Light nuclei production and connections to astrophysics

CosmicAntiNuclei

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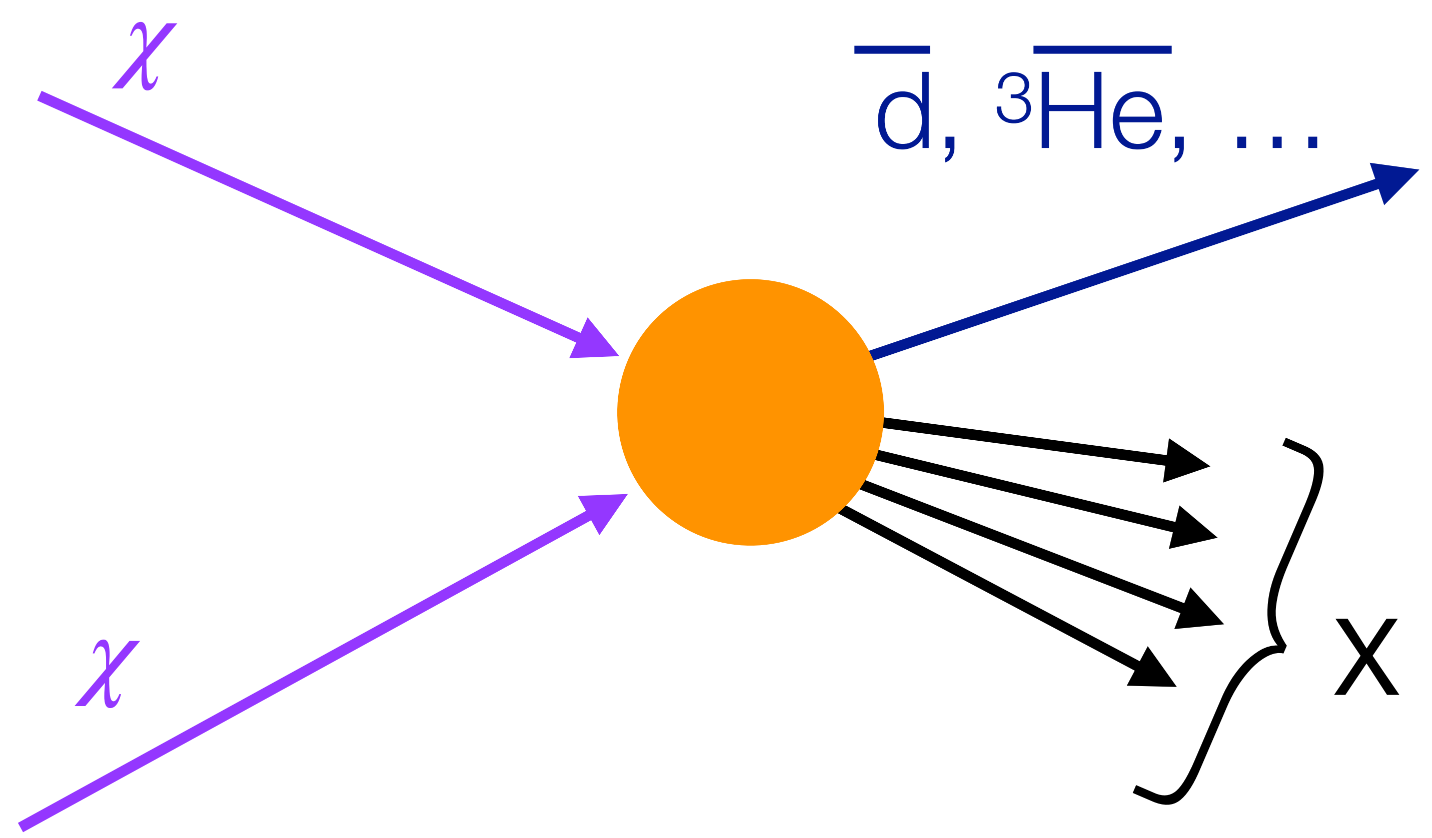
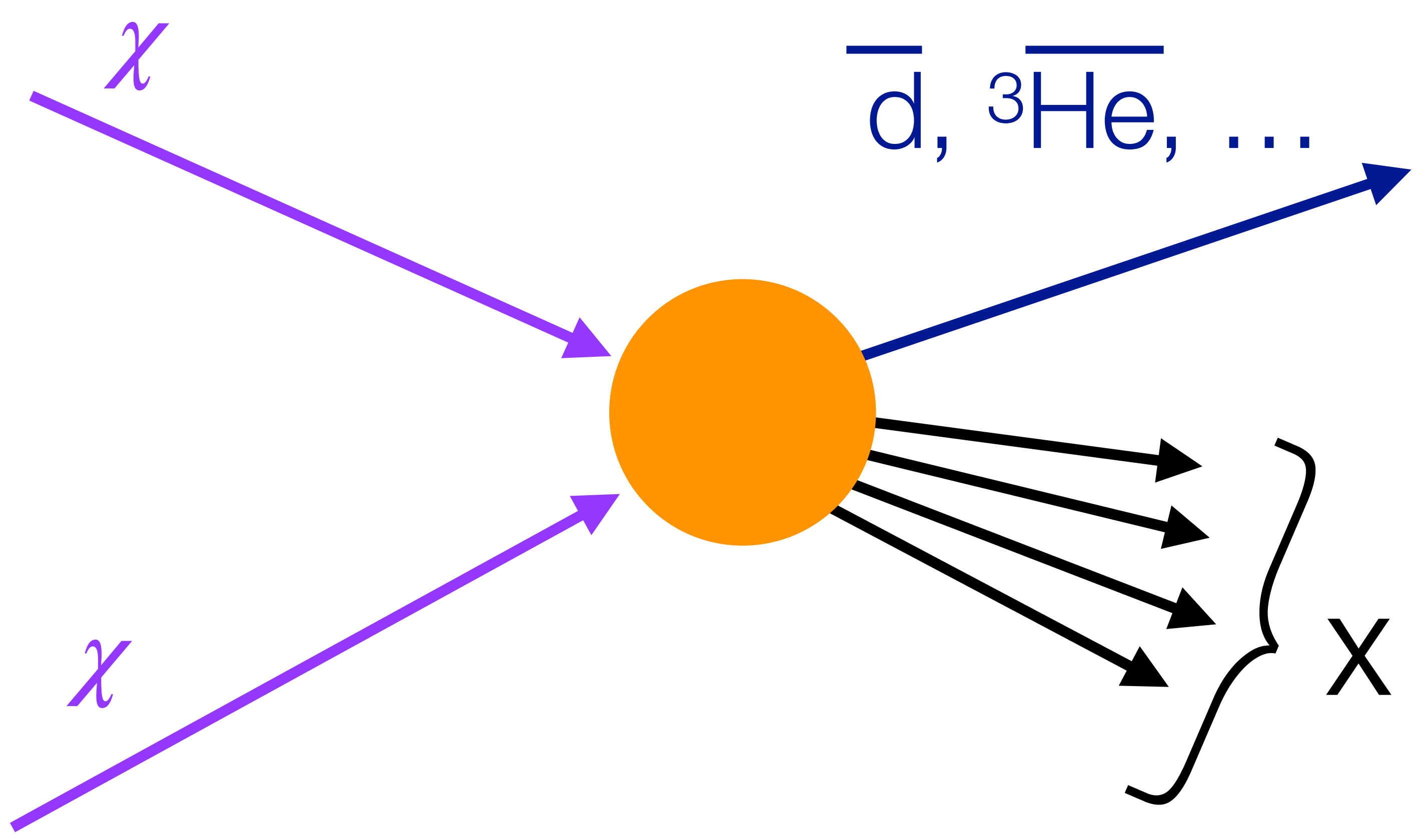
Antinuclei as dark matter probe

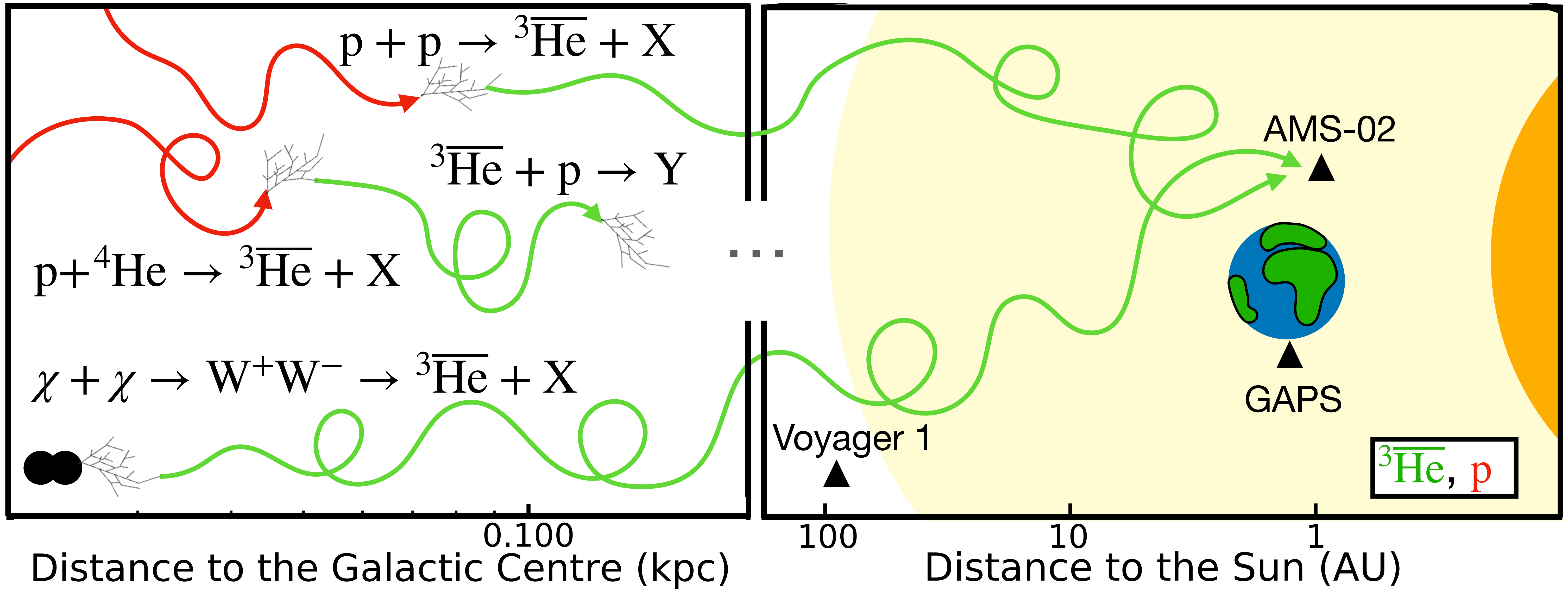
- Antinuclei are scarcely produced in space:
  - they have been considered for a long time a smoking gun of dark matter annihilation



Antinuclei as dark matter probe

- Antinuclei are scarcely produced in space:
  - they have been considered for a long time a smoking gun of dark matter annihilation
- Background is present:
  - Secondary production in the interaction of CRs with the ISM (pp, p-A collisions with small Z)
- Production, propagation and annihilation of antinuclei must be properly described



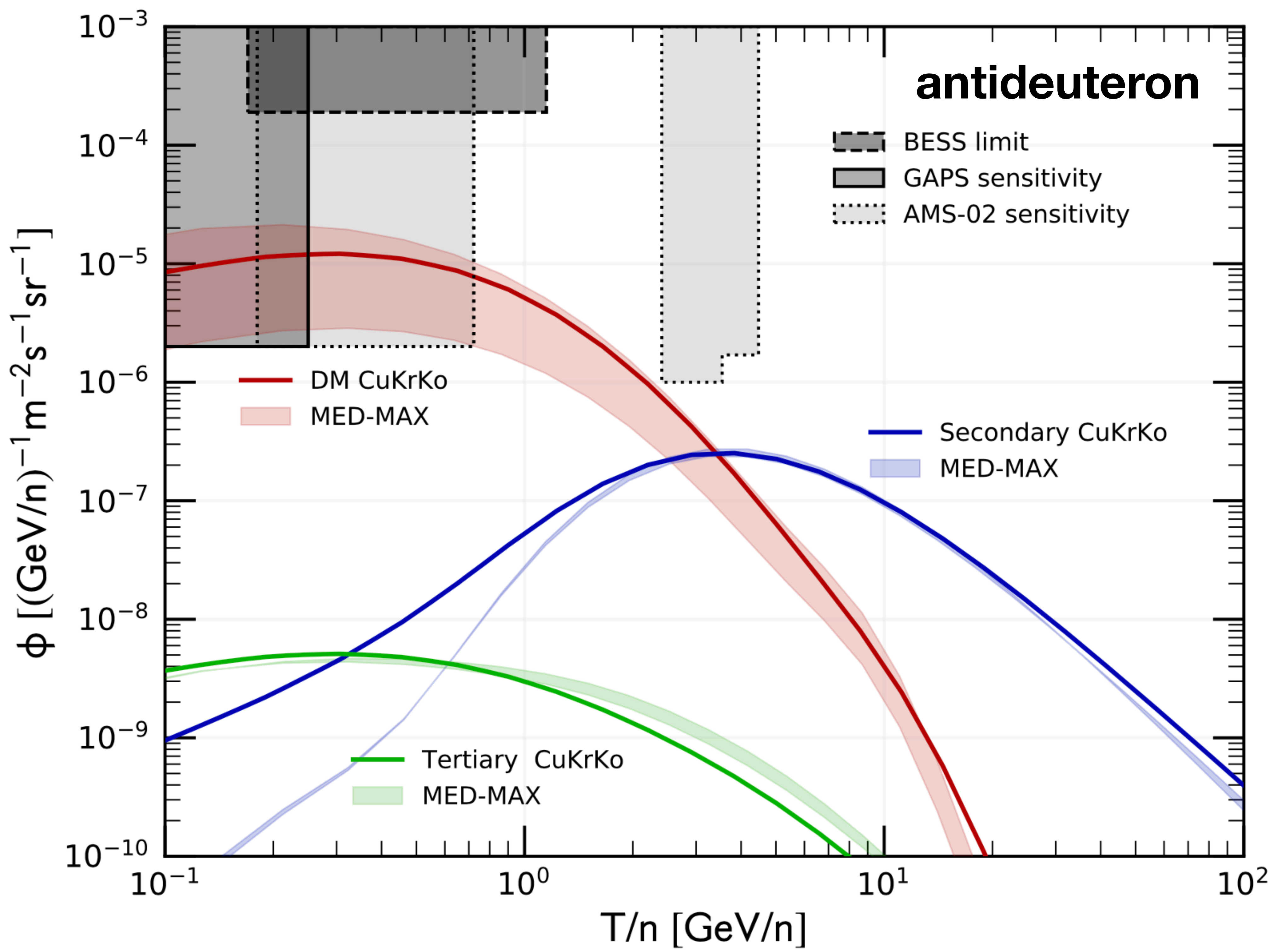


Antinuclei in cosmic rays

$$q_{\bar{A}} = \nabla \cdot \left(-K \nabla N_{\bar{A}} + V_c N_{\bar{A}}\right) + \partial_t \left(b_{tot} N_{\bar{A}} - K_{EE} \partial_t N_{\bar{A}}\right) + \Gamma_{ann} N_{\bar{A}}$$

Source **Propagation** **Annihilation**

- **Low-energy** is the most interesting region:
  - Signal/Background ~ 10^4
- Each term of the transport equation has uncertainties:
  - Source: from production mechanism of antinuclei
  - Propagation: convection, diffusion, magnetic fields, solar modulation
  - Annihilation: absorption cross section of antinuclei



Phys.Rev.D 97 (2018) 10, 103011

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  - Source: from **production mechanism** of antinuclei
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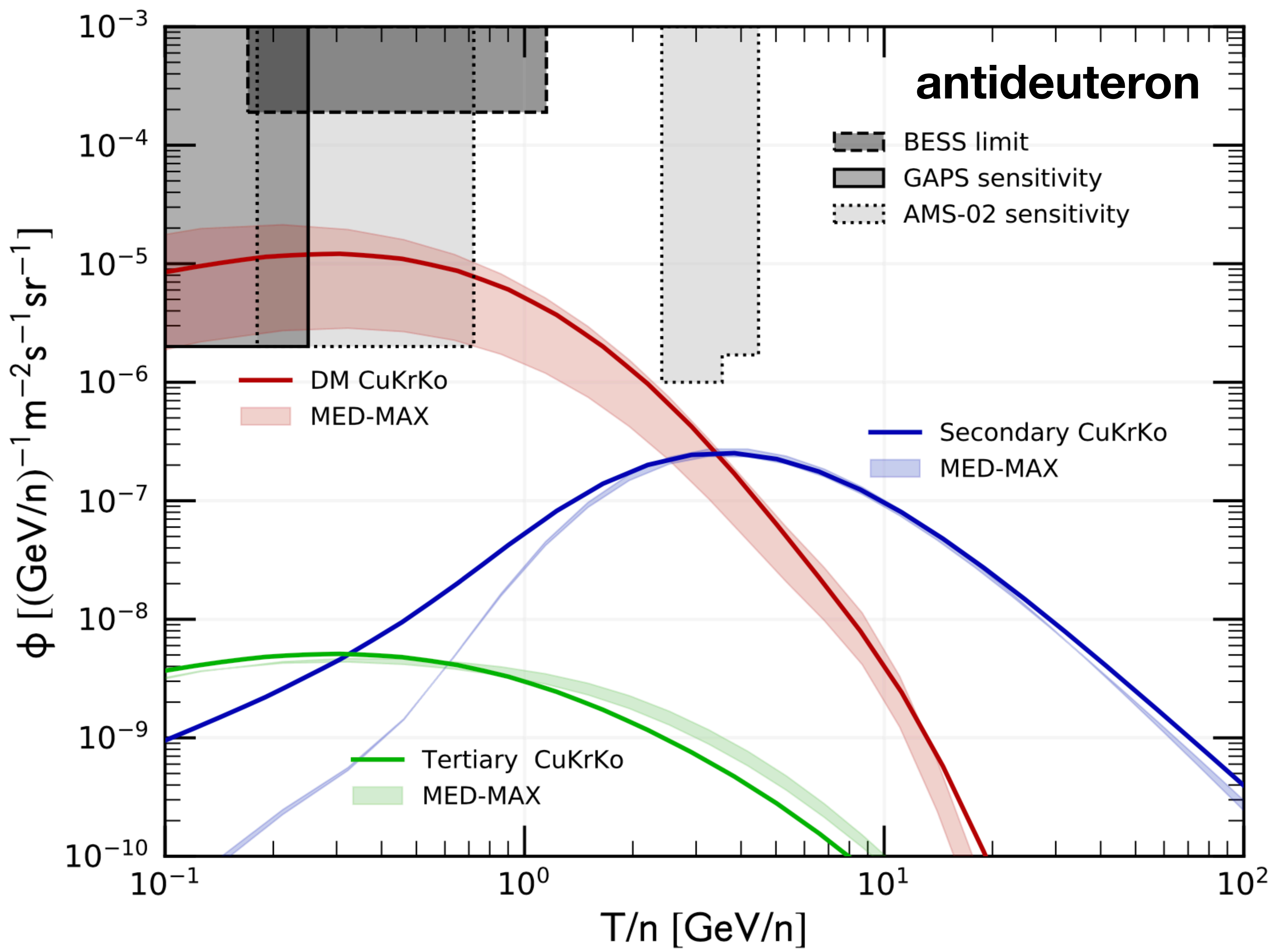
  - Annihilation: **absorption cross section** of antinuclei
- Production and annihilation can be **constrained with experiments** at Earth



Phys.Rev.D 97 (2018) 10, 103011

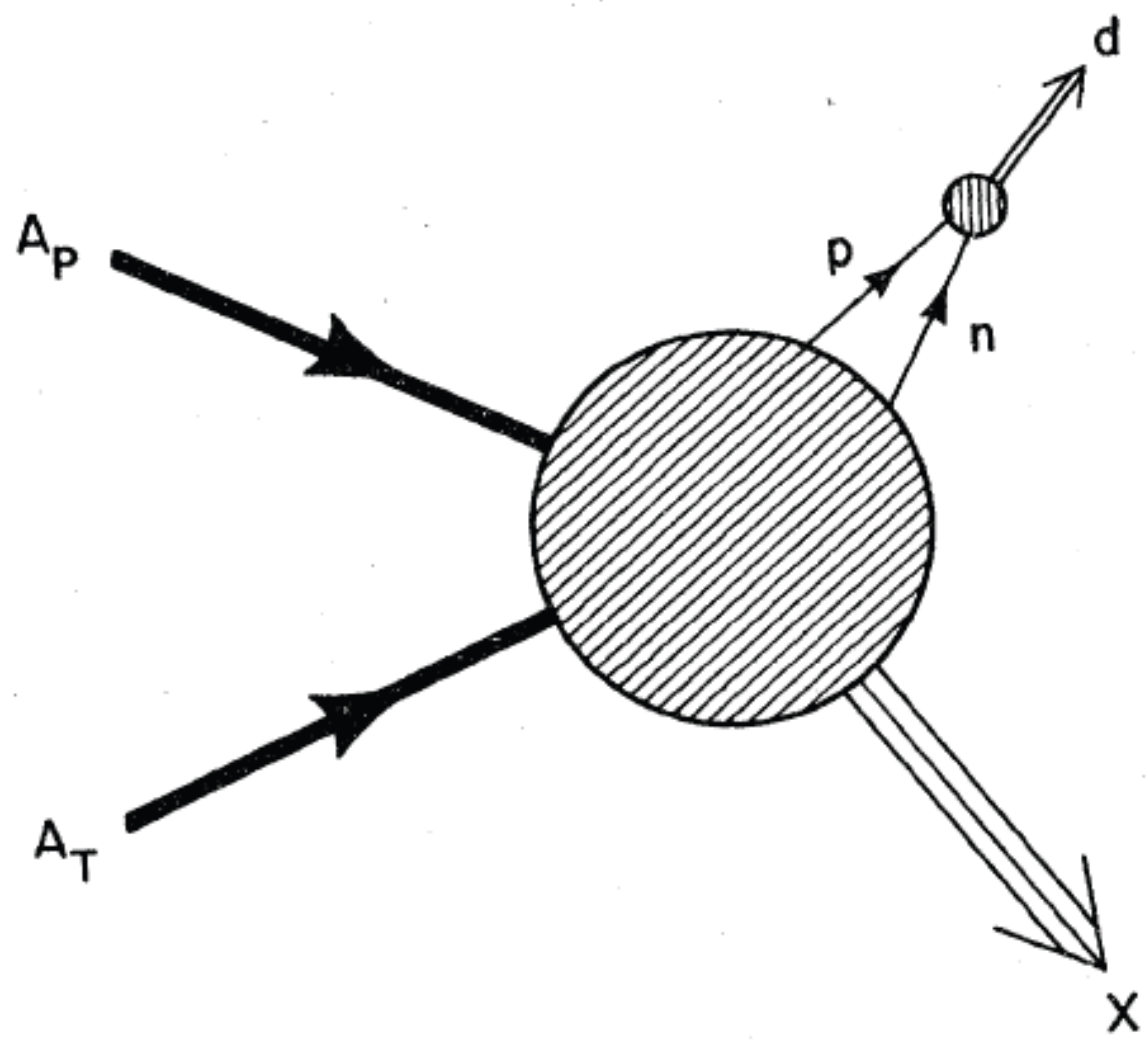
Coalescence model

- Concept introduced in the 60s:
  - Butler & Pearson, Phys. Rev. 129, 836 (1963),
    Schwarzschild & Zupančič, Phys. Rev. 129, 854 (1963)
- Nucleons **close in phase space** at the **freeze-out** can form a nucleus via **coalescence**
- Coalescence parameter $\mathbf{B_A}$:

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

where:

- A is the mass number of the nucleus
- $p_p = p_A / A$



J. I. Kapusta, Phys.Rev.C 21 (1980)

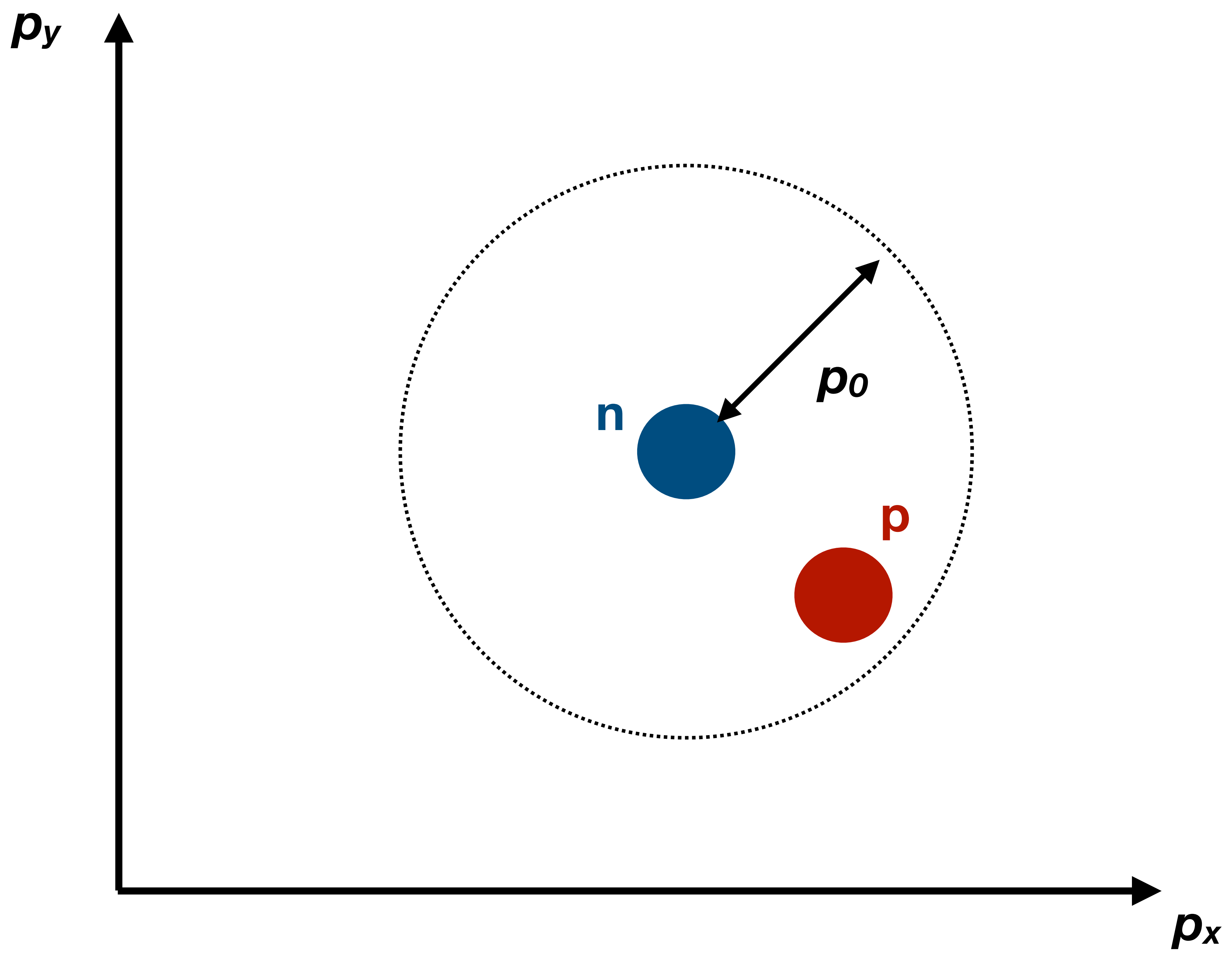
- $\boldsymbol{B_A}$ is related to the **probability** to form a nucleus via coalescence
- **Different implementations** of coalescence model

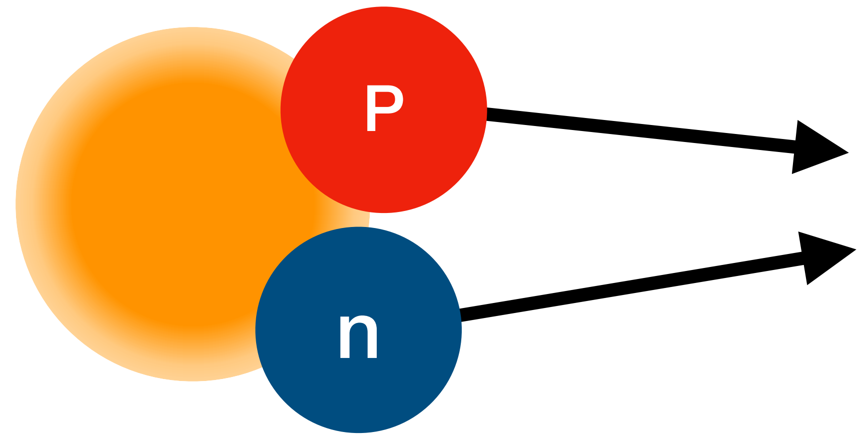
Simple coalescence model

- Hypotheses:
  - **No space-time** distribution of the nucleons considered
  - Nucleons with similar momentum (**Δp < p₀**) form a nucleus

$$B_A = \left(\frac{4\pi}{3}p_0^3\right)^{A-1}\frac{m_A}{m_p^A}$$

- Consequences:
  - B_A vs p_T is **flat**
- Applications:
  - **pp collisions**: small volume (comparable with nucleus size) → nucleons are always close to each other





Simple coalescence model

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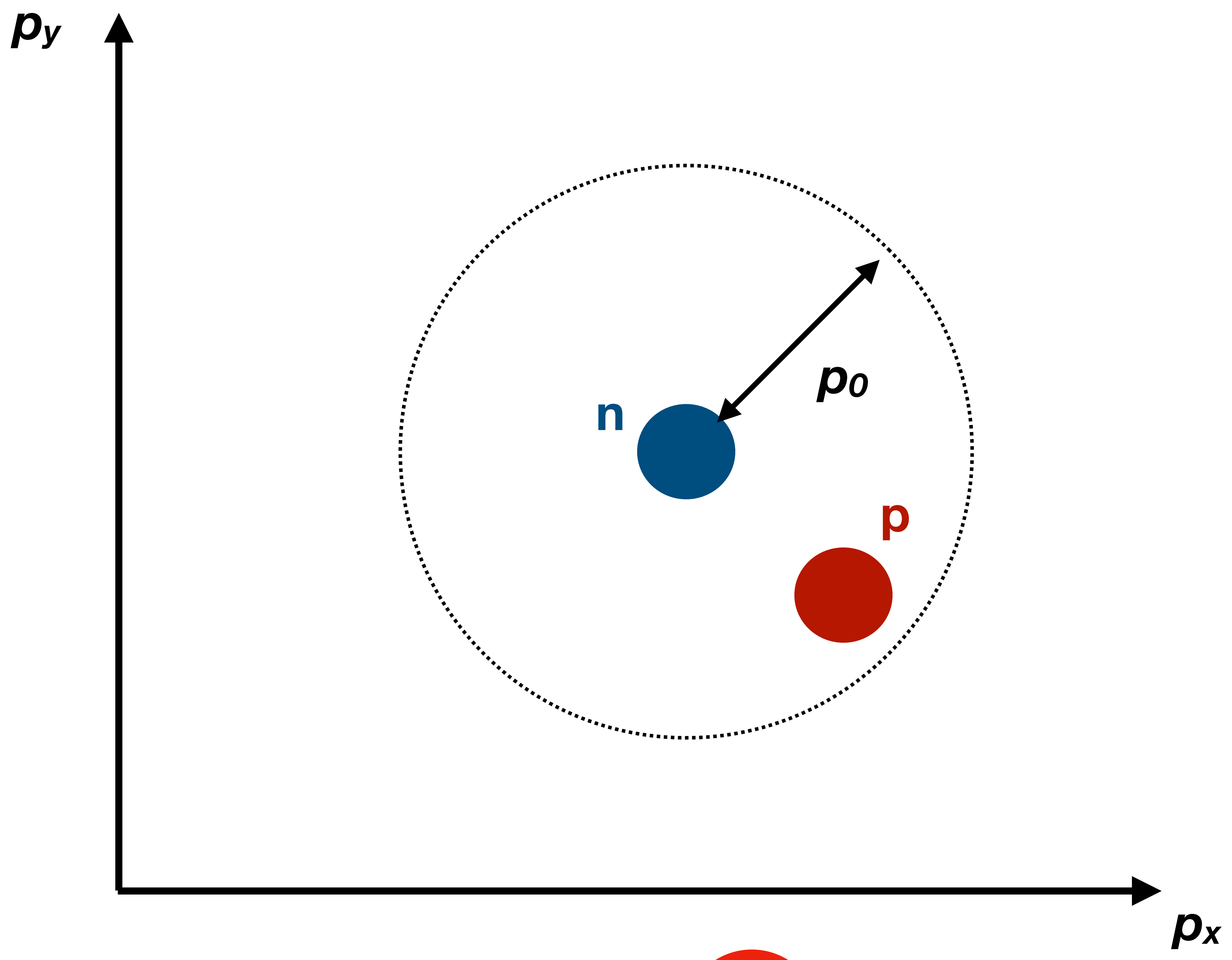
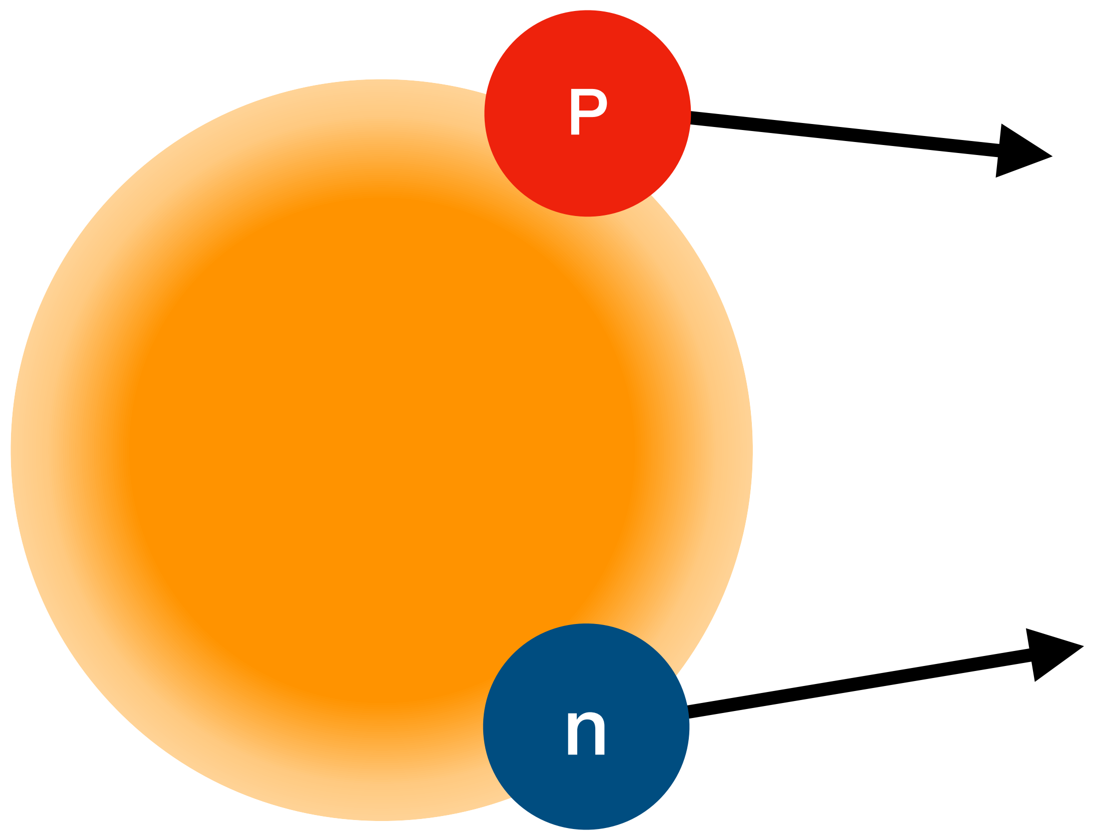
$$B_{\mathrm{A}} = \left(\frac{4\pi}{3}p_0^3\right)^{\mathrm{A}-1} \frac{m_{\mathrm{A}}}{m_{\mathrm{p}}^{\mathrm{A}}}$$

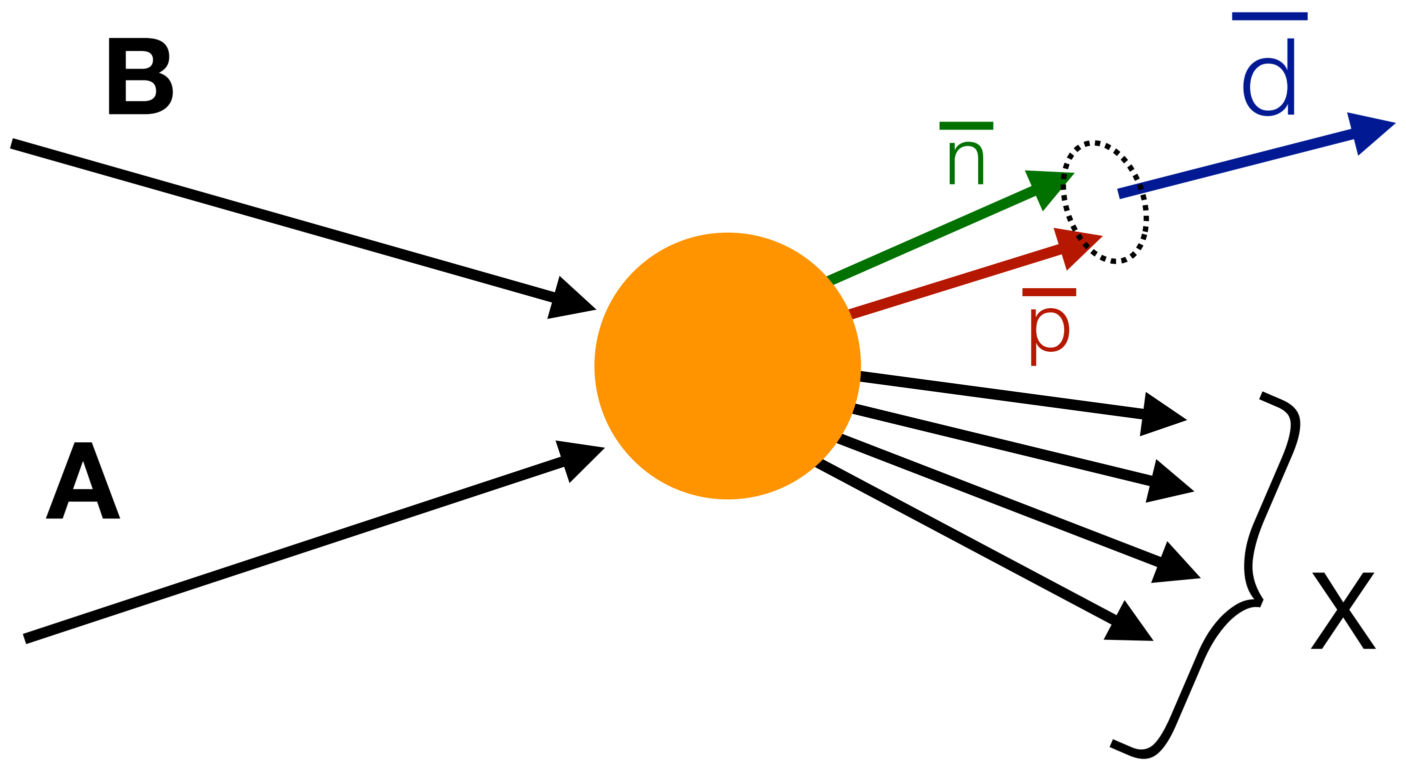
- Consequences:
  - B_{A} vs p_{T} is **flat**
- Applications:
  - **pp collisions**: small volume (comparable with nucleus size) → nucleons are always close to each other
  - ✗ **Pb-Pb collisions**: large volume → space-time distribution must be considered

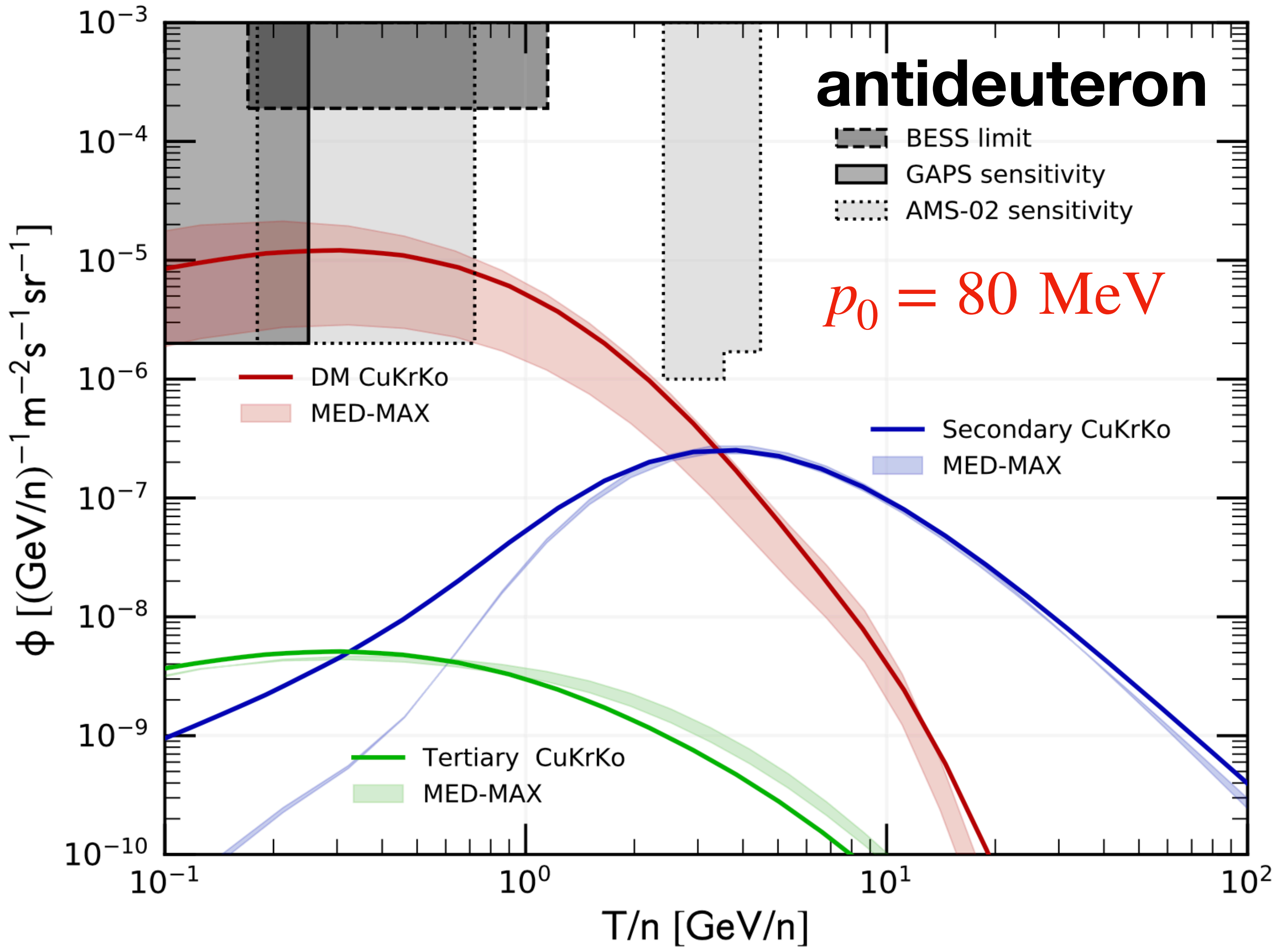




Application of simple coalescence

- Production of antinuclei (both from DM and secondary):
  - antinucleons in final state can form antinuclei via coalescence

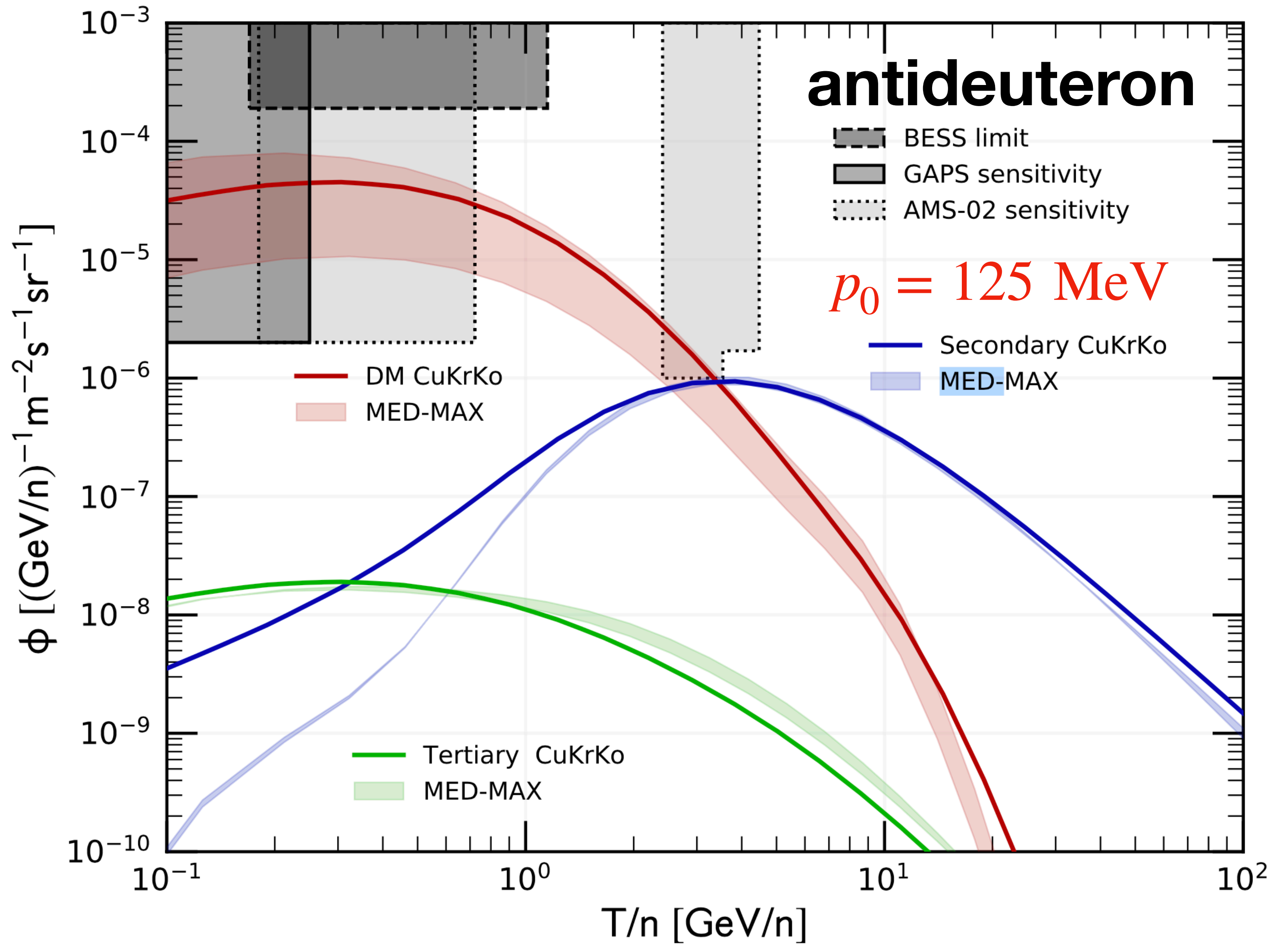




- Simple coalescence:
  - easy to implement in MC afterburners
  - ✗ p_0 must be constrained from experiments

$$B_A = \left(\frac{4\pi}{3}p_0^3\right)^{A-1}\frac{m_A}{m_p^A}$$

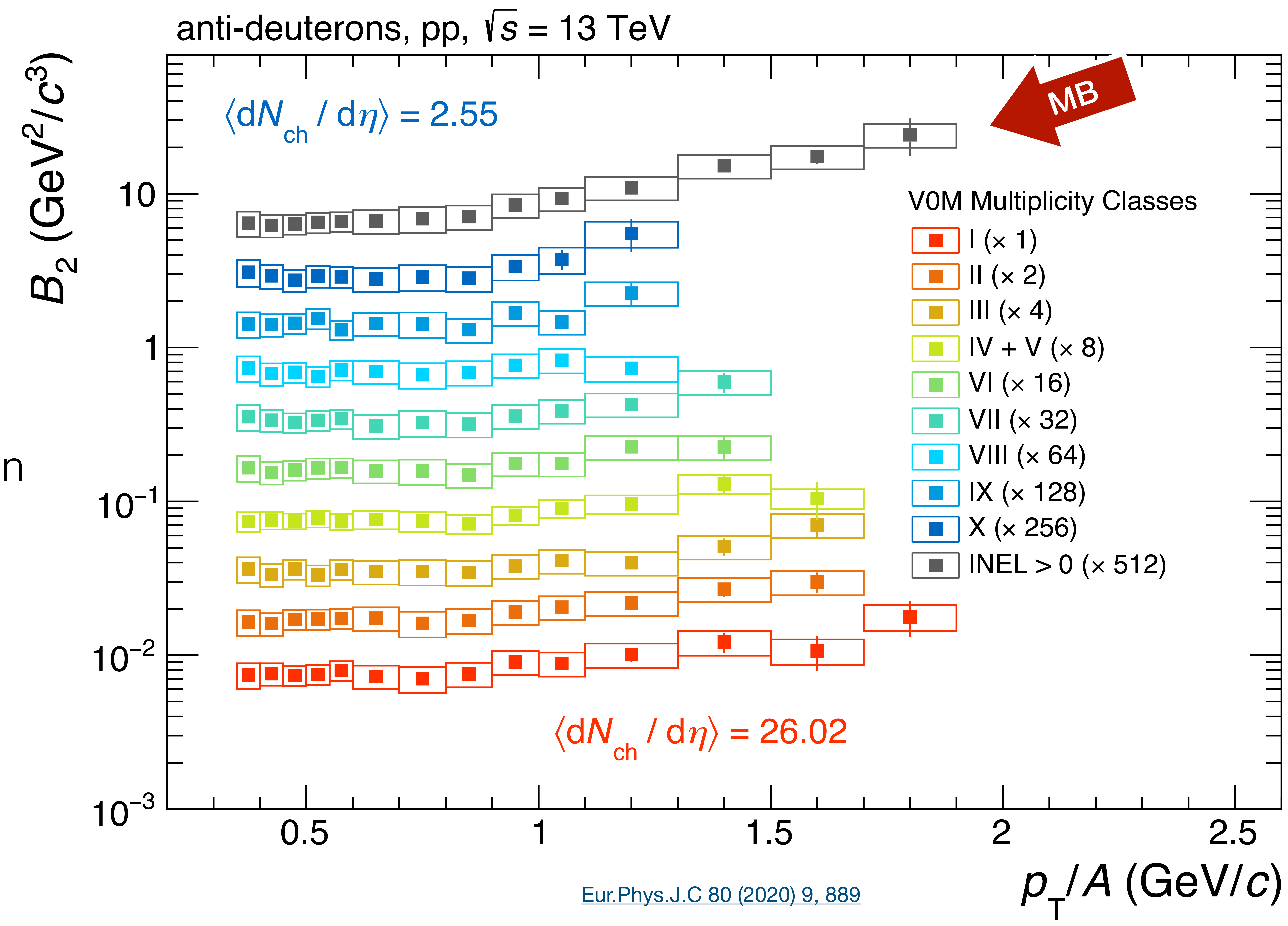
- The production model has a large effect on fluxes
  - Important to provide a precise description



Phys.Rev.D 97 (2018) 10, 103011

B_2 vs p_T in pp collisions

- B_2 vs p_T in **multiplicity** classes:
  - No significant deviations from a **flat** behaviour
- B_2 vs p_T in **MB** analysis:
  - **rise** with p_T
  - due to the hardening of the proton spectra with multiplicity



Eur.Phys.J.C 80 (2020) 9, 889

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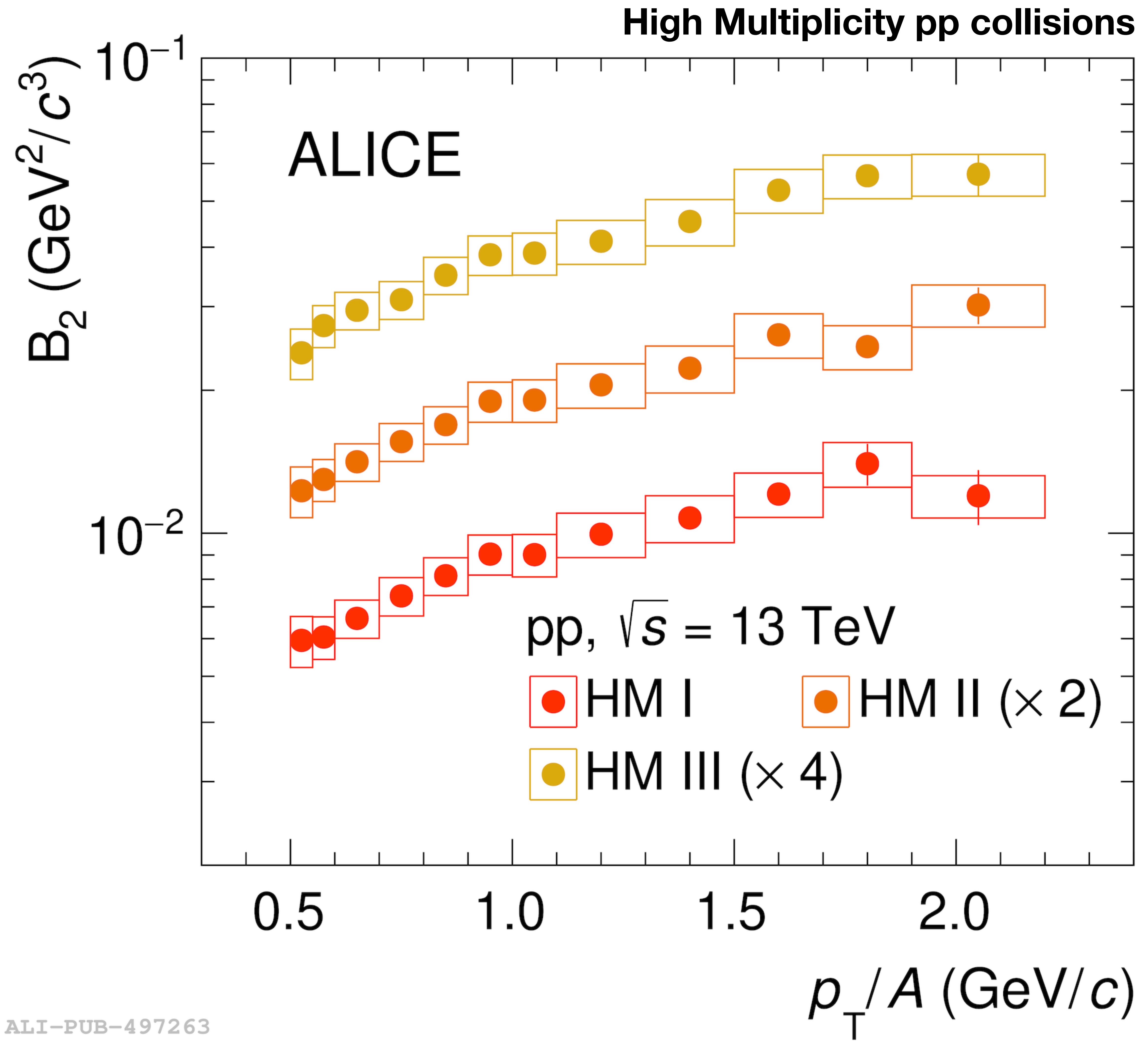
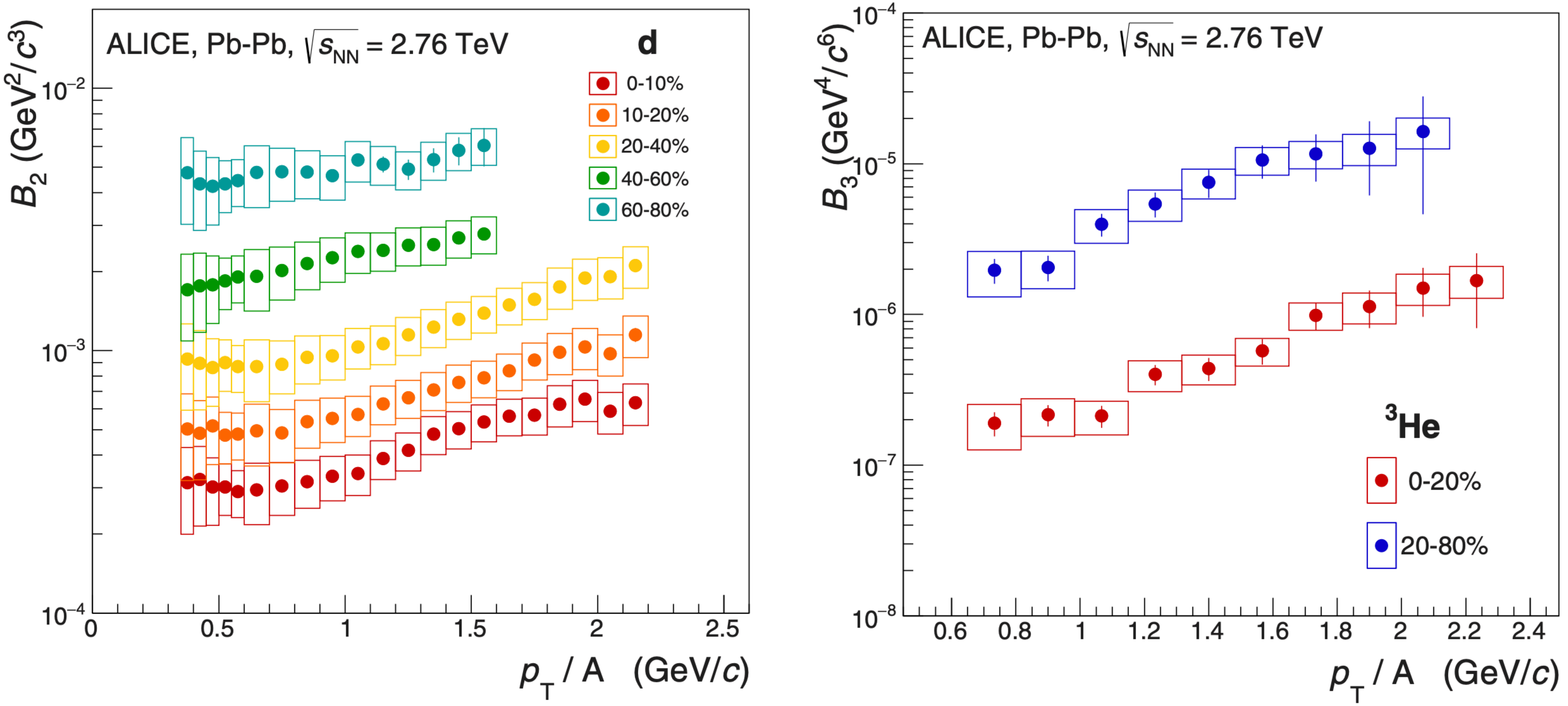
- B_2 vs p_T in **MB** analysis:
  - **rise** with p_T
  - due to the hardening of the proton spectra with multiplicity
- B_2 vs p_T in **HM** pp collisions
  - **rise** with p_T, even in fine multiplicity classes



https://arxiv.org/abs/2109.13026

B_A in Pb-Pb collisions



Phys.Rev.C 93 (2016) 2, 024917

- B_A increases with p_T in Pb-Pb collisions

An advanced coalescence model

- **Space-time** distribution of nucleons must be considered
- Theoretical predictions[1] consider the correlation between antinucleons

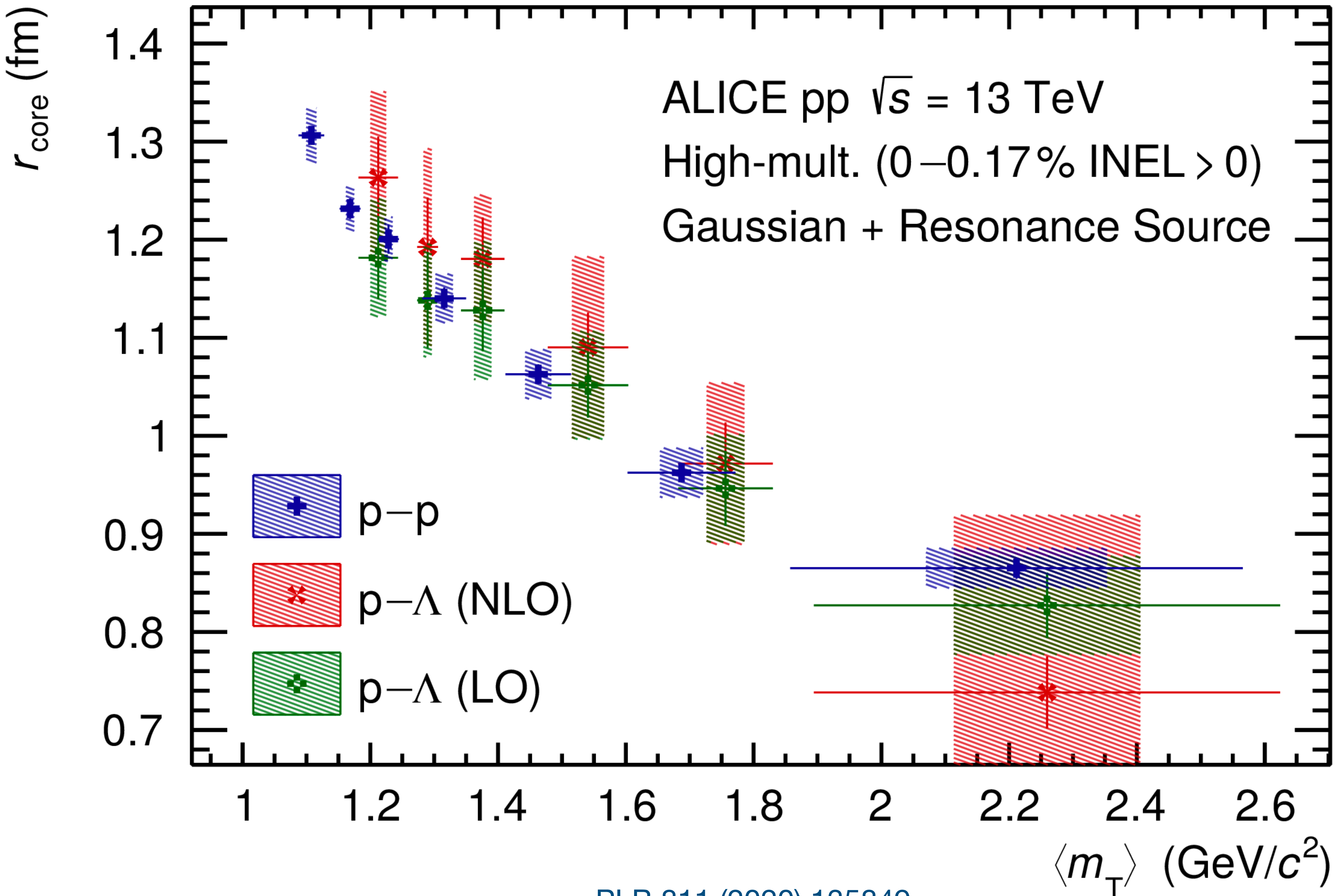
$$B_2(R) \approx \frac{3}{2m} \int \mathrm{d}^3 q \, D(\vec{q}) \, e^{-R(p_\mathrm{T})^2 q^2}$$

[1]PRC 99 (2019) 044913

  - $D(\vec{q}) = \int \mathrm{d}^3 r \, |\phi_\mathrm{d}(\vec{r})|^2 e^{-i\vec{q}\cdot\vec{r}}$ is the **antideuteron density**
    - $\phi_\mathrm{d}(\vec{r})$ is the antideuteron **wave function**
  - The source size ***R*** is a function of the antideuteron p_T
- ALICE measured the **source size** and $\boldsymbol{B_A}$ in the same data sample (HM pp collisions)

B_2 vs p_T/A

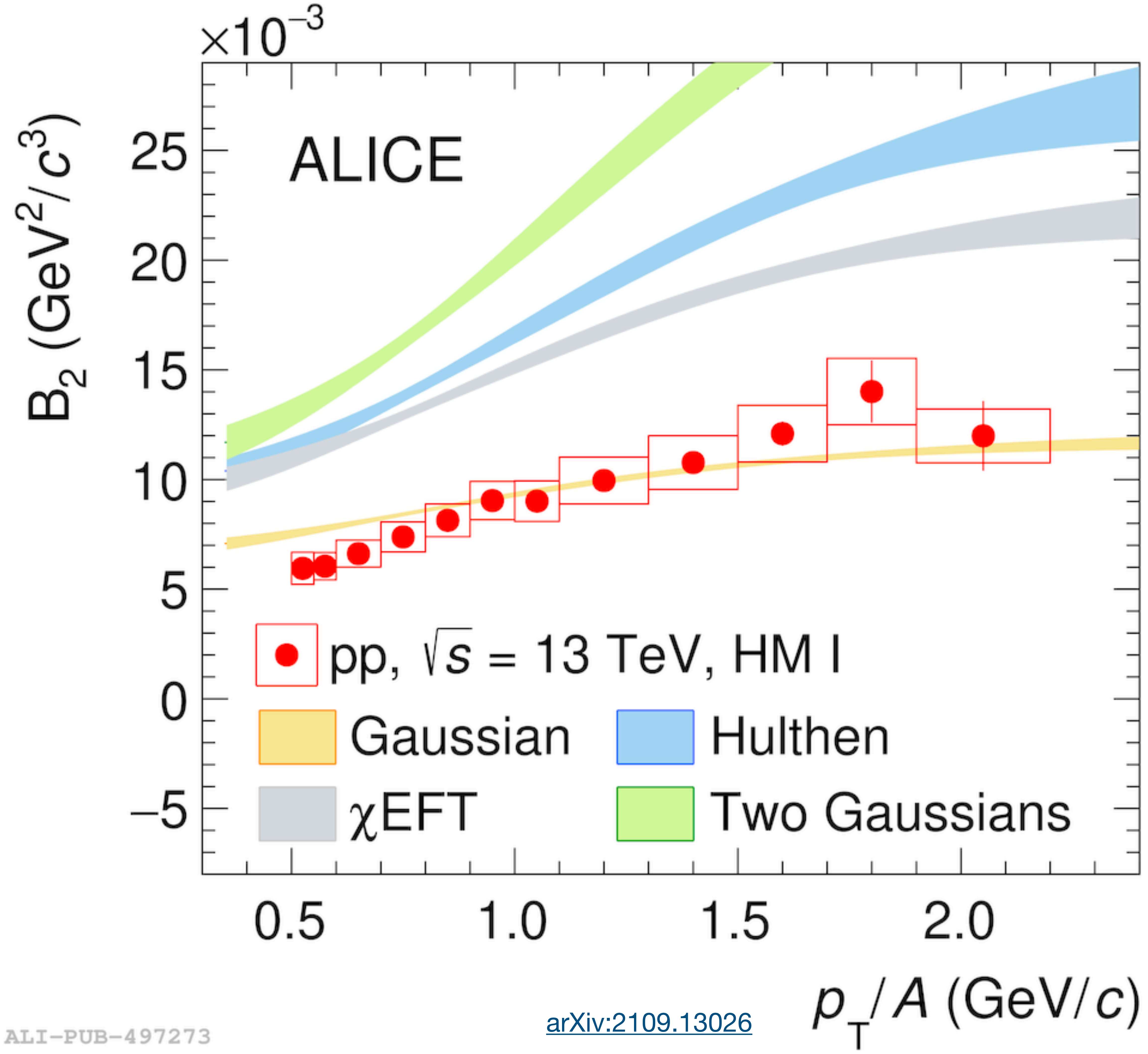
- Through **femtoscopy**, one can obtain **R(p_T)**



PLB 811 (2020) 135849

B_2 vs p_T/A

- Through **femtoscopy**, one can obtain **R(p_T)**
- Putting pieces together, it is possible to get **$B_2(p_T)$**
  - test for different wave function hypotheses
- A simple **Gaussian** provides the best description of the data
  - Hulthen is expected to provide a better description



arXiv:2109.13026

B_2 vs p_T/A

- Through **femtoscopy**, one can obtain **R(p_T)**
- Putting pieces together, it is possible to get ***B*₂(*p*T)**
  - test for different wave function hypotheses
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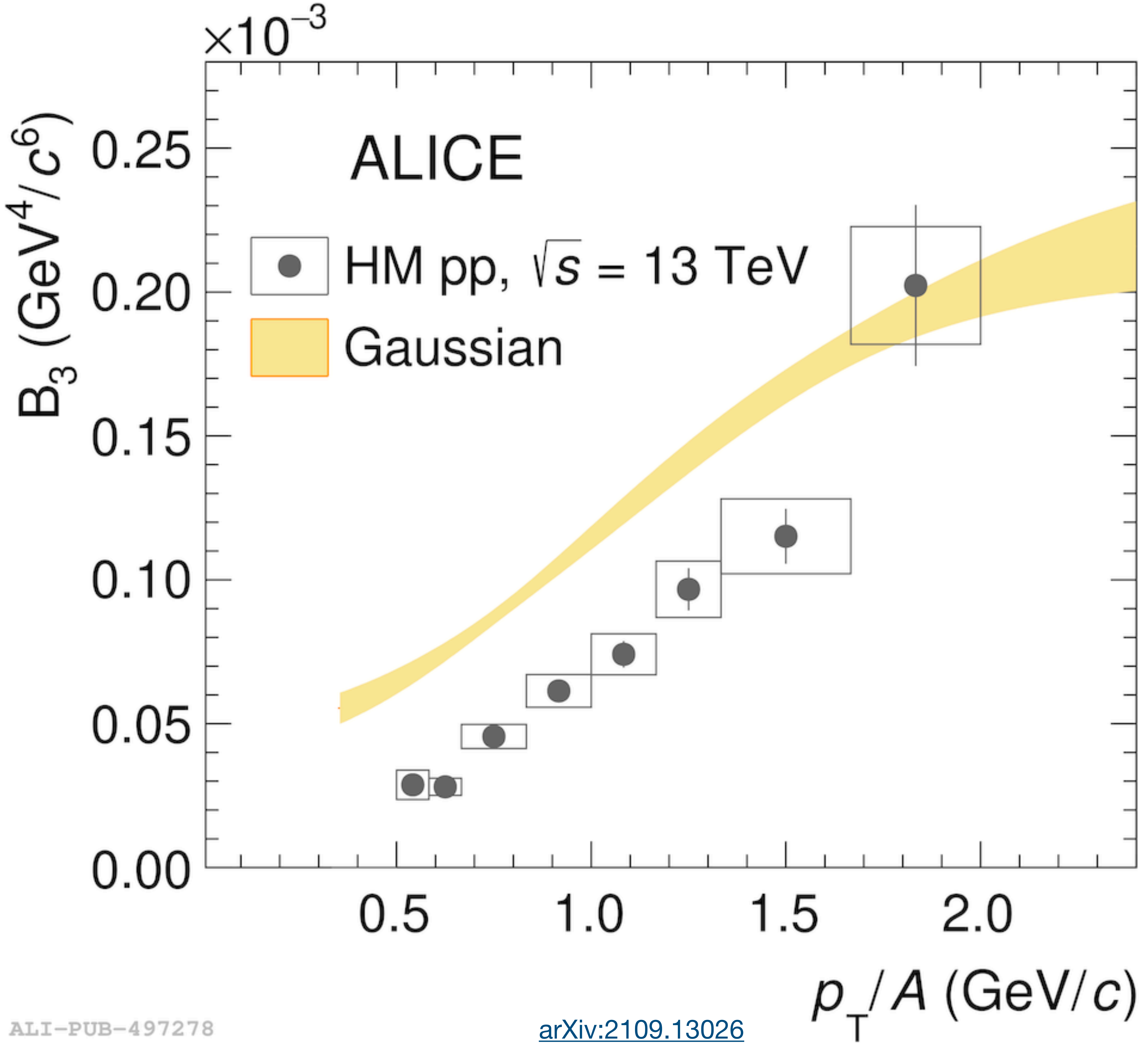
- The same approach can be used to obtain predictions for $\boldsymbol{B_3(p_T)}$
  - reasonably good description with a Gaussian wave function



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B_2 vs p_T/A

- Through **femtoscopy**, one can obtain **R(p_T)**
- Putting pieces together, it is possible to get ***B₂(p_T)***
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- A simple **Gaussian** provides the best description of the data
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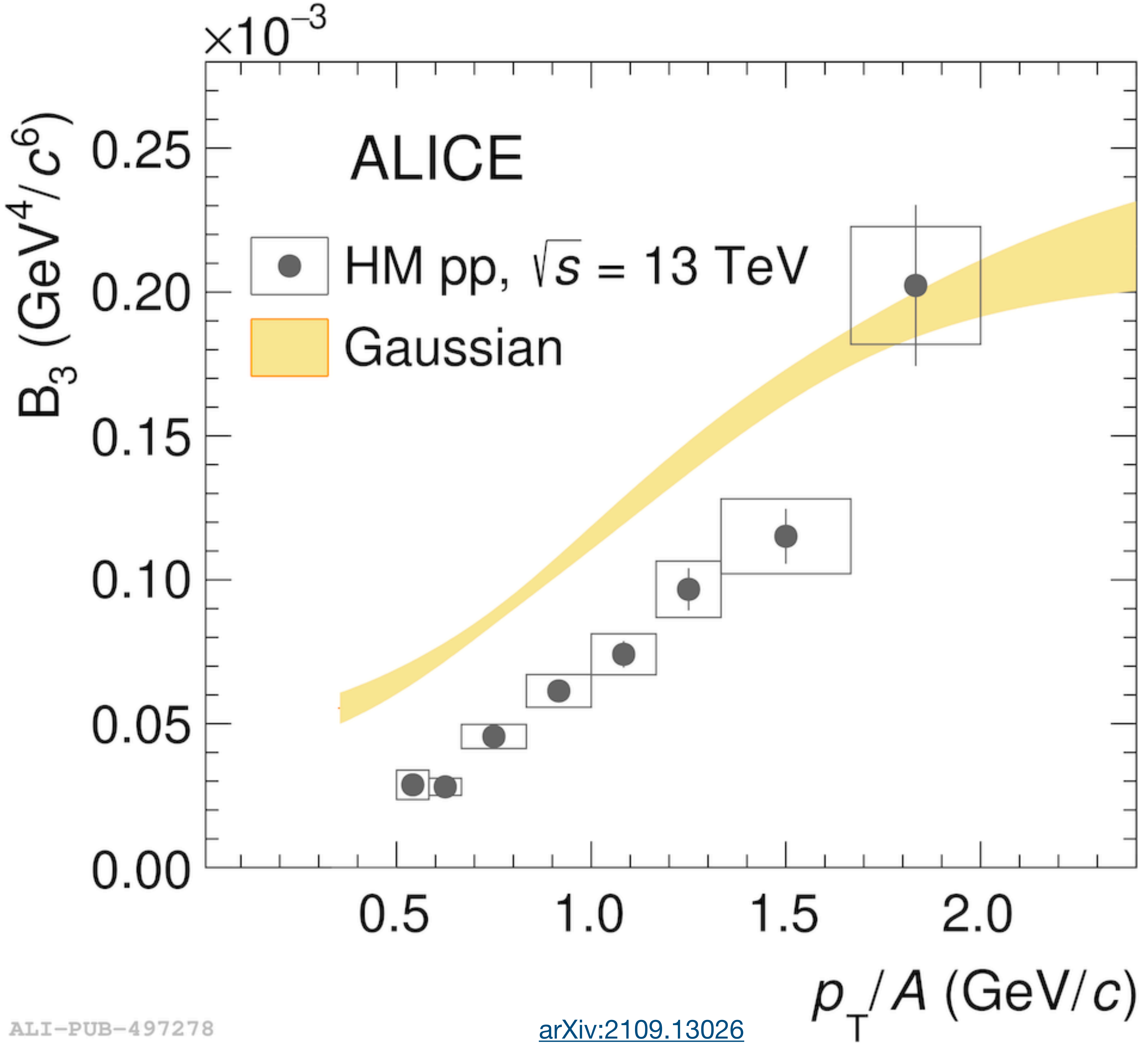
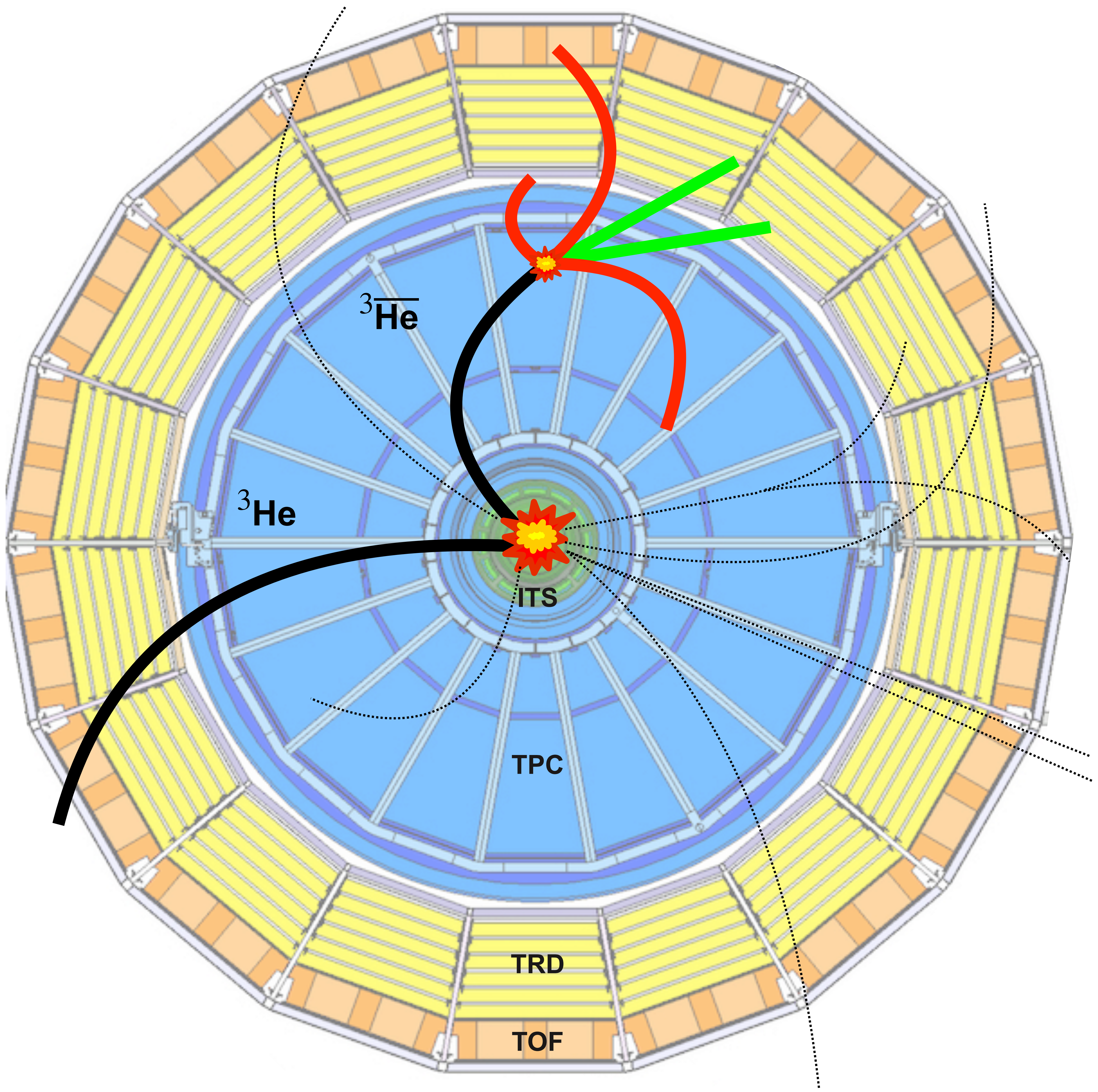
- The same approach can be used to obtain predictions for $\boldsymbol{B_3(p_T)}$
    - reasonably good description with a Gaussian wave function
- Using an **advanced coalescence** model could help in **reducing production uncertainties** in the predictions for **fluxes**!



arXiv:2109.13026

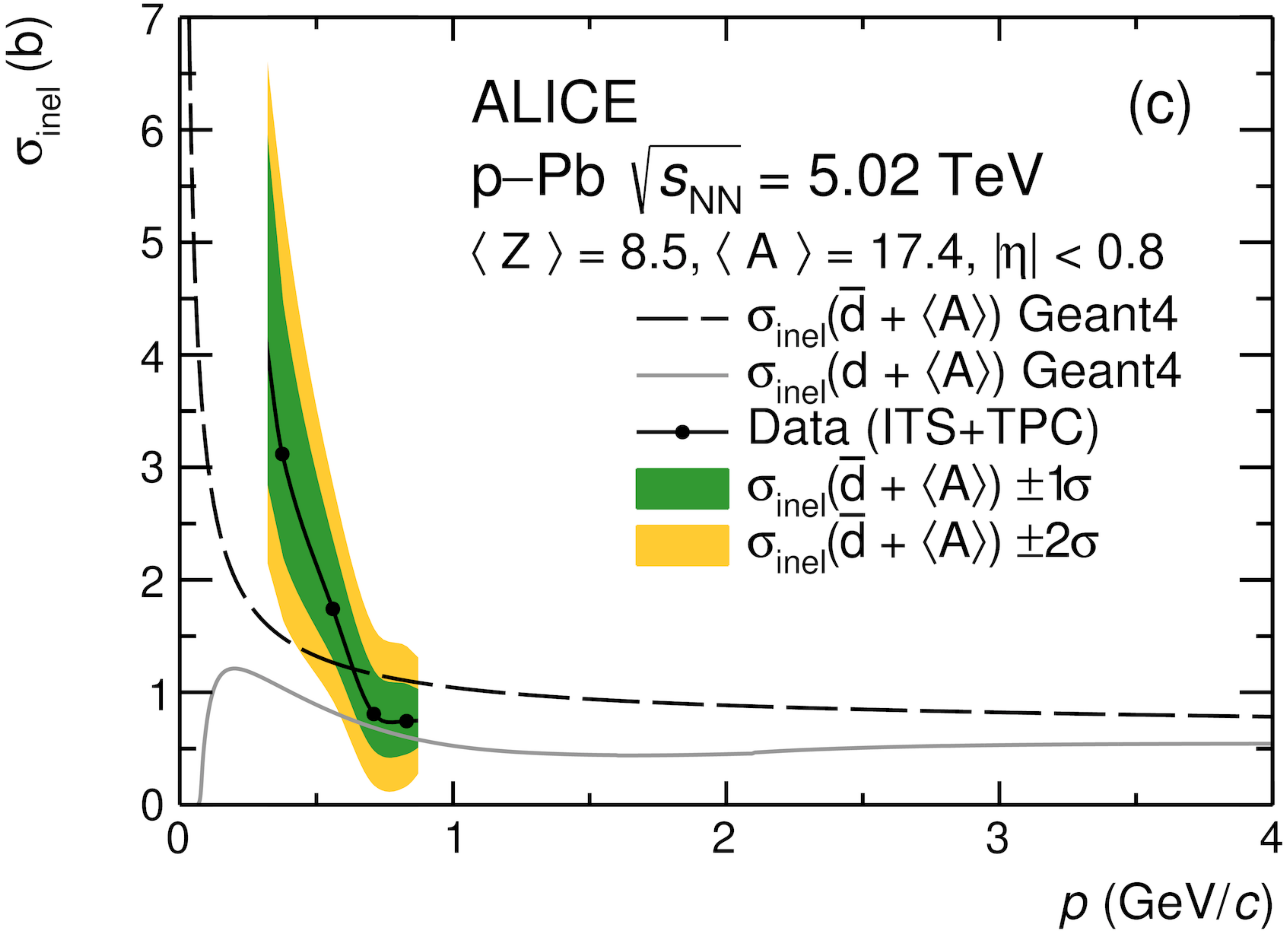
Annihilation of antinuclei

- ALICE measured the **inelastic cross section** for **antinuclei** using the detector as a target
- Two methods are used:
  - Measurement of **antinuclei/nuclei** ratio and **comparison with MC**
  - Measurement of the **absorption in the TRD** detector and **comparison with MC**
- The **inelastic cross section** can be **constrained** by scaling its value in MC until it matches the data

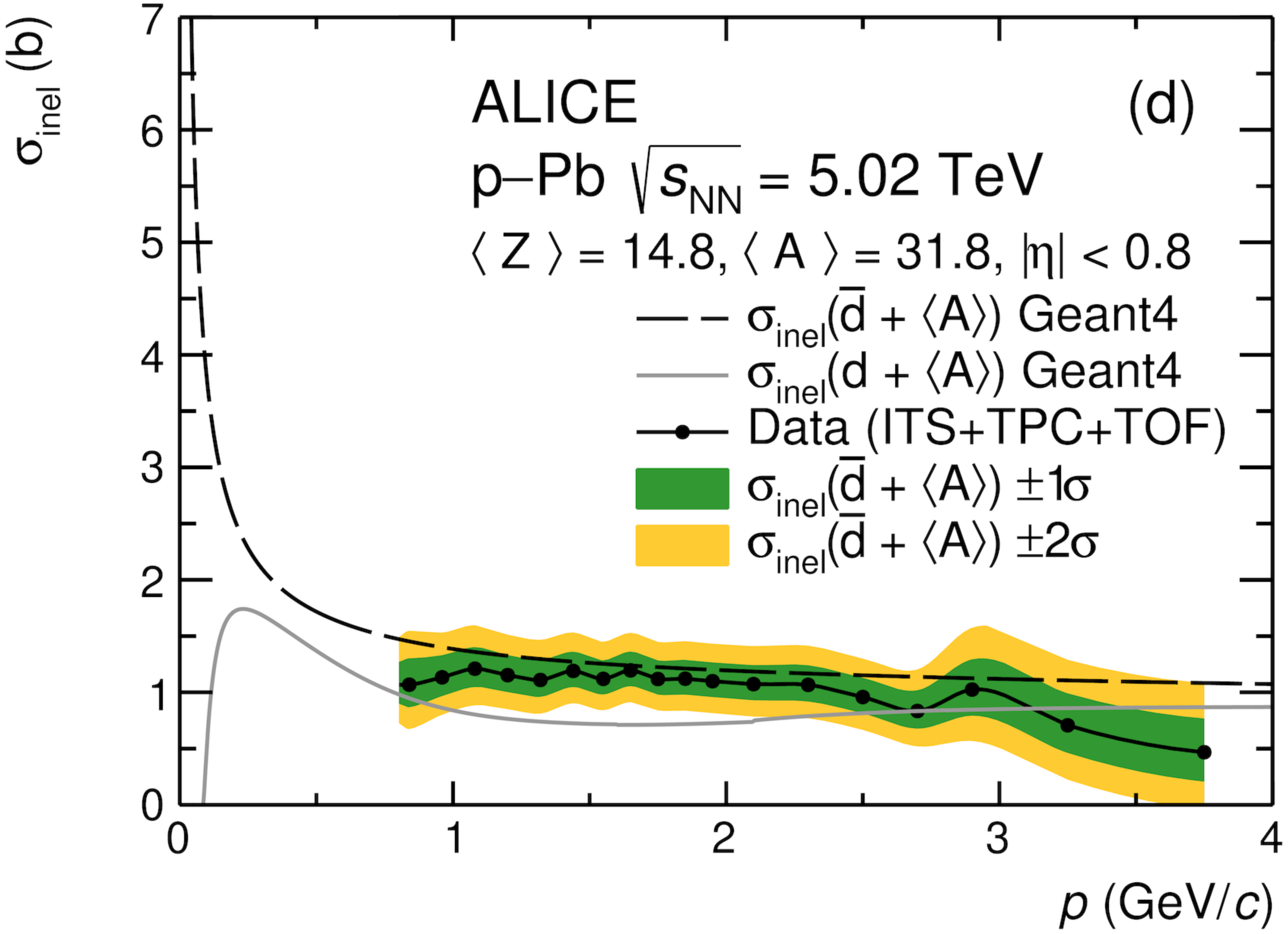


Antiprotons and antideuterons

- Cross section have been measured for different species:
  - **Antideuterons:** good agreement with GEANT4



ALI-PUB-490977

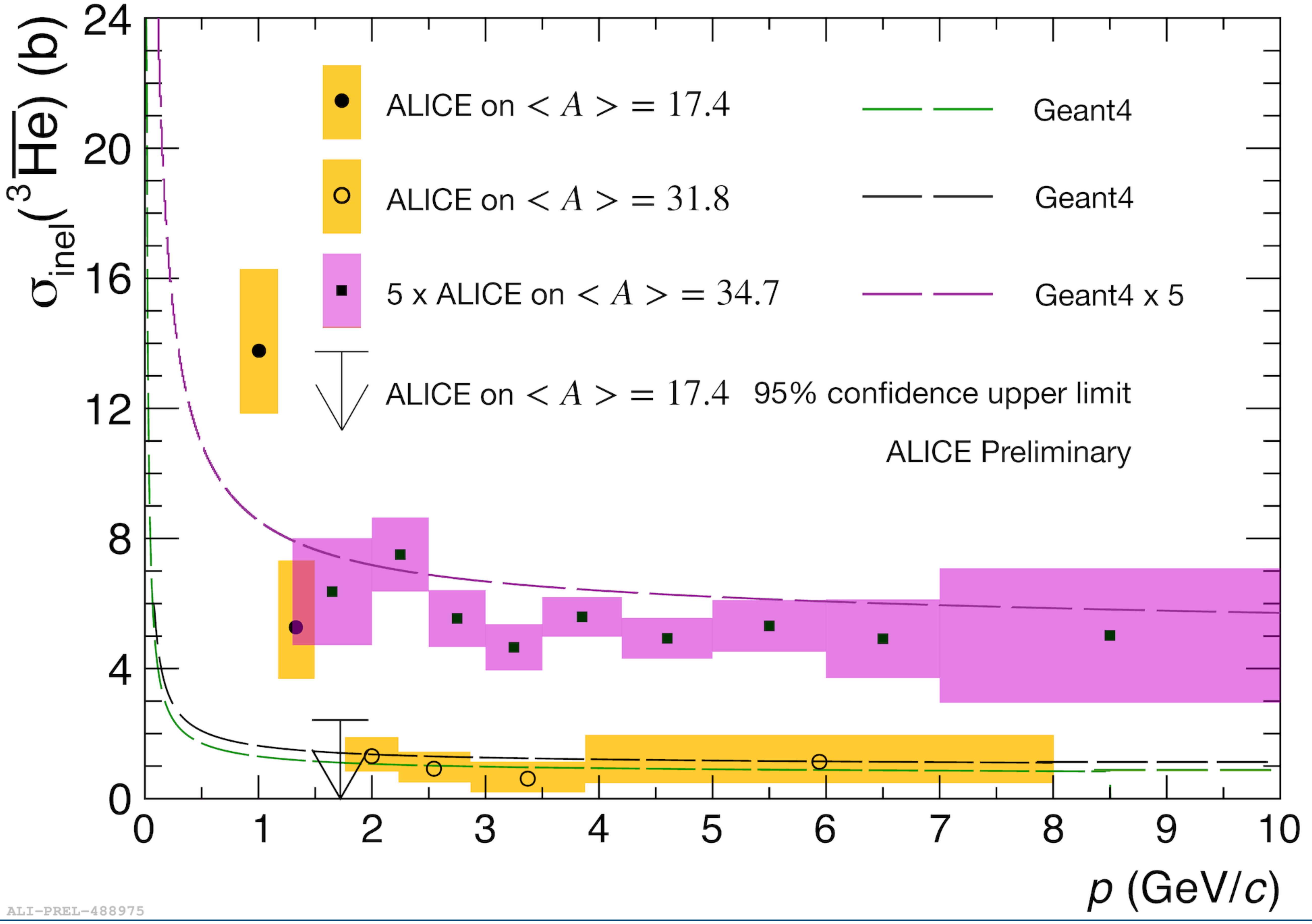


ALI-PUB-490982

PRL 125, 162001 (2020)

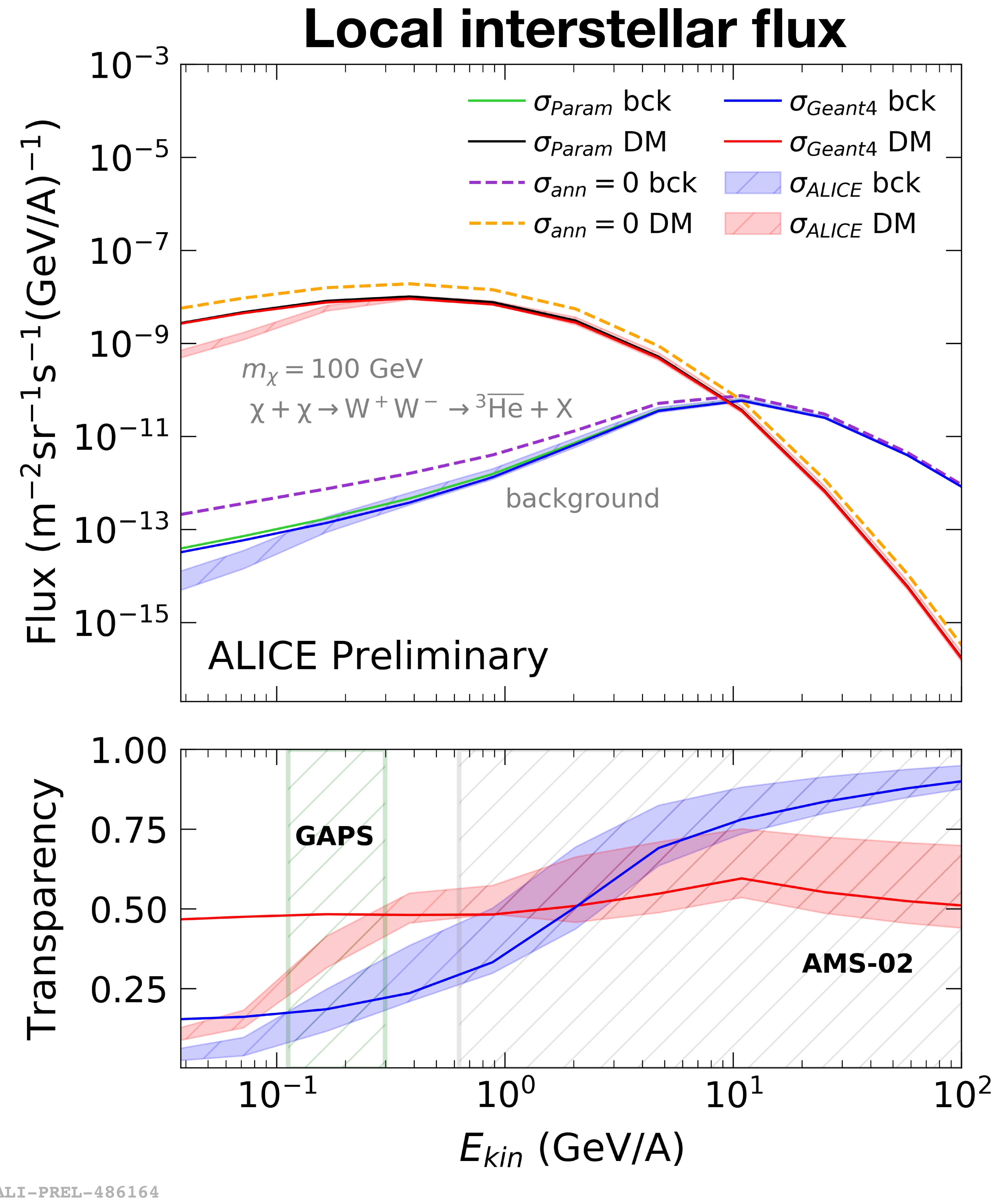
Antiprotons and antideuterons

- Cross section have been measured for different species:
  - **Antideuterons:** good agreement with GEANT4
  - **Antihelions**: rise at low momentum, otherwise compatible with GEANT4



Effect on antihelion fluxes

- The inelastic cross section affects $^{3}\overline{\mathrm{He}}$ fluxes
  - Difference between GEANT4 cross section and the cross section by ALICE
  - Only uncertainties on the cross section are shown (small wrt to the other uncertainties)



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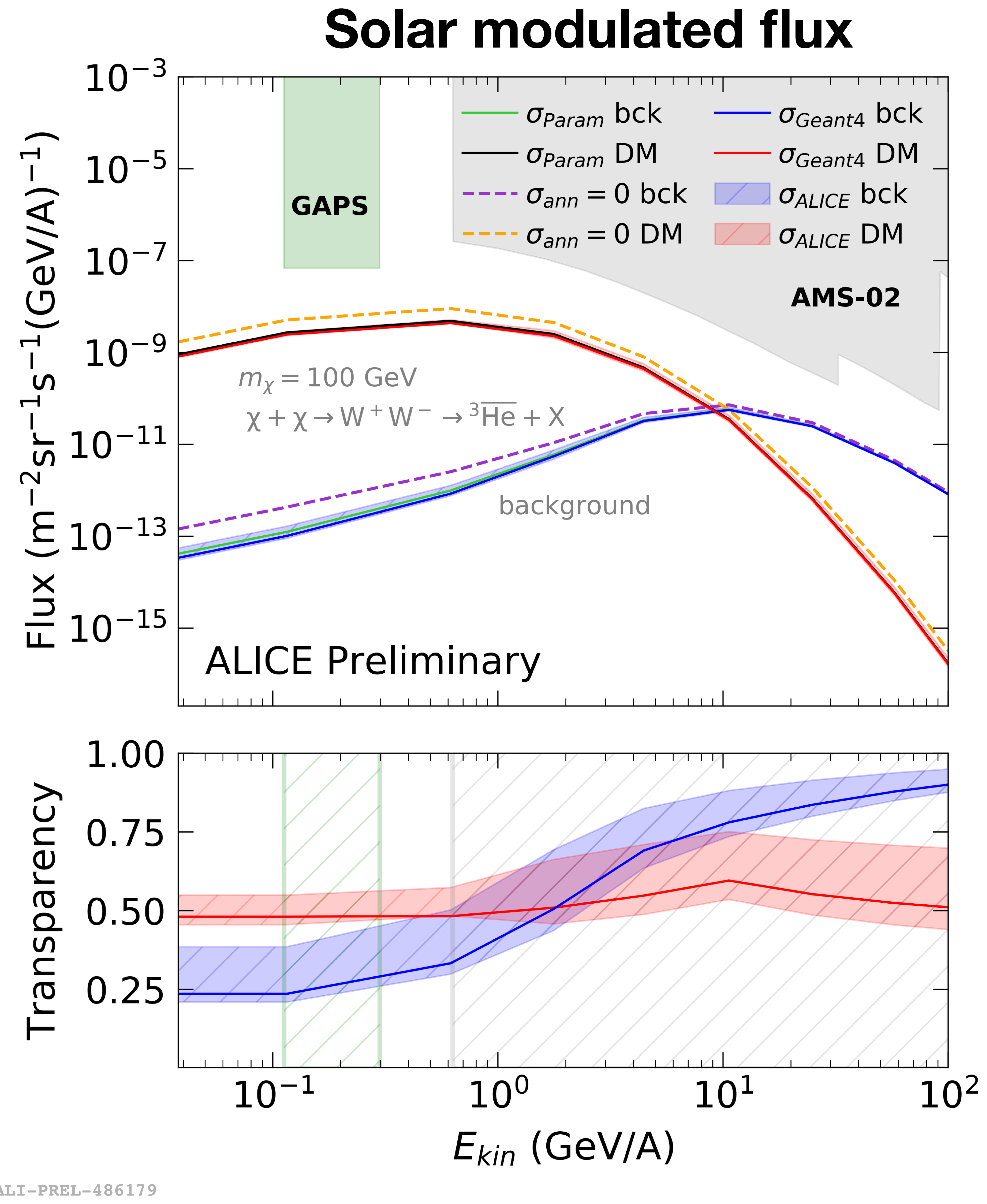
- The inelastic cross section affects $^{3}\overline{\mathrm{He}}$ fluxes
  - Difference between GEANT4 cross section and the cross section by ALICE
  - Only uncertainties on the cross section are shown (small wrt to the other uncertainties)
- After solar modulation, the difference between GEANT4 and ALICE measurement disappears
  - Rather constant transparency of the galaxy to $^{3}\overline{\mathrm{He}}$ nuclei
  - About 50% of $^{3}\overline{\mathrm{He}}$ nuclei are absorbed



Summary and conclusions

- Antinuclei in cosmic rays can be a probe for DM annihilation
- The flux of cosmic antinuclei depends on the nuclear production mechanisms and on the inelastic cross sections
- Thanks to a modern approach to the coalescence model, it is possible to test different hypotheses on the nuclear wave function
- From the measurement of inelastic cross section, about 50% of antihelions are absorbed and the transparency is rather constant wrt the kinetic energy

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- Antinuclei in cosmic rays can be a probe for DM annihilation
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Thank you for your attention!

Backup

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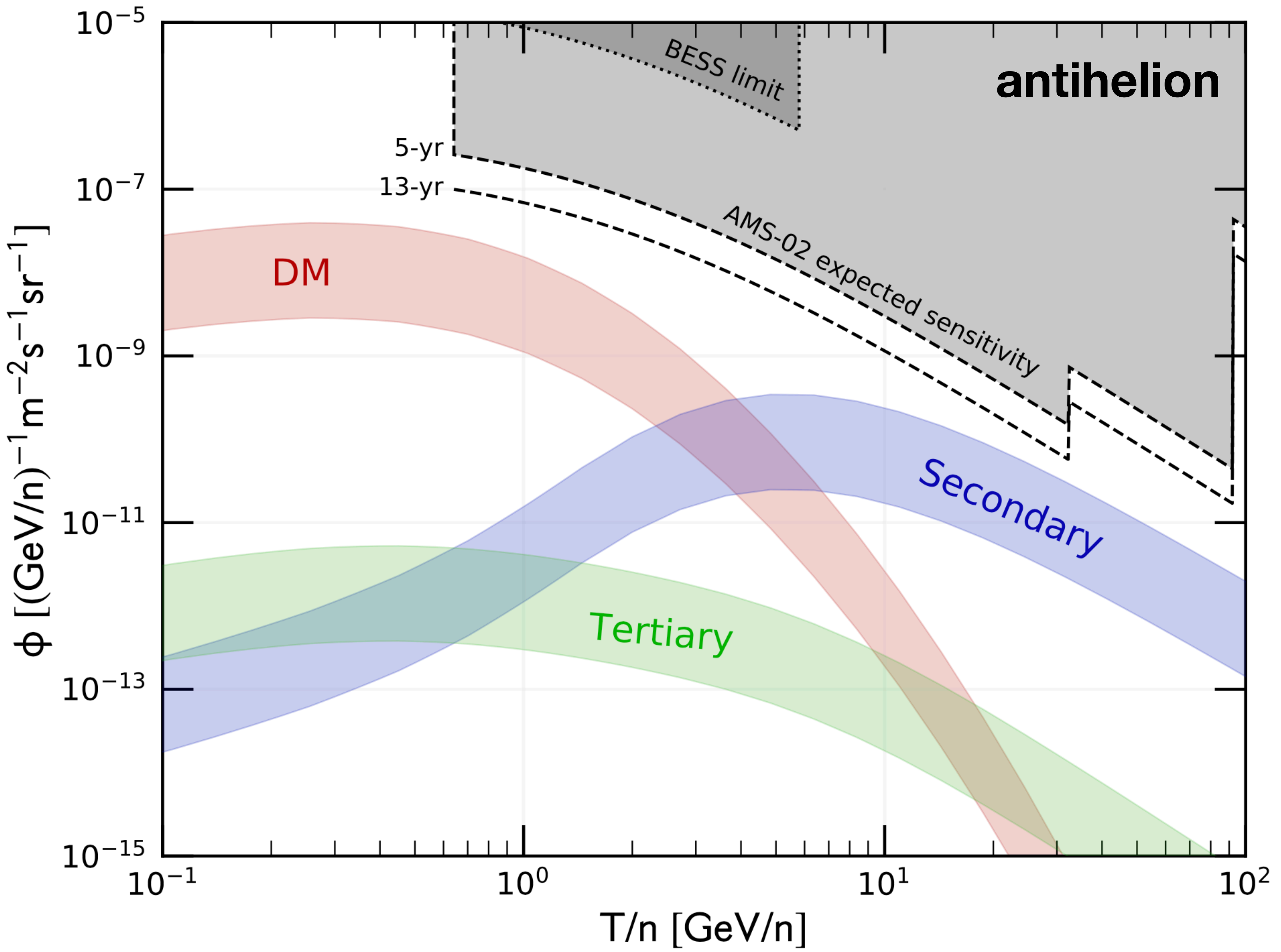
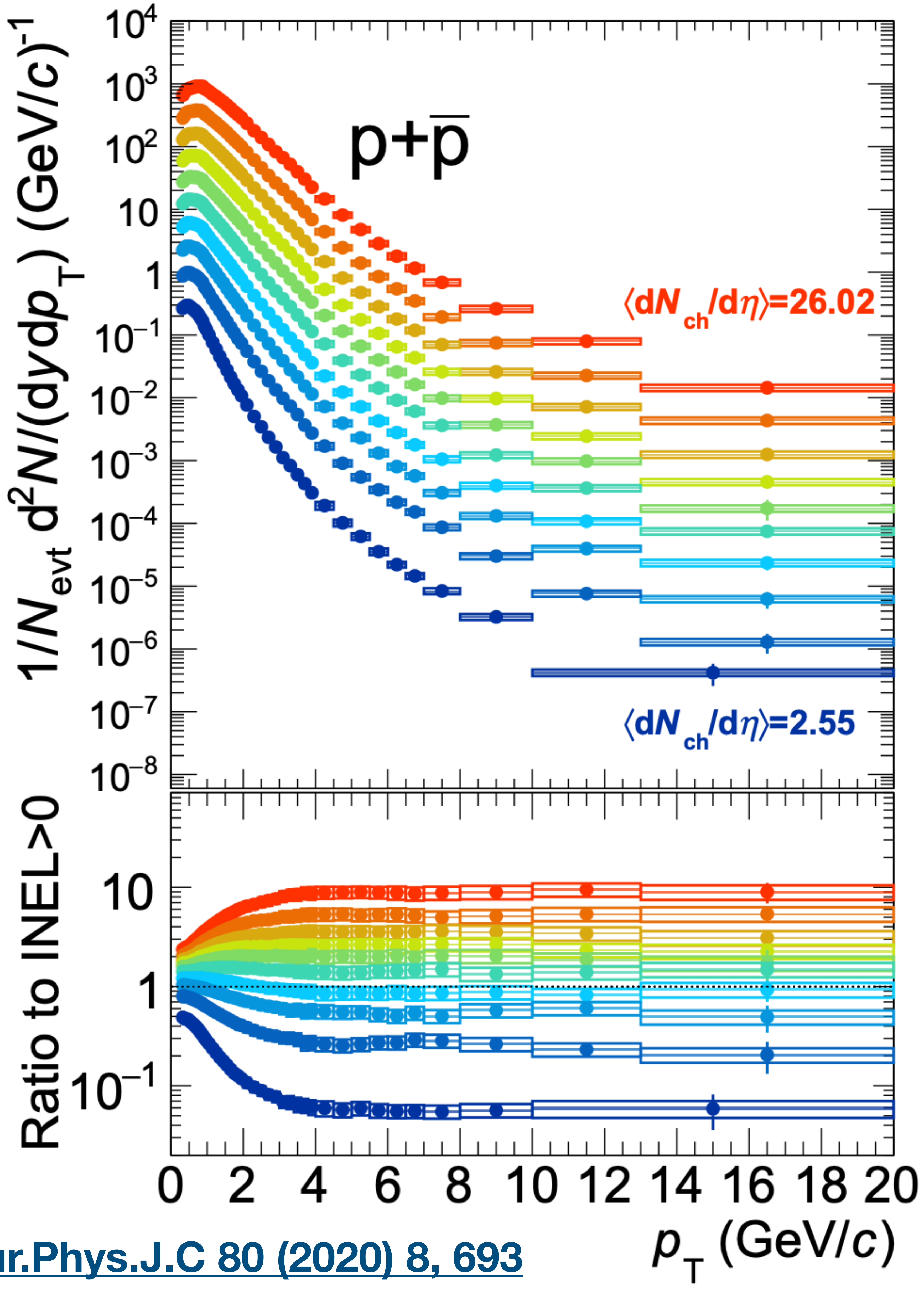
- **Low-energy** is the most interesting region:
  - Signal/Background ~ 10^{-4}
- Each term of the transport equation has uncertainties:
  - Source: from production mechanism of antinuclei
  - Propagation: model, solar modulation
  - Annihilation: absorption cross section of antinuclei



Phys.Rev.D 97 (2018) 10, 103011

B_2 vs B'_2

- An **increasing** $\boldsymbol{B'_2}$ can be obtained from a **flat** $\boldsymbol{B_2}$ in each **multiplicity** class:
  - $S_{d,i} = B_2 \, S^2_{p,i}$
  - $S_d = \sum_i (N_i/N) \, S_{d,i} = B_2 \sum_i (N_i/N) \, S^2_{p,i}$
  - $S_d = B'_2 \, S^2_p = B'_2 \left(\sum_i (N_i/N) \, S_{p,i} \right)^2$
  - $B'_2 = B_2 \dfrac{\sum_i (N_i/N) \, S^2_{p,i}}{\left[\sum_i (N_i/N) \, S_{p,i} \right]^2}$
- Consequence of the **hardening** of the **proton spectra** with increasing multiplicity



Eur.Phys.J.C 80 (2020) 8, 693

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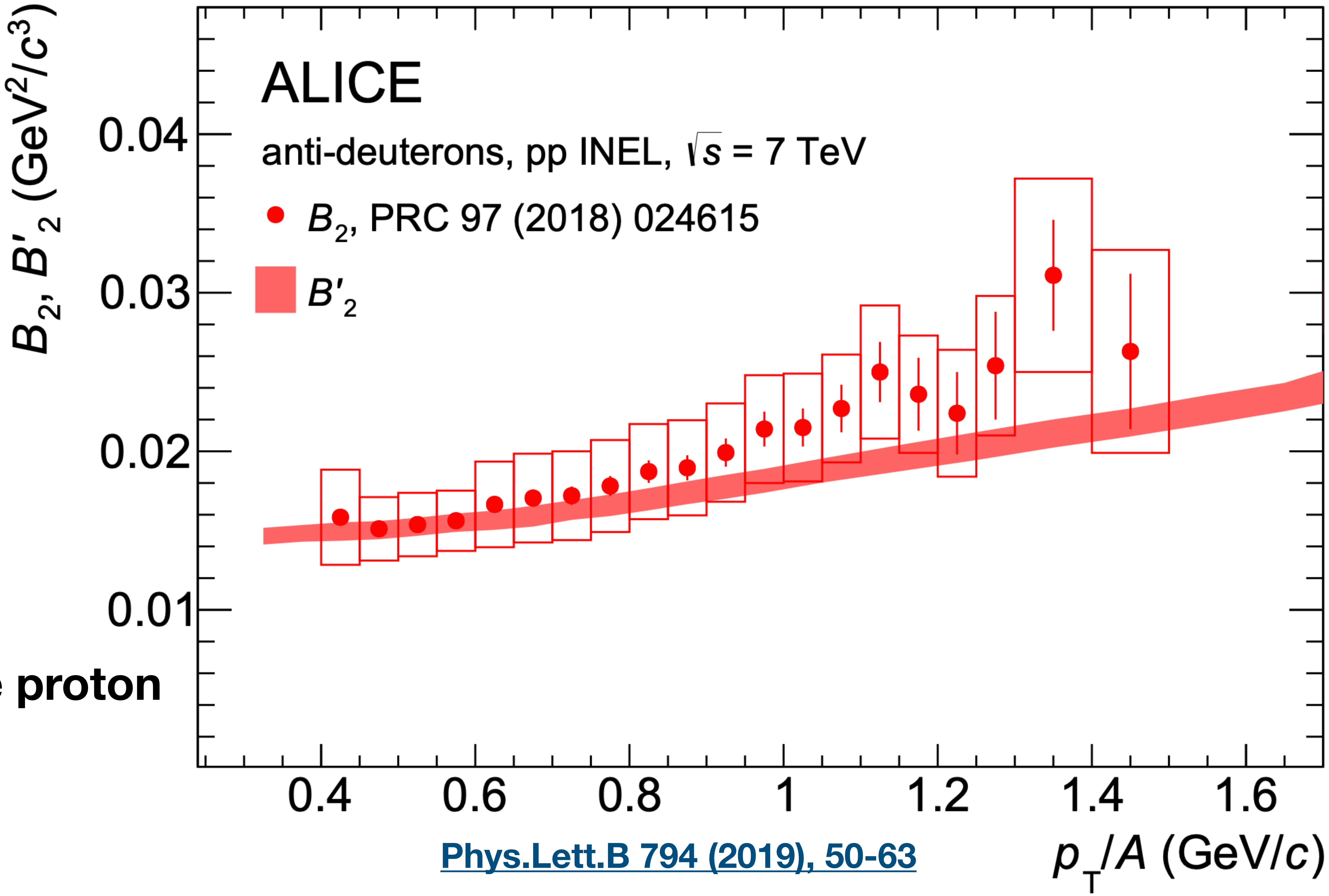
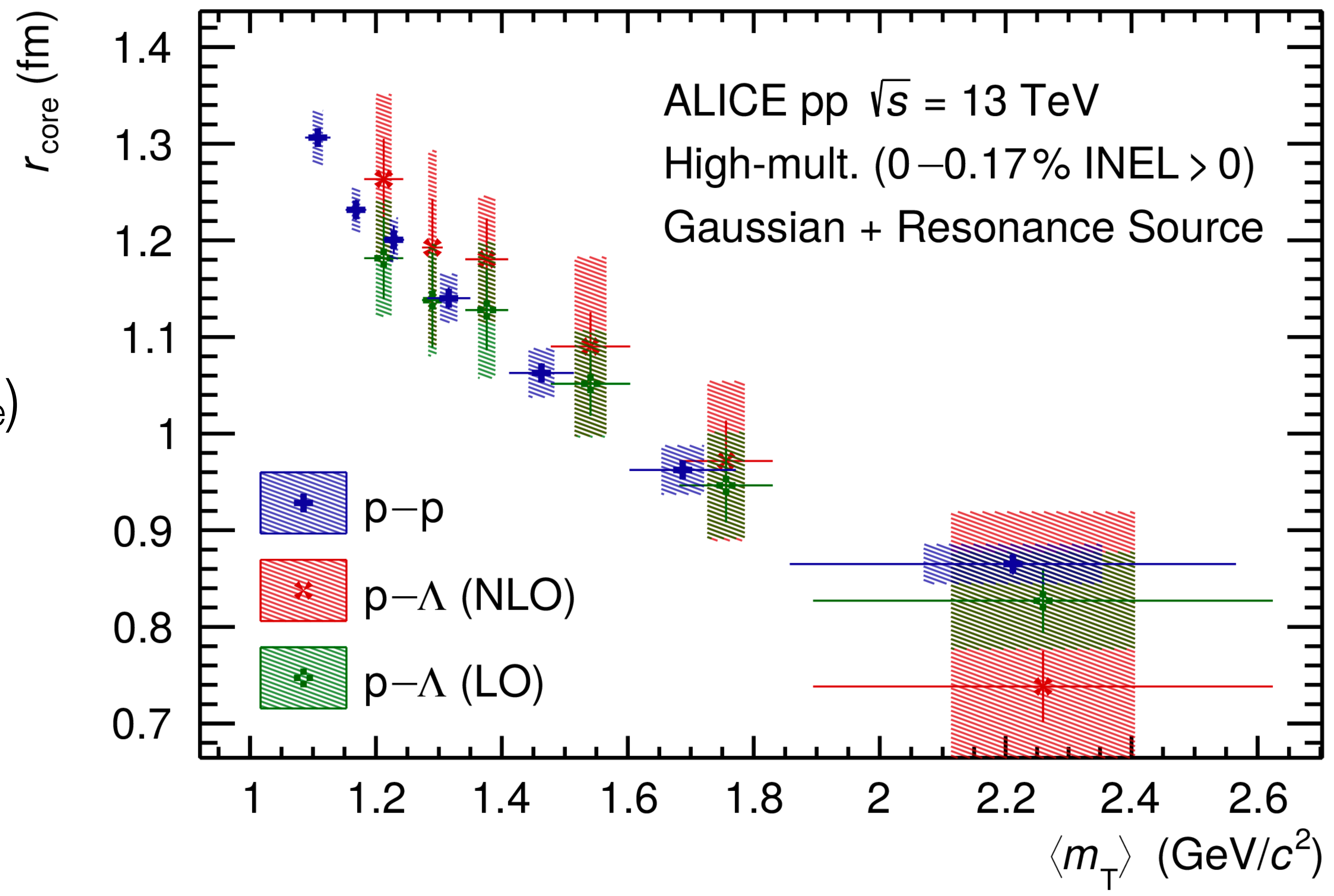


Phys.Lett.B 794 (2019), 50-63

Measure of the source size

$$C(k^*) = \int S(\vec{r}^*)\,|\psi(\vec{k}^*, \vec{r}^*)|^2\, d^3r^*$$

- If the **interaction** is very **well known**, the CF can be used to constrain the **source function**
  - **p-p** and **p-Λ**
- Assumptions
  - Particle emission from a **Gaussian core** source
- Short-lived strongly decaying **resonances** ($c\tau \approx r_{core}$) effectively increase the source radius
  - e.g. Δ-resonances for protons
- **Universal source model**
  - r_{core} fixed for each pair based on $\langle m_T \rangle$



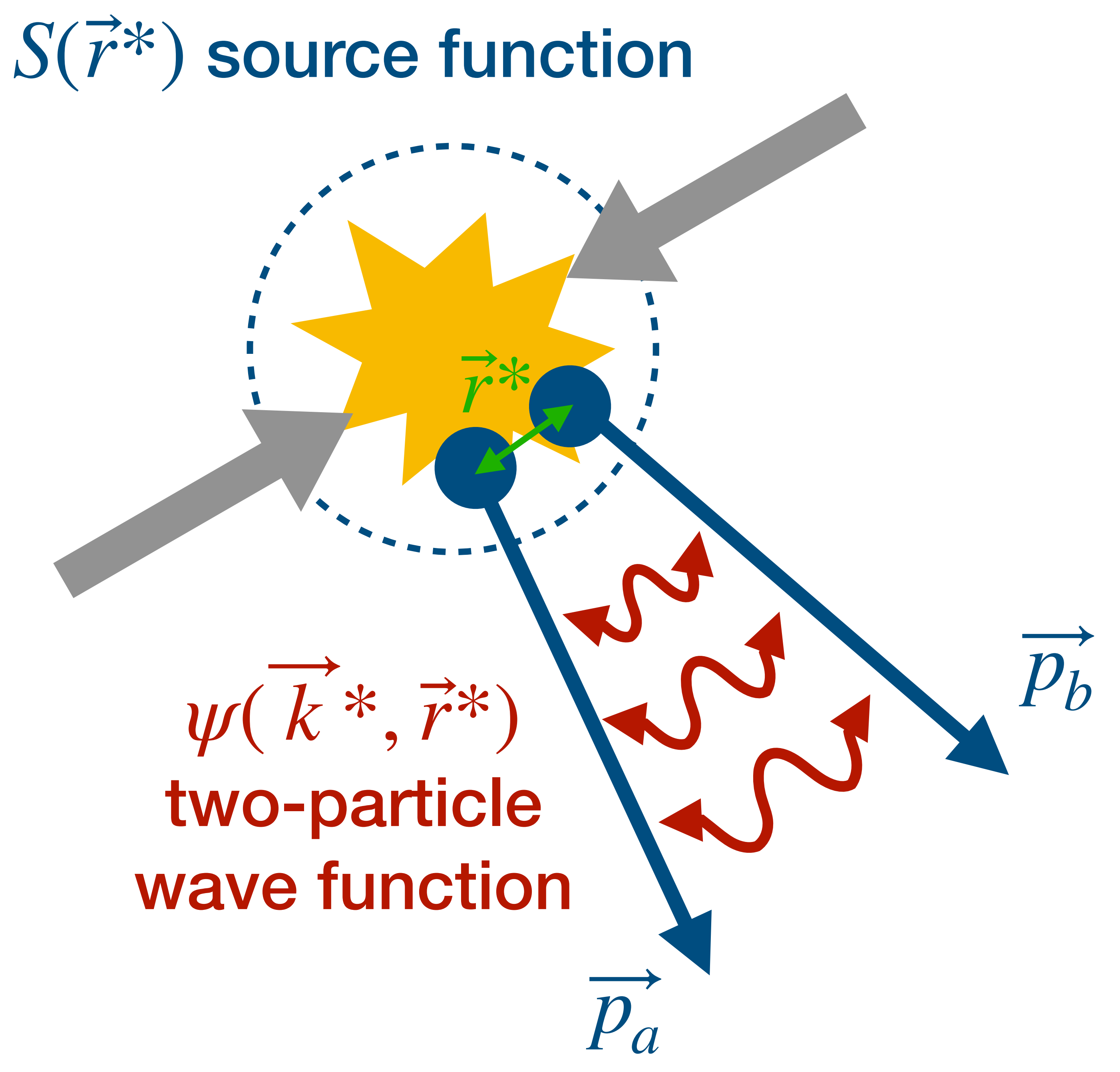
PLB 811 (2020) 135849

The correlation function

- The **correlation function** is defined as:

$$C(k^*) = \underbrace{\int S(\vec{r}^*)\,|\psi(\vec{k}^*, \vec{r}^*)|^2 \mathrm{d}^3 r^*}_{\text{Theory}} = \underbrace{\mathcal{N}\frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)}}_{\text{Experiment}}$$

where $\vec{k}^* = \frac{\vec{p}_a - \vec{p}_b}{2}$ in the pair rest-frame



- Two ingredients:
  - **Emitting source**: hypersurface at kinematic freeze-out of final-state particles
  - **Two-particle wave function**: express the interaction between particles

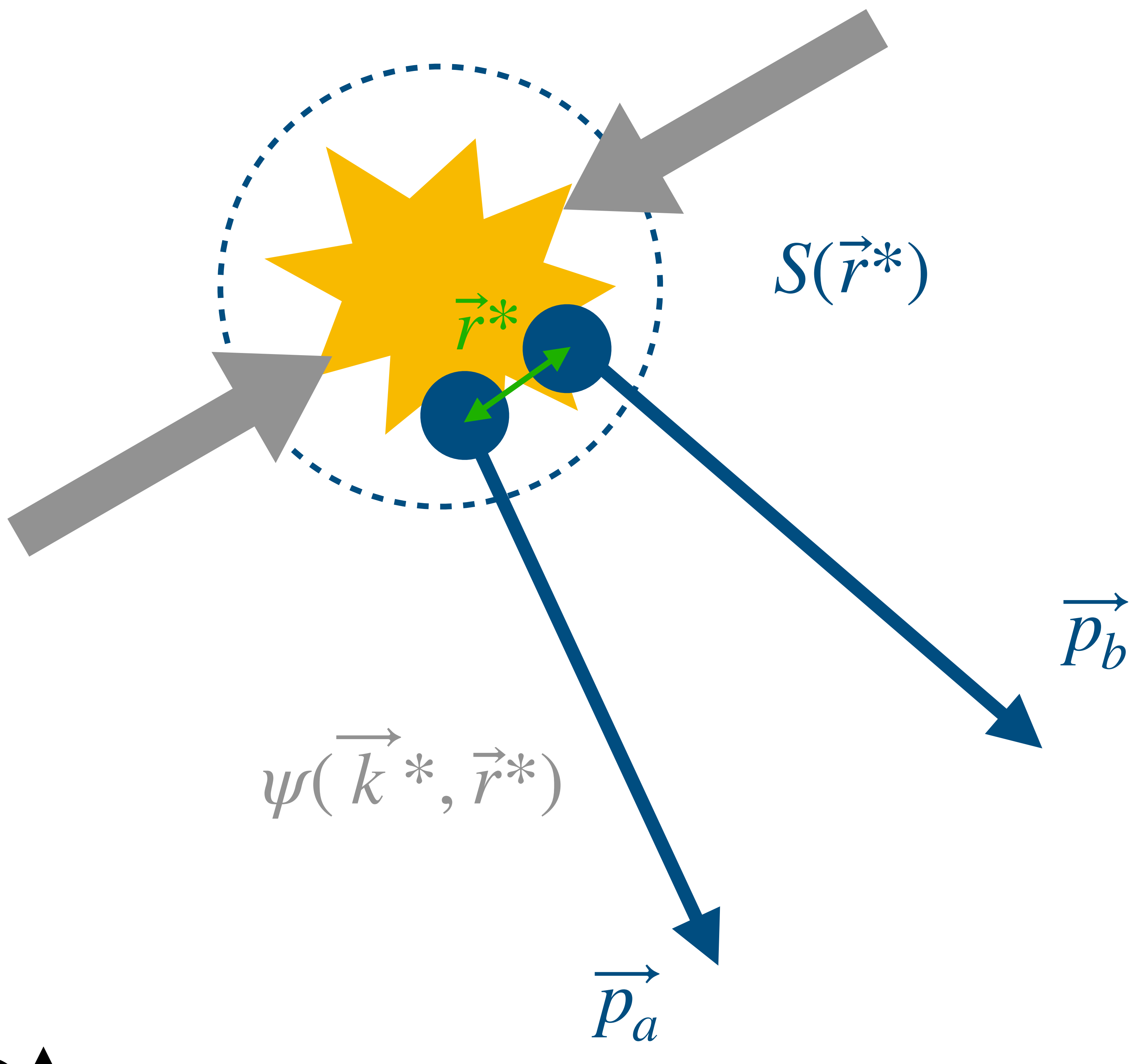
The theoretical CF is obtained using **CATS** (Correlation Analysis Tool using the Schrödinger equation):

- exact solution of the Schrödinger equation for a wave function

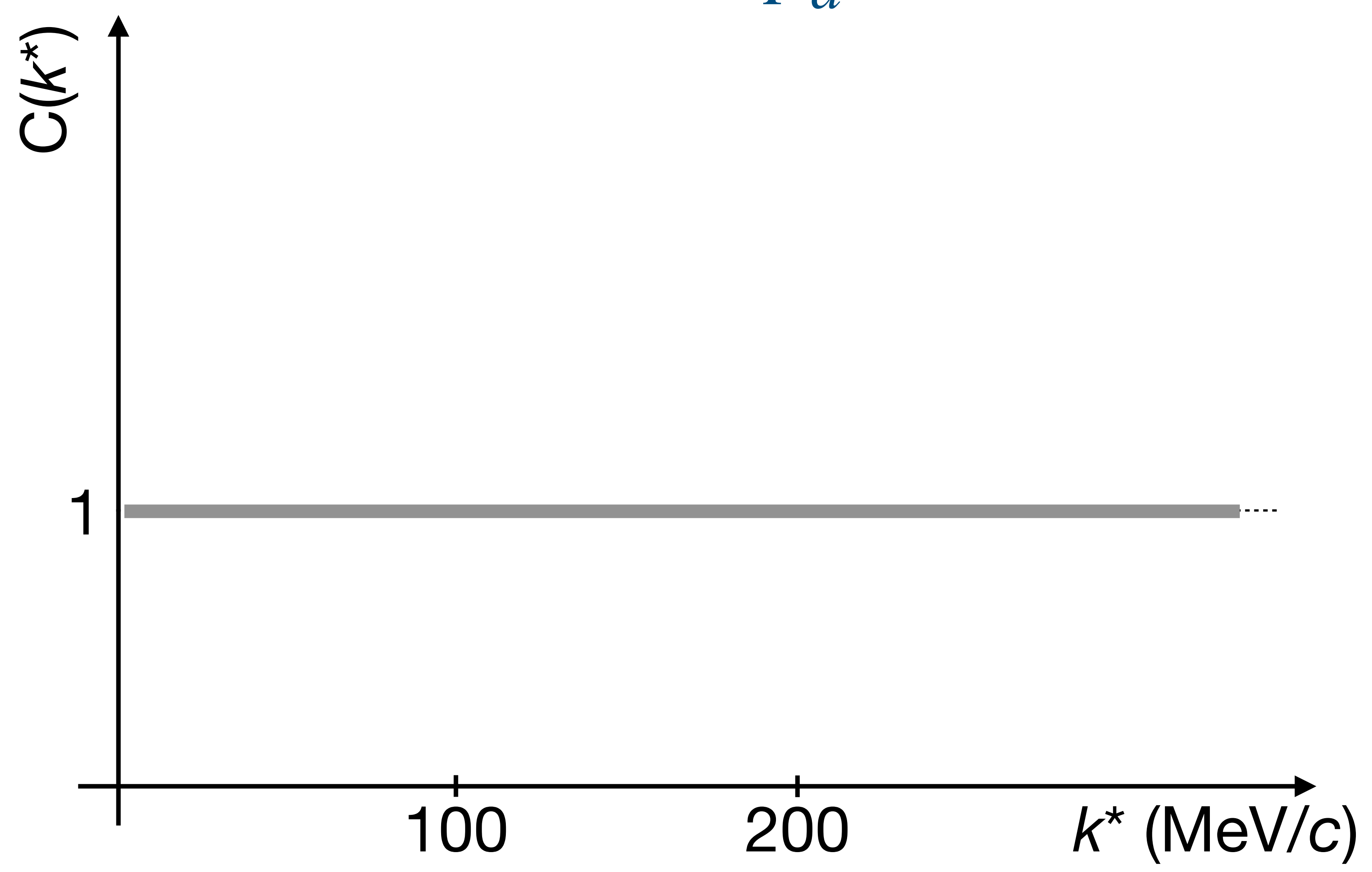
D.L. Mihaylov et al., EPJC 78 (2018) 5, 394

The correlation function

- The **correlation function** reflects the interaction:
  - Absence of interaction: C(k*) = 1



$$C(k*) = \int S(\vec{r}*)\,|\psi(\vec{k}*, \vec{r}*)|^2\,\mathrm{d}^3r* = \mathcal{N}\,\frac{N_{\mathrm{same}}(k*)}{N_{\mathrm{mixed}}(k*)} = 1$$



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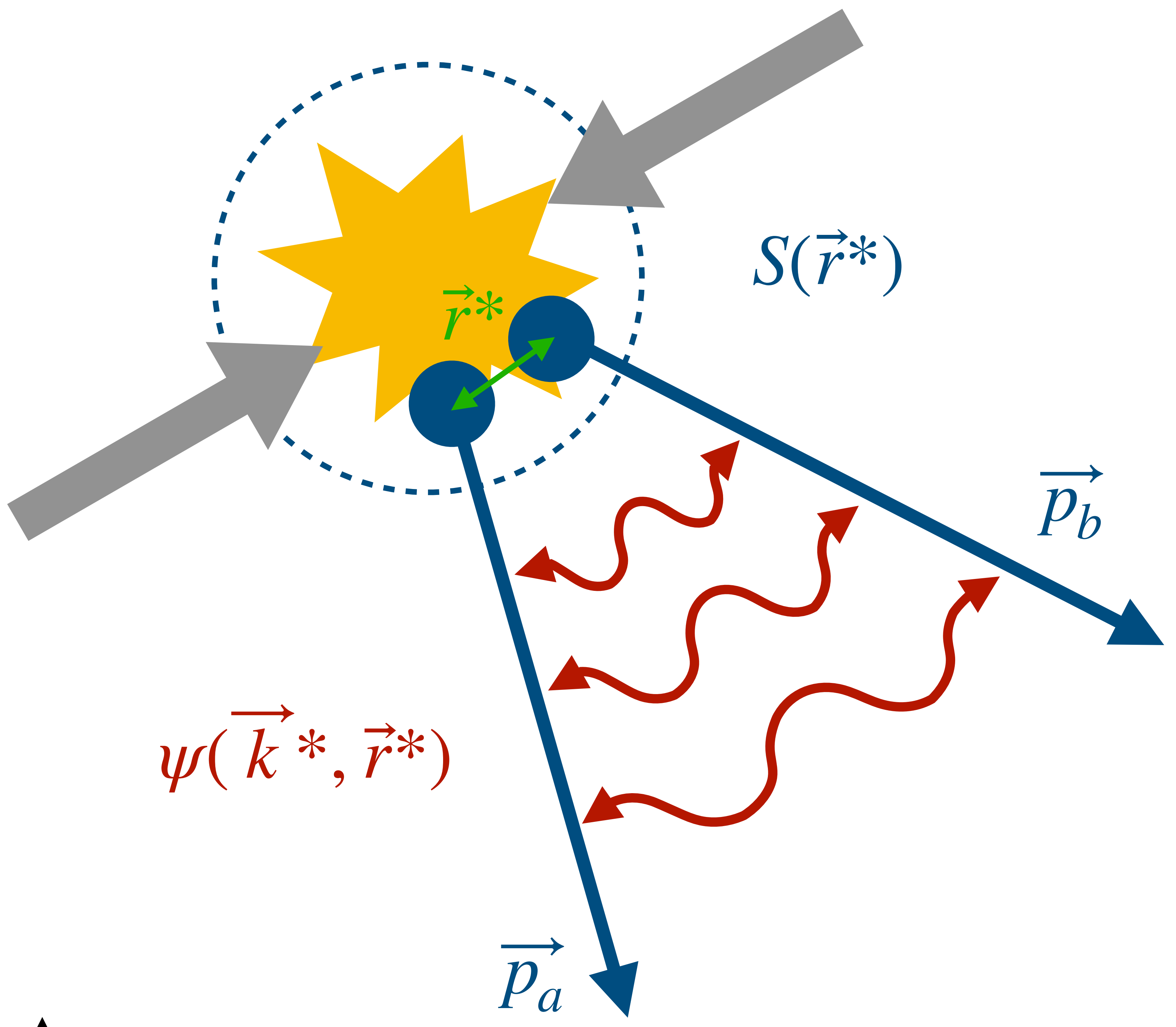
  - Repulsive interaction: C(k*) < 1



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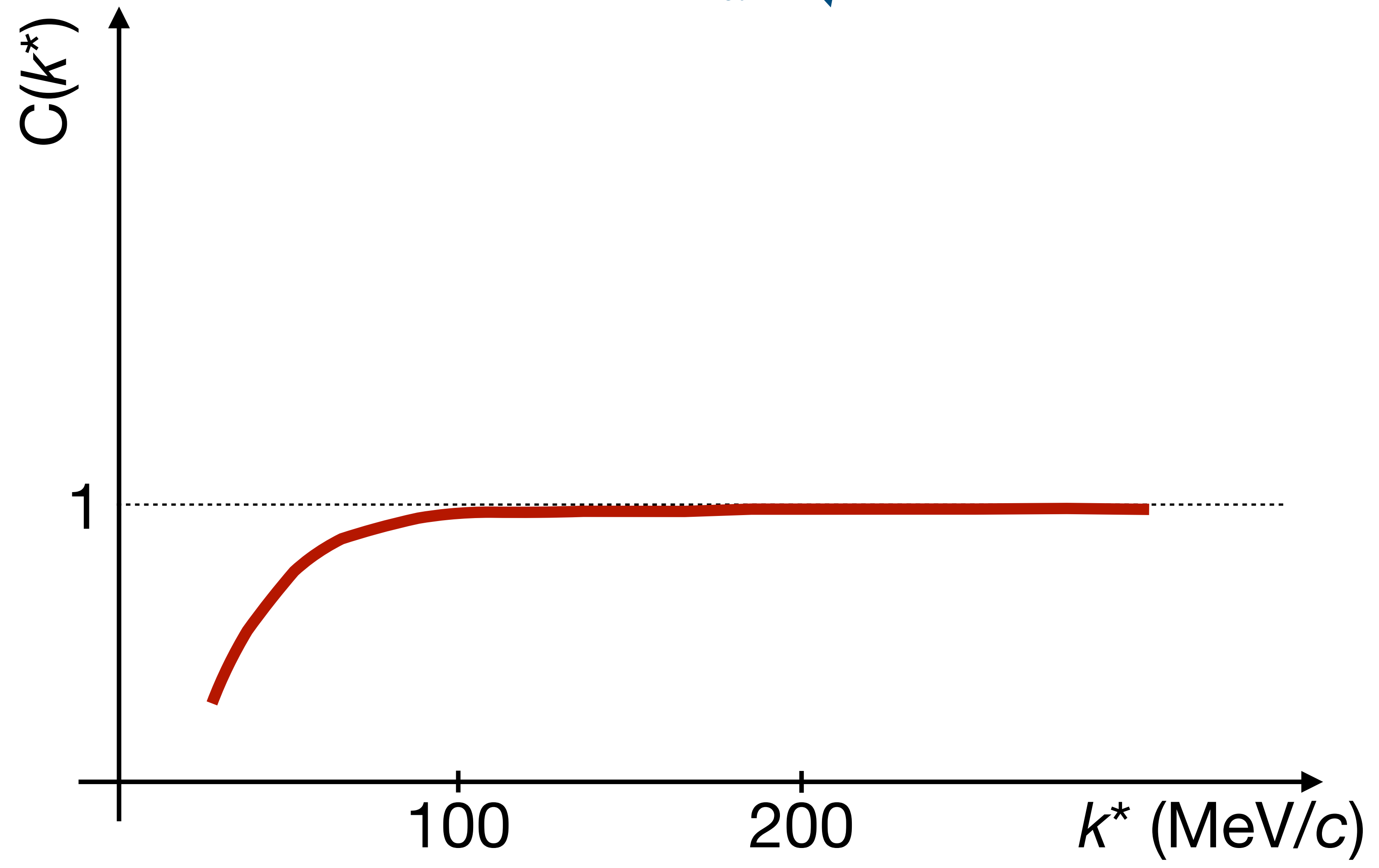

The correlation function

- The **correlation function** reflects the interaction:
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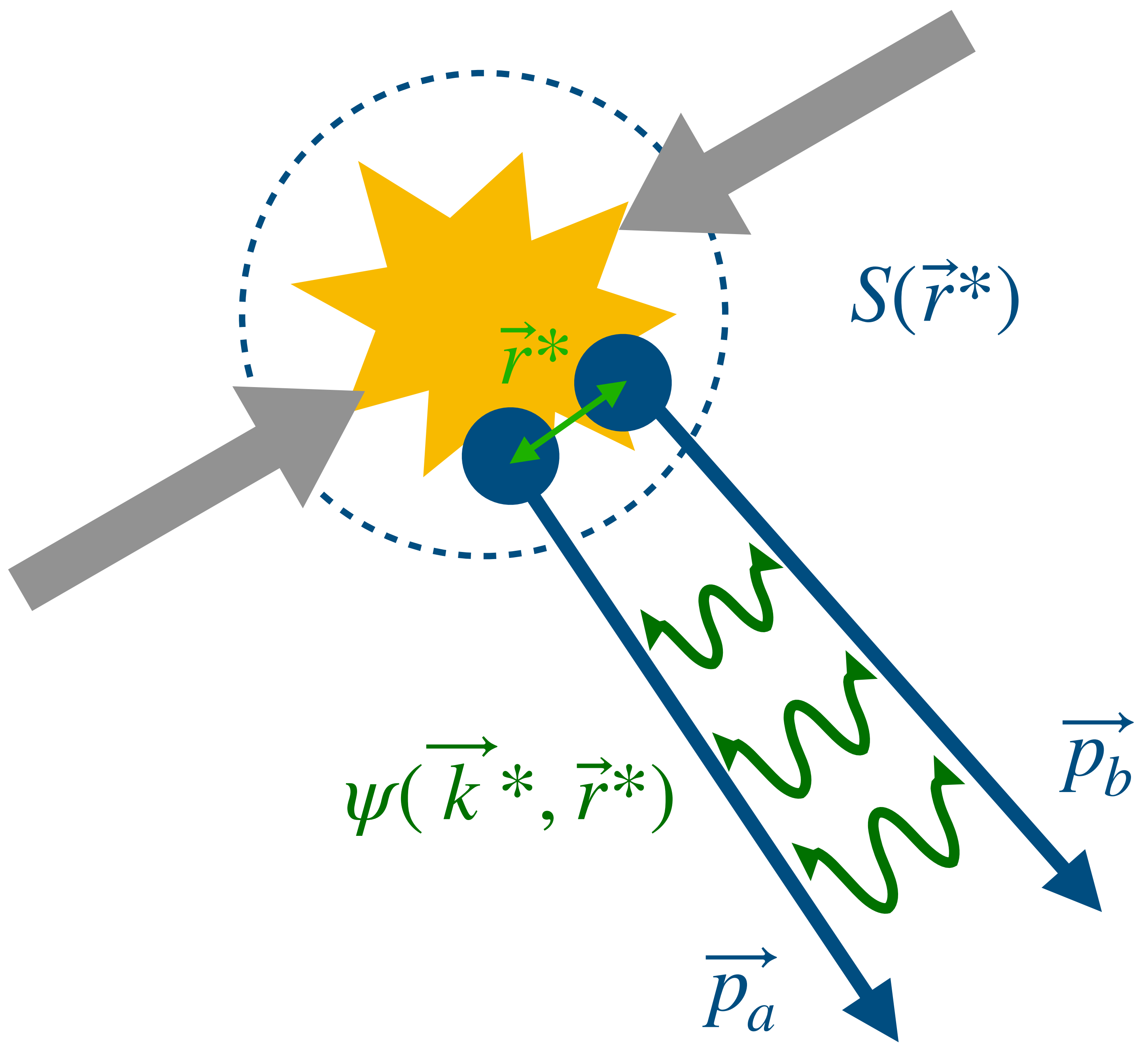
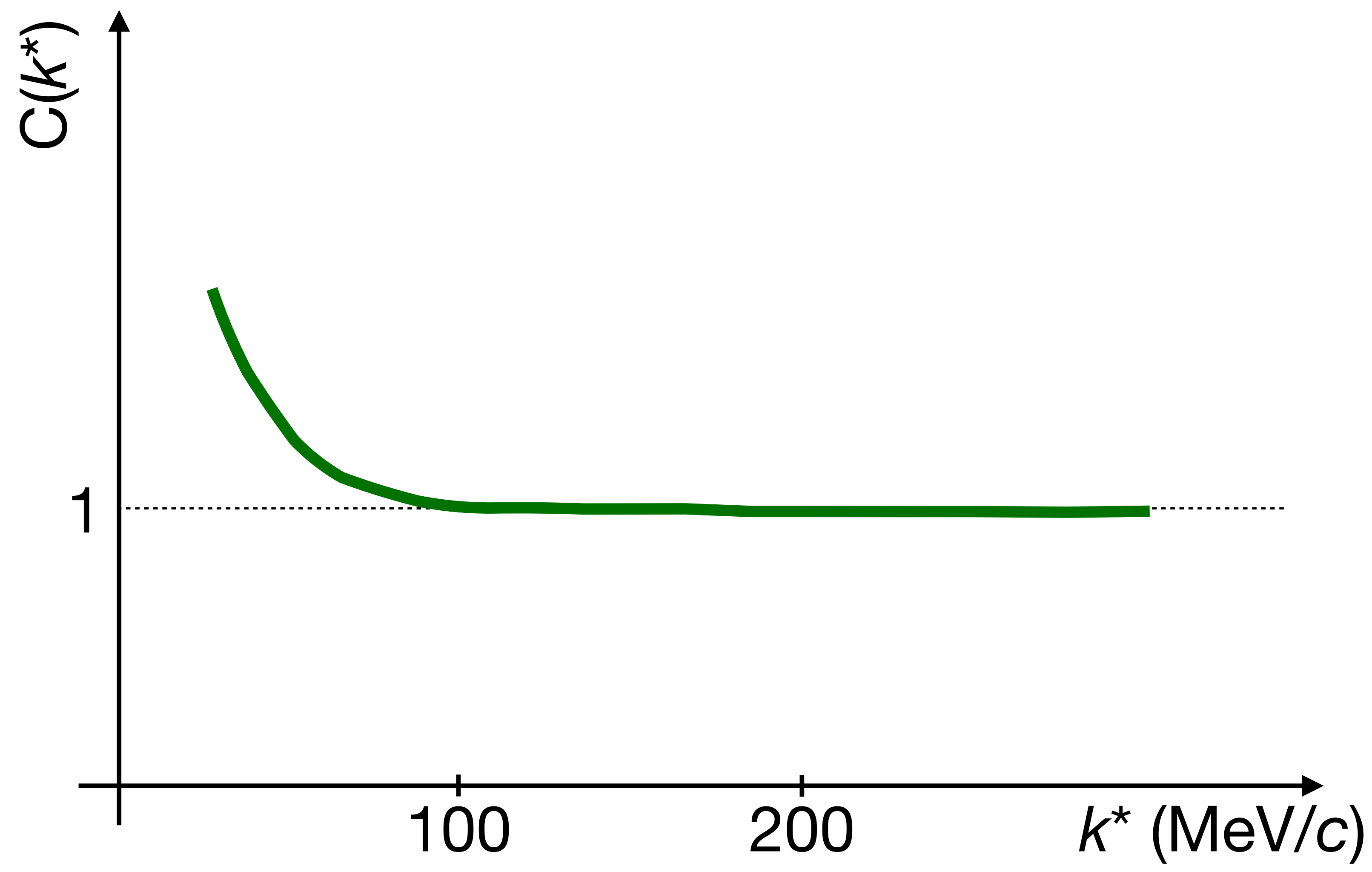
  - Repulsive interaction: C(k*) < 1
  - Attractive interaction: C(k*) > 1

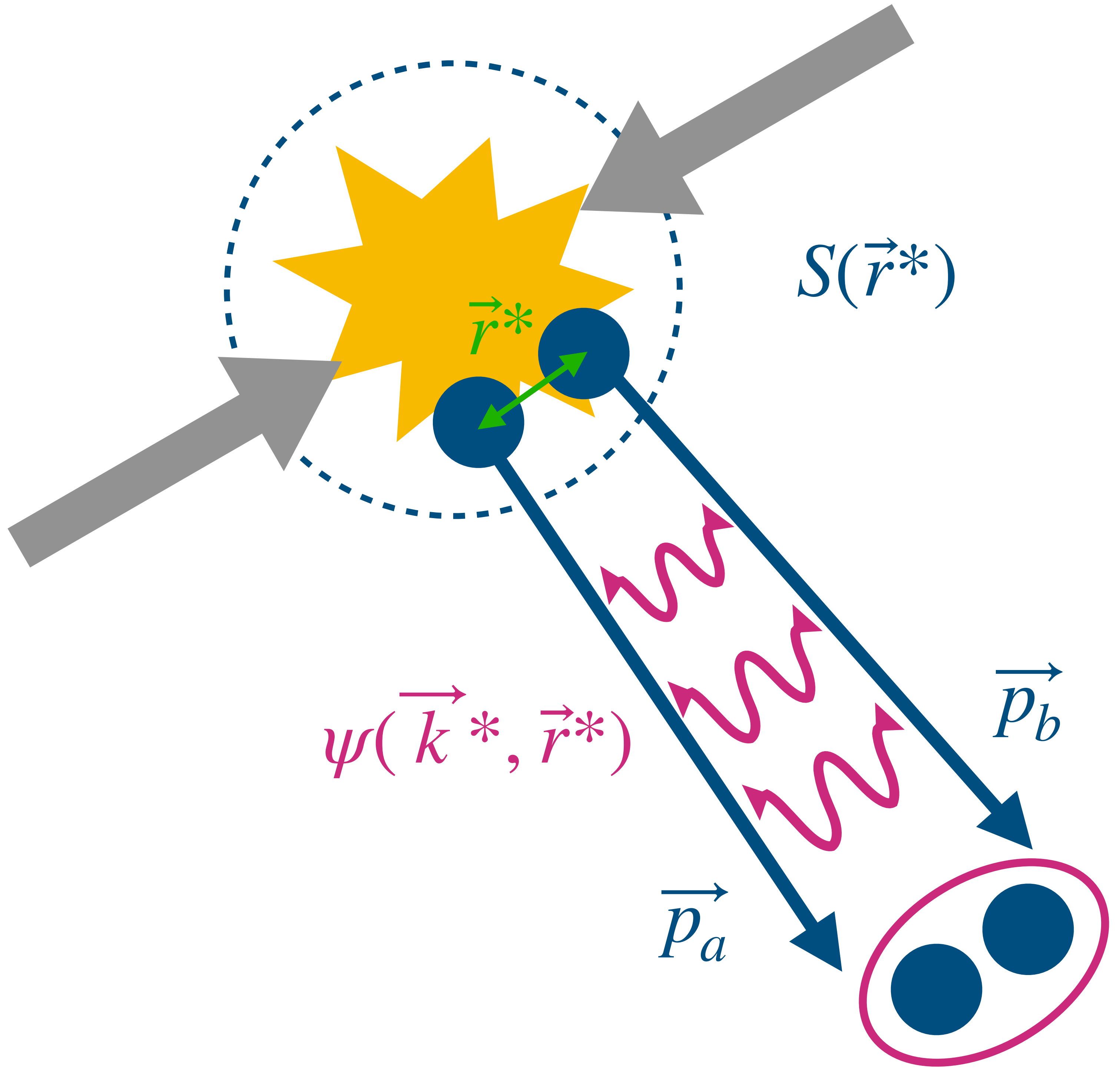


$$C(k^*) = \int S(\vec{r}^*) |\psi(\vec{k}^*, \vec{r}^*)|^2 d^3r^* = \mathcal{N} \frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)} > 1$$



The correlation function

- The **correlation function** reflects the interaction:
  - Absence of interaction: C(k*) = 1
  - Repulsive interaction: C(k*) < 1
  - Attractive interaction: C(k*) > 1
  - Bound state: C(k*) ≶ 1



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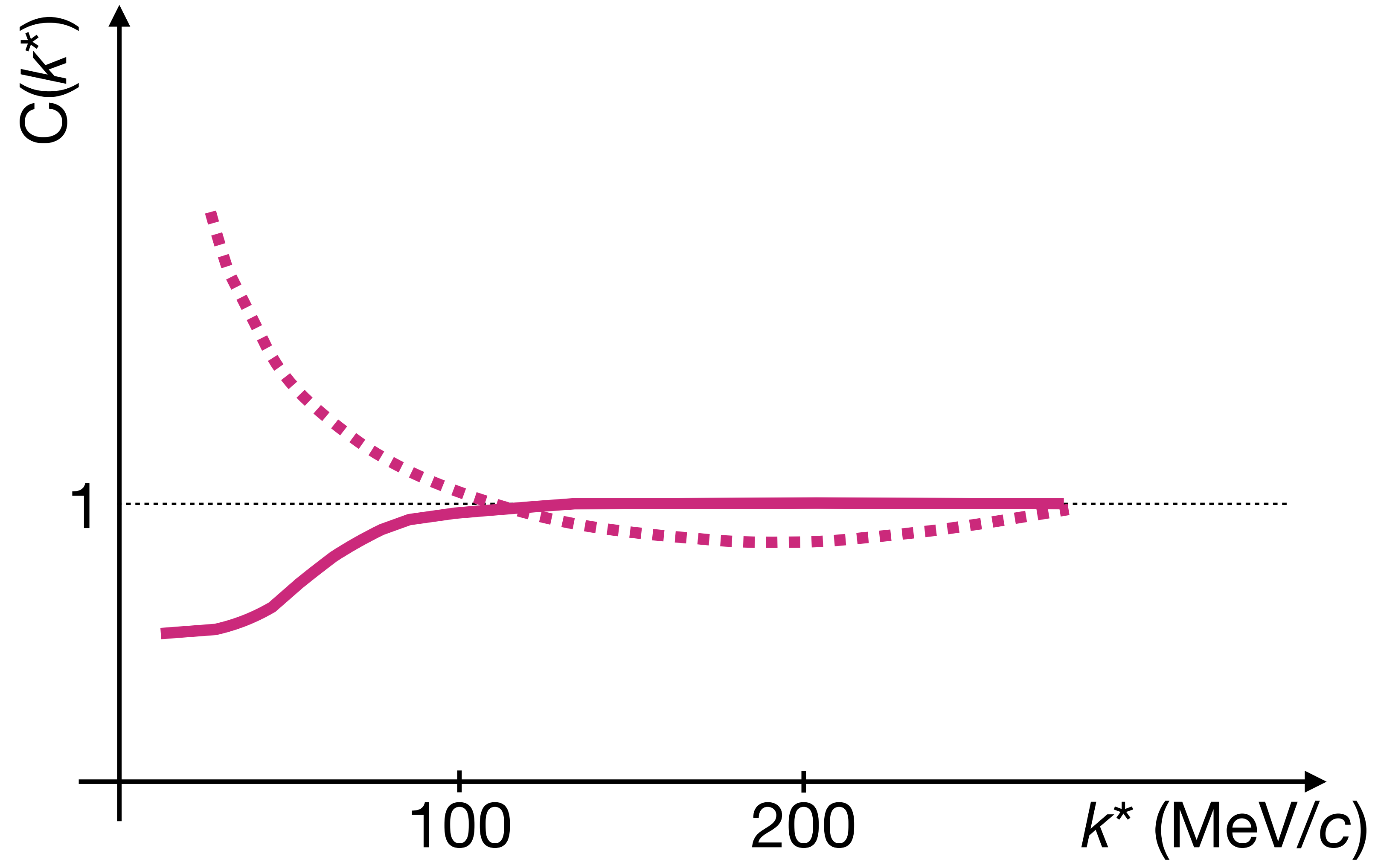
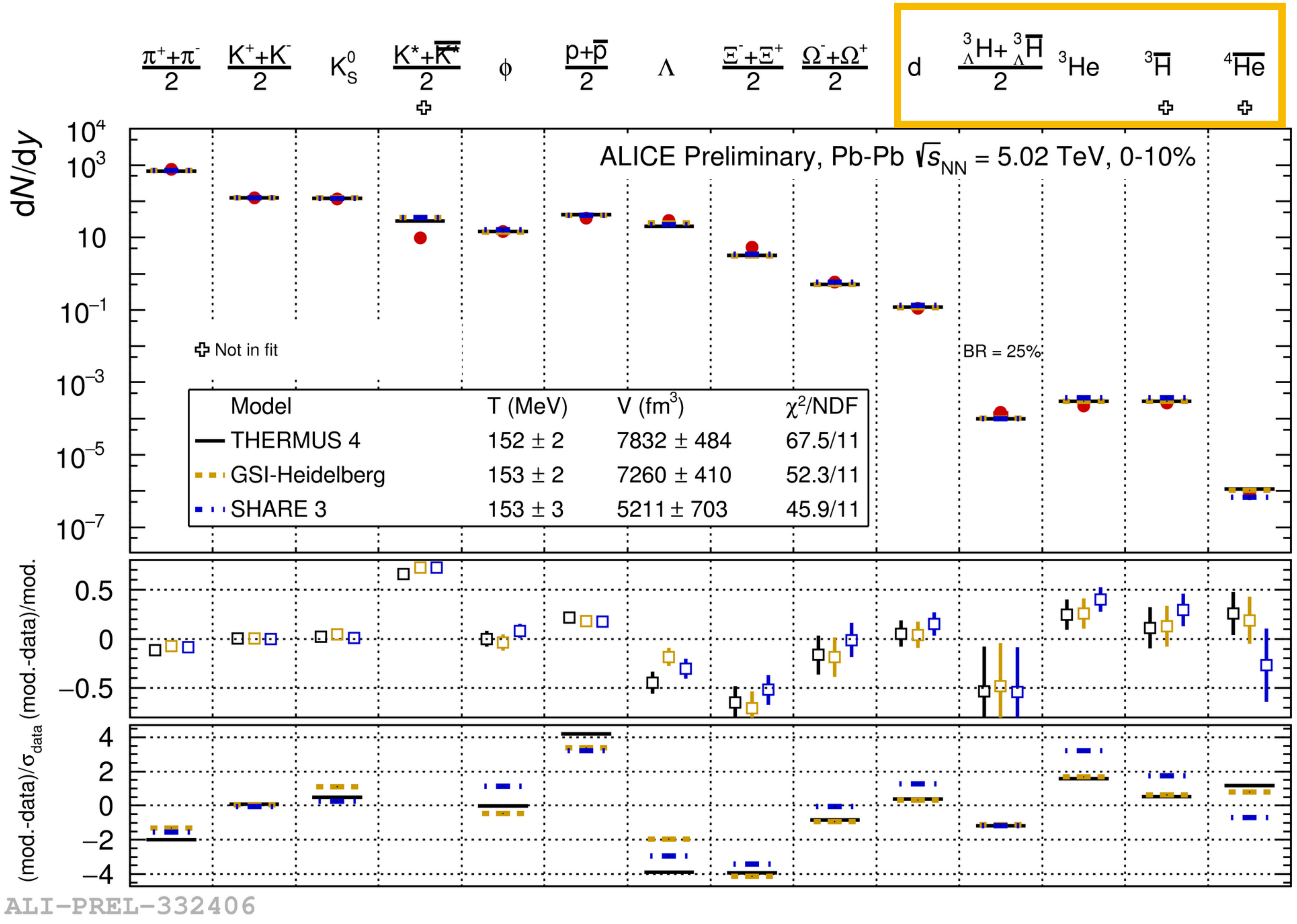


The Statistical Hadronisation Model (SHM)

- It assumes hadron abundances from **statistical equilibrium** at the **chemical freeze-out**
- The chemical freeze-out temperature (***T***) is a key parameter:

$$\mathrm{d}N/\mathrm{d}y \propto \exp(-\frac{m}{T_{ch}})$$

- Large reaction volume ($VT^3 > 1$) in Pb-Pb collisions
  - **grand canonical ensemble**



THERMUS 4: Comput.Phys.Commun. 180 (2009) 84-106
GSI-Heidelberg: Nucl.Phys.A 772 (2006) 167-199
SHARE 3: Comput.Phys.Commun. 167 (2005) 229-251

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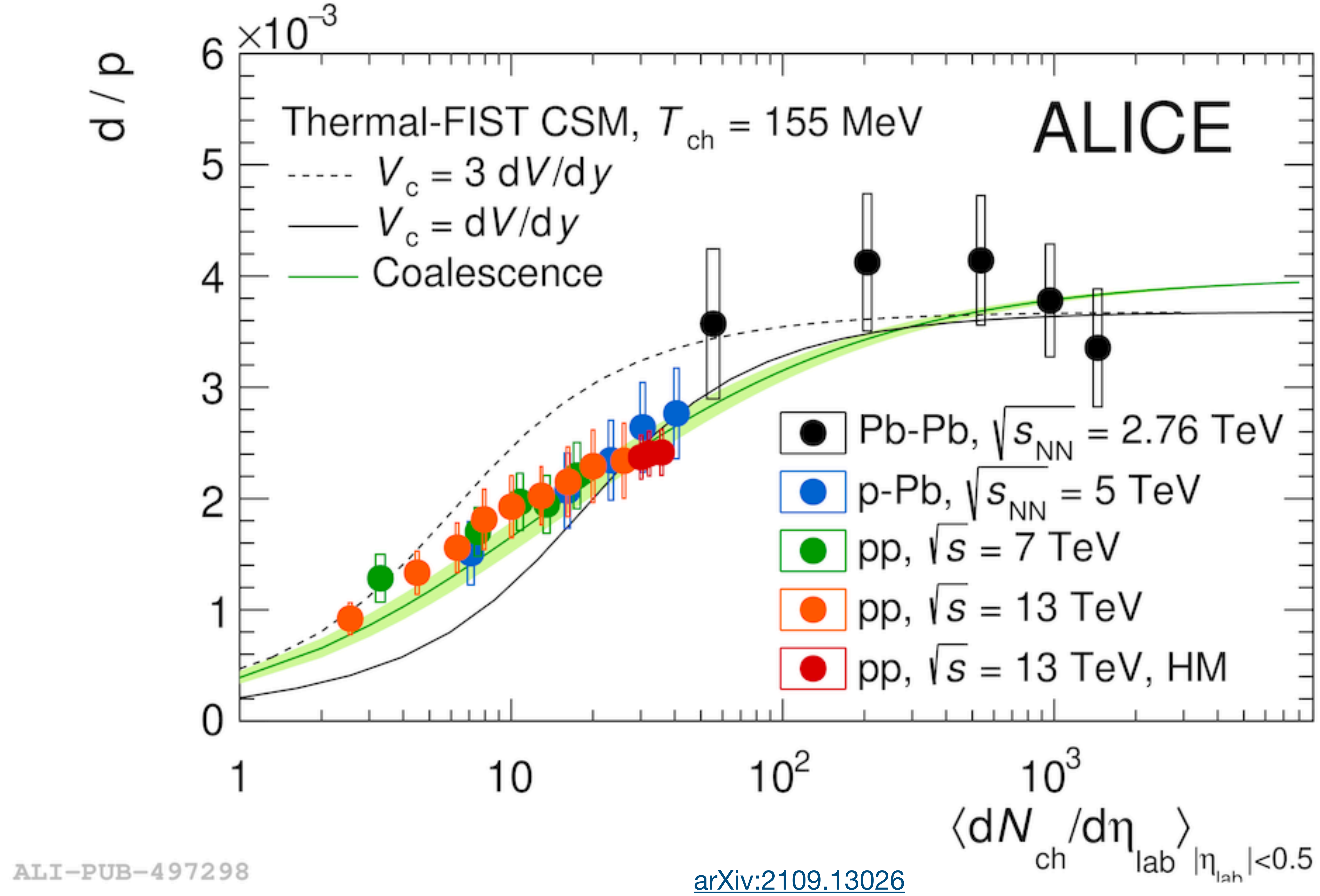
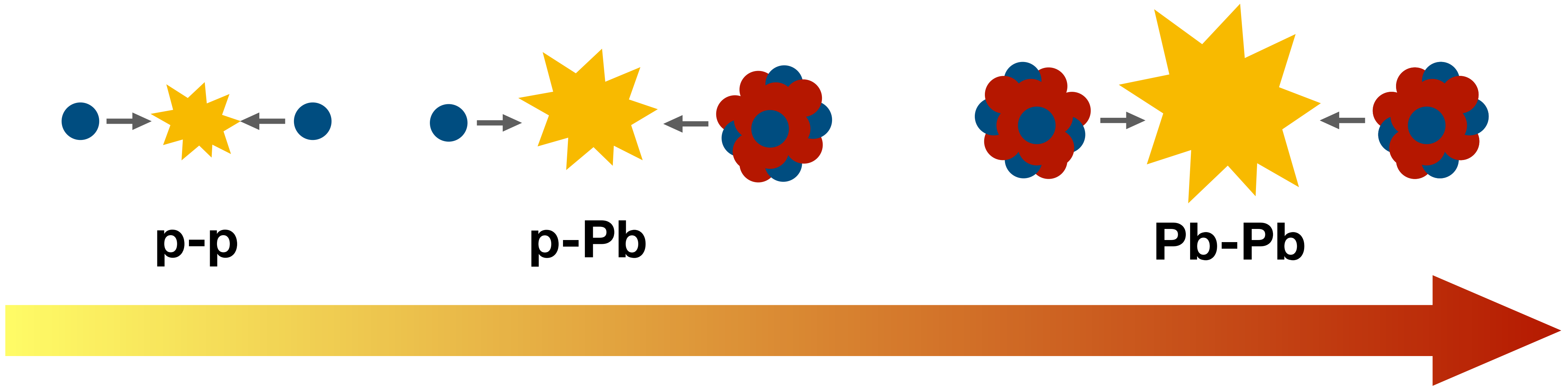
- In **small systems** ($VT^3 < 1$) a local conservation of quantum numbers (*S*, *Q* and *B*) is necessary
  - **canonical ensemble (CSM)**



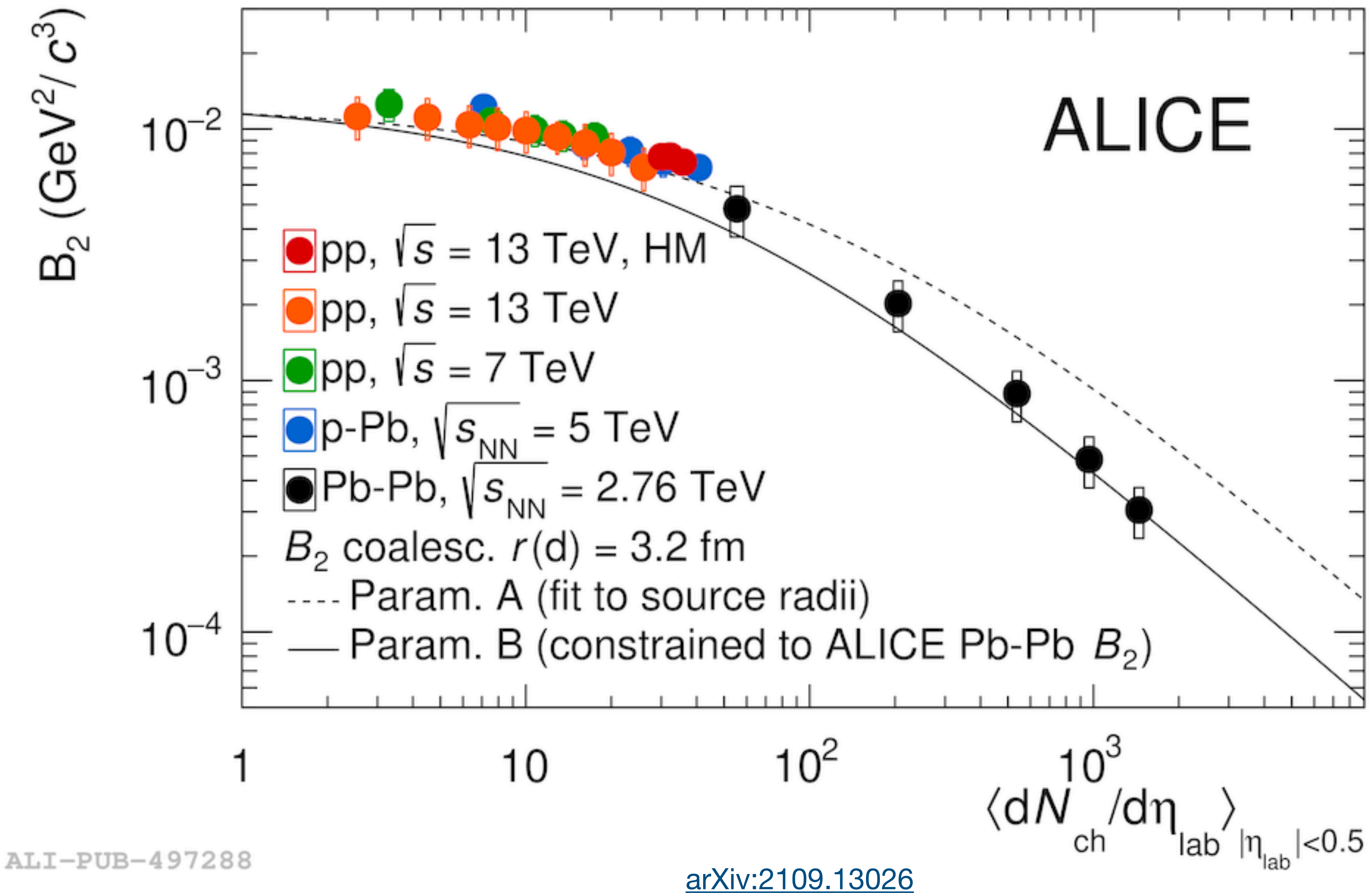
arXiv:2109.13026



The coalescence parameter B_A

- Measuring $\boldsymbol{B_A}$ as a function of $\mathbf{d}\boldsymbol{N_{ch}}/\mathbf{d}\boldsymbol{\eta}$ at fixed p_T it is possible to study the dependence on the **system volume**.
  - $V \propto \mathrm{d}N_{ch}/\mathrm{d}\eta$
- $\boldsymbol{B_A}$ evolves **smoothly** with **multiplicity**
  - **production mechanism depends only on the system size**

$$B_A = \frac{2J_A+1}{2^A\sqrt{A}}\frac{1}{m^{A-1}}\left[\frac{2\pi}{R^2(m_T)+\left(r_A/2\right)^2}\right]^{\frac{3}{2}(A-1)}$$



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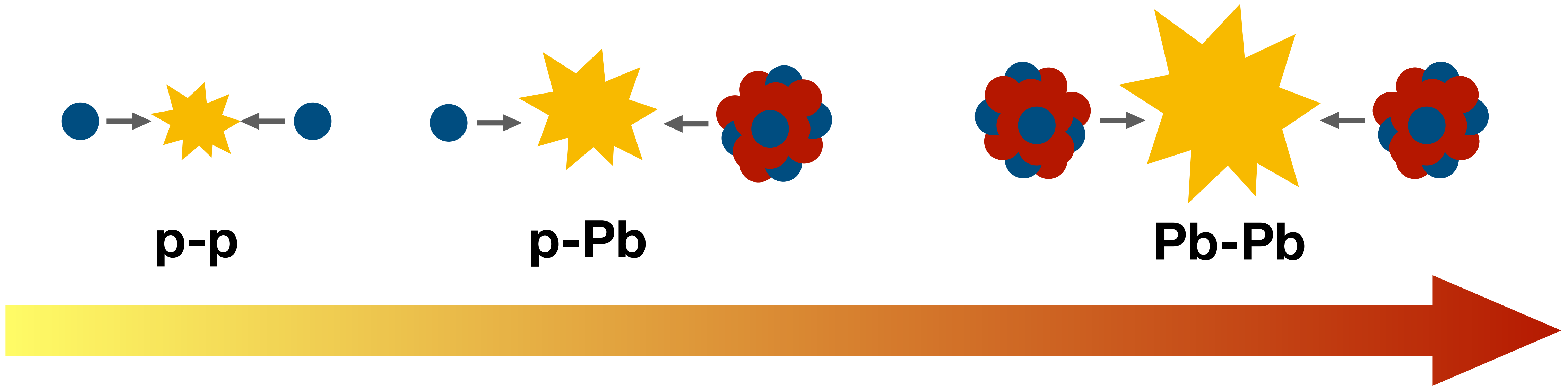

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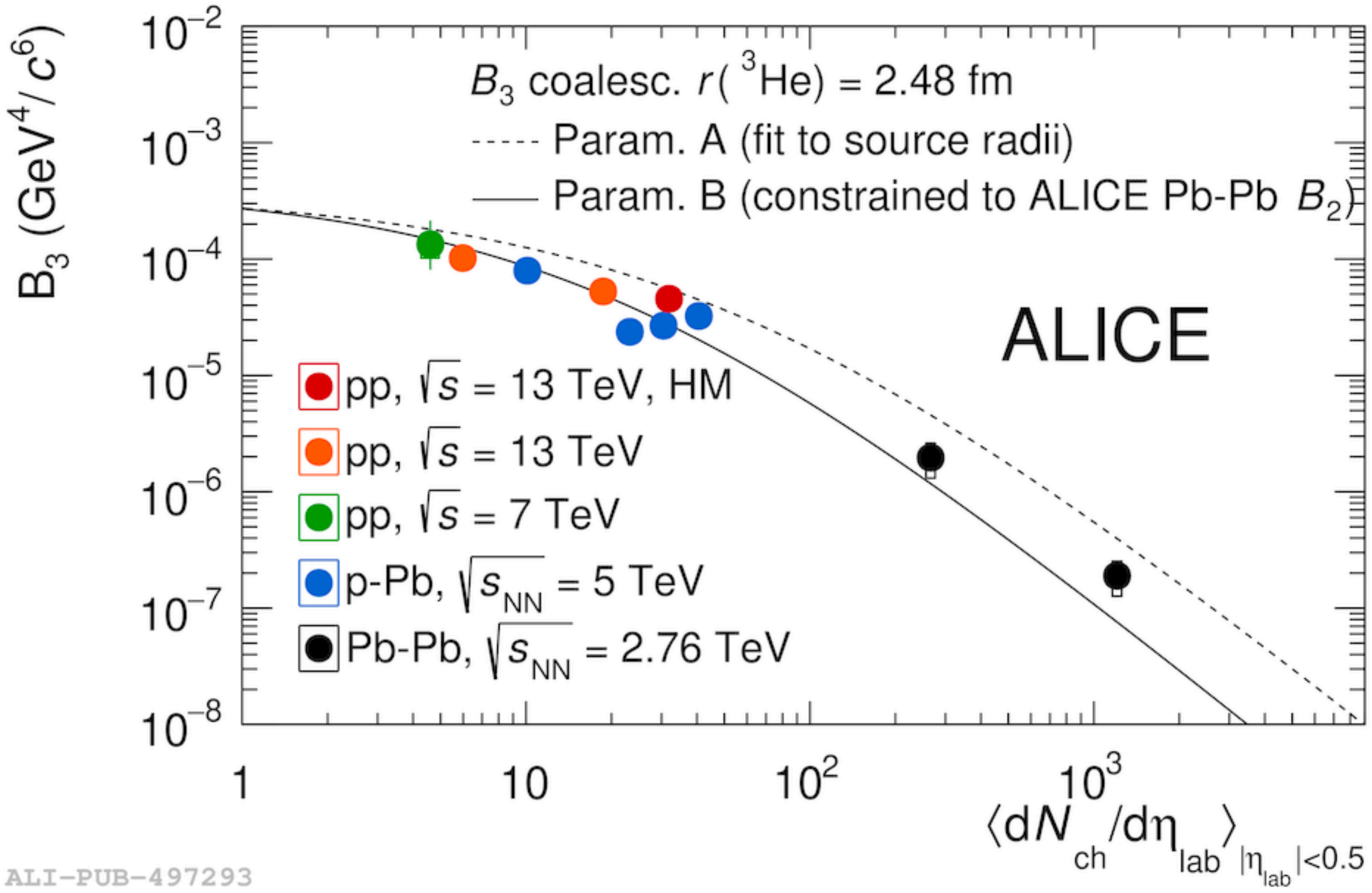

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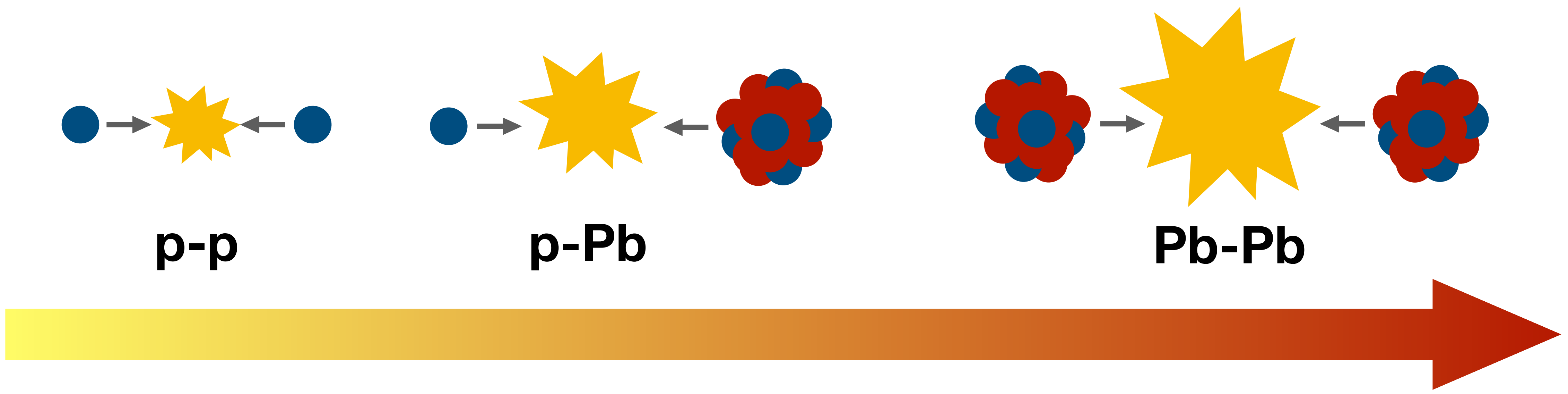
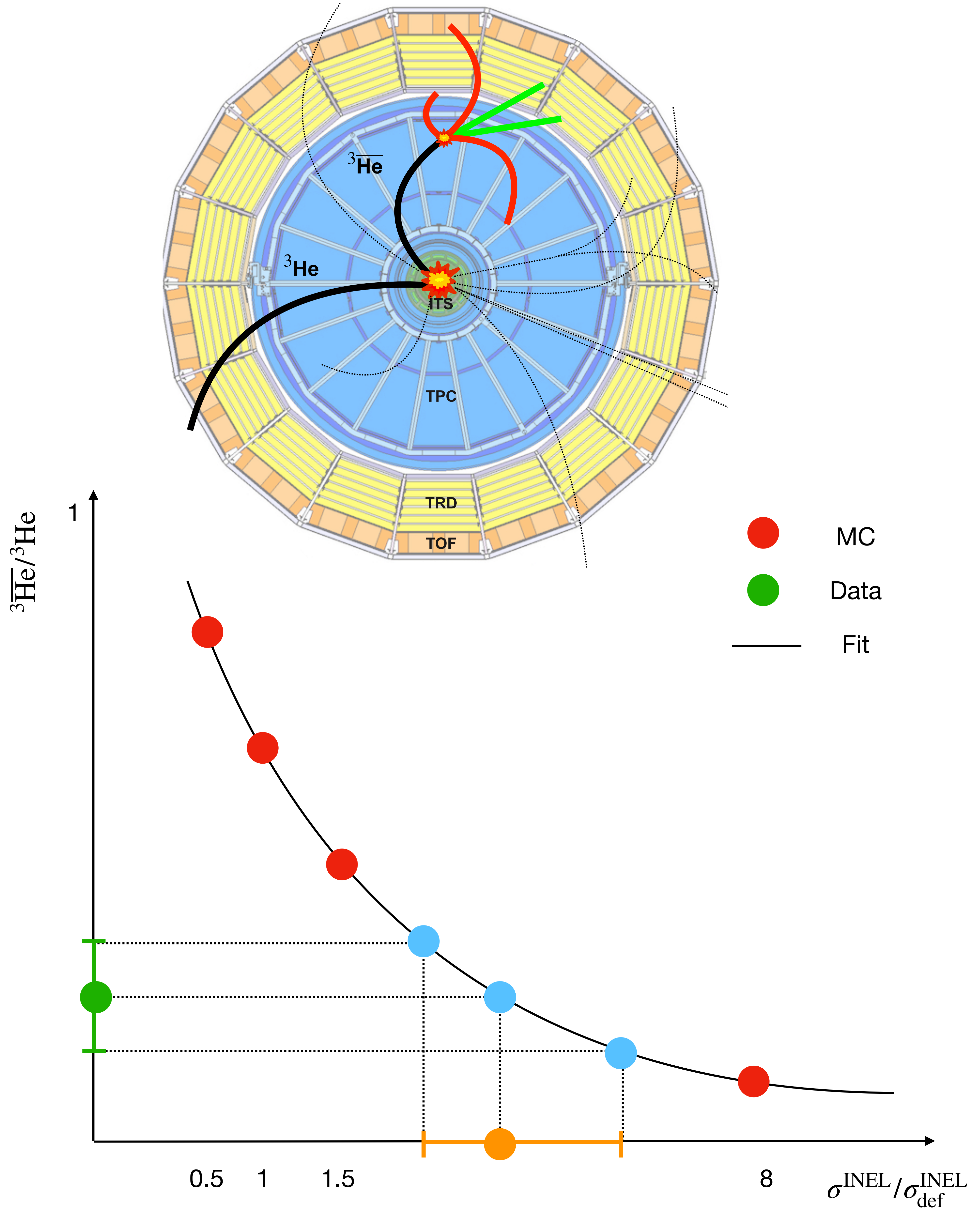


Inelastic cross section of antinuclei

- ALICE measured the **inelastic cross section** for antinuclei using the detector as a target
- Two approaches:
  1. measure the **reconstructed antimatter/matter** ratio and compare it with **MC**, in which **σ** is **varied**



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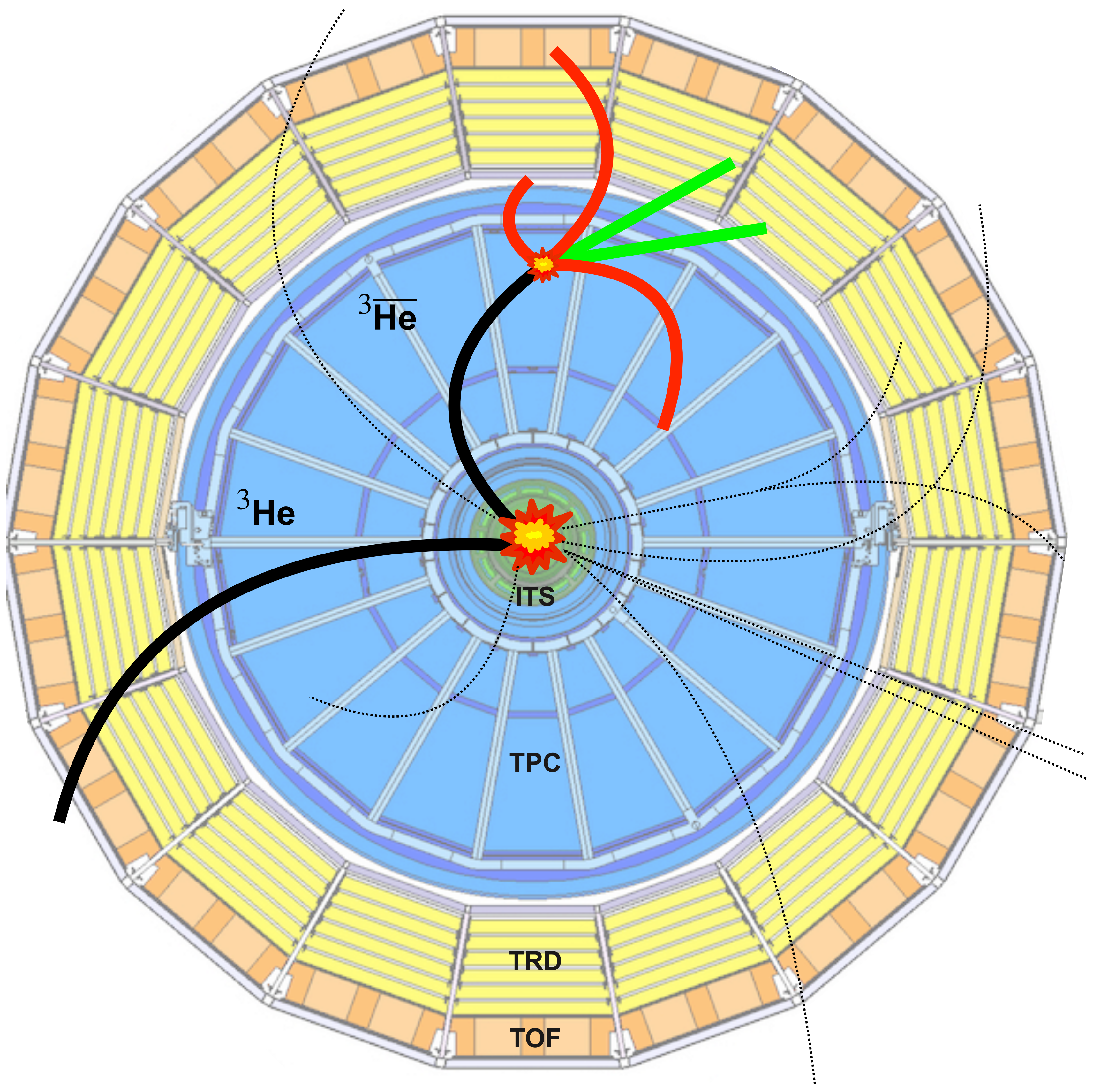
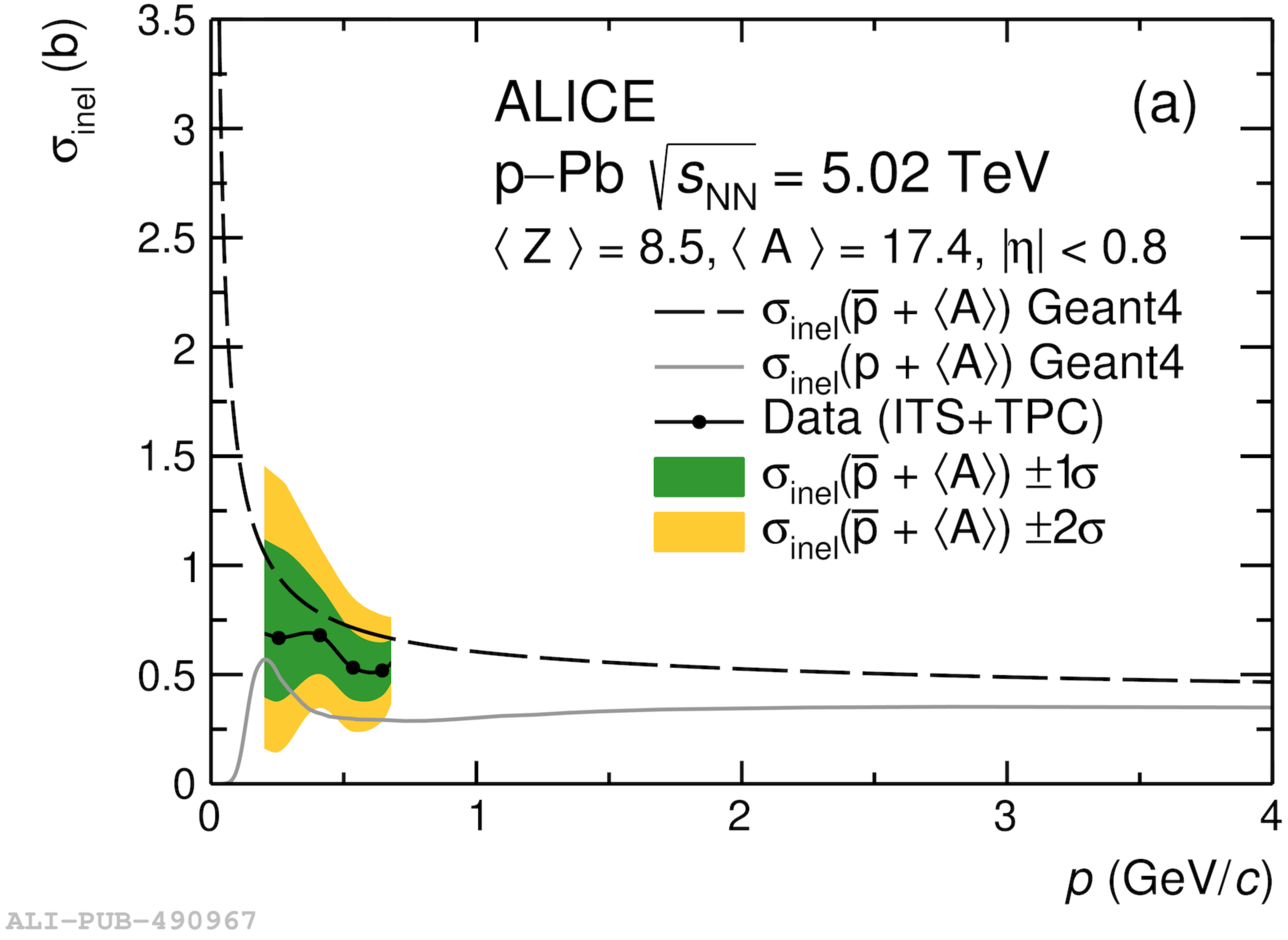
    2. measure the **TPC/TOF ratio** for antimatter and compare it with **MC**

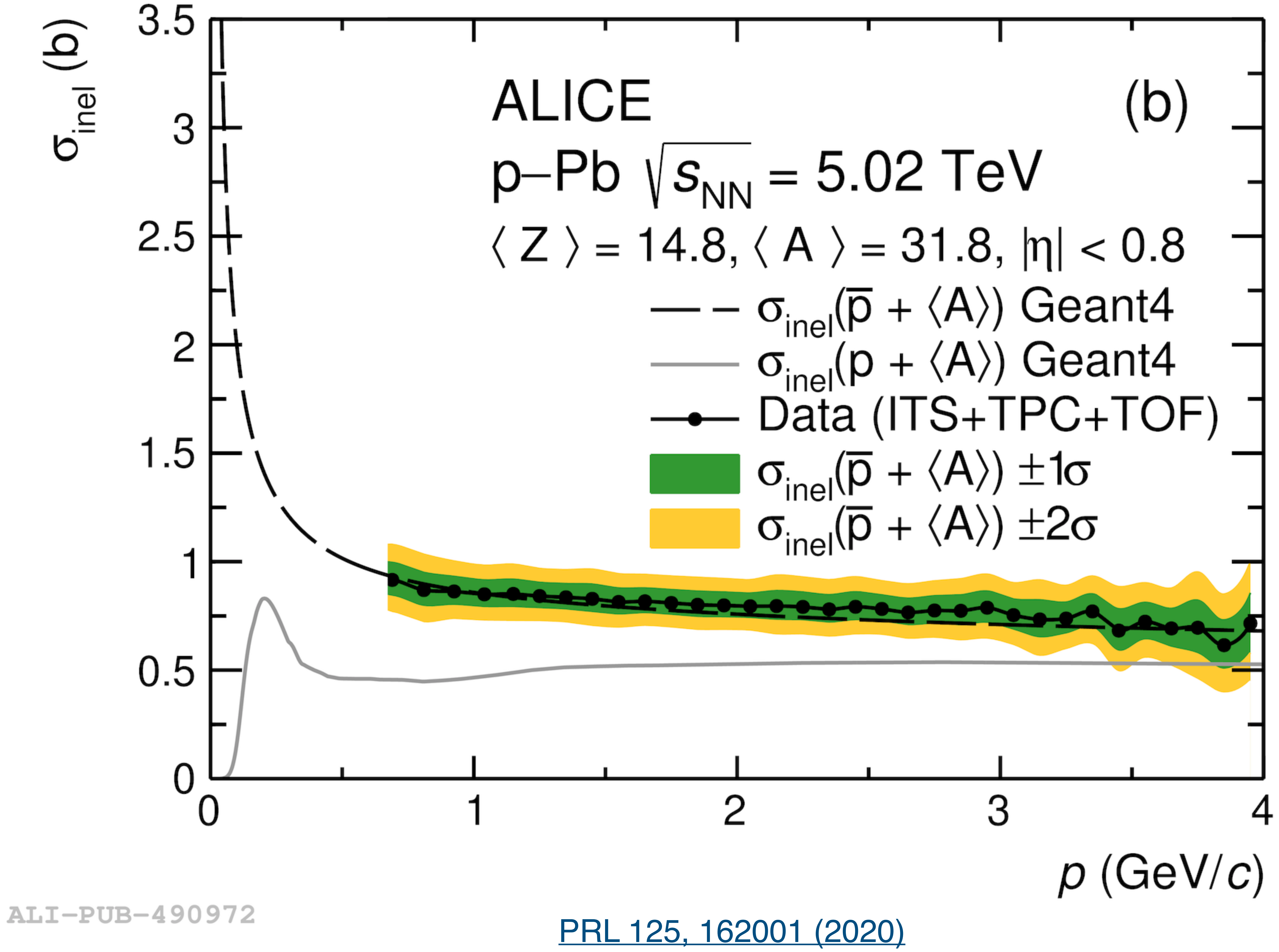
- The measurement was carried out for antiprotons, antideuterons and antihelions



Antiprotons and antideuterons

- Cross section have been measured for different species:
  - **Antiprotons**: good agreement with GEANT4





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