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

Stephan Koenigstorfer on behalf of the ALICE Collaboration
Technische Universität München

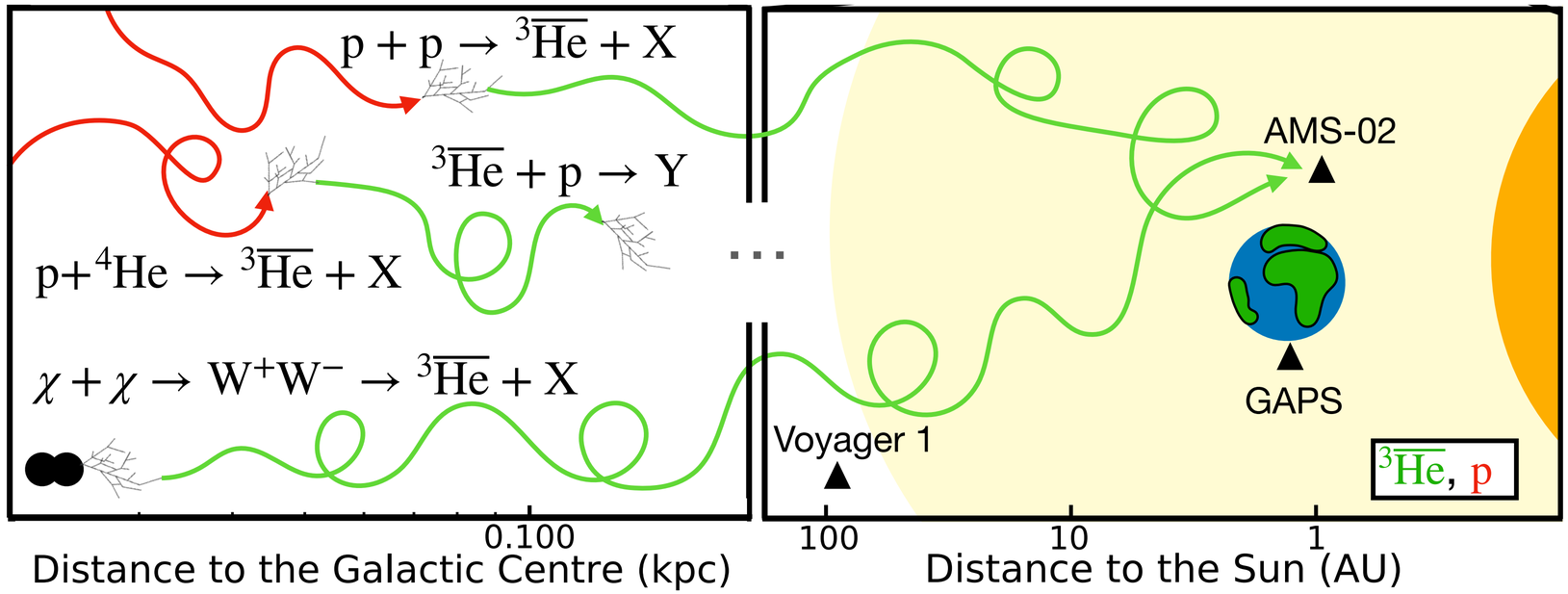
5.9.2021

PANIC 2021

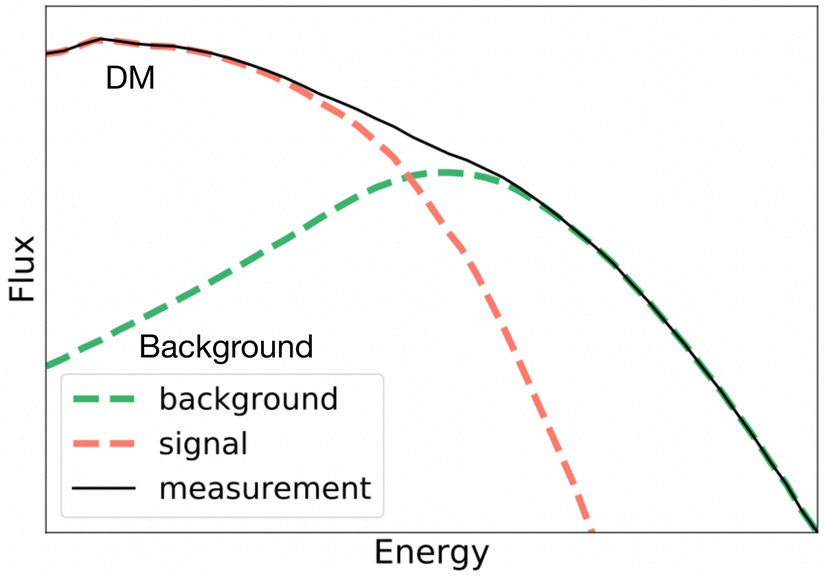
Introduction

Cosmic ray antinuclei - unique Dark Matter probe

- Low background from high energy collisions of cosmic rays with the interstellar medium is expected
- Need to determine exact primary and secondary fluxes, which requires precise knowledge of antinuclei production, propagation and annihilation. **This needs to be studied with experiments near earth!**



Schematic of expected antinuclei fluxes



The ALICE experiment at CERN

General-purpose experiment at the Large Hadron Collider

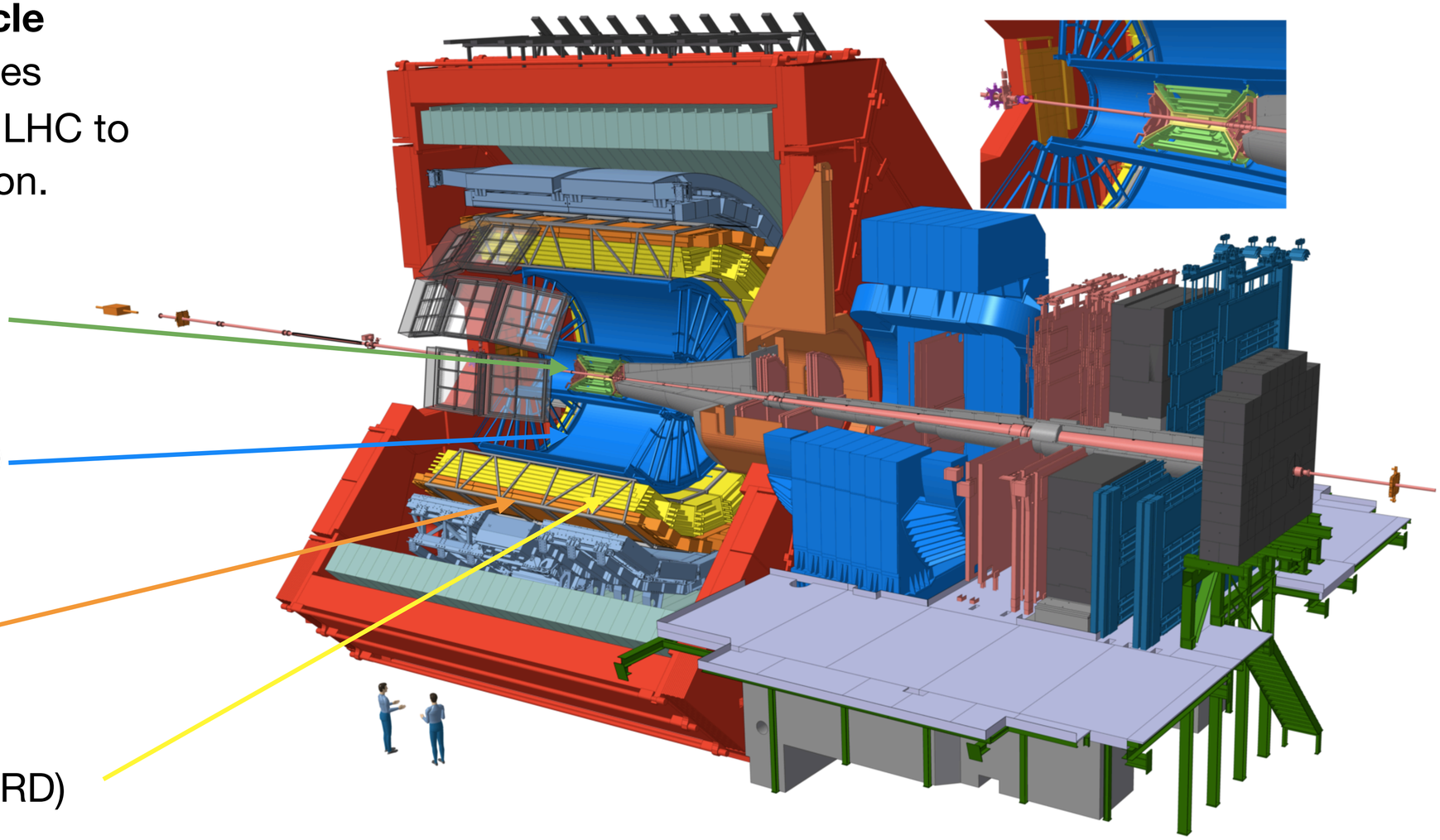
- Excellent **tracking and particle identification (PID)** capabilities
- Most suitable detector at the LHC to measure (anti)nuclei production.

Inner Tracking System (ITS)
- Tracking, vertex, PID, (dE/dx)

Time Projection Chamber (TPC)
- Tracking, PID (d*E*/dx)

Time of Flight detector (TOF)
- PID (TOF measurement)

Transition Radiation Detector (TRD)



Use the LHC as an antimatter factory…

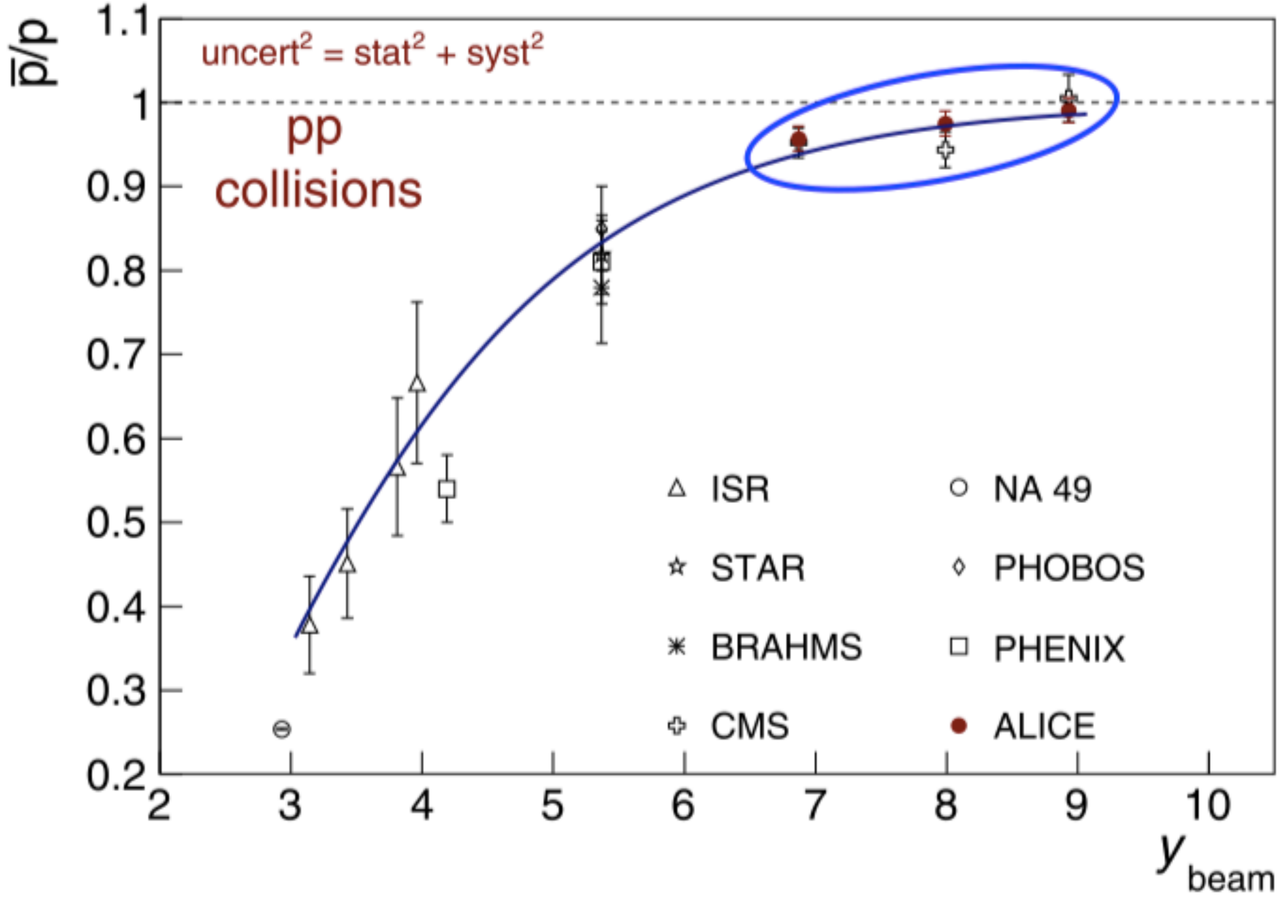
At LHC energies, particles and antiparticles are produced in almost equal amounts in mid-rapidity.

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

This talk contains results from:

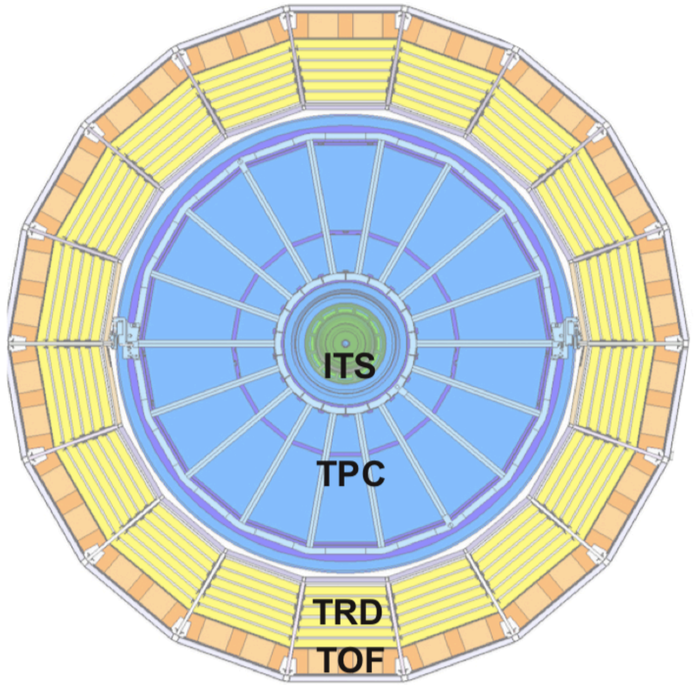
- High multiplicity pp collisions at $\sqrt{s} = 13$ TeV.
- Pb—Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.
- p—Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.

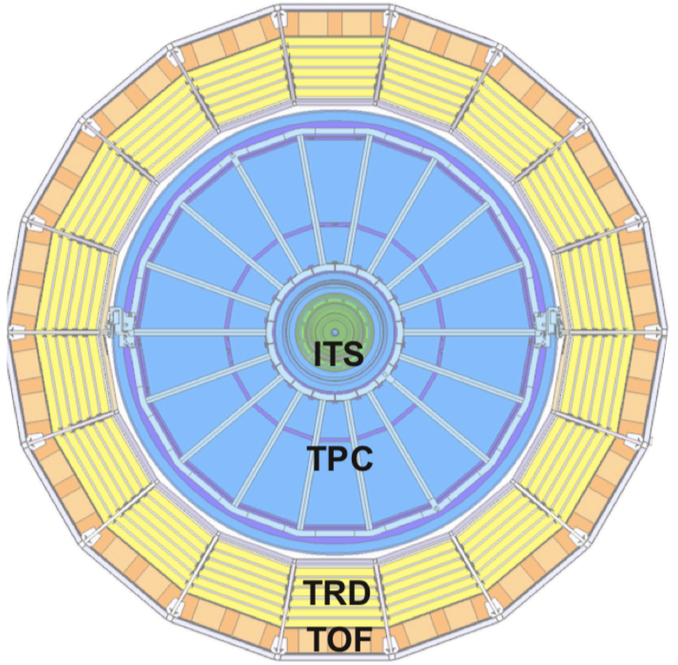
$\bar{p}/p$ ratio at mid-rapidity vs $\sqrt{s}$ [1]



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

… and the ALICE detector material as a target



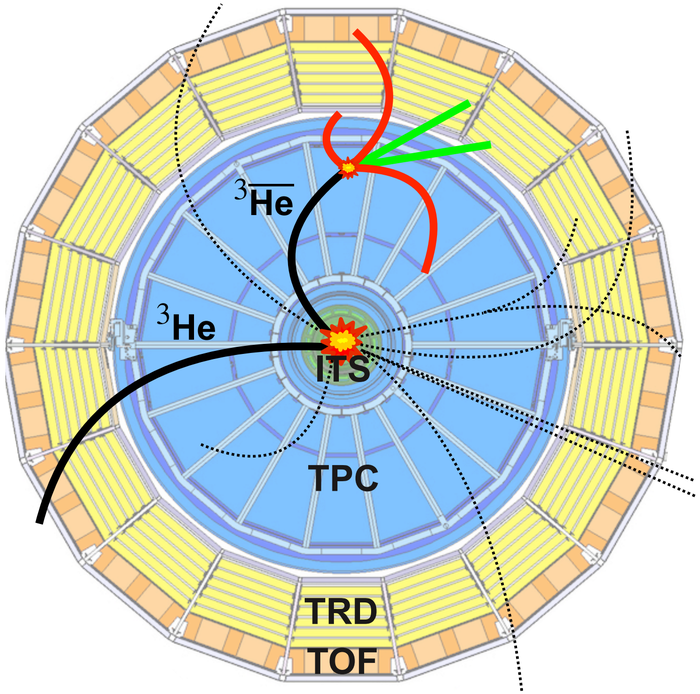


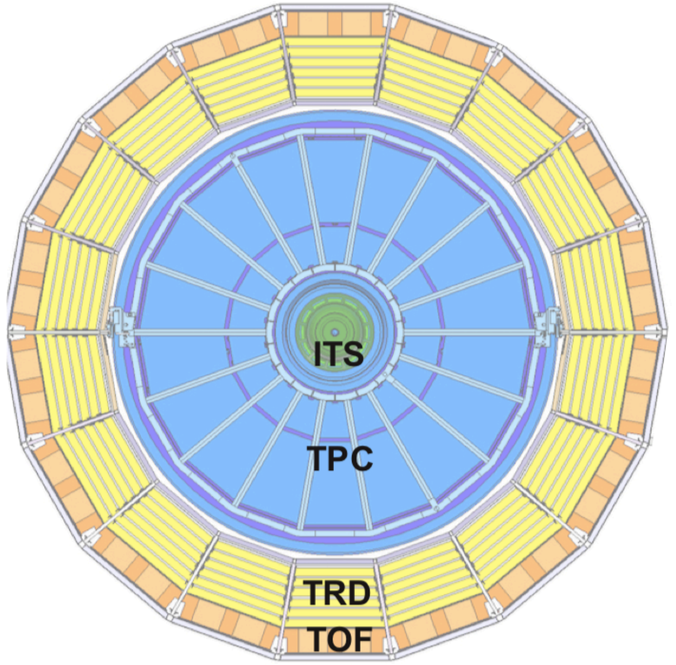
[1] PRL 125, 162001 (2020)

… and the ALICE detector material as a target

Antimatter-to-matter ratio [1] (pp 13 TeV)

- Measure reconstructed $^3\overline{\mathrm{He}}/^3\mathrm{He}$ and compare with MC simulations.



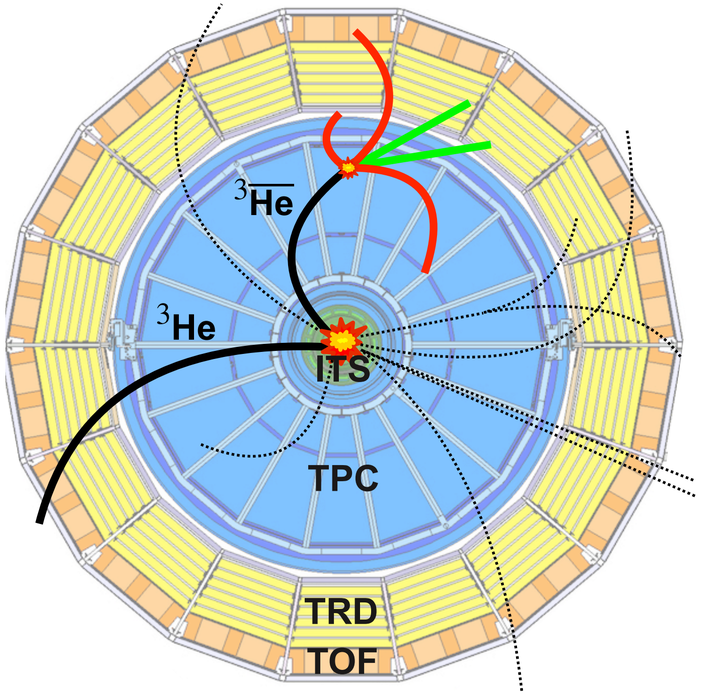


[1] PRL 125, 162001 (2020)

… and the ALICE detector material as a target

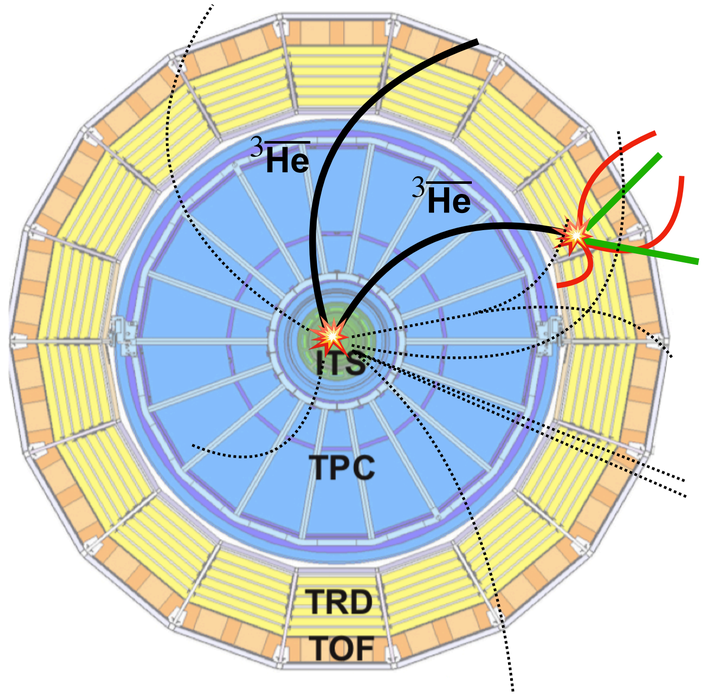
Antimatter-to-matter ratio [1] (pp 13 TeV)

- Measure reconstructed $^3\overline{\mathrm{He}}/^3\mathrm{He}$ and compare with MC simulations.



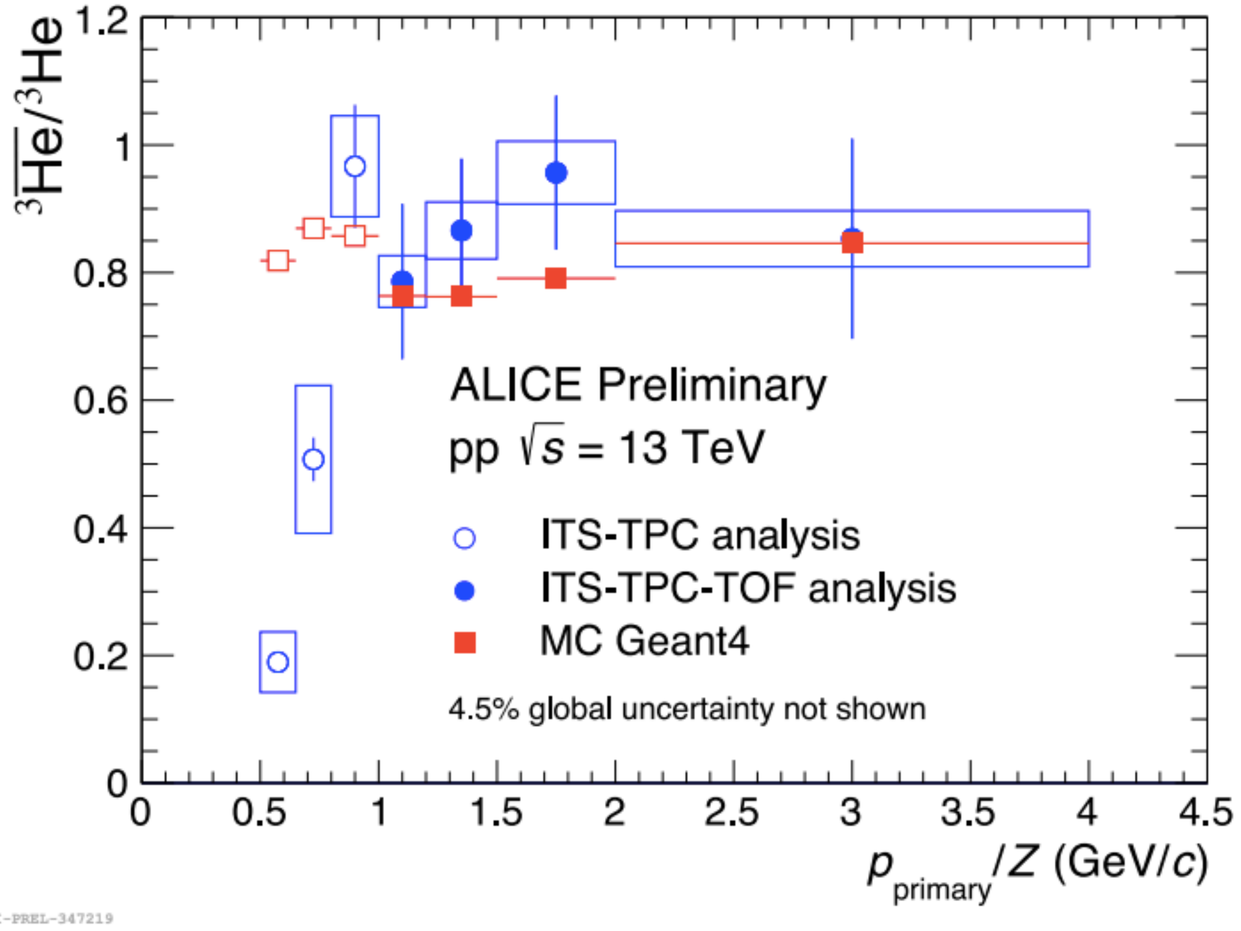
TOF-TPC-matching (Pb—Pb 5.02 TeV)

- Measure reconstructed $^3\overline{\mathrm{He}}_{TOF}/^3\overline{\mathrm{He}}_{TPC}$ and compare with MC simulations.



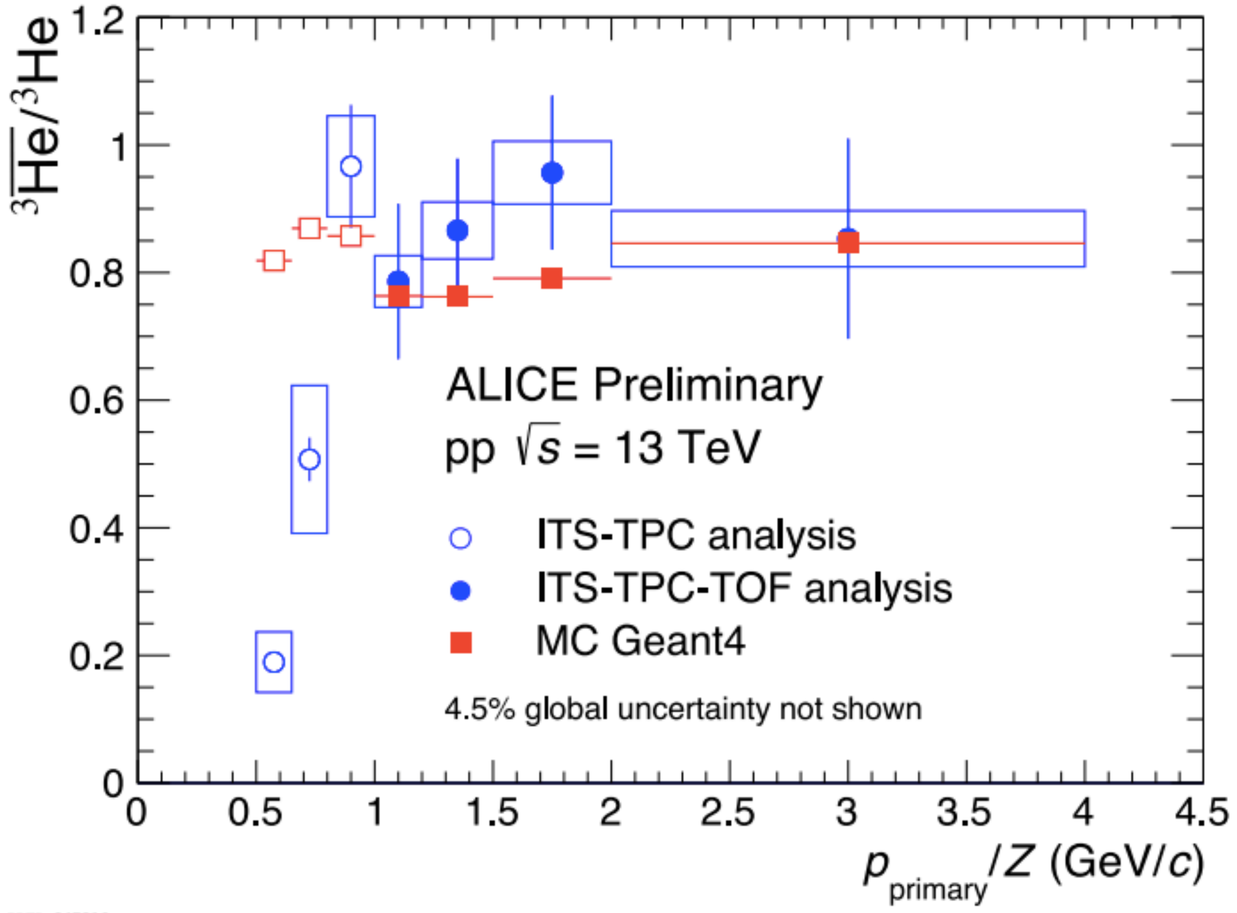
[1] PRL 125, 162001 (2020)

Extracting σ_{inel} from data and Monte Carlo



Extracting σ_{inel} from data and Monte Carlo

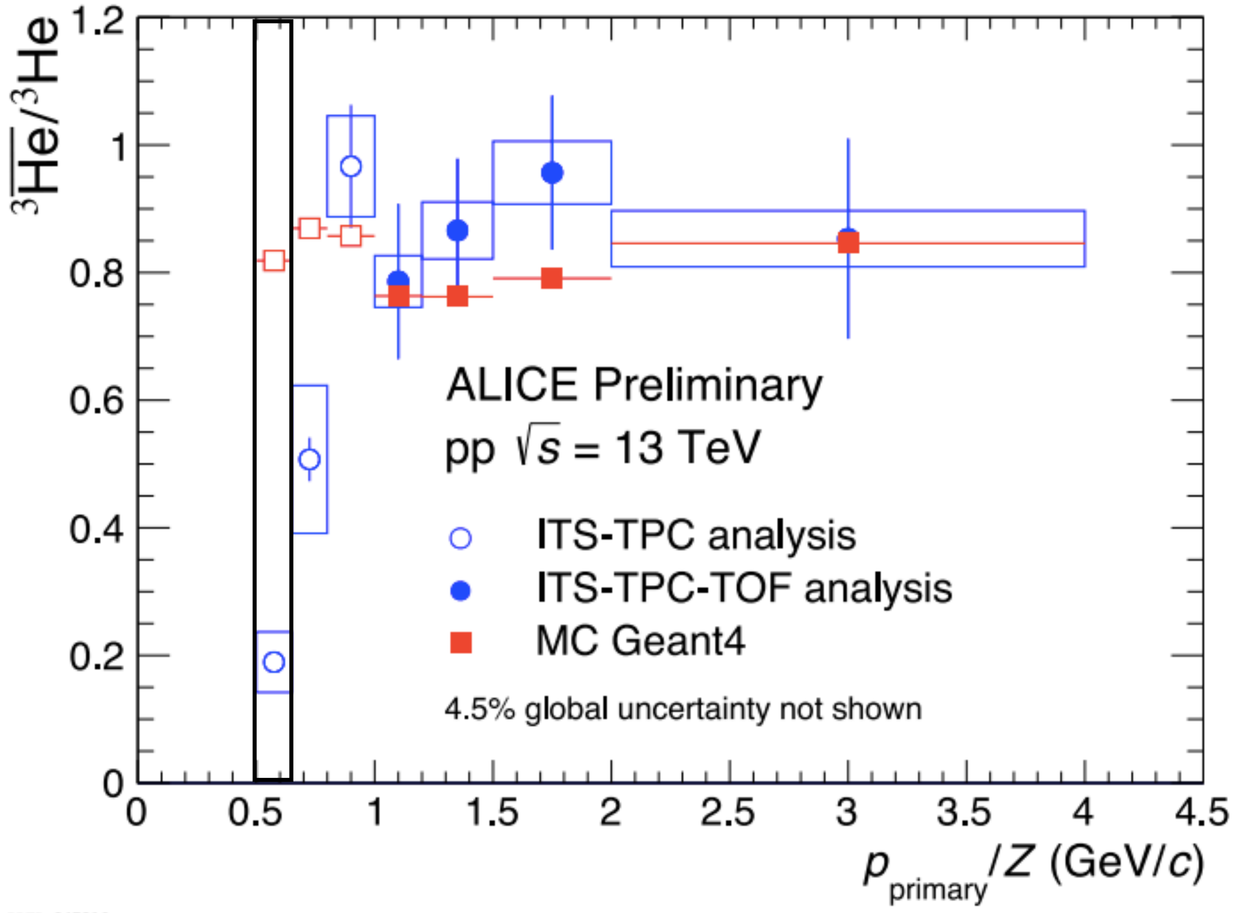
- Monte Carlo (MC) simulations with varied σ_{inel} (0.5x, 1x, 1.5x, 8x)



Extracting σ_{inel} from data and Monte Carlo

- Monte Carlo (MC) simulations with varied σ_{inel} (0.5x, 1x, 1.5x, 8x)
- In each momentum bin, compare the antiparticle-to-particle ratio in MC to the one in data.
- MC points are fit with an exponential, according to the Lambert-Beer law:

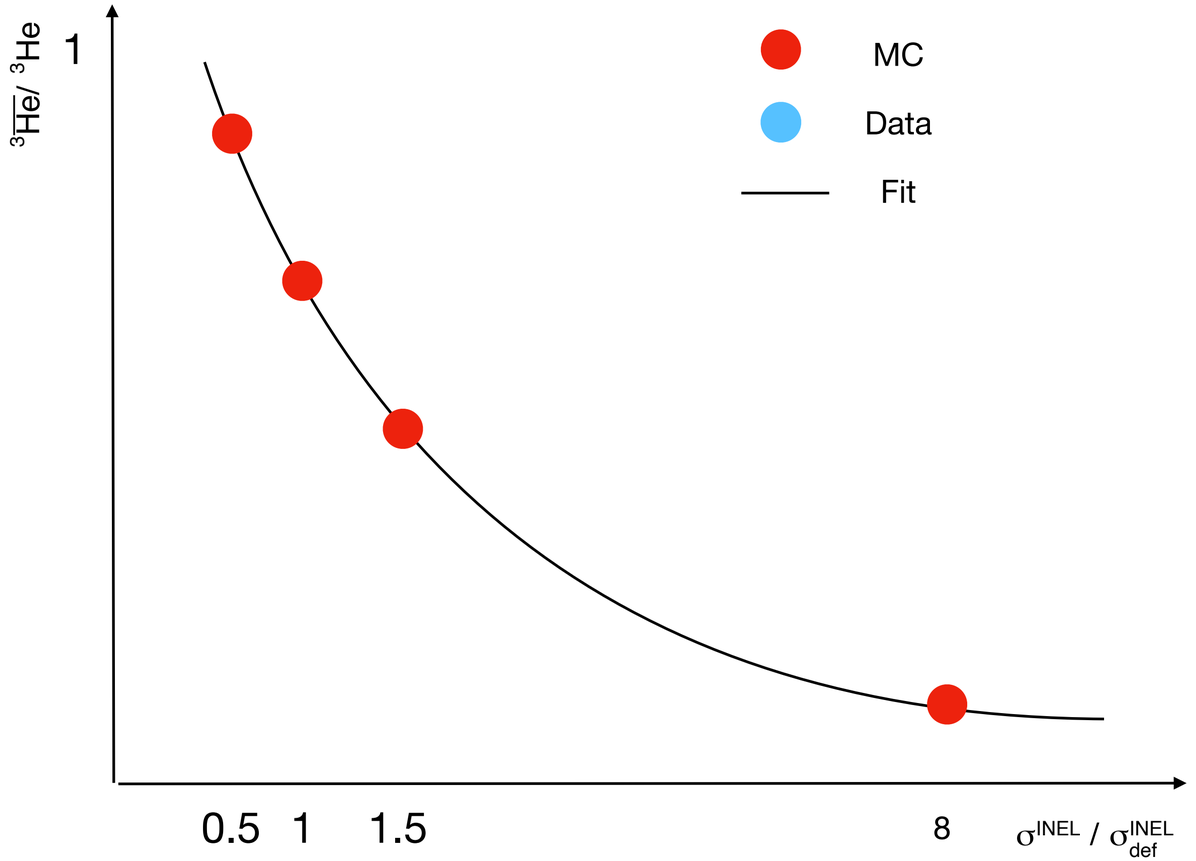
$$\overline{\mathrm{B}}/\mathrm{B} \propto \exp(-\sigma_{inel}/\sigma_{inel}^{def})$$



Extracting σ_{inel} from data and Monte Carlo

- Monte Carlo (MC) simulations with varied σ_{inel} (0.5x, 1x, 1.5x, 8x)
- In each momentum bin, compare the antiparticle-to-particle ratio in MC to the one in data.
- MC points are fit with an exponential, according to the Lambert-Beer law:

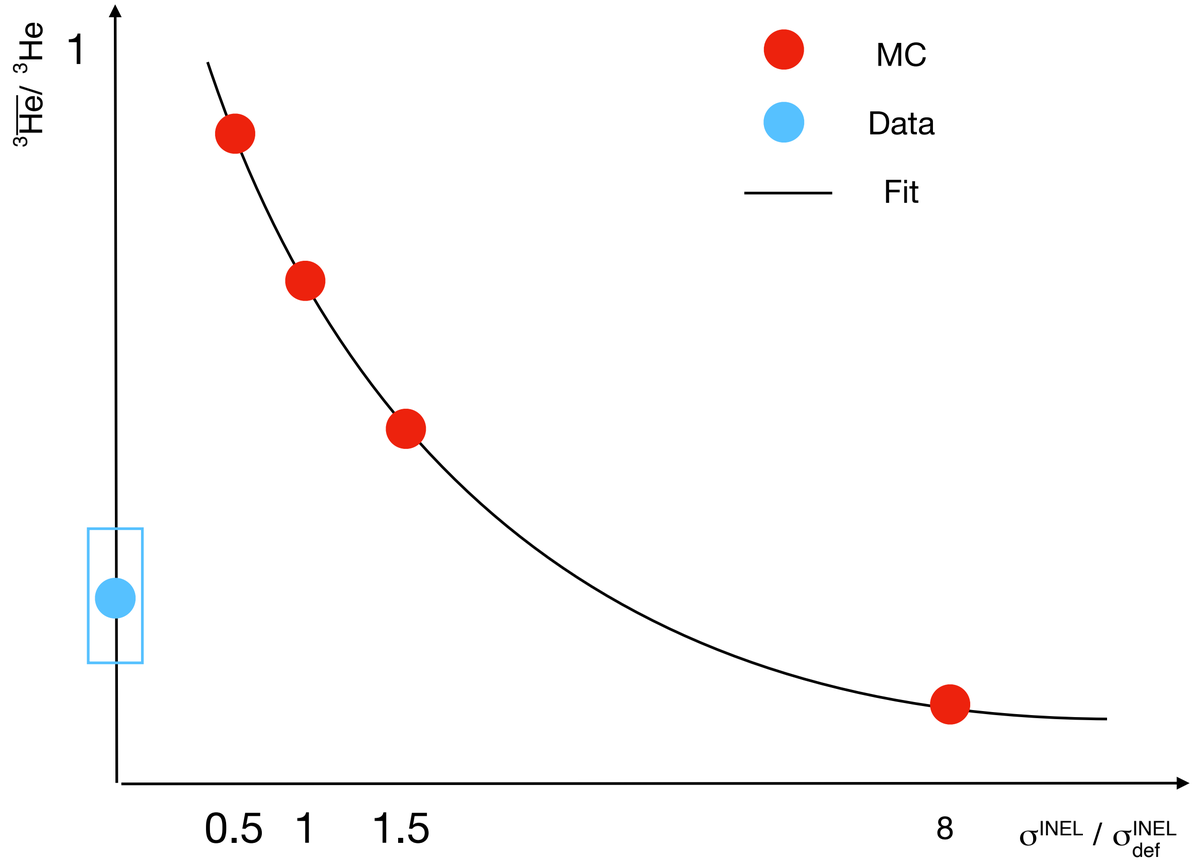
$$\overline{\mathrm{B}}/\mathrm{B} \propto \exp(-\sigma_{inel}/\sigma_{inel}^{def})$$



Extracting σ_{inel} from data and Monte Carlo

- Monte Carlo (MC) simulations with varied σ_{inel} (0.5x, 1x, 1.5x, 8x)
- In each momentum bin, compare the antiparticle-to-particle ratio in MC to the one in data.
- MC points are fit with an exponential, according to the Lambert-Beer law:

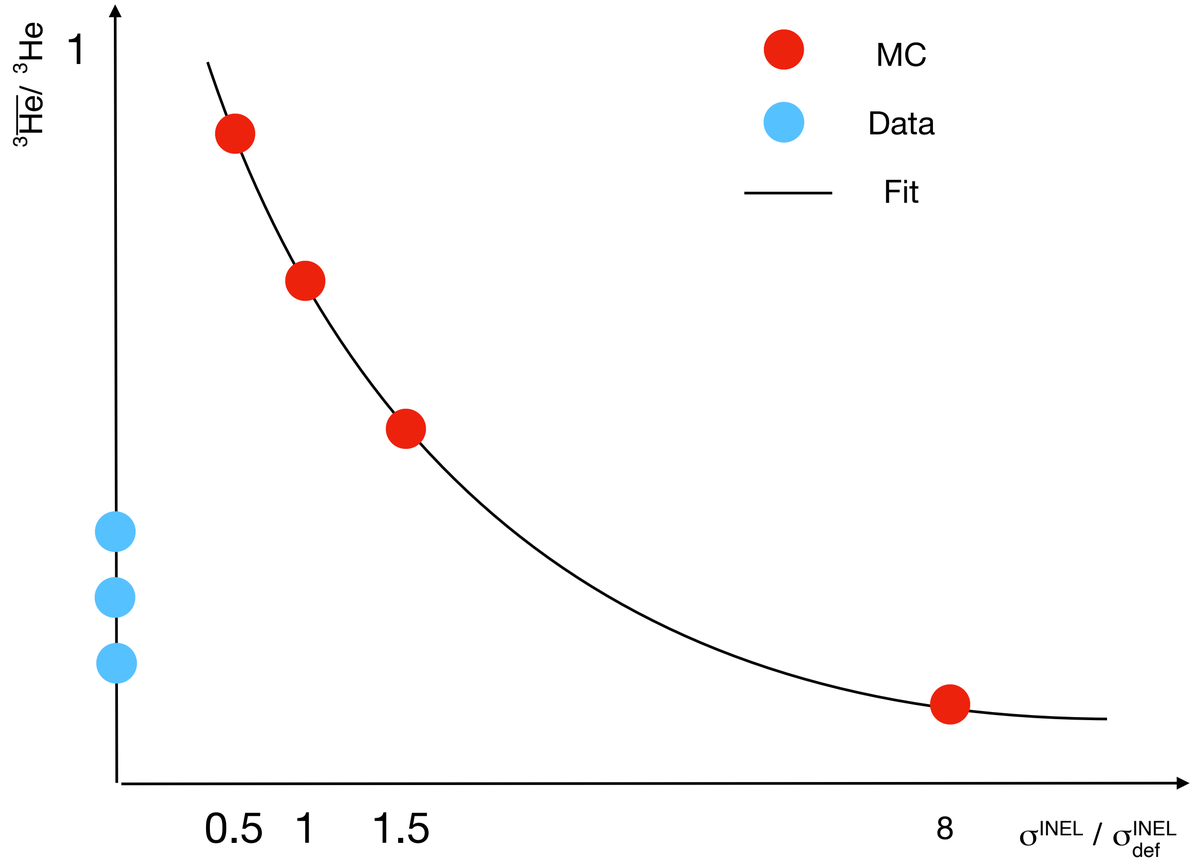
$$\overline{\mathrm{B}}/\mathrm{B} \propto \exp(-\sigma_{inel}/\sigma_{inel}^{def})$$



Extracting σ_{inel} from data and Monte Carlo

- Monte Carlo (MC) simulations with varied σ_{inel} (0.5x, 1x, 1.5x, 8x)
- In each momentum bin, compare the antiparticle-to-particle ratio in MC to the one in data.
- MC points are fit with an exponential, according to the Lambert-Beer law:

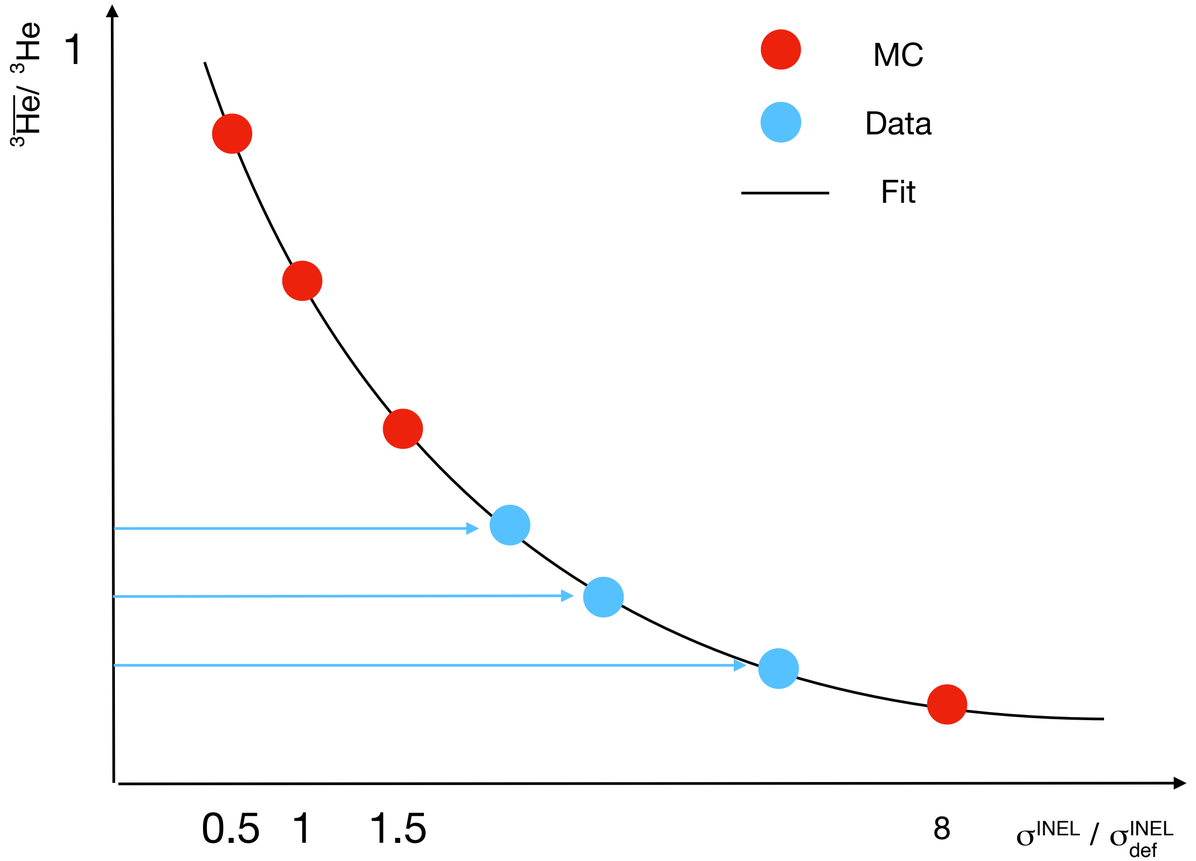
$$\overline{\mathrm{B}}/\mathrm{B} \propto \exp(-\sigma_{inel}/\sigma_{inel}^{def})$$



Extracting σ_{inel} from data and Monte Carlo

- Monte Carlo (MC) simulations with varied σ_{inel} (0.5x, 1x, 1.5x, 8x)
- In each momentum bin, compare the antiparticle-to-particle ratio in MC to the one in data.
- MC points are fit with an exponential, according to the Lambert-Beer law:

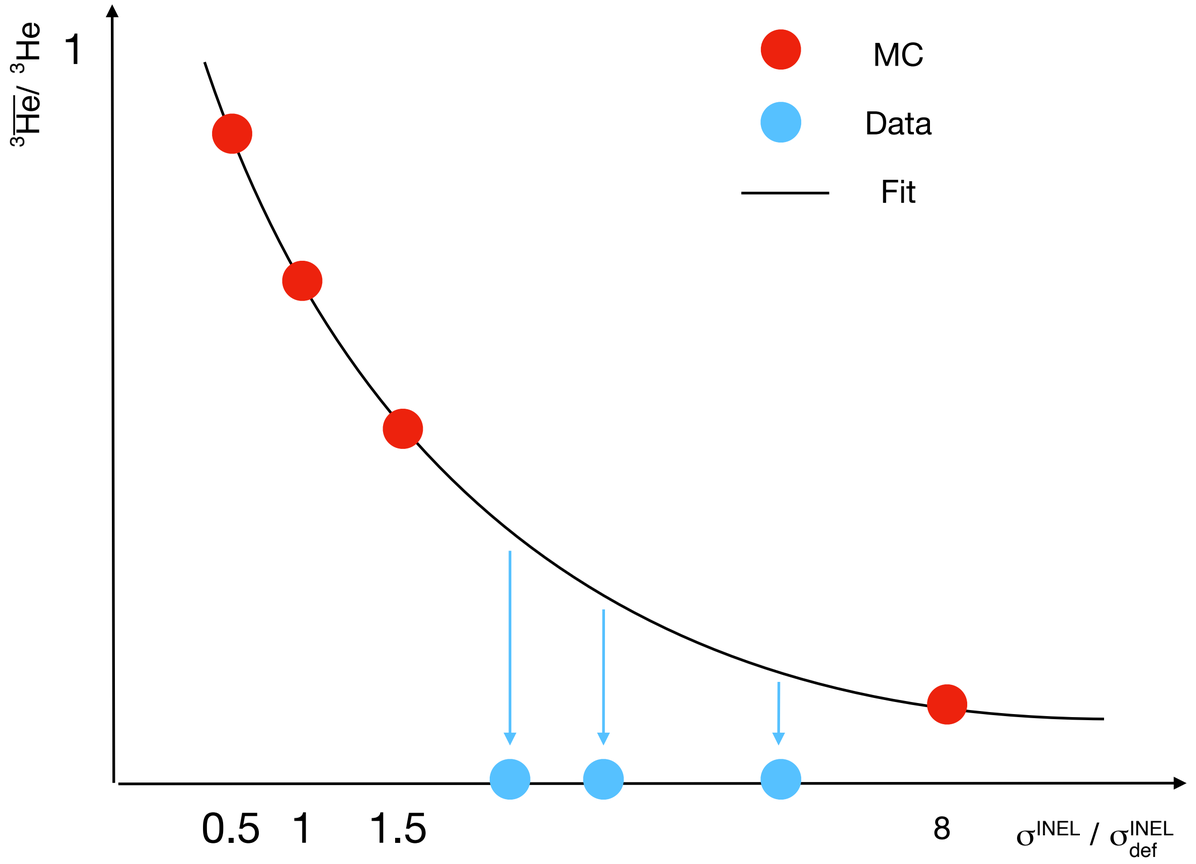
$$\overline{\mathrm{B}}/\mathrm{B} \propto \exp(-\sigma_{inel}/\sigma_{inel}^{def})$$



Extracting σ_{inel} from data and Monte Carlo

- Monte Carlo (MC) simulations with varied σ_{inel} (0.5x, 1x, 1.5x, 8x)
- In each momentum bin, compare the antiparticle-to-particle ratio in MC to the one in data.
- MC points are fit with an exponential, according to the Lambert-Beer law:

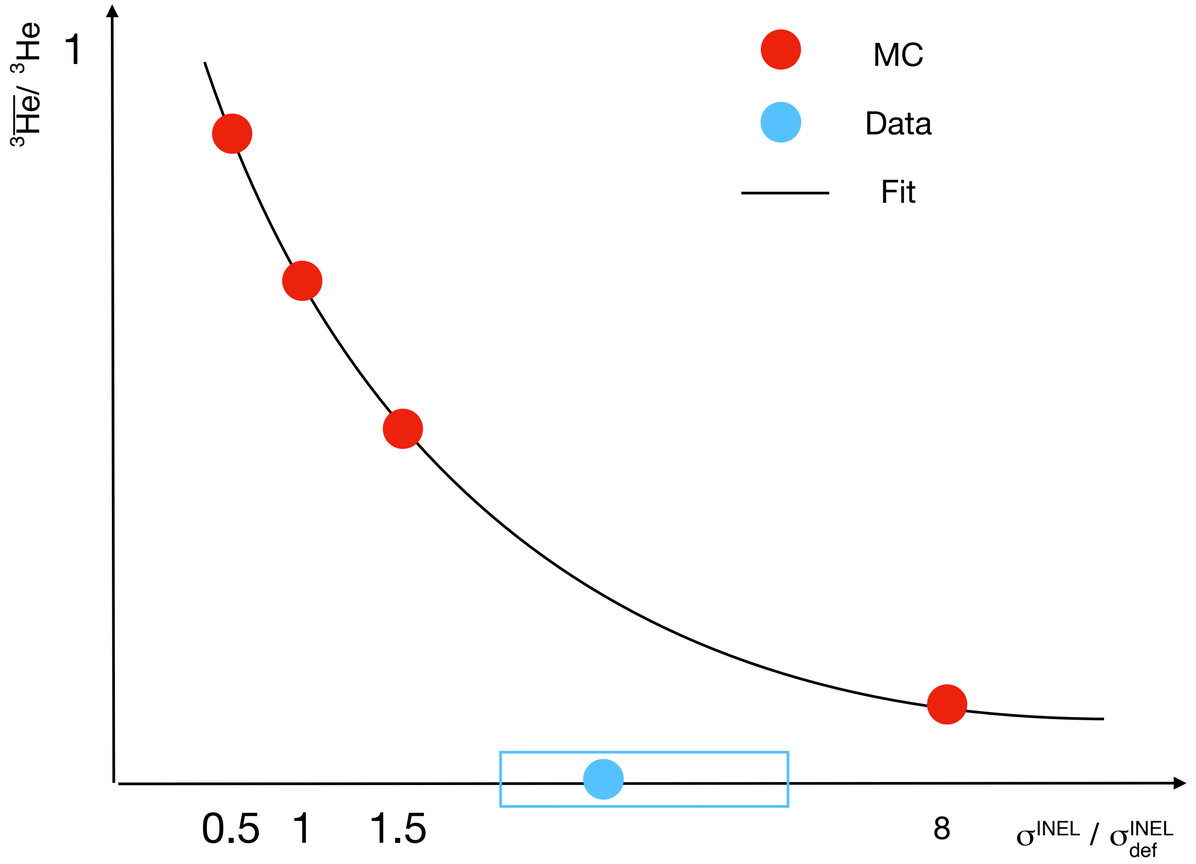
$$\overline{\mathrm{B}}/\mathrm{B} \propto \exp(-\sigma_{inel}/\sigma_{inel}^{def})$$



Extracting σ_{inel} from data and Monte Carlo

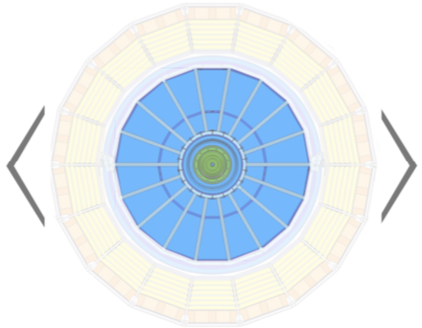
- Monte Carlo (MC) simulations with varied σ_{inel} (0.5x, 1x, 1.5x, 8x)
- In each momentum bin, compare the antiparticle-to-particle ratio in MC to the one in data.
- MC points are fit with an exponential, according to the Lambert-Beer law:

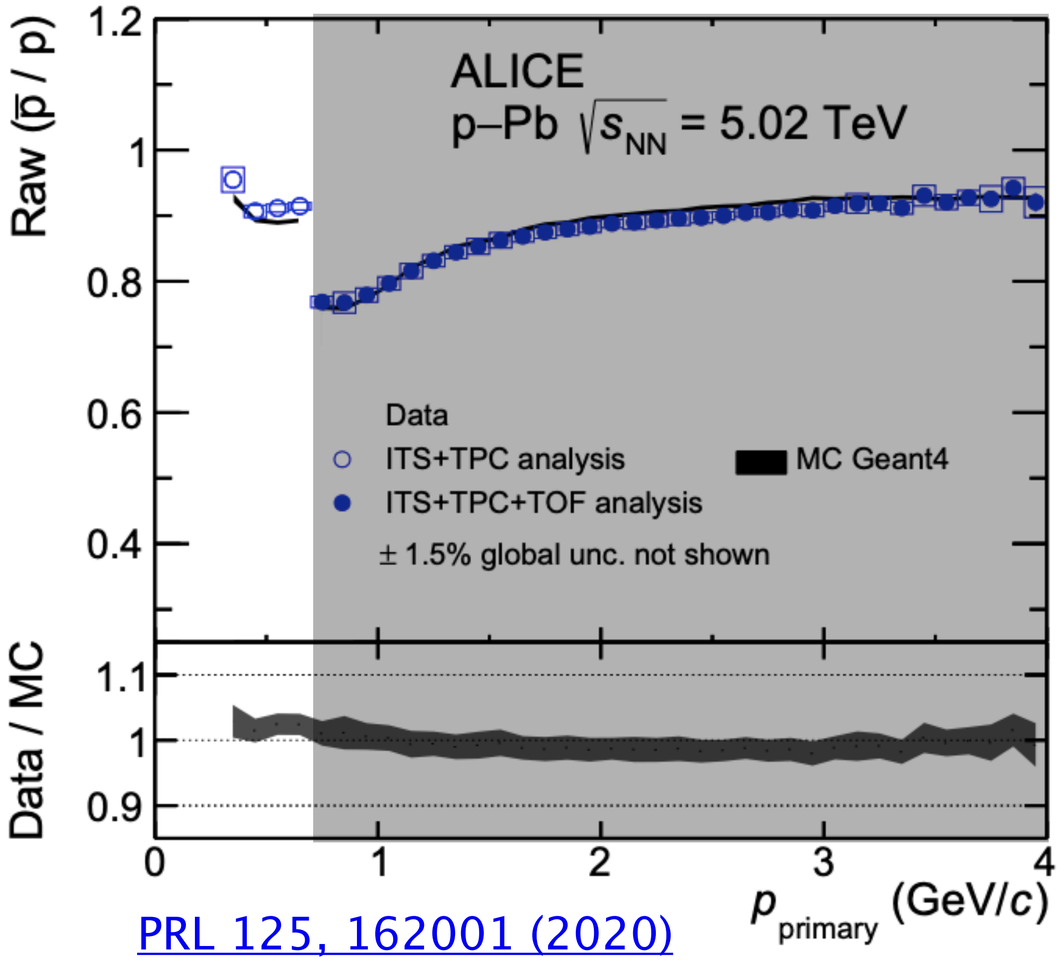
$$\overline{\mathrm{B}}/\mathrm{B} \propto \exp(-\sigma_{inel}/\sigma_{inel}^{def})$$

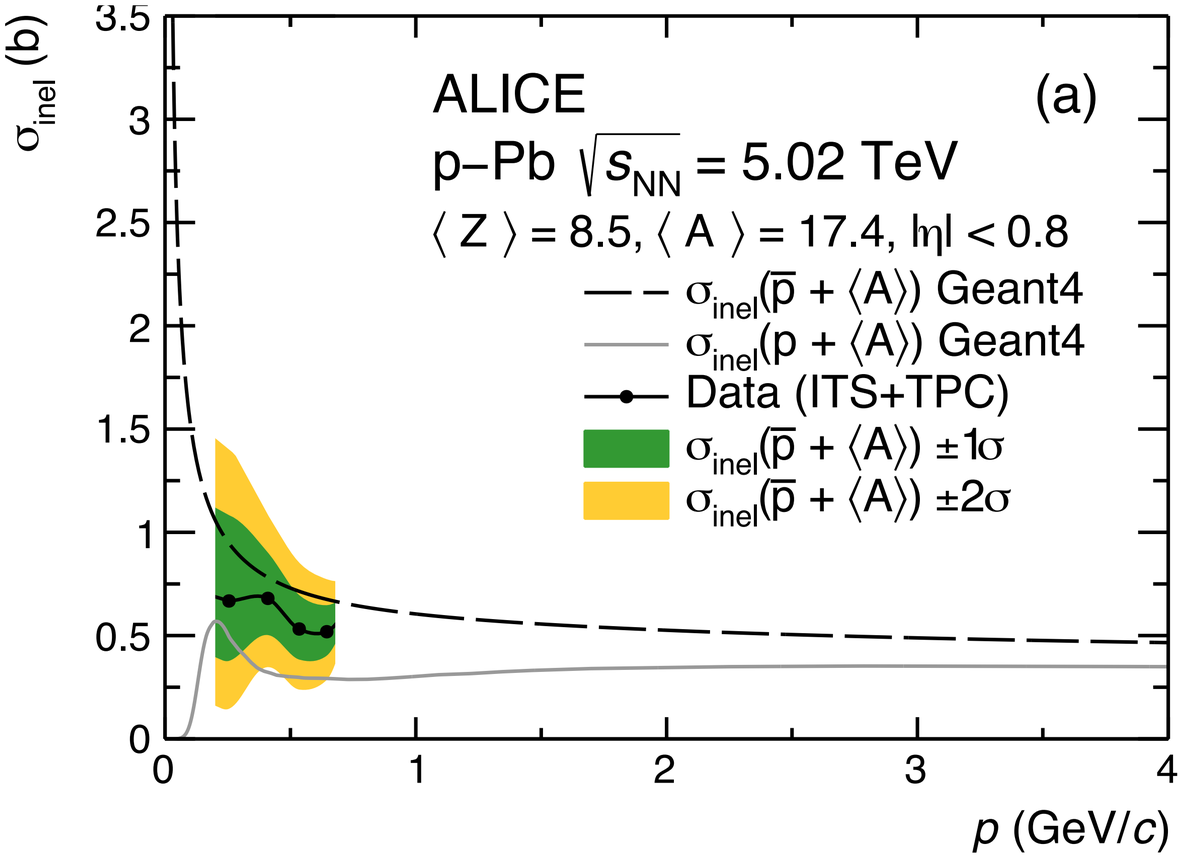


Antiproton inelastic cross section

$\sigma_{\text{inel}}(\overline{\text{p}})$ on average ALICE detector material. Good agreement with Geant4 parameterization confirms analysis method.



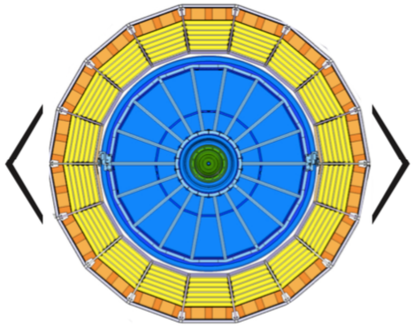


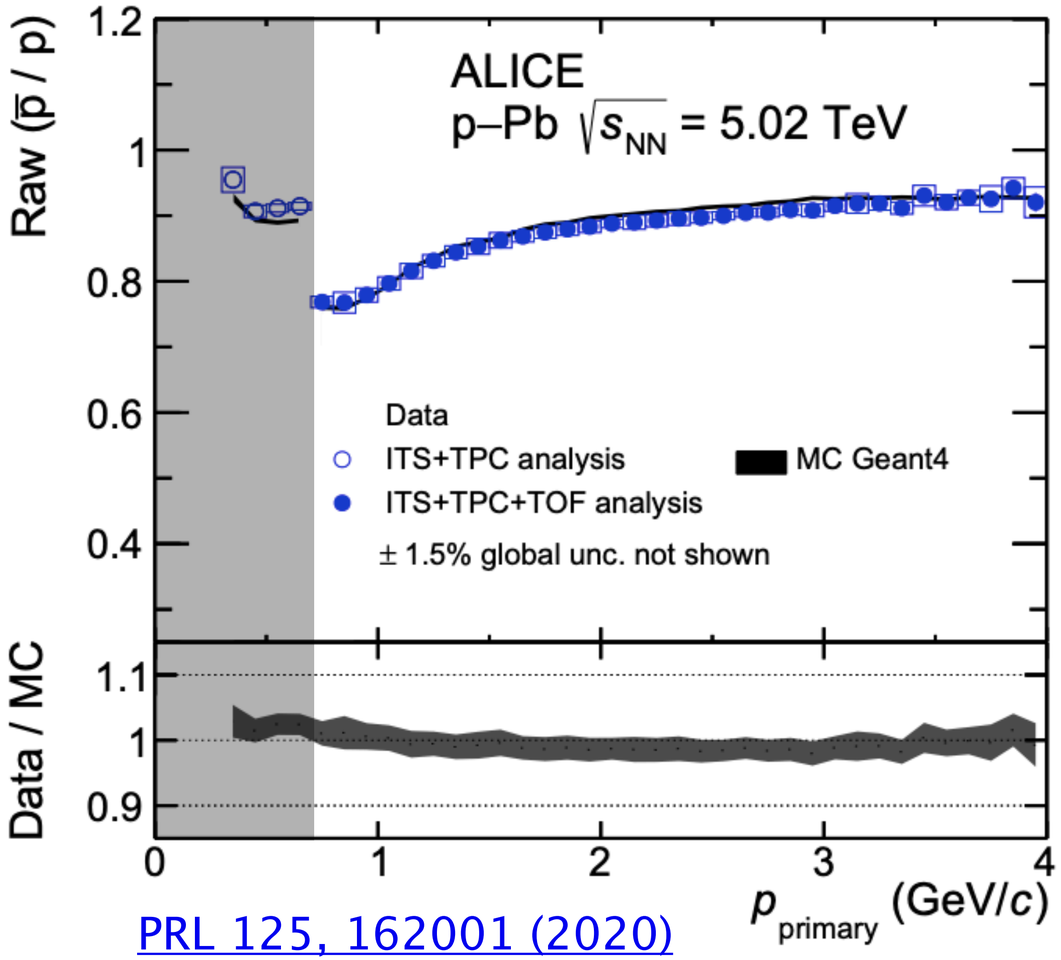


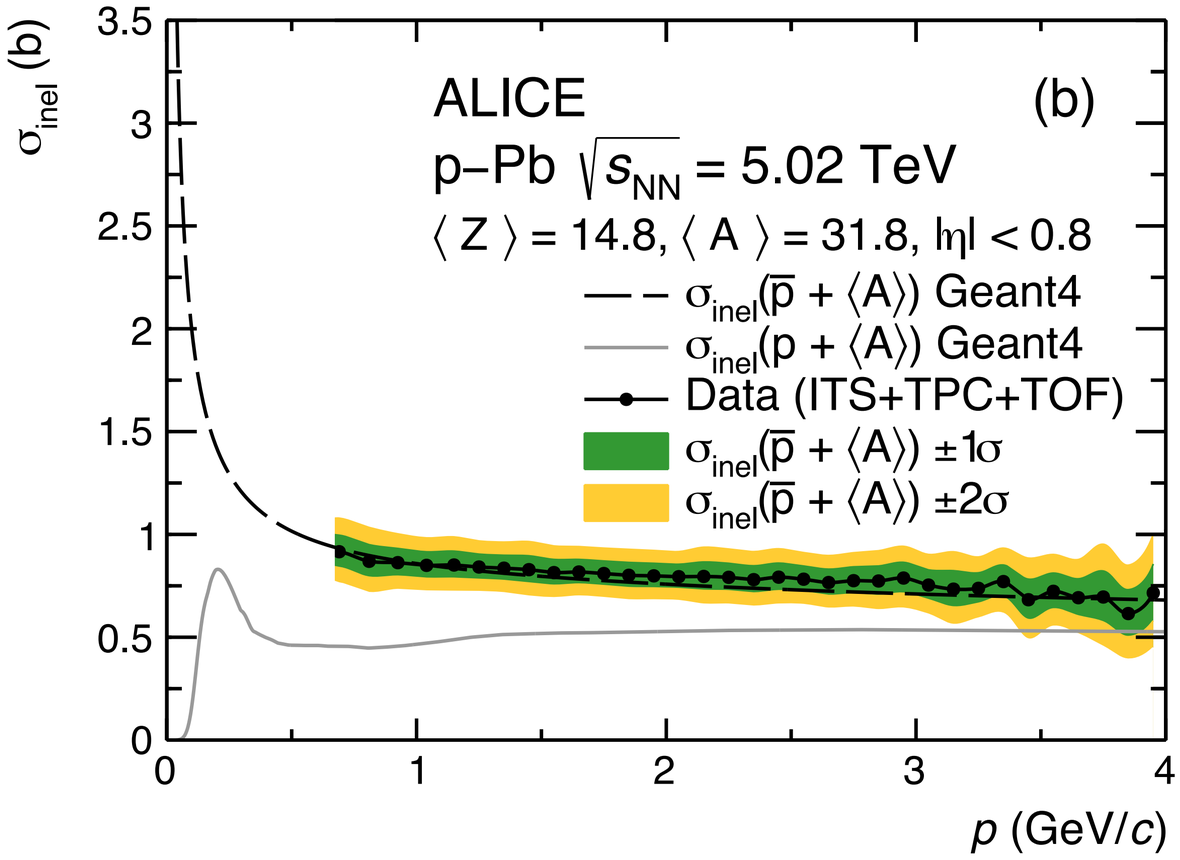
PRL 125, 162001 (2020)

Antiproton inelastic cross section

$\sigma_{\text{inel}}(\overline{\text{p}})$ on average ALICE detector material. Good agreement with Geant4 parameterization confirms analysis method.



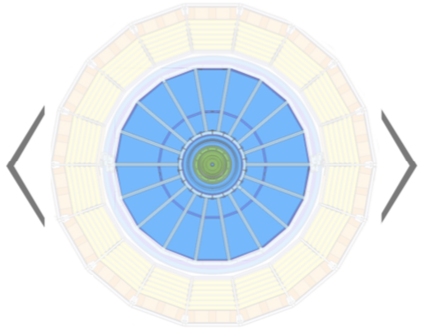


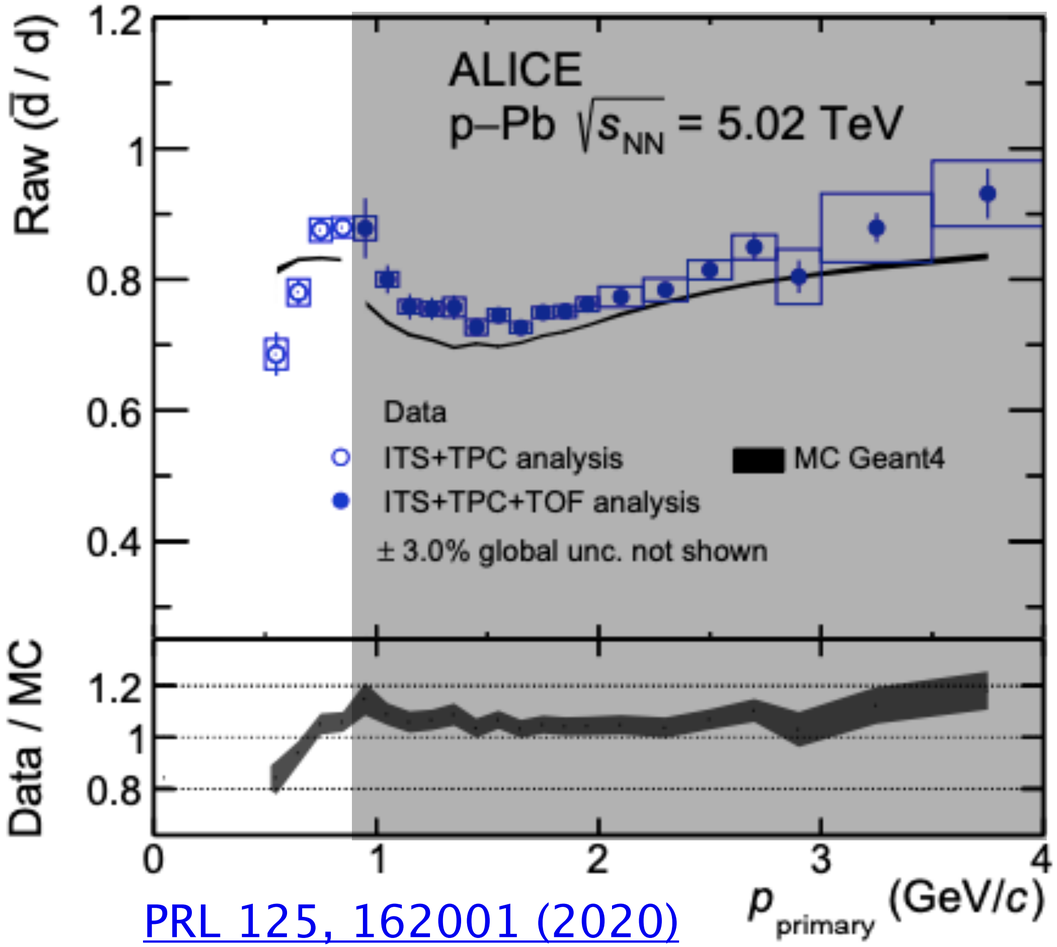


PRL 125, 162001 (2020)

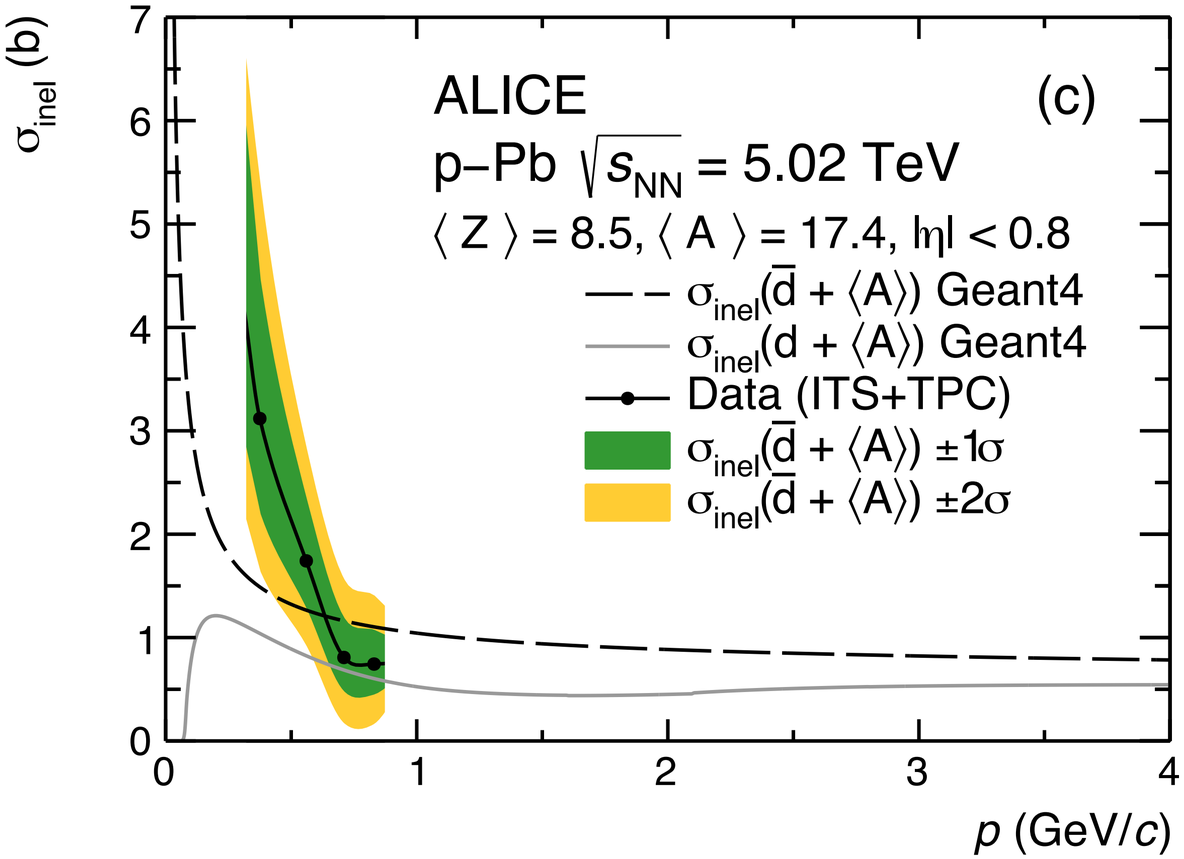
Antideuteron inelastic cross section

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



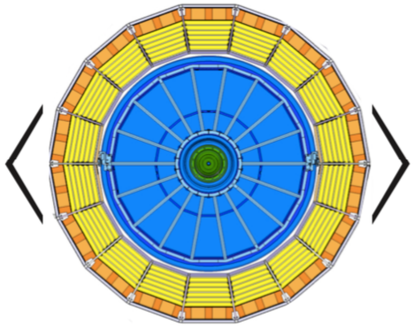


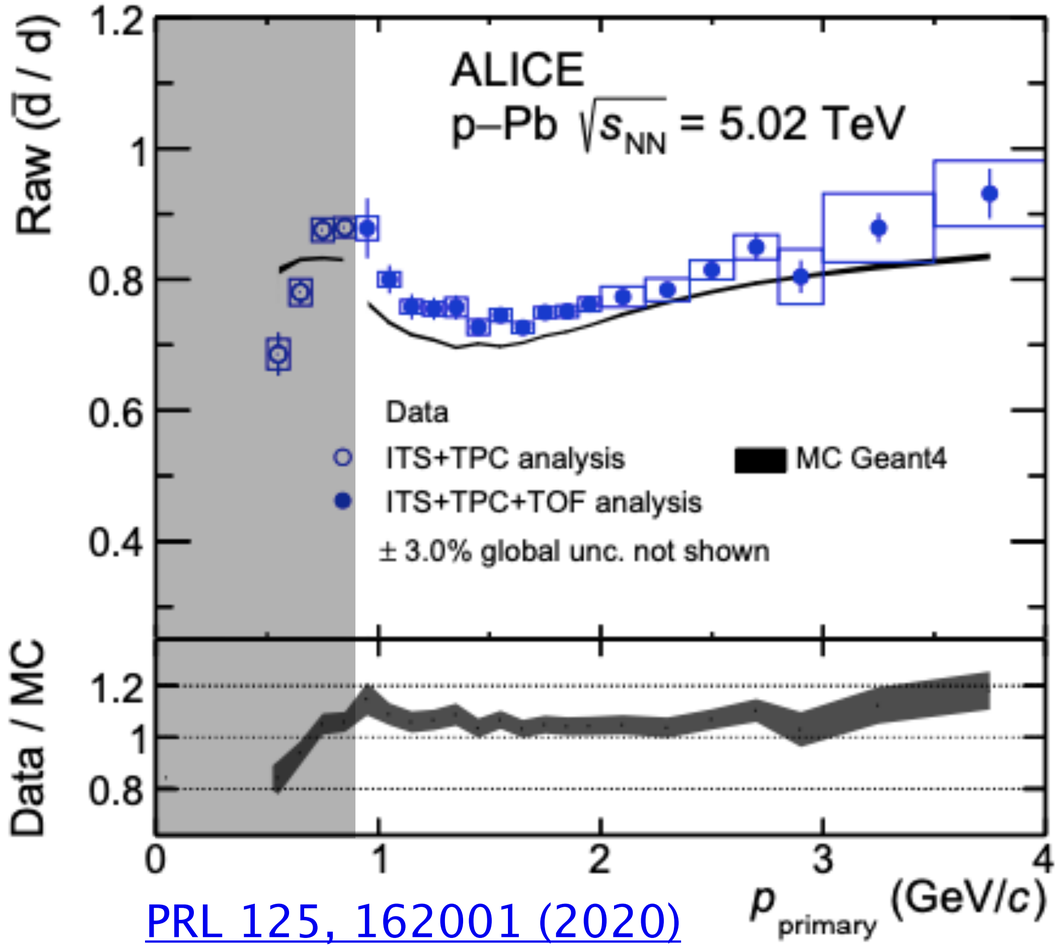
PRL 125, 162001 (2020)



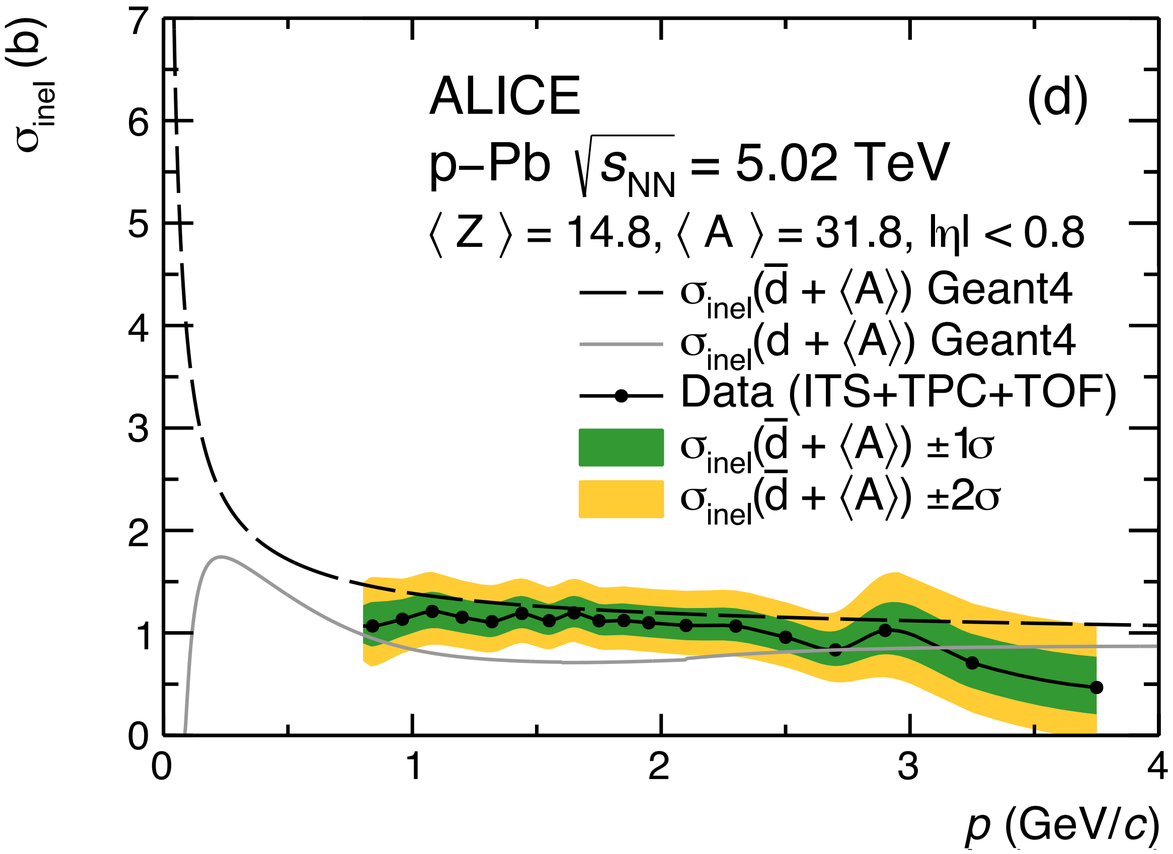
Antideuteron inelastic cross section

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



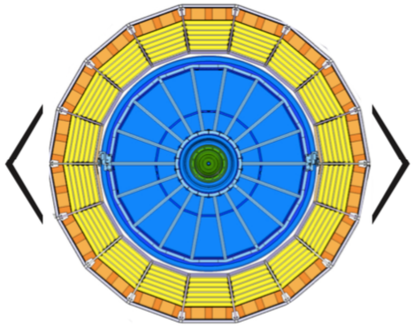


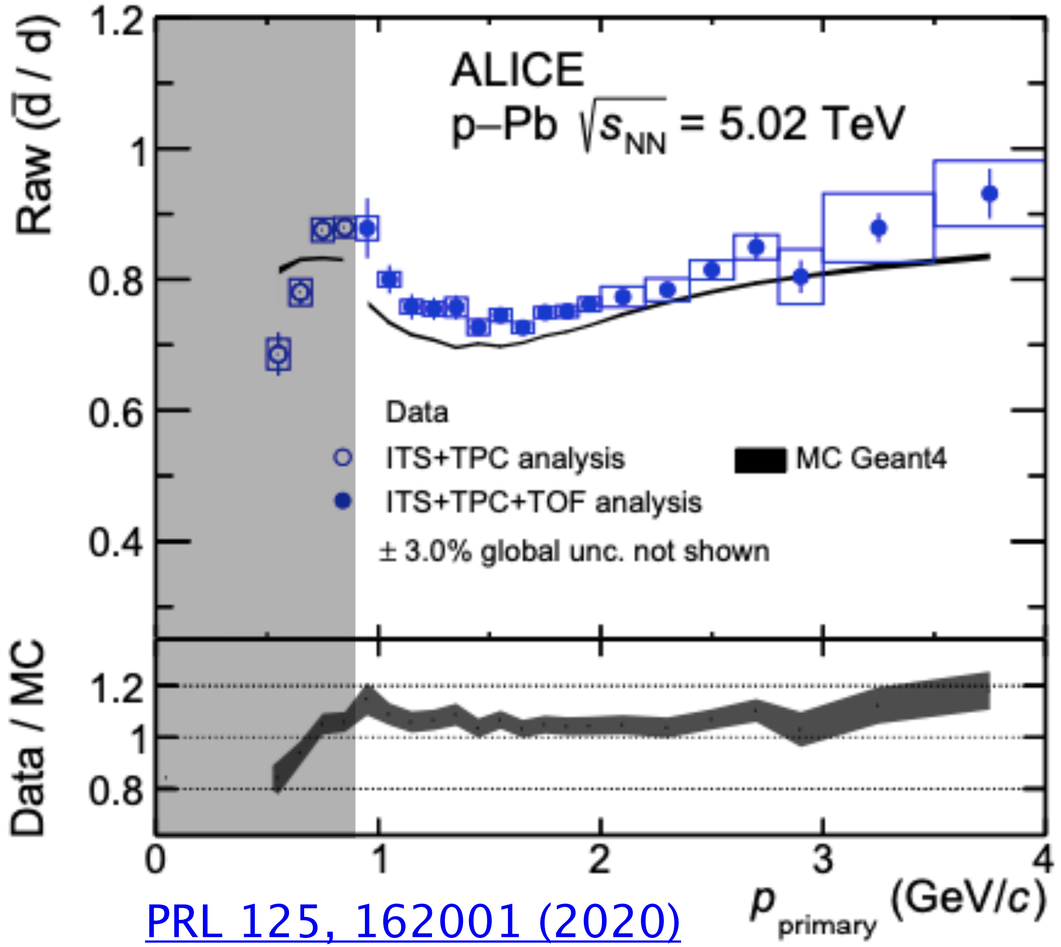
PRL 125, 162001 (2020)



Antideuteron inelastic cross section

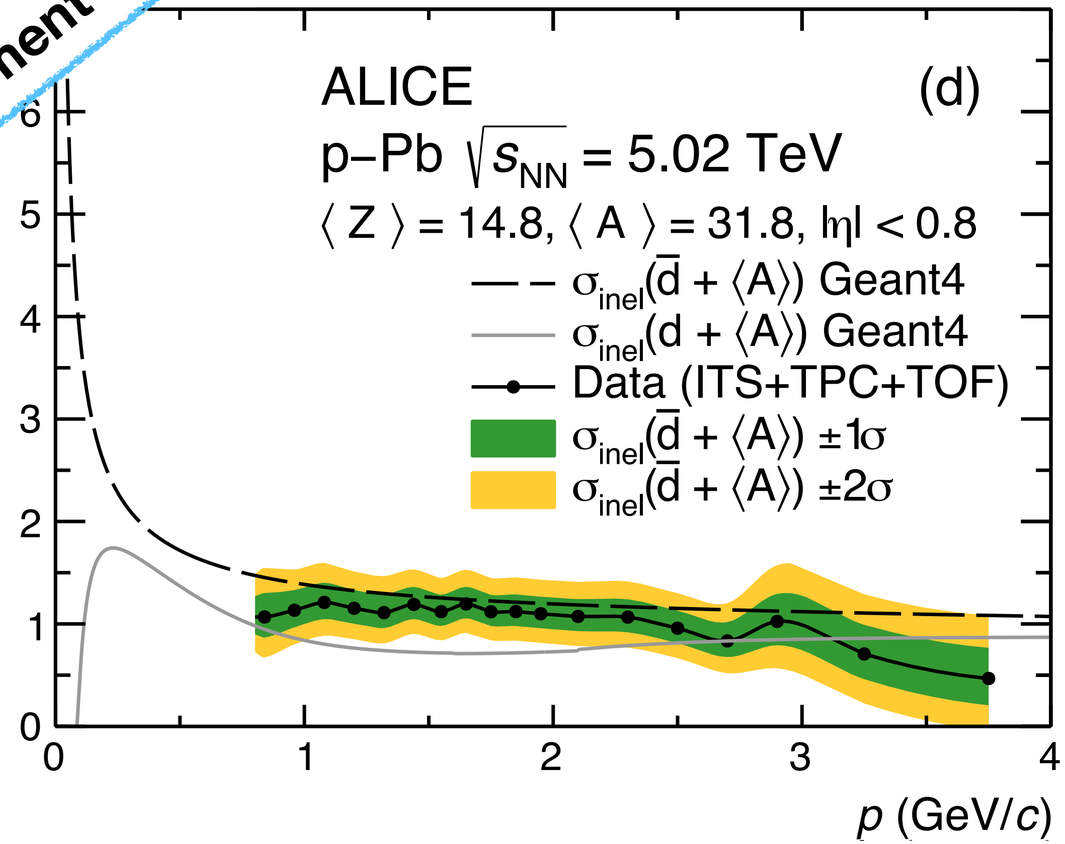
$\sigma_{\text{inel}}(\overline{\text{d}})$ on average ALICE detector material.
Hint of a steeper rise at low momentum.





PRL 125, 162001 (2020)

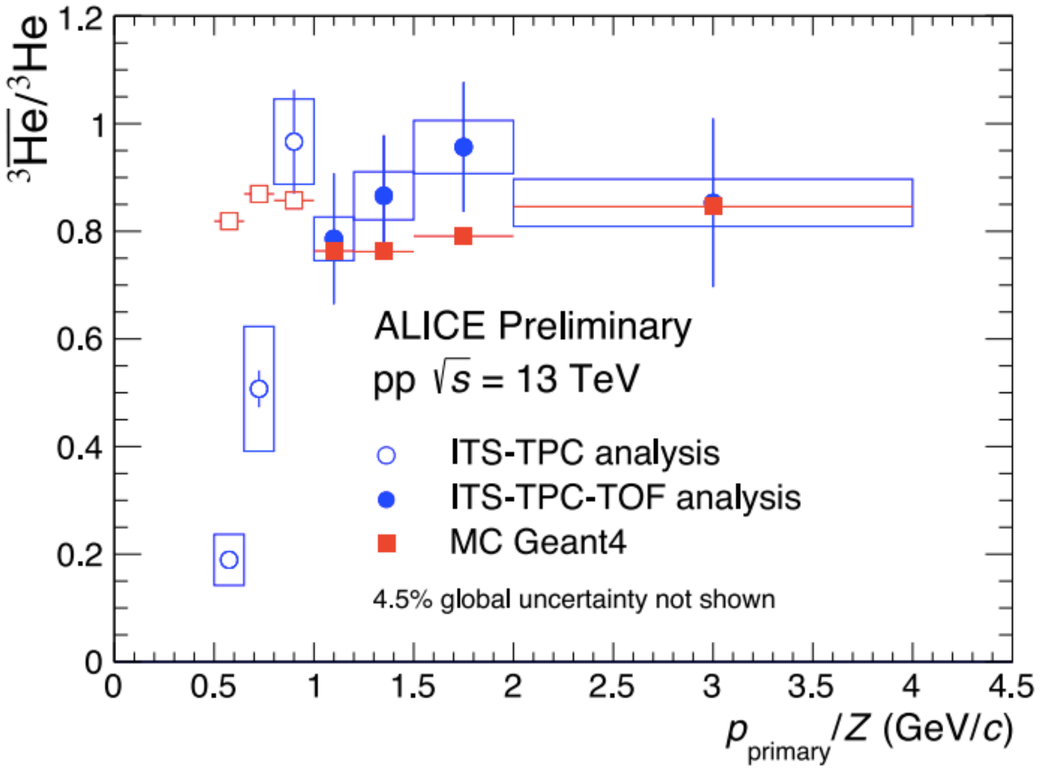
First low energy measurement of $\sigma_{\text{inel}}(\overline{\text{d}})$

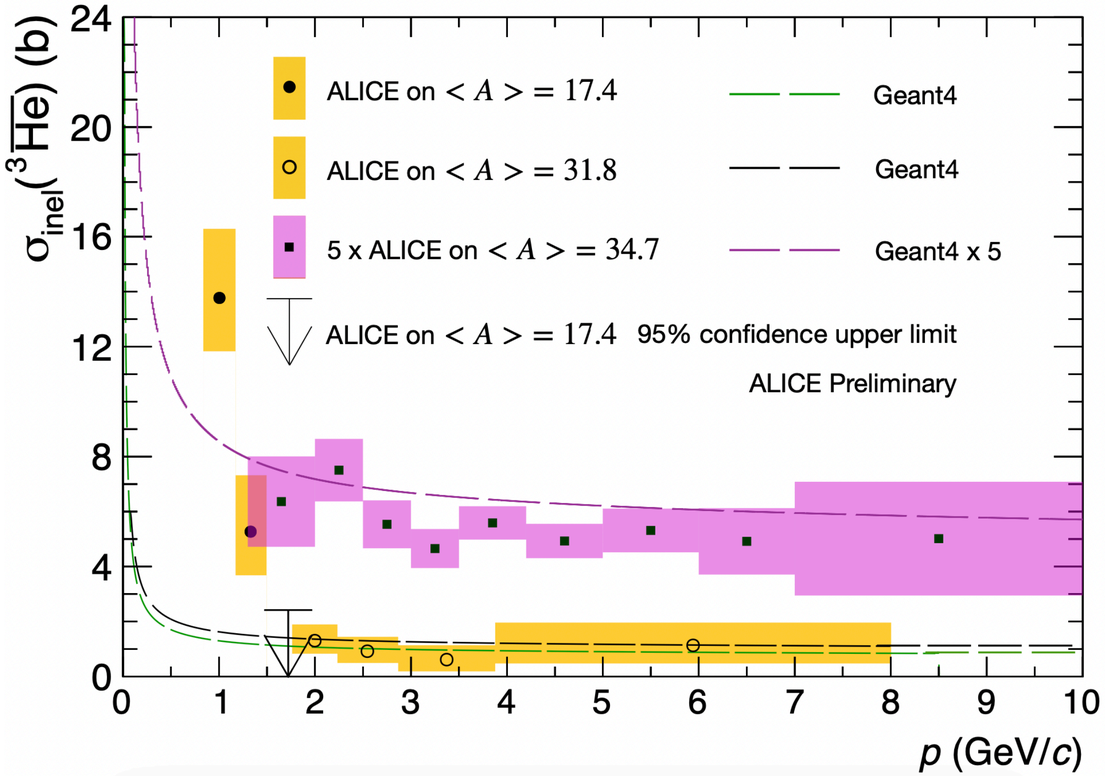


$^3\overline{\text{He}}$ inelastic cross section

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

- Much steeper rise at low momentum than Geant4
- Good agreement for p > 1.5 GeV/c between the measurements and Geant4

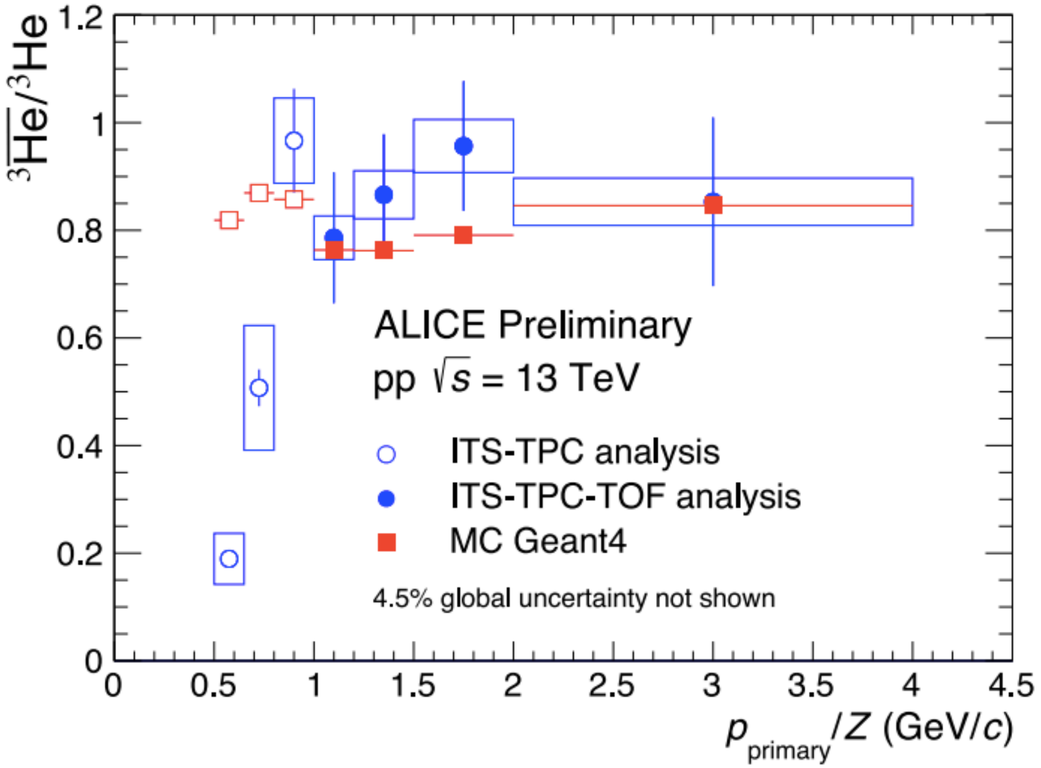


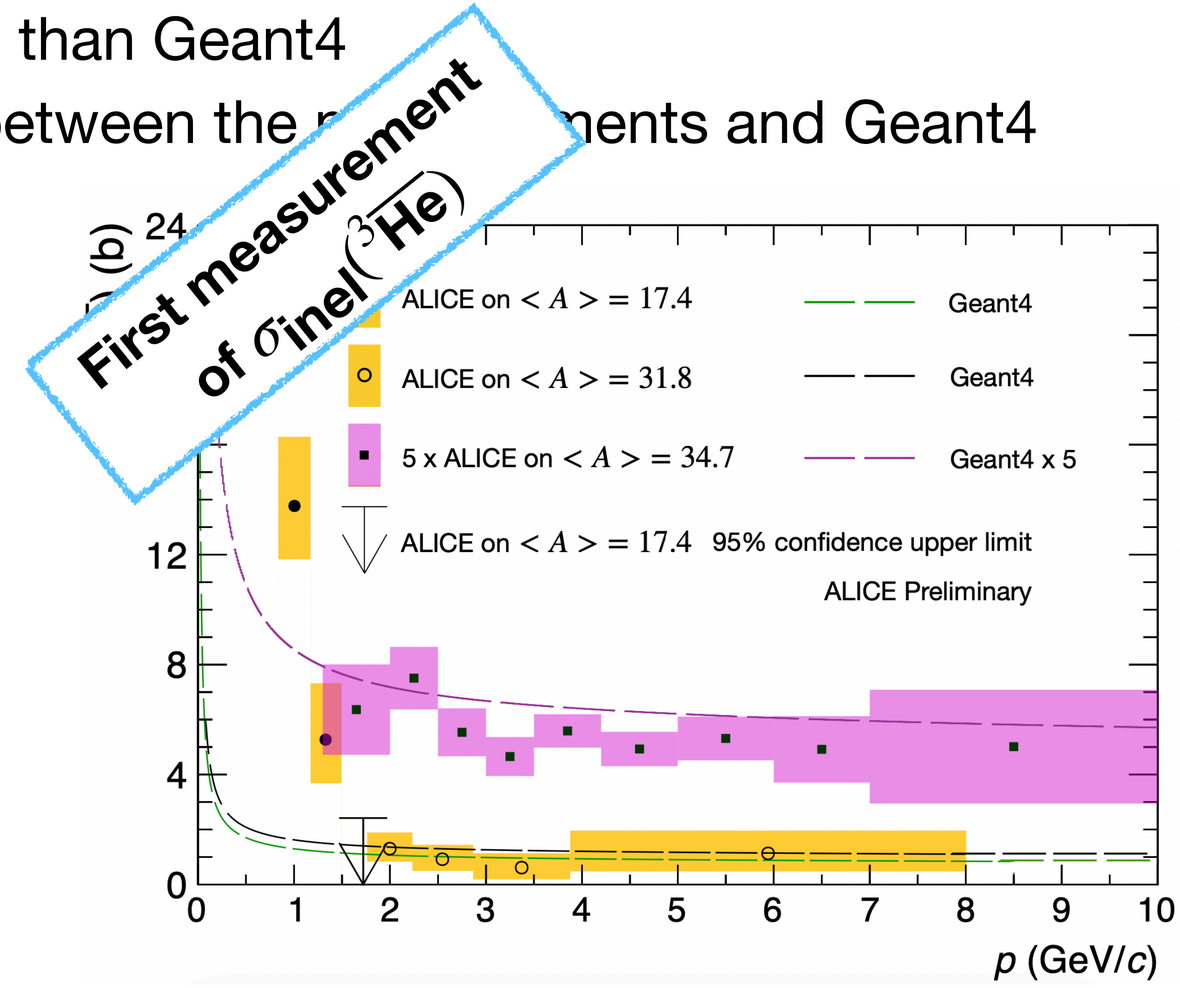


$^3\overline{\text{He}}$ inelastic cross section

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

- Much steeper rise at low momentum than Geant4
- Good agreement for p > 1.5 GeV/c between the m[illegible]ments and Geant4

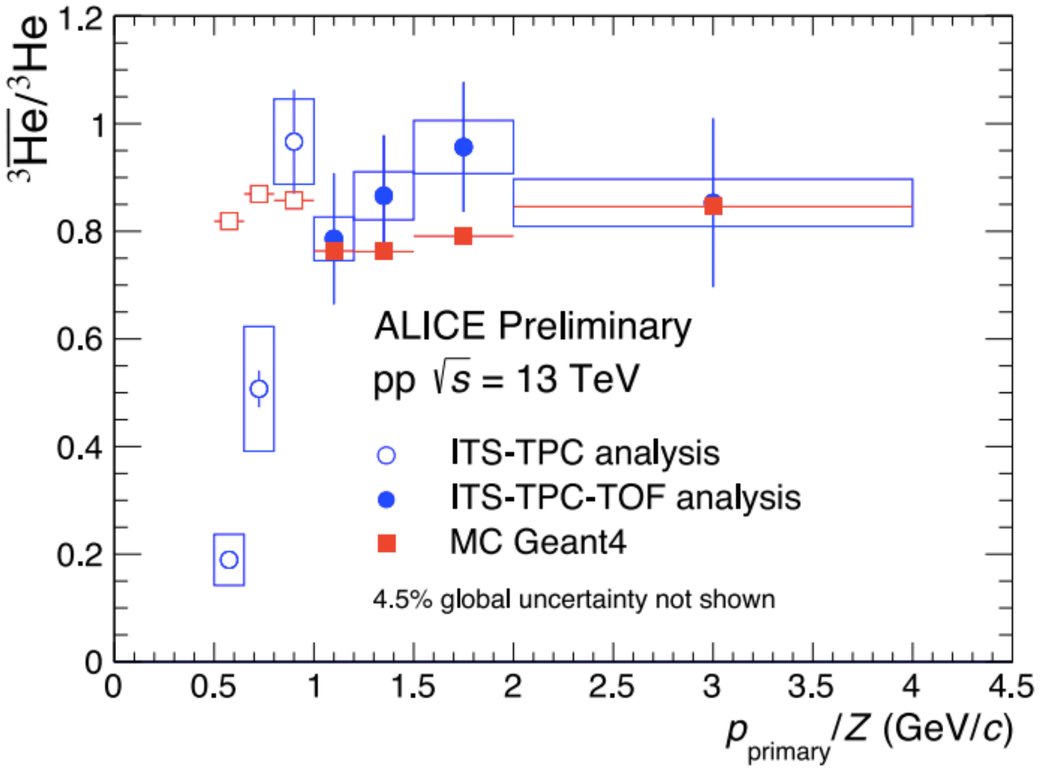




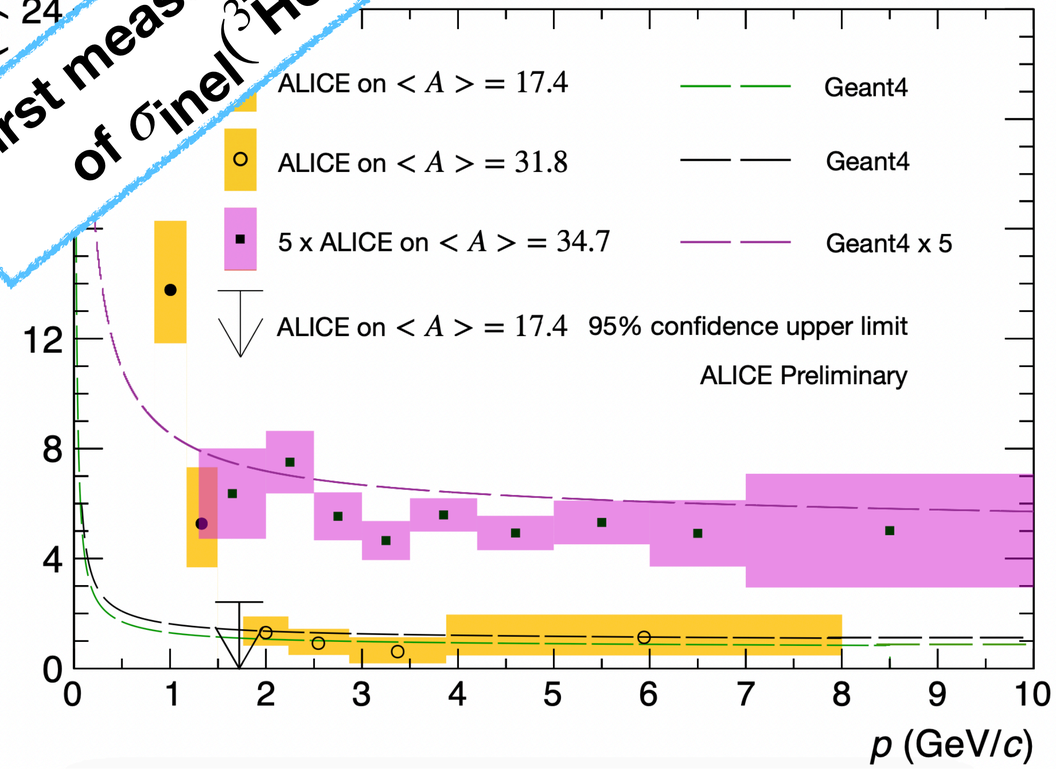
$^3\overline{\text{He}}$ inelastic cross section

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

- Much steeper rise at low momentum than Geant4
- Good agreement for p > 1.5 GeV/c between the m…ments and Geant4

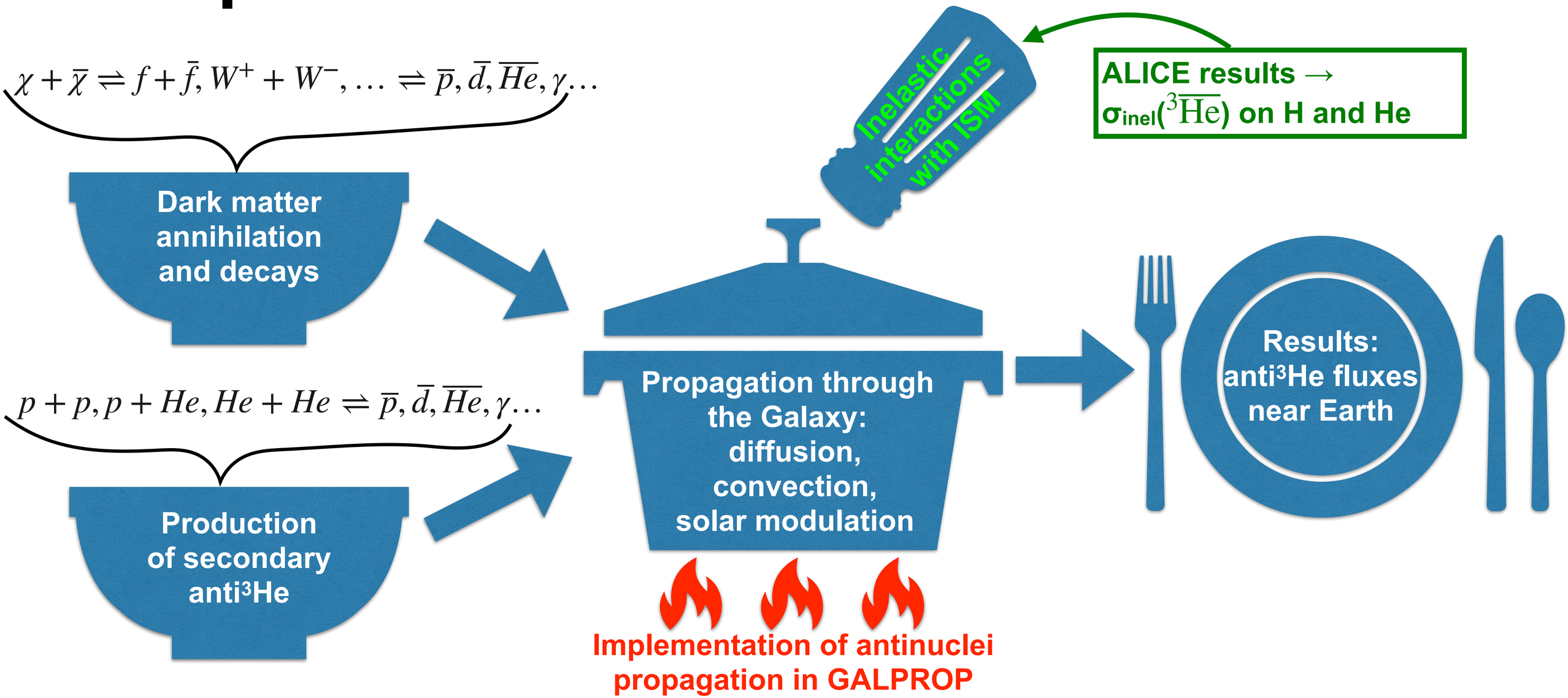


First measurement of $\sigma_{\text{inel}}(^3\overline{\text{He}})$



How do these measurements impact cosmic ray antinuclei?

Recipe to cook antinuclei fluxes



GALPROP

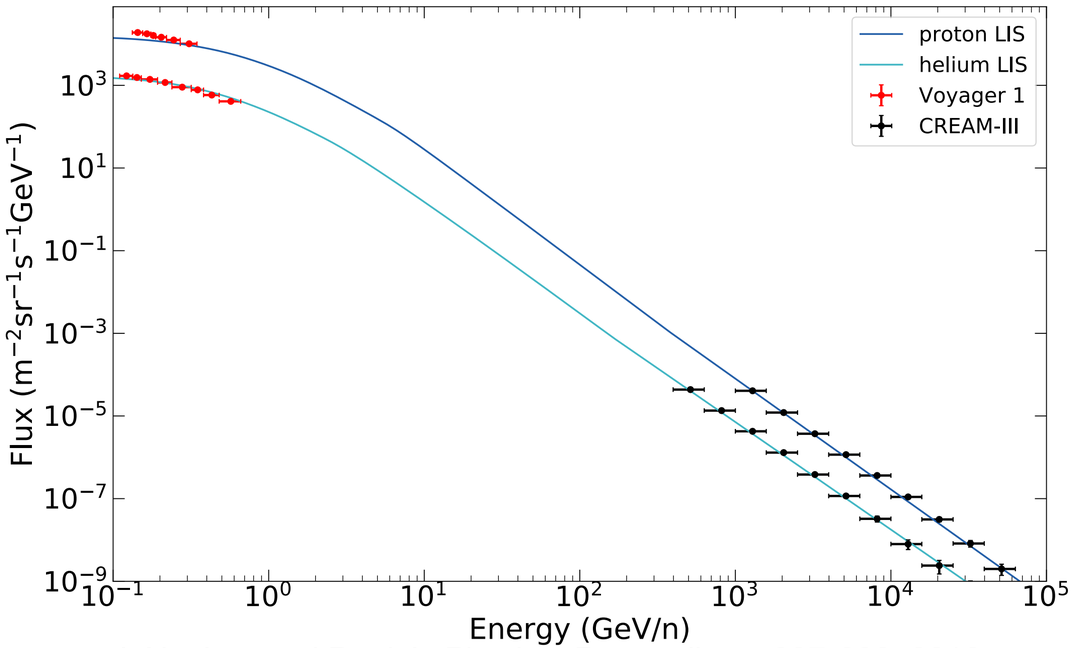
Transport equation

$$\frac{\partial \psi}{\partial t} = q(\mathbf{r}, p) + \mathbf{div}(D_{xx}\mathbf{grad}\psi - \mathbf{V}\psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{\psi}{p^2} - \frac{\partial}{\partial p}\left[\psi \frac{dp}{dt} - \frac{p}{3}(\mathbf{div} \cdot \mathbf{V})\psi\right] - \frac{\psi}{\tau_f} - \frac{\psi}{\tau_r}$$

Source Function

Propagation: diffusion, convection…

Fragmentation, annihilation



A. Strong, et. al. Nuclear and Particle Physics Proceedings, 297-299, 2018

Propagation can be constrained using proton and heavier nuclei cosmic ray measurements

Antinuclei source terms

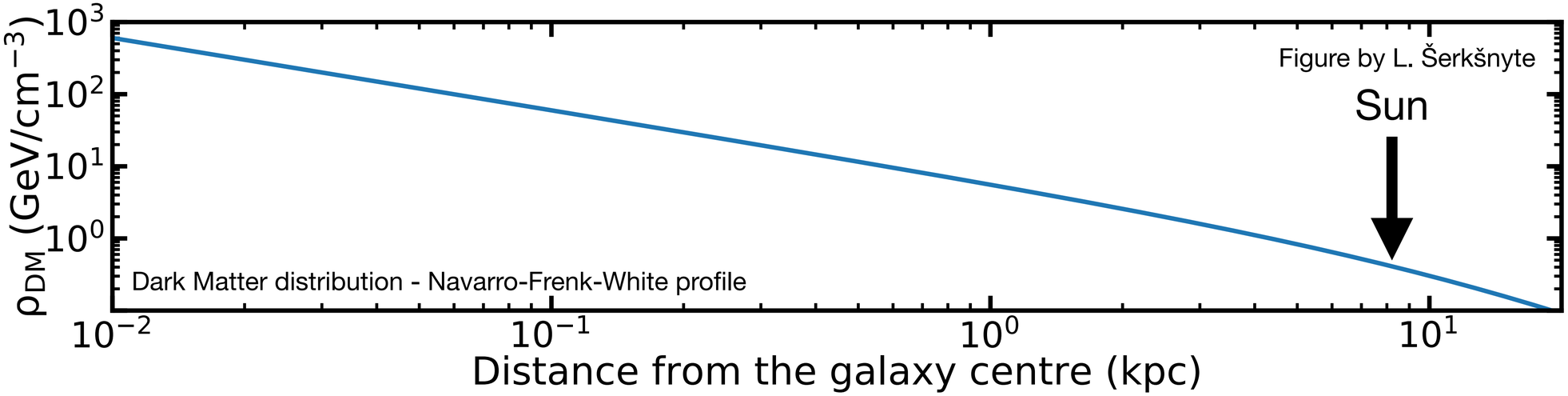
- The source term for antinuclei from dark matter can be written as:

$$q(\mathrm{r}, E_{kin}) = \frac{1}{2}\frac{\rho^2_{\mathrm{DM}}(\mathrm{r})}{m^2_\chi}\langle\sigma v\rangle(1+\epsilon)\frac{dN}{dE_{kin}}$$

Antinuclei source terms

- The source term for antinuclei from dark matter can be written as:

$$q(\mathrm{r}, E_{kin}) = \frac{1}{2}\frac{\rho^2_{\mathrm{DM}}(\mathrm{r})}{m^2_\chi}\langle\sigma v\rangle(1+\epsilon)\frac{dN}{dE_{kin}}$$



Antinuclei source terms

- The source term for antinuclei from dark matter can be written as:

$$q(\mathrm{r}, E_{kin}) = \frac{1}{2}\frac{\rho^2_{\mathrm{DM}}(\mathrm{r})}{m^2_\chi}\langle\sigma v\rangle(1+\epsilon)\frac{dN}{dE_{kin}}$$

This is the thermally averaged annihilation cross section.

We can use $<\sigma v> = 2.6\mathrm{x}10^{-26}\mathrm{cm}^3\mathrm{s}^{-1}$

[1] Korsmeier et al, Phys. Rev. D. 97, 103011 (2018)

Antinuclei source terms

- The source term for antinuclei from dark matter can be written as:

$$q(\mathrm{r}, E_{kin}) = \frac{1}{2}\frac{\rho^2_{\mathrm{DM}}(\mathrm{r})}{m^2_\chi}\langle\sigma v\rangle(1+\epsilon)\frac{dN}{dE_{kin}}$$

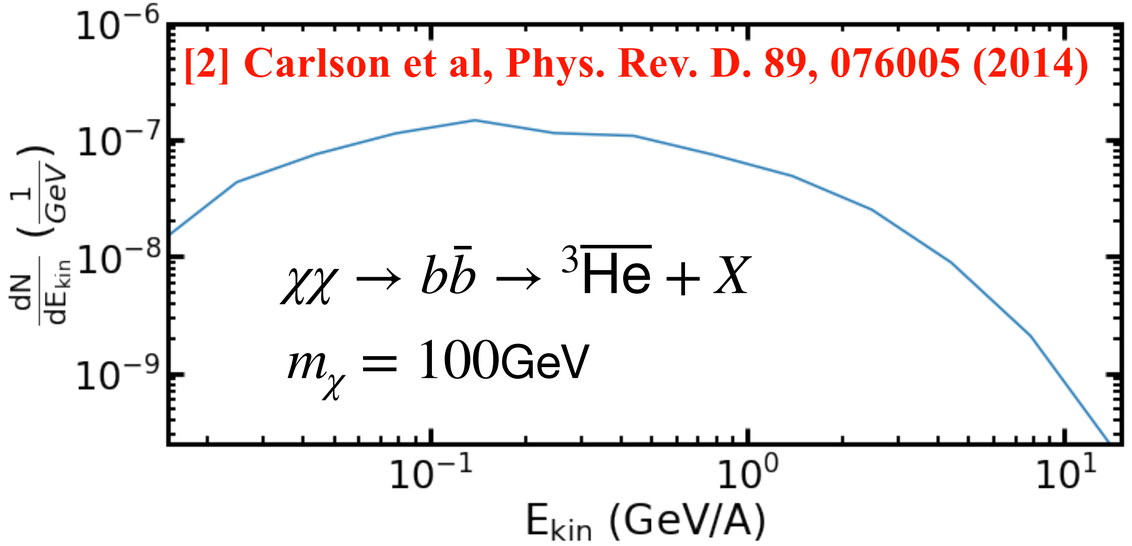
This accounts for anti-tritons which will then decay into $^3\overline{\text{He}}$. $\epsilon \approx 1$

Antinuclei source terms

- The source term for antinuclei from dark matter can be written as:

$$q(\mathrm{r}, E_{kin}) = \frac{1}{2}\frac{\rho^2_{\mathrm{DM}}(\mathrm{r})}{m^2_\chi}\langle\sigma v\rangle(1+\epsilon)\frac{dN}{dE_{kin}}$$

- The final term is the spectra of produced antinuclei, normalized to each dark matter annihilation.

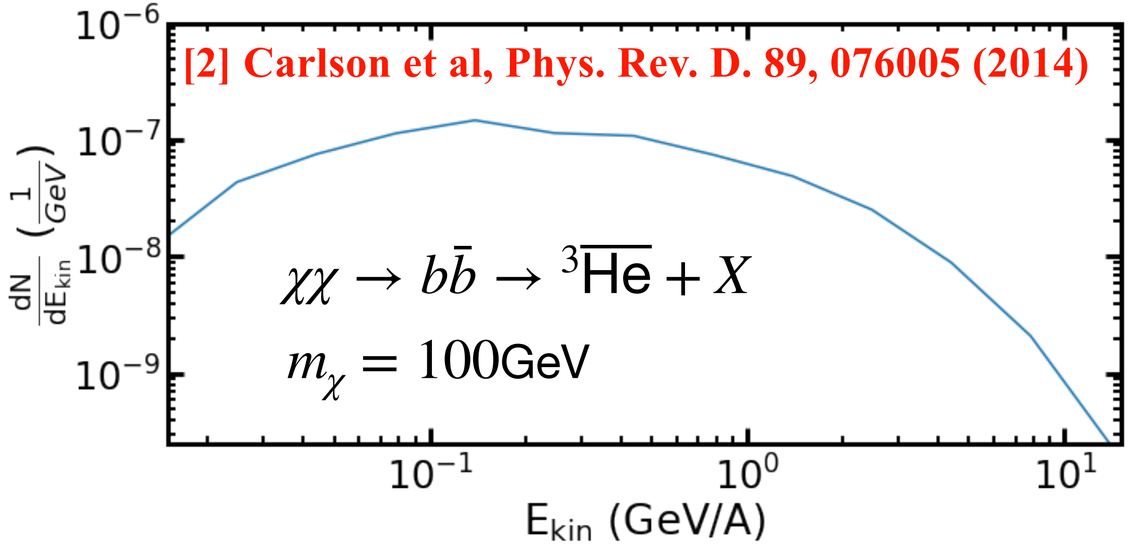


Antinuclei source terms

- The source term for antinuclei from dark matter can be written as:

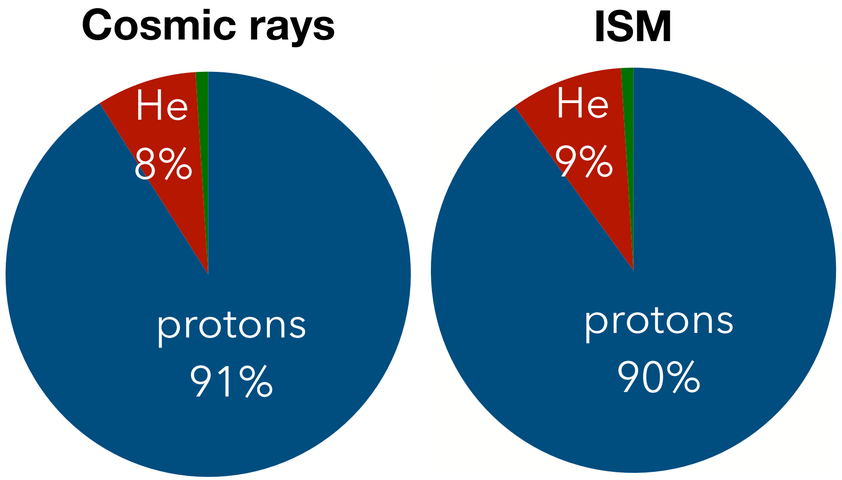
$$q(\mathrm{r}, E_{kin}) = \frac{1}{2}\frac{\rho^2_{\mathrm{DM}}(\mathrm{r})}{m^2_\chi}\langle\sigma v\rangle(1+\epsilon)\frac{dN}{dE_{kin}}$$

- The final term is the spectra of produced antinuclei, normalized to each dark matter annihilation.
- This can be calculated using a coalescence model. [3]



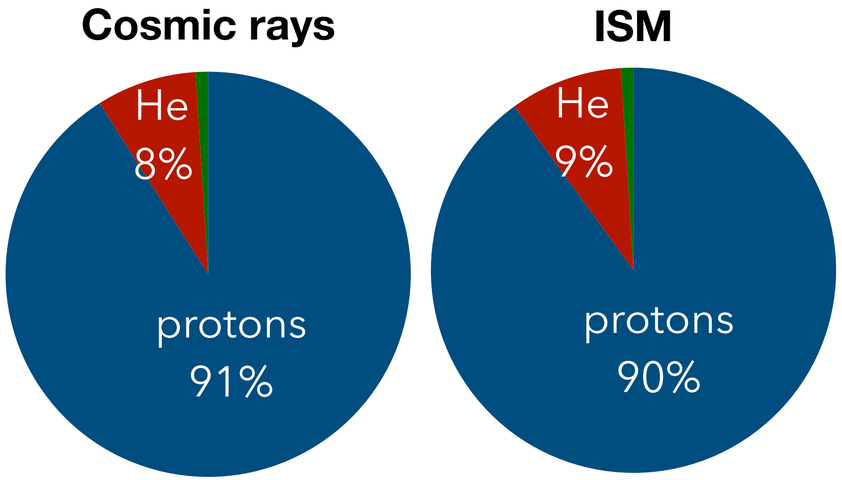
[3] F. Bellini, A. Kelweit, Phys.Rev.C pp (2019)

$^3\overline{\text{He}}$ source function: Cosmic rays + Interstellar medium



$^3\overline{\text{He}}$ source function: Cosmic rays + Interstellar medium

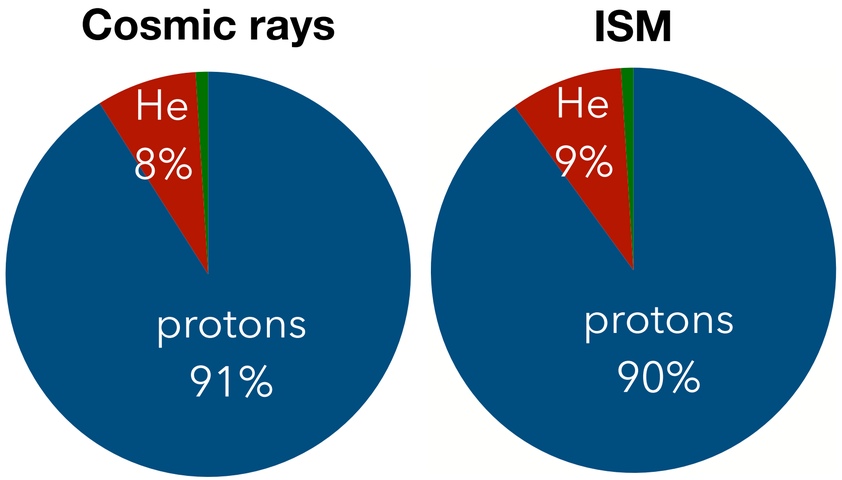
Relevant collision systems: pp, p-He, He-p, He-He

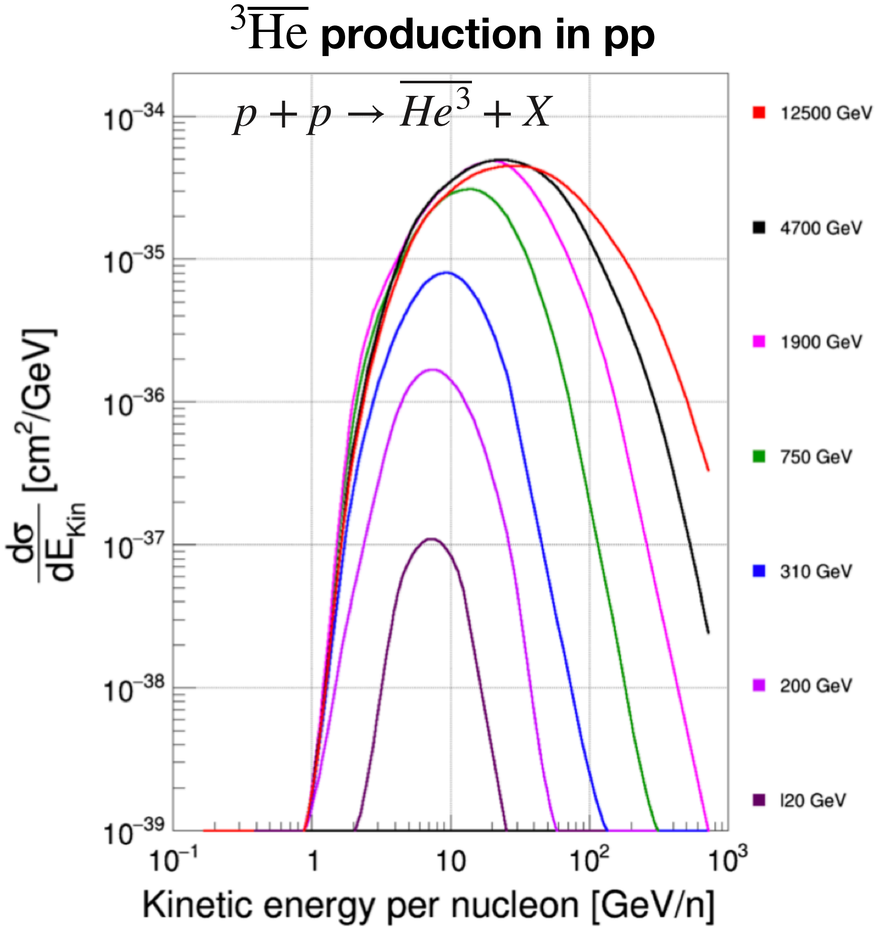


$^3\overline{\text{He}}$ source function: Cosmic rays + Interstellar medium

Relevant collision systems: pp, p-He, He-p, He-He

- Production cross section in pp collisions from [1] (EPOS LHC + event-by-event coalescence)





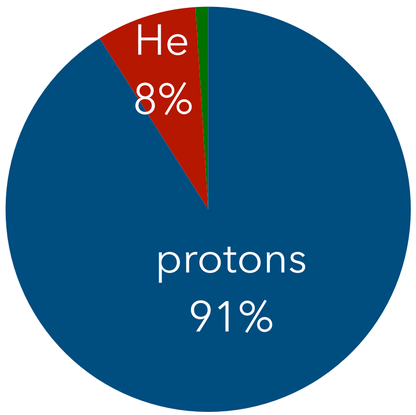
[1] Shukla et al, Phys. Rev. D. 102, 063004 (2020)

$^3\overline{He}$ source function: Cosmic rays + Interstellar medium

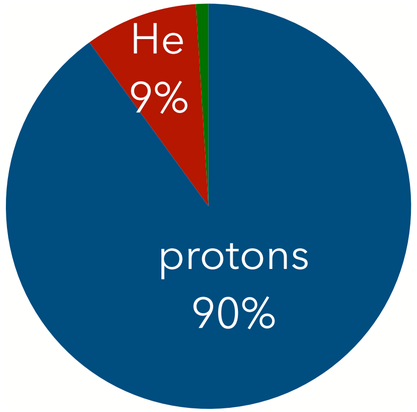
Relevant collision systems: pp, p-He, He-p, He-He

- Production cross section in pp collisions from [1] (EPOS LHC + event-by-event coalescence)
- Other collision types scaled $(A_T A_P)^{2.2/3}$

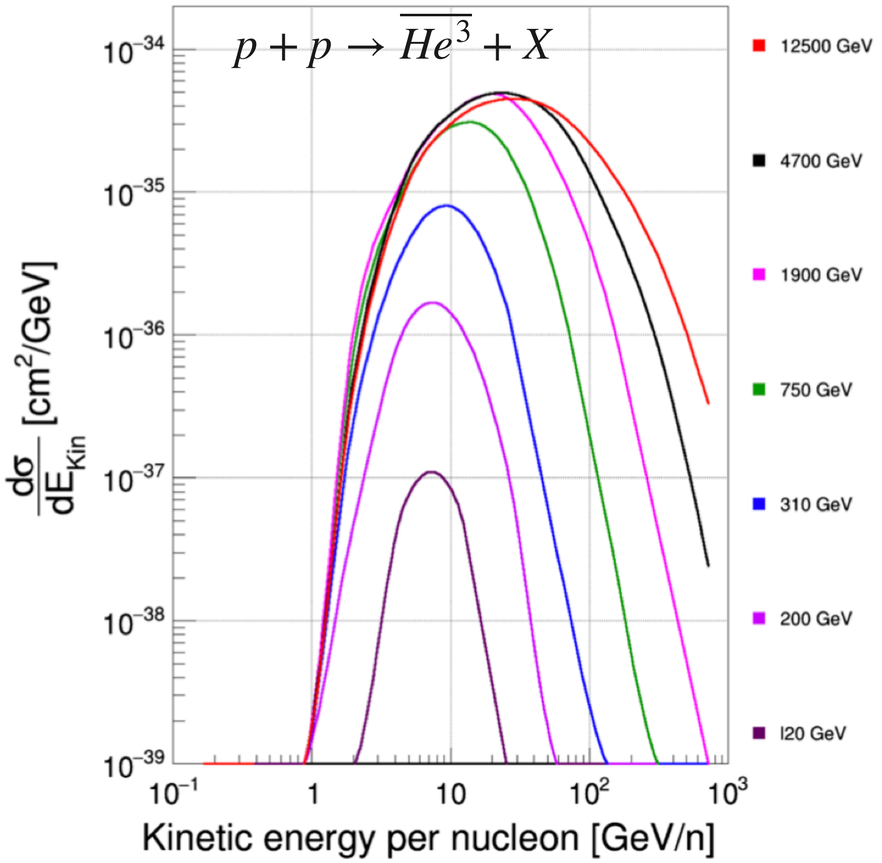
Cosmic rays



ISM



$^3\overline{He}$ production in pp



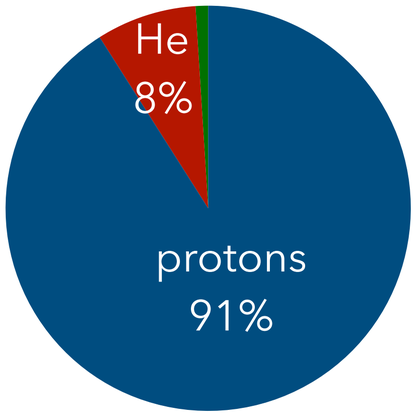
[1] Shukla et al, Phys. Rev. D. 102, 063004 (2020)

$^3\overline{He}$ source function: Cosmic rays + Interstellar medium

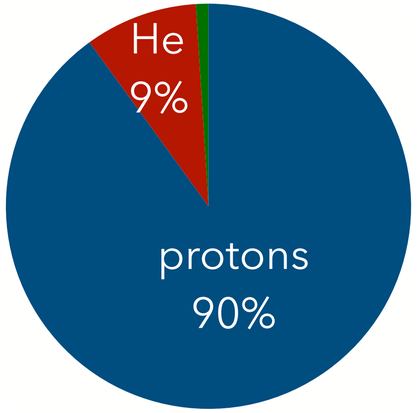
Relevant collision systems: pp, p-He, He-p, He-He

- Production cross section in pp collisions from [1] (EPOS LHC + event-by-event coalescence)
- Other collision types scaled $(A_T A_P)^{2.2/3}$
- Validated by ALICE data

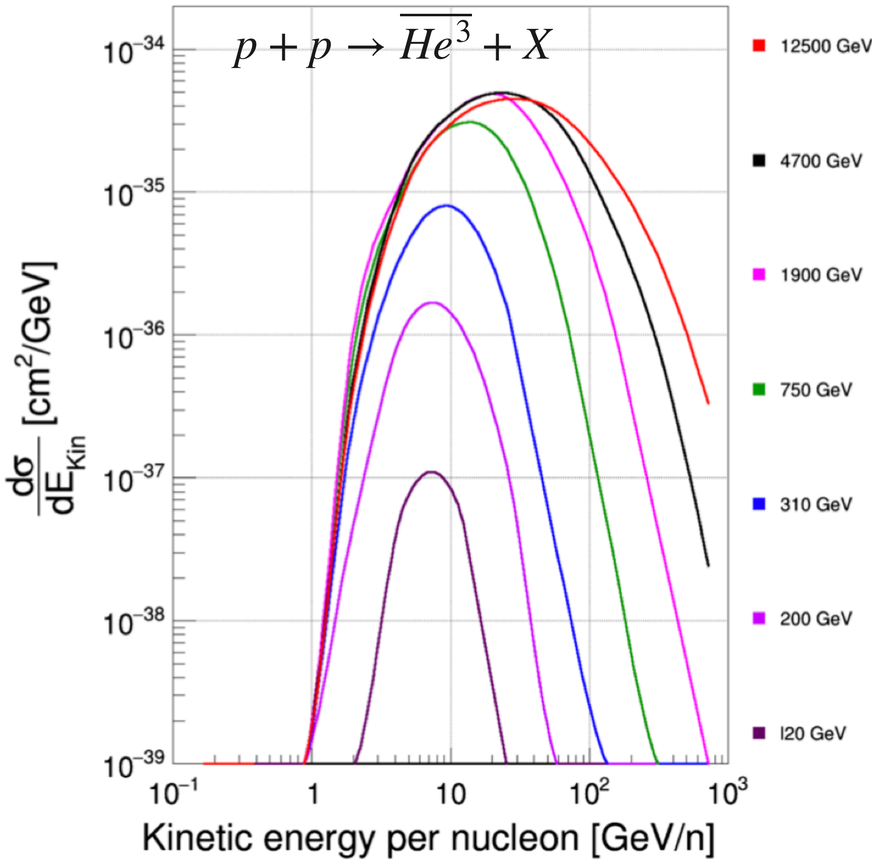
Cosmic rays



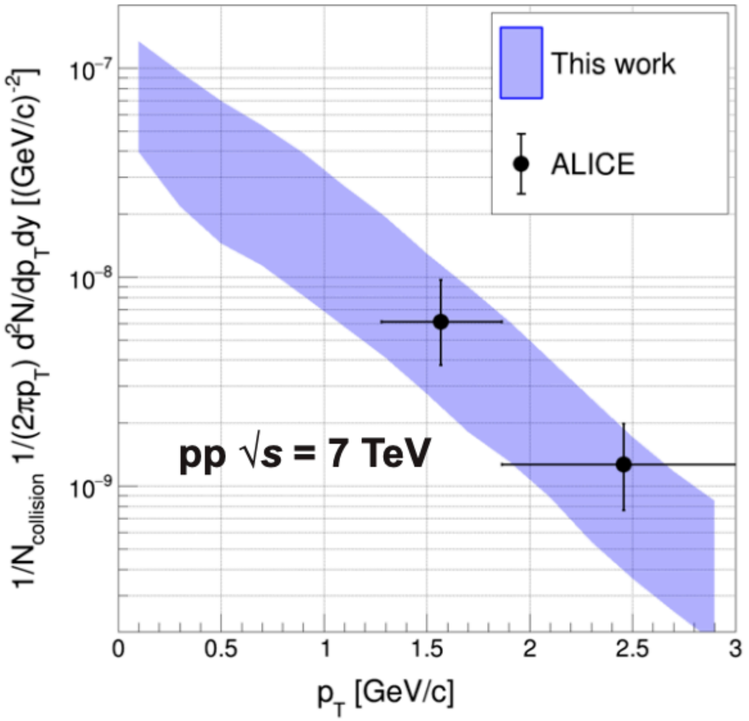
ISM



$^3\overline{He}$ production in pp



Comparison with ALICE results [1,2]



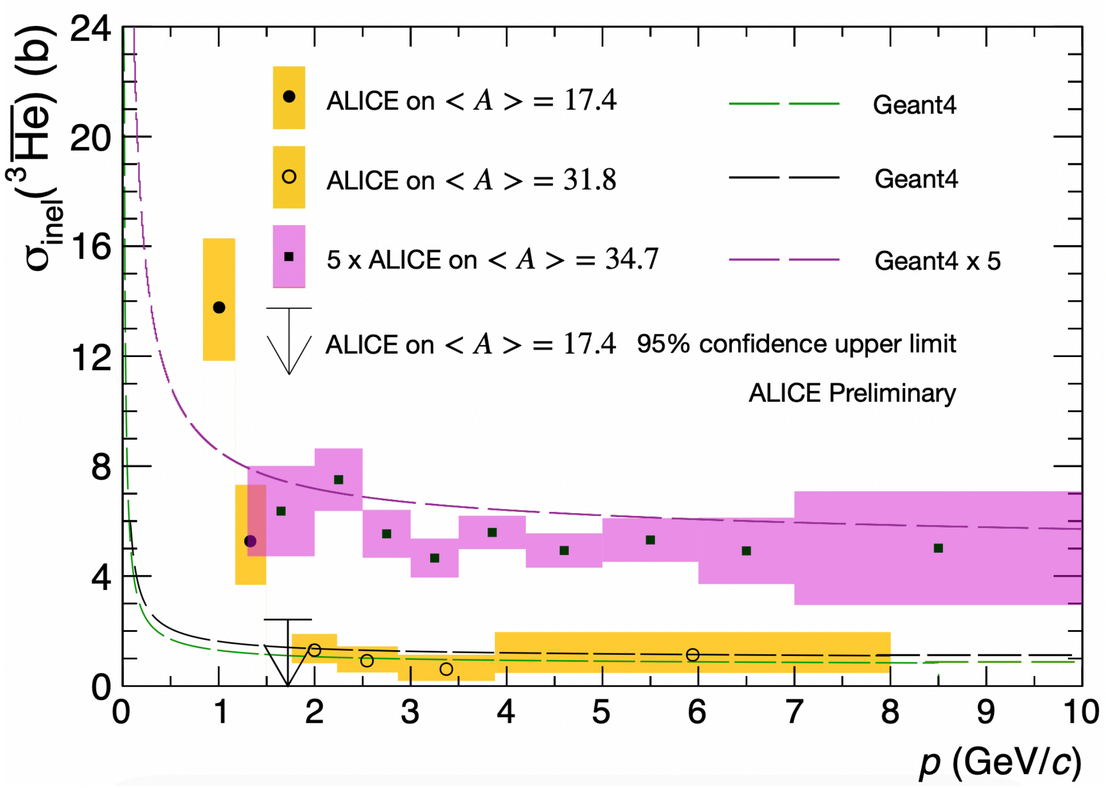
[1] Shukla et al, Phys. Rev. D. 102, 063004 (2020)
[2] ALICE, Phys. Rev. C 97, 024615 (2018)

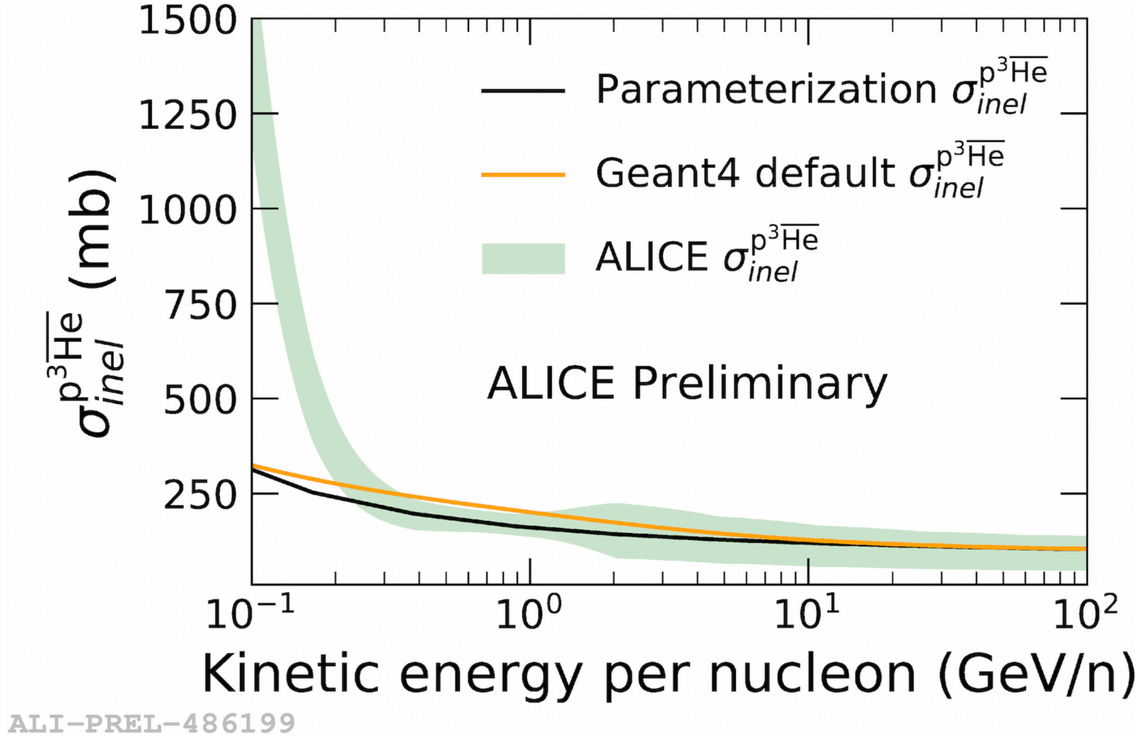
Inelastic interactions

ALICE measurements of σ_{inel} are on heavy targets with $\langle A \rangle = 17.4$ to 34.7

Need to be scaled for proton and helium targets (ISM)

- Obtain correction factor for Geant4 parameterization using ALICE measurements
- Use this correction factor for all targets, with additional 8% uncertainty on possible *A* scaling [1].





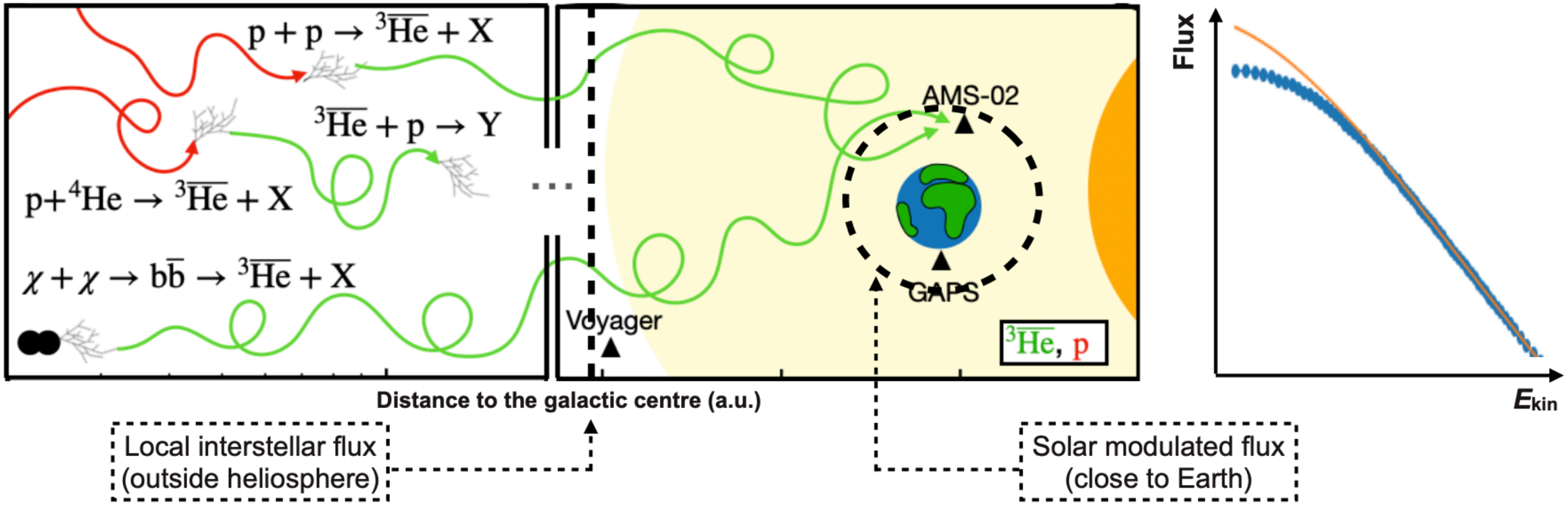
[1] Uzhinsky et al., Phys. Lett. B 705 (2011) 235

Solar environment effects

Solar magnetic field forms heliosphere which shields cosmic rays.

Solar modulation is accounted for using the Force-Field approximation [1] with Fisk potential ϕ = 0.4 GV:

$$F_{mod}(E_{mod}, \phi) = F(E)\frac{(E - Z\phi)^2 - m_{^3He}^2}{E^2 - m_{^3He}^2} \text{ , where } E_{mod} = E - Z\phi$$



[1] Gleeson, Axford, Astrophys. J. 154 (1968) 1011

Results: $^3\overline{\text{He}}$ fluxes

Effect of various inelastic cross sections on $^3\overline{\text{He}}$ fluxes.

Solar modulated flux shifts particles to lower energies.

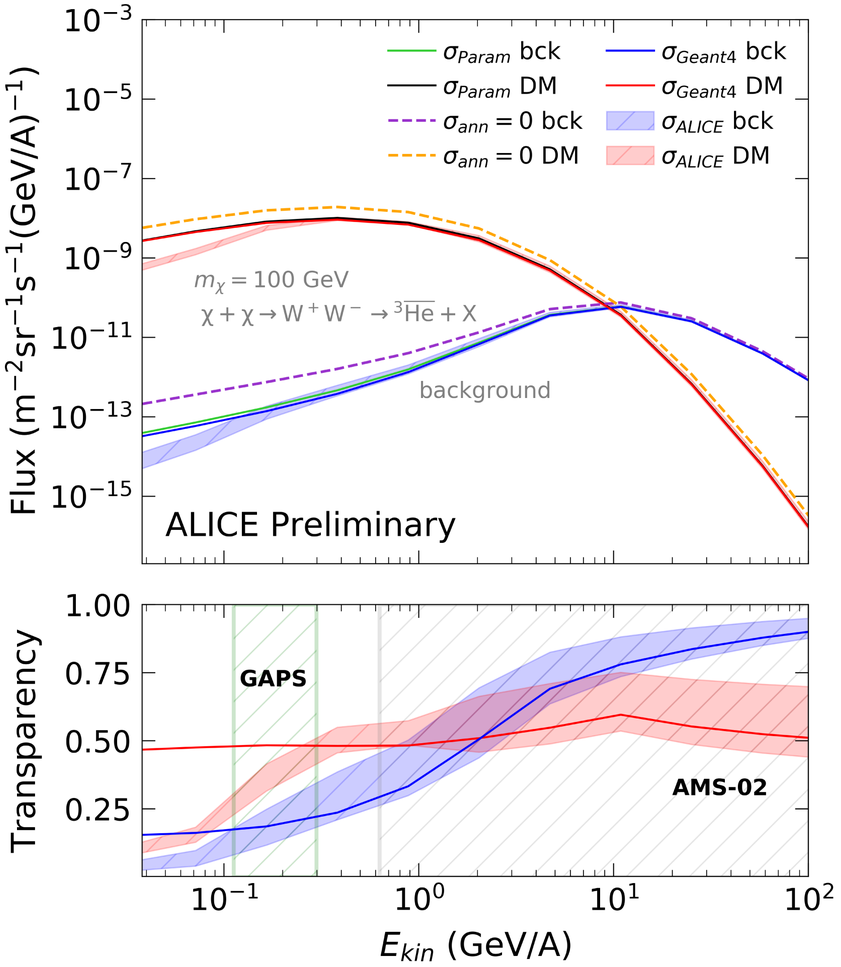
Uncertainties only from ALICE measurement on σ_{inel}

- **Small compared to other uncertainties in the field!**

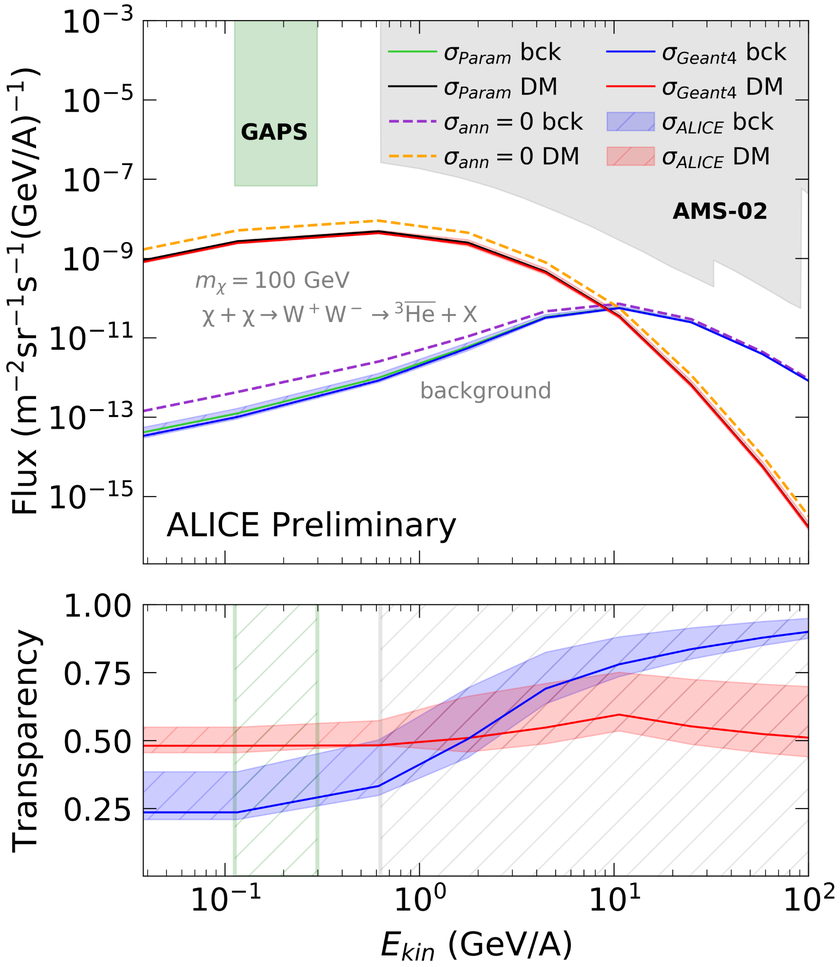
Rather constant transparency of 50% for typical DM scenario and 25%-90% for background.

- **High transparency of the galaxy to $^3\overline{\text{He}}$ nuclei!**

Local interstellar flux



Solar modulated flux



ALI-PREL-486164

LI-PREL-486179

Summary and outlook

Summary and outlook

Analysis of raw reconstructed $\overline{\text{p}}$/p, $\overline{\text{d}}$/d, $^3\overline{\text{He}}/^3\text{He}$ ratios and $^3\overline{\text{He}}_{TOF}/^3\overline{\text{He}}_{TPC}$ ratio.

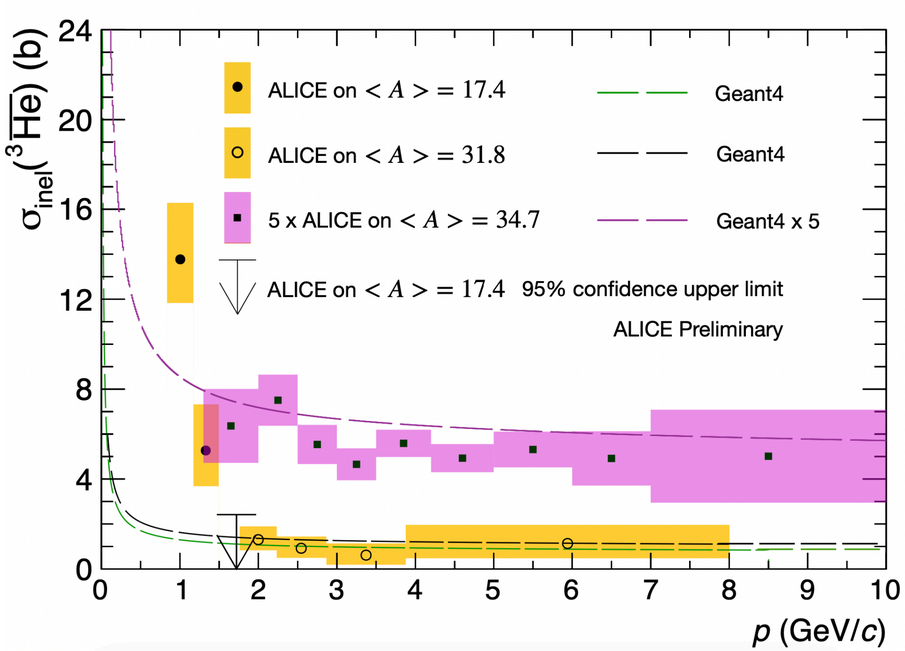
- Measurement of σ_{inel} via comparison with detailed ALICE Monte Carlo simulations using Geant4

First low energy measurement of the antideuteron inelastic cross section.

- Paper: PRL 125, 162001 (2020)

First measurement of the $^3\overline{\text{He}}$ inelastic cross section.

- Paper in preparation



Summary and outlook

Analysis of raw reconstructed $\overline{\text{p}}$/p, $\overline{\text{d}}$/d, $^3\overline{\text{He}}/^3\text{He}$ ratios and $^3\overline{\text{He}}_{TOF}/^3\overline{\text{He}}_{TPC}$ ratio.

- Measurement of σ_{inel} via comparison with detailed ALICE Monte Carlo simulations using Geant4

First low energy measurement of the antideuteron inelastic cross section.

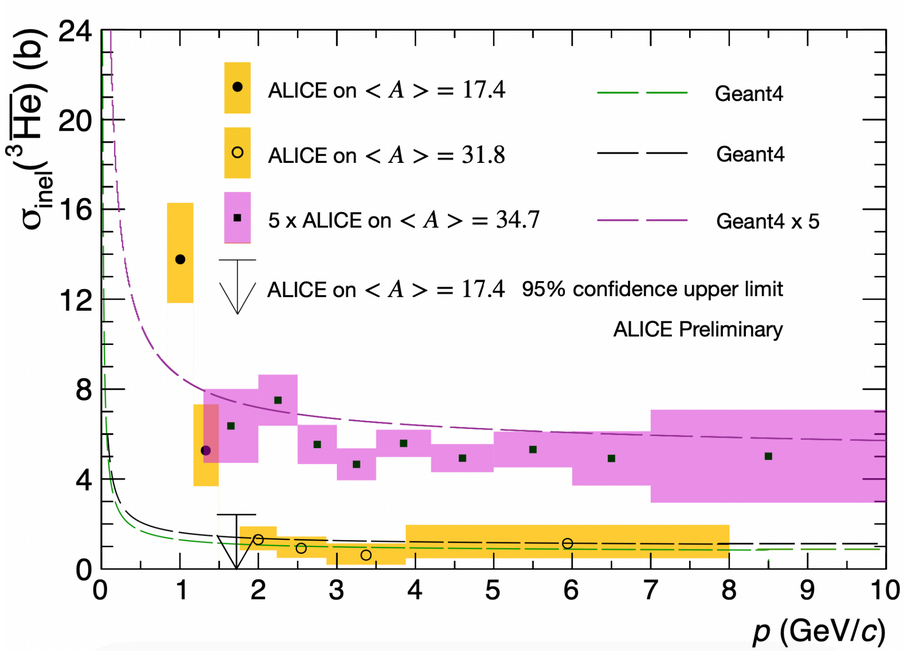
- Paper: PRL 125, 162001 (2020)

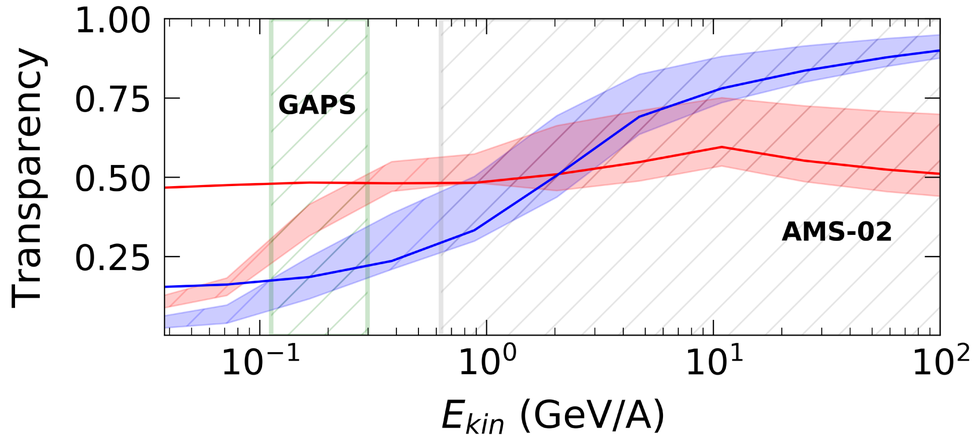
First measurement of the $^3\overline{\text{He}}$ inelastic cross section.

- Paper in preparation

Effect of σ_{inel} measurements:

- Transparency of the galaxy to $^3\overline{\text{He}}$ from different sources.





ALI-PREL-486164

Summary and outlook

Analysis of raw reconstructed $\overline{\text{p}}$/p, $\overline{\text{d}}$/d, $^3\overline{\text{He}}/^3\text{He}$ ratios and $^3\overline{\text{He}}_{TOF}/^3\overline{\text{He}}_{TPC}$ ratio.

- Measurement of σ_{inel} via comparison with det… ALICE Monte Carlo simulations using Geant4

First low energy measurement of the antideuteron inelastic cross section.

- Paper: PRL 125, 162001 (2020)

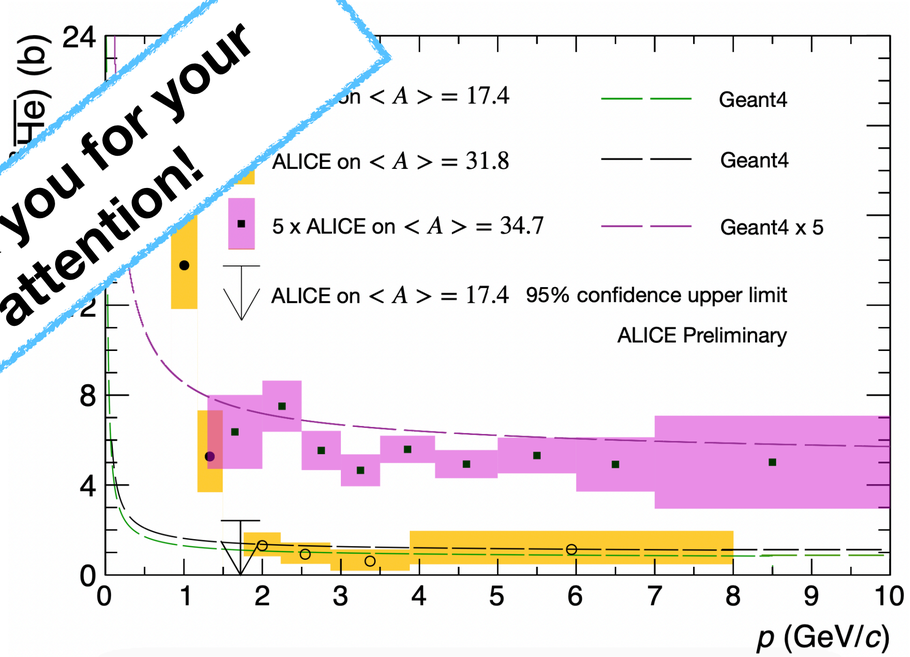
First measurement of the $^3\overline{\text{He}}$ inelastic cross section.

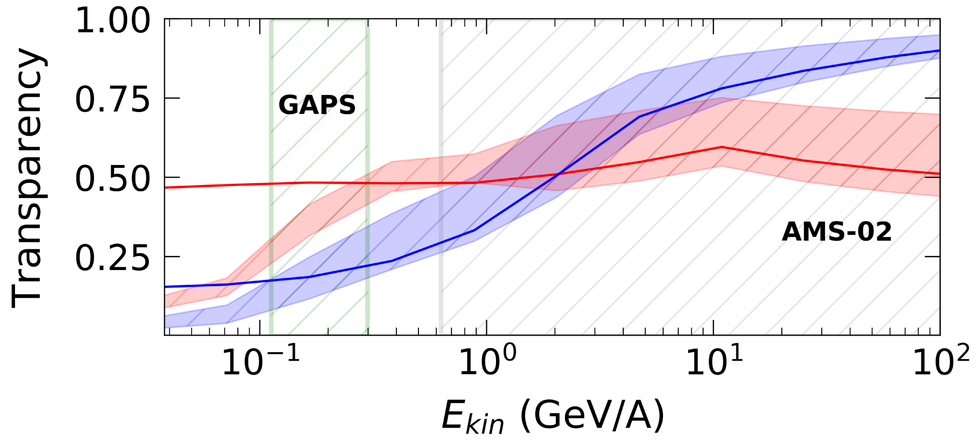
- Paper in preparation

Effect of σ_{inel} measurements:

- Transparency of the galaxy to $^3\overline{\text{He}}$ from different sources.

Thank you for your attention!





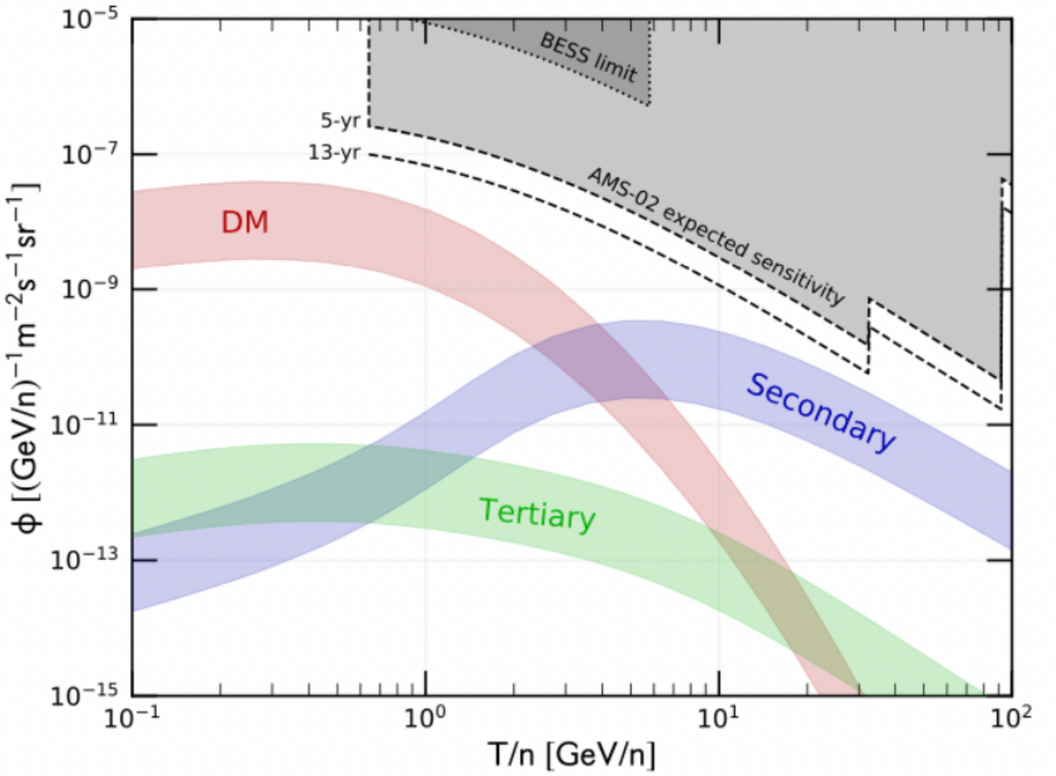
ALI-PREL-486164

Back-up slides

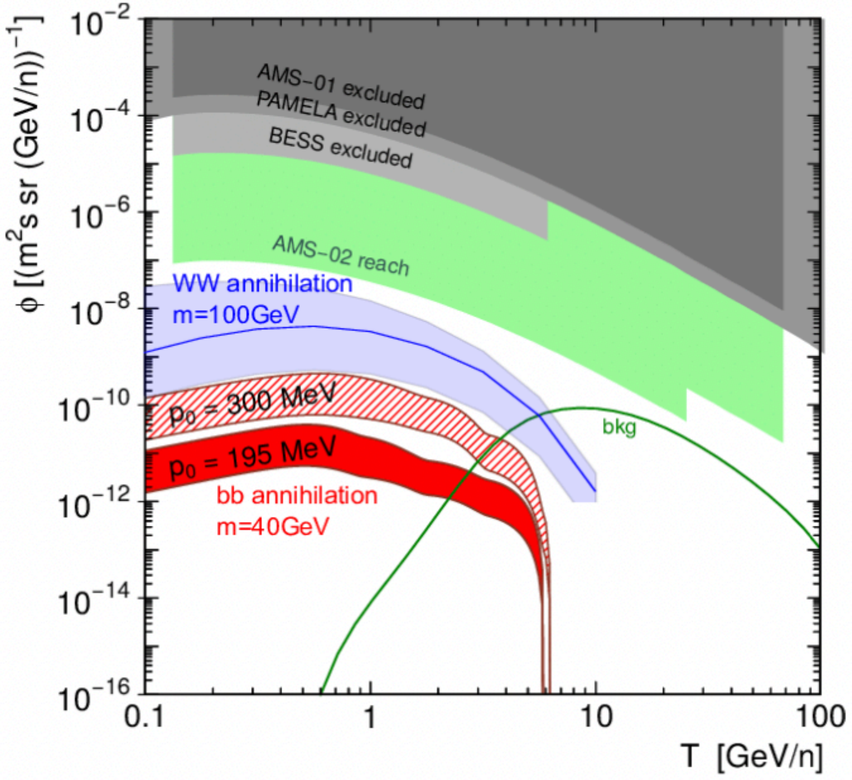
Current predictions of antinuclei fluxes near earth

- Production: constrained using collider measurements - large uncertainty
- Propagation: constrained using cosmic ray measurements - large uncertainty
- Annihilation: no experimental data at low energies - **unknown uncertainty**

Uncertainty bands due to coalescence probability [1]



Uncertainty bands due to propagation model [2]



[1] Korsmeier et.al. Phys.R.D, 97 (2018)

[2] T.Aramaki et al, Physics Report 618, 1 (2016)

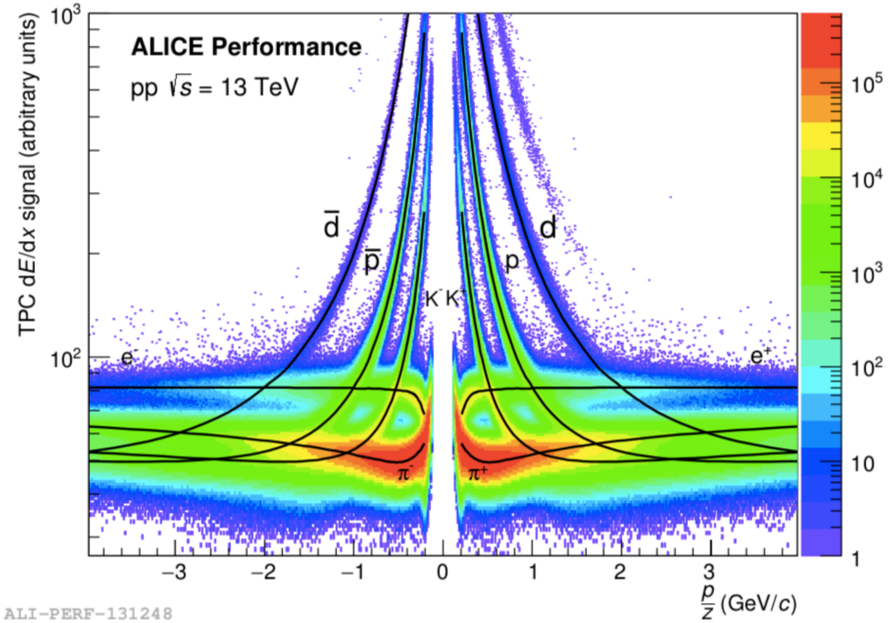
Particle identification in TPC and TOF

Complementary information from TPC and TOF detectors allows us to select high purity (anti)particles:

Particle identification in TPC and TOF

Complementary information from TPC and TOF detectors allows us to select high purity (anti)particles:

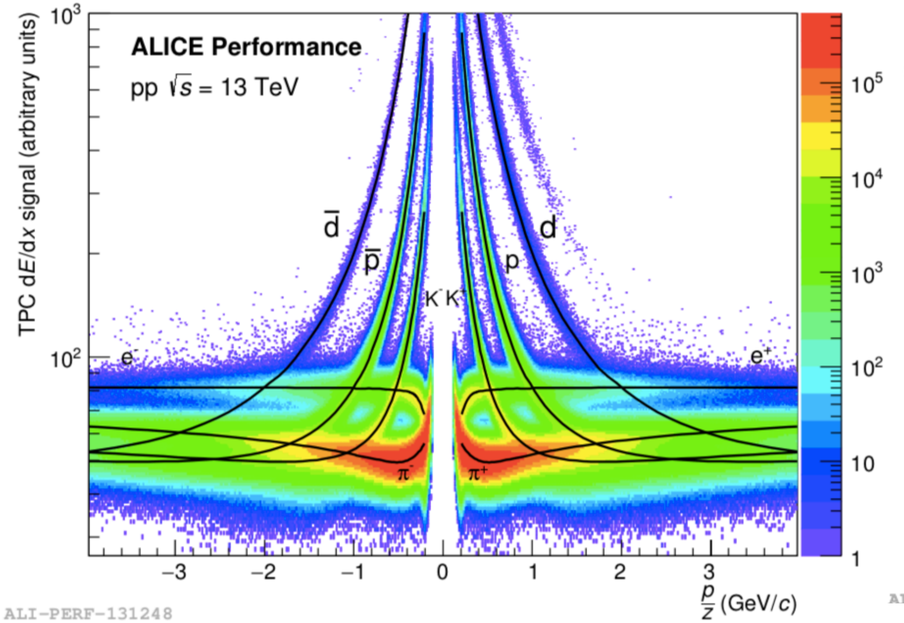
- TPC: dE/dx in gas

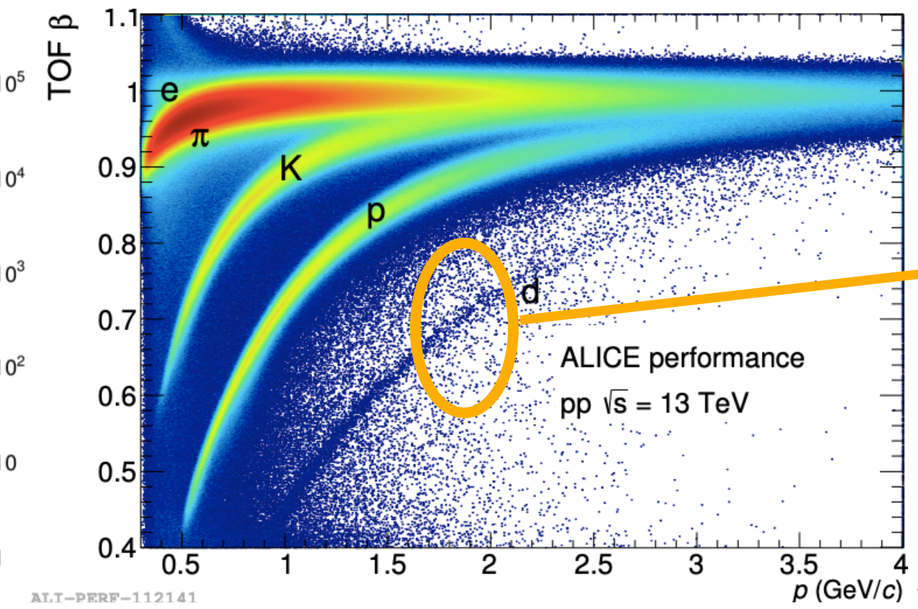


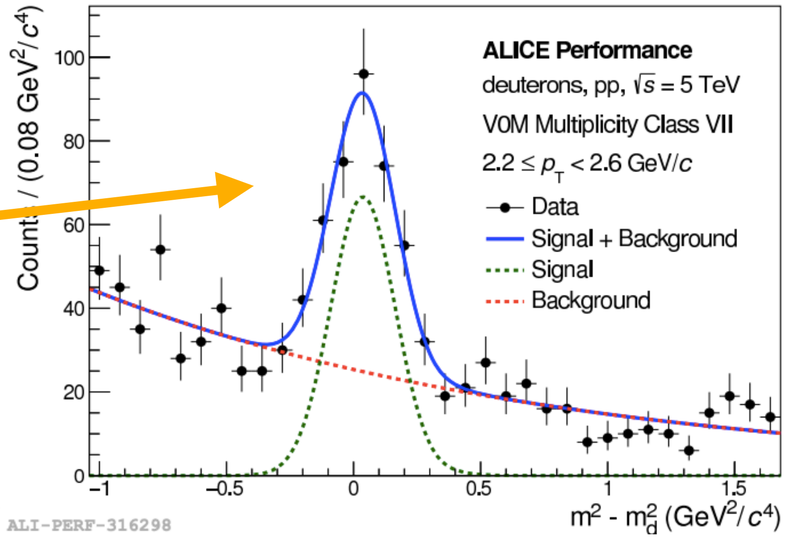
Particle identification in TPC and TOF

Complementary information from TPC and TOF detectors allows us to select high purity (anti)particles:

- TPC: dE/dx in gas
- TOF measurement $\beta = \frac{v}{c}$, $p = \gamma\beta mc$ -> mass



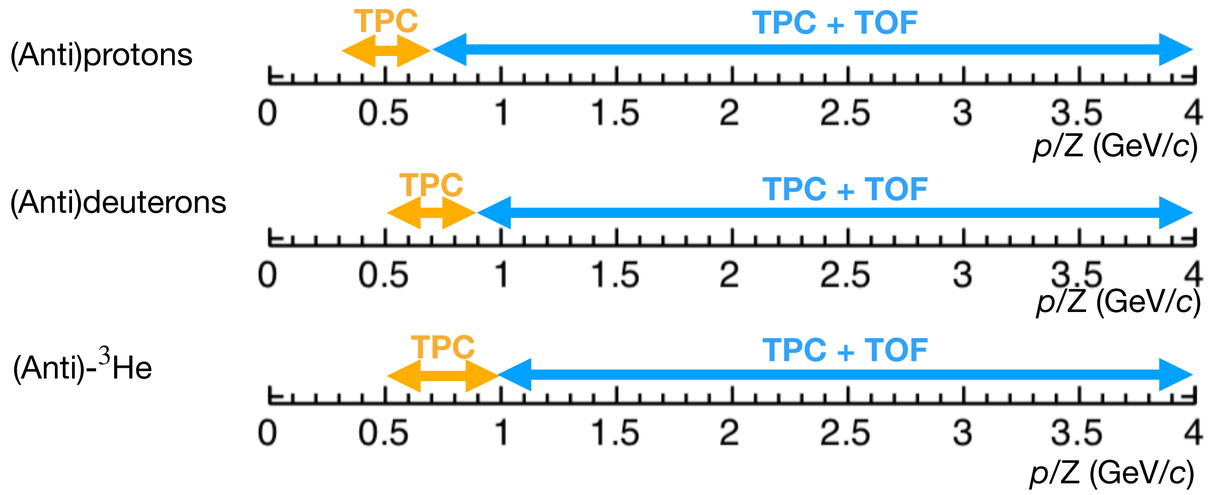


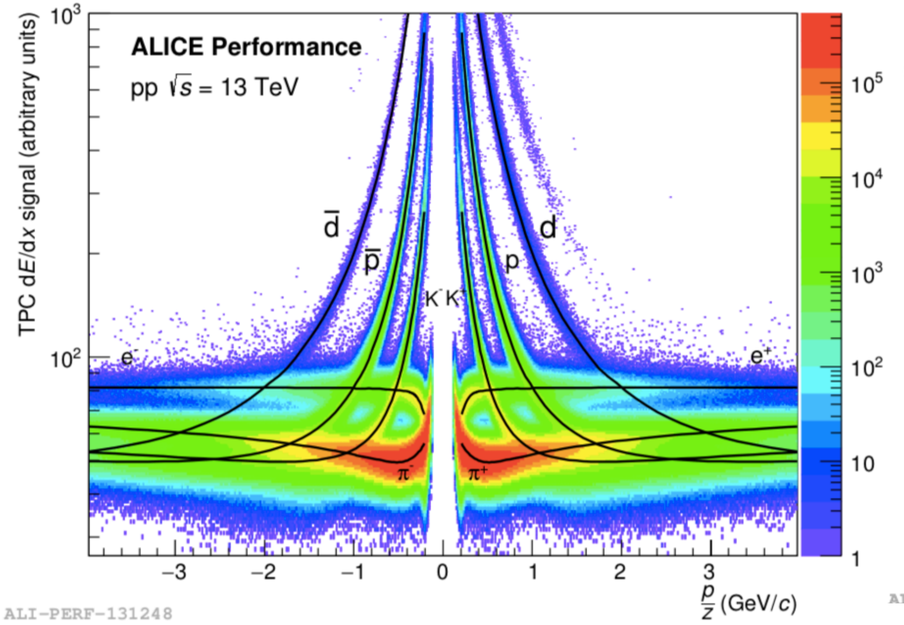


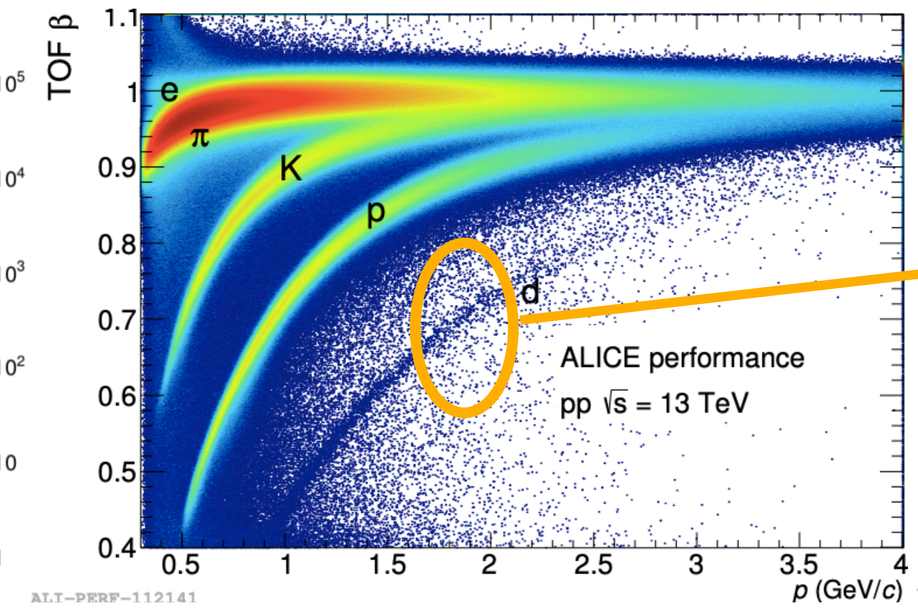
Particle identification in TPC and TOF

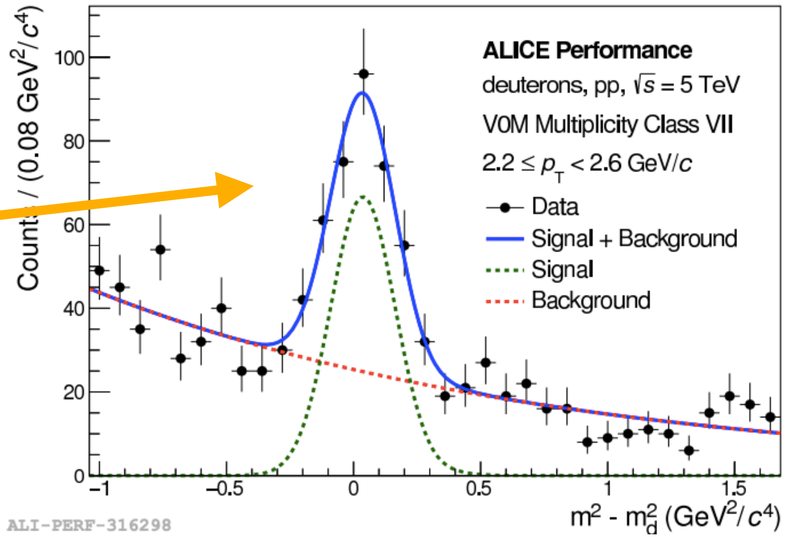
Complementary information from TPC and TOF detectors allows us to select high purity (anti)particles:

- TPC: dE/dx in gas
- TOF measurement $\beta = \frac{v}{c}$, $p = \gamma\beta mc$ -> mass

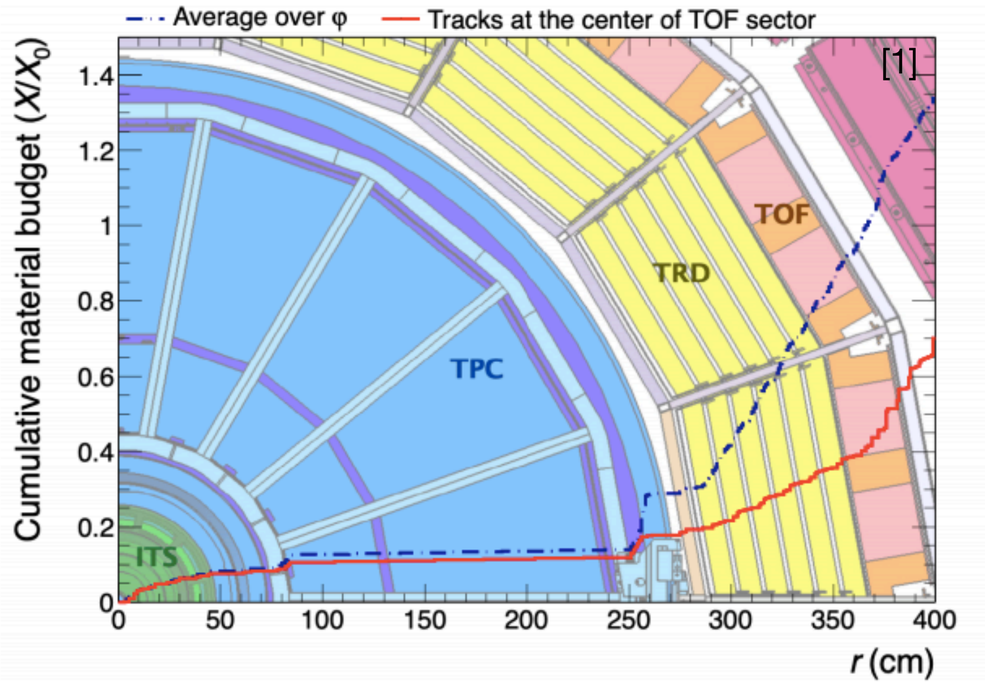


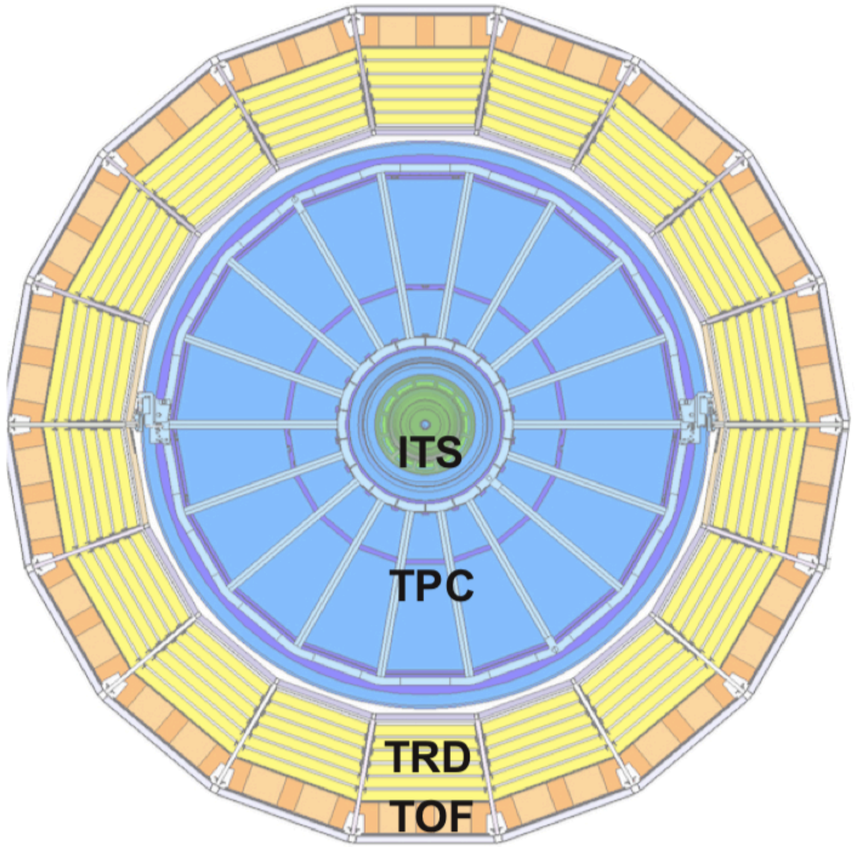






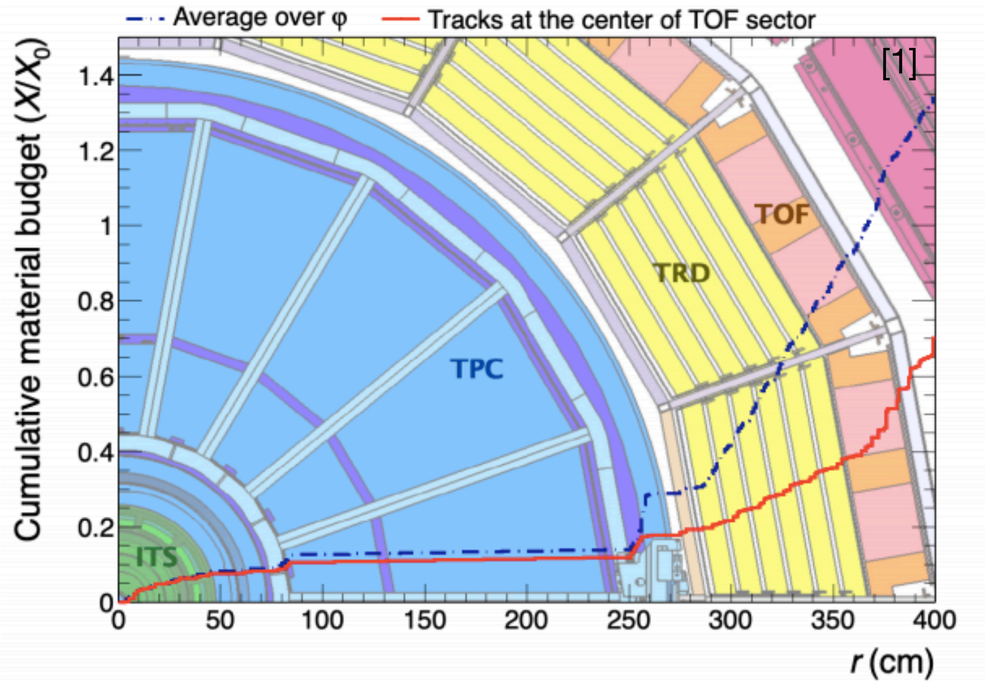
… and the ALICE detector material as a target

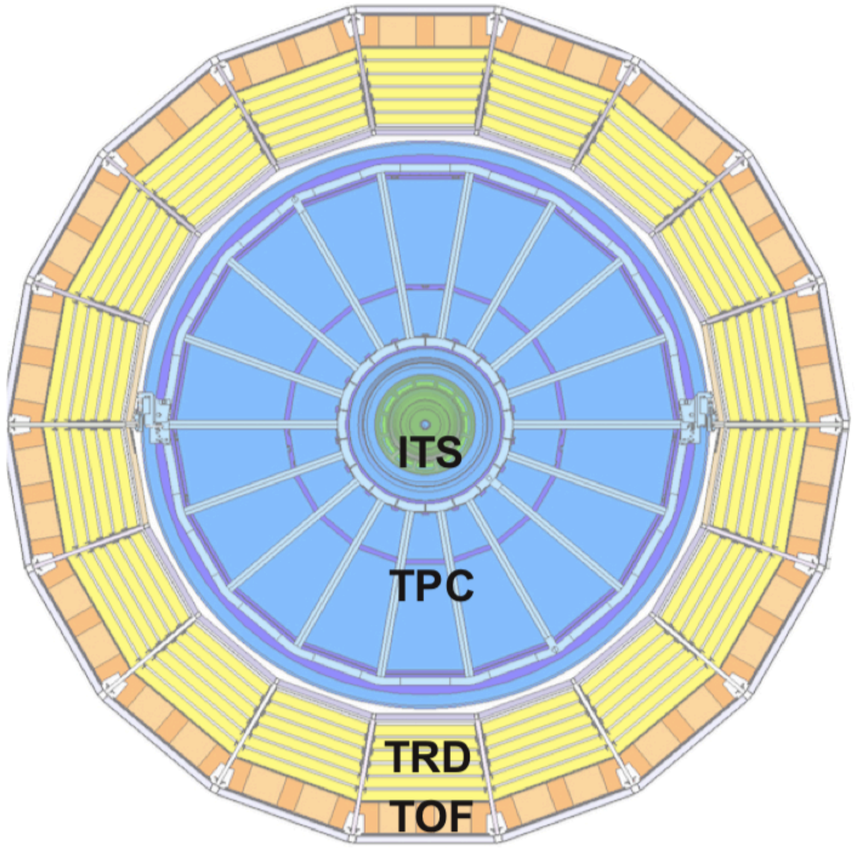




[1] PRL 125, 162001 (2020)

… and the ALICE detector material as a target





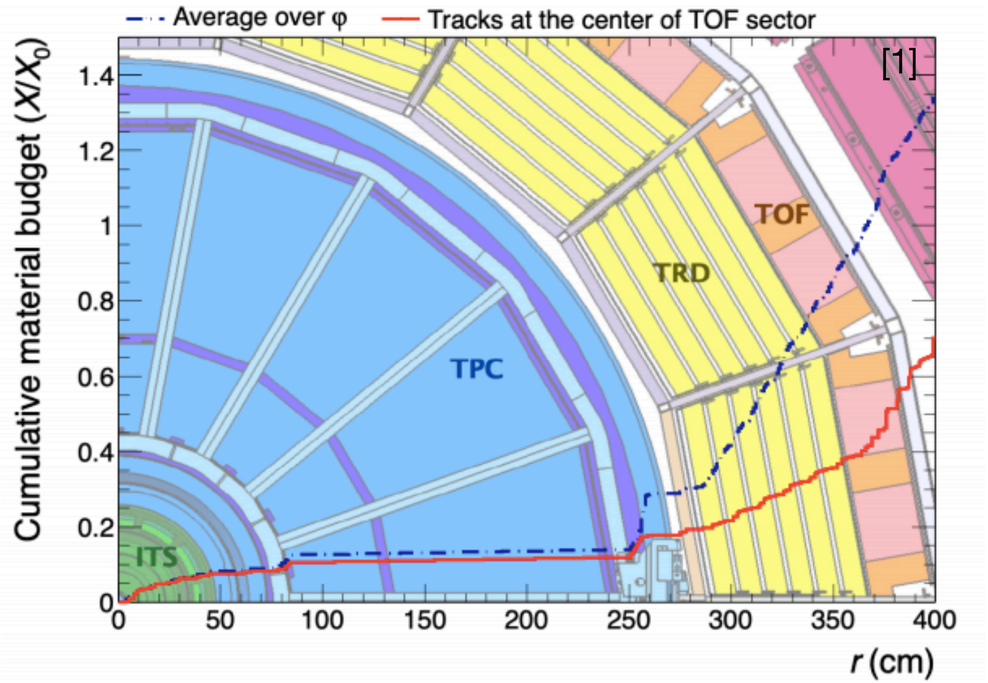
Idea to determine absorption: to use raw reconstructed antiparticle-to-particle ratios ($\overline{\text{p}}$/p, $\overline{\text{d}}$/d, $^{3}\overline{\text{He}}/^{3}\text{He}$, $\overline{\text{t}}$/t)

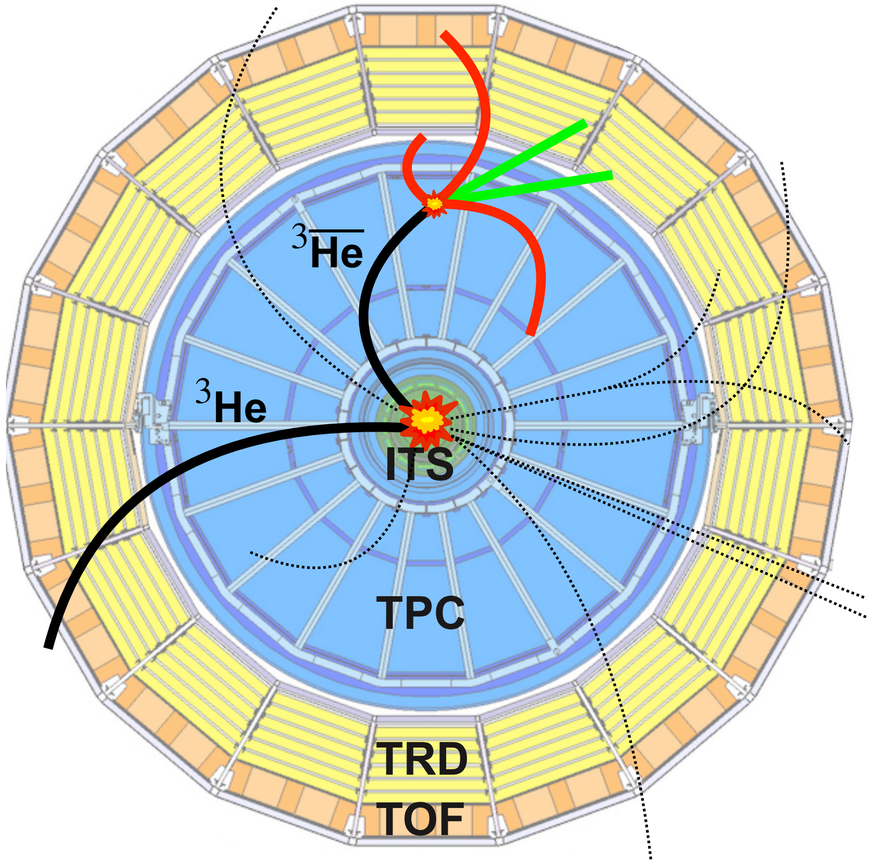
- No correction due to detector efficiency or absorption from material.
- Correct for secondary (anti)particles from weak decays and spallation processes.

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

[1] PRL 125, 162001 (2020)

… and the ALICE detector material as a target





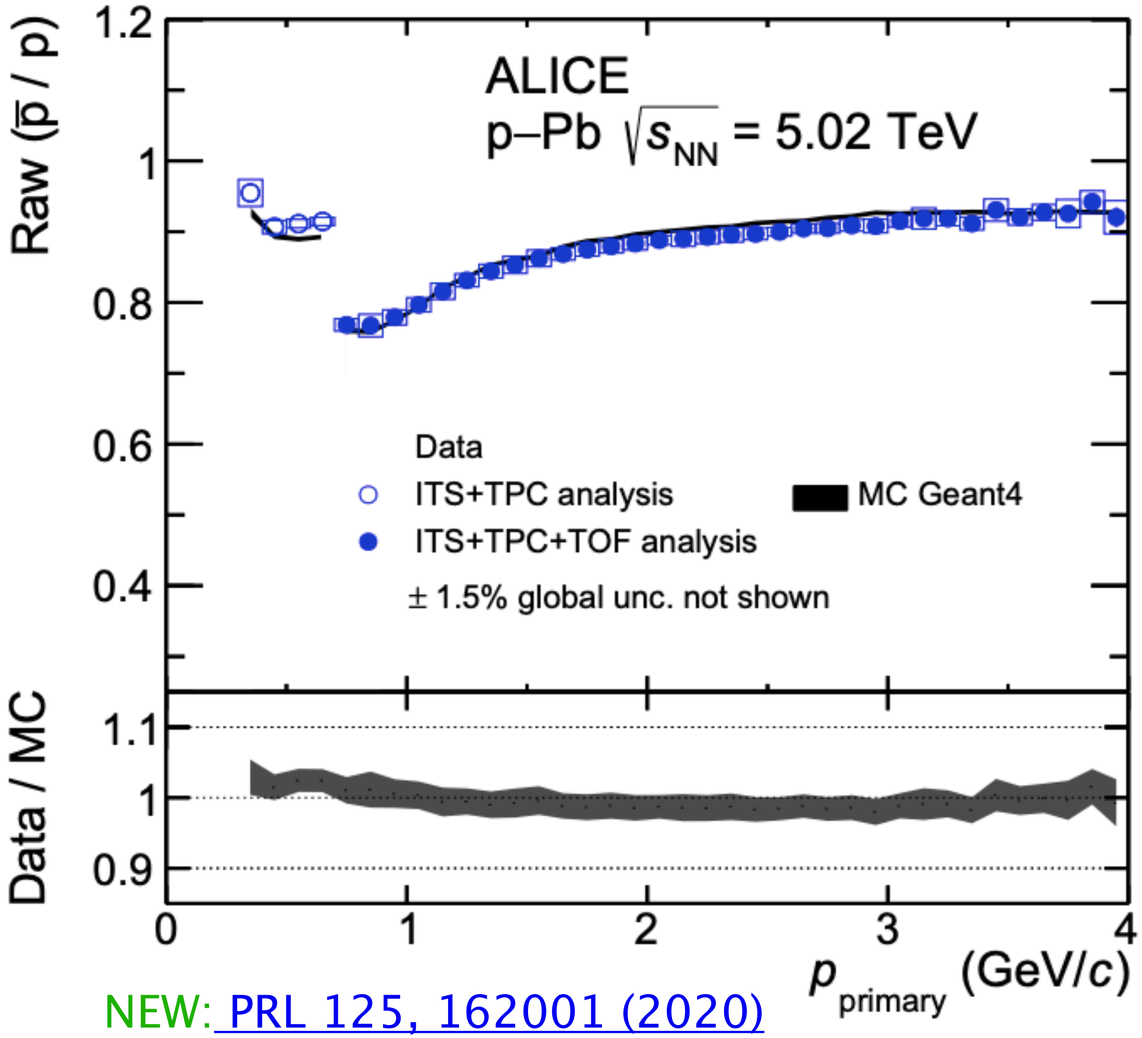
Idea to determine absorption: to use raw reconstructed antiparticle-to-particle ratios ($\overline{p}/p$, $\overline{d}/d$, $^3\overline{He}/^3He$, $\overline{t}/t$)

- No correction due to detector efficiency or absorption from material.
- Correct for secondary (anti)particles from weak decays and spallation processes.

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

[1] PRL 125, 162001 (2020)

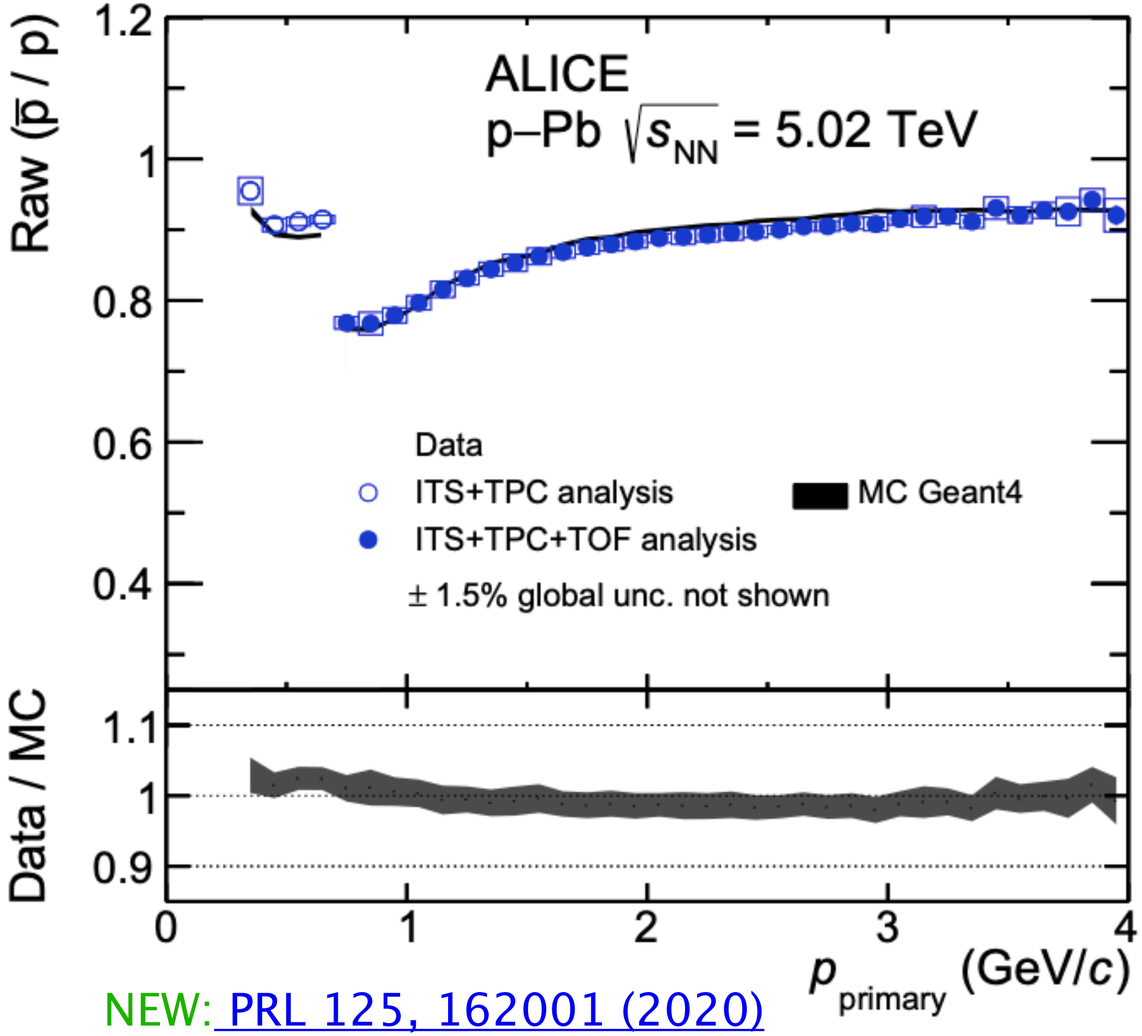
Raw primary antiproton-to-proton ratio



NEW: PRL 125, 162001 (2020)

Raw primary $\bar{p}/p$ ratio:

Raw primary antiproton-to-proton ratio

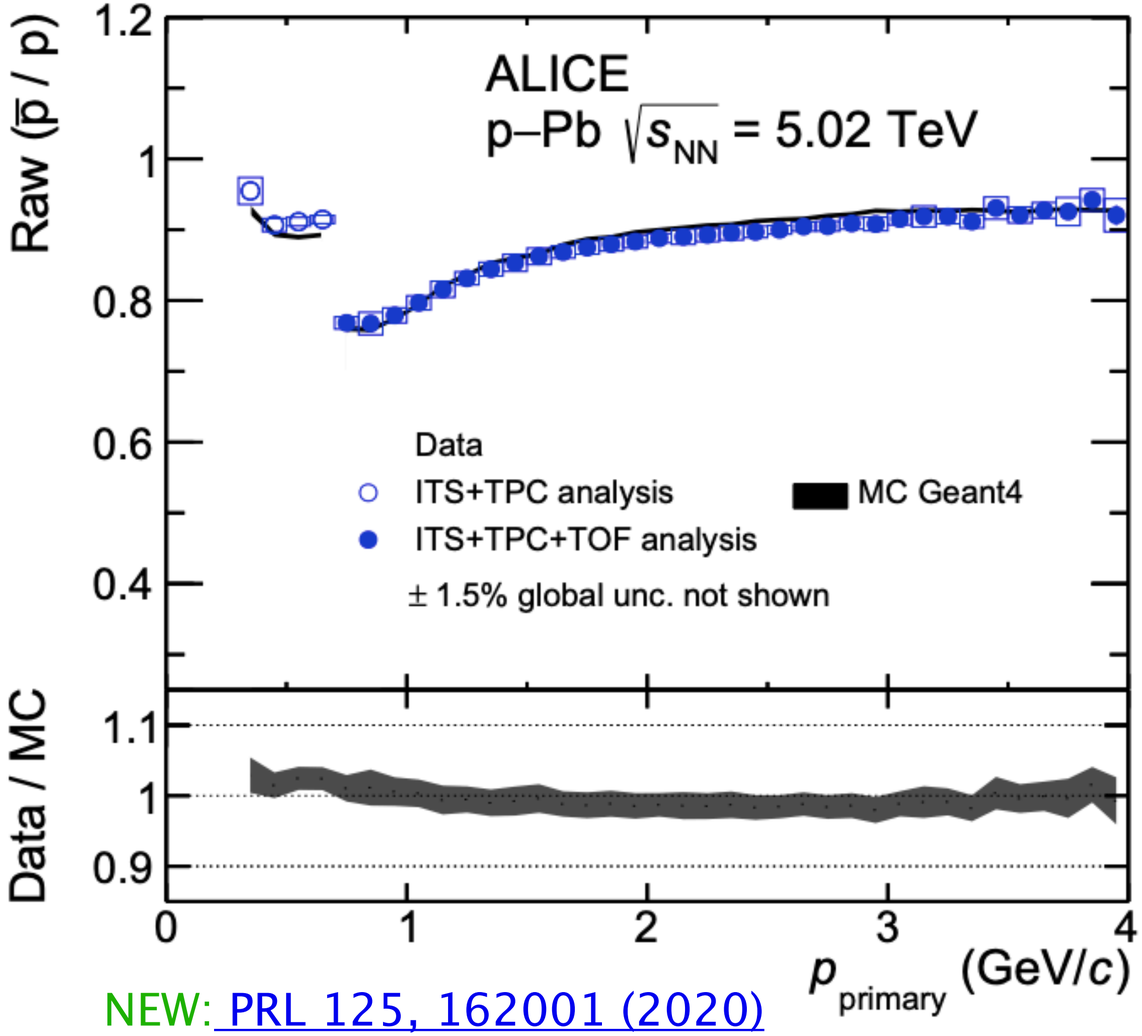


NEW: PRL 125, 162001 (2020)

Raw primary $\bar{p}/p$ ratio:

- Higher loss of antiprotons in detector material
- Step at 0.7 GeV/c due to additional detector material

Raw primary antiproton-to-proton ratio



NEW: PRL 125, 162001 (2020)

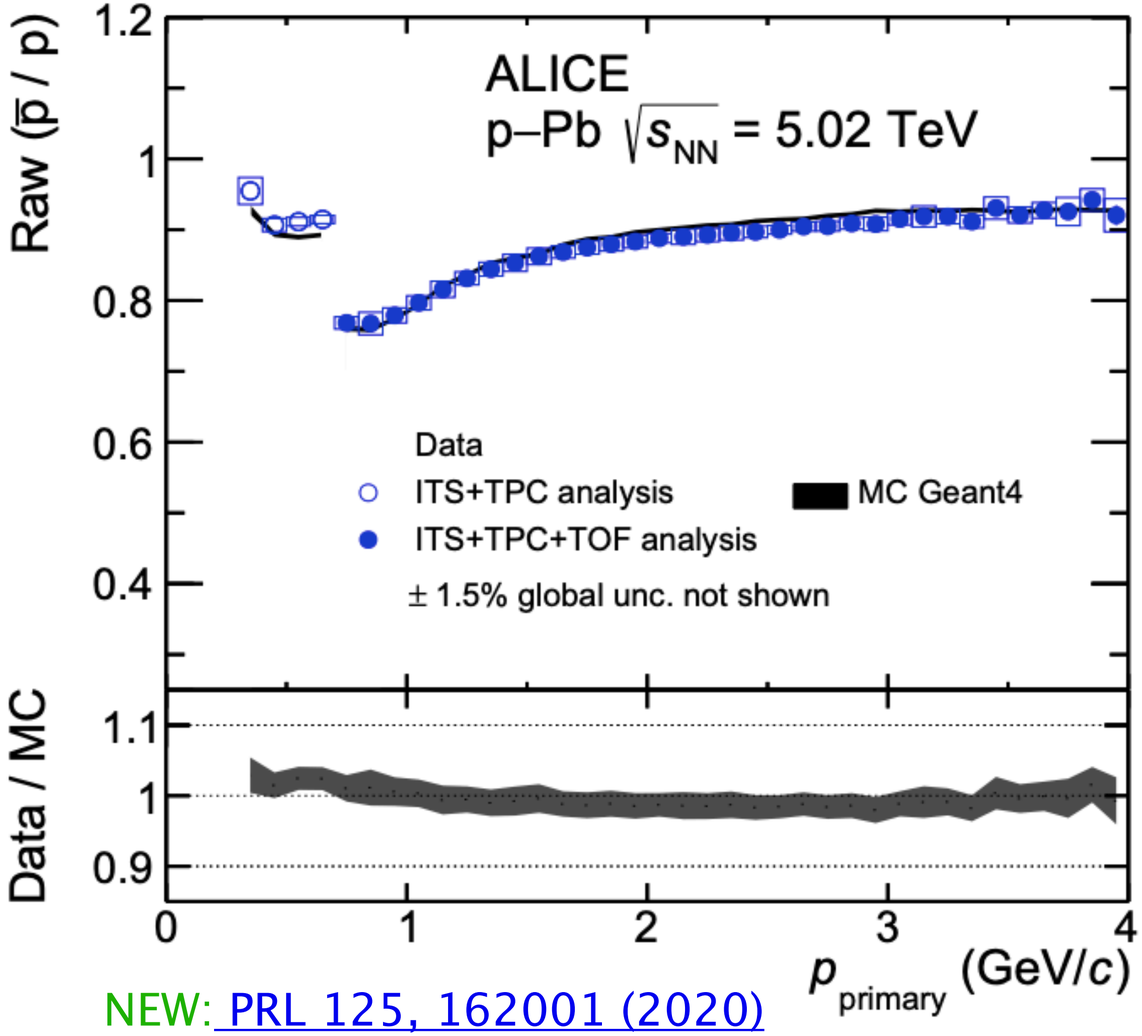
Raw primary $\bar{p}/p$ ratio:

- Higher loss of antiprotons in detector material
- Step at 0.7 GeV/c due to additional detector material

Monte Carlo simulation:

- Detailed simulations of the ALICE detector performance
- Propagation with Geant4

Raw primary antiproton-to-proton ratio



NEW: PRL 125, 162001 (2020)

Raw primary $\bar{p}/p$ ratio:

- Higher loss of antiprotons in detector material
- Step at 0.7 GeV/c due to additional detector material

Monte Carlo simulation:

- Detailed simulations of the ALICE detector performance
- Propagation with Geant4

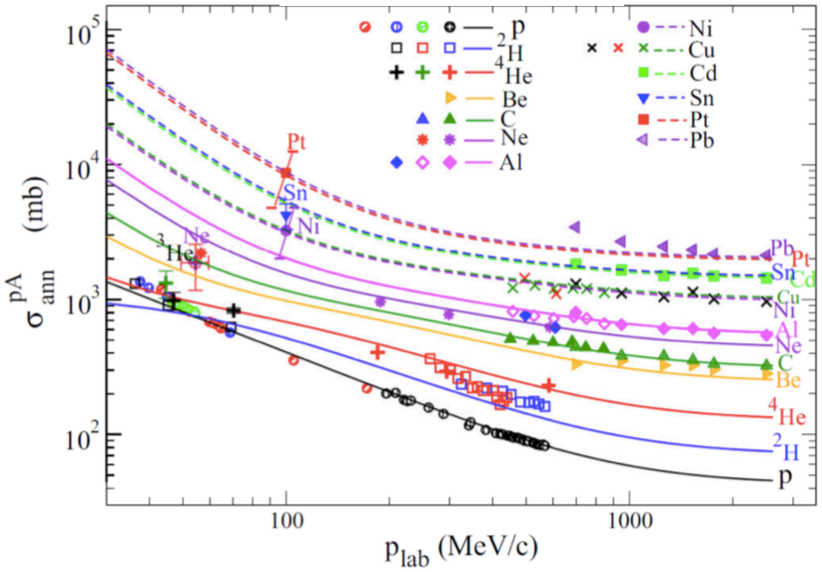
➡Agreement between data and MC confirms the correctness of the procedure.

Propagation: Current status of antinuclei inelastic cross sections

Propagation: Current status of antinuclei inelastic cross sections

- **Antiproton** inelastic cross section is **well known**.

Antiprotons [1]

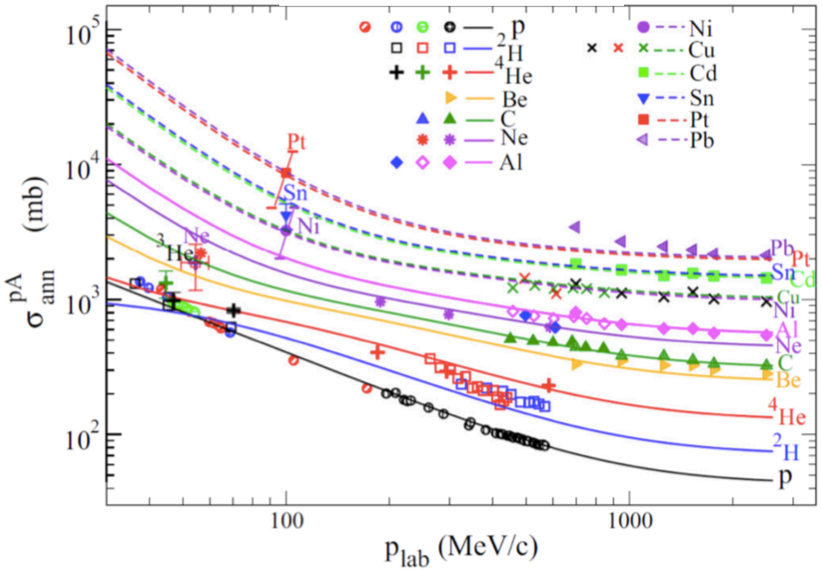


[1] Phys. Rev. C 89, 054601 (2014)

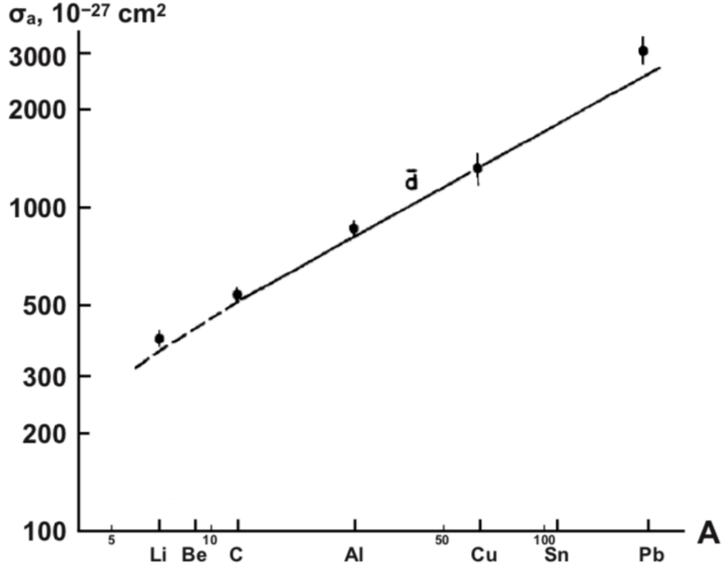
Propagation: Current status of antinuclei inelastic cross sections

- **Antiproton** inelastic cross section is **well known**.
- **Antideuteron** inelastic cross section is **poorly known at low energies**.

Antiprotons [1]



Antideuterons [2]

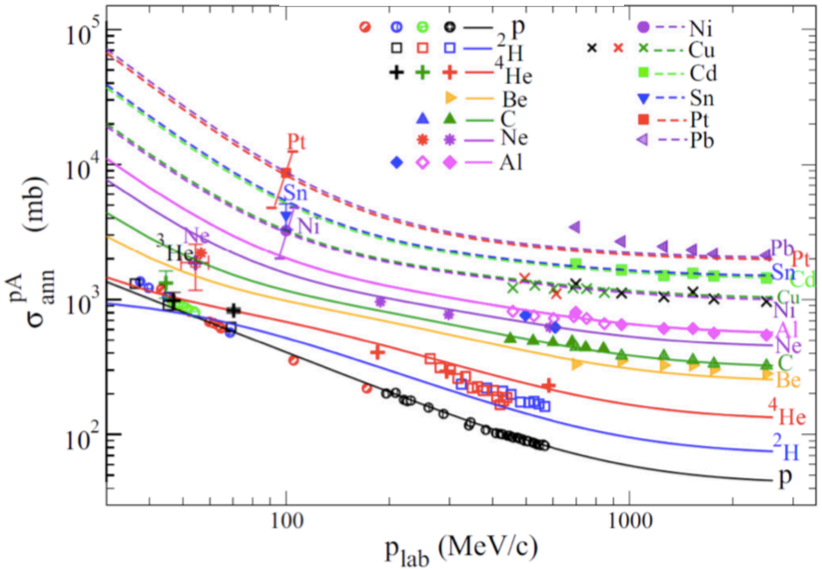


[1] Phys. Rev. C 89, 054601 (2014) [2] Nuclear Physics B 31(2), 253 (1971)

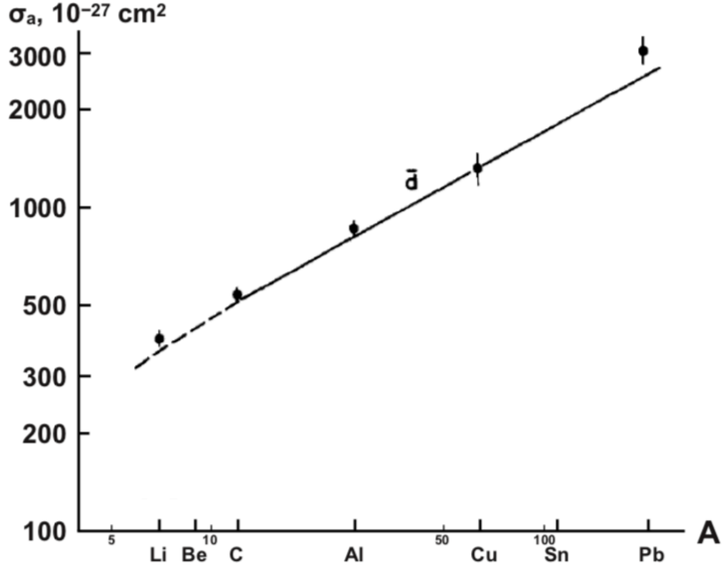
Propagation: Current status of antinuclei inelastic cross sections

- **Antiproton** inelastic cross section is **well known**.
- **Antideuteron** inelastic cross section is **poorly known at low energies**.
- **Antihelium/antitriton** inelastic cross section has **never been measured** before.

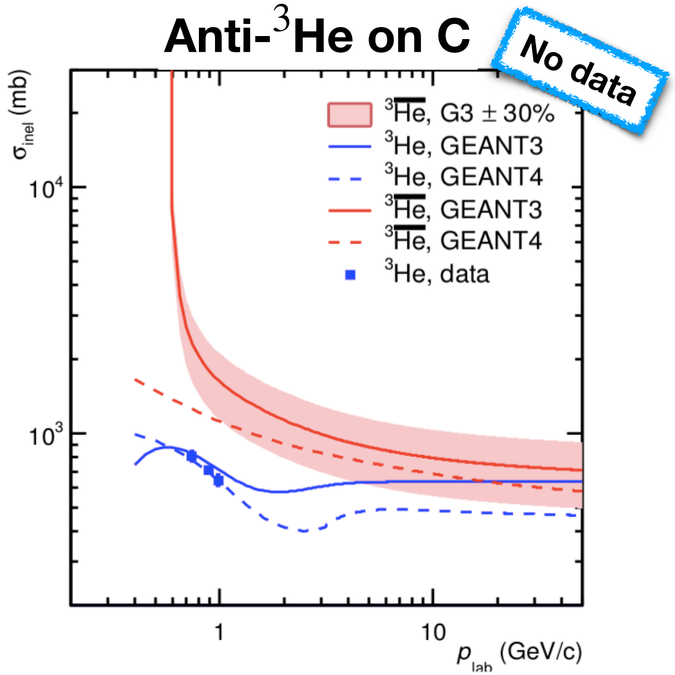
Antiprotons [1]



Antideuterons [2]



Anti-^{3}He on C



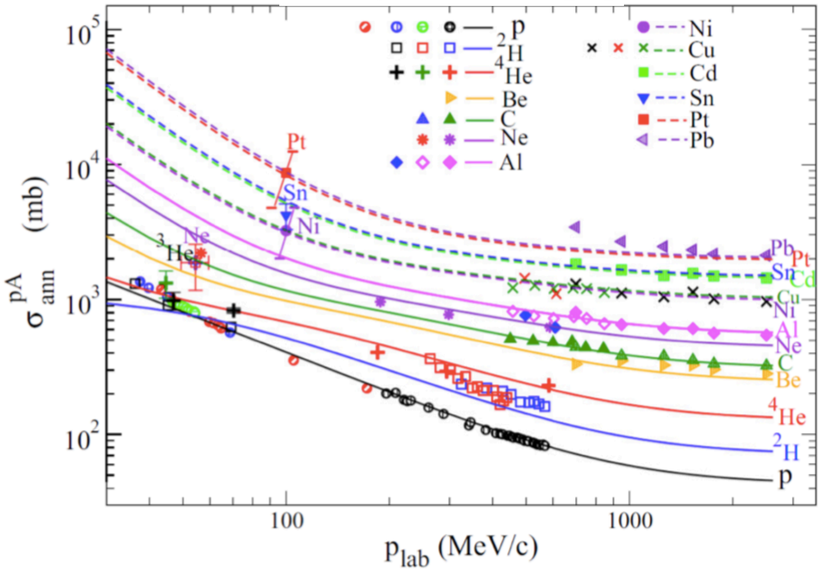
[1] Phys. Rev. C 89, 054601 (2014) [2] Nuclear Physics B 31(2), 253 (1971)

Propagation: Current status of antinuclei inelastic cross sections

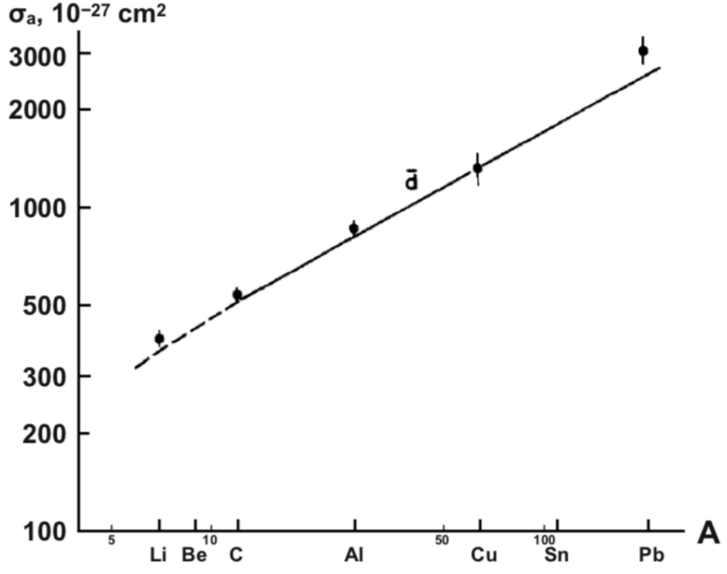
- **Antiproton** inelastic cross section is **well known**.
- **Antideuteron** inelastic cross section is **poorly known at low energies**.
- **Antihelium/antitriton** inelastic cross section has **never been measured** before.

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

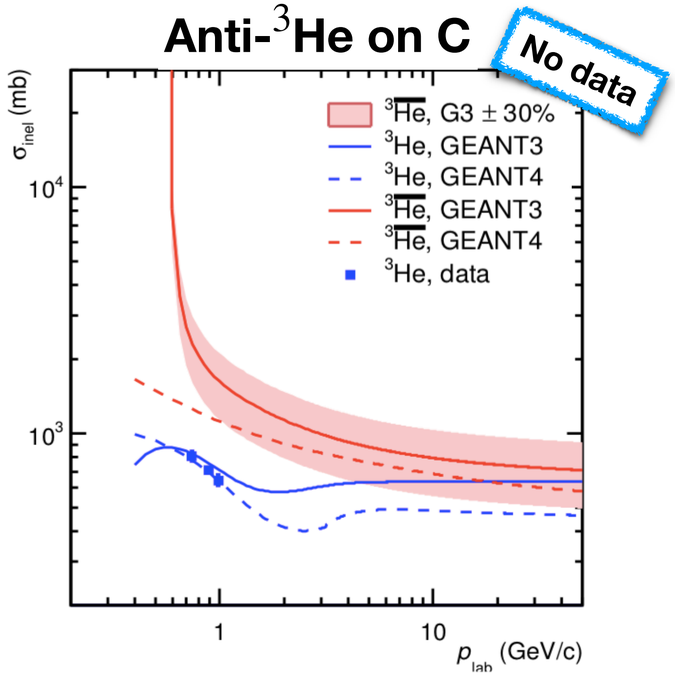
Antiprotons [1]



Antideuterons [2]



Anti-^{3}He on C



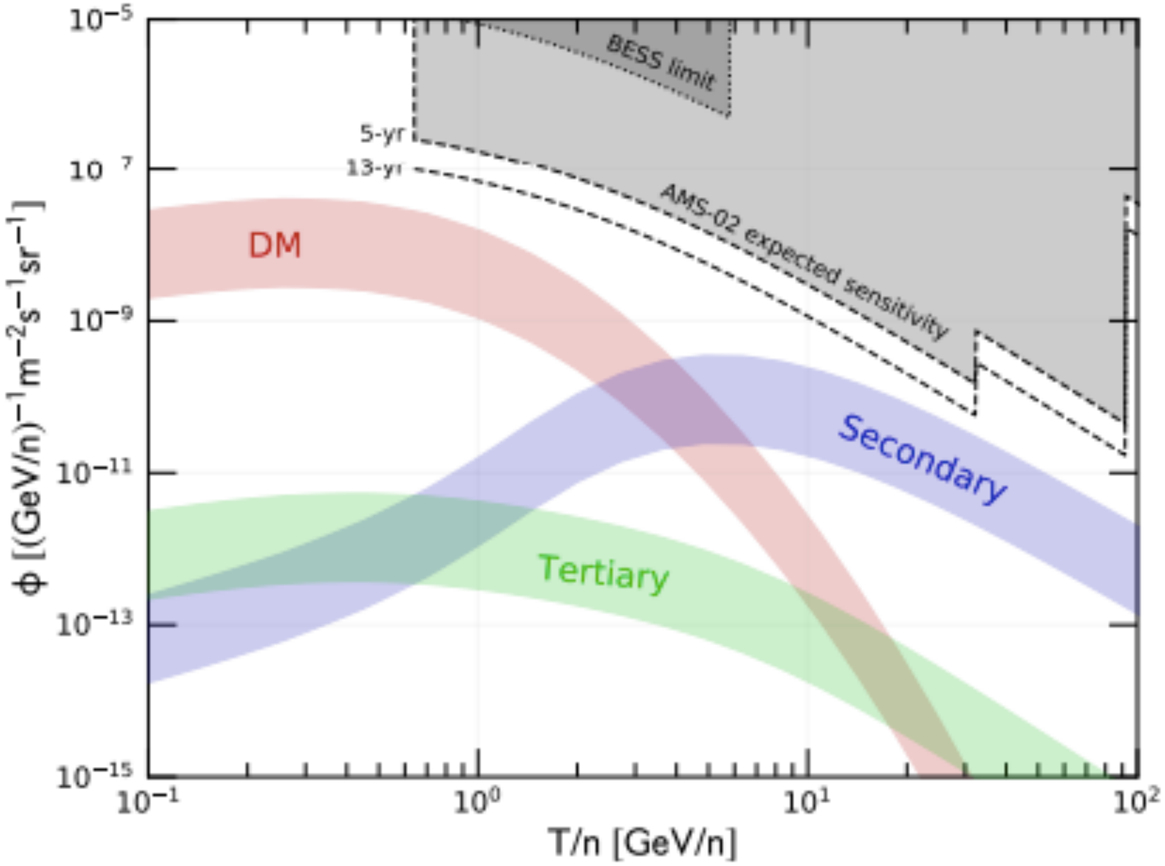
[1] Phys. Rev. C 89, 054601 (2014) [2] Nuclear Physics B 31(2), 253 (1971)

Antinuclei in cosmic rays

Antinuclei in cosmic rays

- Antinuclei flux has two dominant components:
  - Antinuclei from dark matter annihilations
  - Secondary antinuclei from cosmic ray collisions.
- At low energies, the contribution from dark matter annihilations is expected to dominate.

Antihelium flux near earth

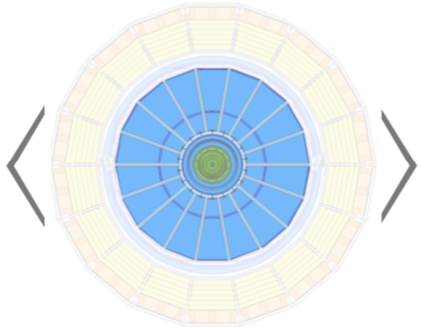


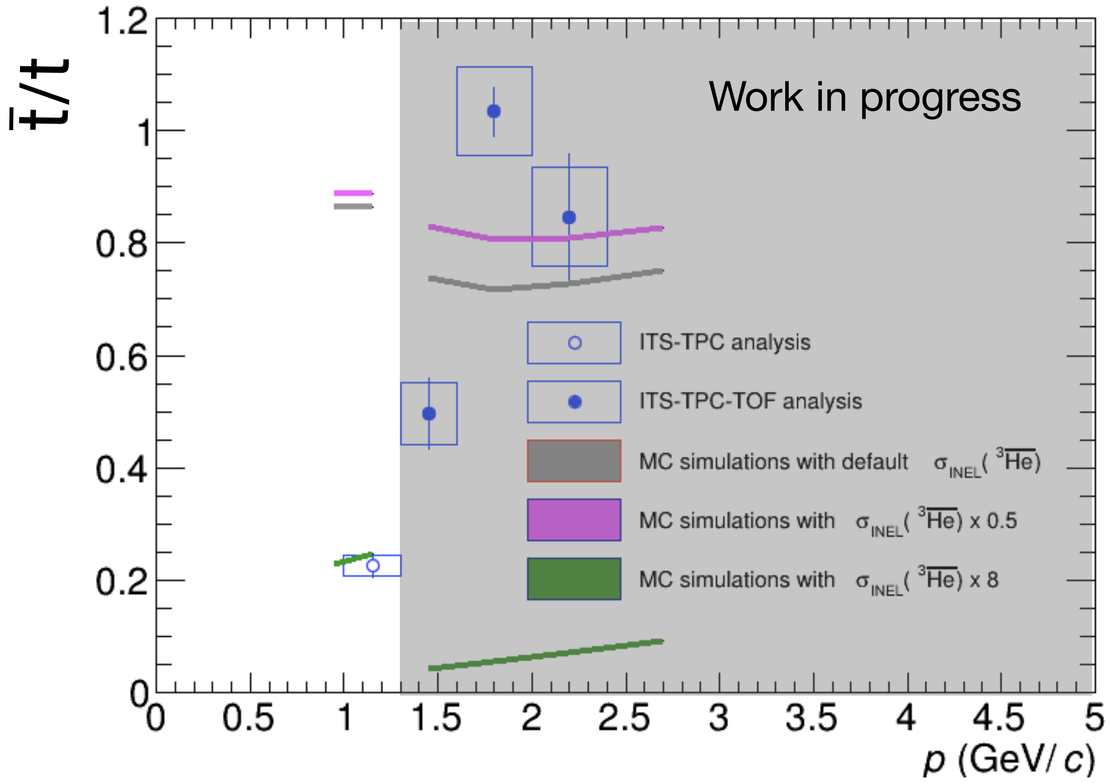
[1] Korsmeier et.al. arXiv:1711.08465

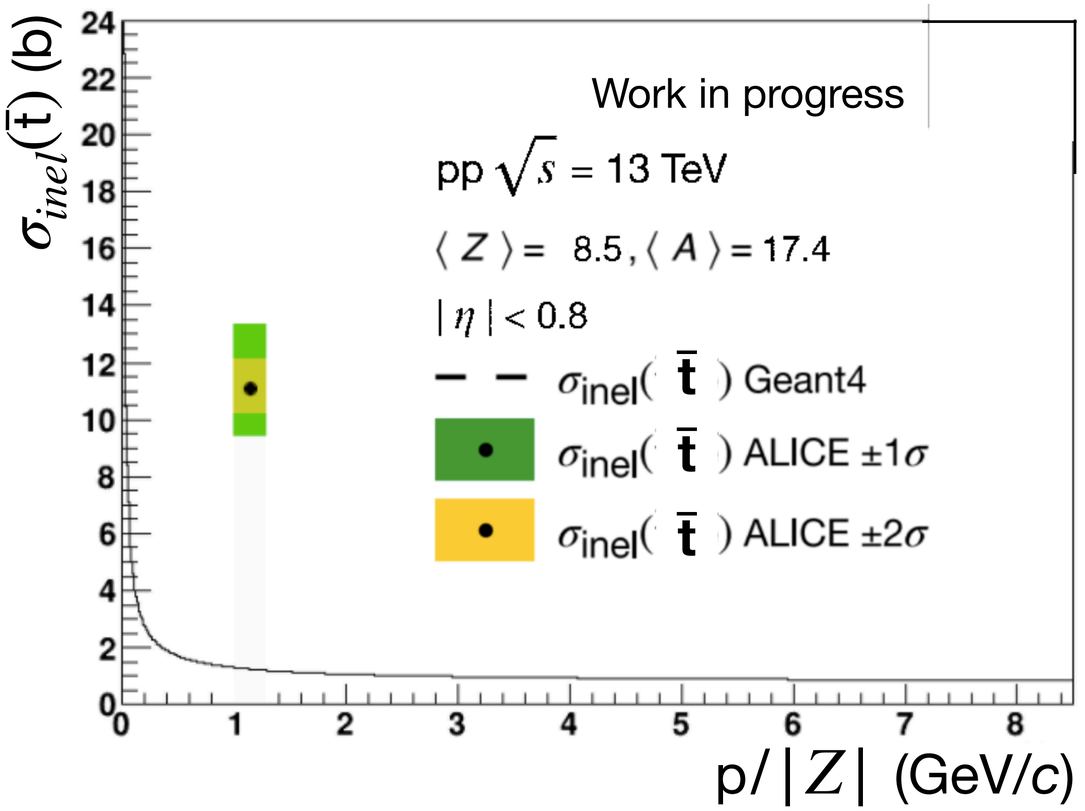
Antitriton inelastic cross section

$\sigma_{\text{inel}}(\bar{t})$ on average ALICE detector material.

- Much steeper rise at low momentum than in G4
- Good crosscheck for $\sigma_{\text{inel}}(^3\overline{\text{He}})$



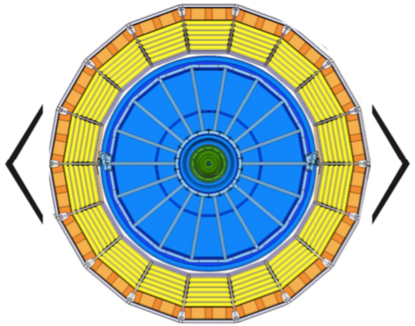


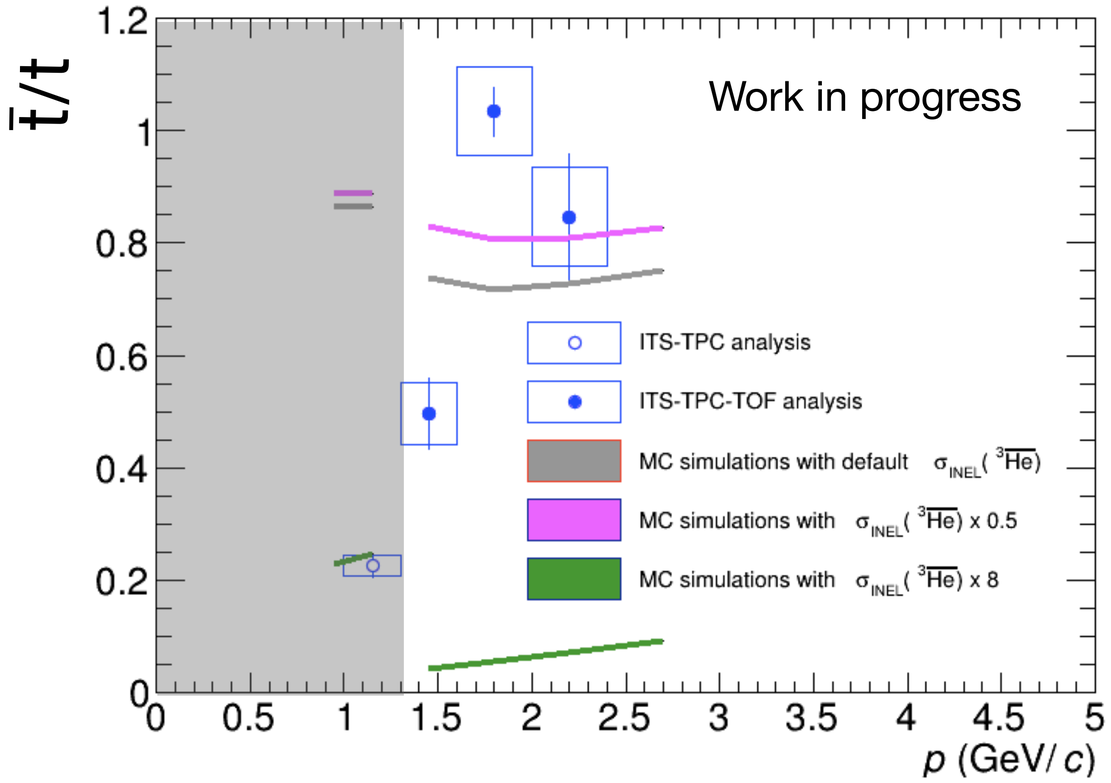


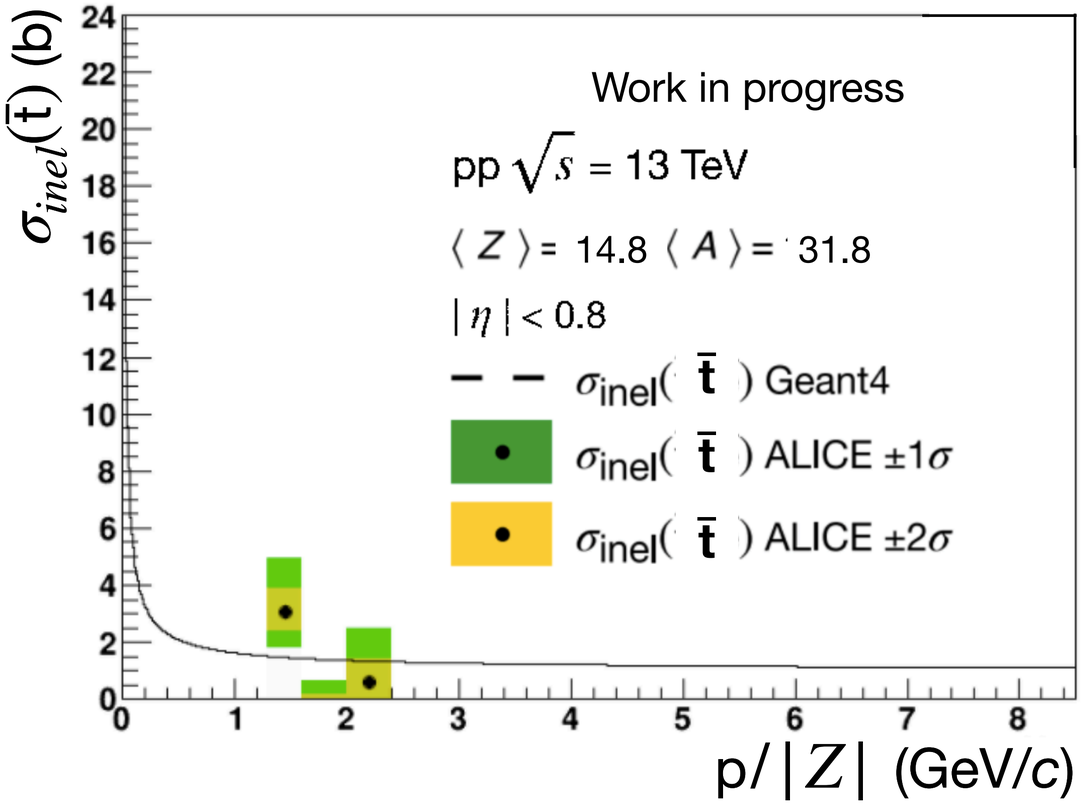
Antitriton inelastic cross section

$\sigma_{\text{inel}}(\bar{t})$ on average ALICE detector material.

- Much steeper rise at low momentum than in G4
- Good crosscheck for $\sigma_{\text{inel}}(^3\overline{\text{He}})$



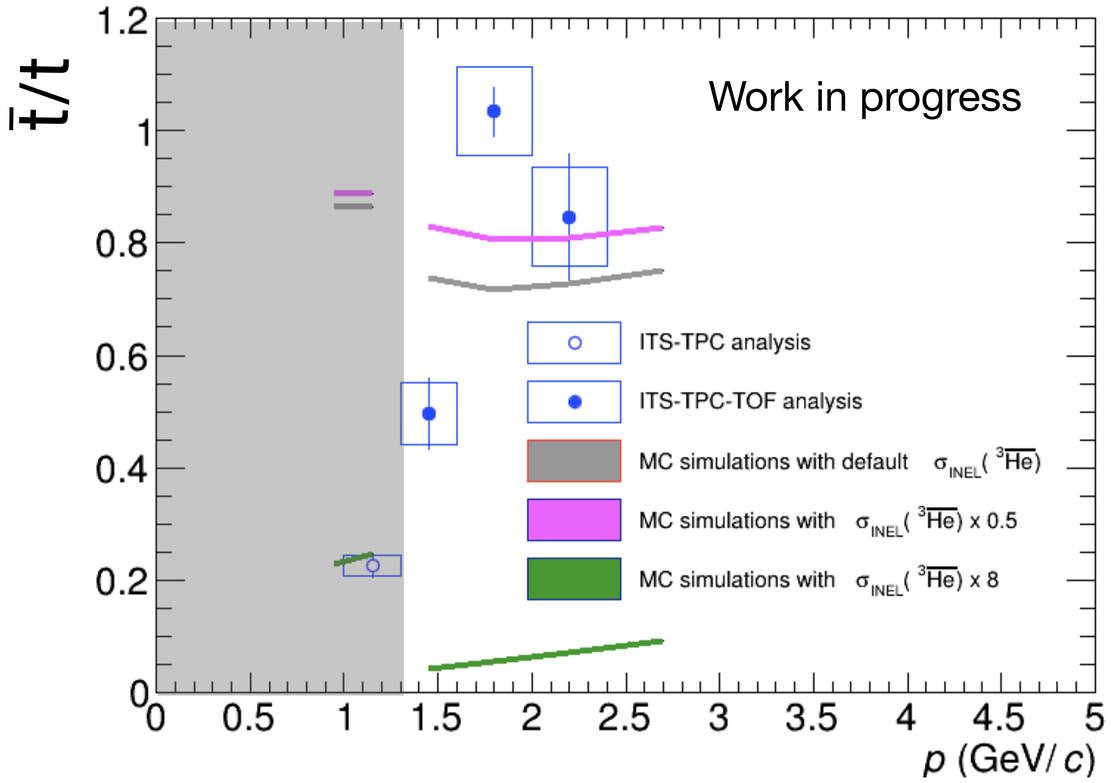




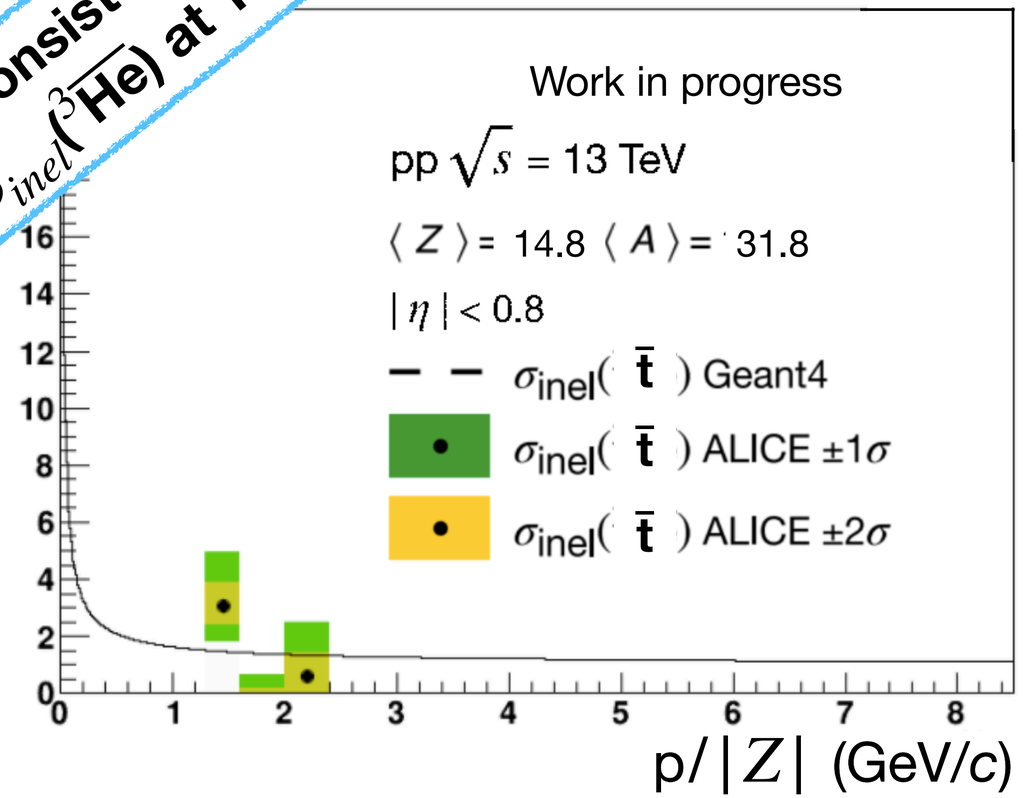
Antitriton inelastic cross section

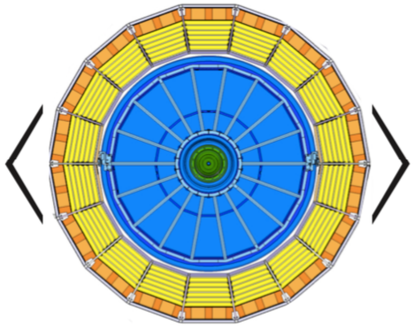
$\sigma_{\text{inel}}(\bar{t})$ on average ALICE detector material.

- Much steeper rise at low momentum than in G4
- Good crosscheck for $\sigma_{\text{inel}}(^3\overline{\text{He}})$



Consistent with $\sigma_{inel}(^3\overline{\text{He}})$ at 1.5 σ_{tot}

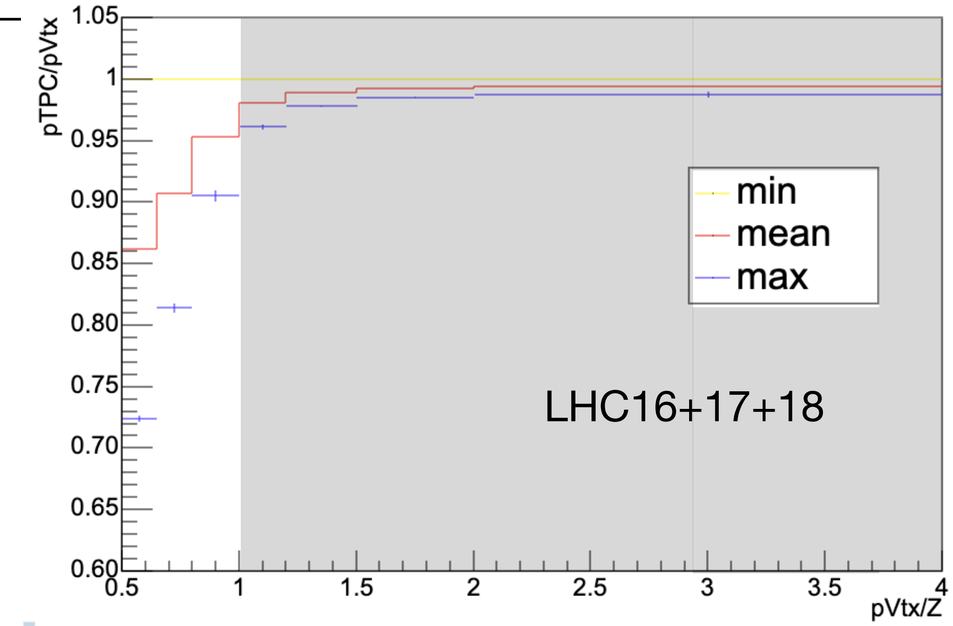


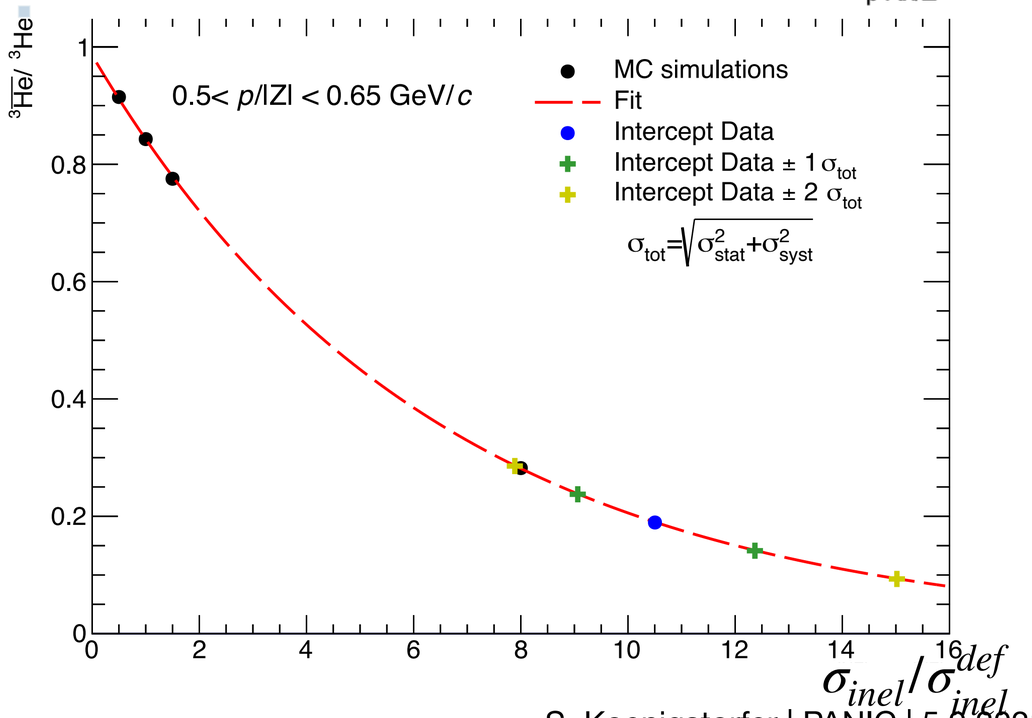


$$\sigma_{tot} = \sqrt{\sigma_1^2 + \sigma_2^2}$$

TPC analysis p->p* correction

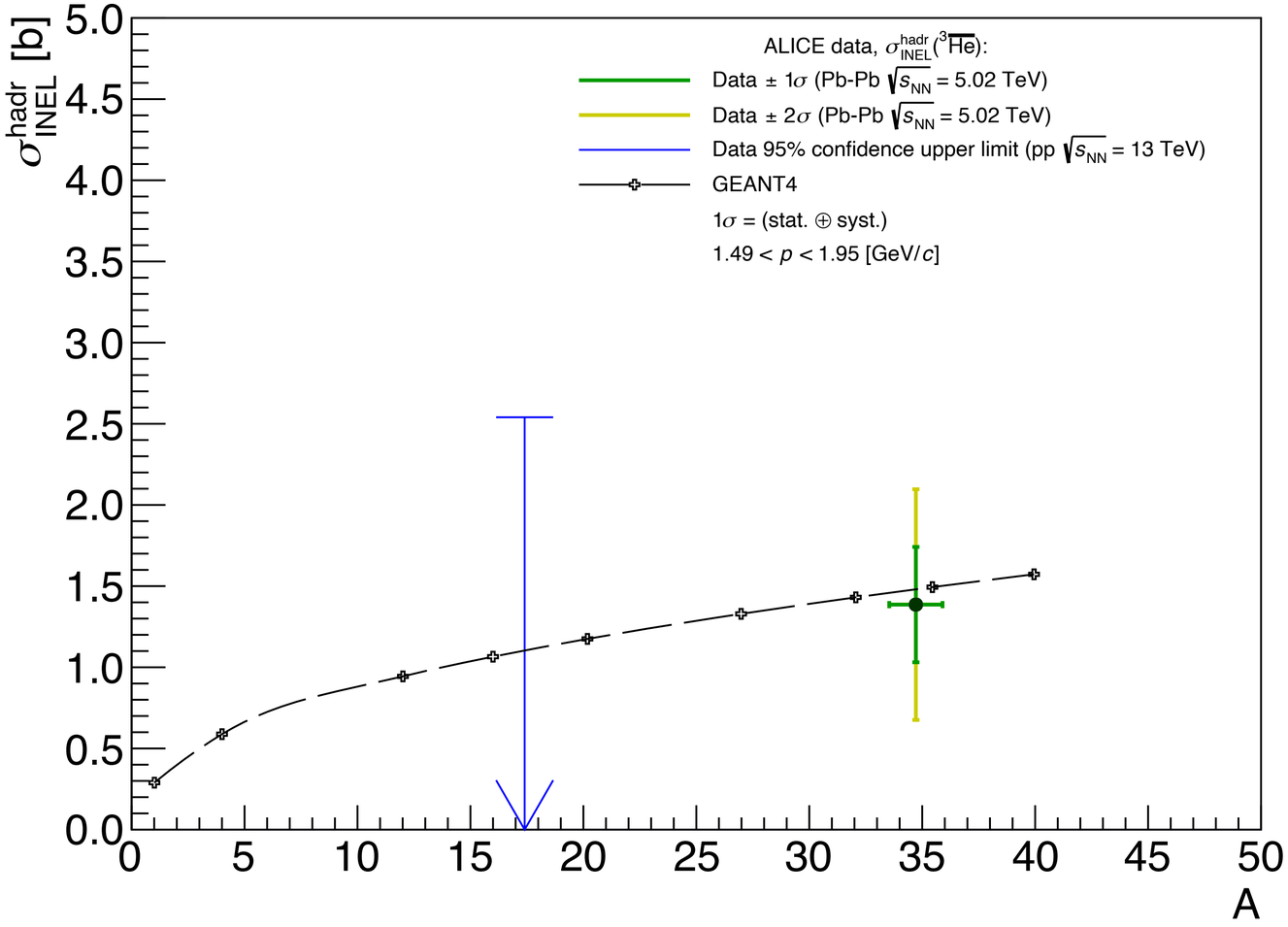
- 3 parameterizations:
  - max (p_TPC)
  - mean: halfway between p_TPC and p_Vtx
  - min: p_Vtx
- Bin boundaries rescaled by these parameterizations.
- Cross-section constraints are calculated for each of the three different binnings.
- Error calculated as st.dev. of the σ_{inel} values between these 3 parameterizations.
- Mean parametrization plotted, with the added error.



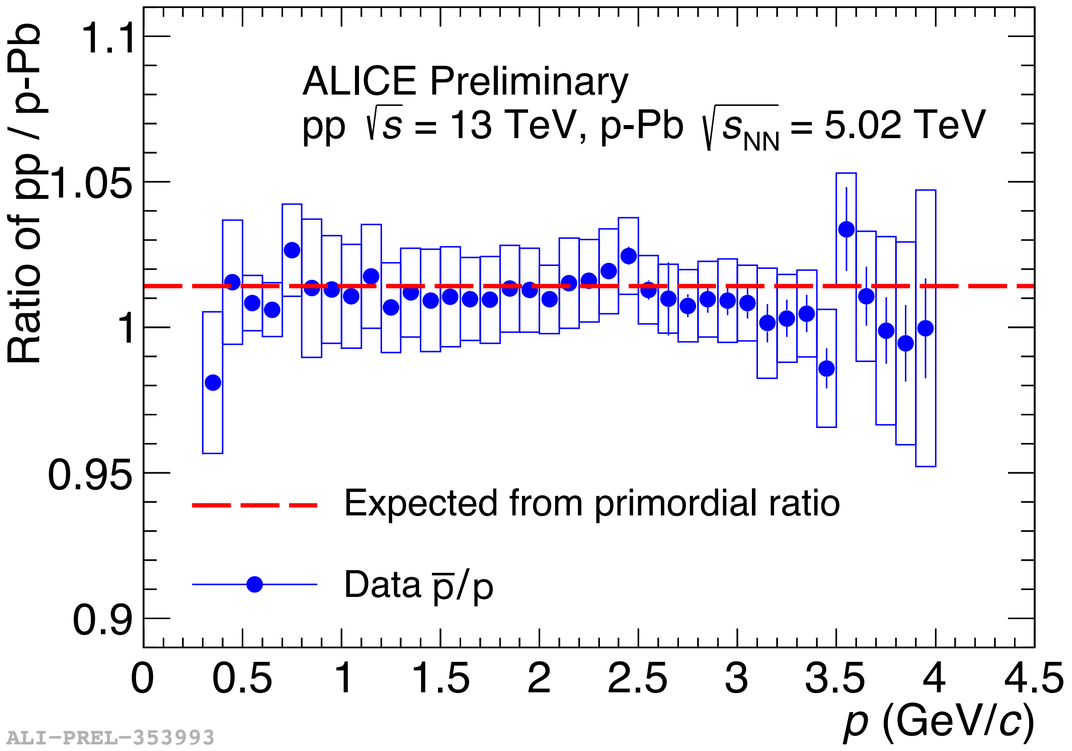


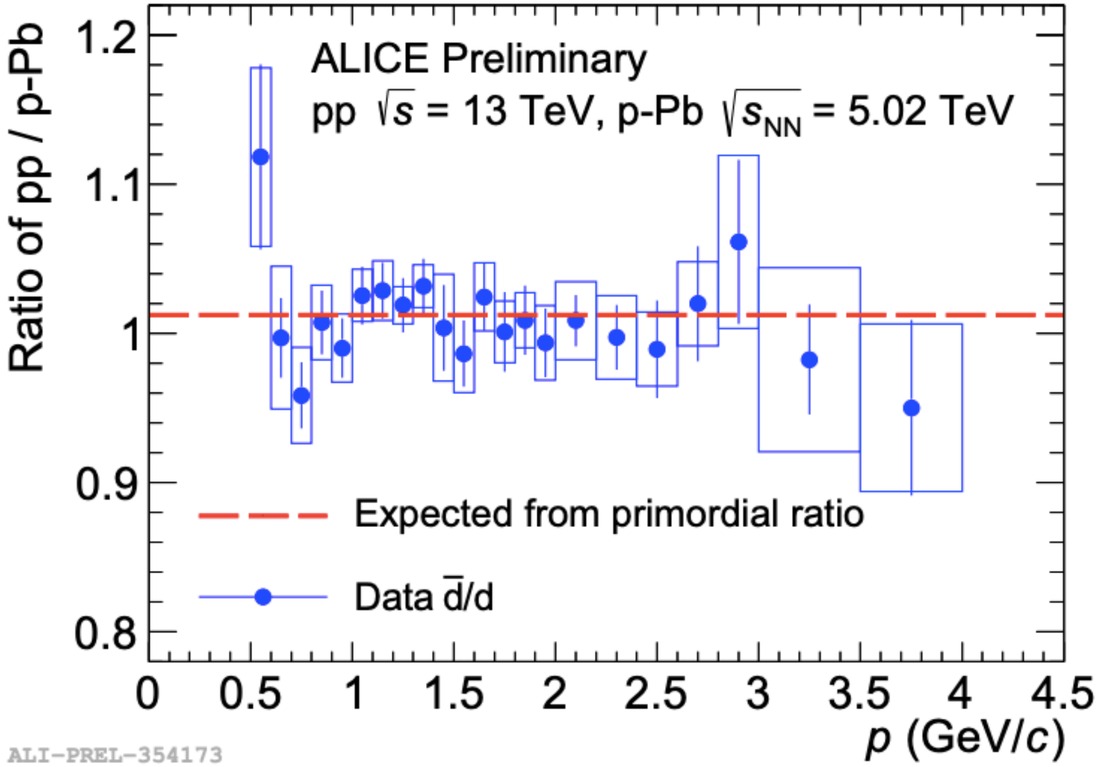
Probing the <A> scaling of $\sigma_{inel}(^3\overline{\mathrm{He}})$

- For anti-3He, we have overlapping analyses with different methods.
  - TPC/TOF ratio (CERN group)
  - Antiparticle-to-particle ratio in TPC
  - Antiparticle-to-particle ratio in TOF
- Each of these is on slightly different A, so we hope to get some insight into how $\sigma_{inel}(^3\overline{\mathrm{He}})$ scales with <A>



Comparison of pp and p-Pb systems





Comparison of raw primary antiparticle-to-particle ratio in p-Pb and pp collisions.

➡Consistent with the difference expected from primordial antimatter-to-matter ratio.

➡The cross section measurements are independent of the collisions system, as expected.

➡Analysis method is consistent.

Parameterisations used in GEANT4

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

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

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

R_A cannot be directly connected with known values due to some simplifications
Use equations as a determination of R_A having calculated σ_{hA} and σ_{BA} with Glauber

For total cross-section:

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

For inelastic cross-section:

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

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

Propagation in the galaxy

$$\frac{\partial \psi}{\partial t} = q(\mathbf{r}, p) + \mathbf{div}(D_{xx}\mathbf{grad}\psi - \mathbf{V}\psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{\psi}{p^2} - \frac{\partial}{\partial p}\left[\psi \frac{dp}{dt} - \frac{p}{3}(\mathbf{div} \cdot \mathbf{V})\psi\right] - \psi\Gamma_{ann}$$

1 2 3 4 5 6 7

1. source function: PRIMARY OR SECONDARY
2. diffusion
3. convection
4. diffusive reacceleration

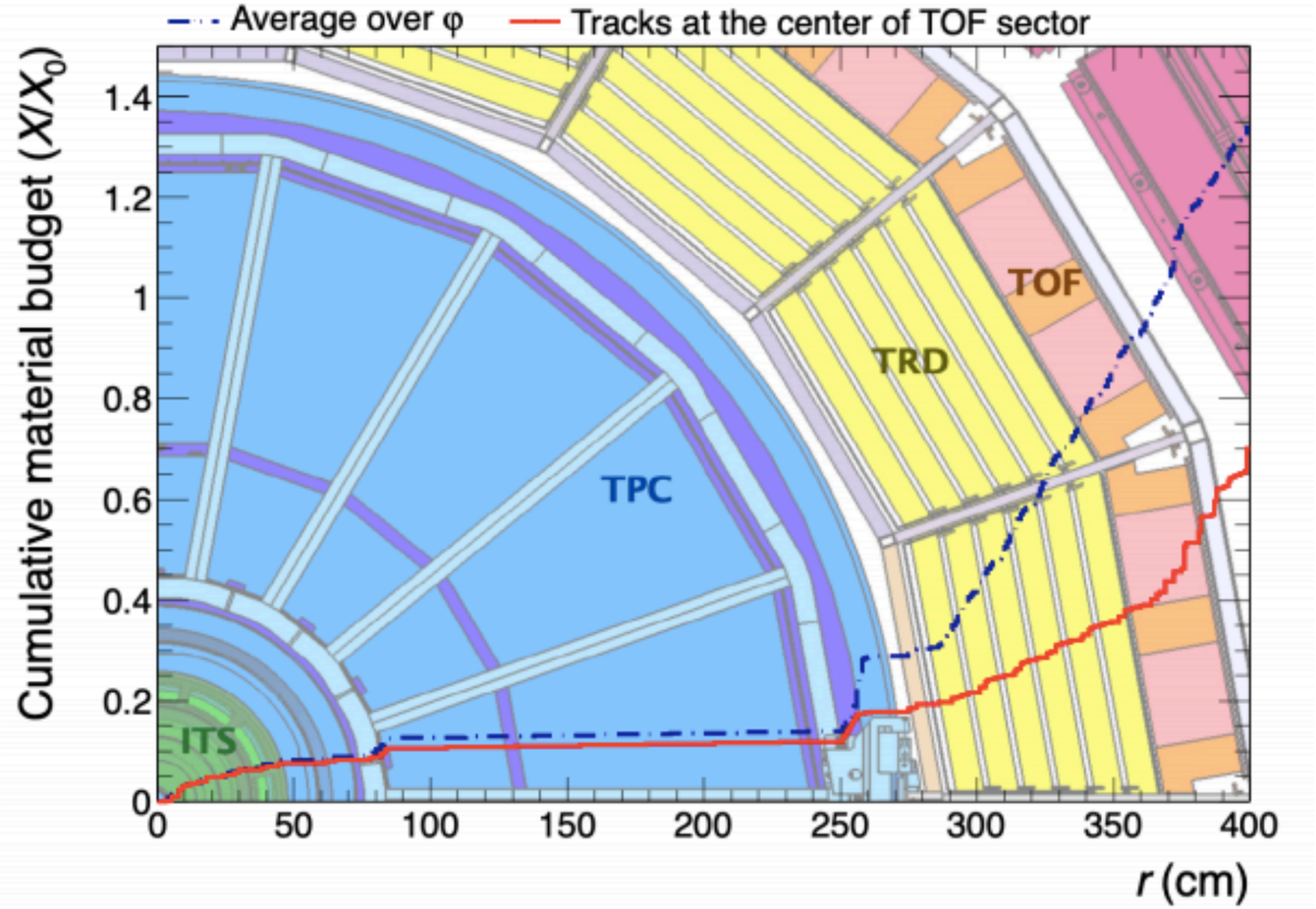
   momentum losses:
   5. via ionisation and bremsstrahlung
   6. adiabatic
7. annihilation

Work of L. Šerkšnytė.

ALICE material budget

ALICE material budget at mid-rapidity [1]:

- **Beryllium beam pipe (~0.3% X_0)**
- **ITS (~8% X_0)**
- **TPC (~4% X_0)**
- **TRD (~25% X_0)**
- **Space frame (~20% X_0** between TPC and TOF)



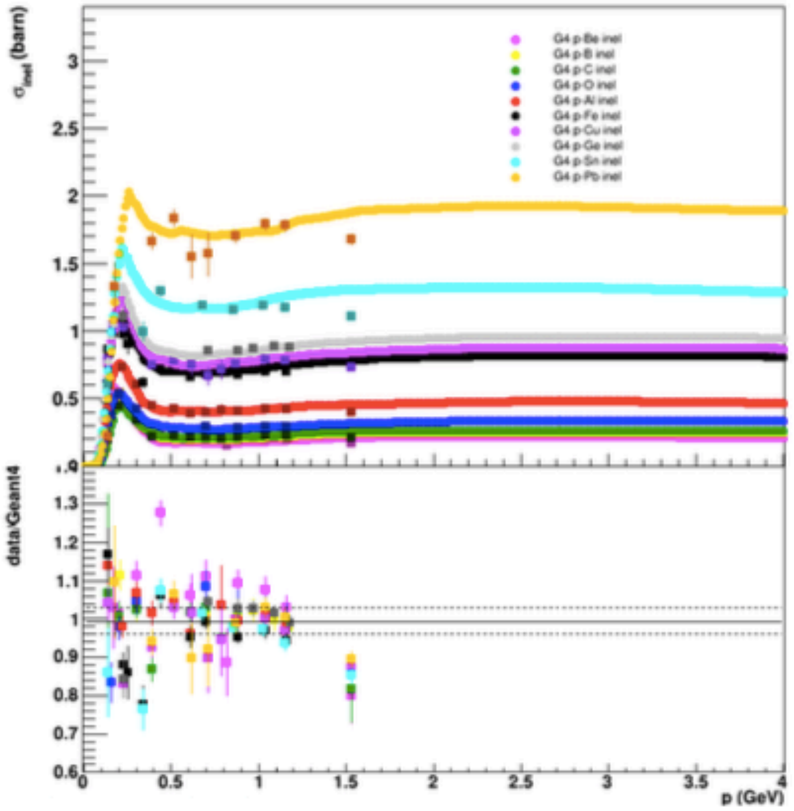
PRL 125, 162001 (2020)

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

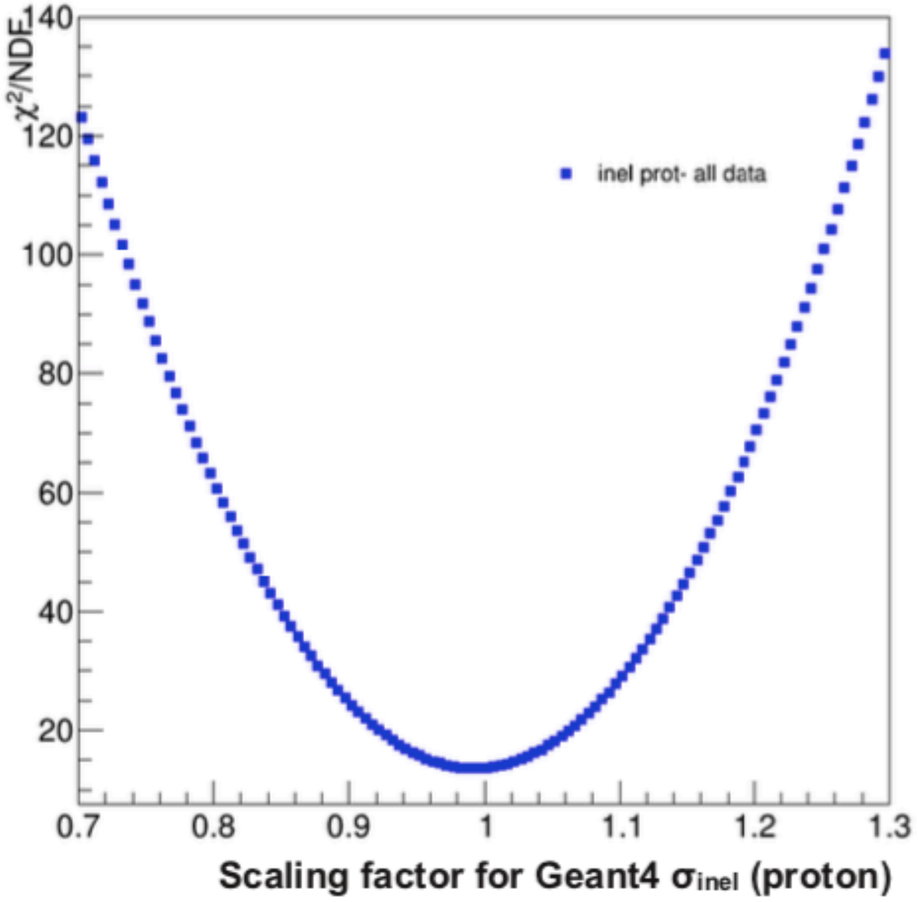
Uncertainty due to σ_{inel} (proton)

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

- Check available experimental data (Be,B,C,O,Al,Fe,Cu,Ge,Sn,Pb)
- Vary Geant4 parametrisation, calculate χ^2 for all data points
- Minimum χ^2 and $\pm1\sigma$: **0.9925** $^{+0.0375}$ $_{-0.0325}$



+1σ
min. χ^2
-1σ

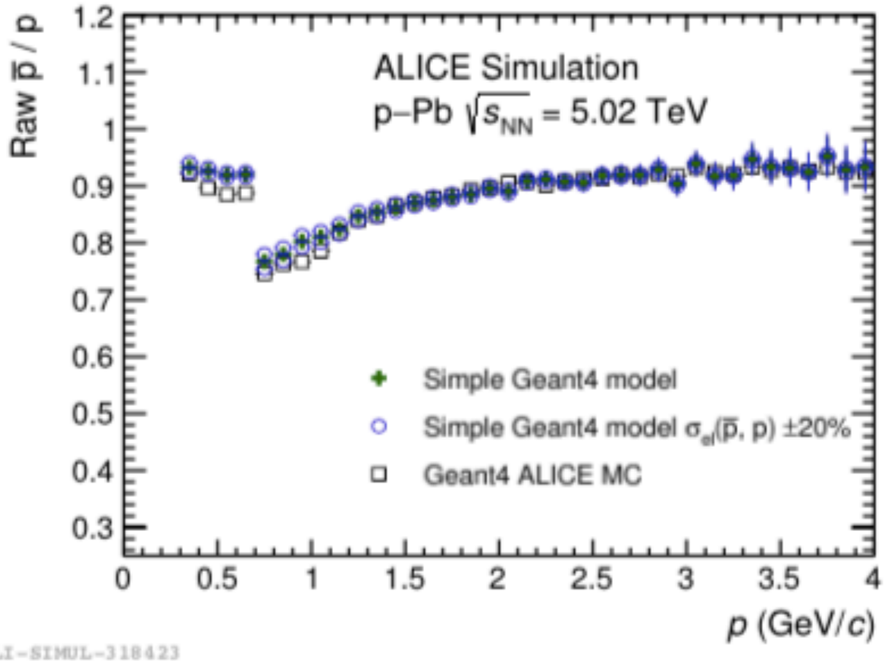


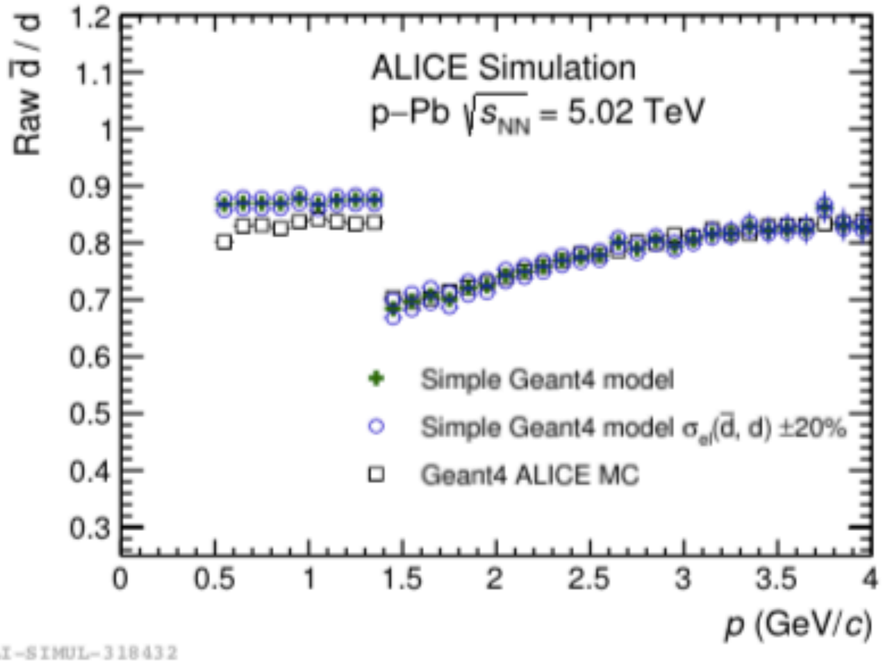
Variations of σ_{el} with simple Geant4 model

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

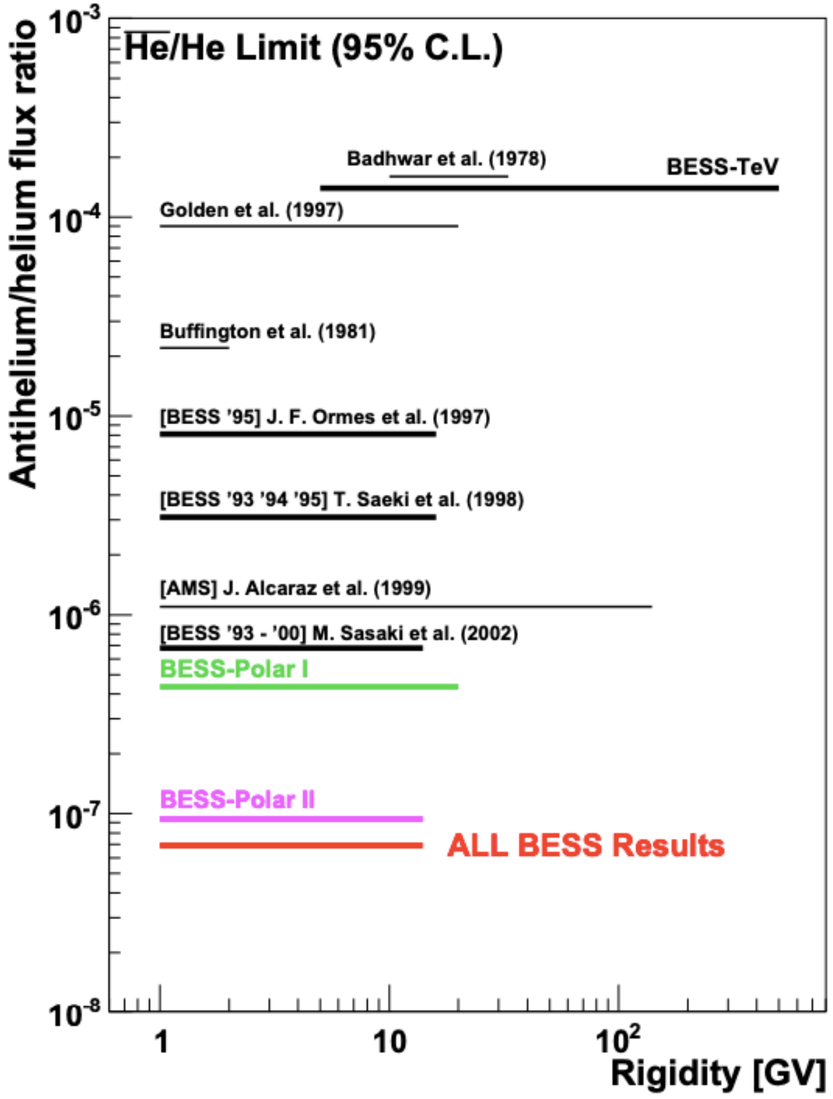
- σ_{el} contributes to scattering effects in ITS, TPC and TRD material
- Only a minor effect on the ratio (≲1% for $\bar{p}$ / p, ≲2% for $\bar{d}$ / d)

For final results: cross-check the variations with full ALICE MC simulations





$^3\overline{He}$ in cosmic rays?

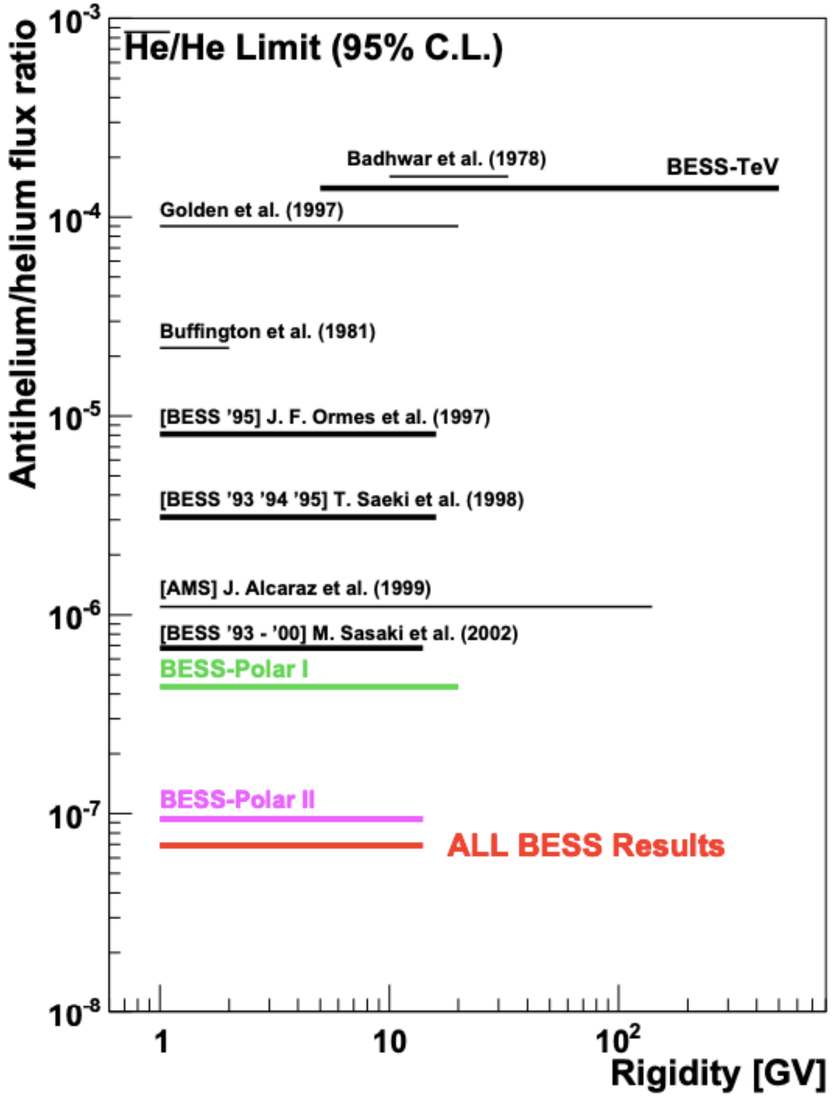


Bess Upper limit on $^3\overline{He}$ flux (latest published limit). [1]

$^3\overline{He}$ in cosmic rays is expected to be exceedingly rare, since the secondary flux expected from cosmic ray collisions is negligible.

[1] Abe et. al. , 2012, arXiv:1201.2967 [astro-ph.CO]
[2] Poulin et. al., 2018, arXiv:1808.08961 [astro-ph.HE]

$^3\overline{He}$ in cosmic rays?



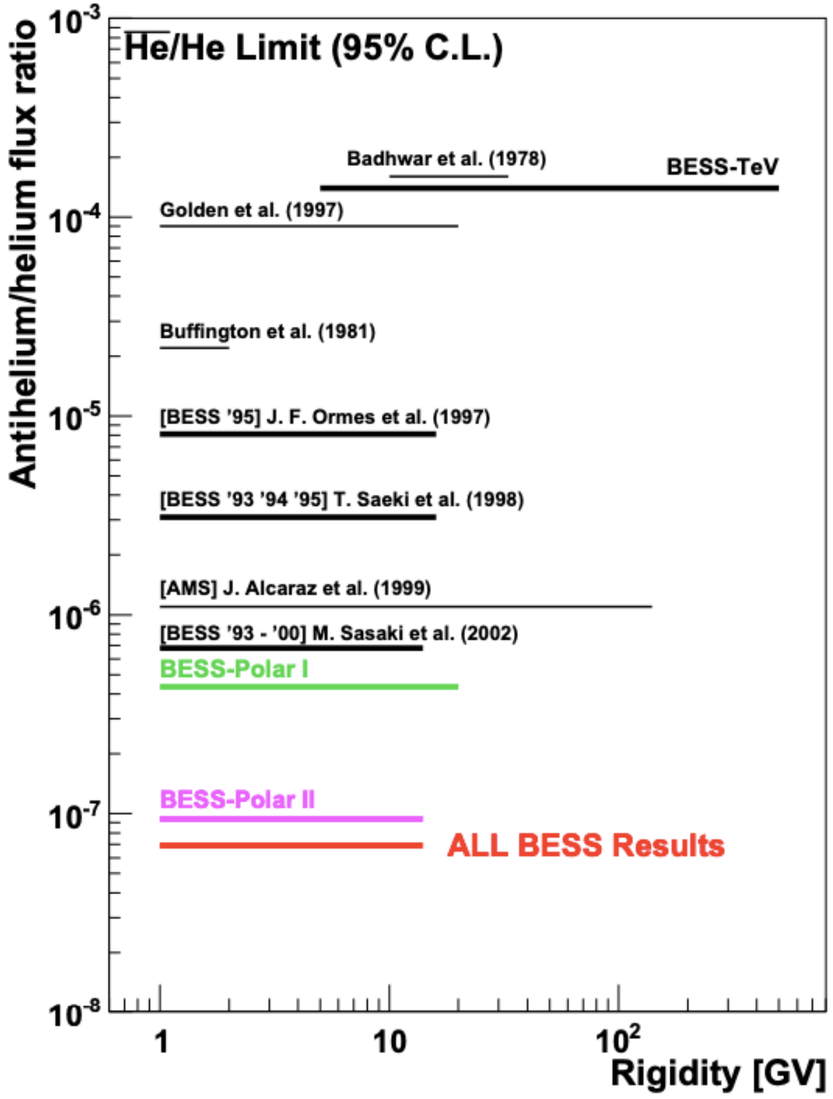
Bess Upper limit on $^3\overline{He}$ flux (latest published limit). [1]

$^3\overline{He}$ in cosmic rays is expected to be exceedingly rare, since the secondary flux expected from cosmic ray collisions is negligible.

- In ALICE, ca. 1 $^3\overline{He}$ per 10^6 high multiplicity pp events at $\sqrt{s}$=13TeV.

[1] Abe et. al. , 2012, arXiv:1201.2967 [astro-ph.CO]
[2] Poulin et. al., 2018, arXiv:1808.08961 [astro-ph.HE]

$^3\overline{He}$ in cosmic rays?



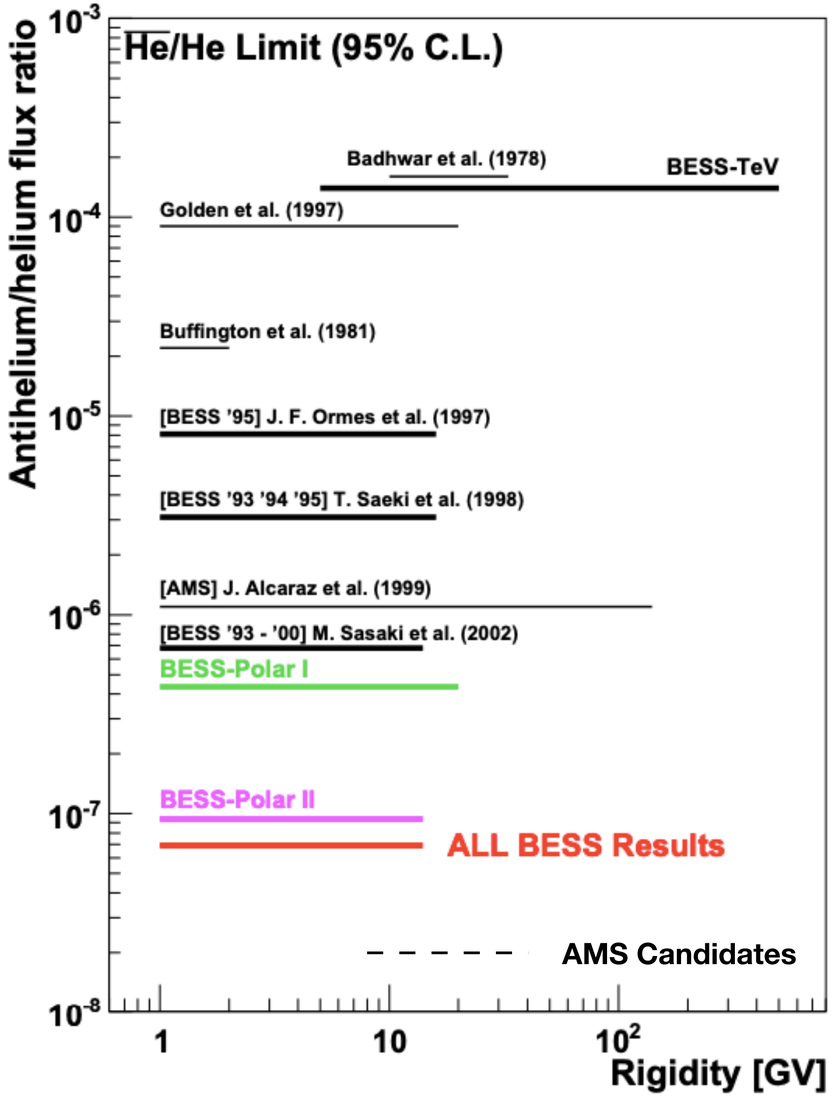
Bess Upper limit on $^3\overline{He}$ flux (latest published limit). [1]

$^3\overline{He}$ in cosmic rays is expected to be exceedingly rare, since the secondary flux expected from cosmic ray collisions is negligible.

- In ALICE, ca. 1 $^3\overline{He}$ per 10^6 high multiplicity pp events at $\sqrt{s}$=13TeV.
- AMS has teased the observation of $^3\overline{He}$ candidates at conferences for the past few years, but the results have not been published yet.

[1] Abe et. al. , 2012, arXiv:1201.2967 [astro-ph.CO]
[2] Poulin et. al., 2018, arXiv:1808.08961 [astro-ph.HE]

$^3\overline{He}$ in cosmic rays?



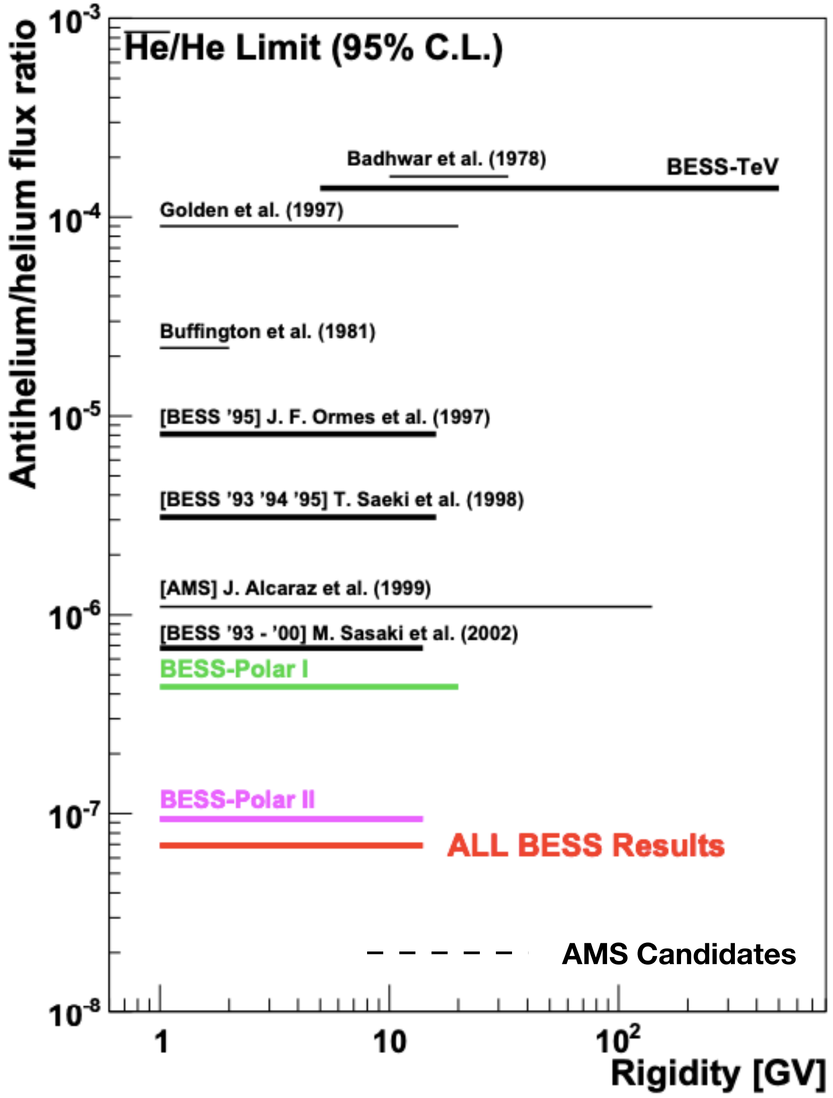
Bess Upper limit on $^3\overline{He}$ flux (latest published limit). [1]

$^3\overline{He}$ in cosmic rays is expected to be exceedingly rare, since the secondary flux expected from cosmic ray collisions is negligible.

- In ALICE, ca. 1 $^3\overline{He}$ per 10^6 high multiplicity pp events at $\sqrt{s}$=13TeV.
- AMS has teased the observation of $^3\overline{He}$ candidates at conferences for the past few years, but the results have not been published yet.

[1] Abe et. al. , 2012, arXiv:1201.2967 [astro-ph.CO]
[2] Poulin et. al., 2018, arXiv:1808.08961 [astro-ph.HE]

$^3\overline{He}$ in cosmic rays?



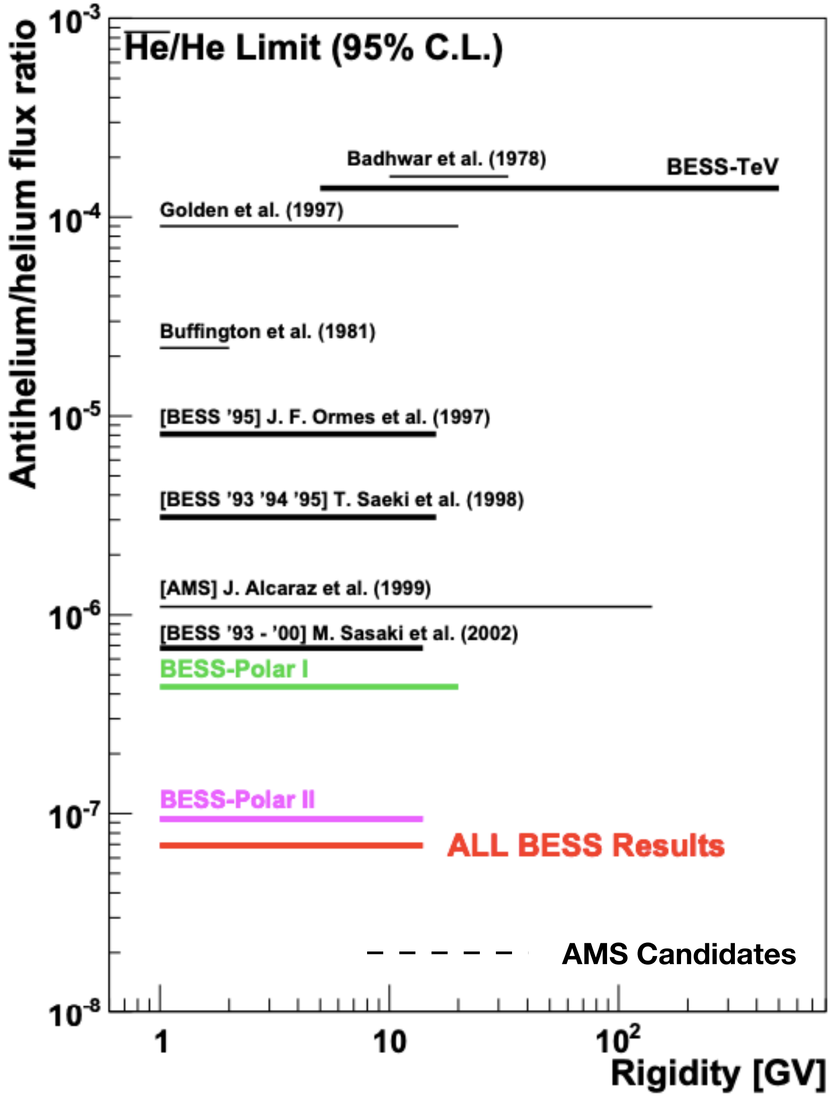
Bess Upper limit on $^3\overline{He}$ flux (latest published limit). [1]

$^3\overline{He}$ in cosmic rays is expected to be exceedingly rare, since the secondary flux expected from cosmic ray collisions is negligible.

- In ALICE, ca. 1 $^3\overline{He}$ per 10^6 high multiplicity pp events at $\sqrt{s}$=13TeV.
- AMS has teased the observation of $^3\overline{He}$ candidates at conferences for the past few years, but the results have not been published yet.
- If published, even the observation of 1 event would signal new physics, because the flux cannot currently be explained by any considered production process (except an anti-star within 1 parsec).

[1] Abe et. al. , 2012, arXiv:1201.2967 [astro-ph.CO]
[2] Poulin et. al., 2018, arXiv:1808.08961 [astro-ph.HE]

$^3\overline{He}$ in cosmic rays?



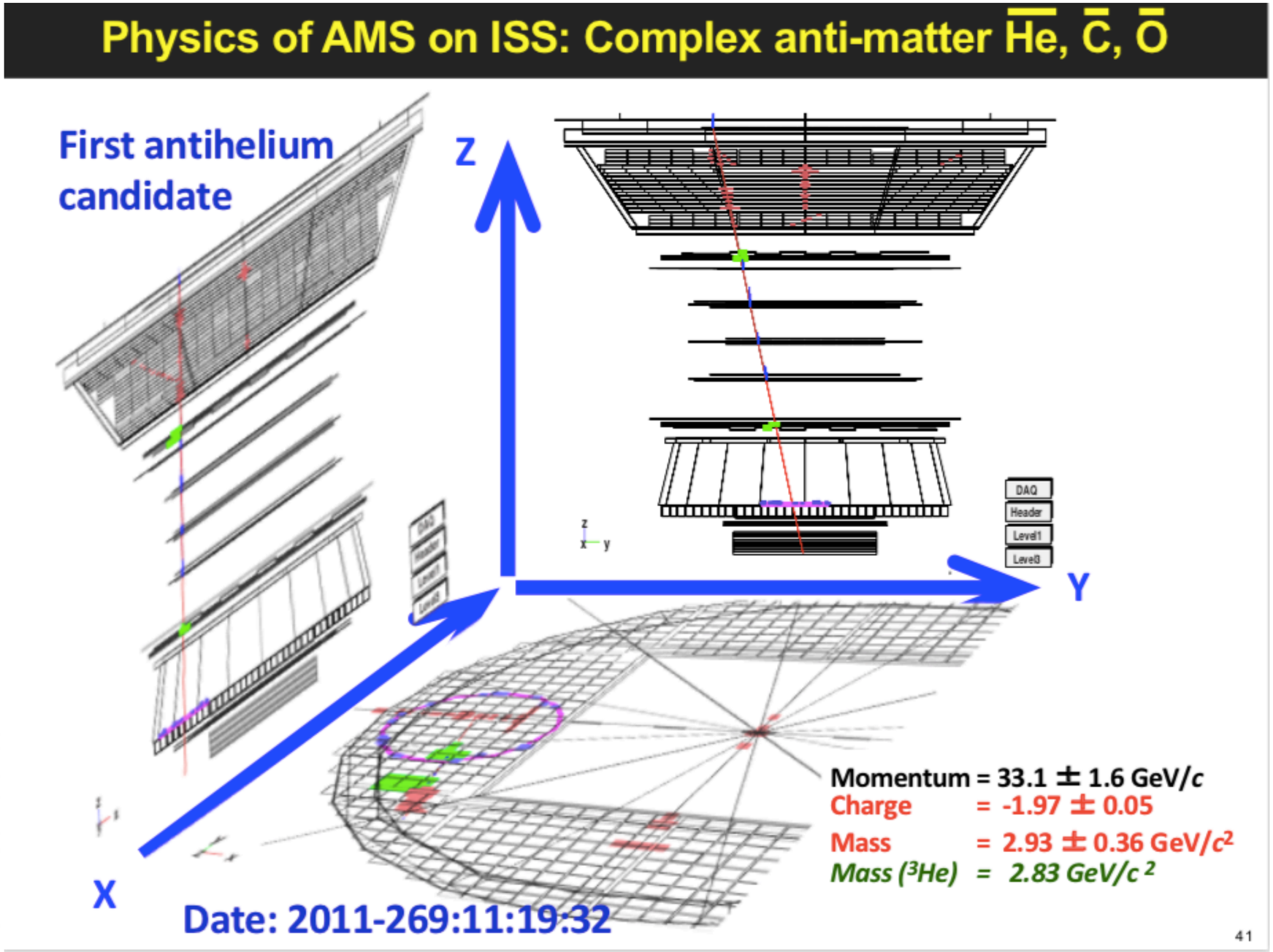
Bess Upper limit on $^3\overline{He}$ flux (latest published limit). [1]

$^3\overline{He}$ in cosmic rays is expected to be exceedingly rare, since the secondary flux expected from cosmic ray collisions is negligible.

- In ALICE, ca. 1 $^3\overline{He}$ per 10^6 high multiplicity pp events at $\sqrt{s}$=13TeV.
- AMS has teased the observation of $^3\overline{He}$ candidates at conferences for the past few years, but the results have not been published yet.
- If published, even the observation of 1 event would signal new physics, because the flux cannot currently be explained by any considered production process (except an anti-star within 1 parsec).
- This is why it is vital to measure these cross sections.

[1] Abe et. al. , 2012, arXiv:1201.2967 [astro-ph.CO]
[2] Poulin et. al., 2018, arXiv:1808.08961 [astro-ph.HE]

AMS $^{3}\overline{He}$ candidates



[1] A. Kounine and S. Ting, 2018, ICHEP Conference