Measurement of anti-^{3}He nuclei absorption in matter and impact on their propagation in the Galaxy

Priv.-Doz. Dr Yvonne Pachmayer

Thanks to S. Königstorfer and L. Serksnyte

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The ALICE Collaboration

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Abstract

In our Galaxy, light antinuclei composed of antiprotons and antineutrons can be produced through high-energy cosmic-ray collisions with the interstellar medium or could also originate from the annihilation of dark-matter particles that have not yet been discovered. On Earth, the only way to produce and study antinuclei with high precision is to create them at high-energy particle accelerators. Although the properties of elementary antiparticles have been studied in detail, the knowledge of the interaction of light antinuclei with matter is limited. We determine the disappearance probability of $^3\overline{\mathrm{He}}$ when it encounters matter particles and annihilates or disintegrates within the ALICE detector at the Large Hadron

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Physics: Antinuclei travel from far, far away

Nature Physics

December 13, 2022

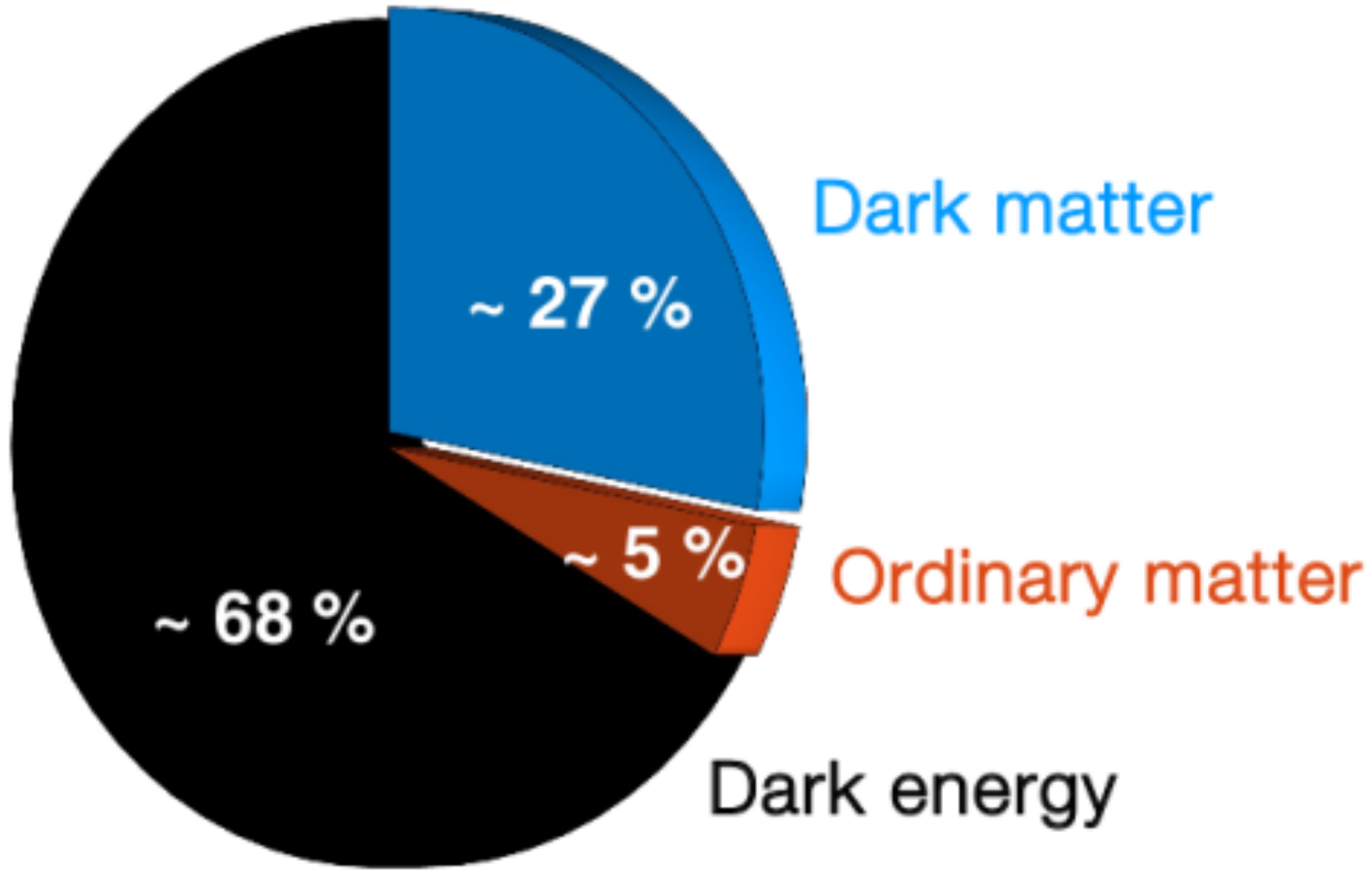
Light antinuclei, comprised of antiprotons and antineutrons, may travel long distances throughout the Galaxy reports a paper published in *Nature Physics*. The findings suggest these antinuclei could be used in the search for dark

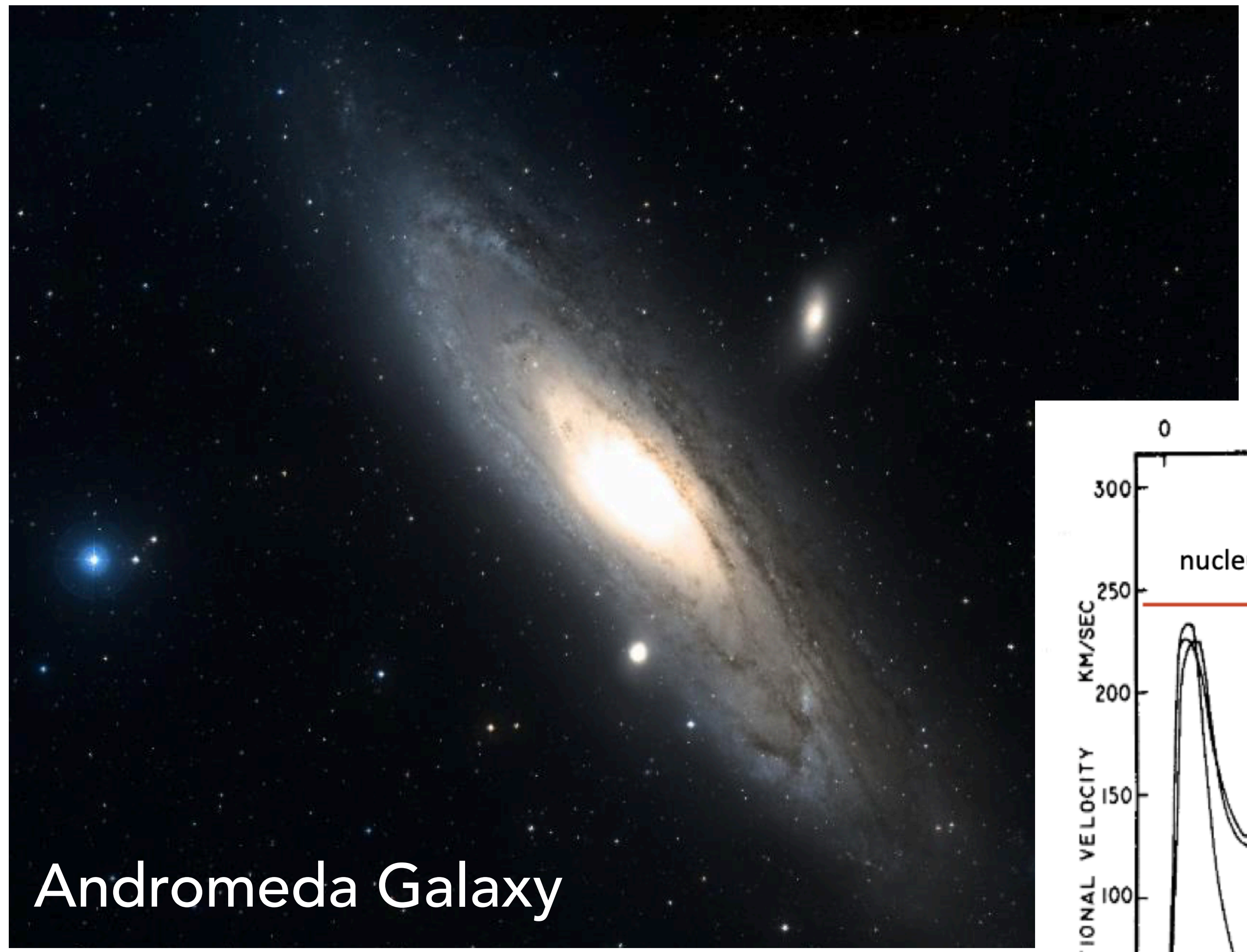
nature physics

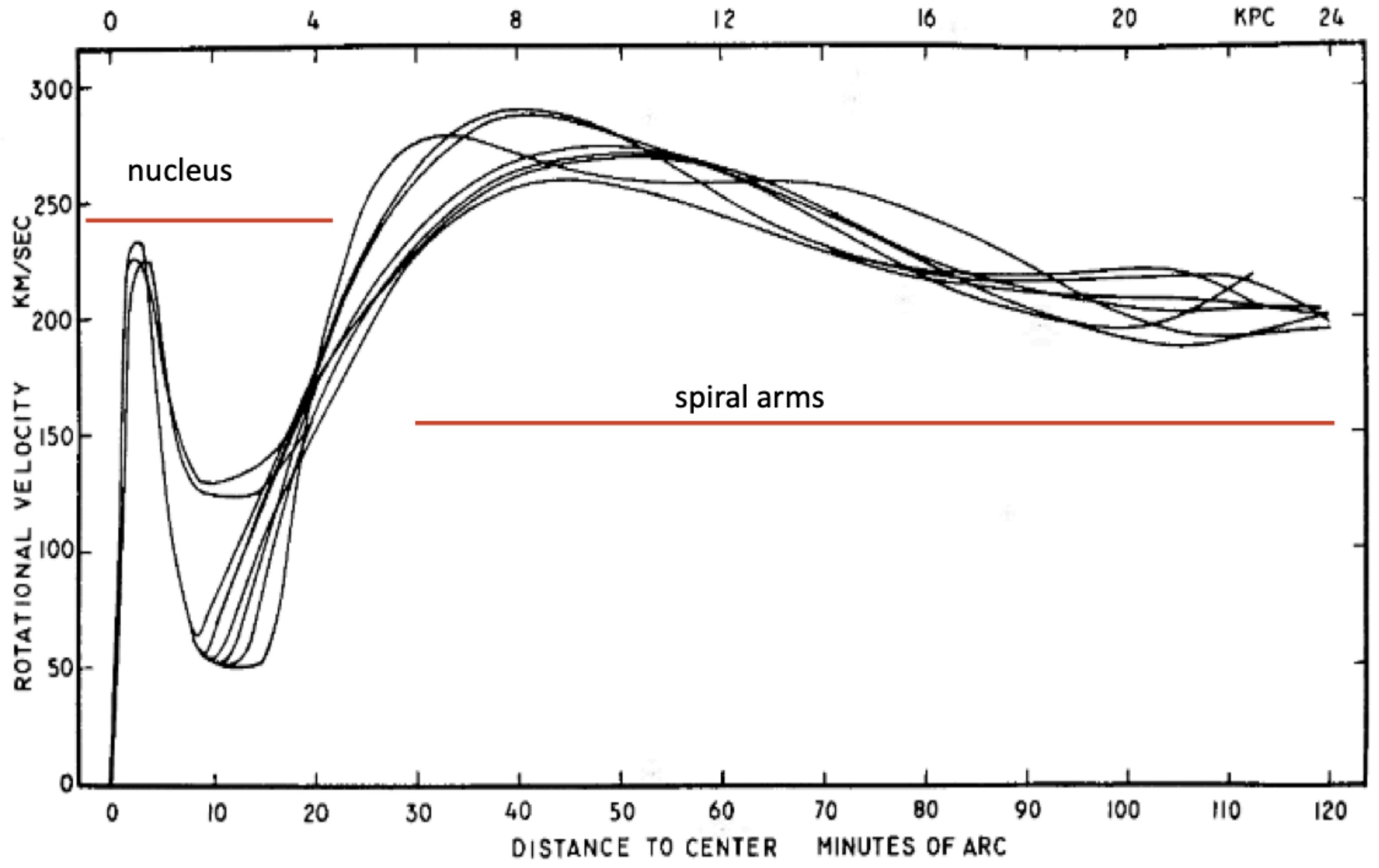
Videos: https://www.youtube.com/watch?v=__1ErCVyzBU&t=1s

Dark Matter

- Dark matter constitutes about 27% of the total energy density budget within our Universe
  - Indirect evidence
    - rotational curves of some galaxies
    - gravitational lensing of galaxy clusters
    - fine structure of the cosmic microwave background




Andromeda Galaxy



Formation of stellar objects not self-sustainable without additional mass from dark matter

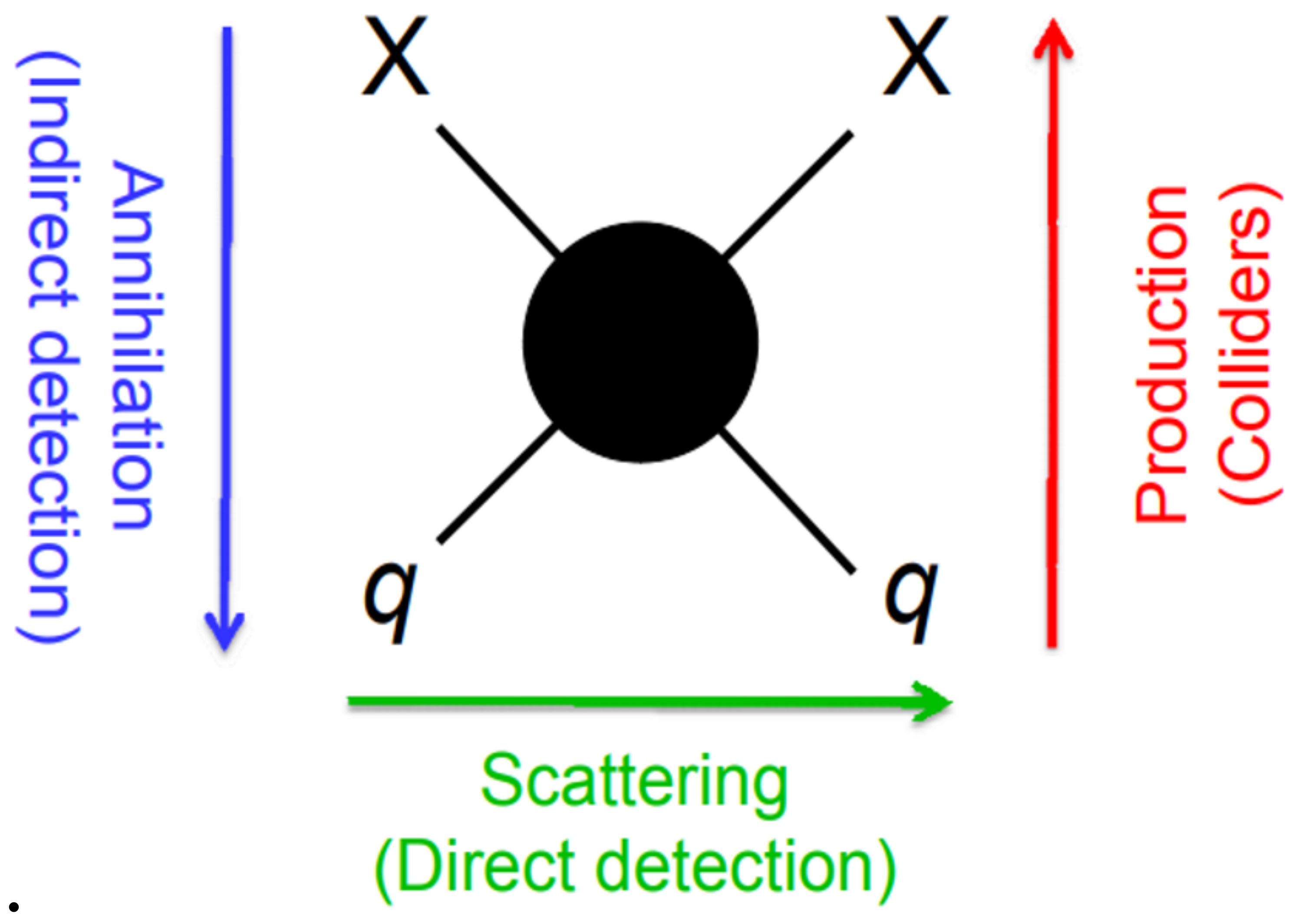
Gravitational lensing

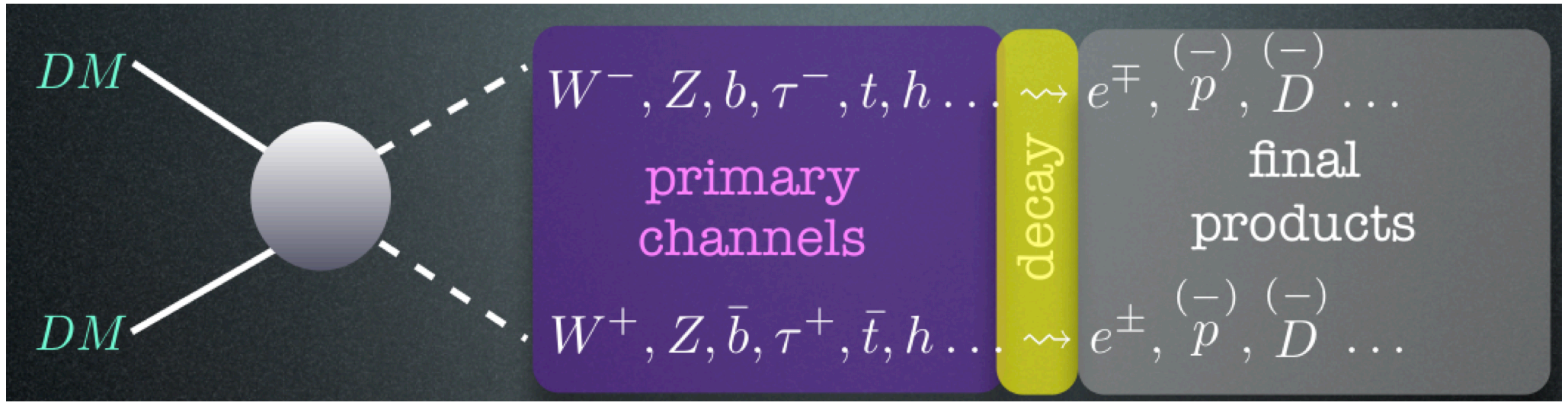
Searches

- Up to now no observations of dark matter particles

- Weakly interacting massive particles (WIMPs)
  - hypothetical particles - proposed candidates for dark matter
  - hypothesis: dark matter particle candidate interacts with ordinary matter through weak-interaction

- Indirect searches via antinuclei cosmic ray measurements
  - Dark matter annihilation
  - Excesses in the spectra of rare cosmic ray components like positrons, antiprotons, … (background from ordinary cosmic ray collisions with interstellar medium)





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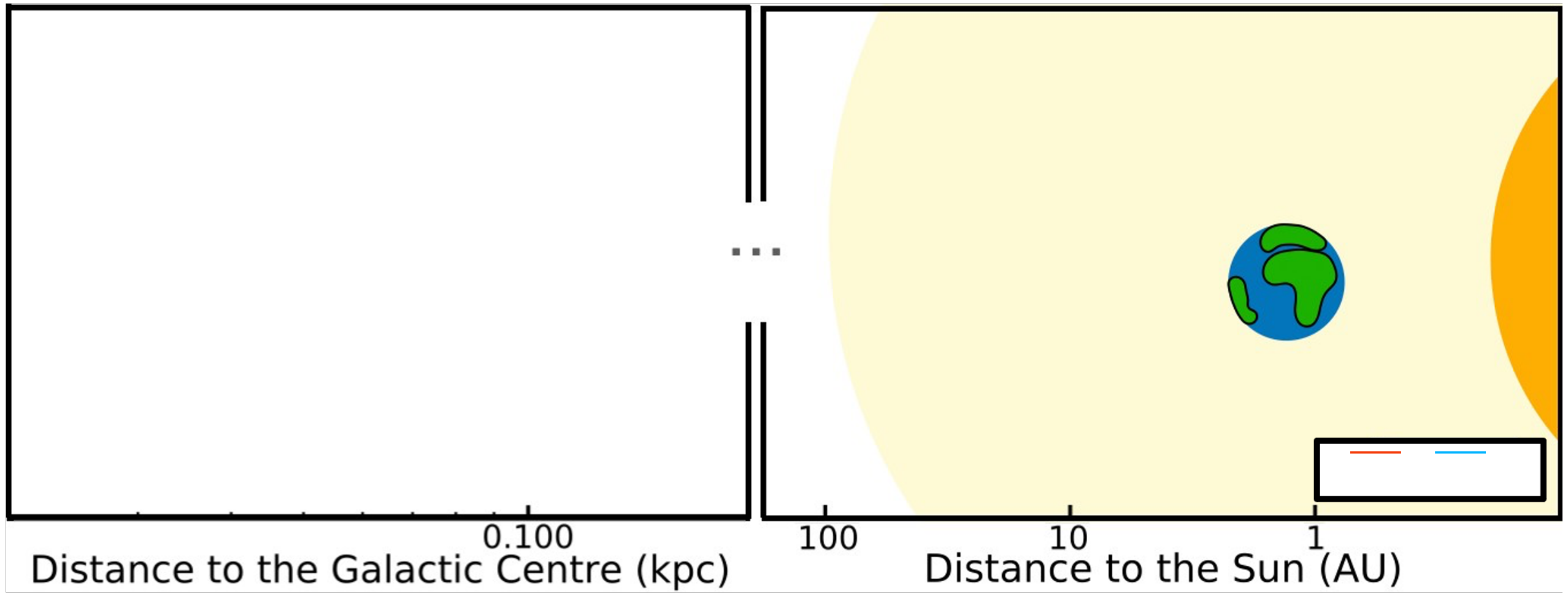

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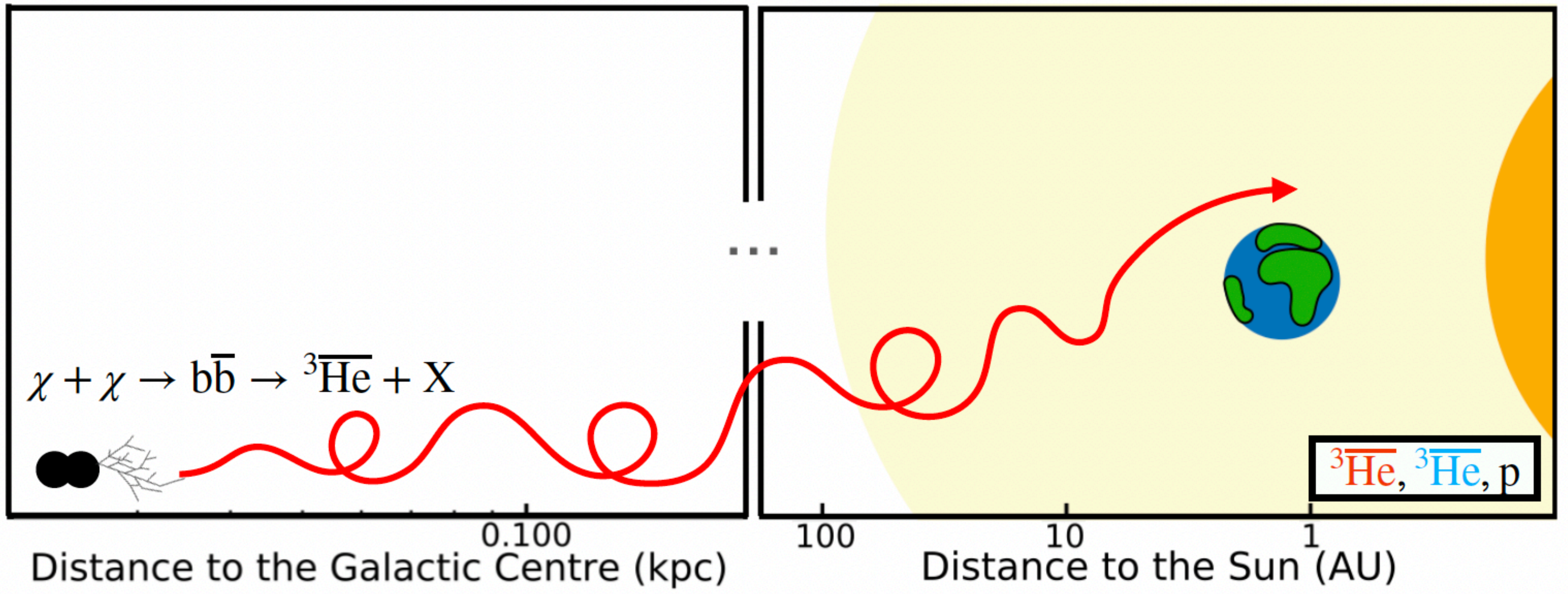

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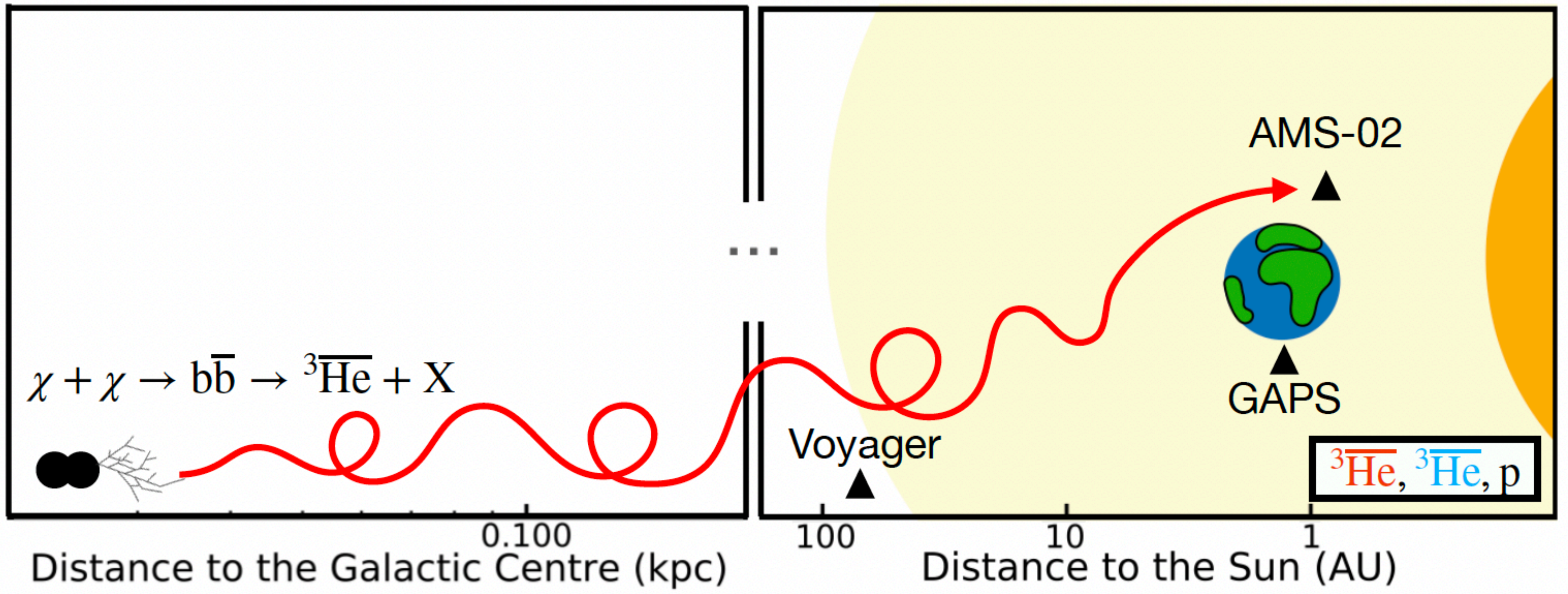

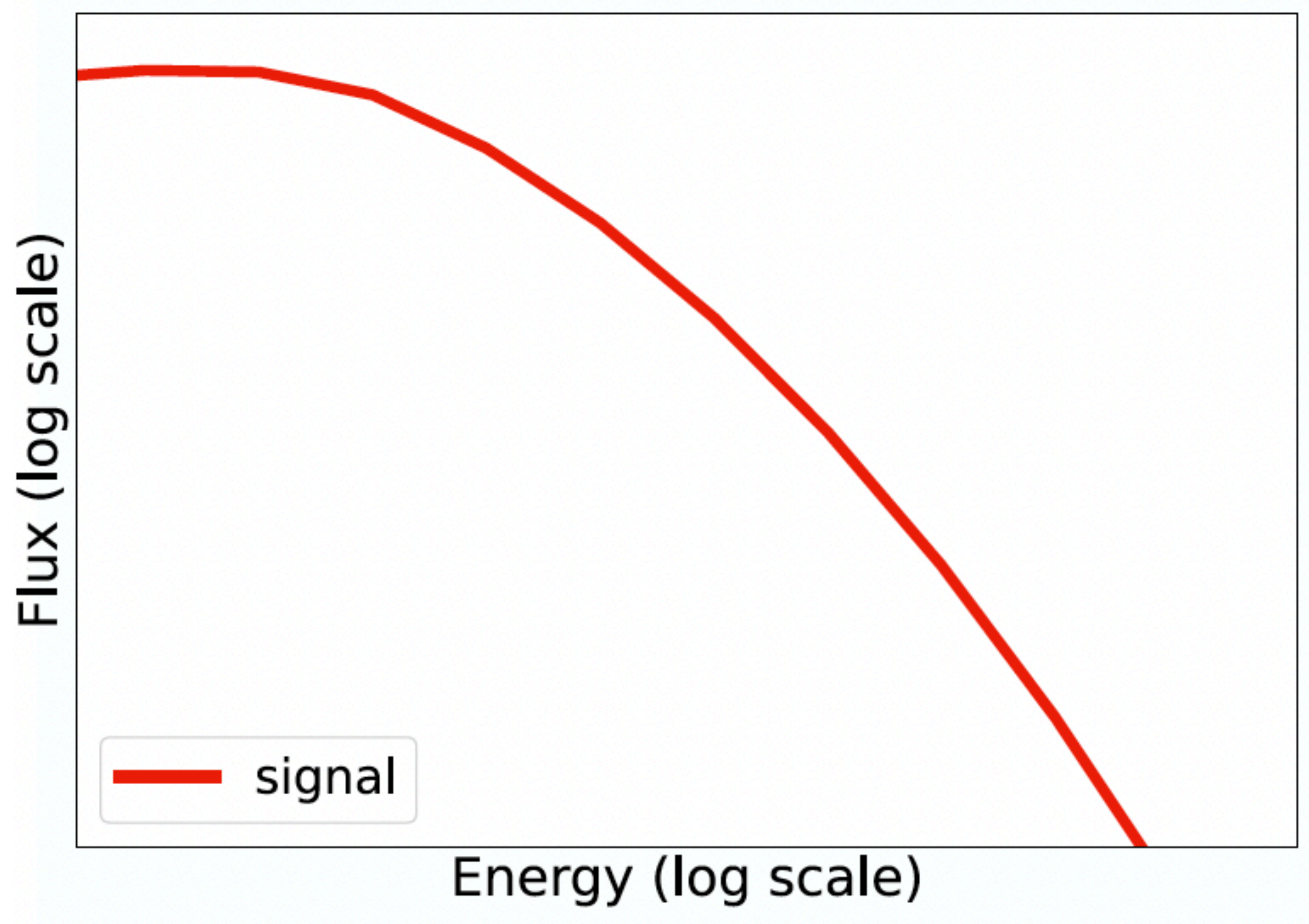

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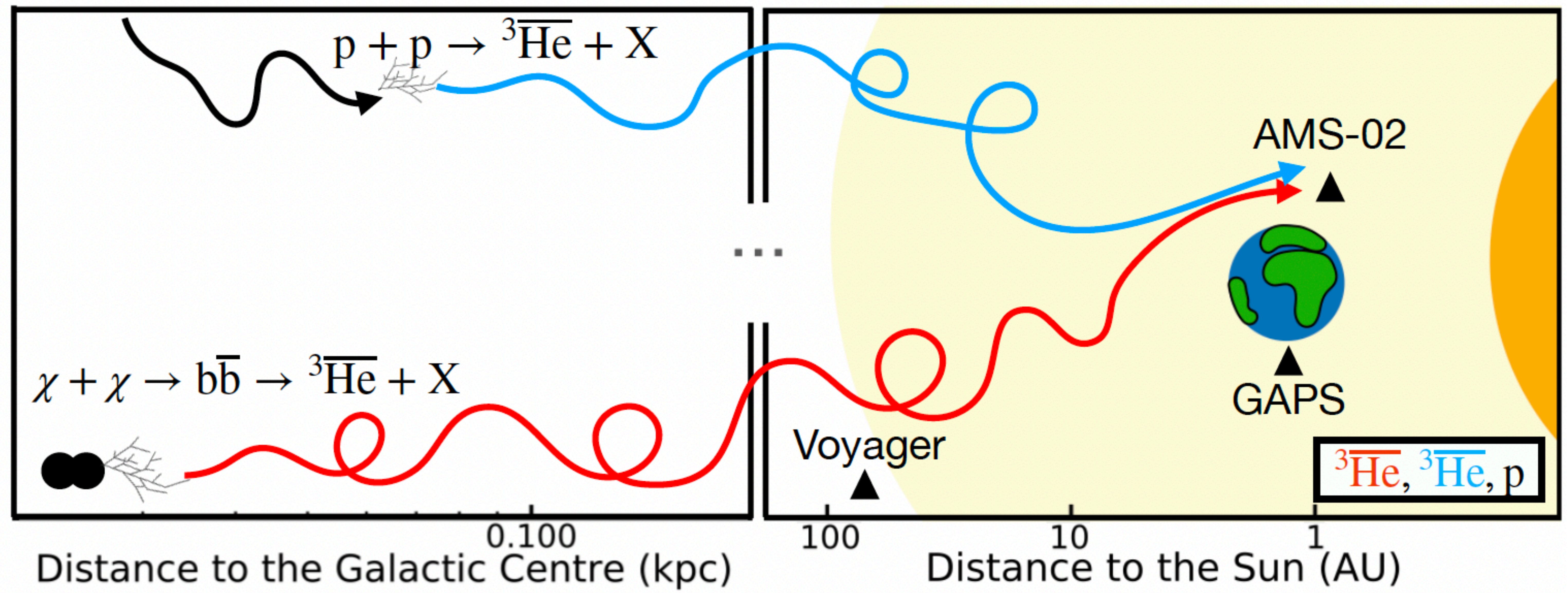

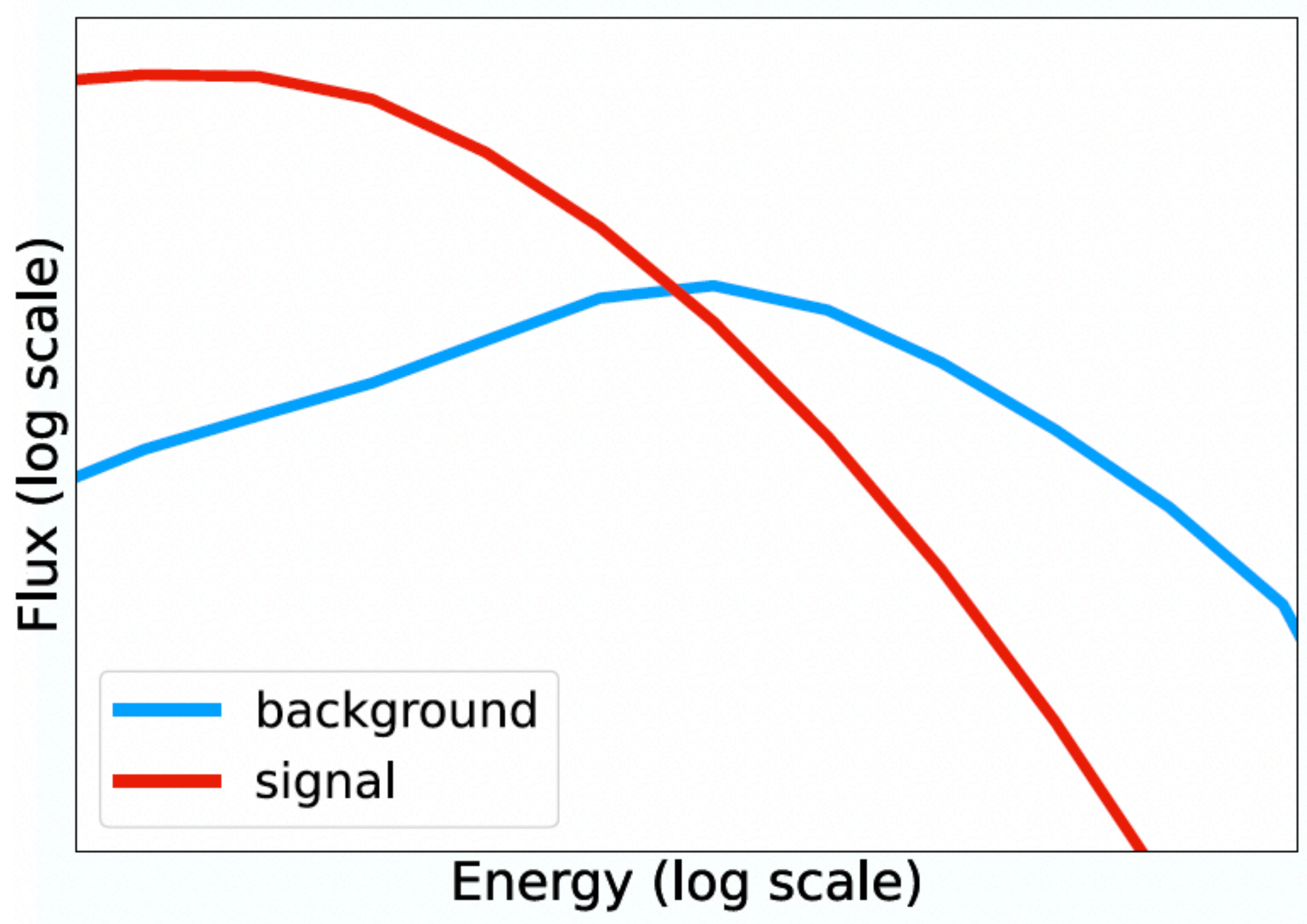

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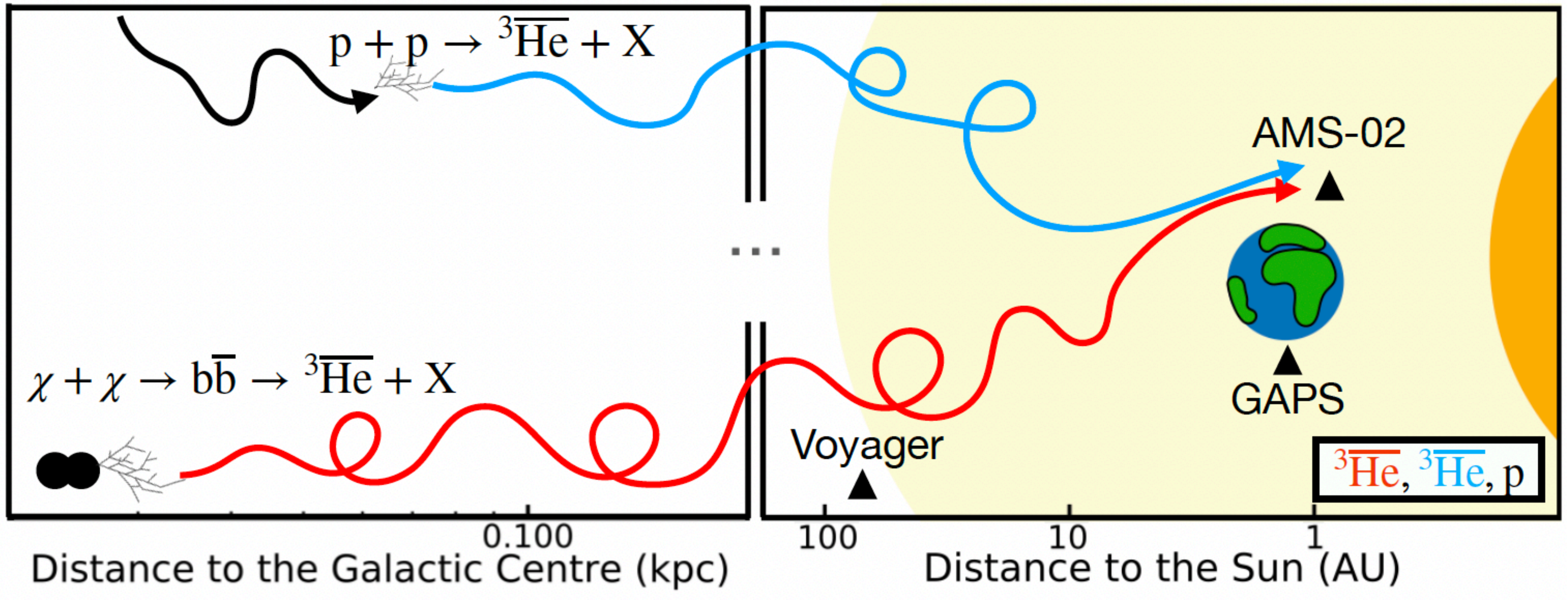

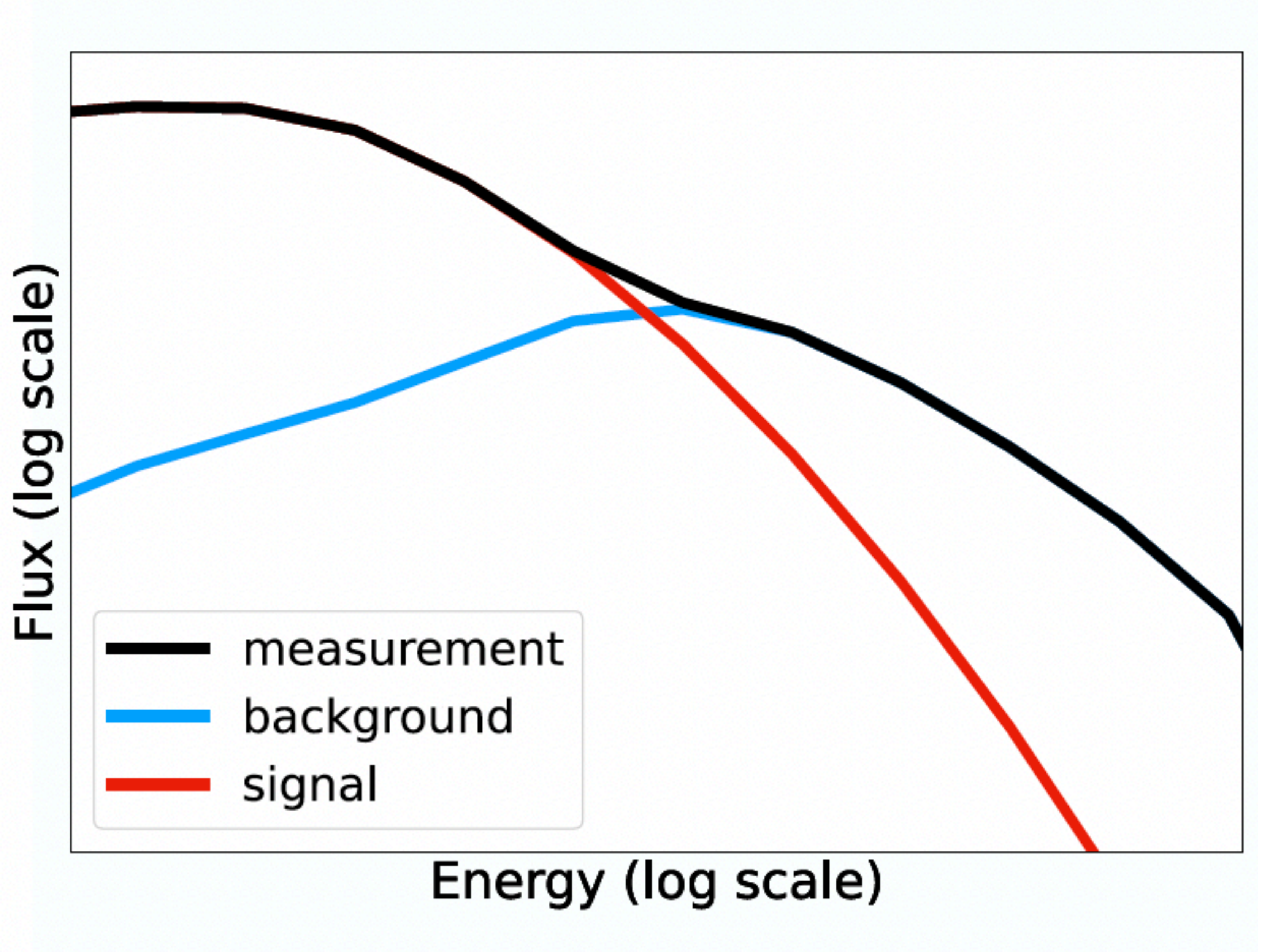

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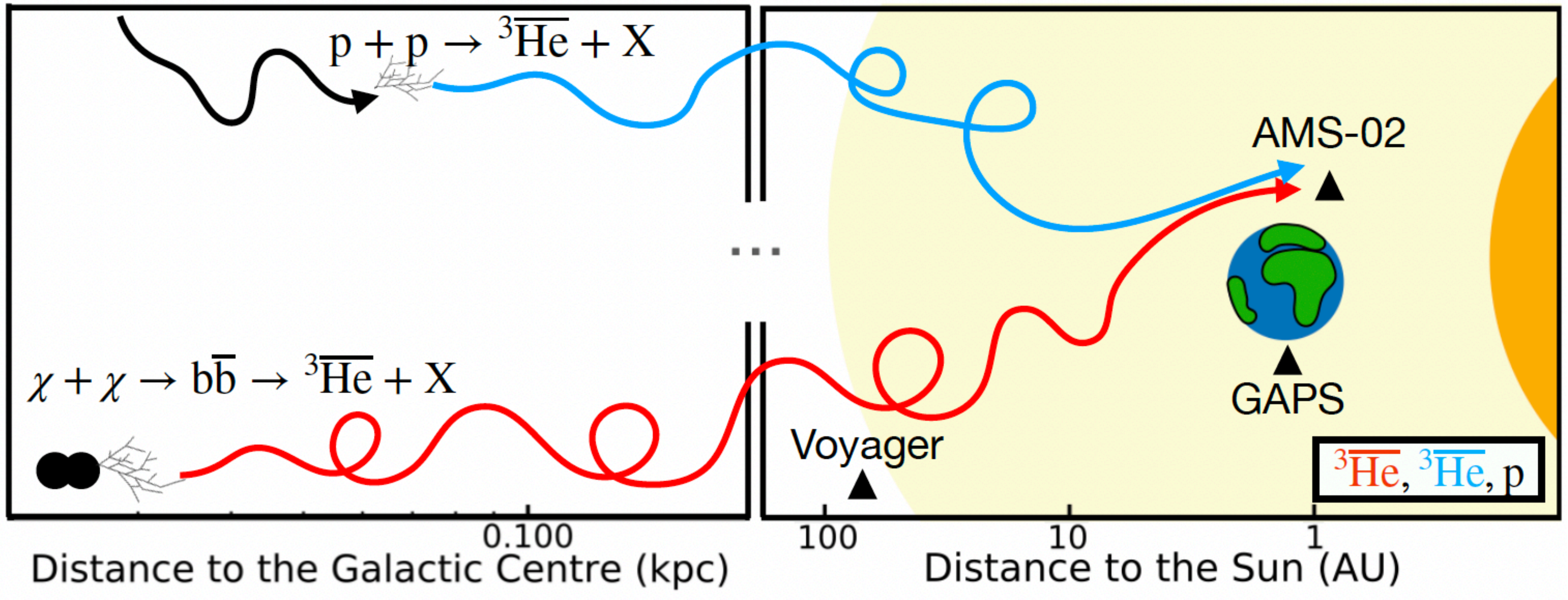
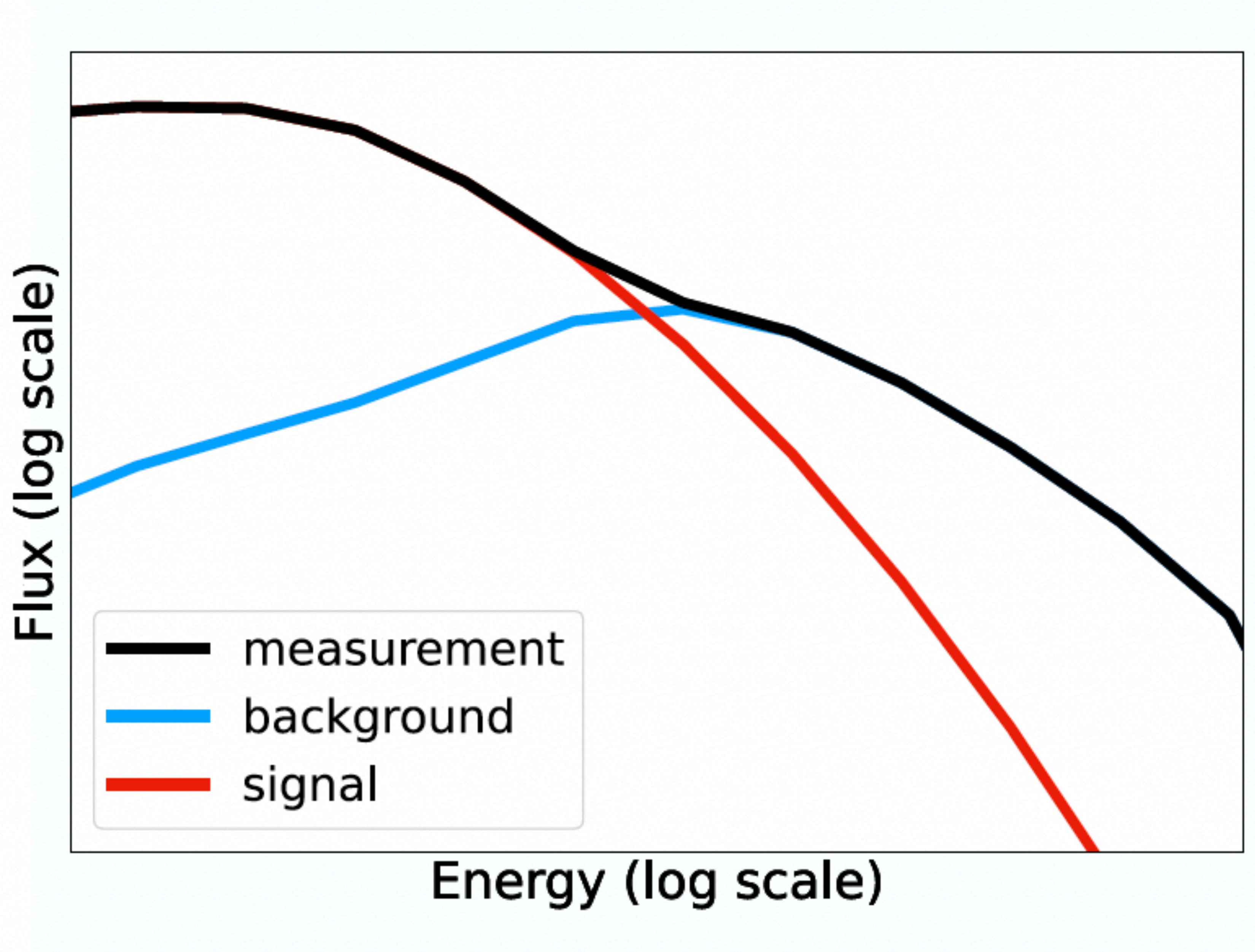
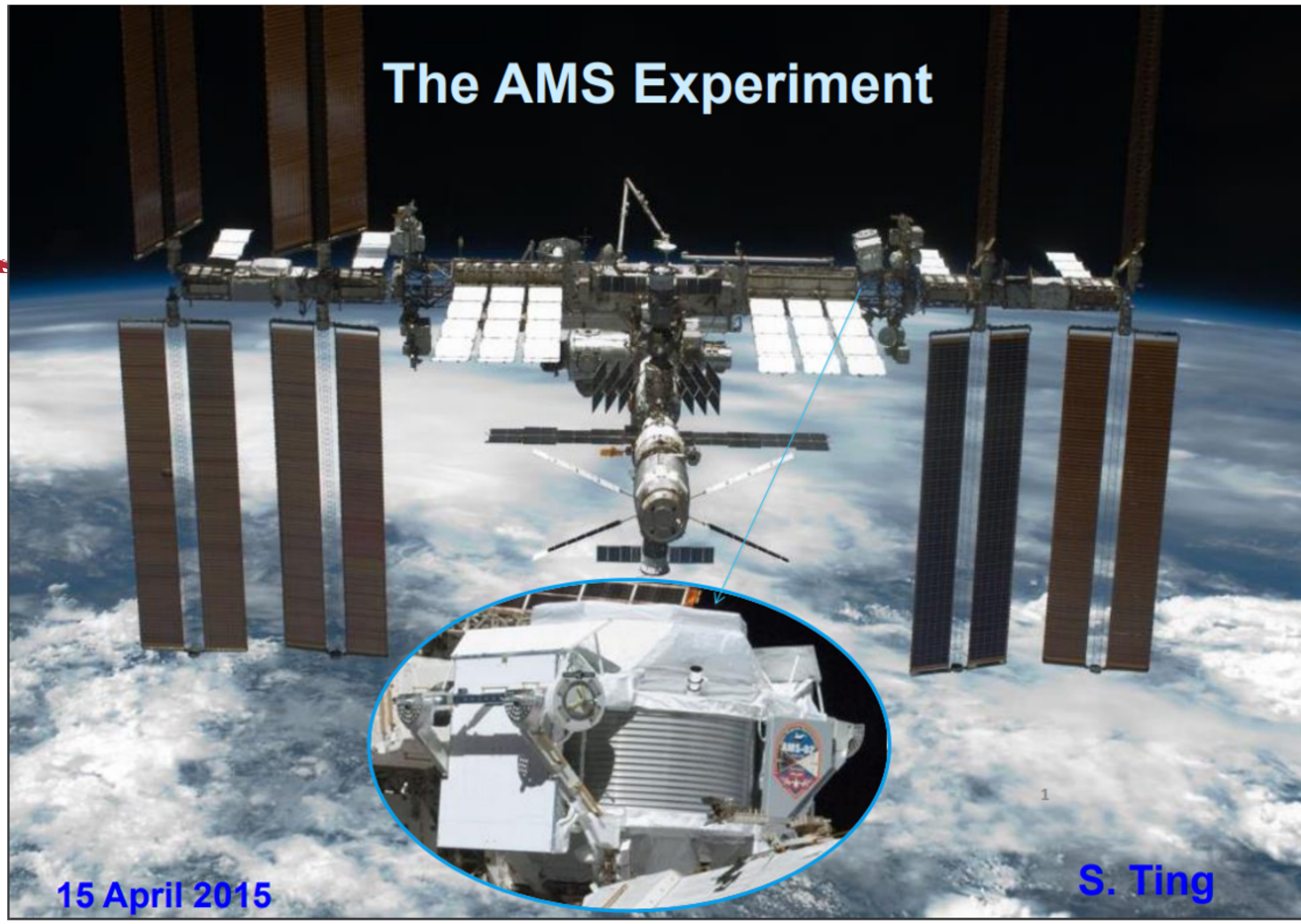
→ Are measurements of the fluxes possible?

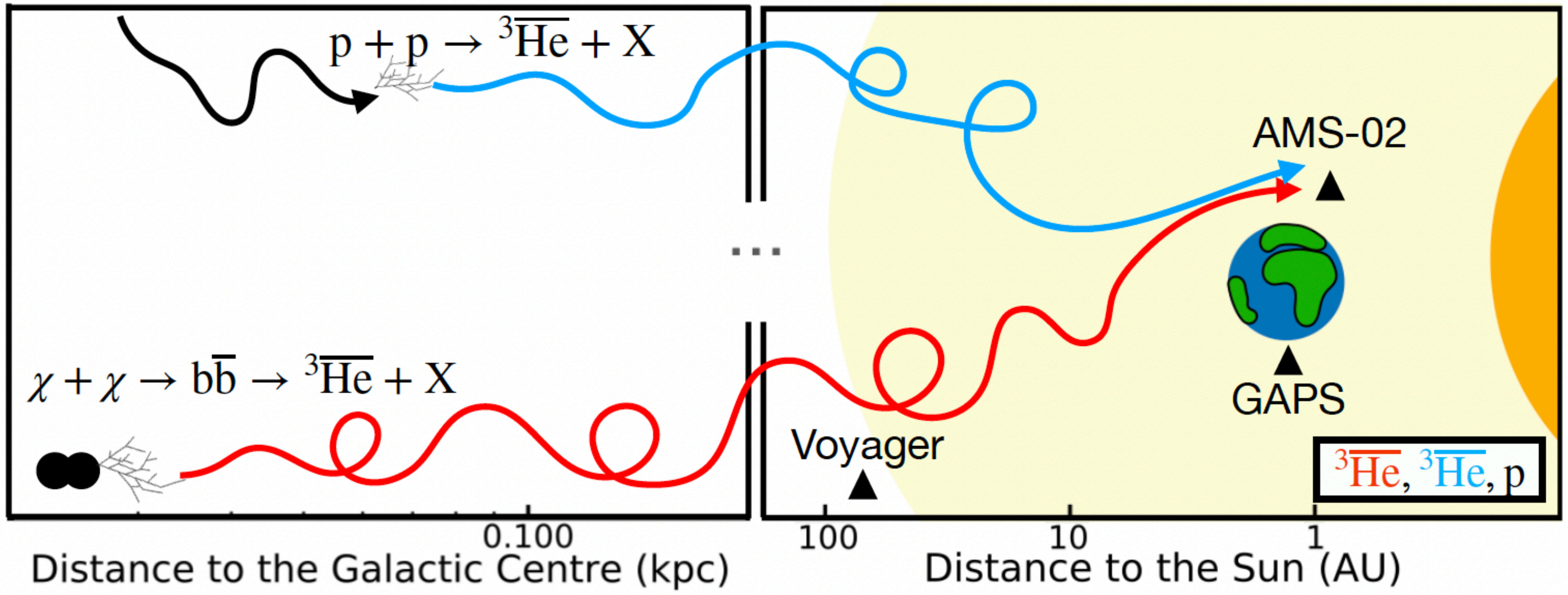


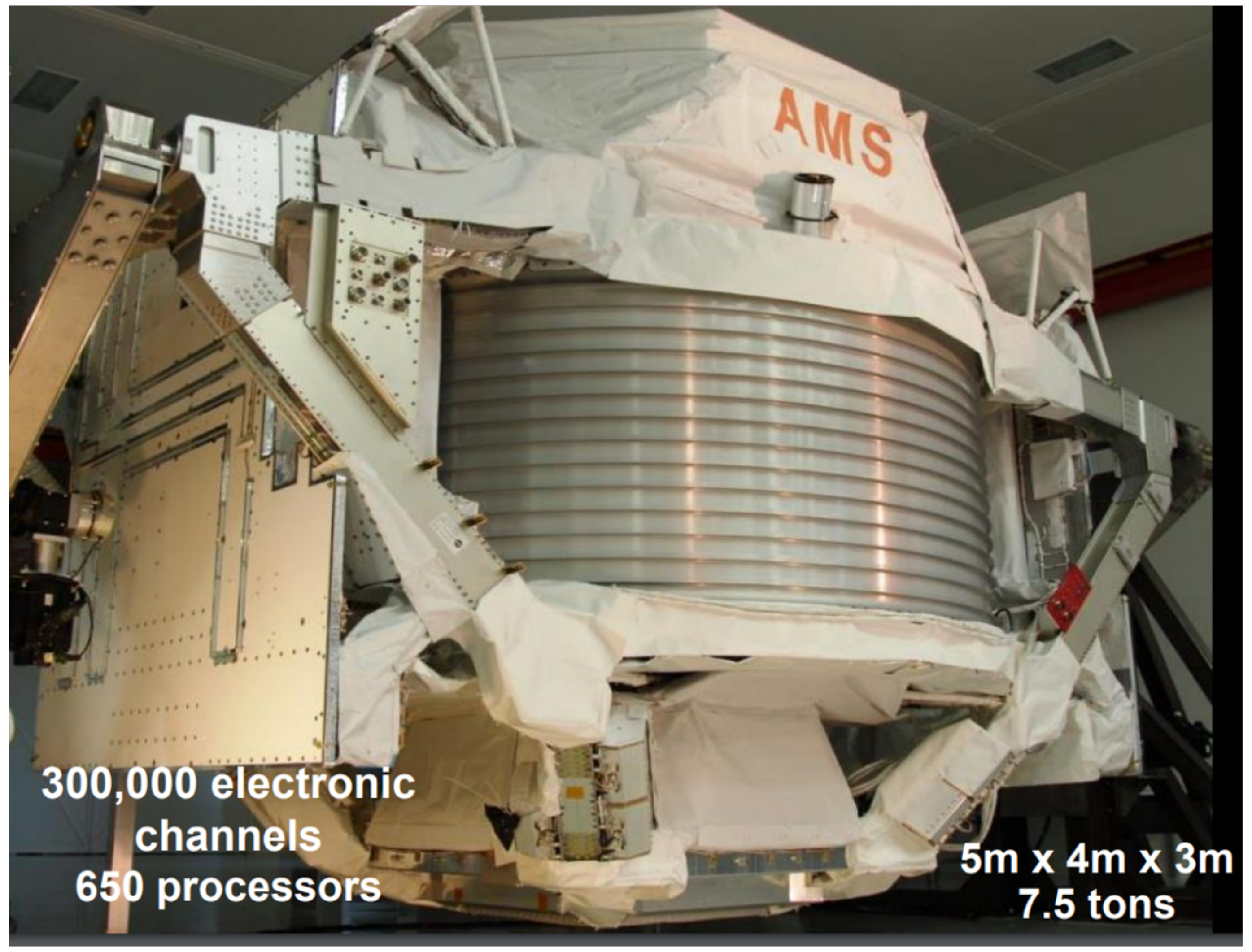


Measurements of antinuclei flux

Alpha Magnetic Spectrometer



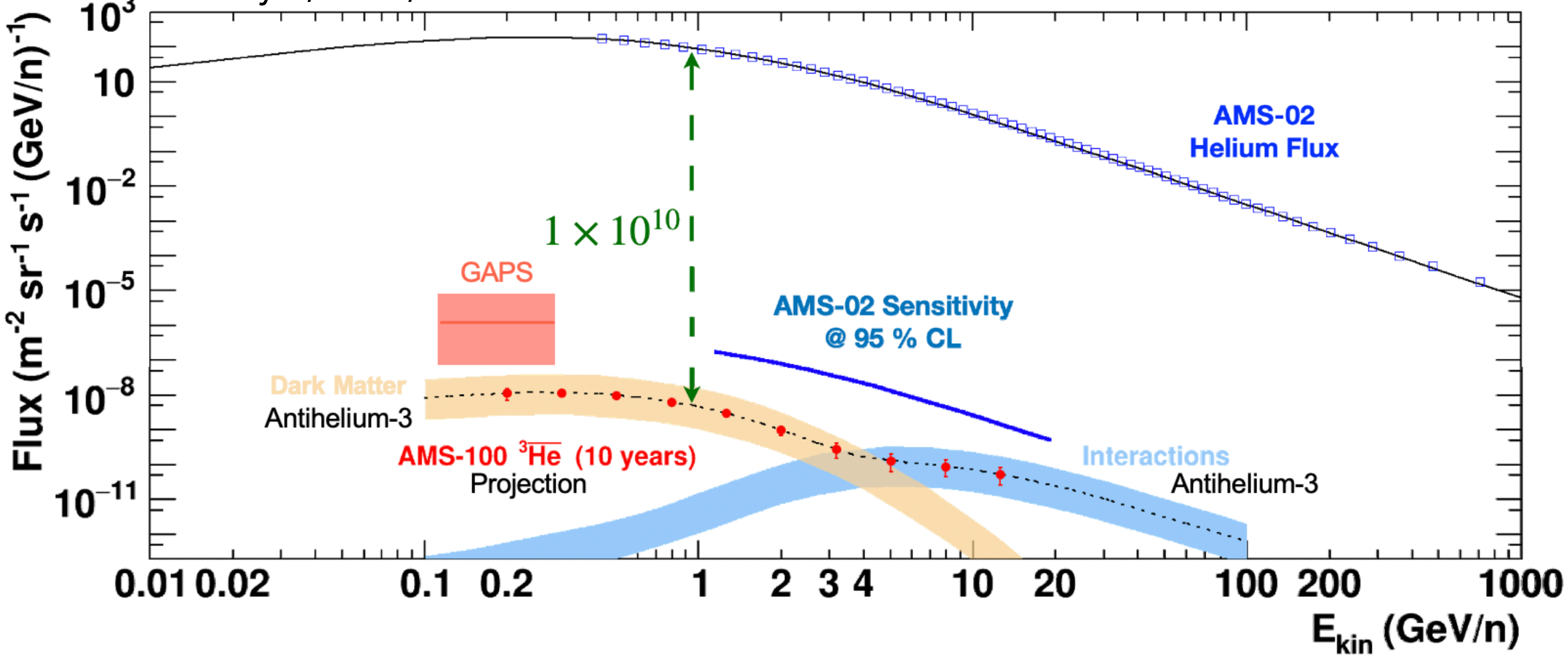


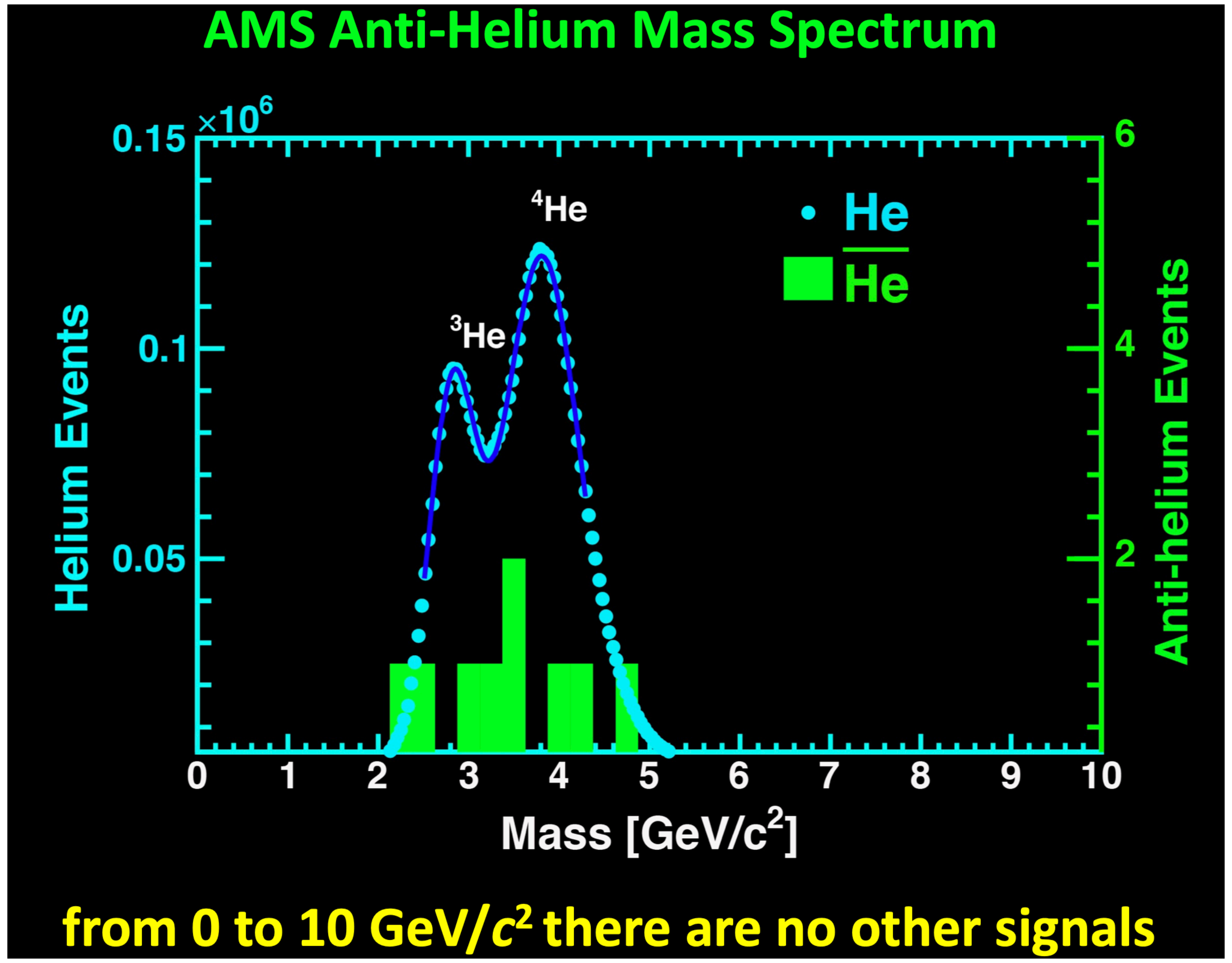


Measurements of antinuclei flux

- AMS found 9 $^{3}\overline{\mathrm{He}}$ candidates (not yet published)
- Future proposed/planned experiments
  - General antiparticle spectrometer (GAPS), a high-altitude balloon flying in Antarctica; low-energy (< 0.25 GeV/*n*) cosmic-ray antinuclei; late 2023
  - AMS-100; x1000 sensitivity; estimated launch 2039

Šerkšnytė, Laura, CERN Seminar Dec 2022





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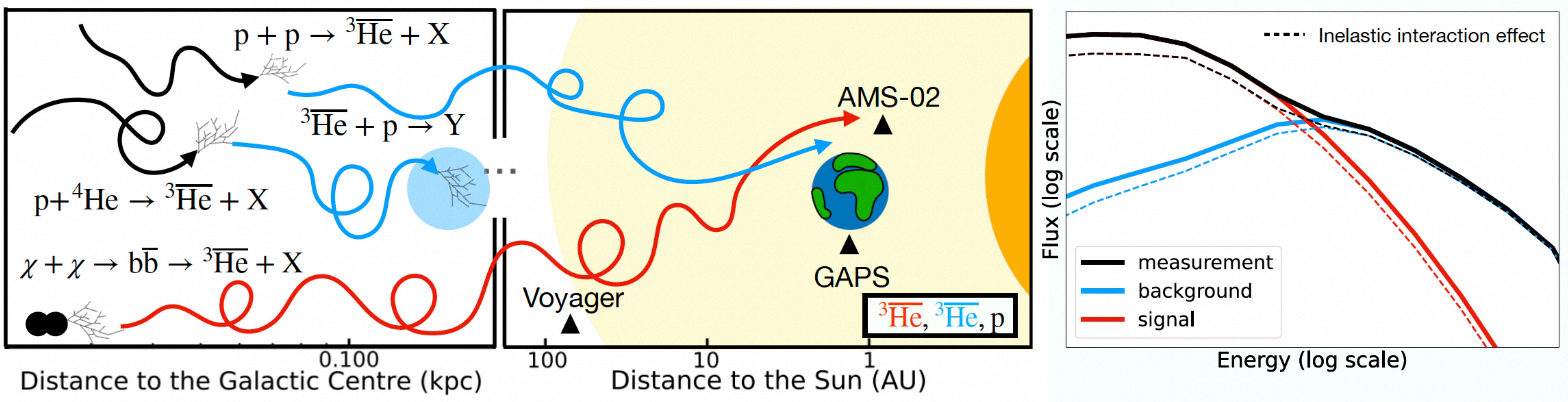
→ Are measurements of the fluxes possible?

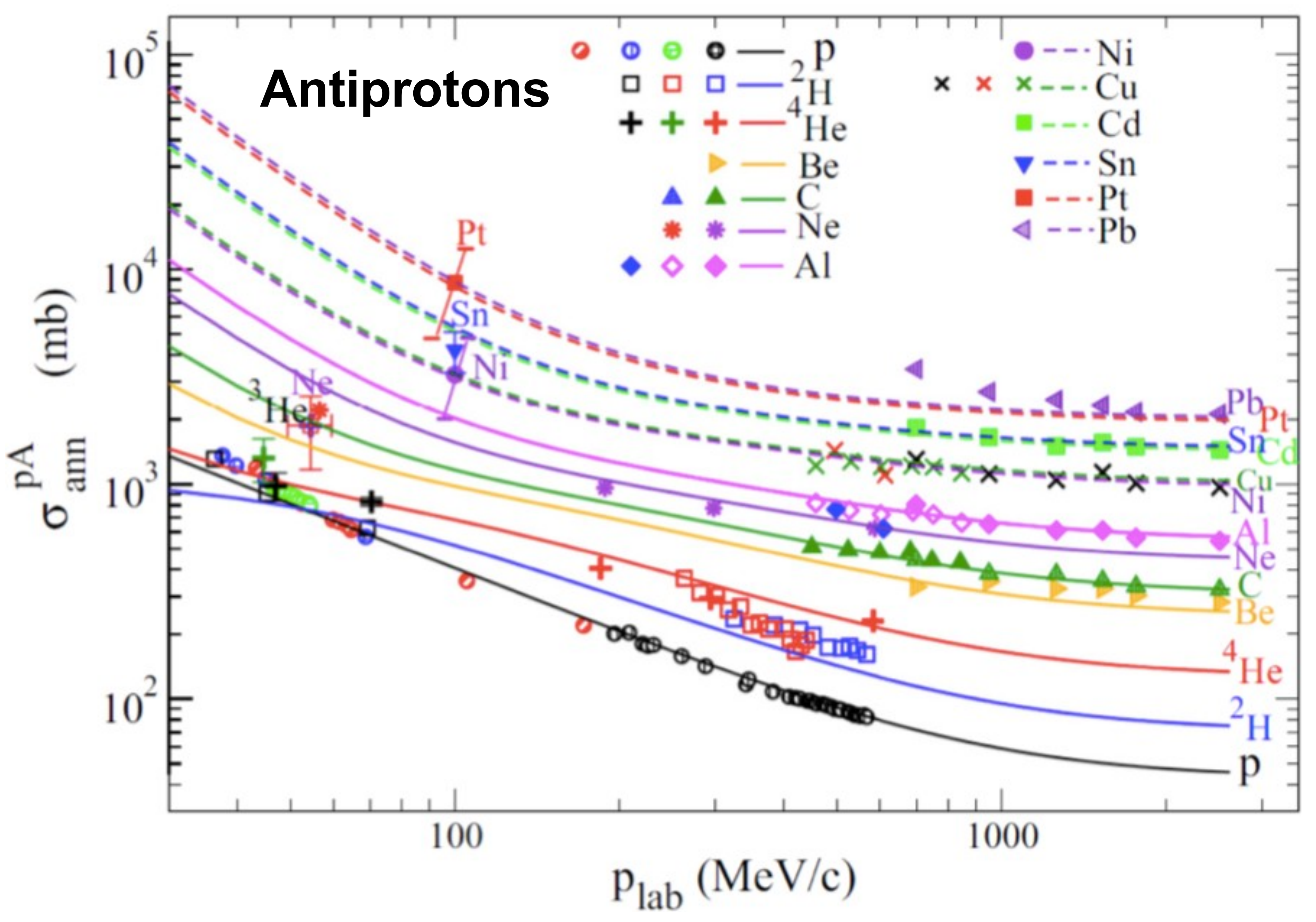
→ Precise knowledge of antinuclei production, propagation and inelastic interactions needed



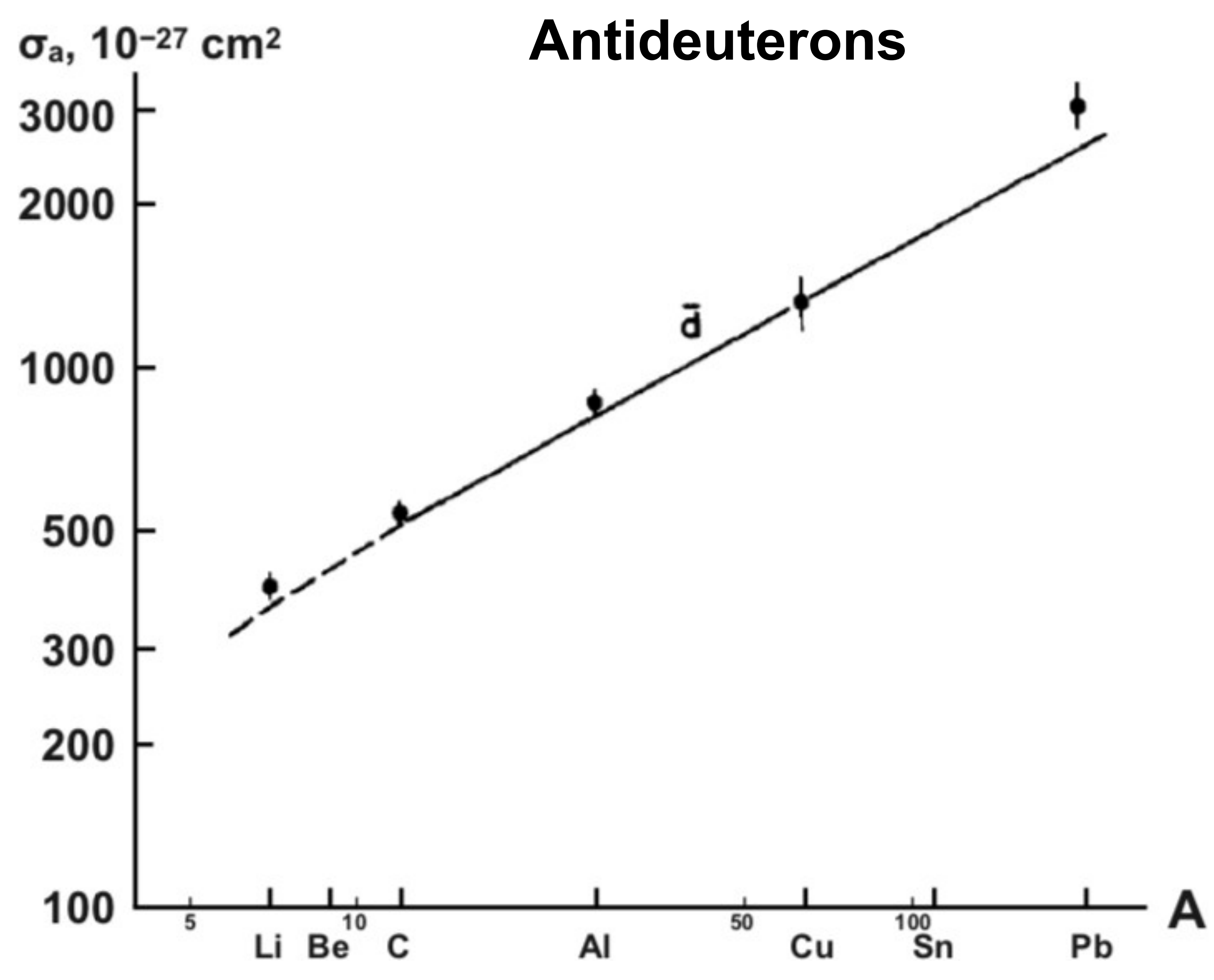
Inelastic cross section measurements

- Inelastic cross section measurements
  - Well constraint for antiprotons
  - No measurements at low energies for antideuterons
  - No measurements for $A \geq 3$ at high energies before ALICE
    In the last years several measurements by ALICE on $\bar{\mathrm{d}}, \bar{\mathrm{t}}, \overline{^{3}\mathrm{He}}$

Denisov et. al. Nuc.Phys. B(1971)31
Binon et al. PLB(1970)31
ALICE: PRL125(2020)162001,
arxiv.org/2202.01549



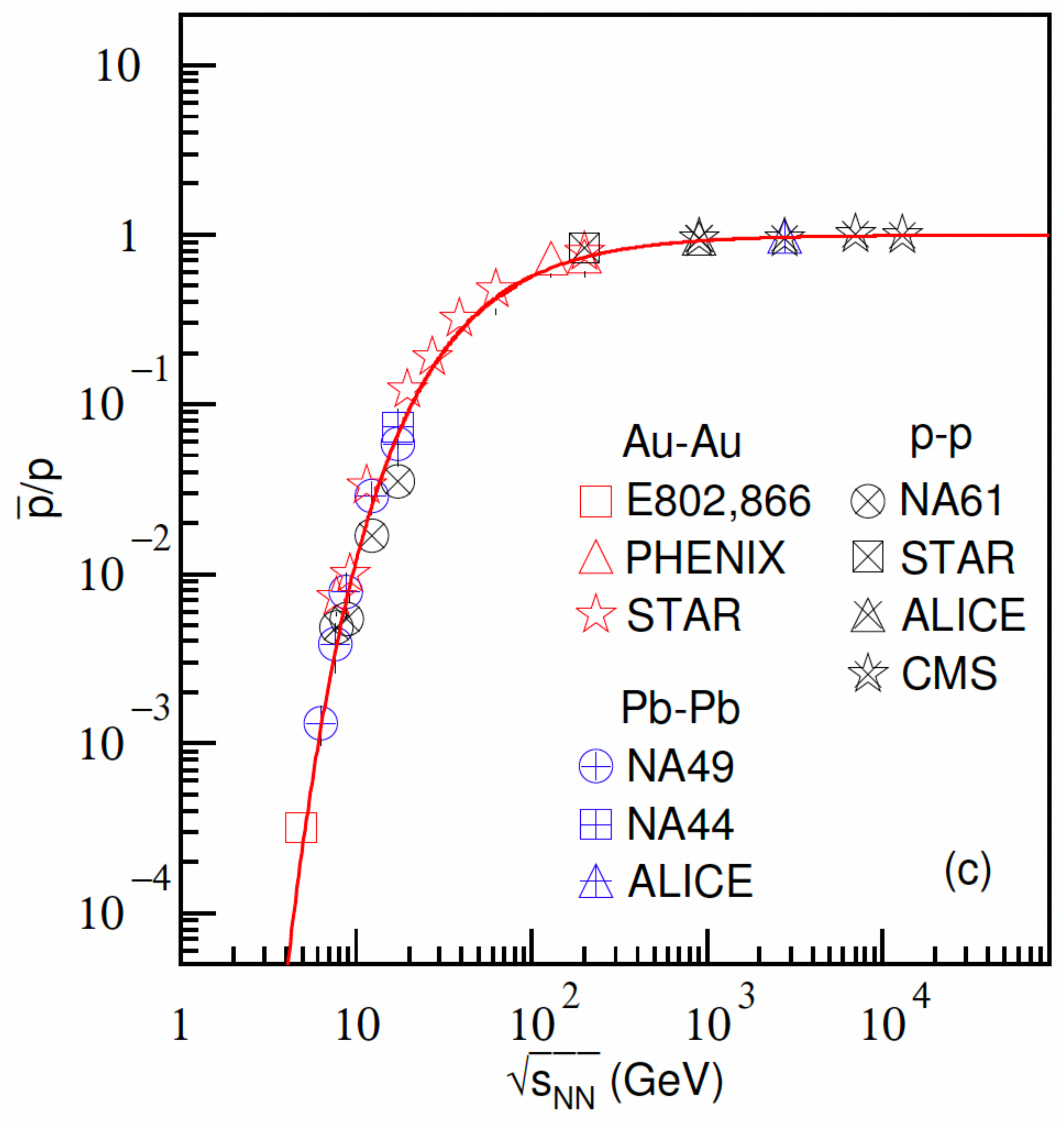
T.G. Lee and C.Y. Wong, Phys. Rev. C 89, 054601 (2014)



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

LHC as an antimatter factory

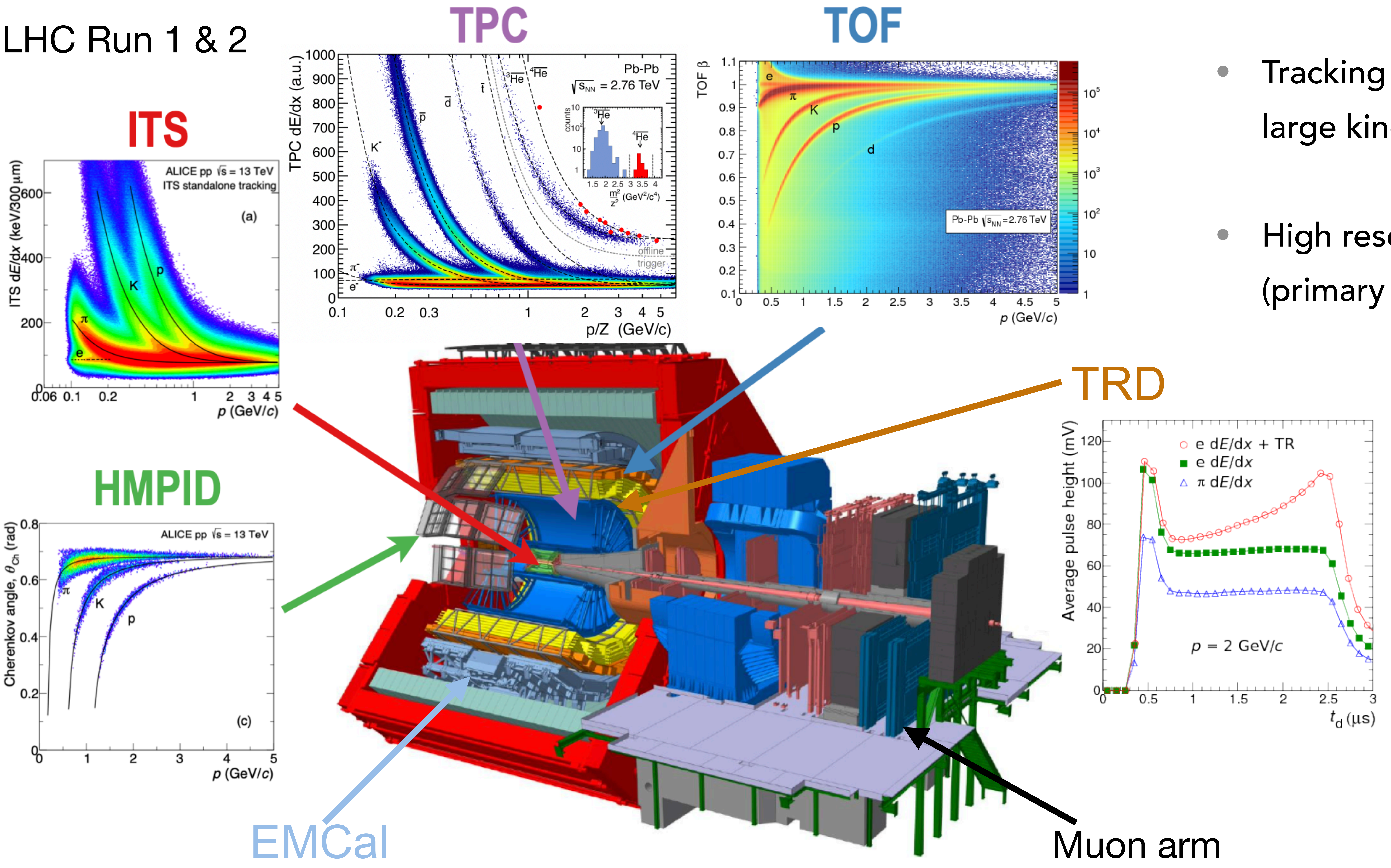
- At LHC energies, particles and antiparticles are produced in almost equal amounts



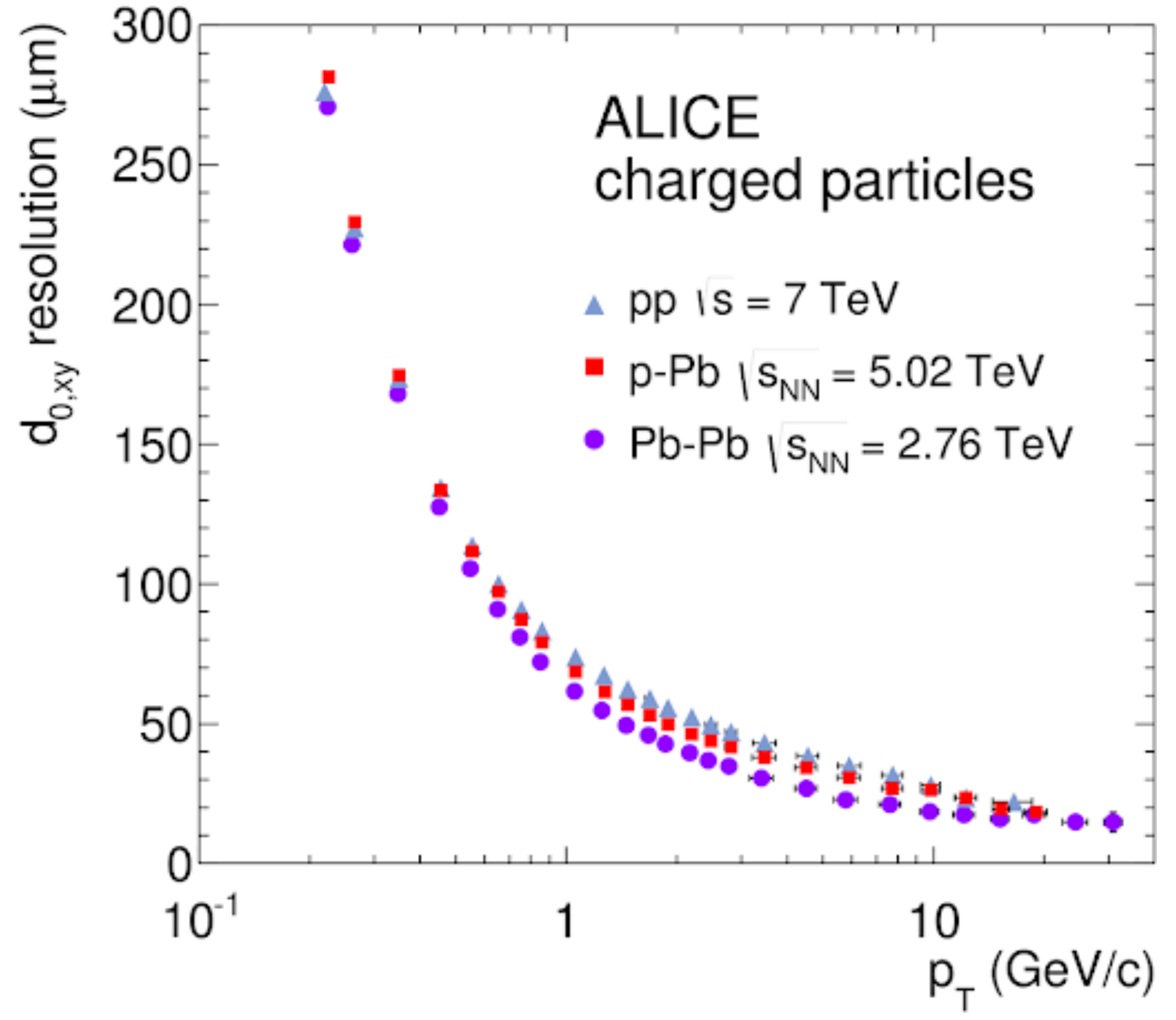
H.-L. Lao et al., Universe5(2019)6

ALICE - A Large Ion Collider Experiment

LHC Run 1 & 2

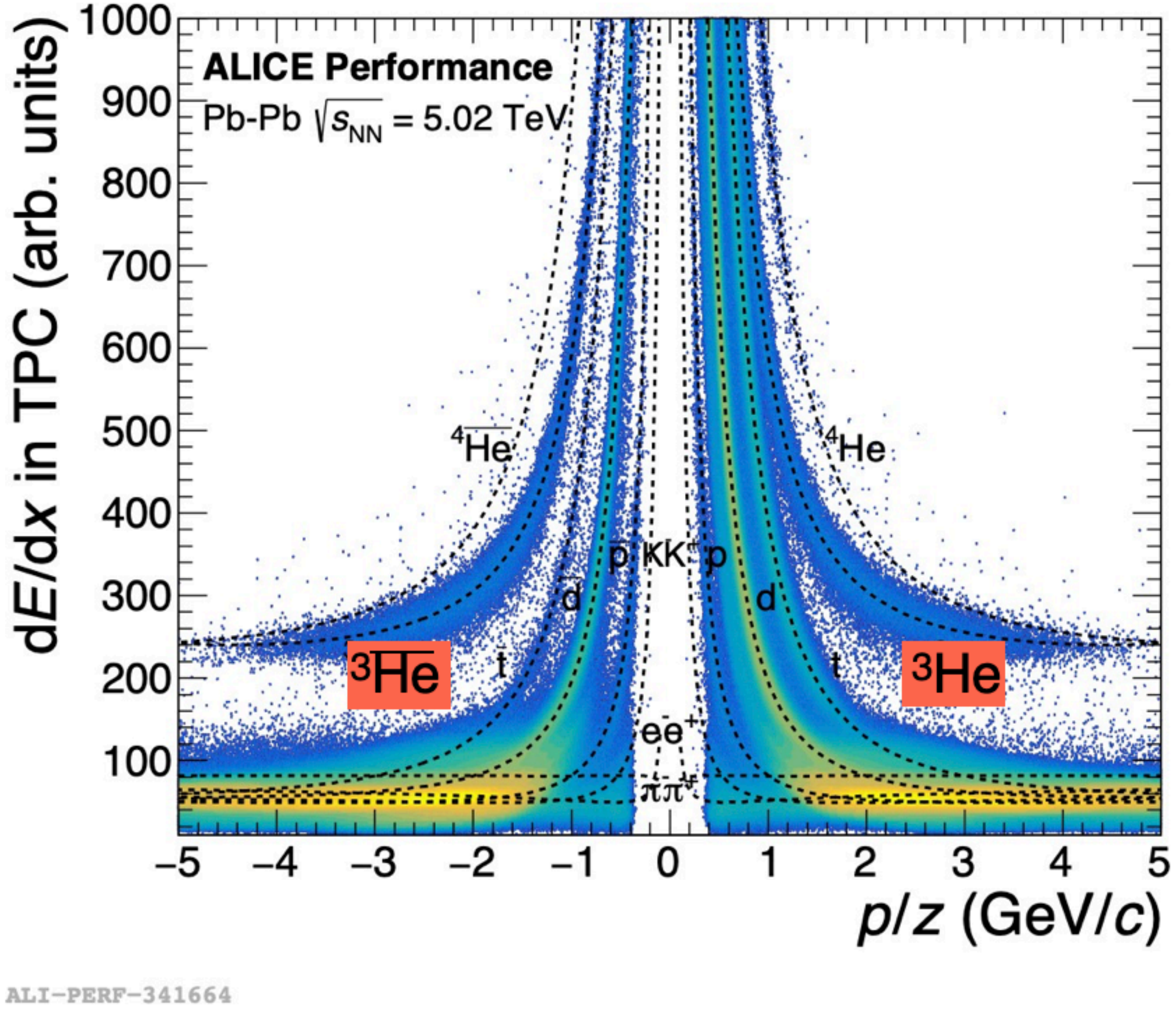


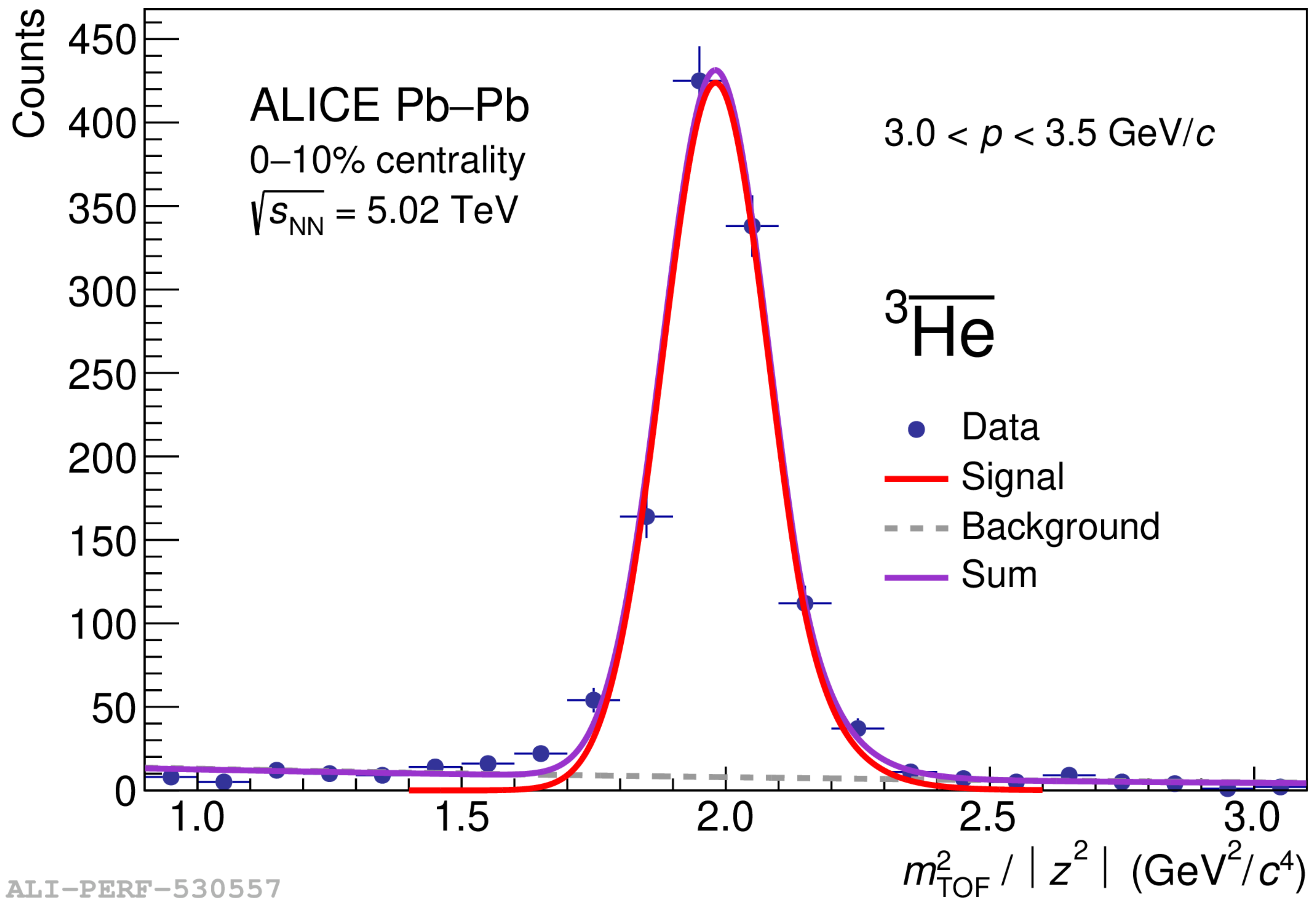
- Tracking and particle identification over large kinematic range, especially to low p_T
- High resolution vertex reconstruction (primary and secondary)



ALICE - particle identification

- Excellent particle identification for antihelium-3





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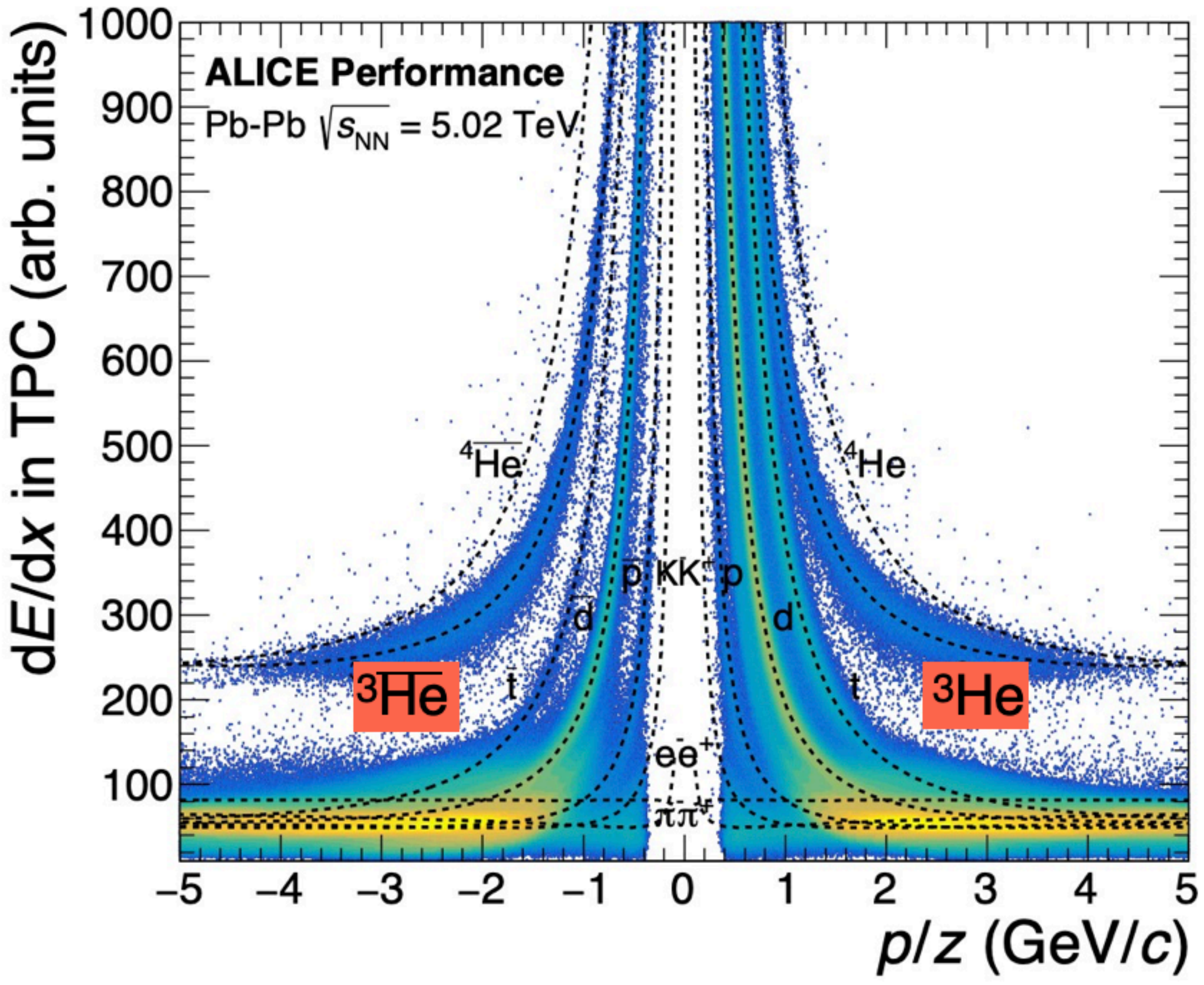

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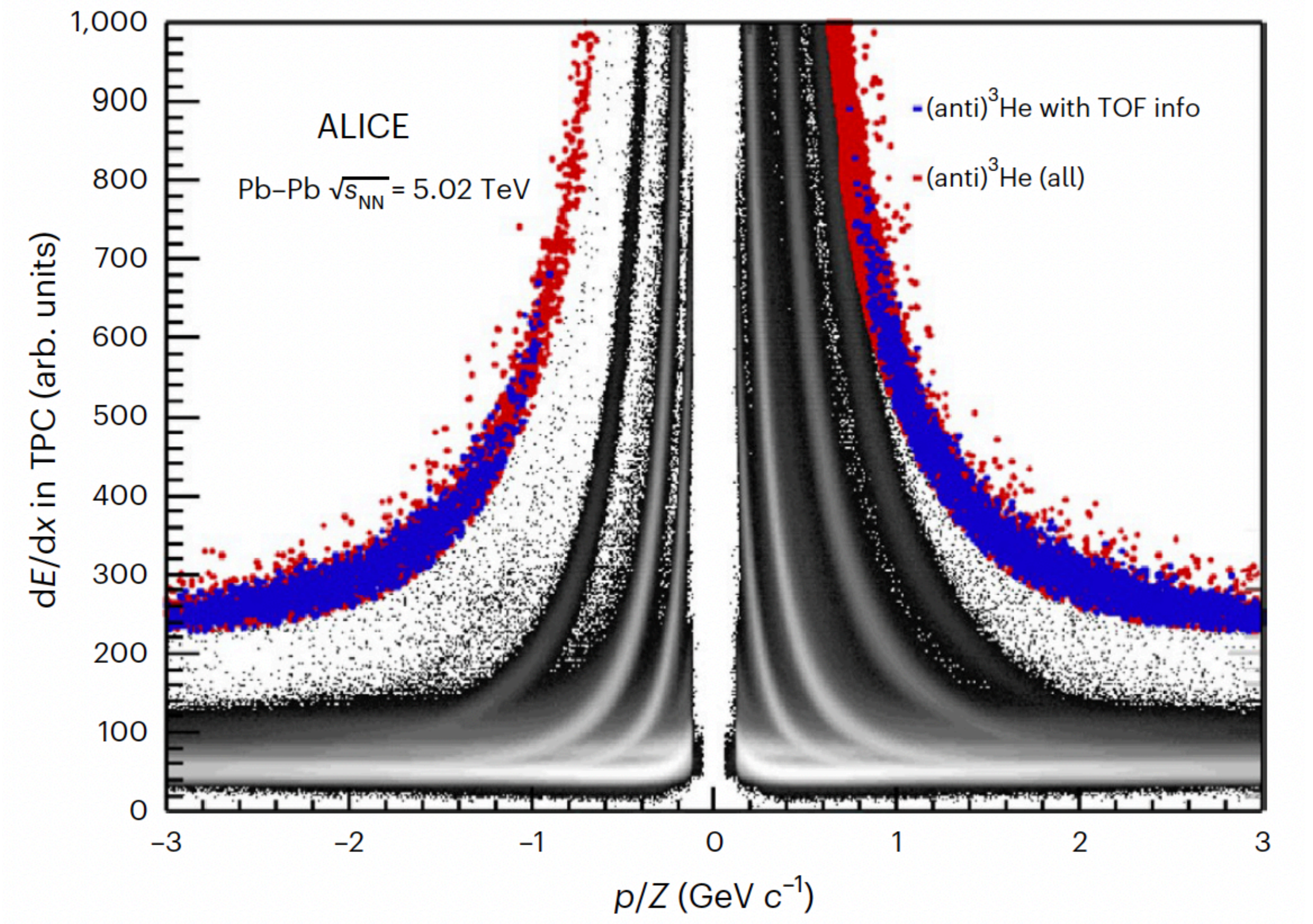
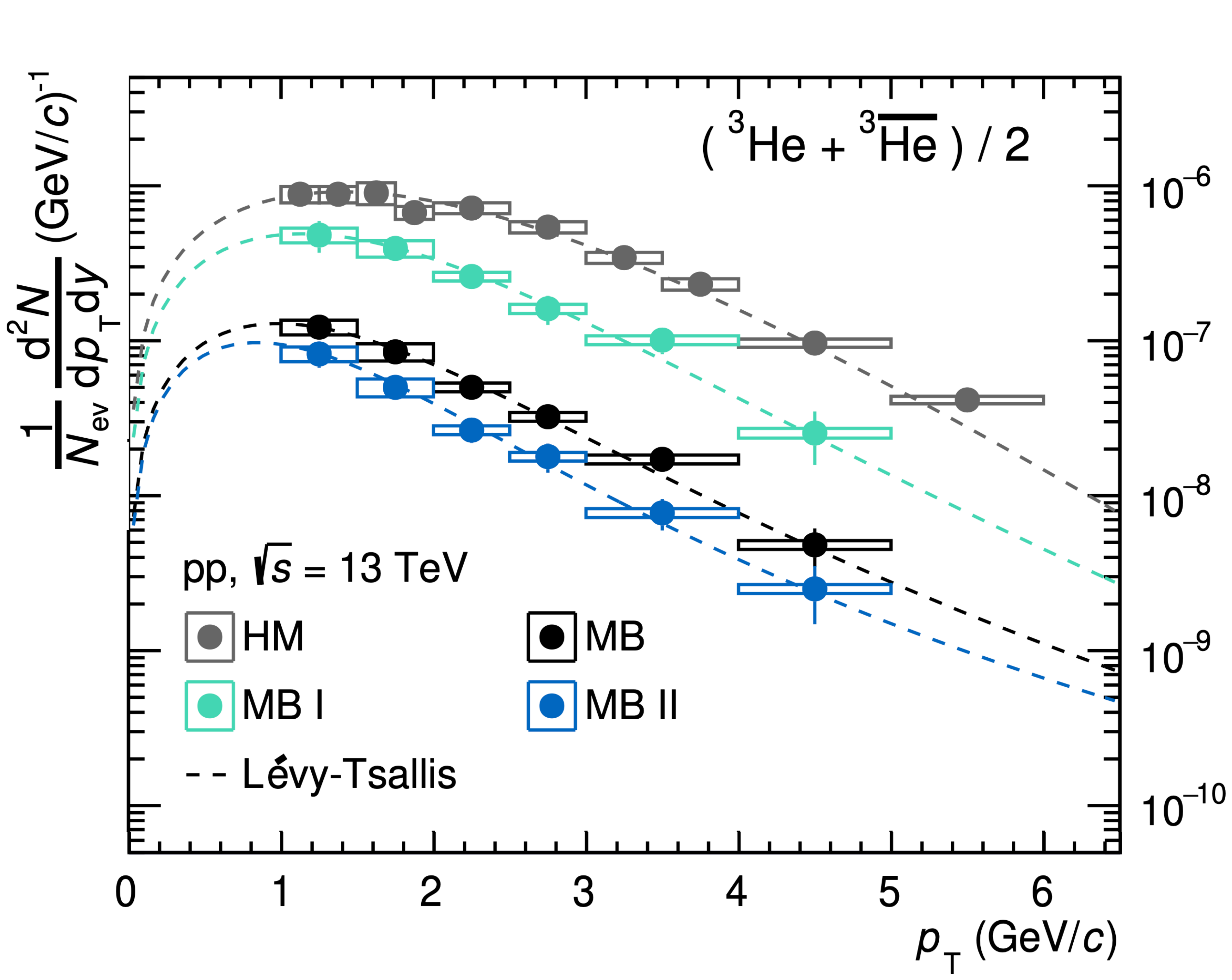
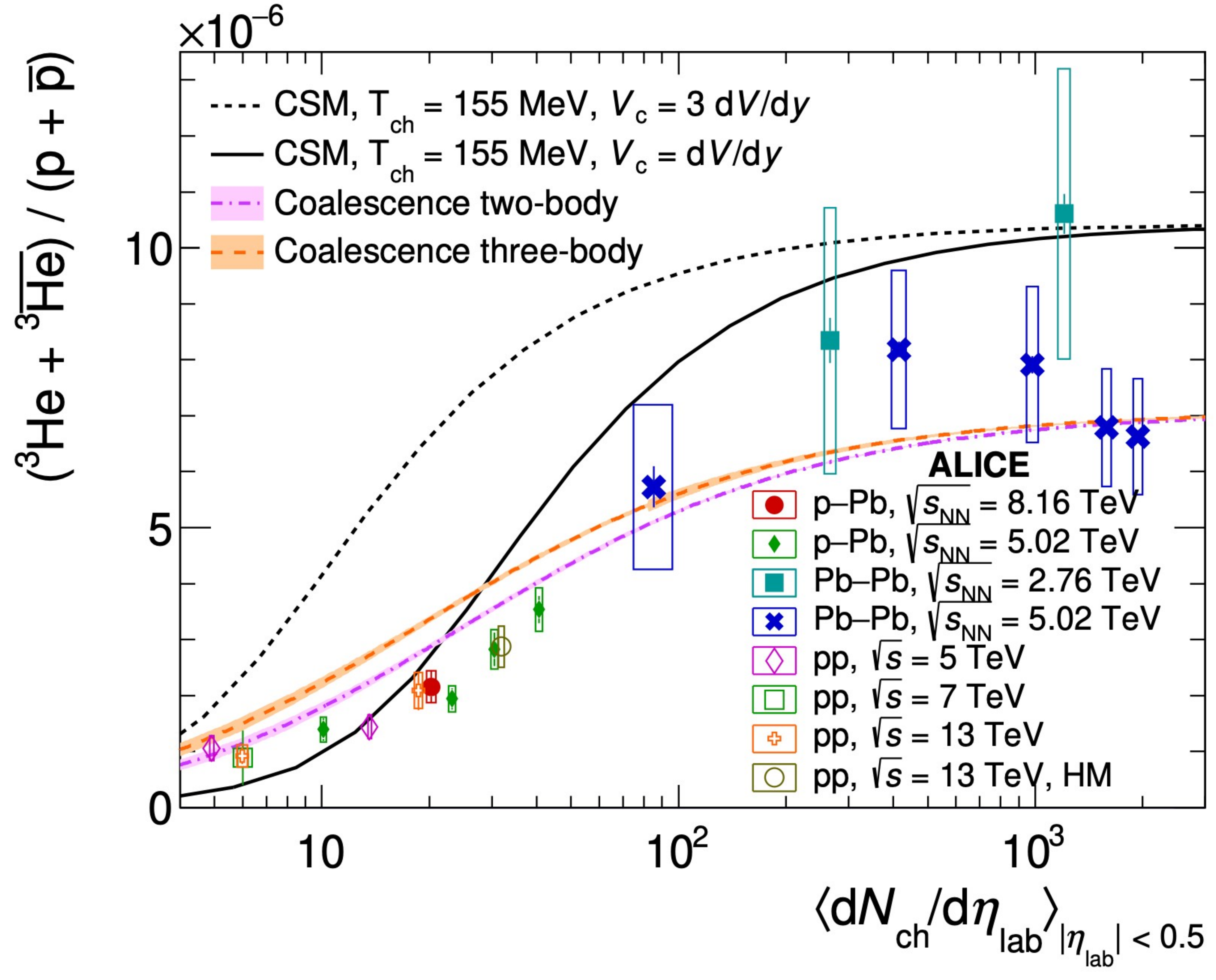


(Anti)helium-3 measurements

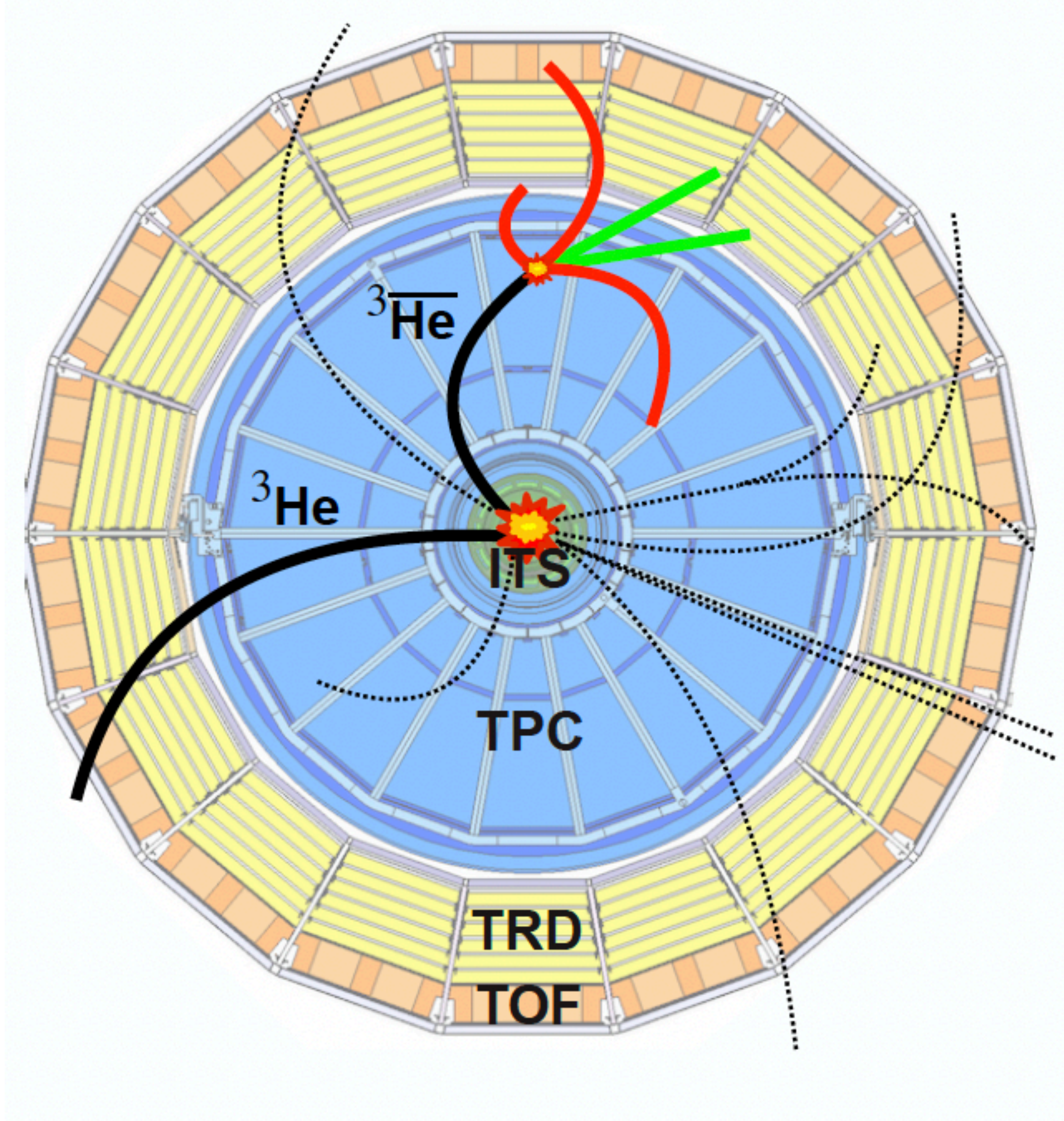
ALICE: JHEP01(2022)106, arXiv:2212.04777

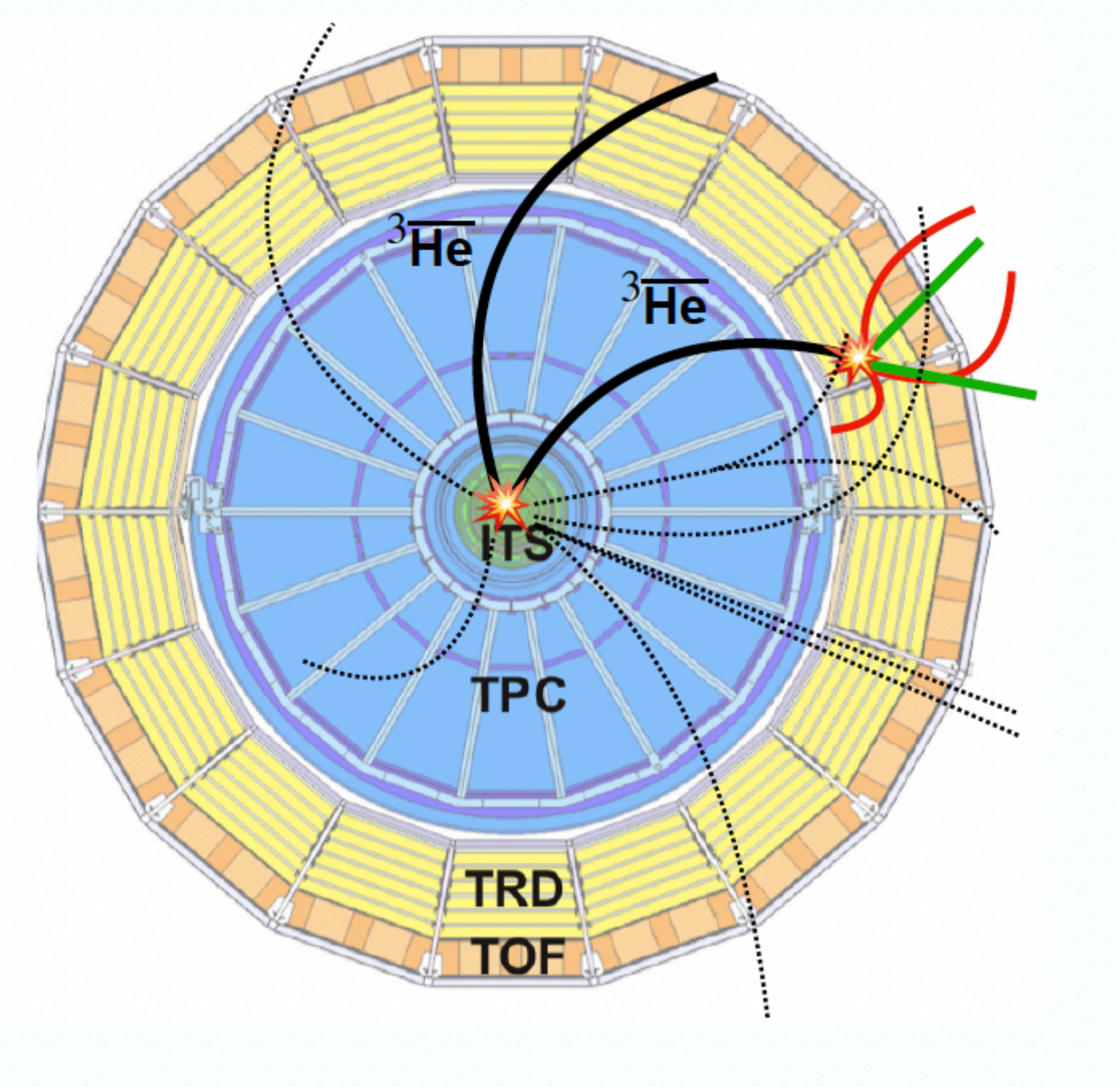
- Measurements in different collision systems
  - Measurements in pp with high precision
  - ~16800 primary $^{3}\overline{\mathrm{He}}$ in 10% most central Pb-Pb collisions (148* 10^6) and about ~650 $^{3}\overline{\mathrm{He}}$ in HM proton-proton collisions (10^9)





Inelastic cross section measurement using ALICE as a target



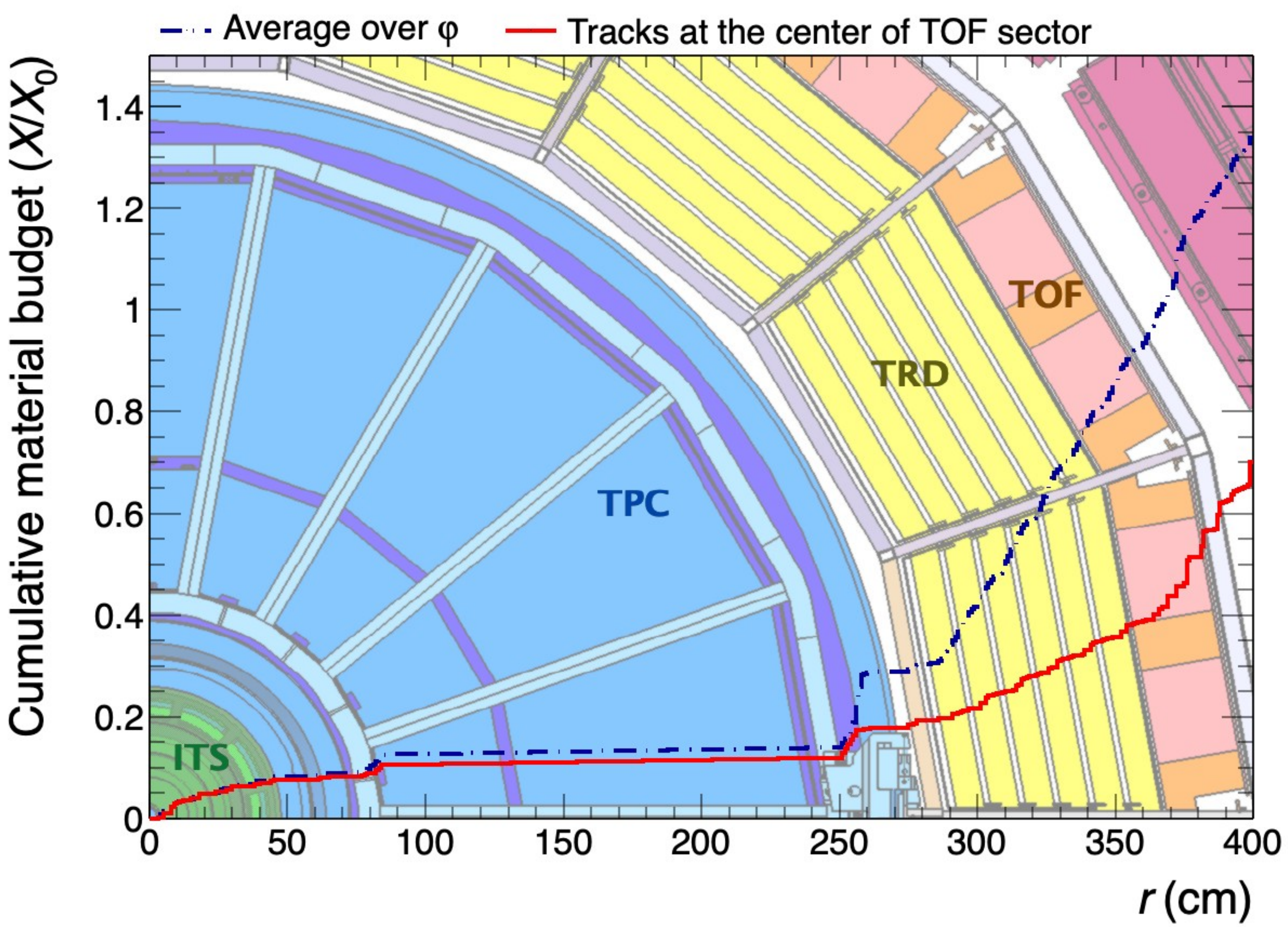


- Method 1: measure antimatter-to-matter ratio of $\frac{^3\overline{\mathrm{He}}}{^3\mathrm{He}}$ and compare with MC simulations (used in pp collisions)
- Method 2: Measure TOF-TPC-matching $\frac{^3\overline{\mathrm{He}}_{\mathrm{TOF}}}{^3\overline{\mathrm{He}}_{\mathrm{TPC}}}$ and compare with MC simulations (used in Pb-Pb collisions)

→ Material budget must be well known

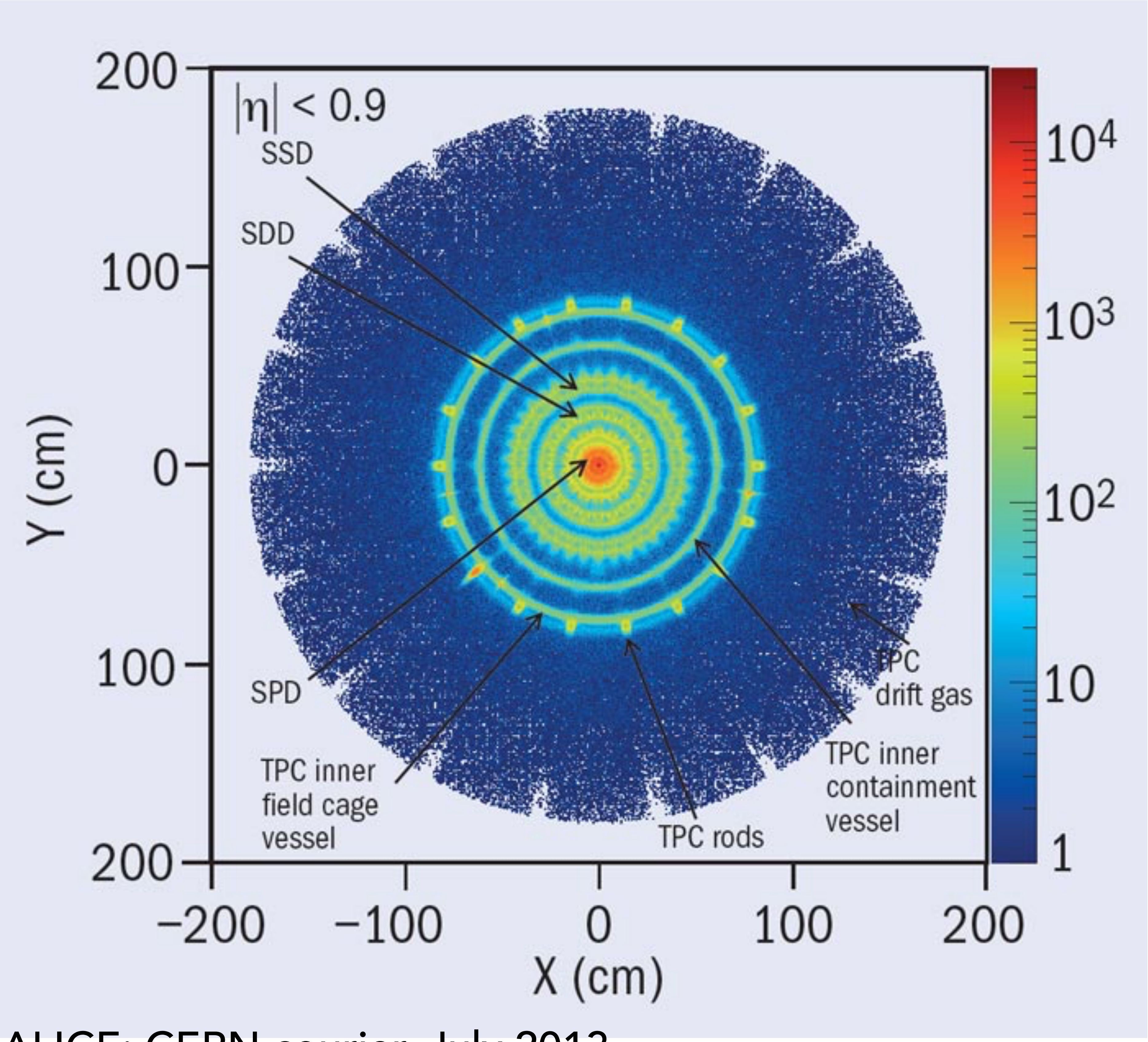
Inelastic cross section measurement using ALICE as a target

- Antiparticle can undergo annihilation while traveling through the detector material
- Reduction in antiparticle yield = measurement of the inelastic cross section of antiparticles
- Average material budget
  - Contribution from different materials weighted with their density times length crossed by the particles
  - Method 1: antimatter-to-matter ratio
  - Method 2: TPC-TOF matching
  - Averaged atomic mass ranges from $\langle A \rangle = 17.4$ to 34.7
  - Averaged charge number ranges from $\langle Z \rangle = 8.5$ to 16.1

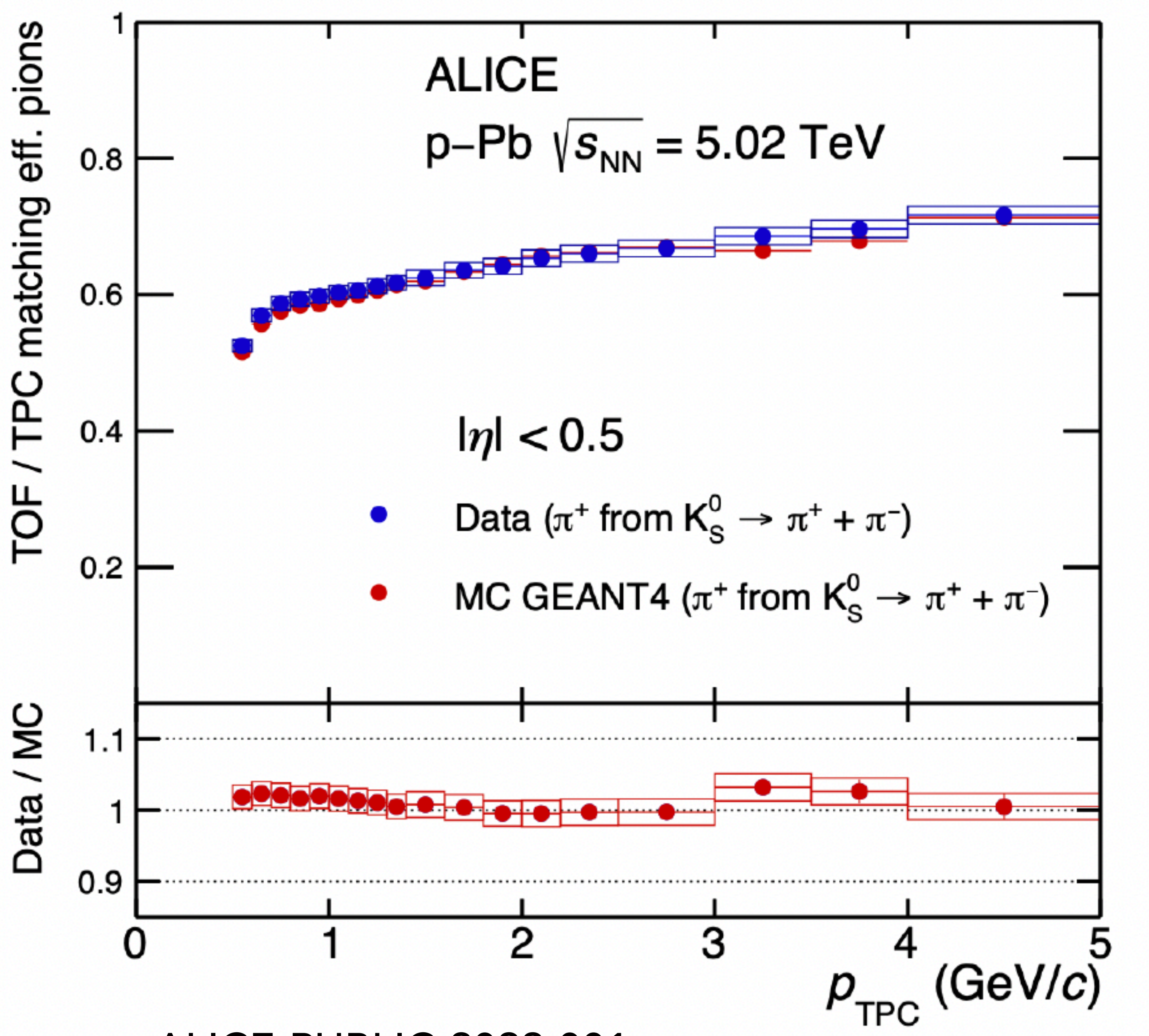


ALICE material budget

- Material budget needs to be known very accurately
  - Determined via the measurement of electrons from photon conversions ($\gamma \rightarrow e^+e^-$), pions from K_S^0 decays and protons from Λ decays
  - Precision of ~4.5%



ALICE: CERN courier, July 2013



ALICE-PUBLIC-2022-001

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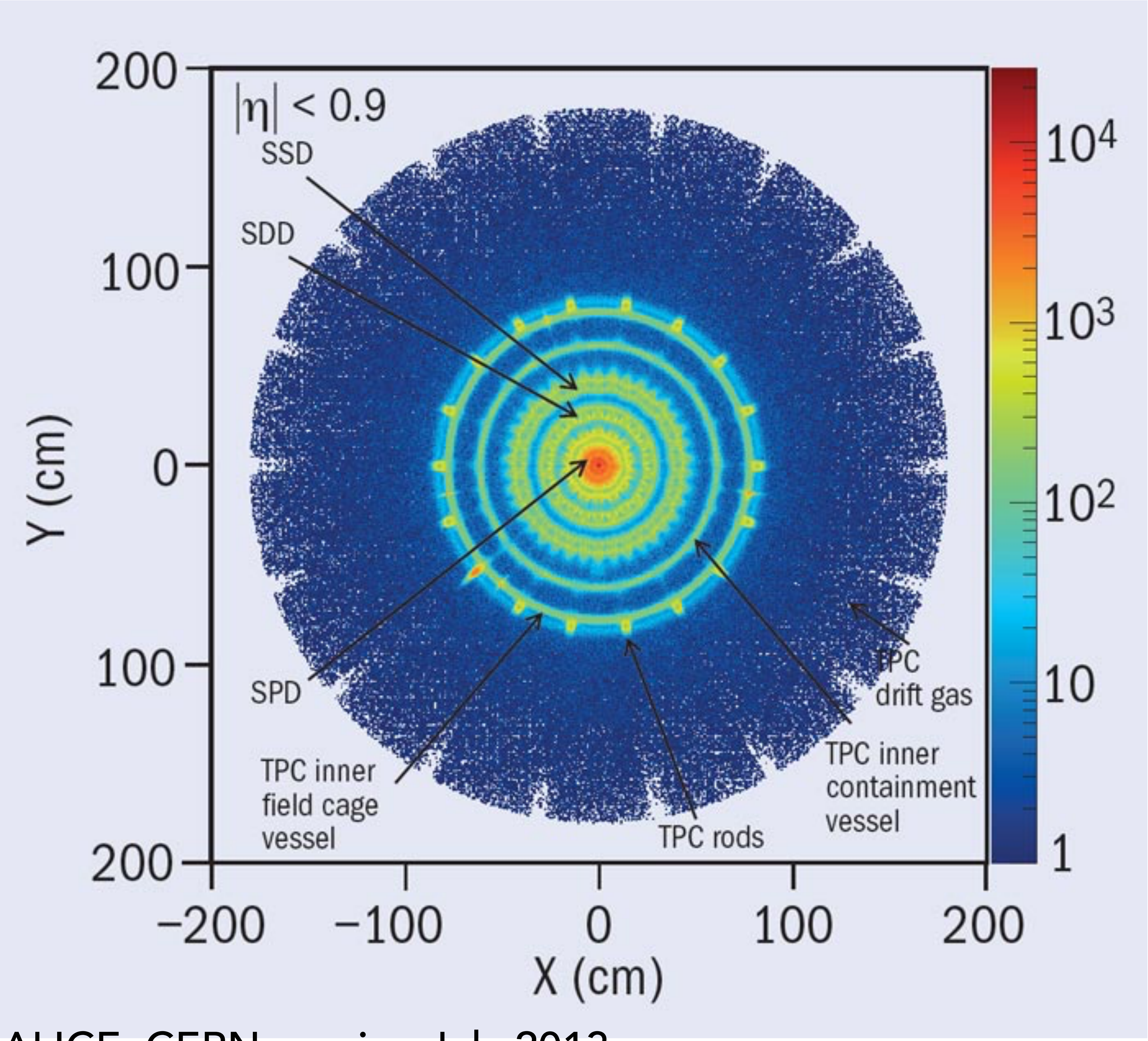

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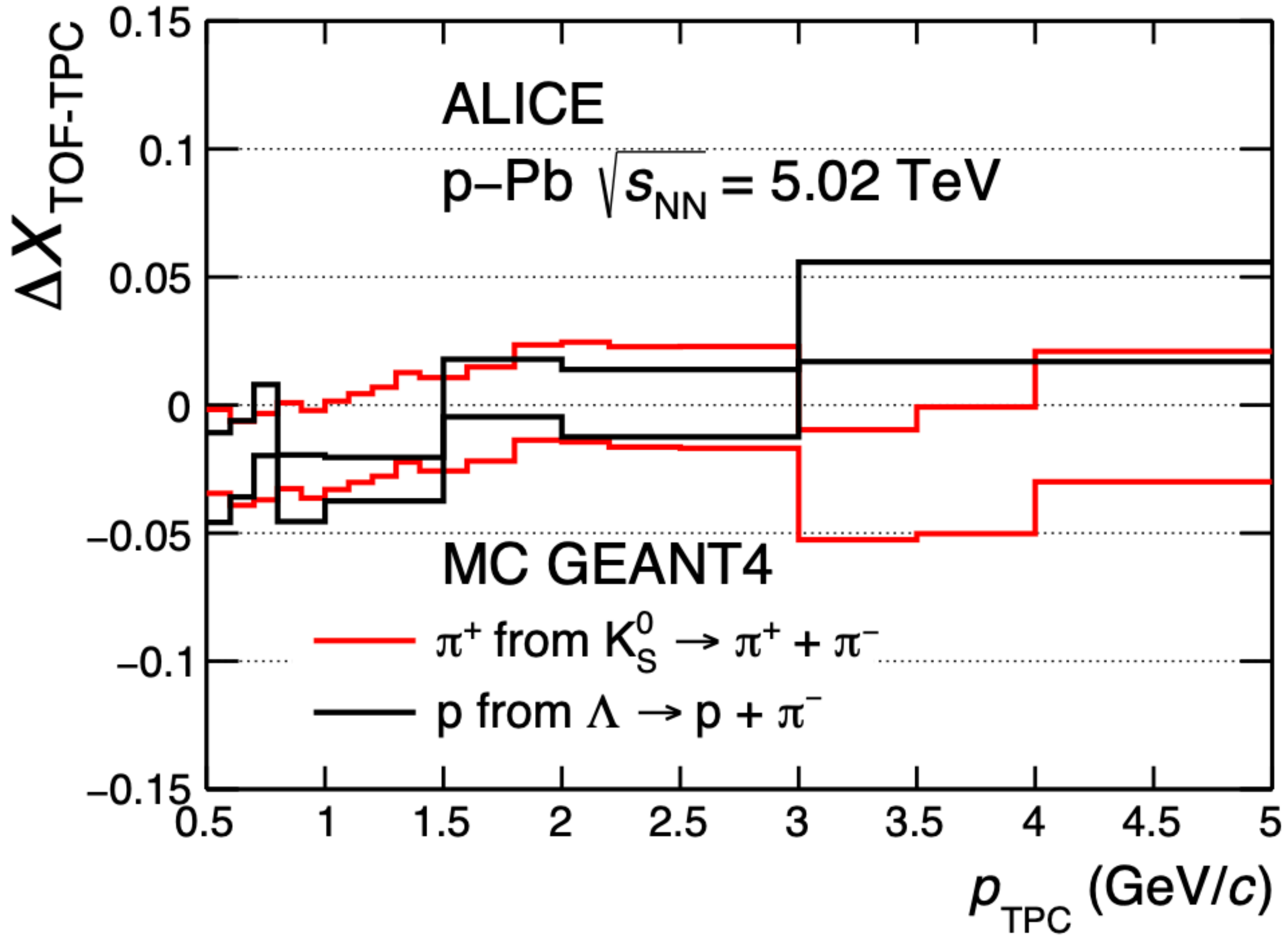

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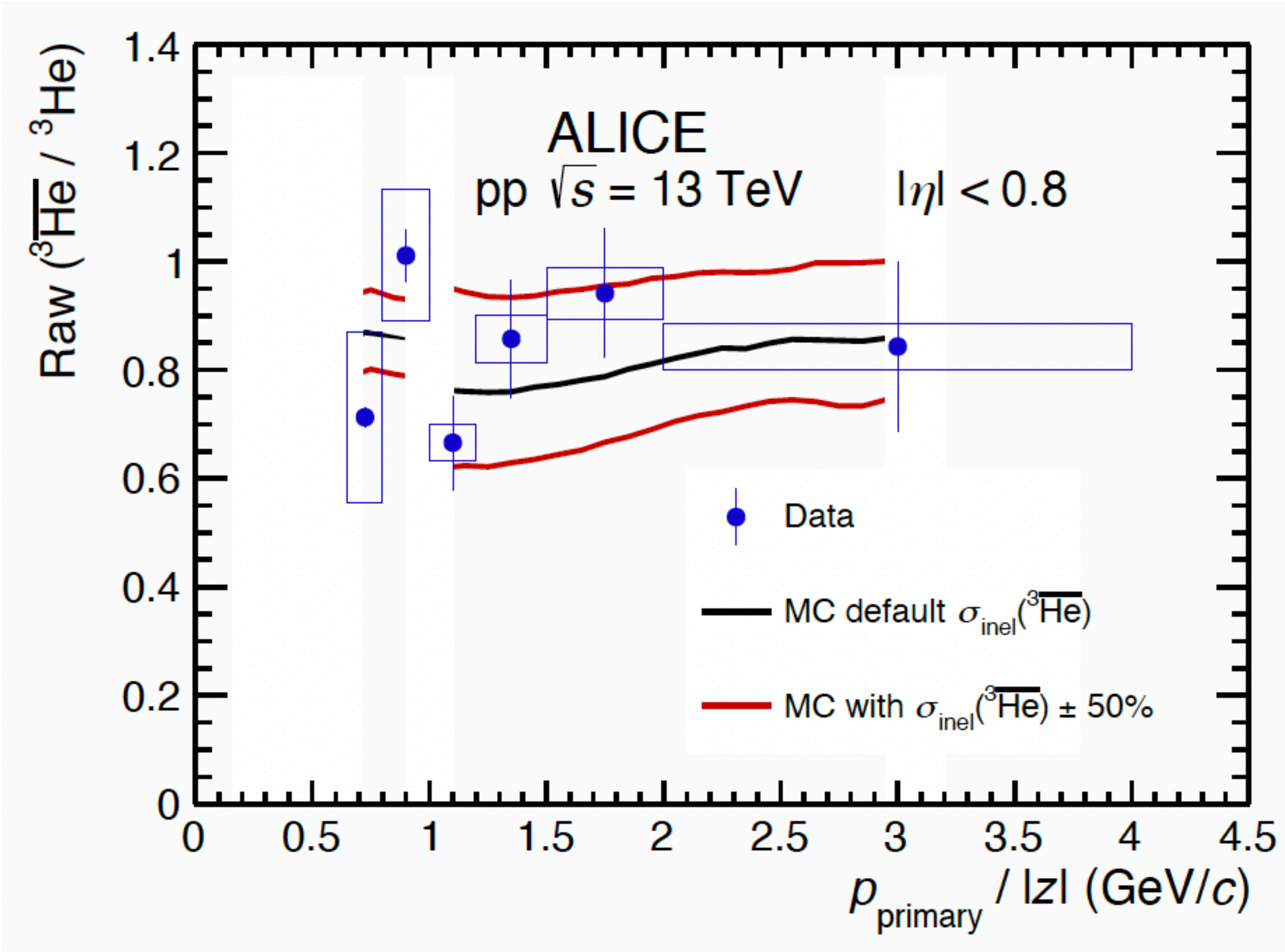
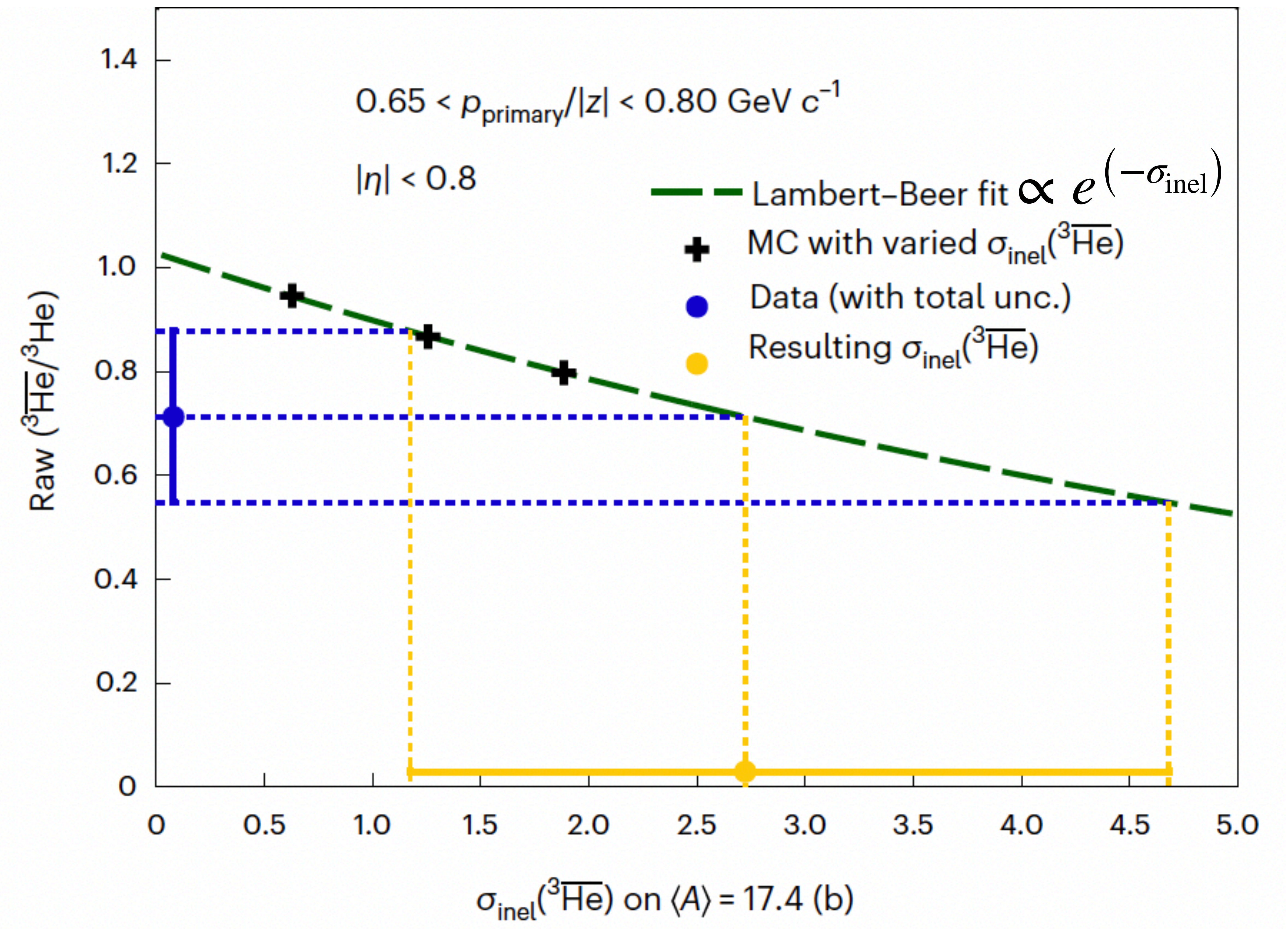
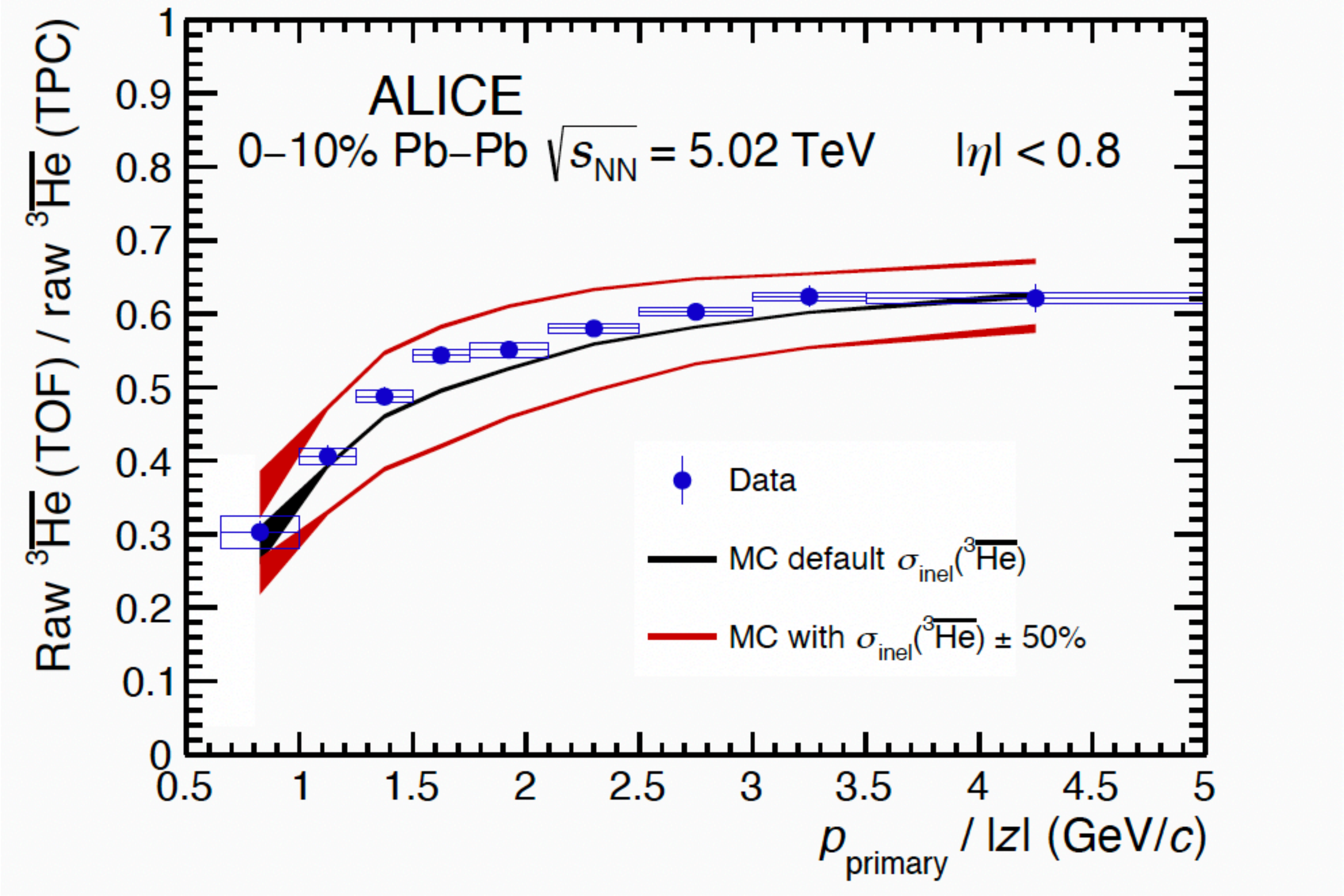
Method 1: Antimatter-to-matter ratio

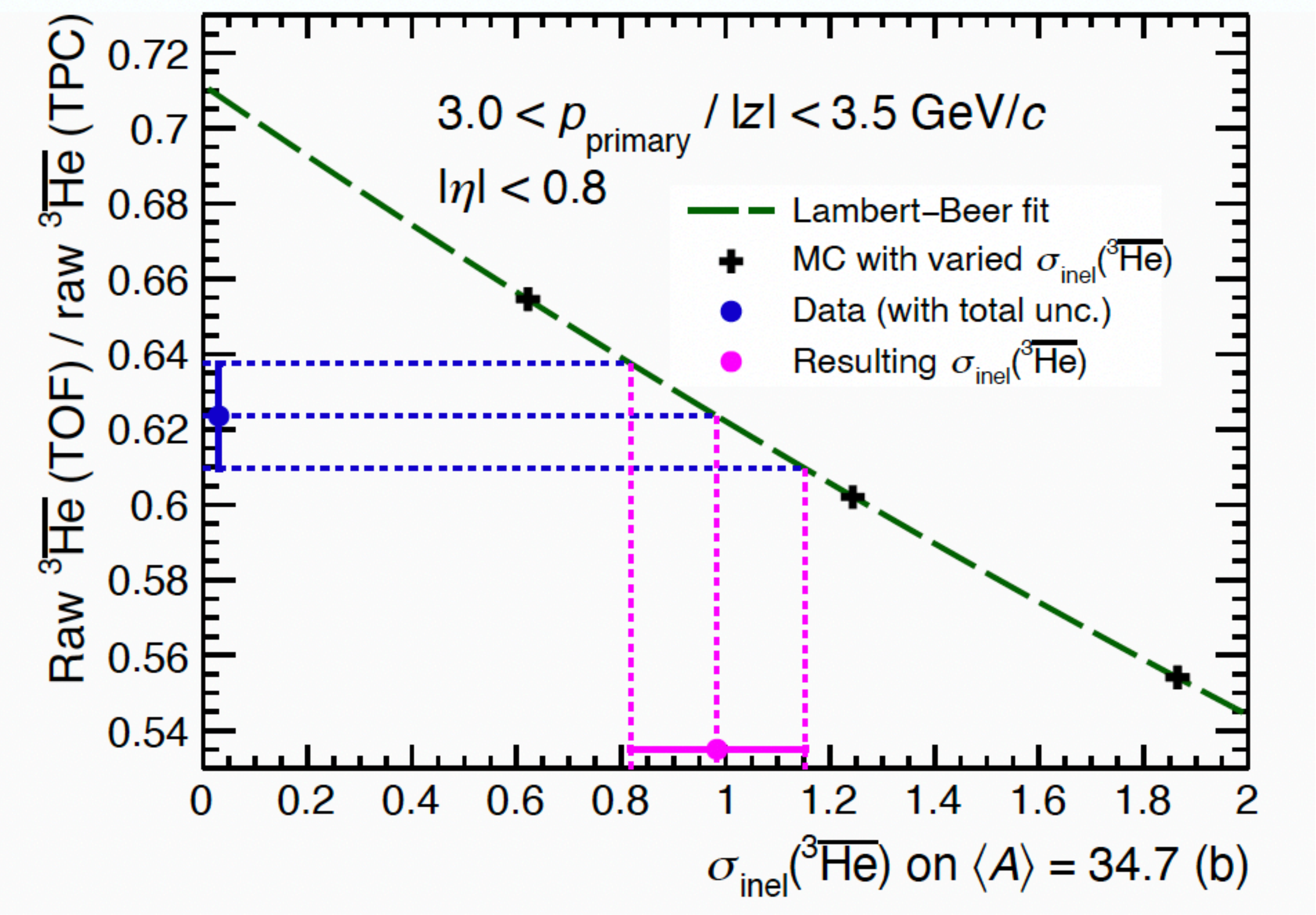




- In Monte Carlo simulations $\sigma_{\text{inel}}^{^3\overline{\text{He}}}$ stepwise varied
- Correlate raw ratio with $\sigma_{\text{inel}}^{^3\overline{\text{He}}}$
- Experimental data point → central value
- Upper/lower edge of the total uncertainty (quadratic sum of stat. and syst. uncertainty) →1**σ** confidence interval

Method 2: TOF-TPC Matching





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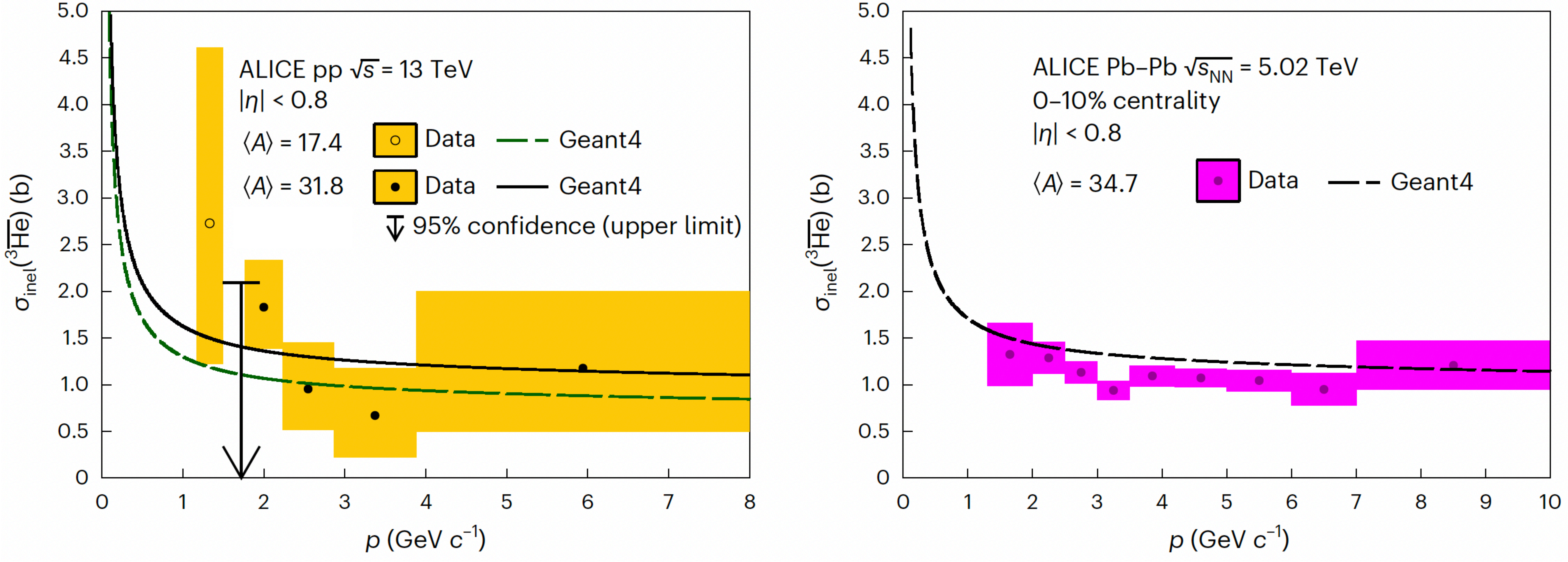
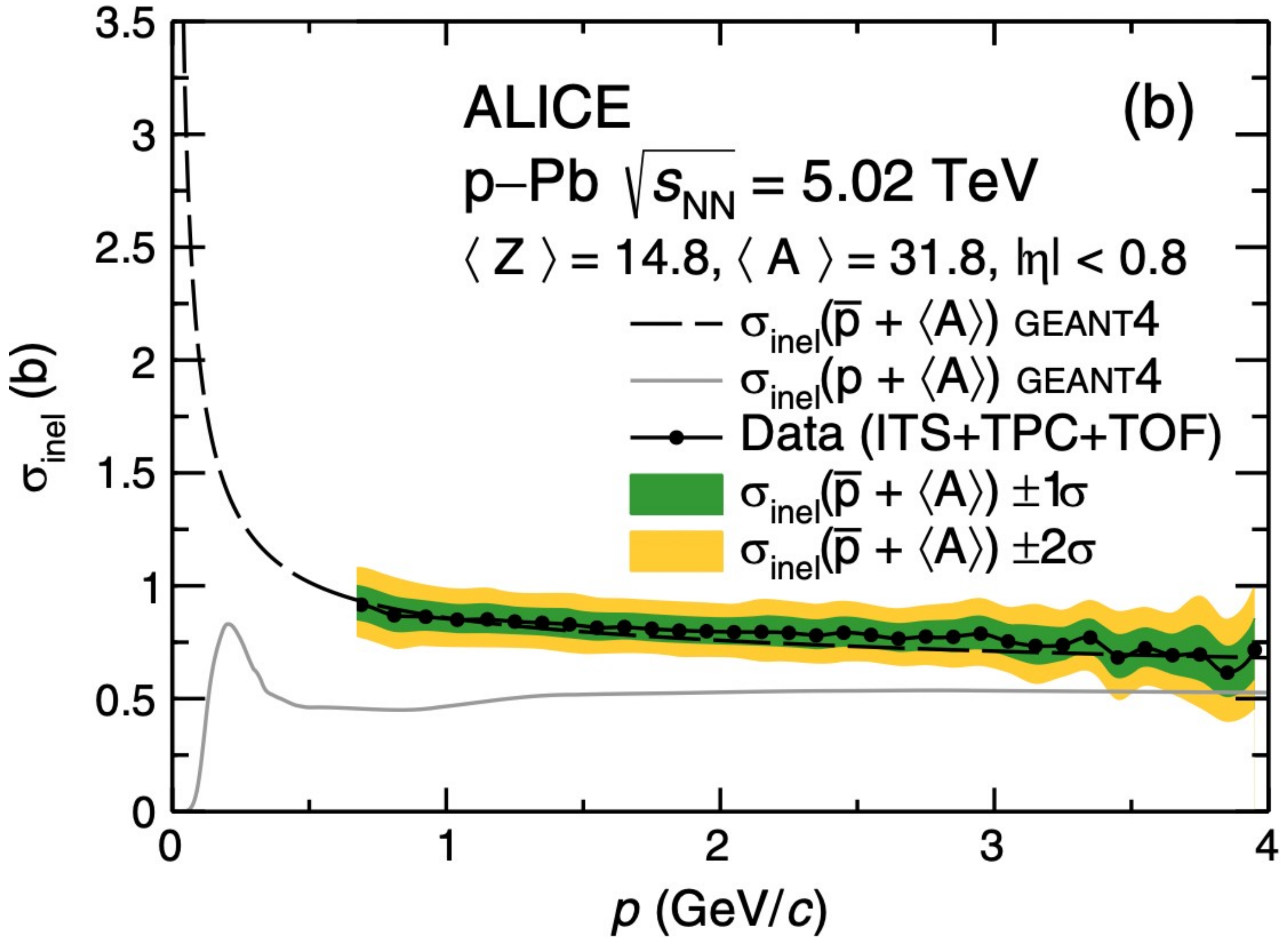
Inelastic cross section $\sigma_{\text{inel}}^{\overline{^3\text{He}}}$



- Inelastic cross section $\sigma_{\text{inel}}^{\overline{^3\text{He}}}$ for average target material *A*
- Uncertainties: material budget at low *p*, at high *p* in addition track selection and particle identification
- Momentum determined at interaction point
- GEANT4 describes low momentum region well, but overestimates the data at high momenta

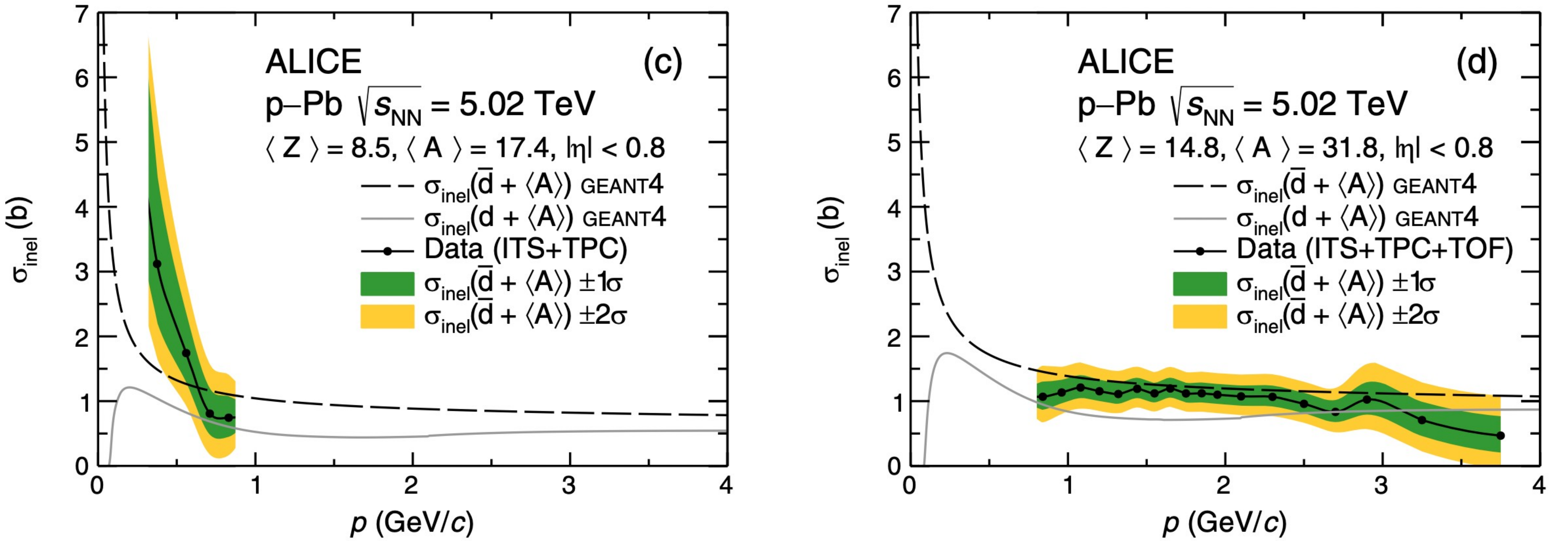
Many more inelastic cross section measurements
Analogous method

Antiproton

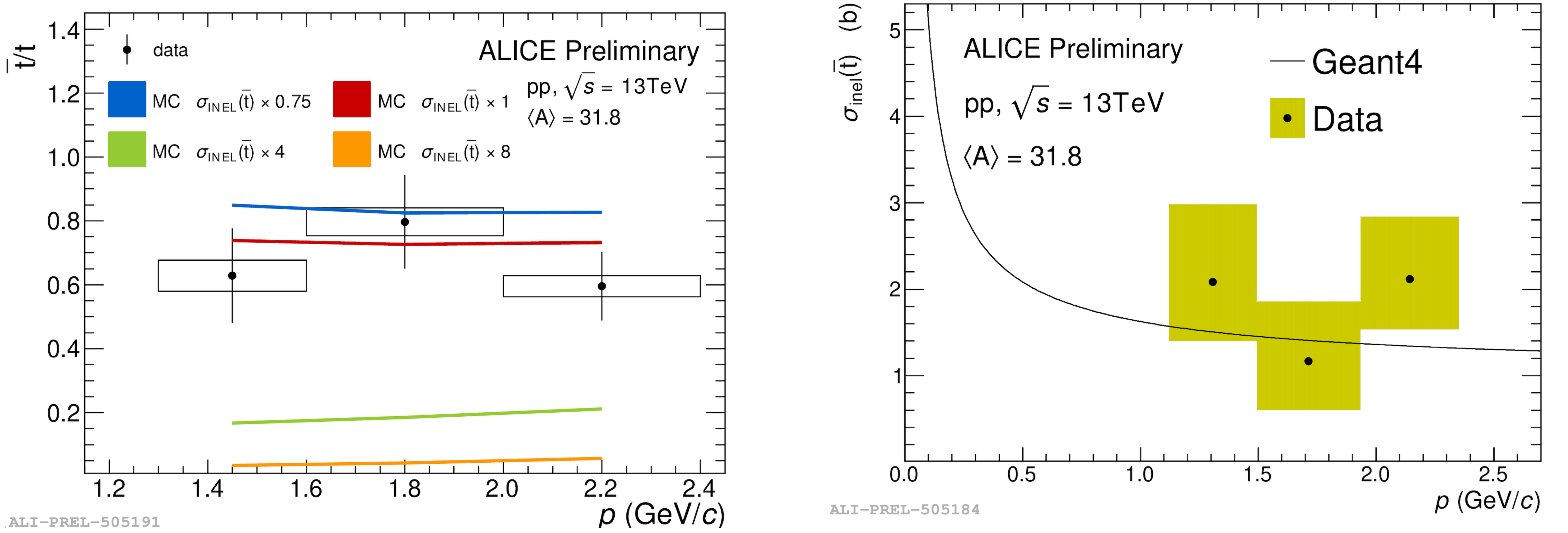


- Analogous method
- Benchmark: antiprotons

Antideuteron (antimatter/matter ratio)



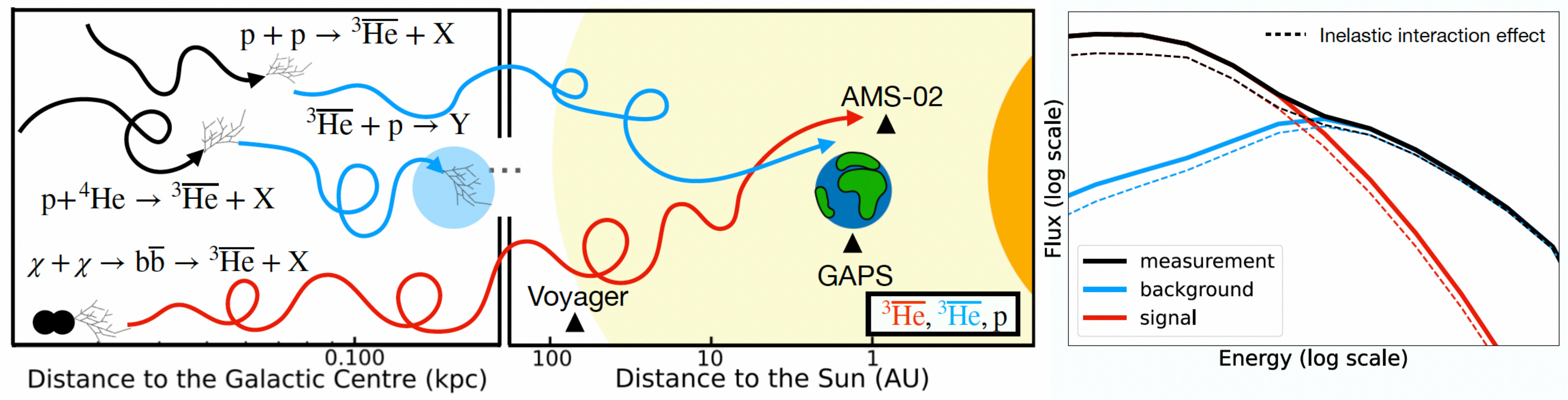
Antitriton



What is the impact on the $^{3}\overline{\mathrm{He}}$ transport in the galaxy?

Antinuclei fluxes near Earth

- Goal: determine $^3\overline{\text{He}}$ fluxes near Earth
- Production
  - Dark matter annihilation and decays
  - Production of secondary $^3\overline{\text{He}}$
- Propagation through the Galaxy
  - Diffusion, convection, solar modulation
- Inelastic interactions



Antinuclei fluxes near Earth

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

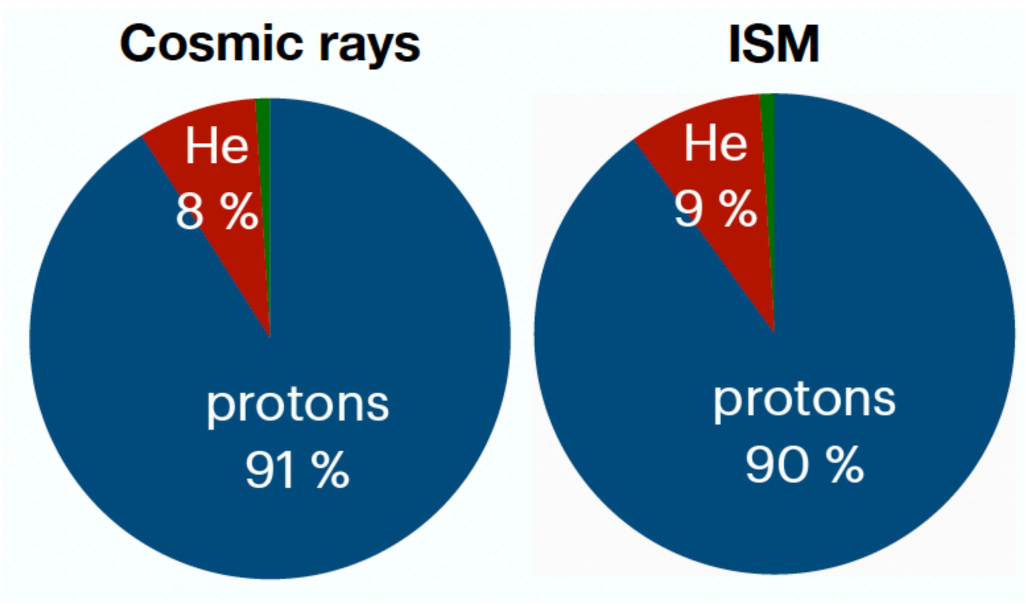
Source Function

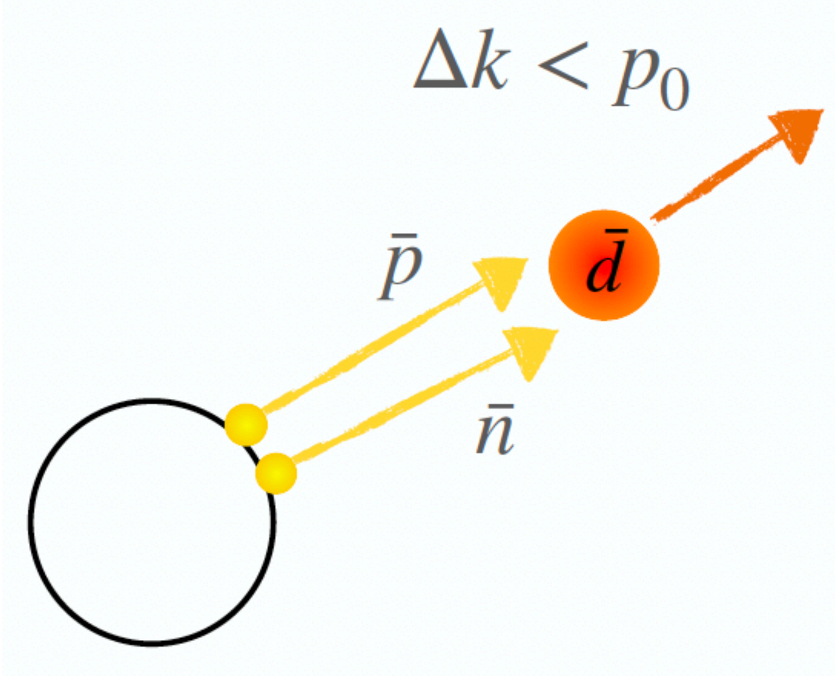
Propagation: Diffusion, convection, solar modulation,…

Fragmentation, annihilation

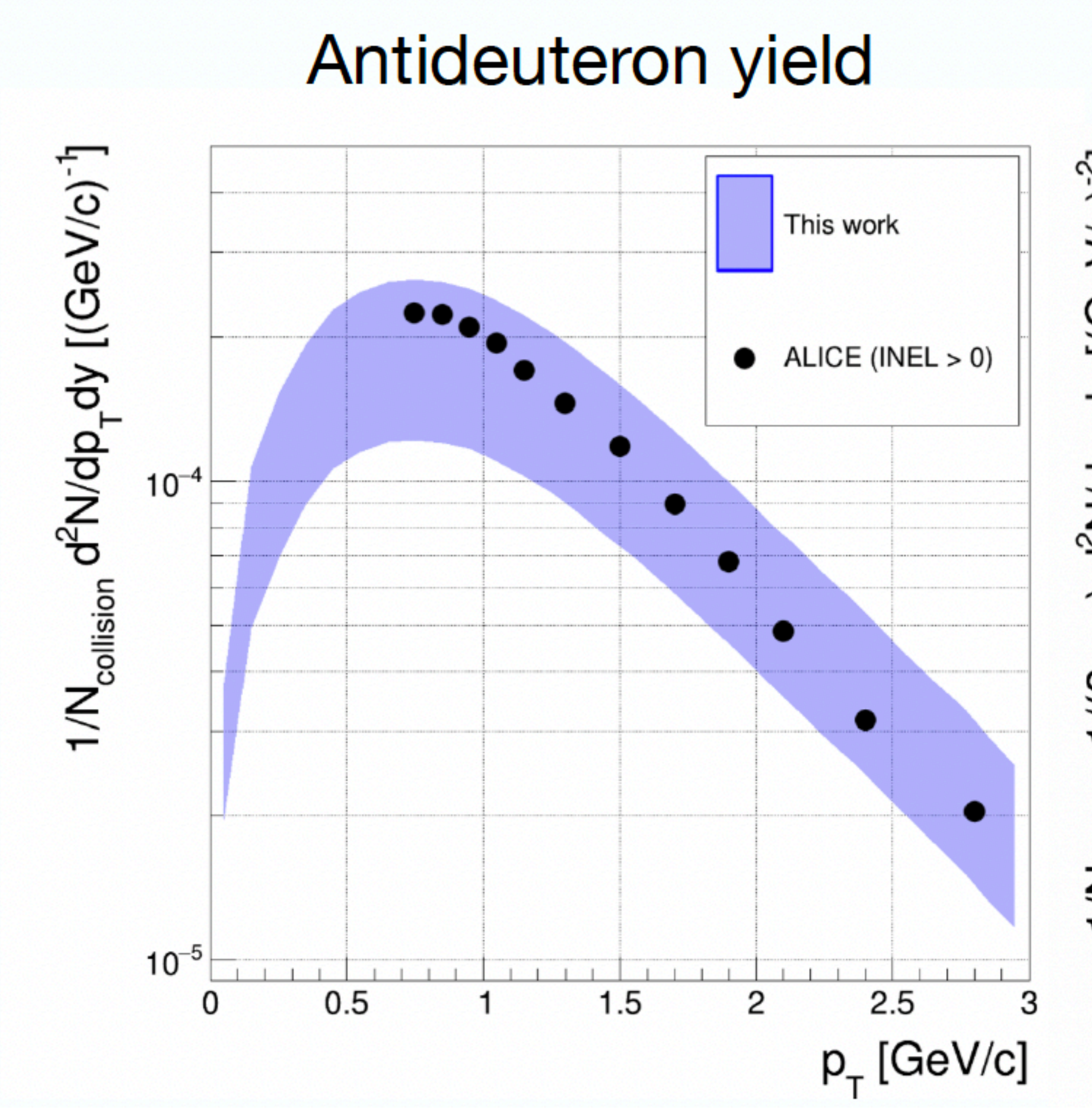
Source function for antinuclei from cosmic ray and interstellar gas

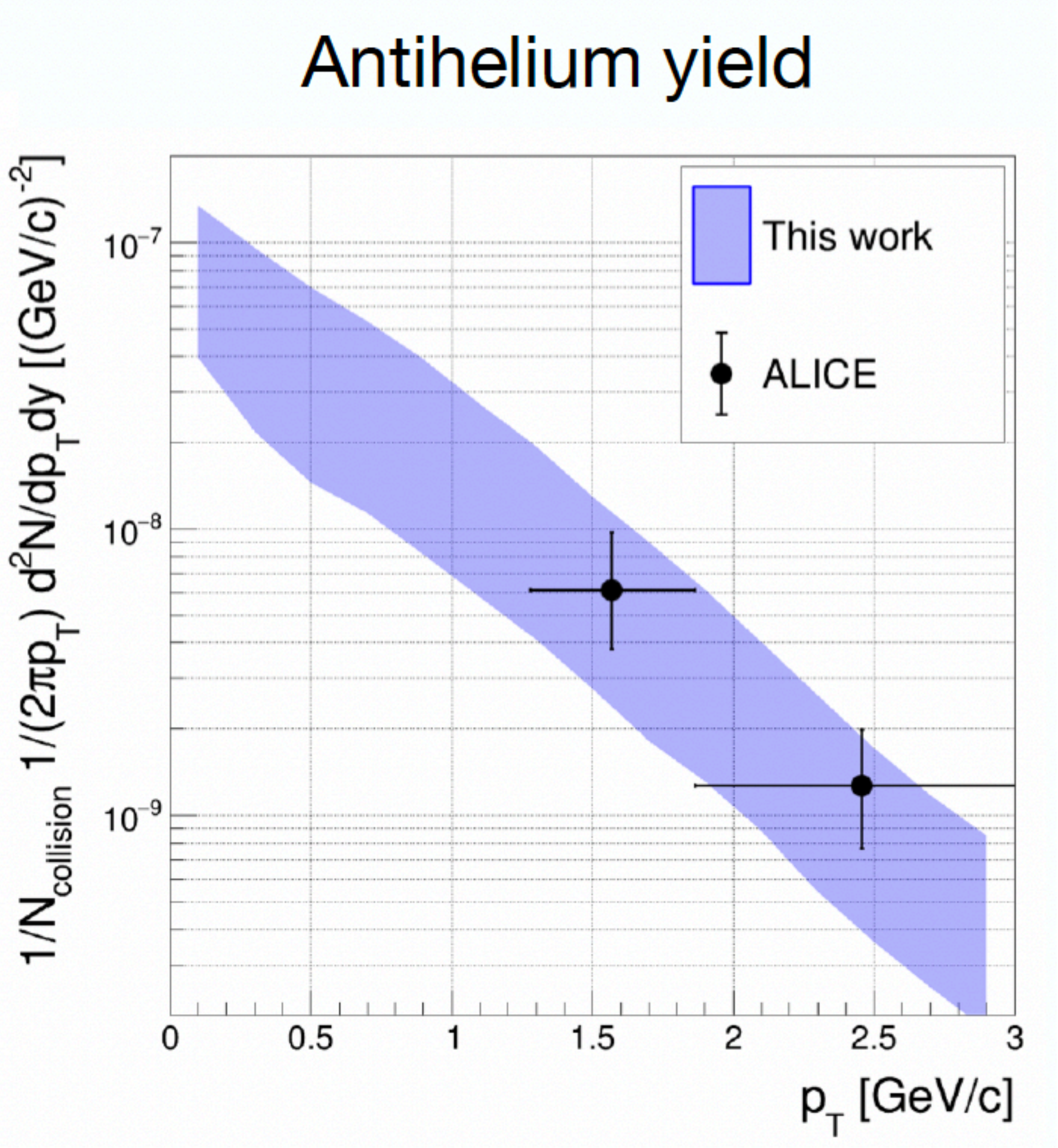
- Secondaries from cosmic ray collisions
  - High energy cosmic ray collisions can produce $^{3}\overline{\mathrm{He}}$
  - pp is dominant collision system, scaled to other systems (pp, p–He, He–p, He–He)
  - Production cross section from EPOS + coalescence model, validated with ALICE measurements

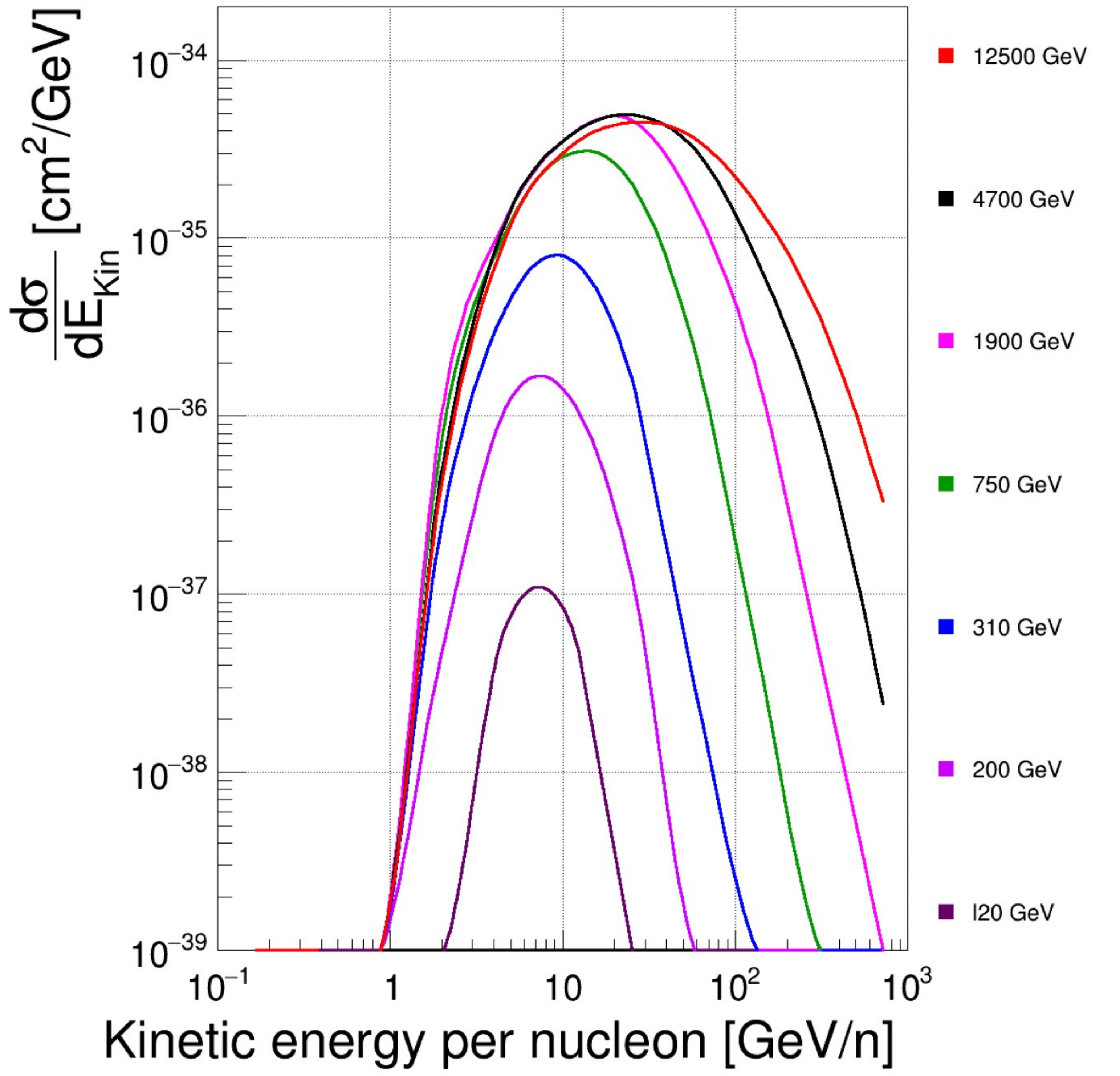




Coalesence model







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

Source function for antinuclei from dark matter

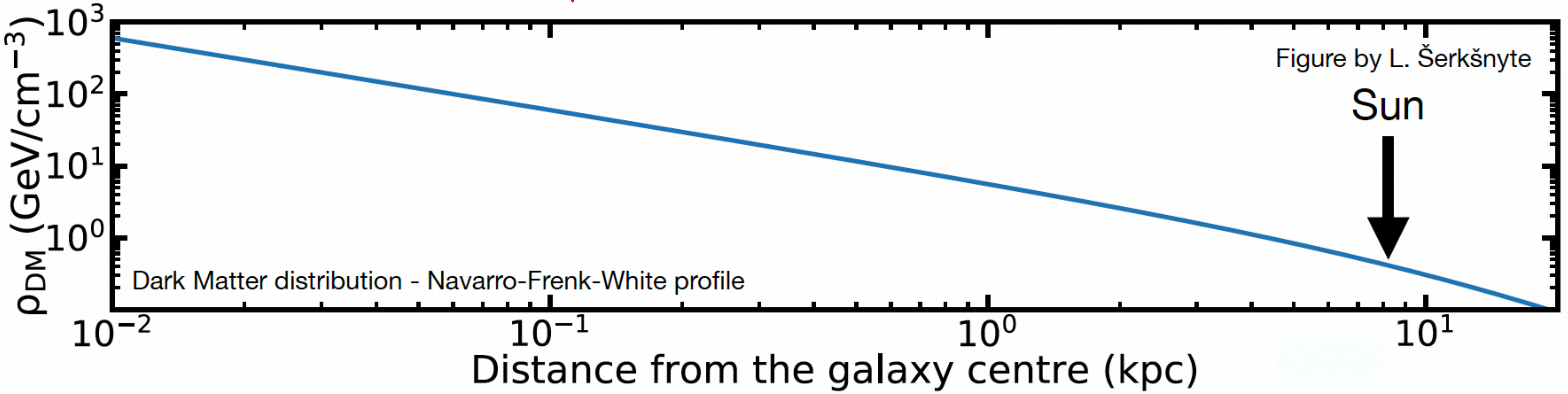
- Source function for antinuclei from dark matter:

Thermally averaged annihilation cross section:
$< \sigma v > = 2.6 \cdot 10^{-26} \mathrm{cm}^3 \mathrm{s}^{-1}$ (Korsmeier et al, PRD97(2018)103011

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

Feeddown from antitriton ($\epsilon \approx 1$)

m_χ = 100 GeV for W^+W^-



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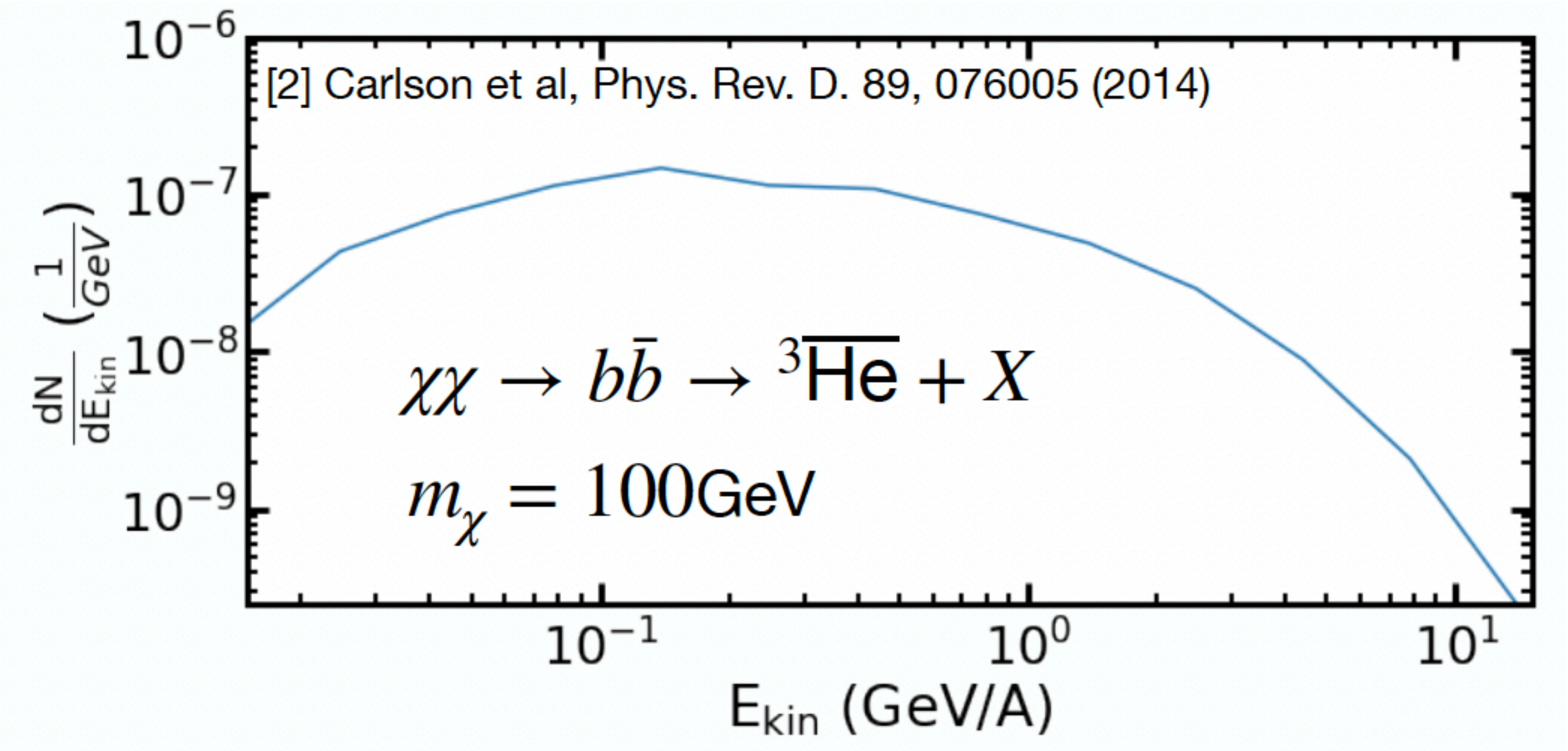
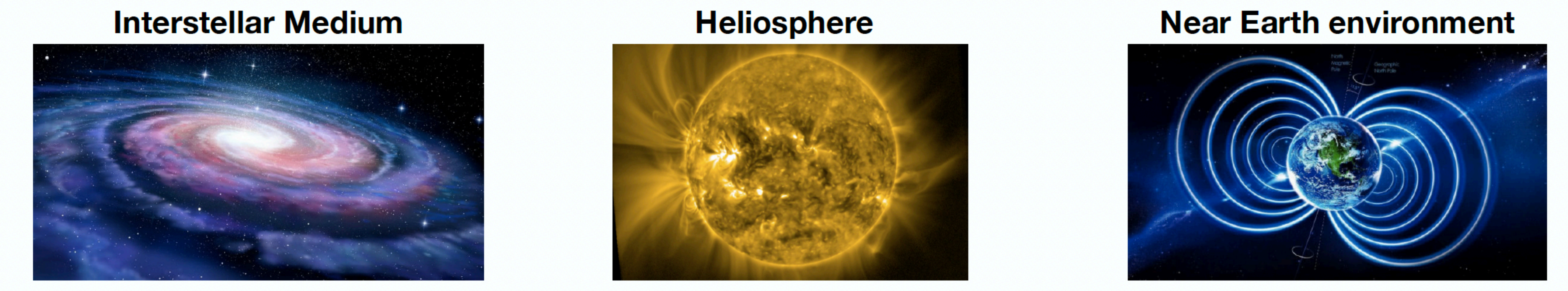
$$q(\mathrm{r}, E_{kin}) = \frac{1}{2}\frac{\rho^2_{\mathrm{DM}}(\mathrm{r})}{m^2_\chi}\langle\sigma v\rangle(1+\epsilon)\frac{dN}{dE_{kin}}$$

Spectra of produced antinuclei, normalised to each dark matter annihilation. Calculated using a coalescence model



Propagation - GALPROP



- Galprop: https://galprop.stanford.edu

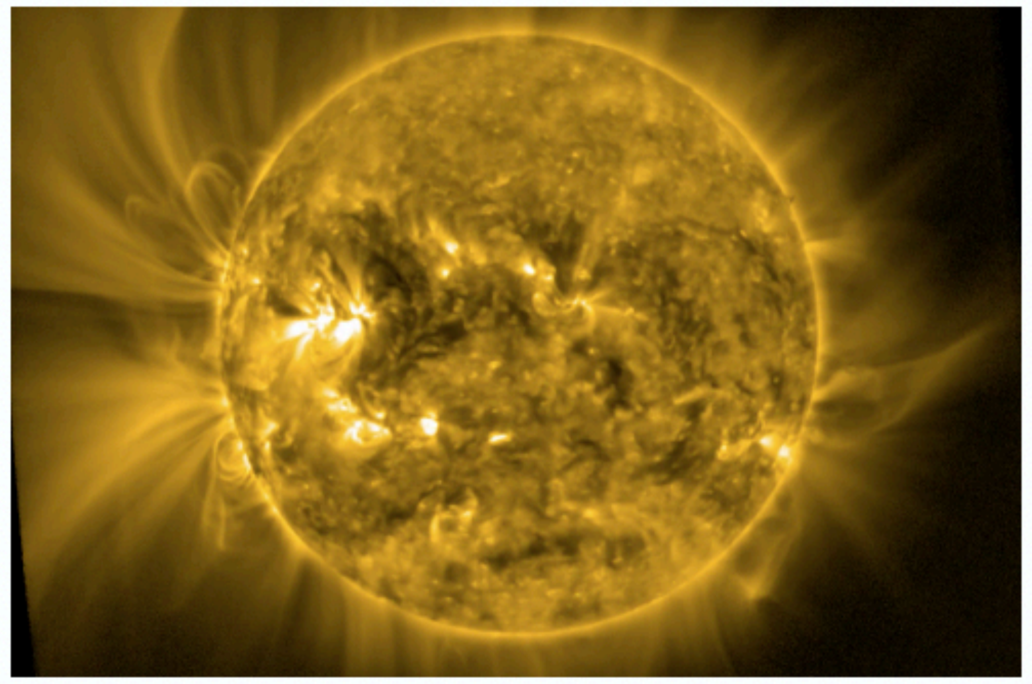
- Numerical code for calculating the propagation of relativistic charged particles and the diffuse emissions produced during their propagation
  - Propagation of cosmic-ray nuclei, antiprotons, electrons and positrons, and computes diffuse **γ**-rays and synchrotron emission in the same framework

- Incorporates as much realistic astrophysical input as possible together with latest theoretical developments

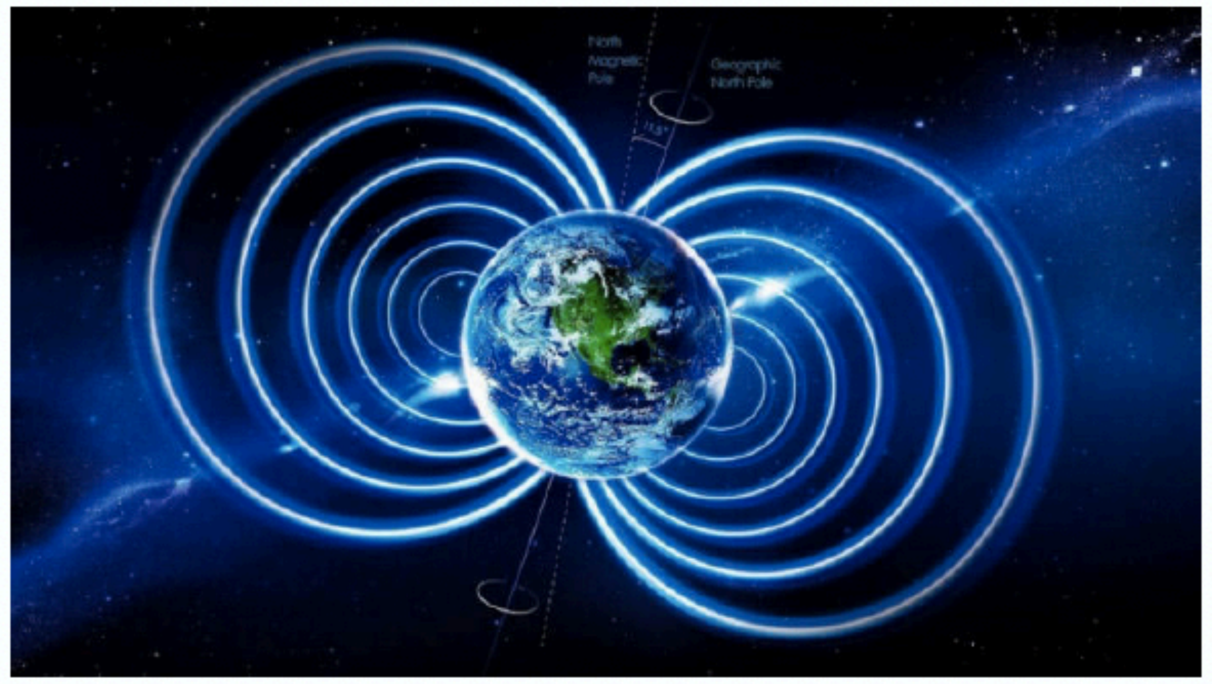
Propagation - GALPROP

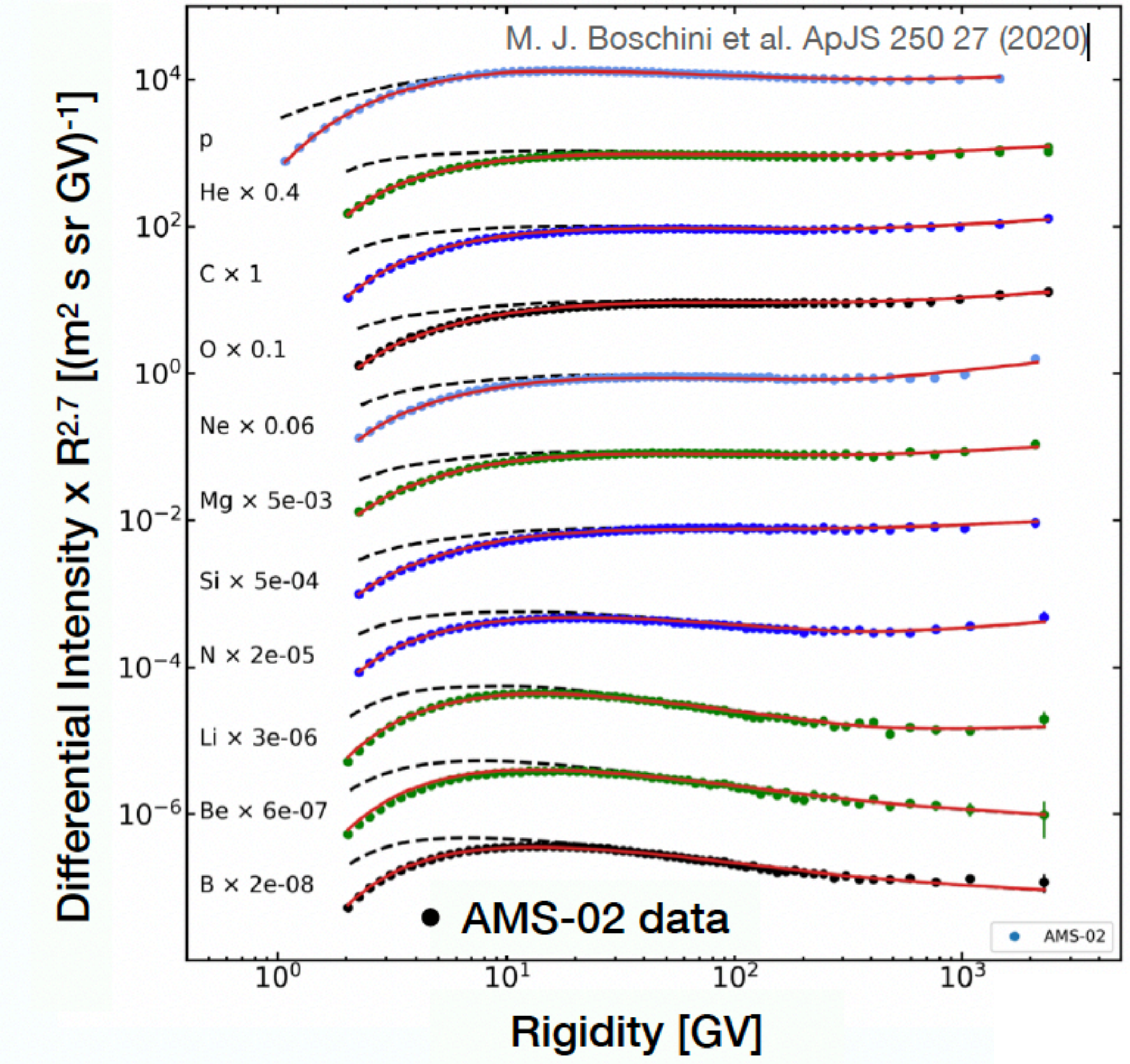
Interstellar Medium

Heliosphere



Near Earth environment



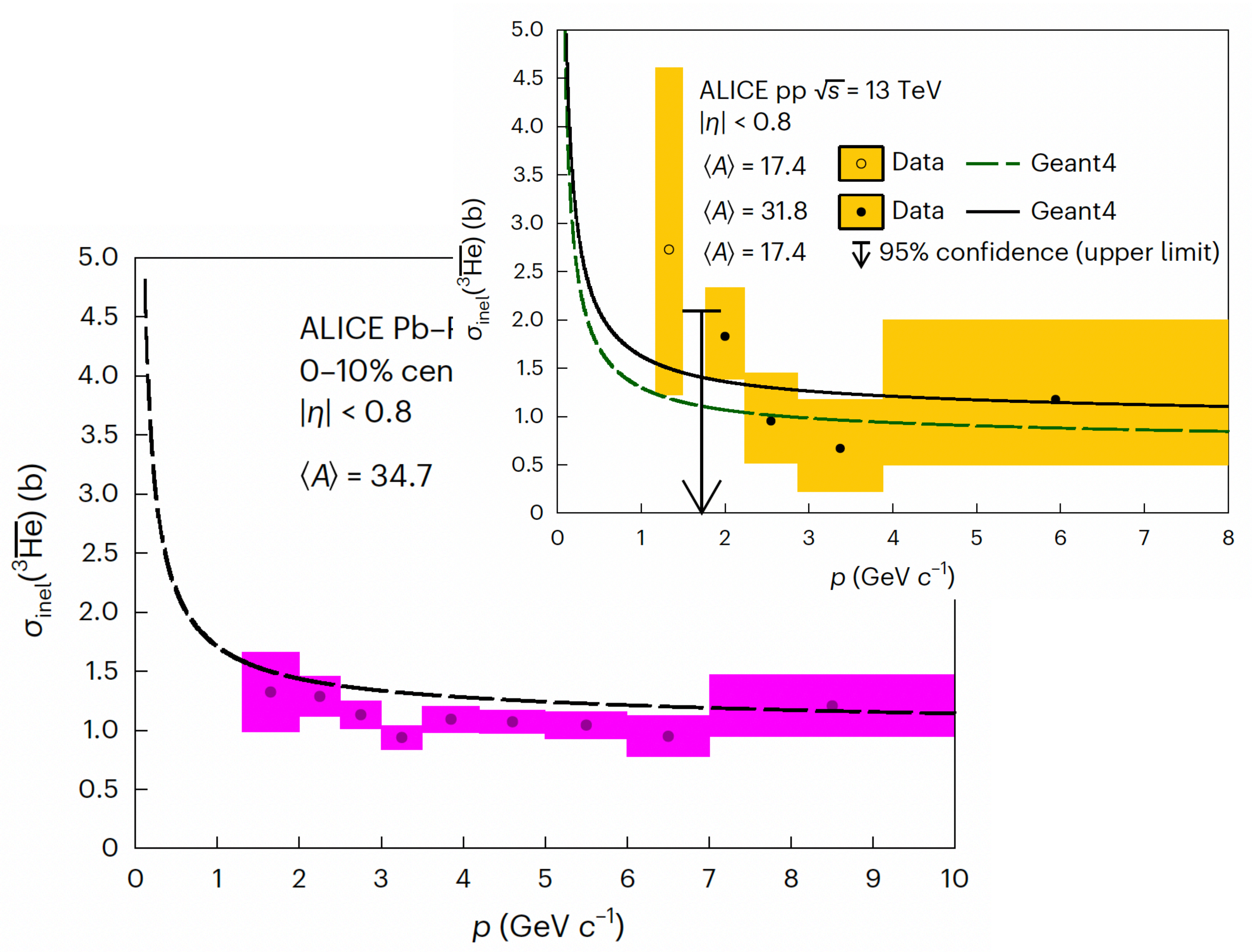


- Constrained using proton and heavier nuclei from cosmic ray measurements

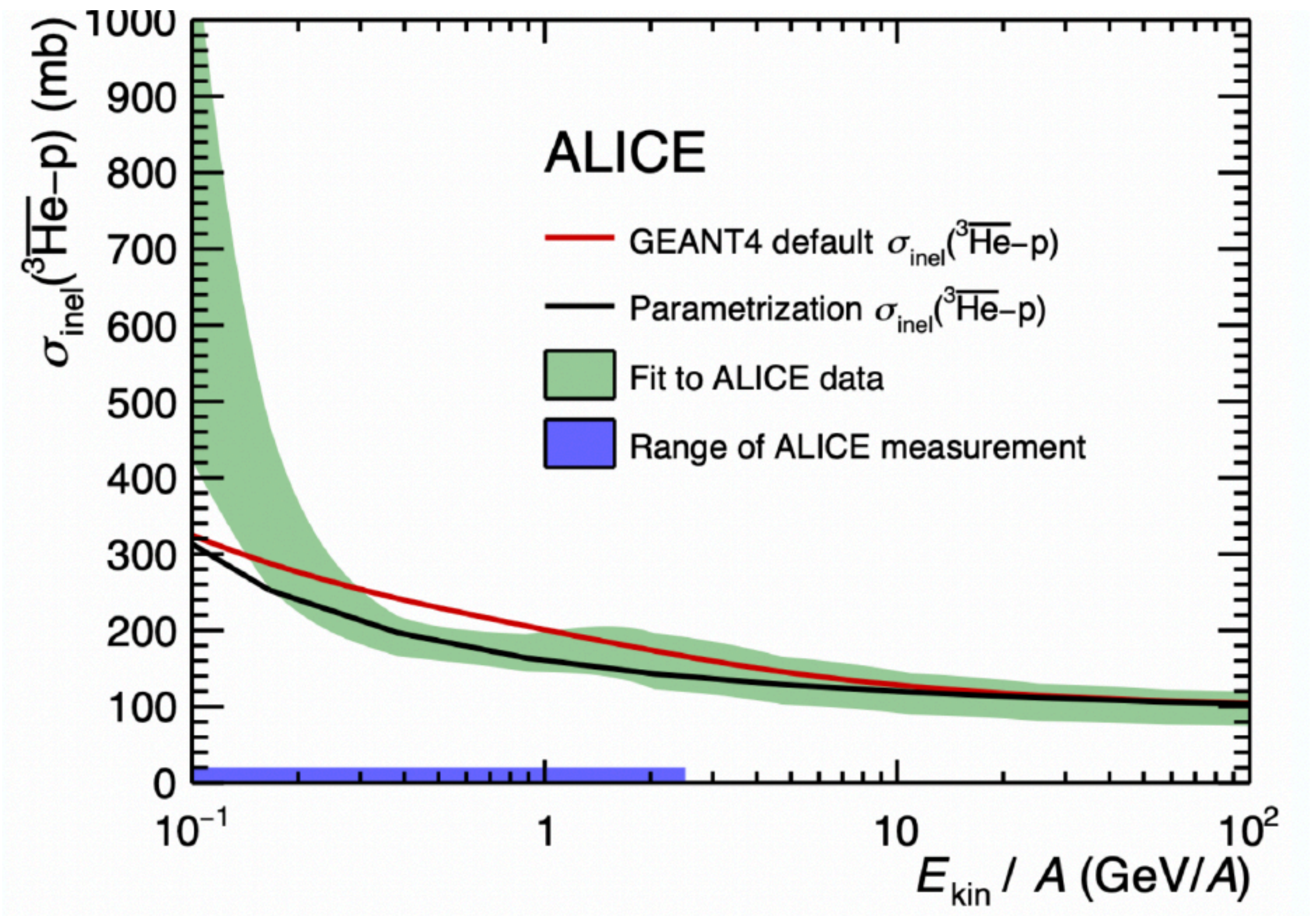
- Not considered in GALPROP
  - Effect of the solar modulation
  - Introduced as force-field approximation

Inelastic cross sections for light targets

- ALICE measurement: $^{3}\overline{\mathrm{He}}$ inelastic cross section on heavy targets <*A*> = 17.4 to 34.7
- Need to be scaled for proton and helium targets (ISM)
- Extrapolation to light targets for GEANT4 parameterisation using ALICE measurement
- Use a correction factor for all target materials, 8% uncertainty on the *A* scaling



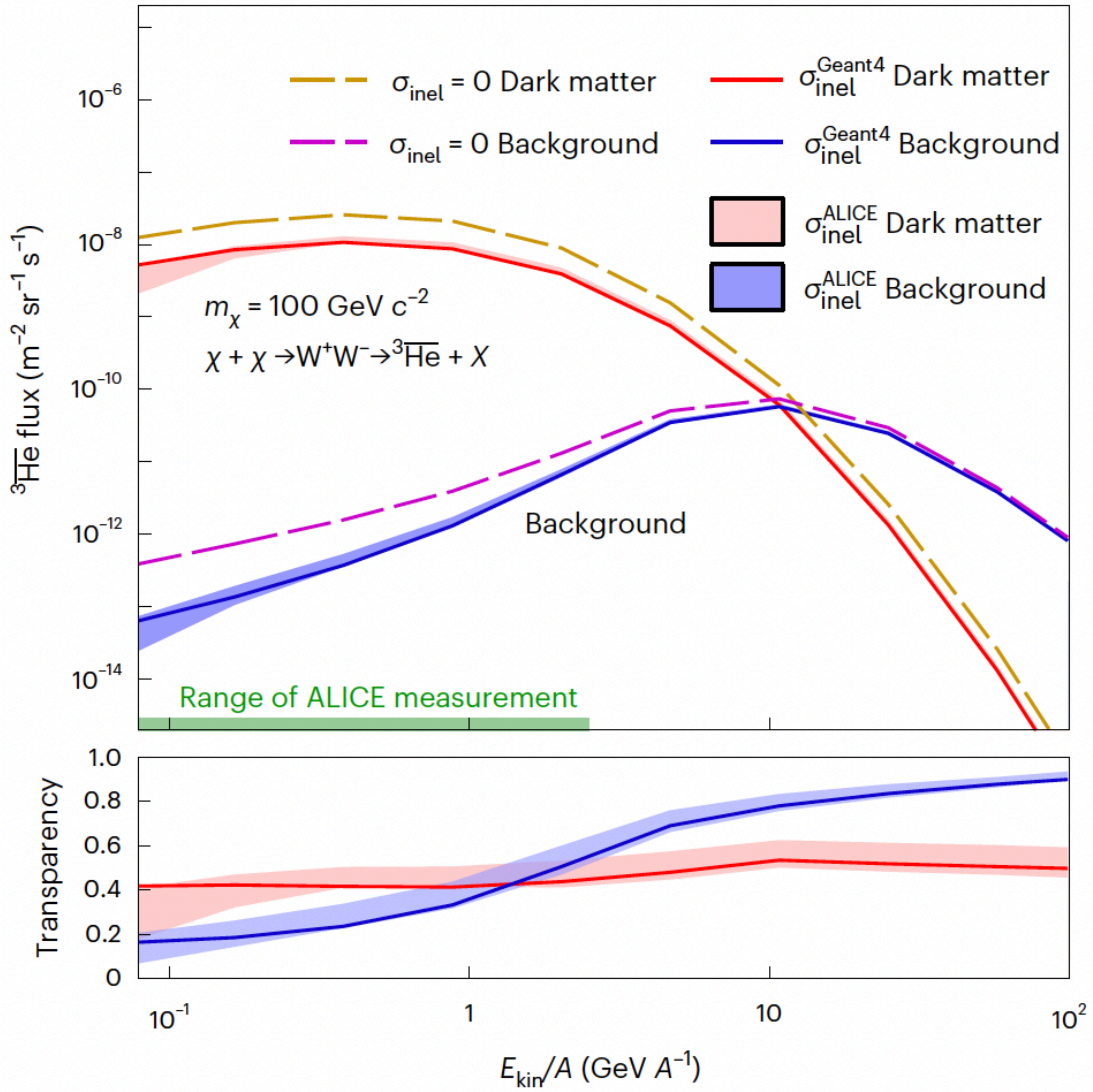
$$corr = \frac{\sigma_{ALICE}}{\sigma_{Geant4}}$$



$^3\overline{\text{He}}$ fluxes near earth

- Effect of various inelastic cross sections on fluxes
- Solar modulated flux shifts particles to lower energies
- Uncertainties only from ALICE measurement small compared to other uncertainties in the field
- Rather constant transparency of 50% for typical DM scenario and 25%-90% for background
    - Transparency: $\dfrac{\text{Flux}(\sigma_{\text{inel}})}{\text{Flux}(\sigma_{\text{inel}}=0)}$

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



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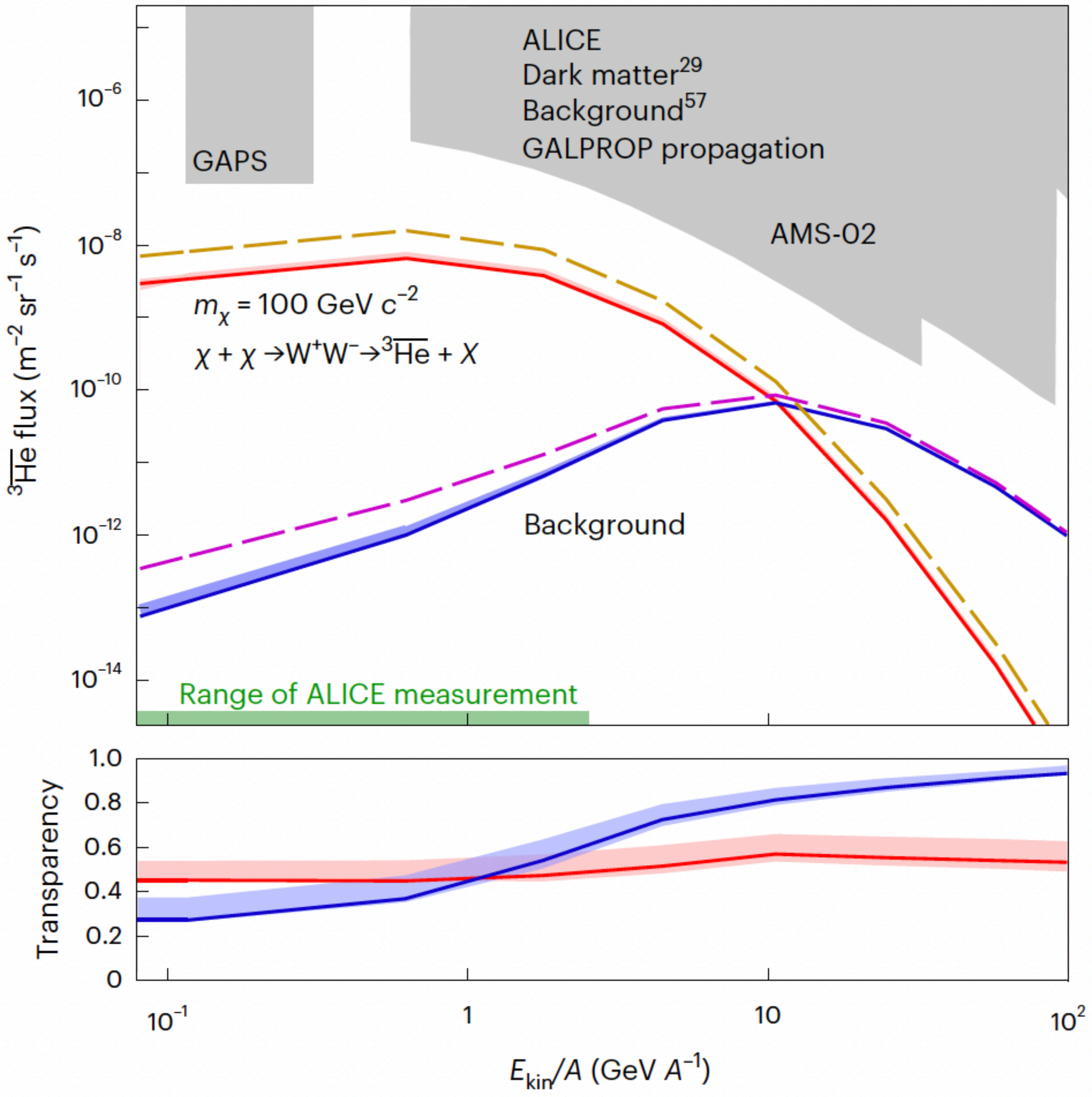

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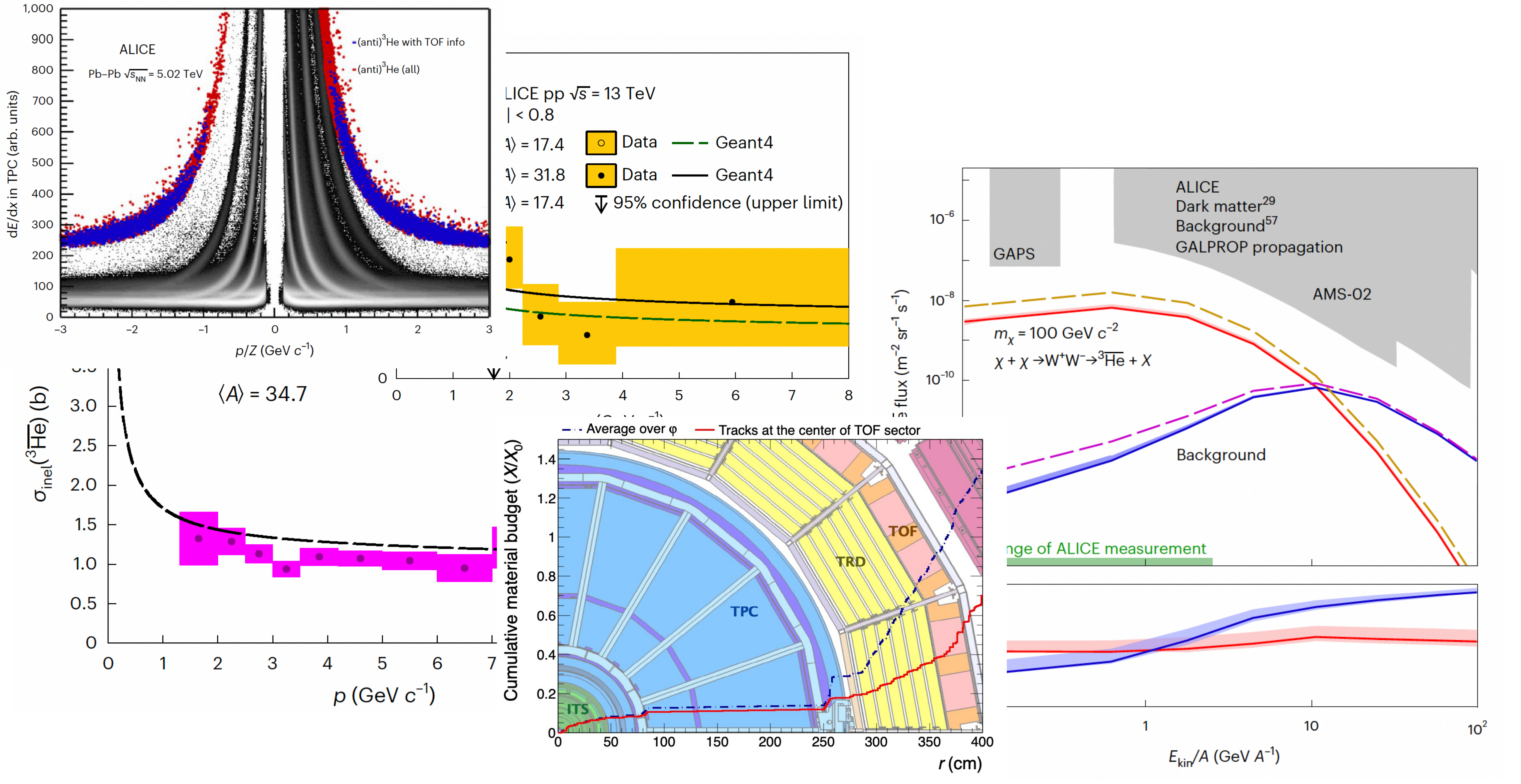
Measurement of anti-^{3}He nuclei absorption in matter and impact on their propagation in the Galaxy

The ALICE Collaboration

Nature Physics **19**, 61–71 (2023) | Cite this article

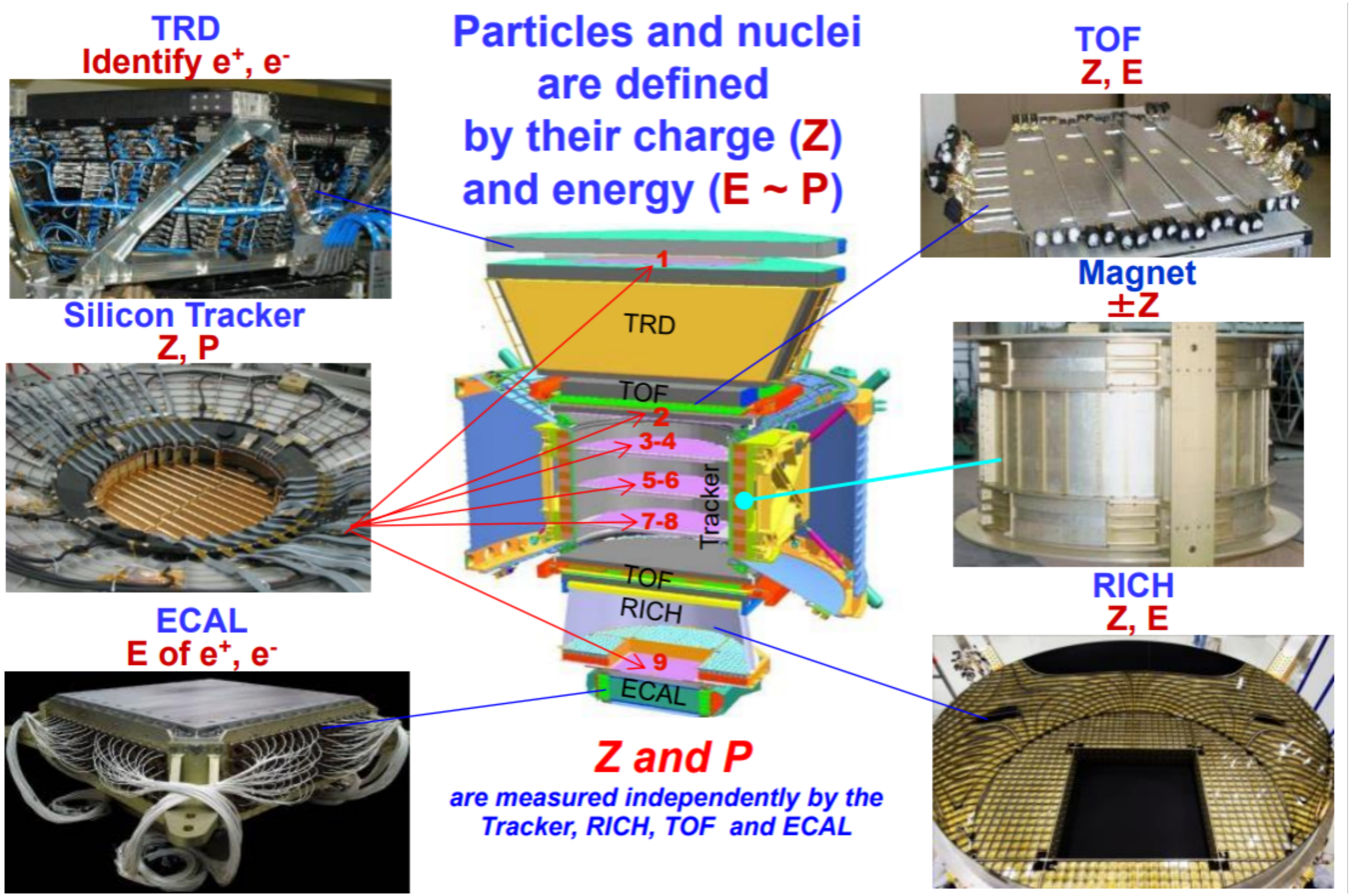
Abstract

In our Galaxy, light antinuclei composed of antiprotons and antineutrons can be produced through high-energy cosmic-ray collisions with the interstellar medium or could also originate from the annihilation of dark-matter particles that have not yet been discovered. On Earth, the only way to produce and study antinuclei with high precision is to create them at high-energy particle accelerators. Although the properties of elementary antiparticles have been studied in detail, the knowledge of the interaction of light antinuclei with matter is limited. We determine the disappearance probability of $^{3}\overline{\mathrm{He}}$ when it encounters matter particles and annihilates or disintegrates within the ALICE detector at the Large Hadron



Further material

AMS


TRD
Identify e+, e-
Silicon Tracker
Z, P
ECAL
E of e+, e-
Particles and nuclei
are defined
by their charge (Z)
and energy (E ~ P)
TRD
1
TOF
2
3-4
5-6
7-8
Tracker
TOF
RICH
9
ECAL
Z and P
are measured independently by the
Tracker, RICH, TOF and ECAL
TOF
Z, E
Magnet
±Z
RICH
Z, E