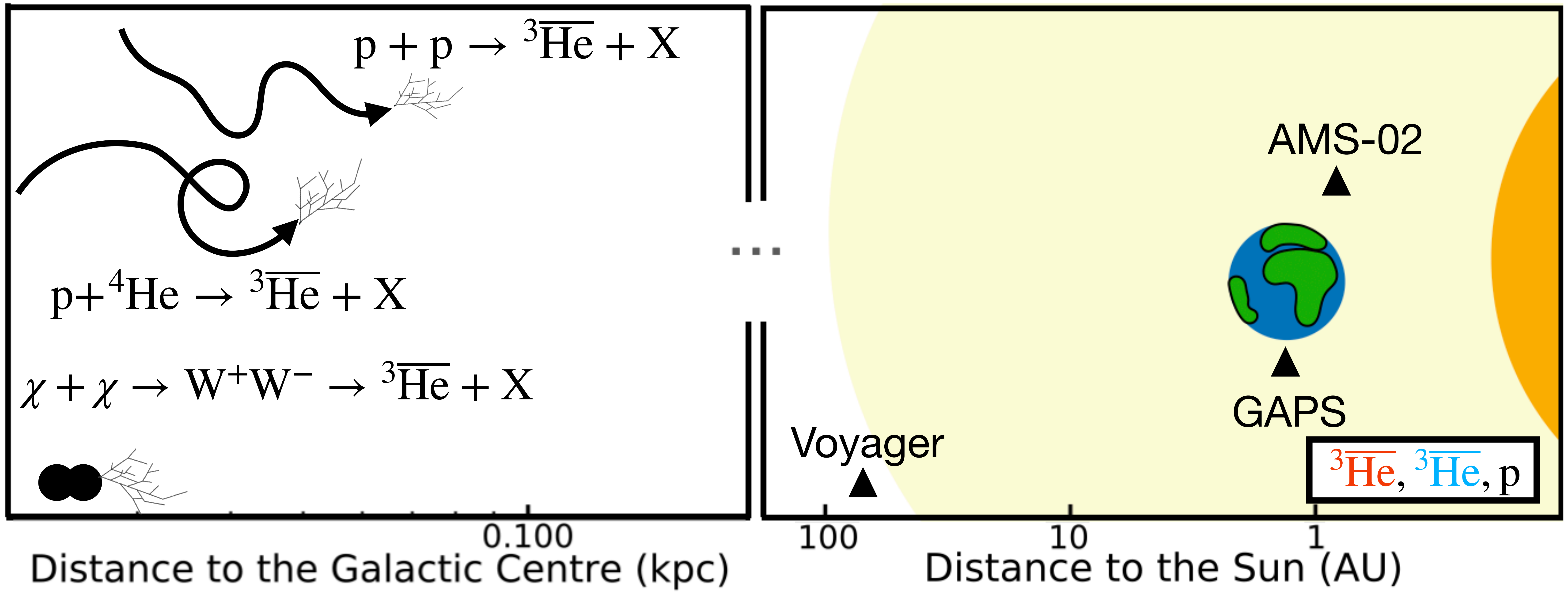
ALICE measurements for cosmic rays

Laura Šerkšnytė
Technical University of Munich

XSCRC24 Workshop
17.10.2024

Understanding cosmic ray fluxes

- Production



Understanding cosmic ray fluxes

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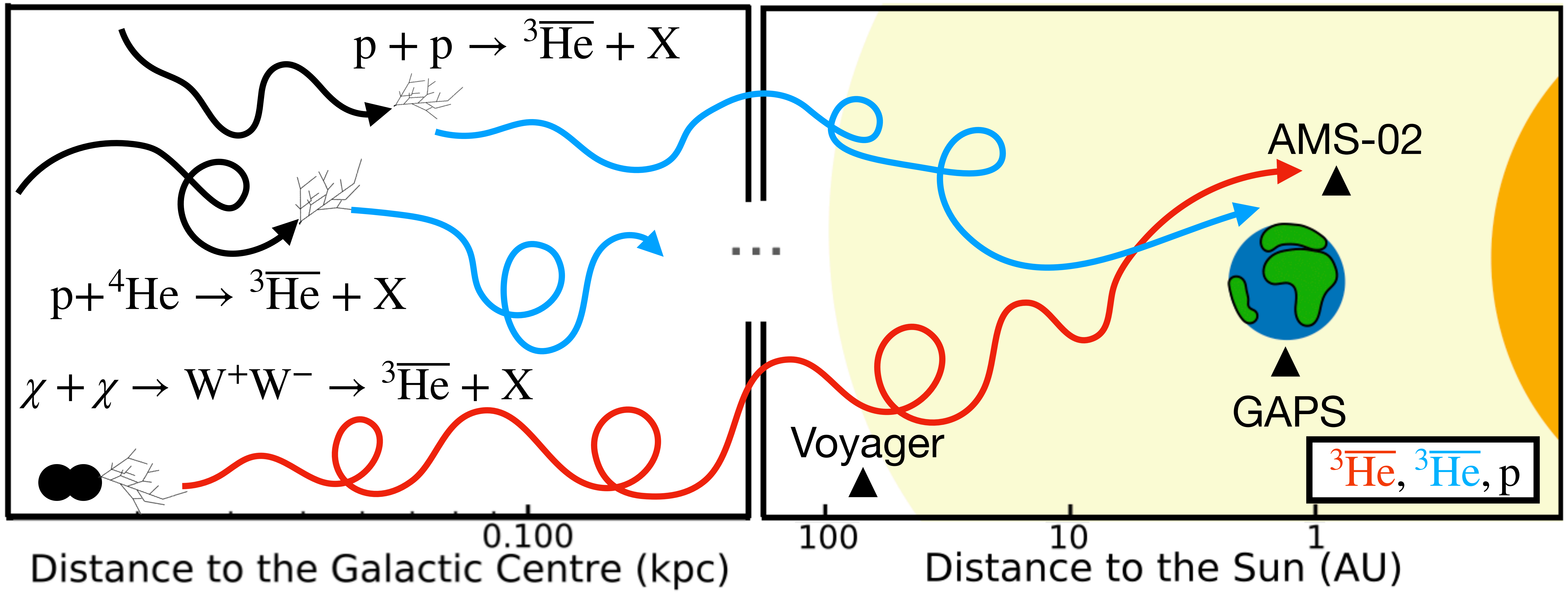
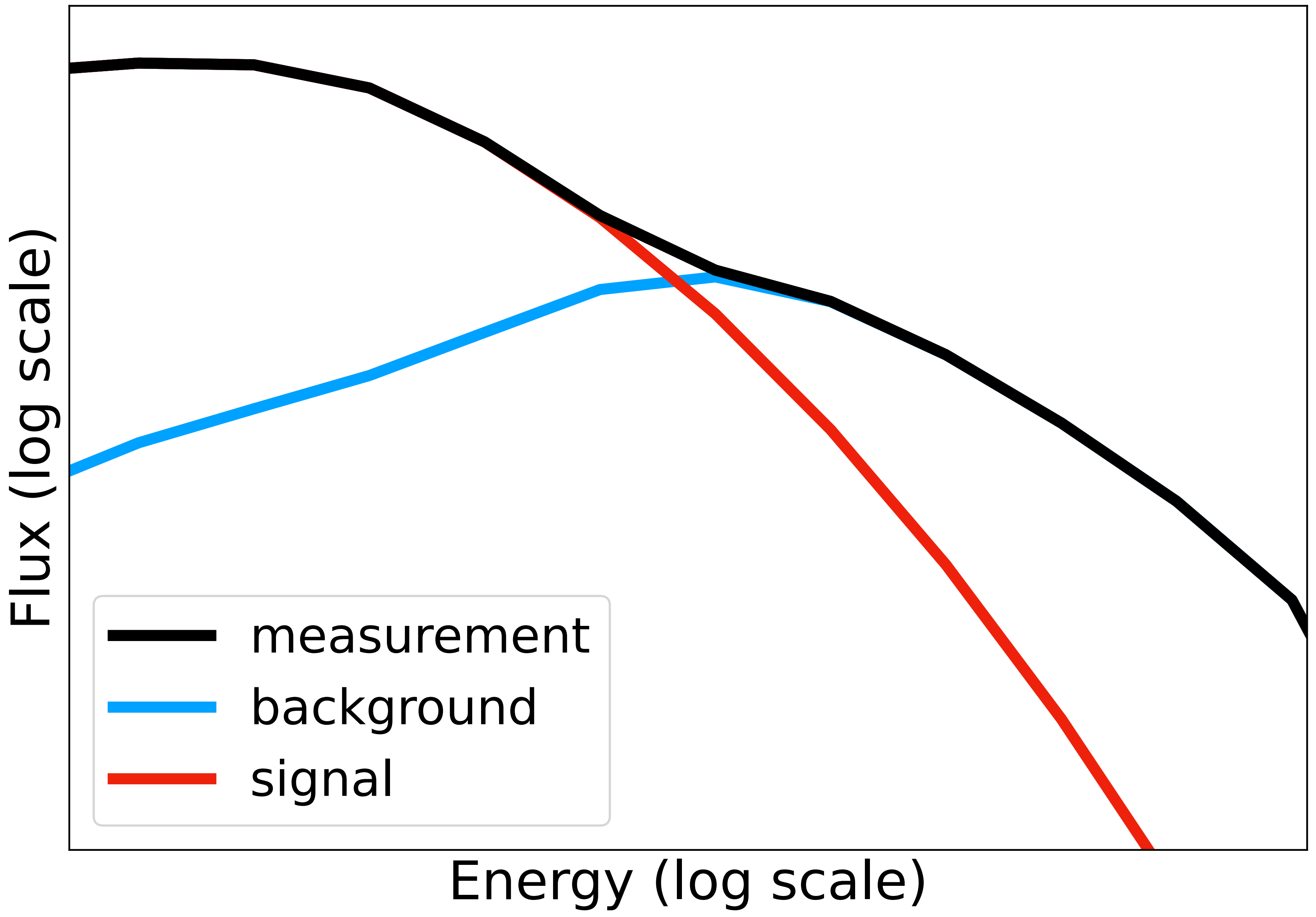
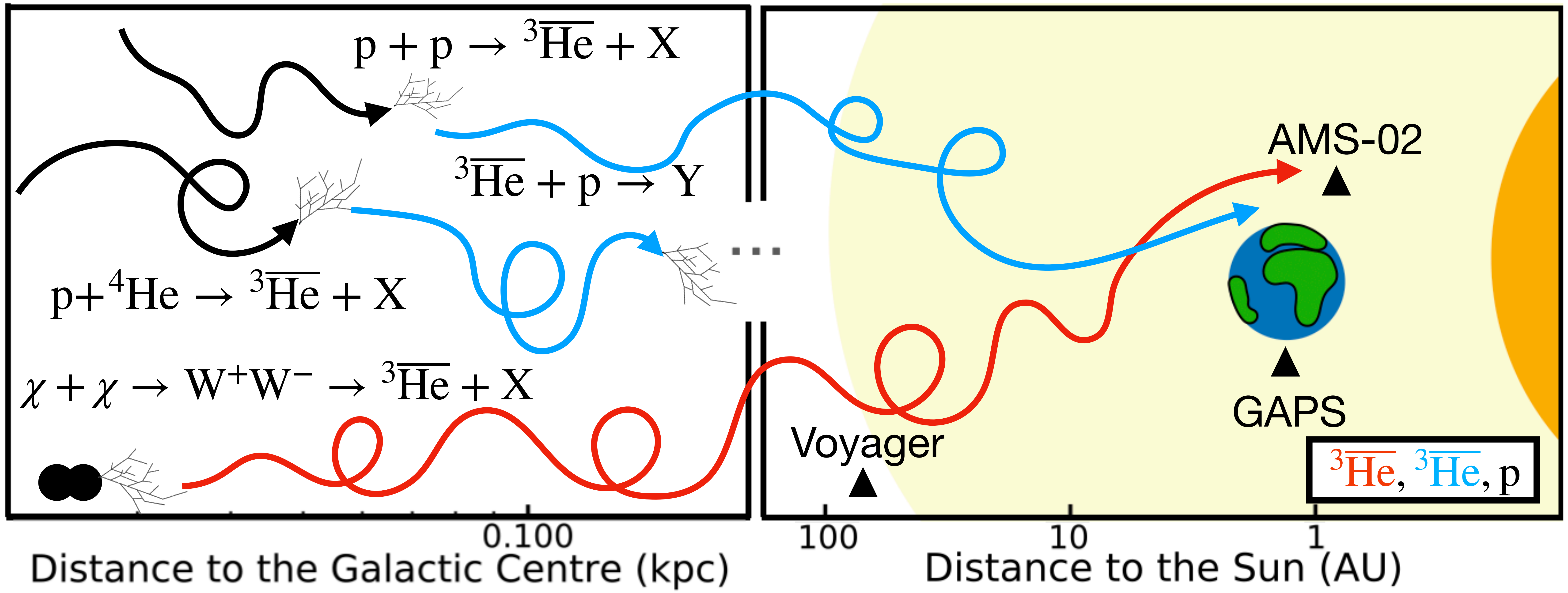
- Propagation

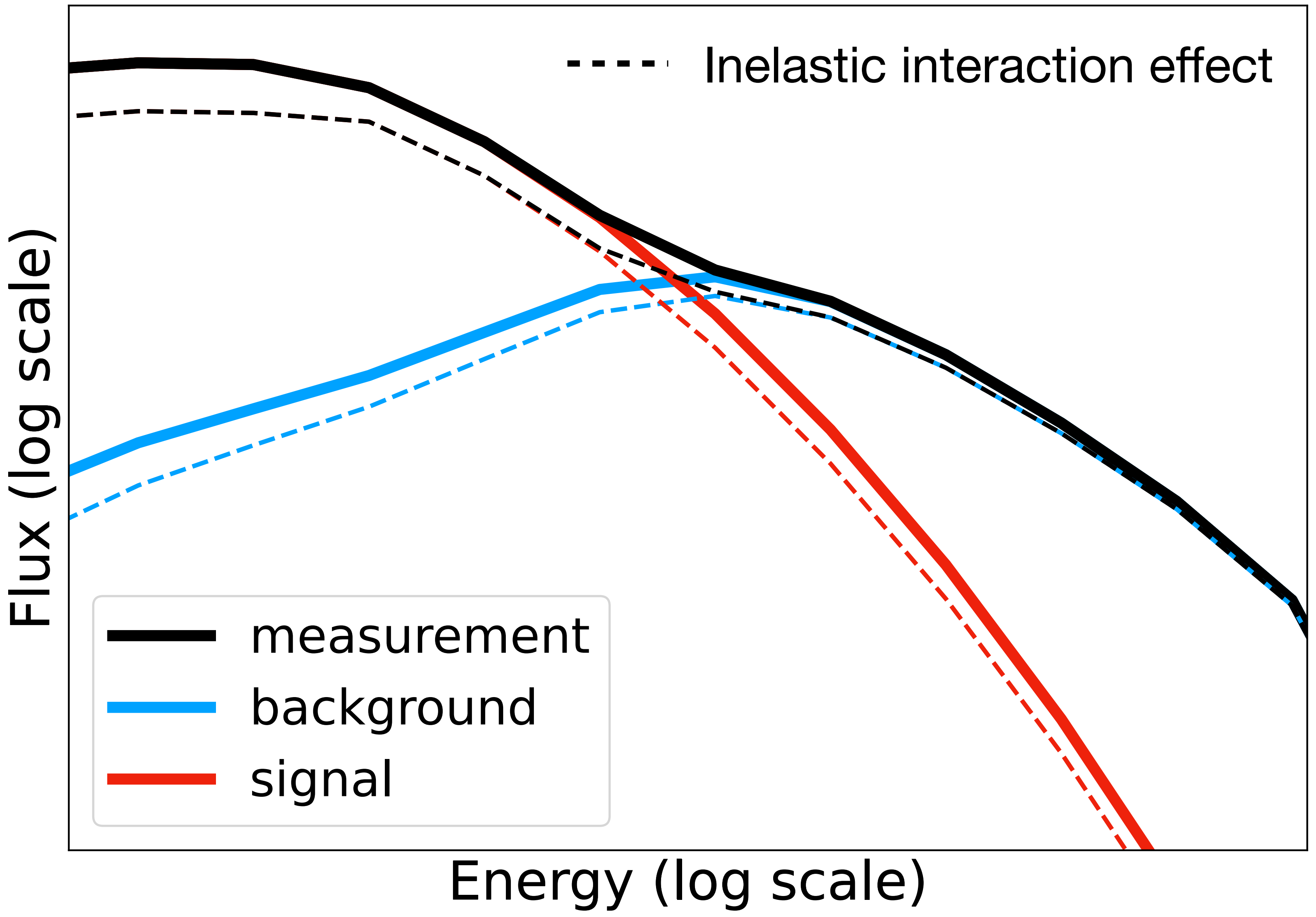




Understanding cosmic ray fluxes

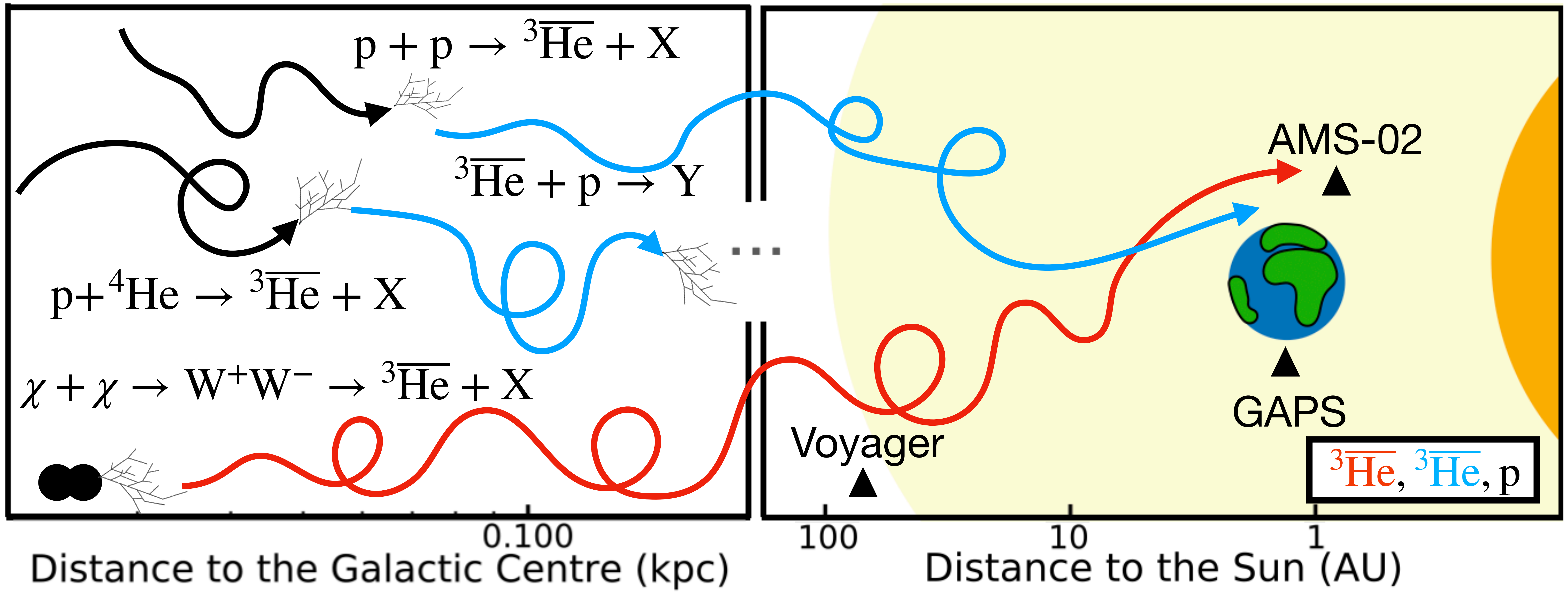
- Production
- Propagation
- Inelastic interactions

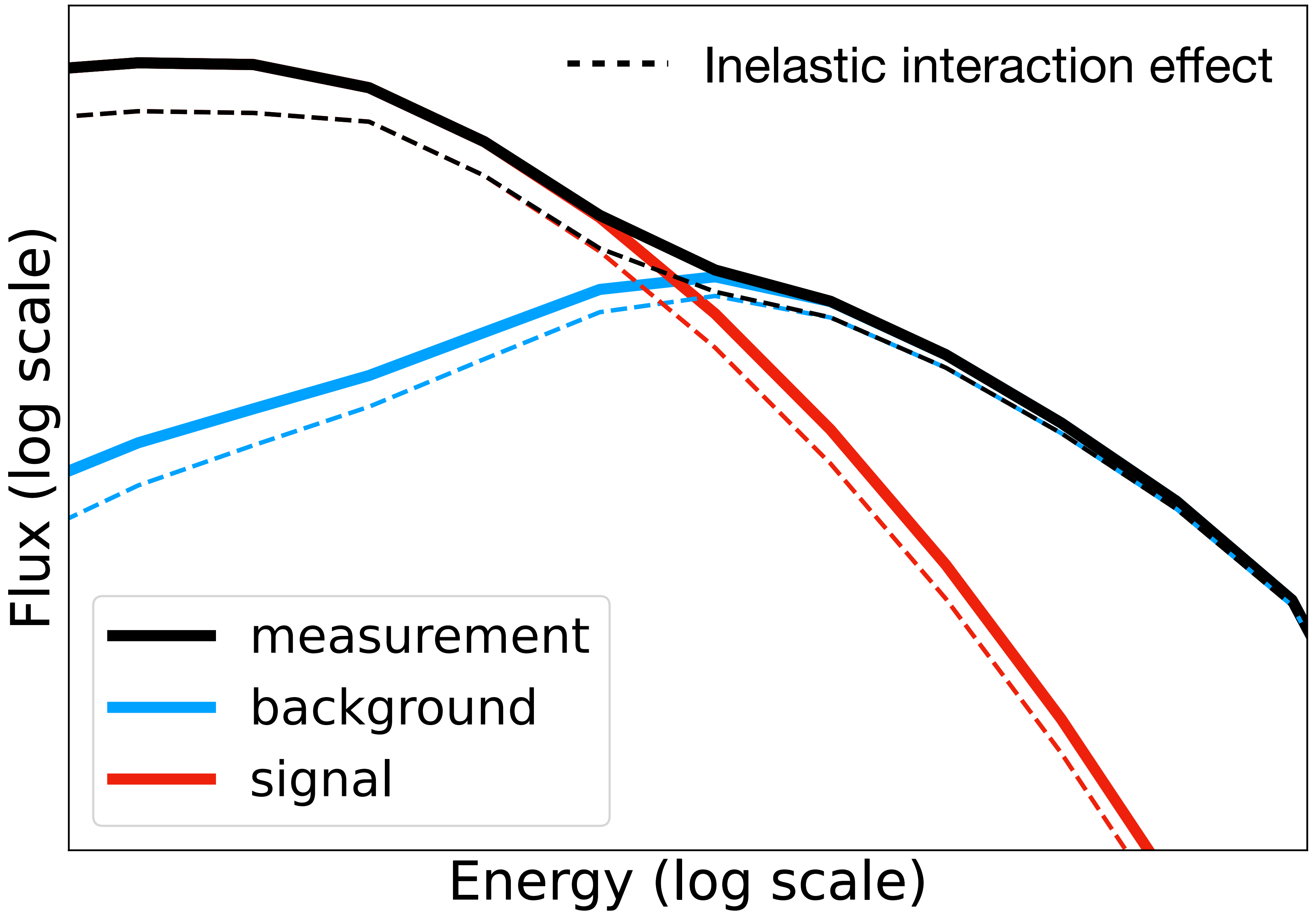




Understanding cosmic ray fluxes

- Production ← **Production cross section measurements and production mechanism studies**
- Propagation
- Inelastic interactions





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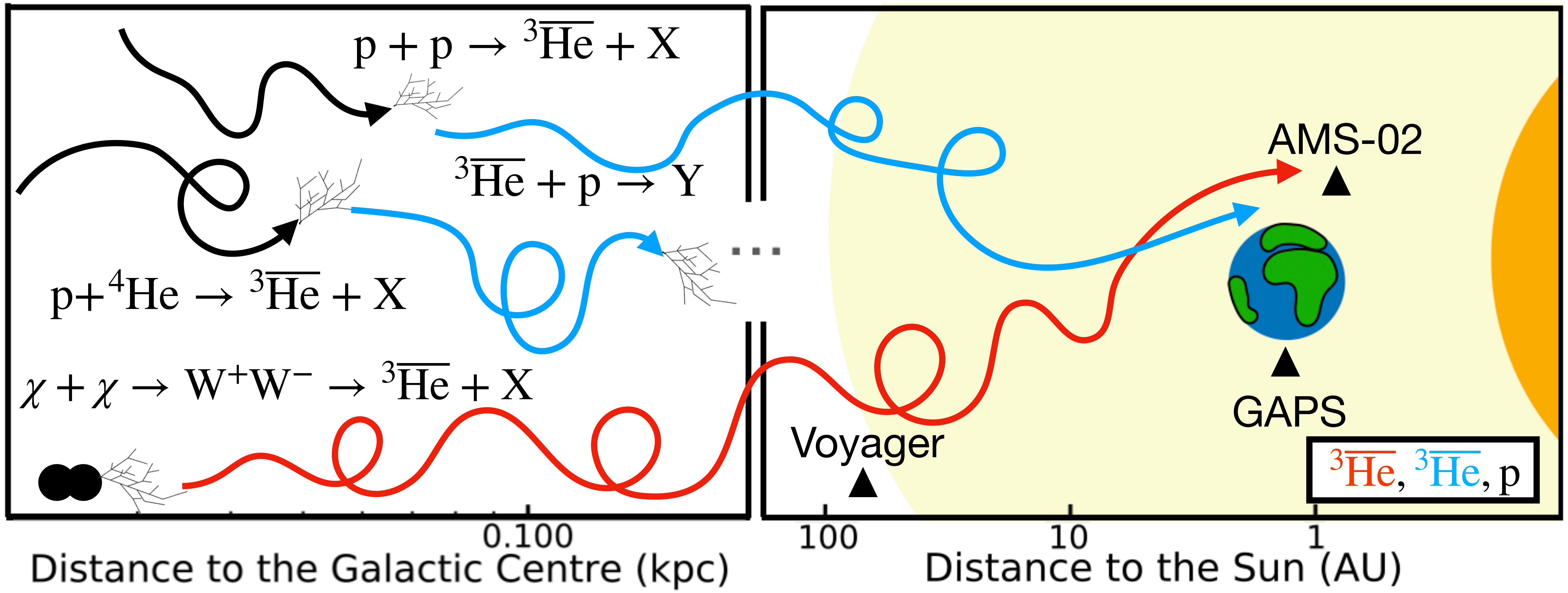
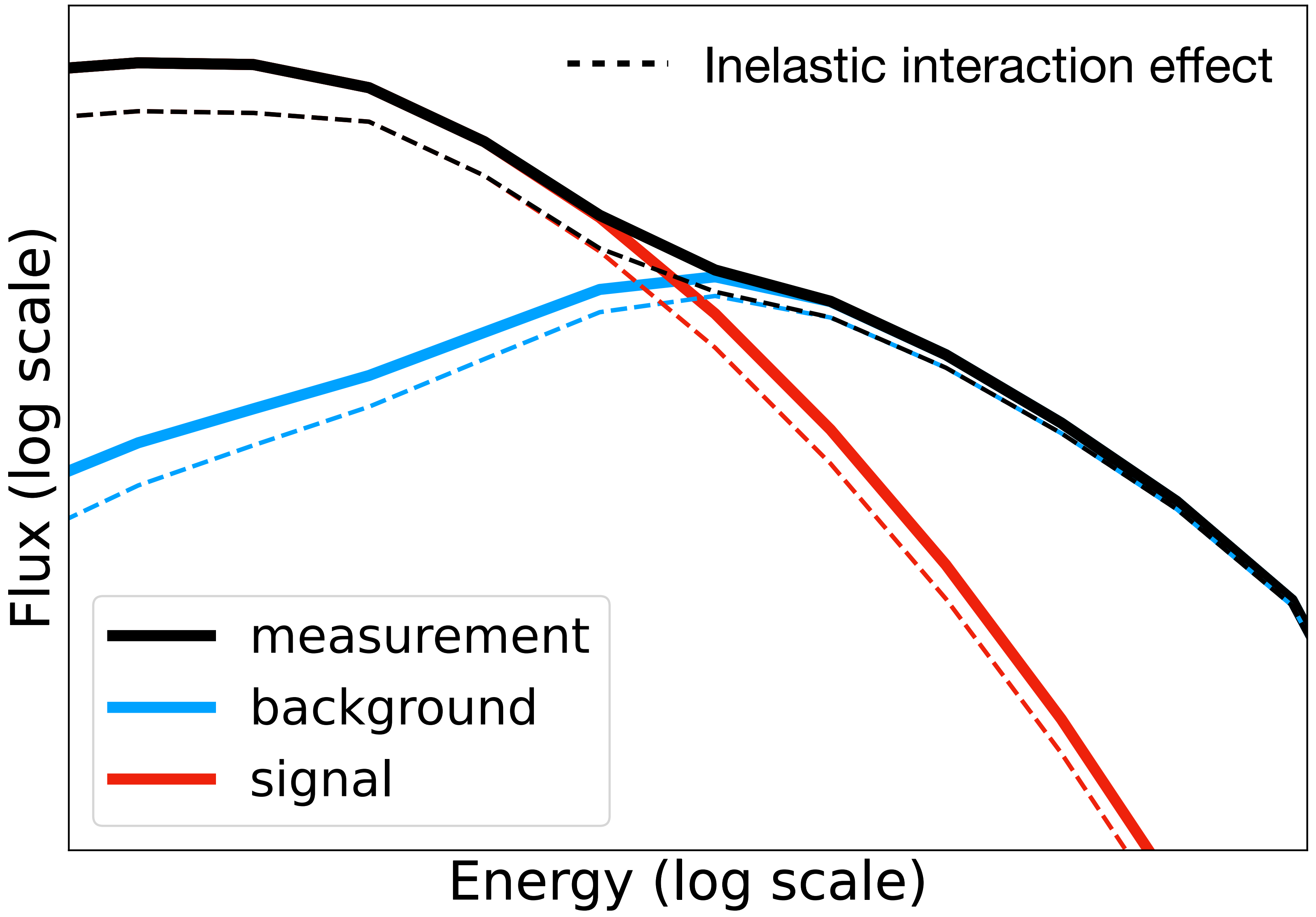
- Inelastic interactions ← **Inelastic cross section measurements**





A Large Ion Collider Experiment

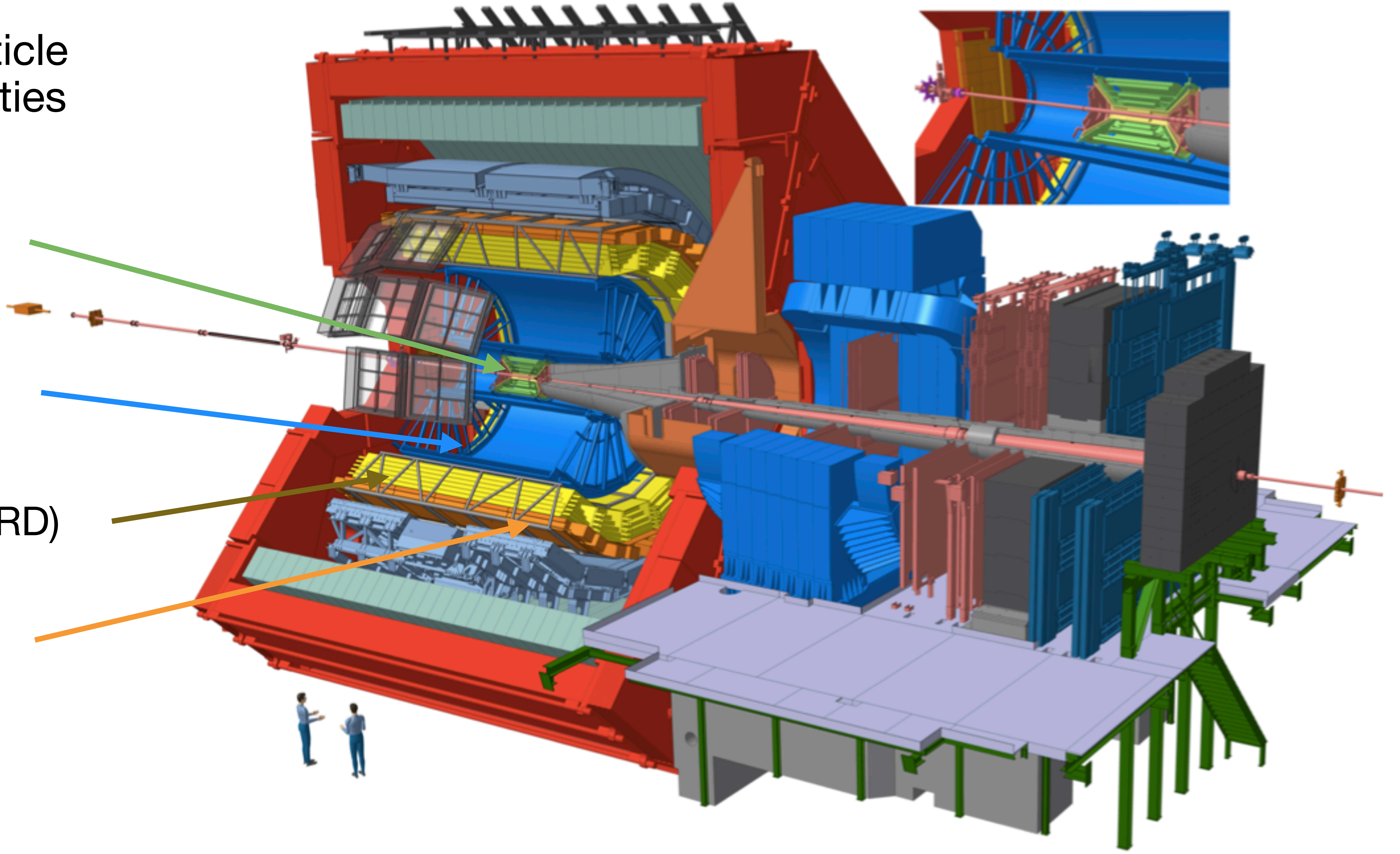
- Excellent tracking and particle identification (PID) capabilities

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)



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

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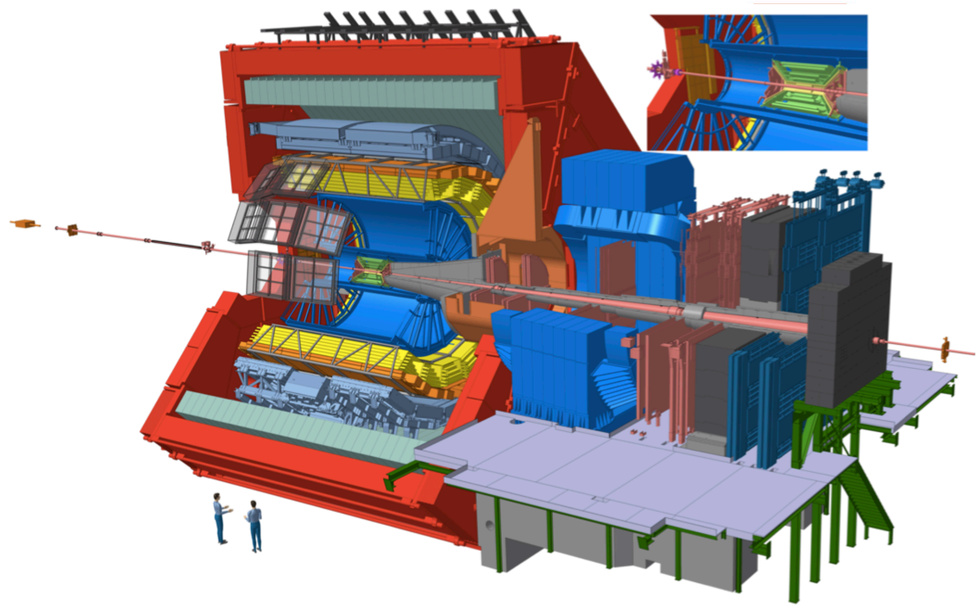
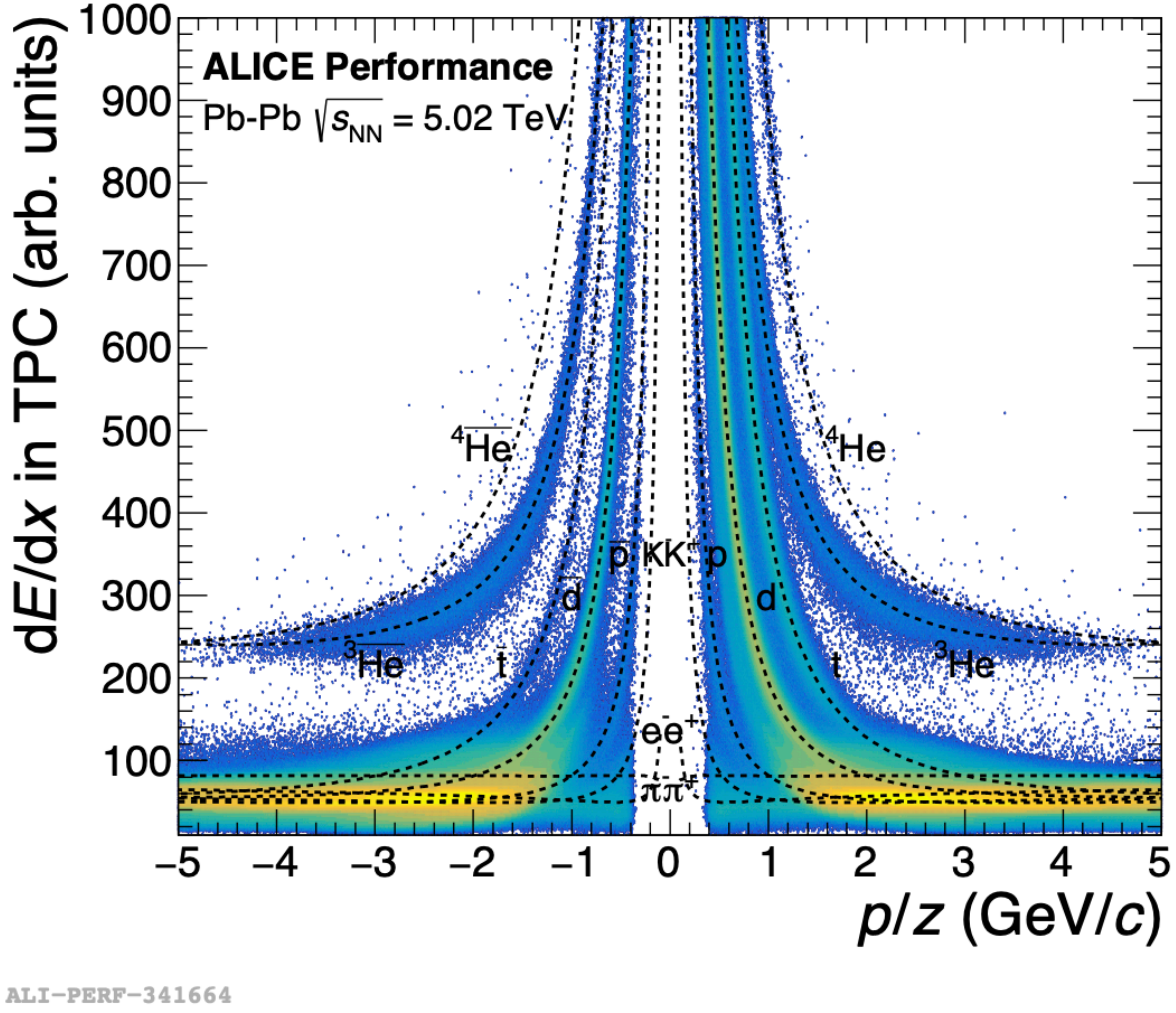


Time Projection Chamber (TPC)
Tracking, PID (d*E*/d*x*)



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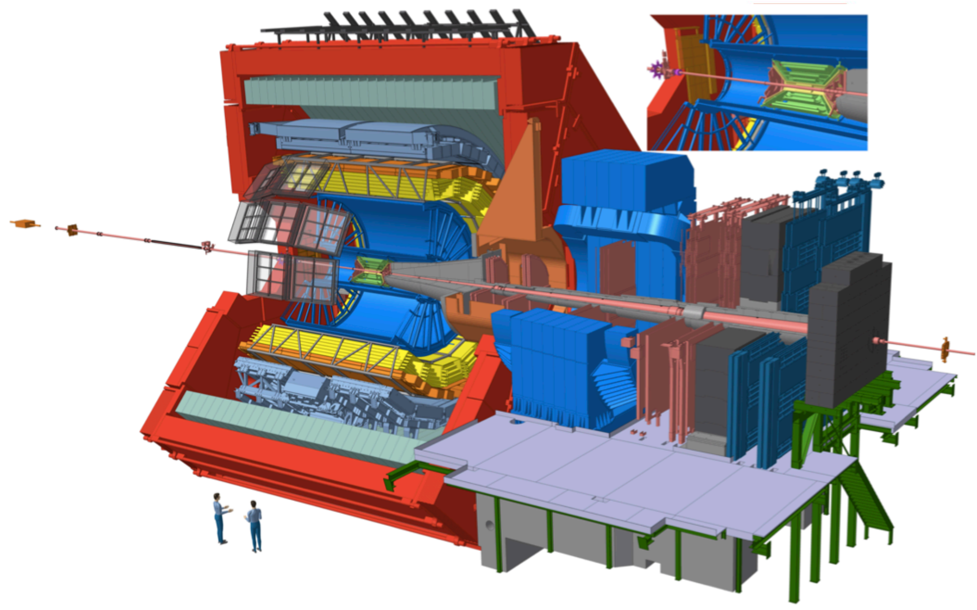

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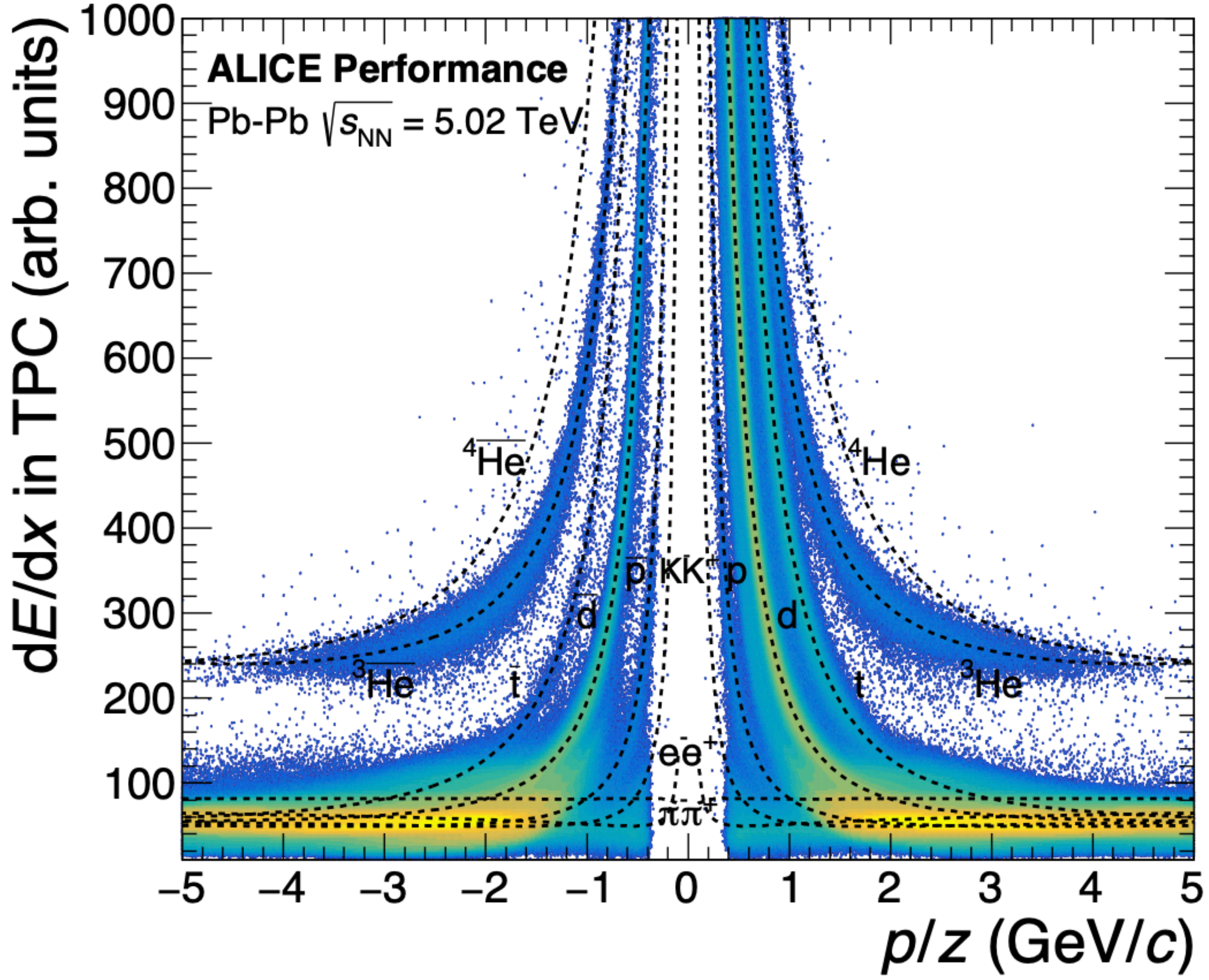

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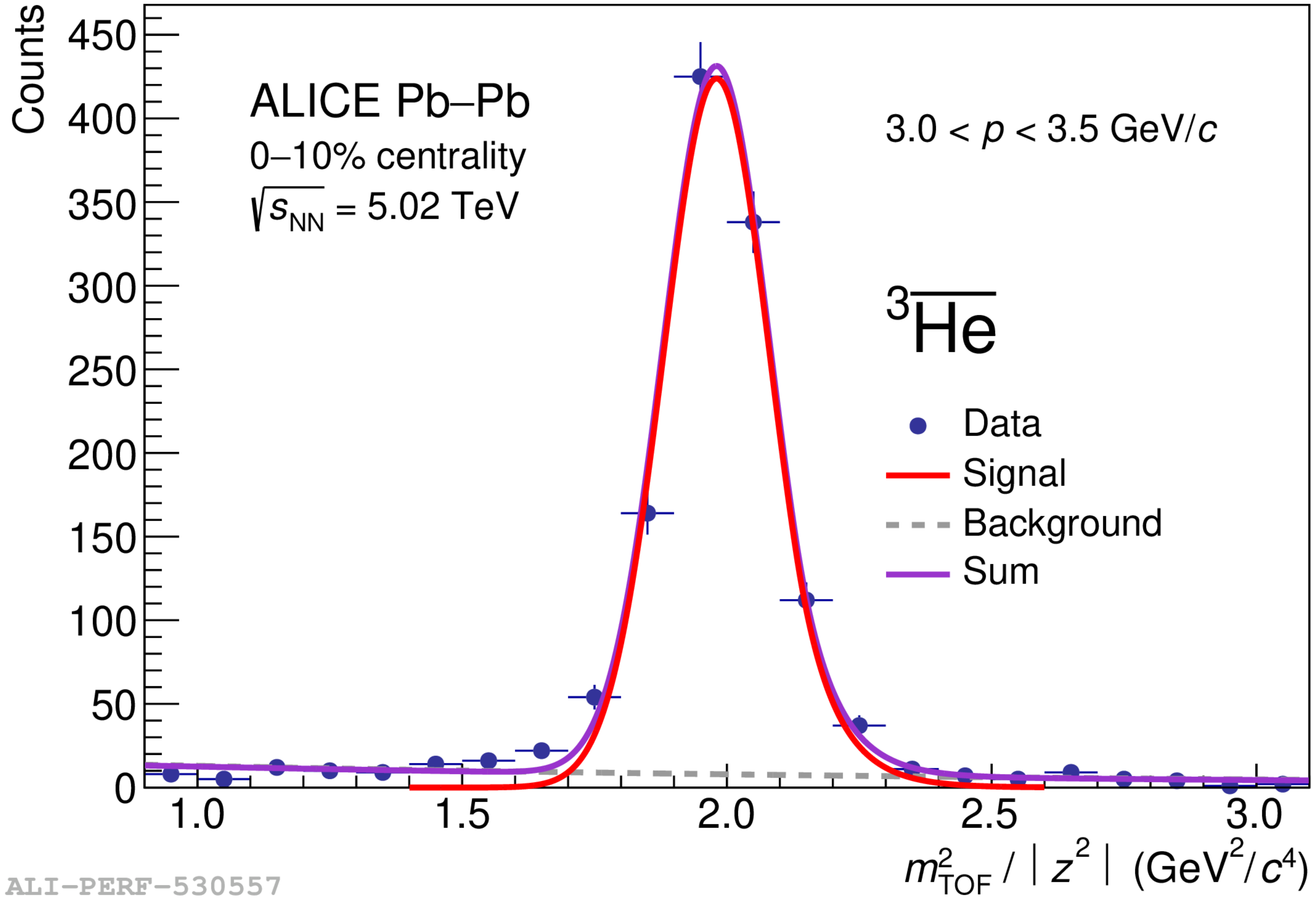
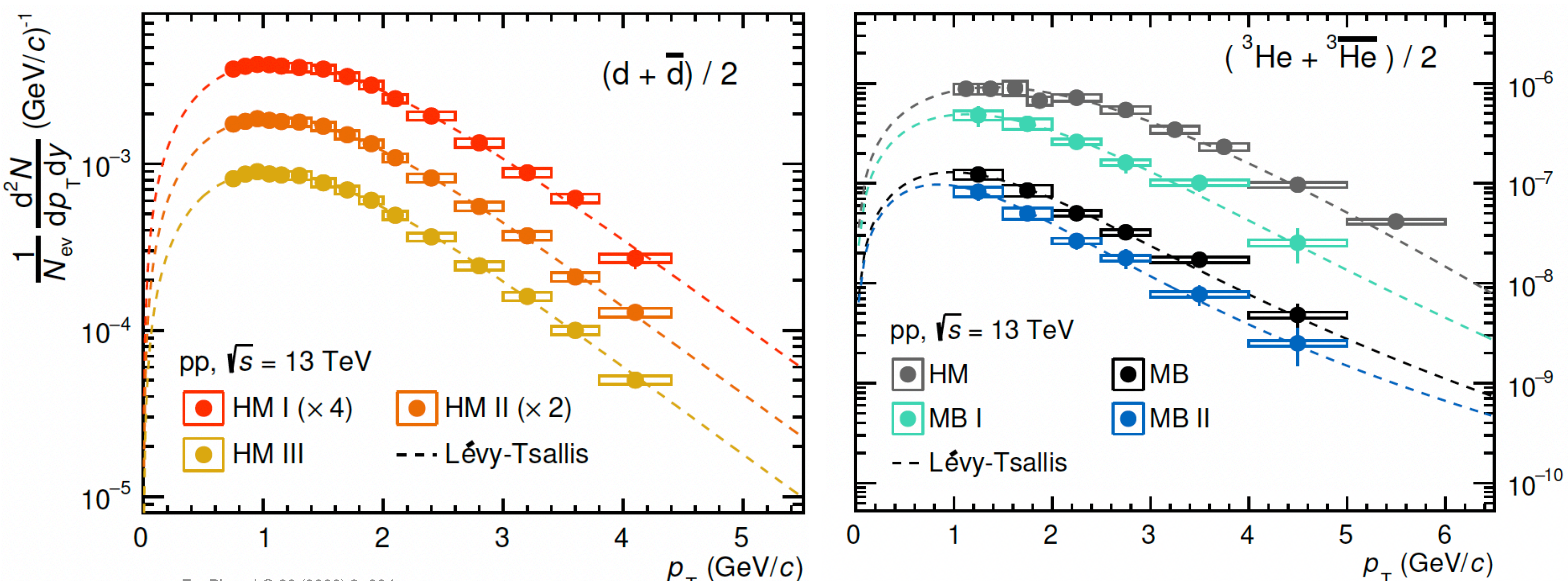


LHC - antimatter factory

- High precision measurement of different (anti)nuclei spectra

ALICE, JHEP 01 (2022) 106

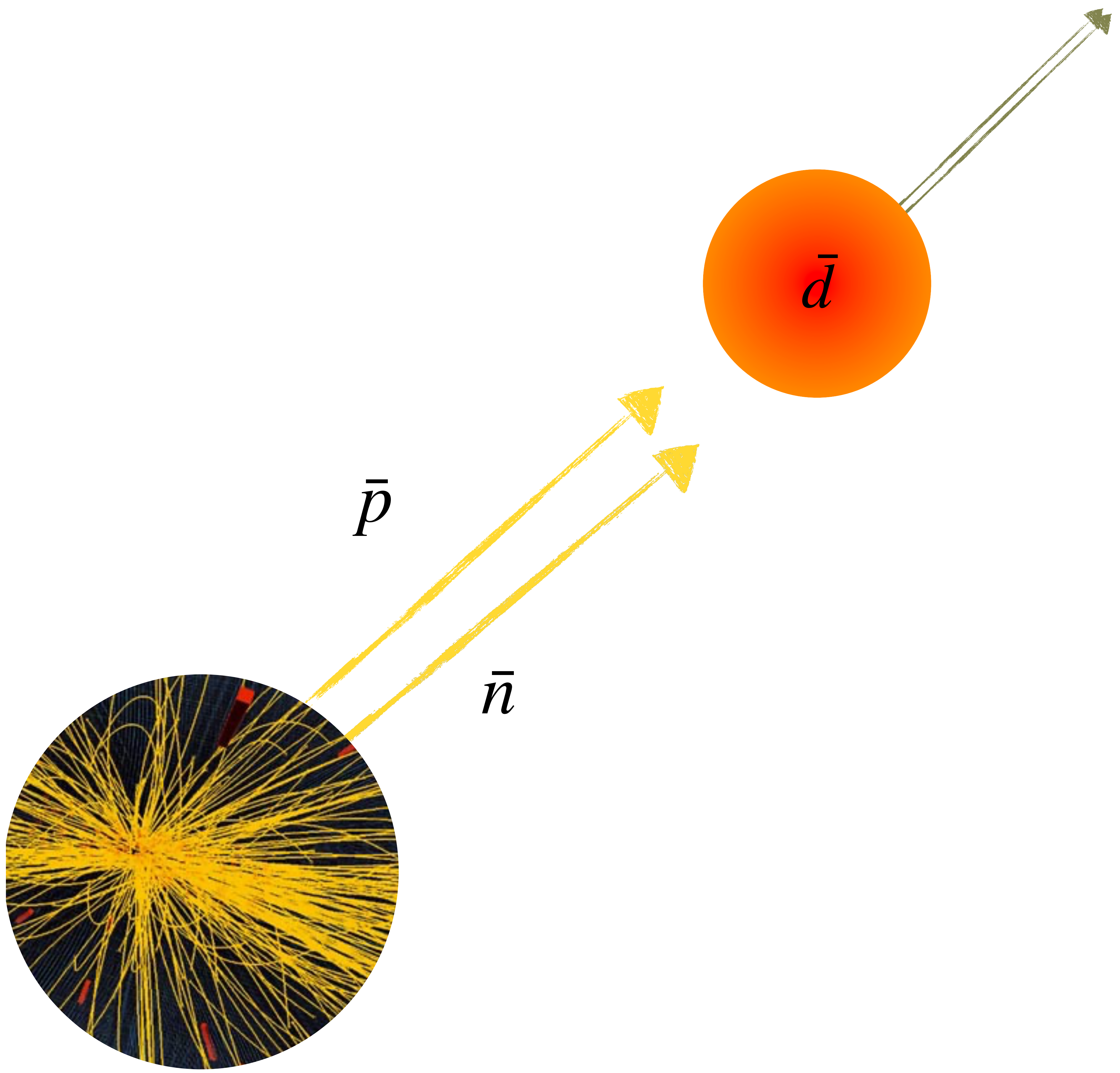


Eur.Phys.J.C 83 (2023) 9, 804

(Anti)nuclei production mechanism

- Coalescence Model
  - Nuclei are formed by nucleons coalescing after freeze-out
  - Depends on phase-space of produced nucleons (momentum, distance) and nucleus Wigner function

$$B_A = \frac{E_A \frac{d^3N_A}{d^3p_A}}{\left(E_p \frac{d^3N_p}{d^3p_p}\right)^A}$$



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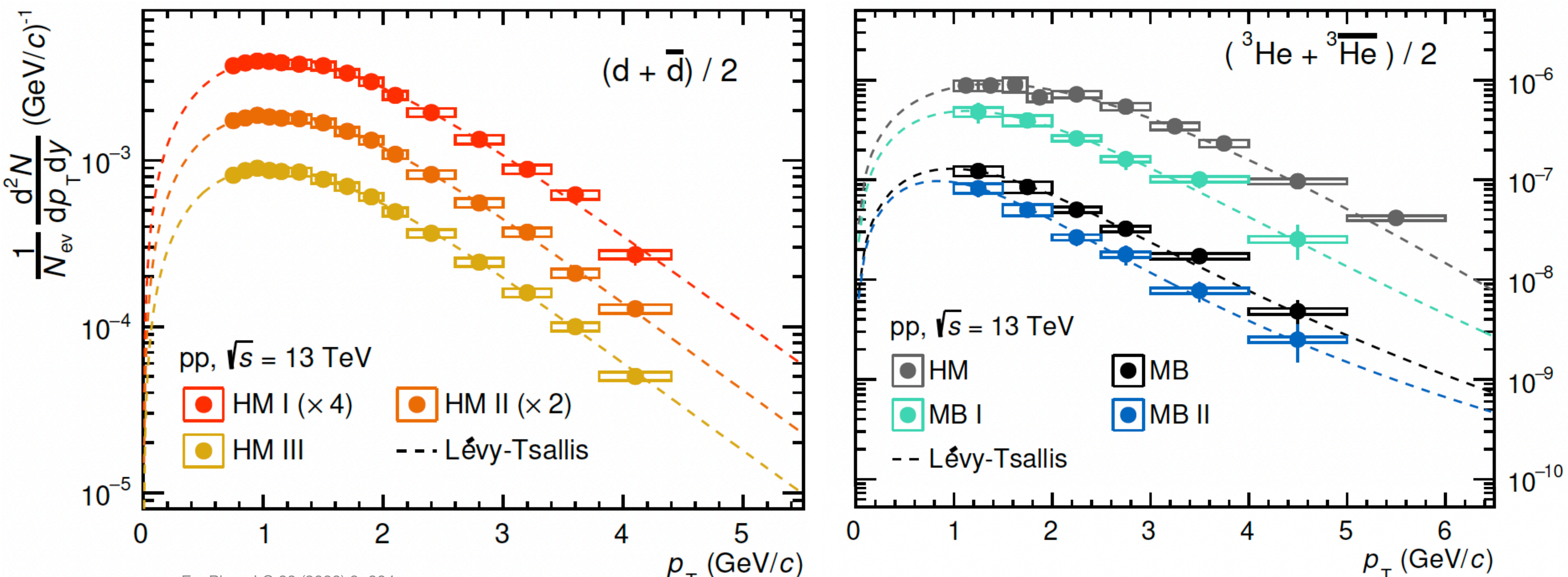

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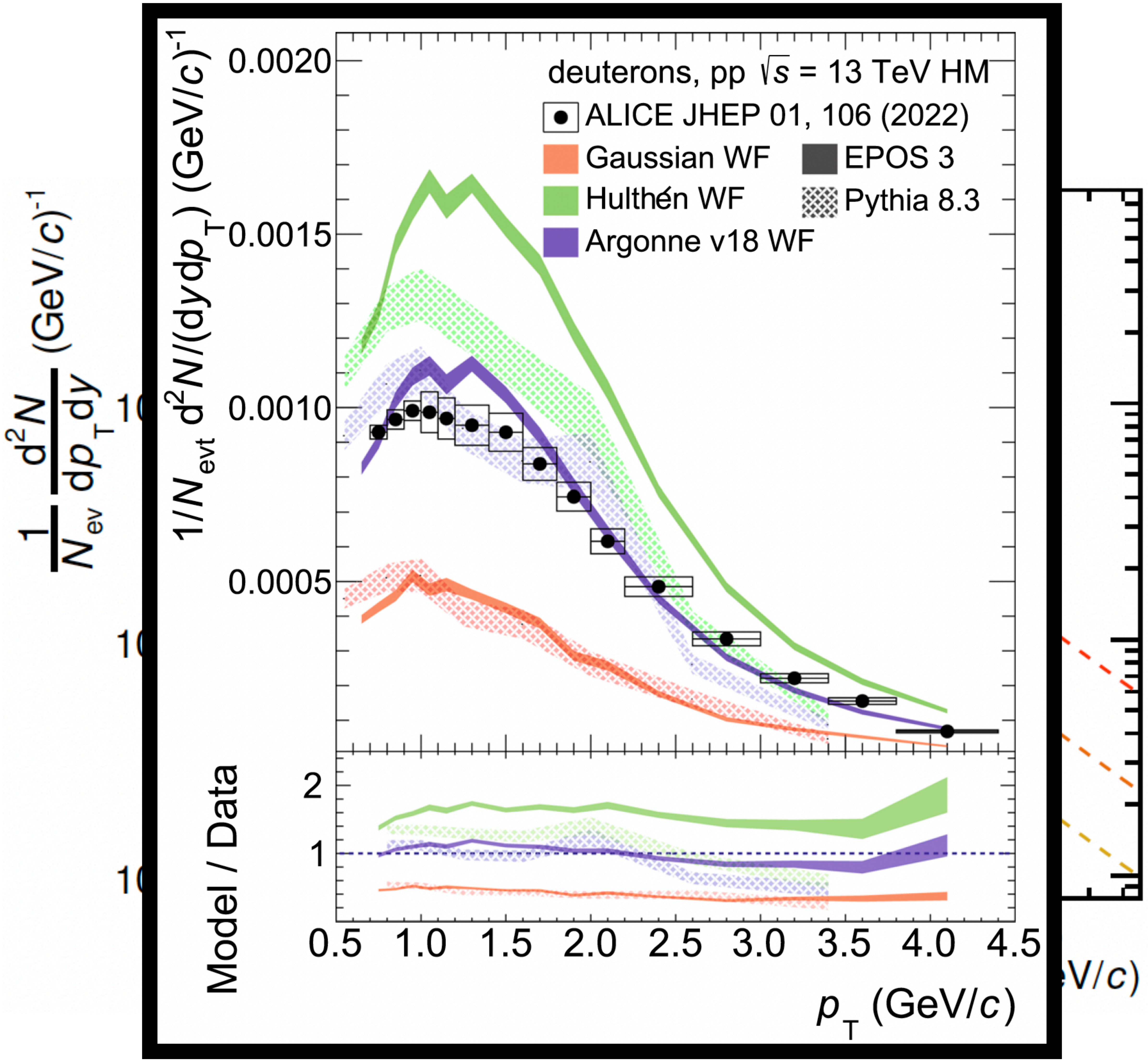
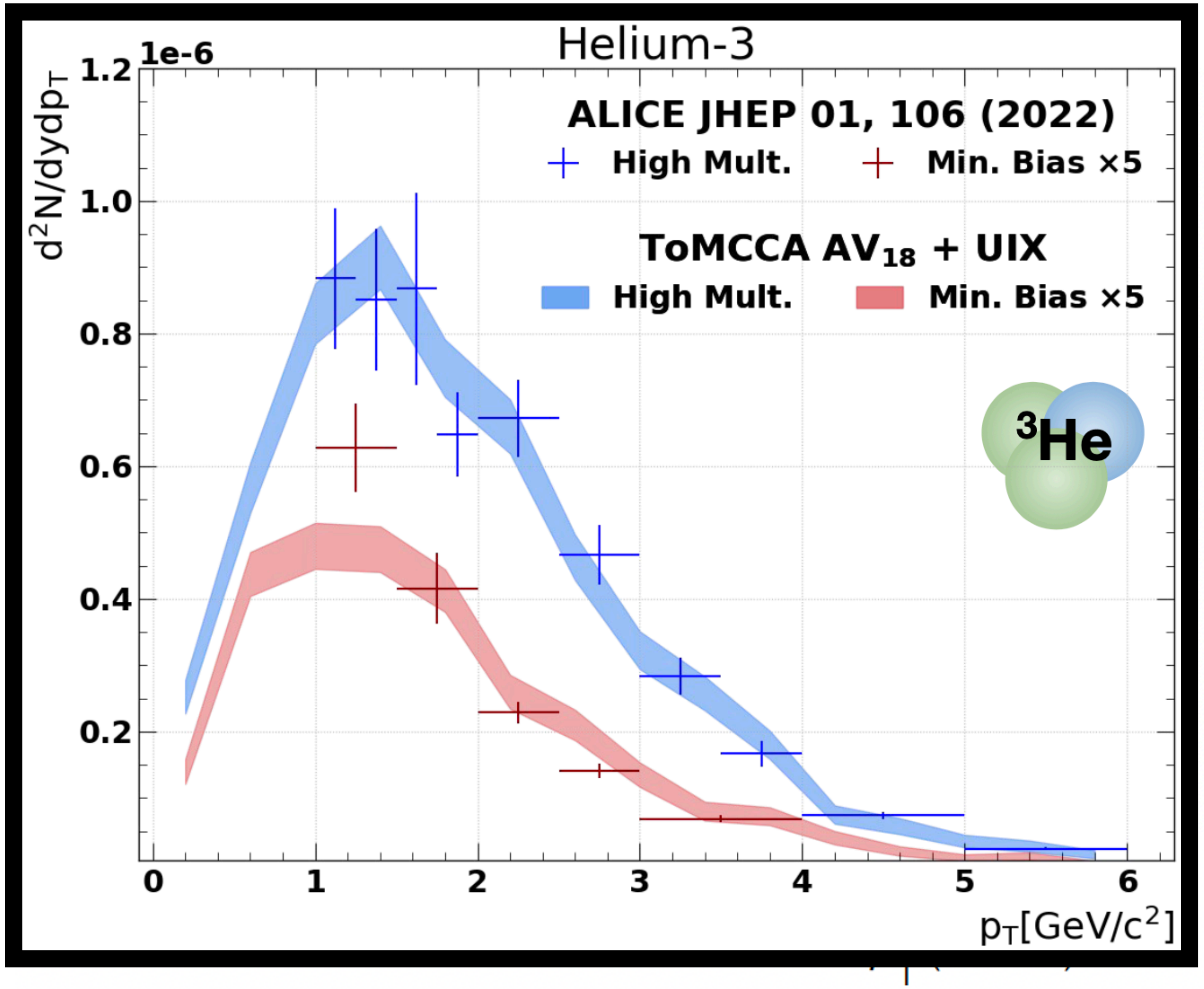


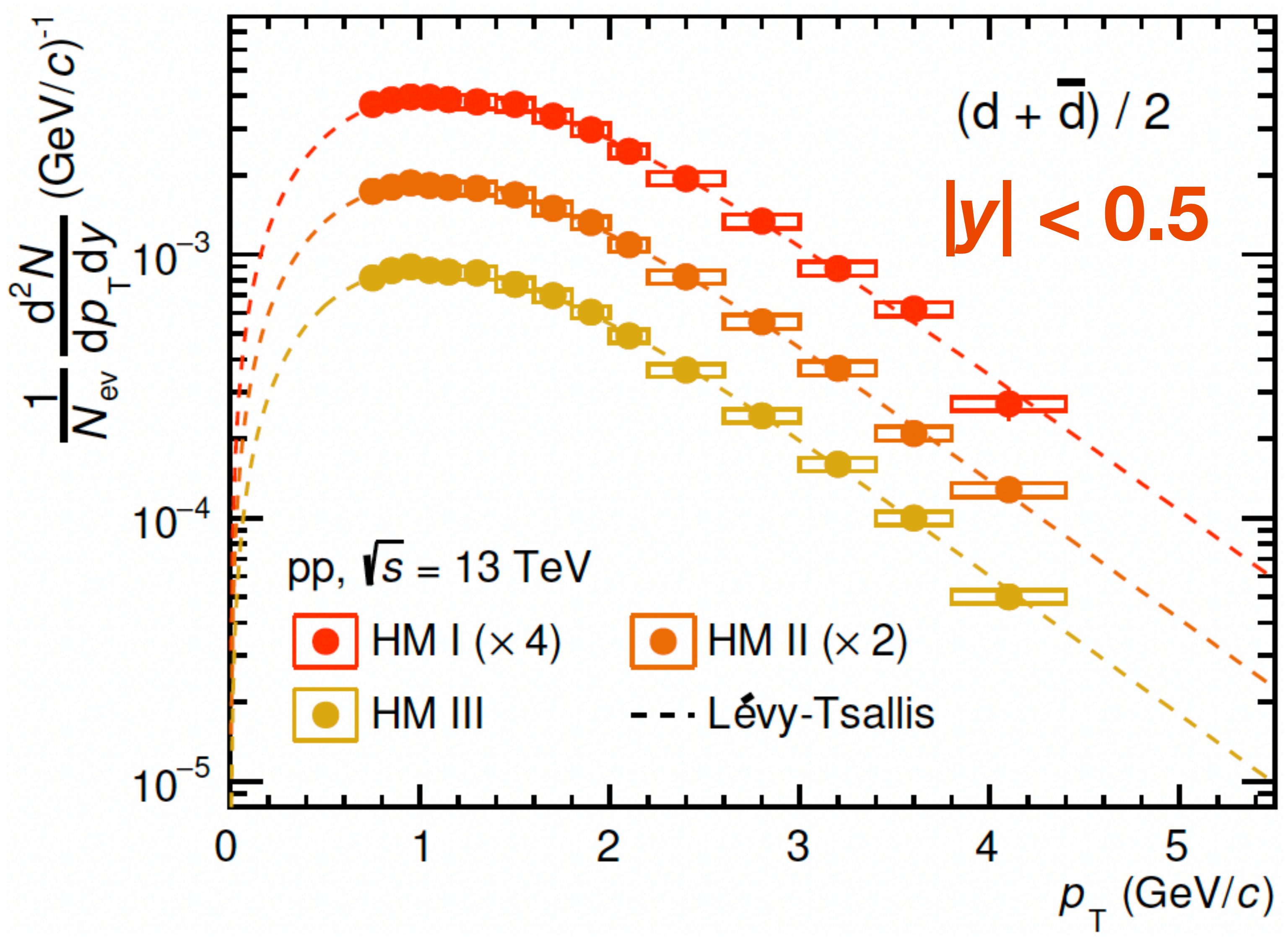


Mahlein et al, Eur.Phys.J.C 83 (2023) 9, 804

Talk by Mahlein at 12:45

Rapidity dependence

- Antideuteron yields usually measured at $|y| < 0.5$
  - At rapidities lower than ~5 GV and larger than ~100 GV, most of the antideuteron flux is produced at rigidities larger than 0.5
  - Assumption based on event generators: coalescence parameter is independent on rapidity



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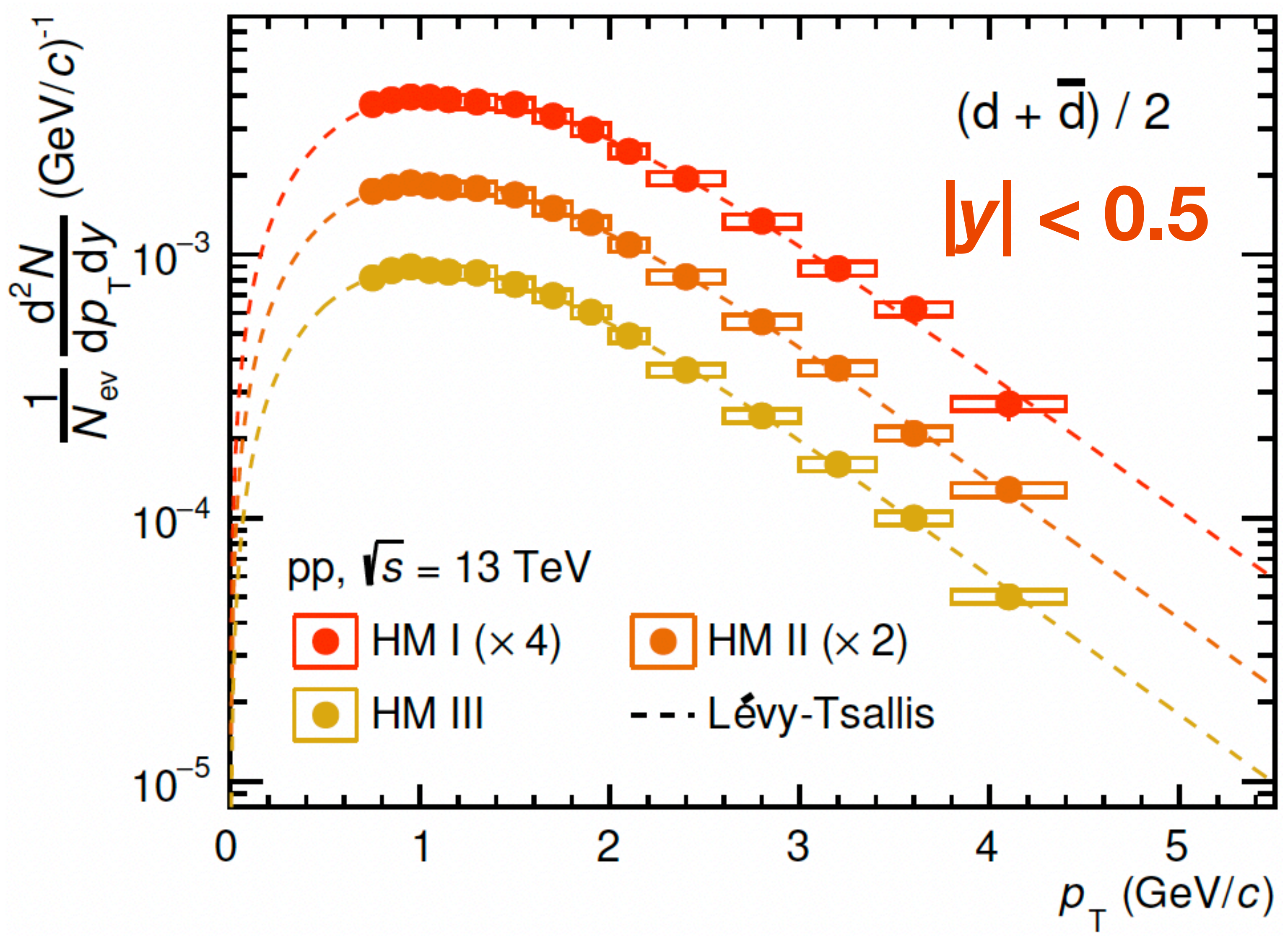

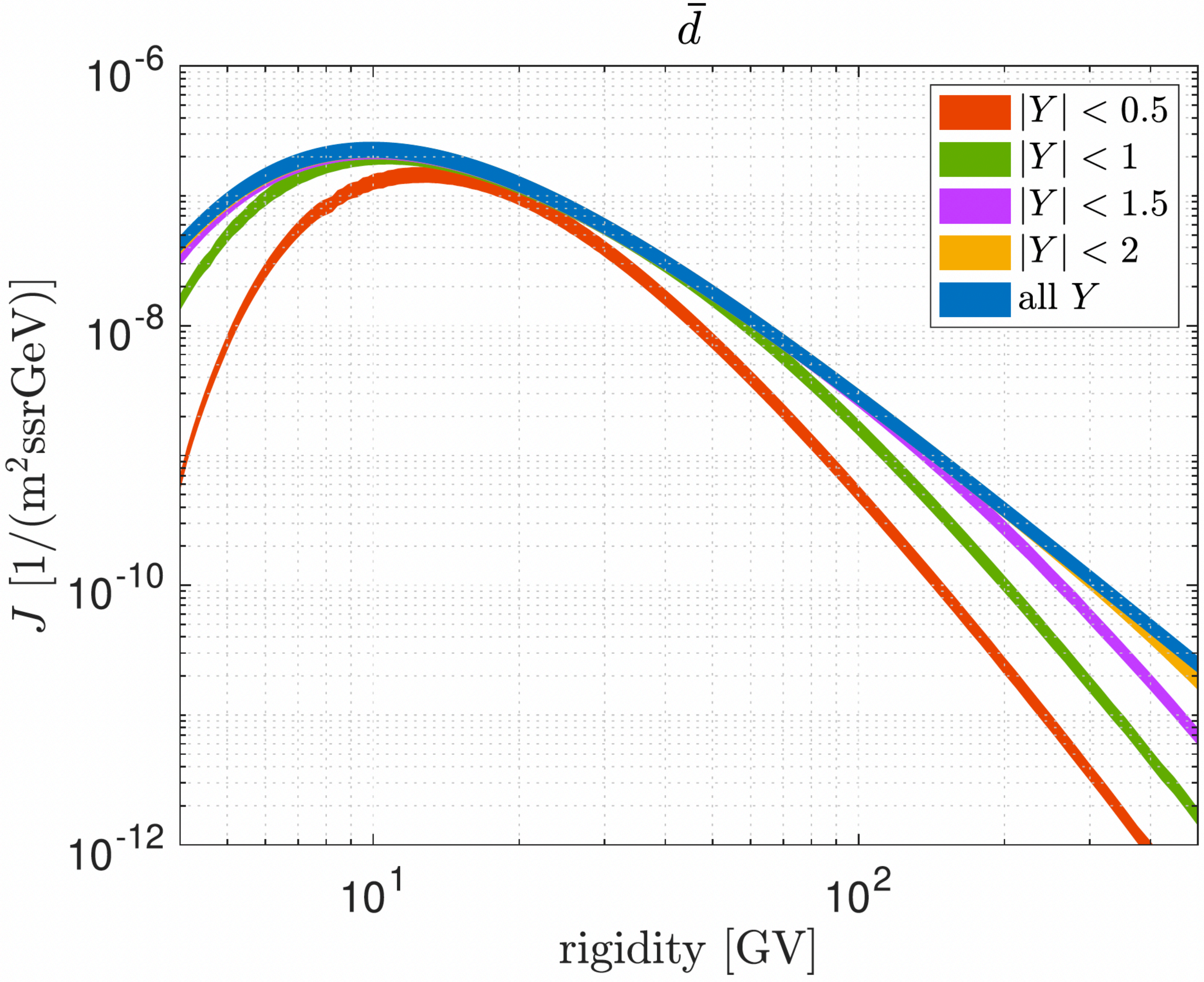

Blum, Phys.Rev.C 109 (2024) 3, L031904

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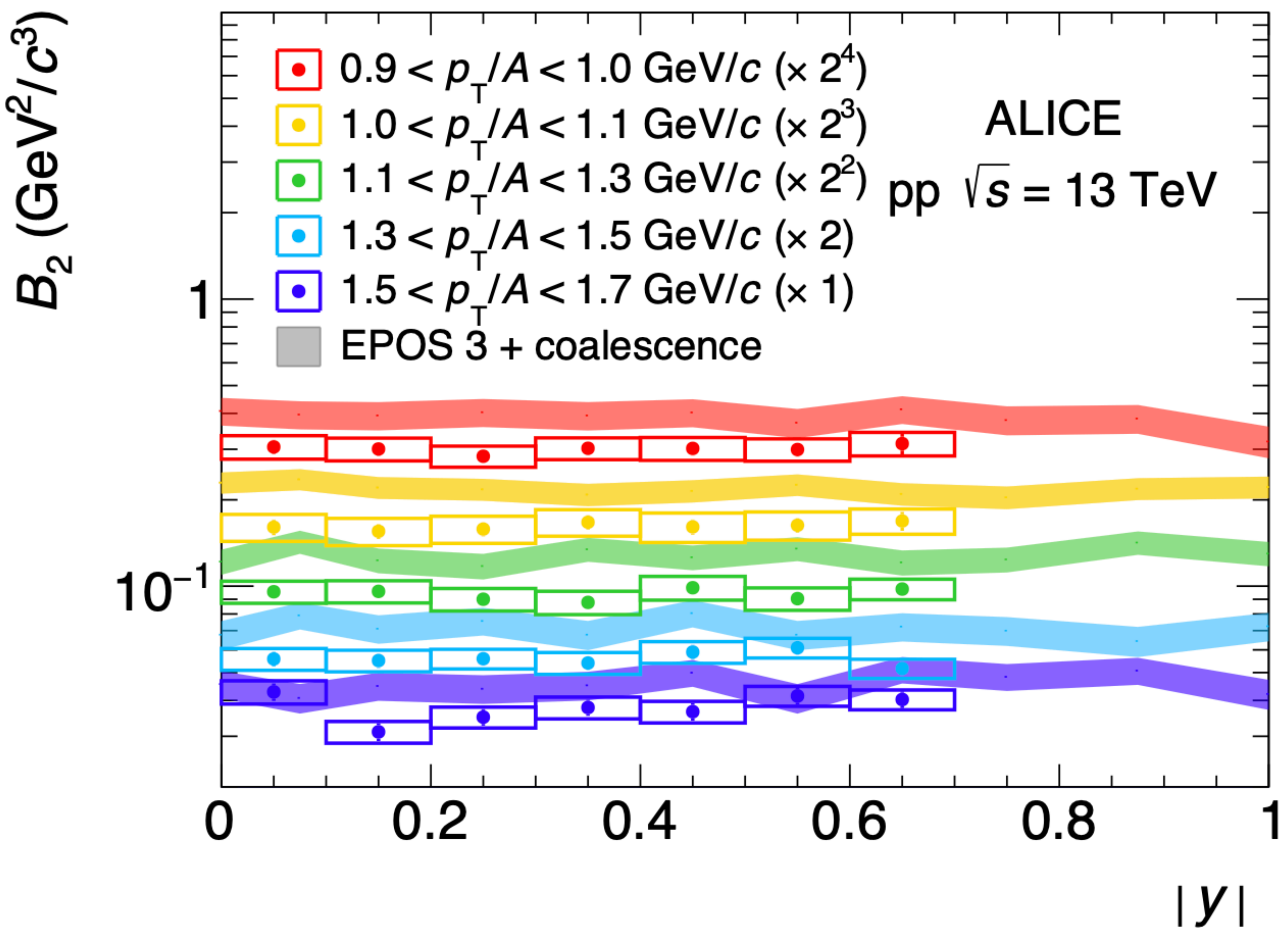
- ALICE extended the measurement range of antideuterons to $|y| < 0.7$
- Results:
  - Confirmed flat shape of B_2

$$B_A = \frac{E_A \frac{d^3 N_A}{d^3 p_A}}{\left(E_p \frac{d^3 N_p}{d^3 p_p}\right)^A}$$



ALICE Collaboration, arXiv:2407.10527

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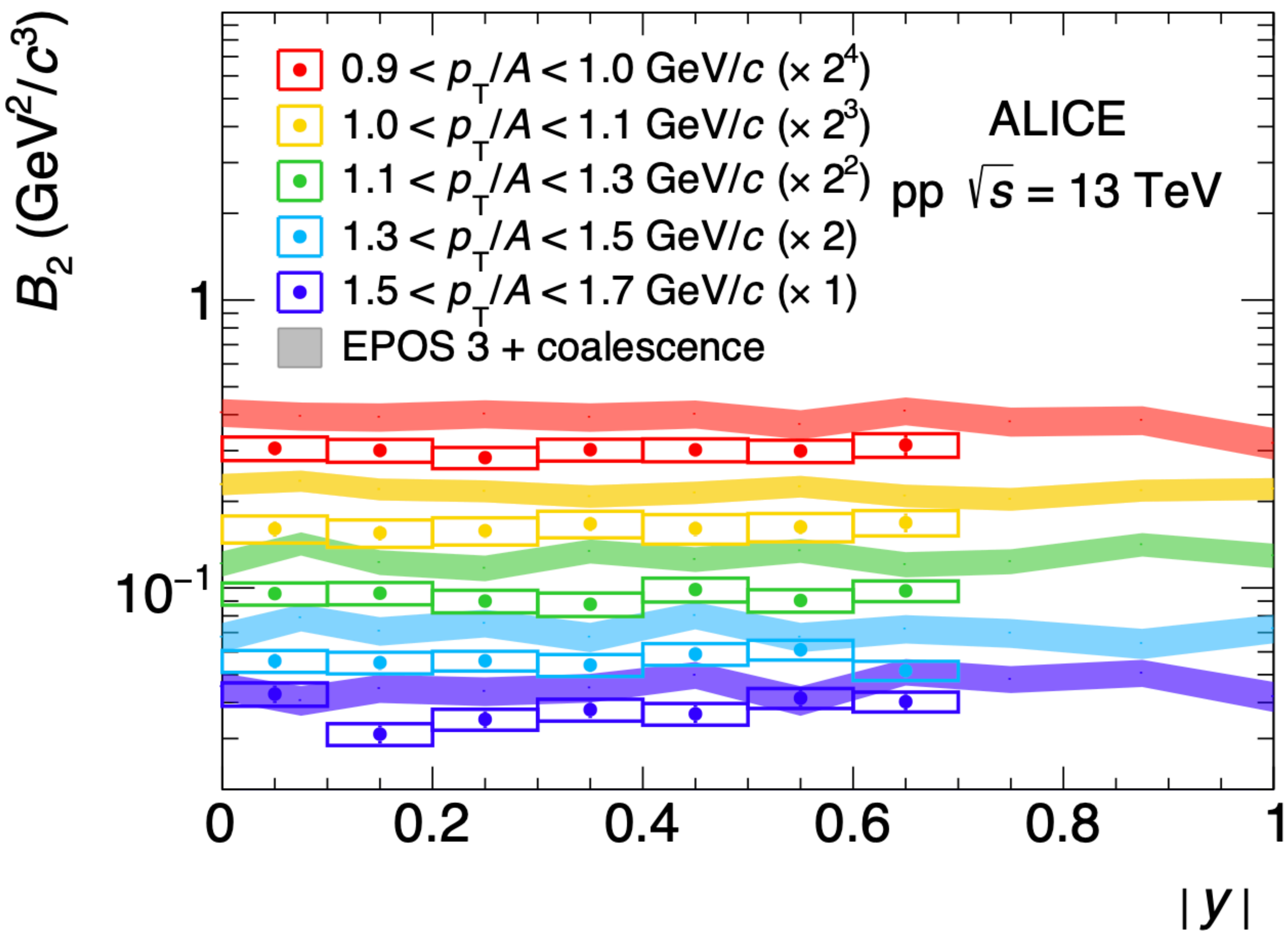

$$B_A = \frac{E_A \frac{d^3 N_A}{d^3 p_A}}{\left(E_p \frac{d^3 N_p}{d^3 p_p}\right)^A}$$

Safe to use mid-rapidity data to extrapolate to forward rapidities

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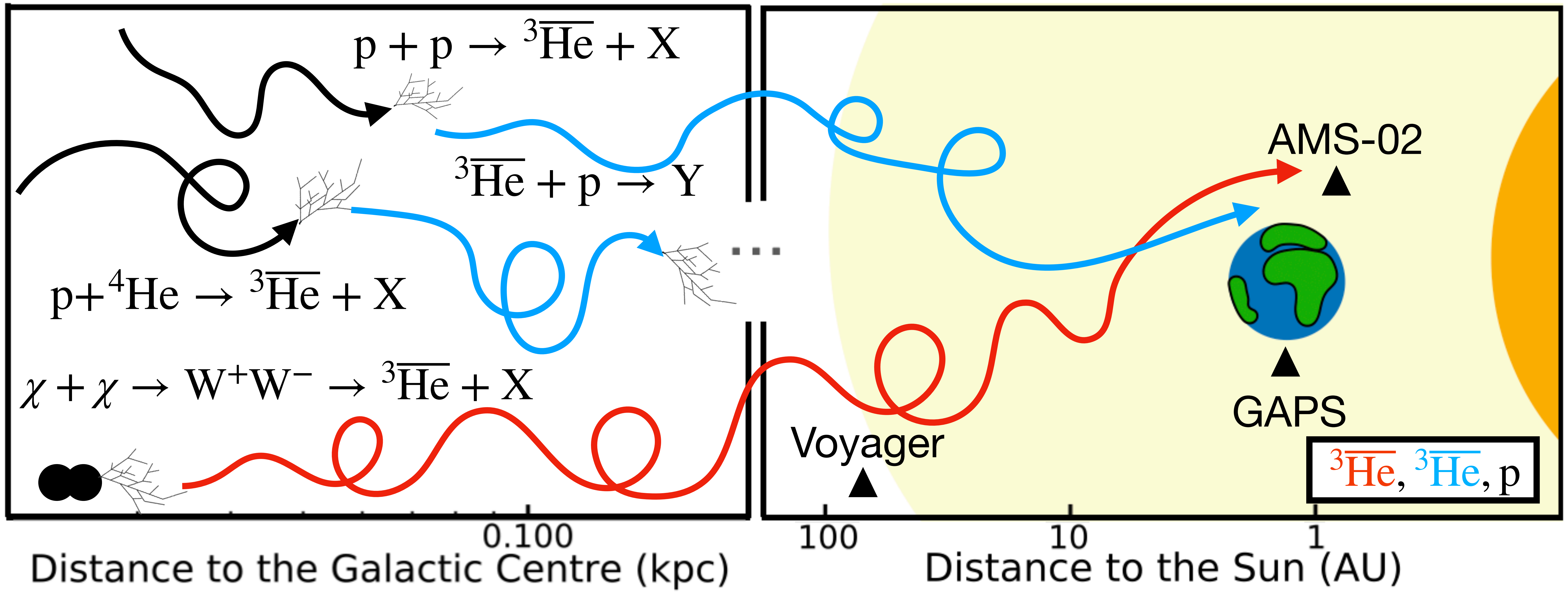
- Propagation
- Inelastic interactions

ALICE: measurements to understand the production and constrain models

ALICE: Inelastic cross section measurements



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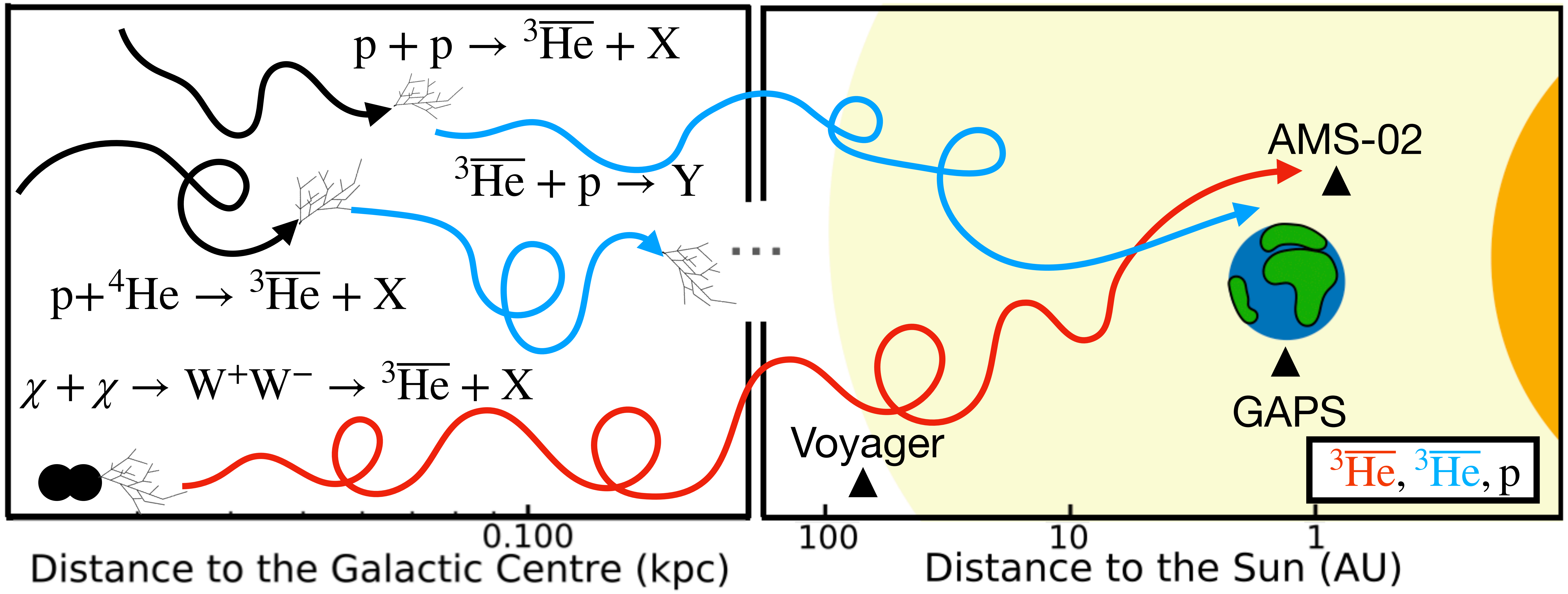
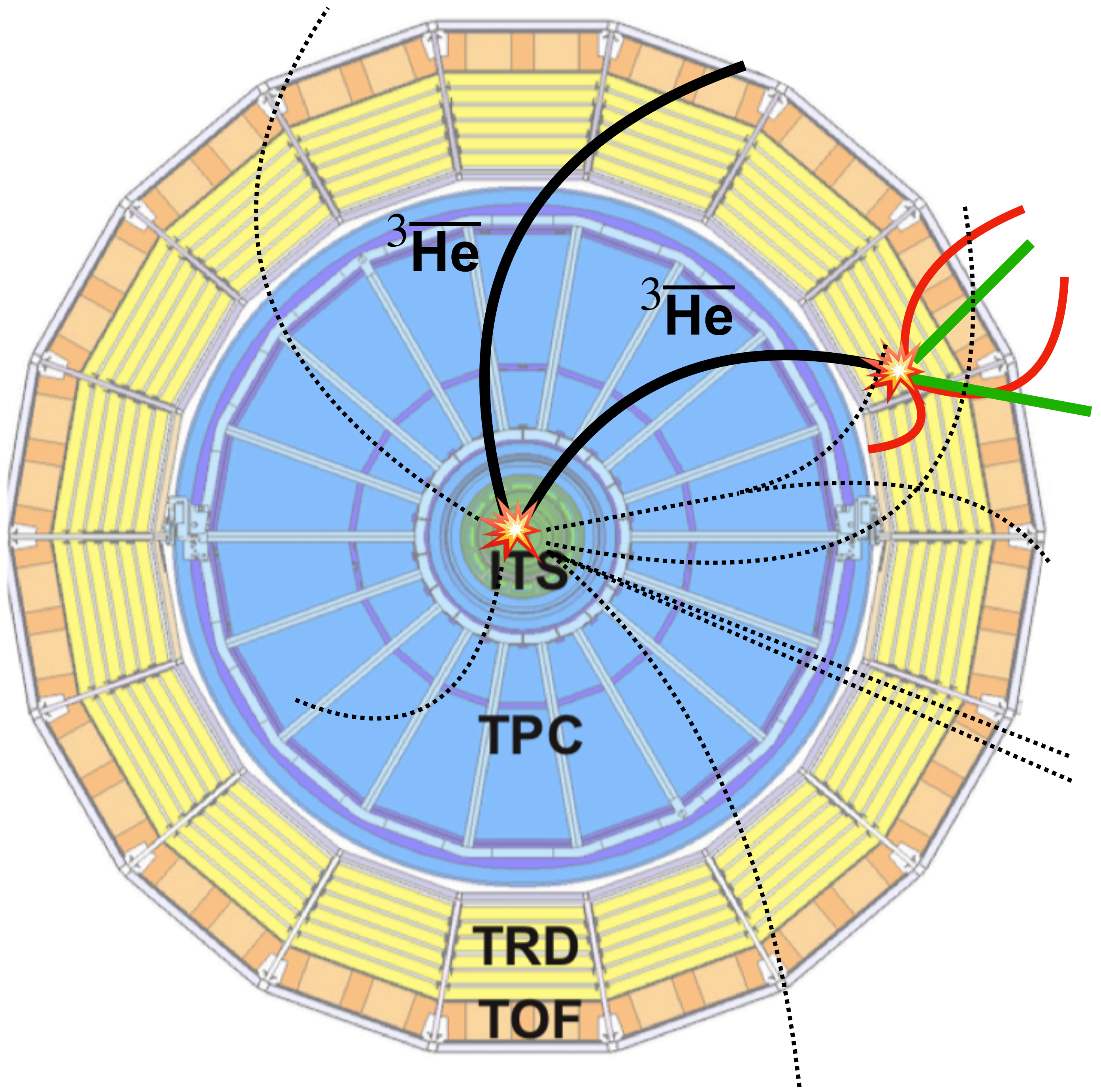
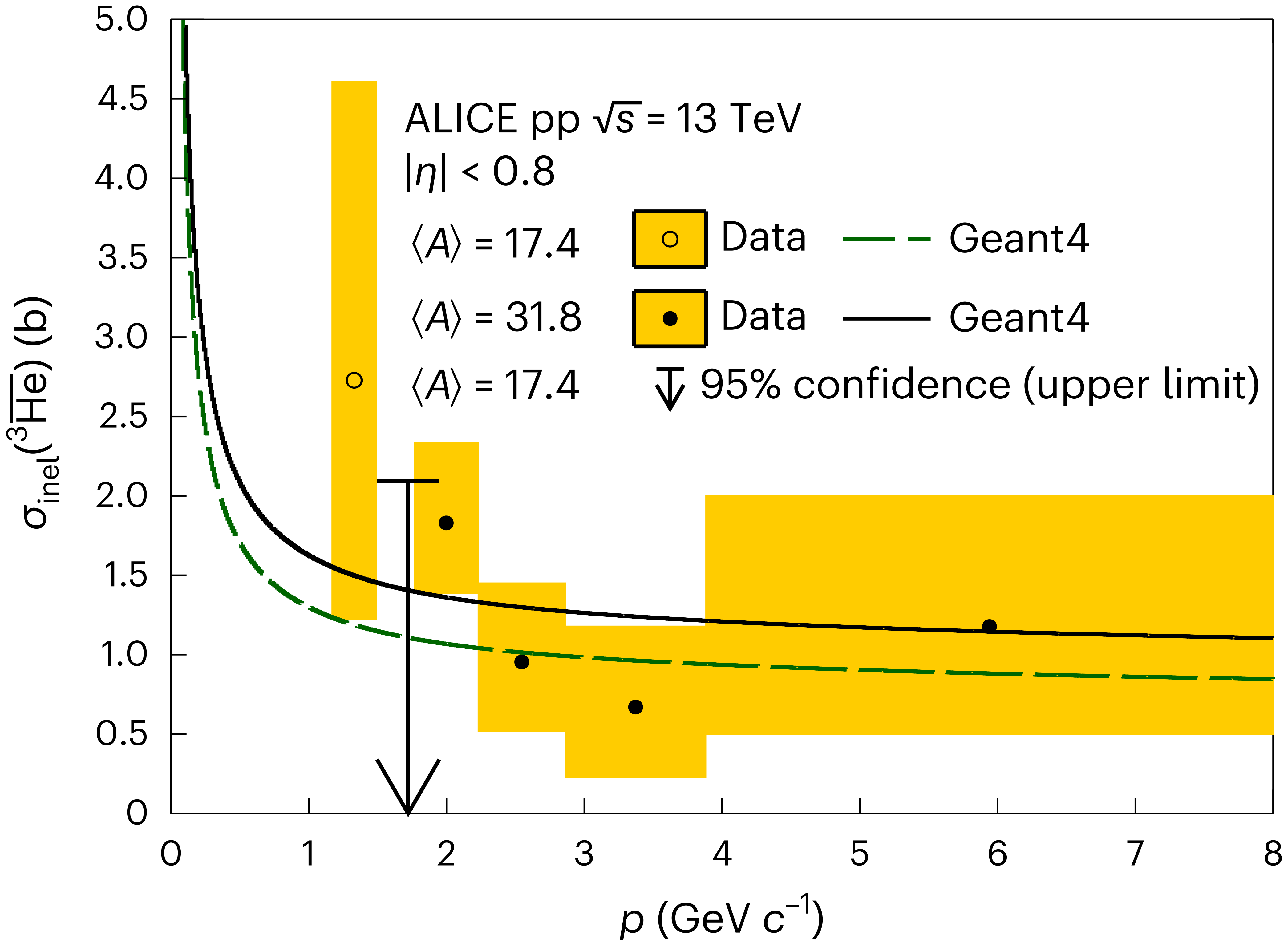




Results

- 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



ALICE, Nature Phys. 19 (2023) 1, 61-71

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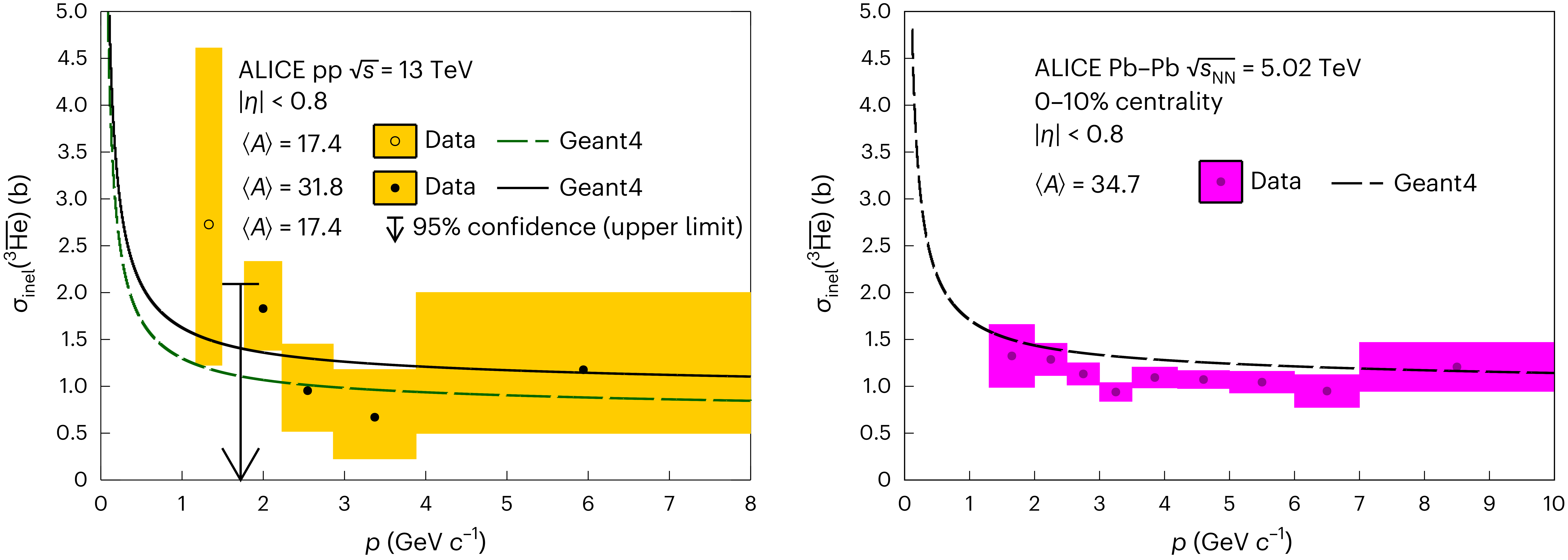

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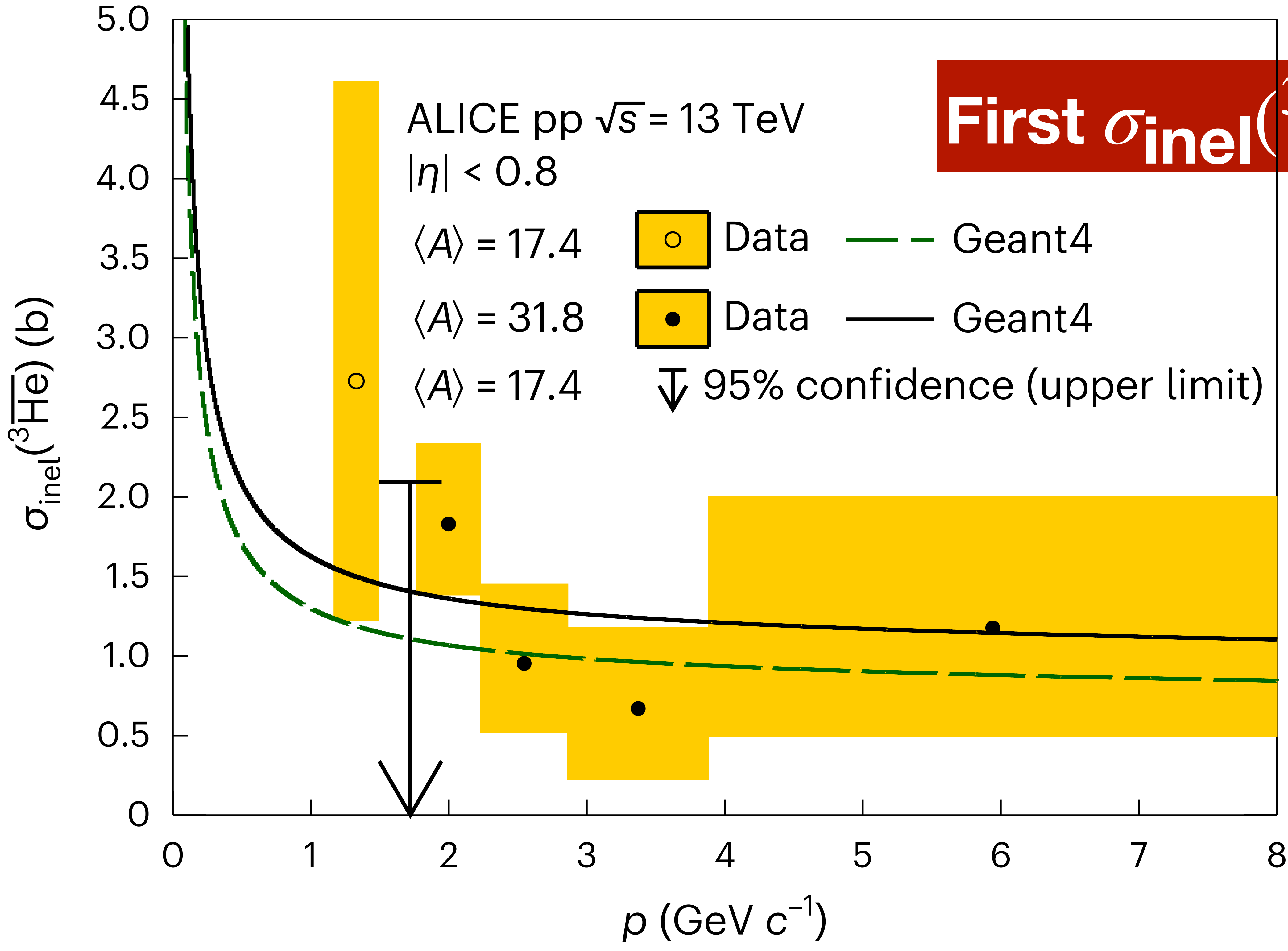
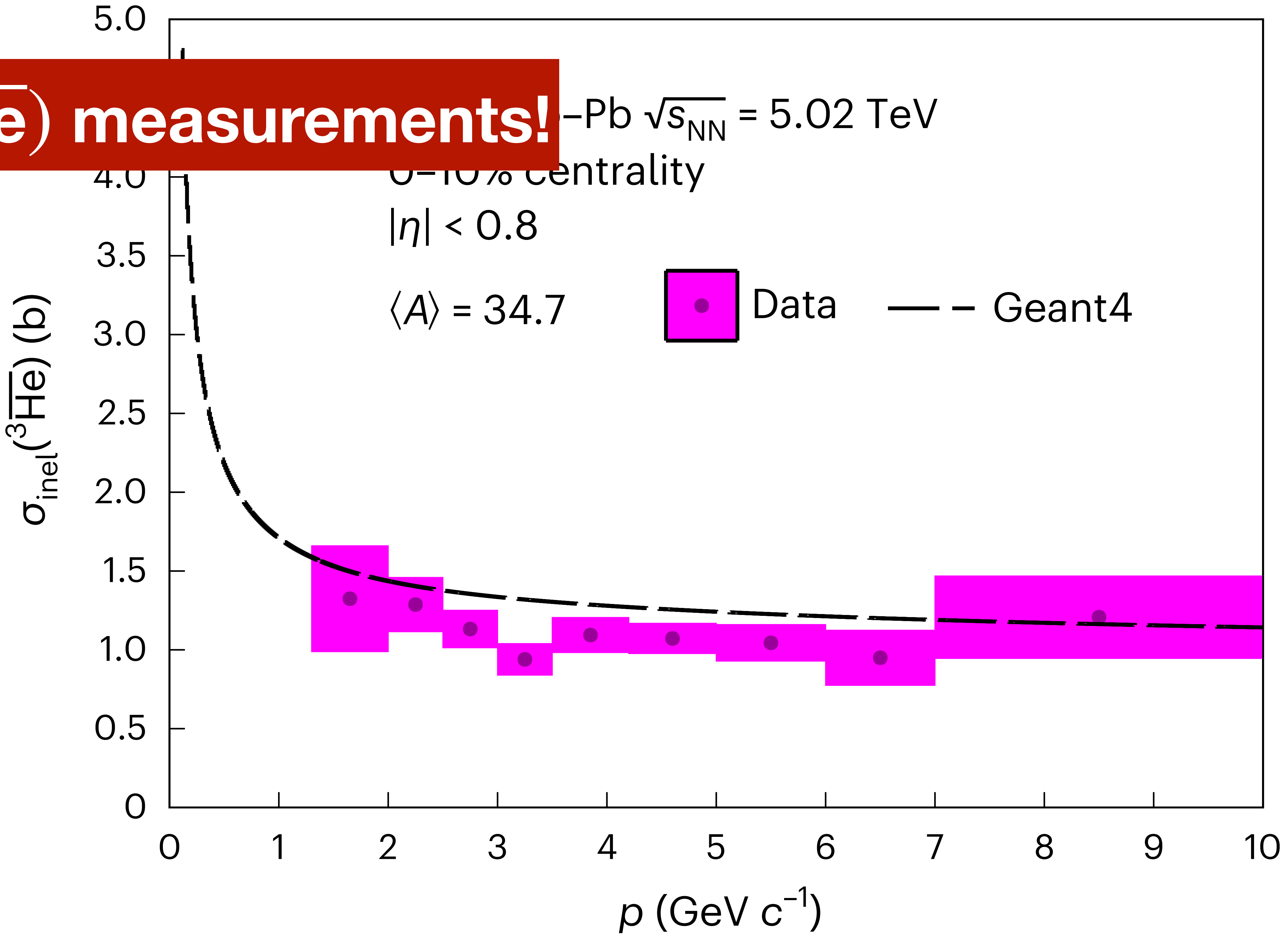


First $\sigma_{inel}(^3\overline{He})$ measurements!



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Solar modulated antihelium flux

- Coalescence model validated with ALICE antideuteron and antihelium-3 data
- Uncertainties shown only from ALICE measurement, small compared to other uncertainties in the field
- Disappearance effect strongly depends on the cosmic ray flux shape
- Large transparency to both signal and background components

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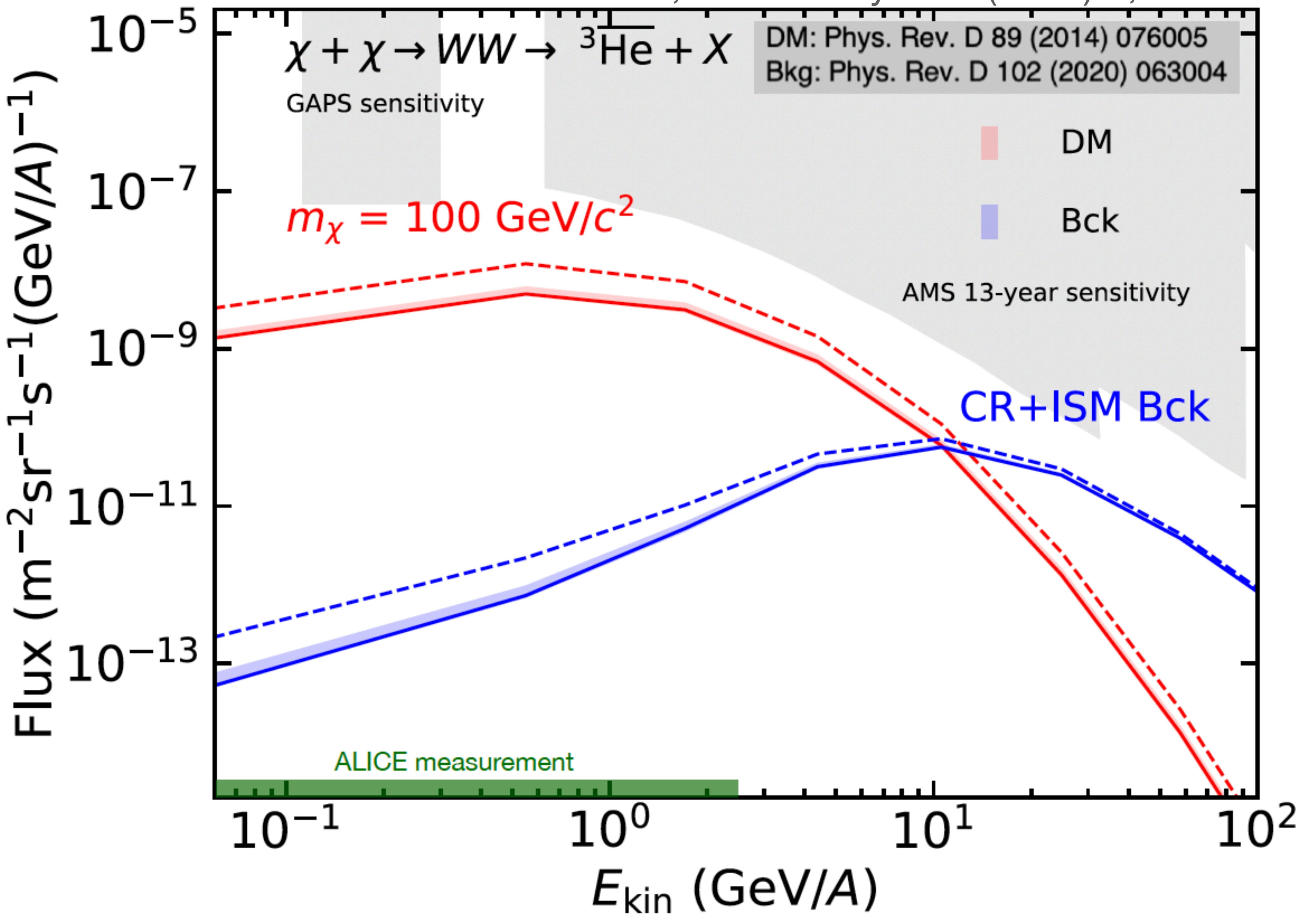

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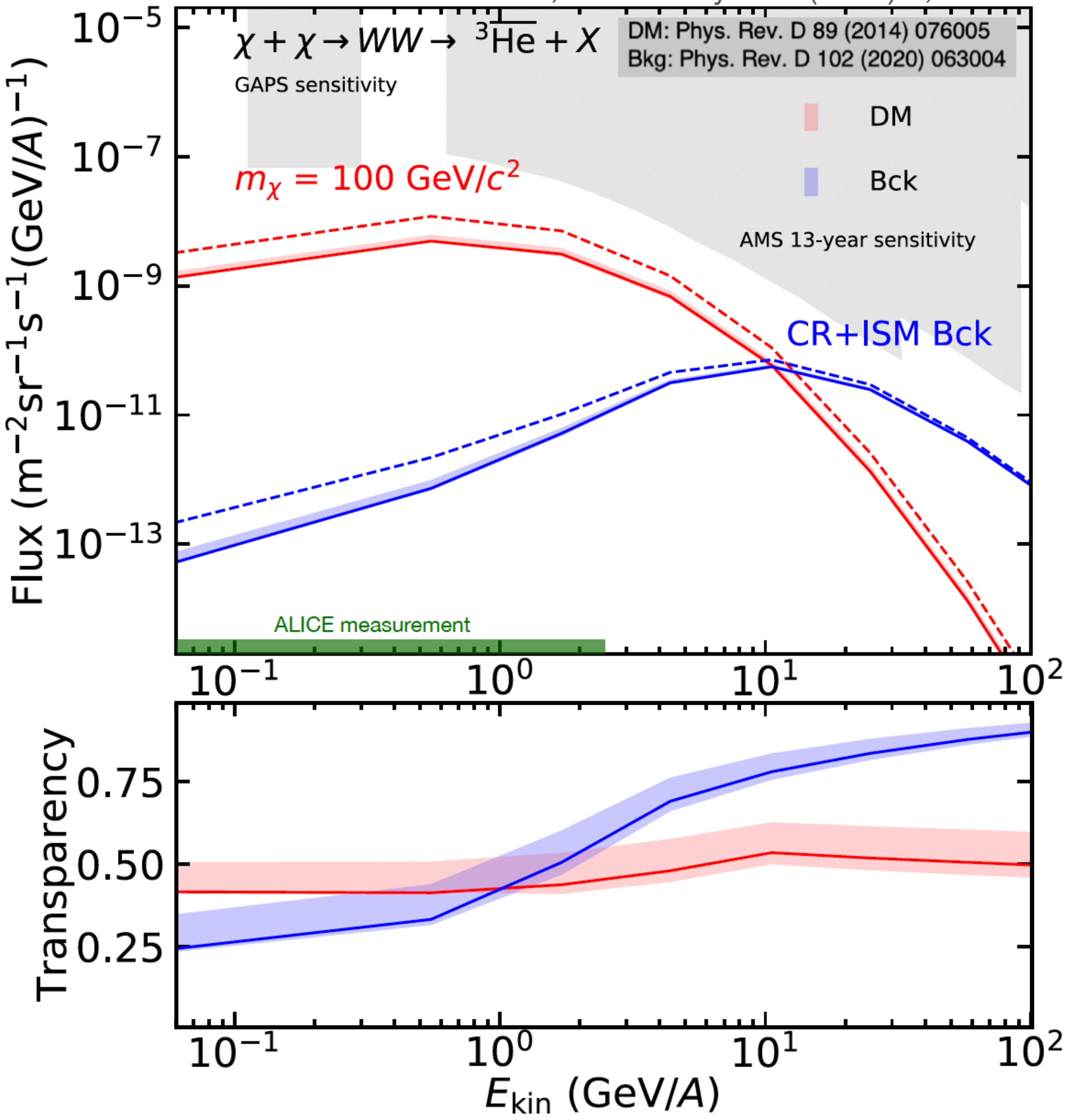

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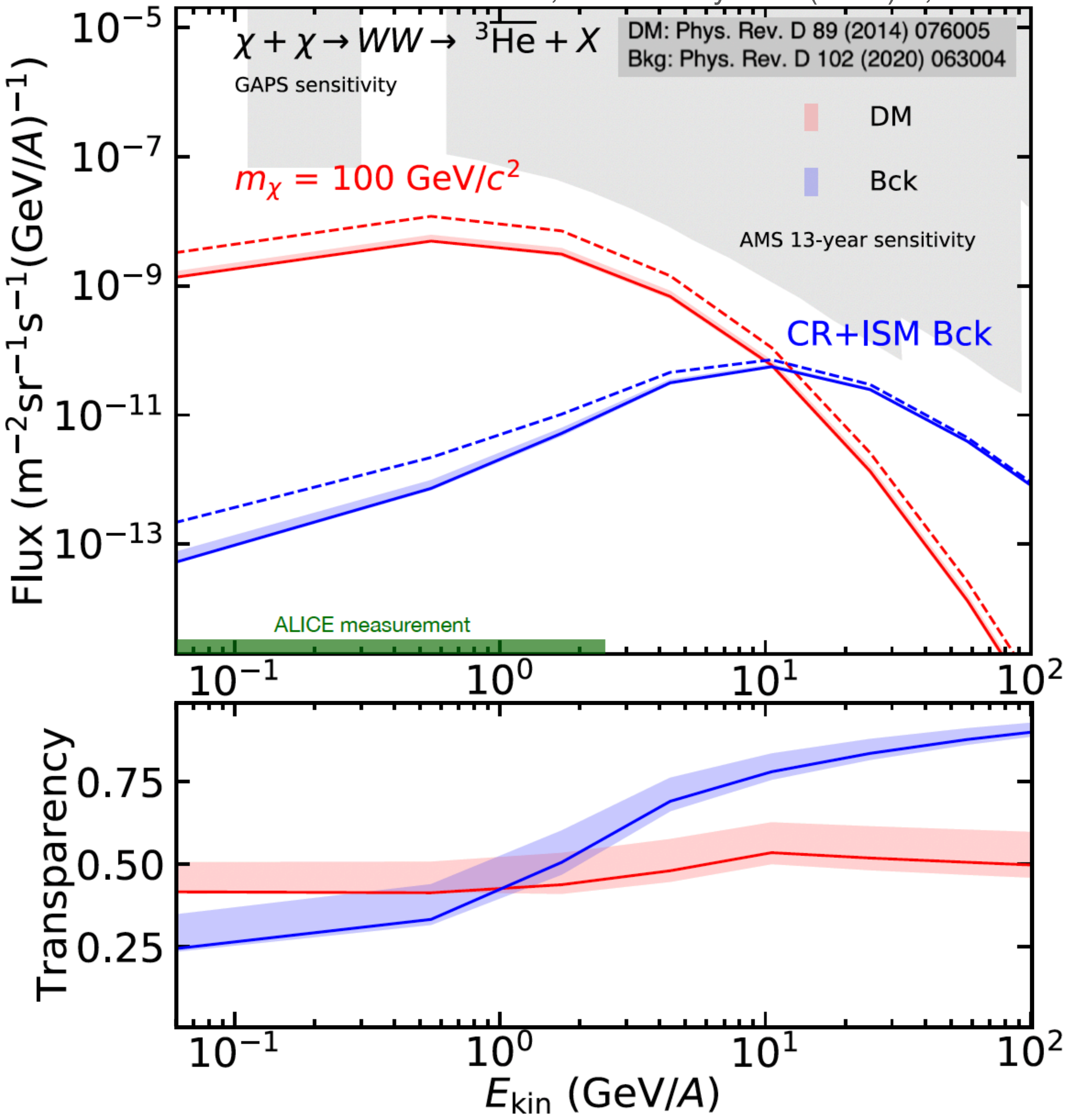
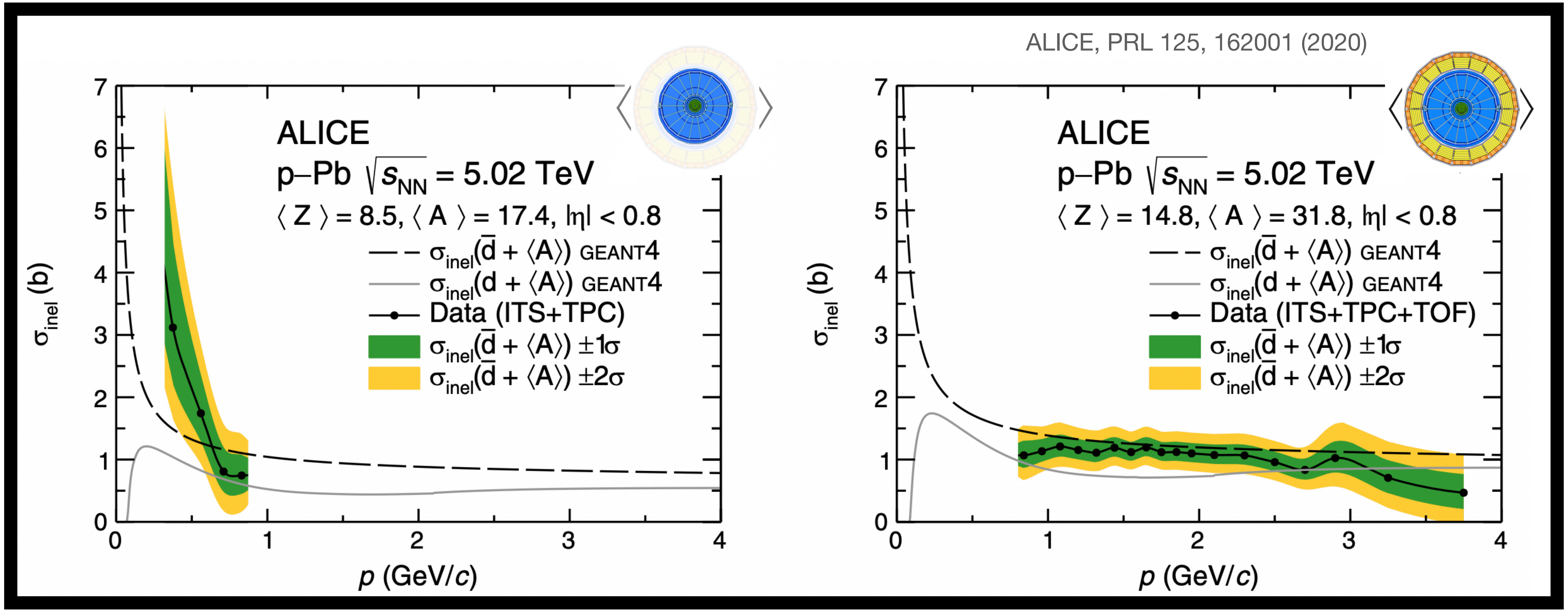
ALICE measurement of antihelium-3 inelastic cross sections can be used in all future studies of antihelium-3 cosmic rays!

ALICE, Nature Phys. 19 (2023) 1, 61-71



Same studies for antideuterons



First low energy antideuterons inelastic cross section measurement

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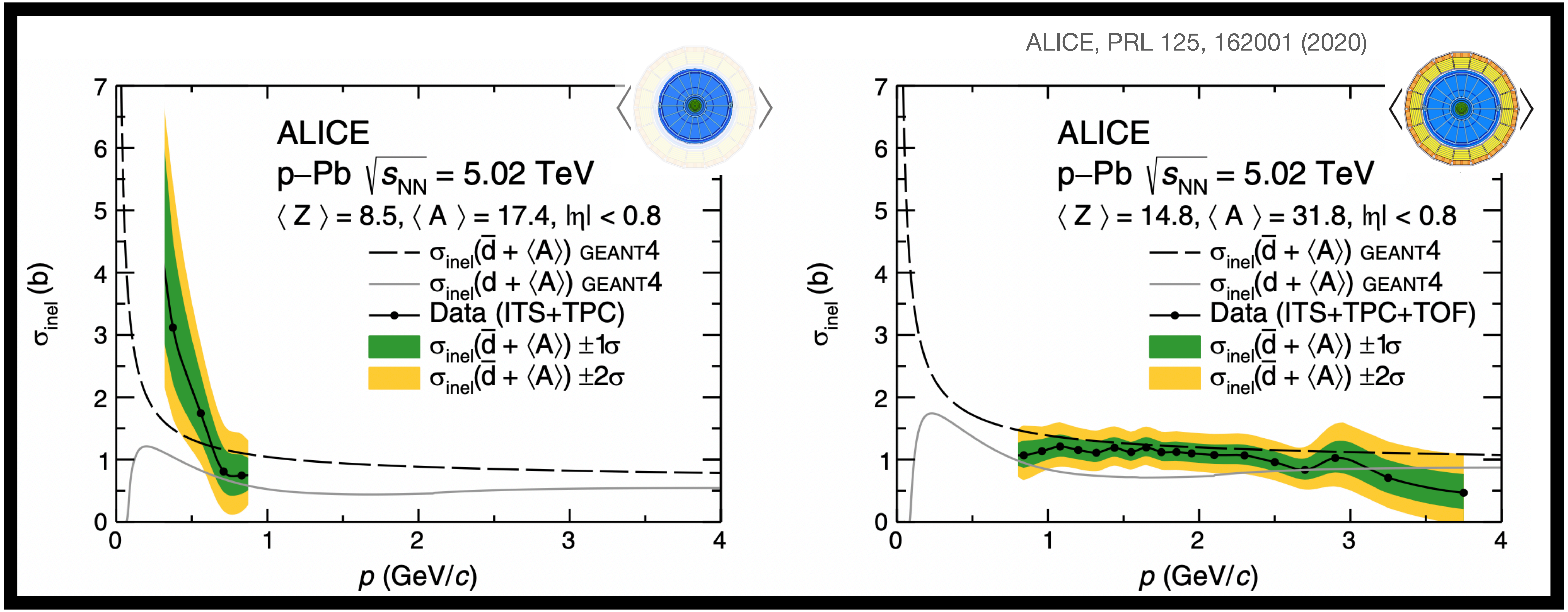

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Talk by David at 13:10

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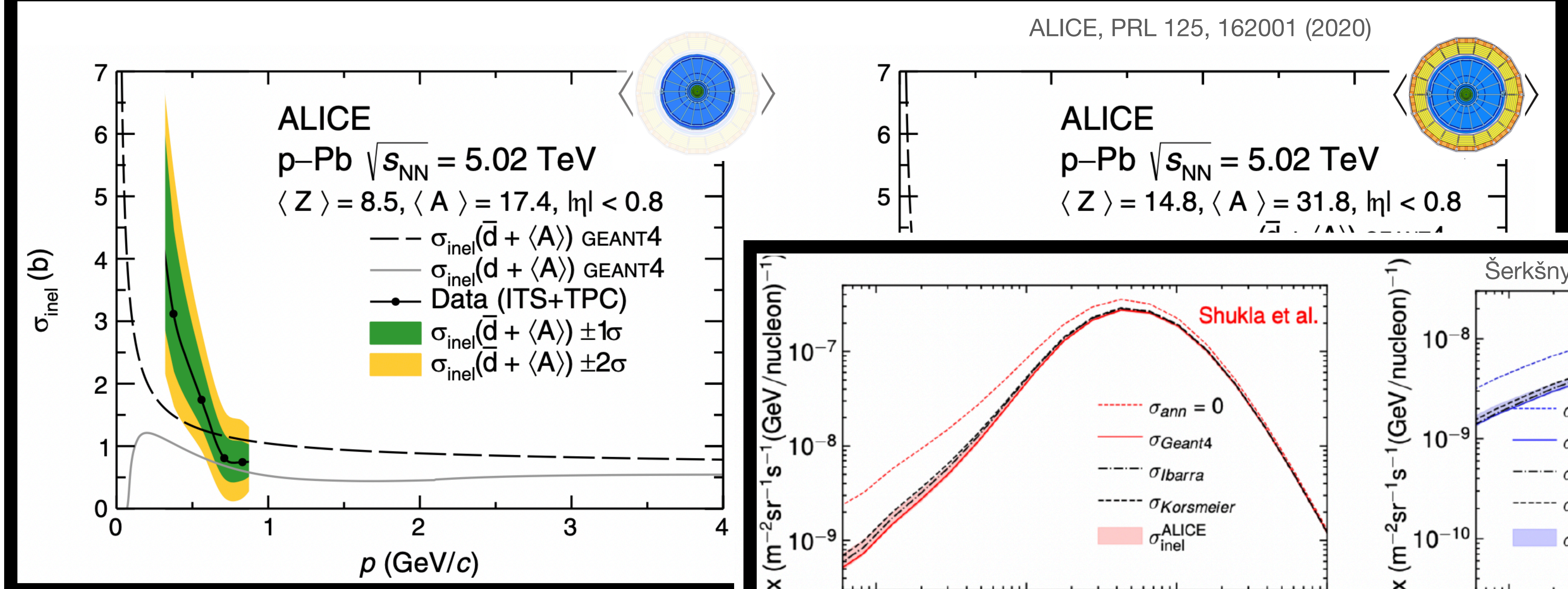

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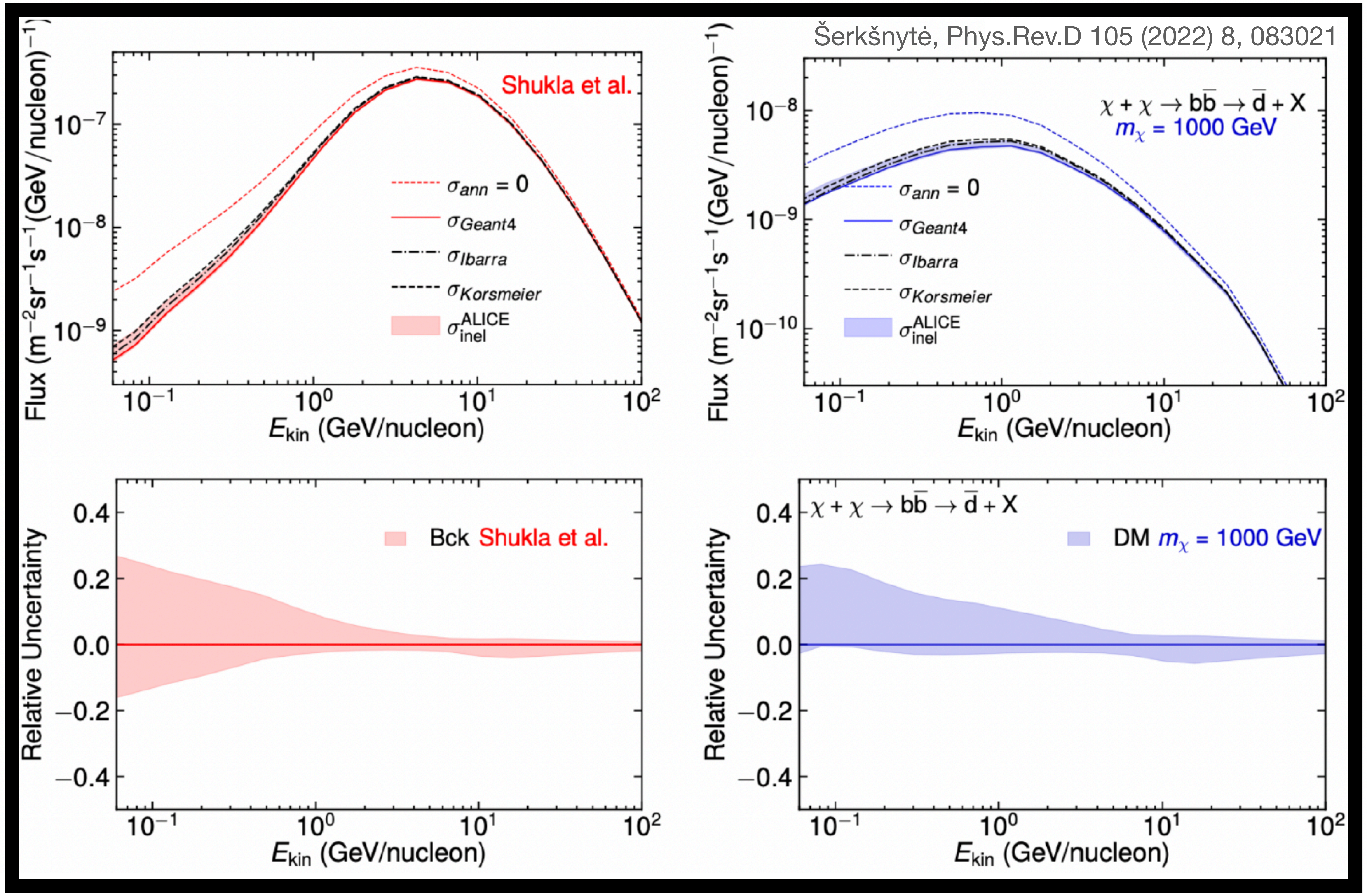
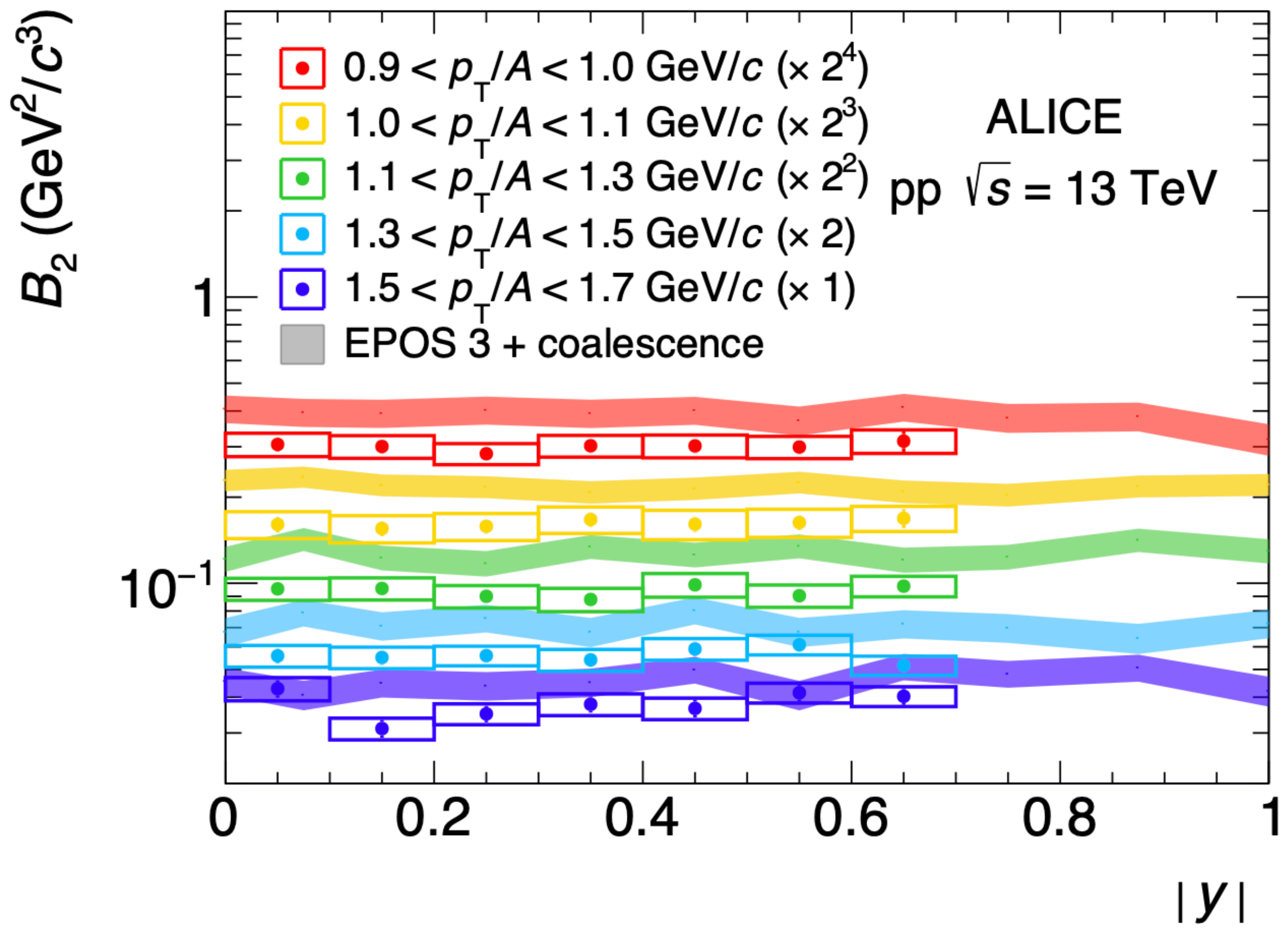
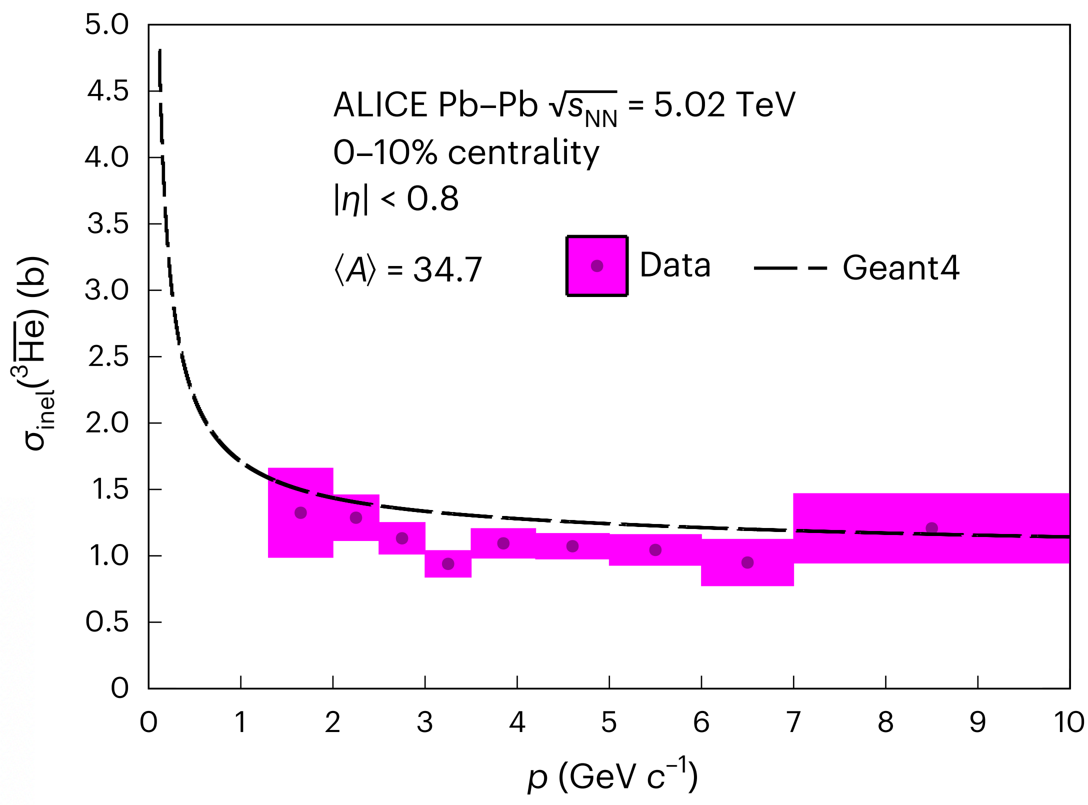


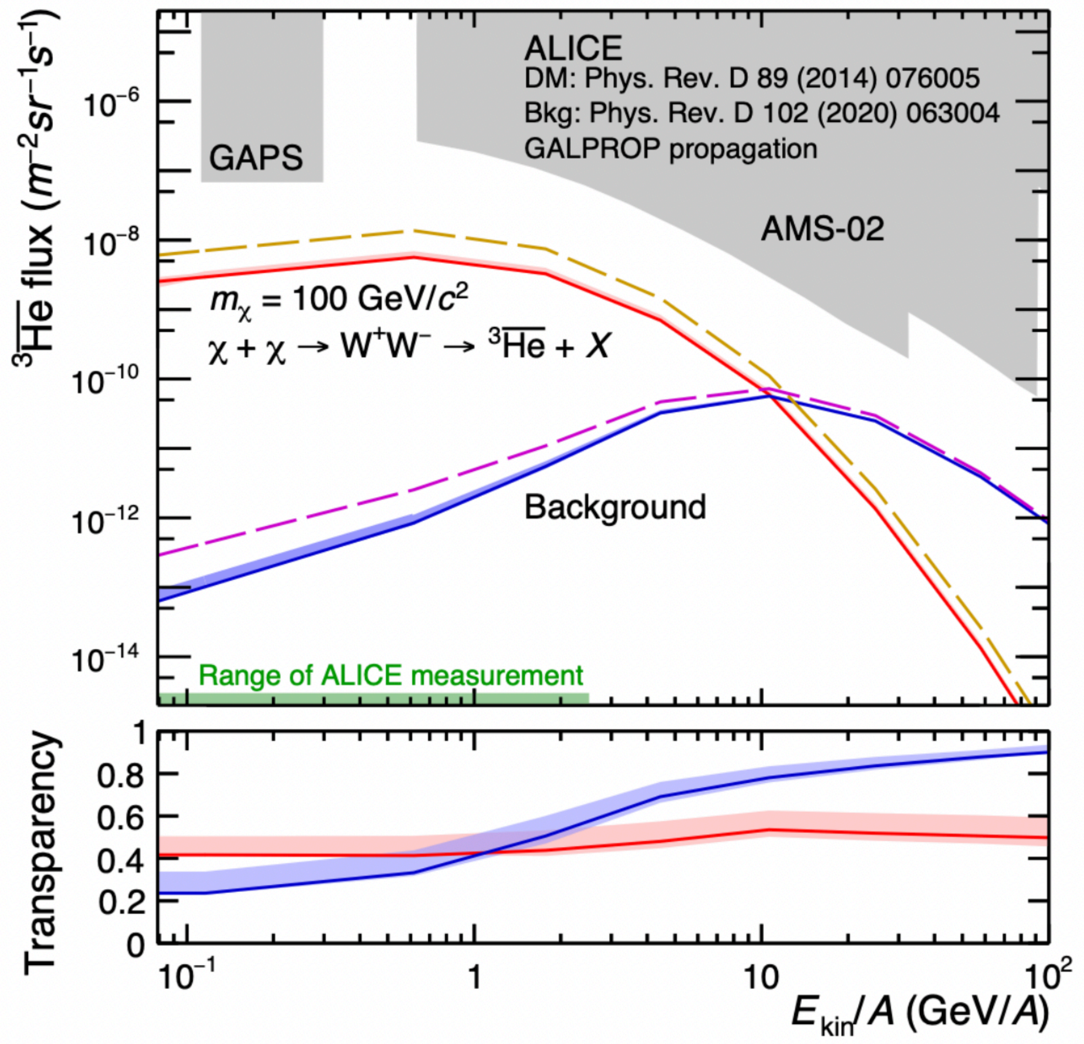
Resulting uncertainties on cosmic rays ~25%

Summary

- Production
  - High precision differential (anti)deuteron and (anti)helium yields in pp collisions
  - Coalescence parameter B_2 is flat as a function of rapidity: extrapolation from mid-rapidity to forward rapidity should be safe
- Annihilation:
  - First ever low momentum antideuteron measurement
  - First ever antihelium-3 measurement
- Future/ongoing:
  - high-pT deuterons with HMPID
  - inelastic cross-section of antihelium-4
  - First observation of antihelium-4 in pp collisions
  - …





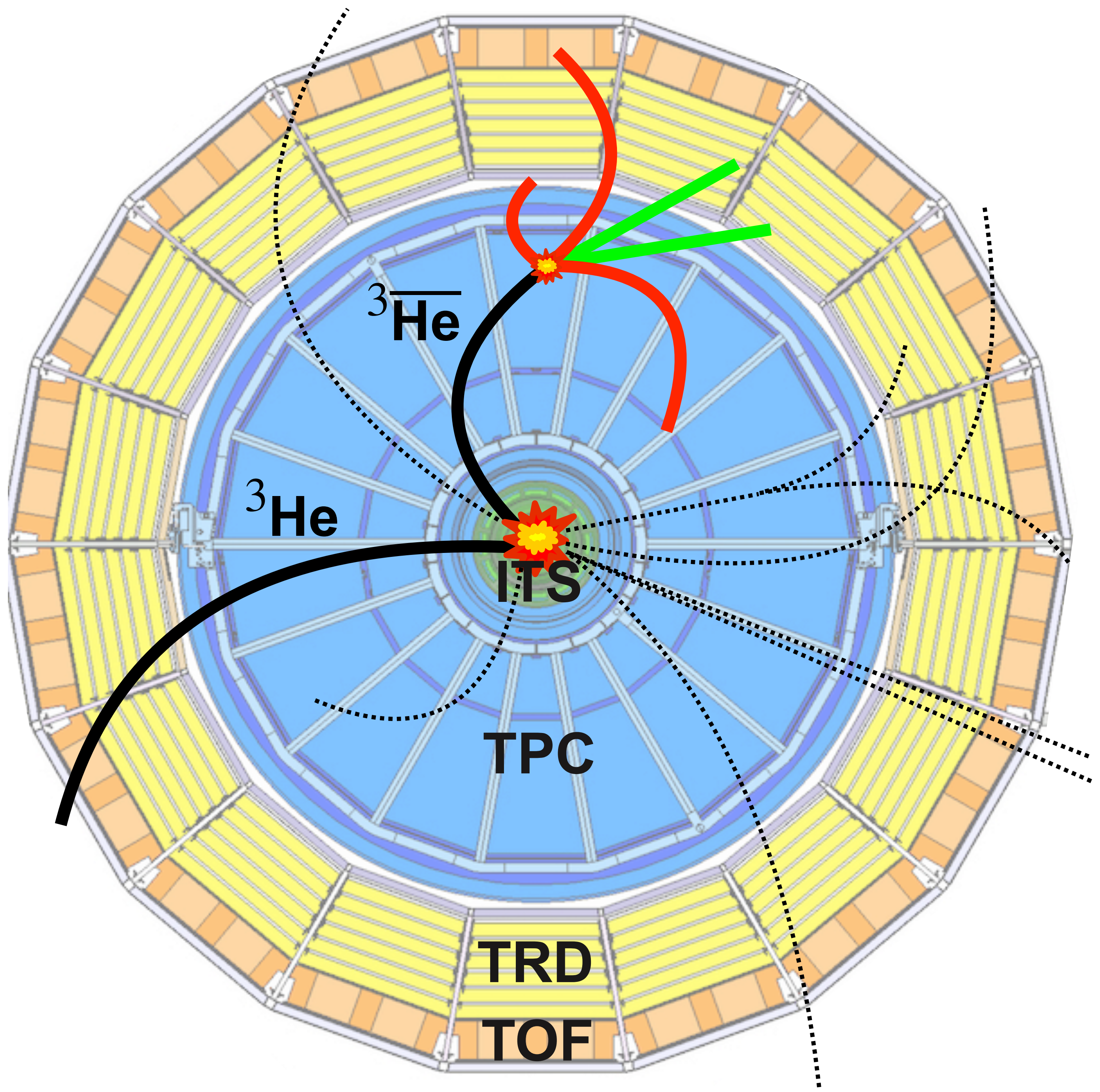


Thank you for your attention!

Method: ALICE as a target

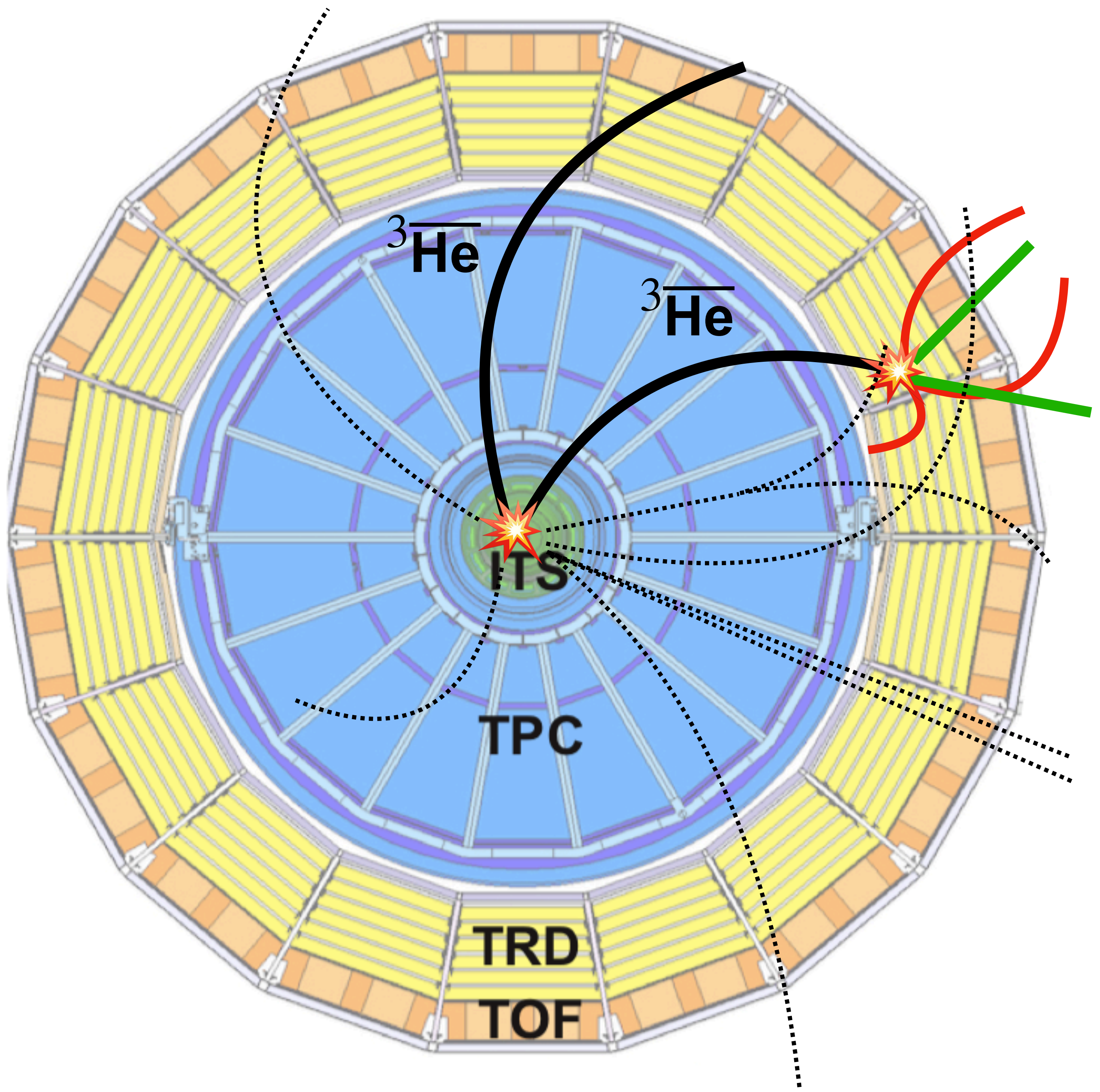
Antimatter-to-matter ratio

- 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



(Anti)nuclei production mechanisms

Andronic et al., Nature 561 (2018) 7723, 321-330

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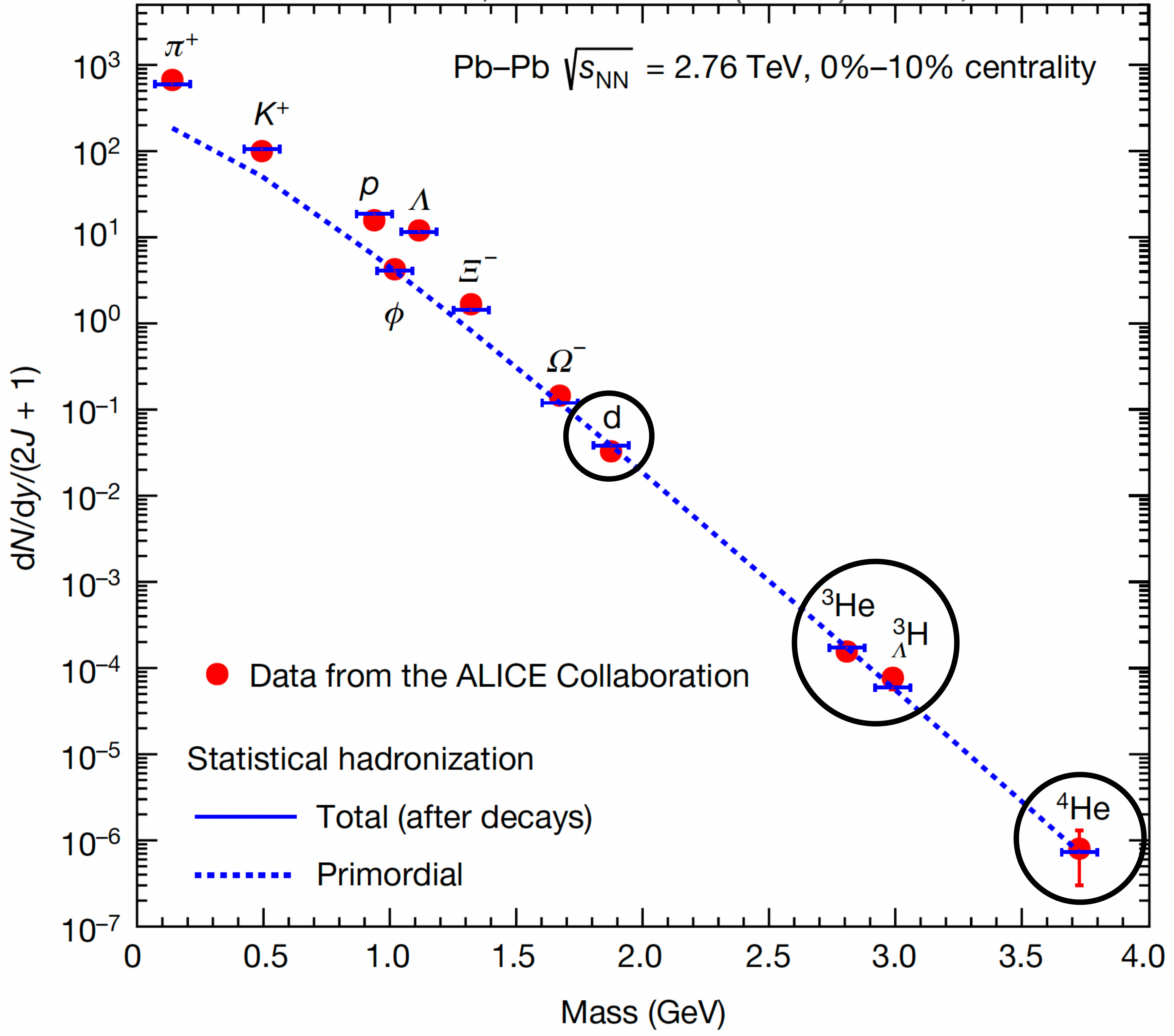
  - describes the yields of light-flavoured hadrons by requiring thermal and hadron-chemical equilibrium



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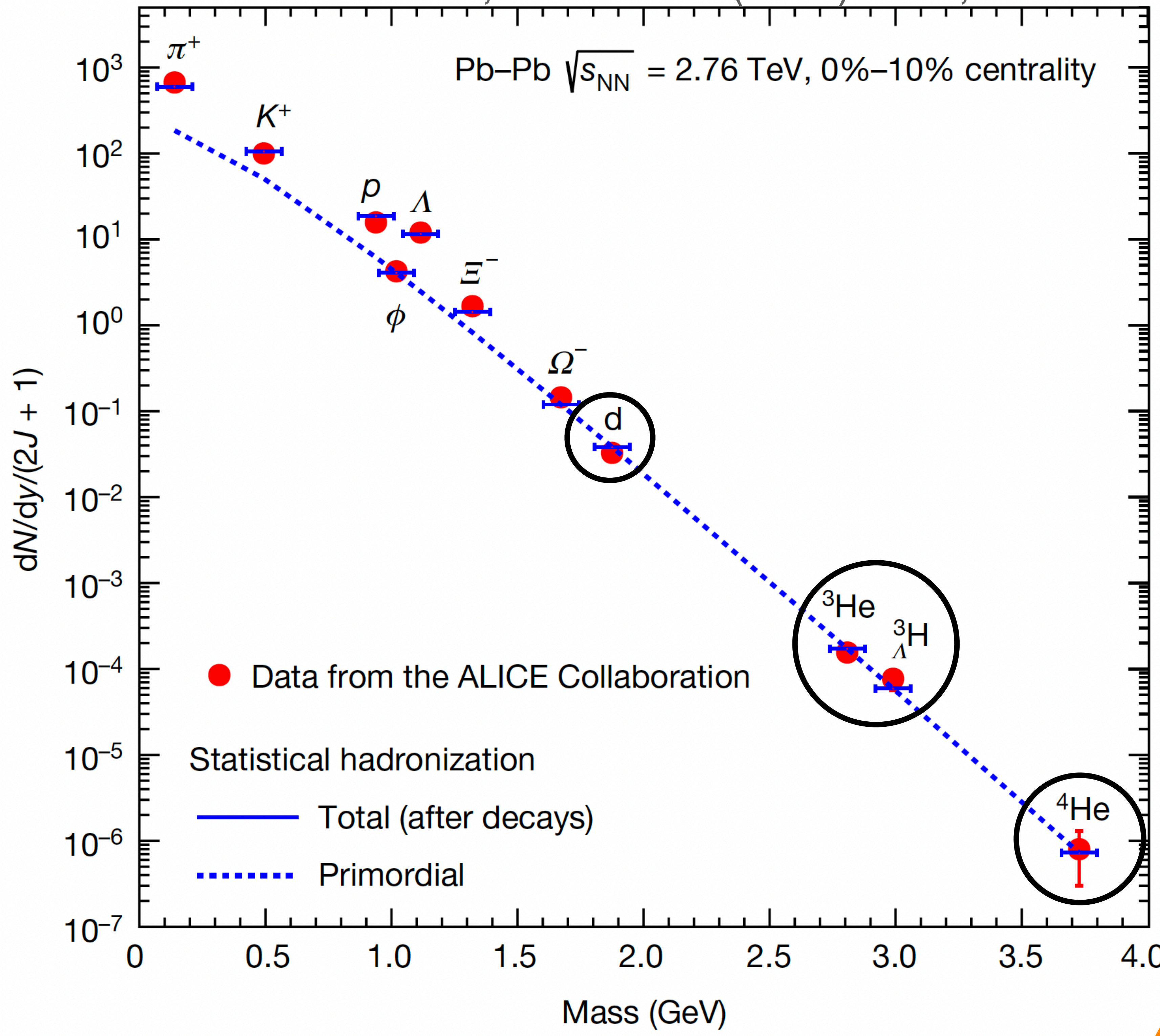

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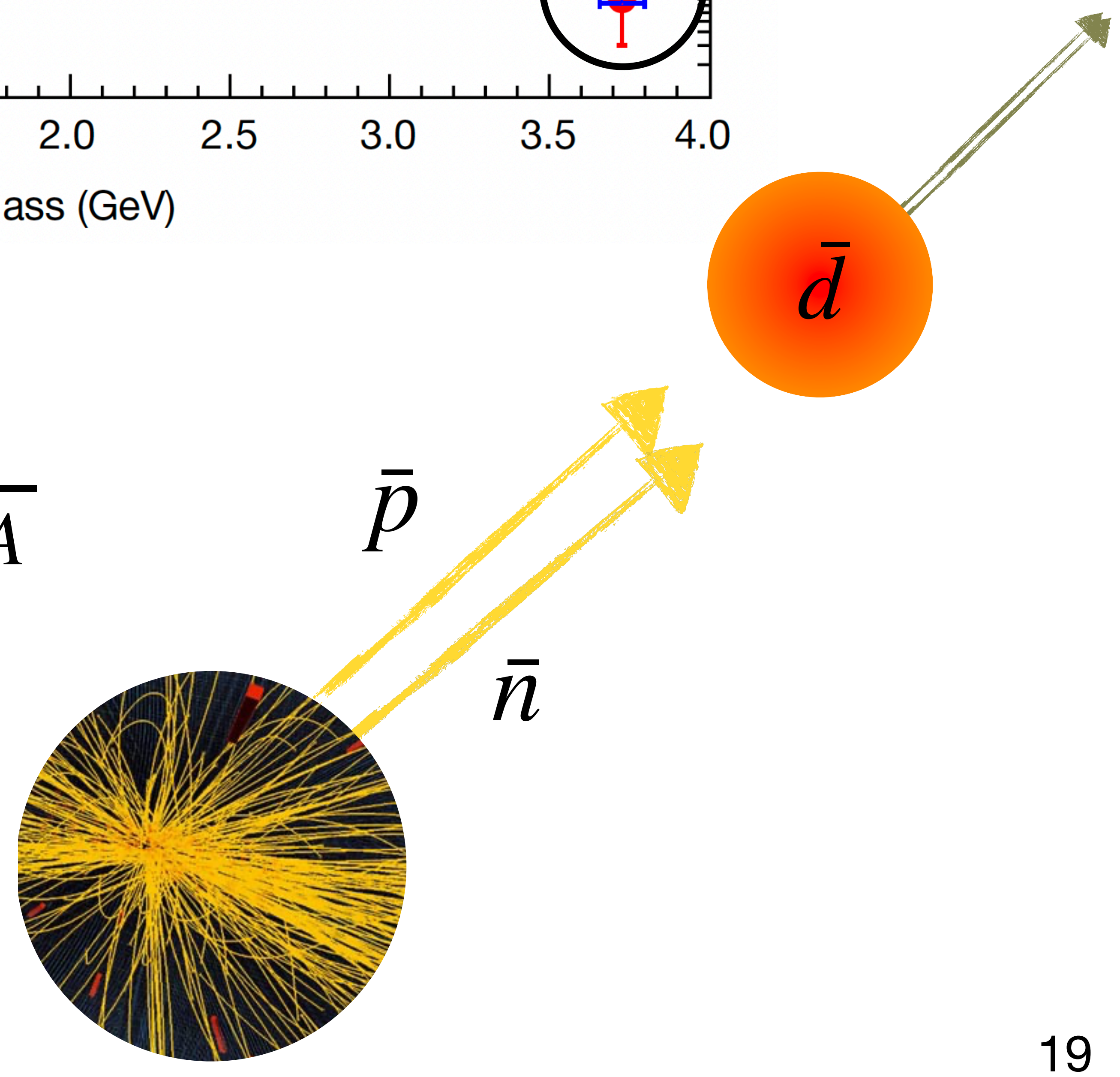
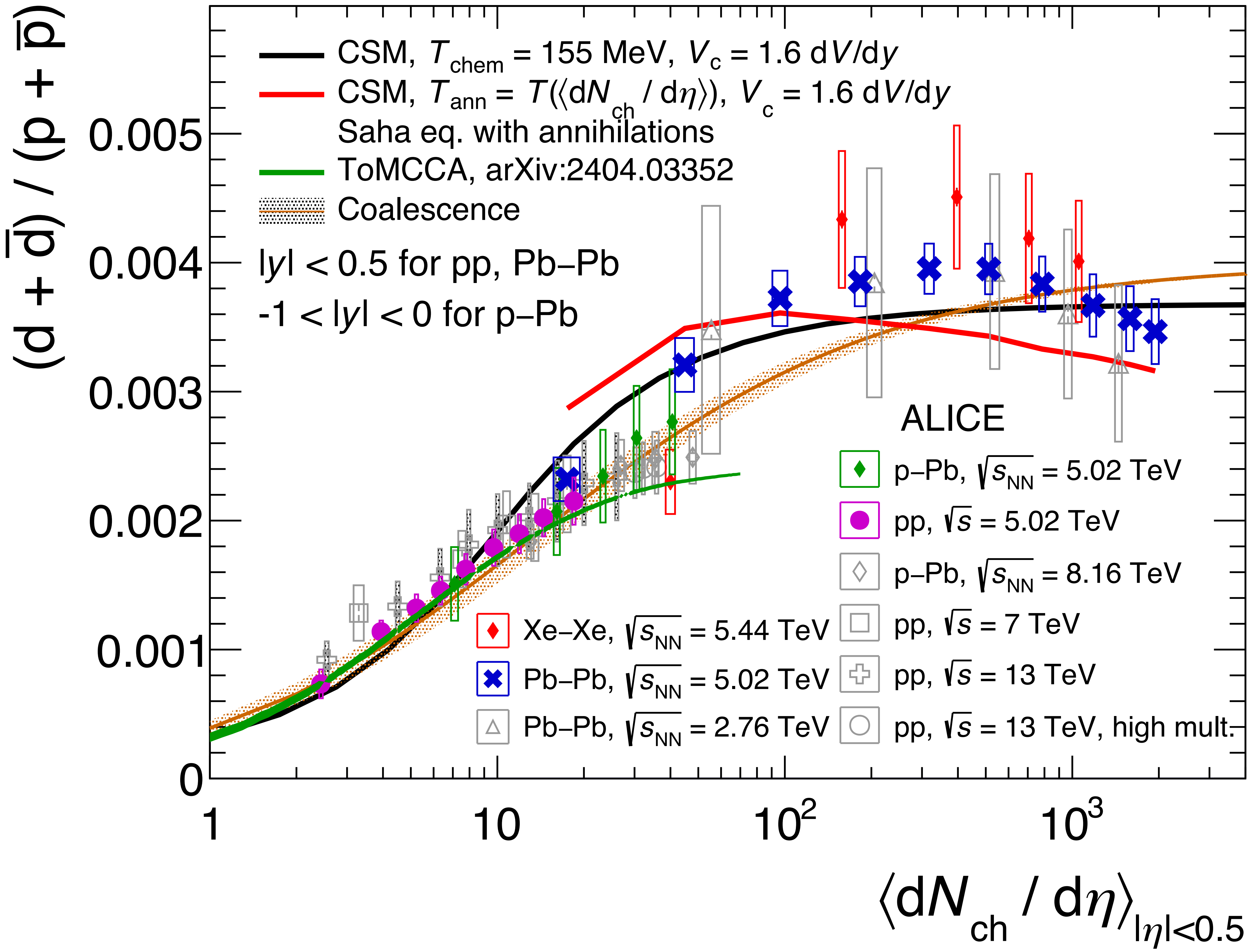


Comparison

- Nucleus to nucleon yield ratio evolves smoothly with multiplicity
  - Dependence on the system size
- Deuterons: no conclusion on the different models
- Helium-3: model predictions different but insufficient data precision

ALICE, arxiv:2405.19826



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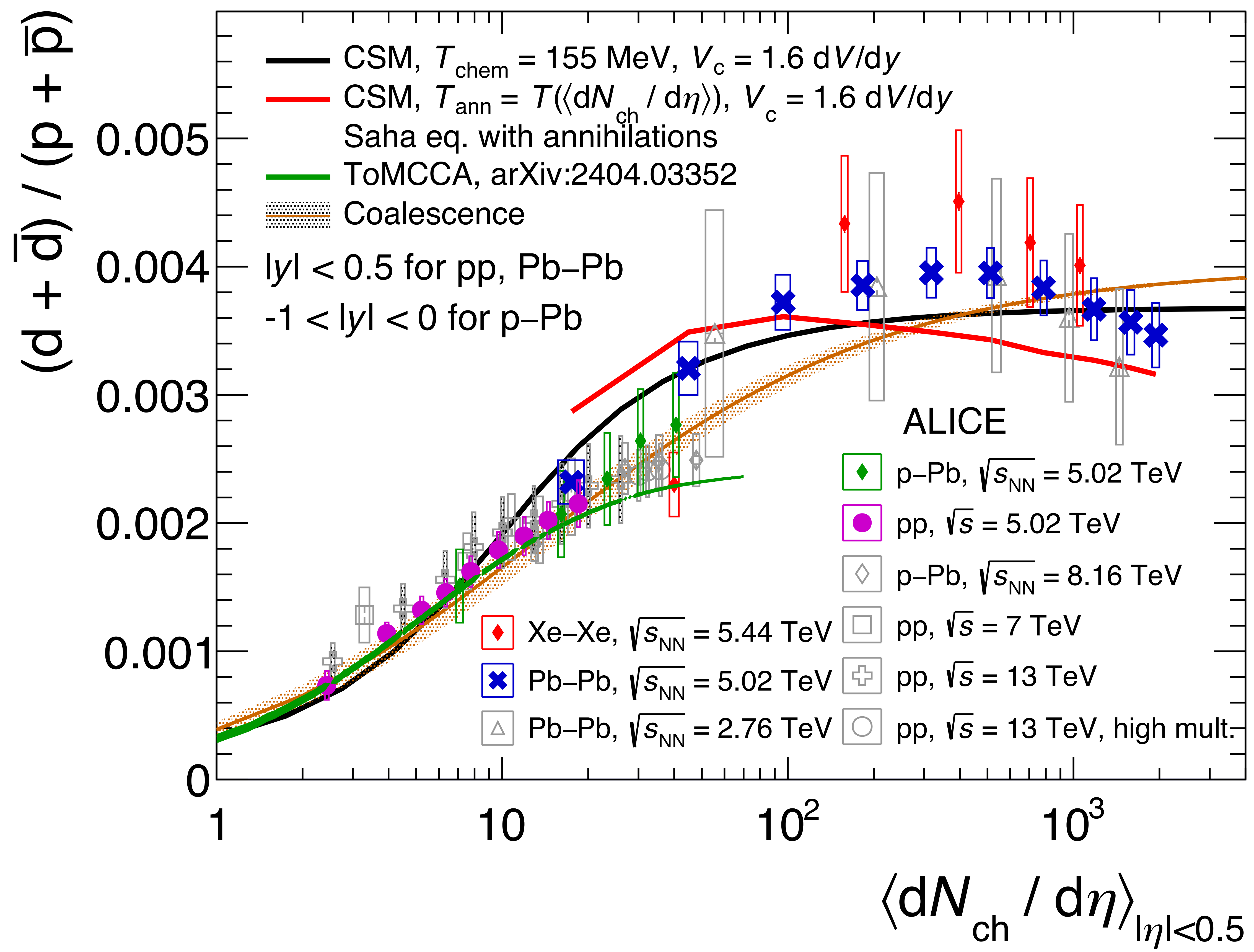

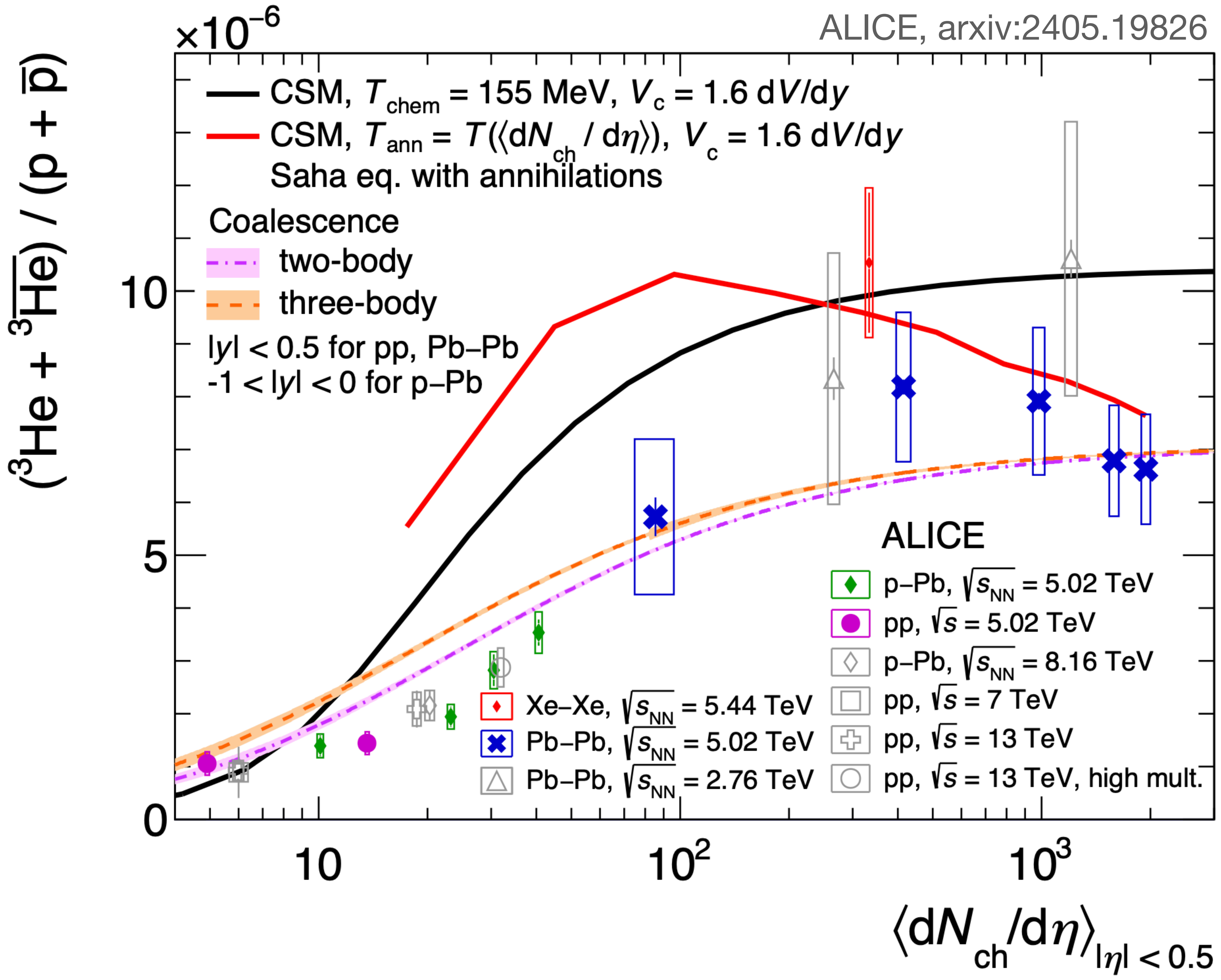

CSM vs Coalescence

- Nucleus to nucleon yield ratio evolves smoothly with multiplicity
  - Dependence on the system size
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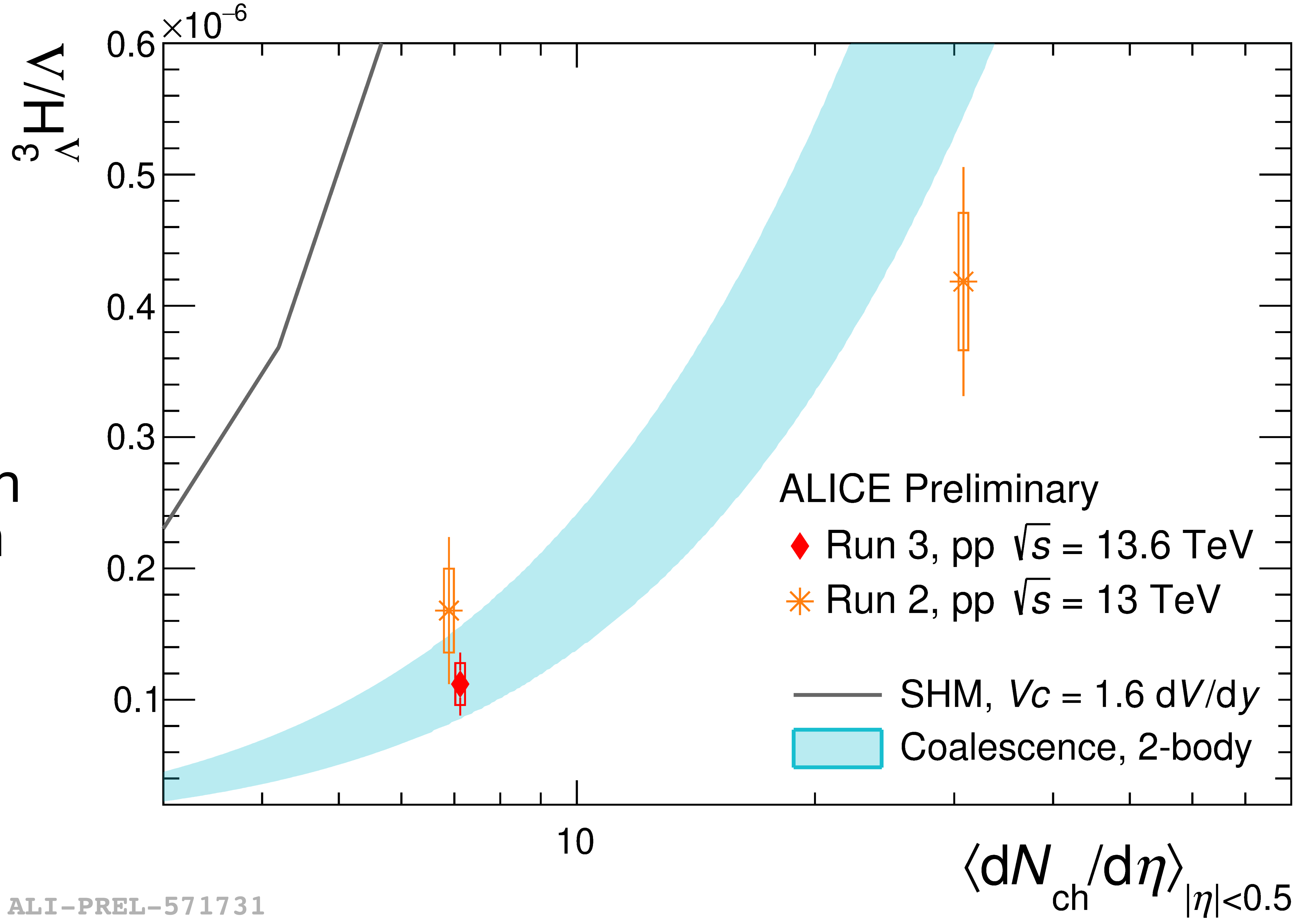
- Hypertriton has a size of ~10 fm
  - Relevant for coalescence but not SHM
- Coalescence provides the best description of hypertriton measurement in pp collision system



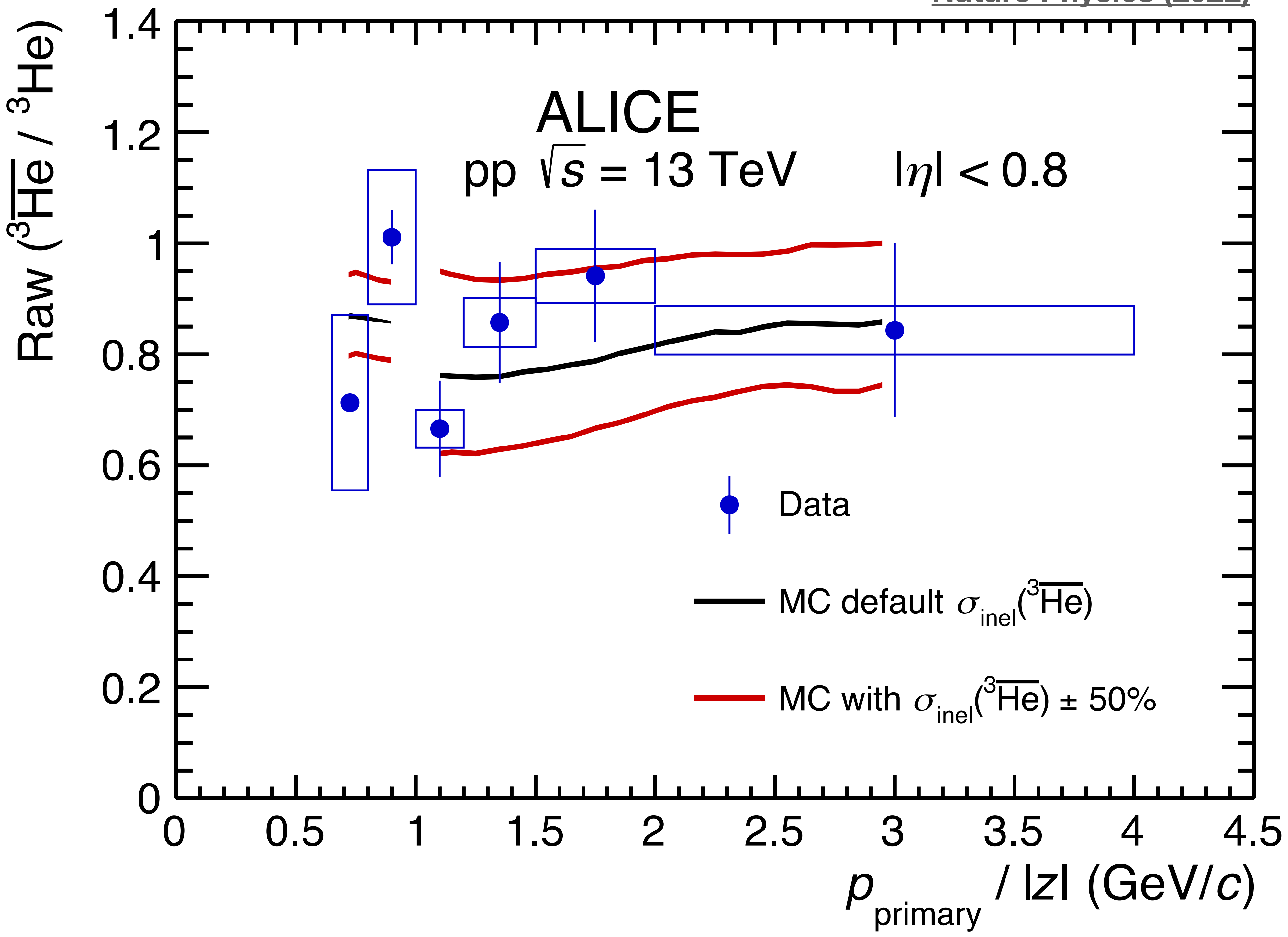
Antimatter-to-matter method

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

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

Raw antimatter-to-matter ratio

Nature Physics (2022)



Antimatter-to-matter method

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

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

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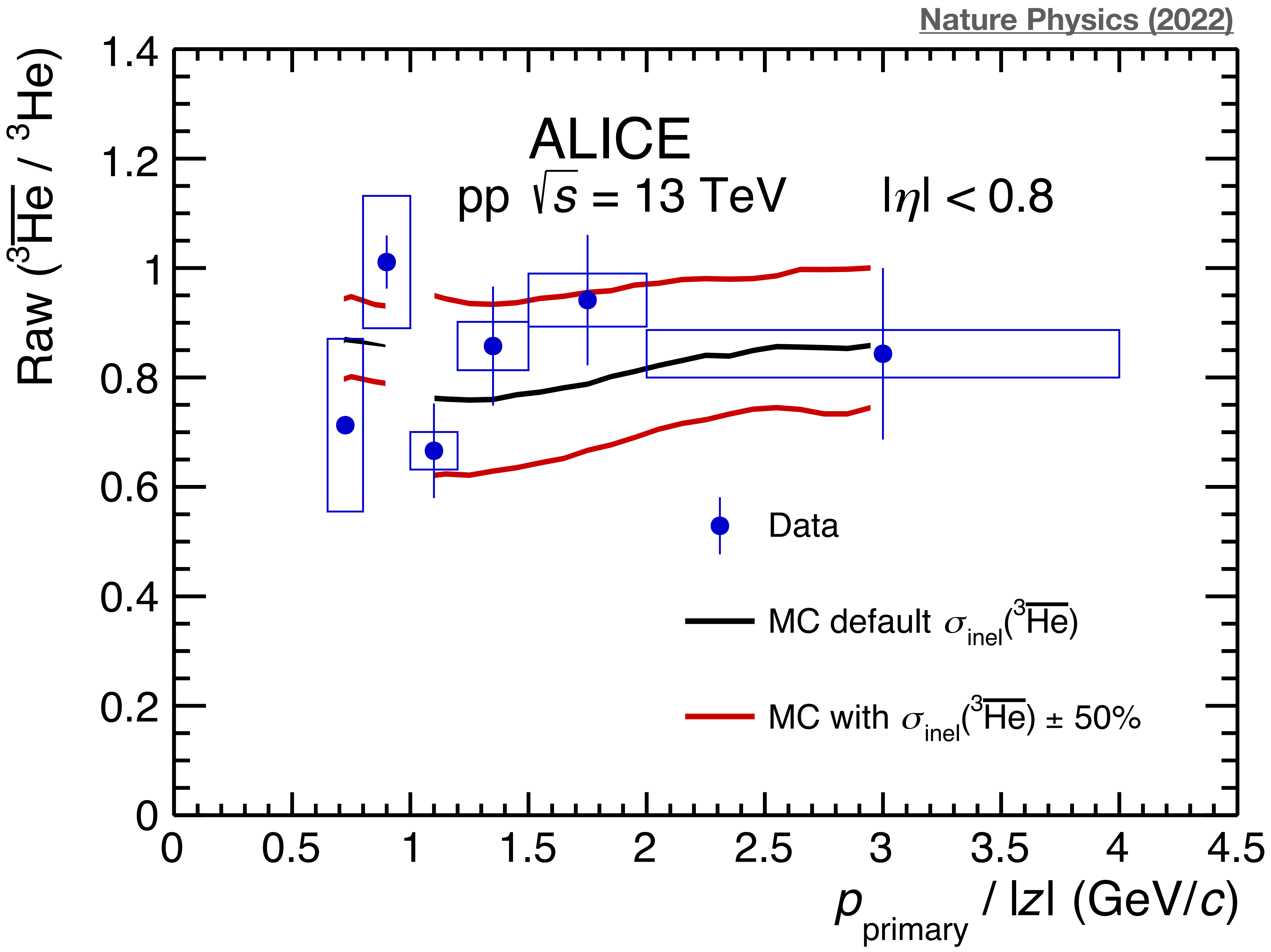

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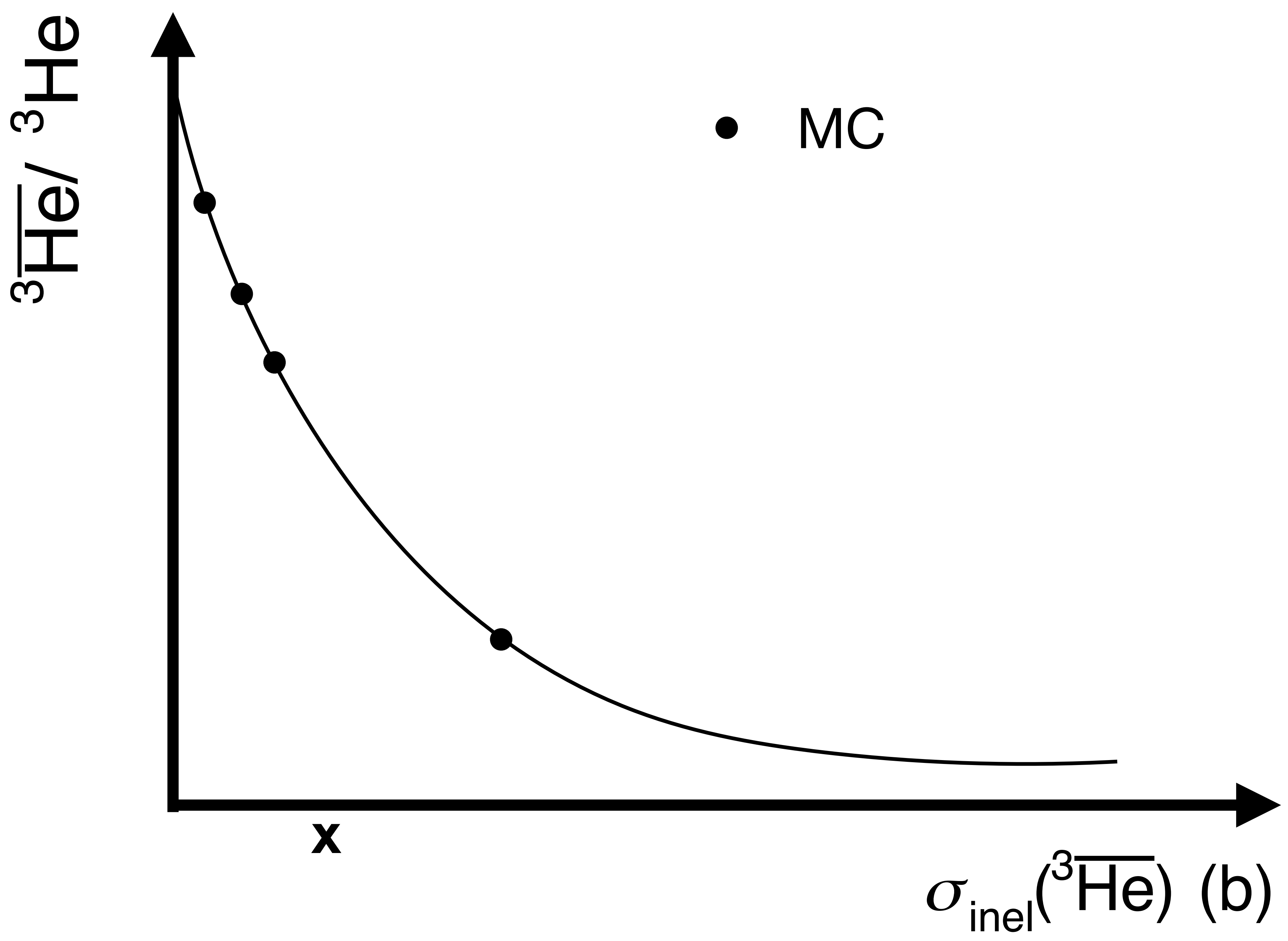

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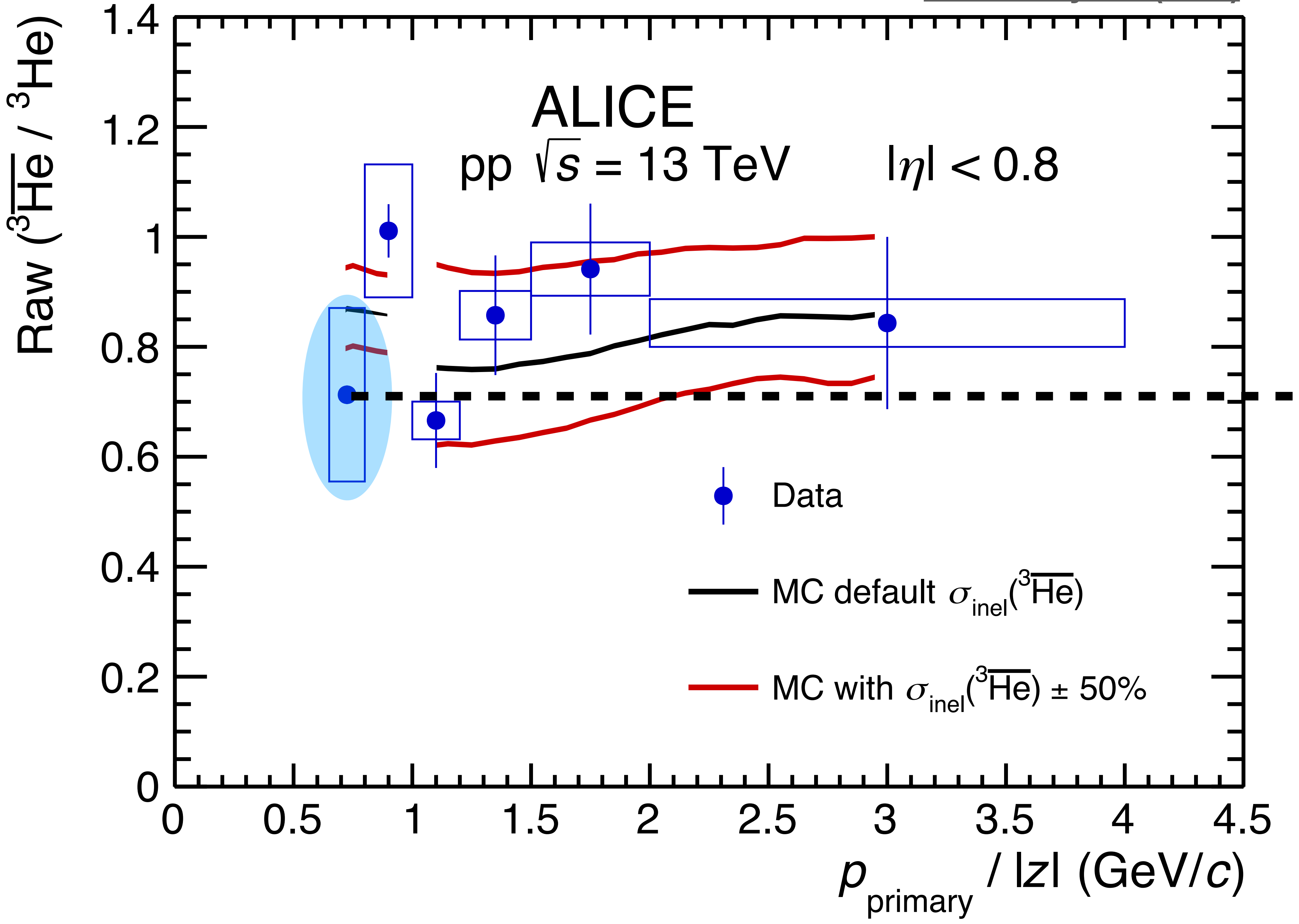

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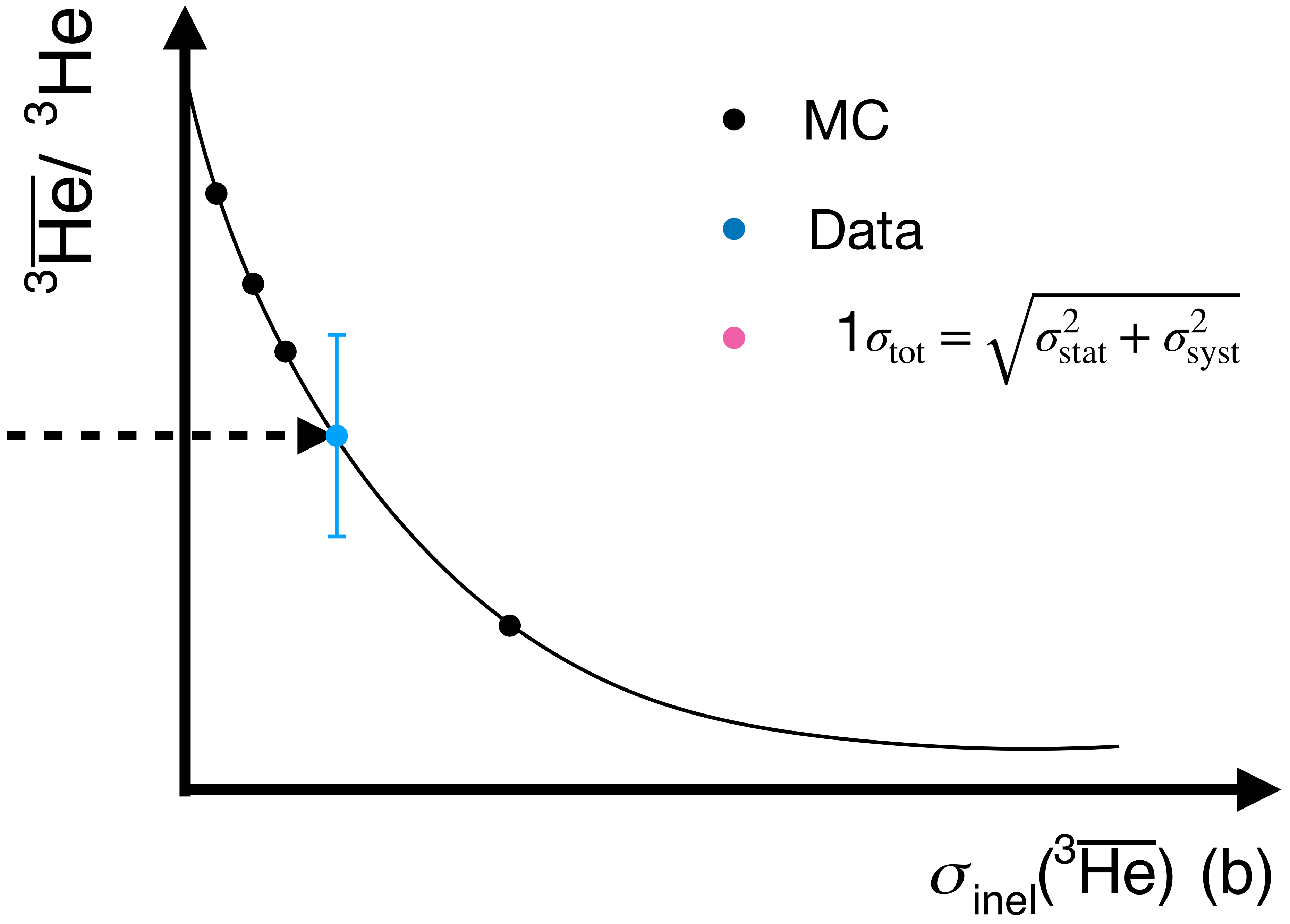

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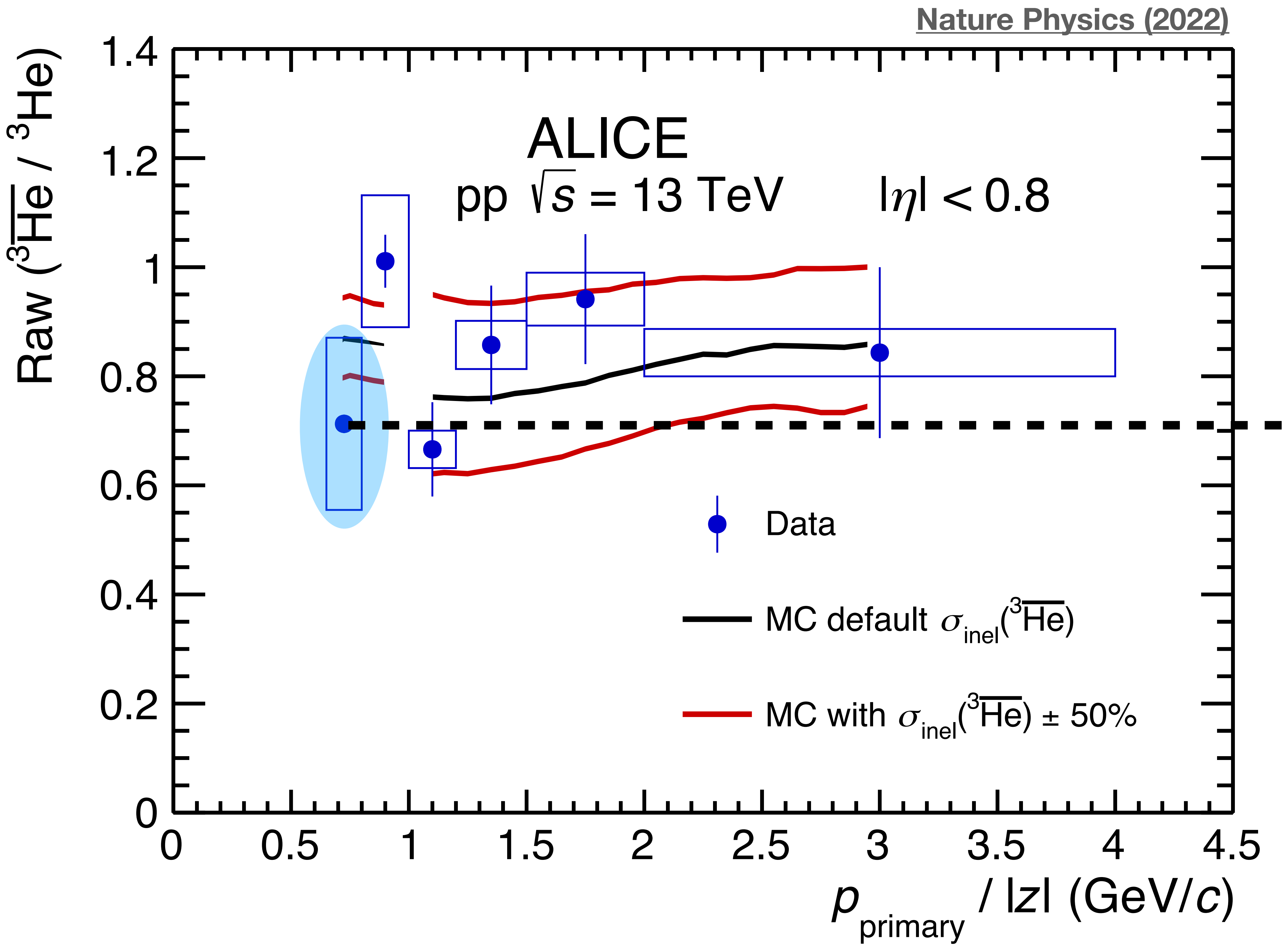

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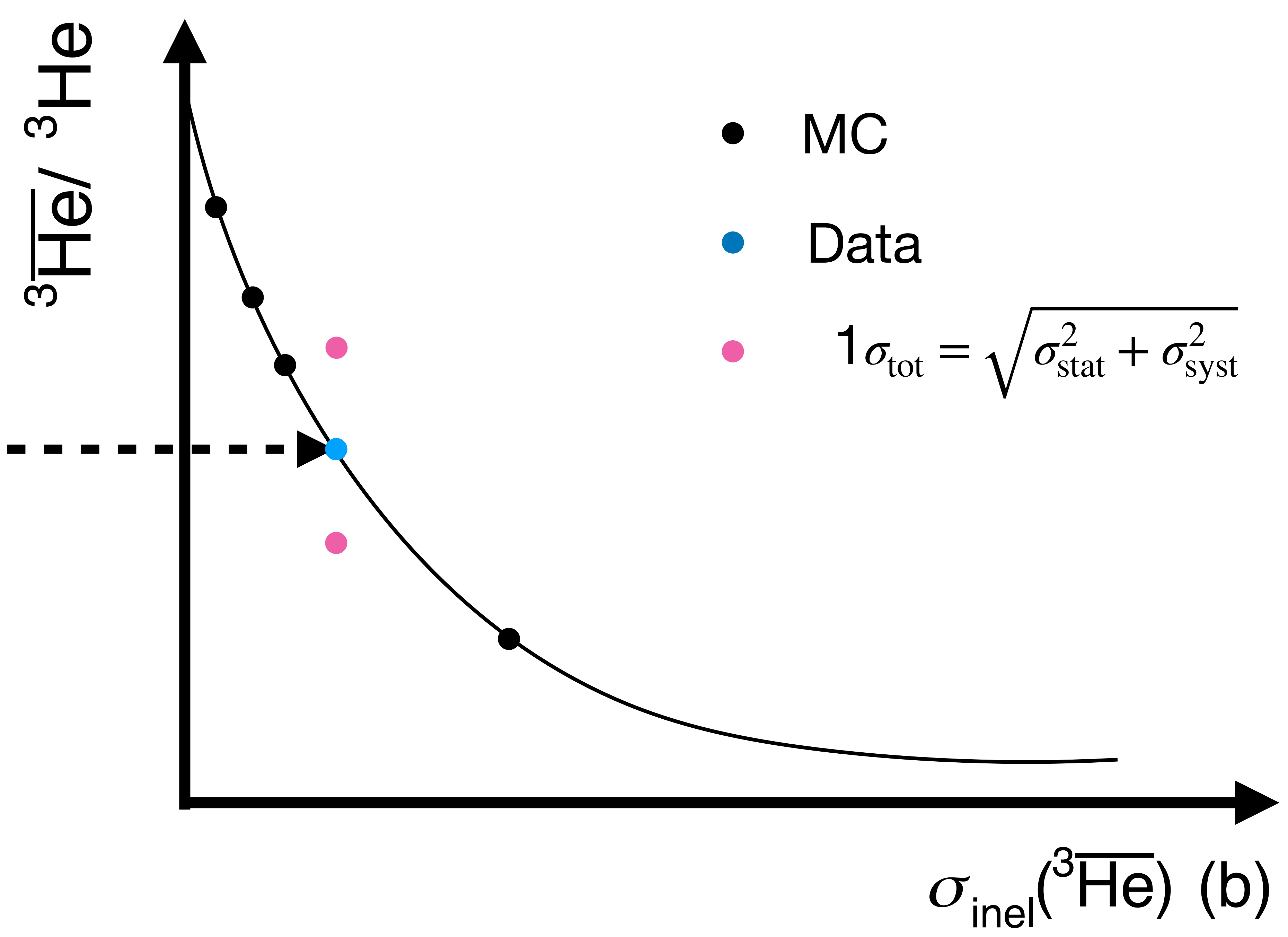

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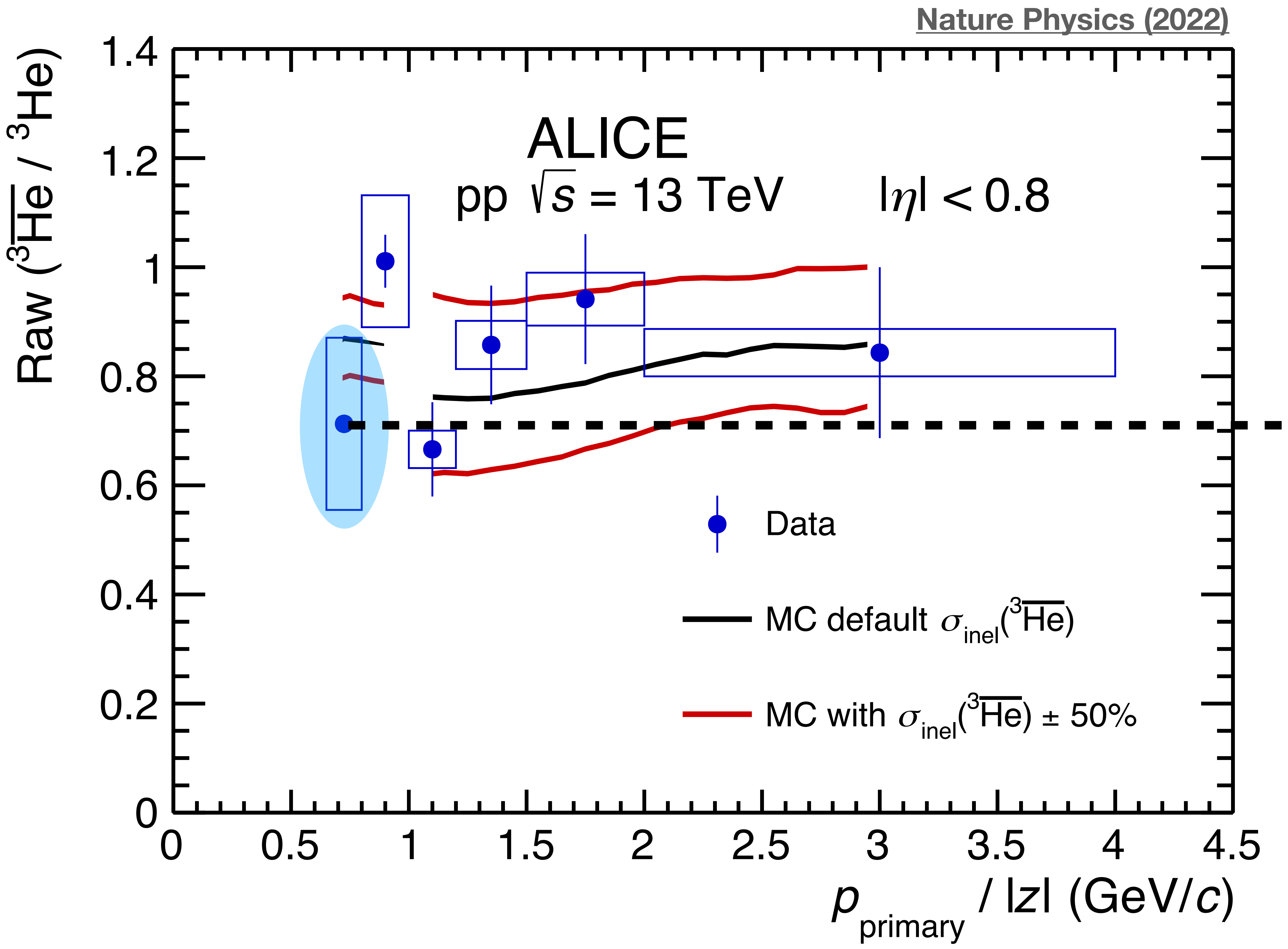

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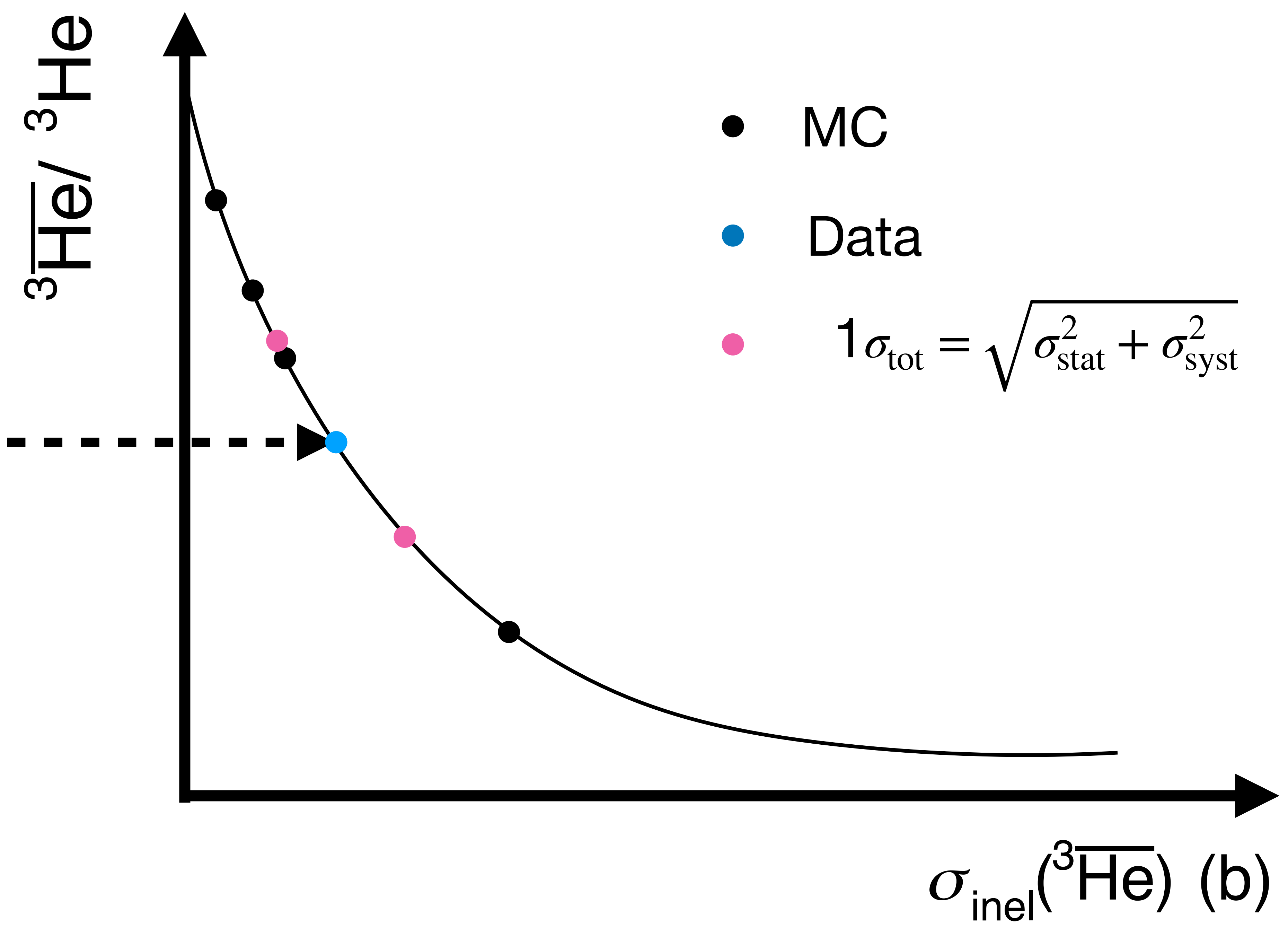

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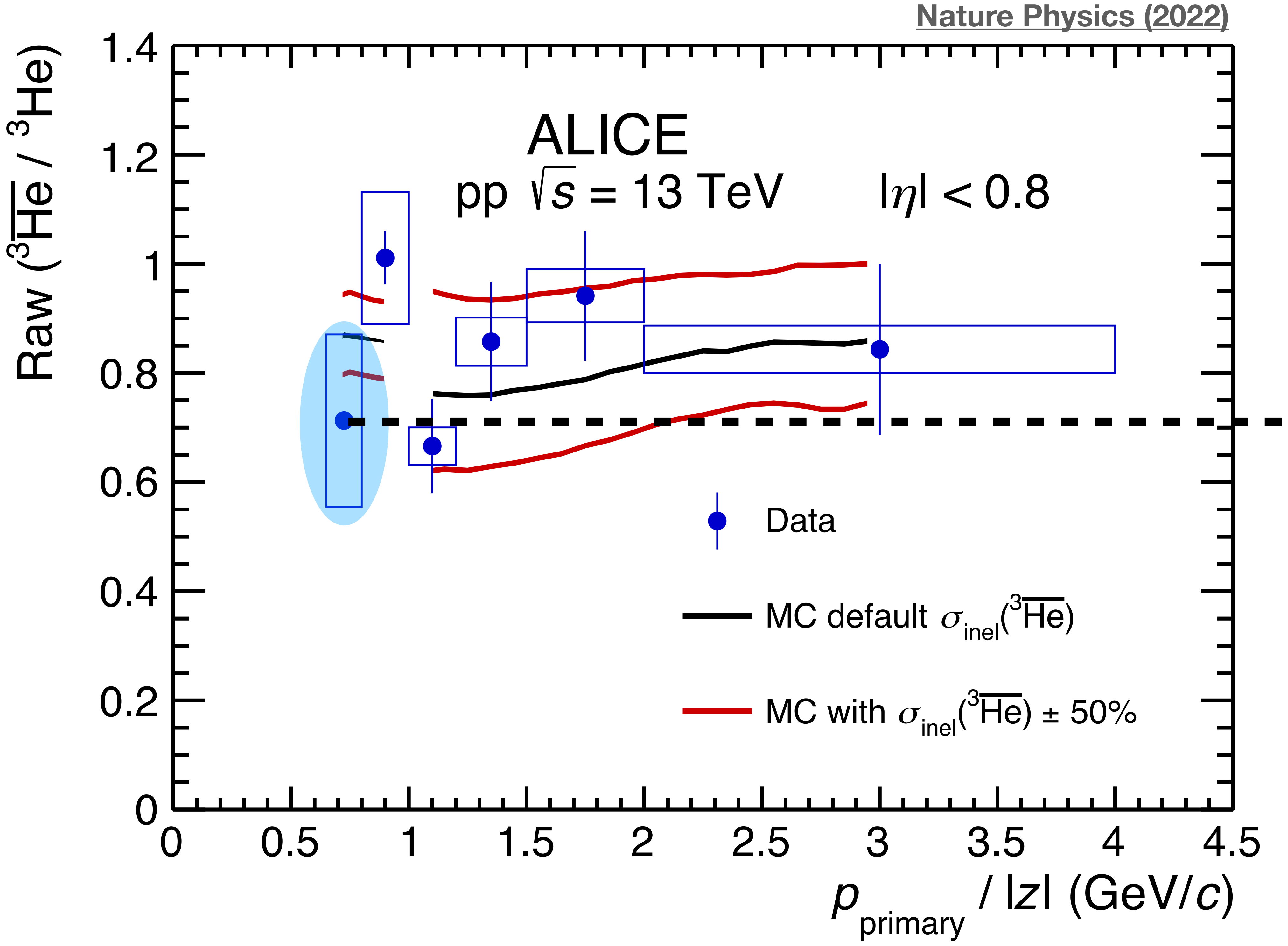

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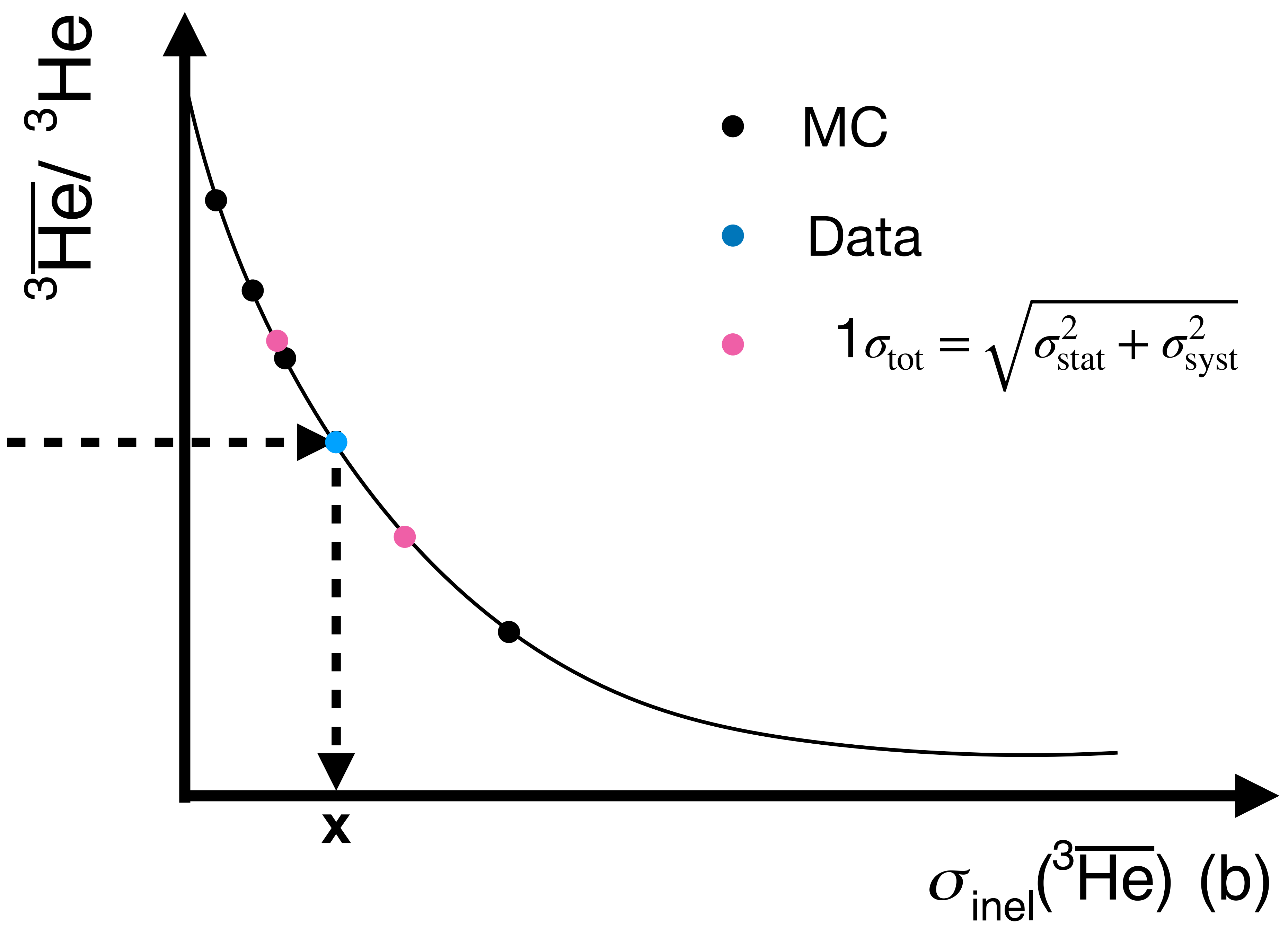

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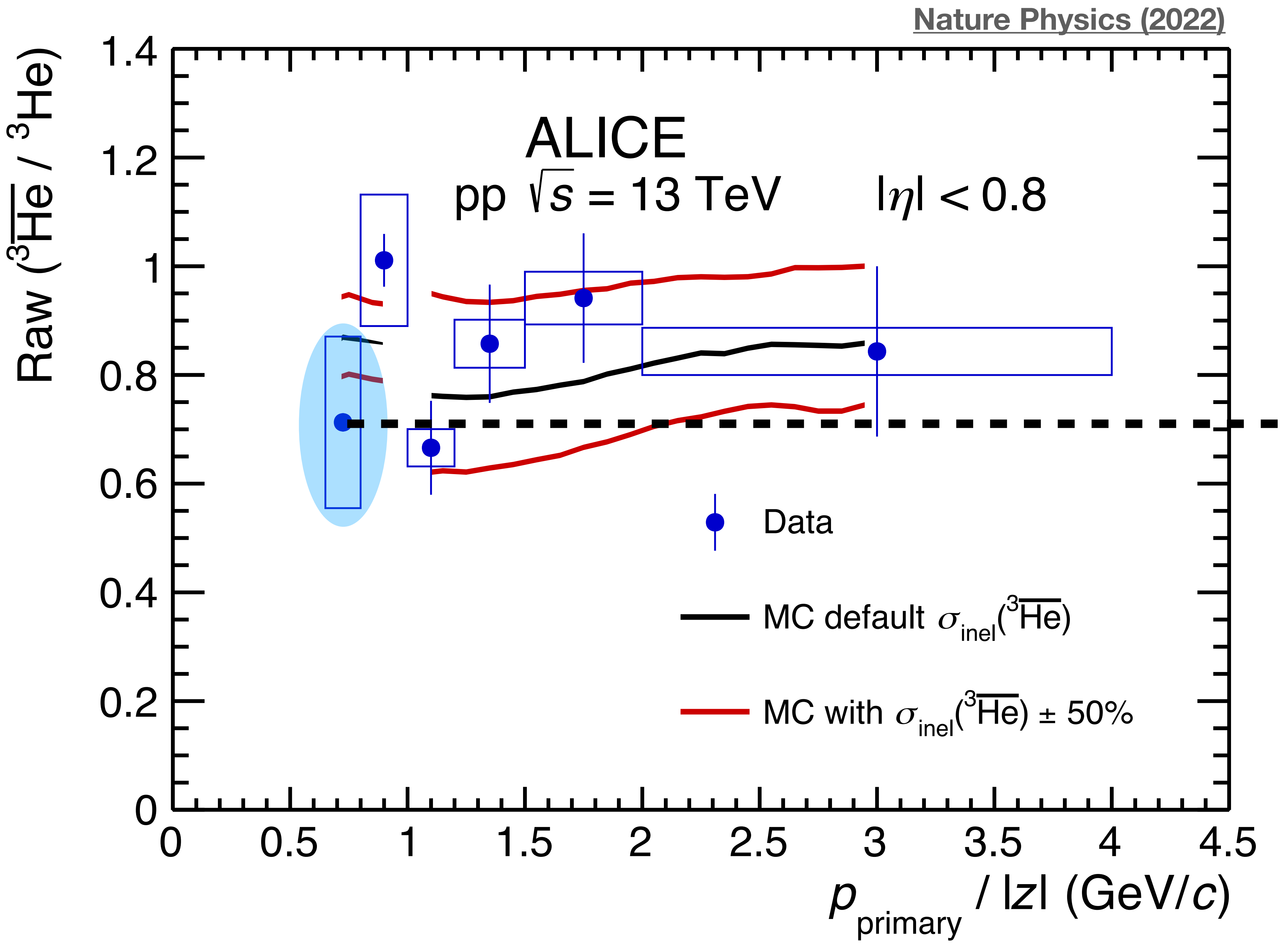

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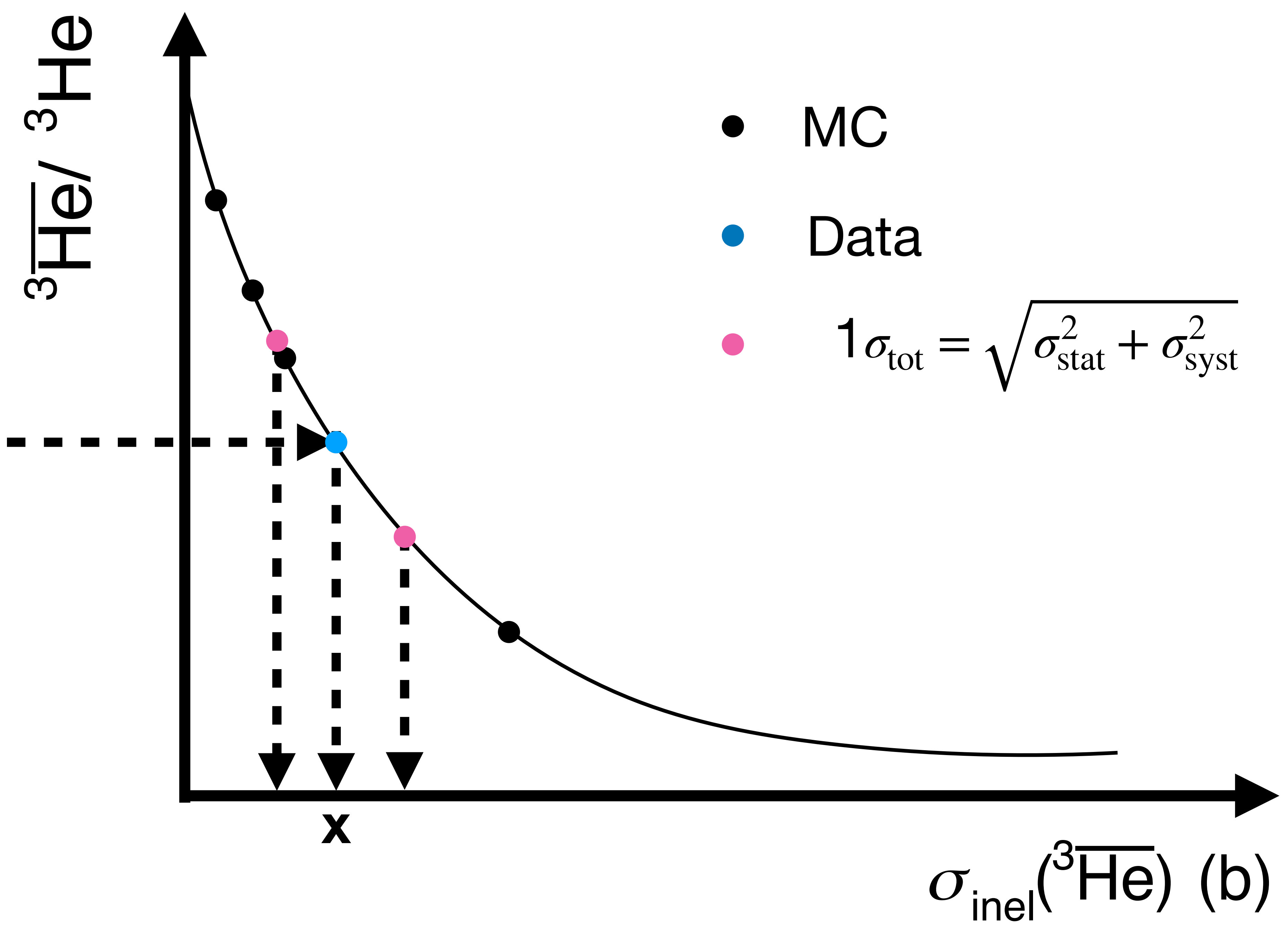

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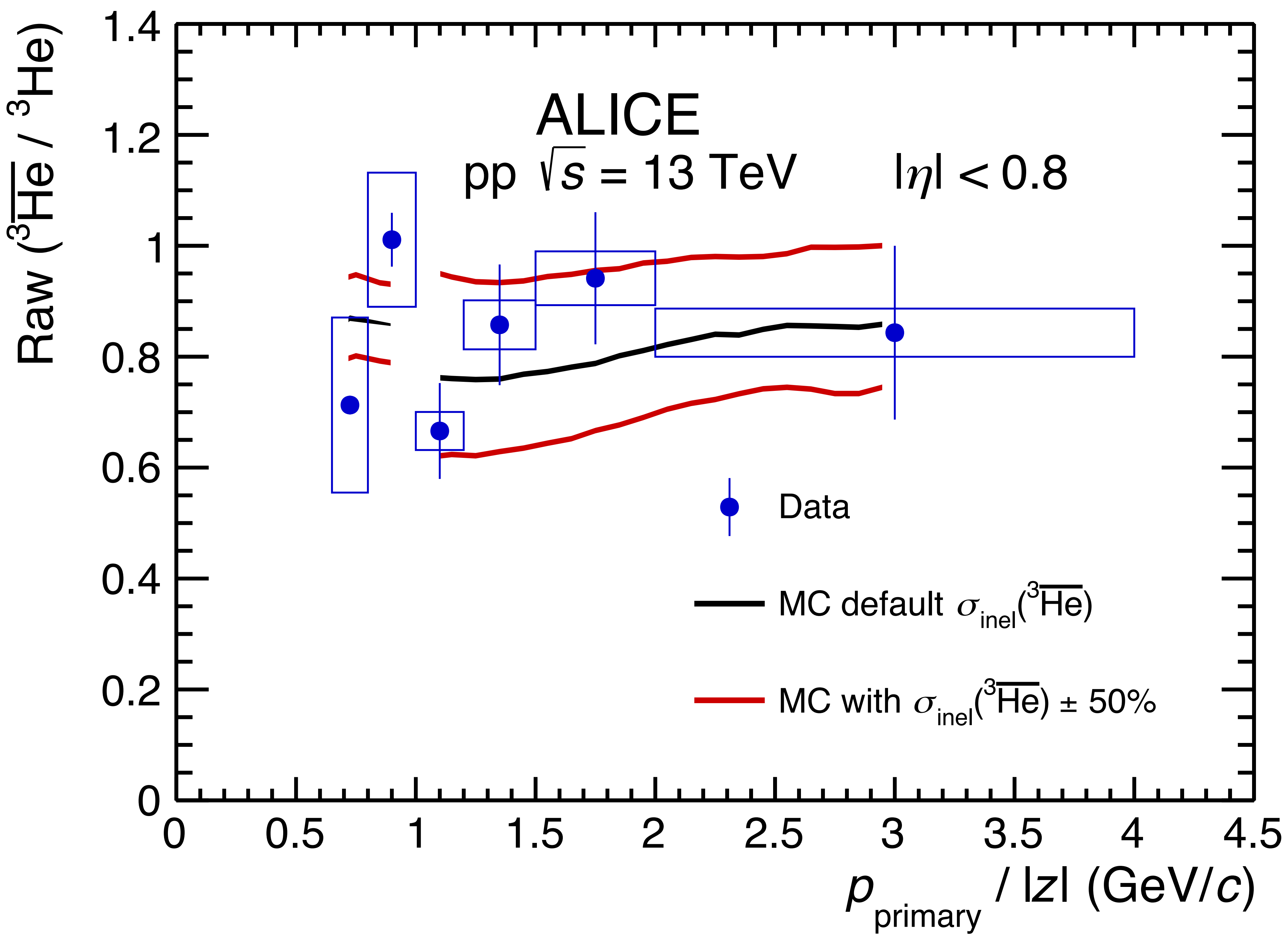

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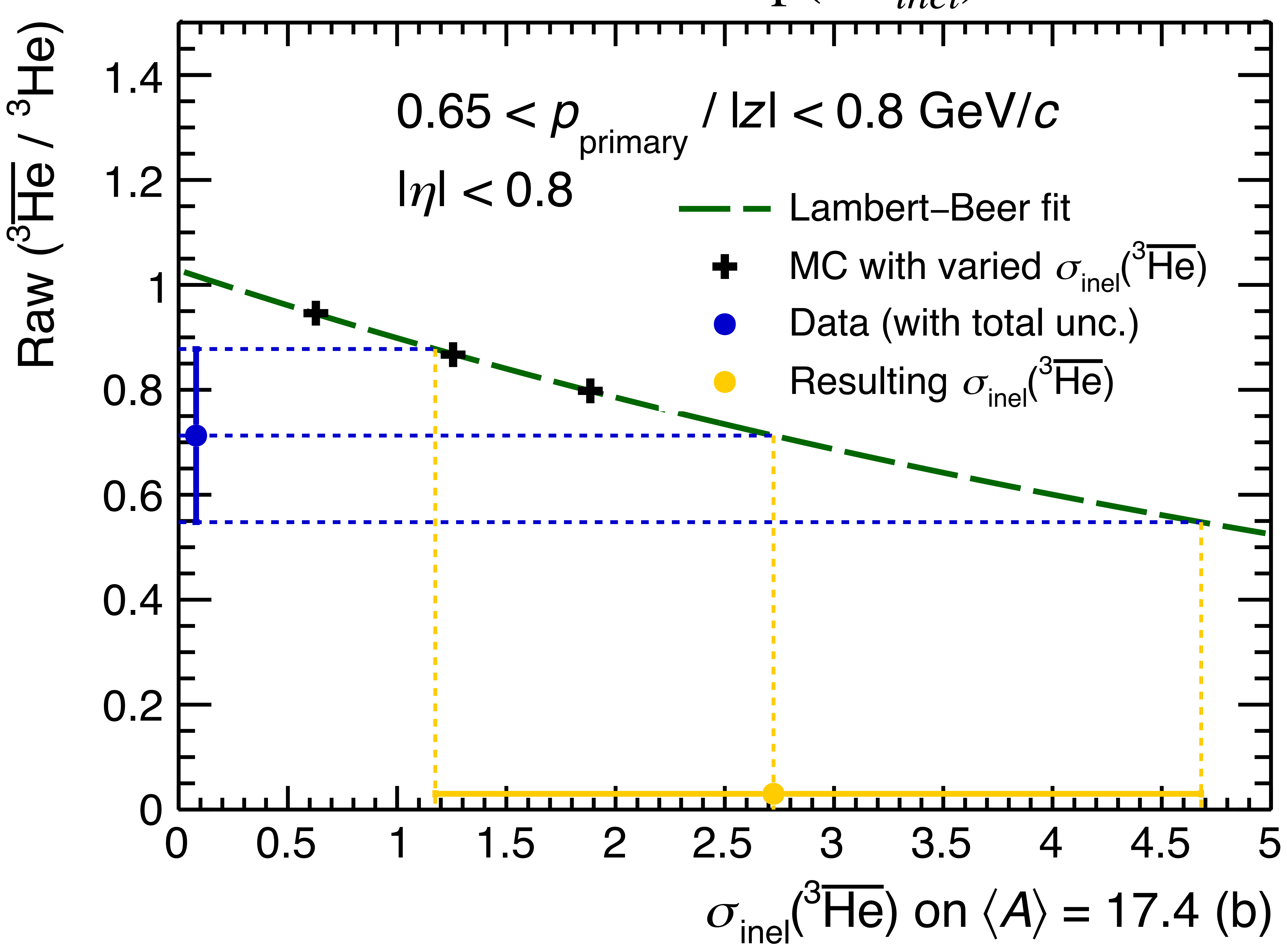

Nature Physics (2022)

TOF-to-TPC method

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

- experimental data → central value
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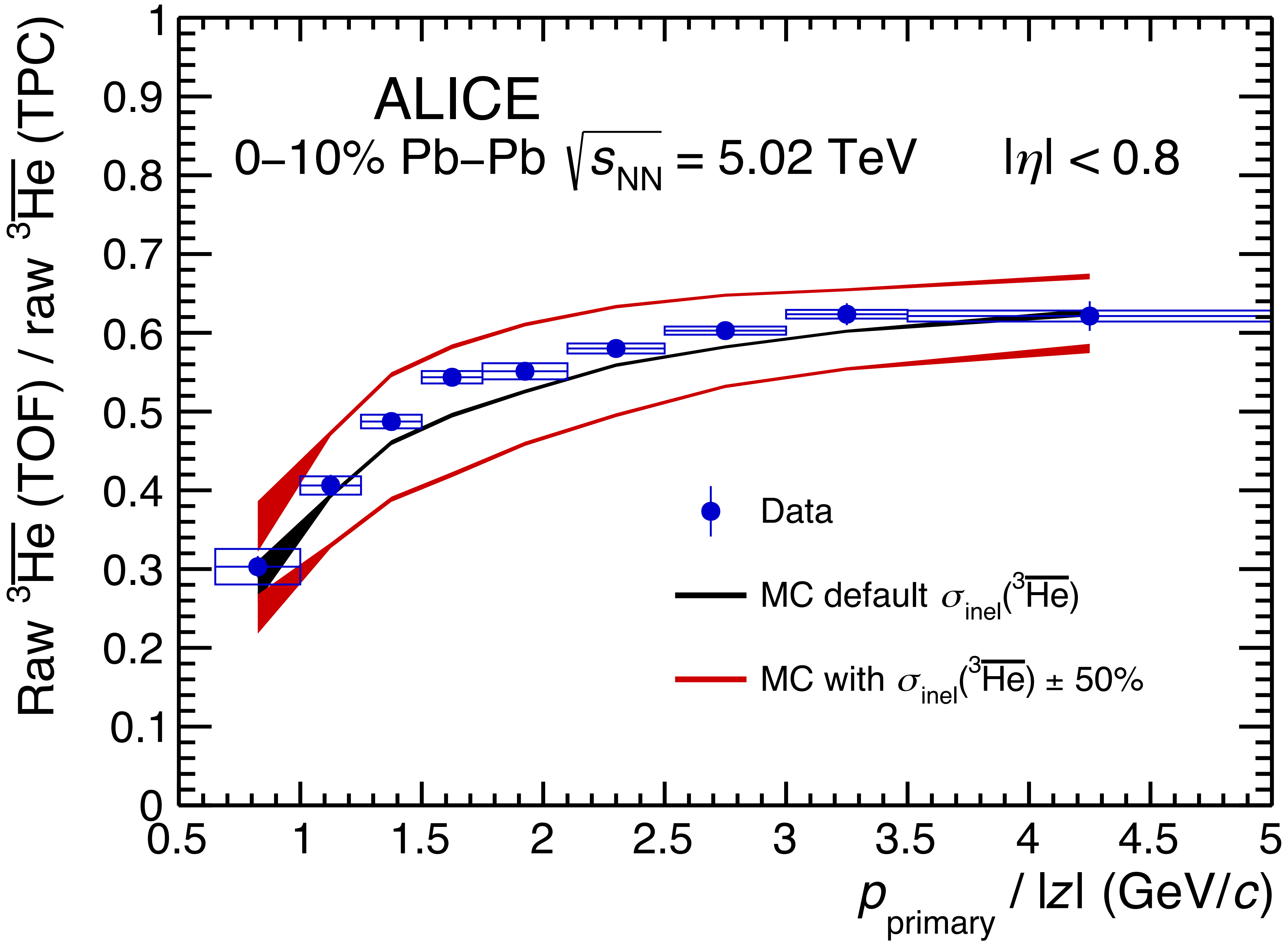
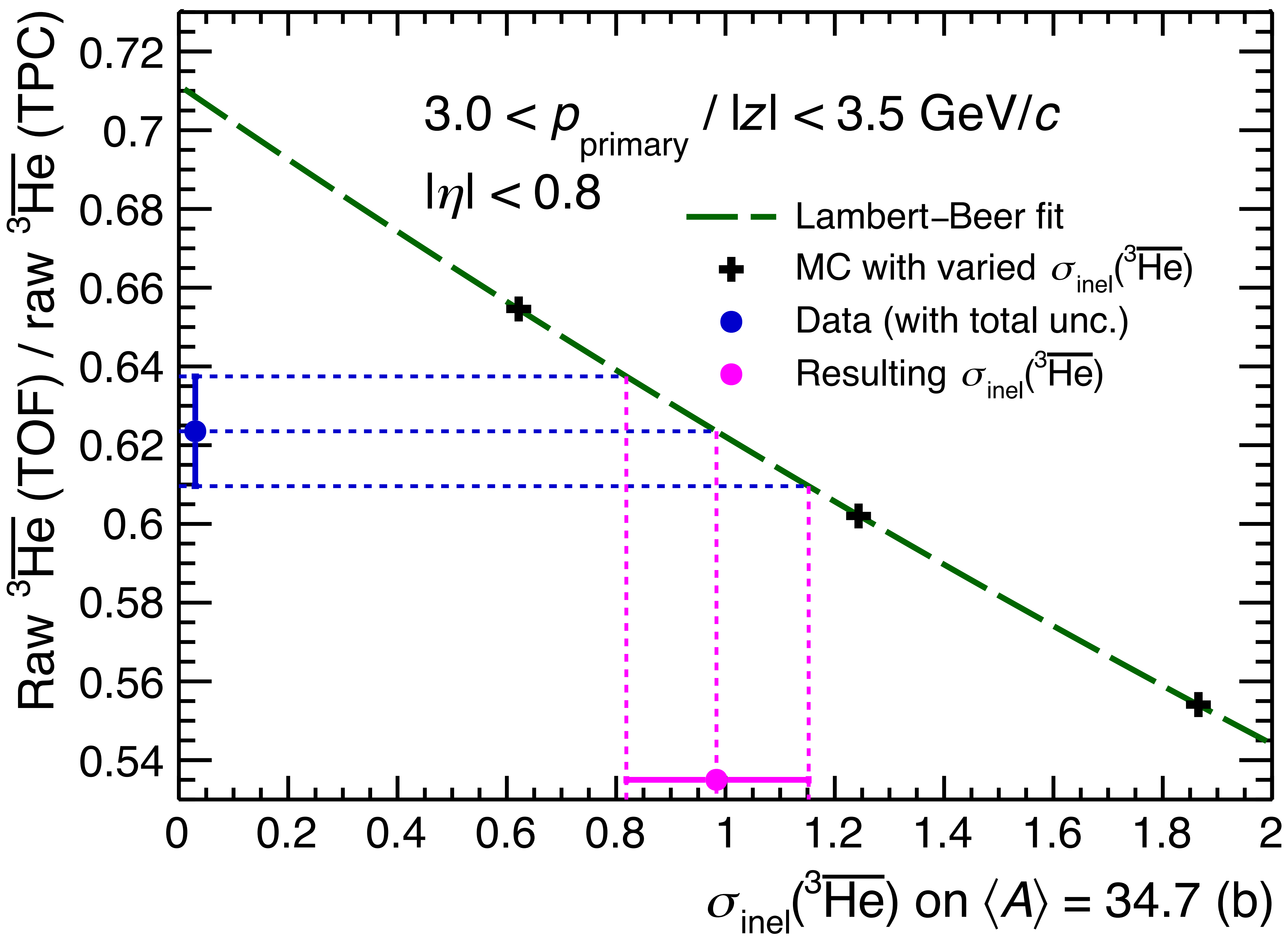
Same procedure applied for TOF-to-TPC matching method

TOF-to-TPC matching



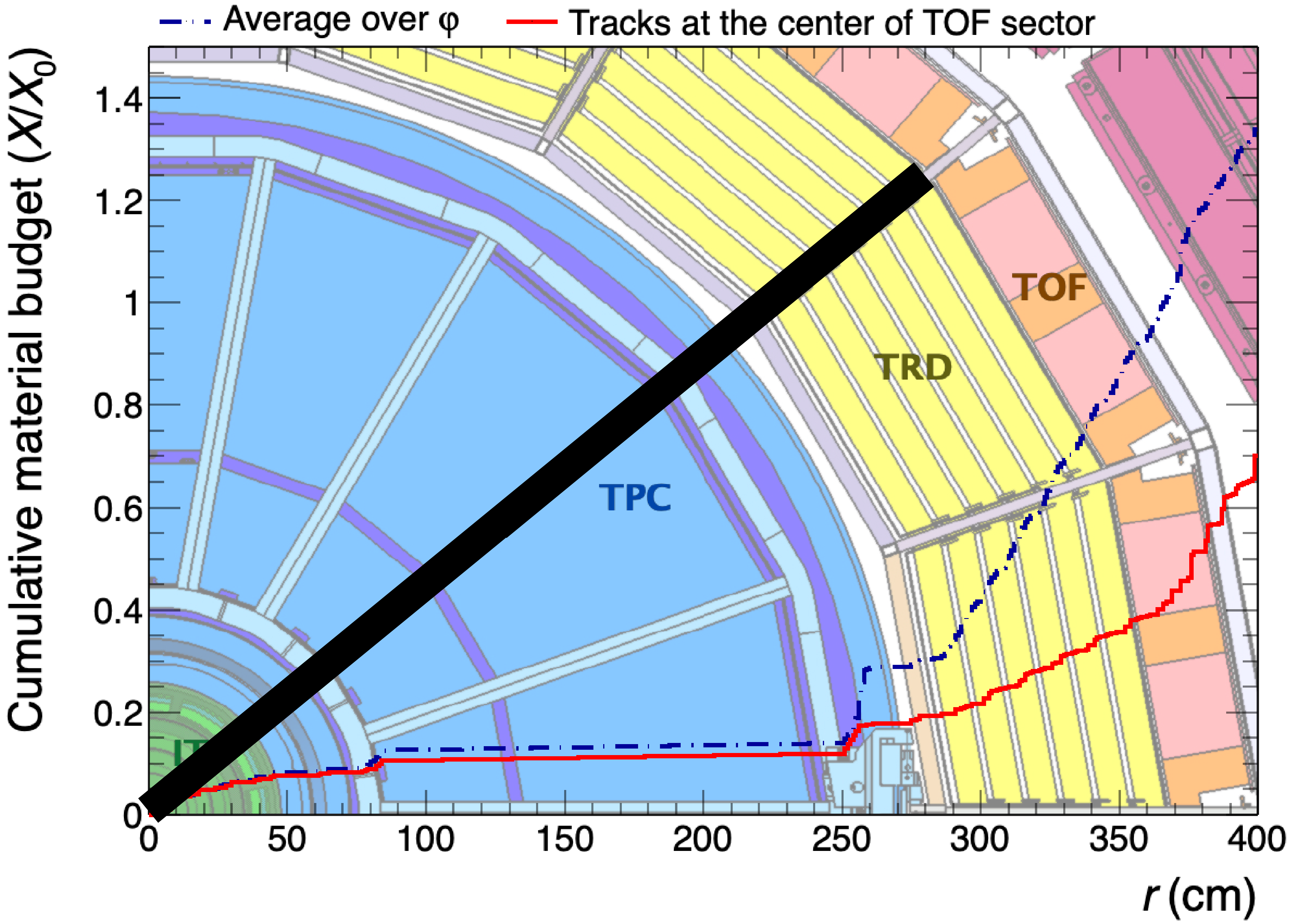
TOF/TPC ∝ $\exp(-\sigma_{inel})$



Nature Physics (2022)

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



PRL 125, 162001 (2020)

- Average material

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

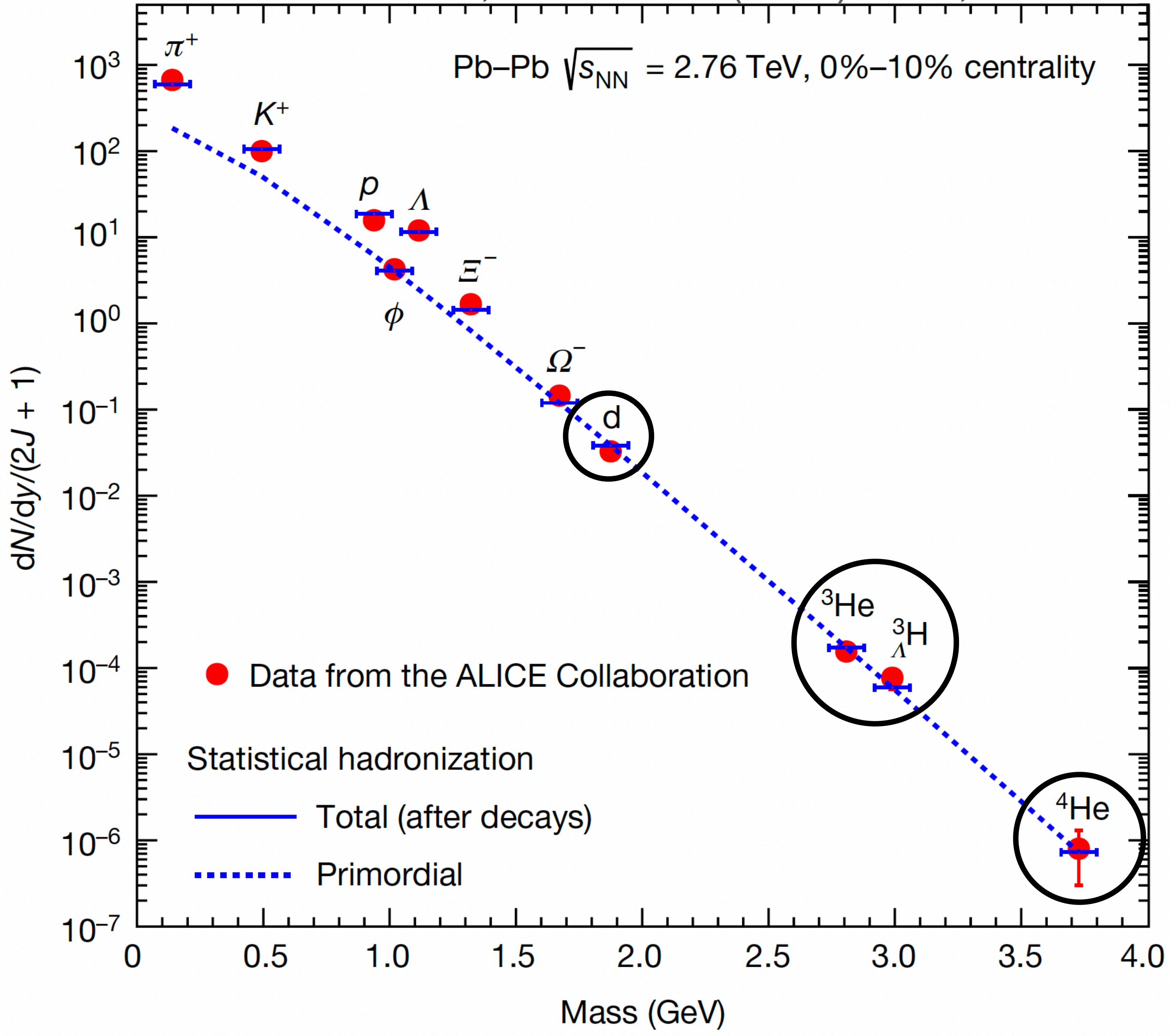
- Antimatter-to-matter method: 31.8
- TOF-to-TPC method: 34.7

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

(Anti)nuclei production mechanisms

- Statistical Hadronisation Model (SHM)
  - describes the yields of light-flavoured hadrons by requiring thermal and hadron-chemical equilibrium
  - canonical ensemble (CSM): local conservation of quantum numbers (S, Q and B)

Andronic et al., Nature 561 (2018) 7723, 321-330



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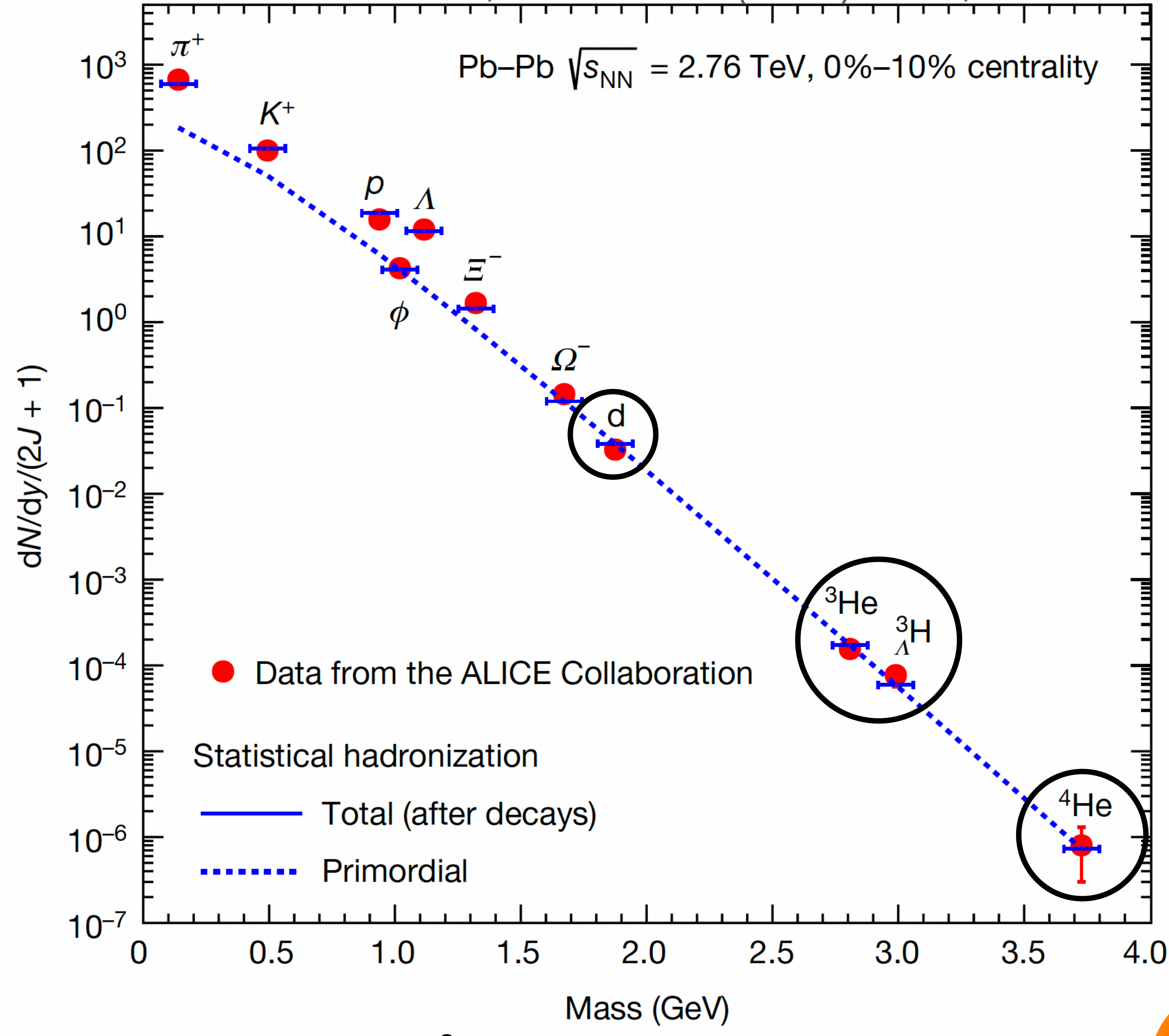
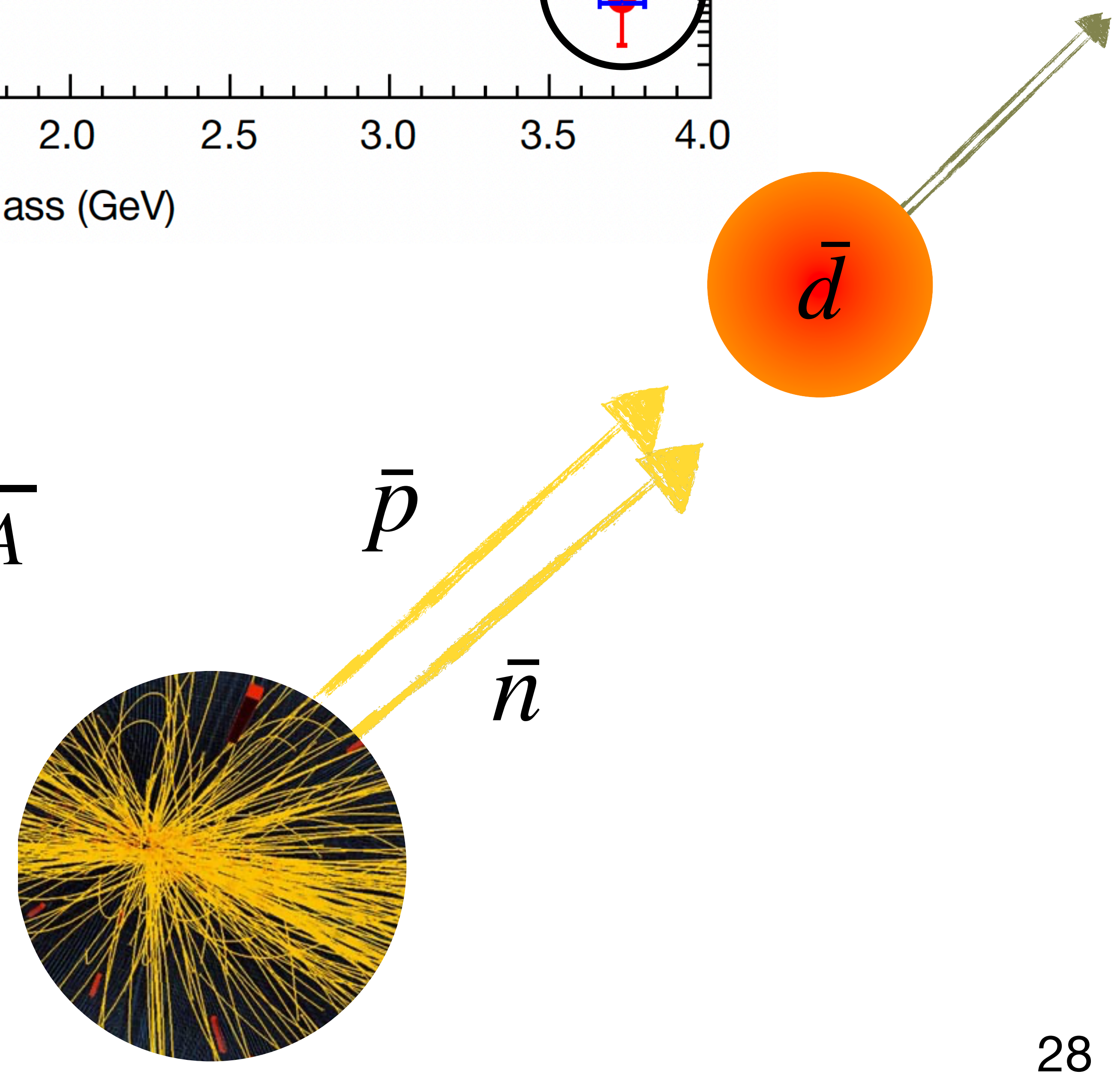
- Coalescence Model
  - Nuclei are formed by nucleons coalescing after freeze-out
  - Depends on phase-space of produced nucleons (momentum, distance) and deuteron Wigner function

Andronic et al., Nature 561 (2018) 7723, 321-330



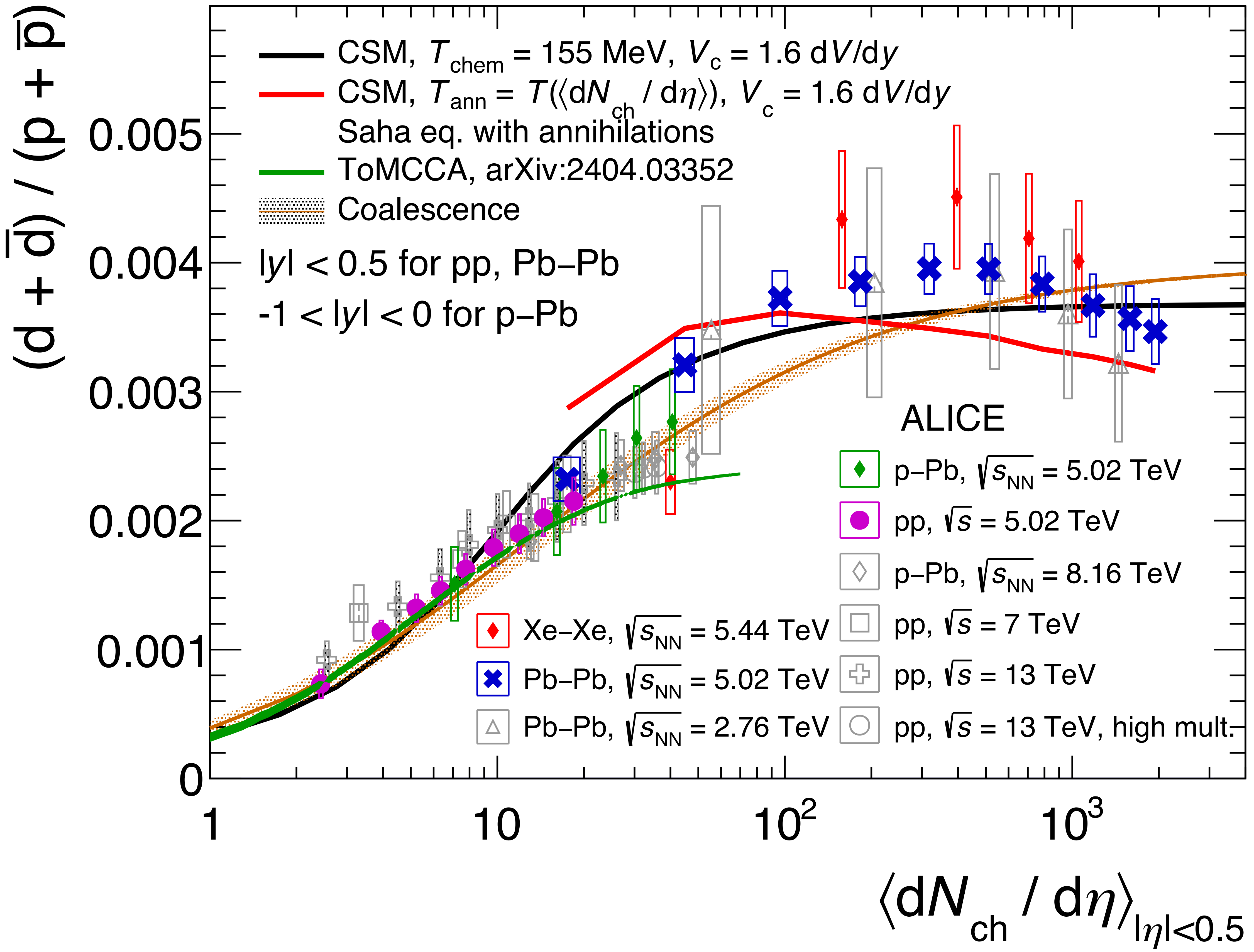
$$B_A = \frac{E_A \frac{d^3 N_A}{d^3 p_A}}{\left(E_p \frac{d^3 N_p}{d^3 p_p}\right)^A}$$



CSM vs Coalescence

- Nucleus to nucleon yield ratio evolves smoothly with multiplicity
  - Dependence on the system size
- Deuterons: no conclusion on the different models
- Helium-3: model predictions different but insufficient data precision

ALICE, arxiv:2405.19826



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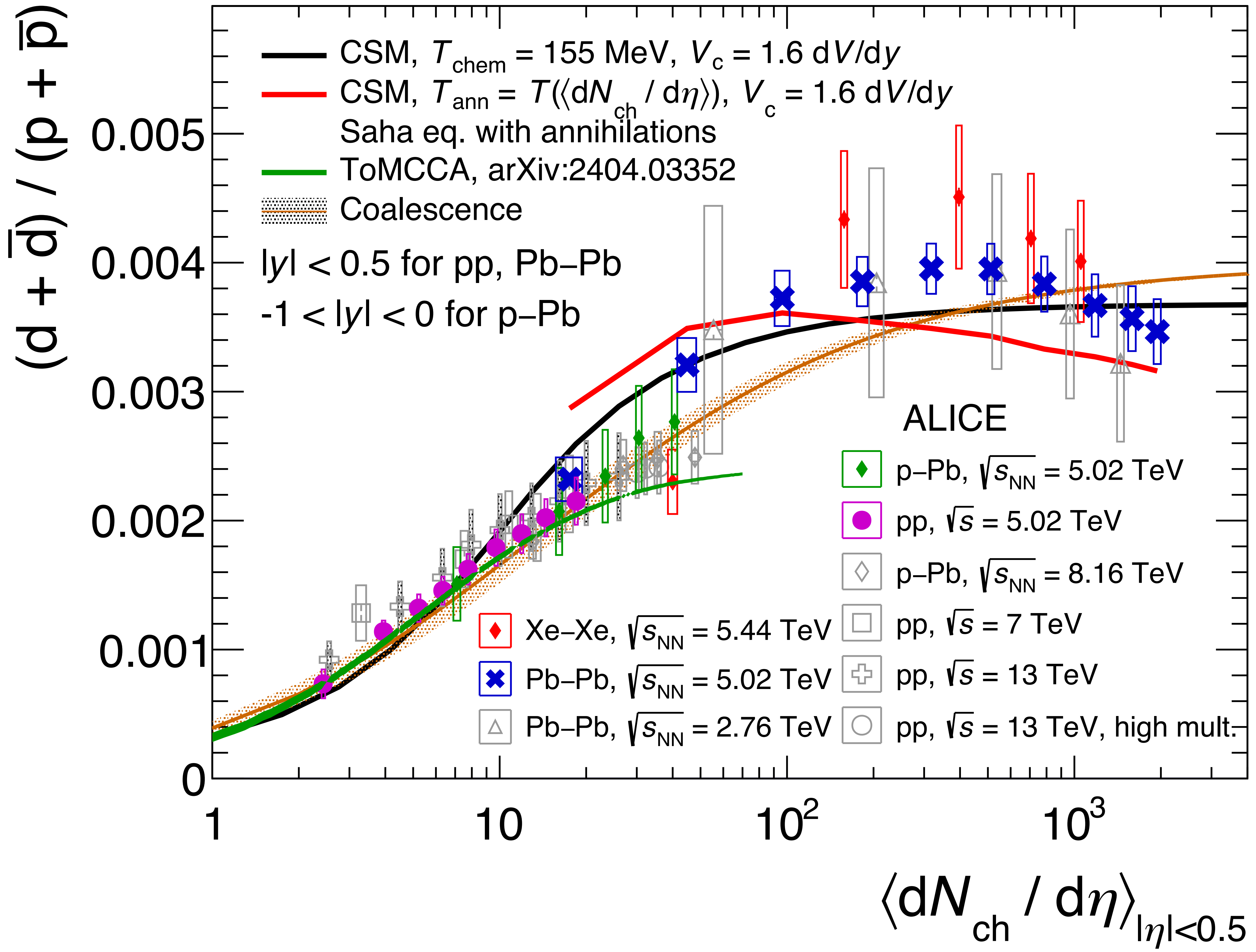

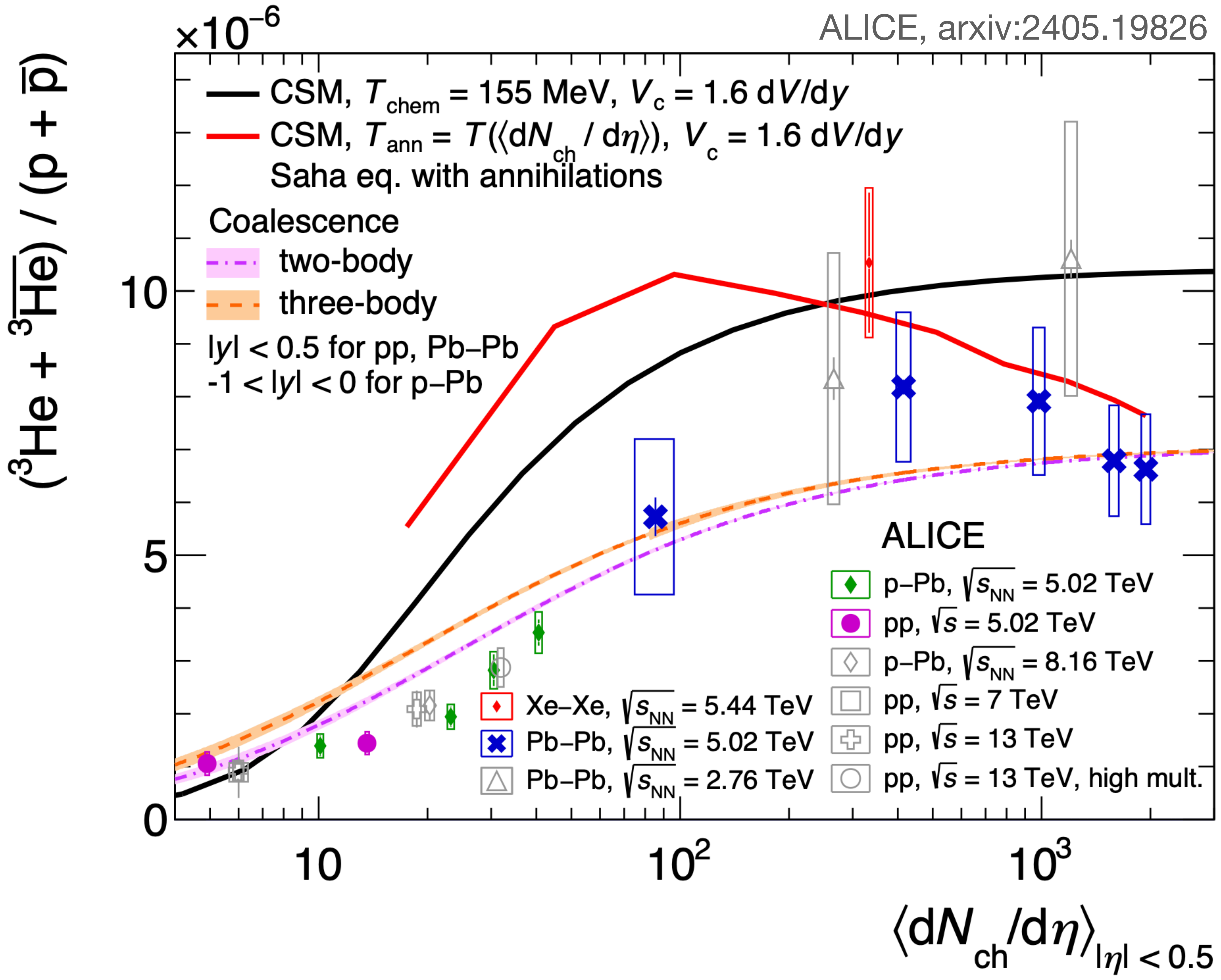

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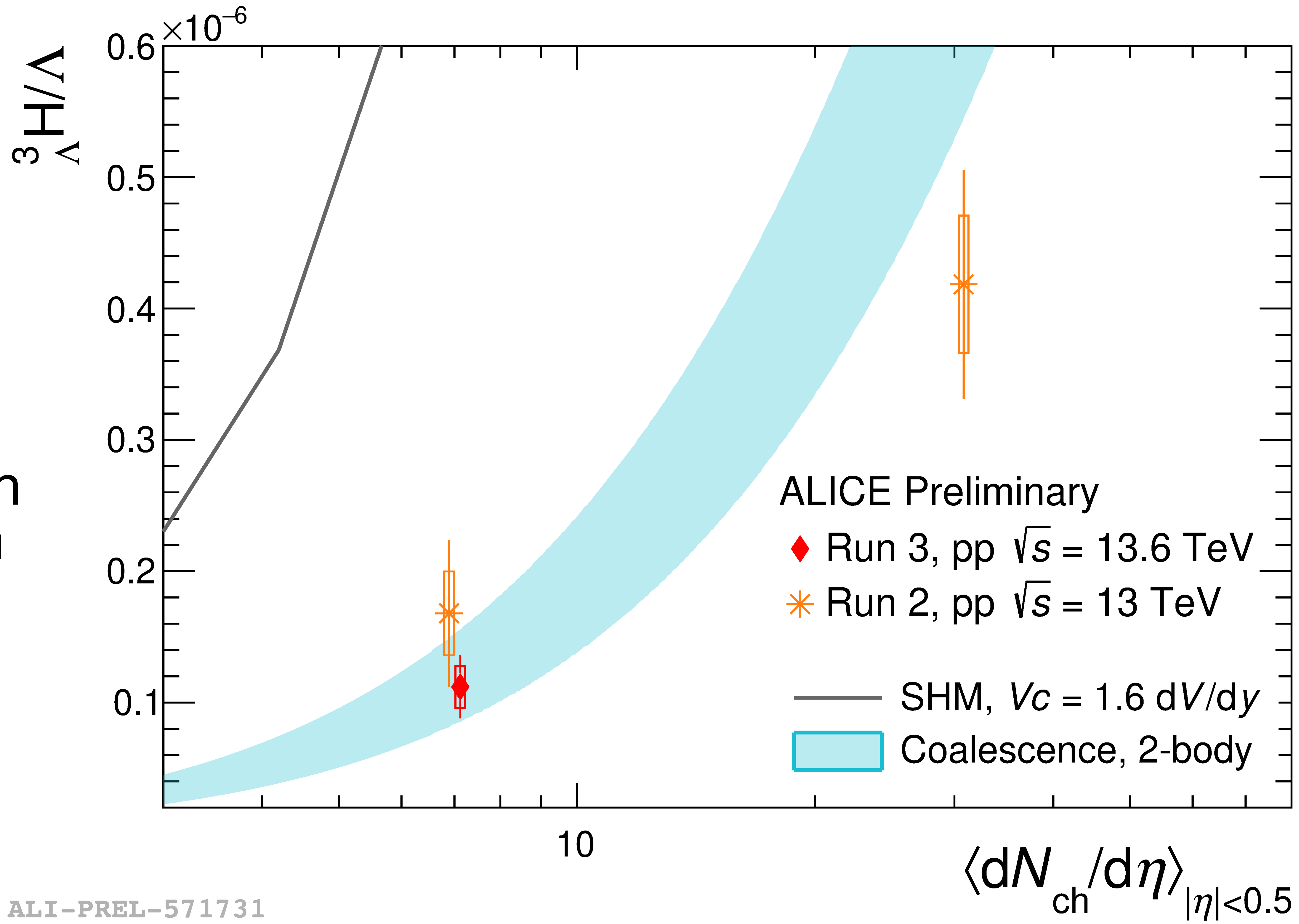
- Hypertriton has a size of ~10 fm
  - Relevant for coalescence but not SHM
- Coalescence provides the best description of hypertriton measurement in pp collision system



ALI-PREL-571731

Inelastic cross section

- Relation between annihilation term and the inelastic cross section

$$\frac{1}{\tau} = \beta c \left(n_H(\mathbf{r})\sigma_{\text{inel}}^{3\overline{\text{He}}}(p) + n_{He}(\mathbf{r})\sigma_{\text{inel}}^{3}\,\overline{\text{He}}^{4}\text{He}(p) \right)$$

- Parametrisation in Geant4, where R_A is a function of target nuclei nucleon number

$$\sigma_{hA}^{\text{inel}} = \pi R_A^2 \ln \left(1 + \frac{A\sigma_{hN}^{\text{tot}}}{\pi R_A^2} \right)$$

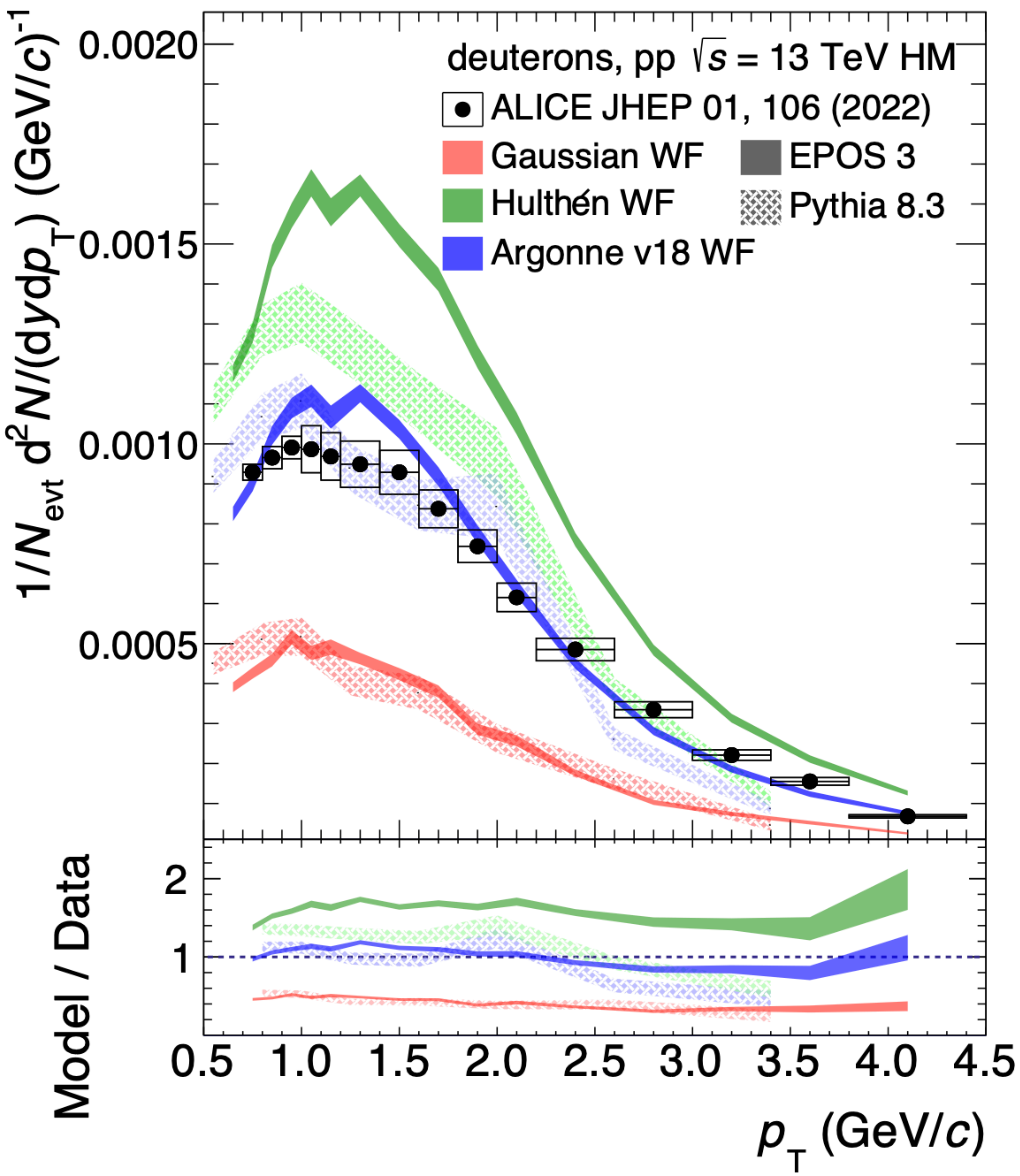
Sophisticated Coalescence

- Largest uncertainty: production models
- Wigner formalism - the new era of coalescence studies

$$\mathscr{D}(\vec{q},\vec{r}) = \int \mathrm{d}^3\xi e^{-i\vec{q}\cdot\vec{\xi}}\varphi_{\mathrm{d}}(\vec{r}+\vec{\xi}/2)\varphi^*_{\mathrm{d}}(\vec{r}-\vec{\xi}/2)$$

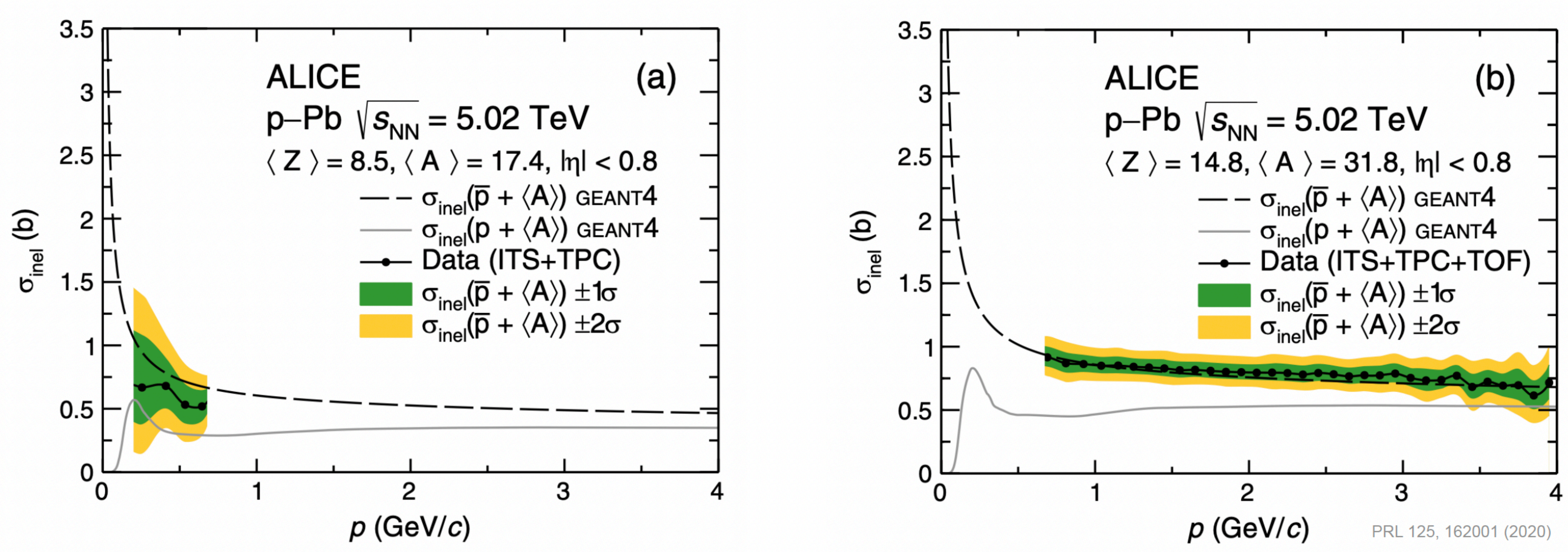
$$\mathscr{P}\left(r_0, q\right) = \int d^3r_{\mathrm{d}} \int d^3r H_{\mathrm{pn}}\left(\vec{r},\vec{r}_{\mathrm{d}}; r_0\right)\mathscr{D}(\vec{q},\vec{r})$$

$$\frac{\mathrm{d}^3N_{\mathrm{d}}}{\mathrm{d}P^3_{\mathrm{d}}} = S_{\mathrm{d}}\int d^3q\mathscr{P}\left(r_0,q\right)\frac{G_{\mathrm{np}}\left(\vec{P}_{\mathrm{d}}/2+\vec{q},\vec{P}_{\mathrm{d}}/2-\vec{q}\right)}{(2\pi)^6}$$



Method benchmark: antiprotons

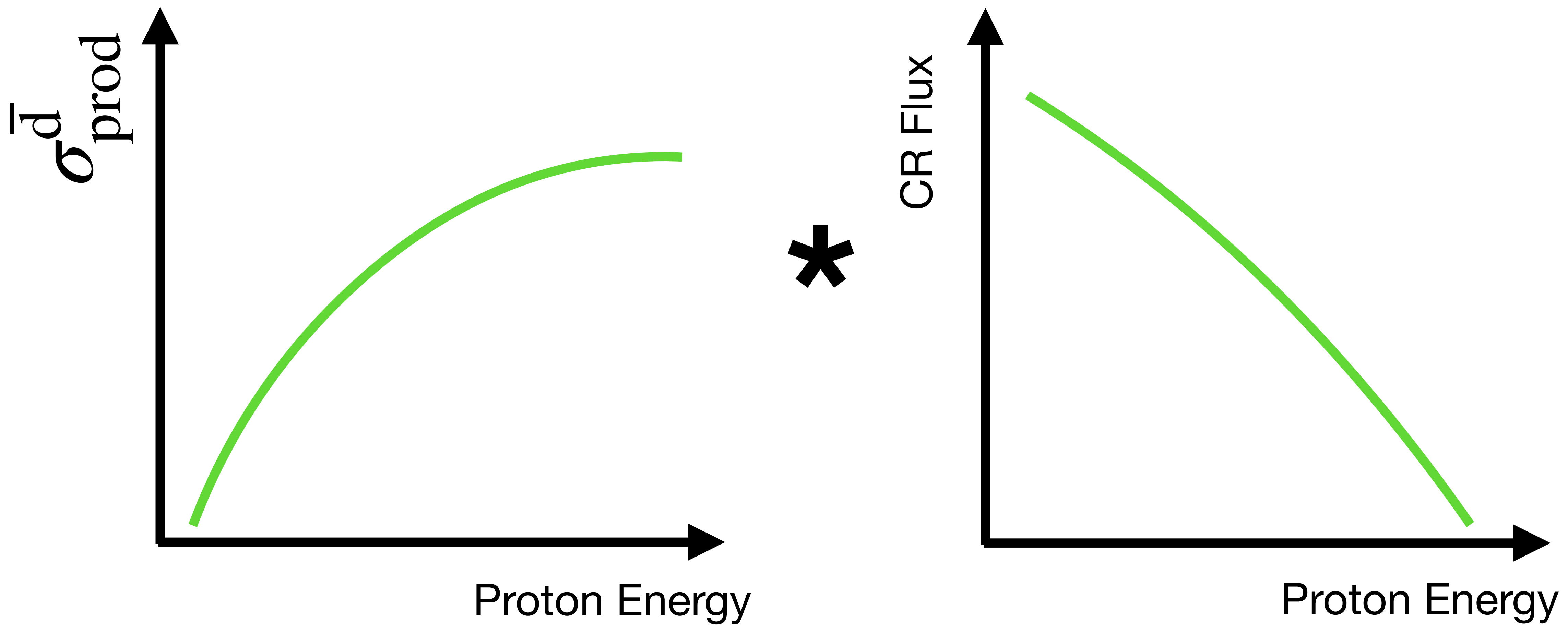
- Benchmark with well known inelastic cross-section measurement: antiprotons
- Good agreement between the data and Geant4 parametrisation constrained to available measurements



PRL 125, 162001 (2020)

Collisions in interstellar medium

Source Function



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

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

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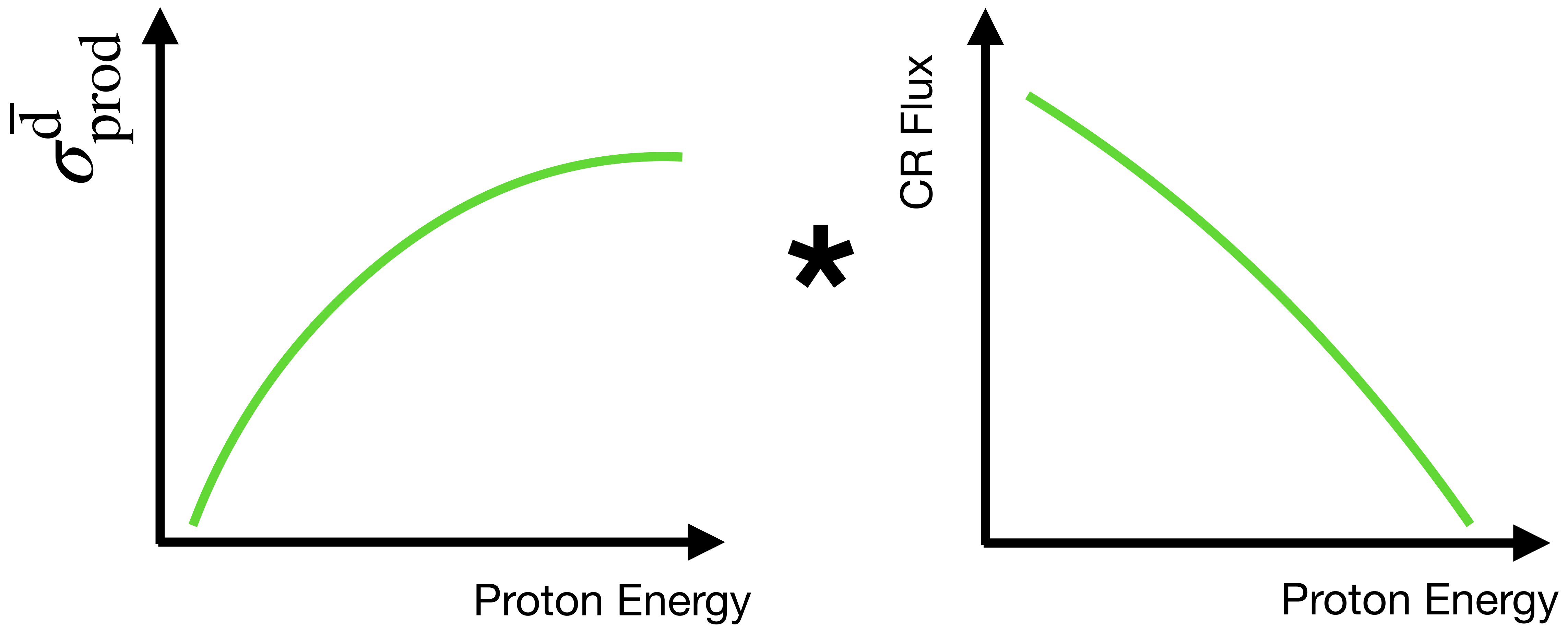

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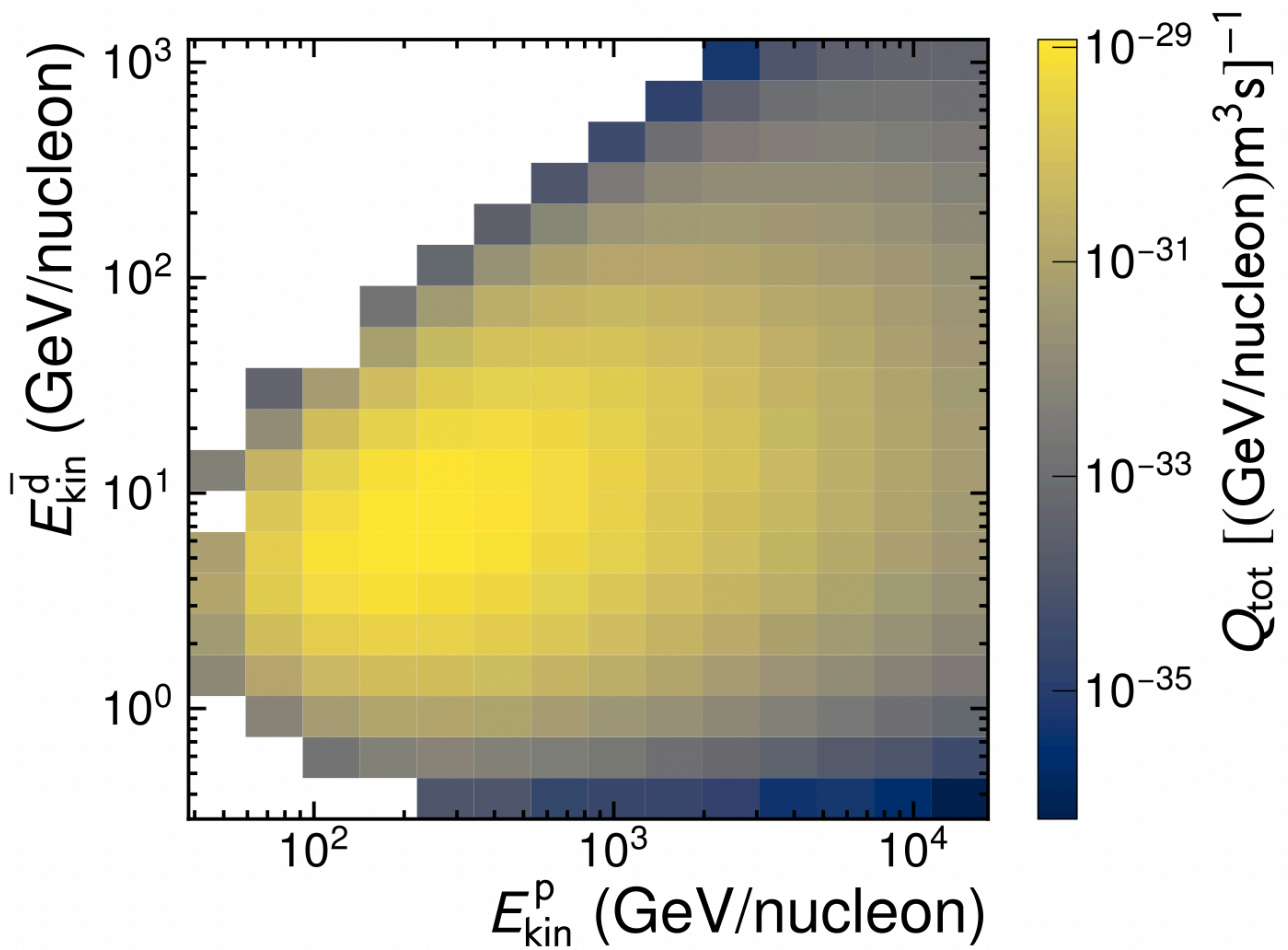

L.Šerkšnytė, S. Königstorfer et al, Phys. Rev. D 105, 083021 (2022)

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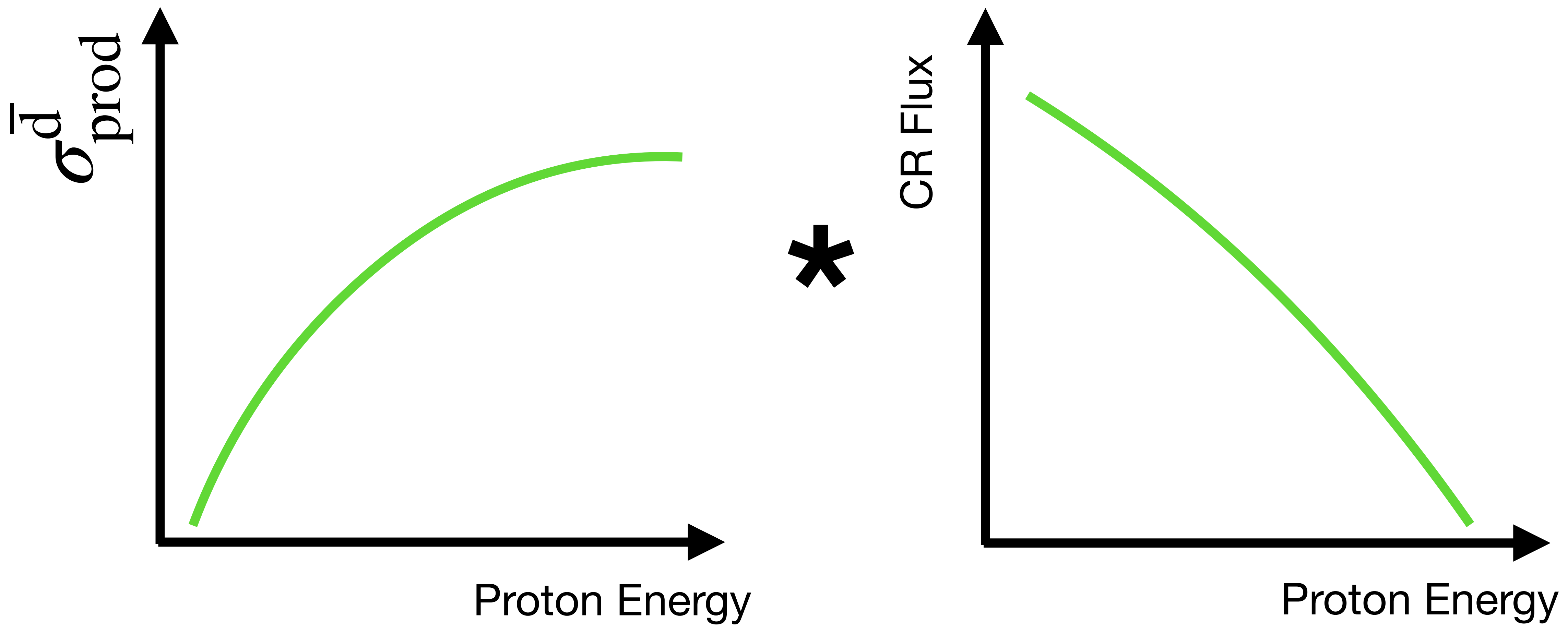

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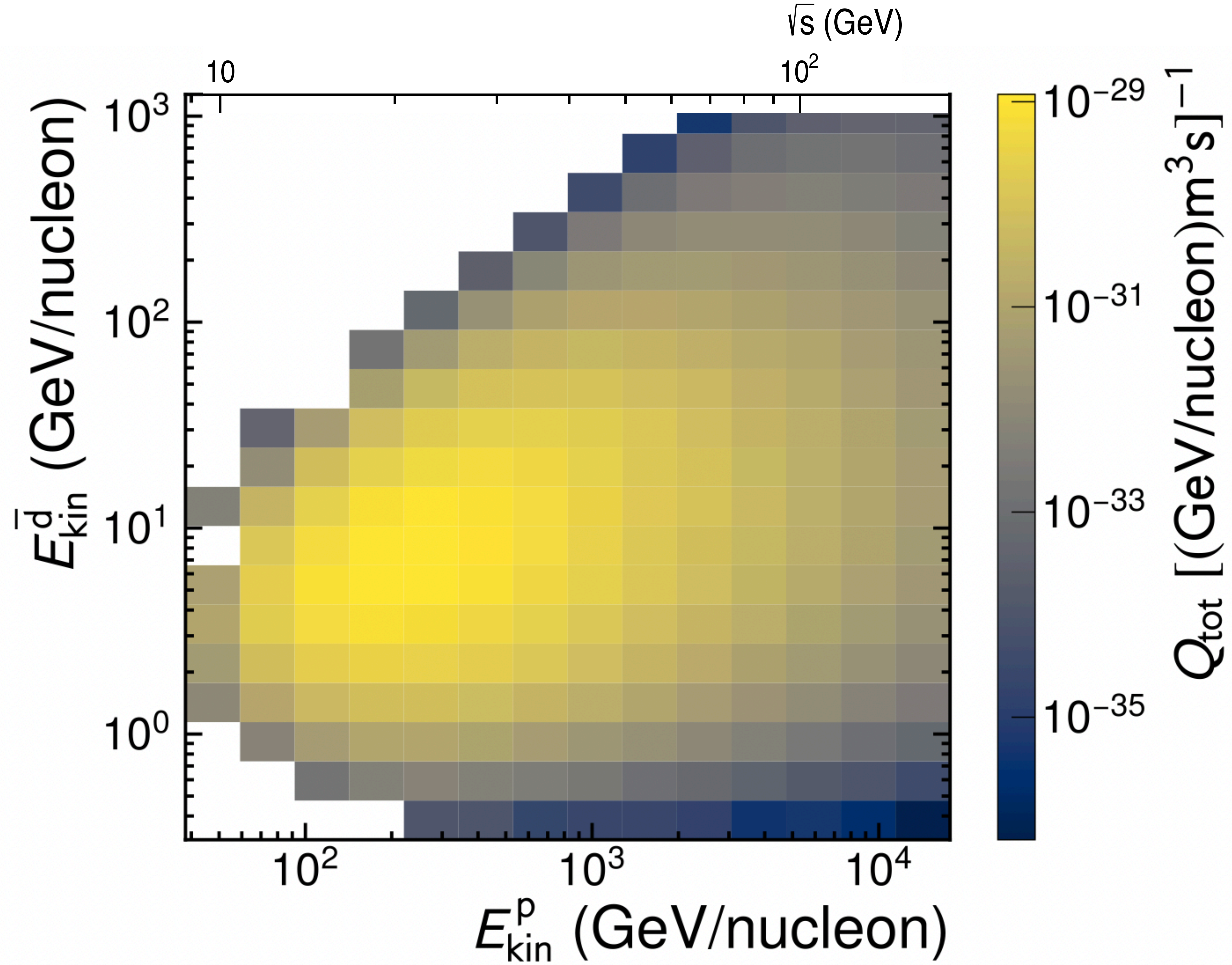

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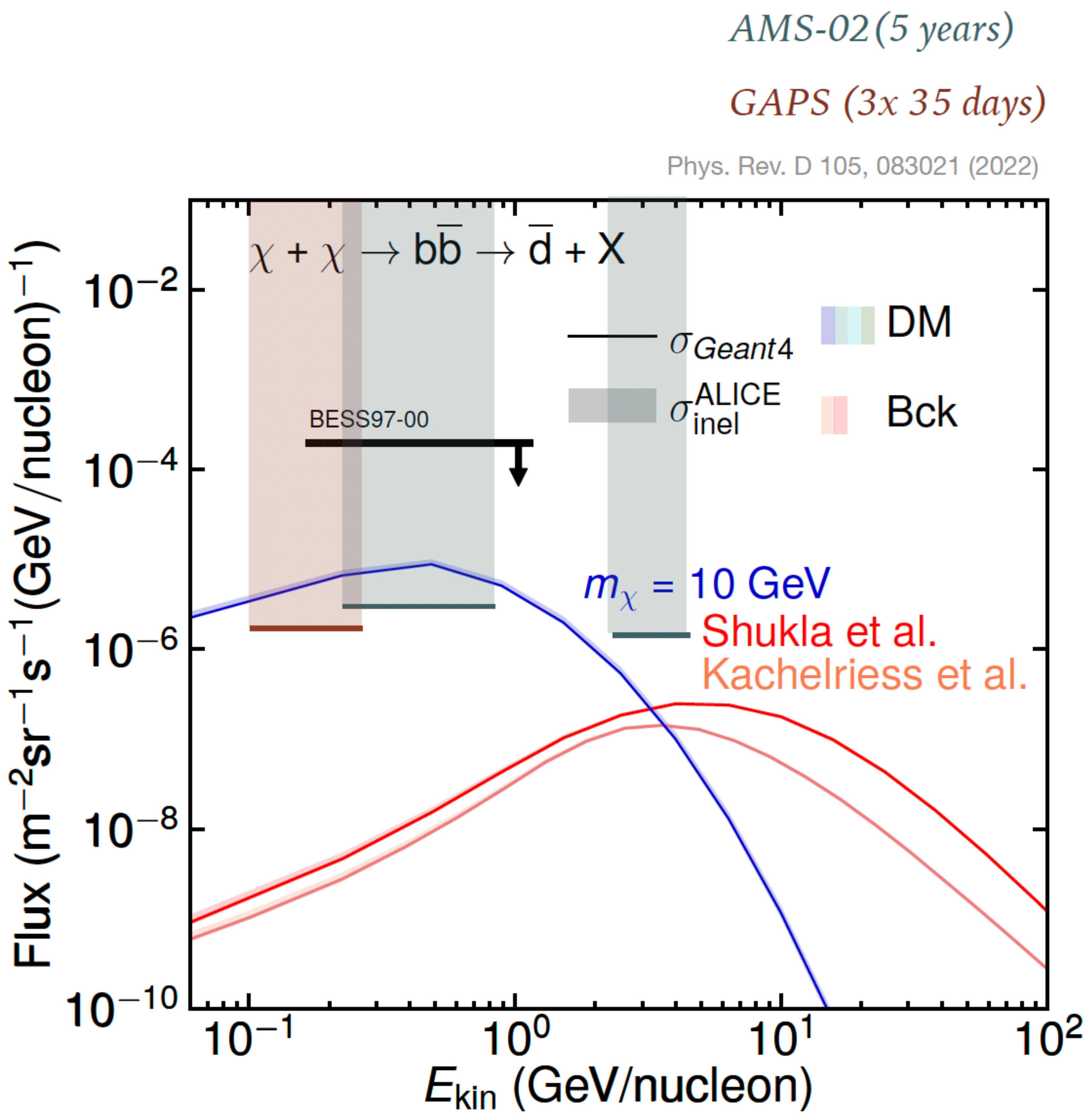
Antideuteron cosmic ray fluxes

- Uncertainty only from inelastic cross section measurement
- Different coalescence models provide order of magnitude difference
- Signal to background ratio 2-3 orders of magnitude!
- Signal fluxes decreasing with increasing DM mass



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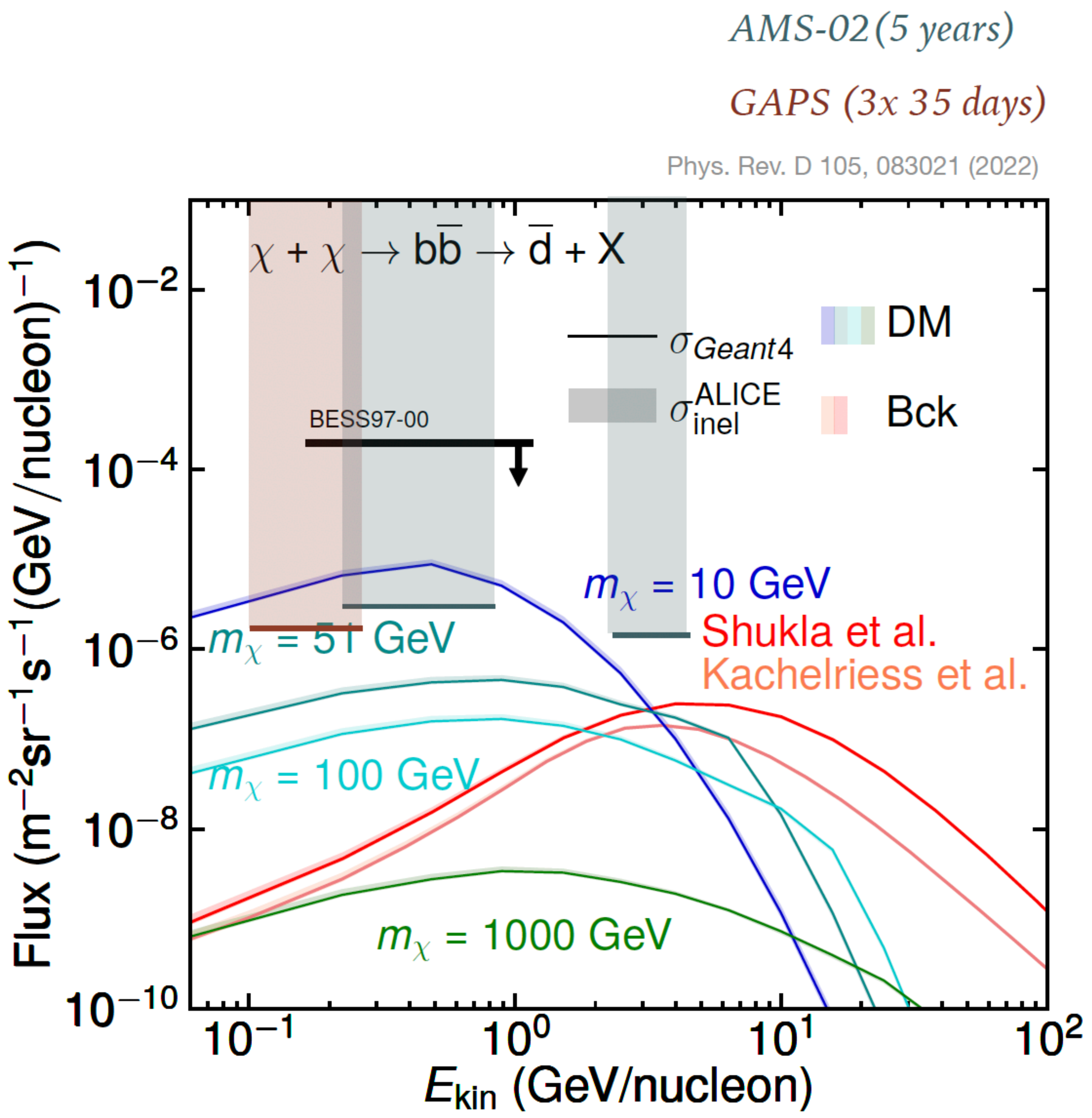
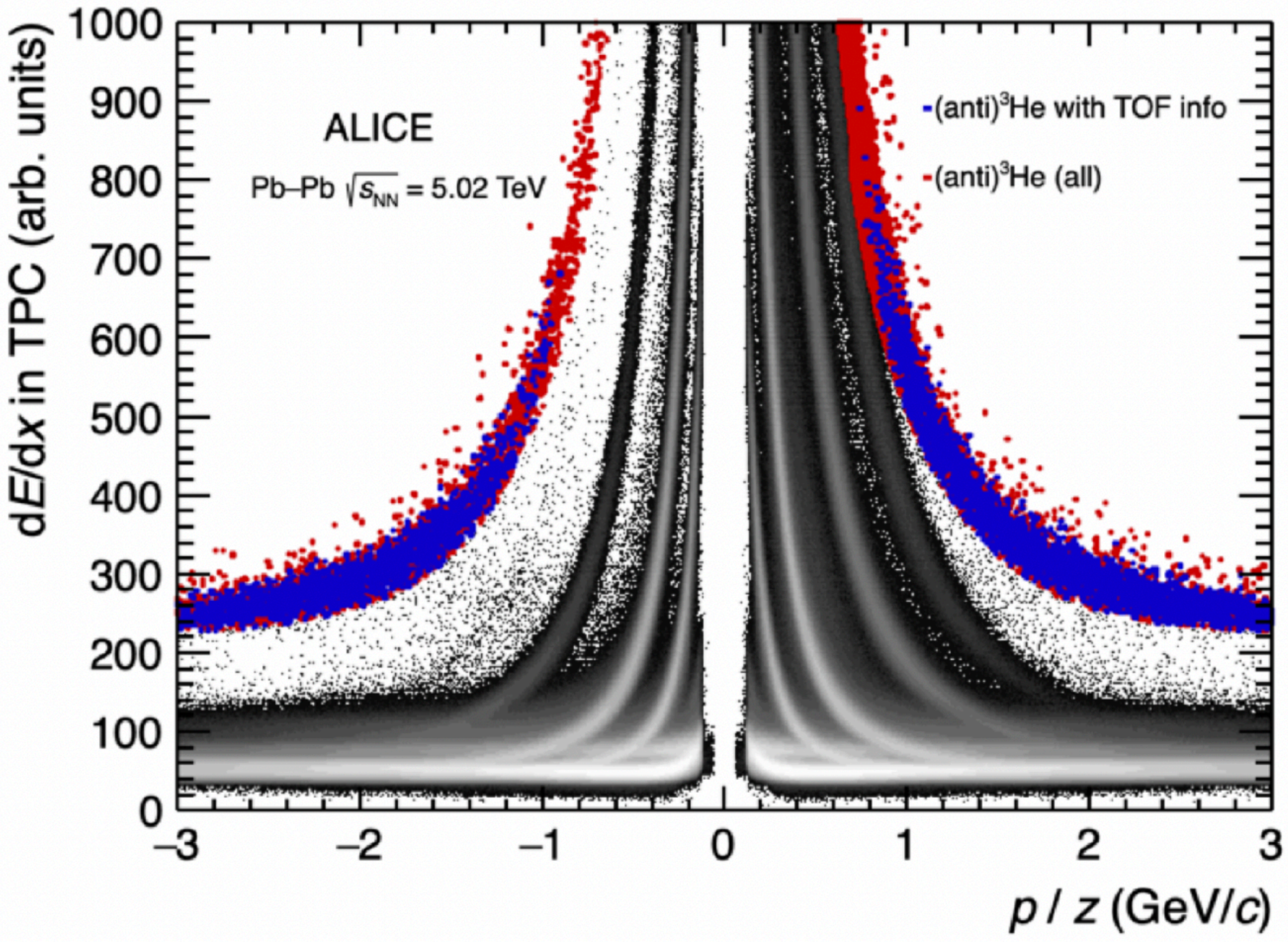


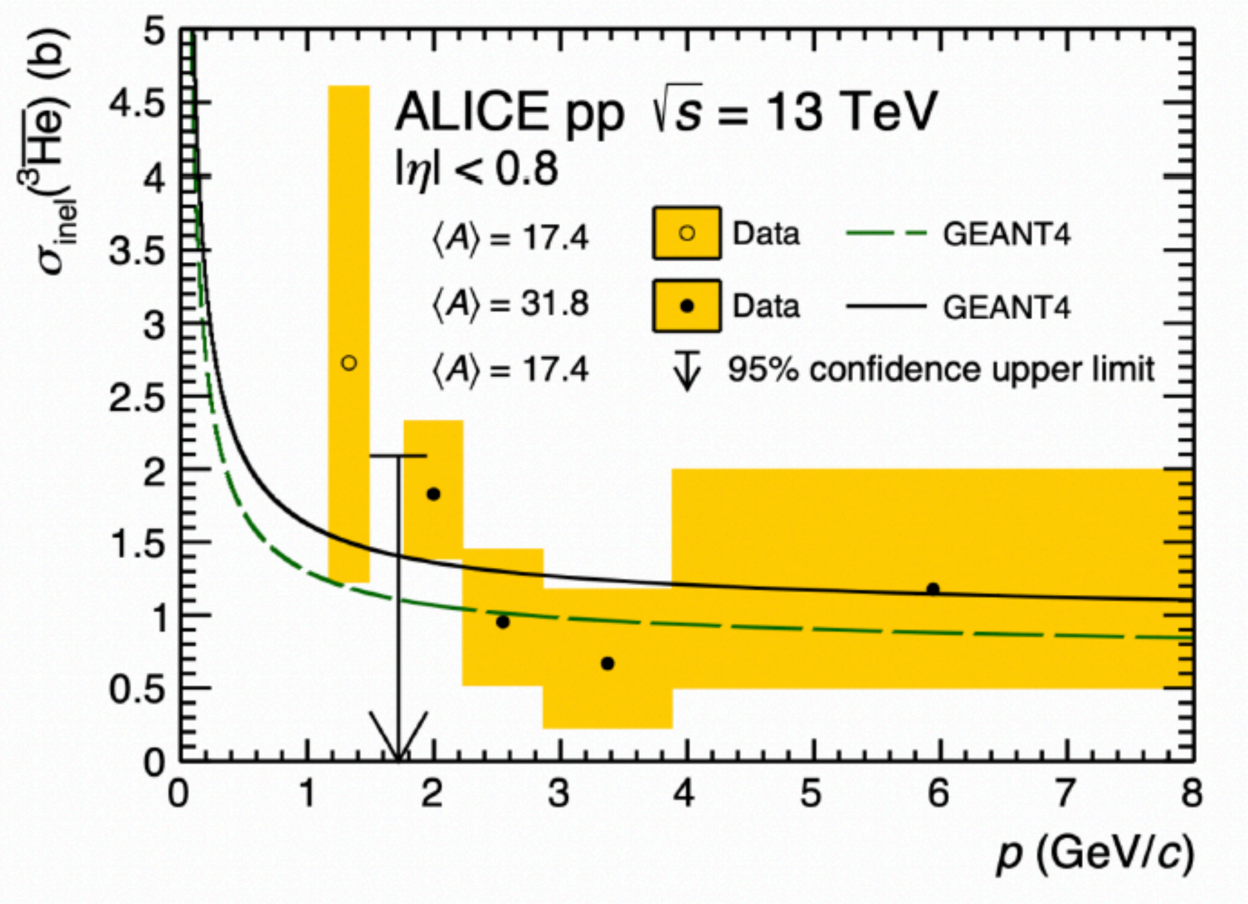
All antihelium vs which reaches TOF

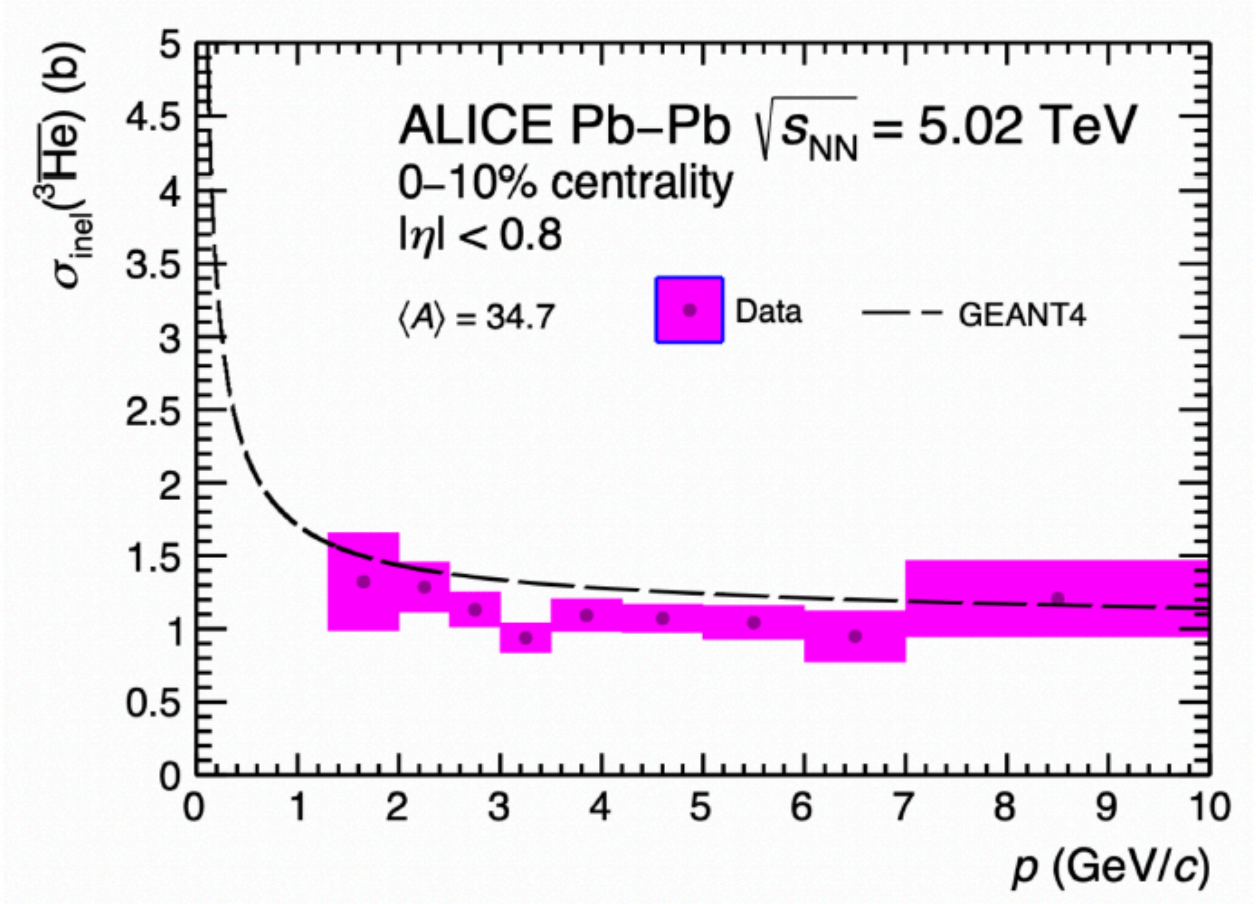


Inelastic cross sections

All antinuclei up to A=3 measured!

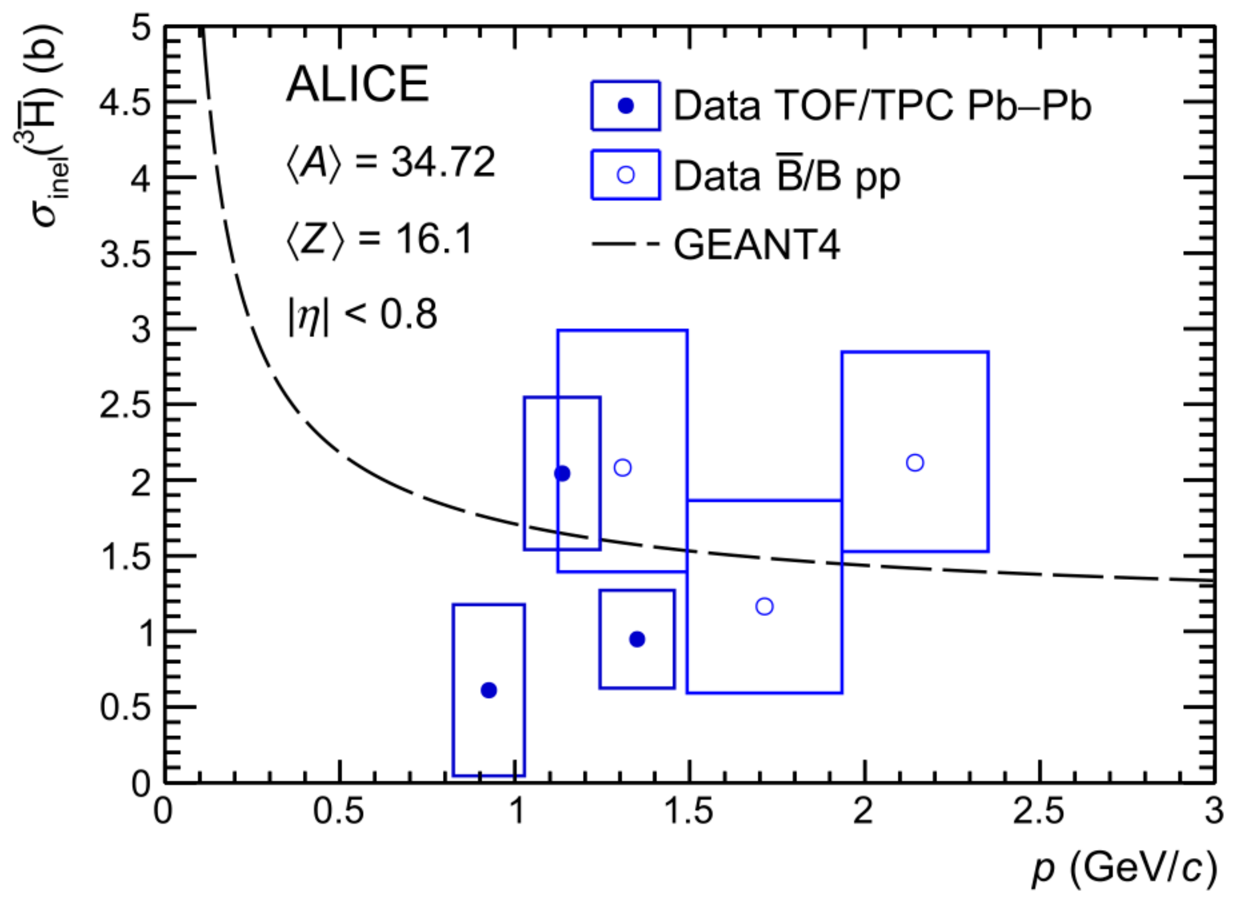
Antihelium-3



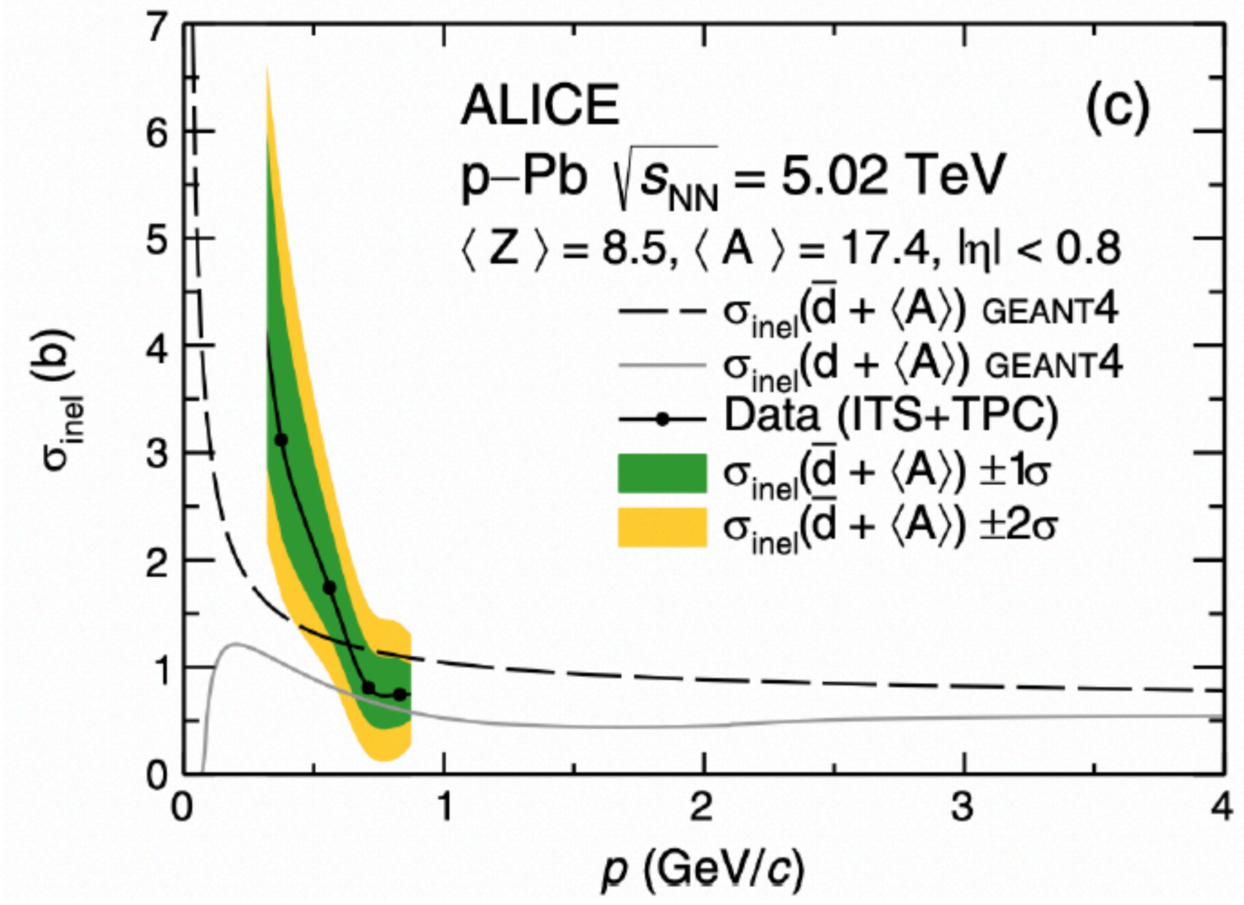


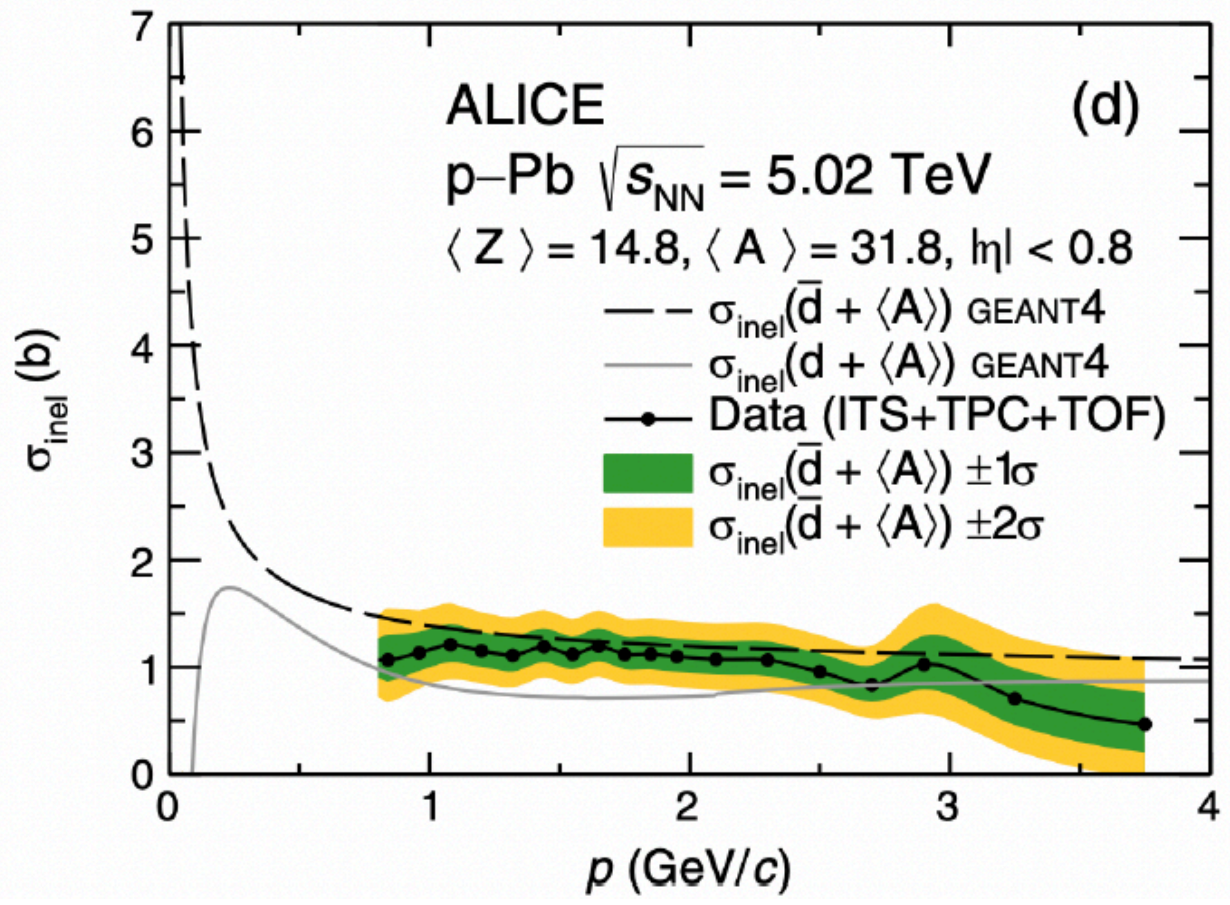
Antitriton

Phys.Lett.B 848 (2024) 138337

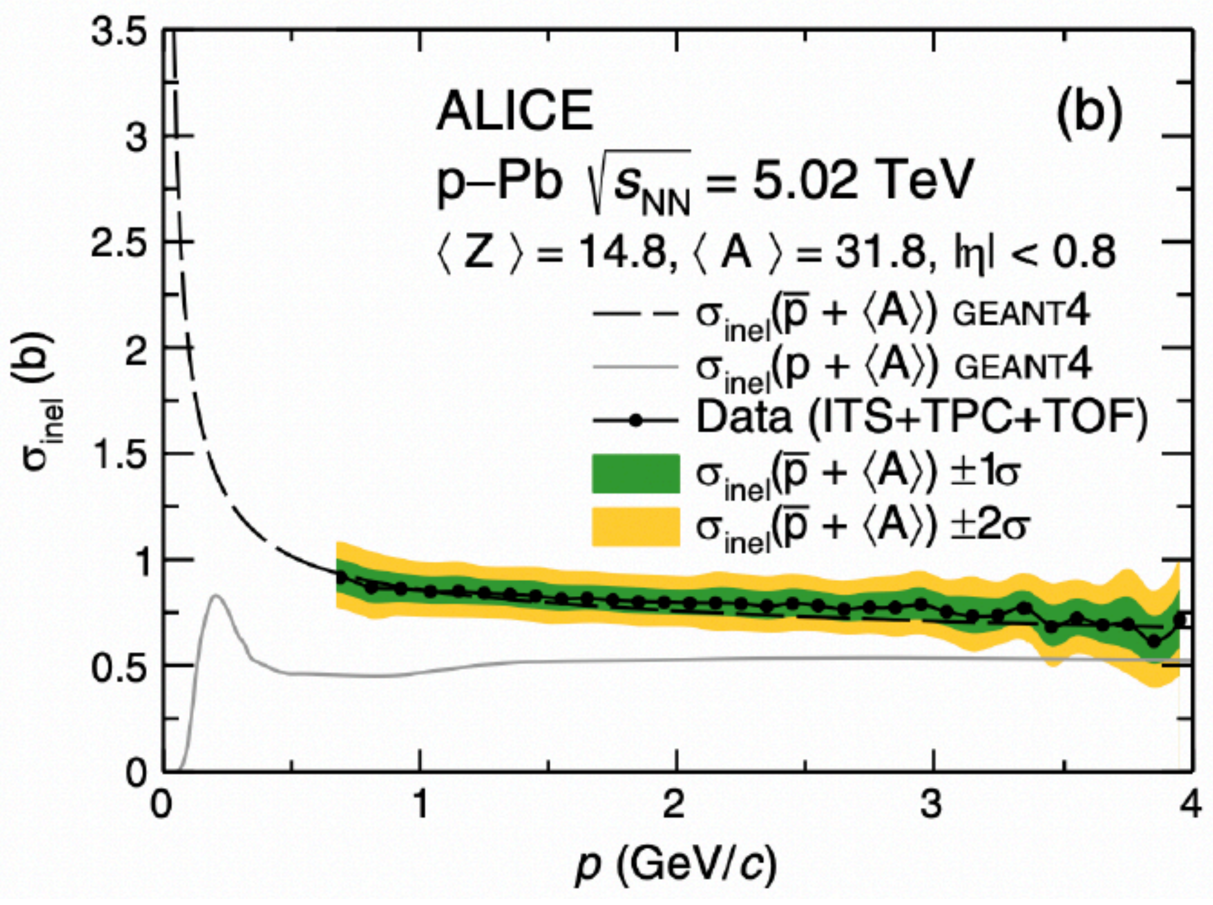


Antideuteron



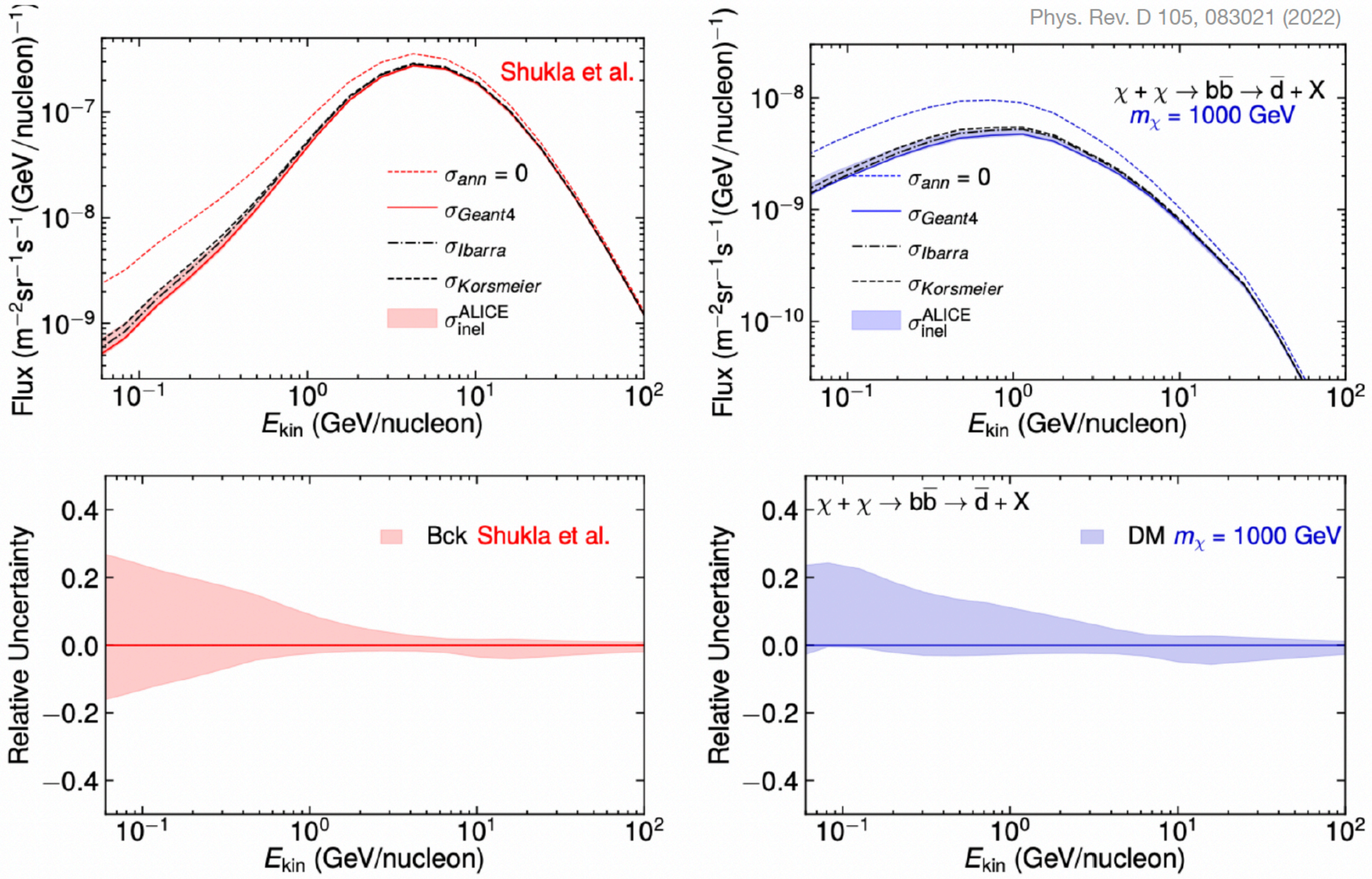


Benchmark: Antiproton



Inelastic cross section uncertainties

- First time data-driven estimate; propagated uncertainties
- Inelastic cross section from now on well constrained with data!

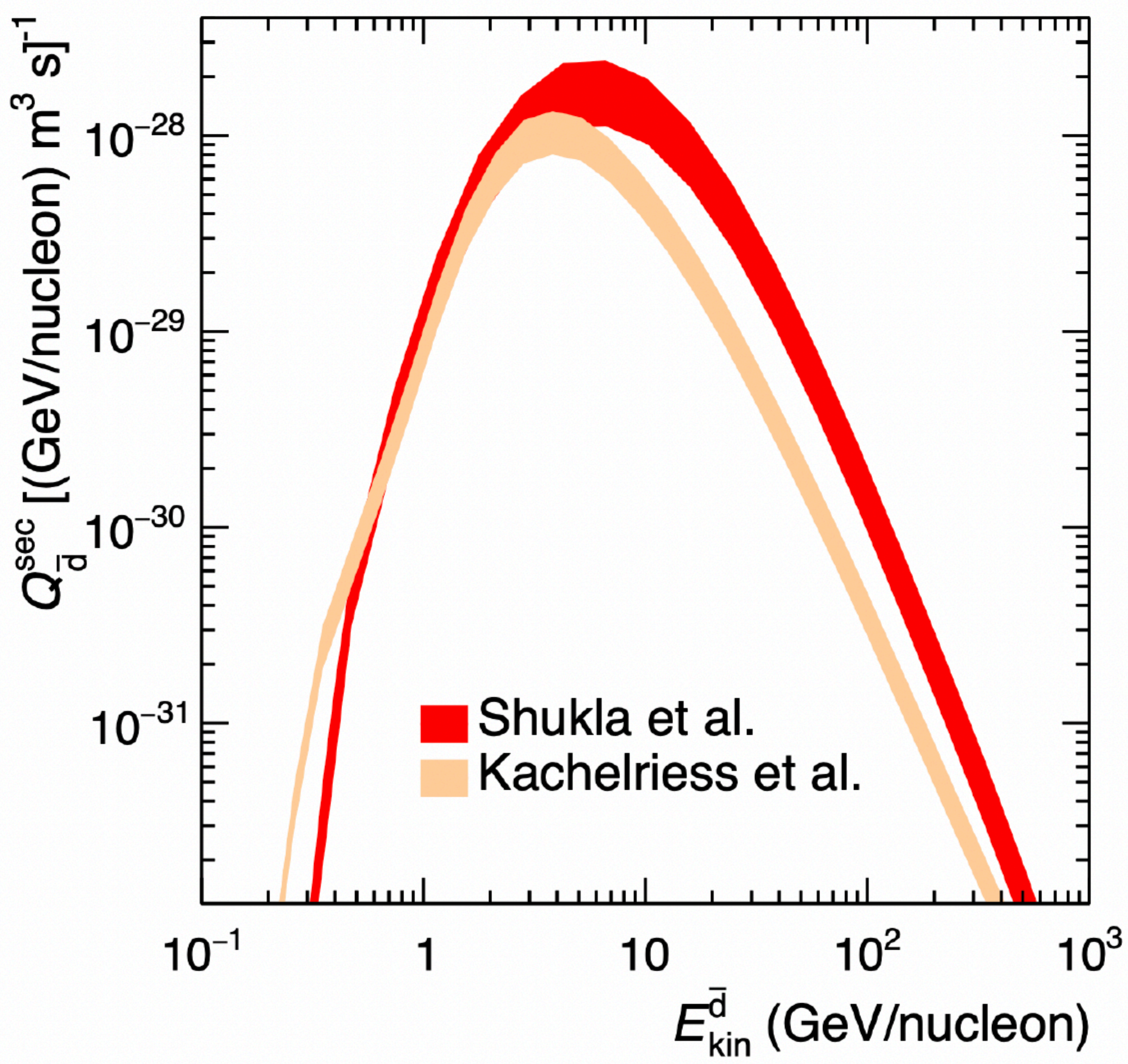


Studying light nuclei formation

Light nuclei production must be understood better!

- ALICE studies of light nuclei production
- AMBER experiment at SPS [1]:
  - Proton beam scan from 50 GeV to 250 GeV
  - Proton and helium targets
- LHCb experiment at LHC [2]:
  - p-He collisions
- NA61 experiment at SPS [3]:
  - Proton beam scan from 9 GeV to 400 GeV
  - Antideuteron production

Phys. Rev. D 105, 083021 (2022)

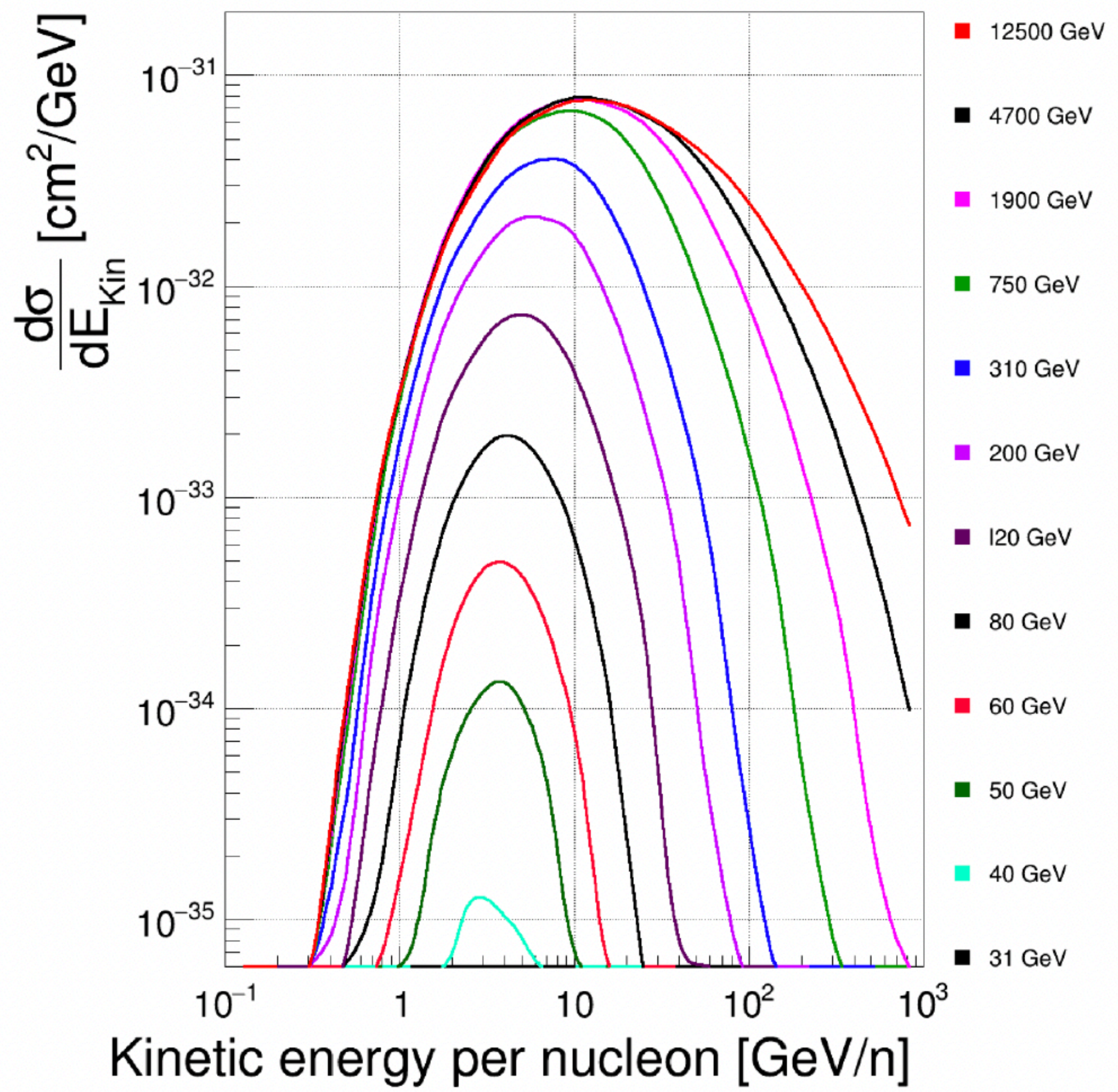


[1] Few Body Syst. 63 (2022) 4, 72
[2] PRL 121, 222001 (2018)
[3] CERN-SPSC-2006-001

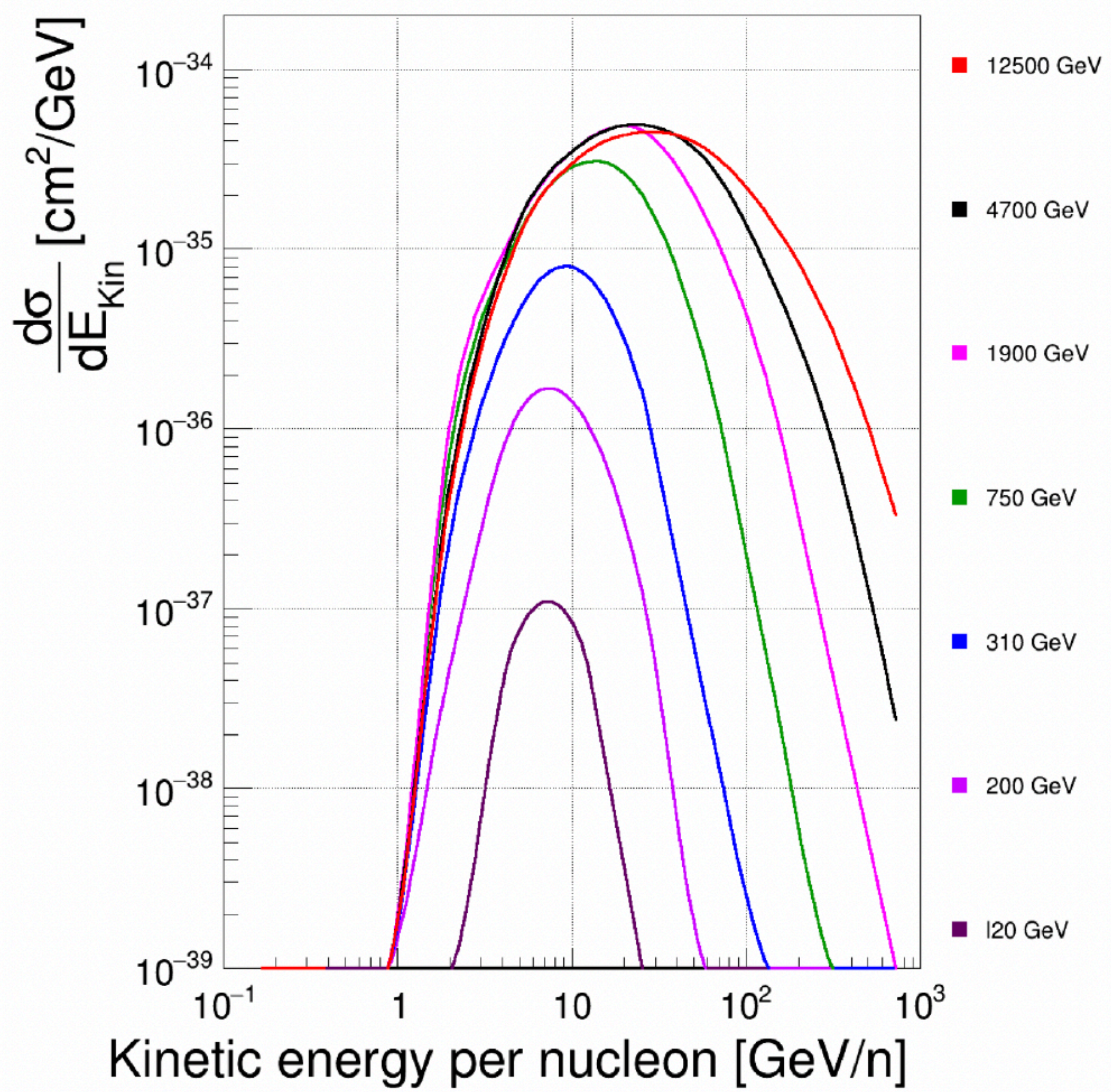
Production cross sections

- Model is used to estimate production cross-section at different collision energies
- These can be used directly as input to account for antinuclei production in cosmic ray collisions with interstellar medium

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



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



CR fluxes for different DM assumptions

PhD Thesis of Stephan Königstorfer