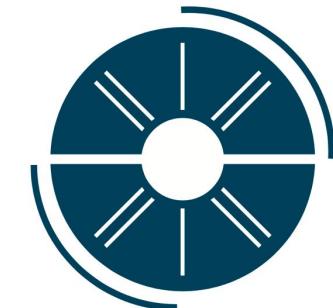


# Study of the dynamics of the production of light nuclei in small systems with ALICE



European Research Council  
Established by the European Commission

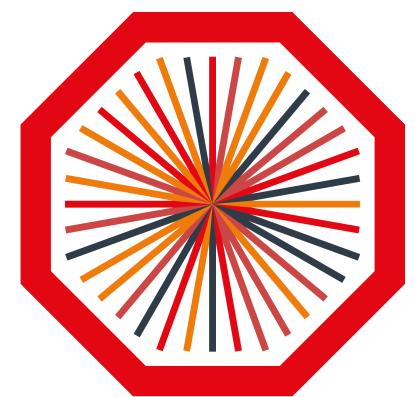


CosmicAntiNuclei

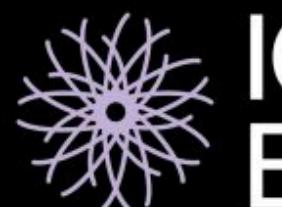
**Luca Barioglio**

Technische Universität München

on behalf of the **ALICE Collaboration**



ALICE



ICHEP 2022  
BOLOGNA



ICHEP 2022

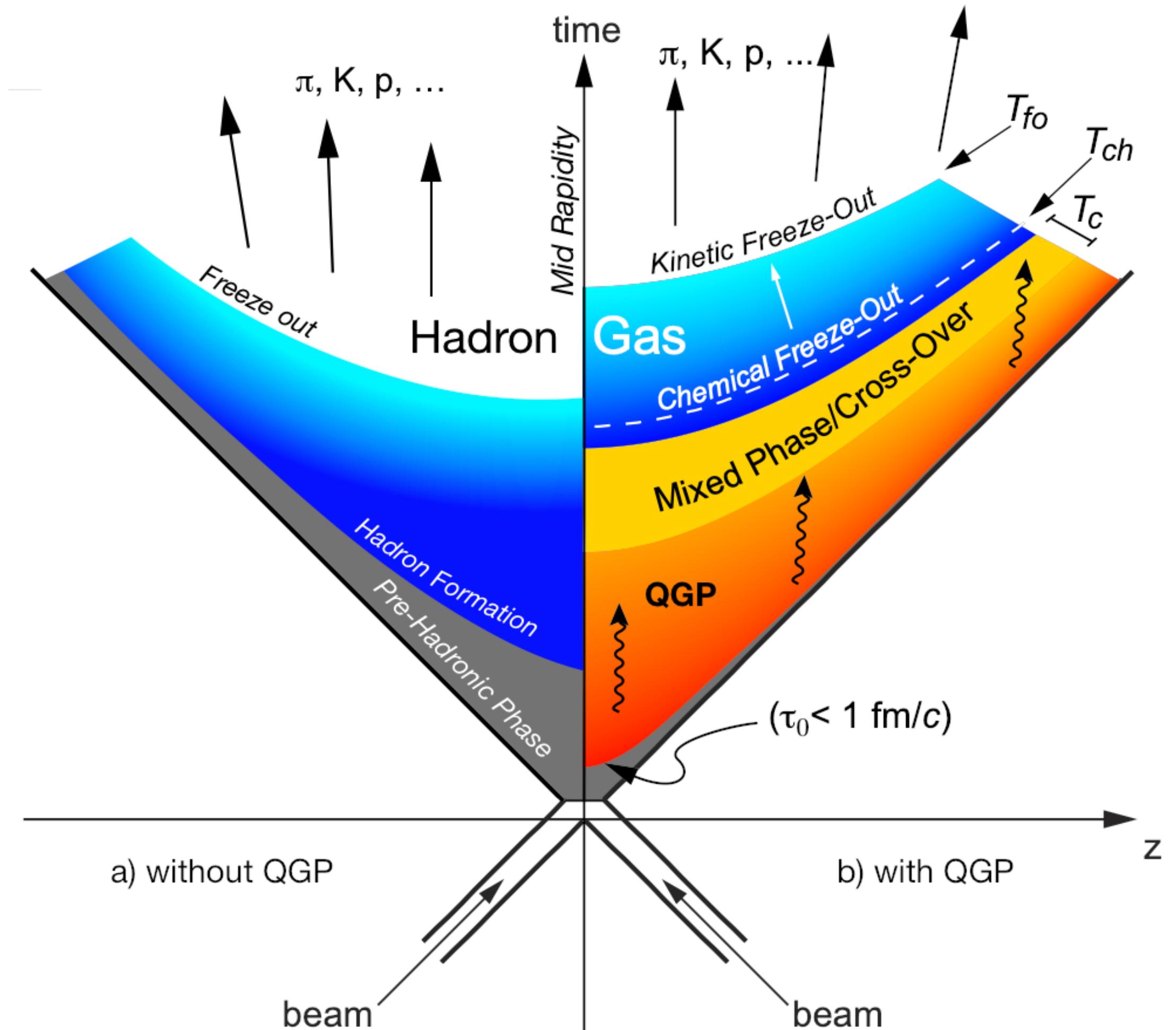
XLI

International Conference  
on High Energy Physics  
Bologna (Italy)

6  
13 07 2022

# Nuclear matter production

- Light (anti)(hyper)nuclei are abundantly produced at the LHC in hadronic collisions
- The **production mechanisms** of light (anti)nuclei in high-energy physics are still not completely understood
  - low binding energy ( $E_B \sim 1 \text{ MeV}$ ) with respect to the kinetic freeze-out temperature ( $T_{fo} \sim 100 \text{ MeV}$ )
- Two classes of models are available:
  - the **statistical hadronisation** model
  - the **coalescence** model

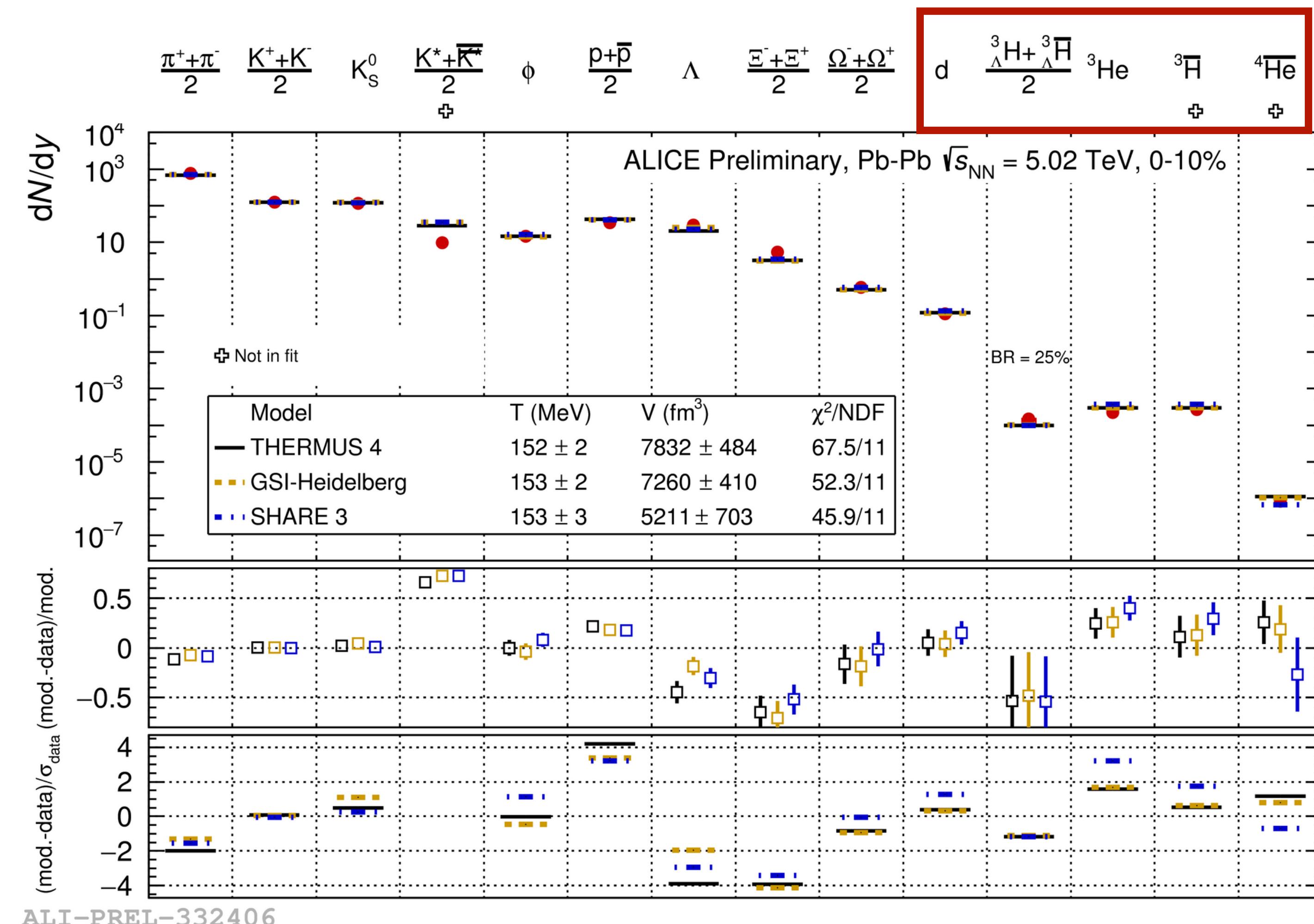


# The Statistical Hadronisation Model (SHM)

- It assumes hadron production from a system in **thermal** and **hadrochemical equilibrium** and that hadron **abundances** are fixed at **chemical freeze-out**

$$dN/dy \propto V \exp\left(-\frac{m}{T_{ch}}\right)$$

- Large reaction volume ( $VT^3 > 1$ ) in Pb-Pb collisions
  - **grand canonical ensemble**
- Production yields  **$dN/dy$**  in central Pb-Pb collisions described over a wide range of  $dN/dy$  (**9 orders of magnitude**), including nuclei
- In **small systems** ( $VT^3 < 1$ ) a local conservation of quantum numbers ( $S$ ,  $Q$  and  $B$ ) is necessary
  - **canonical ensemble (CSM)**



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](#)

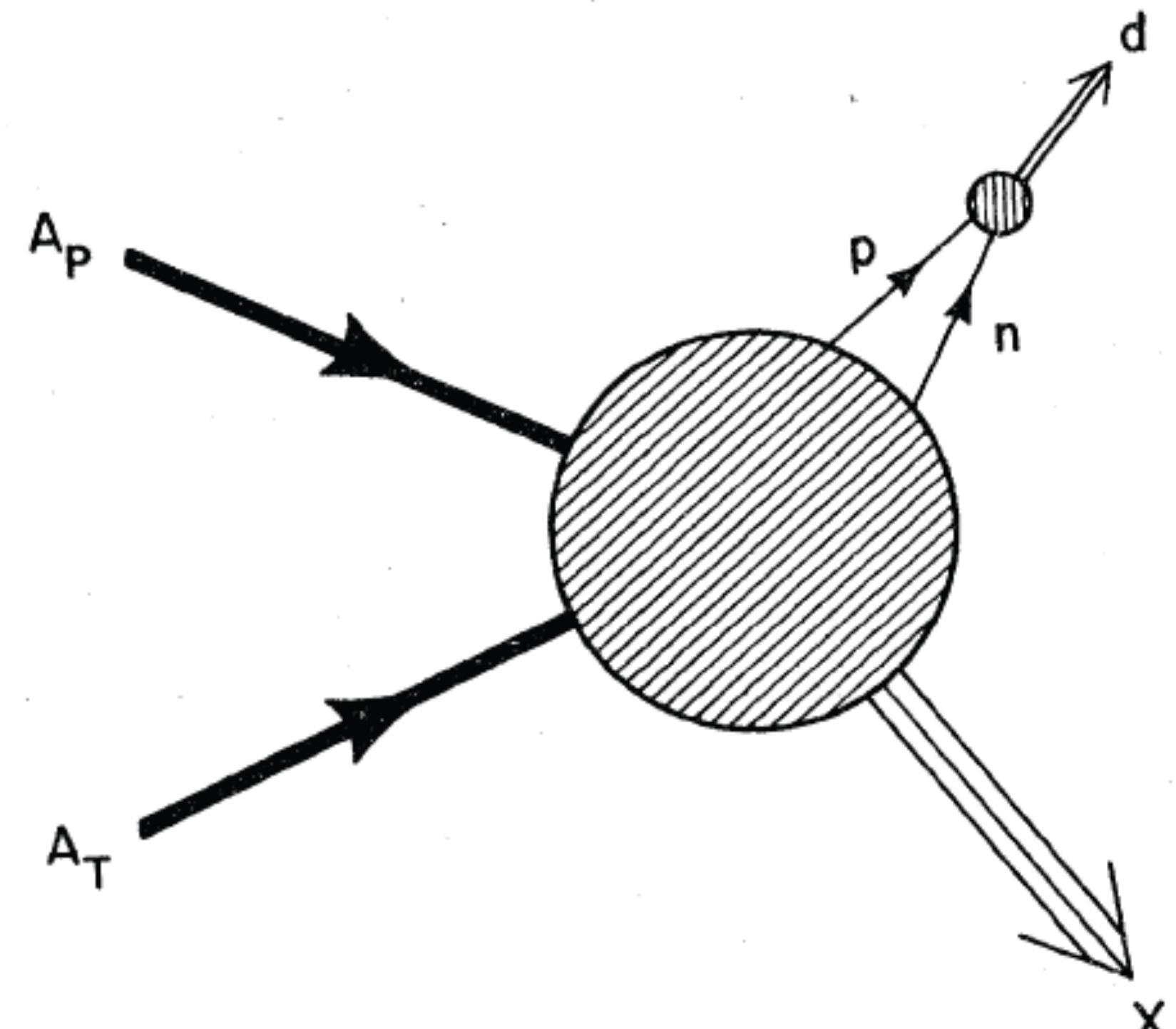
# The coalescence model

- Nucleons that are **close in phase space** at the **freeze-out** can form a nucleus via **coalescence**
- The key concept is the overlap between the **nuclear wave-function** and the **phase space** distribution of the **nucleons**
- The main parameter of the model is:

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

where:

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



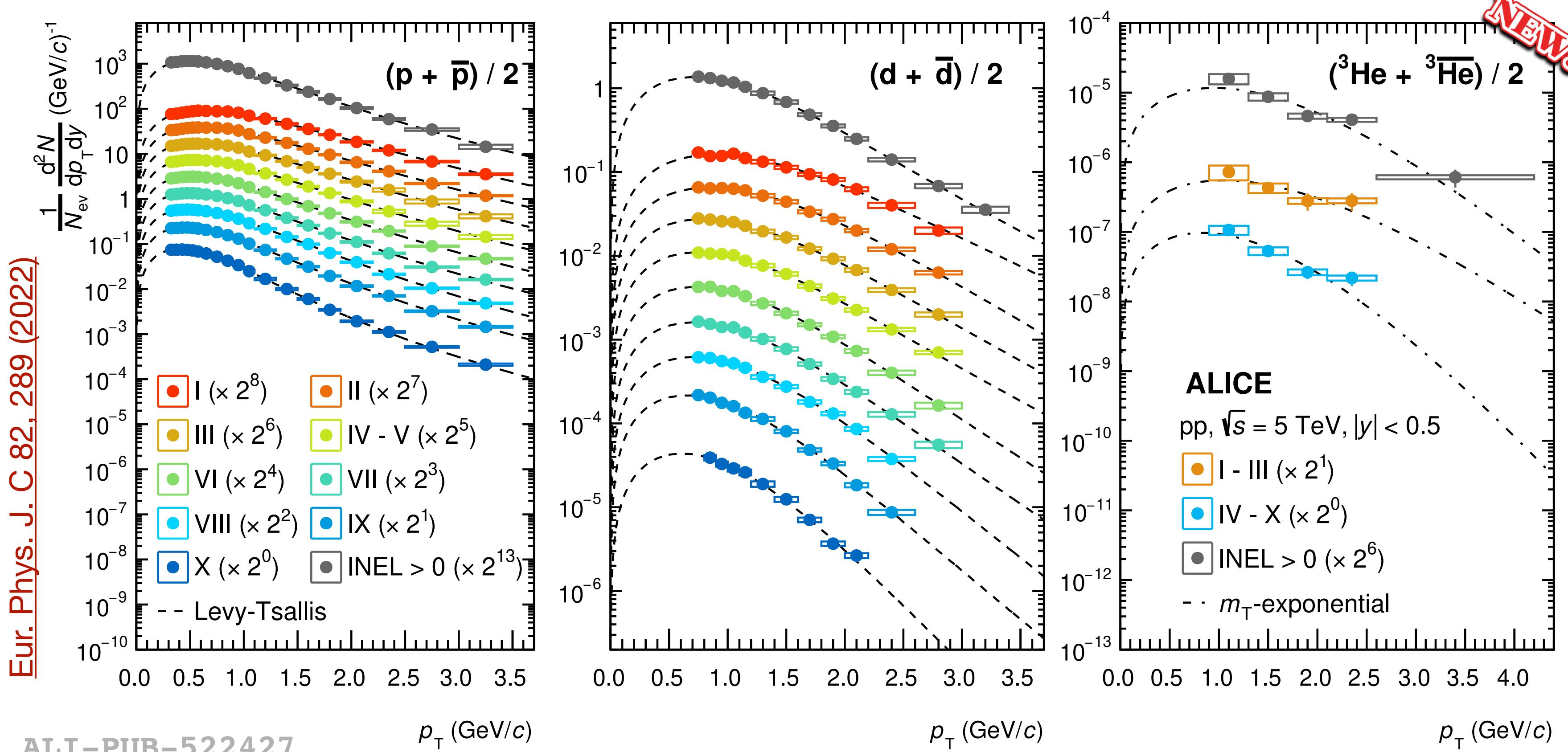
[J. I. Kapusta, PRC 21 \(1980\) 1301](#)

[F. Bellini et al., PRC 103, 014907](#)

- **$B_A$**  is related to the **probability** to form a nucleus via coalescence

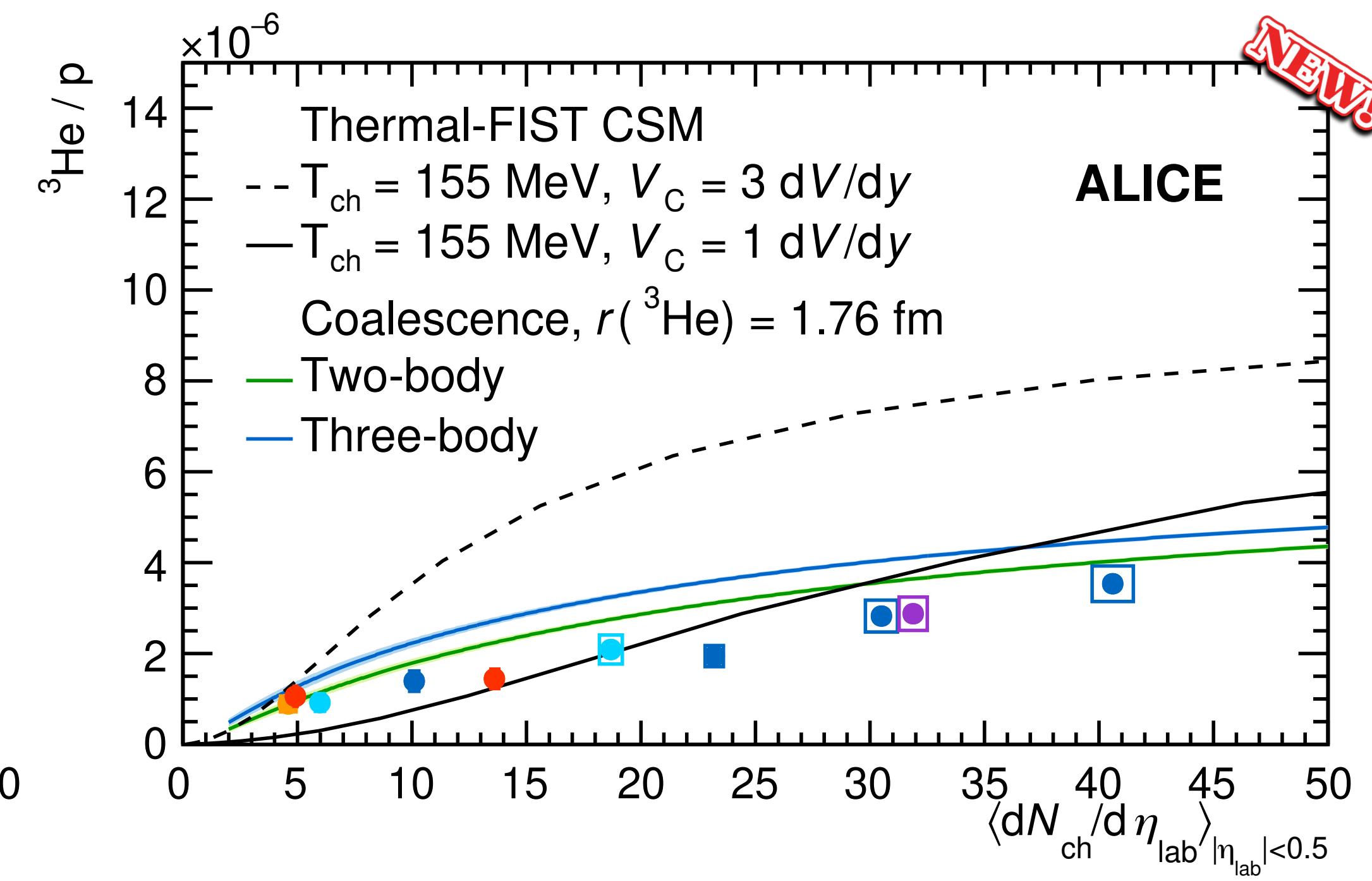
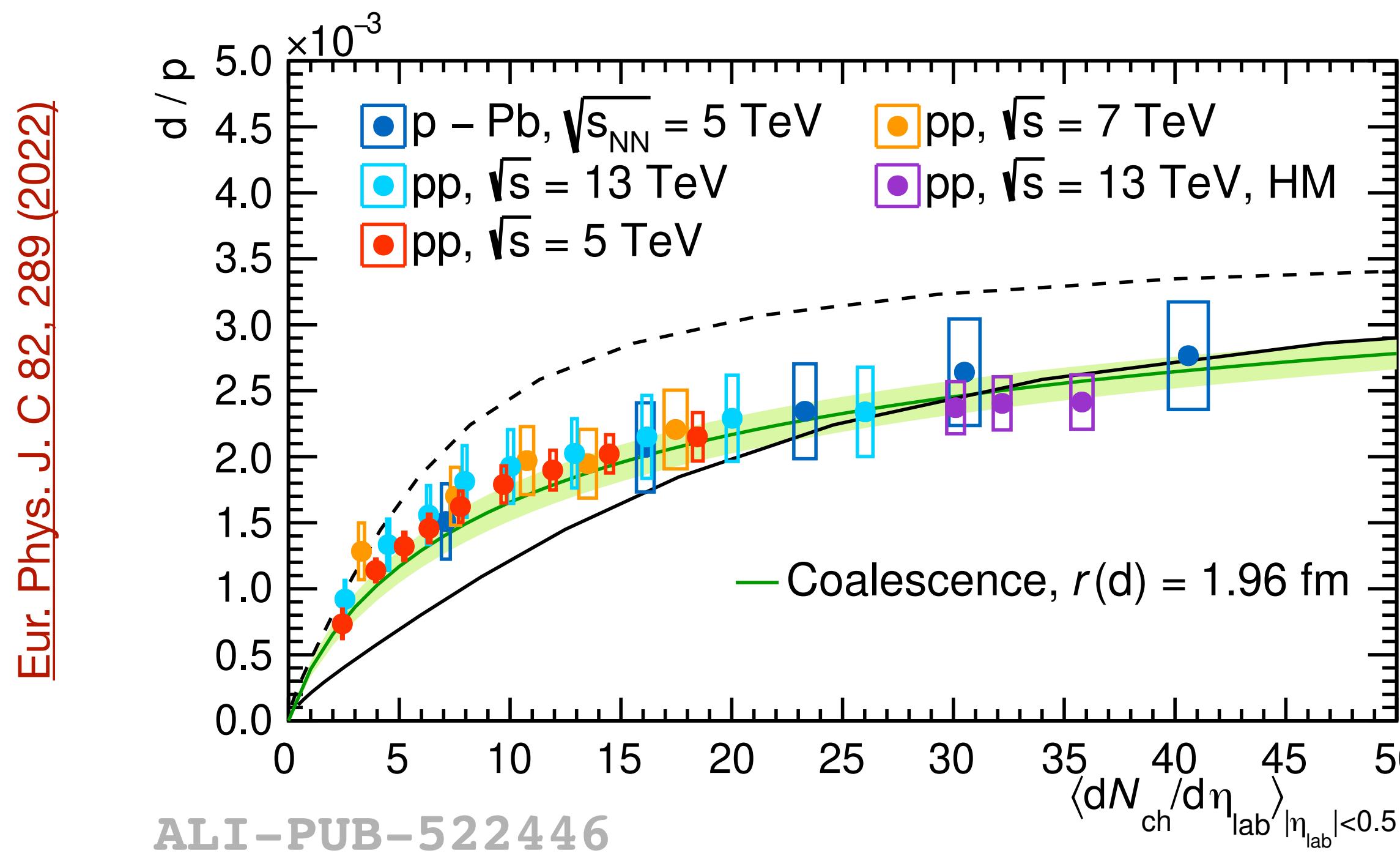
# Production spectra of nuclei with ALICE

- ALICE measured production spectra of nuclei in pp, p-Pb and Pb-Pb collisions
  - excellent PID
- Measurements in **classes** of **multiplicity**
  - related to **system size**

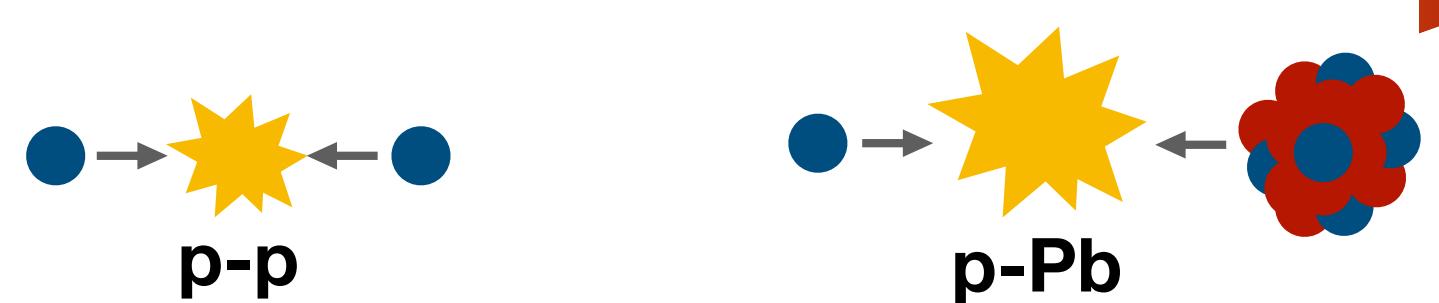


- Main observables:
  - Ratio of  $p_T$ -integrated yields **A/p**
  - Coalescence parameter **B<sub>A</sub>**

# Yield ratios

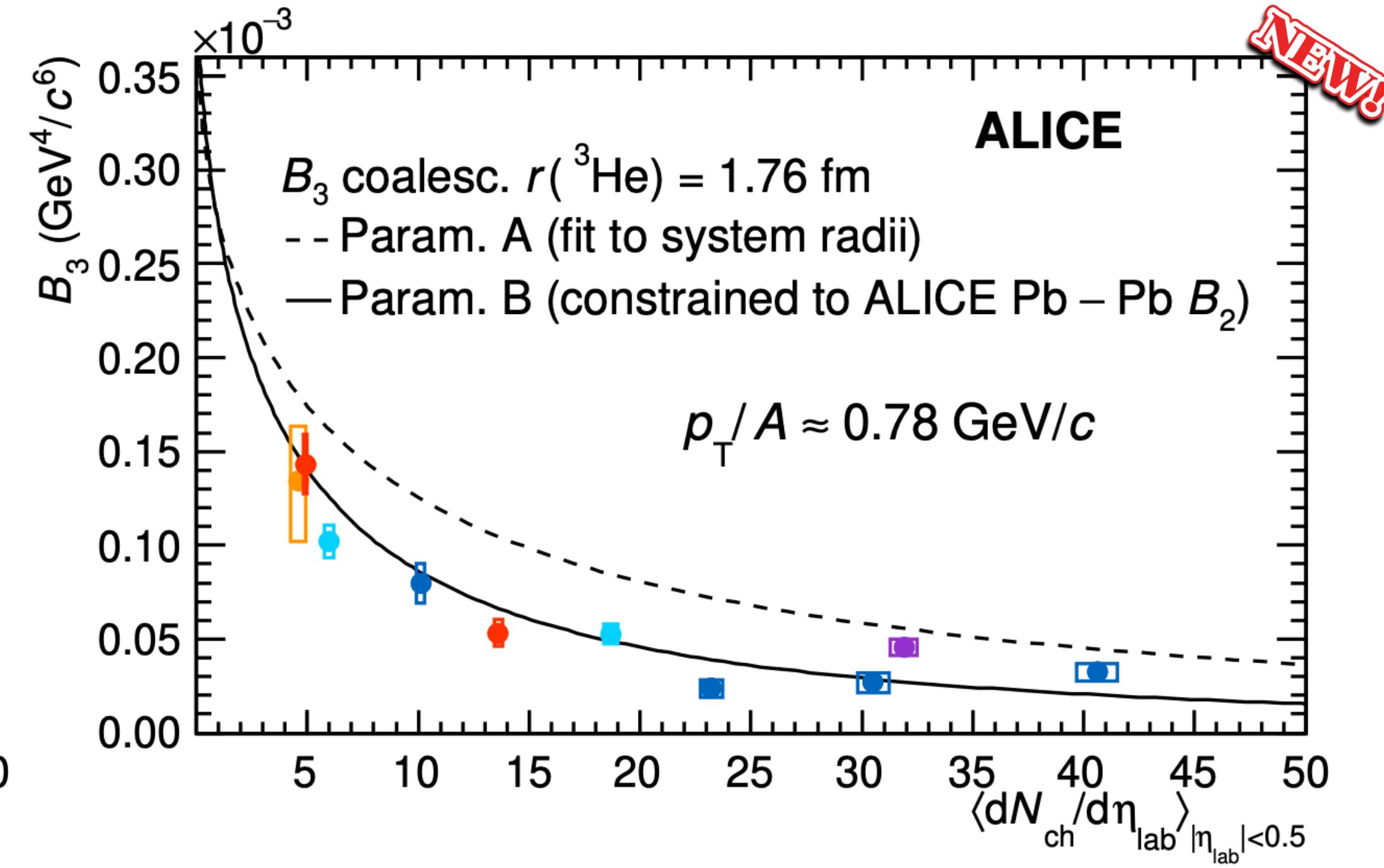
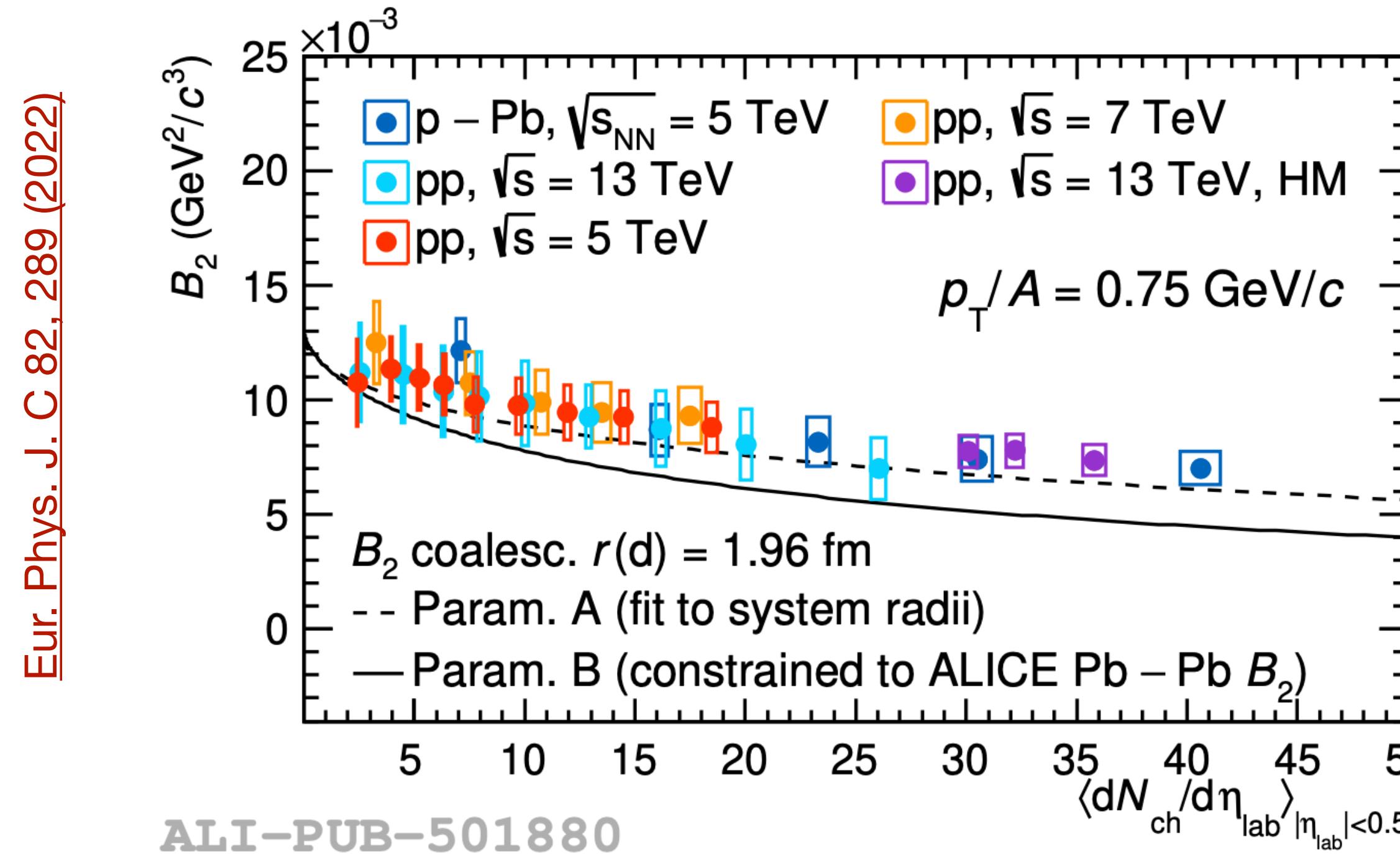


- **$d/p$**  and  **${}^3\text{He}/p$**  ratios evolve **smoothly** with **multiplicity**
  - dependence on the **system size**
- For  **$d/p$**  ratio both the models describe the data:
  - CSM: canonical suppression
  - Coalescence model: interplay between source size and nuclear size



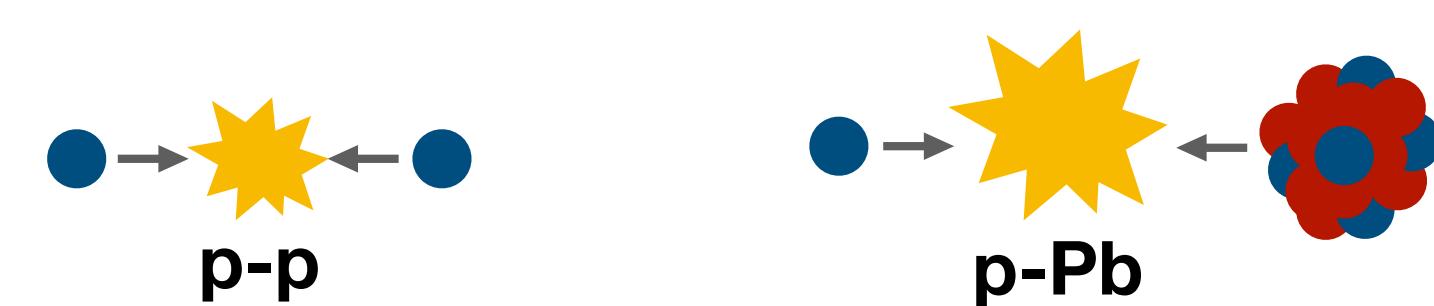
- For  **${}^3\text{He}/p$**  there are more tensions between data and models
- Not possible to discriminate between the two models

# Coalescence parameter $B_A$



- $B_A$  evolves **smoothly** with **multiplicity**
  - dependence on the **system size**
- Comparison with theory:

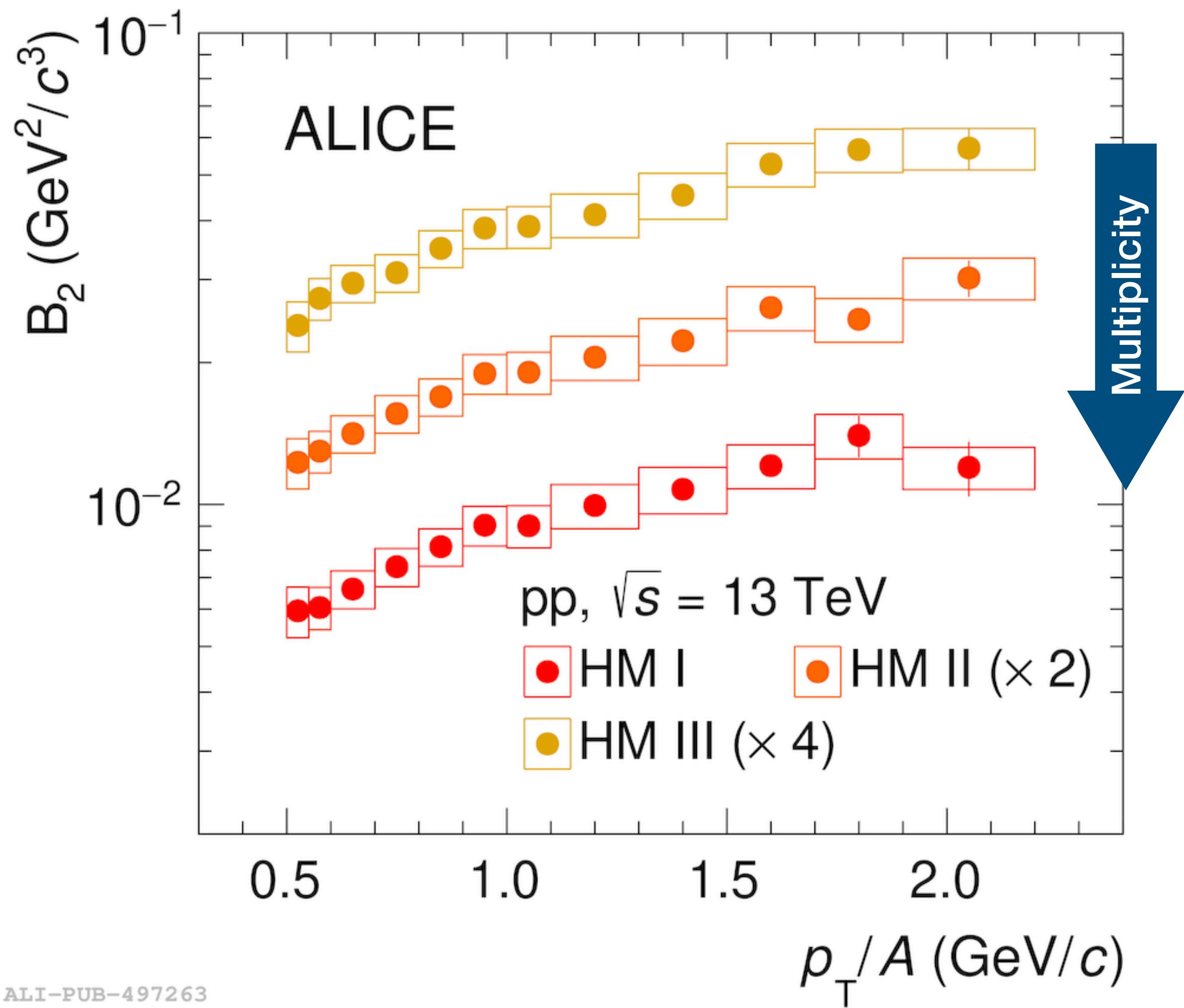
$$B_A = \frac{2J_A + 1}{2^A \sqrt{A}} \frac{1}{m^{A-1}} \left[ \frac{2\pi}{R^2(m_T) + (r_A/2)^2} \right]^{\frac{3}{2}(A-1)}$$



- **Two** different parameterisations for  $\langle dN/d\eta \rangle$  vs  $R$ 
  - None of them can describe simultaneously  $B_2$  and  $B_3$

# $B_A$ vs $p_T$ in HM pp collisions

- $B_2$  and  $B_3$  have been measured in **HM pp** collisions
- In the same data sample also the **source size** has been measured with femtoscopy
  - ▶ comparison with **theoretical predictions** is possible



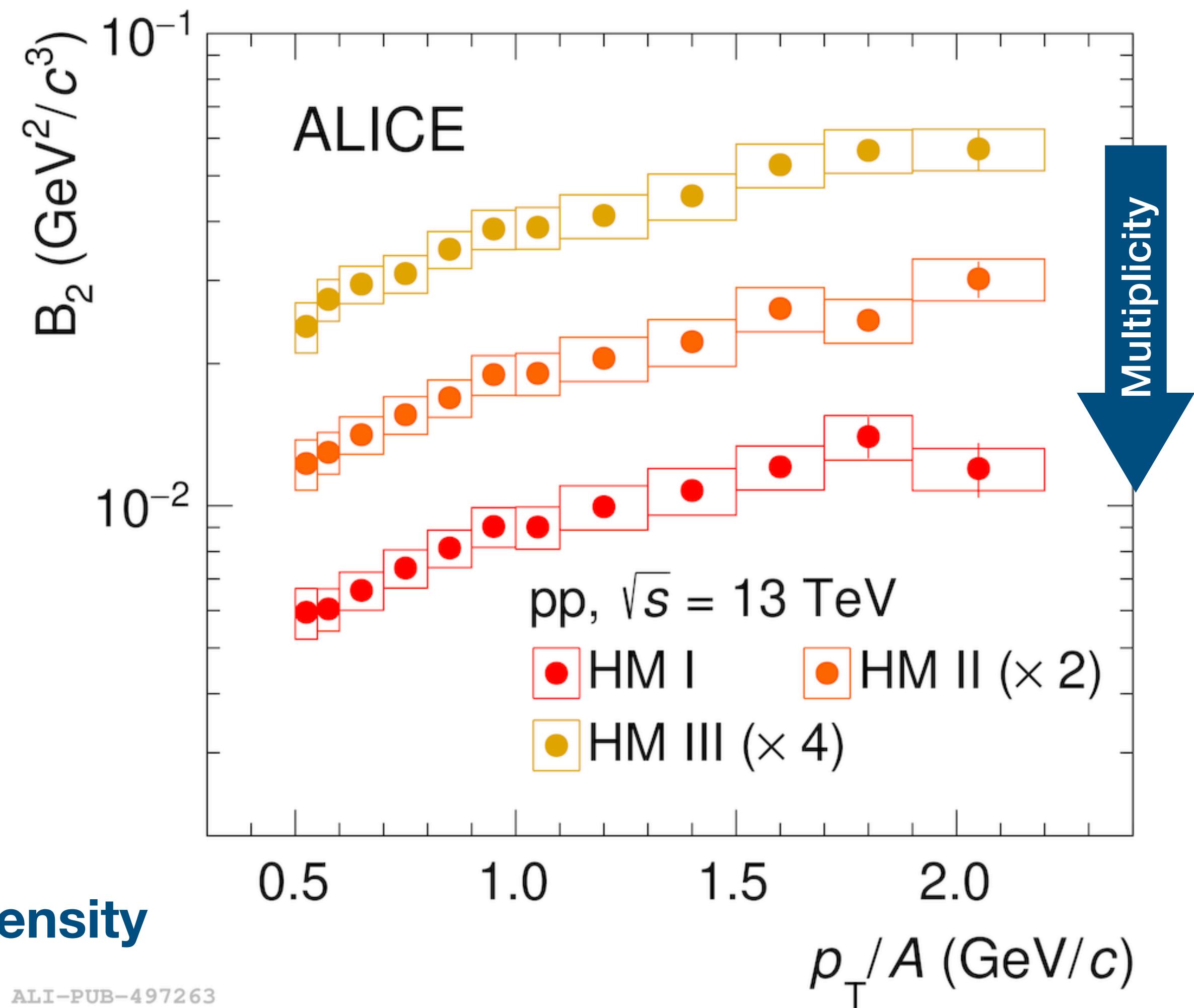
JHEP 01 (2022) 106

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

- ▶ The source size  $R$  is a function of the deuteron  $p_T$
- ▶  $D(\vec{q}) = \int d^3r |\phi_d(\vec{r})|^2 e^{-i\vec{q}\cdot\vec{r}}$  is the **deuteron density**
- $\phi_d(\vec{r})$  is the deuteron wave function



ALI-PUB-497263

[JHEP 01 \(2022\) 106](#)

[K. Blum et al., PRC 99 \(2019\) 044913](#)

# $B_2$ vs $p_T/A$

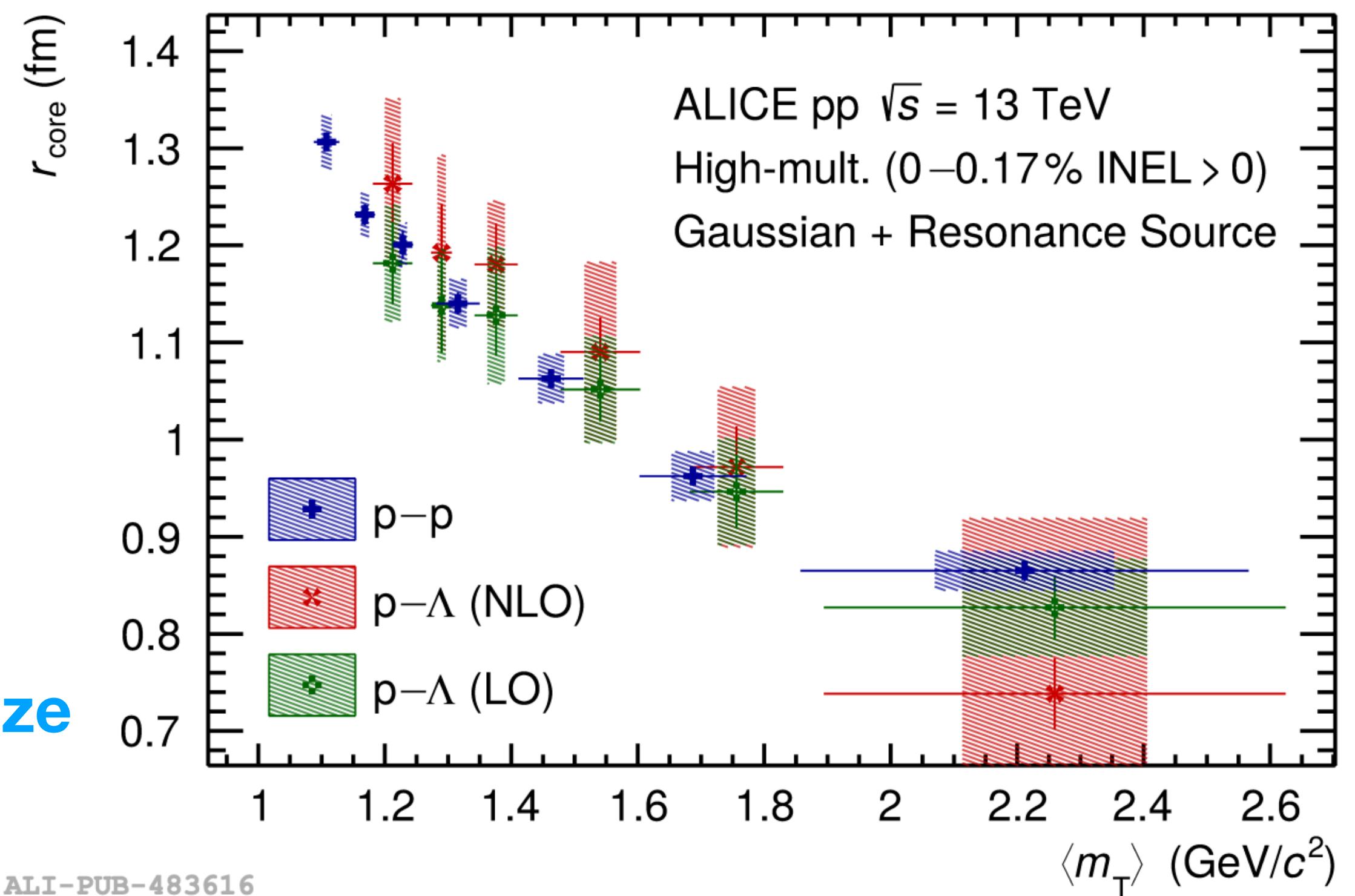
- Putting the pieces together:

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

$$D(\vec{q}) = \int d^3r |\phi_d(\vec{r})|^2 e^{-i\vec{q}\cdot\vec{r}}$$

- We can test different **wave functions**  $\phi_d(\vec{r})$
- We have the precise measurement of the **source size**

- No free parameters!**



PLB 811 (2020) 135849

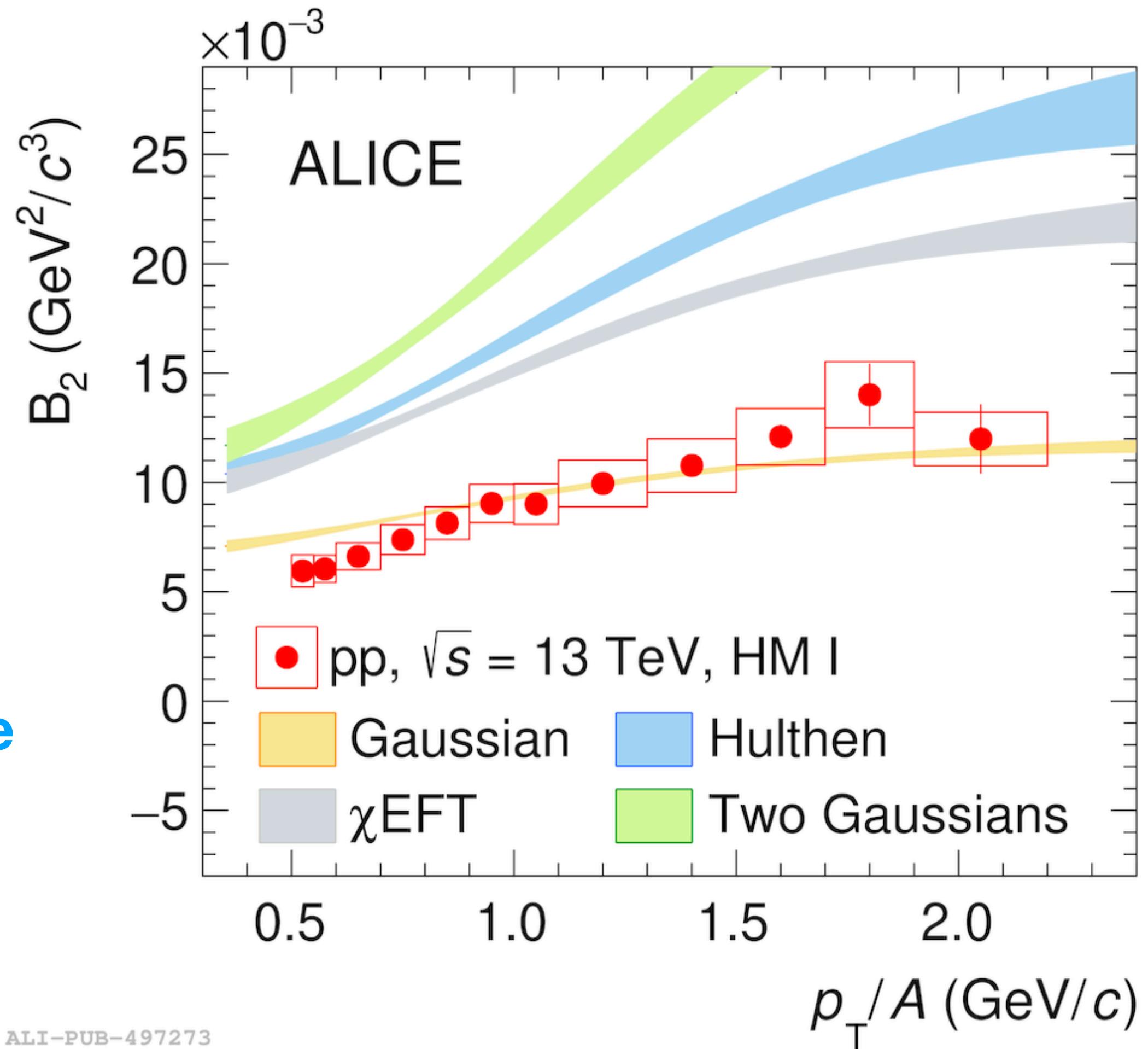
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- We can test different **wave functions**  $\phi_d(\vec{r})$
- We have the precise measurement of the **source size**
- No free parameters!**
- $B_2$  in agreement with Gaussian wave function ( $d = 3.2$  fm)
  - From low-scattering experiment Hulthen is expected to provide the best description

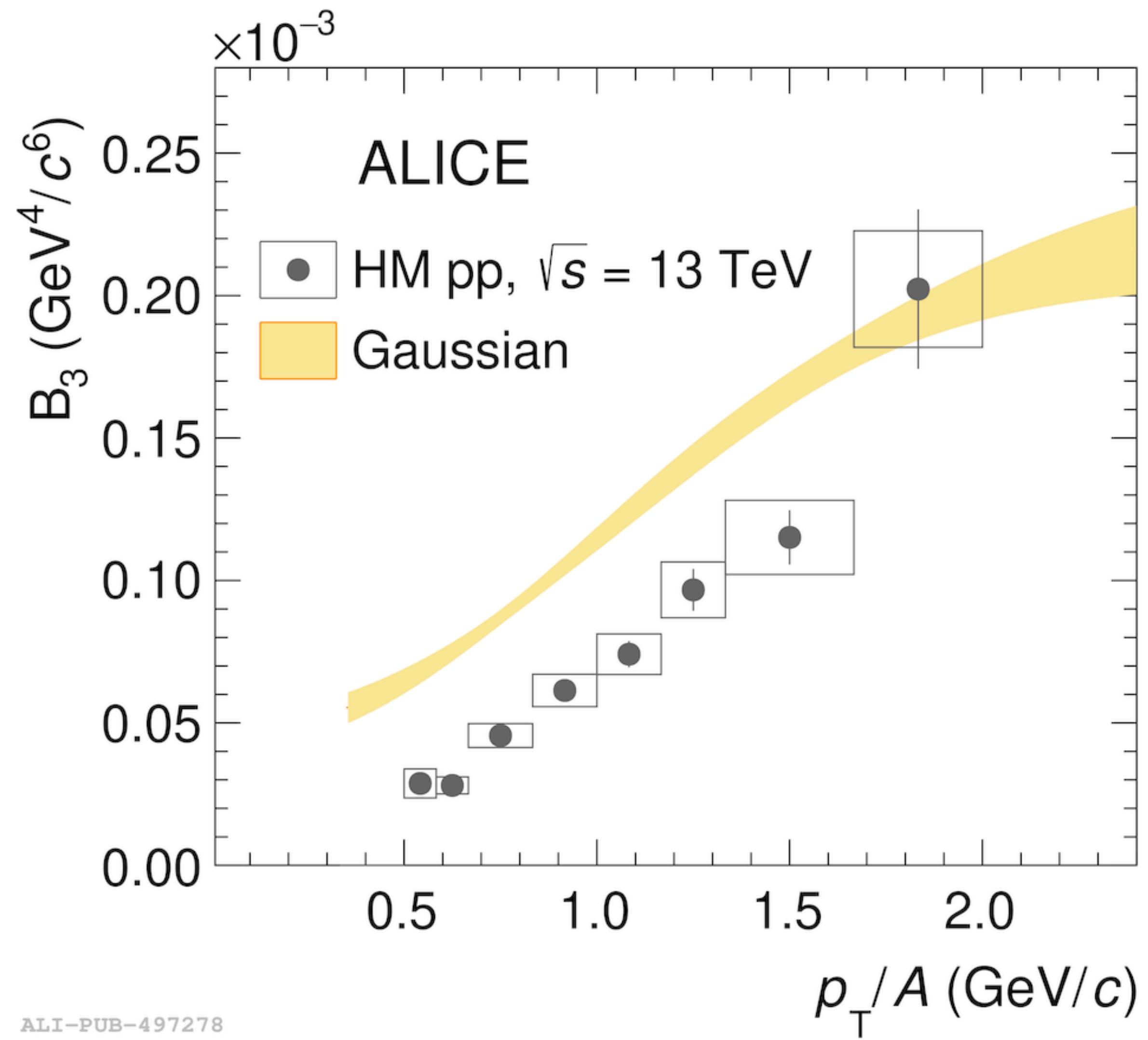


[JHEP 01 \(2022\) 106](#)

# $B_3$ vs $p_T/A$

- $B_3$  is compared with prediction based on a Gaussian wave function
  - reasonable description, but worse with respect to  $B_2$
- Very sensitive to nucleus radius  $d$ :

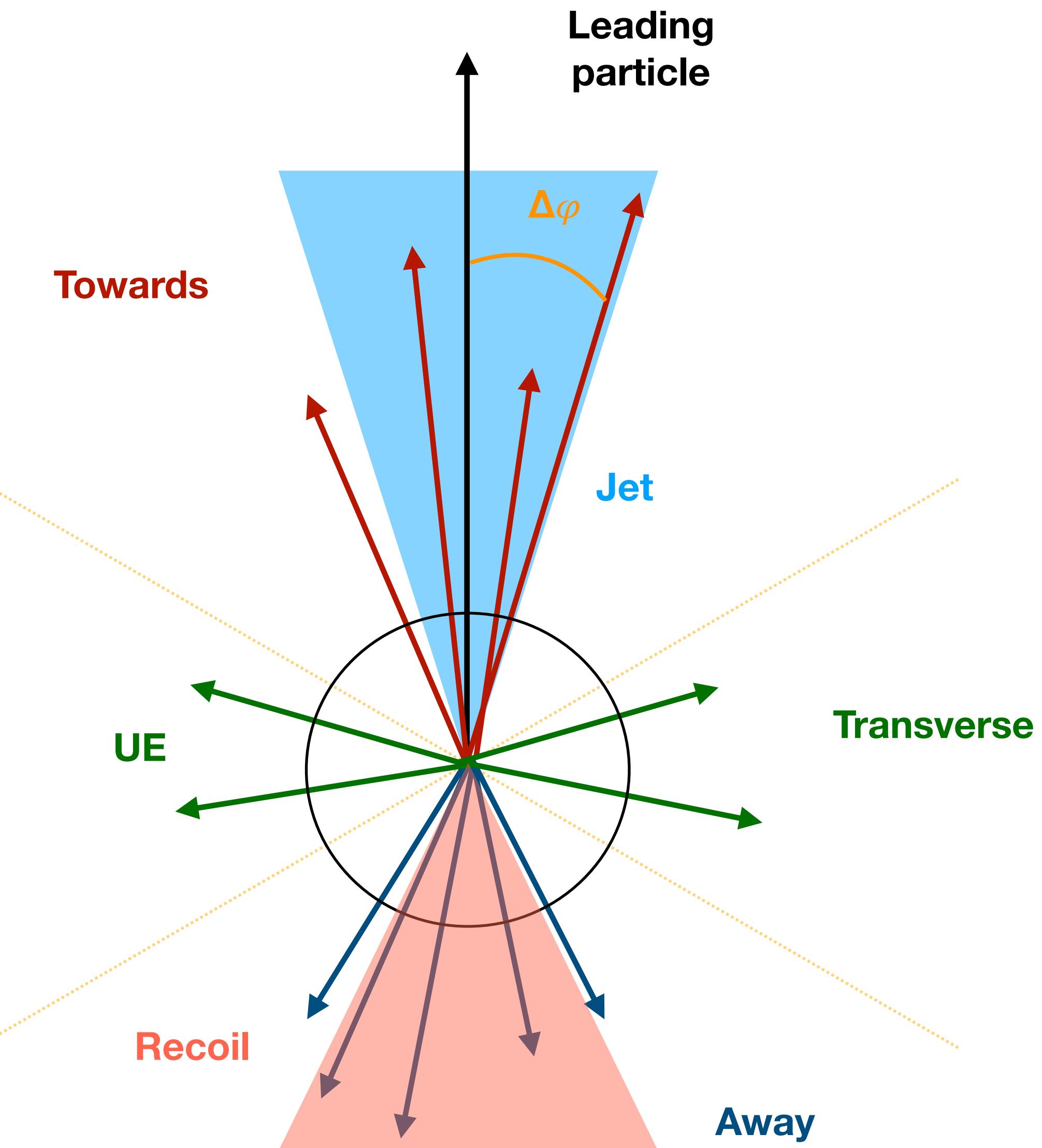
$$B_3 = \frac{2\pi^3}{\sqrt{3} m_p^2} \left[ R^2 + \left( \frac{d}{2} \right)^2 \right]^3$$



[JHEP 01 \(2022\) 106](#)

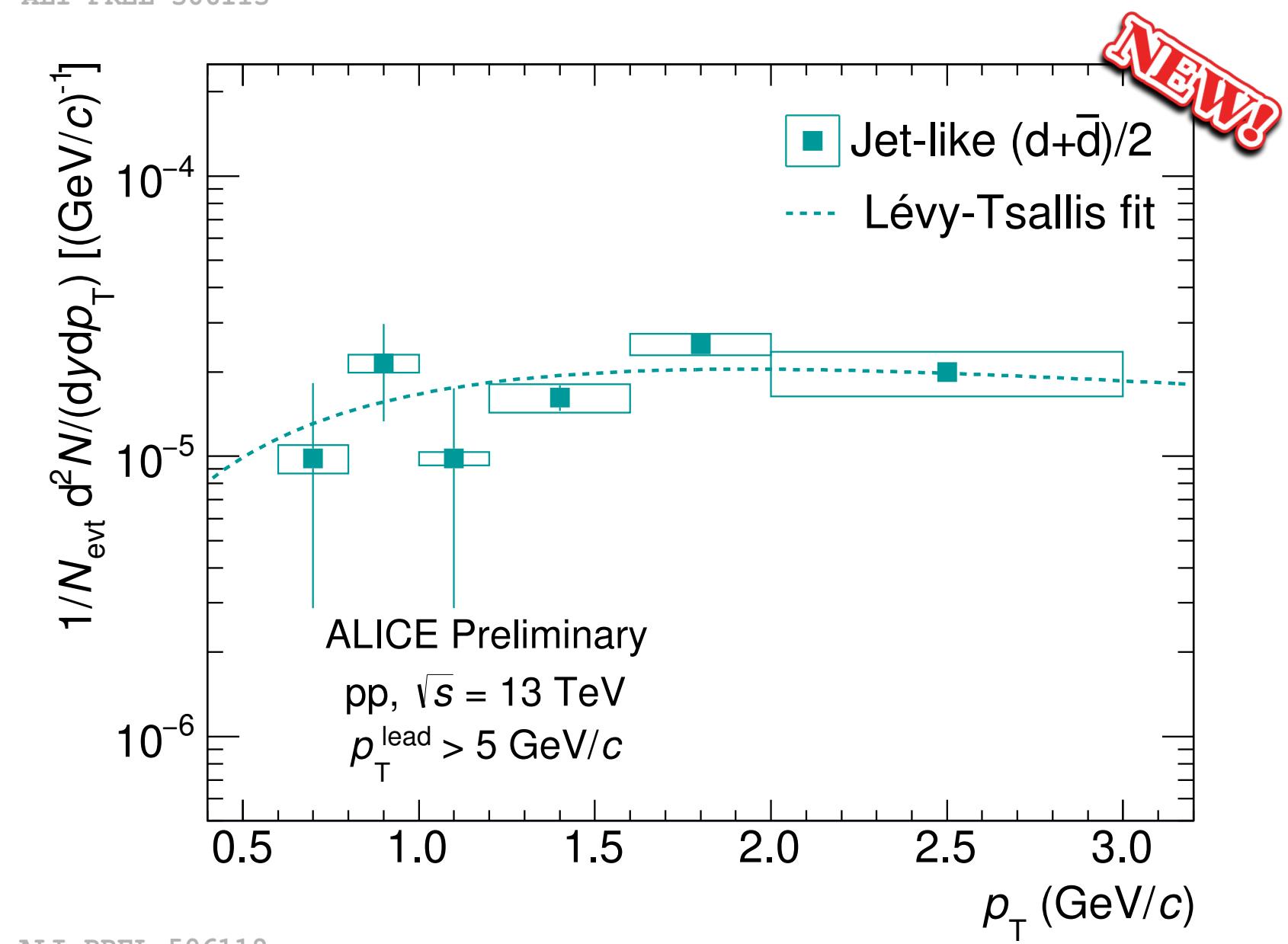
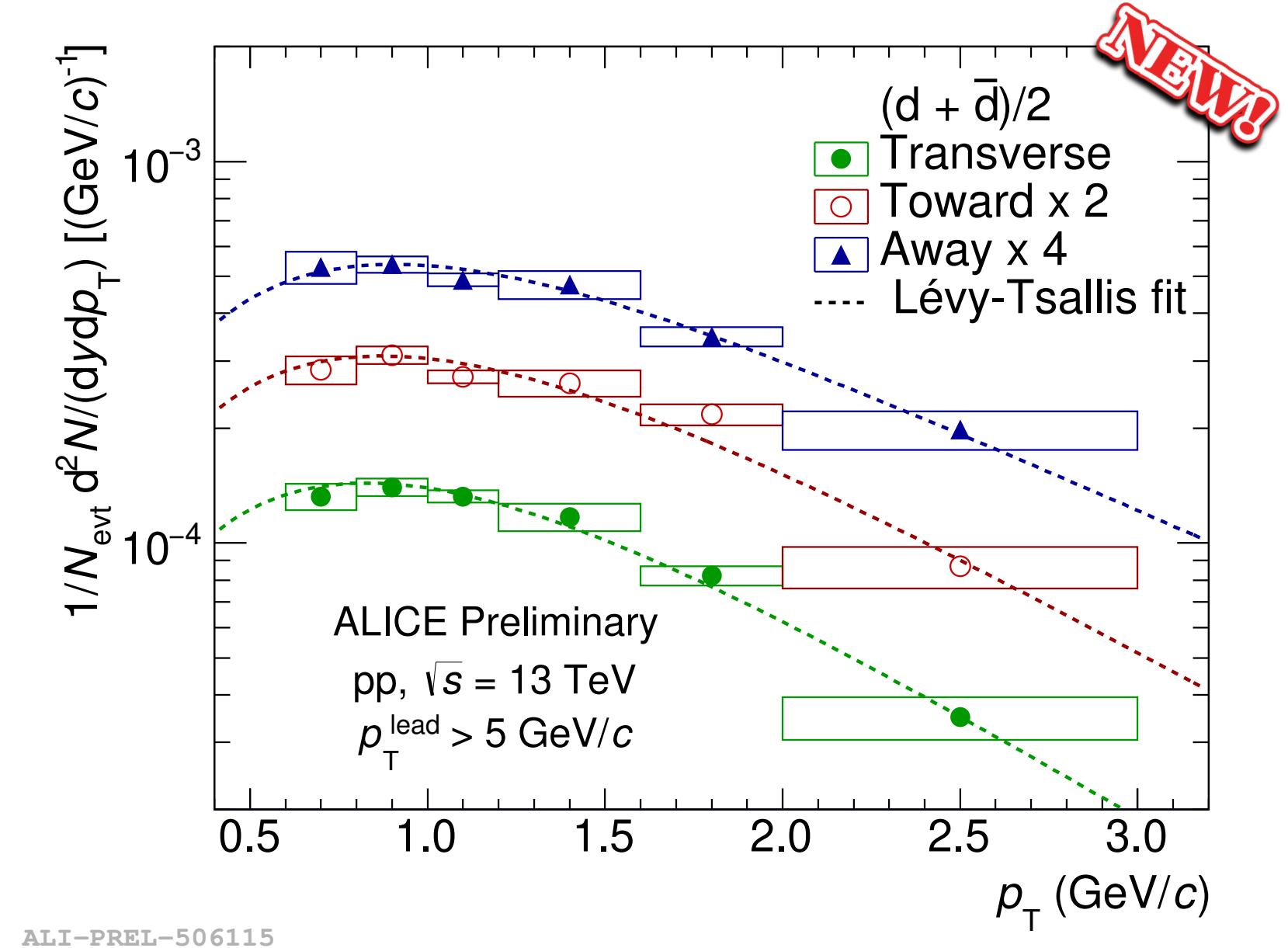
# In and out of jet production

- **Dependence** of nuclear production on the **activity** of the **event**?
- Comparison between **in-jet** production and production in the **underlying event (UE)**
  - jets are **collimated emissions** of hadrons → **coalescence** probability should be **enhanced**
- The leading particle (highest  $p_T$ ,  $p_T > 5 \text{ GeV}/c$ ) is used as jet-proxy
- Three regions are distinguished wrt the leading particle
  - **Toward**:  $|\Delta\varphi| < 60^\circ \rightarrow \text{Jet} + \text{UE}$
  - **Transverse**:  $60^\circ < |\Delta\varphi| < 120^\circ \rightarrow \text{UE}$
  - **Away**:  $|\Delta\varphi| > 120^\circ \rightarrow \text{Recoil} + \text{UE}$



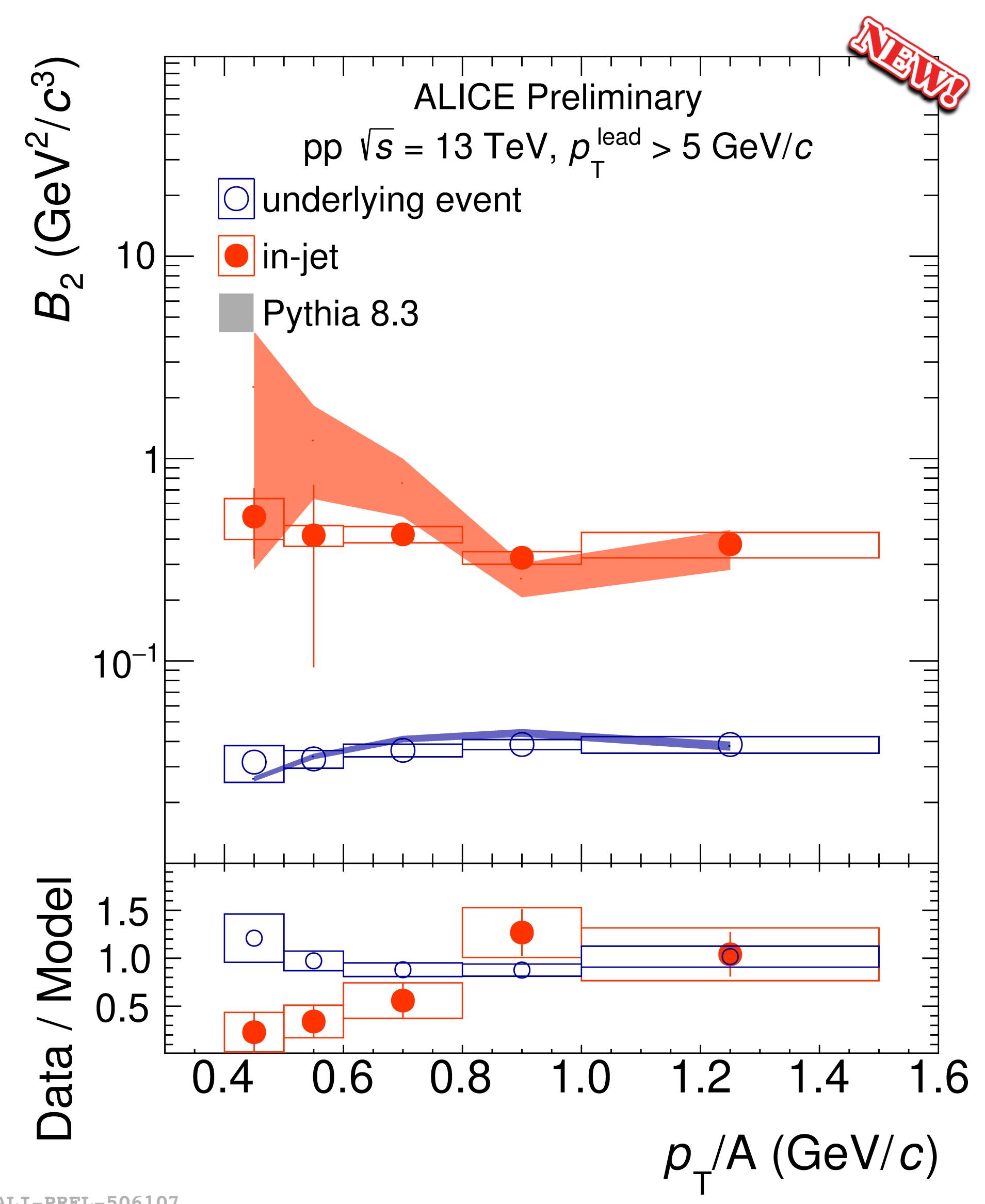
# In and out of jet production

- Deuterons spectra are measured in the azimuthal regions: **towards**, **transverse** and **away**
  - The **transverse** region is considered a good estimation of the **UE**
  - In-jet** spectrum = **towards** - **transverse**



# In and out of jet production

- Deuterons spectra are measured in the azimuthal regions:  
**towards**, **transverse** and **away**
  - The **transverse** region is considered a good estimation of the **UE**
  - In-jet spectrum = **towards** - **transverse**
- **$B_2$**  can be measured in-jet and in the underlying event
  - **In-jet enhancement** is observed
  - **PYTHIA**:
    - describes well the underlying event production
    - decreasing trend not observed in data



# Summary

- Yield ratios vs multiplicity:
  - d/p: good description by coalescence model and CSM
  - $^3\text{He}/\text{p}$ : models struggle in describing the data
- $B_A$  vs multiplicity
  - $B_2$  and  $B_3$  are described by the model
  - Two different parameterisations needed
- $B_A(p_T)$ :
  - Coalescence model reproduces data within a factor of 2 without free parameters
- In-jet  $B_2$  is increased with respect to  $B_2$  in the underlying event

# Summary

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  - d/p: good description by coalescence model and CSM
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To know more about nuclei in ALICE:

- *Measurement of the hypertriton properties and production with ALICE* - J. Ditzel
- *The dark side of ALICE: from antinuclei interactions to dark matter searches in space* - M. Colocci
- *Extending the ALICE strong-interaction studies to nuclei: measurement of proton-deuteron and  $\Lambda$ -deuteron correlations in pp collisions at  $\sqrt{s} = 13 \text{ TeV}$*  - B. Singh

Thanks for your attention!

# Backup

# The ALICE experiment

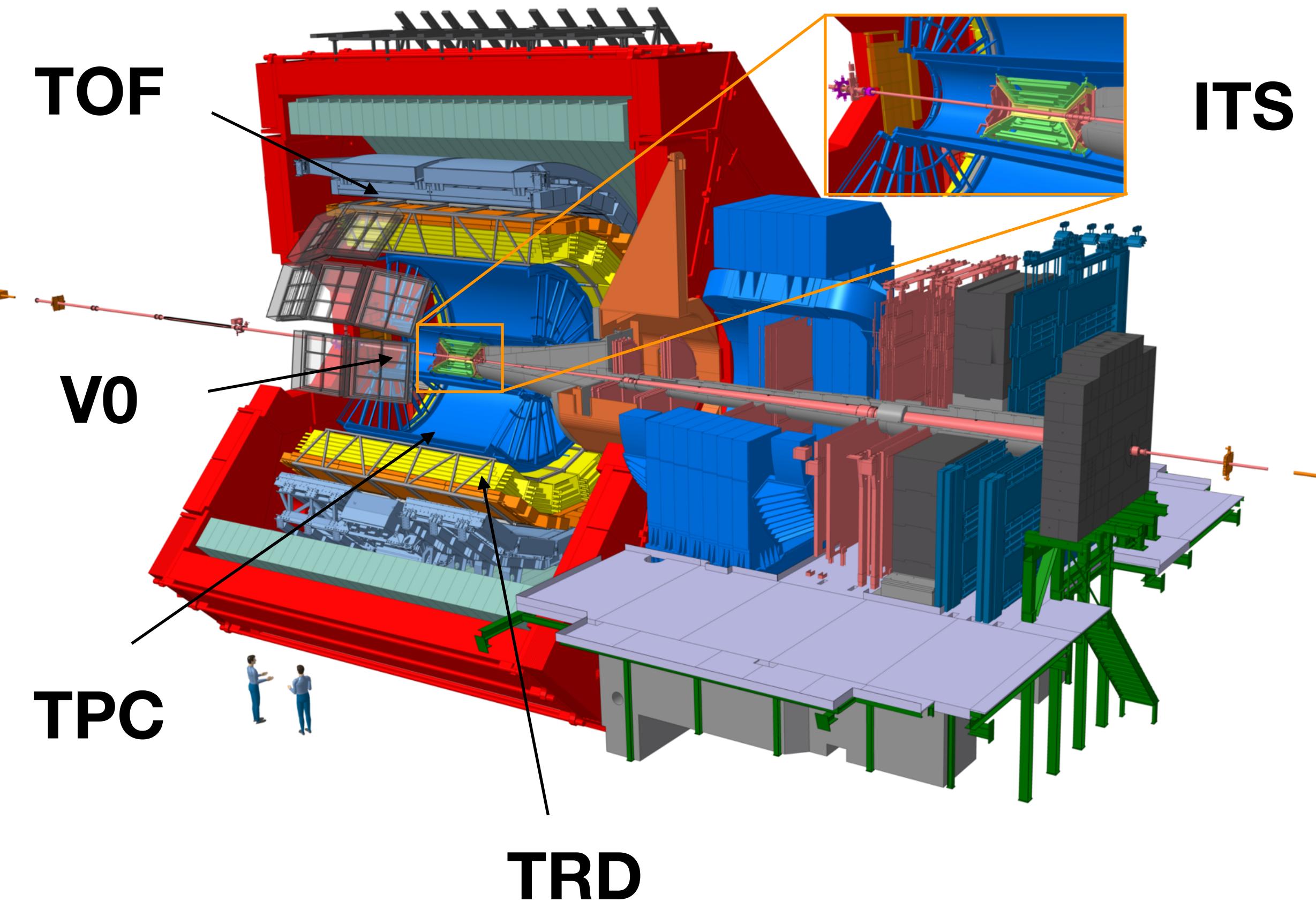
- General purpose heavy-ion experiment
  - 19 different sub-systems
  - Excellent particle identification (**PID**)
  - Most suited LHC experiment for studying the production of nuclei

## Inner Tracking System

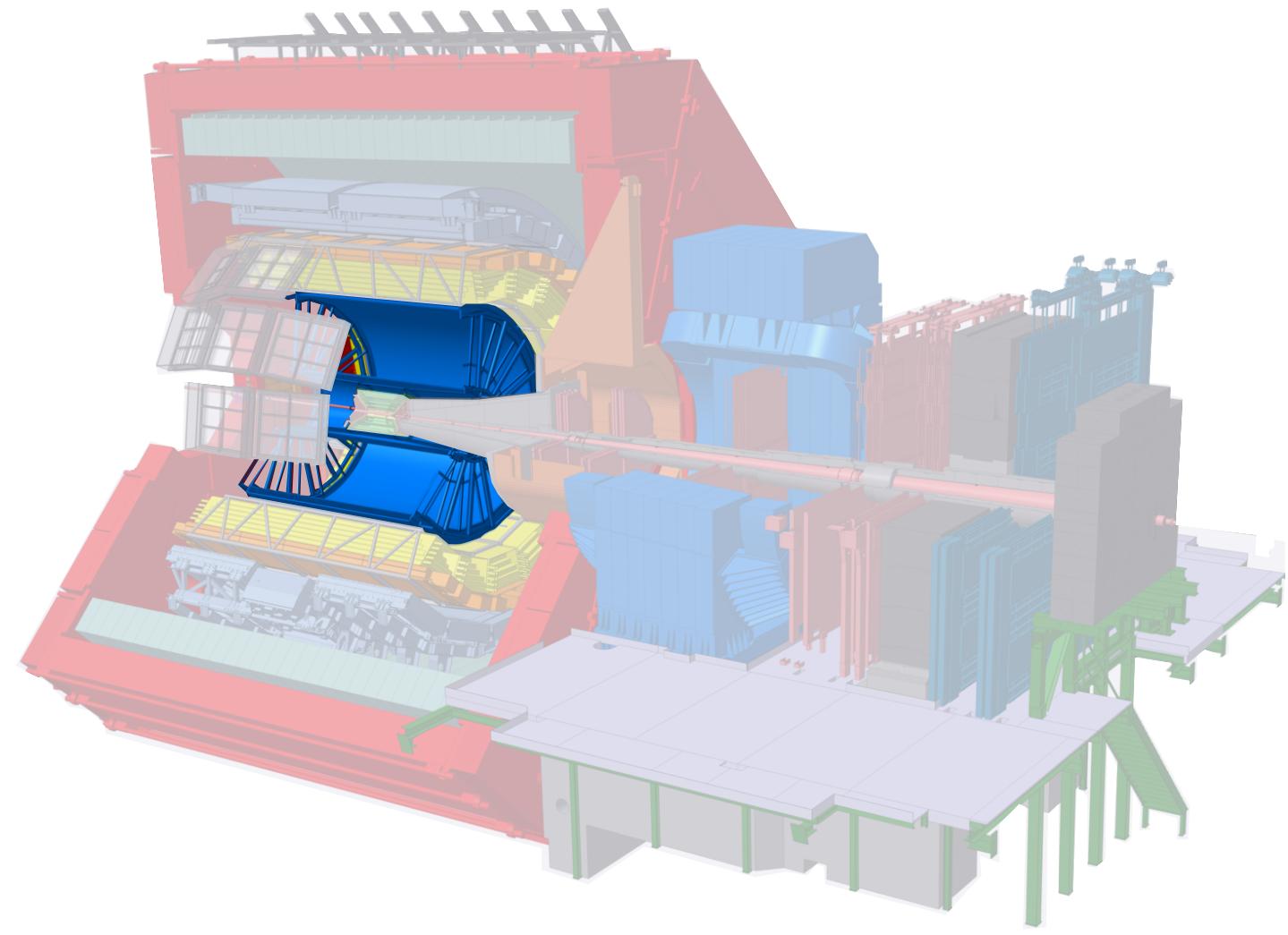
- **Tracking** and **Vertex** reconstruction
- $\sigma_{\text{DCA}_{xy}} < 100 \mu\text{m}$  for  $p_T > 0.5 \text{ GeV}/c$  in Pb-Pb
  - Separation of **primary** and **secondary nuclei** (coming from material knock-out)
  - Separation of **primary** and **secondary vertices**

## V0

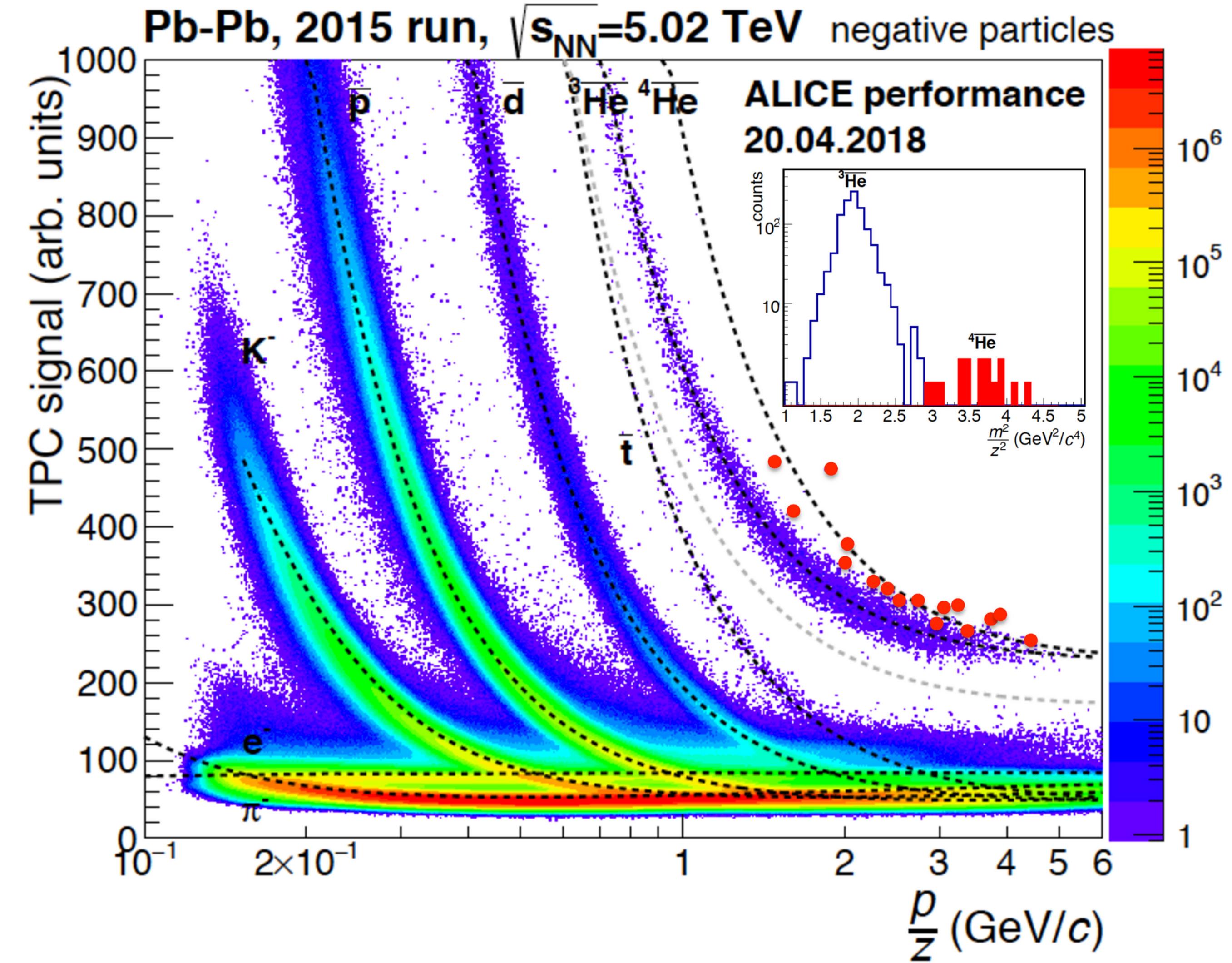
- **Multiplicity/centrality** determination



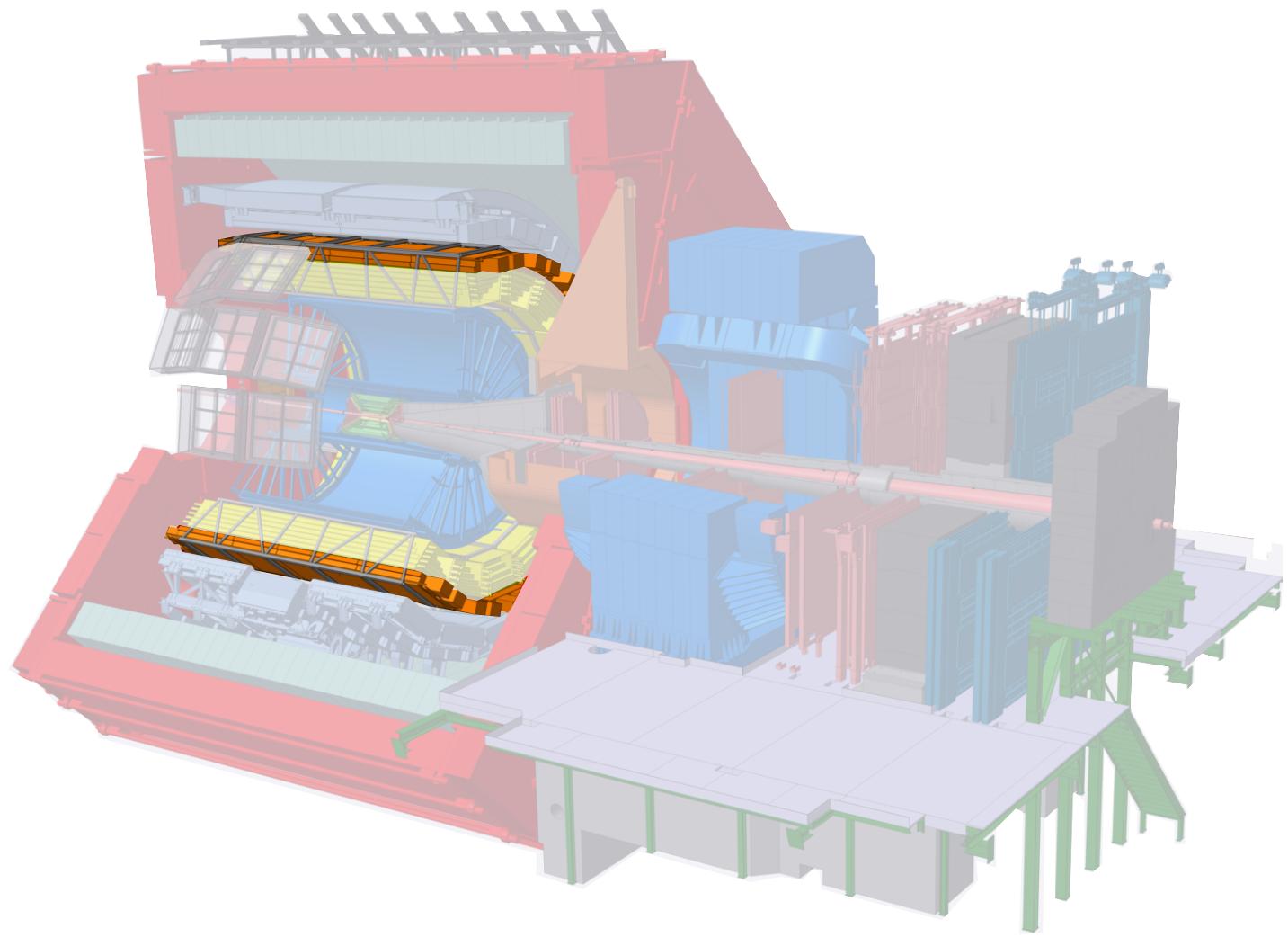
# PID with the Time Projection Chamber



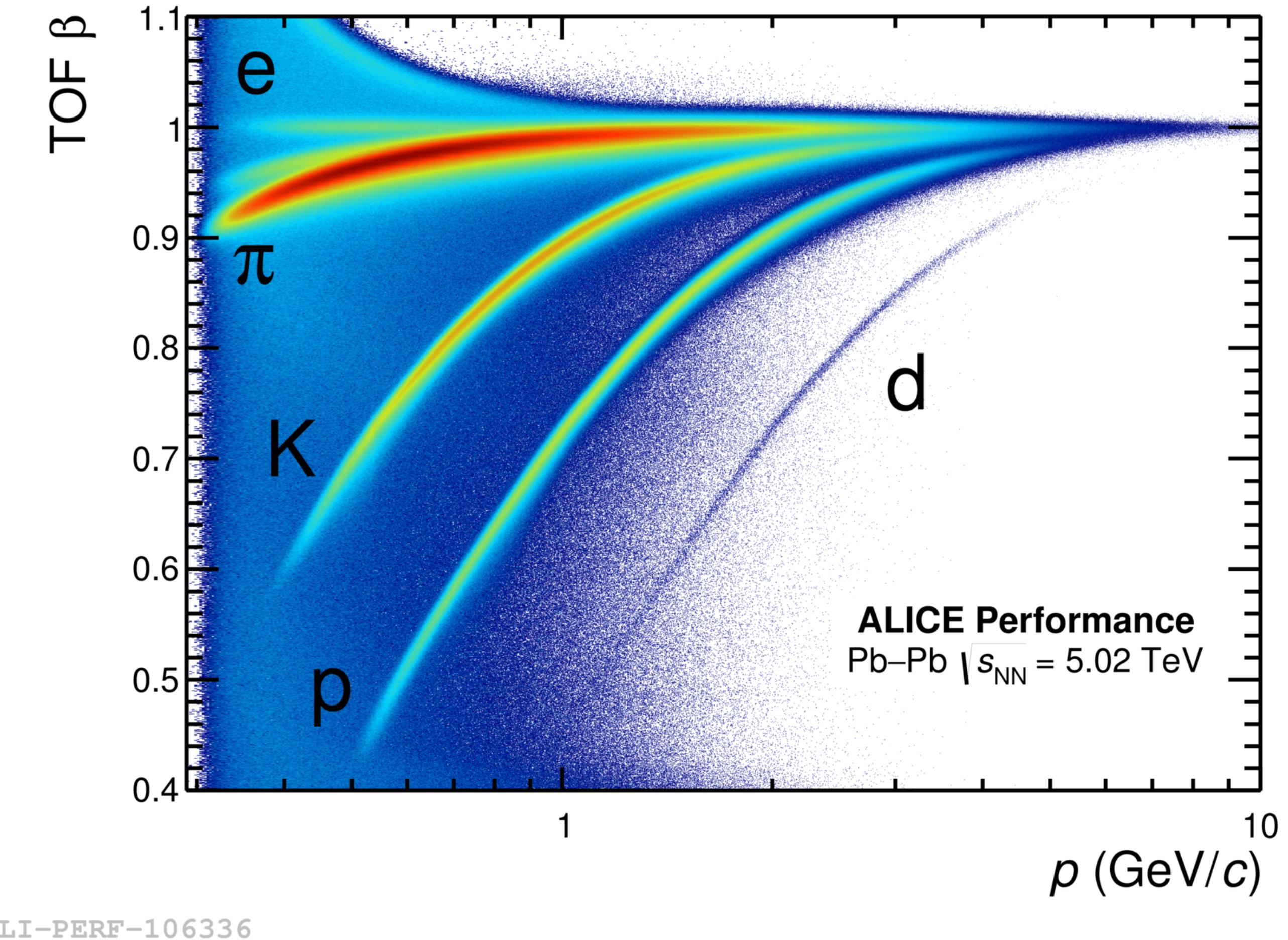
- **Tracking**
- **PID via  $dE/dx$  measurement**
  - $\sigma_{dE/dx} \sim 5.5\%$  (in pp collisions)
  - $\sigma_{dE/dx} \sim 7\%$  (in Pb-Pb collisions)
- ${}^3\text{He}$  and  ${}^4\text{He}$  well separated



# PID with the Time Of Flight



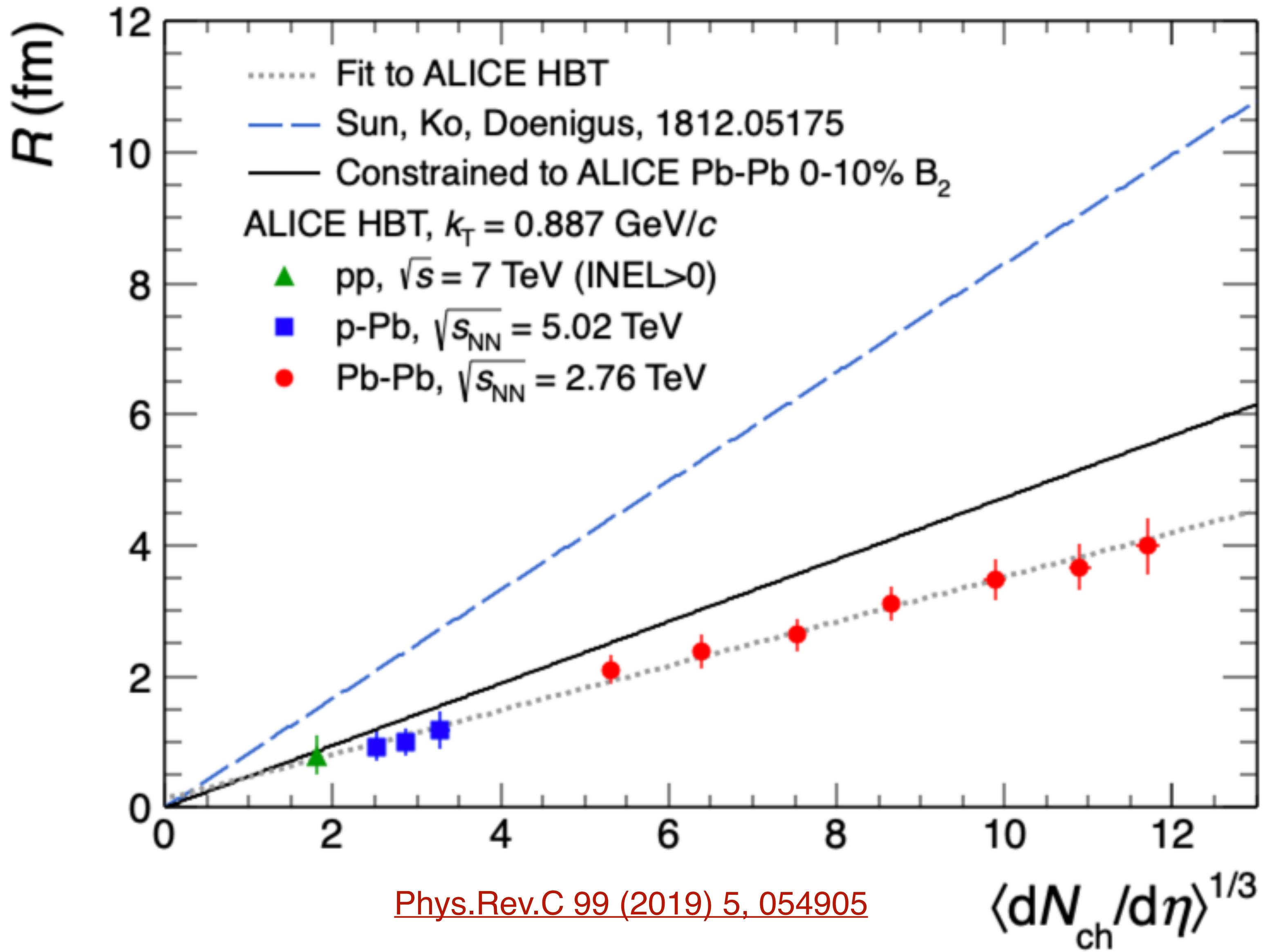
- **PID** via  $\beta$  measurement
  - $\sigma_{\text{TOF-PID}} \sim 60 \text{ ps}$  in **Pb-Pb** collisions
  - $\sigma_{\text{TOF-PID}} \sim 70 \text{ ps}$  in **pp** collisions  
(lower precision on event collision time)



# Charged particle multiplicity

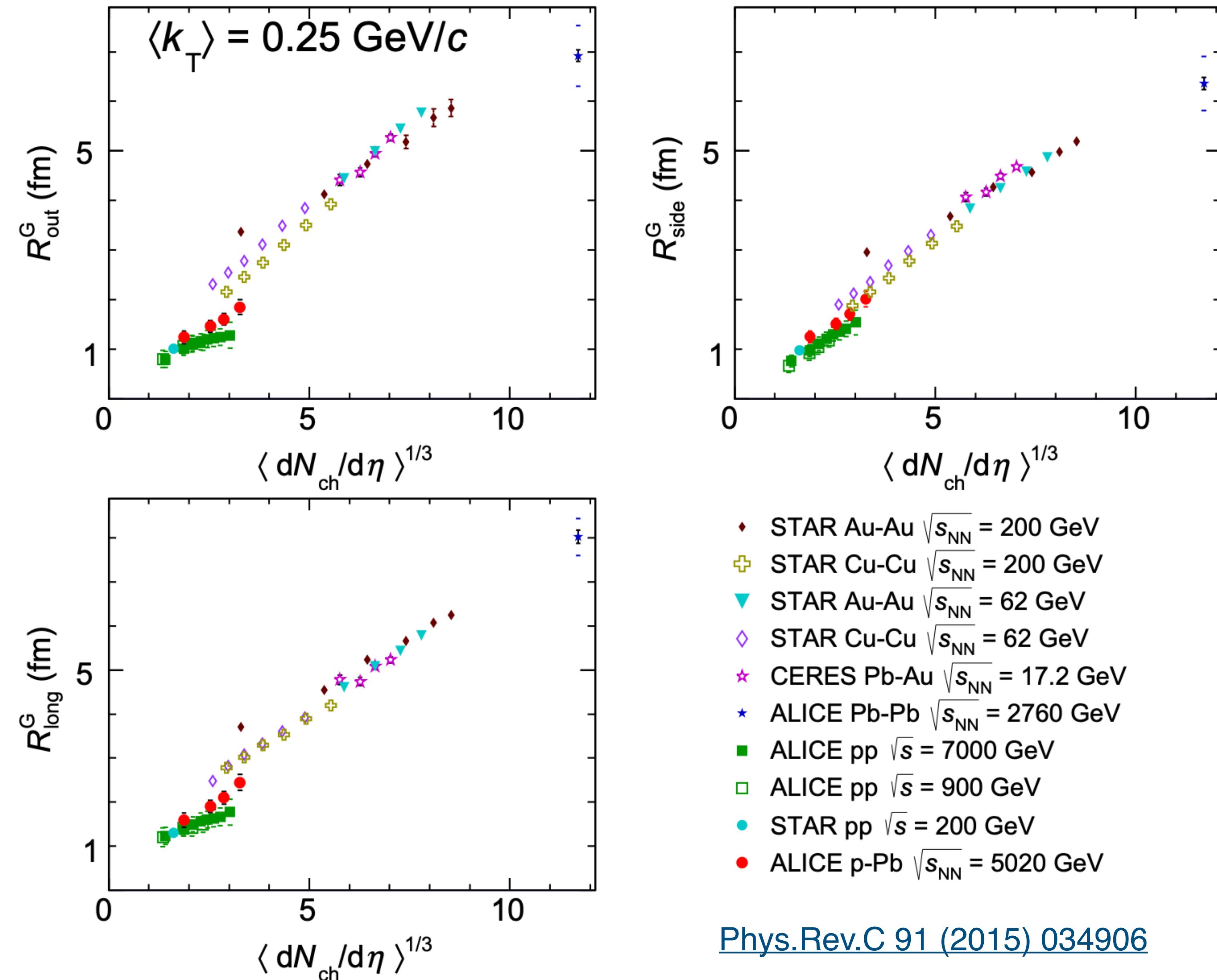
- Measurements are carried out vs multiplicity
- $\langle dN_{ch}/d\eta \rangle \leftrightarrow \text{system size}$
- System size: **HBT radius R**
  - R vs multiplicity:

$$R = a \langle dN/d\eta \rangle^{1/3} + b$$



# Charged particle multiplicity

- Adding more points to the  $R$  vs  $\langle dN_{ch}/d\eta \rangle$ , it is visible that the evolution is **not smooth** from pp to p-Pb
- This discontinuity could be the reason why models do not reproduce data along the whole multiplicity range
  - Possible solution:  $B_2$  vs  $R$
  - $R$  vs  $\langle dN_{ch}/d\eta \rangle$  needed



[Phys.Rev.C 91 \(2015\) 034906](#)

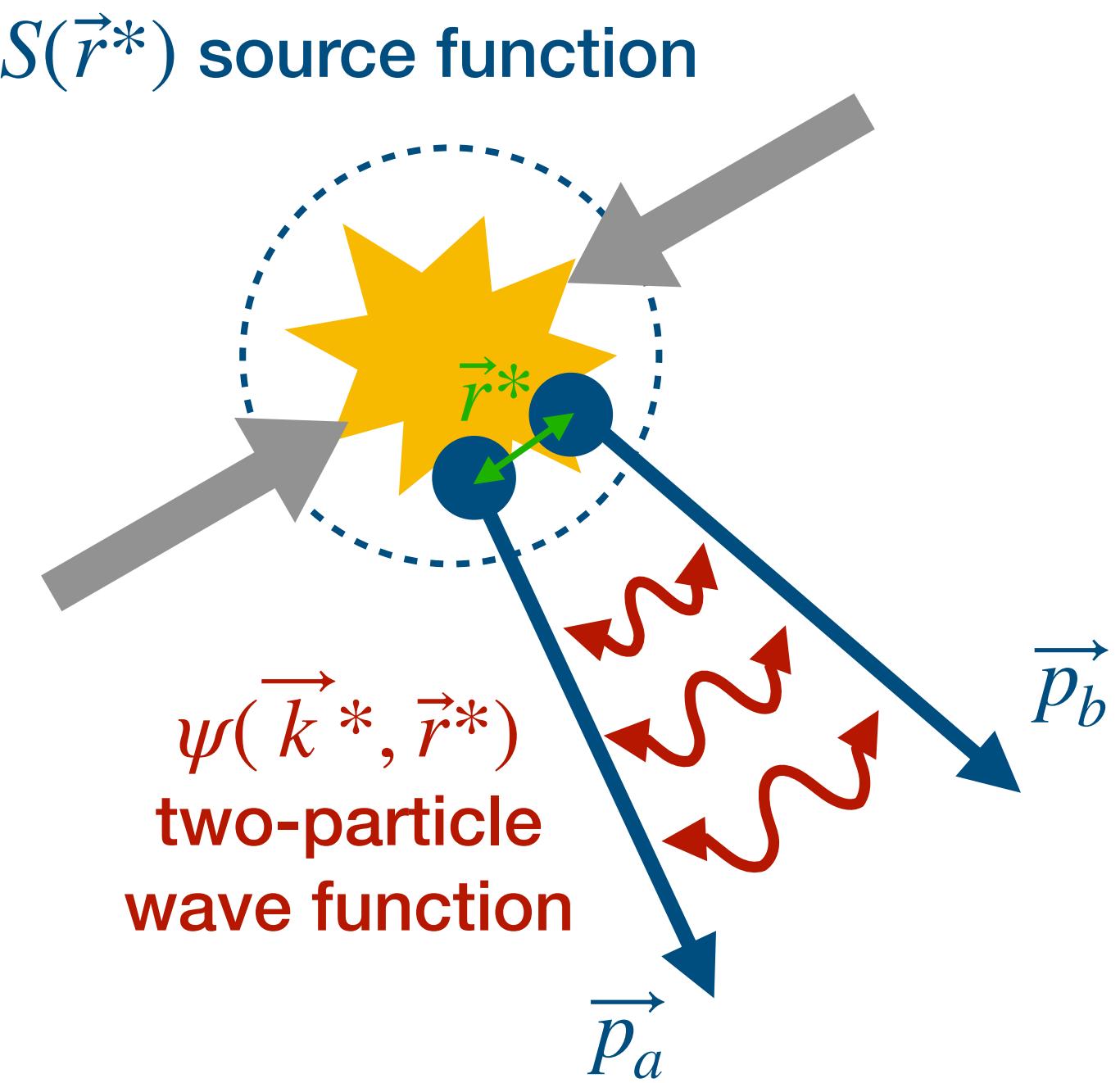
# Femtoscopy

- The main observable is the **correlation function**:

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

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

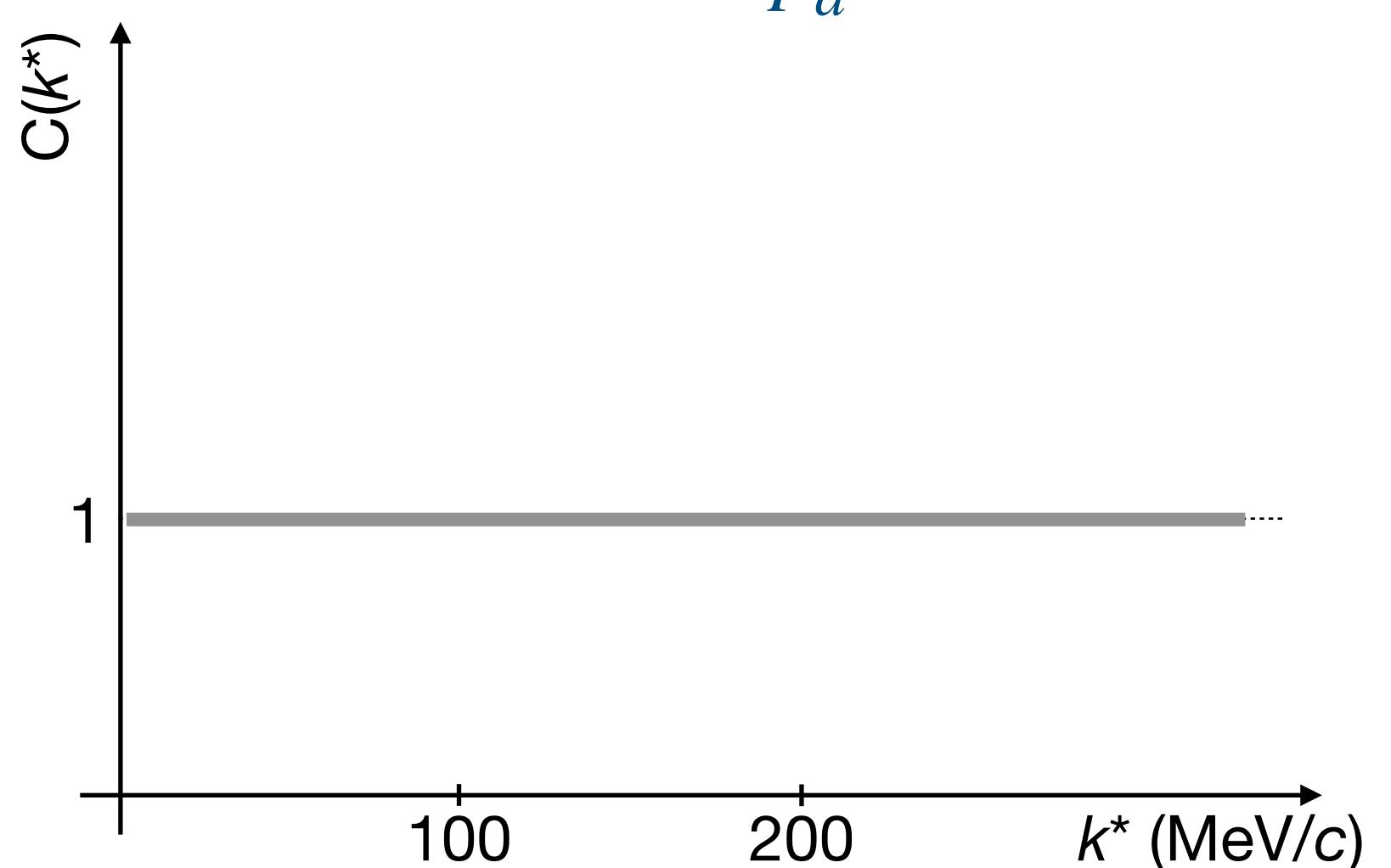
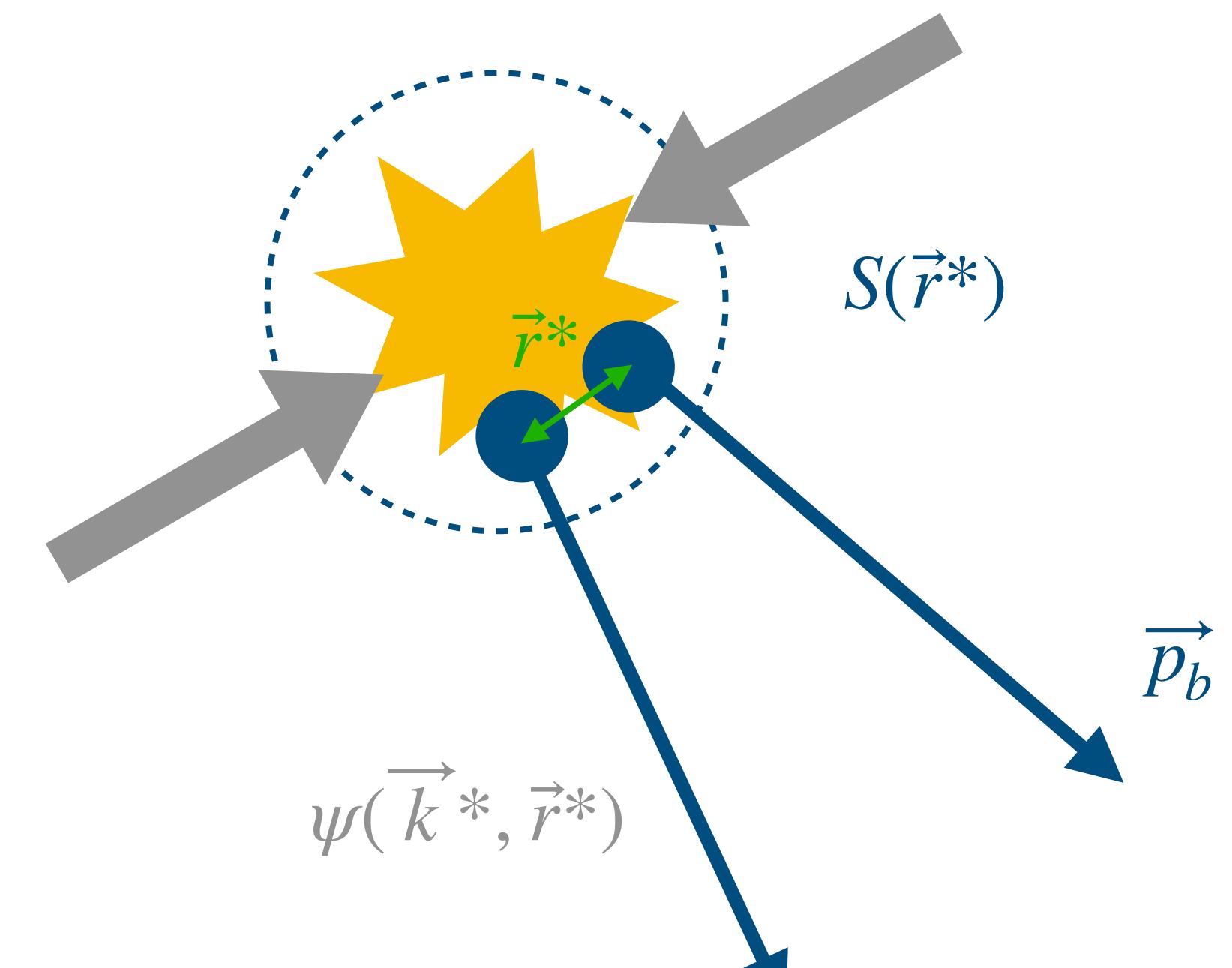
D.L. Mihaylov et al., EPJC 78 (2018) 5, 394

# The correlation function

- The **correlation function** reflects the interaction:

- Absence of interaction:  $C(k^*) = 1$

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

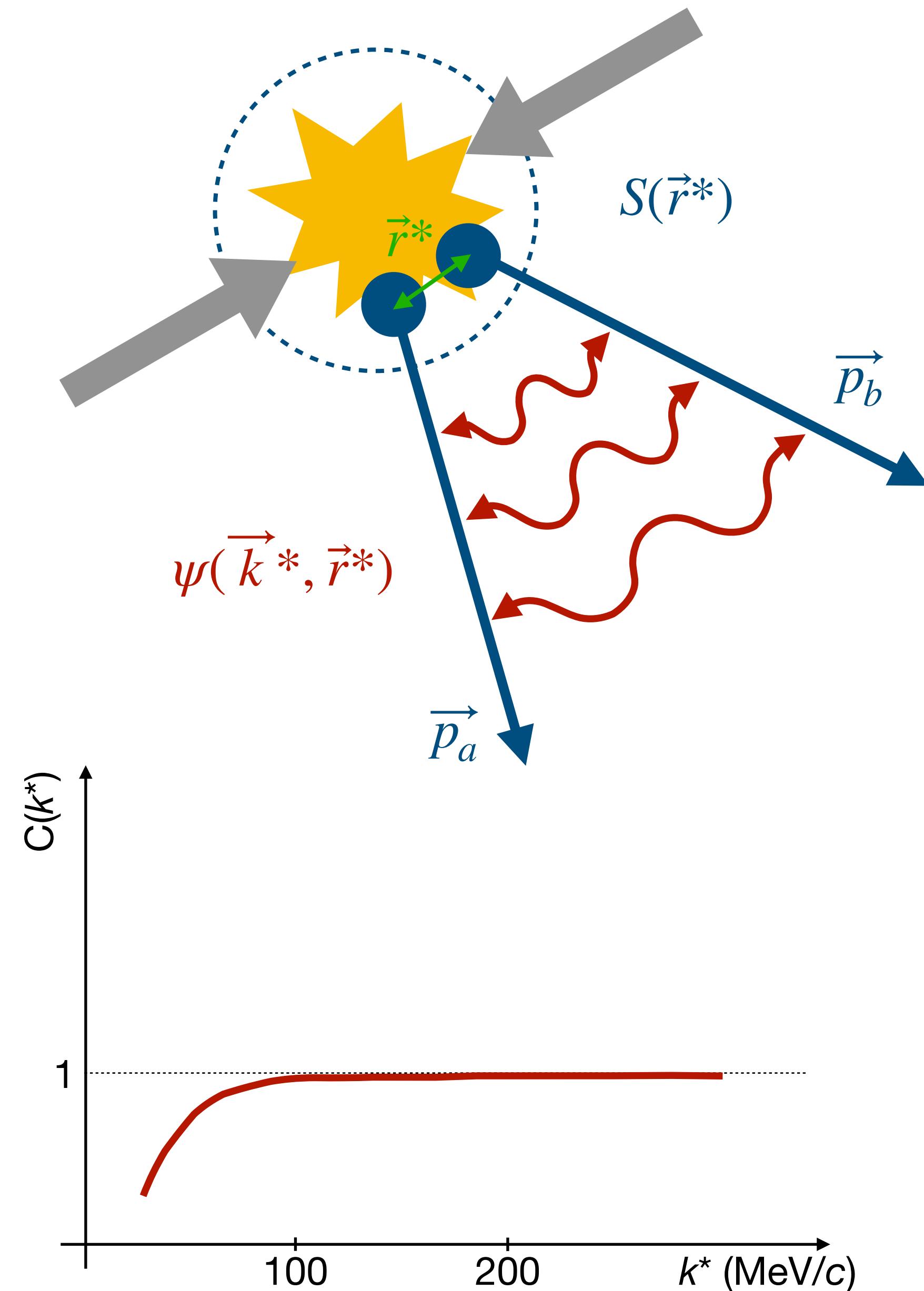


# The correlation function

- The **correlation function** reflects the interaction:

- Absence of interaction:  $C(k^*) = 1$
- Repulsive interaction:  $C(k^*) < 1$

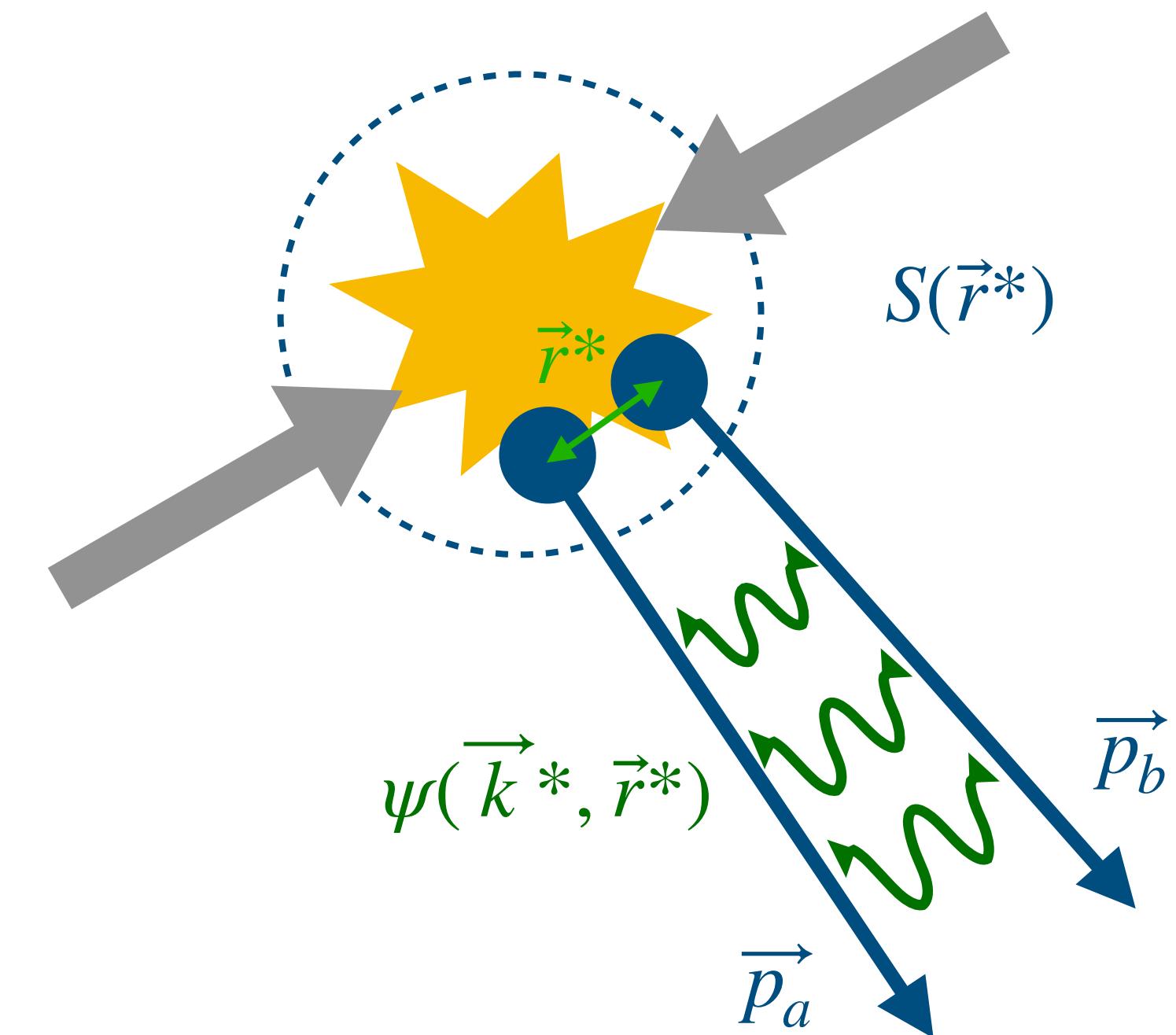
$$C(k^*) = \int S(\vec{r}^*) |\psi(\vec{k}^*, \vec{r}^*)|^2 d^3 r^* = \mathcal{N} \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)} < 1$$



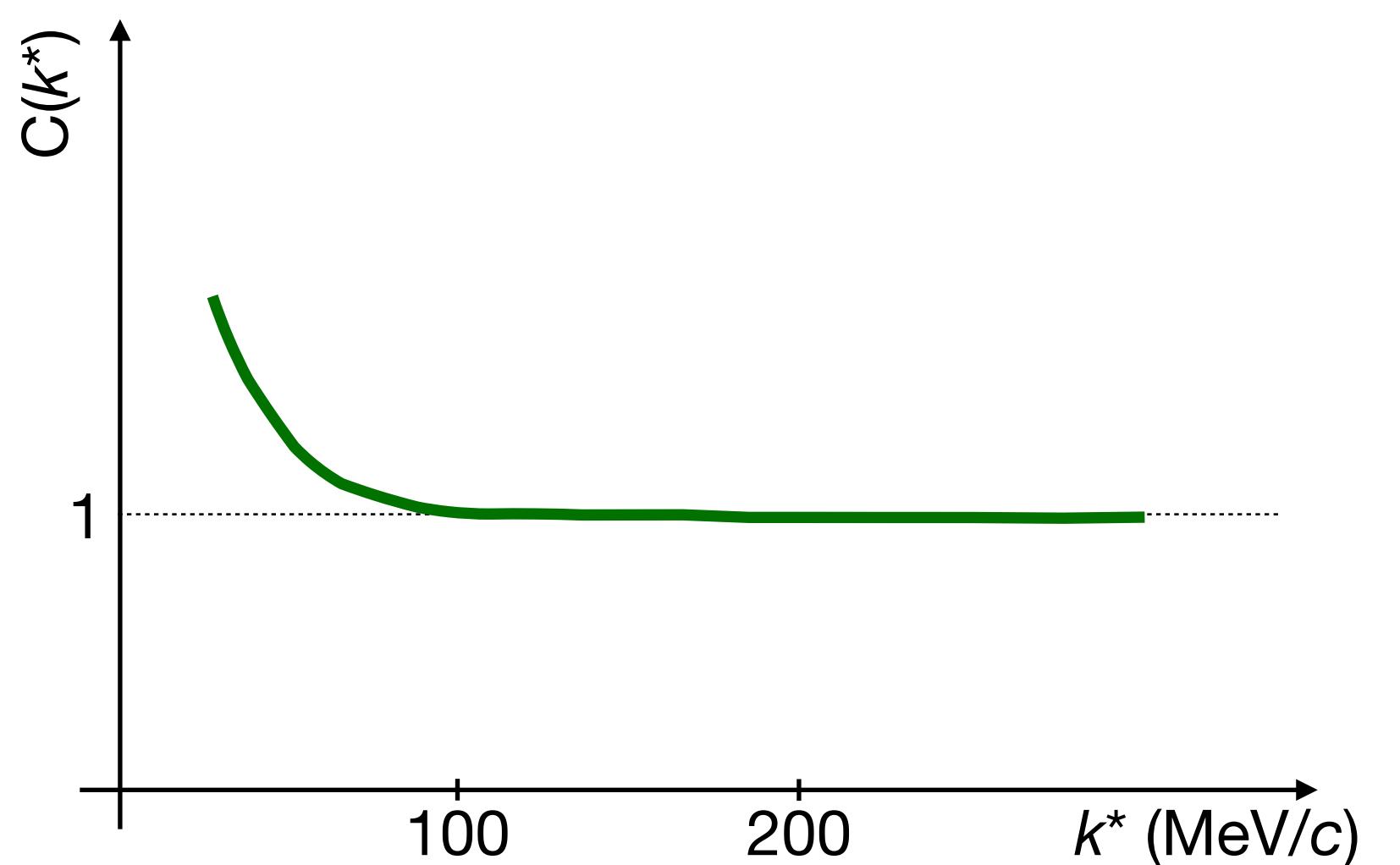
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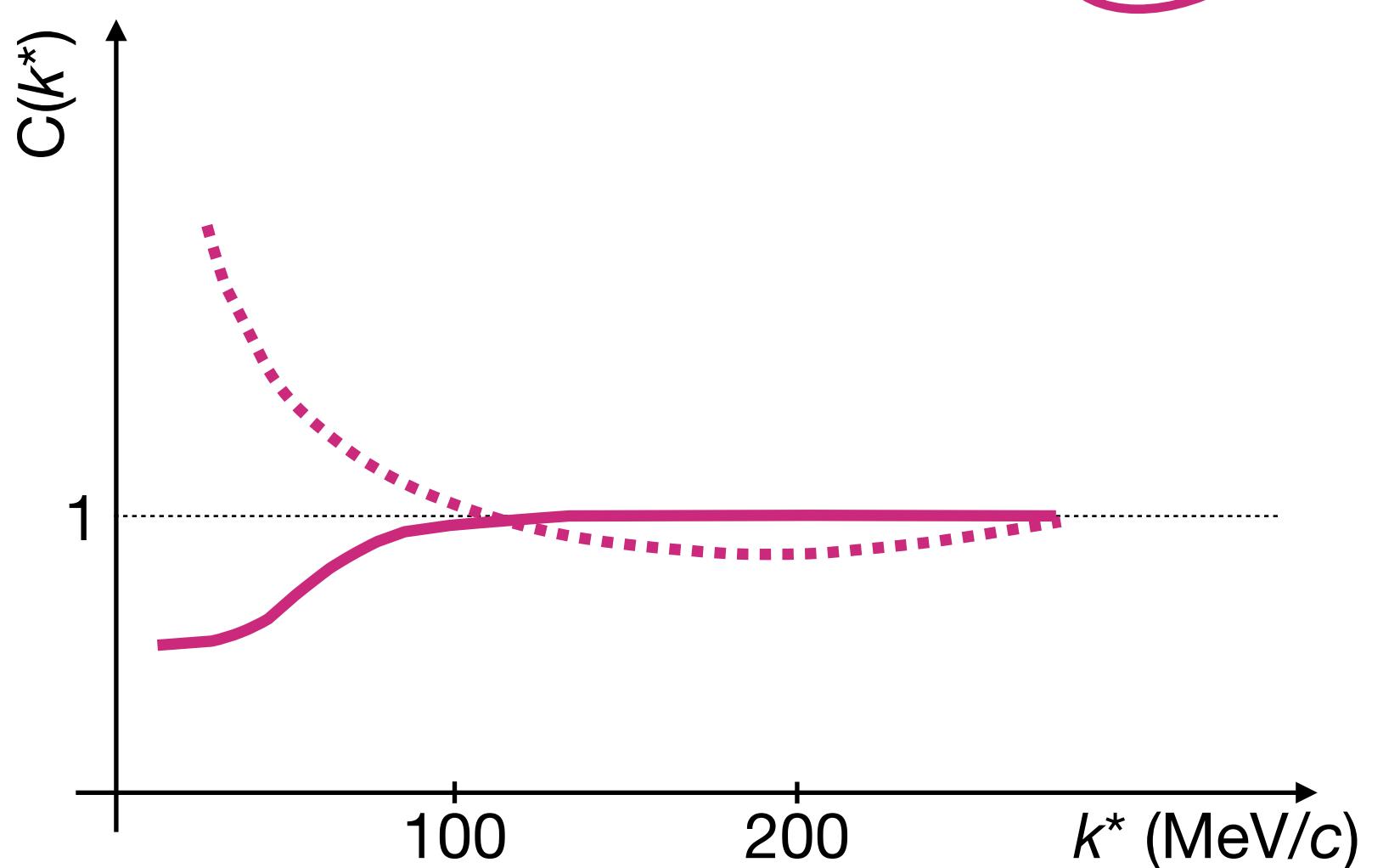
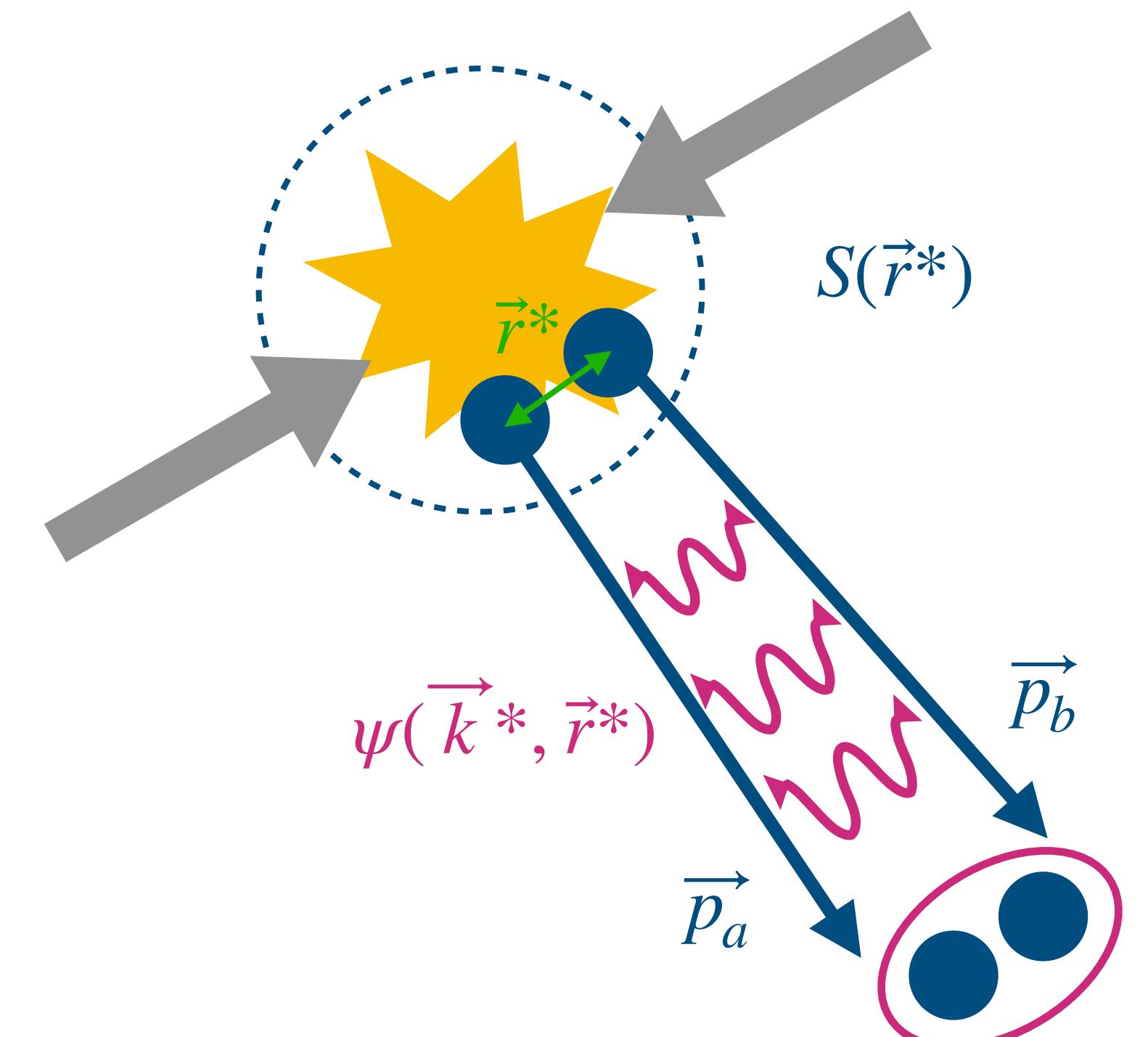


# The correlation function

- The **correlation function** reflects the interaction:

- Absence of interaction:  $C(k^*) = 1$
- Repulsive interaction:  $C(k^*) < 1$
- Attractive interaction:  $C(k^*) > 1$
- Bound state:  $C(k^*) \leq 1$

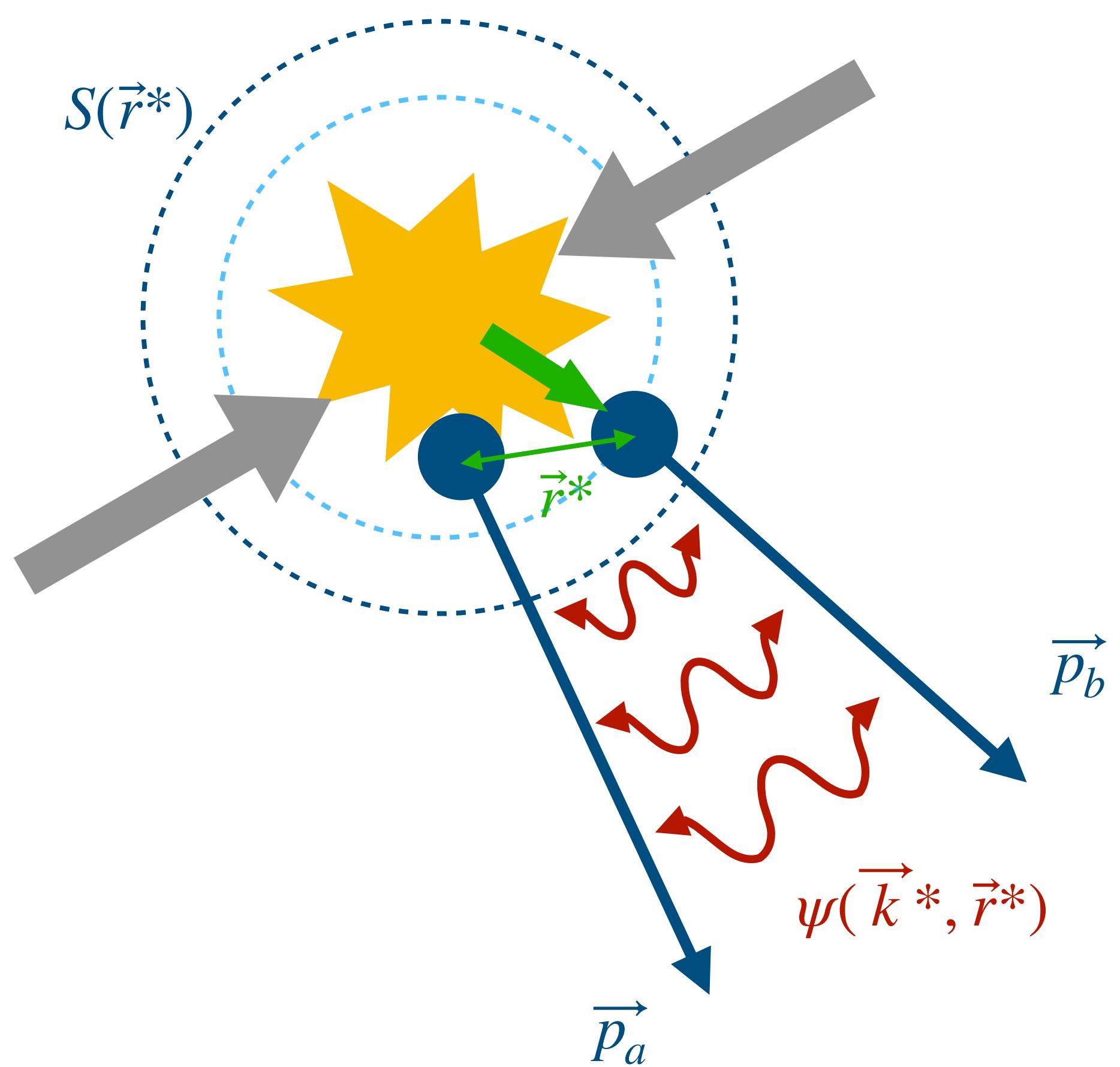
$$C(k^*) = \int S(\vec{r}^*) |\psi(\vec{k}^*, \vec{r}^*)|^2 d^3 r^* = \mathcal{N} \frac{N_{\text{same}}(k^*)}{N_{\text{mixed}}(k^*)} \leq 1$$



# Measure of the source size

- If the **interaction** is very **well known**, the CF can be used to constrain the **source function**
  - p-p and p- $\Lambda$
- Assumptions
  - Particle emission from a **Gaussian core** source
- Short-lived strongly decaying **resonances** ( $c\tau \approx r_{\text{core}}$ ) effectively increase the source radius
  - e.g.  $\Delta$ -resonances for protons

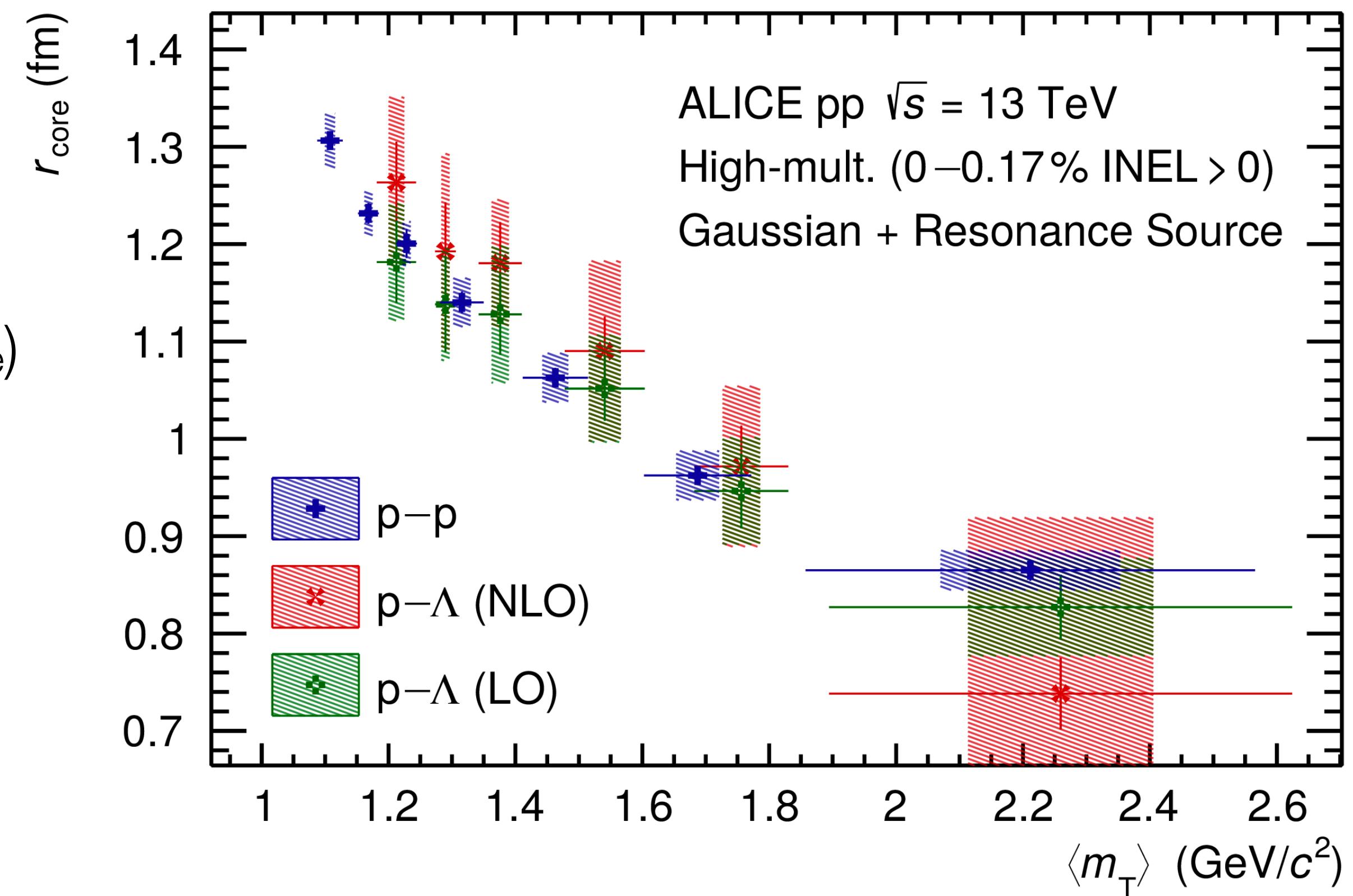
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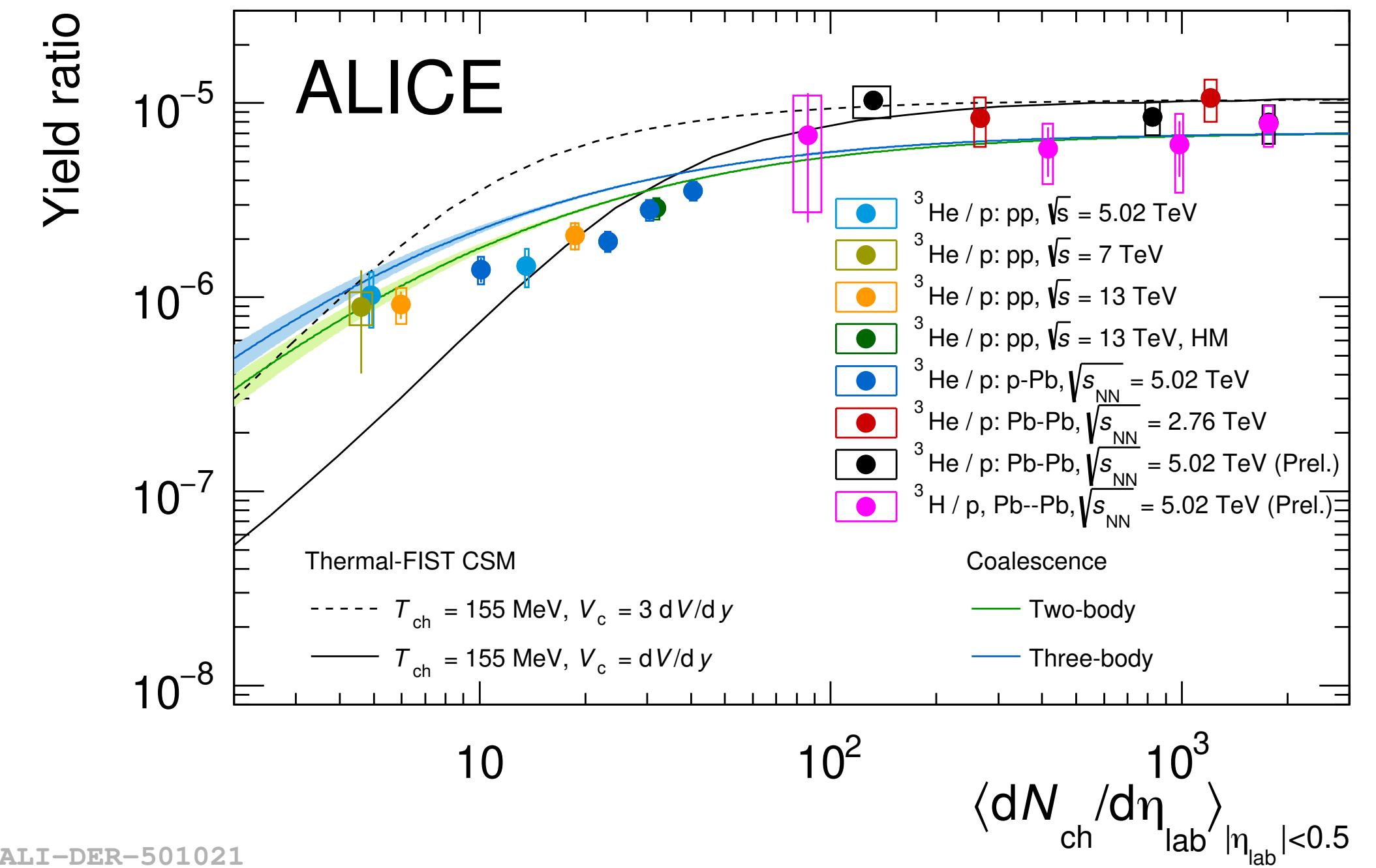
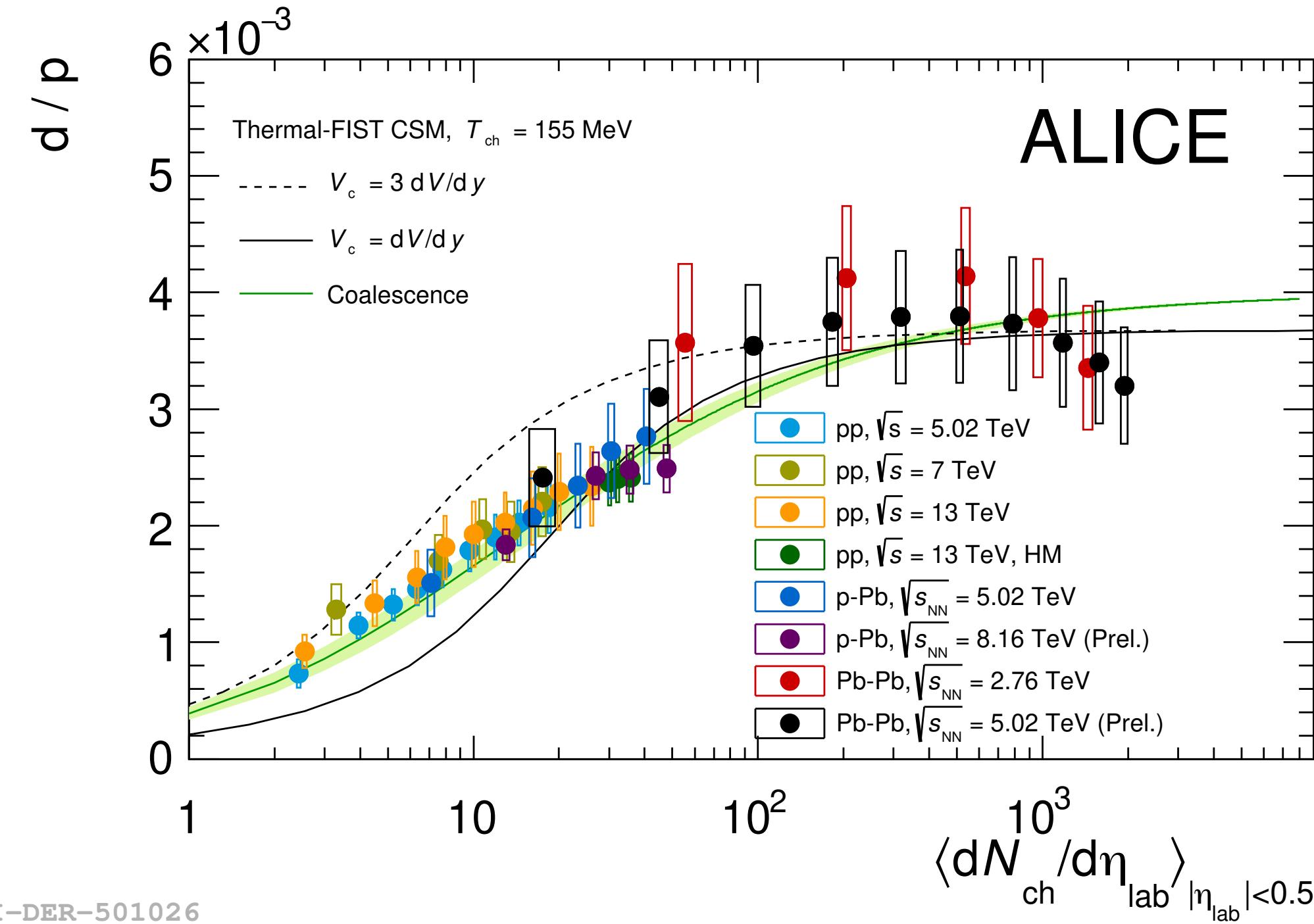
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  - Particle emission from a **Gaussian core** source
- Short-lived strongly decaying **resonances** ( $c\tau \approx r_{\text{core}}$ ) effectively increase the source radius
  - e.g.  $\Delta$ -resonances for protons
- **Universal source model**
  - $r_{\text{core}}$  fixed for each pair based on  $\langle m_T \rangle$

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



[PLB 811 \(2020\) 135849](#)

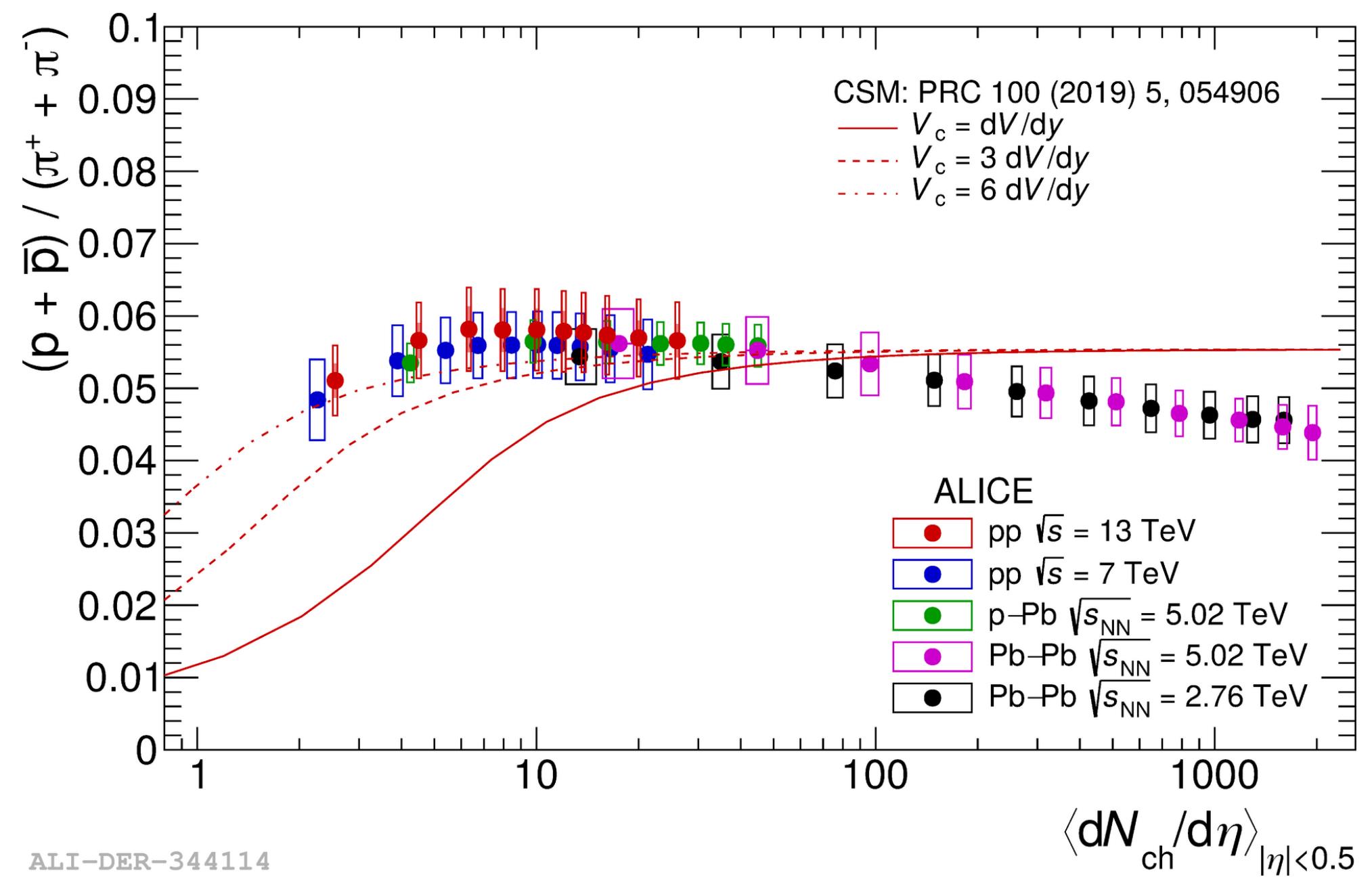
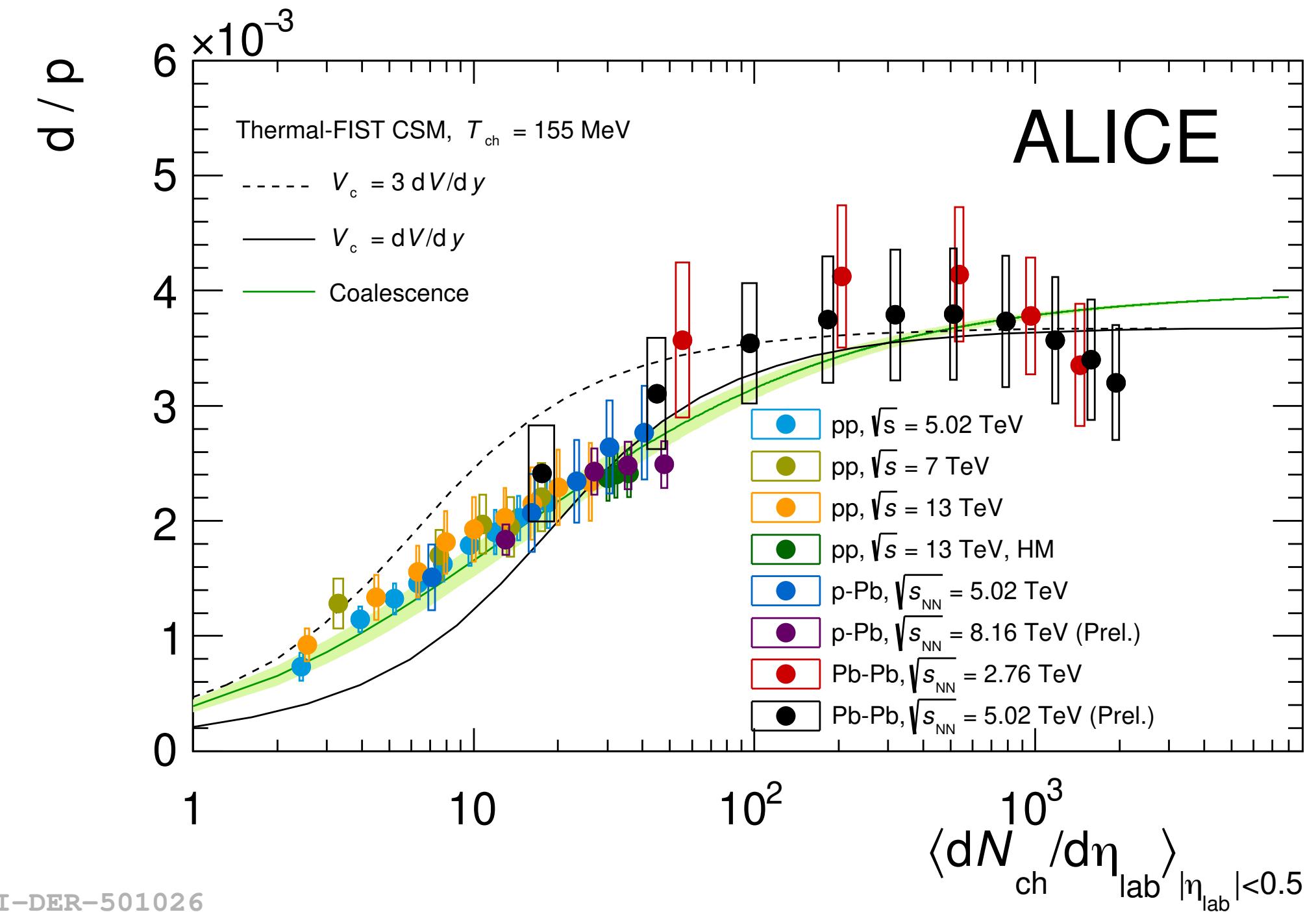
# Yield ratios



- **$d/p$**  and  **${}^3\text{He}/p$**  ratios evolve **smoothly** with **multiplicity**
  - dependence on the **system size**
- For  **$d/p$**  ratio both the models describe the data:
  - CSM: canonical suppression
  - Coalescence model: interplay between source size and nuclear size

- For  **${}^3\text{He}/p$**  there are more tensions between data and models
- Not possible to discriminate between the two models

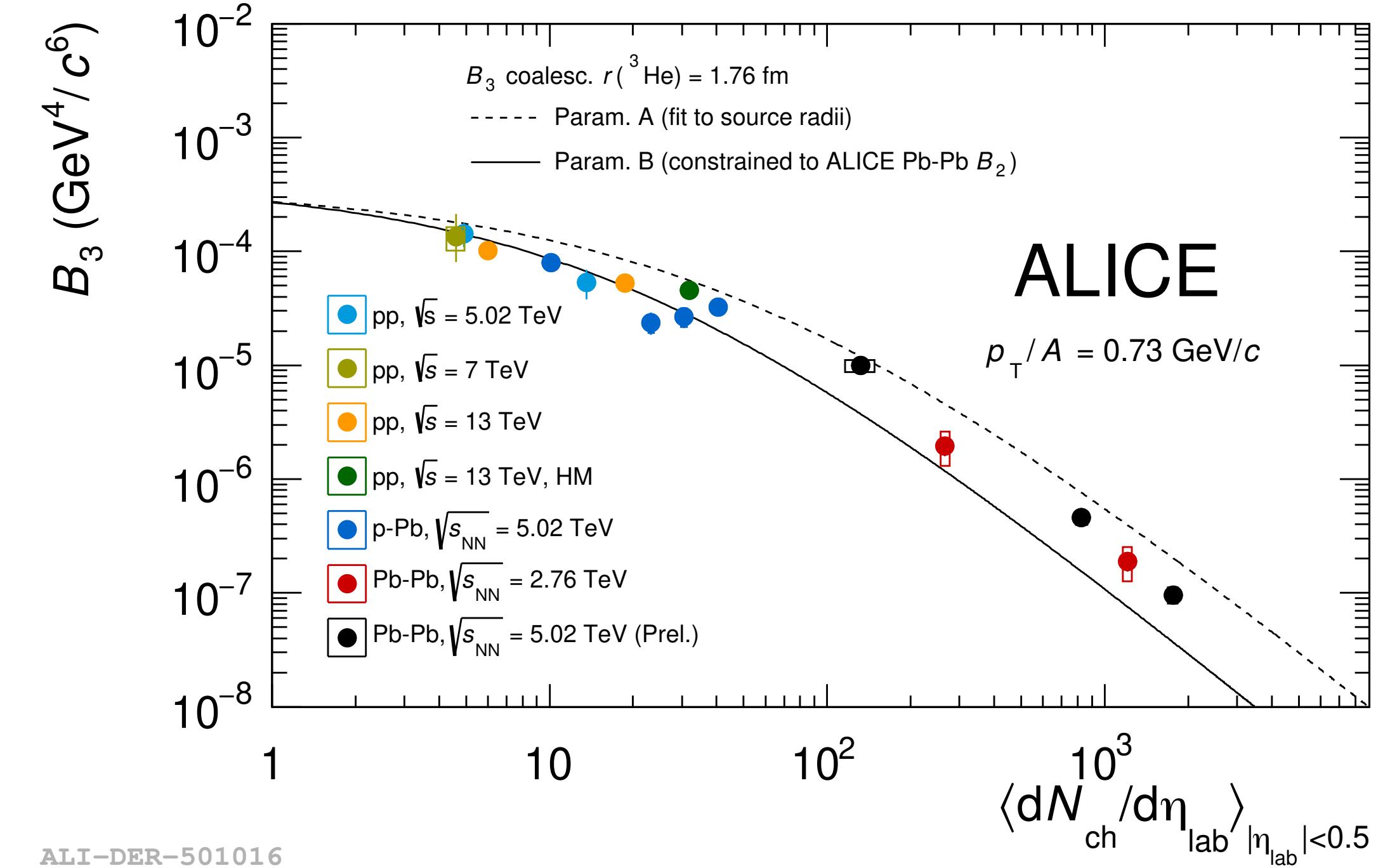
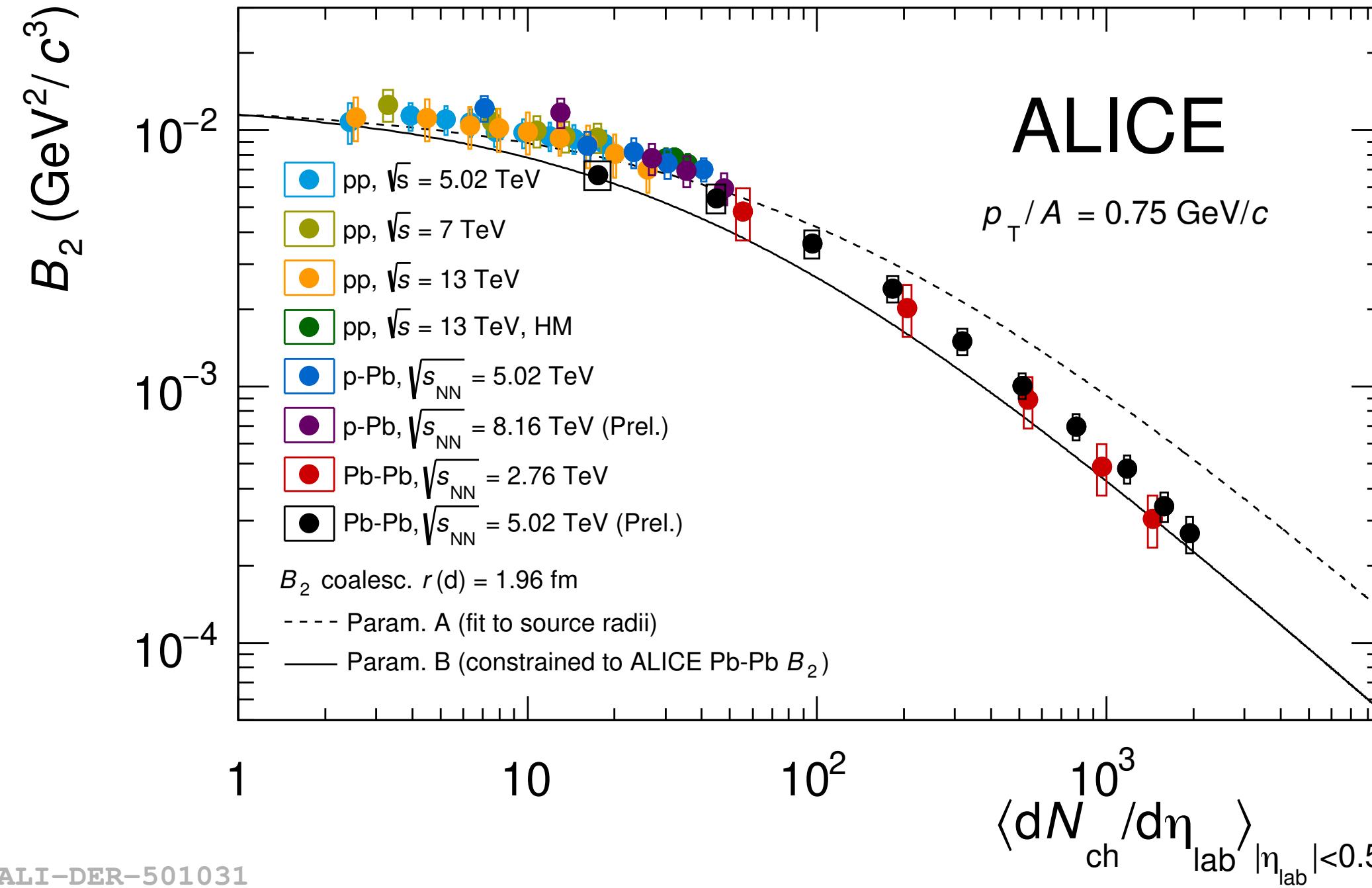
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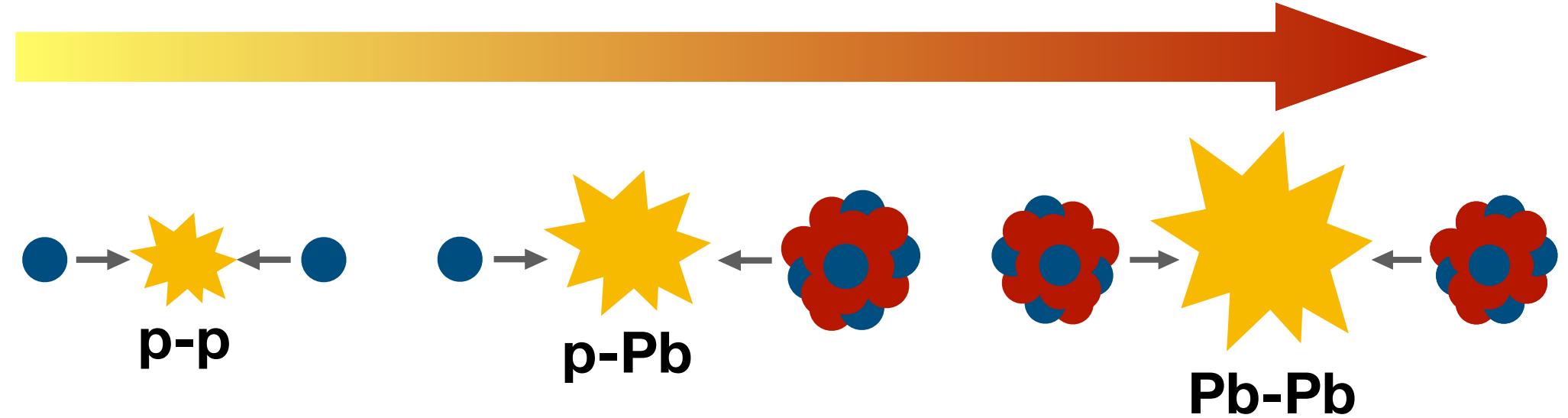
- For  **${}^3\text{He}/p$**  there are more tensions between data and models
- Not possible to discriminate between the two models
- **CSM cannot describe  $p/\pi$**  with the same correlation volume used for  $d/p$

# Coalescence parameter $B_A$



- $B_A$  evolves **smoothly** with **multiplicity**
  - dependence on the **system size**
- Comparison with theory:

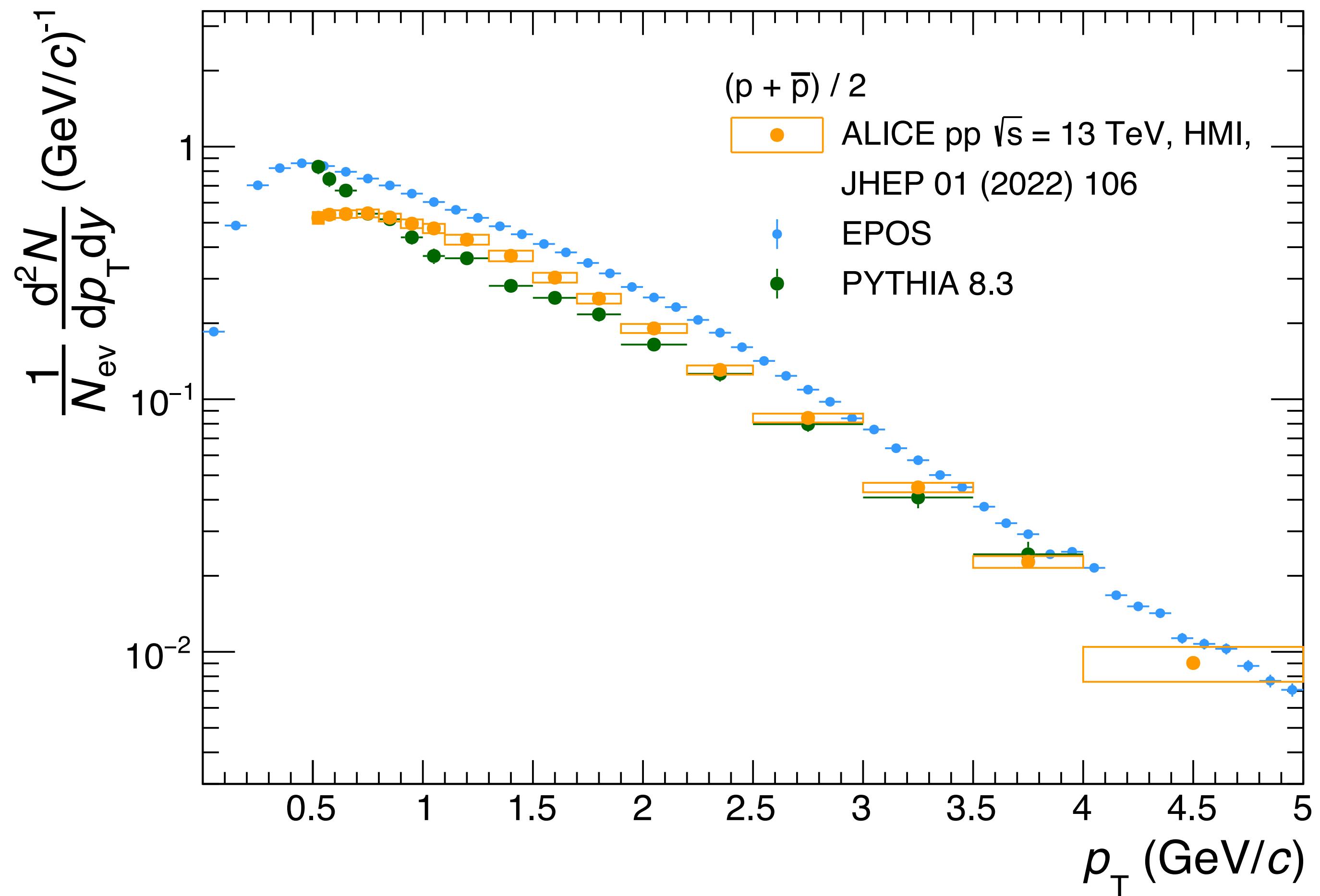
$$B_A = \frac{2J_A + 1}{2^A \sqrt{A}} \frac{1}{m^{A-1}} \left[ \frac{2\pi}{R^2(m_T) + (r_A/2)^2} \right]^{\frac{3}{2}(A-1)}$$



- **Two** different parameterisations for **dN/deta** vs **R**
  - None of them can describe simultaneously  $B_2$  and  $B_3$

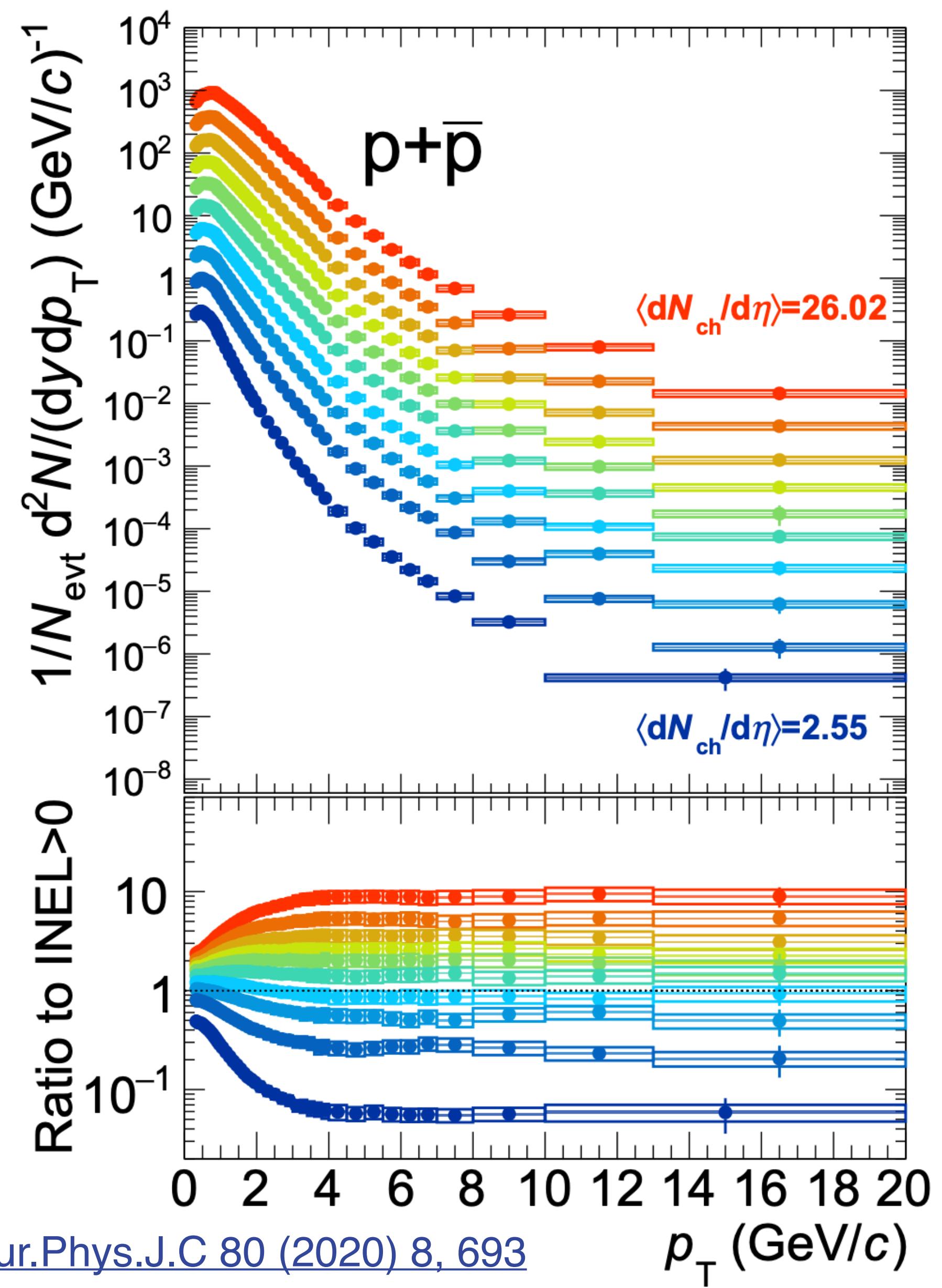
# Proton spectra in HM pp collisions

- Proton spectra are measured by ALICE in HM pp collisions at 13 TeV
  - Multiplicity class HMI :  $\langle dN/d\eta \rangle = 35.8 \pm 0.5$
- Data are compared with MC simulations based on EPOS and PYTHIA 8.3
  - Selection on forward multiplicity to match the average multiplicity at mid rapidity measured by ALICE



# Yield ratios

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



[Eur.Phys.J.C 80 \(2020\) 8, 693](https://doi.org/10.1140/epjc/s10050-020-08532-0)

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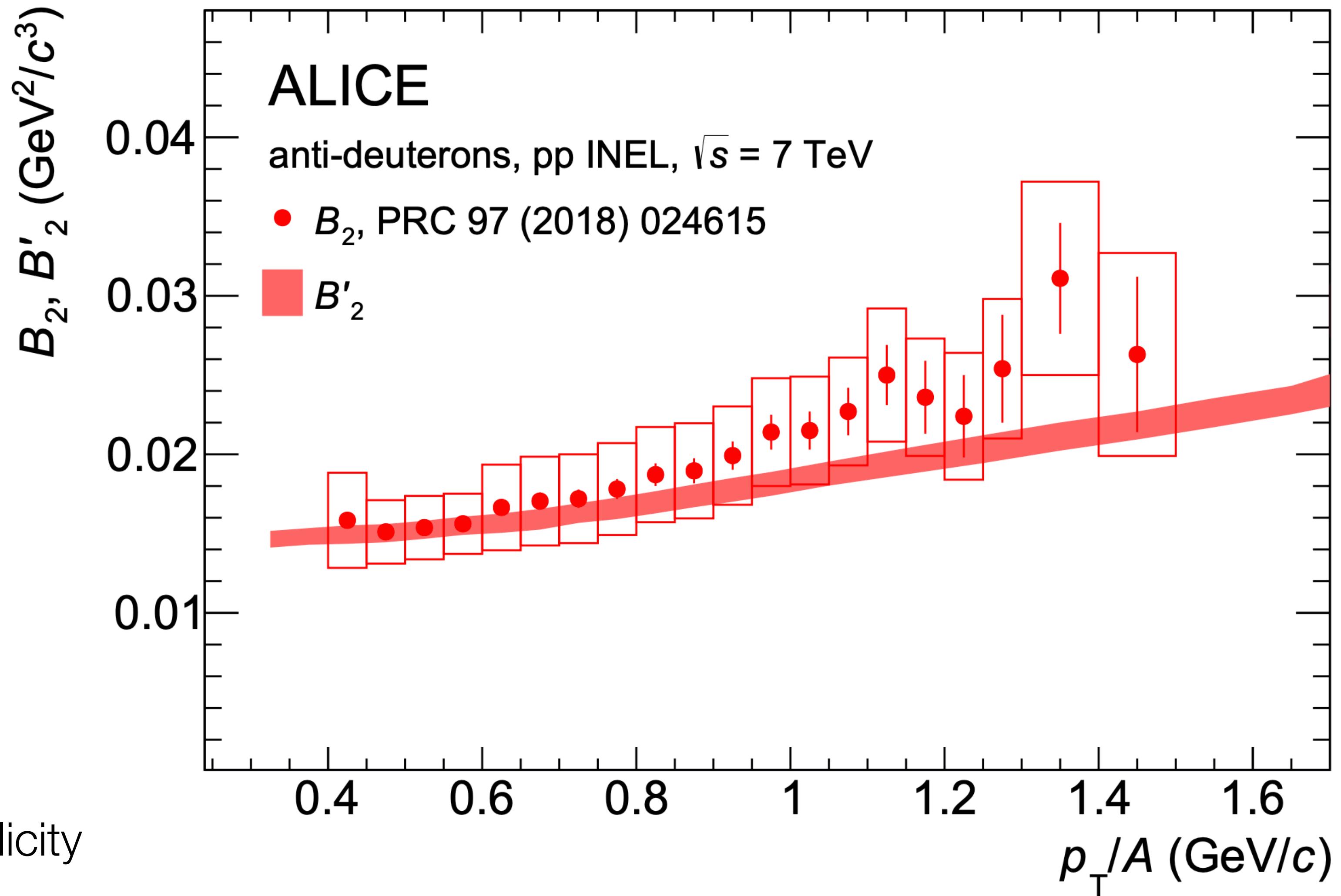
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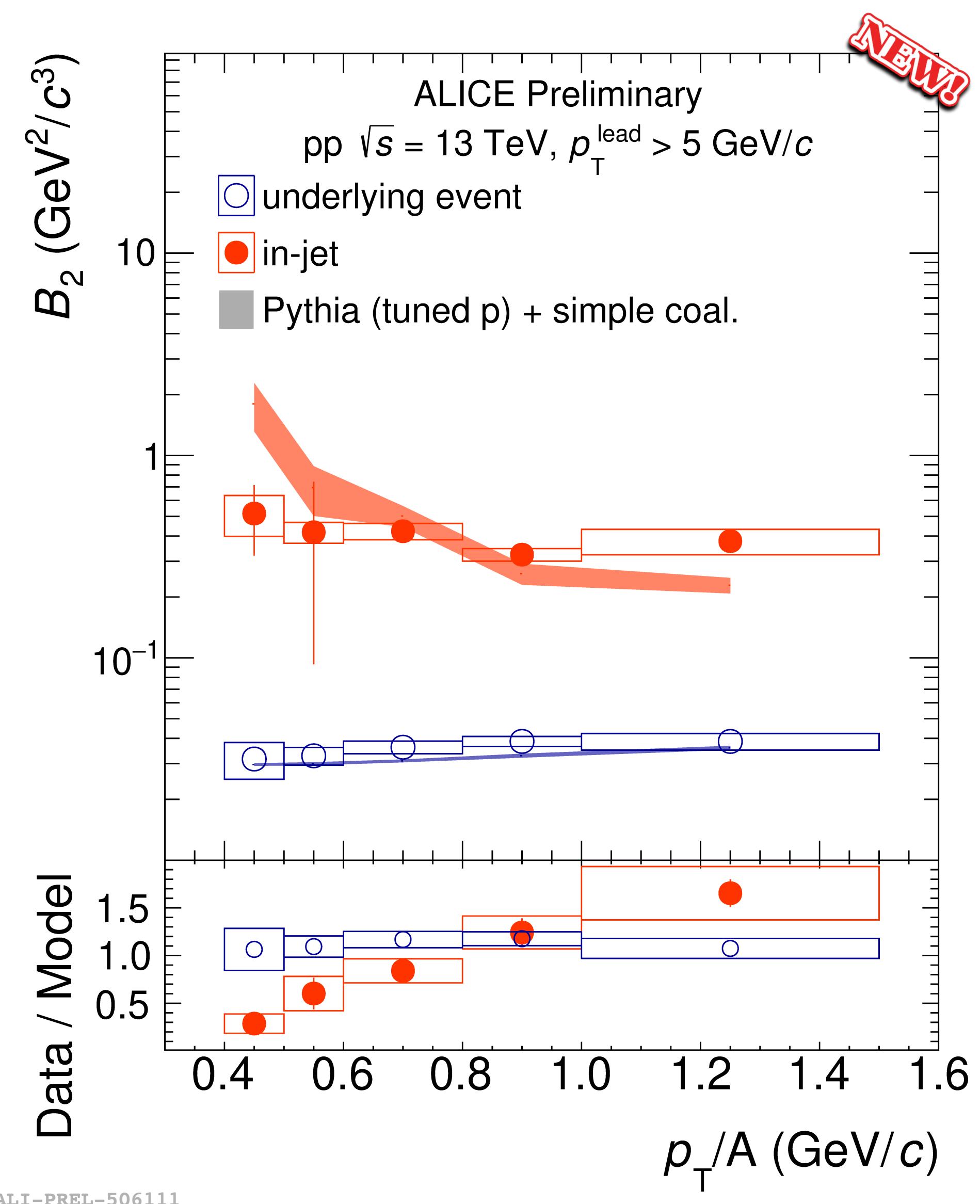
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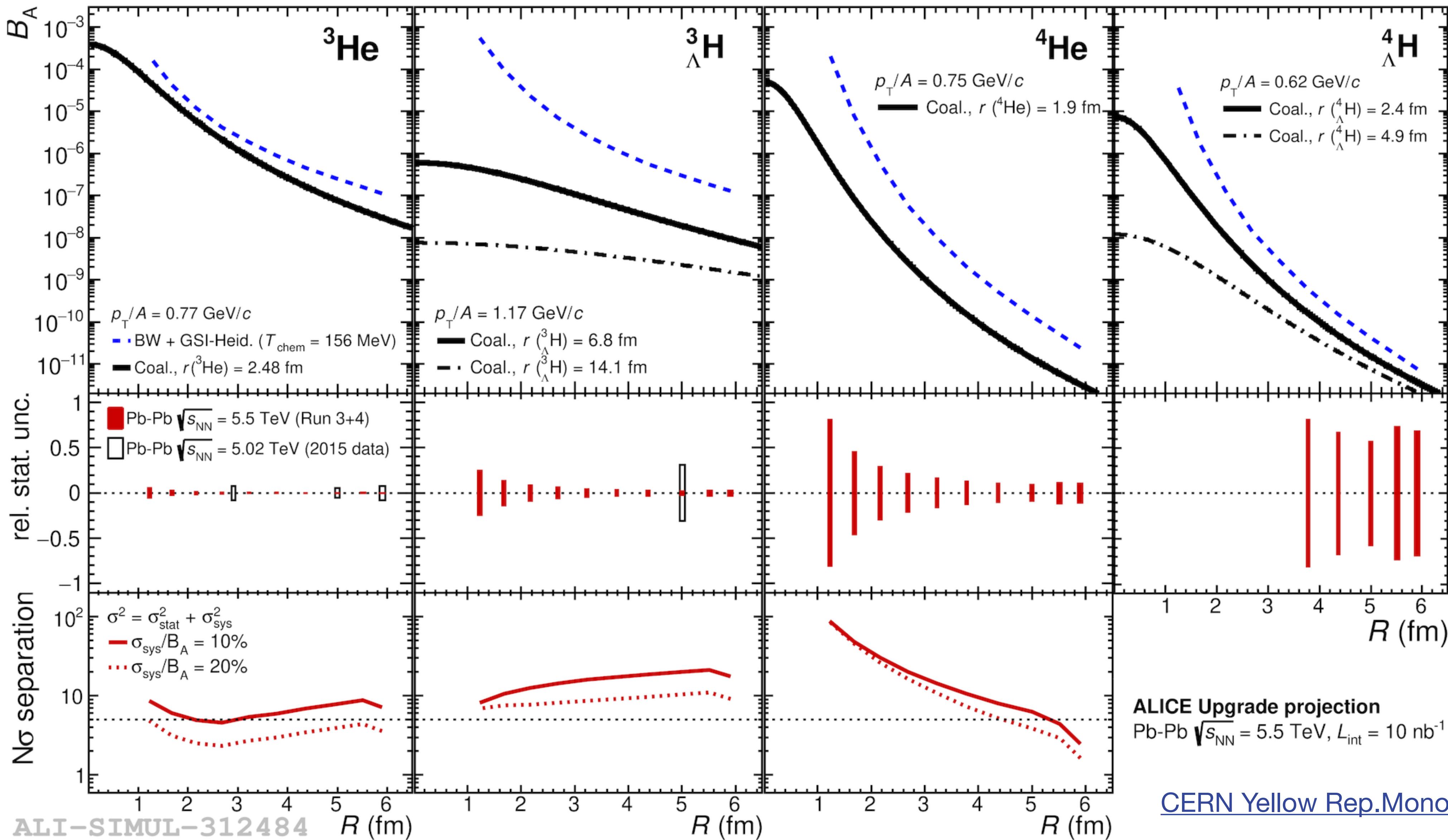
[Phys.Lett.B 794 \(2019\) 50-63](#)

# In-jet deuteron production

- Deuterons spectra are measured in the azimuthal regions:  
**towards**, **transverse** and **away**
  - The **transverse** region is considered a good estimation of the **UE**
  - **In-jet** spectrum = **towards** - **transverse**
- **$B_2$**  can be measured in-jet and in the underlying event
  - **In-jet enhancement** is observed
  - **PYTHIA + afterburner**:
    - describes well the underlying event production
    - decreasing trend not observed in data

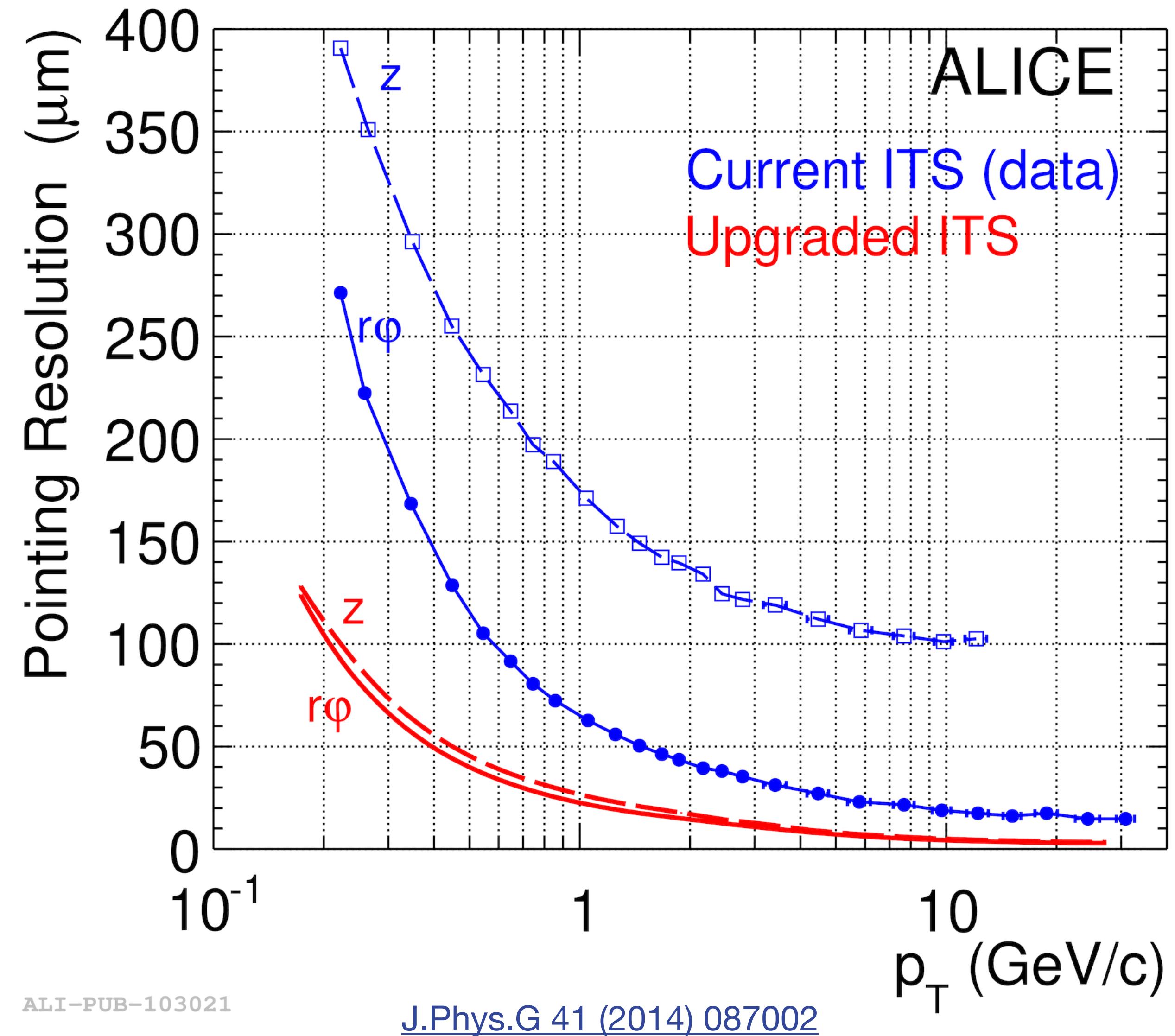


# (Hyper)nuclei in Pb-Pb collisions



# Upgrade of the ITS

- **Seven cylindrical layers** of silicon pixel sensors
  - Inner barrel: 3 layers with turbo geometry
  - Outer barrel: 4 layers with overlapping edges
- **Low material budget:**
  - 0.3%  $X_0$  for the I.B.
  - 1%  $X_0$  for the O.B.
- **Improved tracking precision**



ALI-PUB-103021

[J.Phys.G 41 \(2014\) 087002](#)