ALICE determines the transparency of our galaxy to the passage of antihelium nuclei

Nature Phys. (2022)

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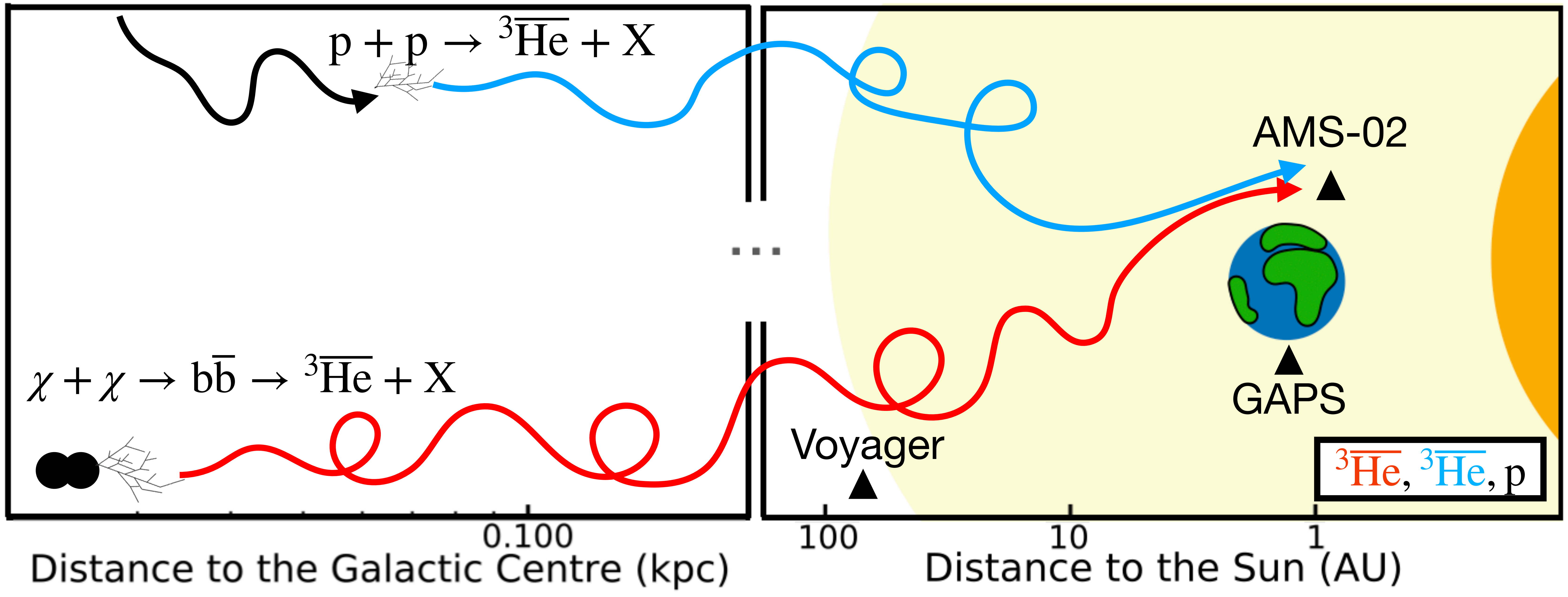
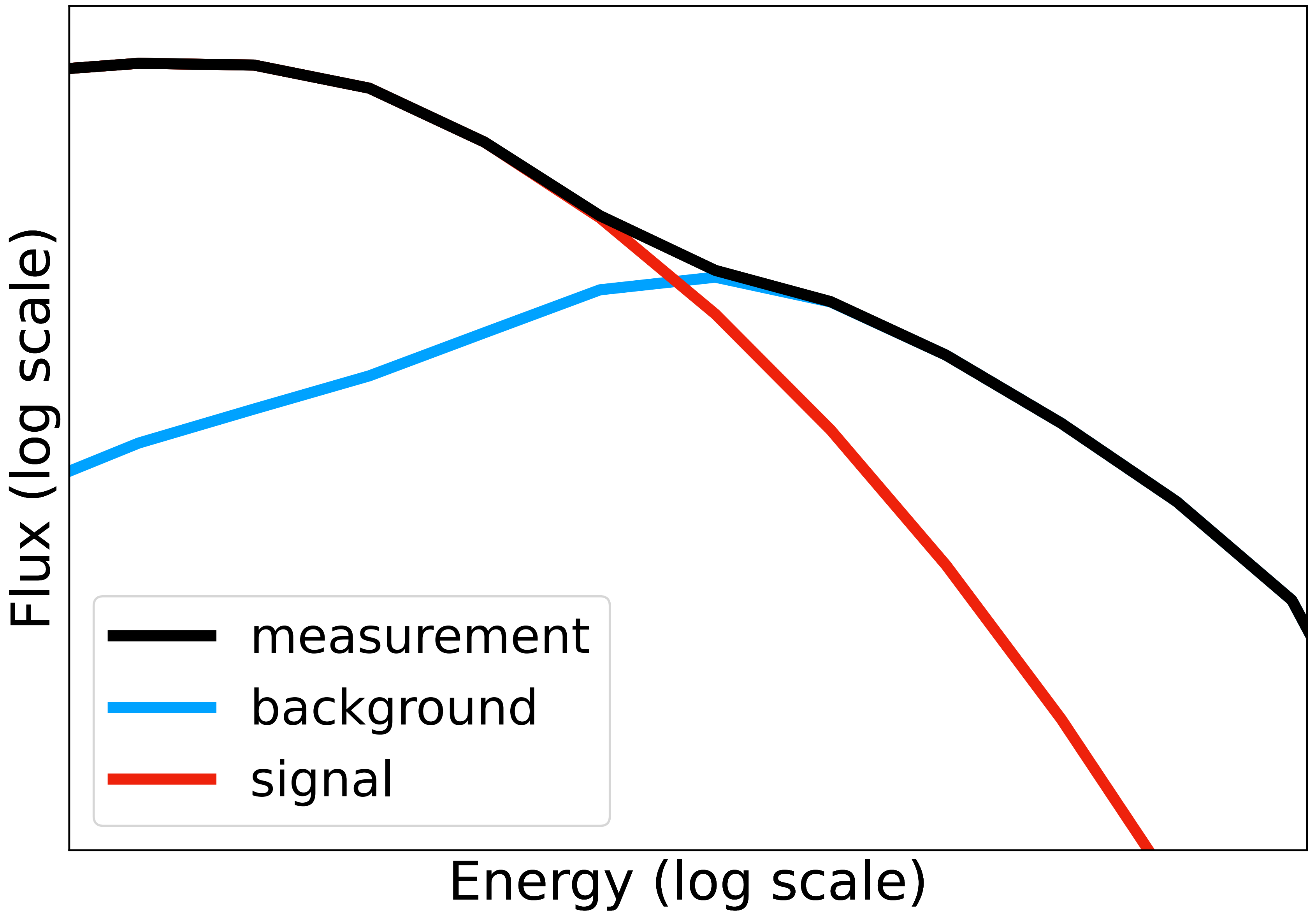
Technical University of Munich

Cosmic rays in our Galaxy

- No observations of dark matter particles yet!
- Indirect searches: antinuclei cosmic ray measurements
  - Dark matter annihilation
  - Ordinary cosmic ray collisions with interstellar medium
- **Precise modelling of the fluxes required**



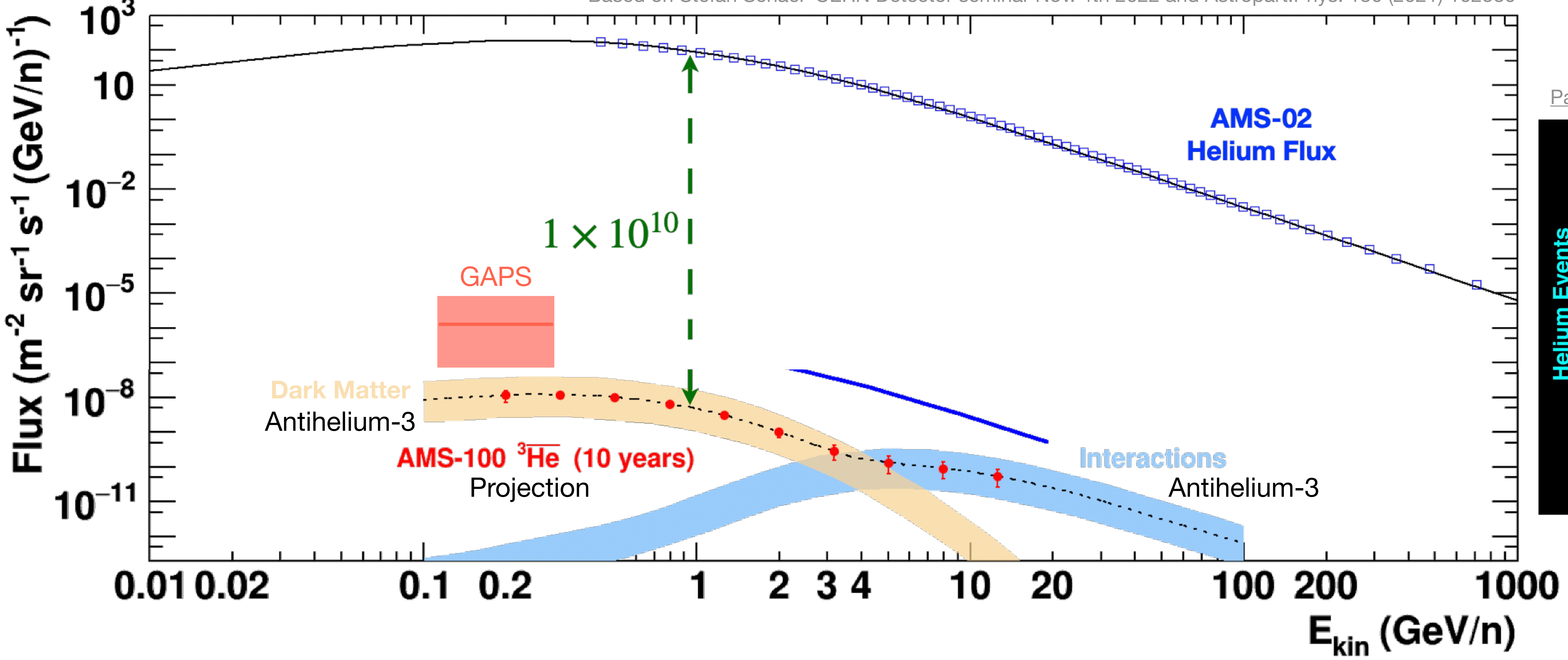
Are such measurements realistic?



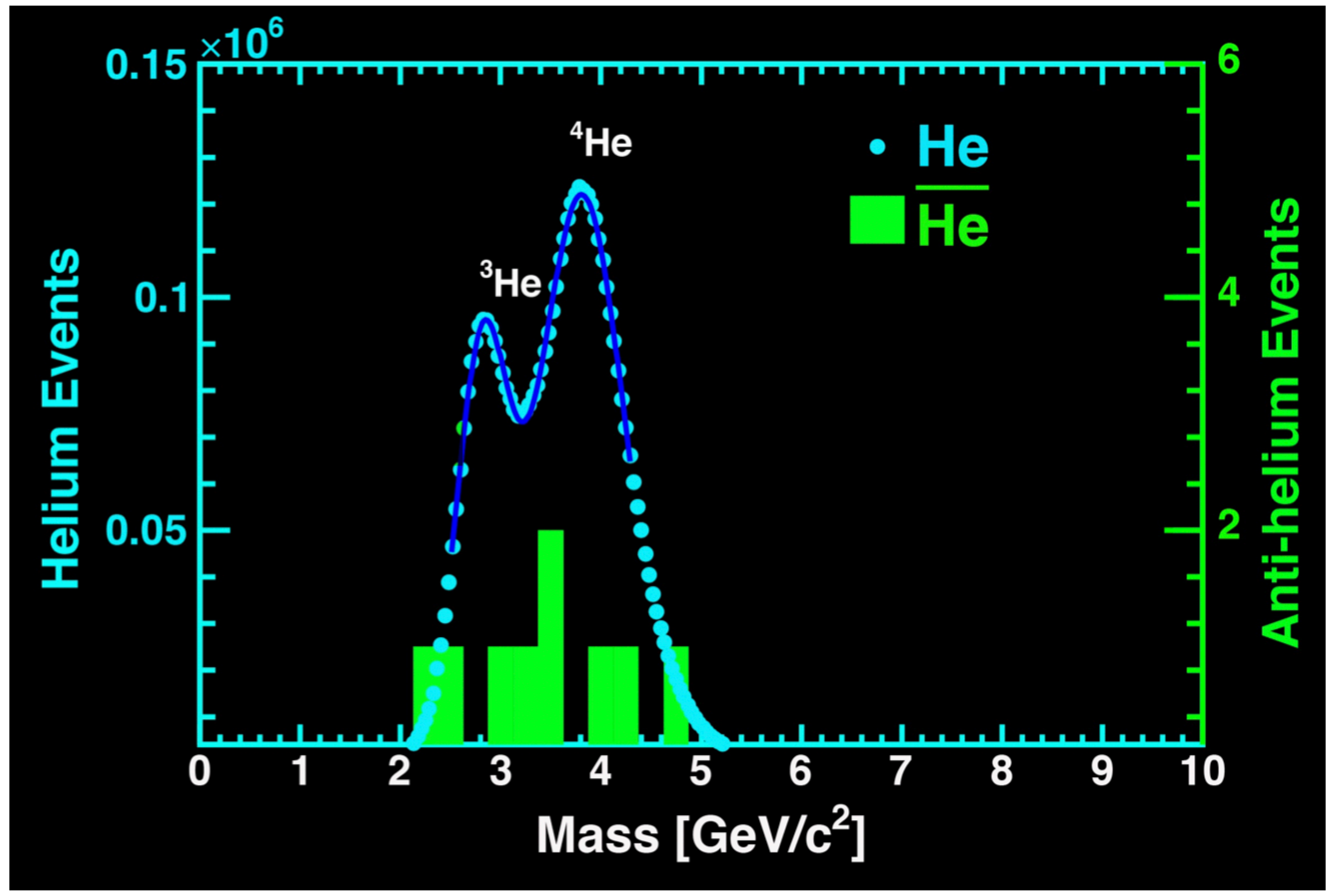
Measuring antinuclei fluxes

- AMS-02: Magnetic spectrometer on ISS; 9 antihelium candidates; not published yet

Based on Stefan Schael CERN Detector seminar Nov. 4th 2022 and Astropart.Phys. 130 (2021) 102580



Paolo Zuccon for AMS-02 Collaboration in MIAPP22 workshop

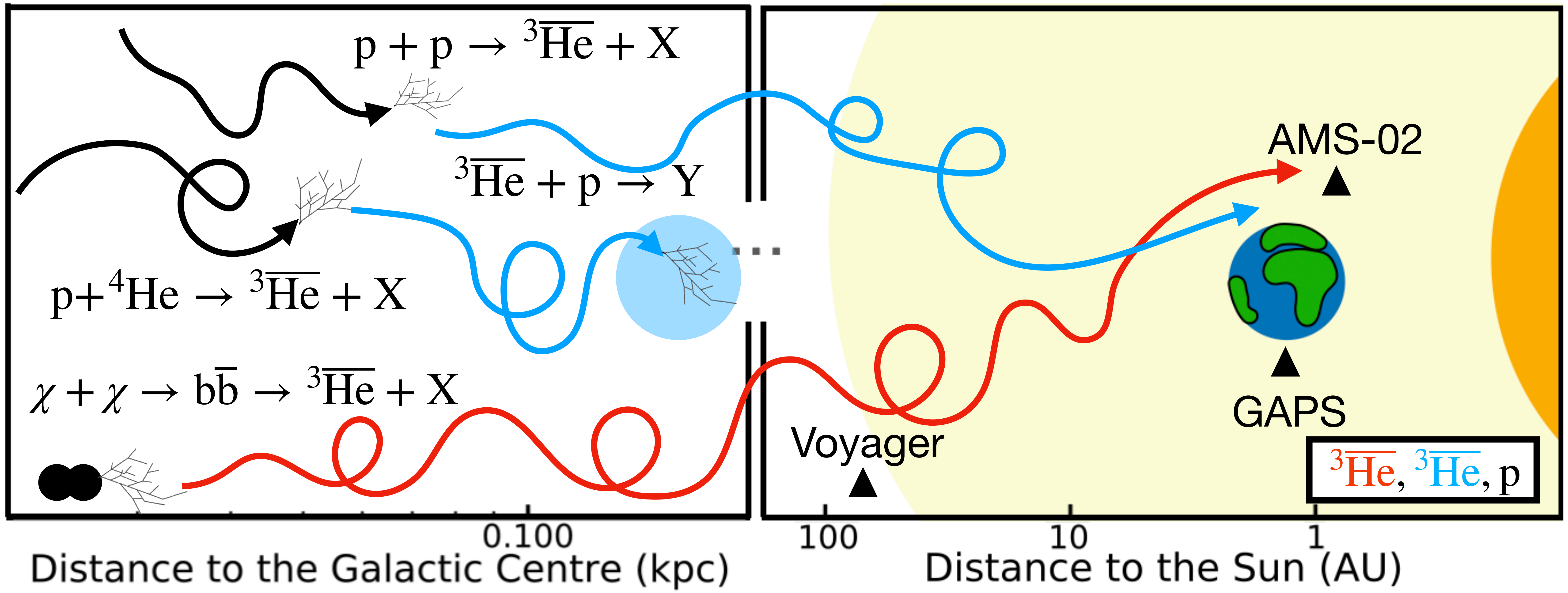


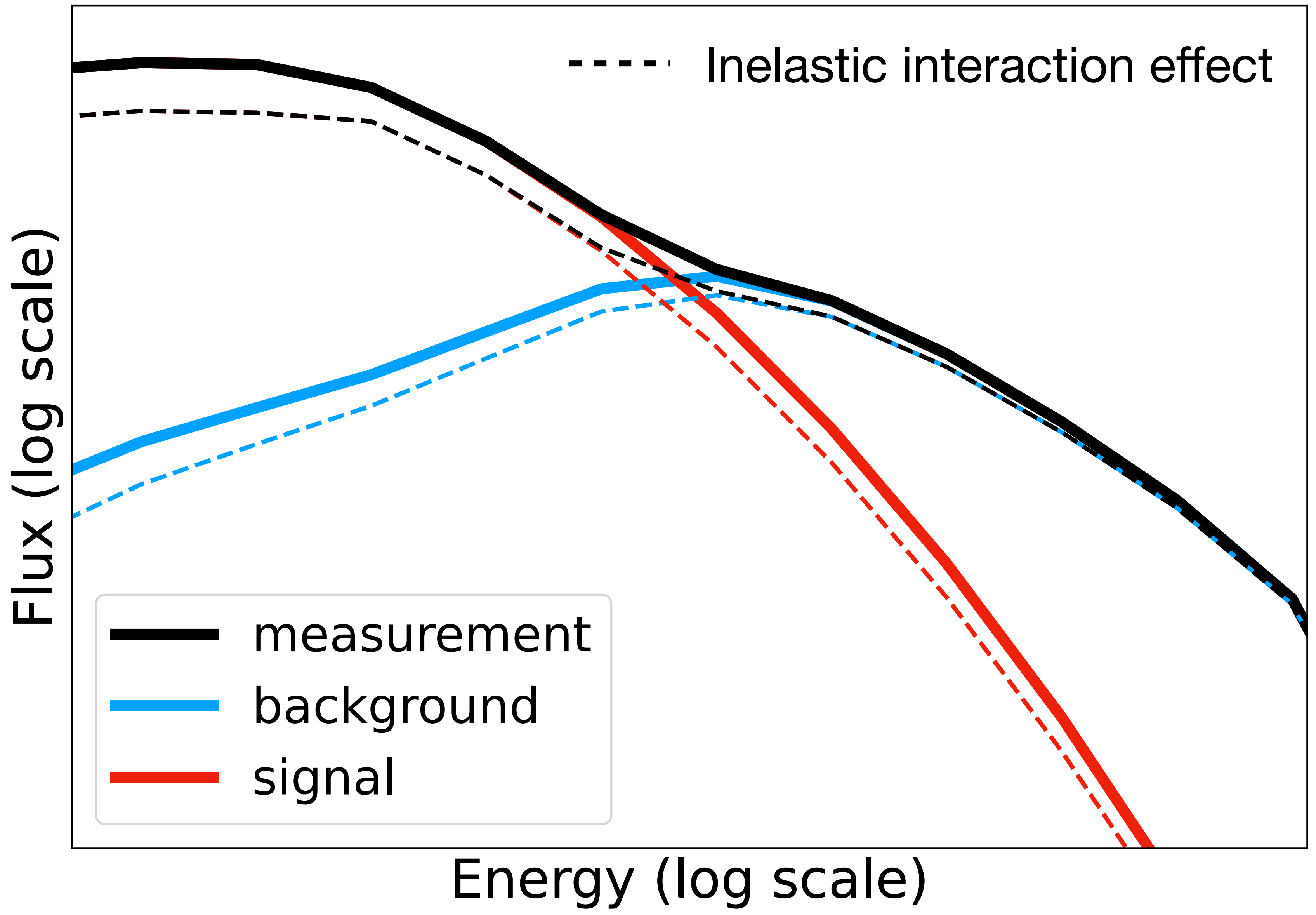
Understanding cosmic ray fluxes

- Production
- Propagation
- Inelastic interactions

How many antihelium-3 survive?

ALICE inelastic cross section measurement



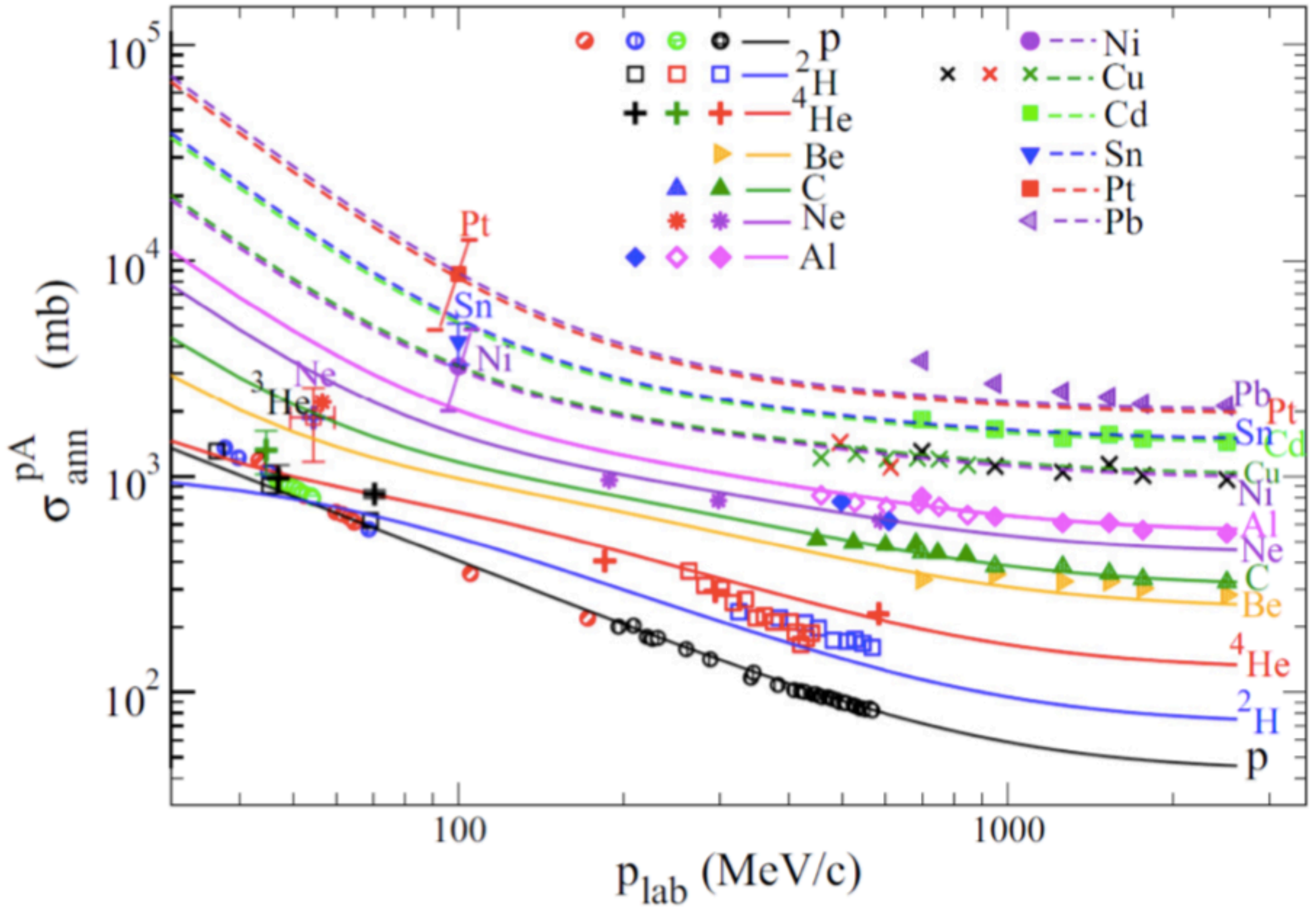


Inelastic cross section measurement

Status of σ_{inel} before ALICE

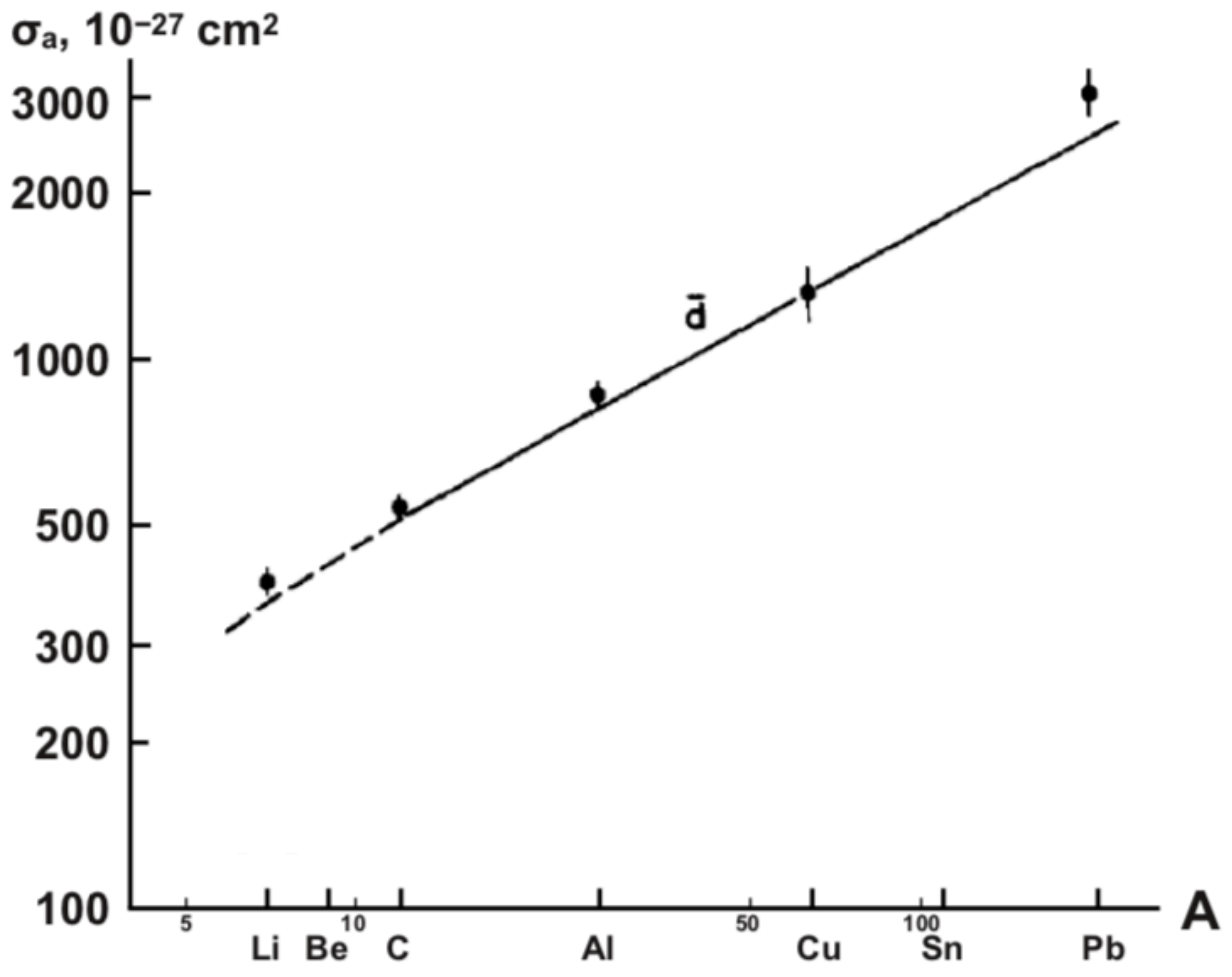
- Antiproton inelastic cross section - well known

Antiprotons



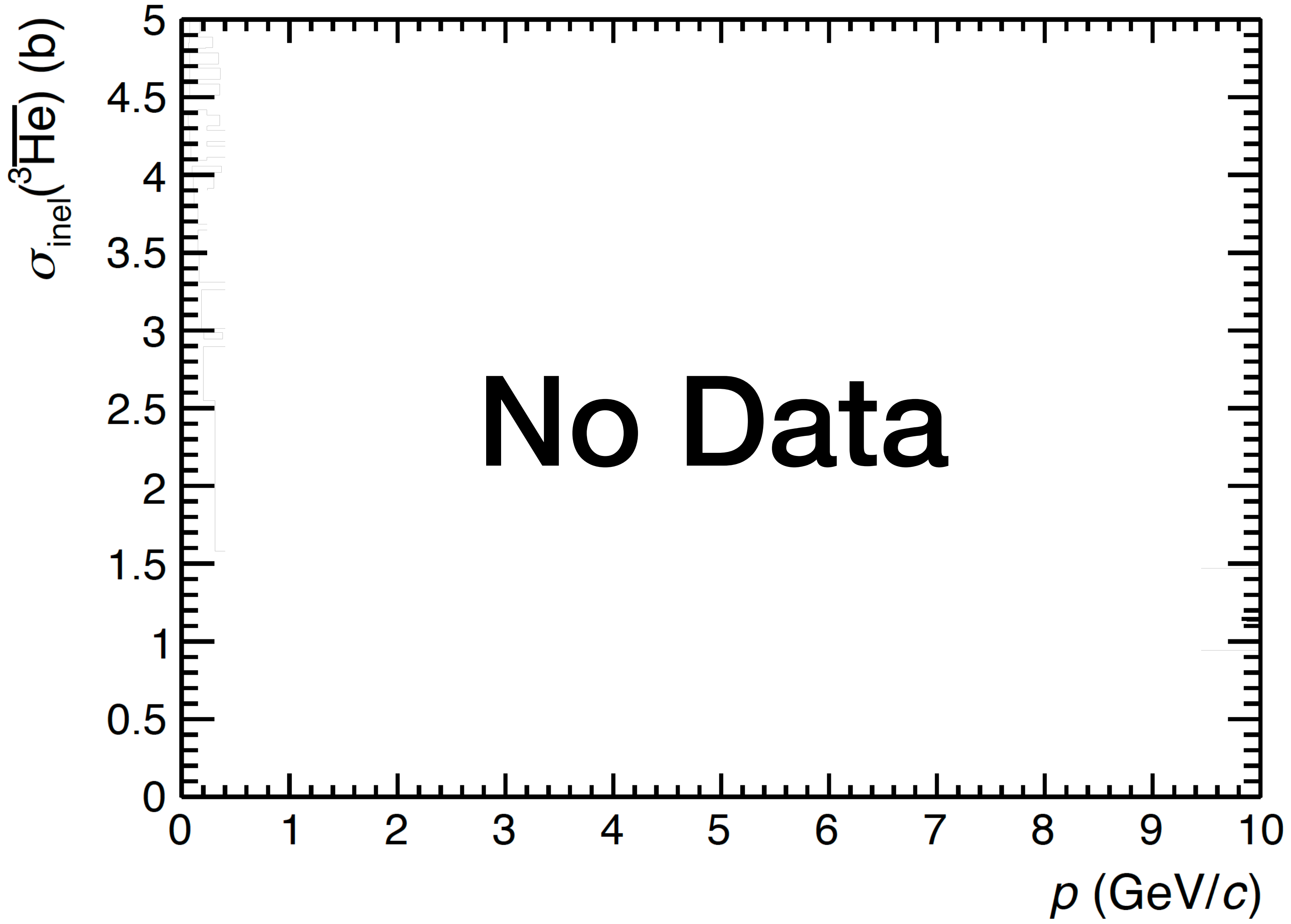
T.G. Lee and C.Y. Wong, Phys. Rev. C 89, 054601 (2014)

Antideuterons



S. P. Denisov et al. Nuclear Physics B 31(2), 253 (1971)

Anti-^{3}He

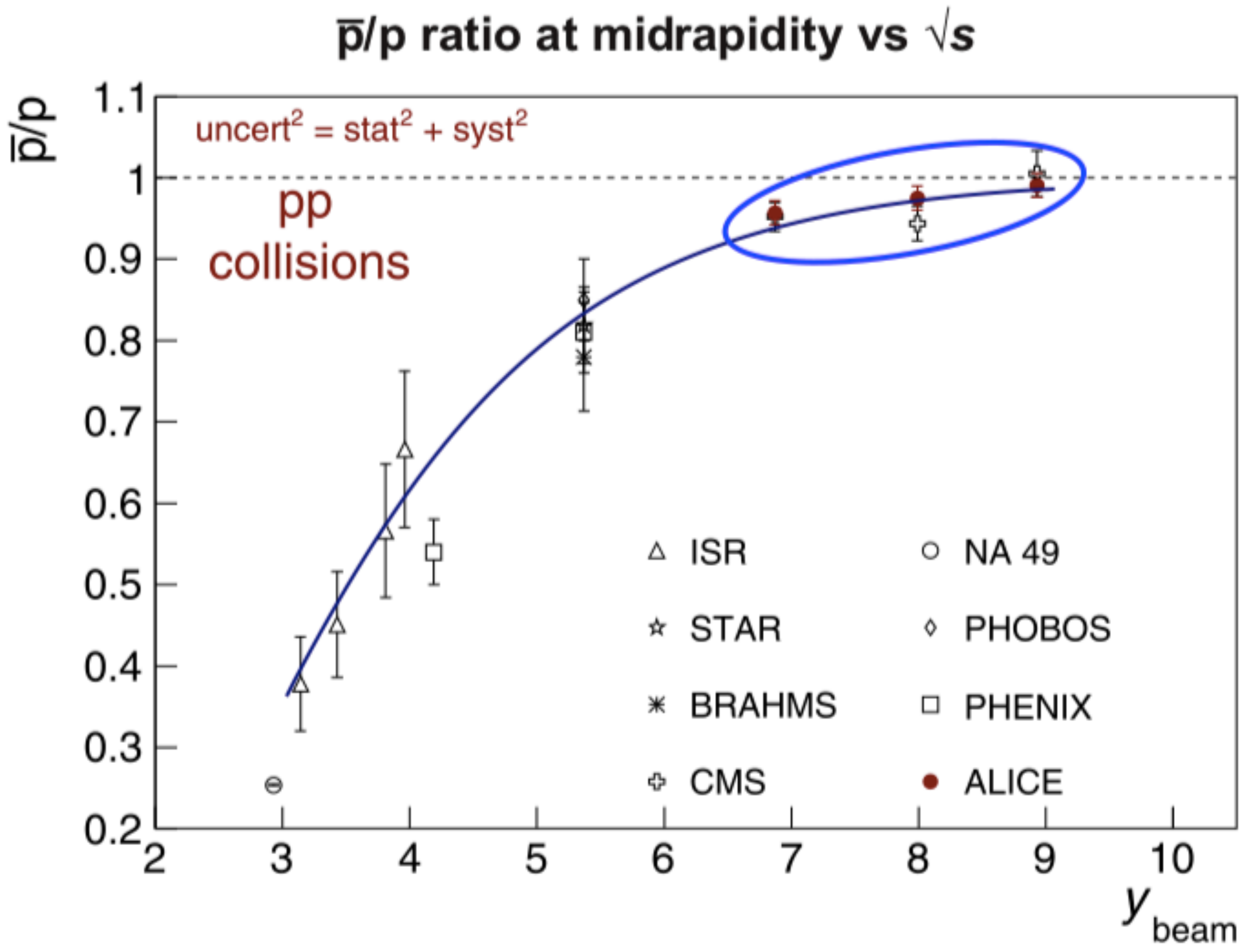


LHC - antimatter factory

- Primordial antimatter to matter ratio approaches unity with increasing centre-of-mass energy!
- Based on coalescence model, the ratio of antinuclei/nuclei can be estimated as follows:

$$\frac{\overline{A}}{A} \approx \left(\frac{\overline{p}}{p}\right)^{A}$$

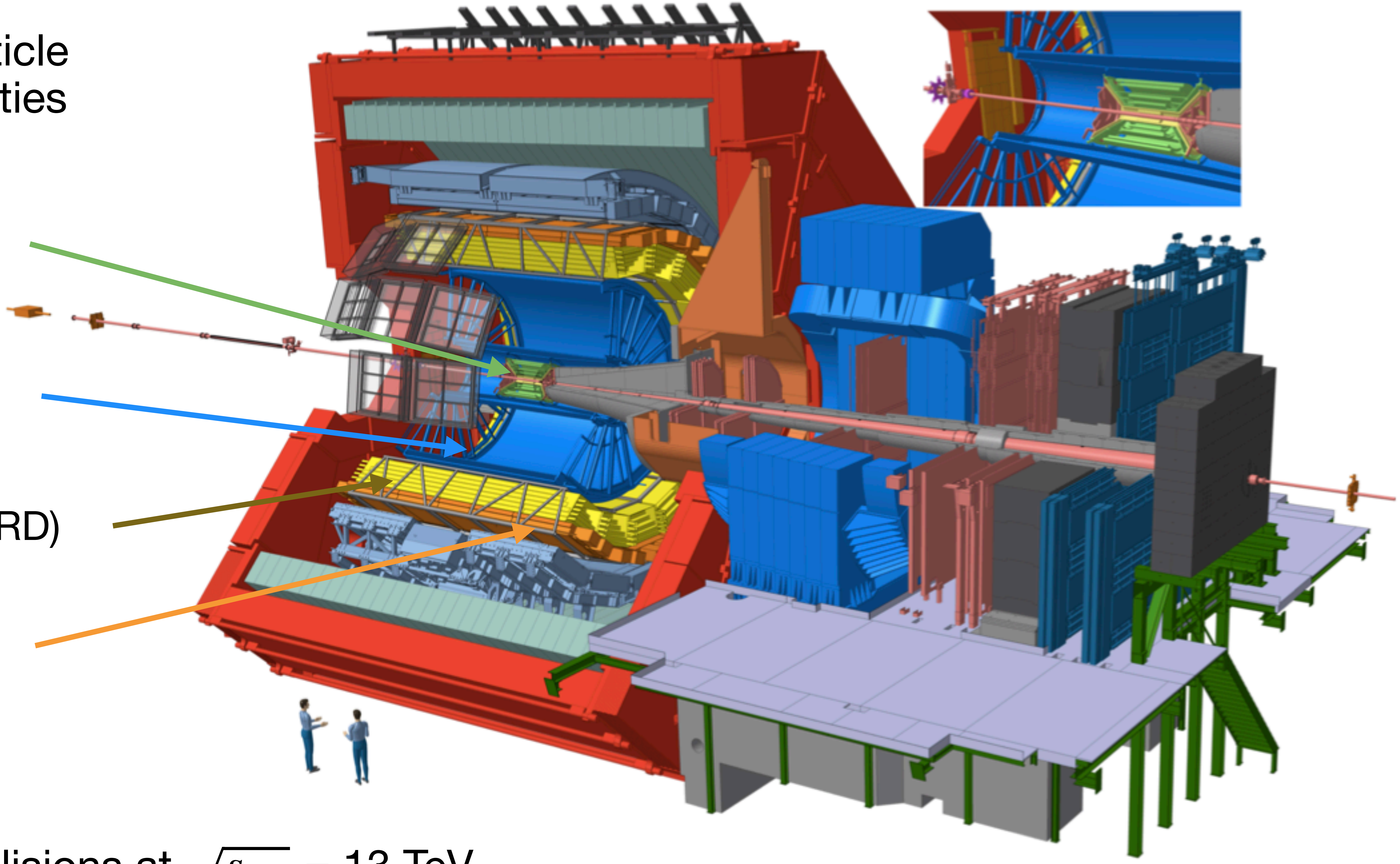
Can we measure and identify the produced antinuclei well?



EPJC 73 (2013) 2496

A Large Ion Collider Experiment

- Excellent tracking and particle identification (PID) capabilities



Inner Tracking System (ITS)
Tracking, vertex

Time Projection Chamber (TPC)
Tracking, PID (dE/dx)

Transition Radiation Detector (TRD)

Time Of Flight detector (TOF)
PID (TOF measurement)

Run 2 data

- 10^9 high-multiplicity pp collisions at $\sqrt{s_{\mathrm{NN}}}$ = 13 TeV
- 150×10^6 Pb-Pb collisions at $\sqrt{s_{\mathrm{NN}}}$ = 5.02 TeV

Int.J.Mod.Phys.A 29 (2014) 1430044
JINST 3 (2008) S08002

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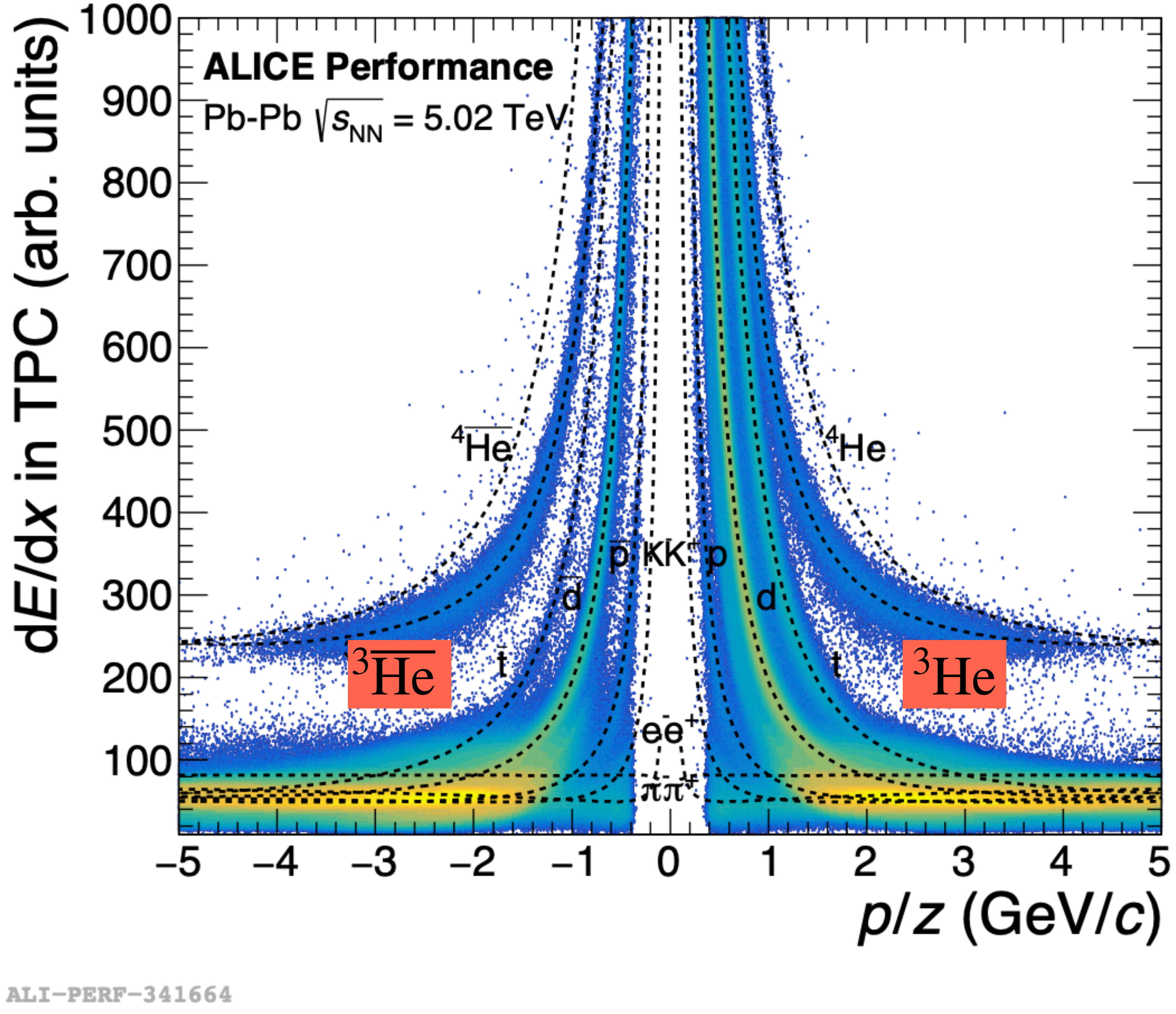

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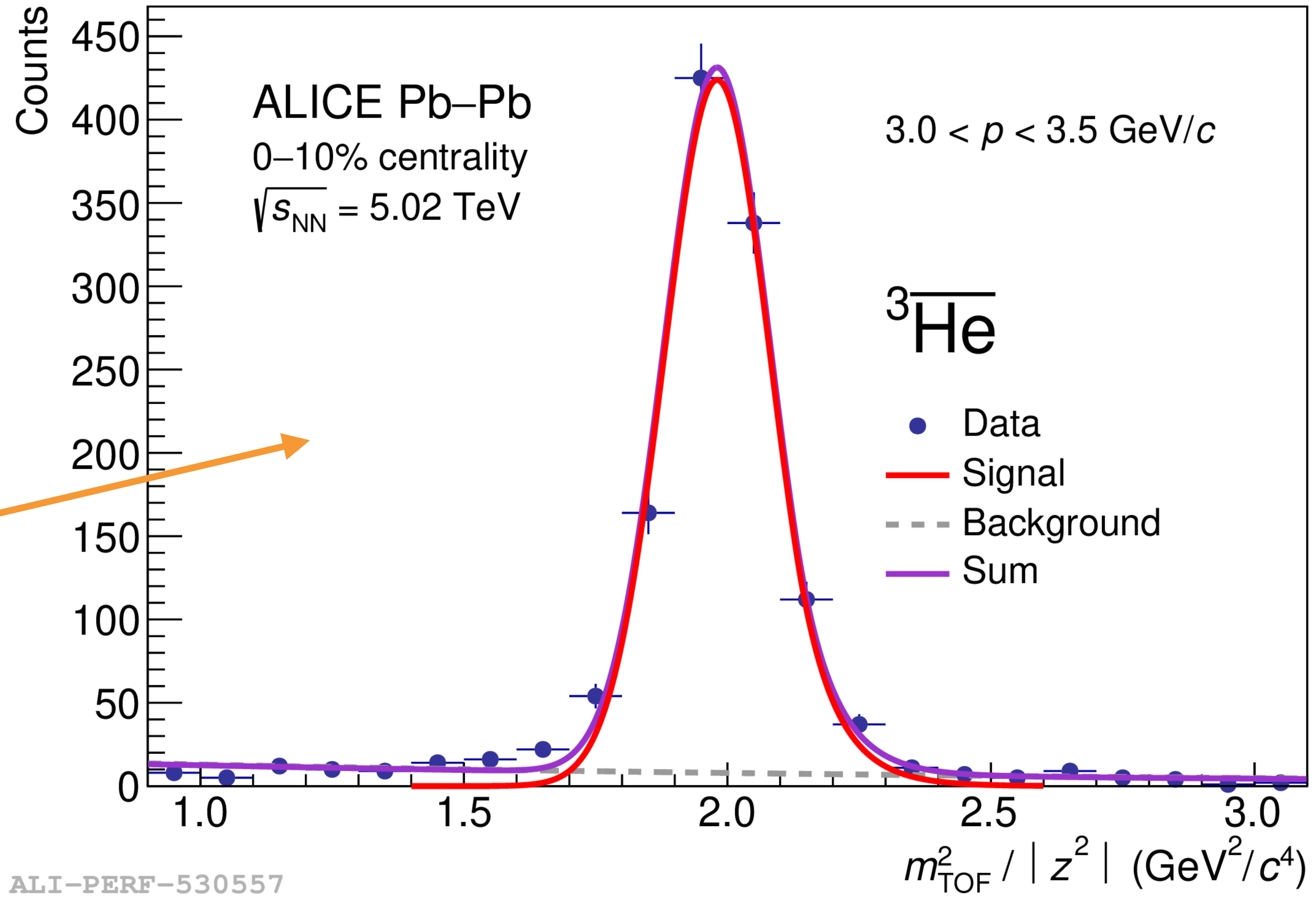
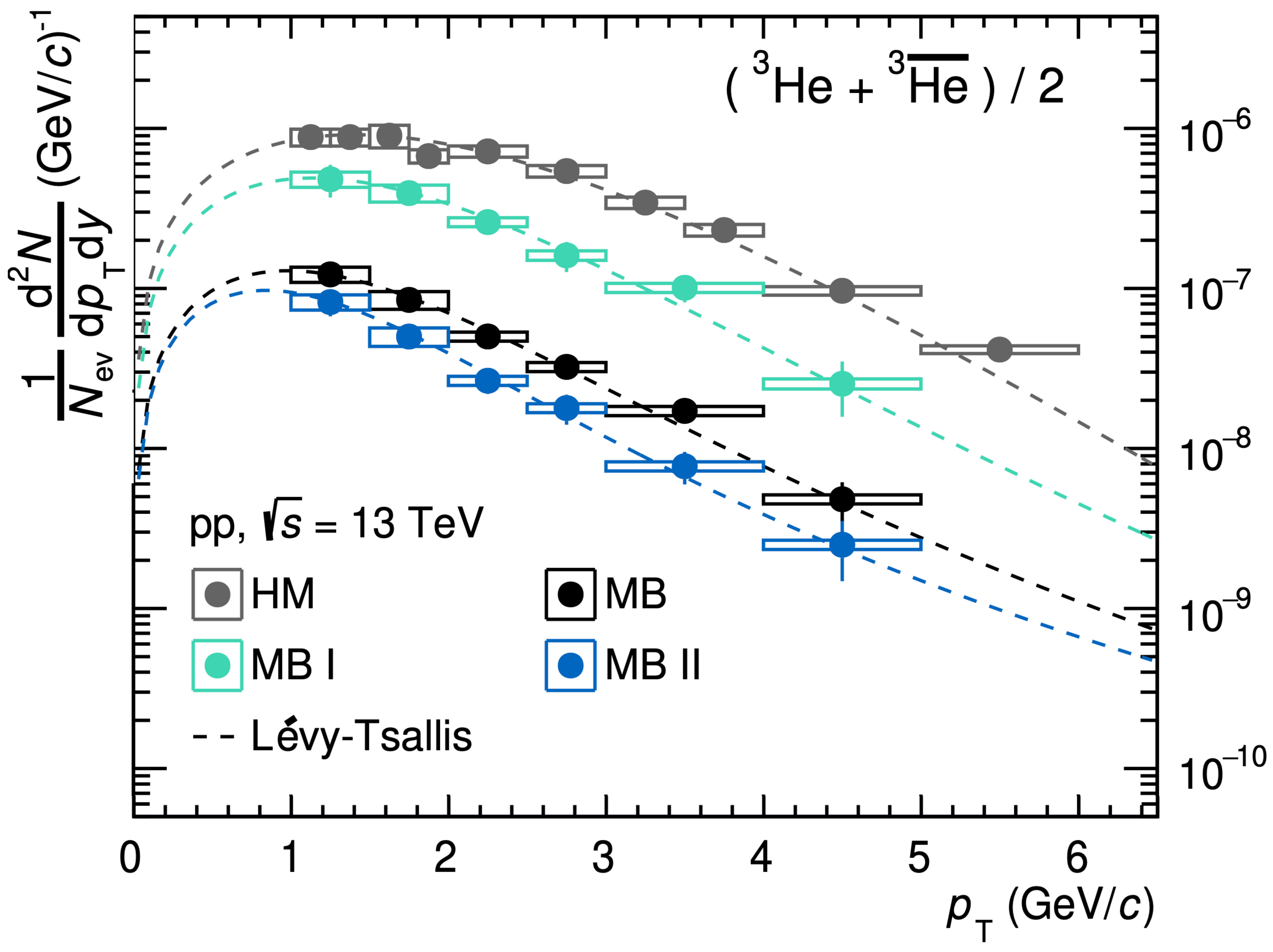


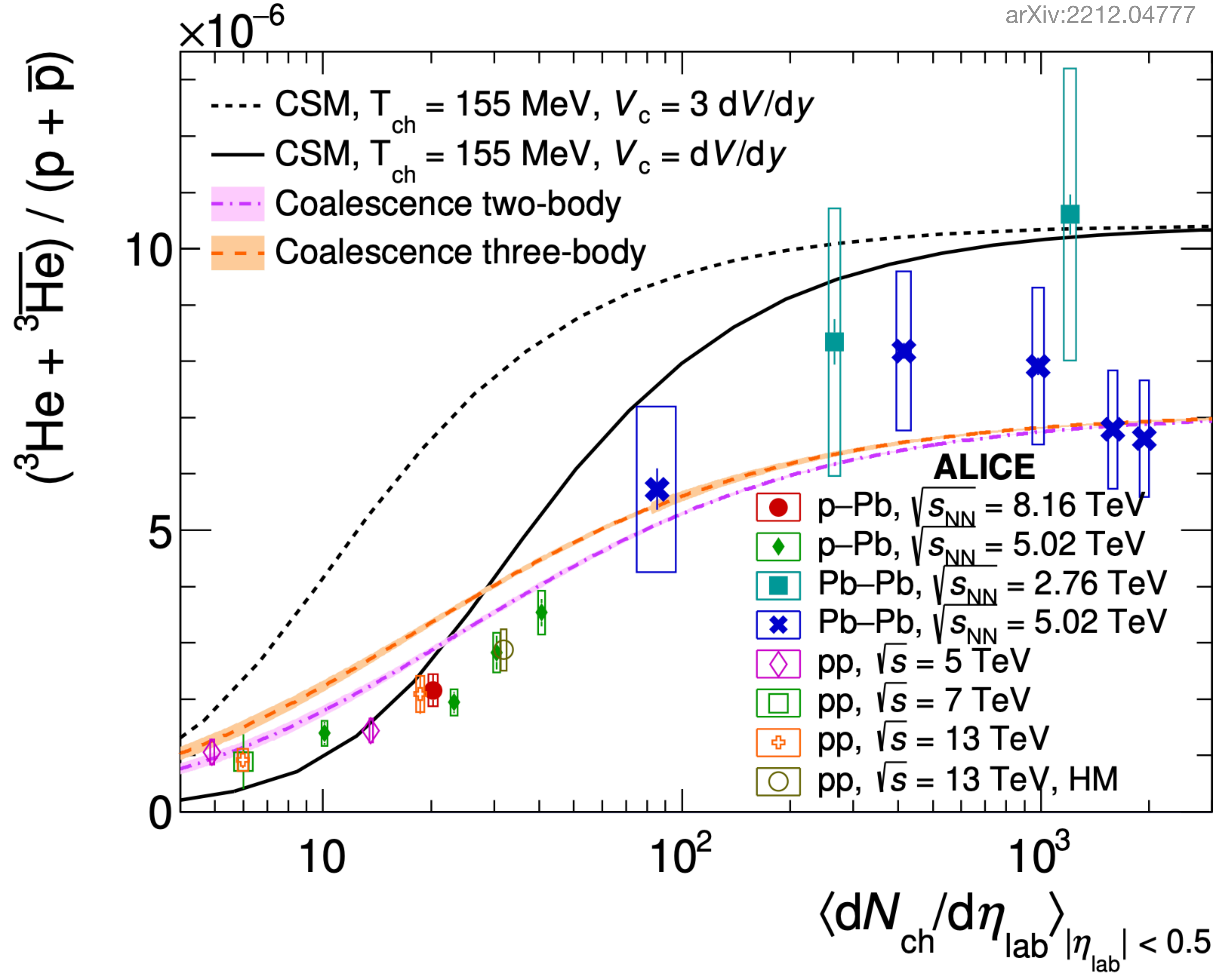
(Anti)helium-3 spectrum

- (Anti)helium-3 spectra have been measured with high precision in high-multiplicity (HM) and minimum-bias (MB) events!
- (Anti)helium-3 have been measured in different colliding systems.

JHEP 01 (2022) 106



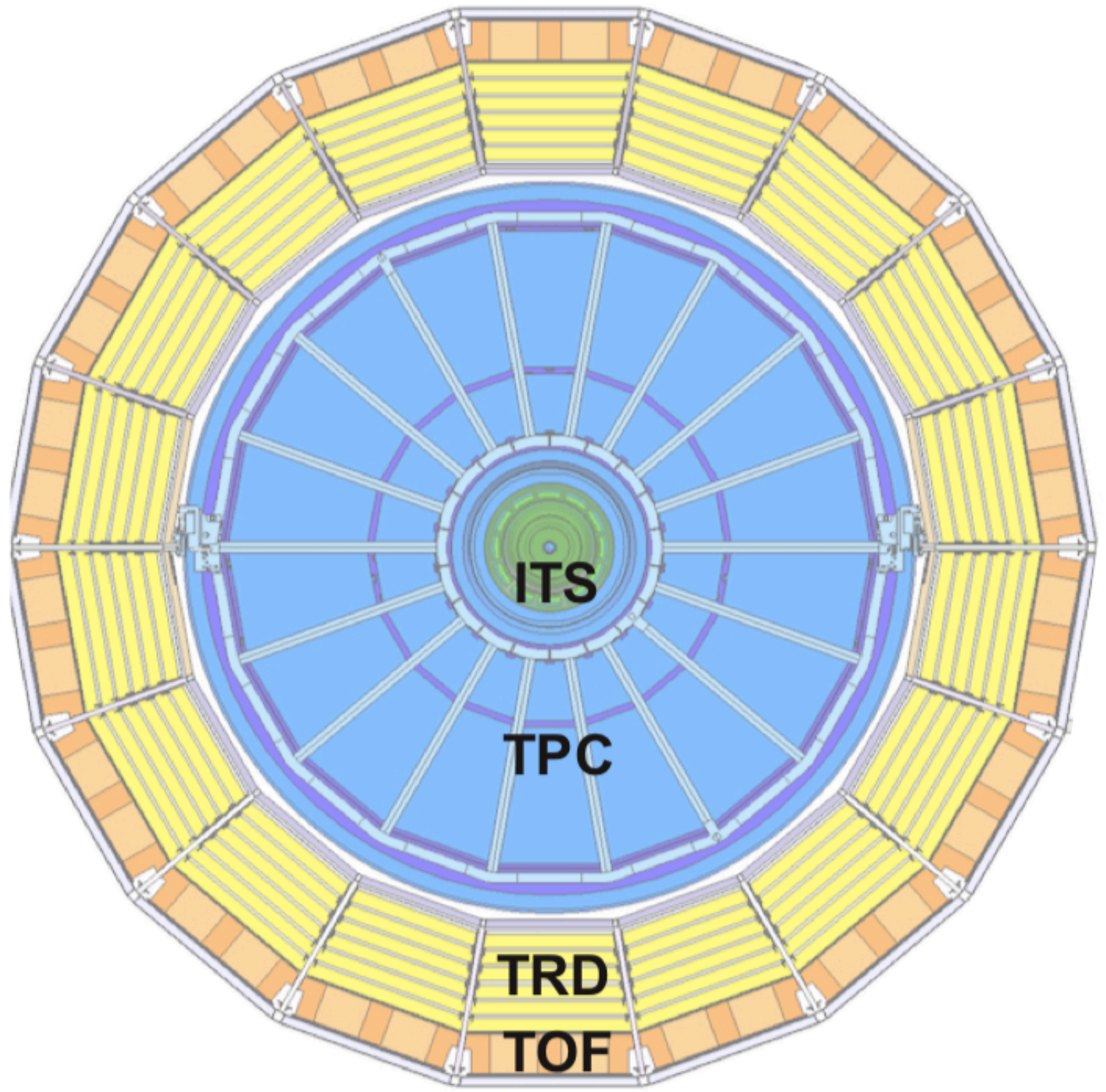
arXiv:2212.04777



Method: ALICE as a target

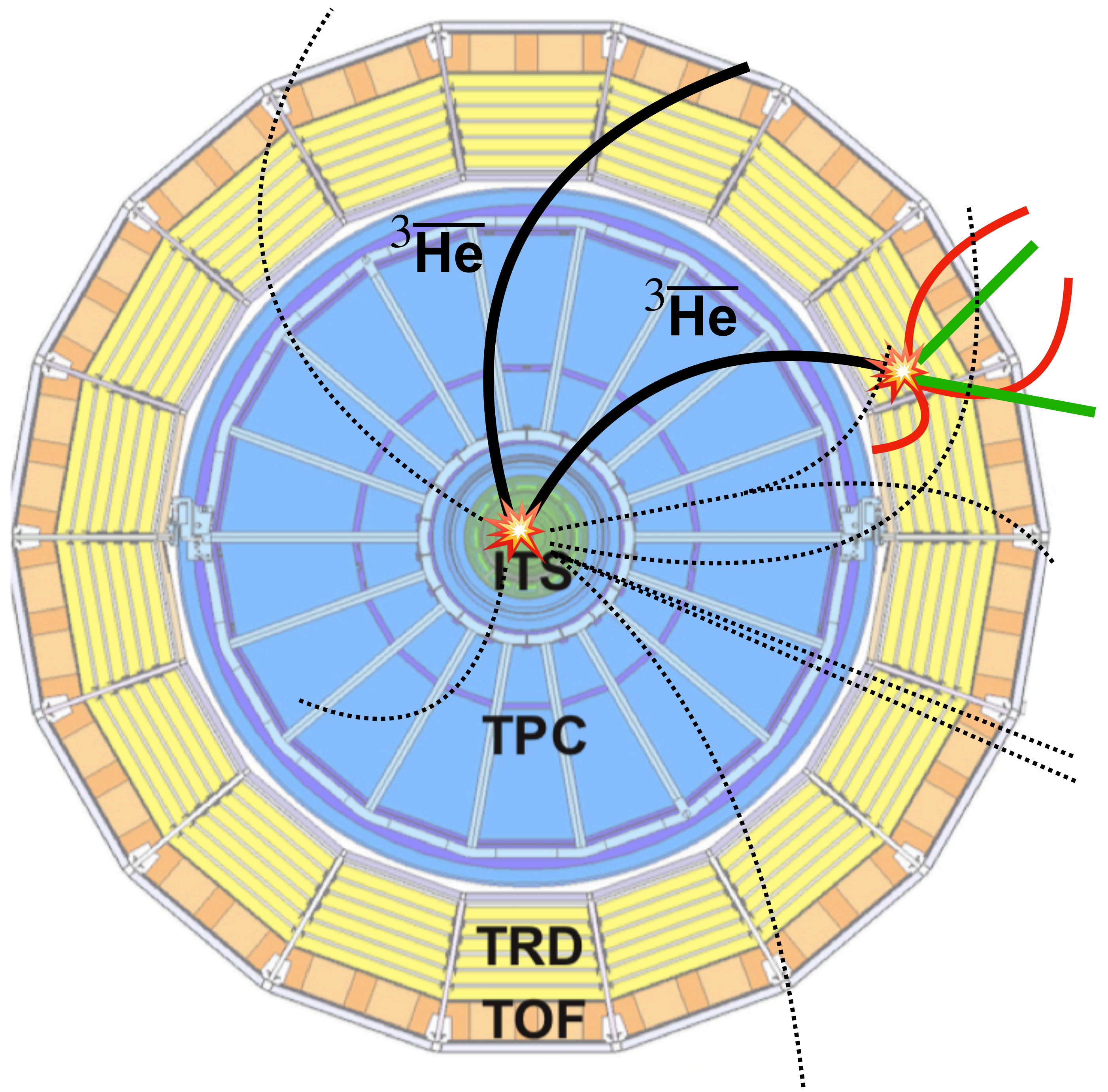
Antimatter-to-matter ratio

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



TOF-to-TPC-matching

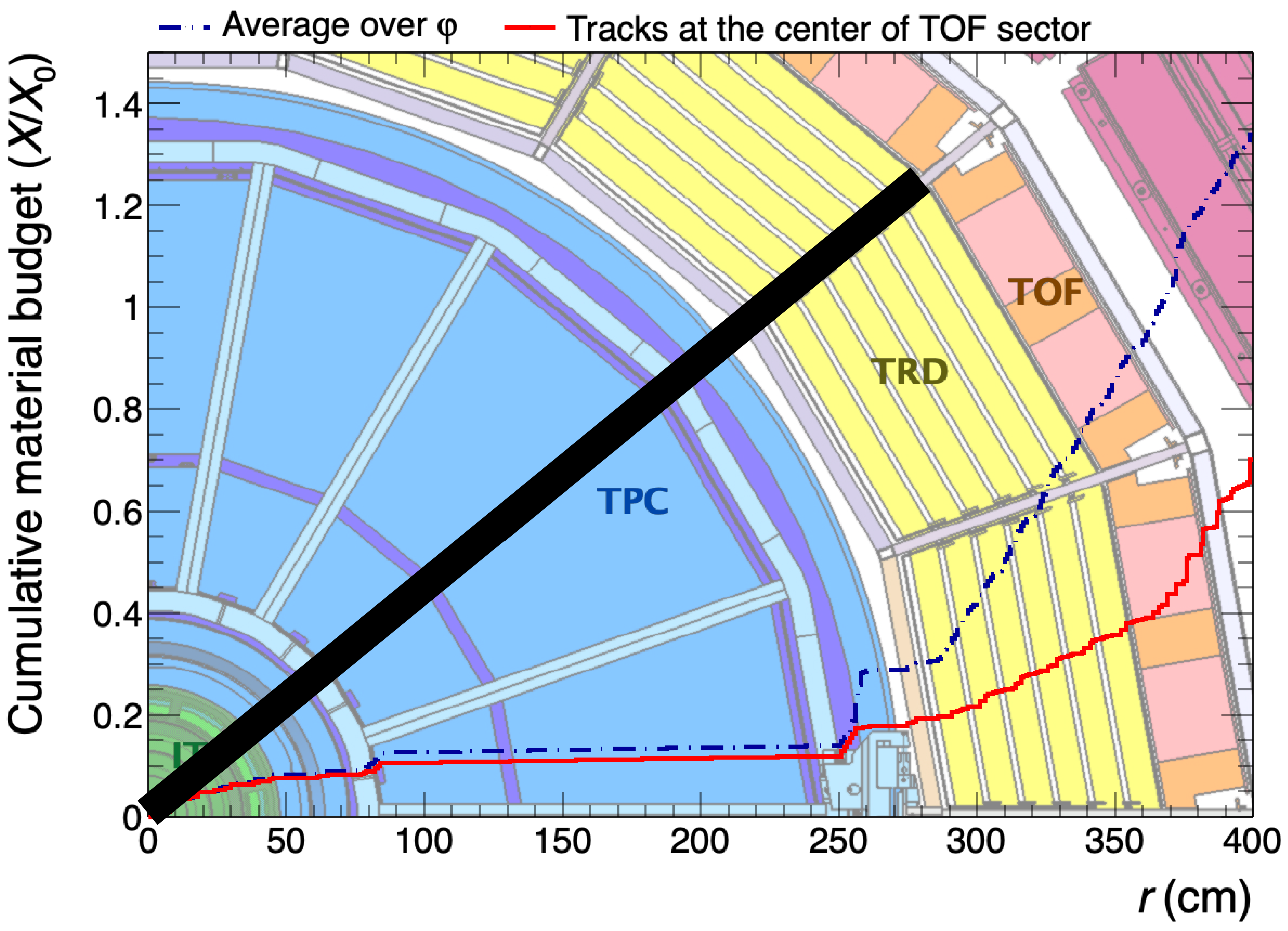
- Measure reconstructed $^{3}\overline{\mathrm{He}}_{\mathrm{TOF}}/^{3}\overline{\mathrm{He}}_{\mathrm{TPC}}$ and compare with MC simulations



Material budget must be very well known!

ALICE material budget

- Material budged distribution can be modelled and studied in Geant4
- Was validated with:
    - Photon conversion analyses (up to outer TPC vessel) [1]
    - Tagged pion and proton absorption studies (for the material between TPC and TOF detectors) [2]



PRL 125, 162001 (2020)

- Result: total material budget known to a precision of ~4.5%!

- Average material

$$< A > = \frac{\sum_{i=1}^{R} \sum_{j=1}^{N} \rho_{ij} A_{ij}}{\sum_{i=1}^{R} \sum_{j=1}^{N} \rho_{ij}}$$

- Antimatter-to-matter method: 31.8
- TOF-to-TPC method: 34.7

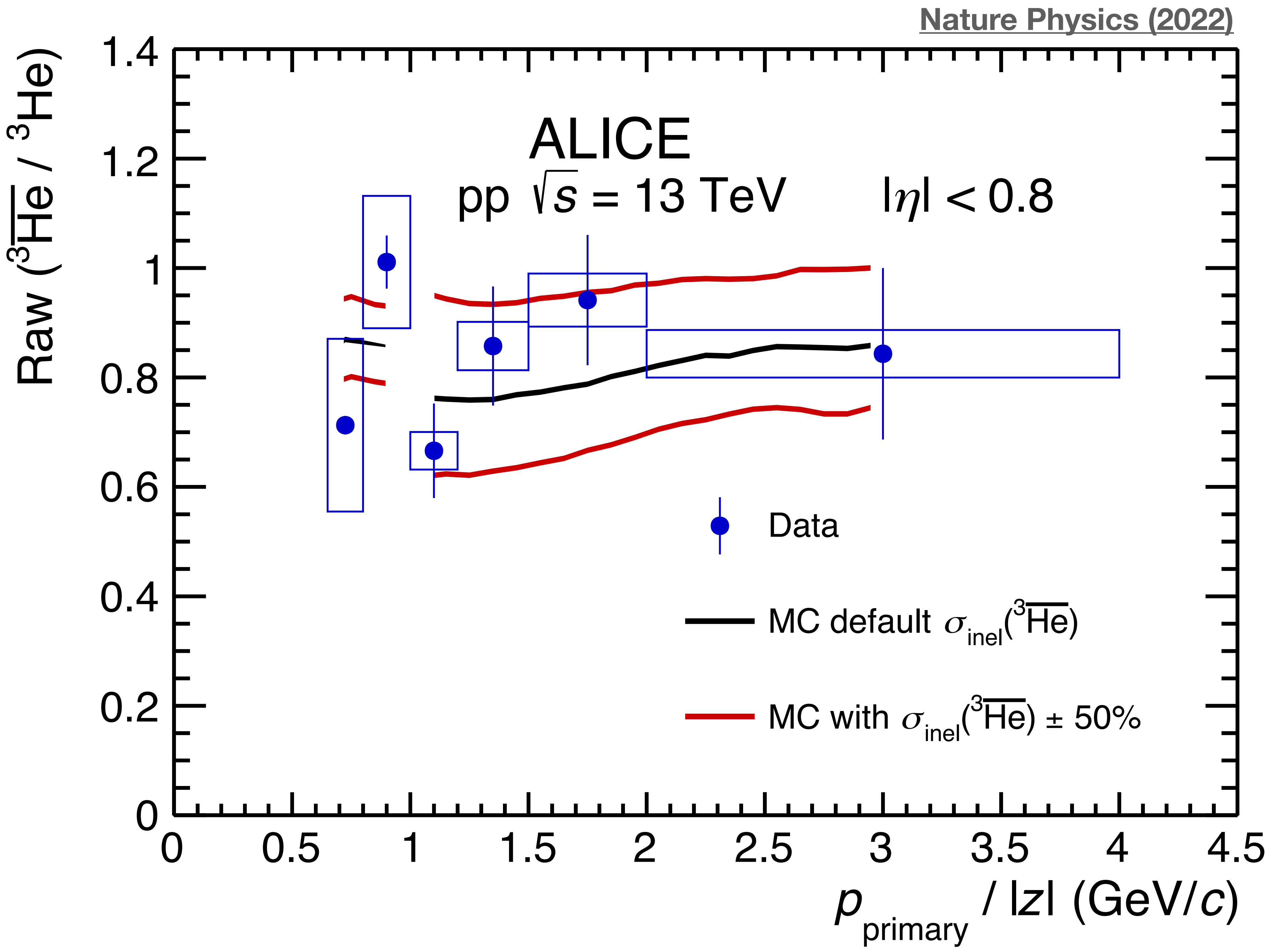
[1] Int.J.Mod.Phys.A 29 (2014) 1430044
[2] Public Note https://cds.cern.ch/record/2800896

Antimatter-to-matter method

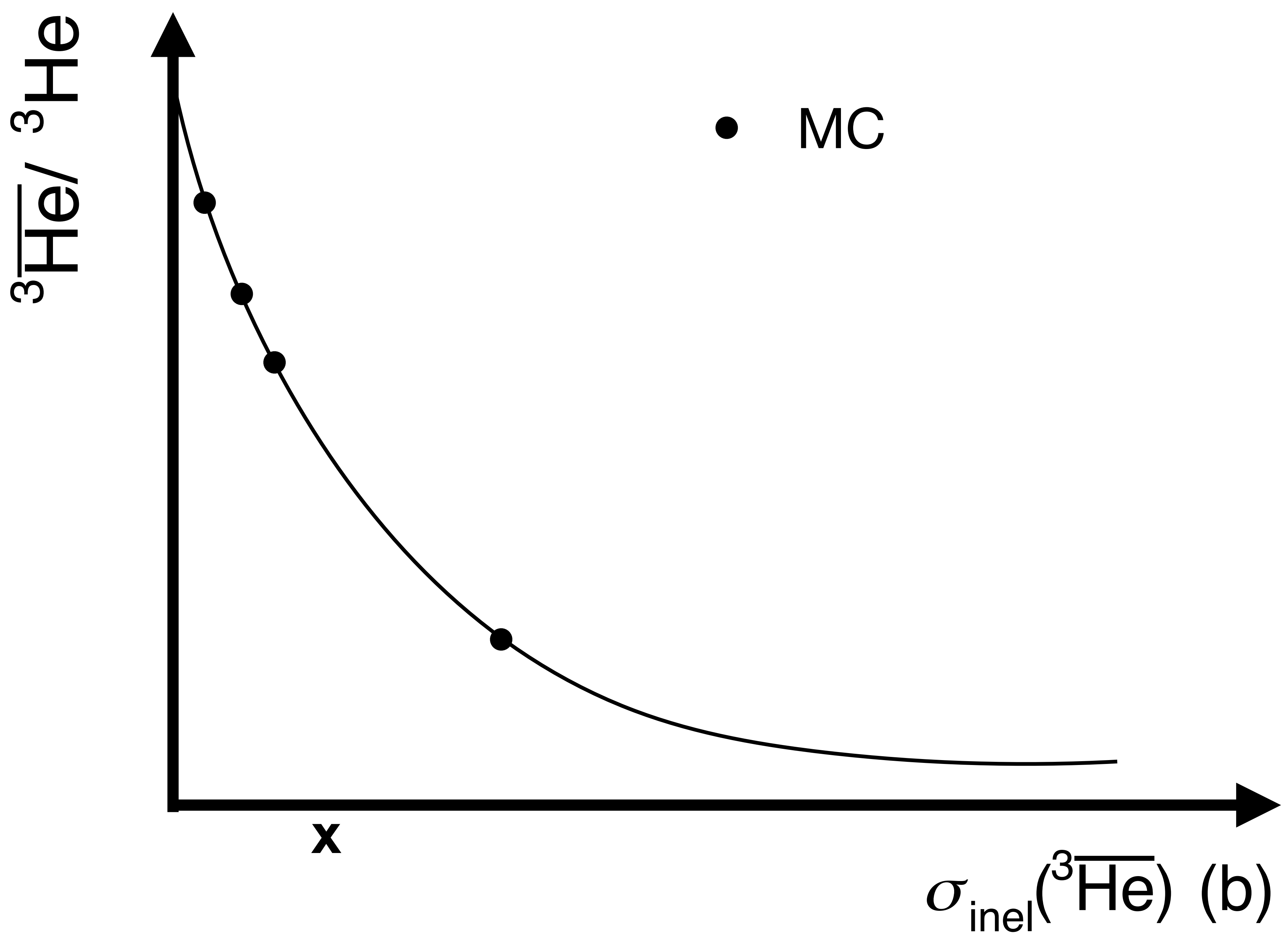
$\sigma_{\mathrm{inel}}(^{3}\overline{\mathrm{He}})$ in MC varied for each momentum bin to match:

- experimental data → central value
- upper/lower edge of the total error bar → 1σ confidence interval

Raw antimatter-to-matter ratio



Lambert-Beer law: $\overline{\mathrm{B}}/\mathrm{B} \propto \exp(-\sigma_{\mathrm{inel}})$



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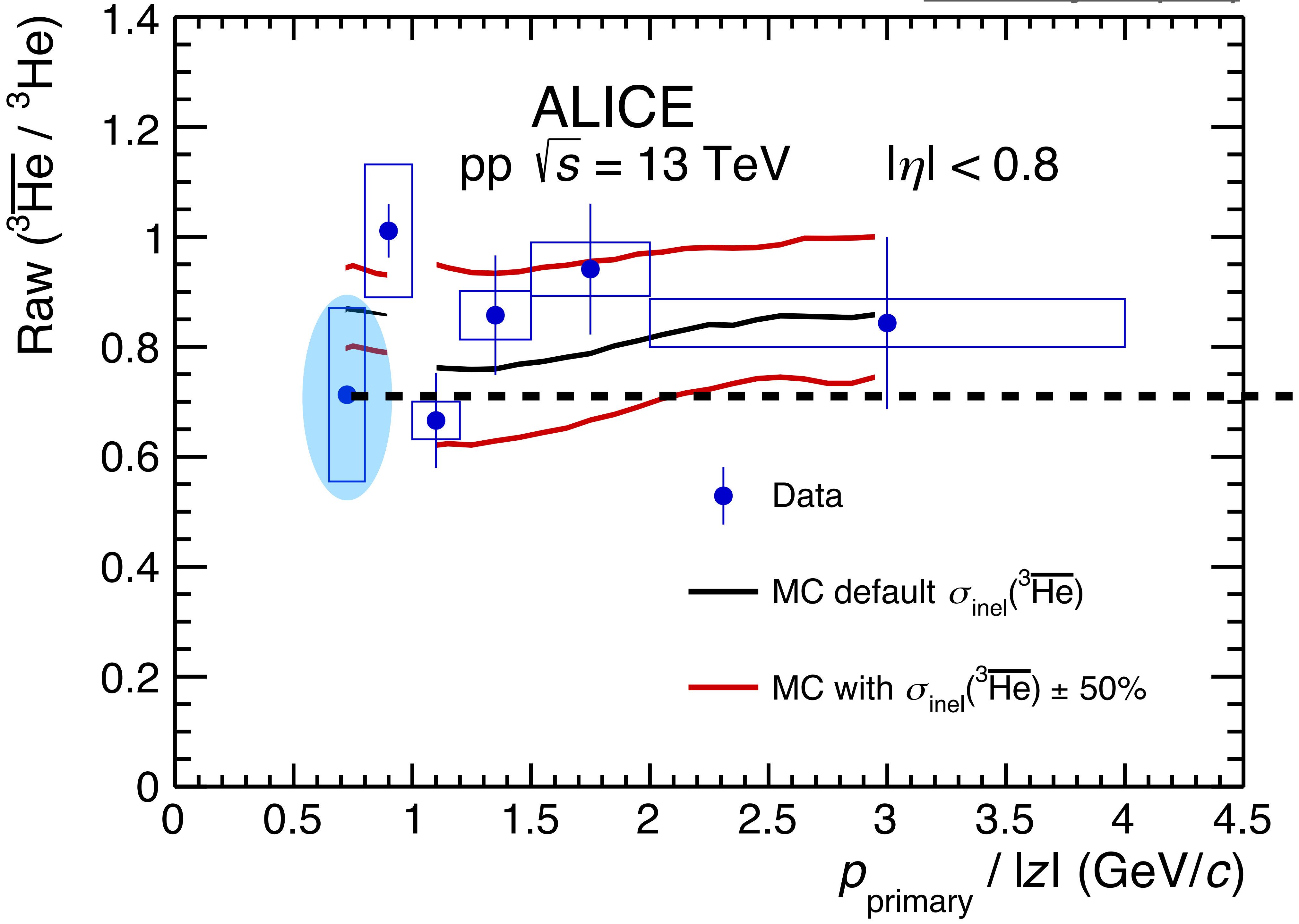

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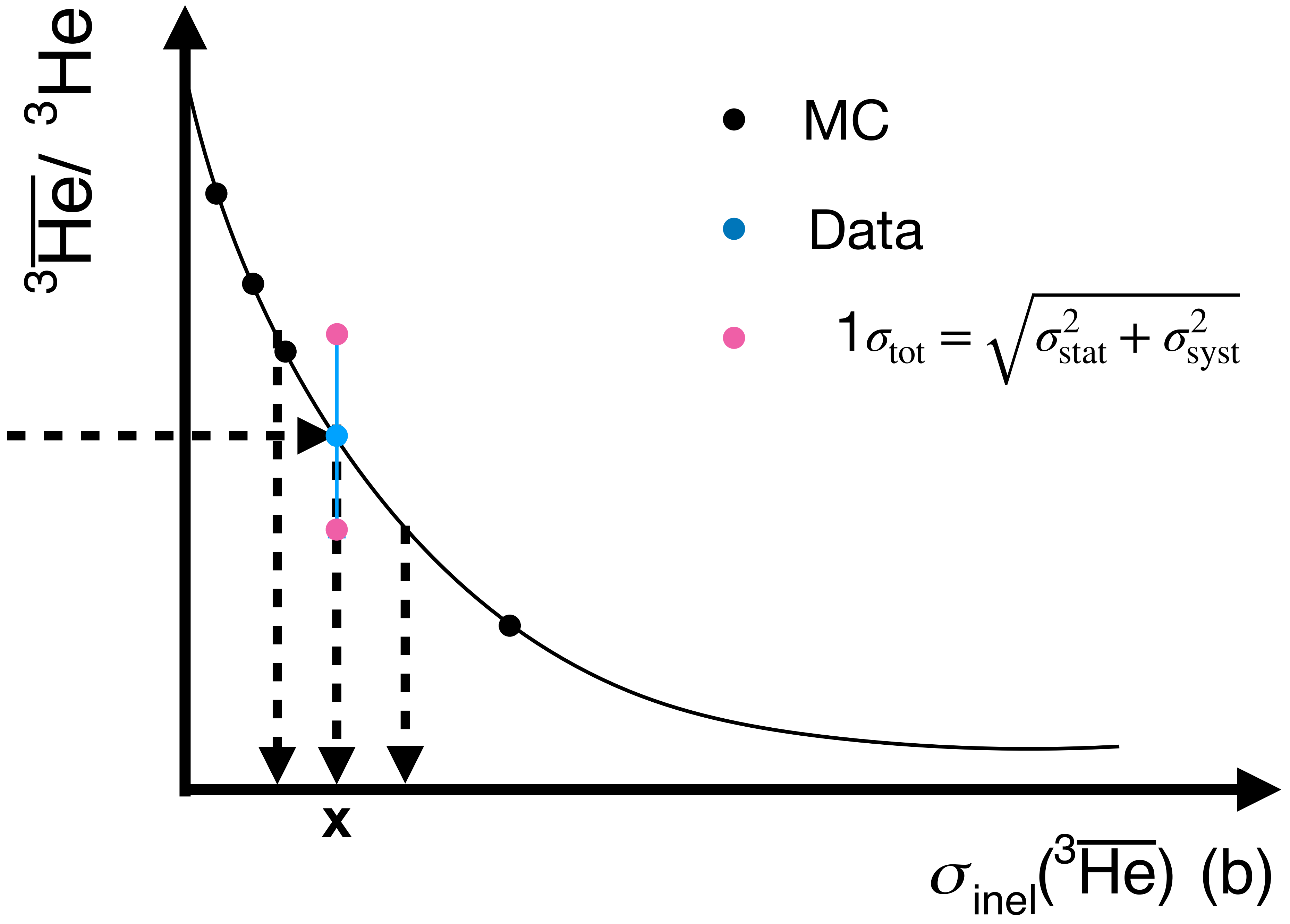

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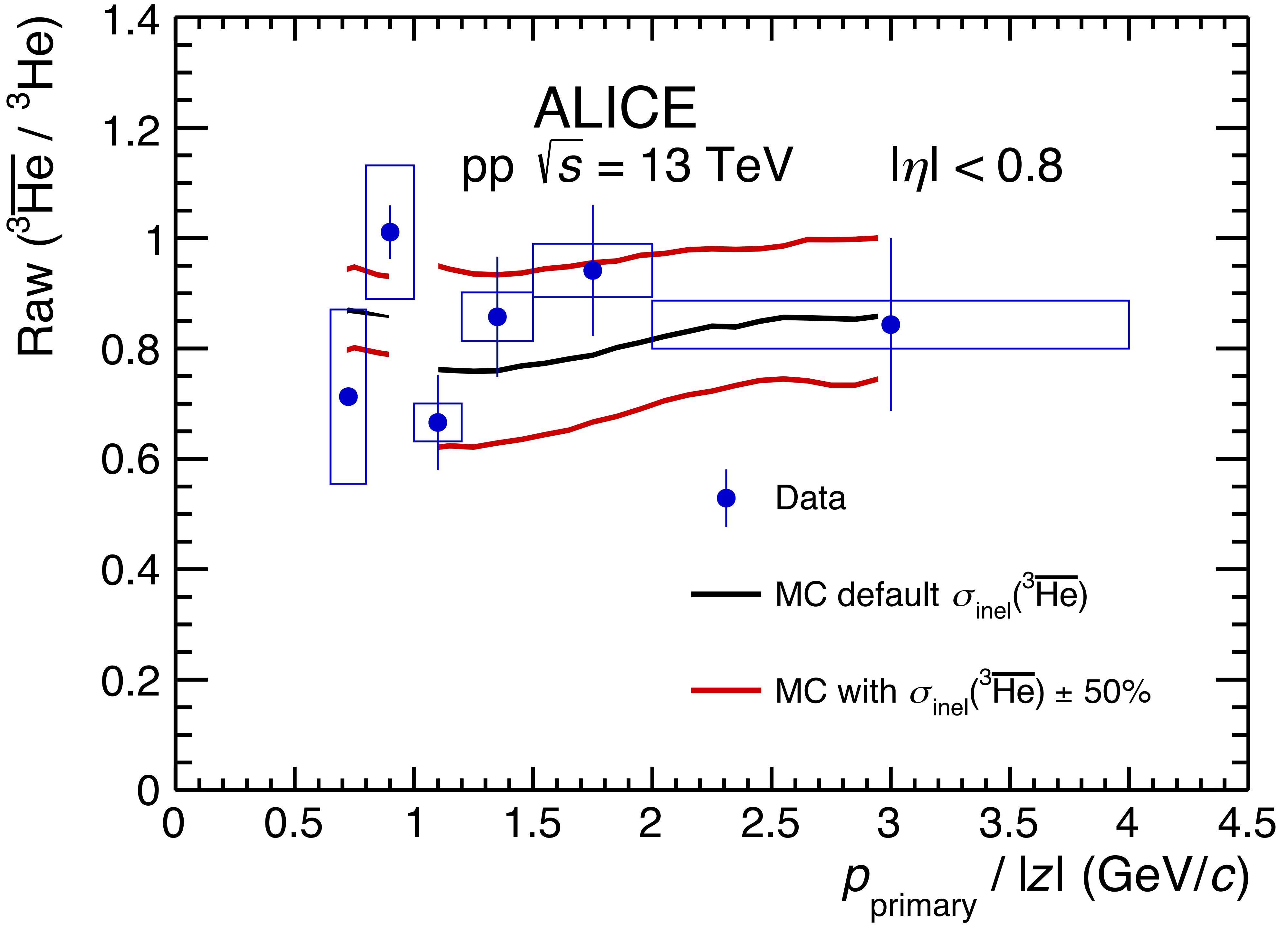
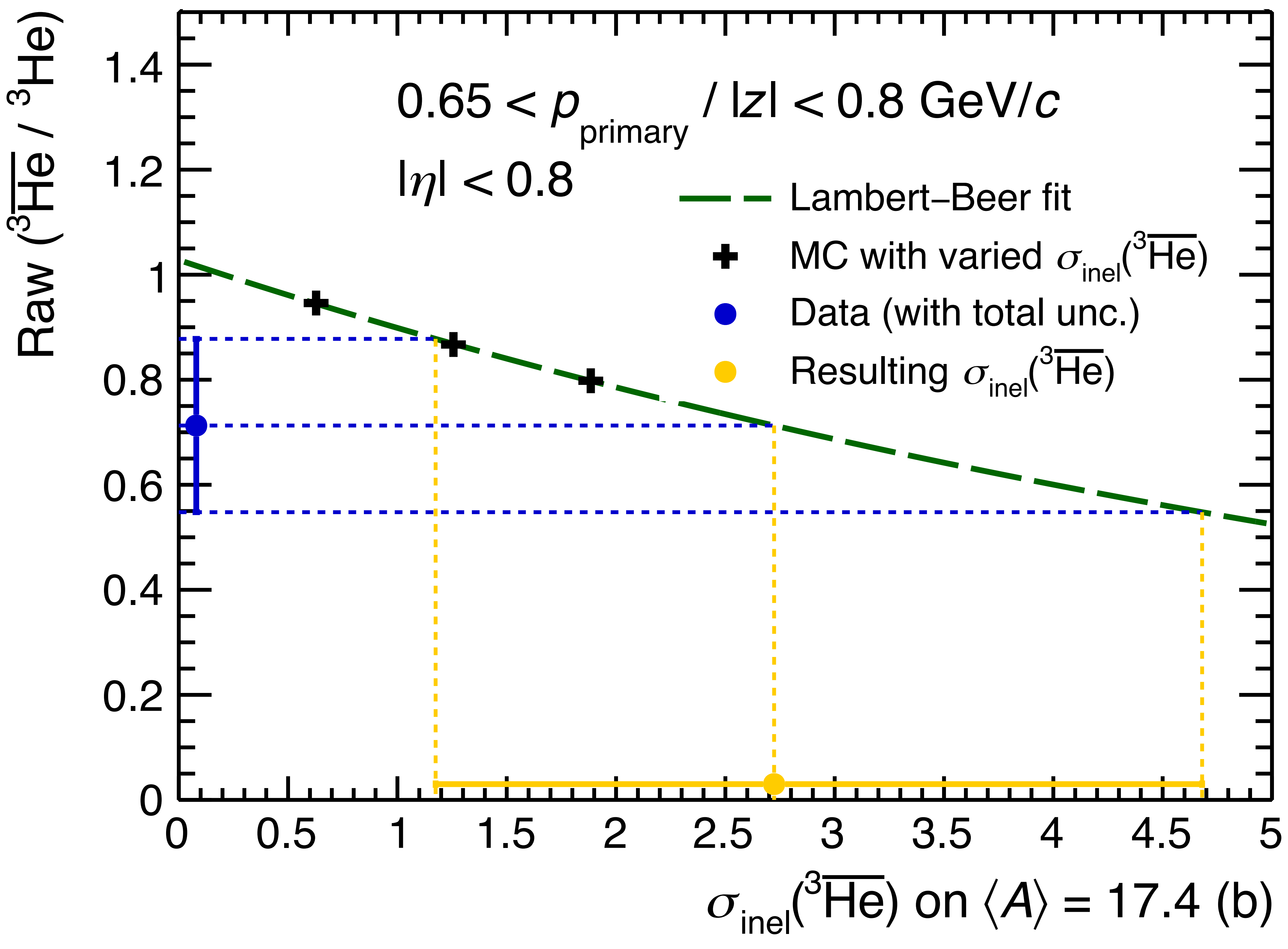


$\overline{\text{B}}/\text{B} \propto \exp(-\sigma_{inel})$



Nature Physics (2022)

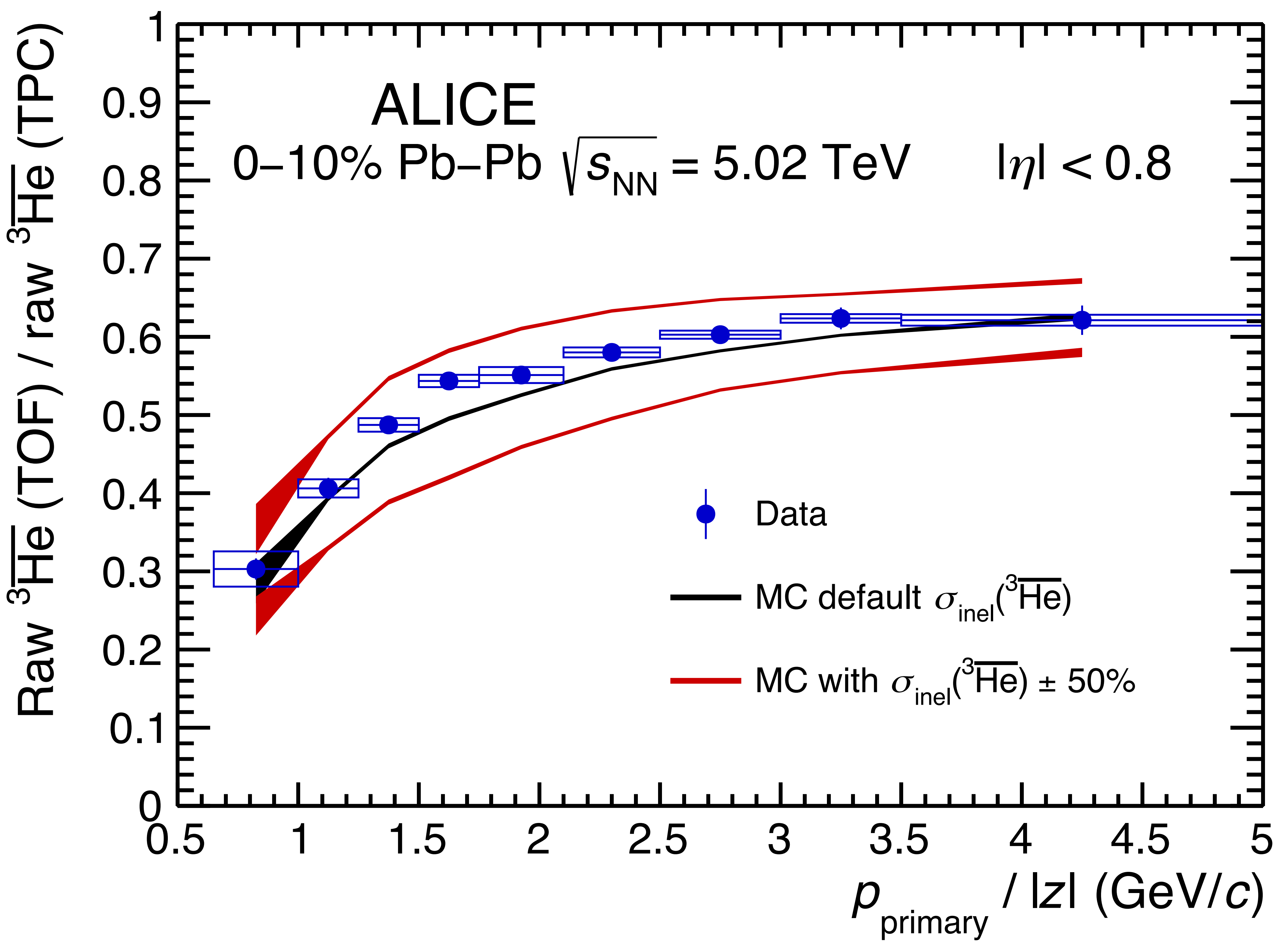
TOF-to-TPC method

$\sigma_{inel}(^3\overline{He})$ in MC varied for each momentum bin to match:

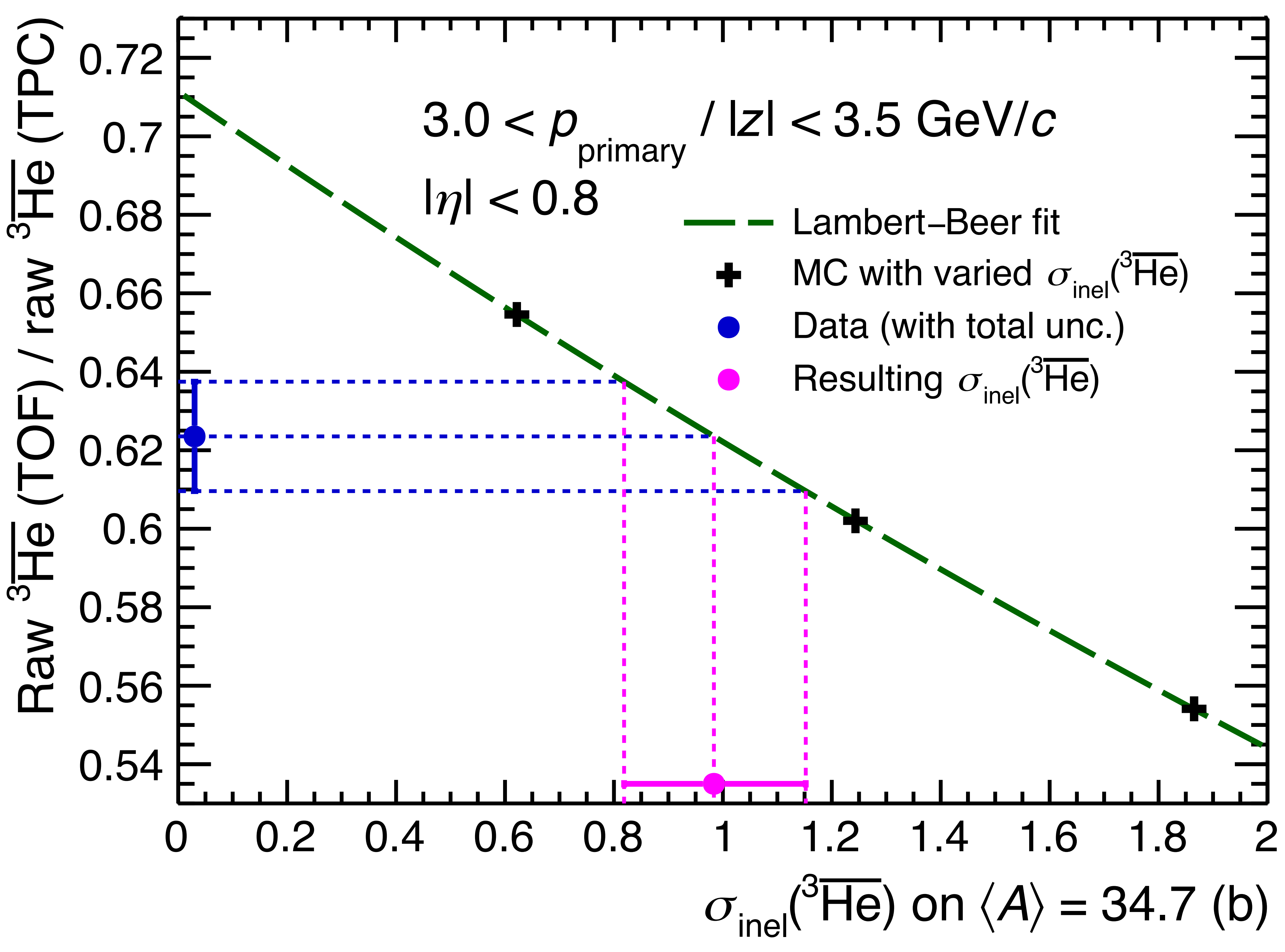
- experimental data → central value
- upper/lower edge of the total error bar → 1σ confidence interval

Same procedure applied for TOF-to-TPC matching method

TOF-to-TPC matching



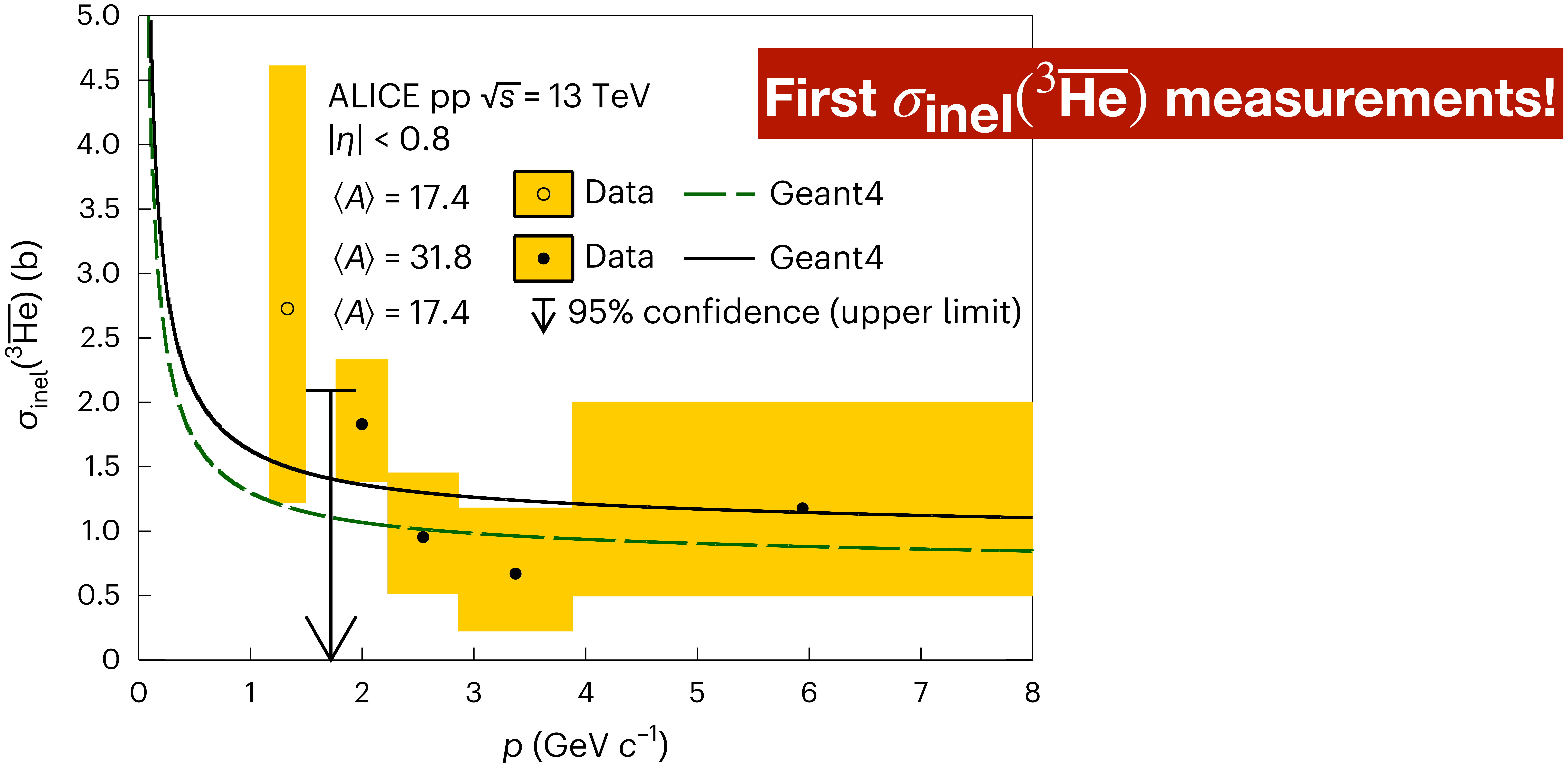
TOF/TPC $\propto \exp(-\sigma_{inel})$



Nature Physics (2022)

Results

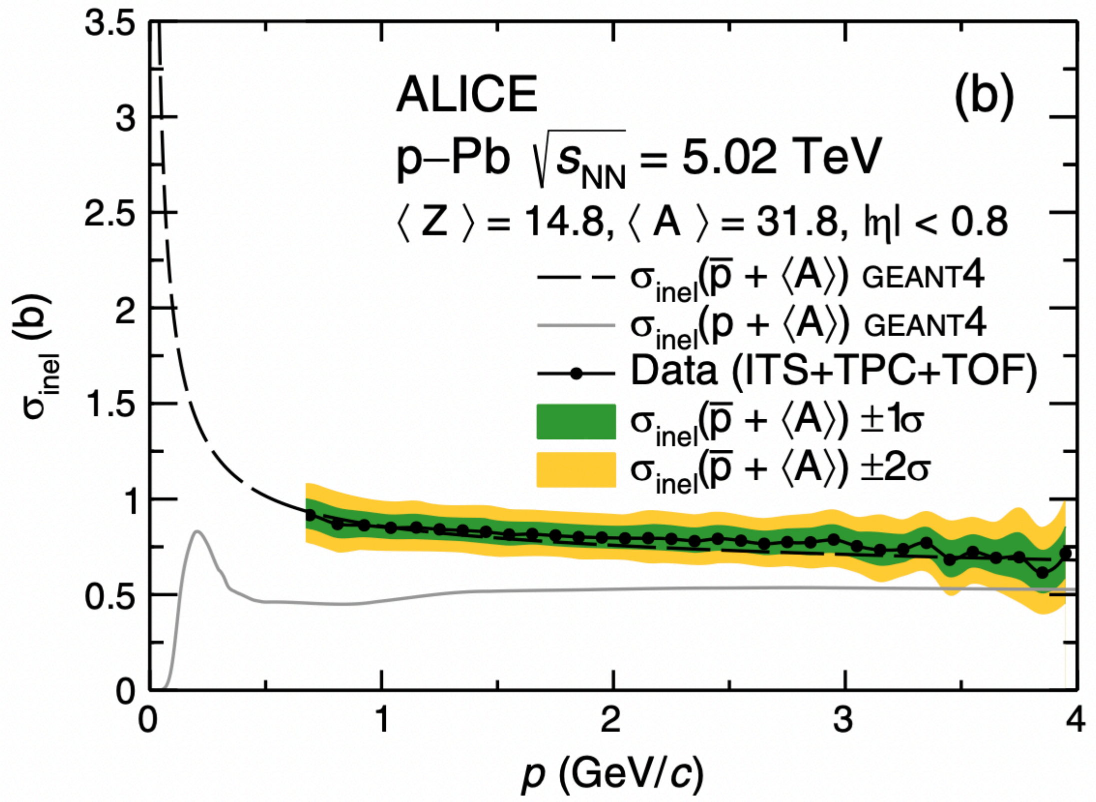
- Momentum estimated at the inelastic interaction point
- Inelastic antihelium-3 cross section on average target material
- At low momentum, rather good agreement between data and Geant4 prediction observed



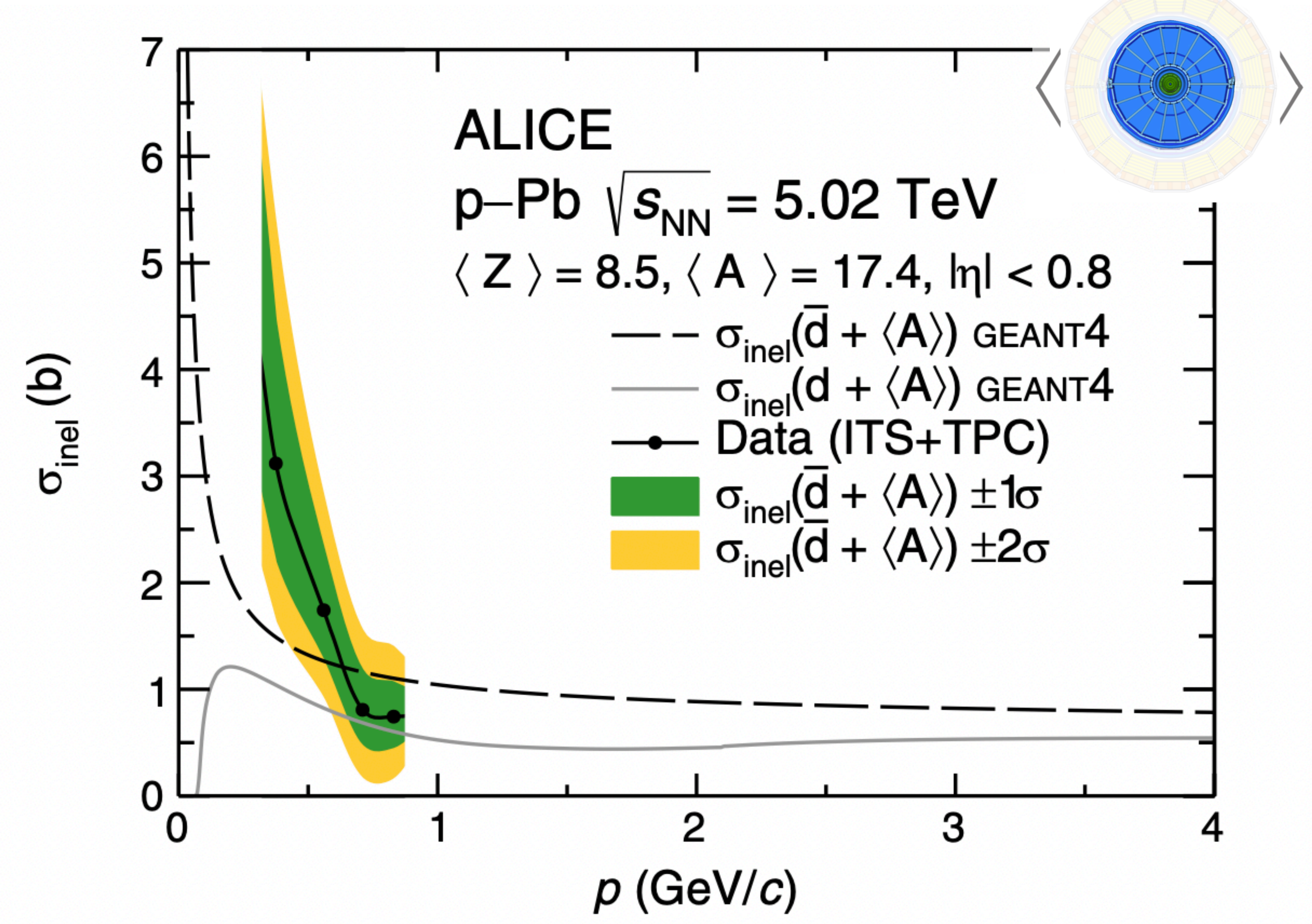
Nature Physics (2022)

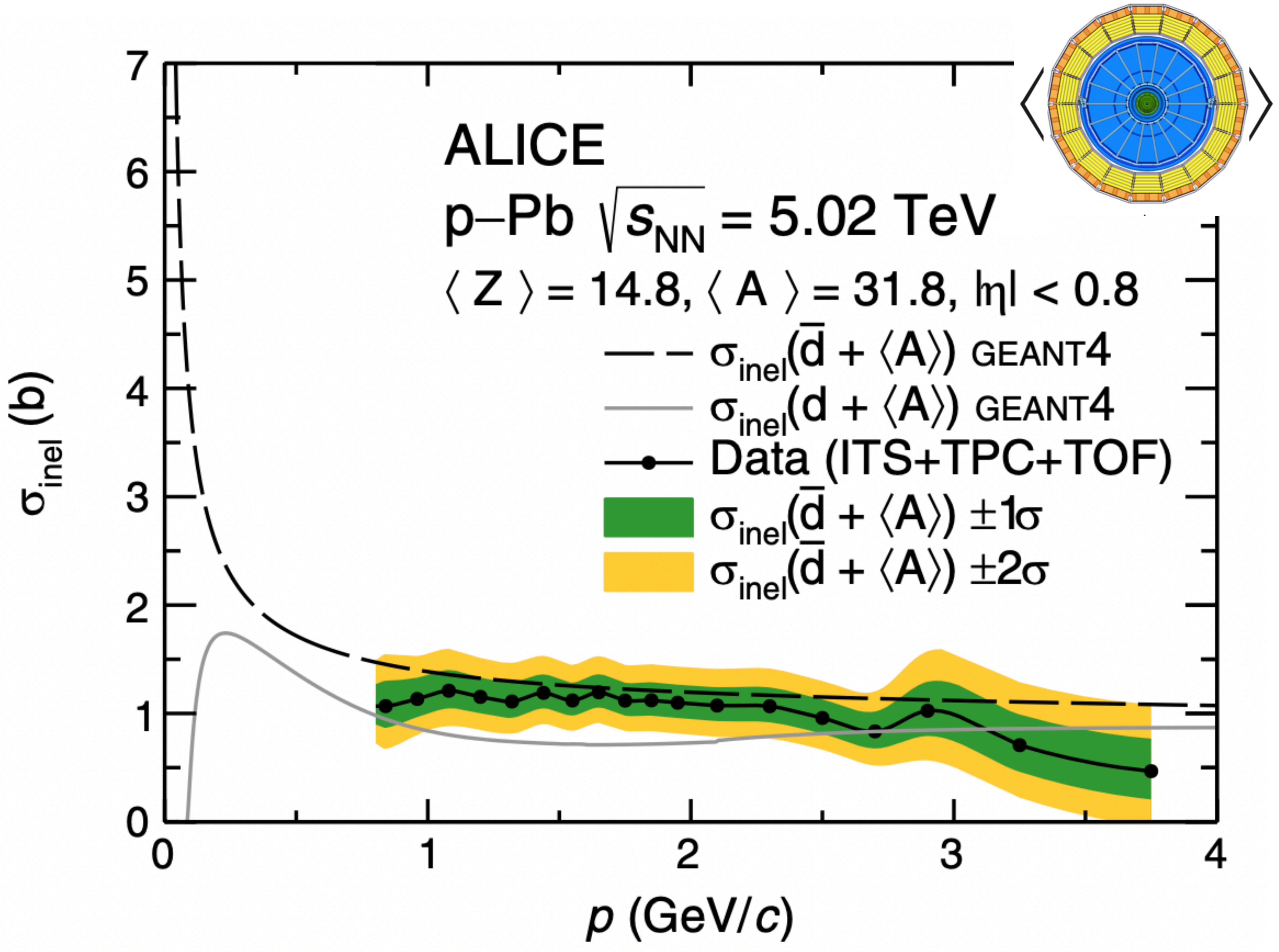
Antideuteron measurements

- Antimatter-to-matter ratio was as well used to measure antideuterons
- At low momentum, a hint of a steeper rise is observed in data
- At large momentum, the data and Geant4 are in good agreement



First low-energy $\sigma_{inel}(\bar{d})$ measurements!



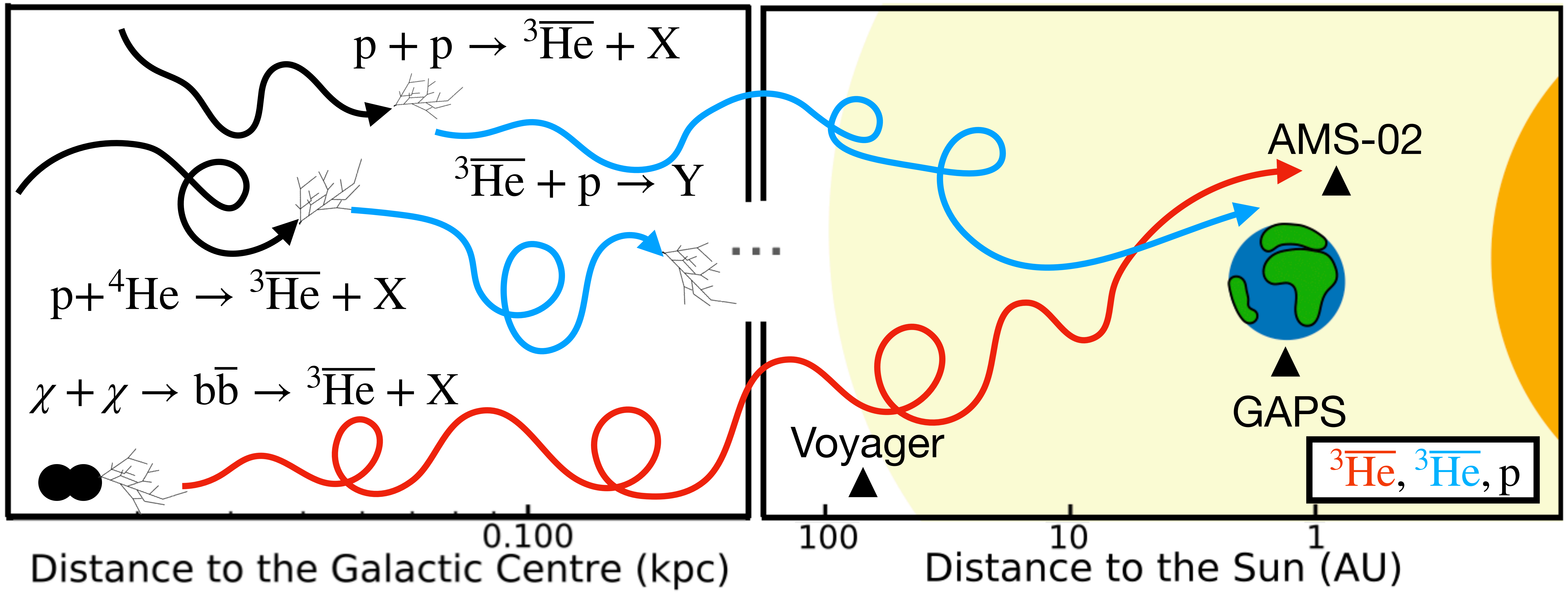


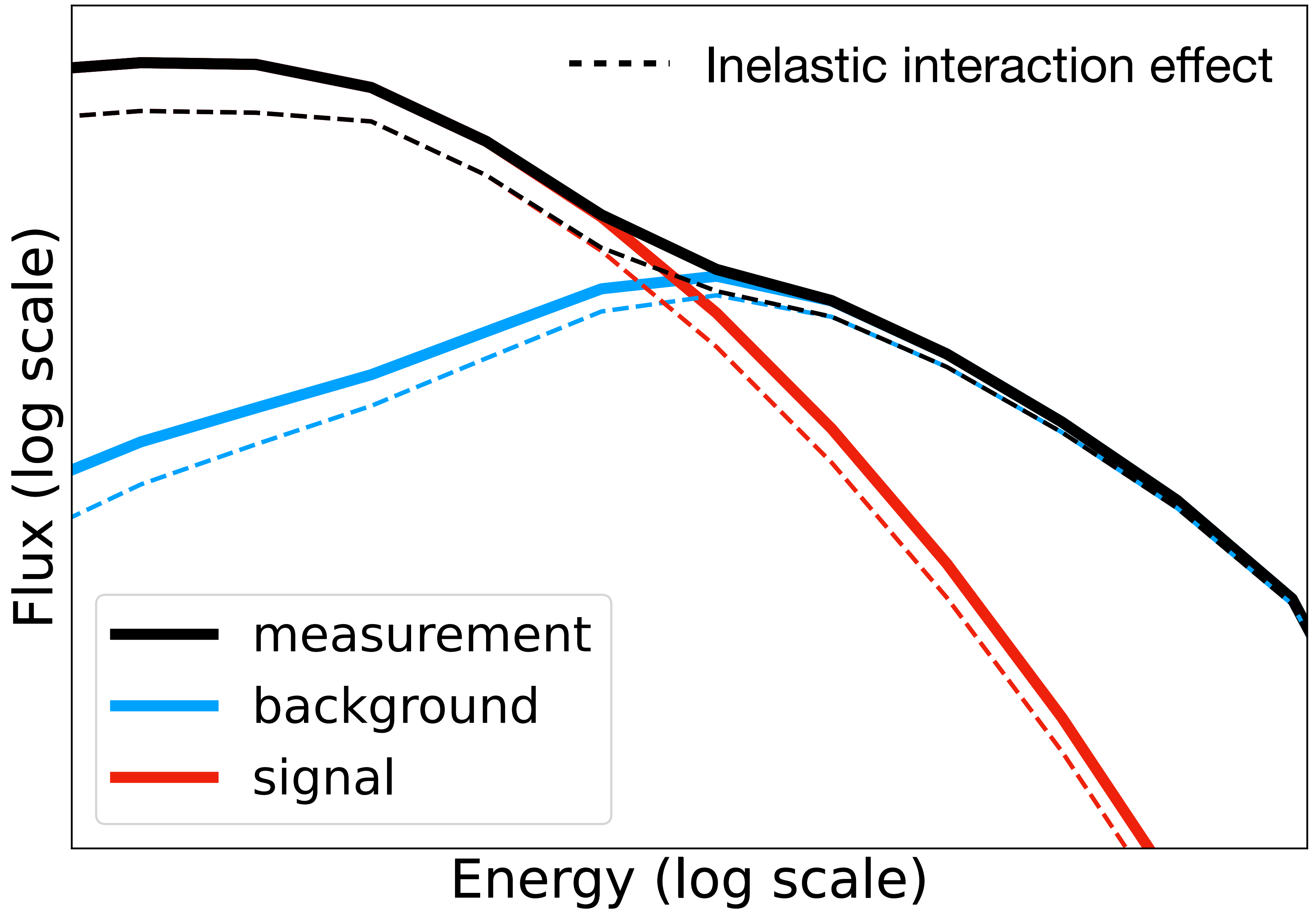
PRL 125, 162001 (2020)

Impact to antihelium-3 propagation in the galaxy

How many antihelium-3 survive?

- Production
- Propagation
- Inelastic interactions





Propagation

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

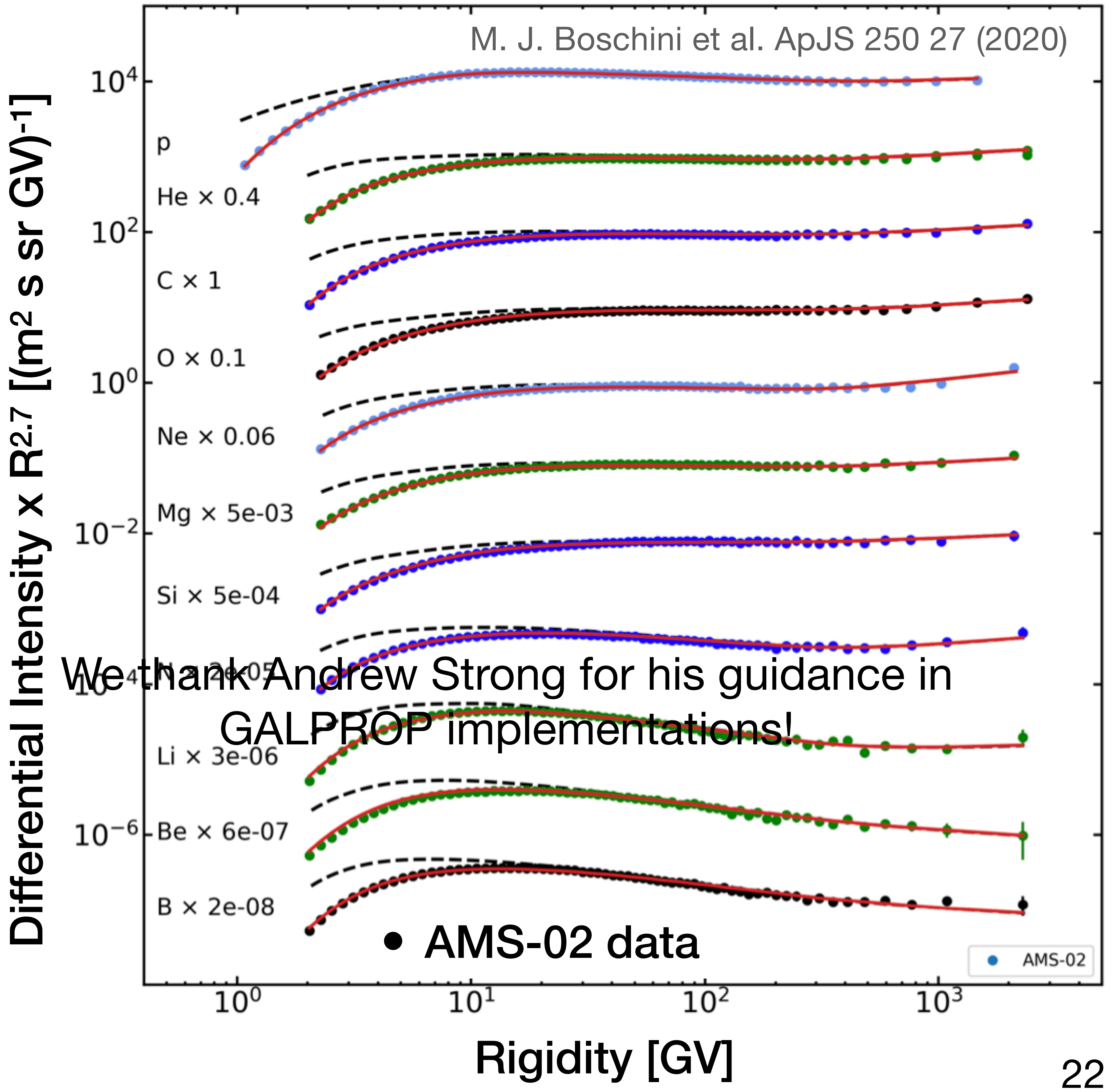
Propagation: diffusion, convection…

Fragmentation, annihilation

Can be numerically solved using the GALPROP code!
Publicly available at: https://galprop.stanford.edu.

Implementation of antinuclei in GALPROP requires:

- source function
  - cosmic ray collisions in interstellar medium
  - dark matter annihilation
- antihelium-3 inelastic cross section



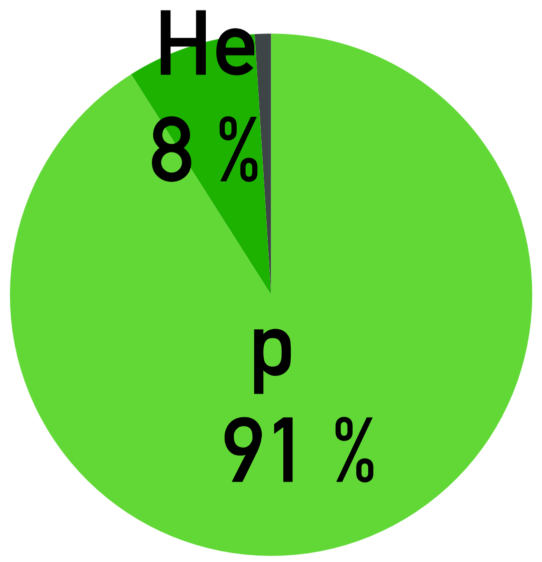
We thank Andrew Strong for his guidance in GALPROP implementations!

Source: cosmic ray + interstellar gas

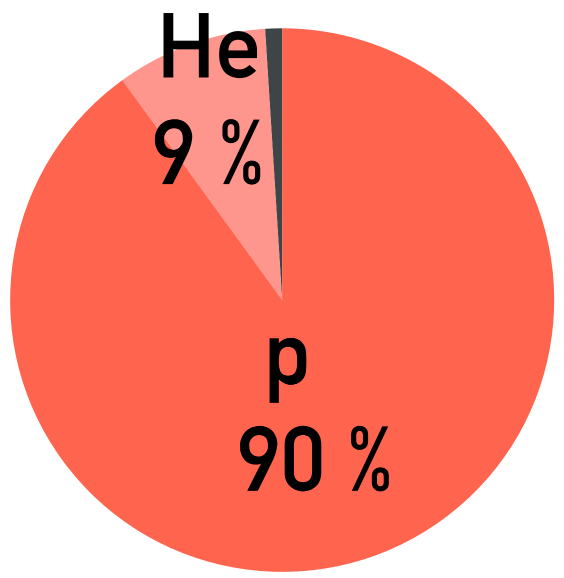
- Relevant collisions included: pp, p-He, He-p, He-He

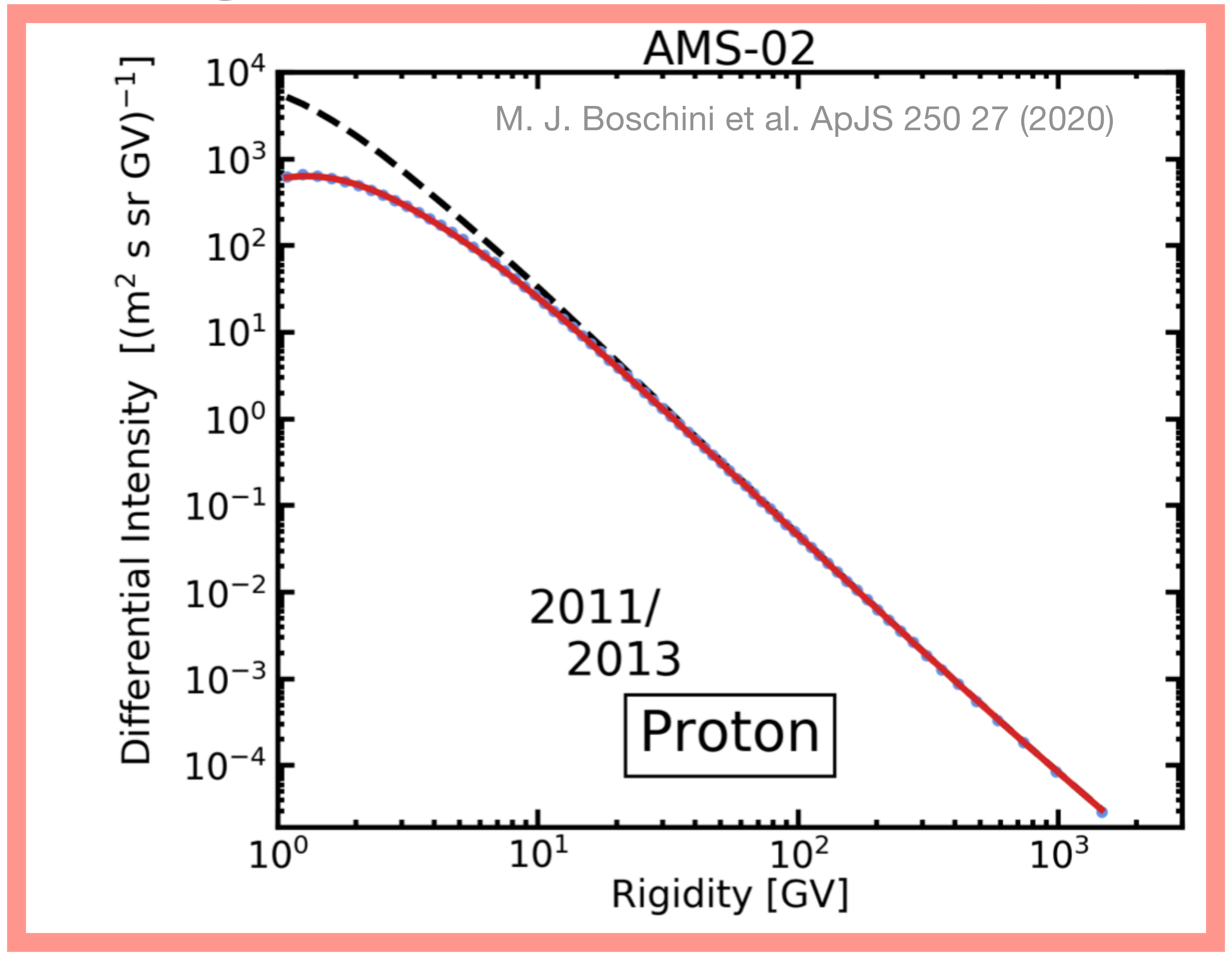
gas (target) — *production cross section* — *cosmic ray (projectile)*

$$q(\mathbf{r},p) = \sum_{\mathrm{CR=H,He}} \sum_{\mathrm{ISM=H,He}} n_{\mathrm{ISM}}(\mathbf{r}) \int \mathrm{d}p'_{\mathrm{CR}} \beta_{\mathrm{CR}} c \frac{\mathrm{d}\sigma\left(p,p'_{\mathrm{CR}}\right)}{\mathrm{d}p} n_{\mathrm{CR}}\left(\mathbf{r},p'_{\mathrm{CR}}\right)$$



?





Propagation
Sources
Annihilation

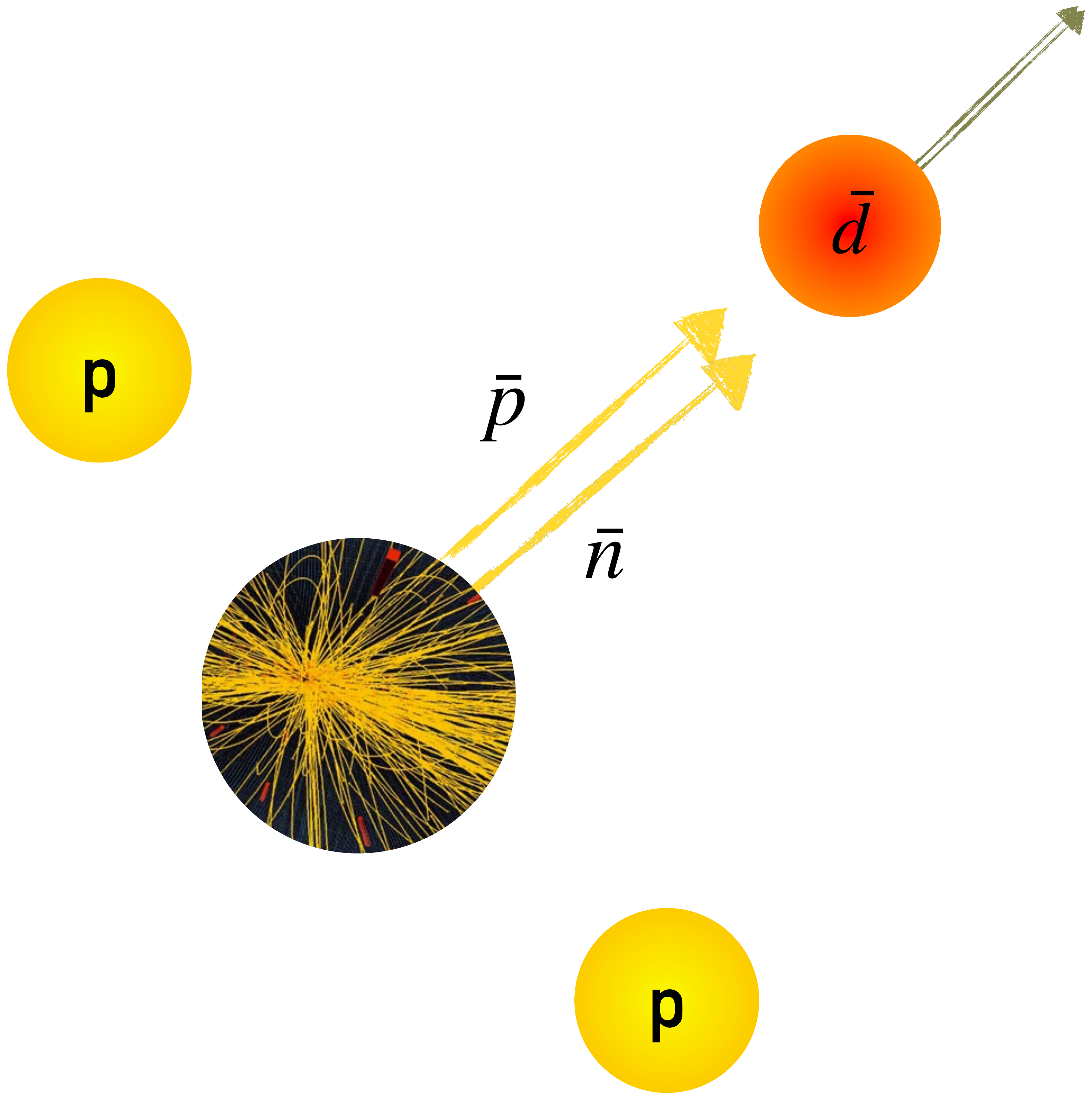
How are light nuclei formed?

- Coalescence model: nucleons are produced as degrees of freedom which then coalesce to form light nuclei

- Coalescence parameter B_A proportional to the probability for nucleons to coalesce

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

- B_A can be measured experimentally!

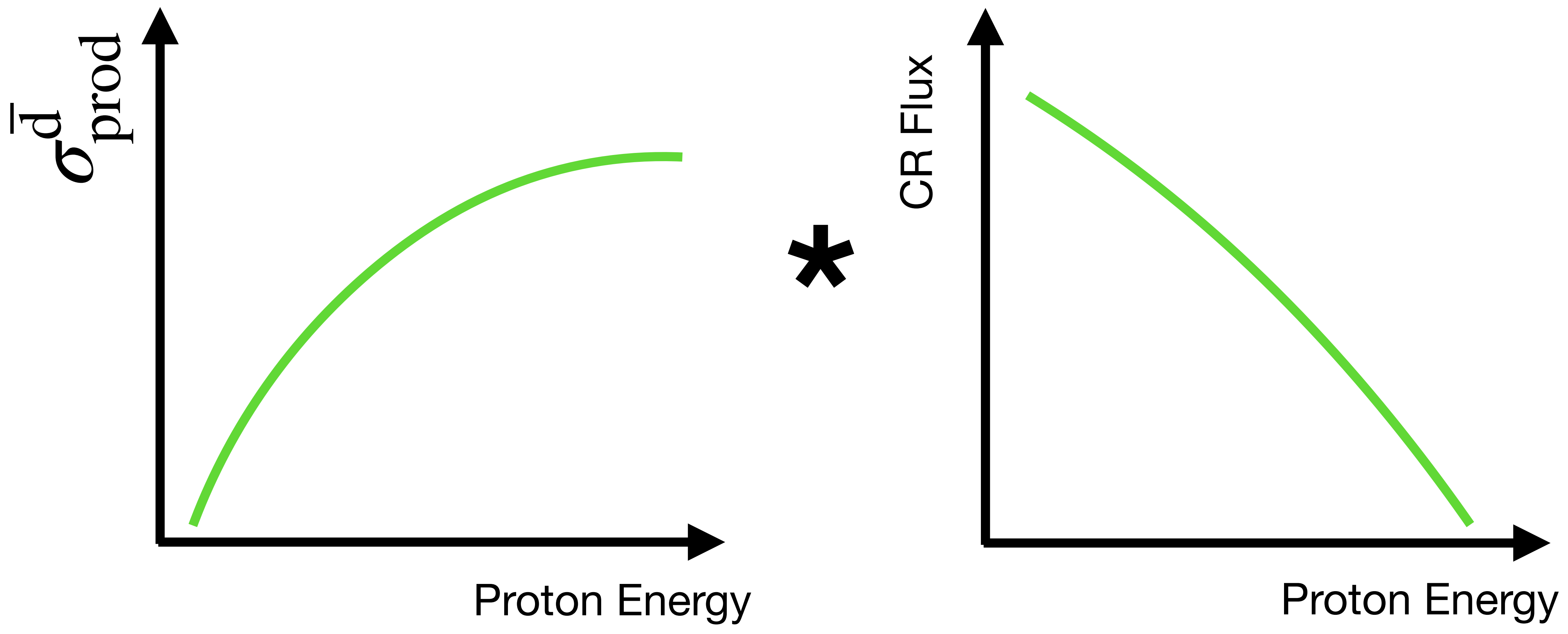


[1] S. T. Butler et al., Phys. Rev. 129 (1963) 836, Bellini et al. Phys. Rev. C 99, 054905 (2019)

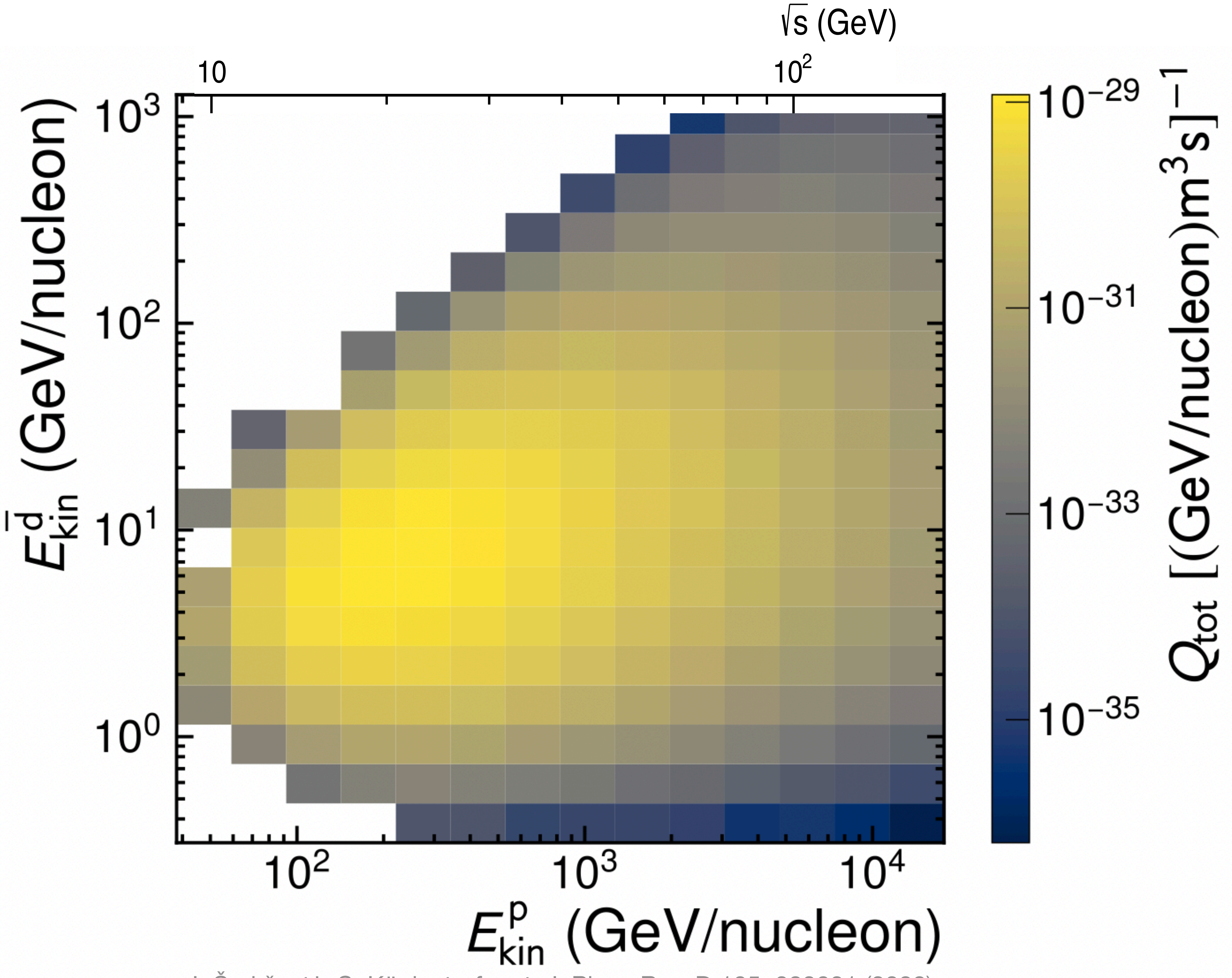
Collisions in interstellar medium

- Largest antideuteron yield from collisions of protons of kinetic energy ~200-500 GeV
- Corresponds to SPS centre-of-mass energies!
- The antinuclei inelastic cross sections must be evaluated at many different collision energies

Source Function



$$q(\mathbf{r},p) = \sum_{CR=H,He} \sum_{ISM=H,He} n_{ISM}(\mathbf{r}) \int dp'_{CR} \beta_{CR} c \frac{d\sigma(p,p'_{CR})}{dp} n_{CR}(\mathbf{r},p'_{CR})$$



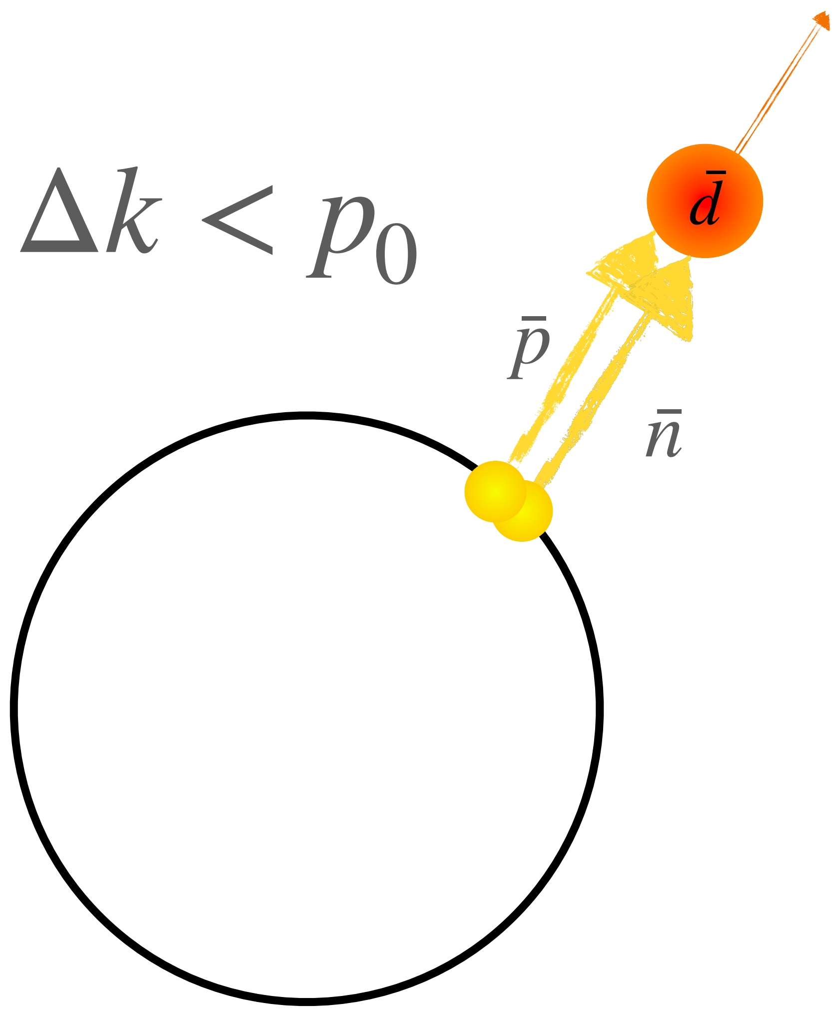
L.Šerkšnytė, S. Königstorfer et al, Phys. Rev. D 105, 083021 (2022)

Modeling antinuclei production

- Event generators used to obtain the antiproton spectra for different collision energies

$$p_0 = \frac{A}{1 + \exp(B - \ln(\mathrm{T/GeV})/C)}$$

$$\Delta k < p_0$$



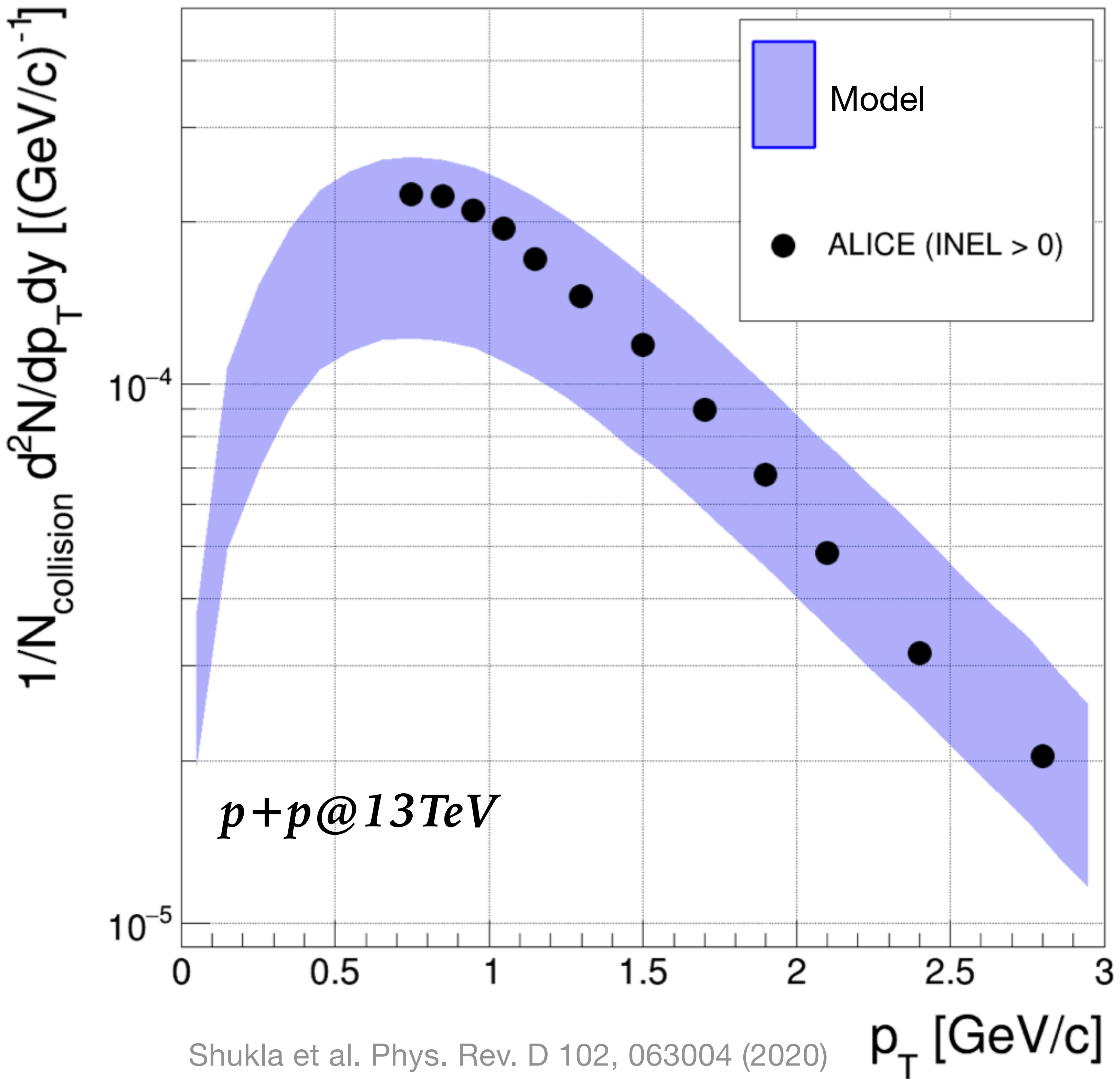
Experiment or Laboratory	Collision	p_{lab} (GeV/c)	$\sqrt{s}$ (GeV)
CERN	p + p	19	6.15
CERN	p + p	24	6.8
Serpukhov	p + p	70	11.5
	p + Be		
CERN-SPS	p + Be	200	19.4
	p + Al		
Fermilab	p + Be	300	23.8
CERN-ISR	p + p	1497.8	53
CERN-ALICE	p + p	4.3×10^5	900
CERN-ALICE	p + p	2.6×10^7	7000

[1] Shukla et al. Phys. Rev. D 102, 063004 (2020)
[2] Gomez-Coral et al. Phys. Rev. D 98, 023012 (2018)

Production cross sections

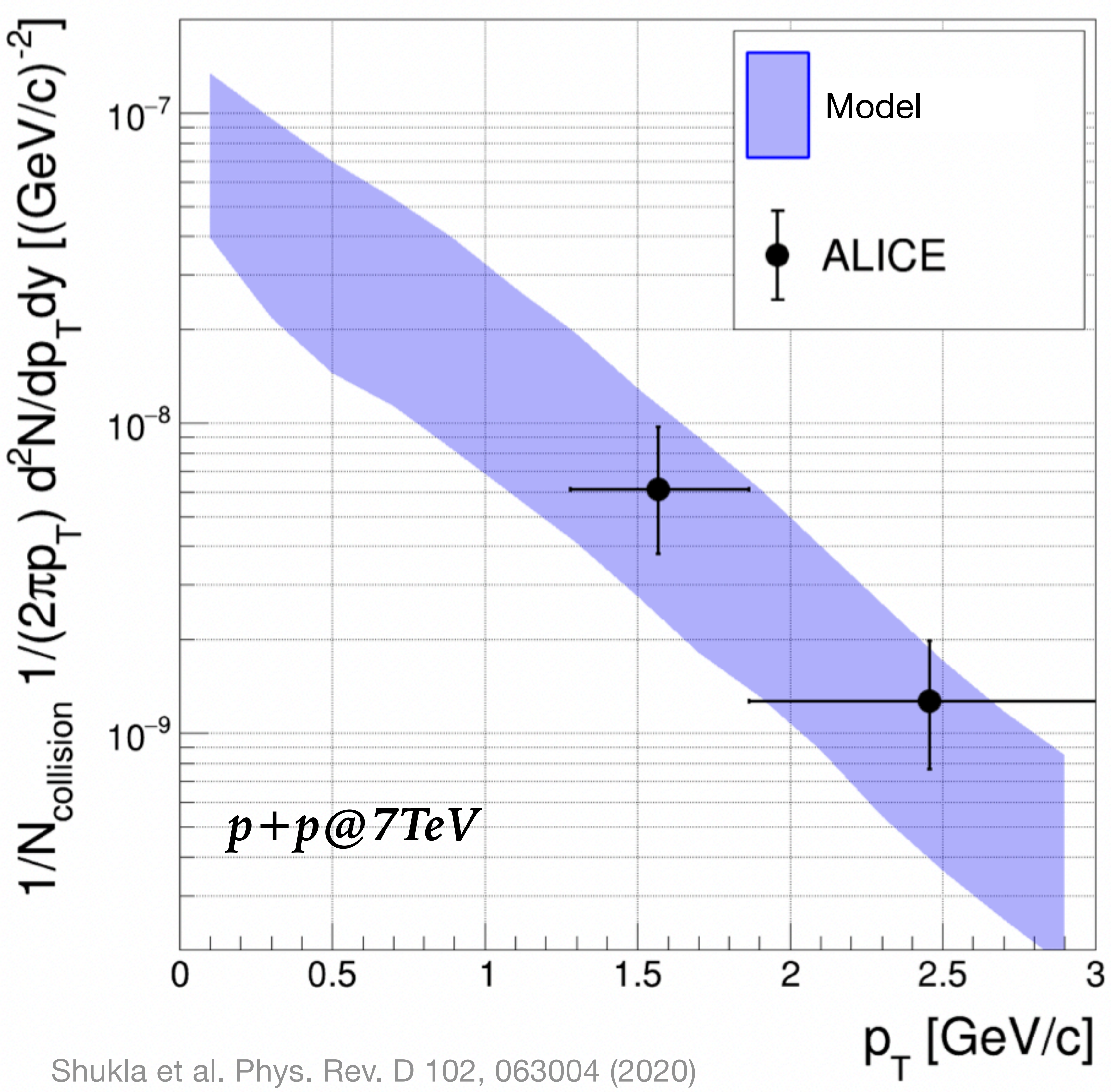
- EPOS-LHC generator used
- The model can reproduce well ALICE data

Antideuteron yield



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

Antihelium yield

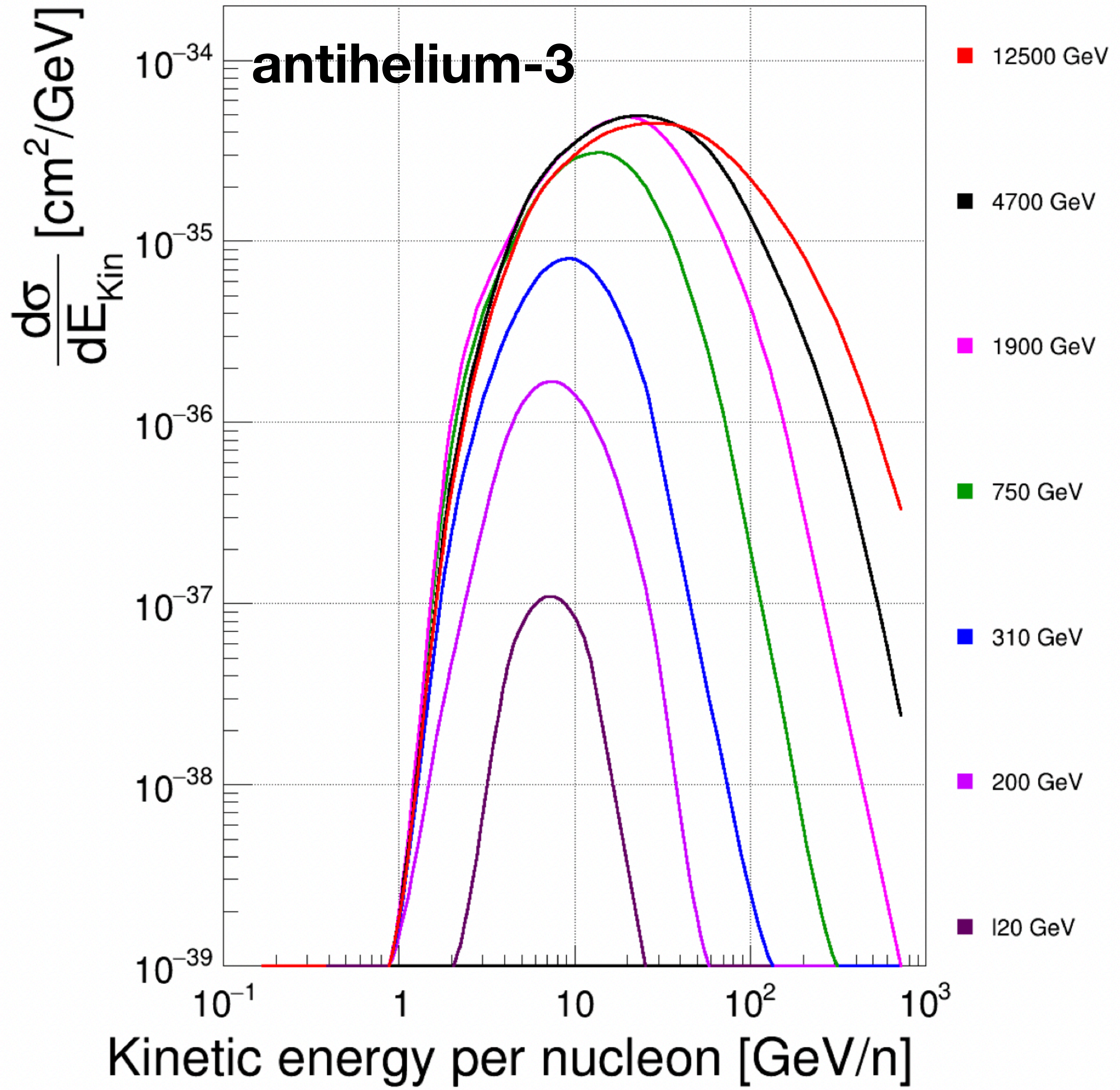


Shukla et al. Phys. Rev. D 102, 063004 (2020)

Production cross sections

- Model is used to estimate production cross section at different collision energies

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



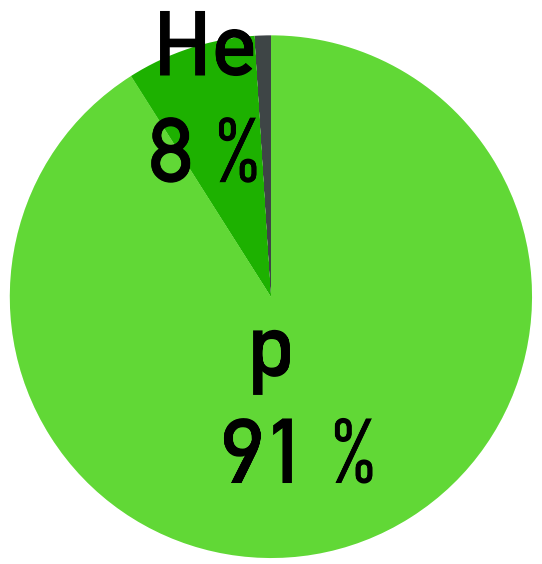
We thank A. Shukla and P. von Doetinchem for providing the 3He production cross sections!

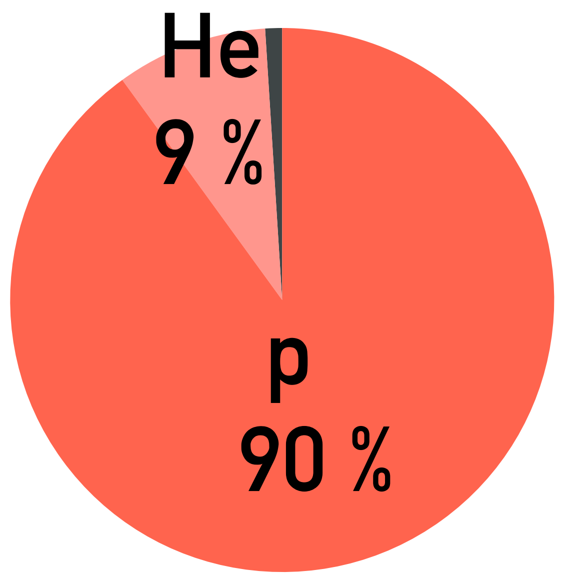
Source: cosmic ray + interstellar gas

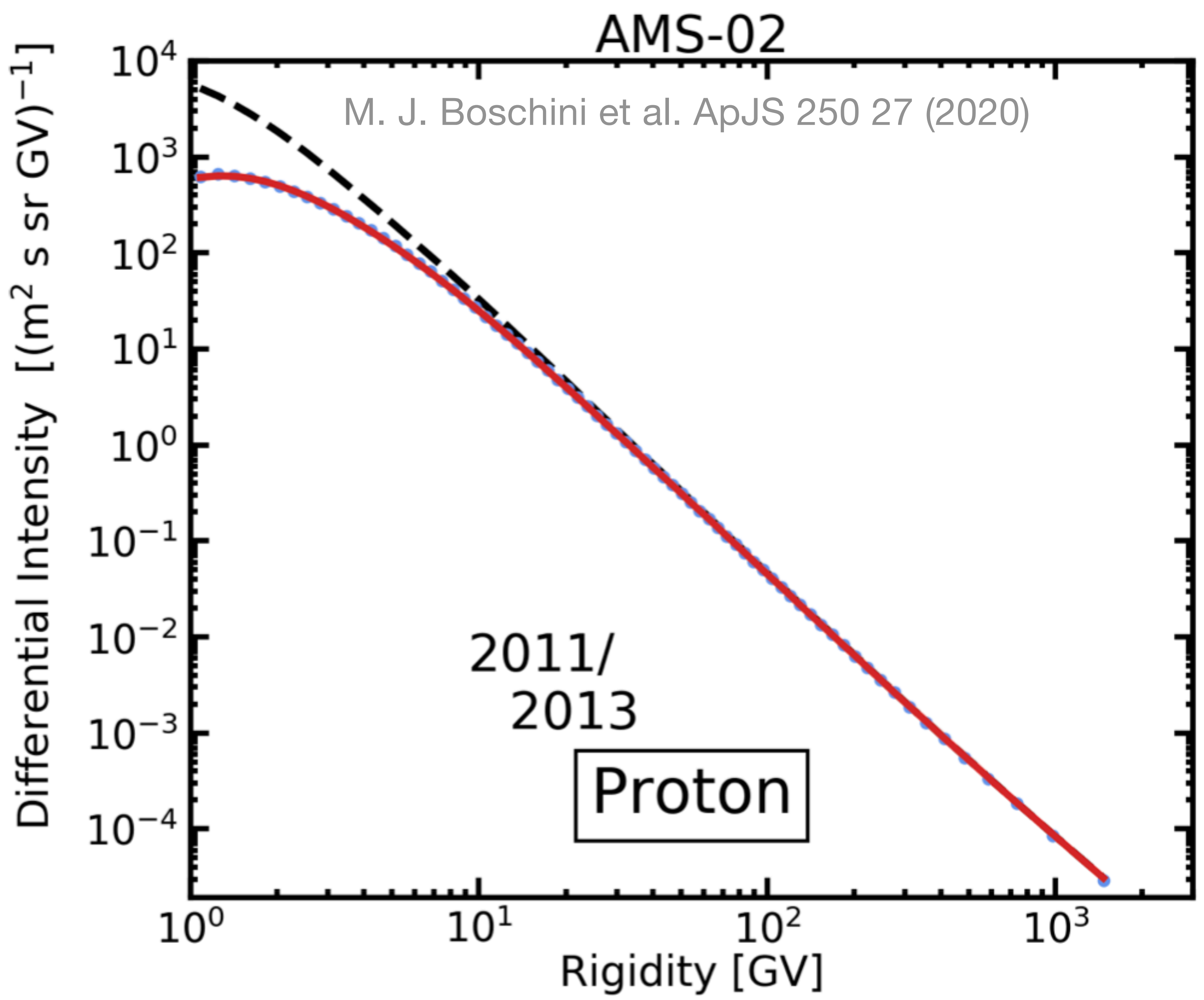
- Relevant collisions included: pp, p-He, He-p, He-He
- Production cross section in pp collisions from [1]; scaling factor $(A_\mathrm{T} A_\mathrm{P})^{2.2/3}$ applied for the rest

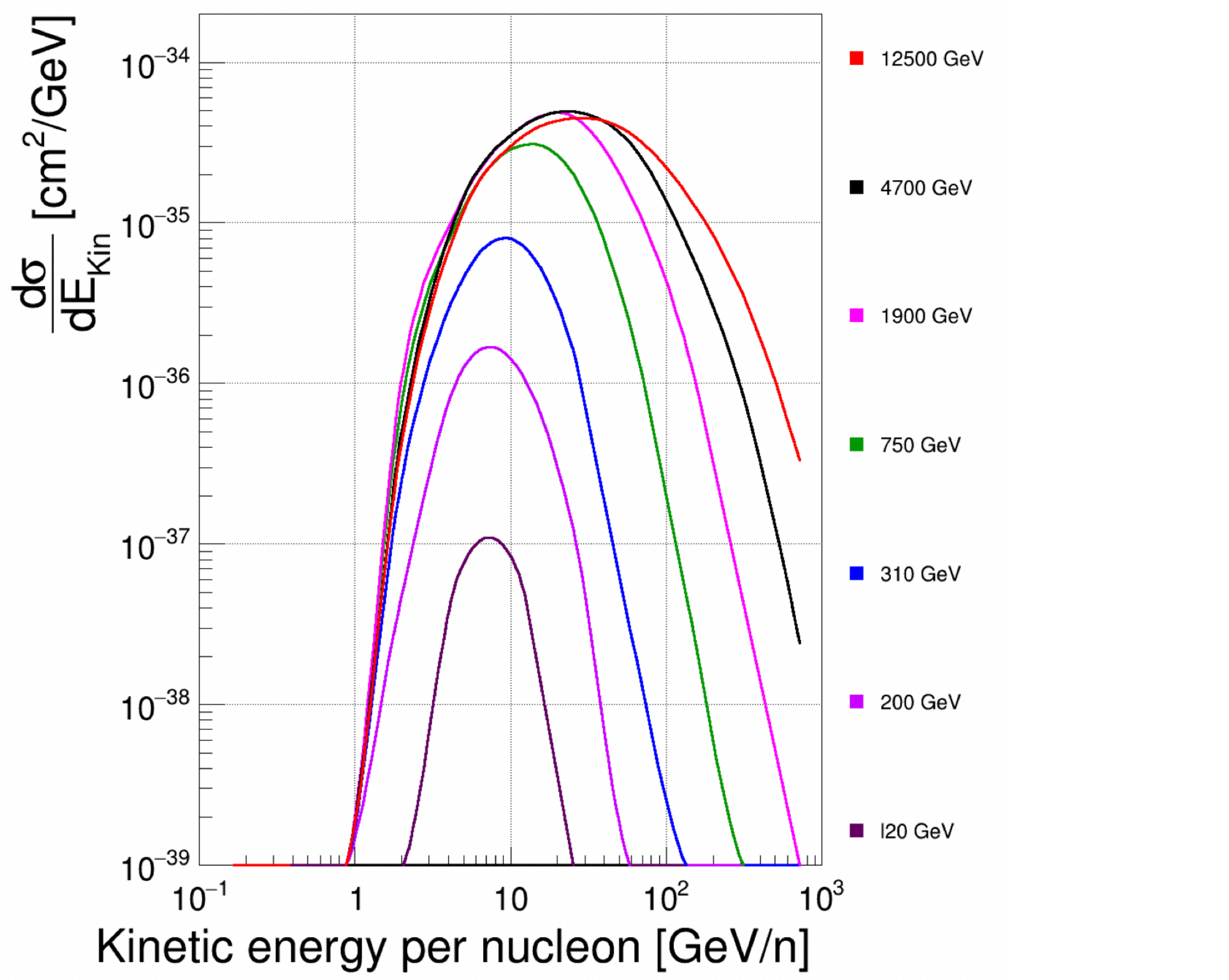
gas (target) — production cross section — cosmic ray (projectile)

$$q(\mathbf{r},p) = \sum_{\mathrm{CR=H,He}} \sum_{\mathrm{ISM=H,He}} n_{\mathrm{ISM}}(\mathbf{r}) \int \mathrm{d}p'_{\mathrm{CR}} \beta_{\mathrm{CR}} c \frac{\mathrm{d}\sigma\left(p, p'_{\mathrm{CR}}\right)}{\mathrm{d}p} n_{\mathrm{CR}}\left(\mathbf{r}, p'_{\mathrm{CR}}\right)$$









Propagation

Transport equation

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

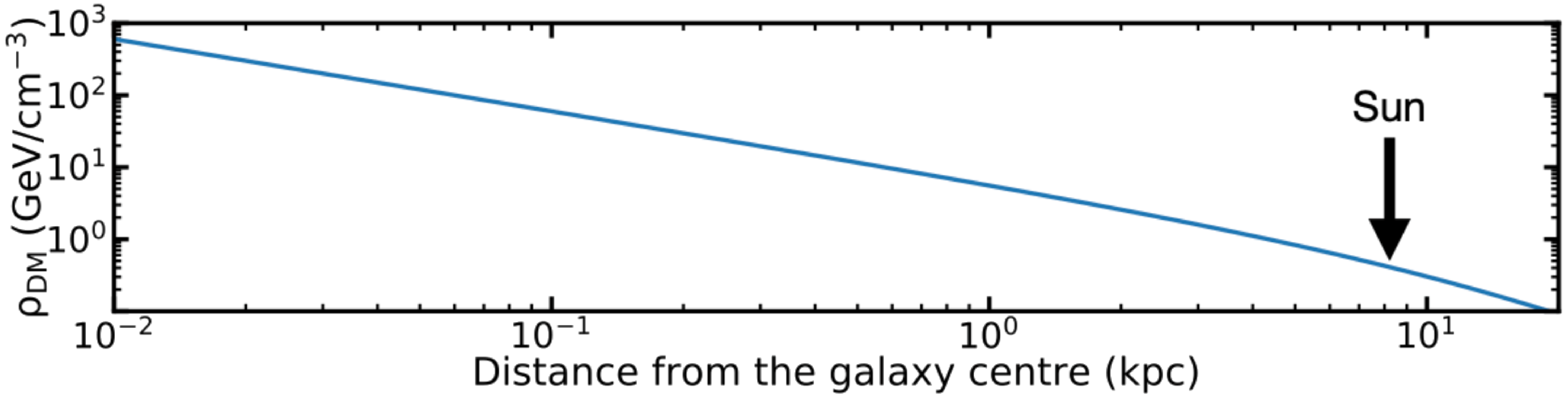
Source Function

Implementation of antinuclei in GALPROP requires:

- source function
  - cosmic ray collisions in interstellar medium ✓
  - dark matter annihilation ←
- antihelium-3 inelastic cross section

Source: dark matter annihilation

$$q\left(\mathbf{r}, E_{\text{kin}}\right) = \frac{1}{2}\frac{\rho_{\text{DM}}^2(\mathbf{r})}{m_\chi^2}\langle\sigma v\rangle\frac{\mathrm{d}N}{\mathrm{d}E_{\text{kin}}}$$



[1] Carlson et al, Phys. Rev. D. 89, 076005 (2014)
[2] Korsmeier et al, Phys. Rev. D. 97, 103011 (2018)

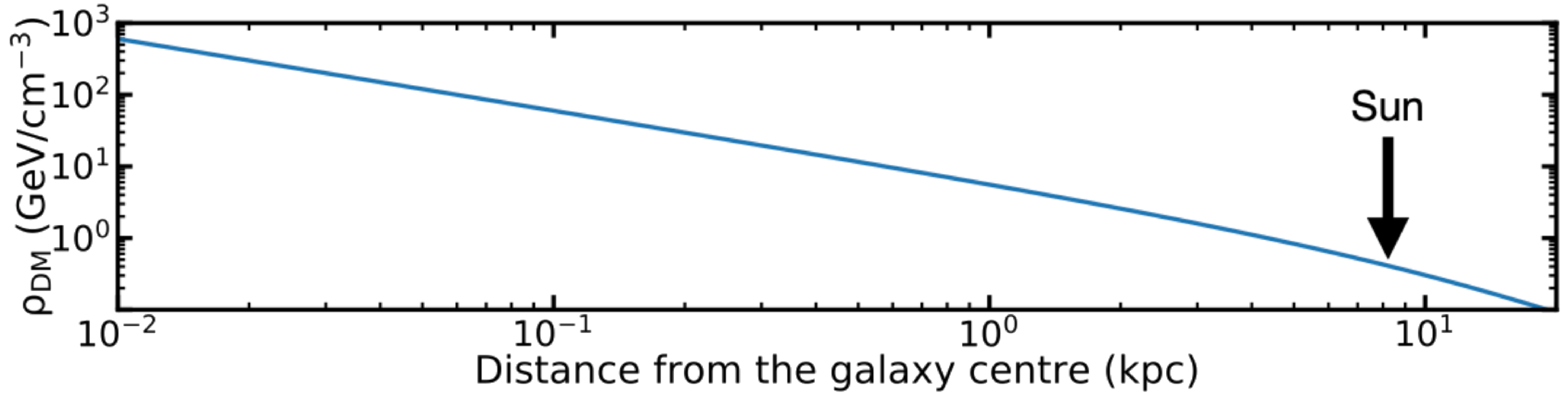
Propagation

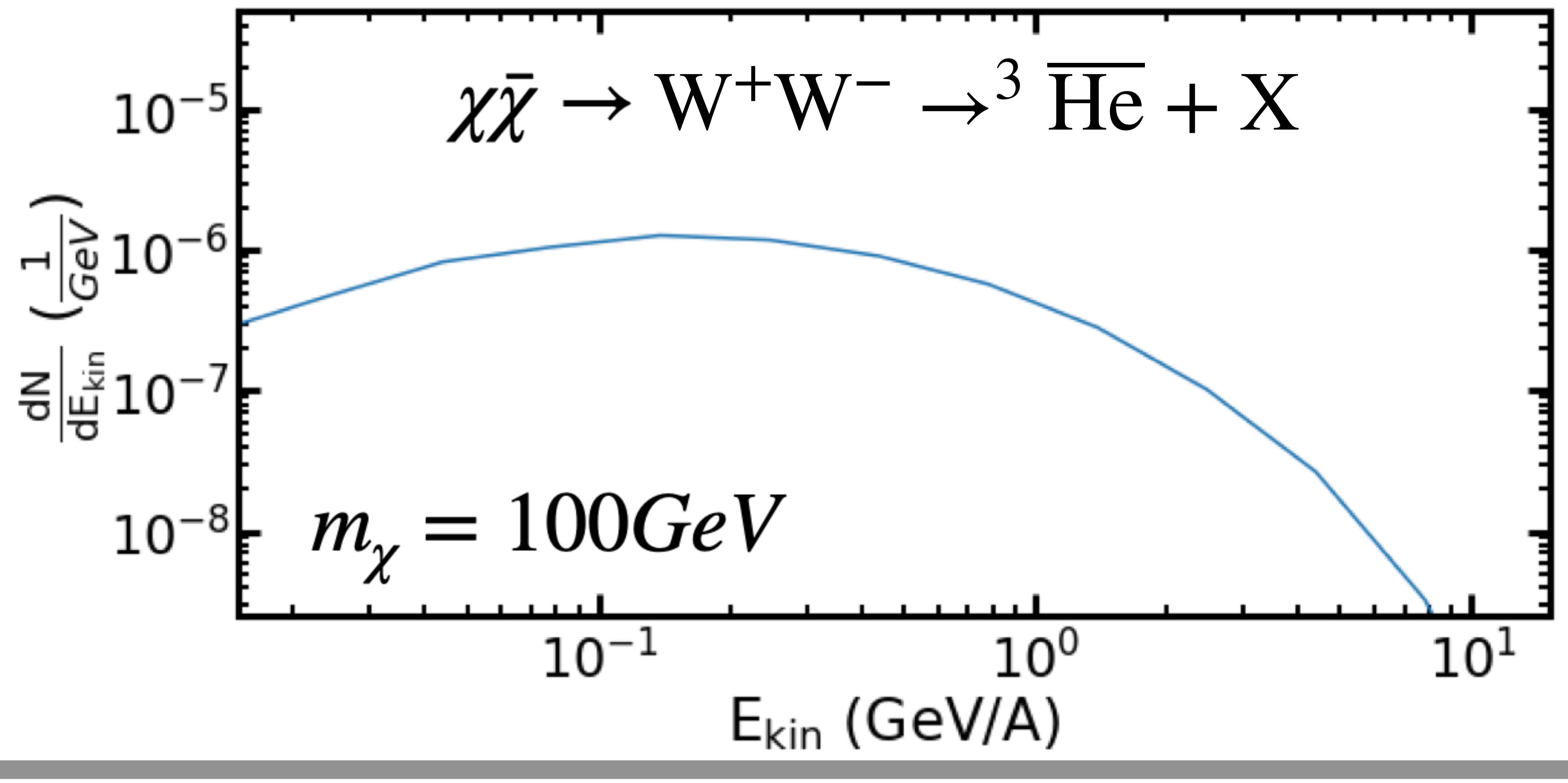
Sources

Annihilation

Source: dark matter annihilation

$$q\left(\mathbf{r}, E_{\text{kin}}\right) = \frac{1}{2}\frac{\rho^2_{\text{DM}}(\mathbf{r})}{m^2_\chi}\langle\sigma v\rangle\frac{\mathrm{d}N}{\mathrm{d}E_{\text{kin}}}$$





- ρ_{DM} - NFW profile [1]
- m_χ = 100 GeV for W^+W^-
- $\langle\sigma v\rangle$ = 2.6x10^{-26} $\mathrm{cm^3 s^{-1}}$ [2]
- $\mathrm{d}N/\mathrm{d}E_{\text{kin}}$ from [1], obtained using PYTHIA 8.156 and event-by-event coalescence afterburner
- Constrained to ALEPH data

We thank J. Herms and A. Ibarra for model calculations of the antihelium-3 spectra stemming from DM annihilation.

[1] Carlson et al, Phys. Rev. D. 89, 076005 (2014)
[2] Korsmeier et al, Phys. Rev. D. 97, 103011 (2018)

Propagation

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Fragmentation, annihilation

Implementation of antinuclei in GALPROP requires:

- source function
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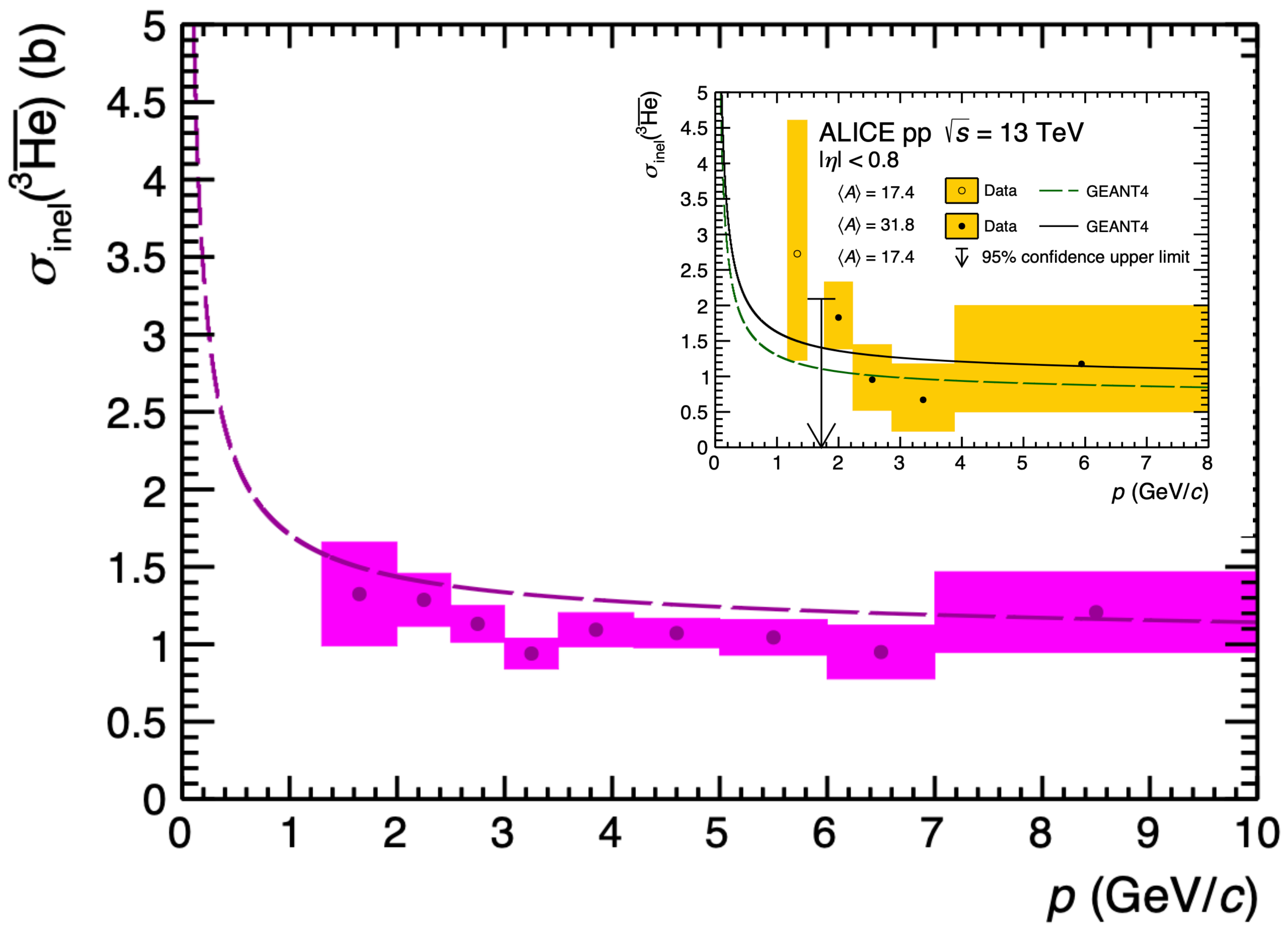
  - dark matter annihilation ✓
- antihelium-3 inelastic cross section ←

σ_{inel} scaling to H and He targets

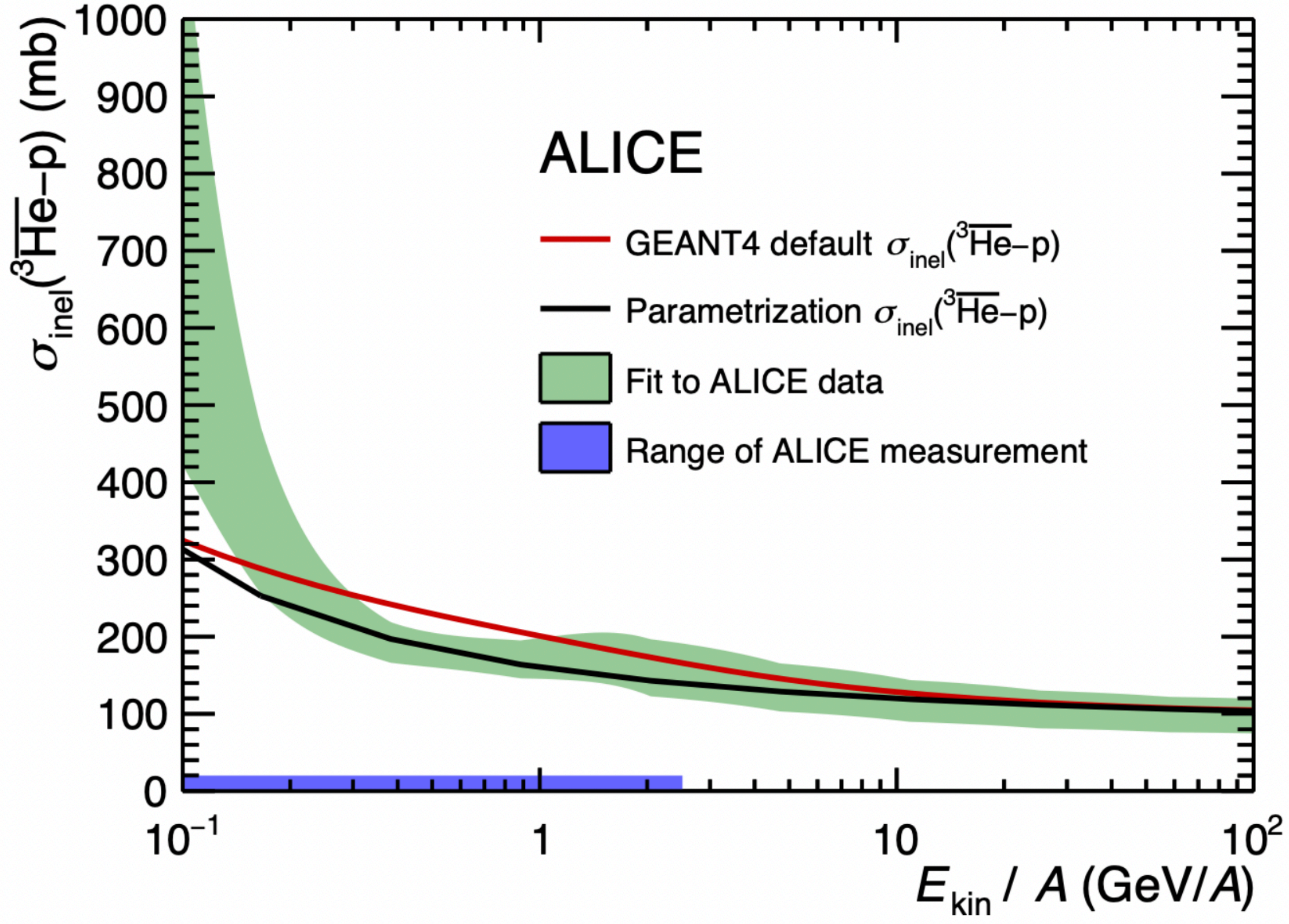
- ALICE measurement: anti-^{3}He inelastic cross section on heavy targets
- Cosmic rays: proton and ^{4}He targets
- Extrapolation to light targets for Geant4 parameterisation using ALICE measurement
- Use a correction factor for all target materials, 8% uncertainty on the A scaling

Measured by ALICE: <A> = 17.4, 34.7



$$corr = \frac{\sigma_{ALICE}}{\sigma_{Geant4}}$$

Nature Physics (2022)



Propagation

Transport equation

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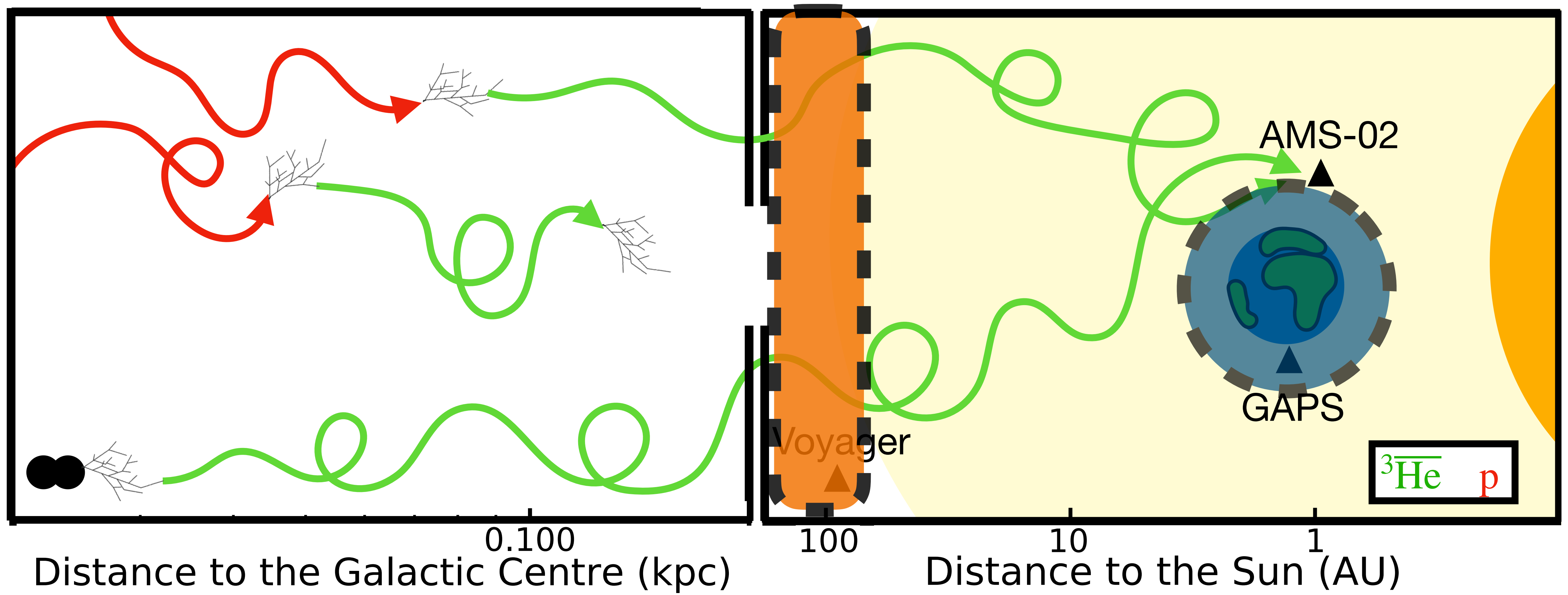
Source Function

Propagation: diffusion, convection…

Fragmentation, annihilation

Implementation of antinuclei in GALPROP requires:

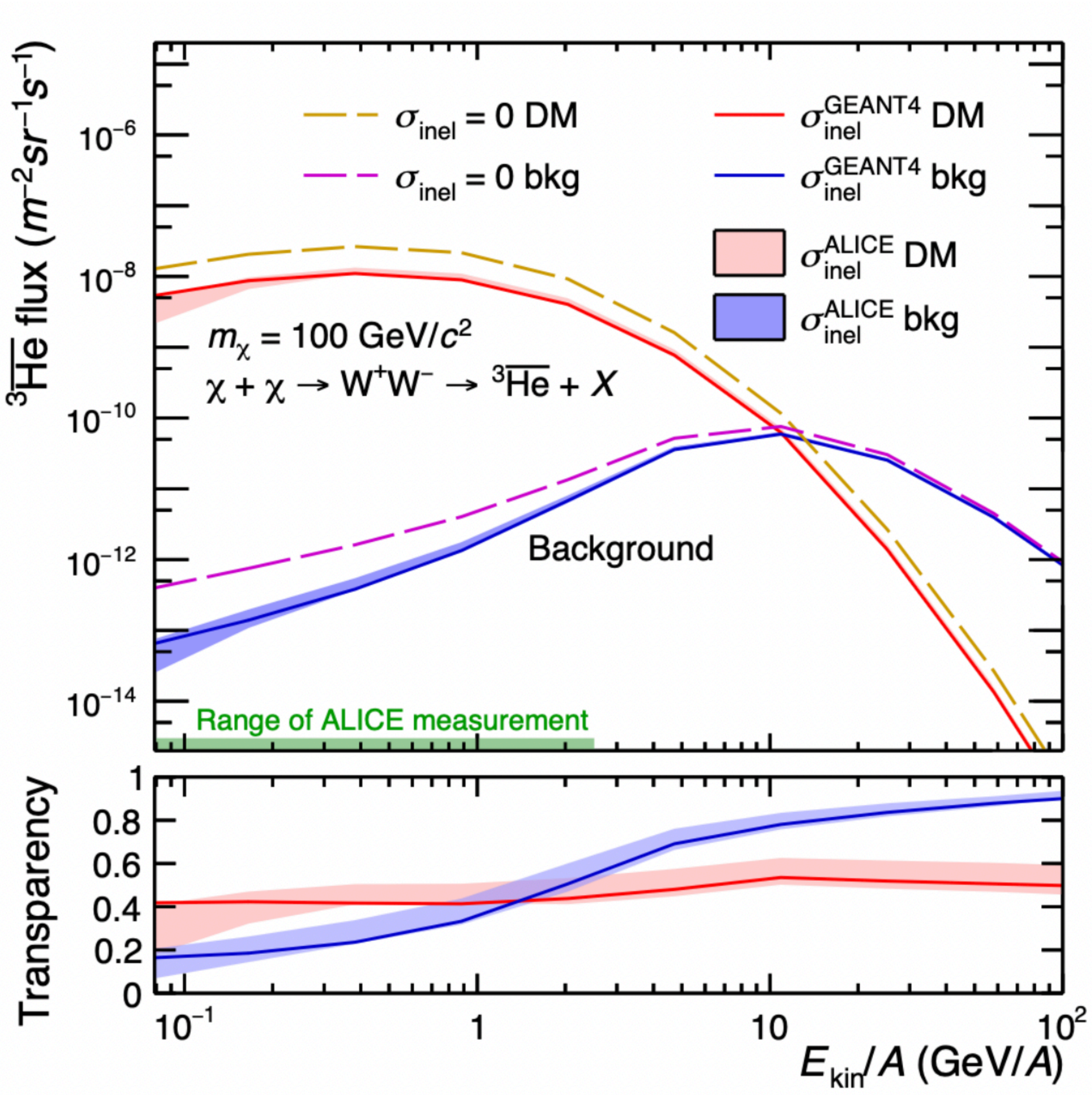
- source function
  - cosmic ray collisions in interstellar medium ✓
  - dark matter annihilation ✓
- antihelium-3 inelastic cross section ✓



Interstellar antihelium flux

[Nature Physics (2022)]

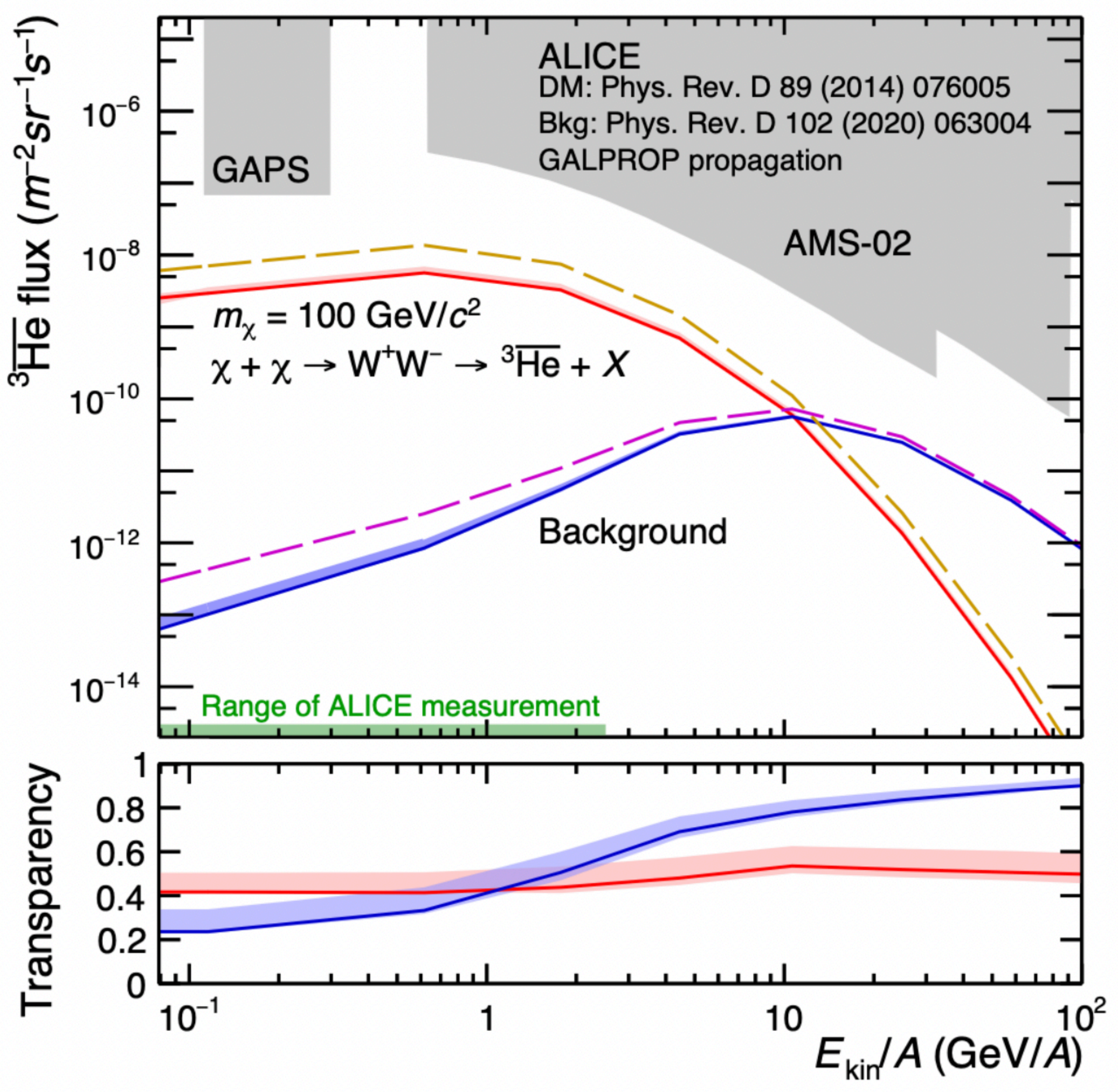
- Uncertainties shown only from ALICE measurement, small compared to other uncertainties in the field
- Disappearance effect strongly depends on the cosmic ray flux shape



Solar modulated antihelium flux

- Force-field approximation used to account for solar magnetic field; evaluated at solar minimum

Nature Physics (2022)

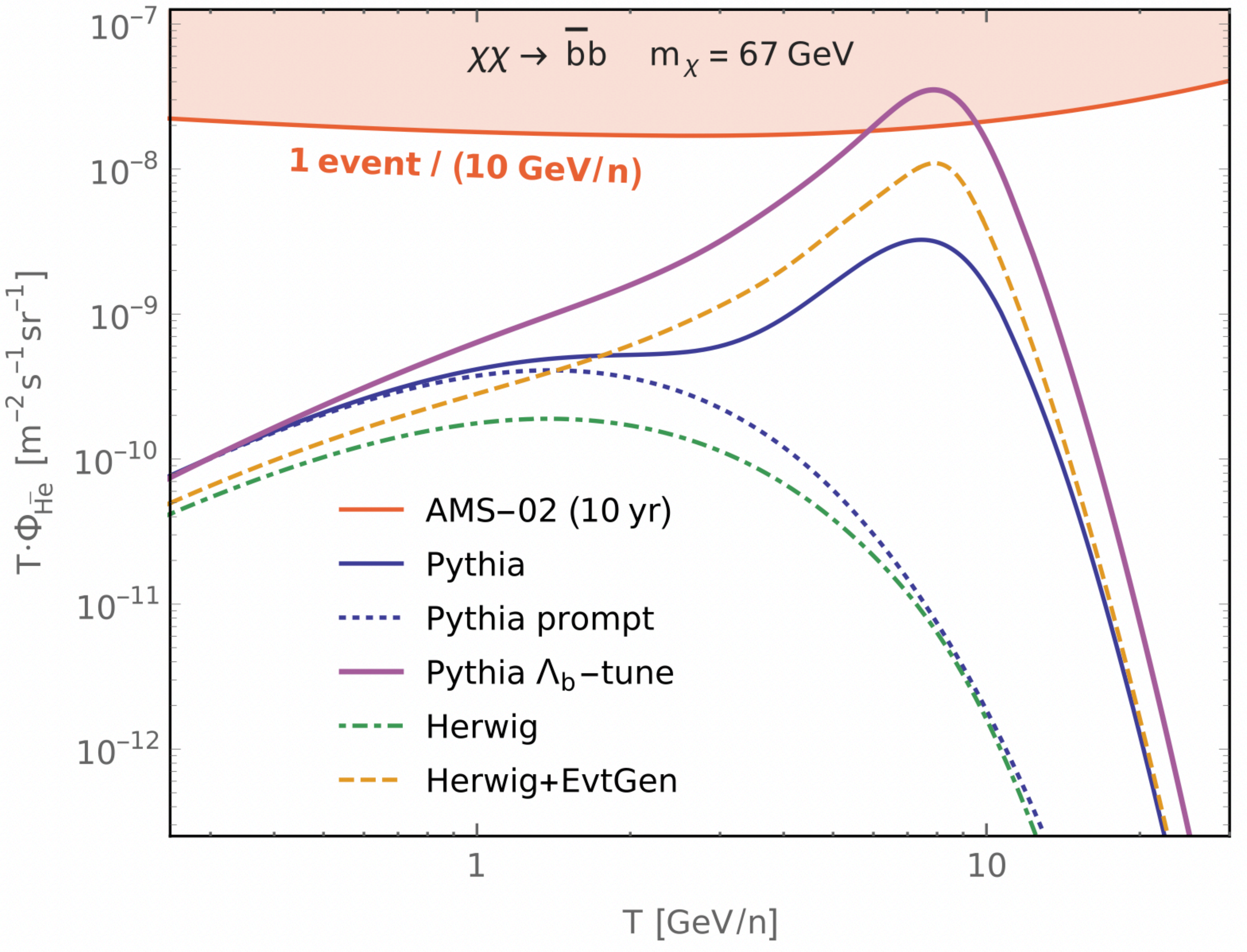


ALICE measurement of antihelium-3 inelastic cross sections can be used in all future studies of antihelium-3 cosmic rays!

Outlook

- Antihelium-3 production in $\overline{\Lambda}_b$ baryon decays from dark matter annihilation
  - Higher production rate
  - Boosted to higher energies
- Experimental proof needed!
  - ALICE 3
  - CMS with Run 4 data
  - LHCb with Run 2 data

M.W. Winkler and T. Linden Phys. Rev. Lett. 126, 101101



Outlook

ALICE 3 LOI (CERN-LHCC-2022-009)

- Antihelium-3 production in $\overline{\Lambda}_b$ baryon decays from dark matter annihilation
  - Higher production rate
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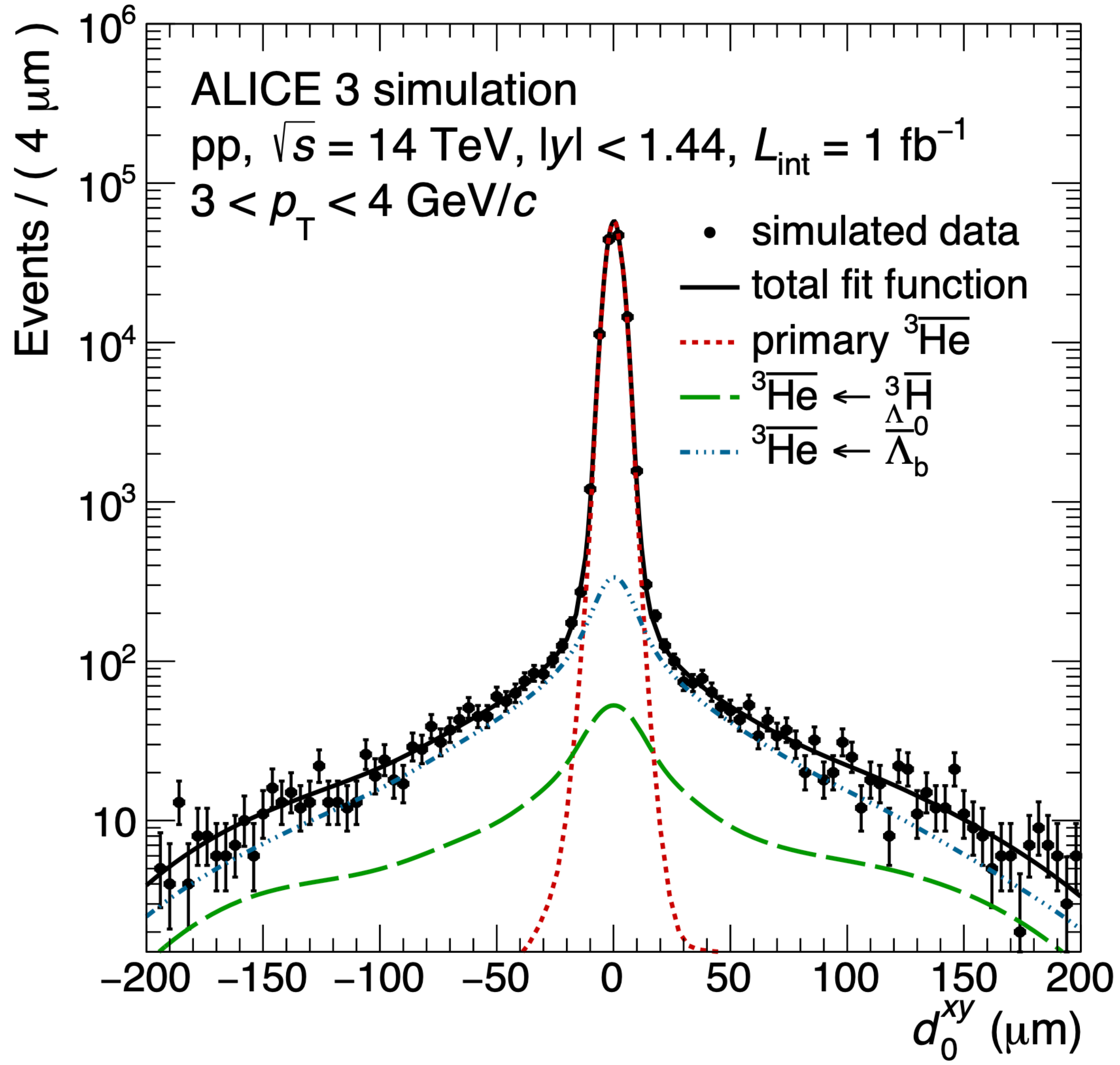
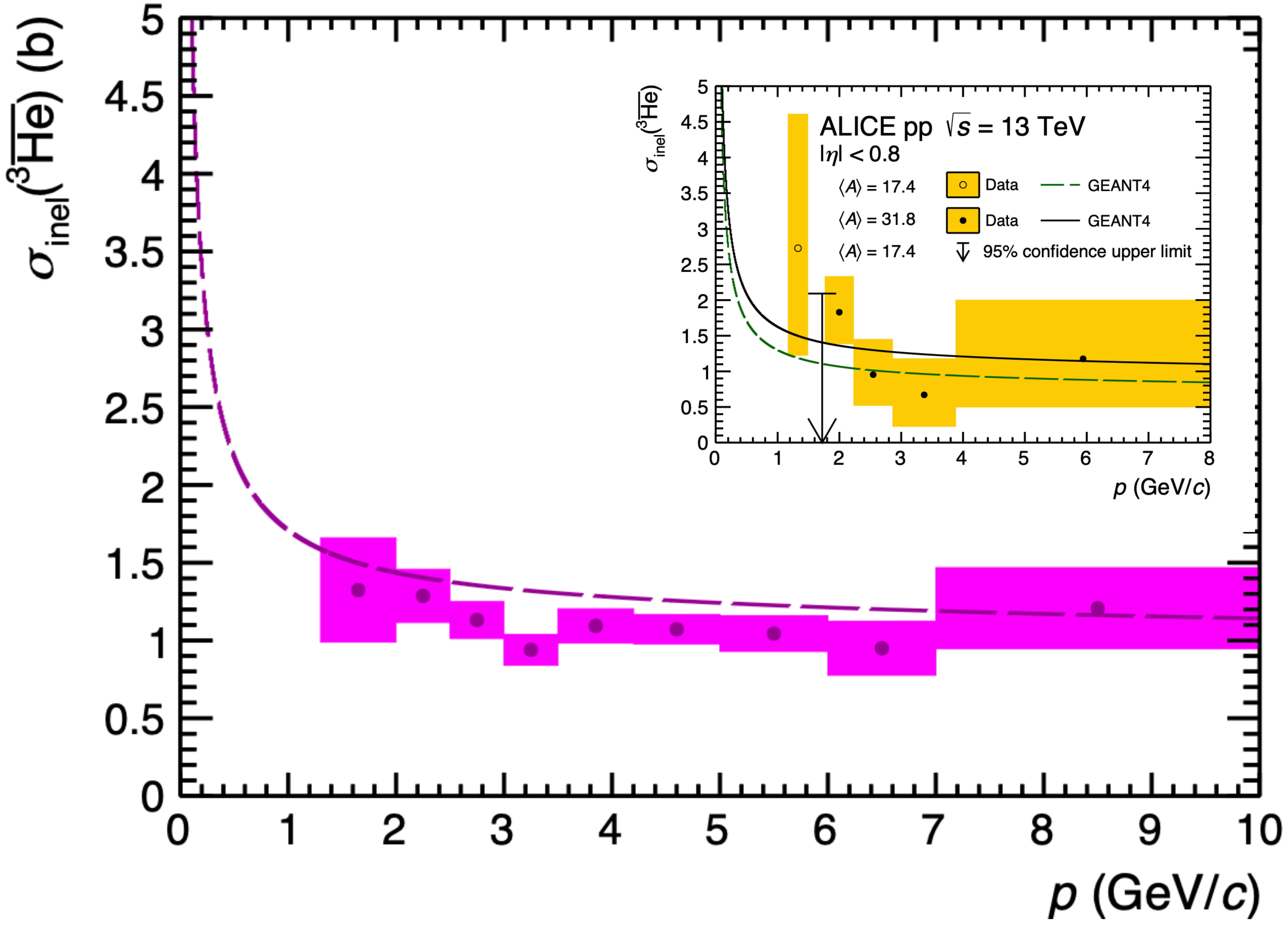


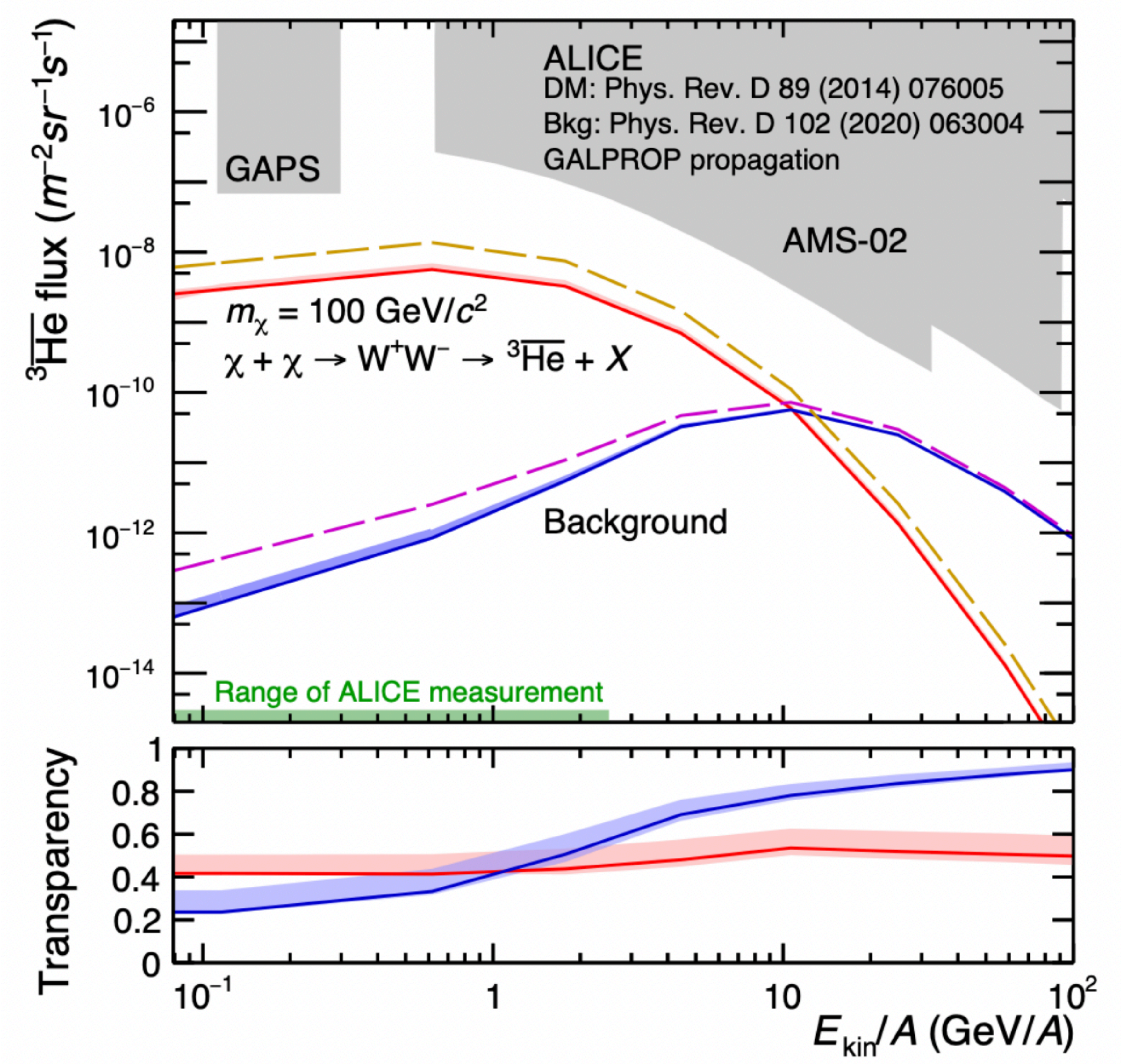
- Inelastic cross section measurements by ALICE in Run 3:
  - Antihelium-4
  - Improved antideuteron with dedicated setup
- Antimatter production measurements at low collision energies:
  - AMBER
  - NA61

Summary

- First ever measurement of antihelium-3 inelastic cross sections
- High transparency of 50% for typical DM scenario and 25-90% for background
- Antihelium is a promising candidate for dark matter searches!

Nature Phys. (2022)

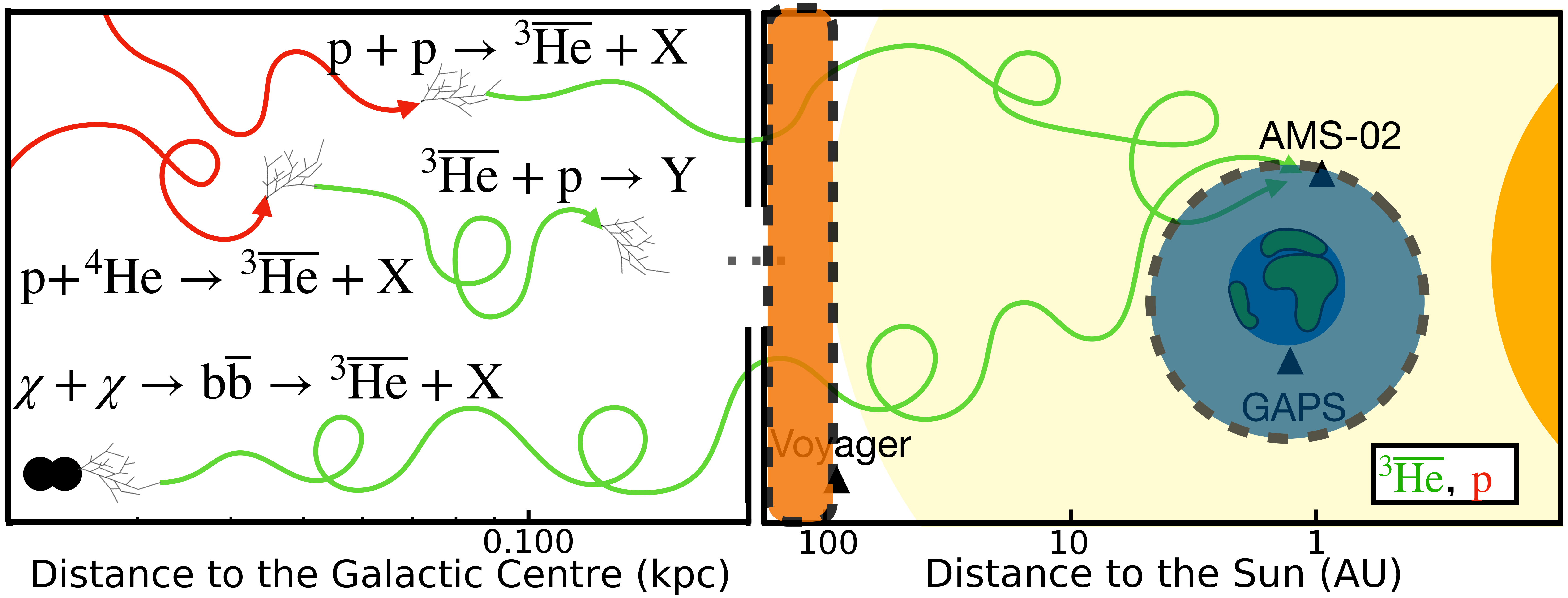




Thank you for your attention!

Solar modulation

- Local interstellar flux - measured outside the heliosphere
- Solar modulated flux - measured close to Earth



Force-field approximation to account for solar modulation used with Fisk potential ϕ = 0.4 GV:

$$F_{mod}\left(E_{mod}, \phi\right) = F(E)\frac{(E - Z\phi)^2 - m_{He^3}^2}{E^2 - m_{\overline{He}^3}^2} \qquad E_{mod} = E - Z\phi$$

Backup