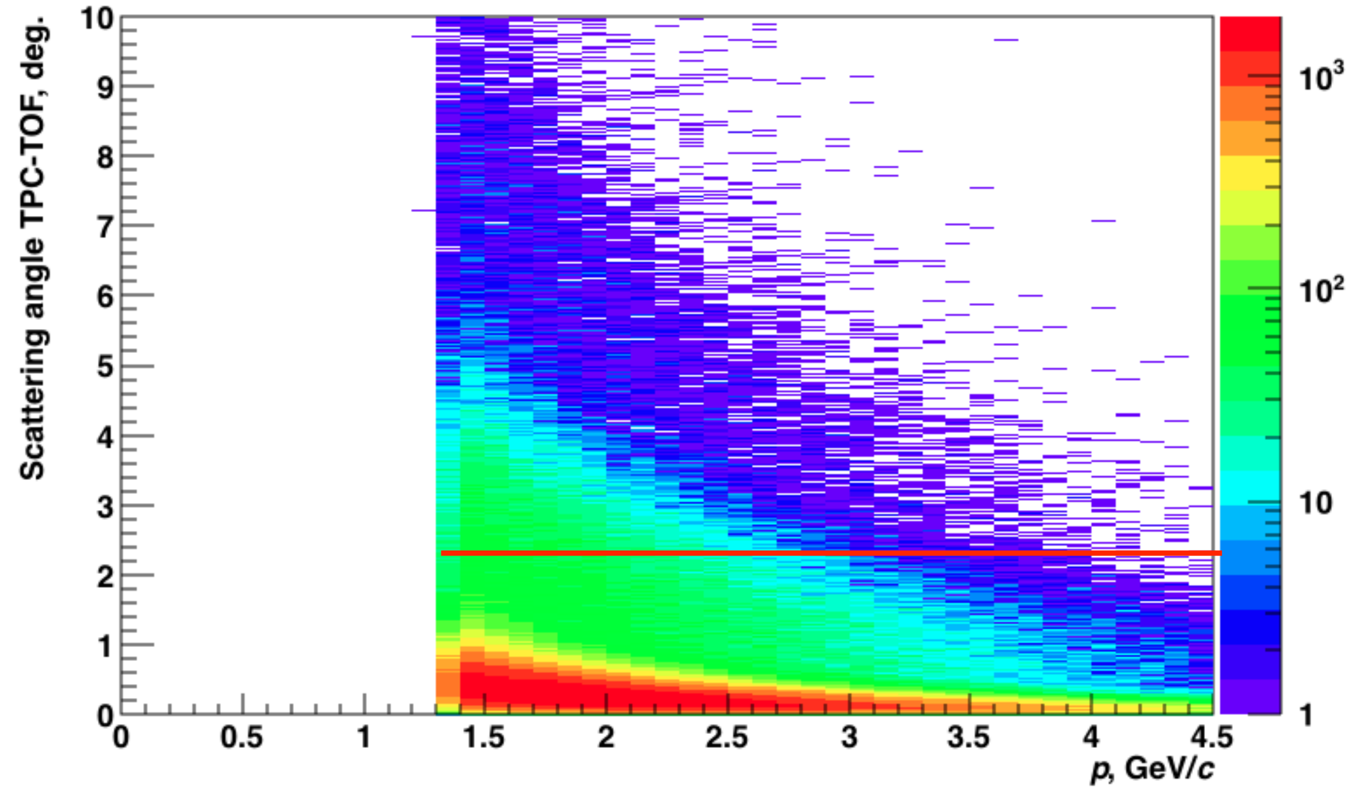
- Big difference whether track is a passive scatterer or its parameters are updated in TRD layers
- Approximate window with a circle of r = 5 cm
  - → cut on 2.32º angle between TPC and TOF

Scattering angle TPC-TOF (deuterons)



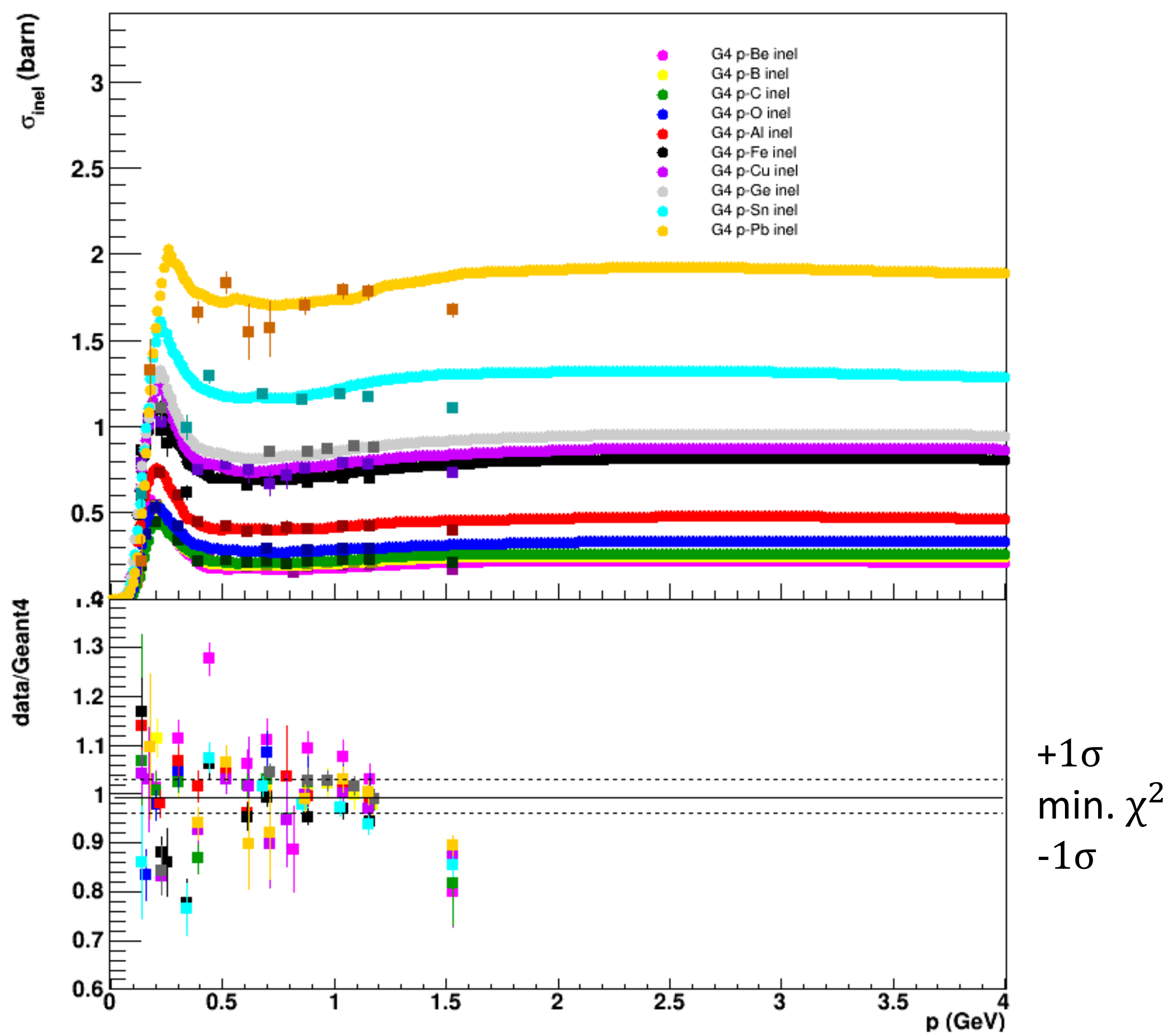
Scattering angle TPC-TOF (anti-deuterons)

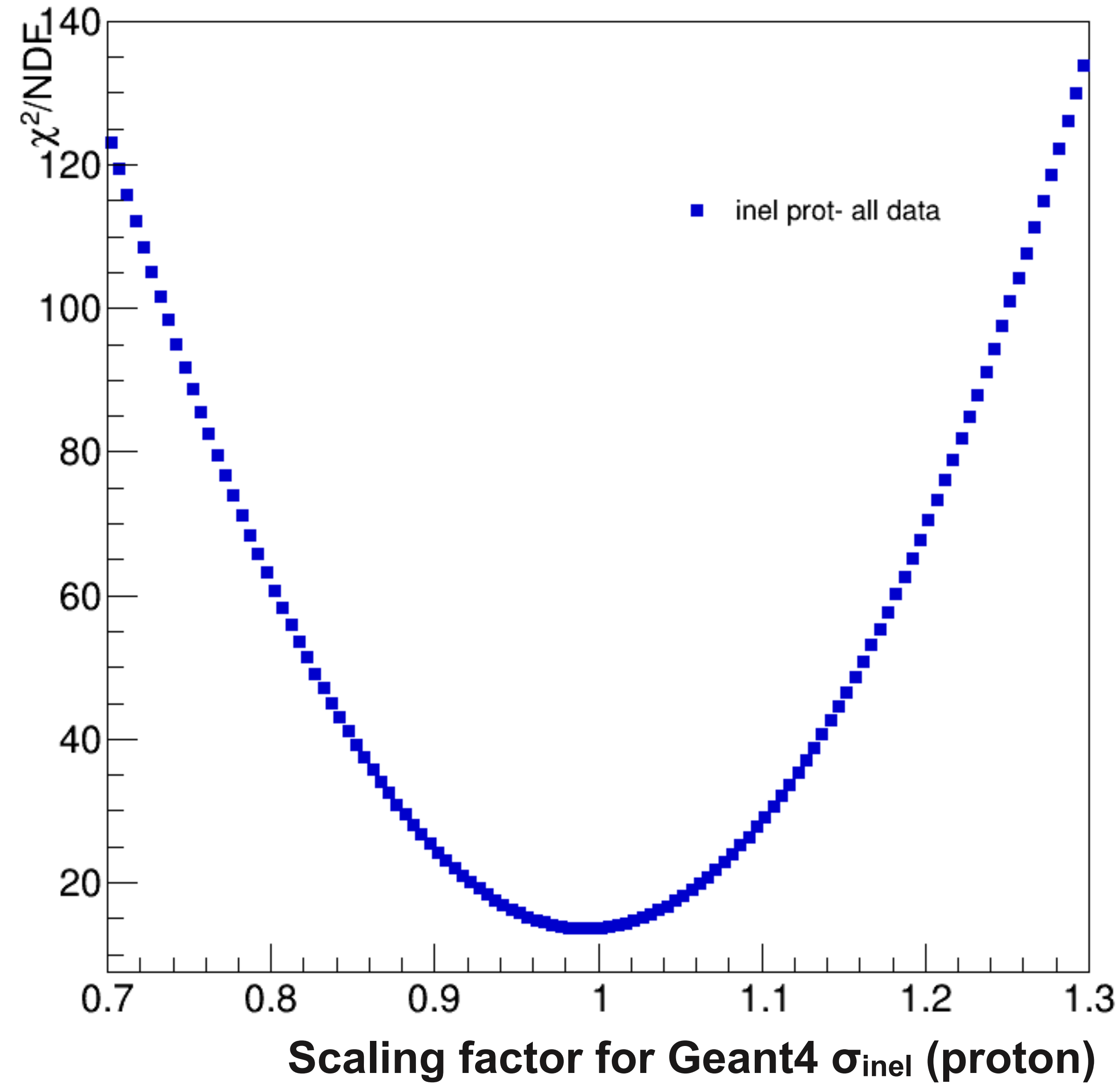


Uncertainty due to σ_{inel} (proton)

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

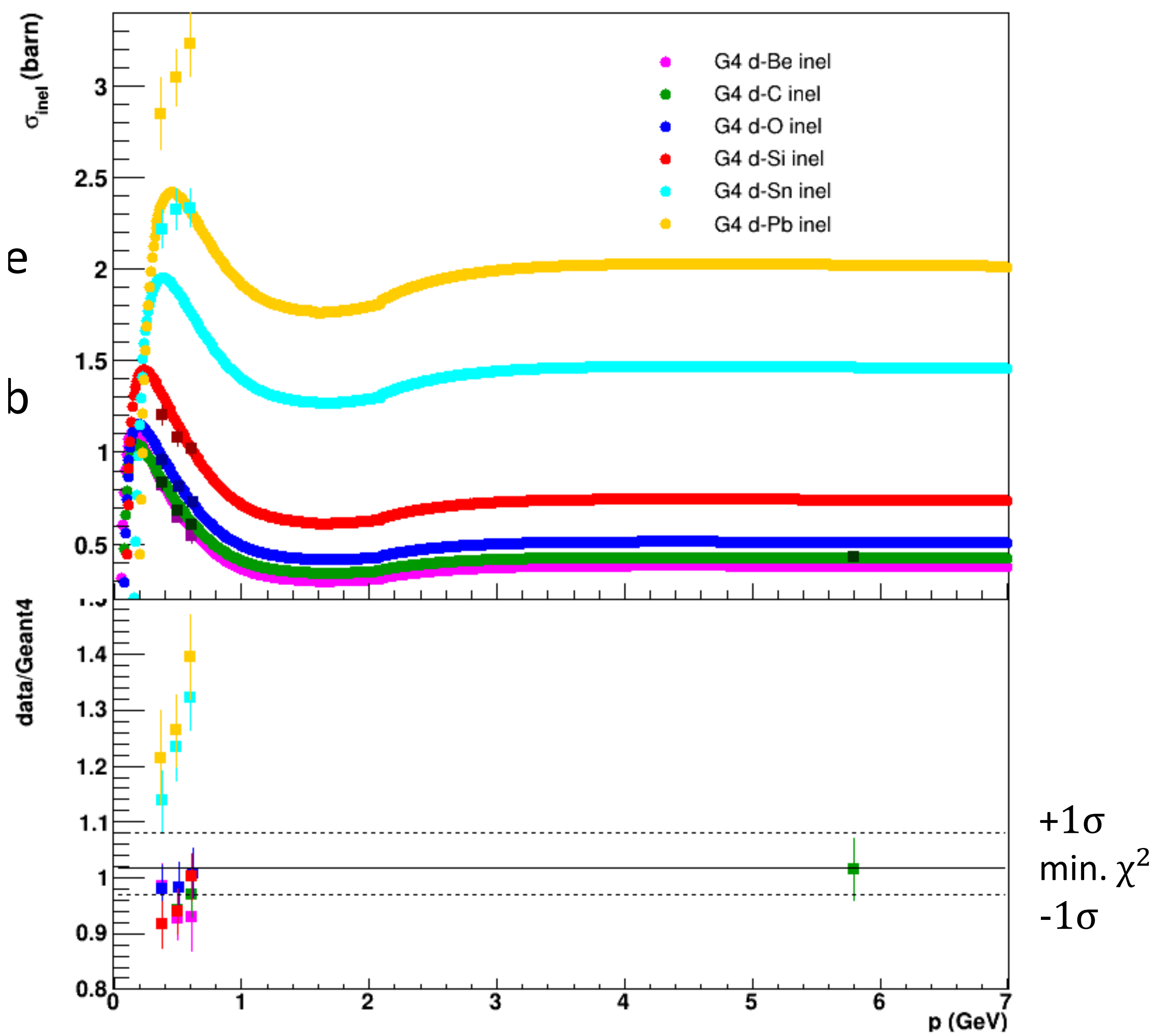


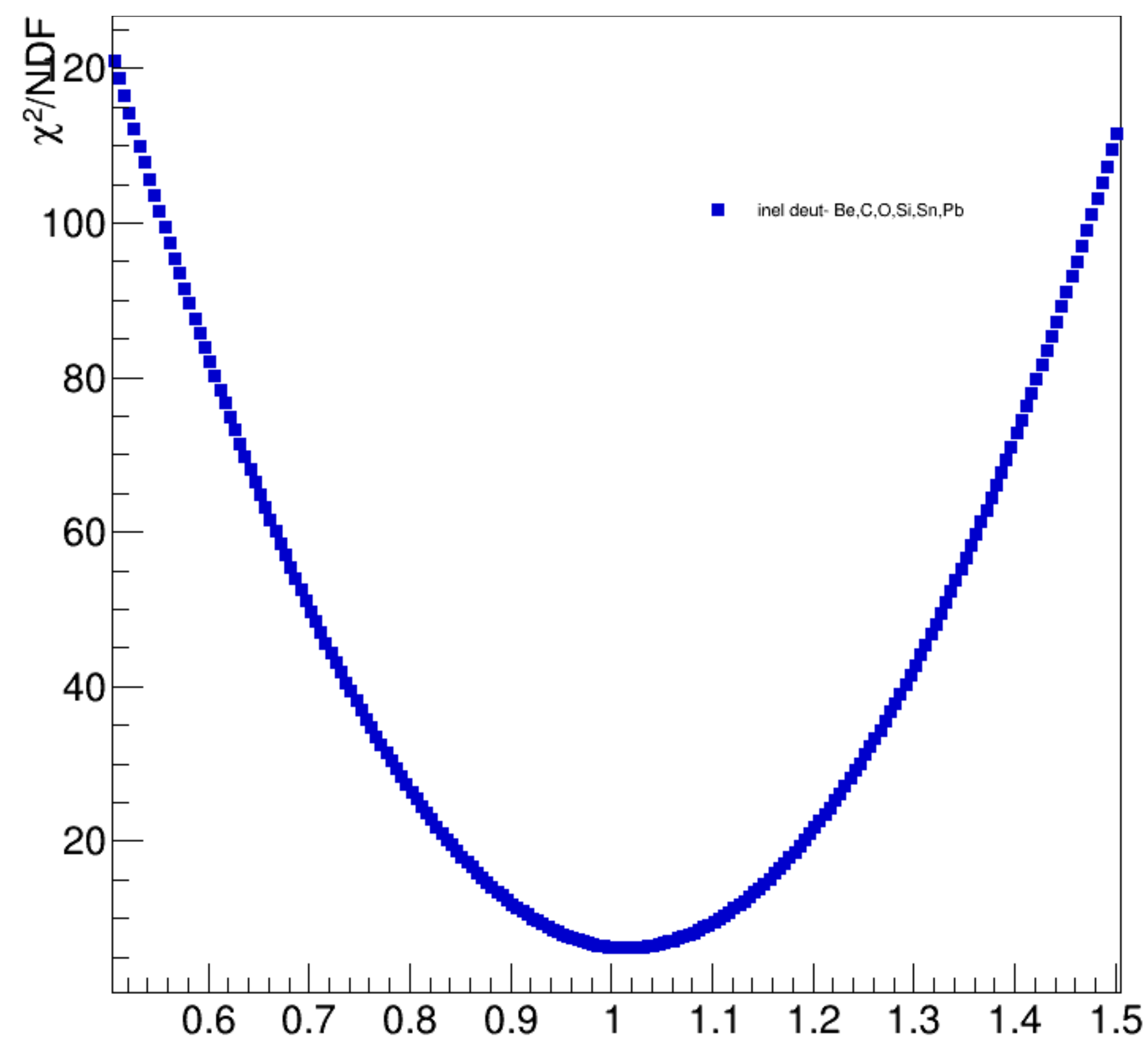


Uncertainty due to σ_{inel} (deuteron)

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 $^{+0.0625}_{-0.0475}$**
  - Agreement is worse for Sn and Pb





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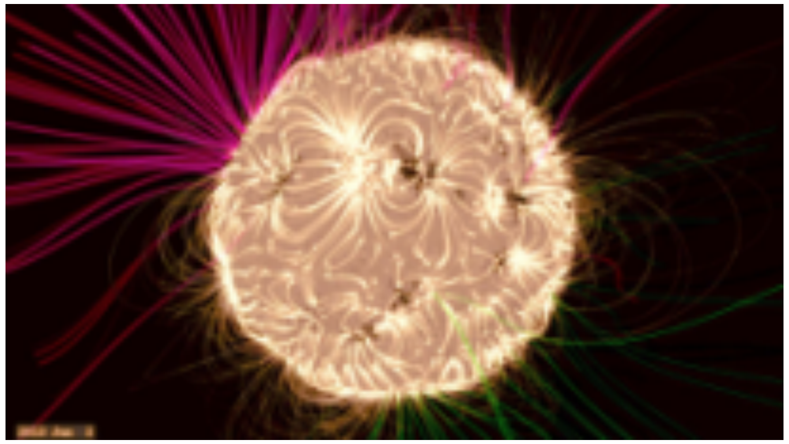
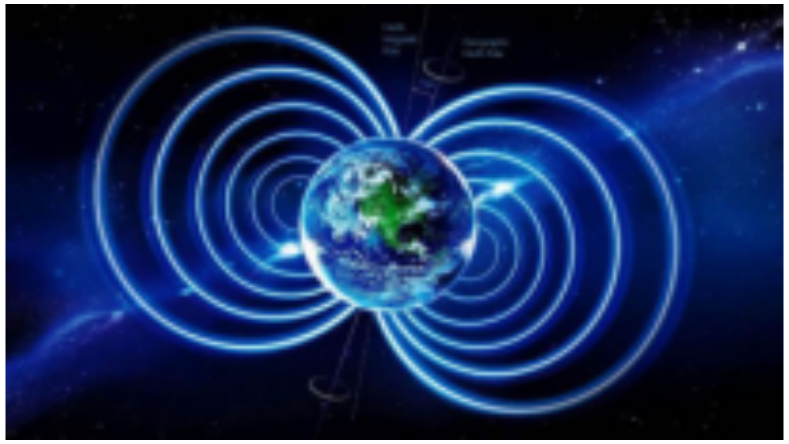
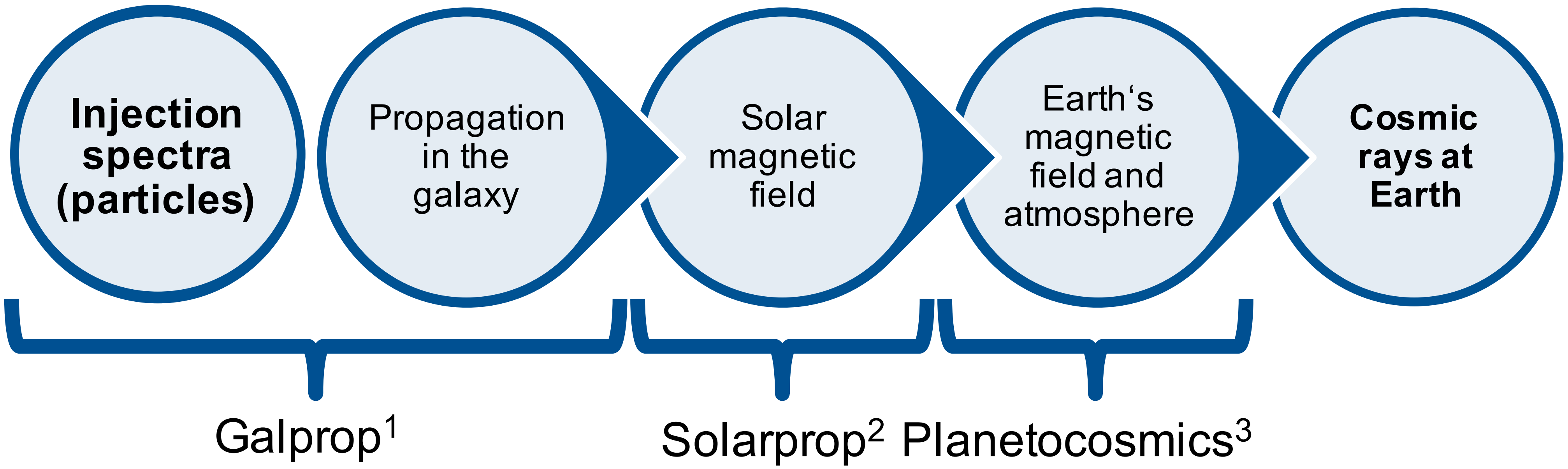
The Propagation of Galactic Cosmic Rays to Earth --- Modelling







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

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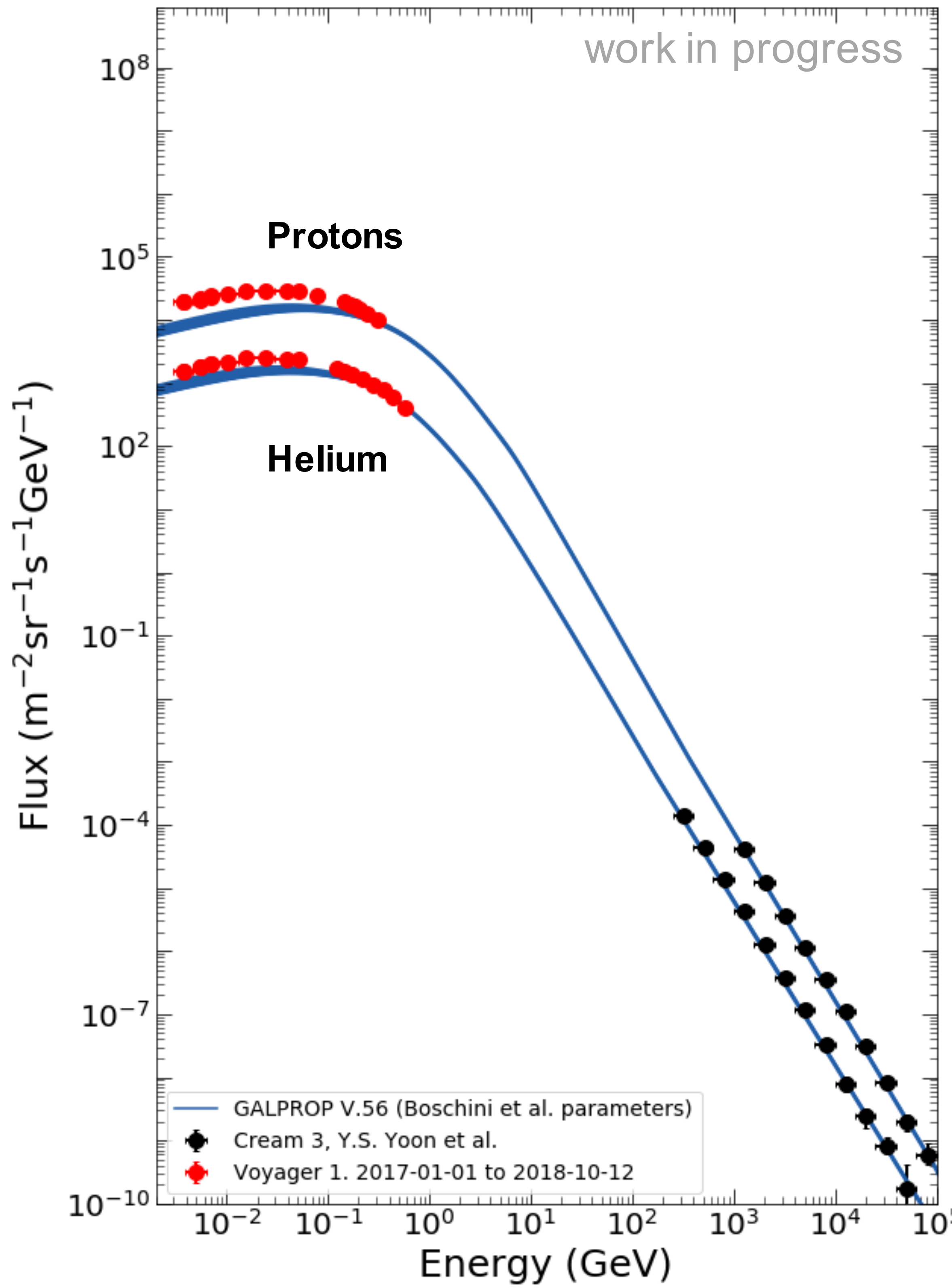
Protons: Local Interstellar Flux – GALPROP Model



GALPROP

(https://galprop.stanford.edu/)

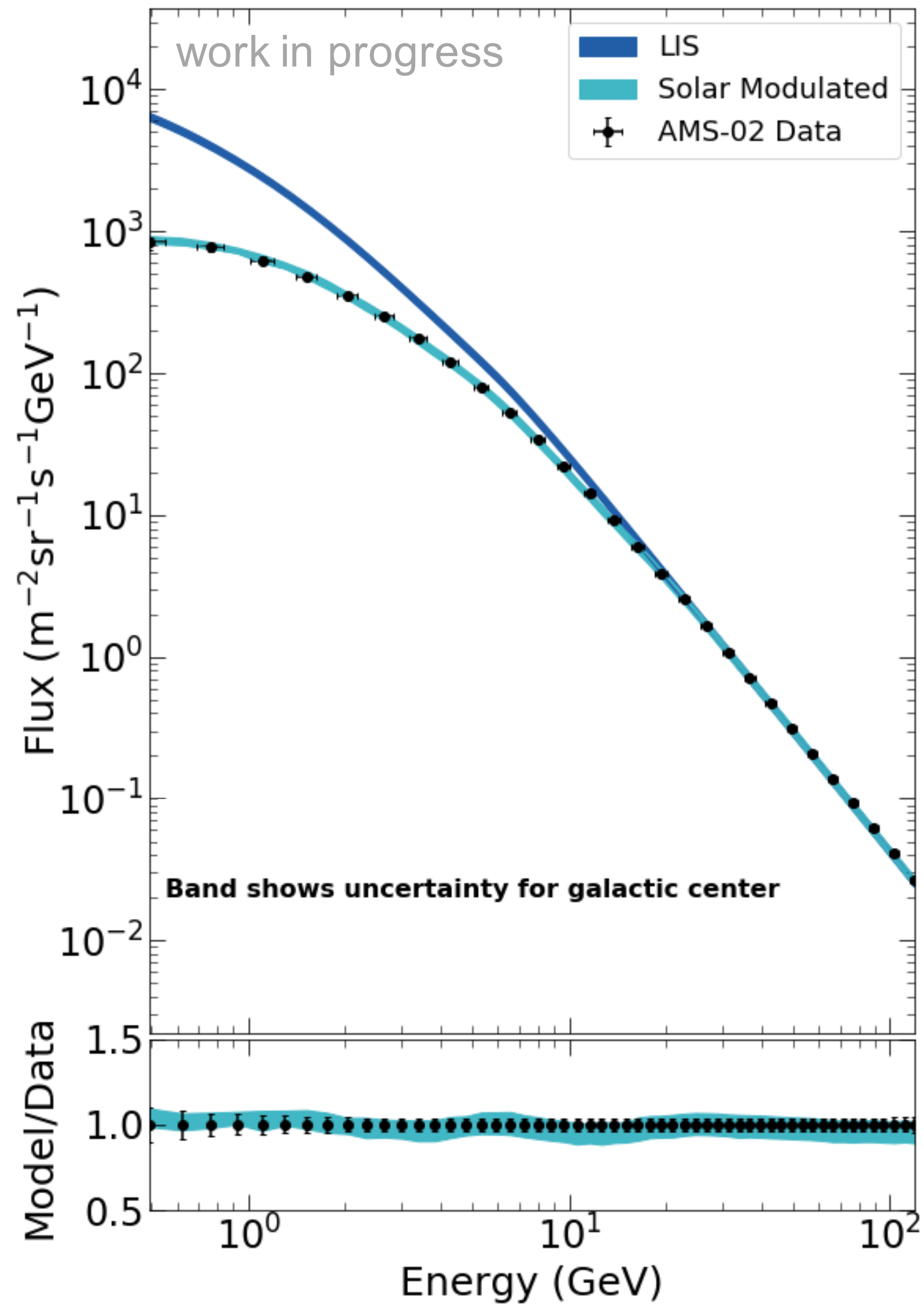
- version 56
- parameters updated with Voyager data (Boschini et al. 2017 Astr. Phys J. 840:115)
- can reproduce proton and helium flux
- uncertainty on distance to galactic center (7.83 kpc – 8.7 kpc)



Protons: Solar Modulated Flux

- Modelling of solar modulation
  - various models available
  - force-field method lacks charge-sign dependence
    → influences antiparticle – particle ratio at low energies

- **SOLARPROP** calculation tool (R. Kappl et al.)
  - includes polarity-dependence
  - numerically solves the Fokker-Planck equation
  - one free normalizing constant (κ)
  - can describe various datasets well (AMS-II, BESS flights, PAMELA)



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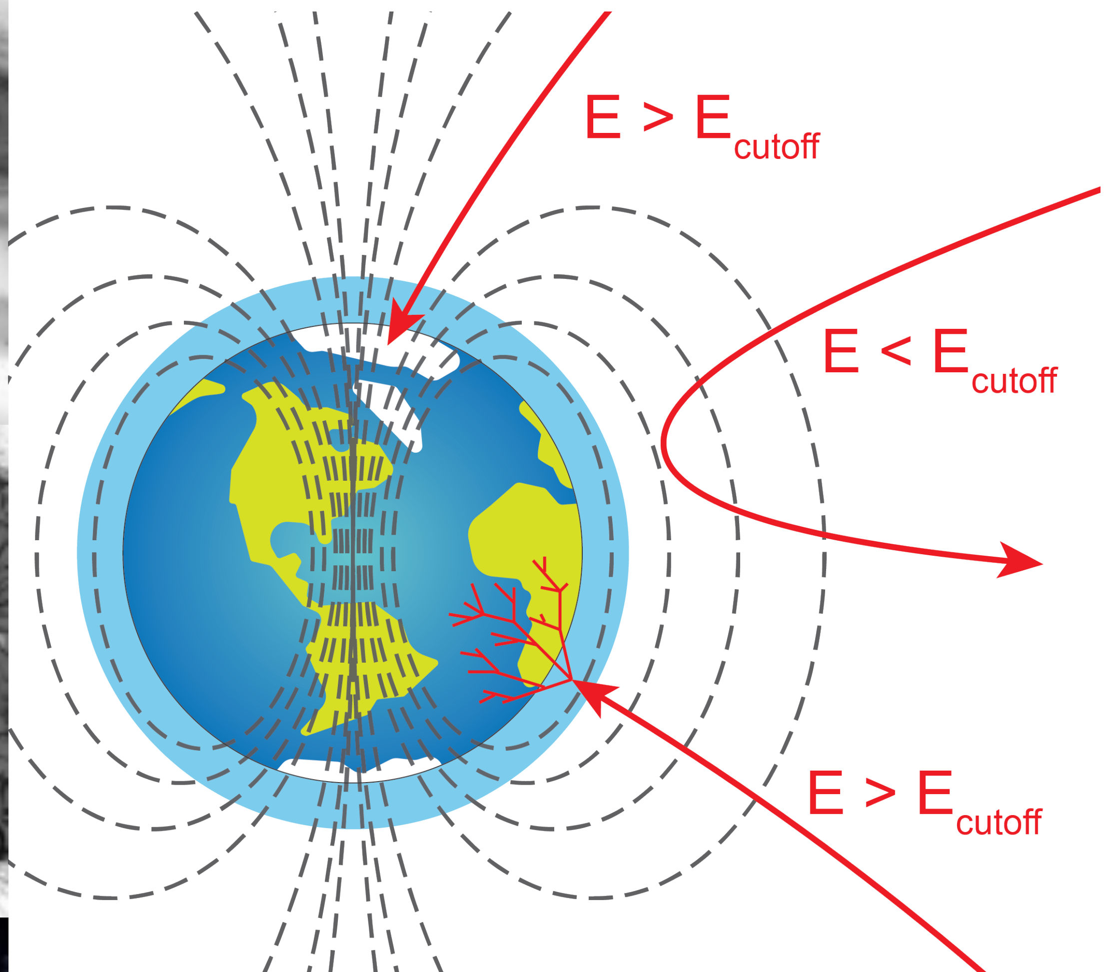
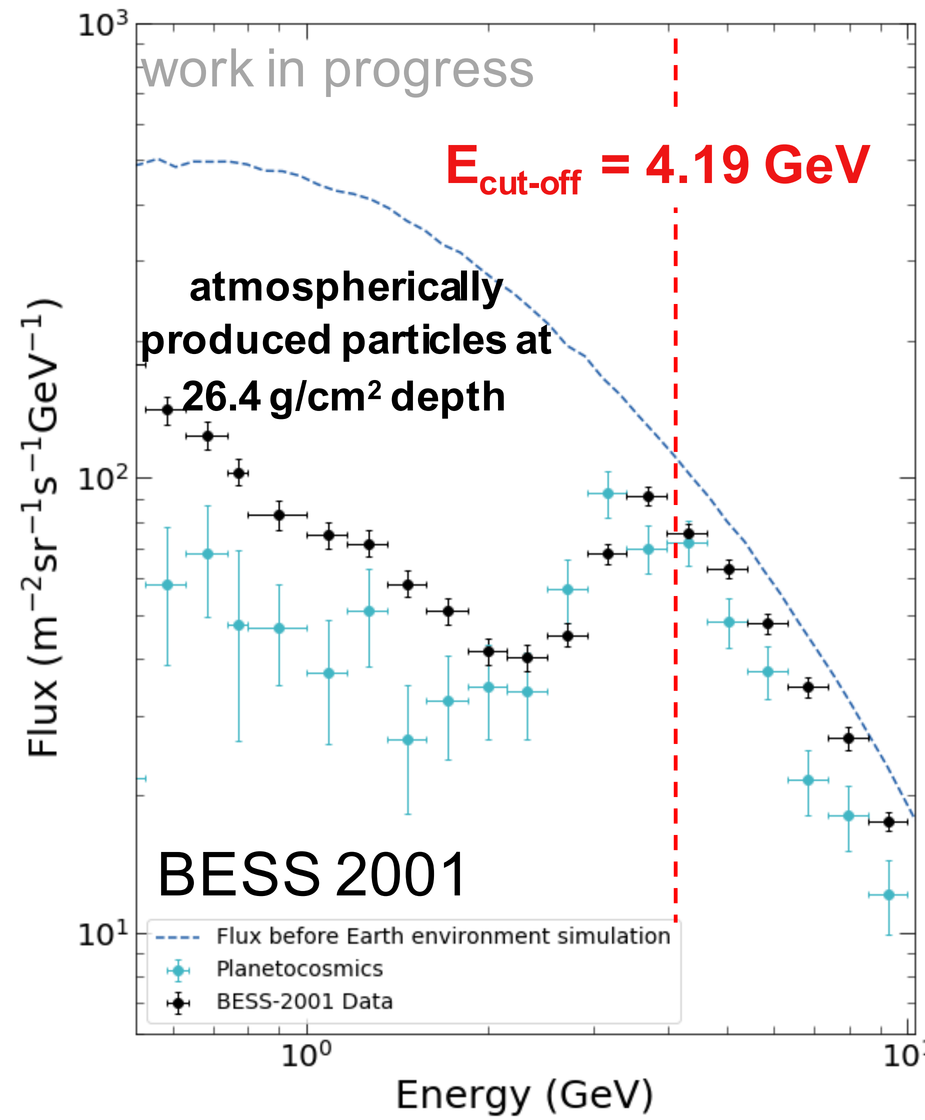
Protons: Influence of Near-Earth Environment

Earth's magnetosphere



- dipole field
- deflects low-energy cosmic rays
- shields particles with rigidities < $R_{Cut-off}$

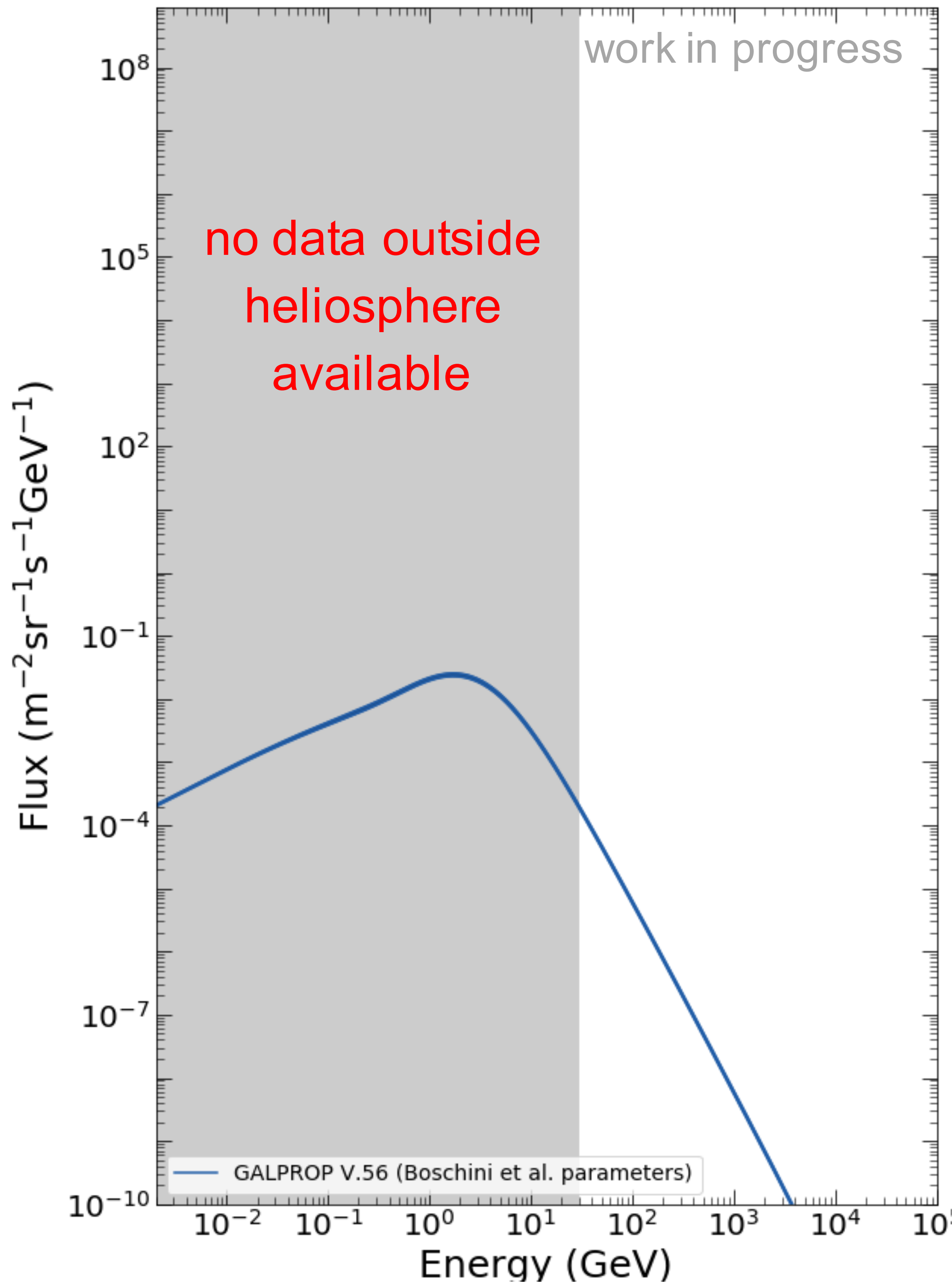
Earth's atmosphere



- absorption of cosmic rays
- production of atmospheric particles
- products can be trapped or quasi-trapped by Earth's magnetic field

Antiprotons: Local Interstellar Flux

No data outside heliosphere available



Antiprotons: Solar Modulated Flux

- AMS-02 data does not match model
- cannot be explained by solar modulation

→ deviation already in antiproton LIS

Reasons

- additional antiproton source
- different diffusion coefficients
- wrong modelling of secondary production (or absorption)

  → investigate production cross section

work in progress