Recent results from ALICE on (anti)(hyper)nuclei

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INFN, Sezione di Torino

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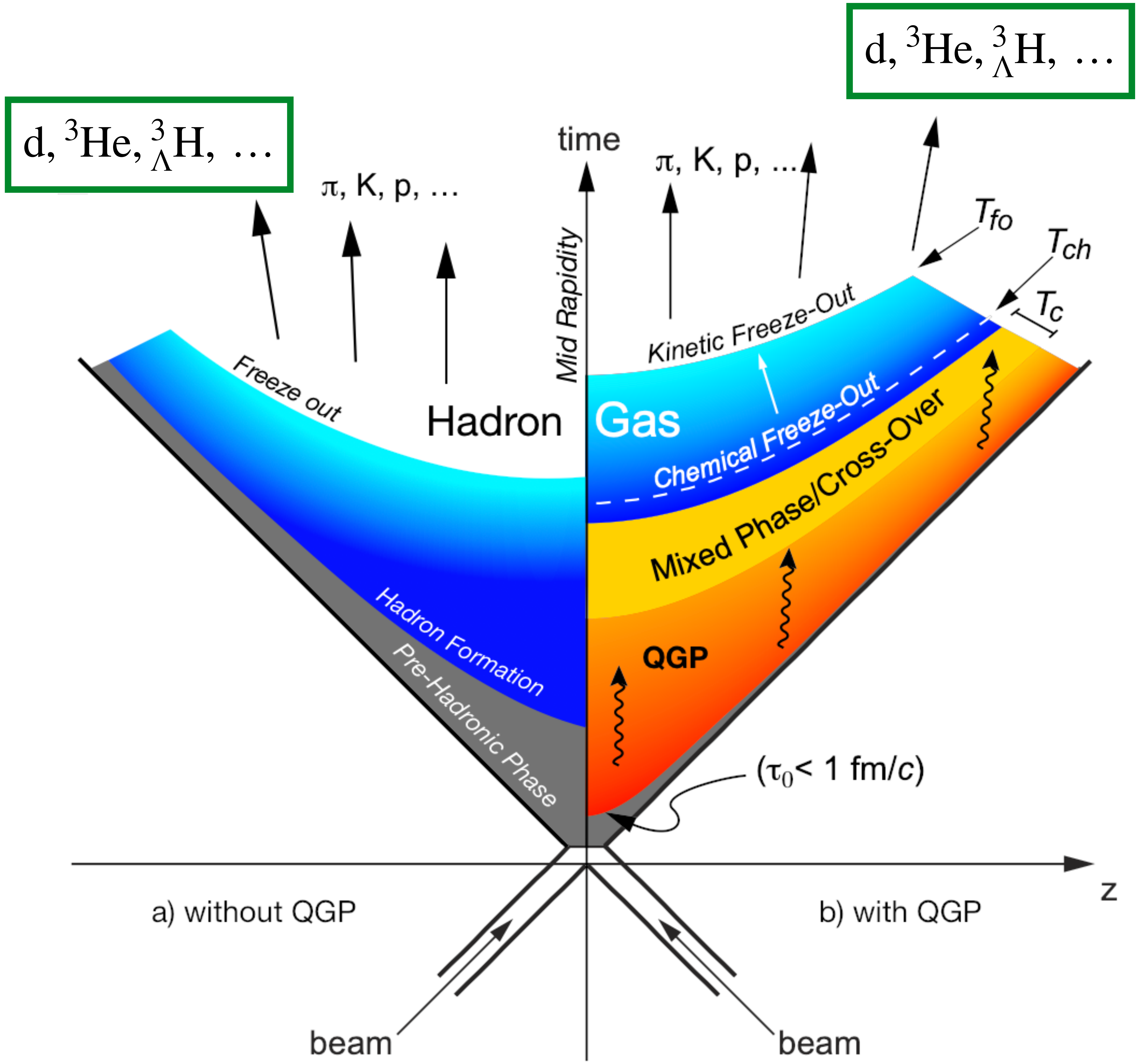
4th EMMI workshop

Nuclear and hypernuclear matter production

- Light (anti)(hyper)nuclei are abundantly produced at the LHC in hadronic collisions
- Two classes of models to describe the production:
  - the **statistical hadronisation** model
  - the **coalescence** model
- Years of measurements at the LHC (and not only):
  - improved understanding of the production mechanisms



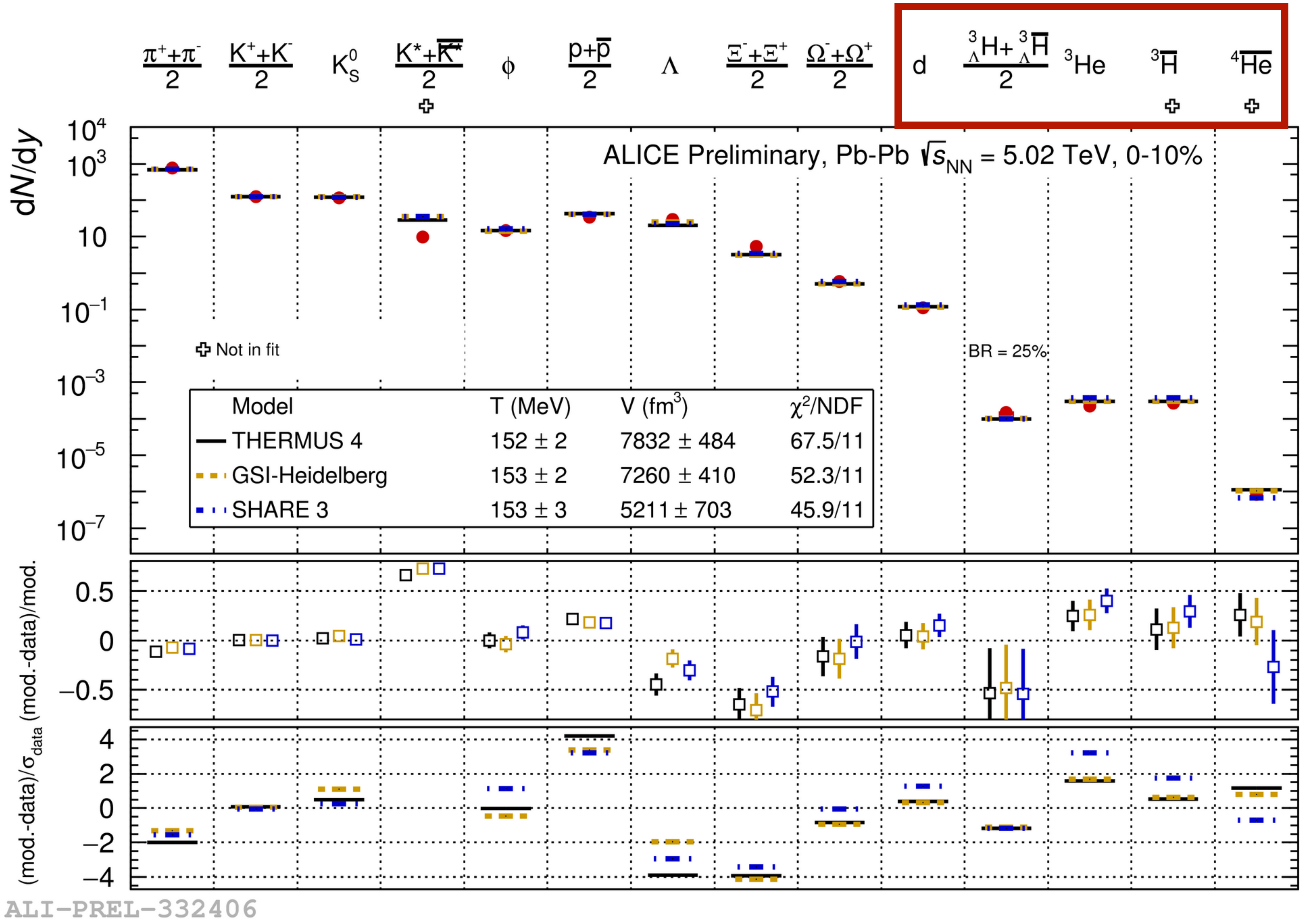
The Statistical Hadronisation Model (SHM)

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

V. Vovchenko et al., PLB 785 (2018) 171-174



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

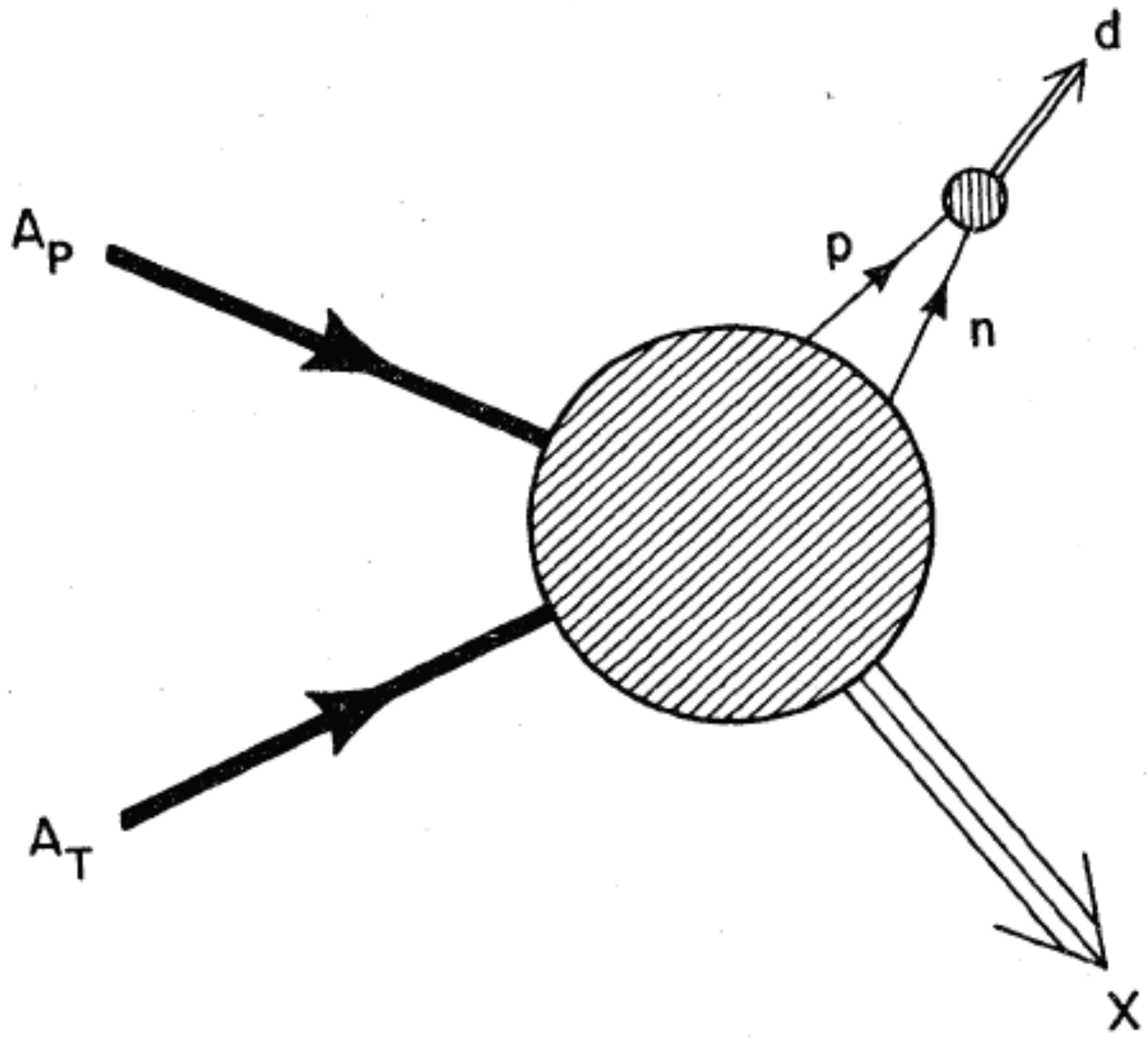
- Nucleons that are **close in phase space** and with the correct spin configuration at the **freeze-out** can form a nucleus via **coalescence**
- The key concept is the overlap between the **nuclear wave-function** and the **phase space** distribution of the **nucleons**
- The main parameter of the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

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

where:

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

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

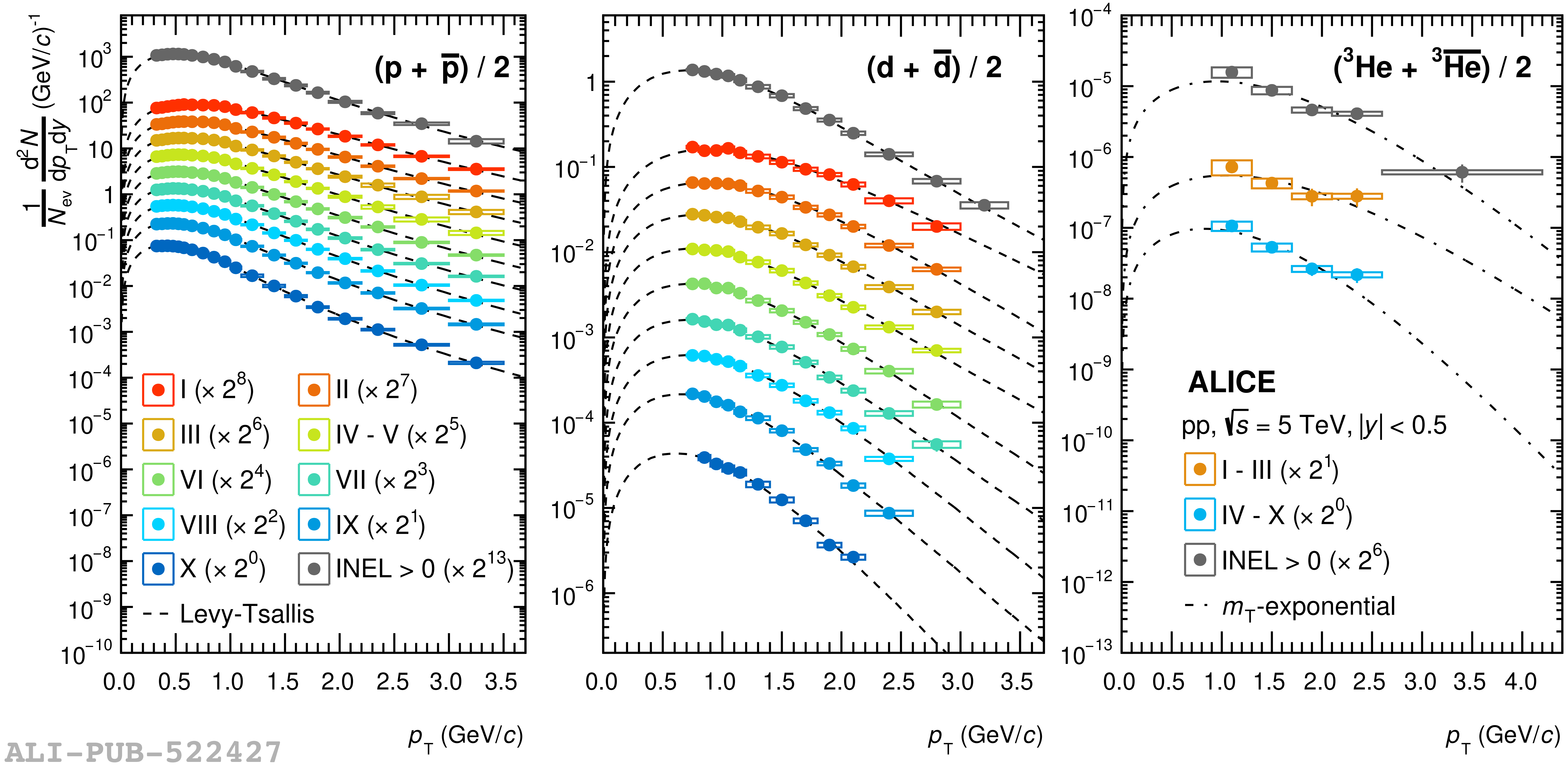


J. I. Kapusta, PRC 21 (1980) 1301

F. Bellini et al., PRC 103, 014907

Production spectra of (anti)nuclei with ALICE

- ALICE measured production spectra of nuclei in pp, p-Pb and Pb-Pb collisions
  - excellent PID

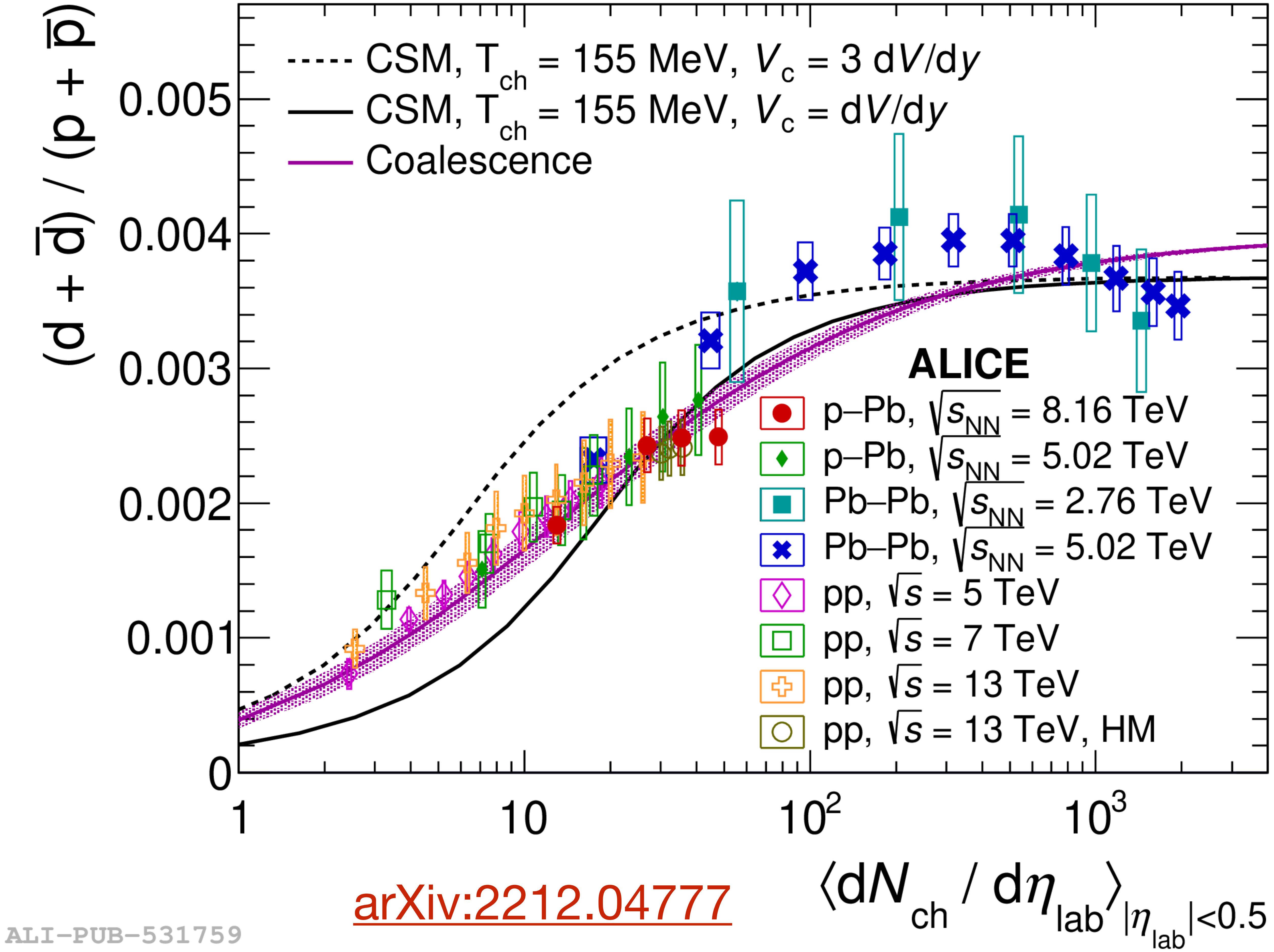


Eur. Phys. J. C 82, 289 (2022)

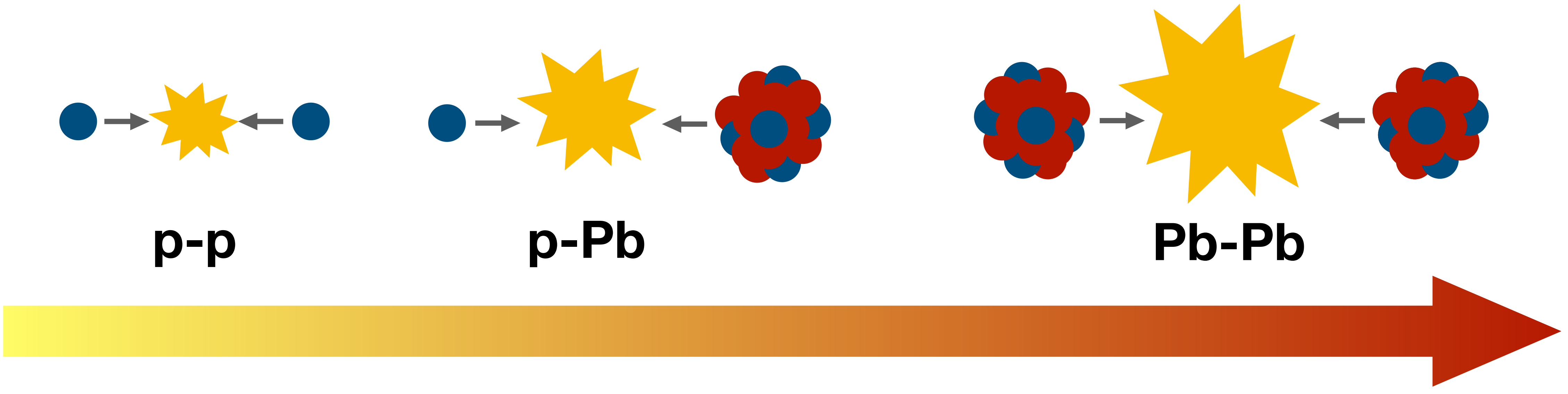
- Measurements in classes of multiplicity
  - related to system size
- Main observables:
  - Ratio of p_T-integrated yields **A/p**
  - Coalescence parameter $\boldsymbol{B_A}$

Yield ratios

- **d/p** ratio evolves **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



arXiv:2212.04777



Yield ratios

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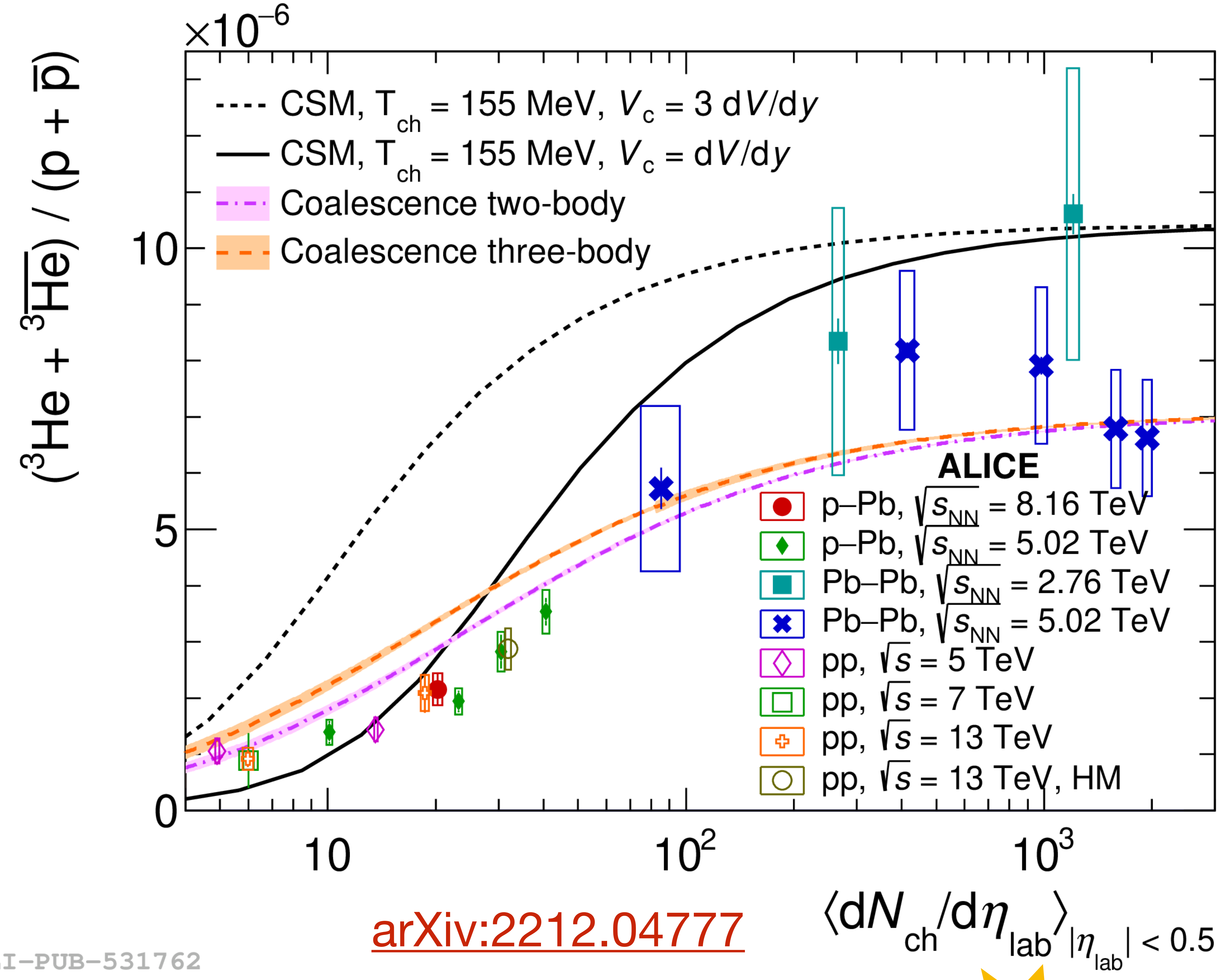
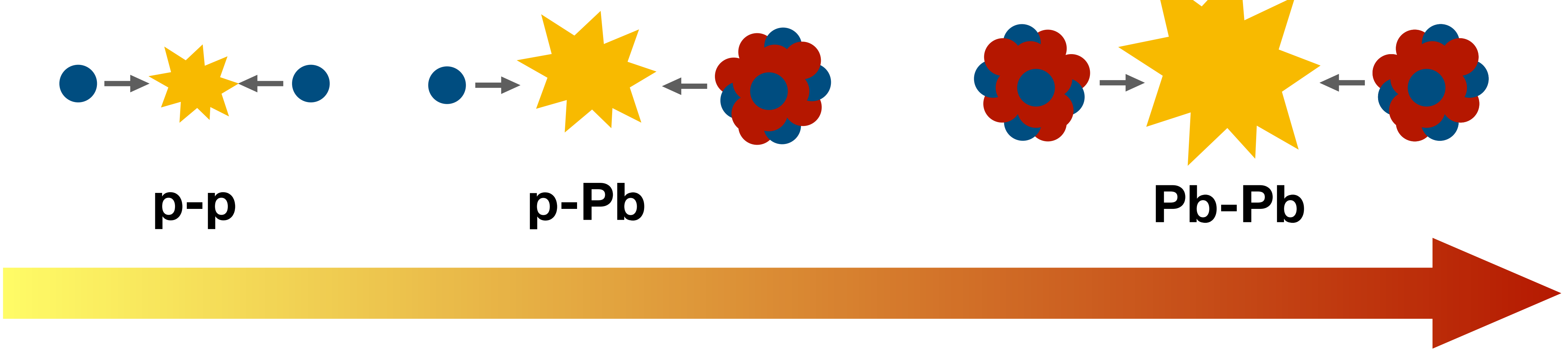
  - dependence on the **system size**
- For **d/p** ratio both the models describe the data:
  - CSM: canonical suppression
  - Coalescence model: interplay between source size and nuclear size
- Also ^{3}**He/p** evolves **smoothly** with **multiplicity**
  - But there are more tensions between data and models
- Coalescence seems to describe better data for A > 2

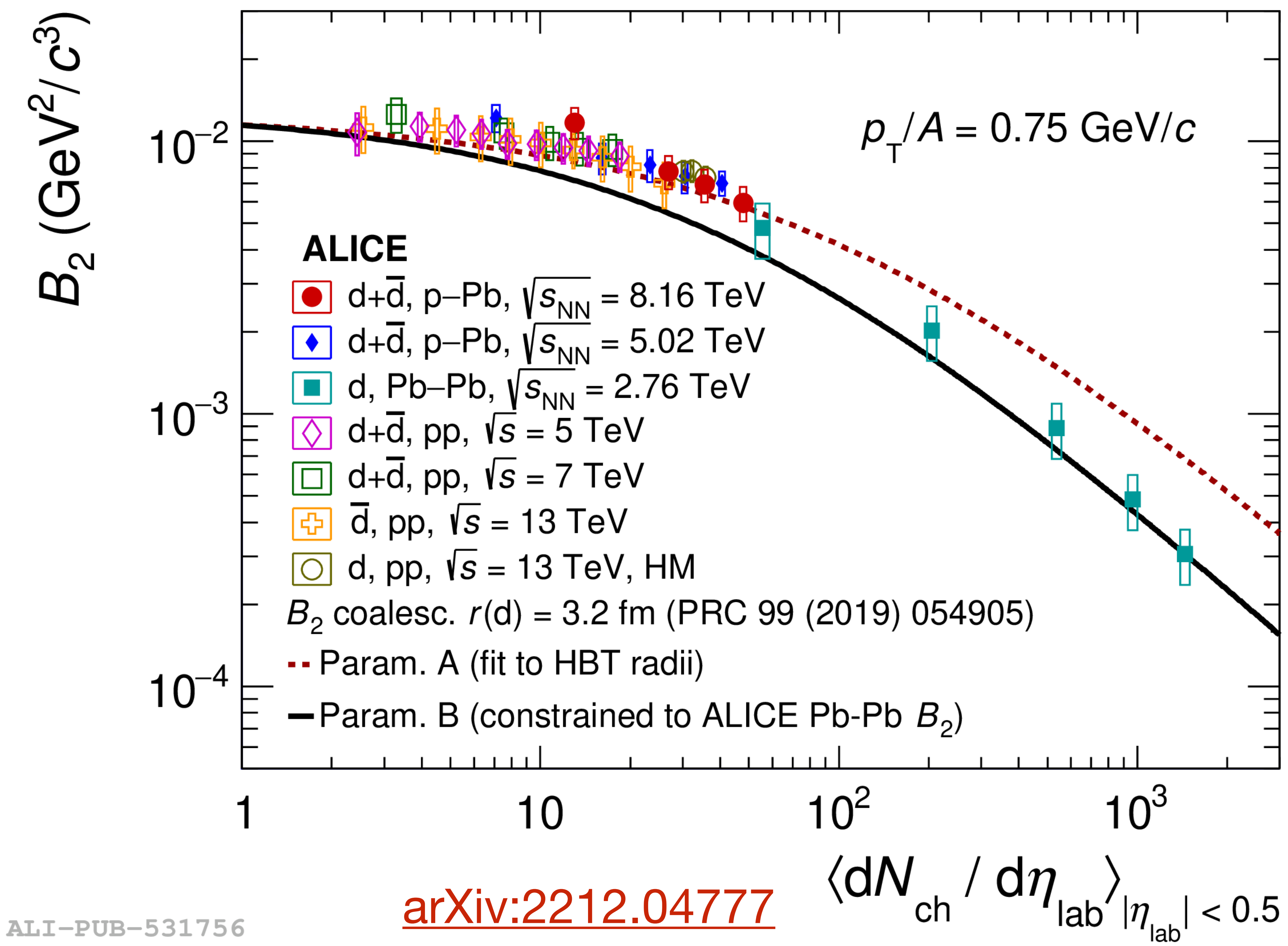


ALI-PUB-531762

arXiv:2212.04777



Coalescence parameter B_A



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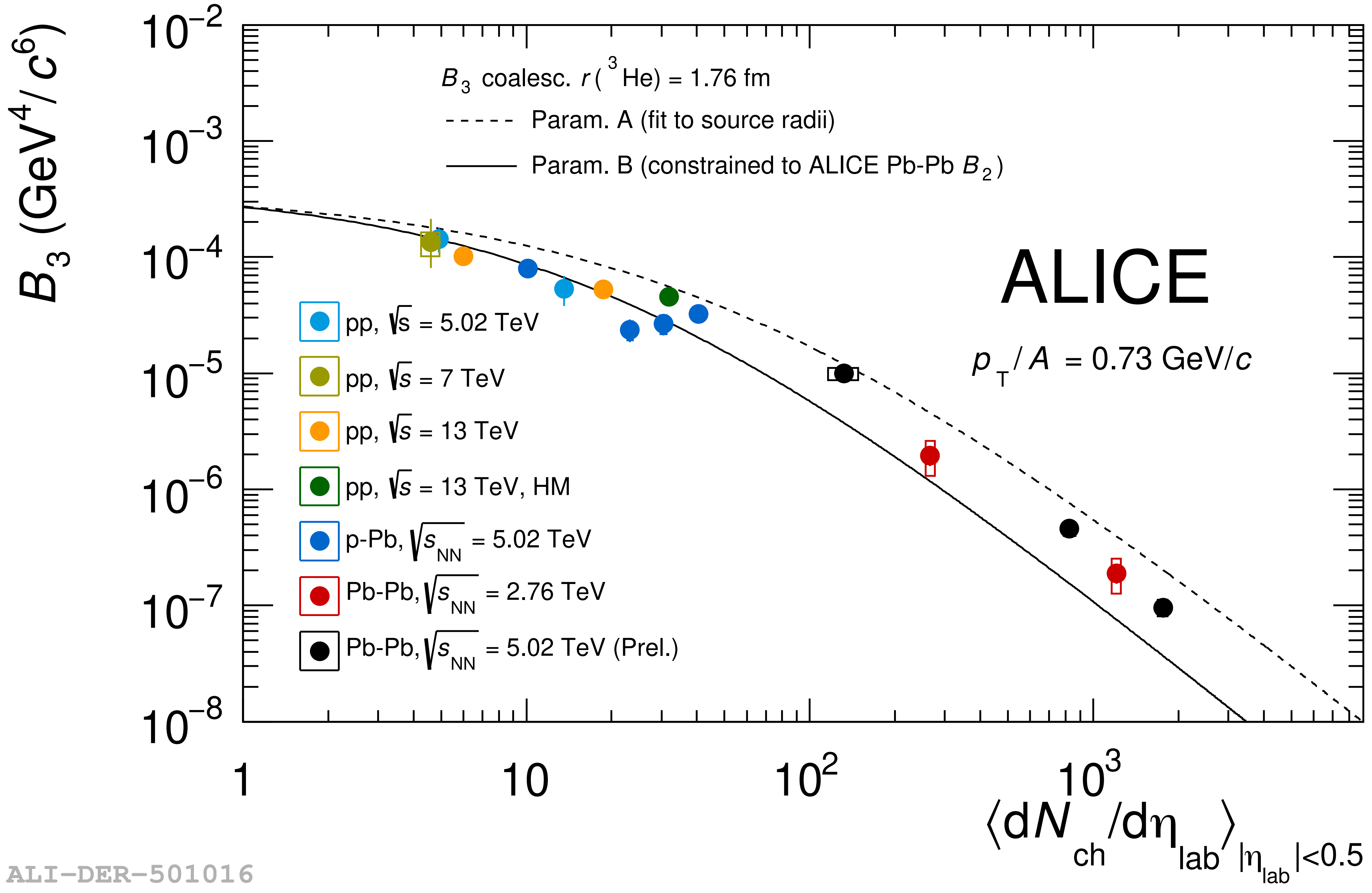
arXiv:2212.04777



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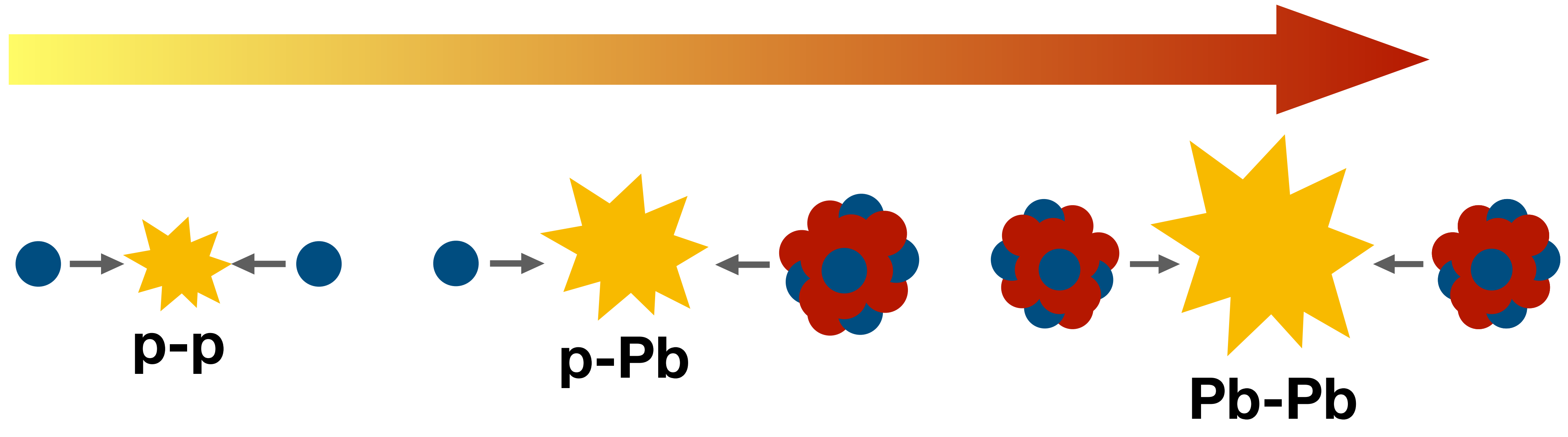


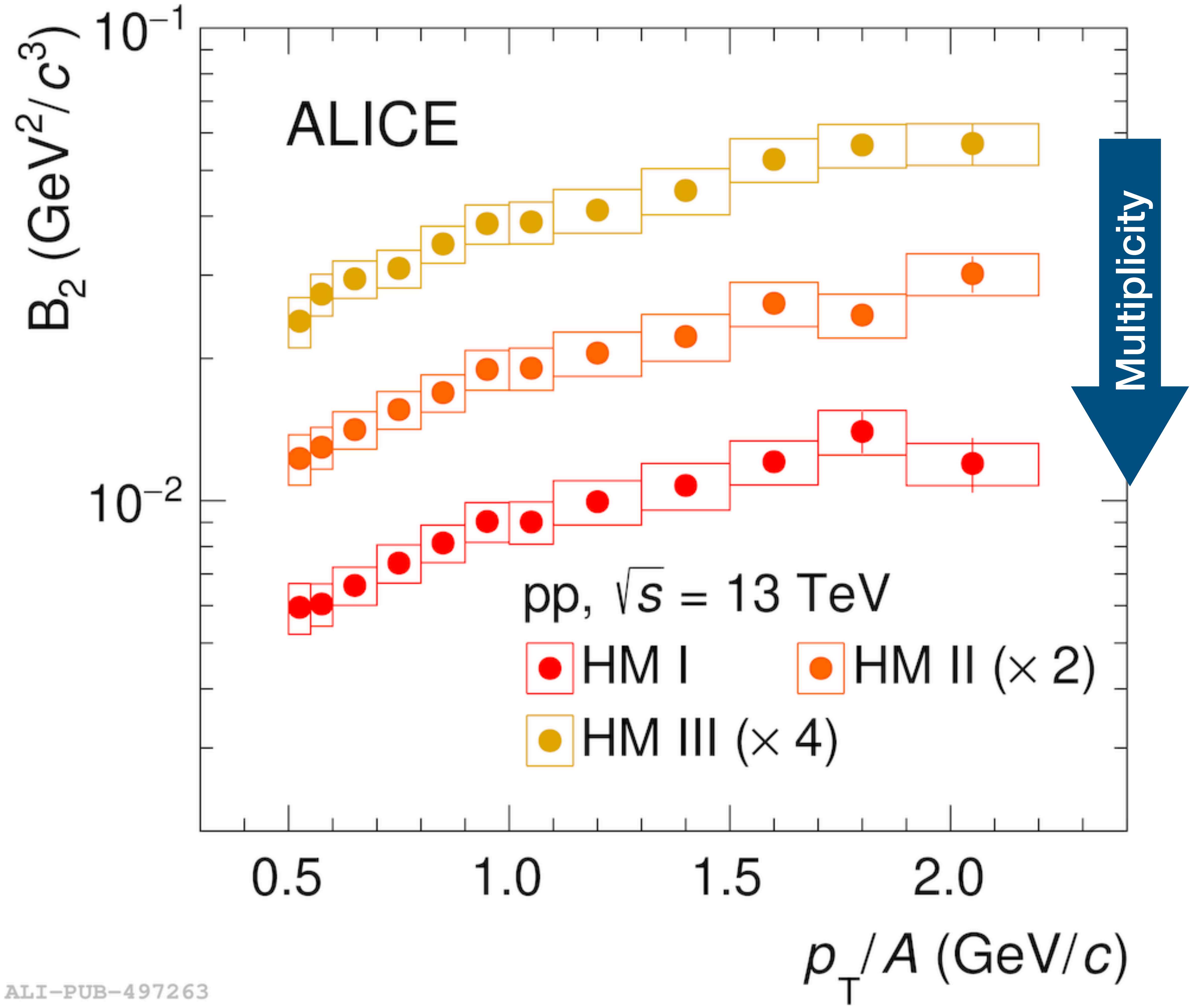
- **B_A** evolves **smoothly** with **multiplicity**
  - dependence on the **system size**
- Comparison with theory:

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

- **Two** different parameterisations for **d*N*/d*η*** 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
- Using the same data sample, the **source size** has been measured exploiting femtoscopic techniques
  - comparison with **theoretical predictions** is possible



JHEP 01 (2022) 106

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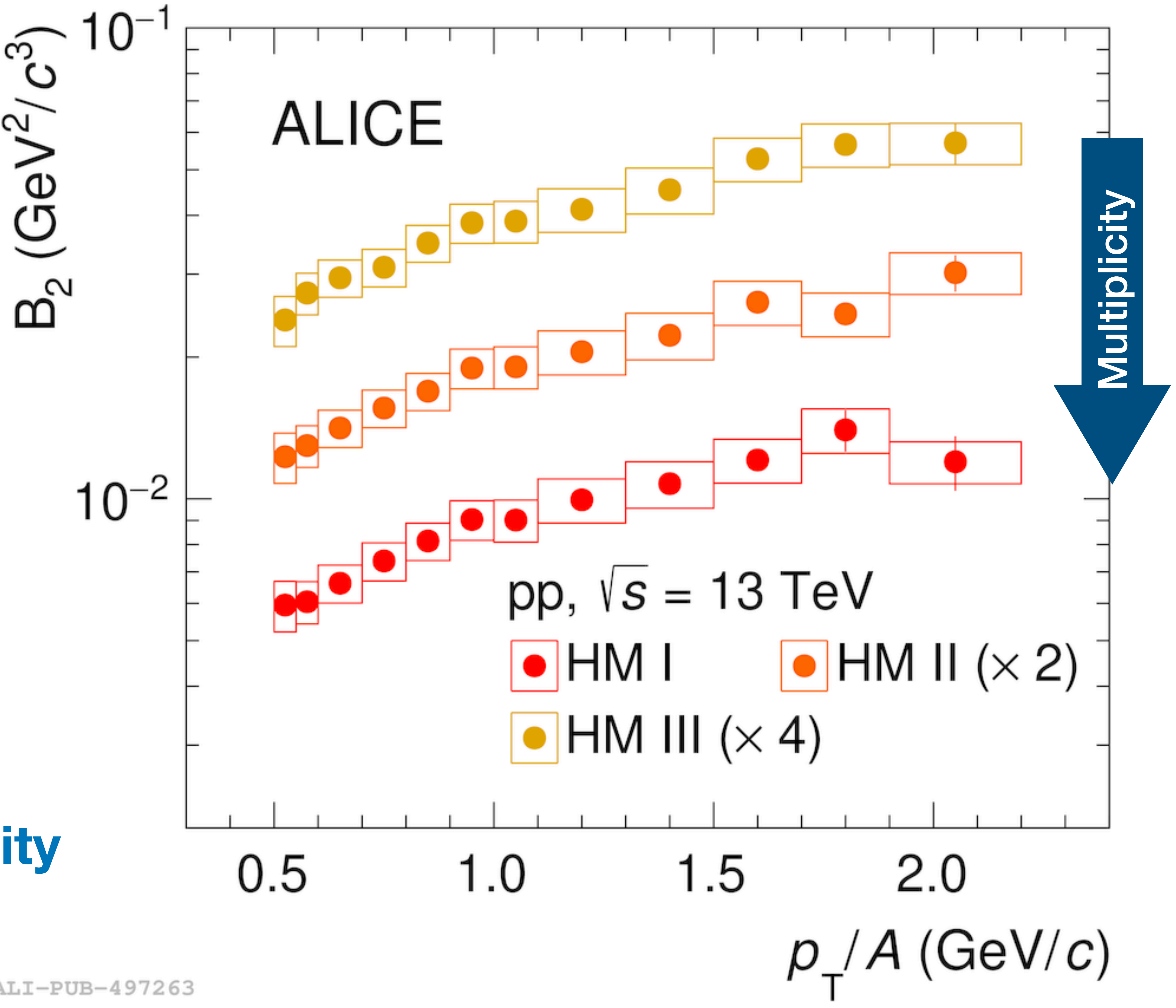
  - comparison with **theoretical predictions** is possible

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

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

K. Blum et al., PRC 99 (2019) 044913



JHEP 01 (2022) 106

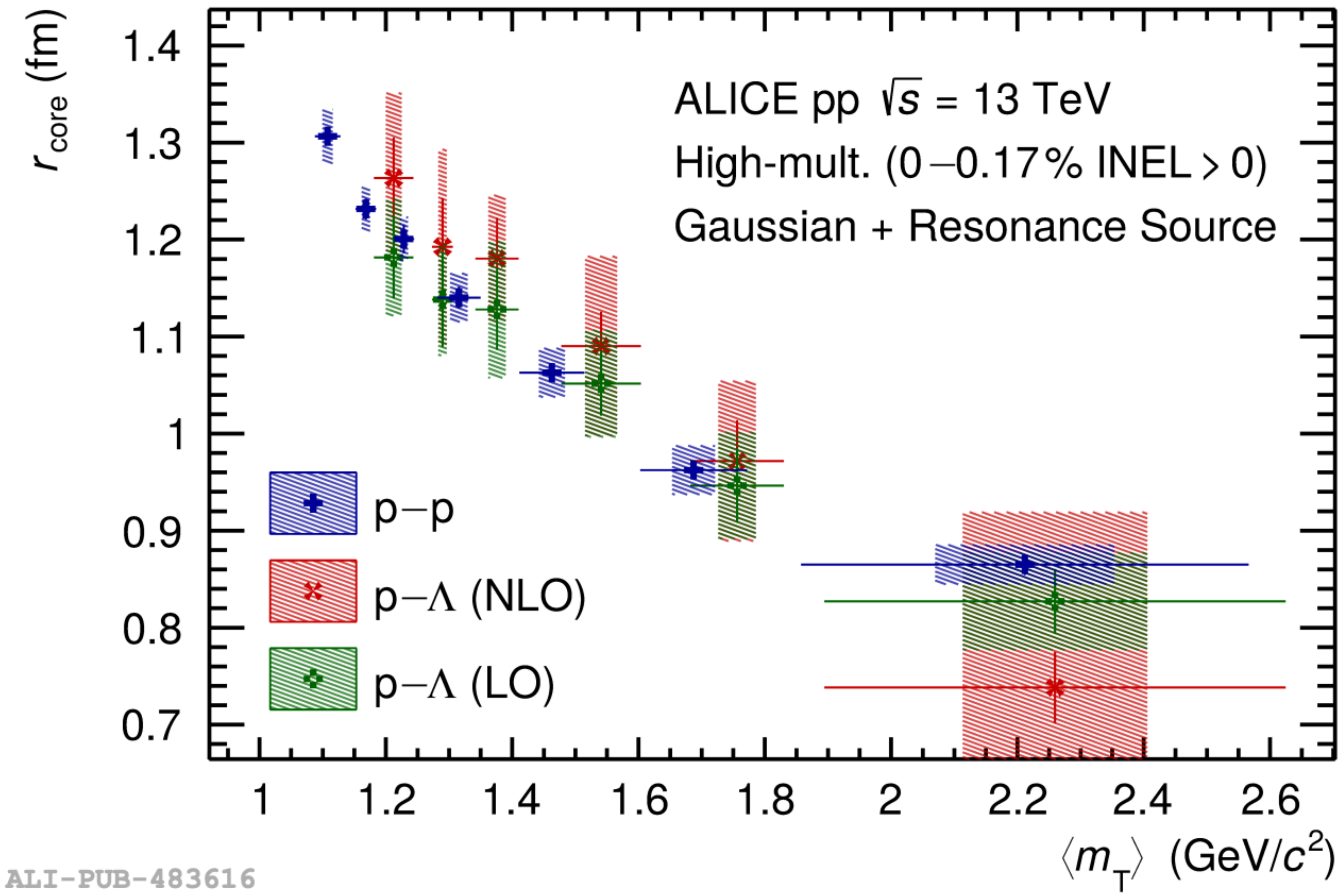
B_A vs p_T in HM pp collisions

- Putting the pieces together:

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

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

- We can test different **wave functions** $\phi_\mathrm{d}(\vec{r})$
- We have the precise measurement of the **source size** with femtoscopy
- **No free parameters!**



PLB 811 (2020) 135849

B_A vs p_T in HM pp collisions

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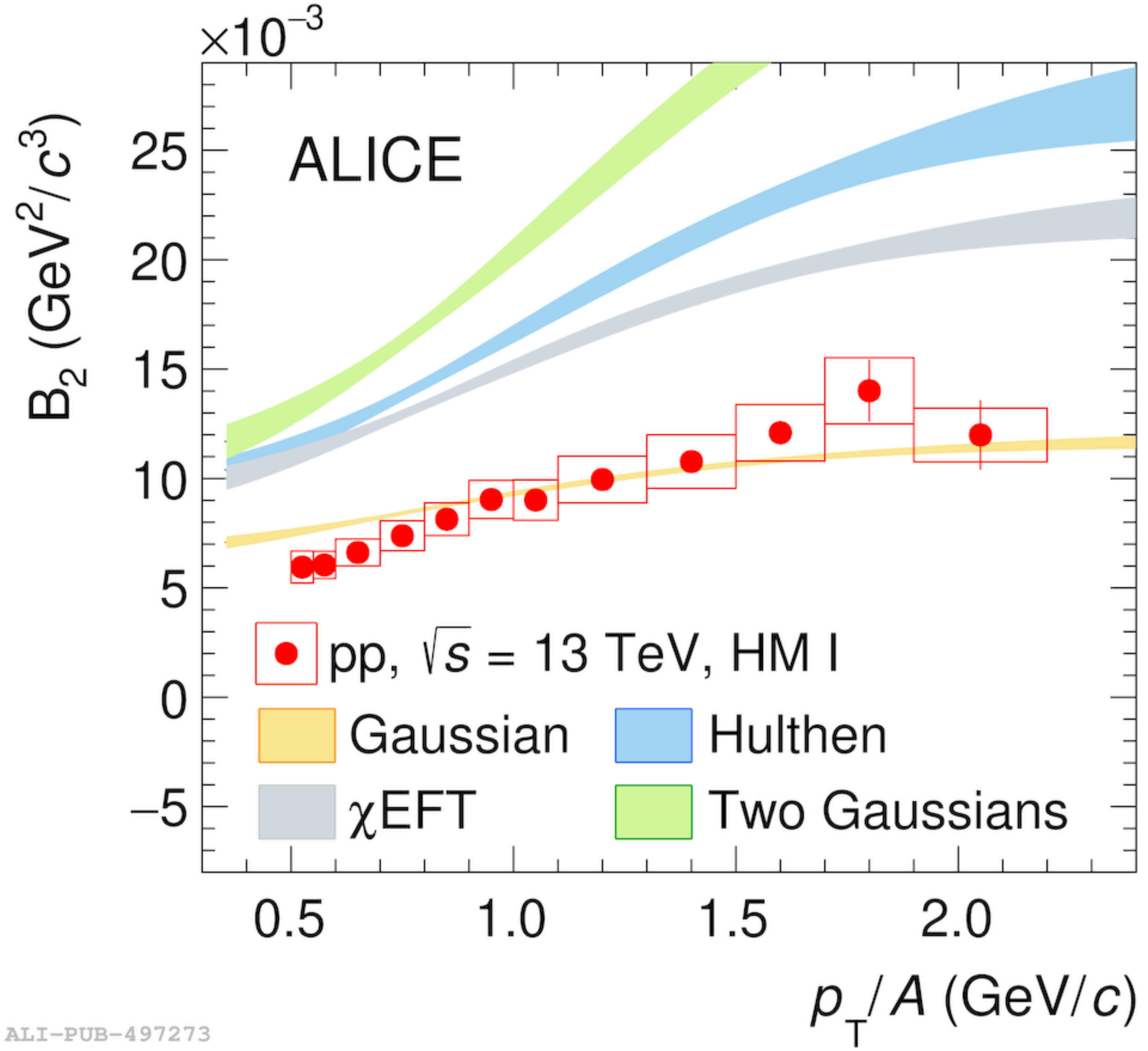

ALI-PUB-497273

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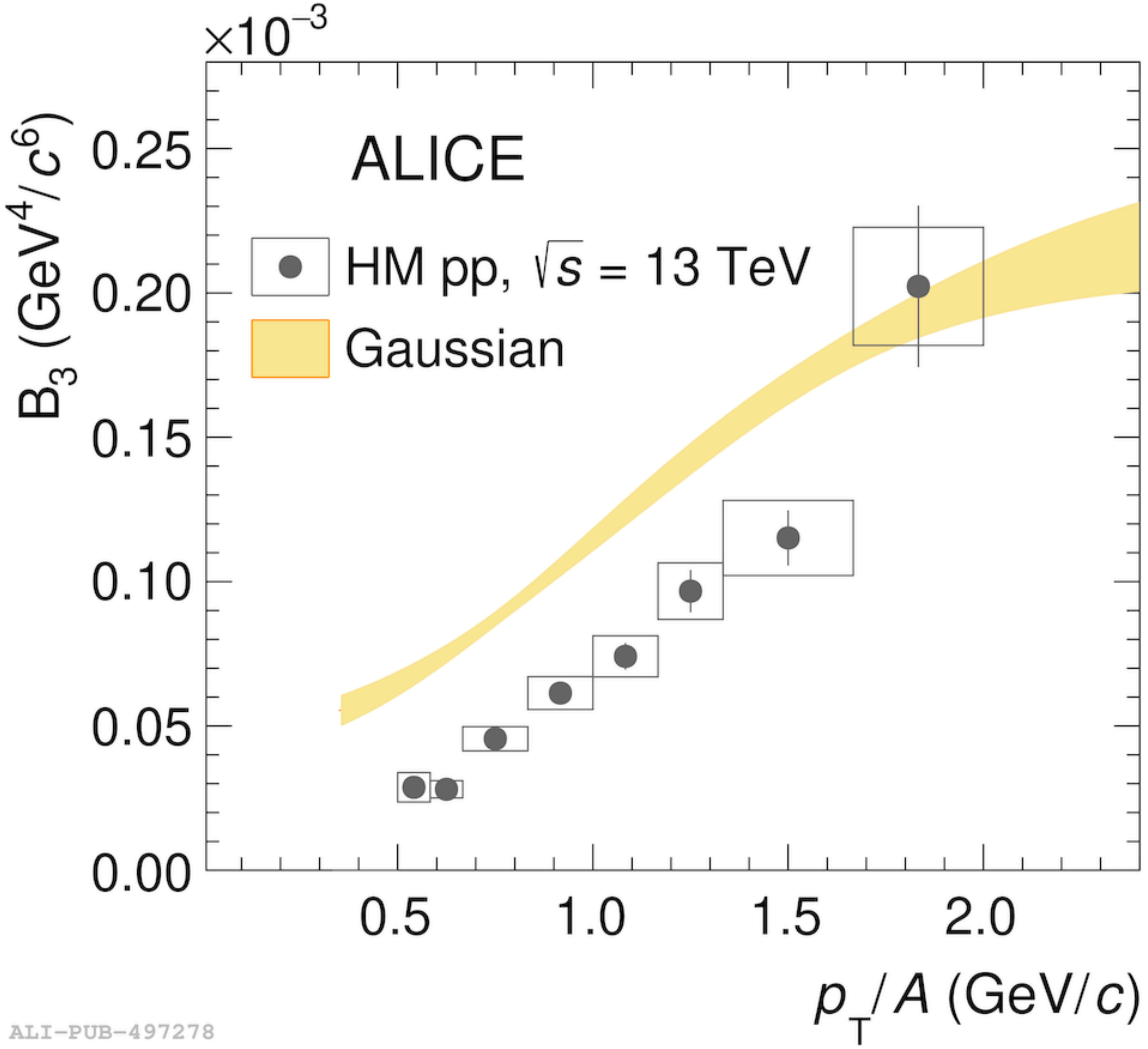
- B_2 in agreement with Gaussian wave function (d = 3.2 fm)
  - From low-scattering experiment Hulthén is expected to provide the best description

→ See Maximilian's talk, this afternoon!

B_A vs p_T in HM pp collisions

- 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:

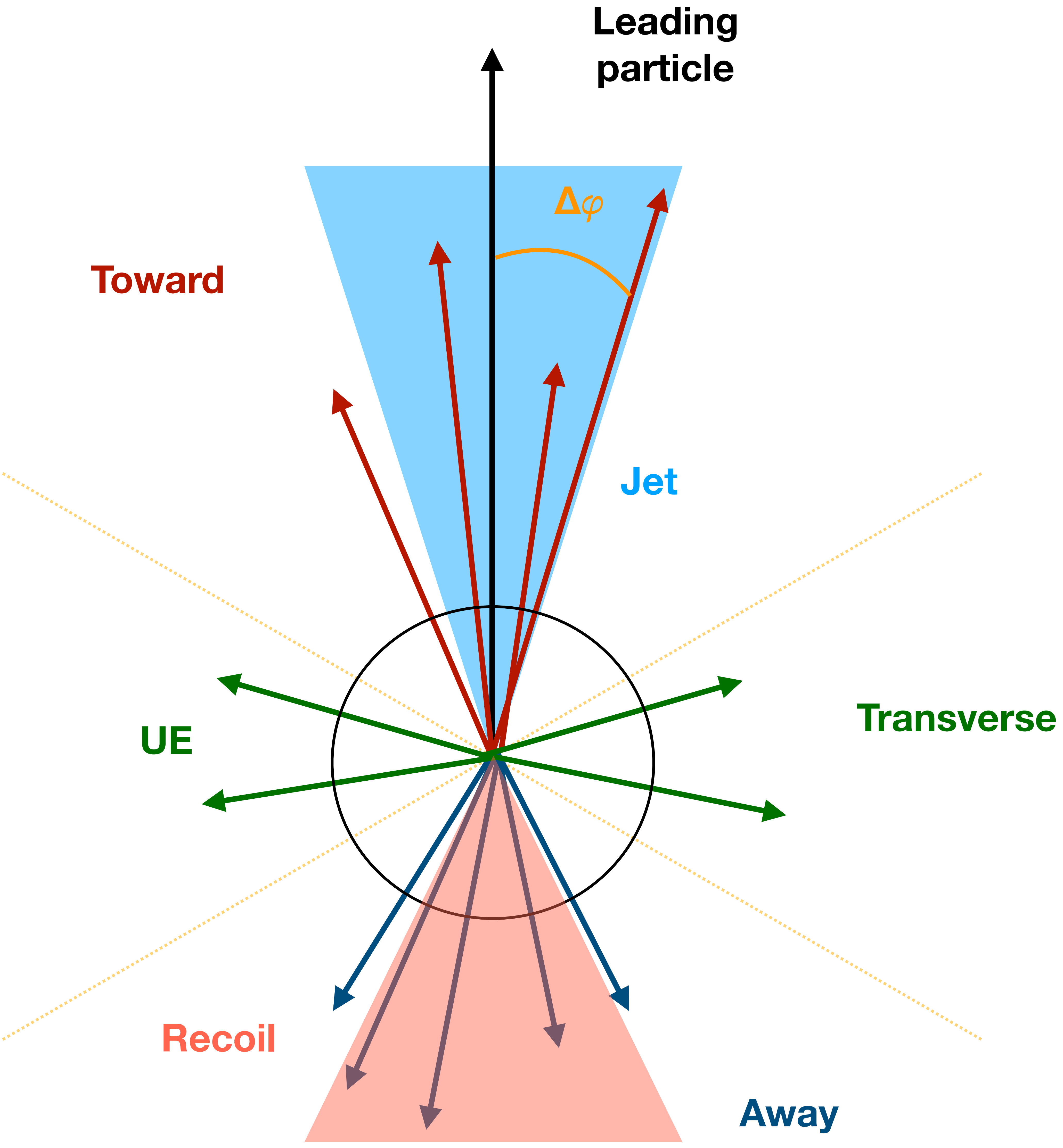
$$B_3 = \frac{2\pi^3}{\sqrt{3}\, m_p^2} \Big/ \left[R^2 + \left(\frac{d}{2}\right)^2\right]^3$$



JHEP 01 (2022) 106

In- and out-of-jet production

- 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, $p_T > 5$ GeV/c) is used as jet-proxy
- Three regions are distinguished wrt the leading particle
  - **Toward**: $|\Delta\varphi| < 60°$ → Jet + UE
  - **Transverse**: $60° < |\Delta\varphi| < 120°$ → UE
  - **Away**: $|\Delta\varphi| > 120°$ → Recoil + UE



In- and out-of-jet production

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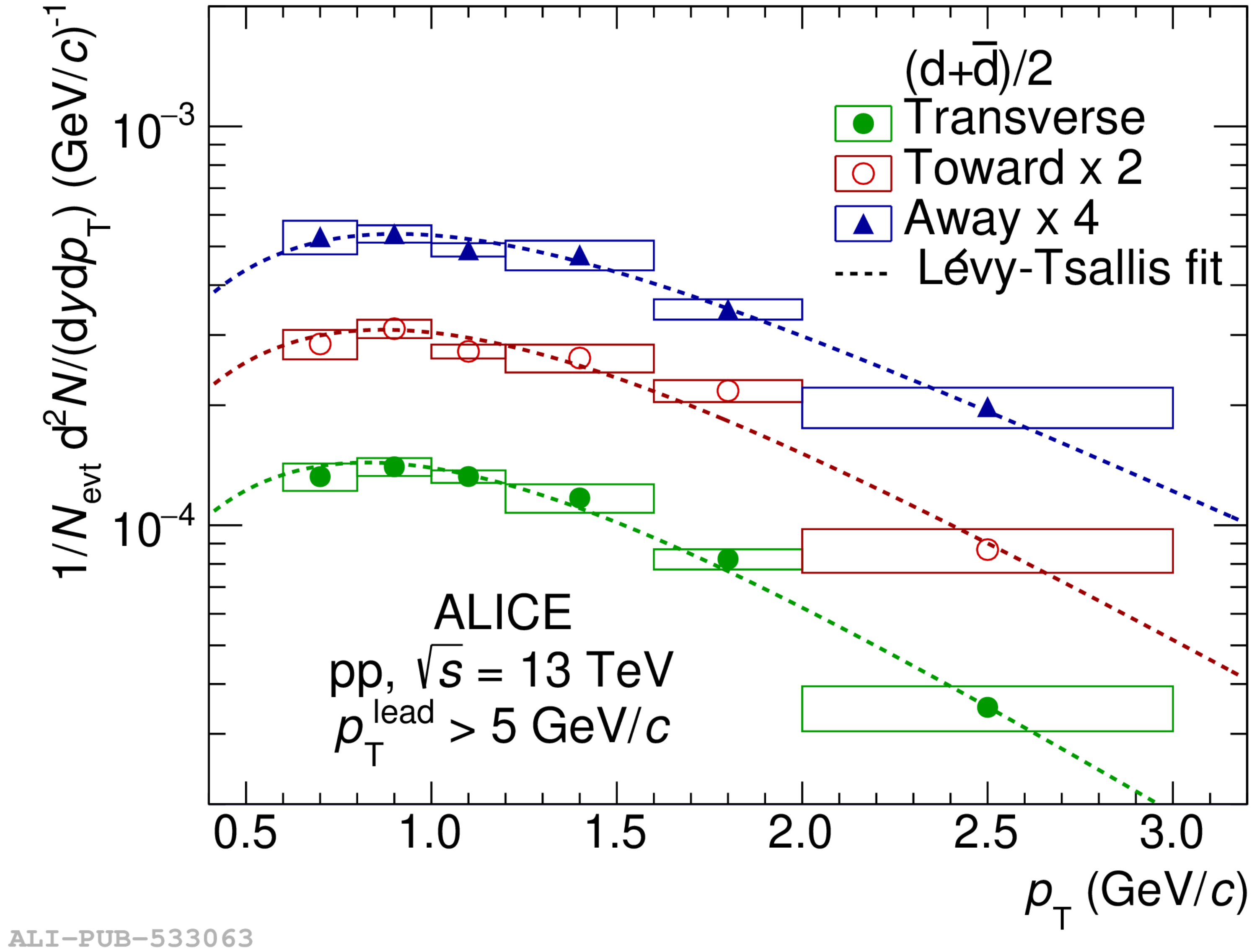
- Deuteron spectra are measured in the azimuthal regions: toward, transverse and away
  - The transverse region to good approximation coincides with the **UE**
  - In-jet spectrum = toward - transverse



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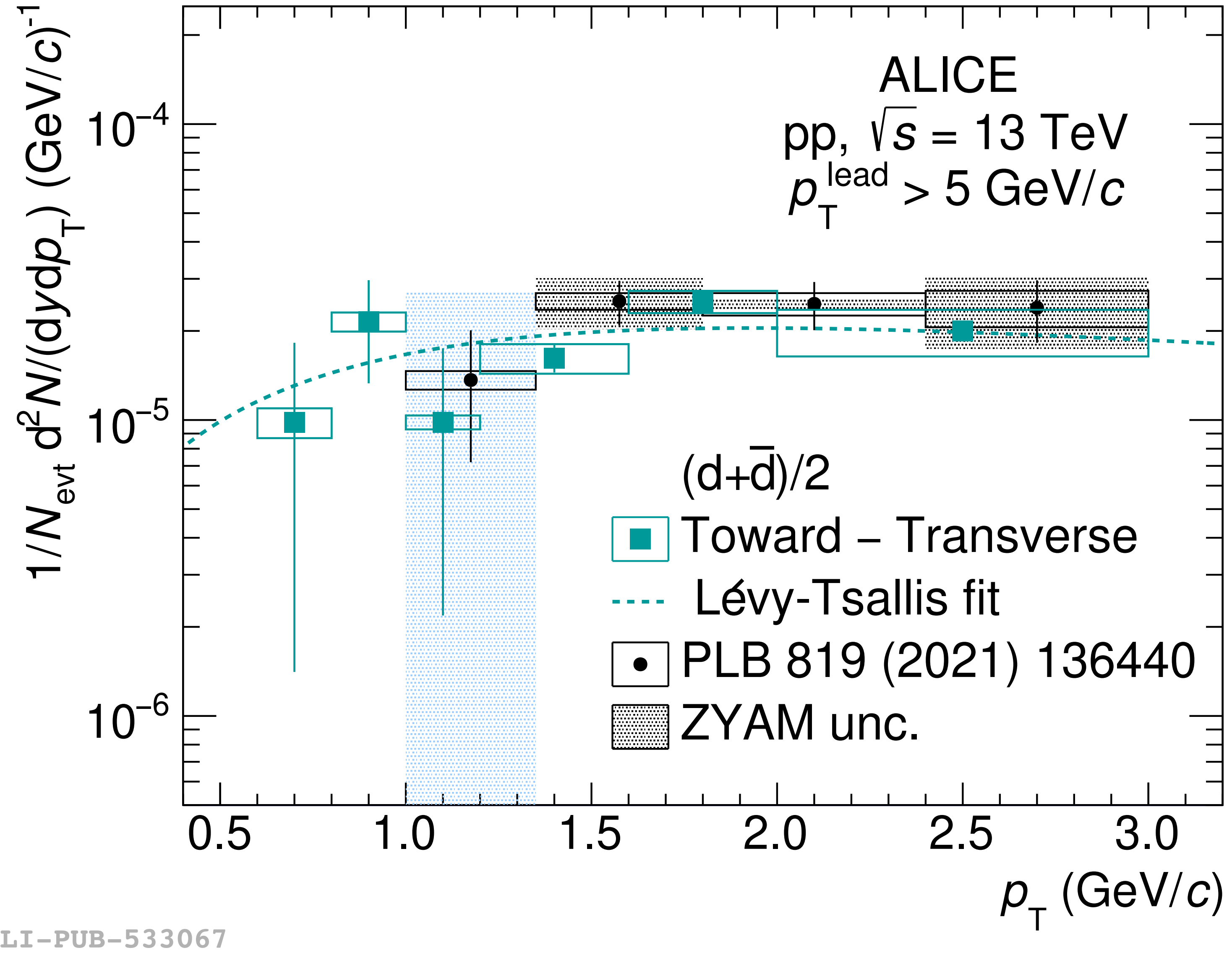
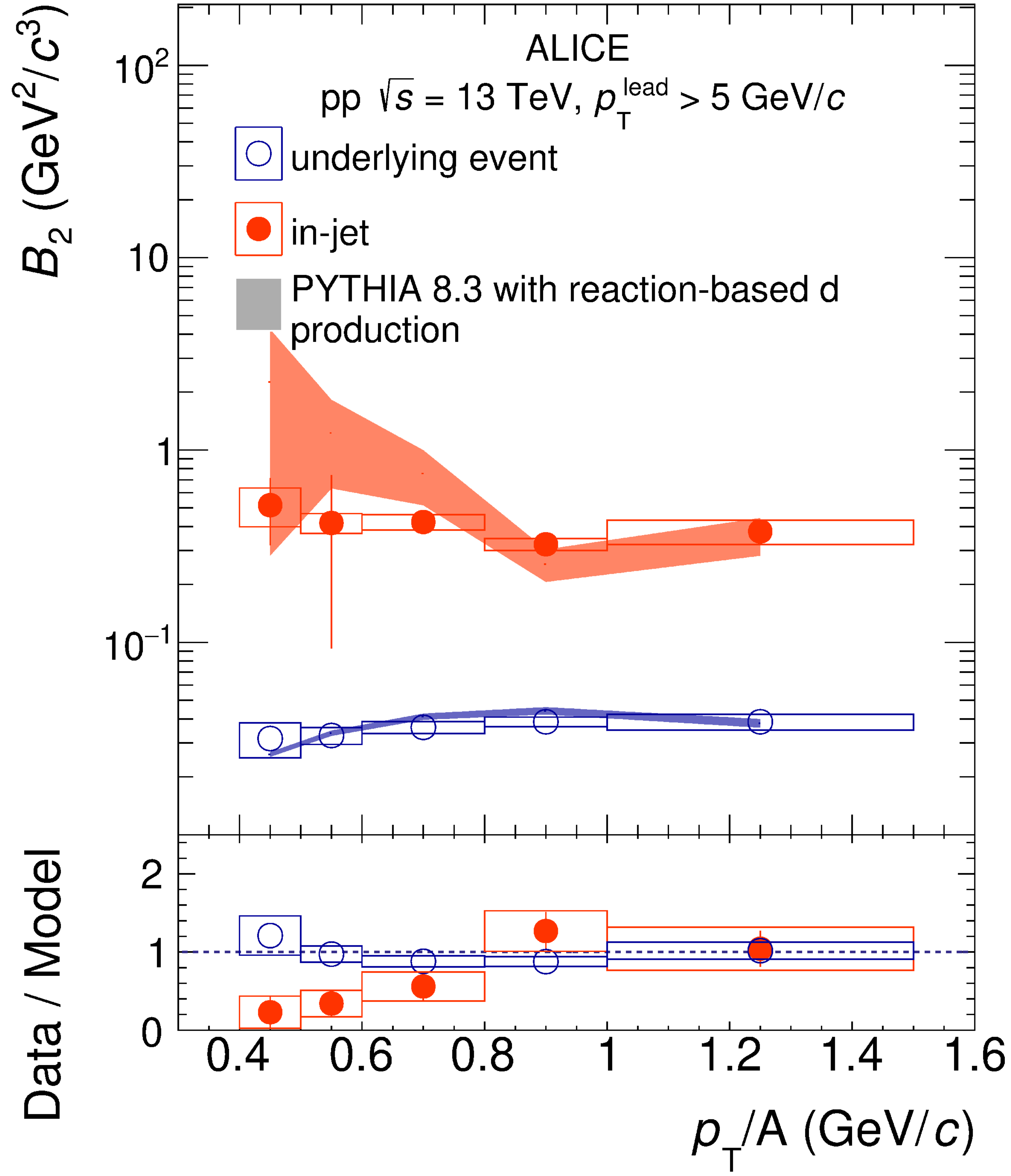


ALI-PUB-533067

arXiv:2211.15204

In- and out-of-jet production

- Deuteron spectra are measured in the azimuthal regions: toward, transverse and away
  - The transverse region to good approximation coincides with the **UE**
  - In-jet spectrum = toward - 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
    - quite good description of in-jet production

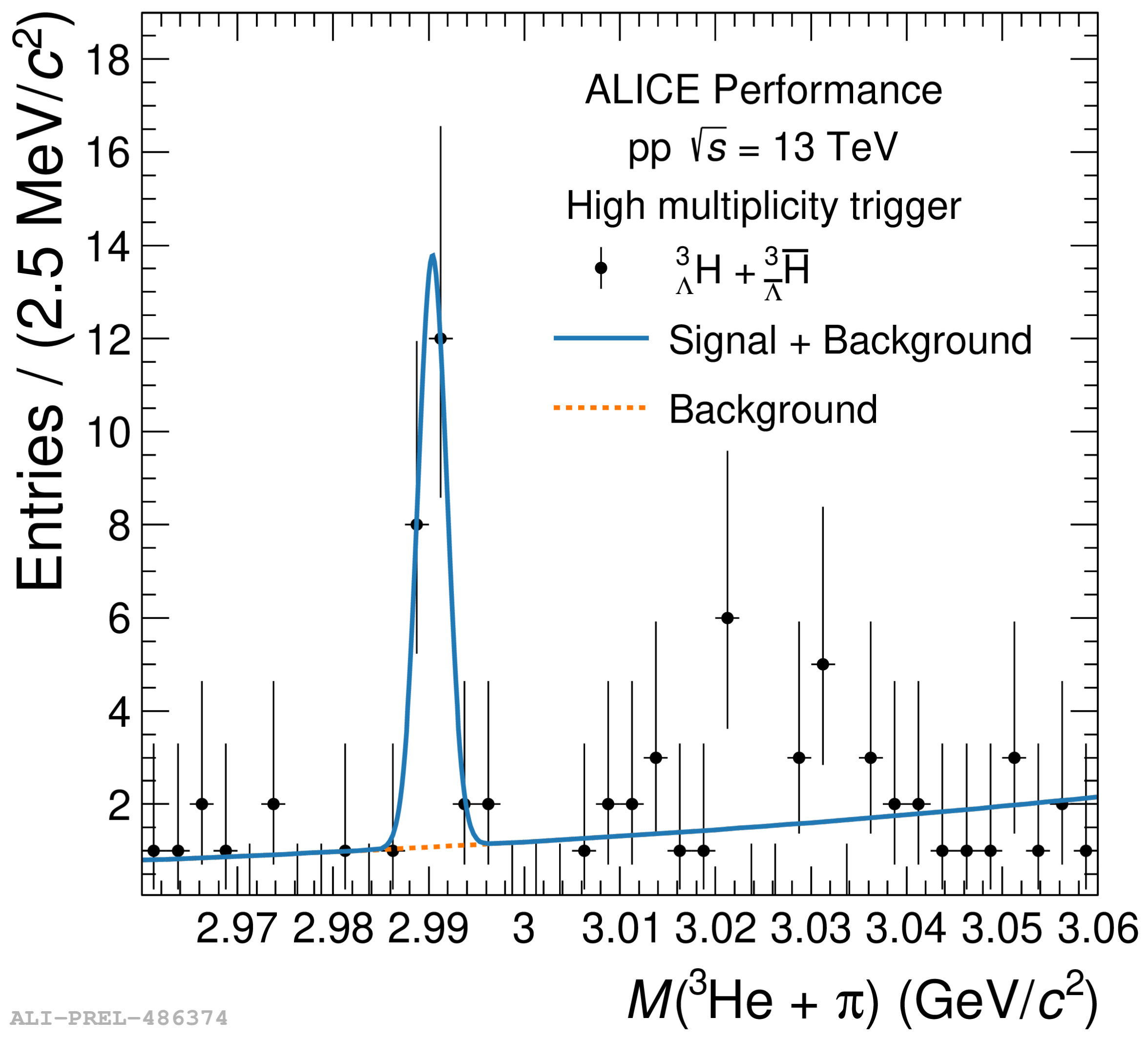


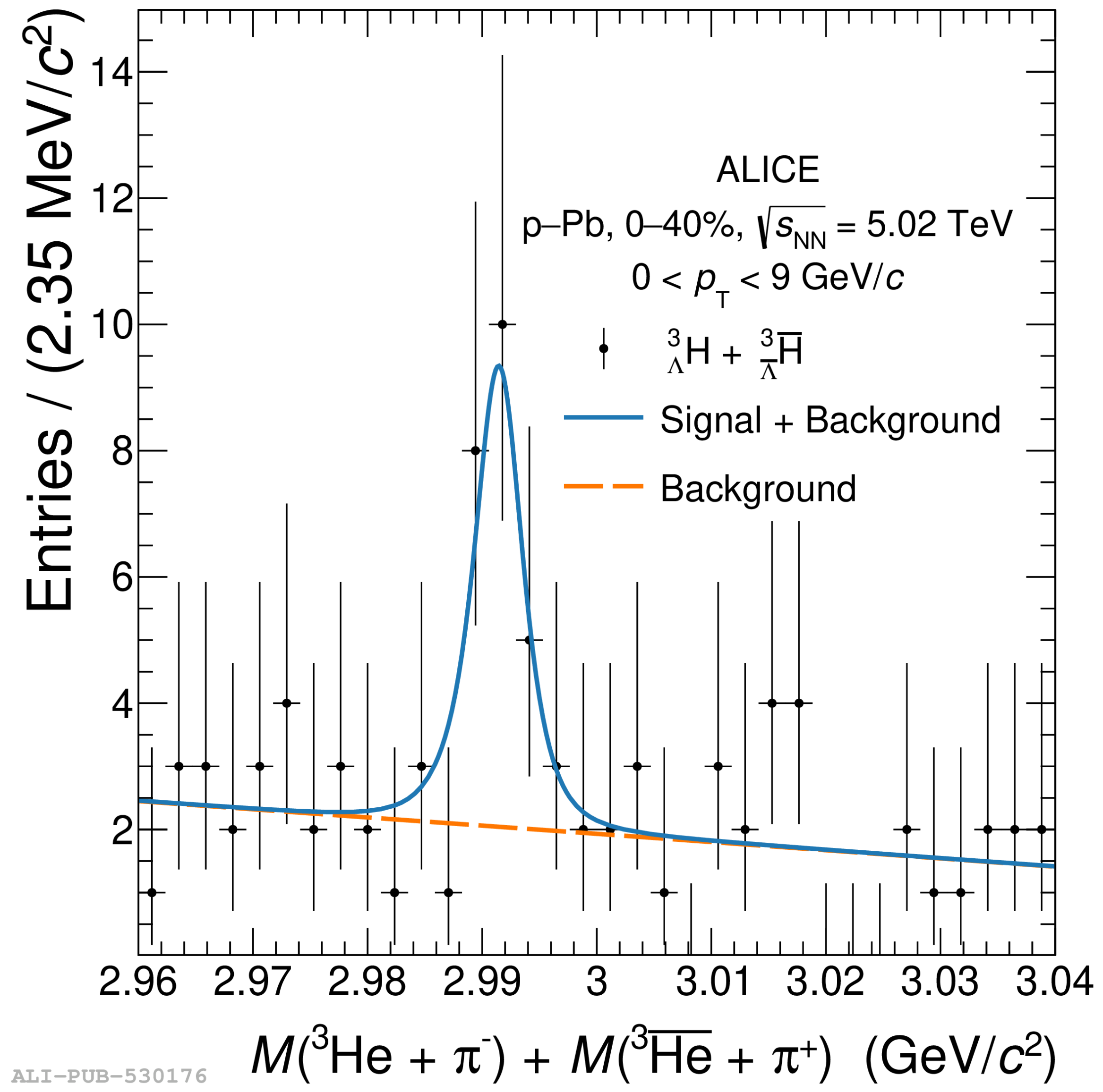
ALI-PUB-533075

arXiv:2211.15204

Hypertriton

- For the first time, $^{3}_{\Lambda}\mathrm{H}$ has been observed in small systems
    - in **pp** collisions at 13 TeV with **High Multiplicity trigger**
    - in **p-Pb** collisions at 5.02 TeV
- $^{3}_{\Lambda}\mathrm{H}$ has a large radius:
    - $r\left(^{3}_{\Lambda}\mathrm{H}\right) = 10.79\ \mathrm{fm}$ (1), $r\left(^{3}\mathrm{He}\right) = 1.76\ \mathrm{fm}$, $r\left(\mathrm{d}\right) = 1.96\ \mathrm{fm}$
    - $^{3}_{\Lambda}\mathrm{H}$ production is a test-bench for coalescence production models
- **Hypertriton** measurement in **pp** and **p-Pb** collisions is expected to be a **conclusive test** for the **production** models (2)





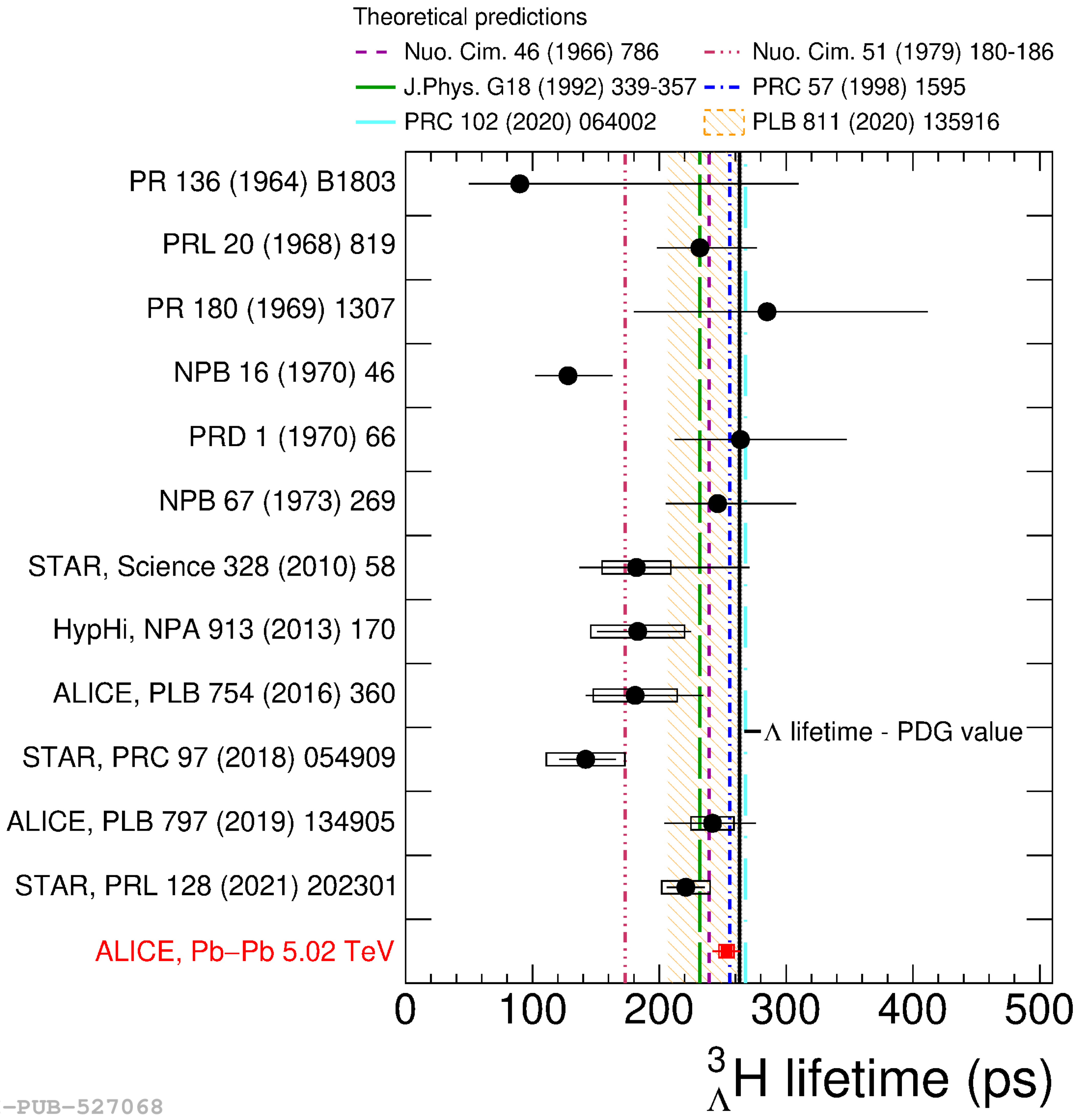
PRL 128 (2022) 252003

(1) F. Hildenbrand and H.-W. Hammer, Phys. Rev. C 100, 034002

(2) F. Bellini et al., Phys.Rev.C 103 (2021) 1, 014907

Hypertriton lifetime and Λ separation energy

- **Lifetime** measured with the highest precision so far:
  - compatible with that of the **free Λ**
    - **loosely bound** state



arXiv:2107.10627

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- **Lifetime** measured with the highest precision so far:
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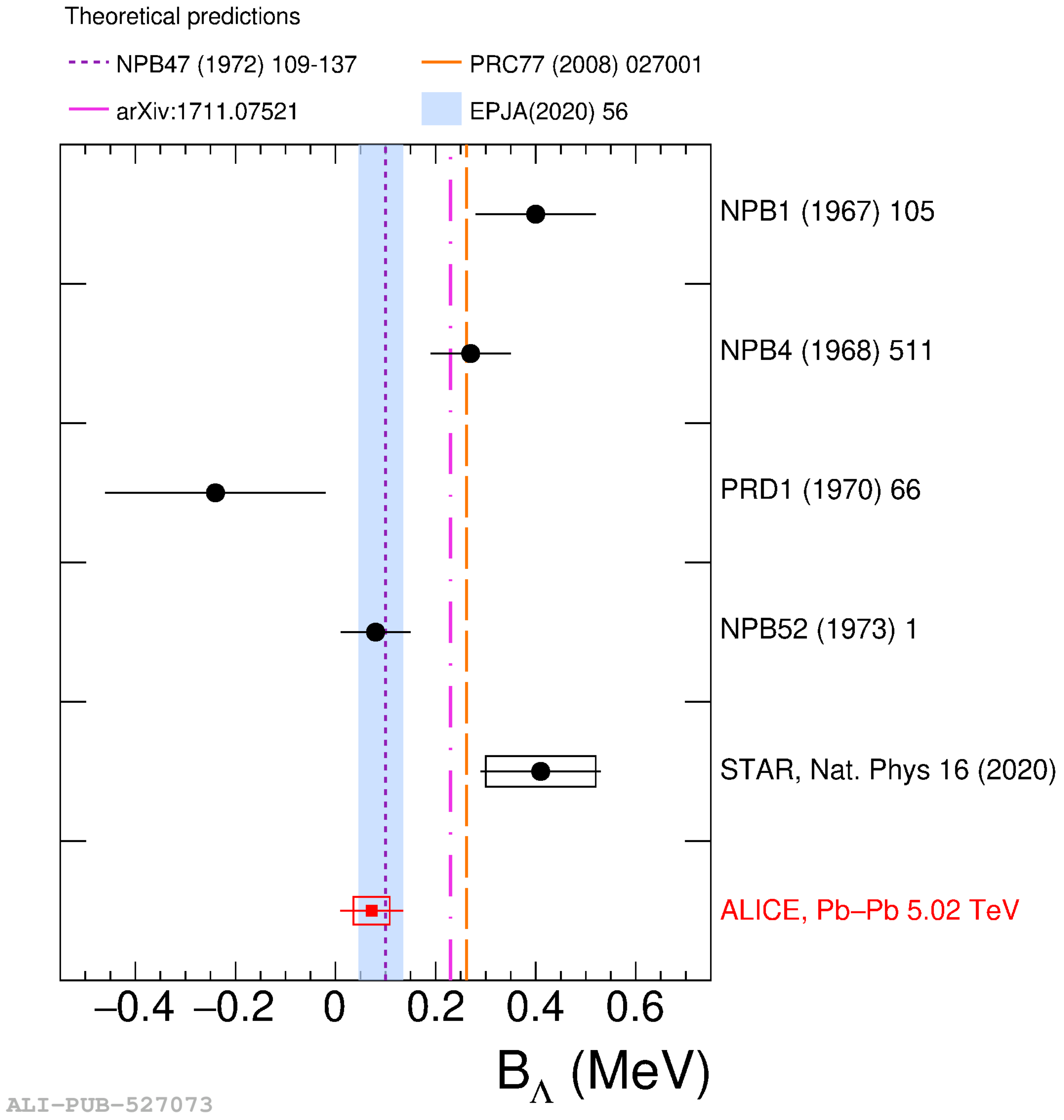
- **B**$_\Lambda$ has been measured with a **high precision**
  - **1.9 σ** difference w.r.t. last **STAR** results
  - compatible with χEFT and **Dalitz**'s predictions
    - **loosely bound** state



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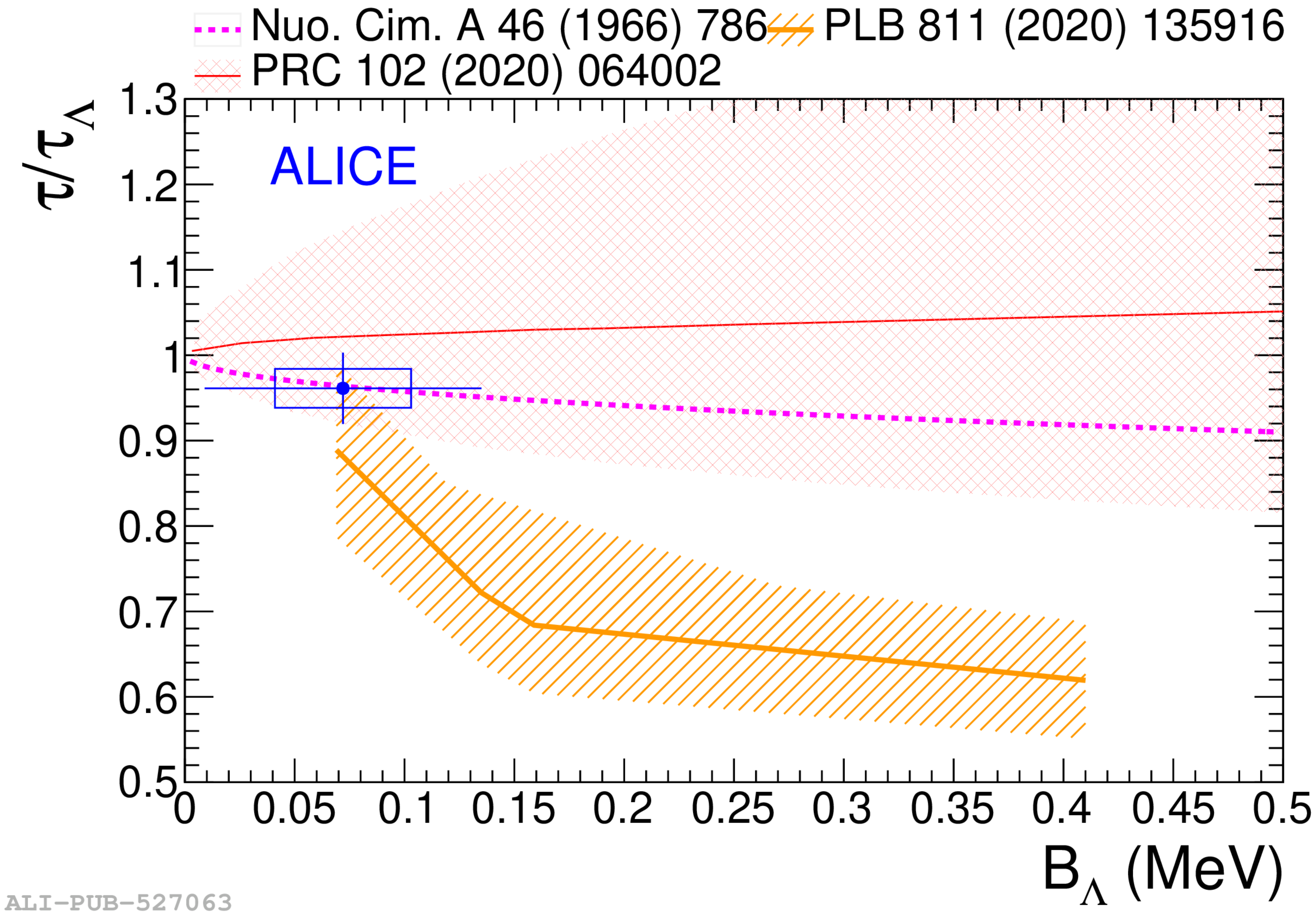
  - **1.9 σ** difference w.r.t. last **STAR** results
  - compatible with χ**EFT** and **Dalitz**'s predictions
    - **loosely bound** state
- All the models provide a simultaneous description of τ and **B**$_\Lambda$



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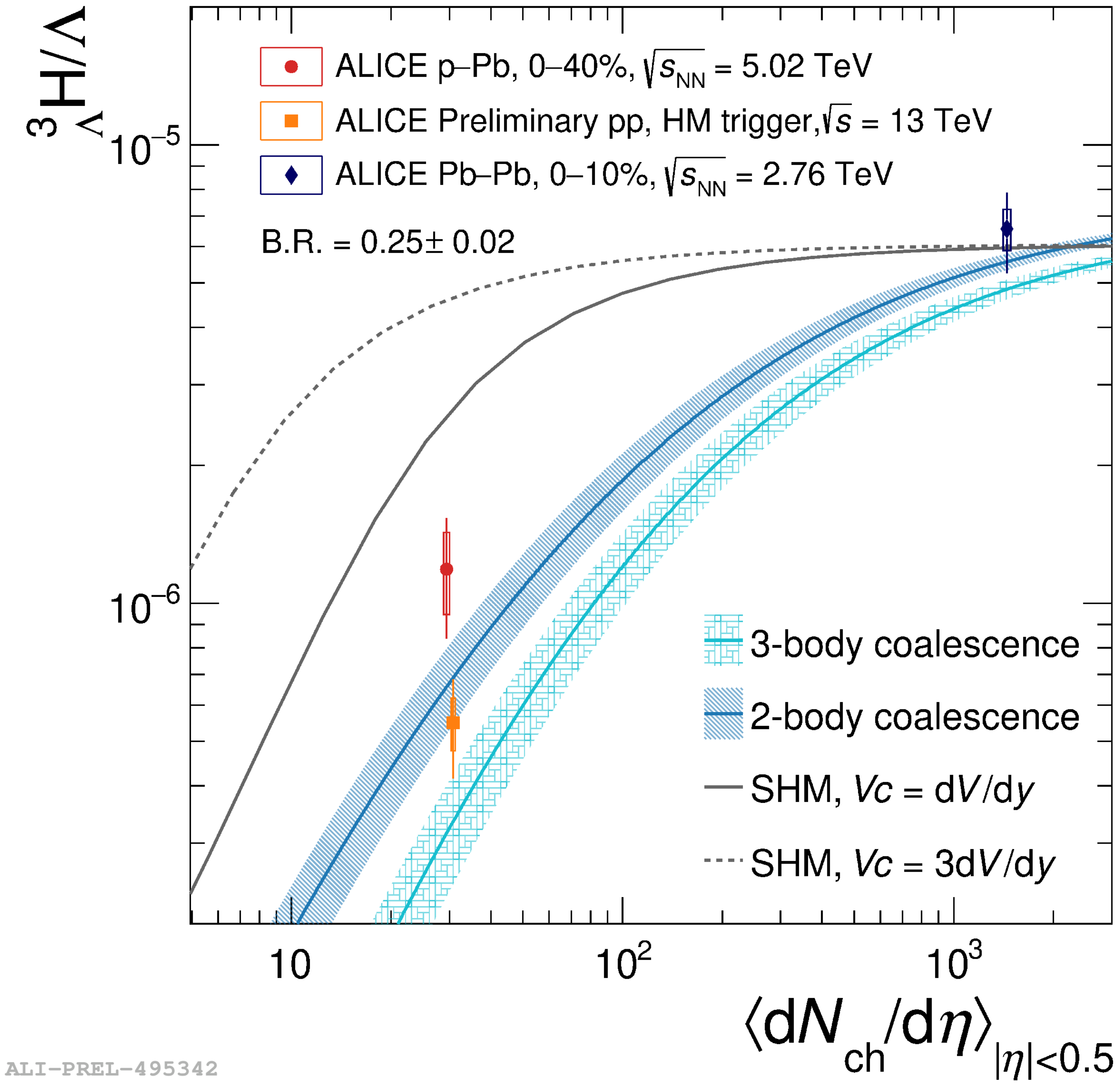
Hypertriton production in small systems

- ${}^{3}_{\Lambda}\mathrm{H}/\Lambda$ is compared with the prediction of CSM and coalescence model
    - **Two-body coalescence** model provides the best description of data

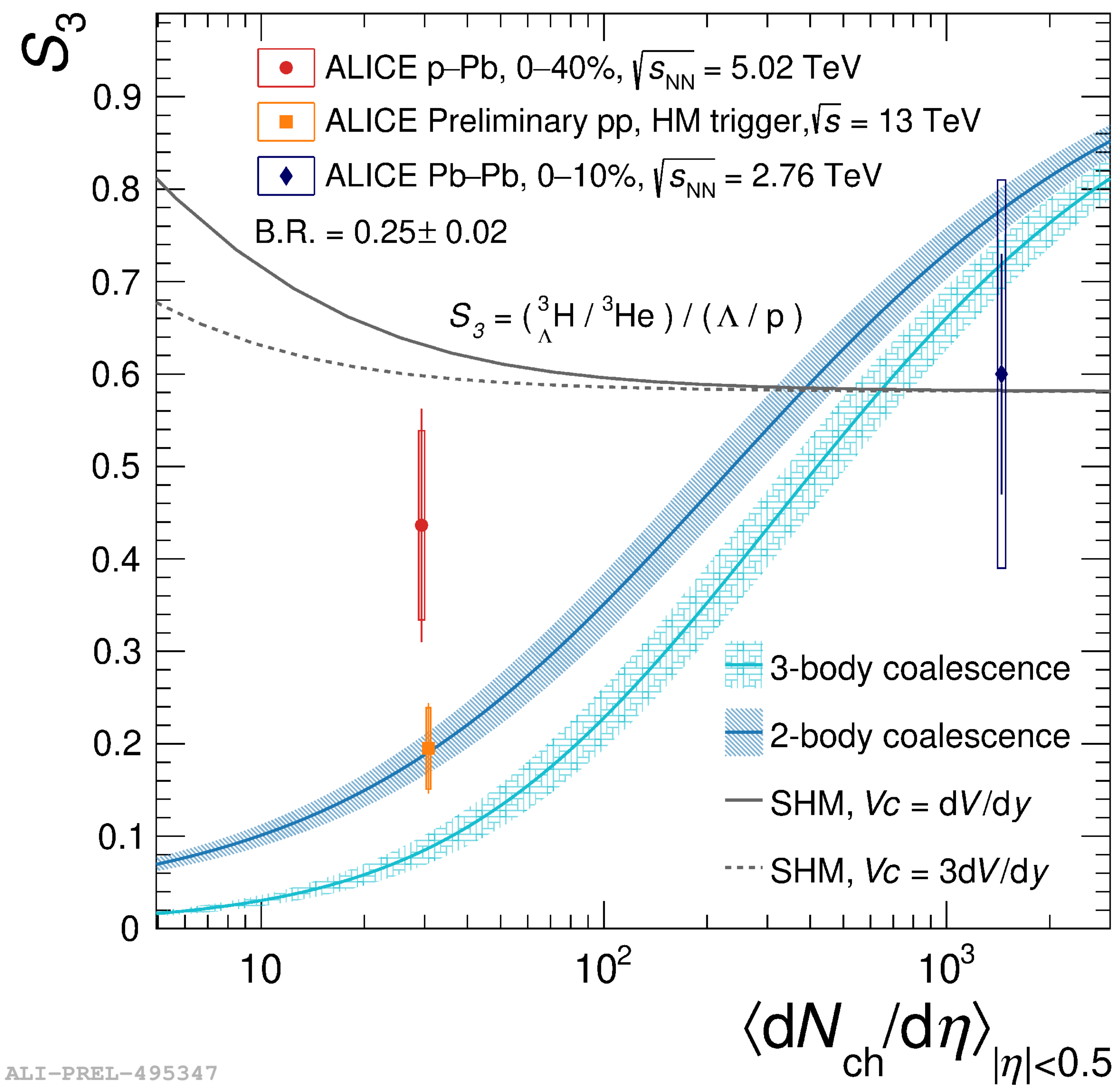


ALI-PREL-495342

PRL 128 (2022) 252003

Hypertriton production in small systems

- ${}^{3}_{\Lambda}\mathrm{H}/\Lambda$ is compared with the prediction of CSM and coalescence model
  - **Two-body coalescence** model provides the best description of data
- Also $S_3 = \dfrac{{}^{3}_{\Lambda}\mathrm{H}/{}^{3}\mathrm{He}}{\Lambda/\mathrm{p}}$ is a valuable observable to discriminate between production mechanisms
  - Also in this case **coalescence** is favoured, even though with less sensitivity



PRL 128 (2022) 252003

Summary and conclusions

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- Measurements vs multiplicity
  are crucial to study the production mechanisms
- B_A vs multiplicity:
  - trend qualitatively described
  - not described well by a single parameterisation of R vs dN/dη
- B_A vs p_T/A (with measured emitting source):
  - test different nuclear wave functions
- Yield ratios vs multiplicity:
  - $^{3}_{\Lambda}\mathrm{H}$ weakly bound → large radius → sensitive probe
  - $^{3}_{\Lambda}\mathrm{H}/\mathrm{p}$ favours production via coalescence

Thanks for your attention!

ADDITIONAL SLIDES

The ALICE experiment

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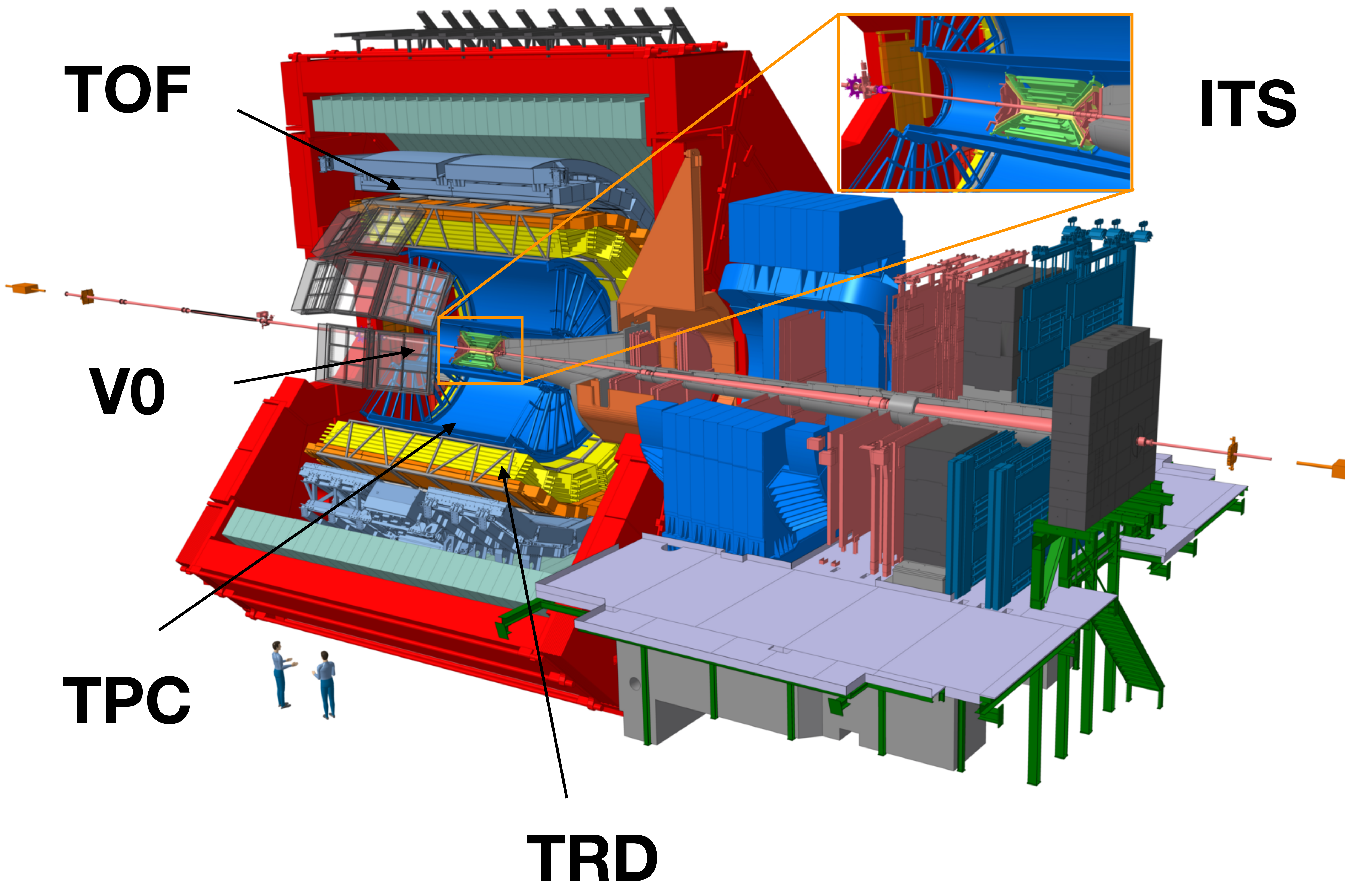
- General purpose heavy-ion experiment
  - 19 different sub-systems
  - Excellent particle identification (**PID**)
  - Most suited LHC experiment for studying the production of nuclei

Inner **T**racking **S**ystem

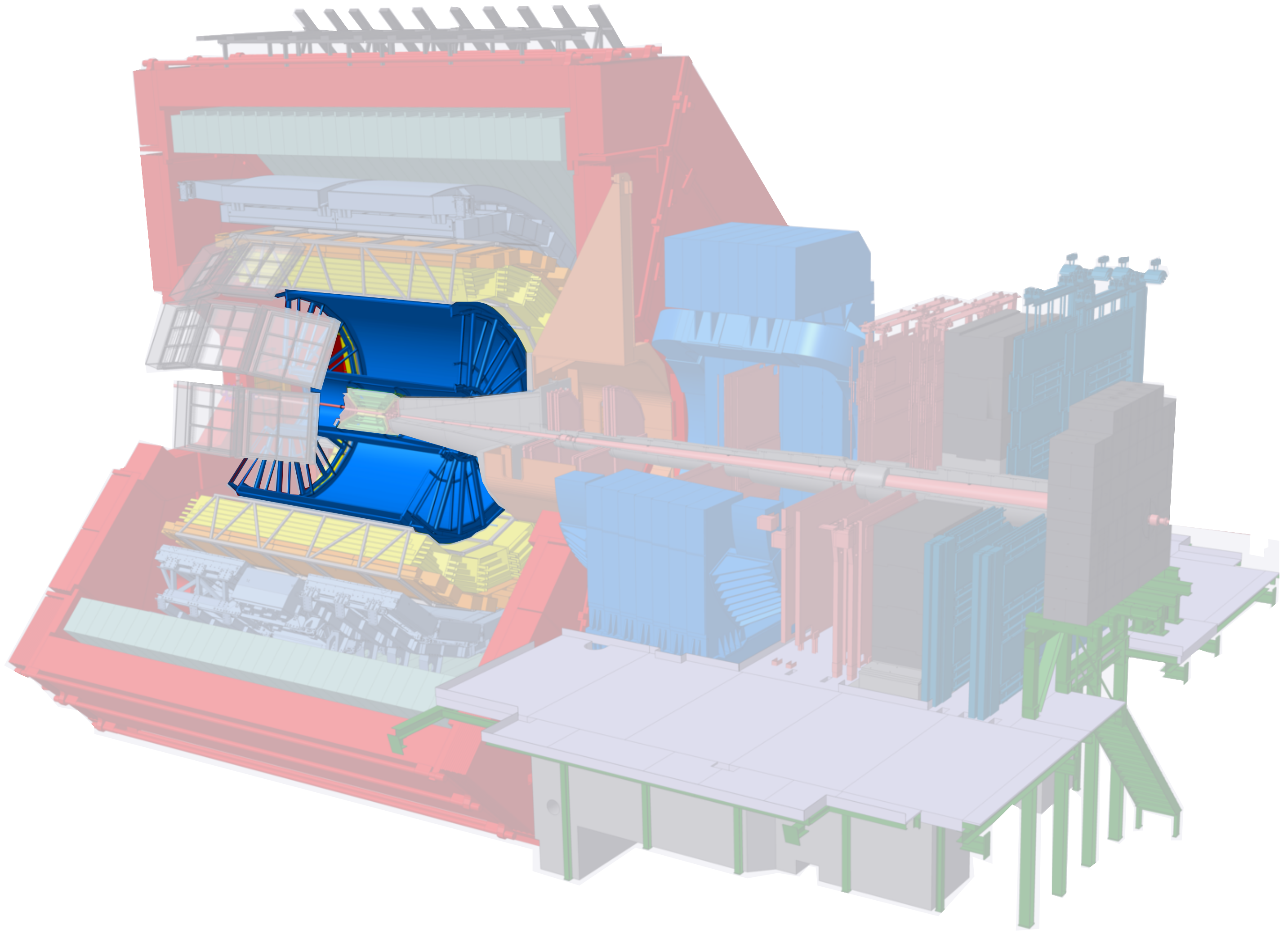
- **Tracking** and **Vertex** reconstruction
- $\boldsymbol{\sigma_{\mathrm{DCA}_{xy}} < 100\ \mu\mathrm{m}}$ for $p_{\mathrm{T}} > 0.5$ GeV/c in Pb-Pb
  - Separation of **primary** and **secondary nuclei** (coming from material knock-out)
  - Separation of **primary** and **secondary vertices**

V0

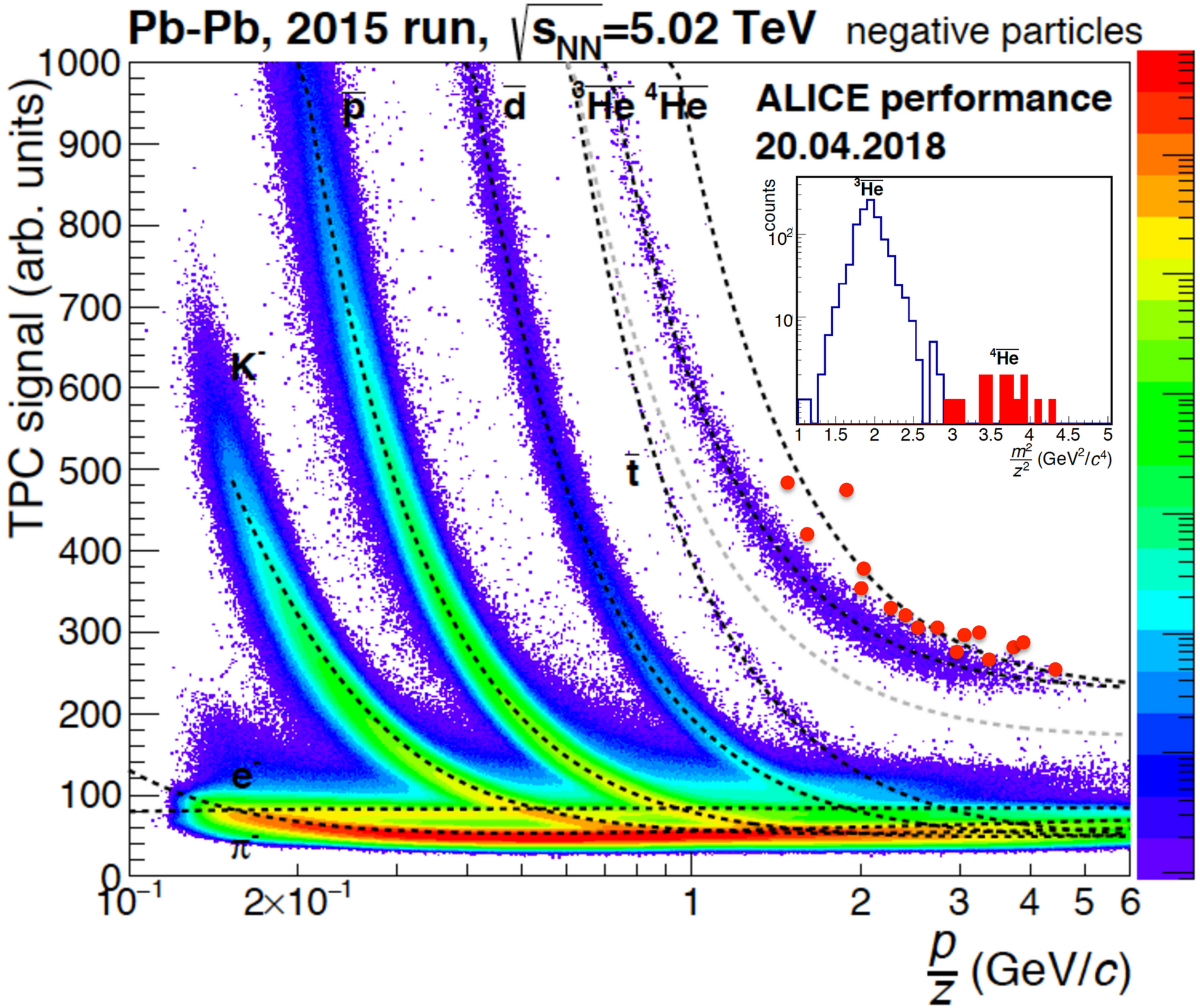
- **Multiplicity/centrality** determination



PID with the Time Projection Chamber



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



PID with the Time Of Flight

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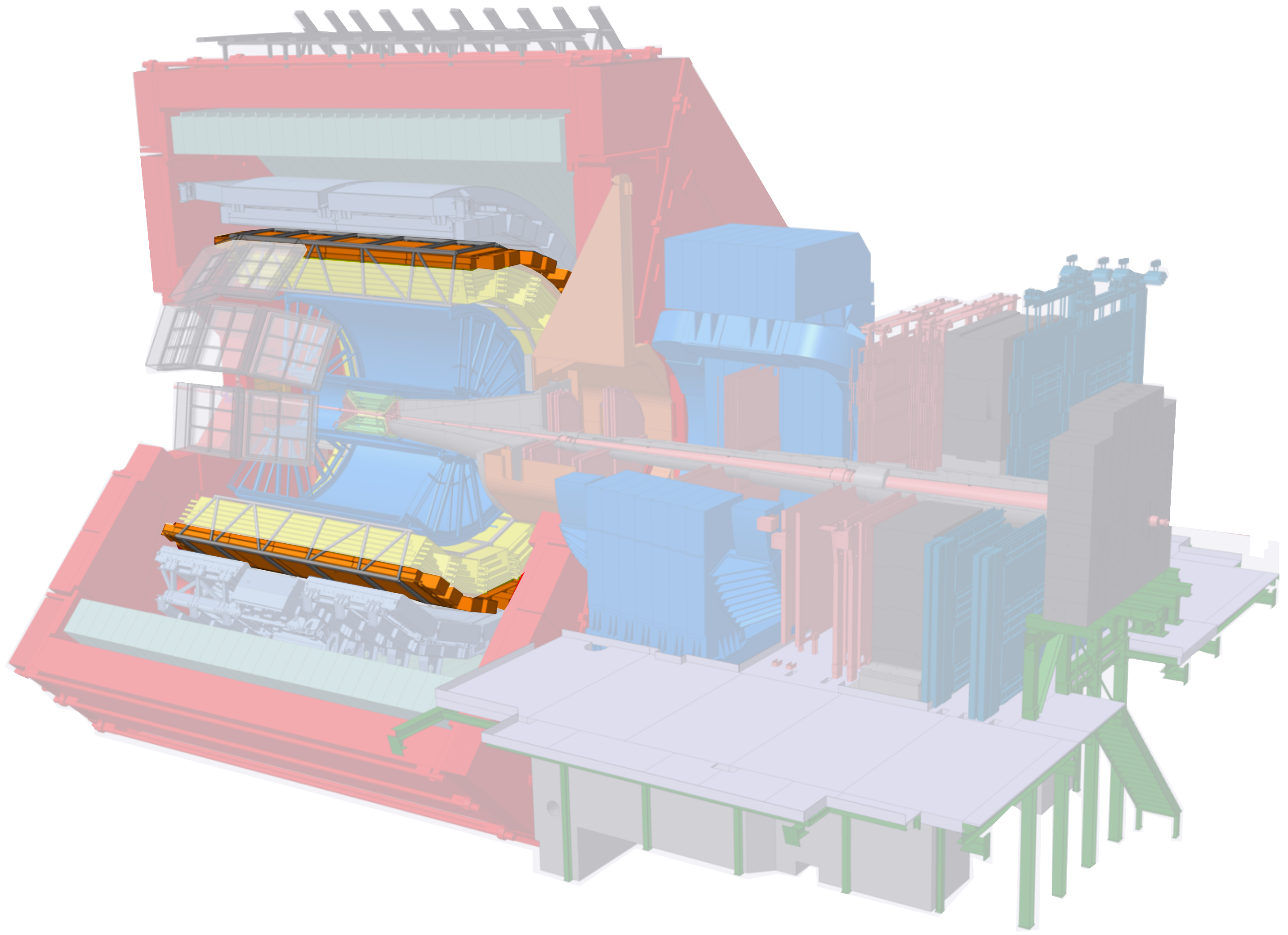

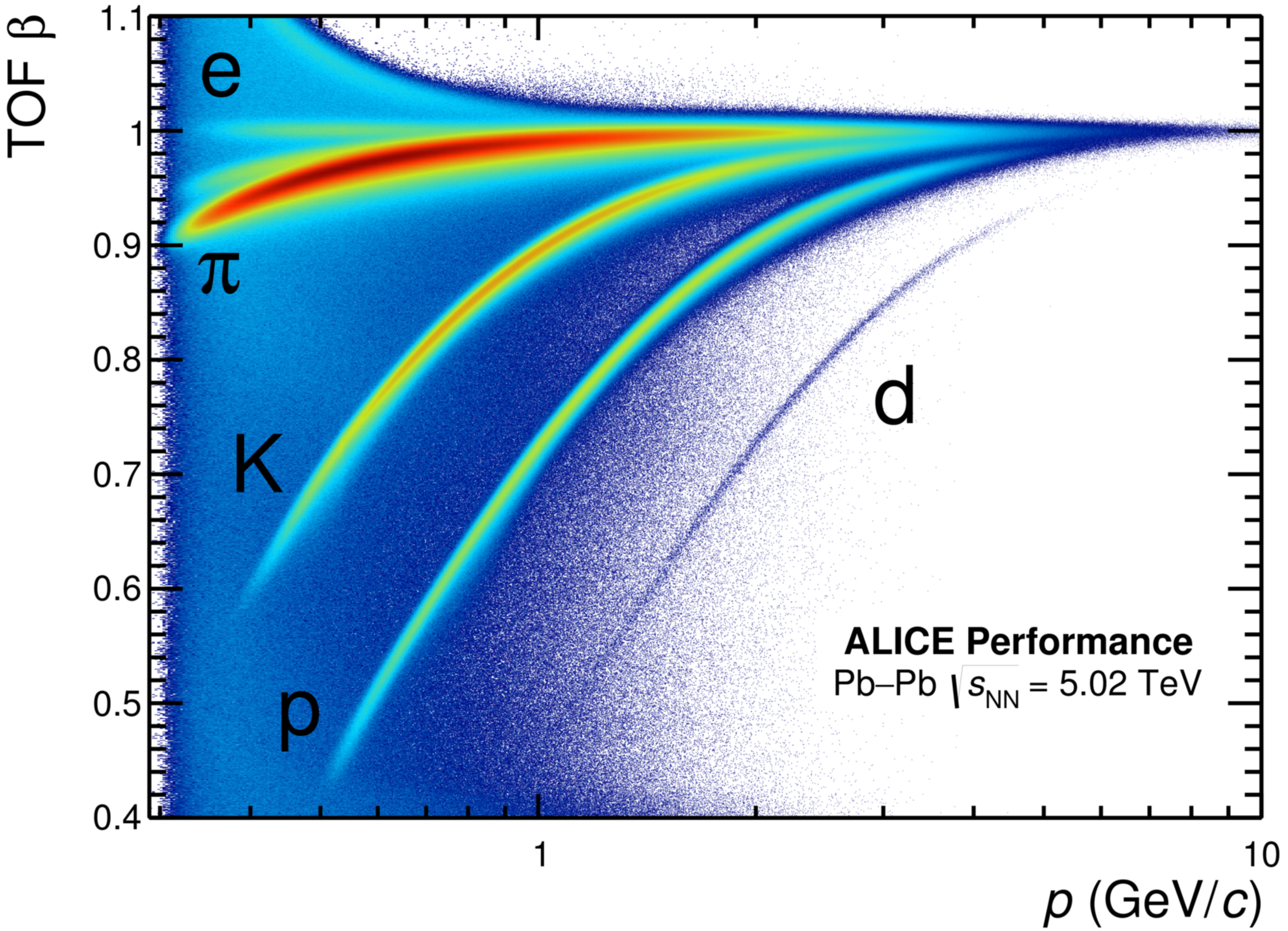

ALI-PERF-106336

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

Charged particle multiplicity

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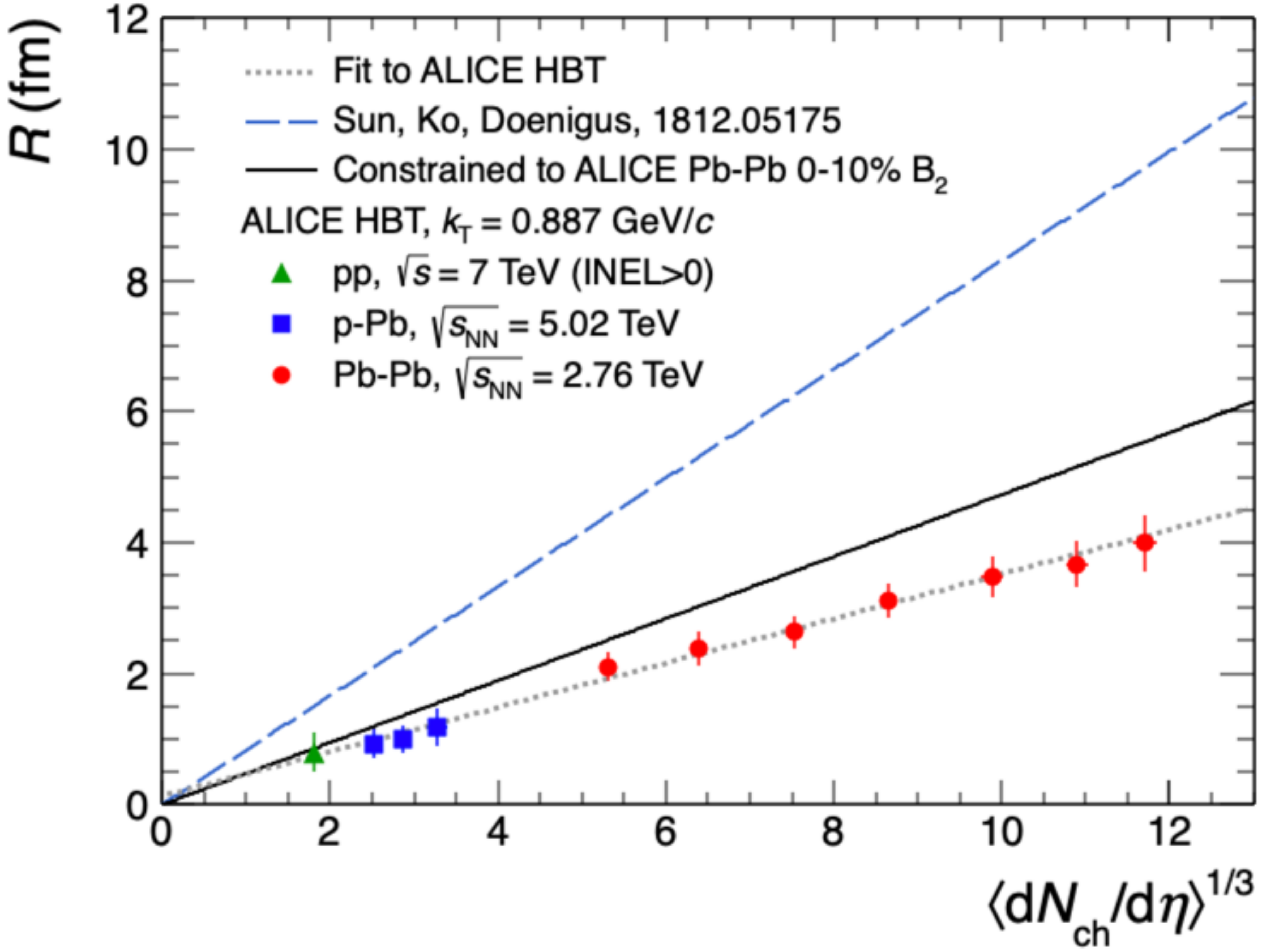
- Measurements are carried out vs multiplicity
- $\langle \mathrm{d}N_{ch}/\mathrm{d}\eta \rangle$ ↔ **system size**
- System size: **HBT radius R**
  - R vs multiplicity:

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



Phys.Rev.C 99 (2019) 5, 054905

Charged particle multiplicity

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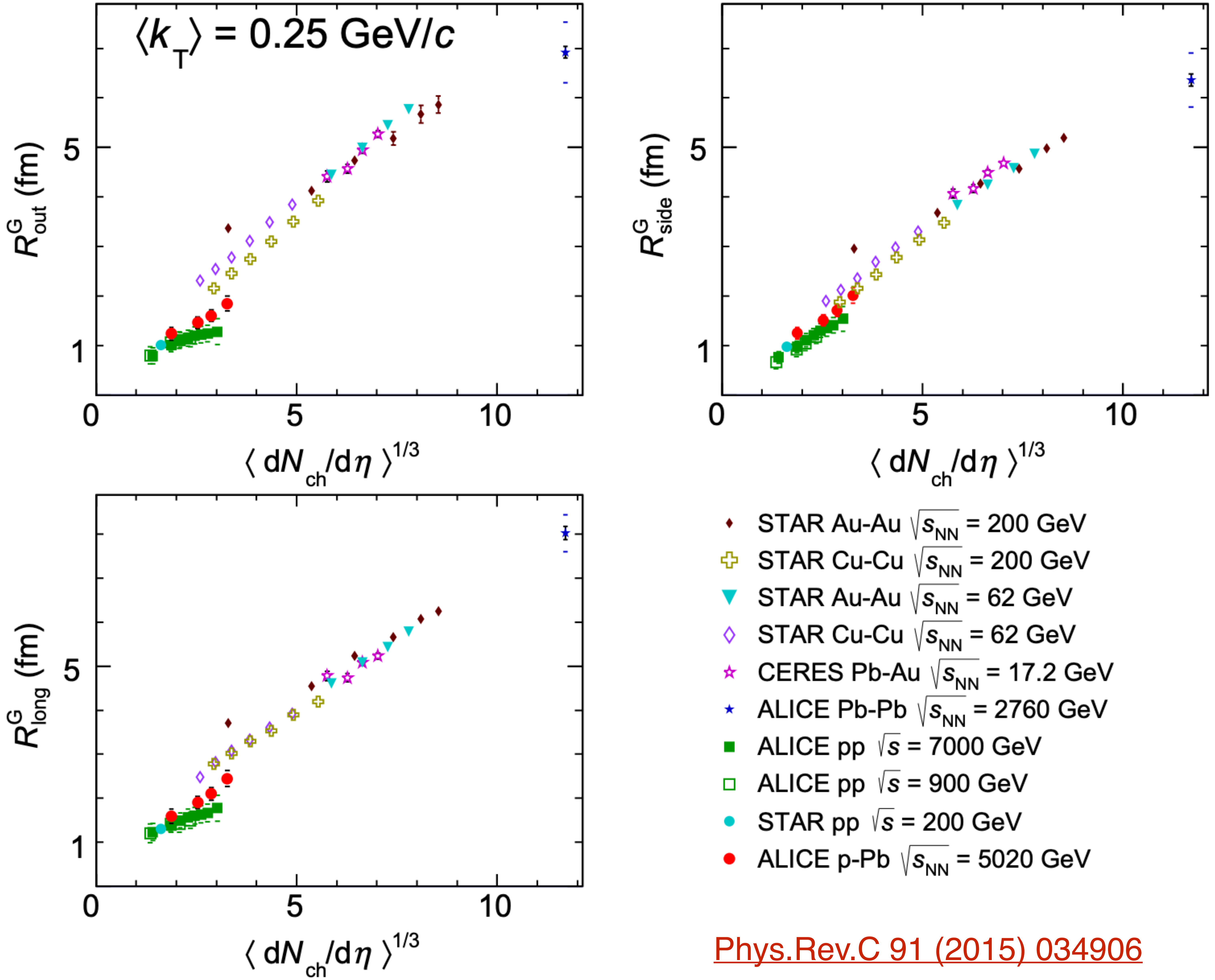
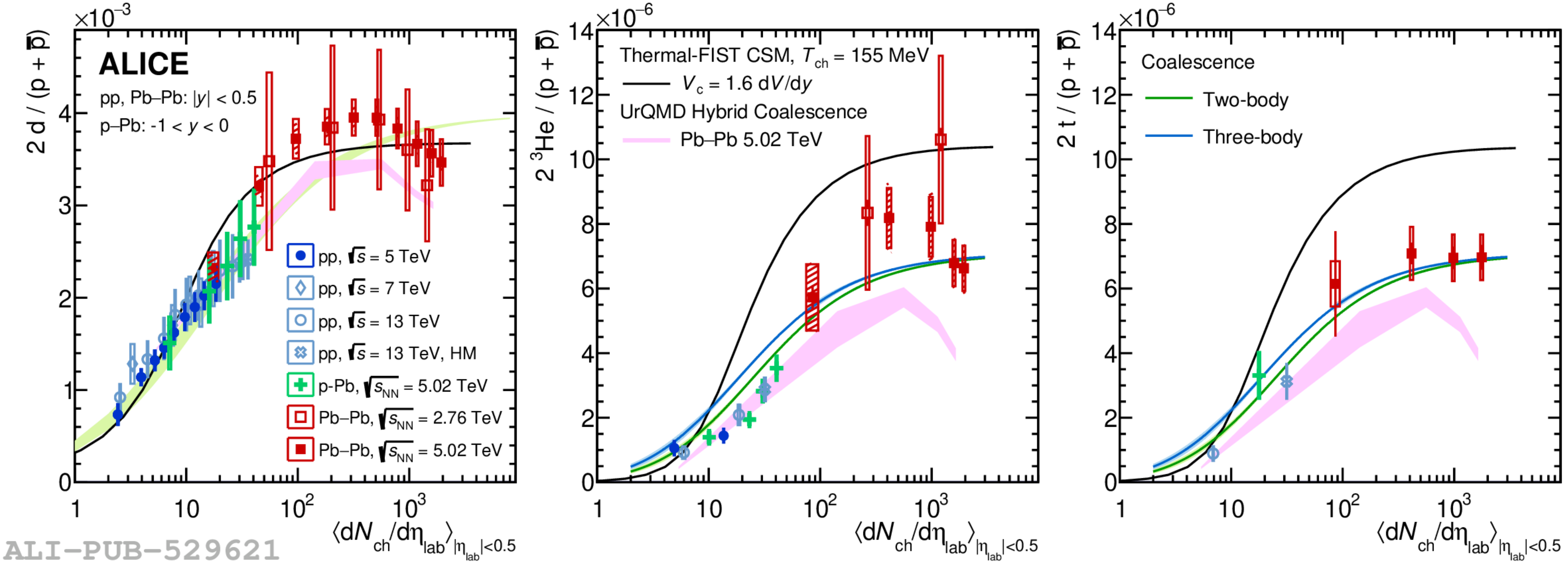
- Adding more points to the R vs $\langle \mathrm{d}N_{ch}/\mathrm{d}\eta \rangle$, it is visible that the evolution is **not smooth** from pp to p-Pb
- This discontinuity could be the reason why models do not reproduce data along the whole multiplicity range
  - Possible solution: B_2 vs R
  - R vs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



Phys.Rev.C 91 (2015) 034906

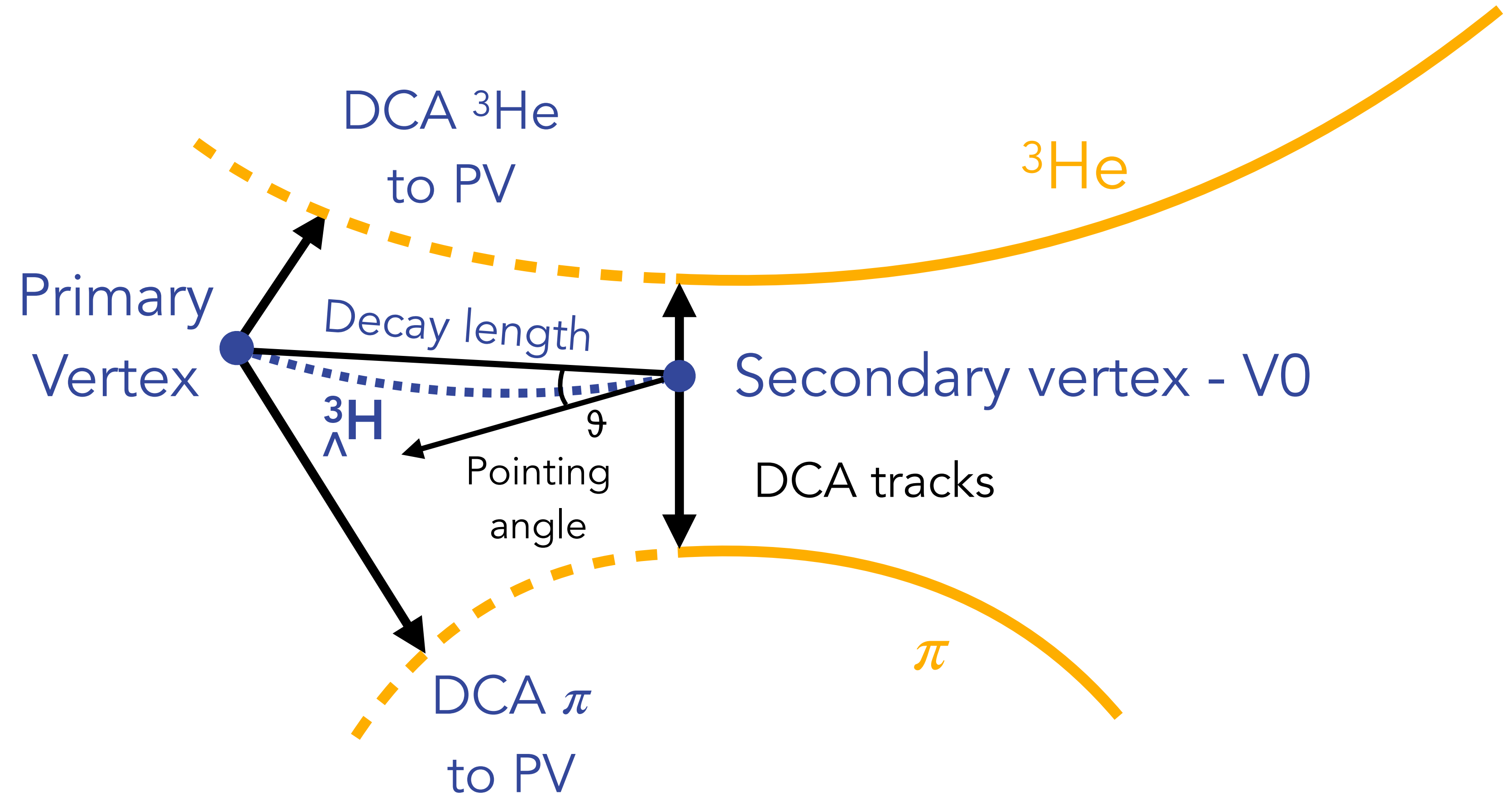
Yield ratios

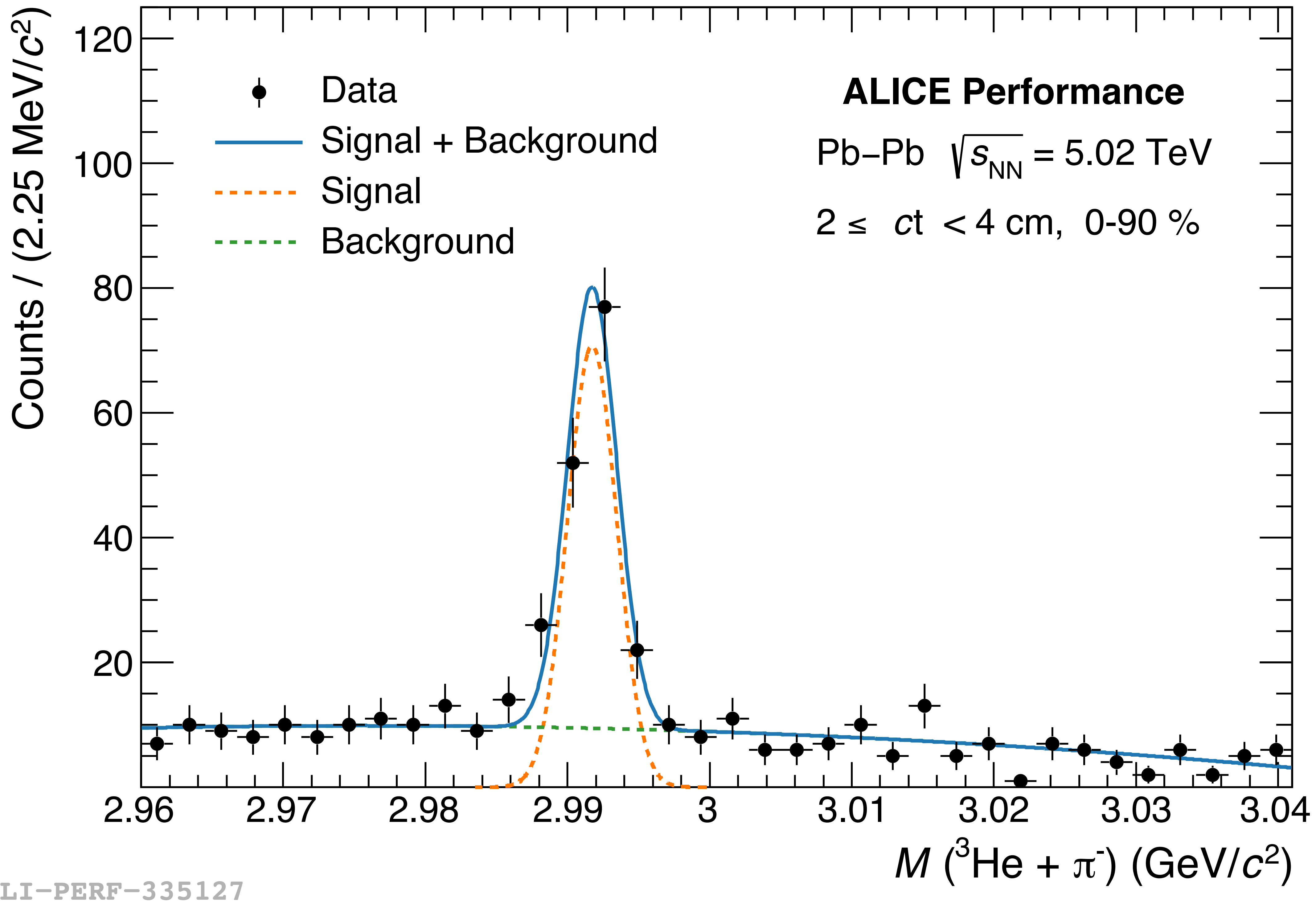


arXiv:2211.14015

Hypertriton reconstruction

- **Hypertriton** is reconstructed through its **two-body** mesonic decay (B.R. 25%):
  - ${}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-} \quad + \mathrm{c.c.}$
- Candidates are selected with:
  - Standard selections on **single-track** and **topological** variables
  - **Boosted Decisions Trees** (BDT) models, trained on dedicated MC samples used to discriminate signal and background
    - BDT selections are optimised to **improve** the **significance** of the signal
    - Use of the package hipe4ML





ALI-PERF-335127

Femtoscopy

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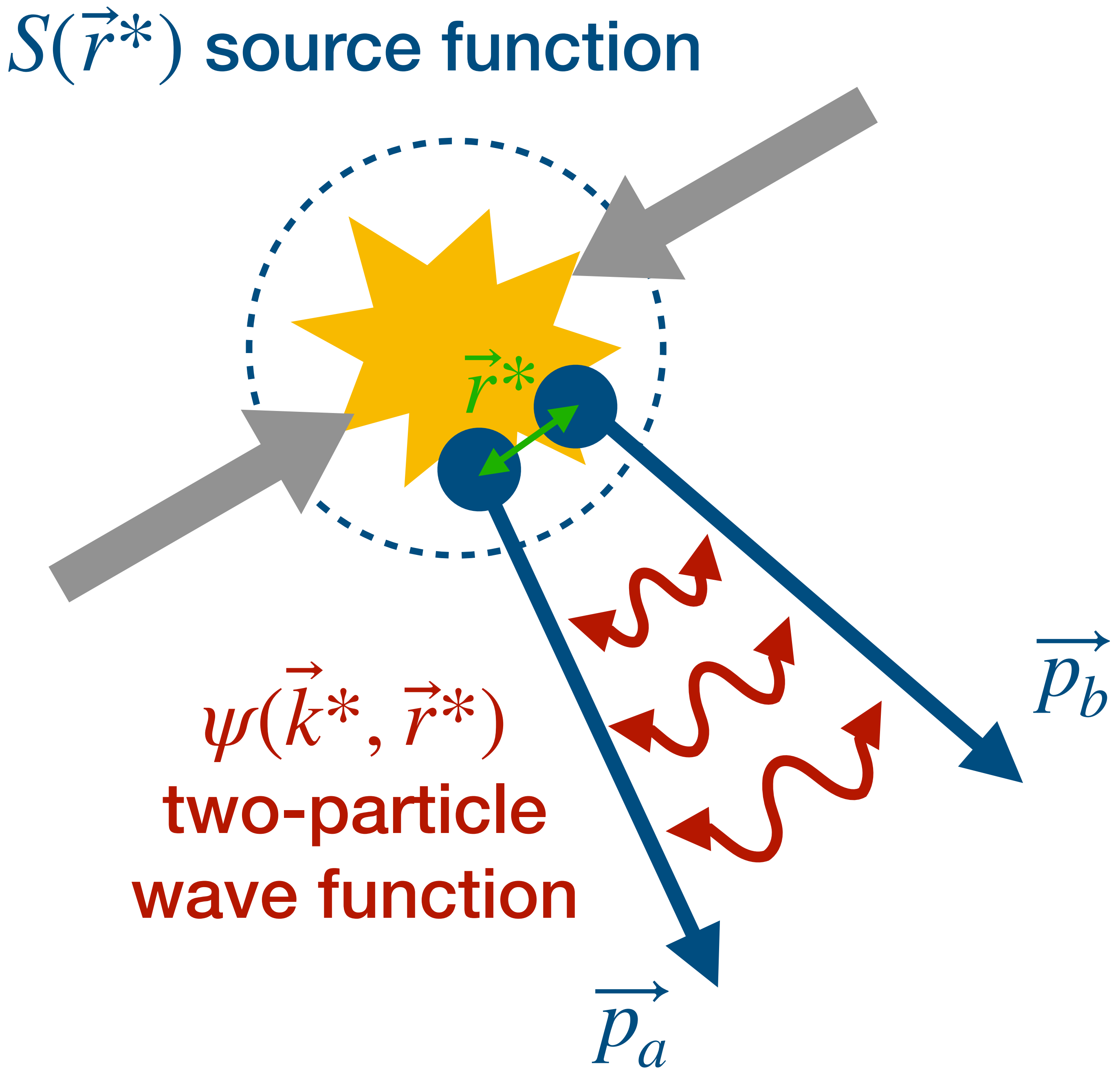
- The main observable is the **correlation function**:

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

where $\vec{k}^* = \dfrac{\vec{p_a} - \vec{p_b}}{2}$ 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

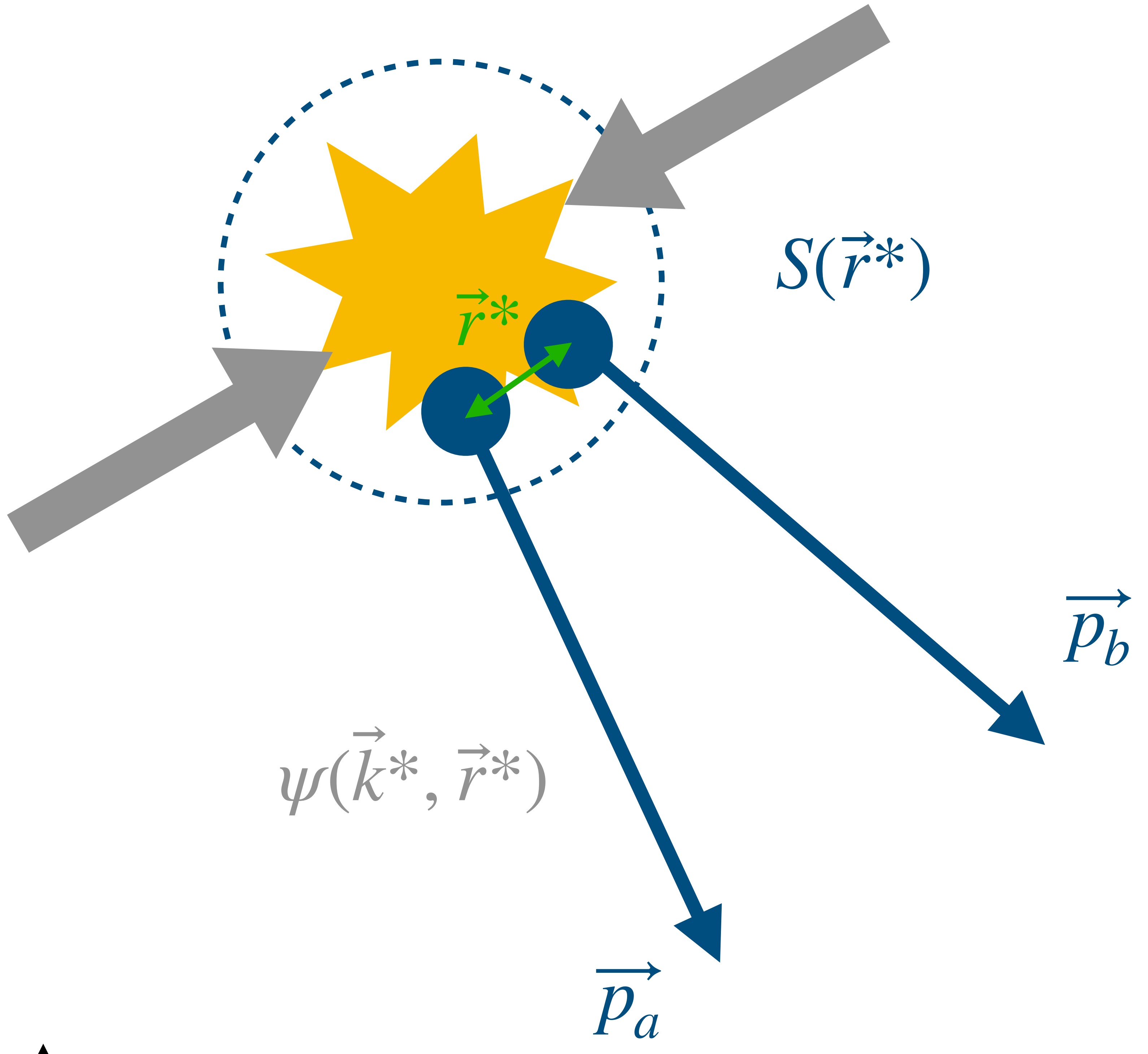
The theoretical CF is obtained using **CATS** (Correlation Analysis Tool using the Schrödinger equation):

- exact solution of the Schrödinger equation for a wave function

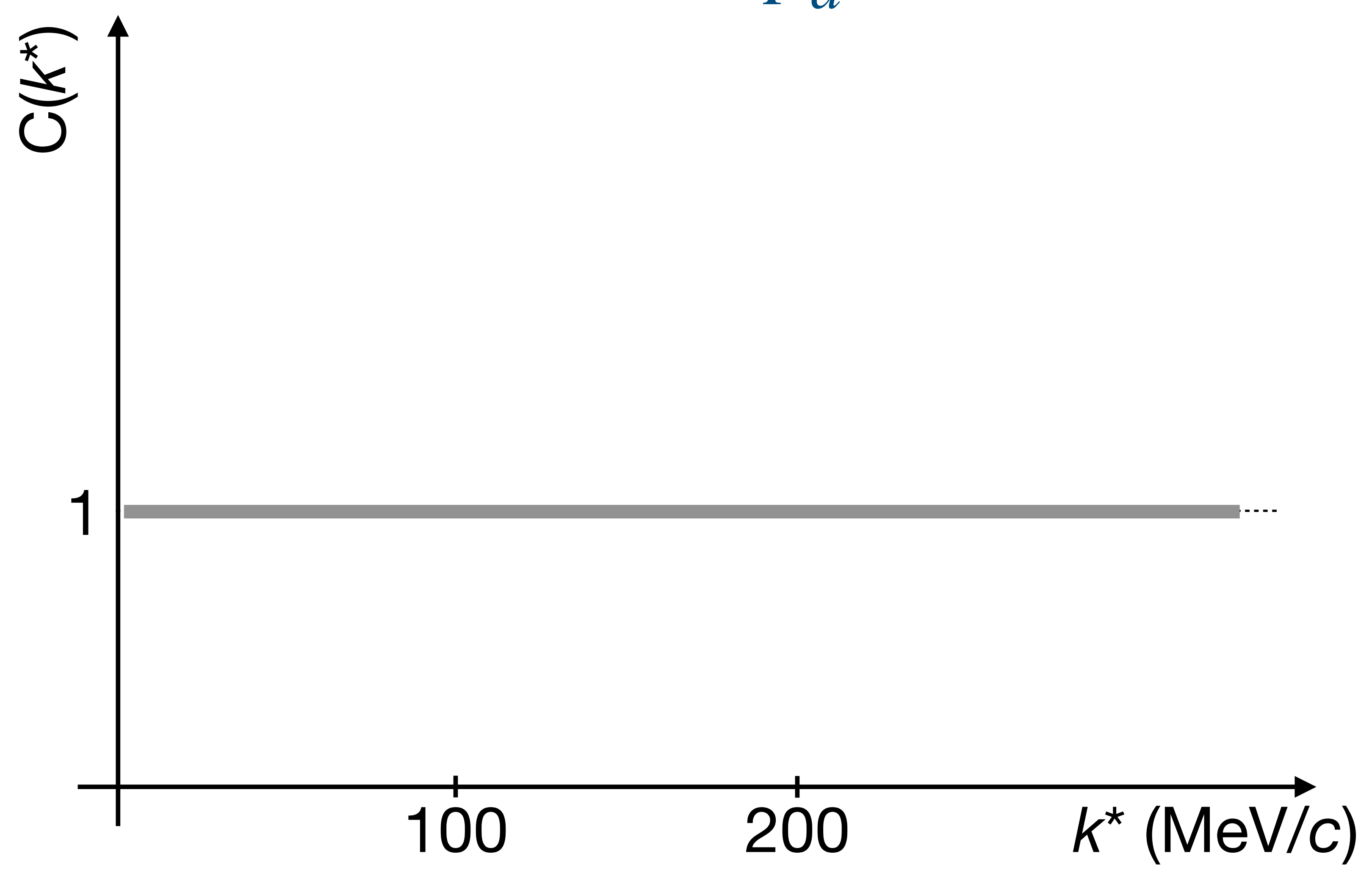
D.L. Mihaylov et al., EPJC 78 (2018) 5, 394

The correlation function

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



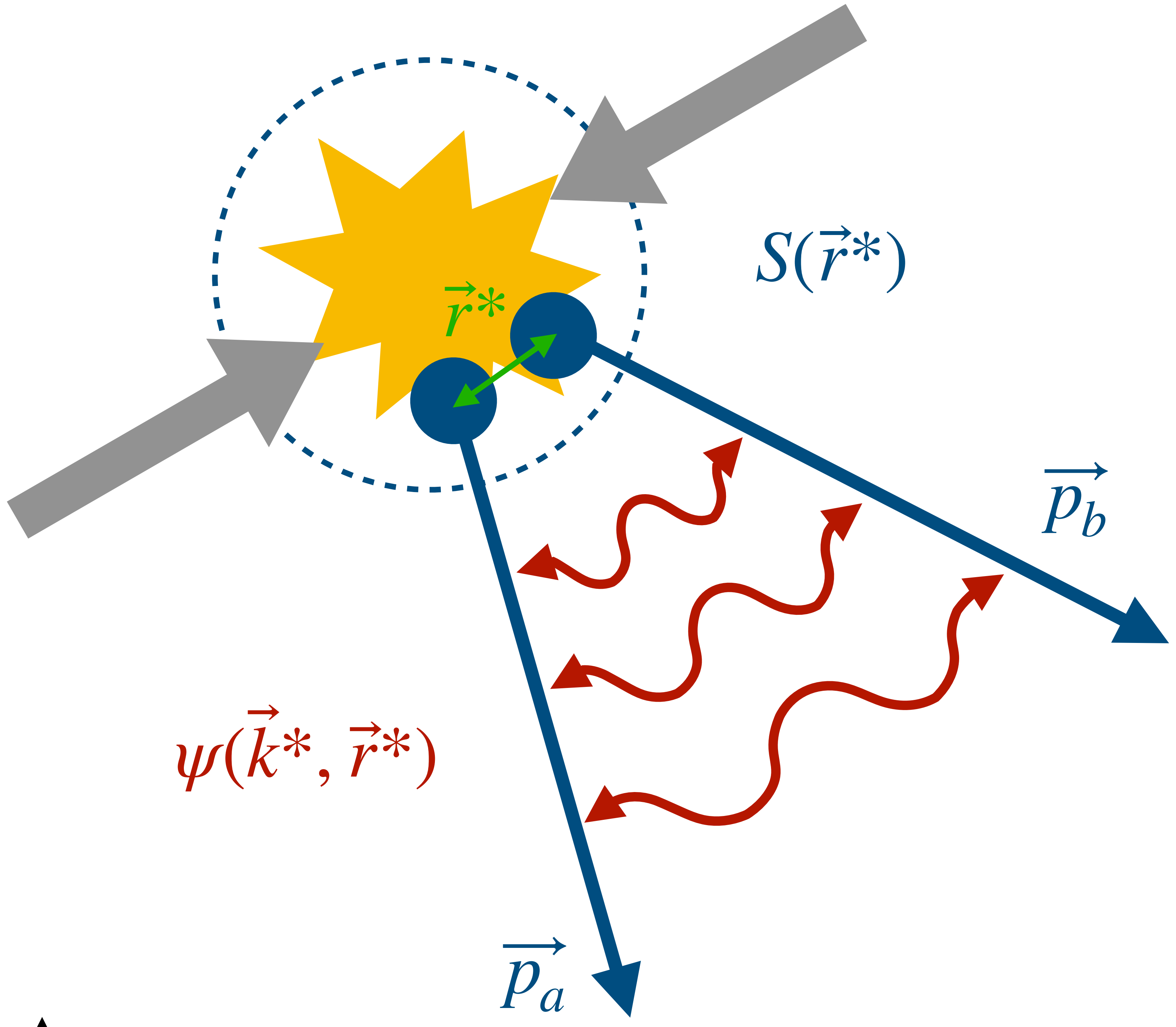
$$C(k^*) = \int S(\vec{r}^*)\,|\psi(\vec{k}^*, \vec{r}^*)|^2\, \mathrm{d}^3r^* = \mathcal{N}\frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)} = 1$$

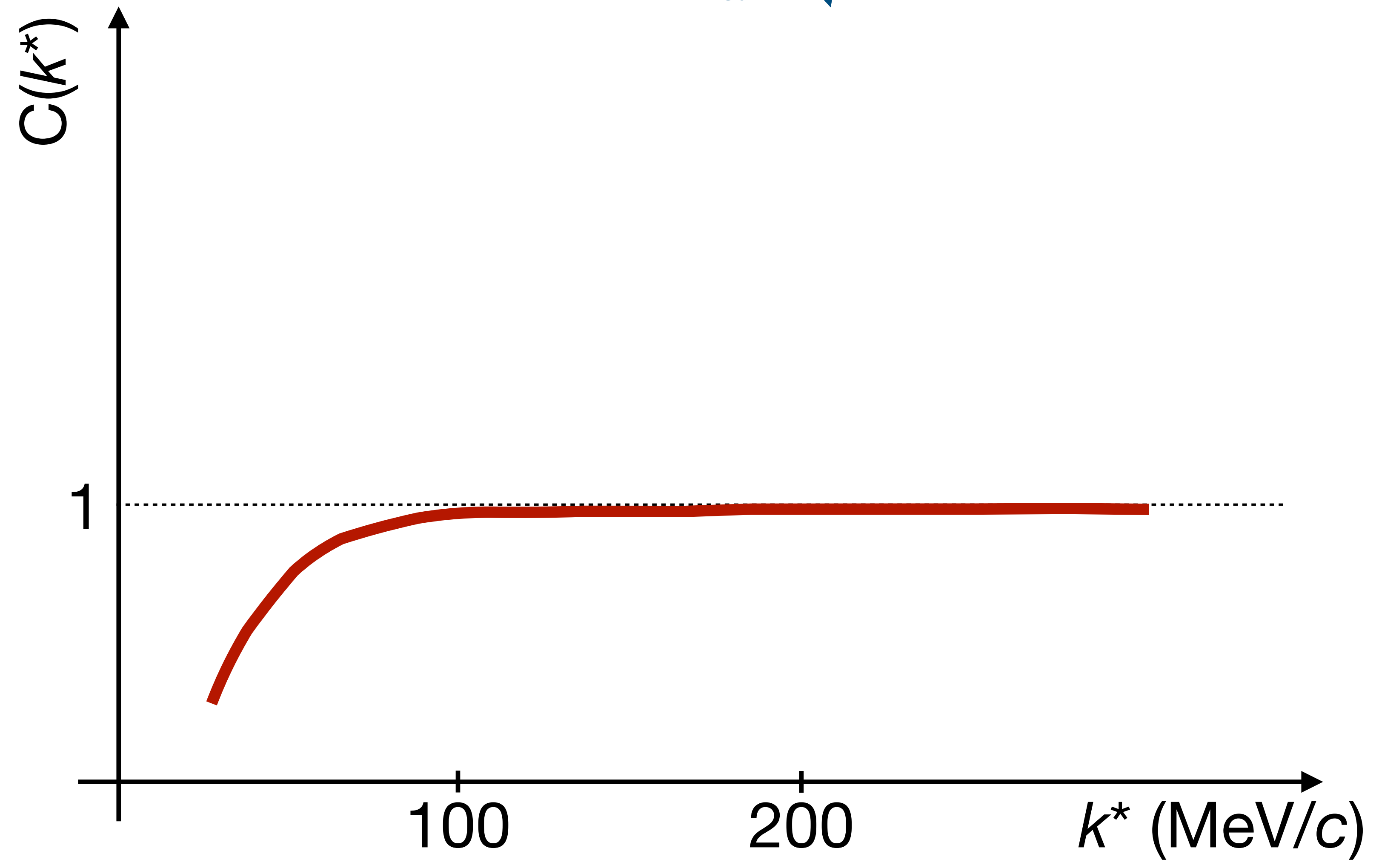


The correlation function

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

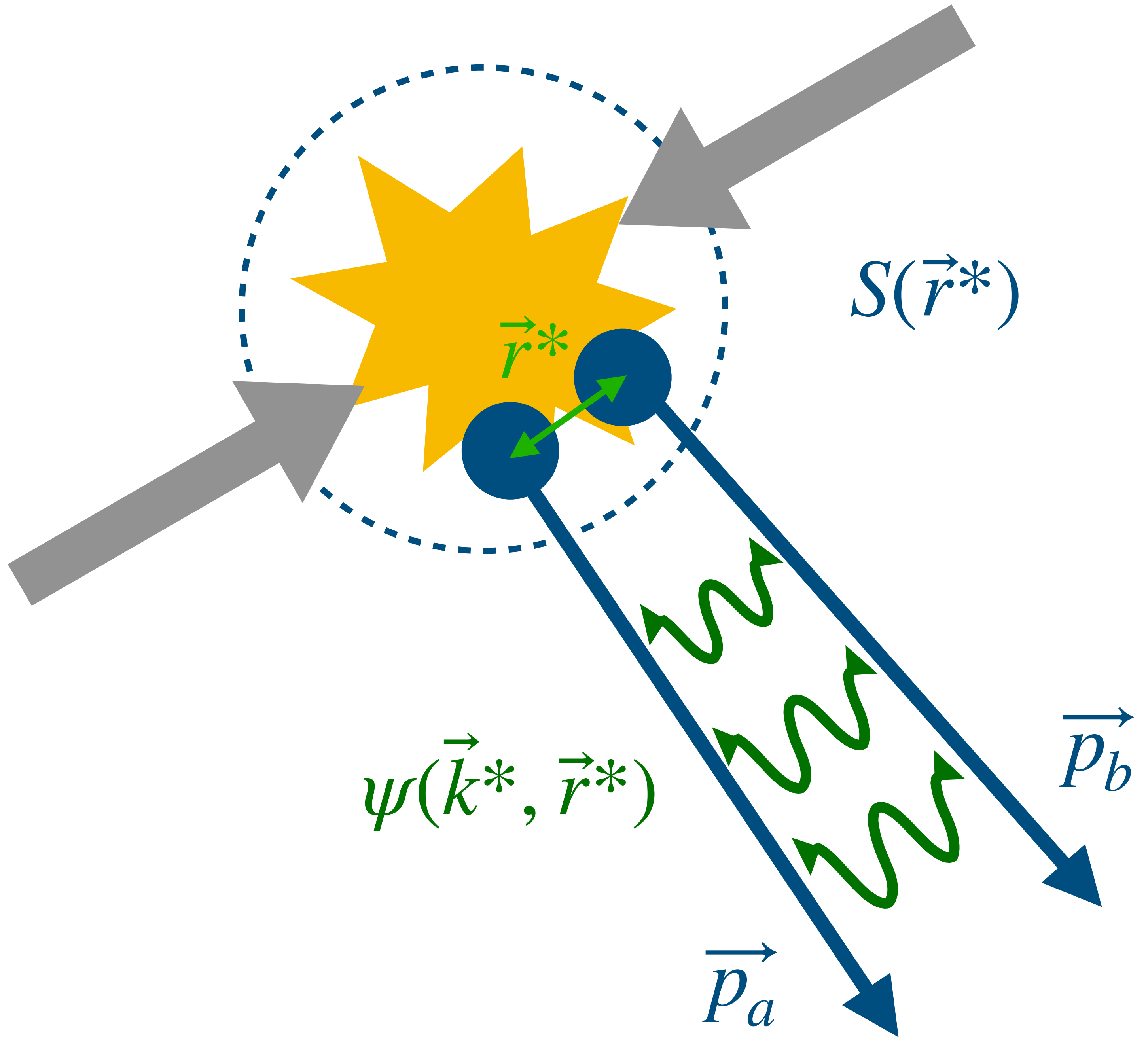
$$C(k^*) = \int S(\vec{r}^*)\,|\psi(\vec{k}^*, \vec{r}^*)|^2\,\mathrm{d}^3r^* = \mathcal{N}\frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)} < 1$$



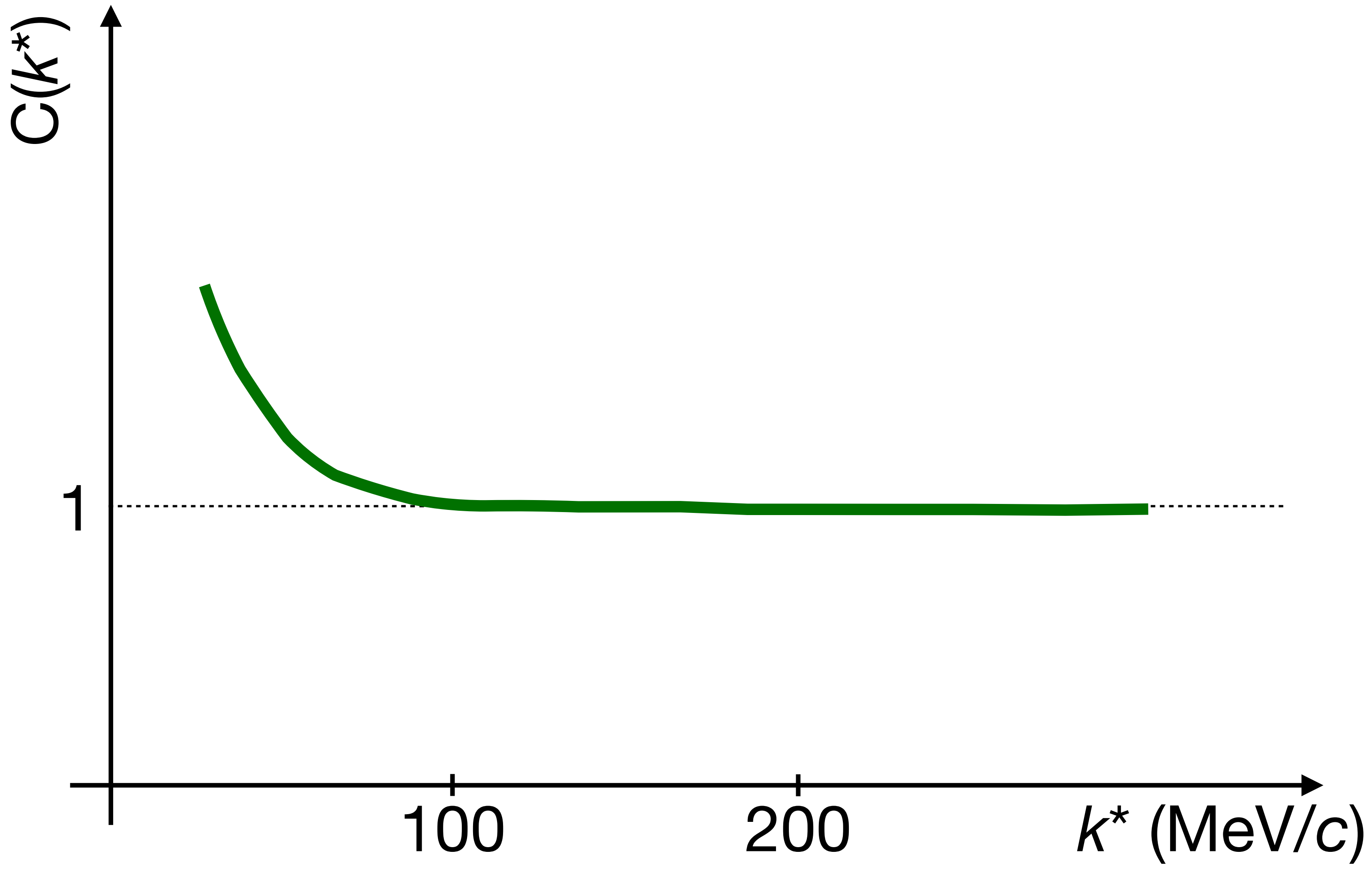


The correlation function

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

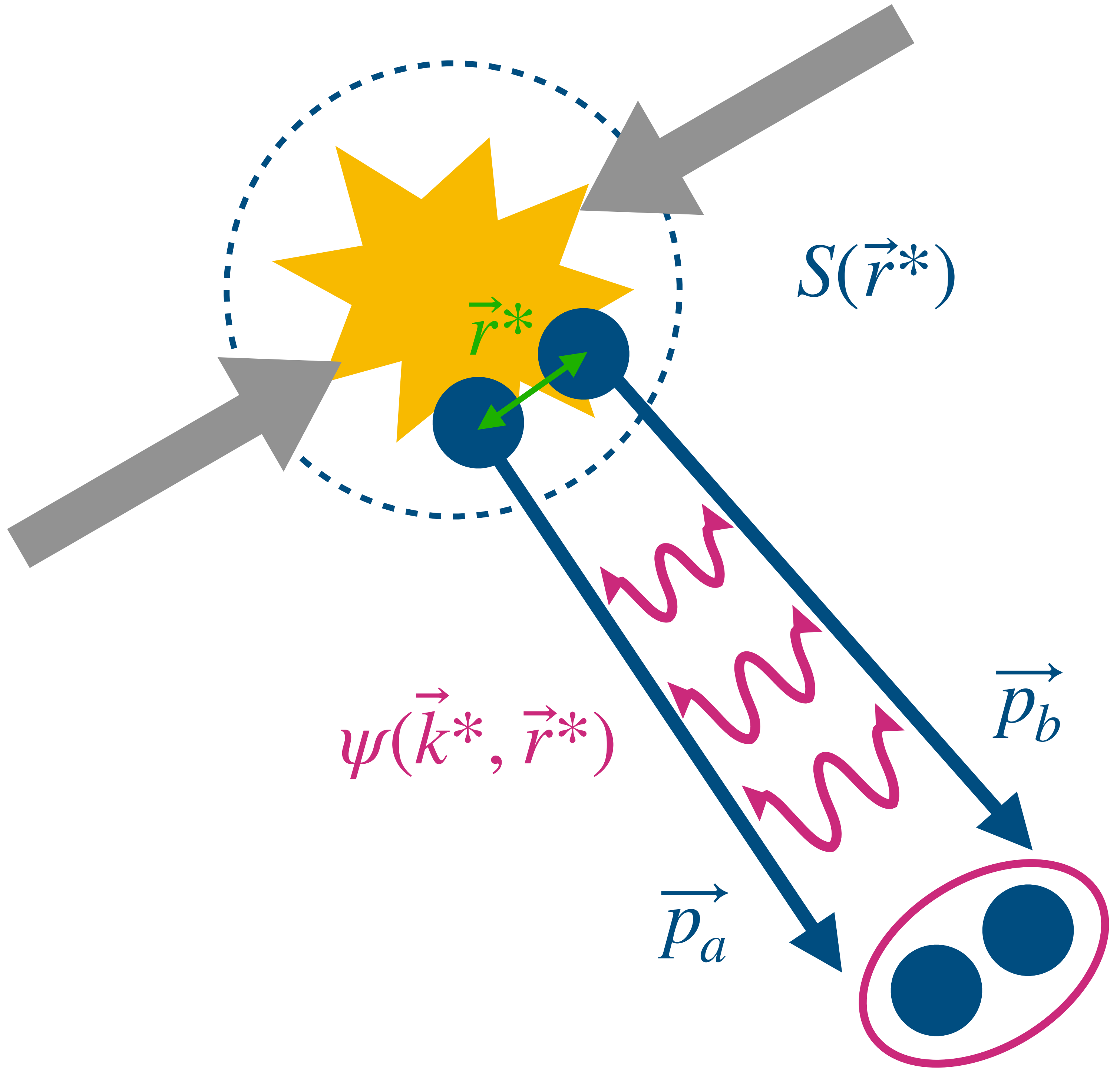


$$C(k^*) = \int S(\vec{r}^*)\,|\psi(\vec{k}^*, \vec{r}^*)|^2\,\mathrm{d}^3 r^* = \mathcal{N}\frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)} > 1$$

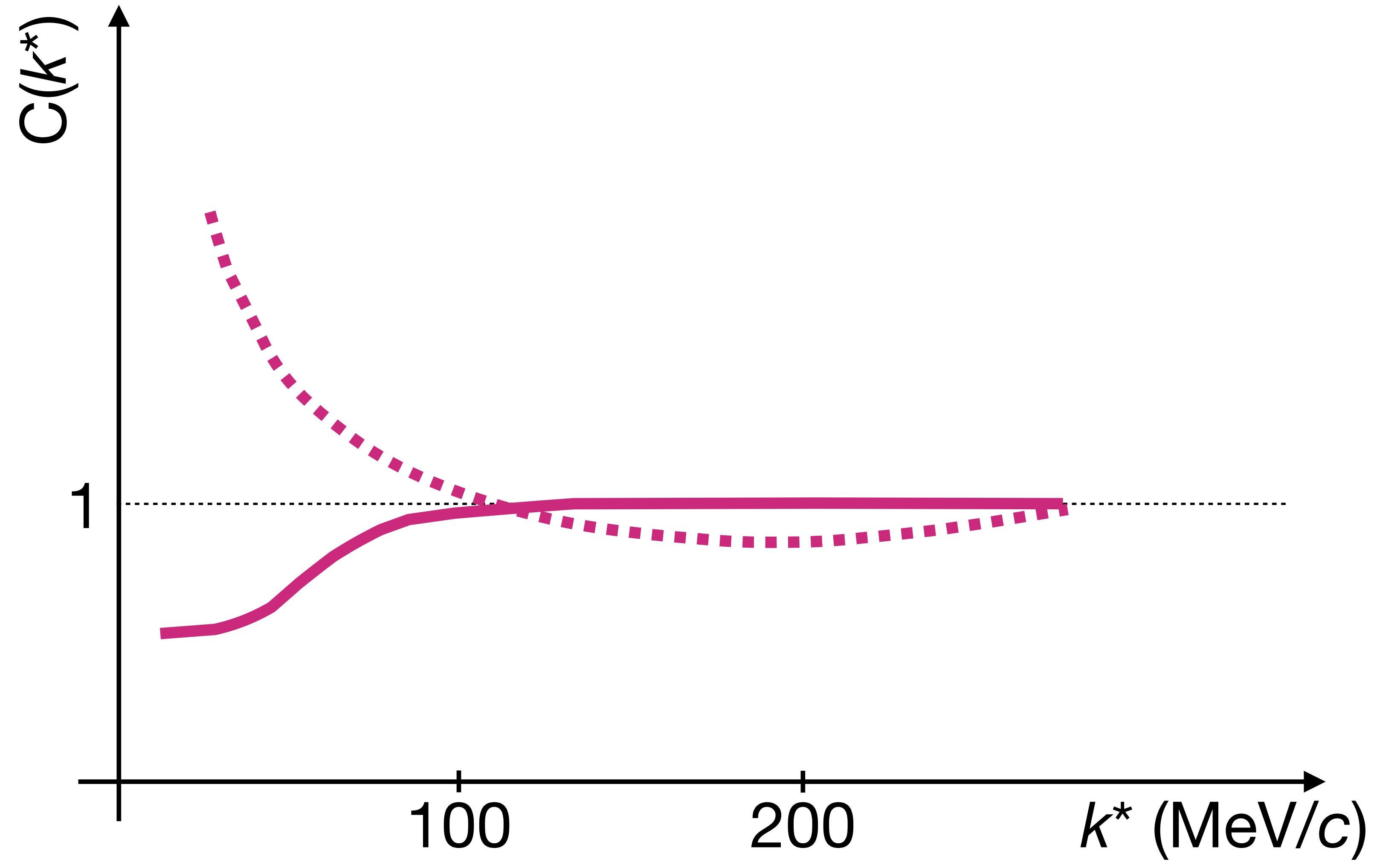


The correlation function

- 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



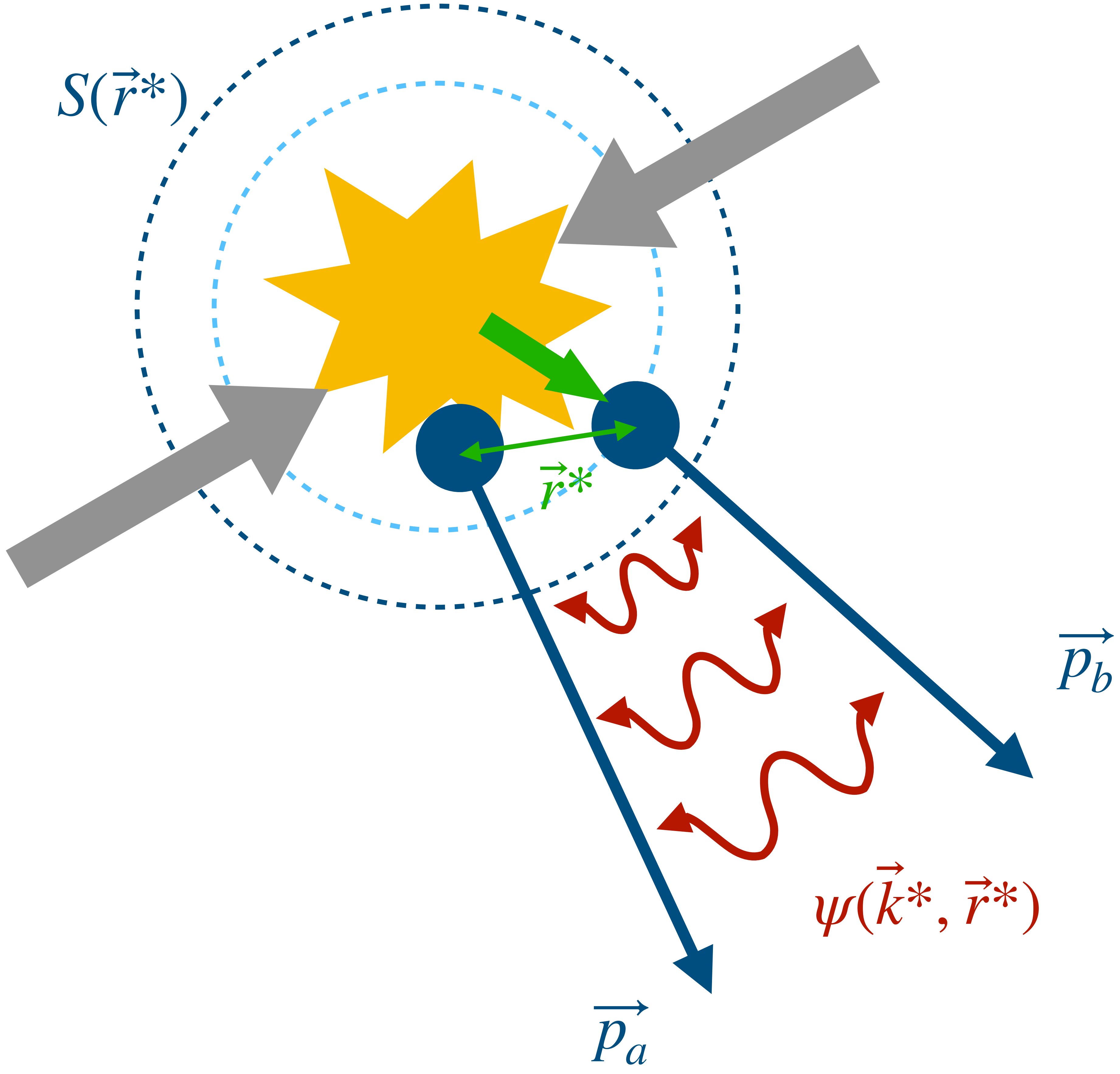
$$C(k^*) = \int S(\vec{r}^*)\,|\psi(\vec{k}^*, \vec{r}^*)|^2\, \mathrm{d}^3 r^* = \mathcal{N}\,\frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)} \lessgtr 1$$



Measure of the source size

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

- 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** ($c\tau \approx r_{\mathrm{core}}$) effectively increase the source radius
  - e.g. Δ-resonances for protons



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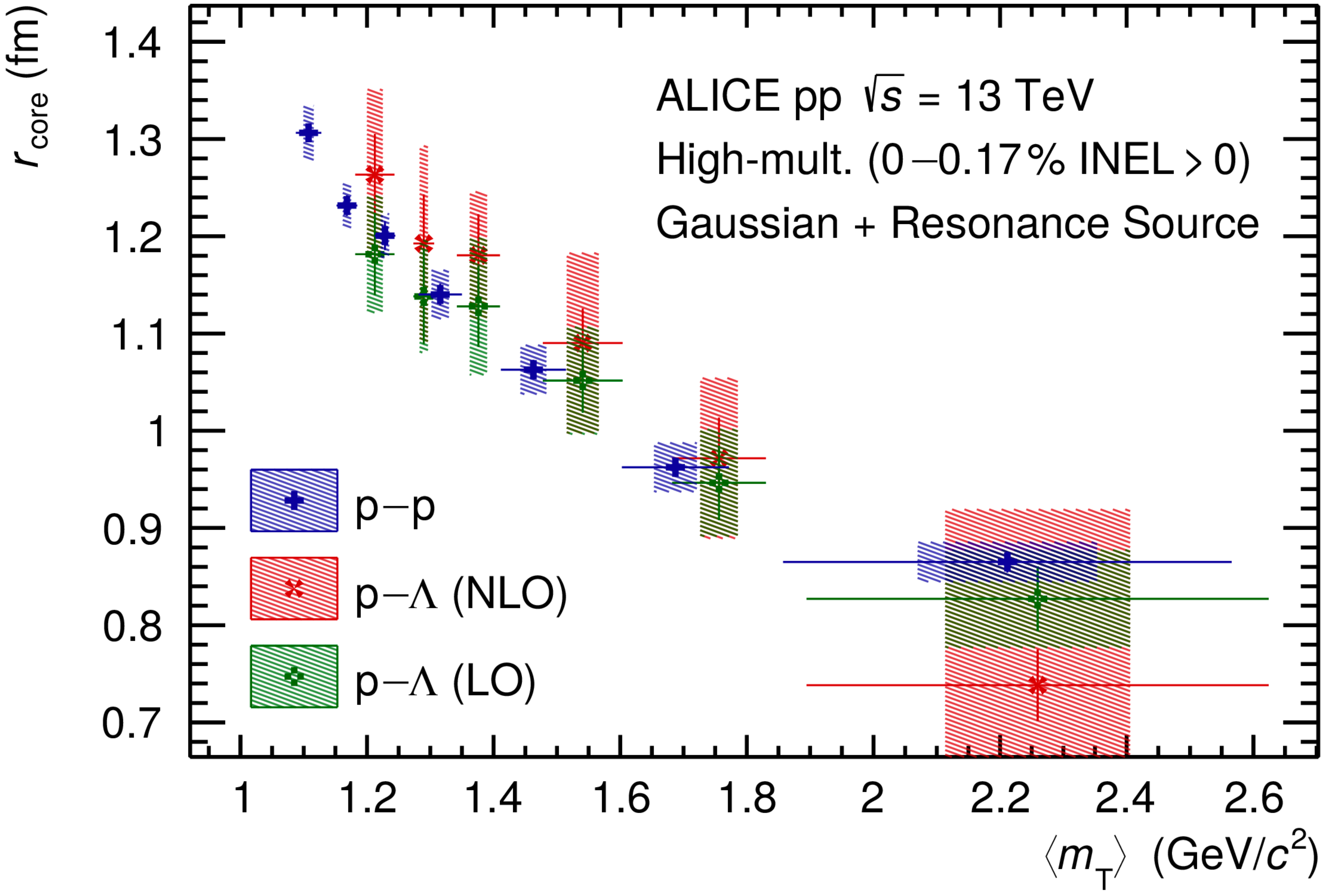
  - Particle emission from a **Gaussian core** source
- Short-lived strongly decaying **resonances** ($c\tau \approx r_{\mathrm{core}}$)
effectively increase the source radius
  - e.g. Δ-resonances for protons
- **Universal source model**
  - r_{core} fixed for each pair based on $\langle m_T \rangle$

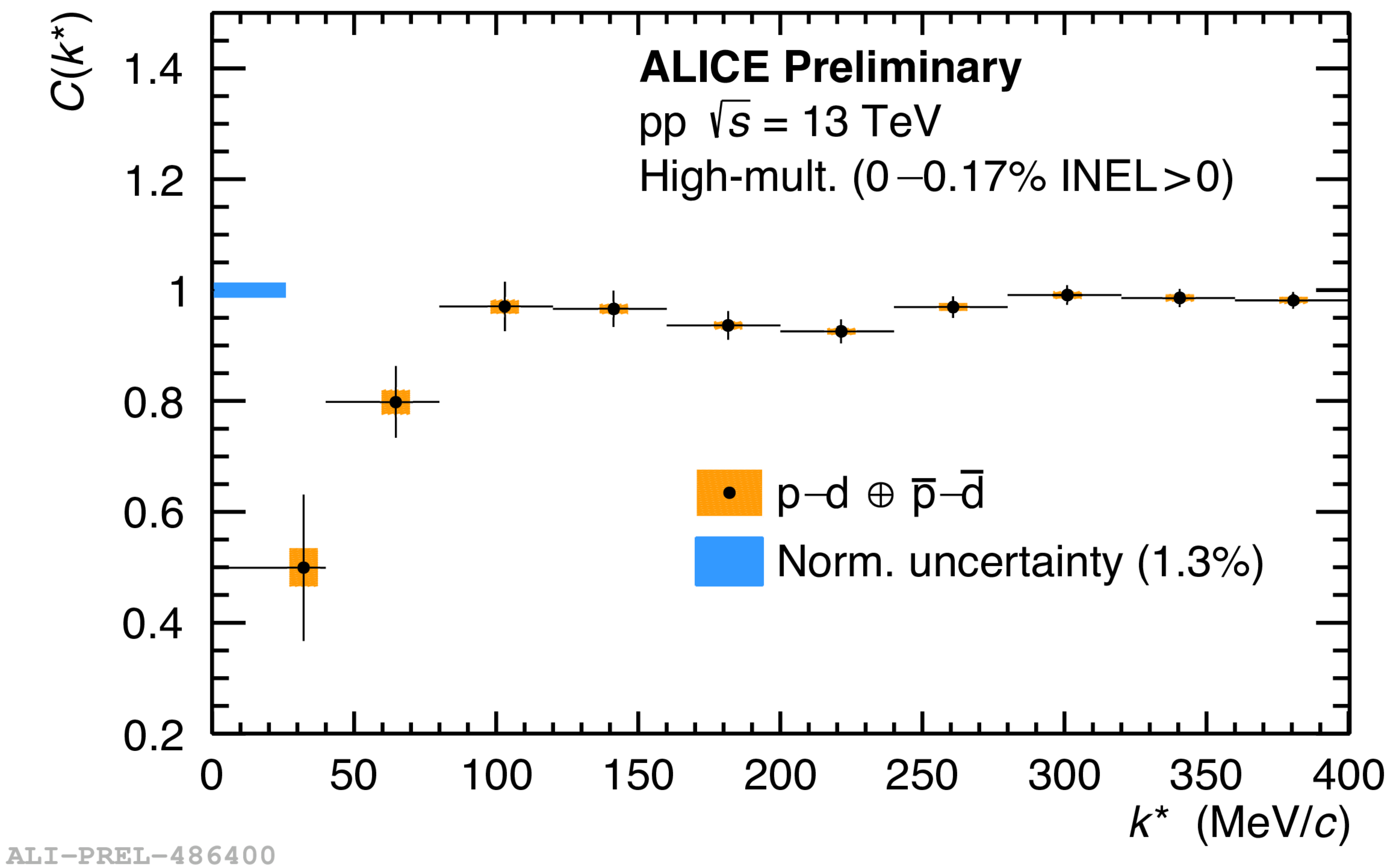
$$C(k^*) = \int S(\vec{r}^*)\,|\psi(\vec{k}^*, \vec{r}^*)|^2\,\mathrm{d}^3 r^* = \mathcal{N}\frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)}$$



PLB 811 (2020) 135849

Proton-deuteron correlation

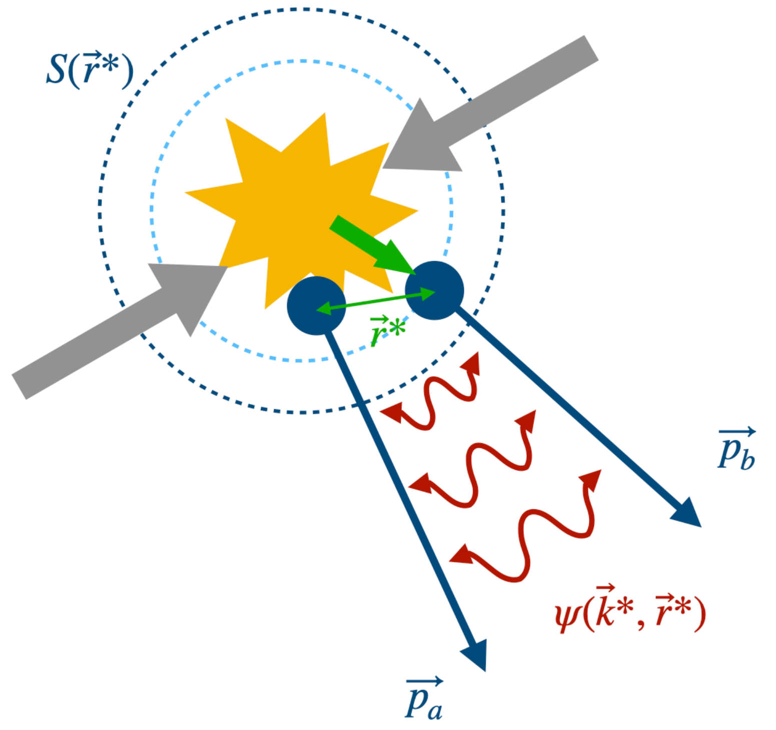
- p-d correlation measured in HM pp collisions:
  - precise measurement of the source $S(k^*)$
    - study of interaction potentials
- The correlation function $C(k^*)$ is below the unity
  - repulsive interaction



ALI-PREL-486400

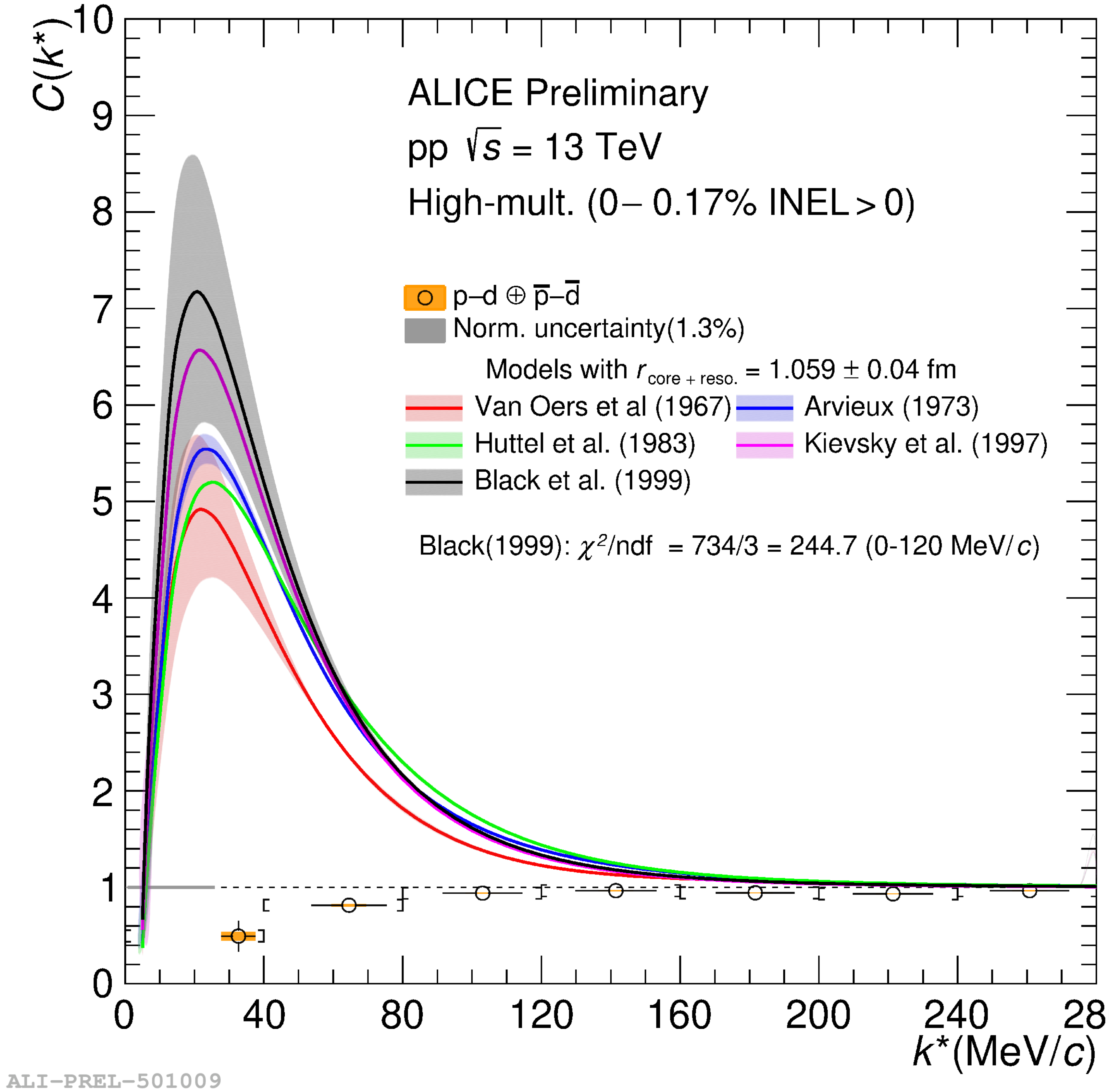
$$C(k^*) = \int S(\vec{r}^*)\,|\psi(\vec{k}^*, \vec{r}^*)|^2\,\mathrm{d}^3r^* = \mathcal{N}\,\frac{N_{\mathrm{same}}(k^*)}{N_{\mathrm{mixed}}(k^*)},$$

with $\vec{k}^* = \dfrac{\vec{p_a} - \vec{p_b}}{2}$



Proton-deuteron correlation

- p-d correlation measured in HM pp collisions:
    - precise measurement of the source $S(k^*)$
        - study of interaction potentials
- The correlation function $C(k^*)$ is below the unity
    - repulsive interaction
- Models with two-body strong interaction do not describe the data:
    - the proton is sensitive to the internal structure of the deuteron
    - three-body interactions must be taken into account



ALI-PREL-501009

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

with $\vec{k}^* = \dfrac{\vec{p_a} - \vec{p_b}}{2}$