

LHCP2021

The Ninth Annual Conference on Large Hadron Collider Physics

Online

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Production of (anti)(hyper)nuclei at the LHC

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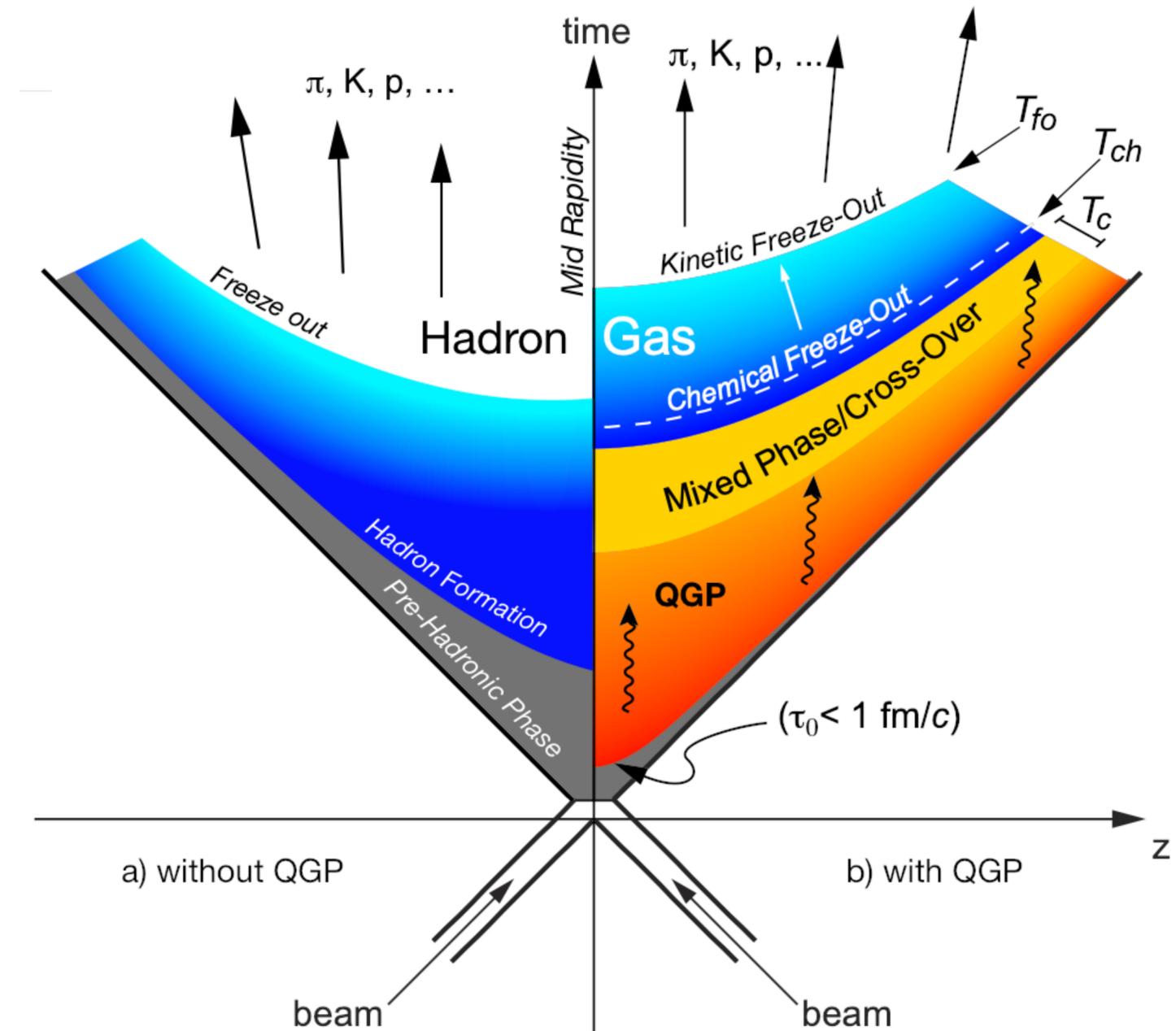
on behalf of the **ALICE Collaboration**



ALICE

Nuclear matter production

- Light (anti)(hyper)nuclei are abundantly produced at the LHC in pp, p-Pb and Pb-Pb 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 abundances from **statistical equilibrium** at the **chemical freeze-out**
- The chemical freeze-out temperature (T_{ch}) is a key parameter:

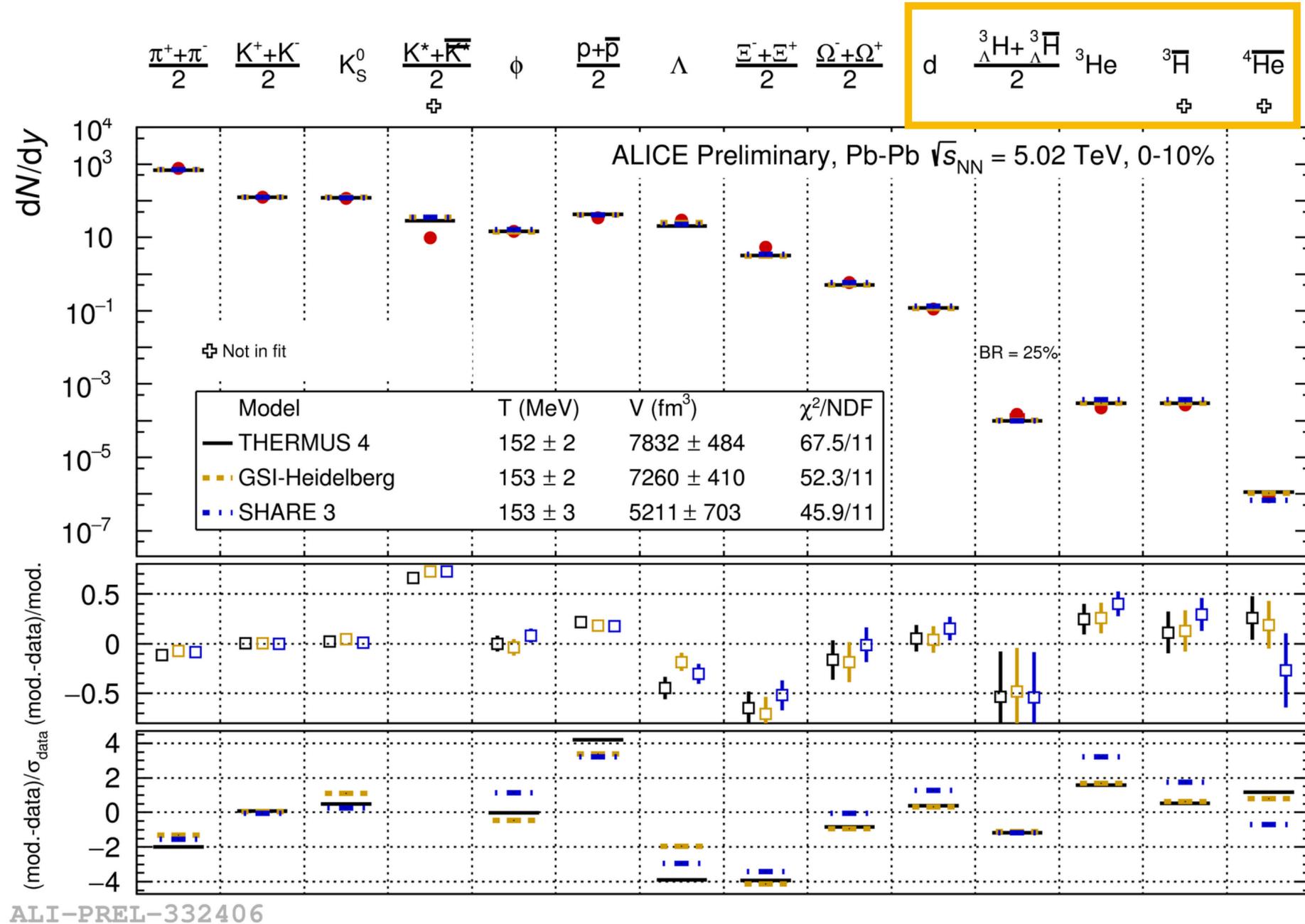
$$dN/dy \propto \exp\left(-\frac{m}{T_{ch}}\right)$$

- 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 (**7 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.Comm. 180 \(2009\) 84-106](#)

GSI-Heidelberg: [Nucl.Phys.A 772 \(2006\) 167-199](#)

SHARE 3: [Comput.Phys.Comm. 167 \(2005\) 229-251](#)

The coalescence model

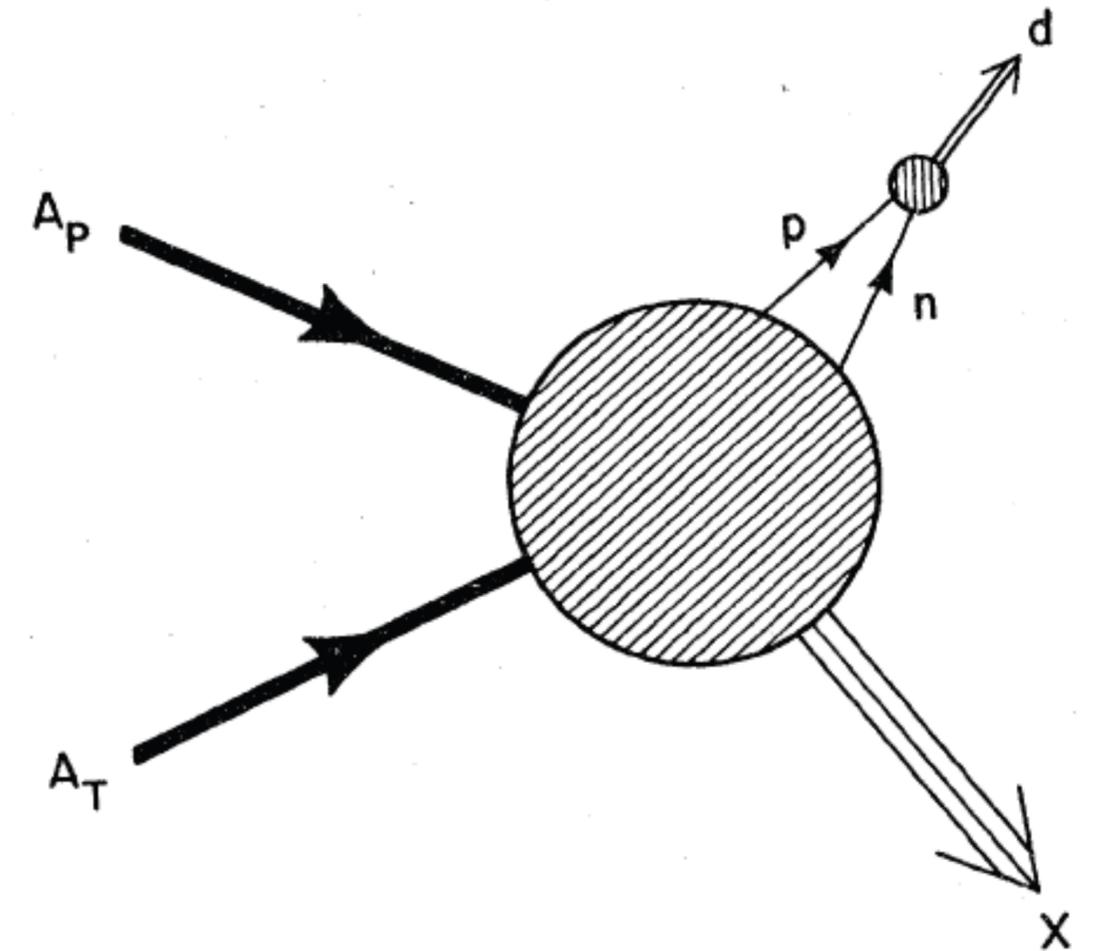
- Nucleons that are **close in phase space** at the **freeze-out** can form a nucleus via **coalescence**
- The key concept is the overlap between the **nuclear wavefunction** and the **phase space** of the **nucleons**
- The main parameter of the model is:

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

where:

- A is the mass number of the nucleus
- $\rho_p = \rho_A / A$

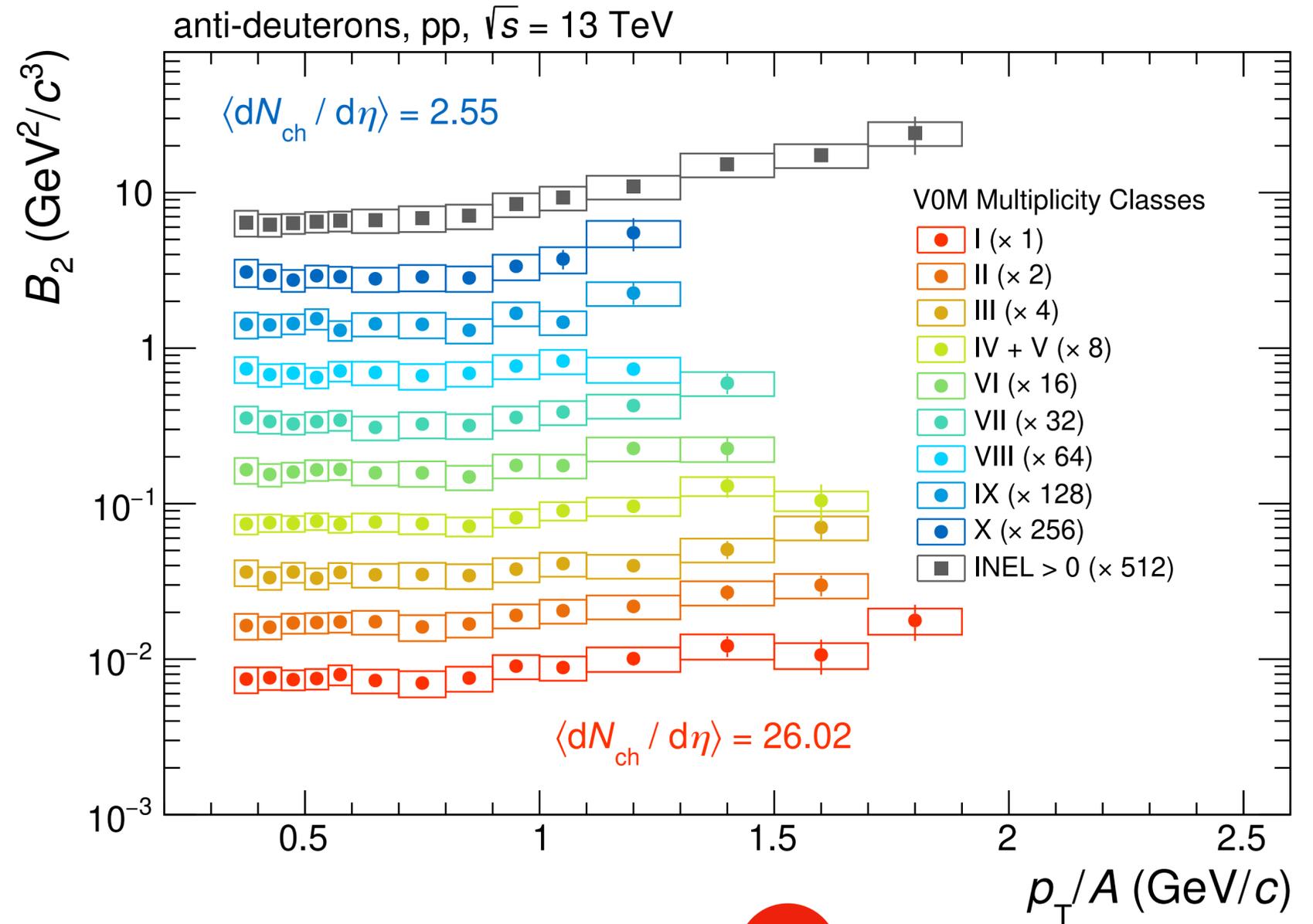
- B_A is related to the **probability** to form a nucleus via coalescence



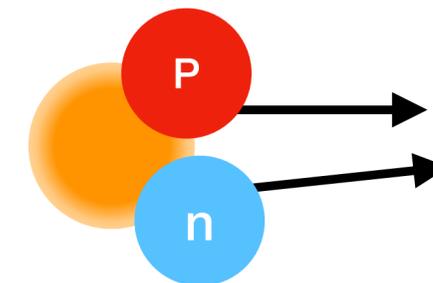
J. I. Kapusta, Phys. Rev. C21, 1301 (1980)

The coalescence parameter B_A

- For pp collisions, B_A is **weakly dependent on p_T**
 - the system size is comparable with the nucleus size

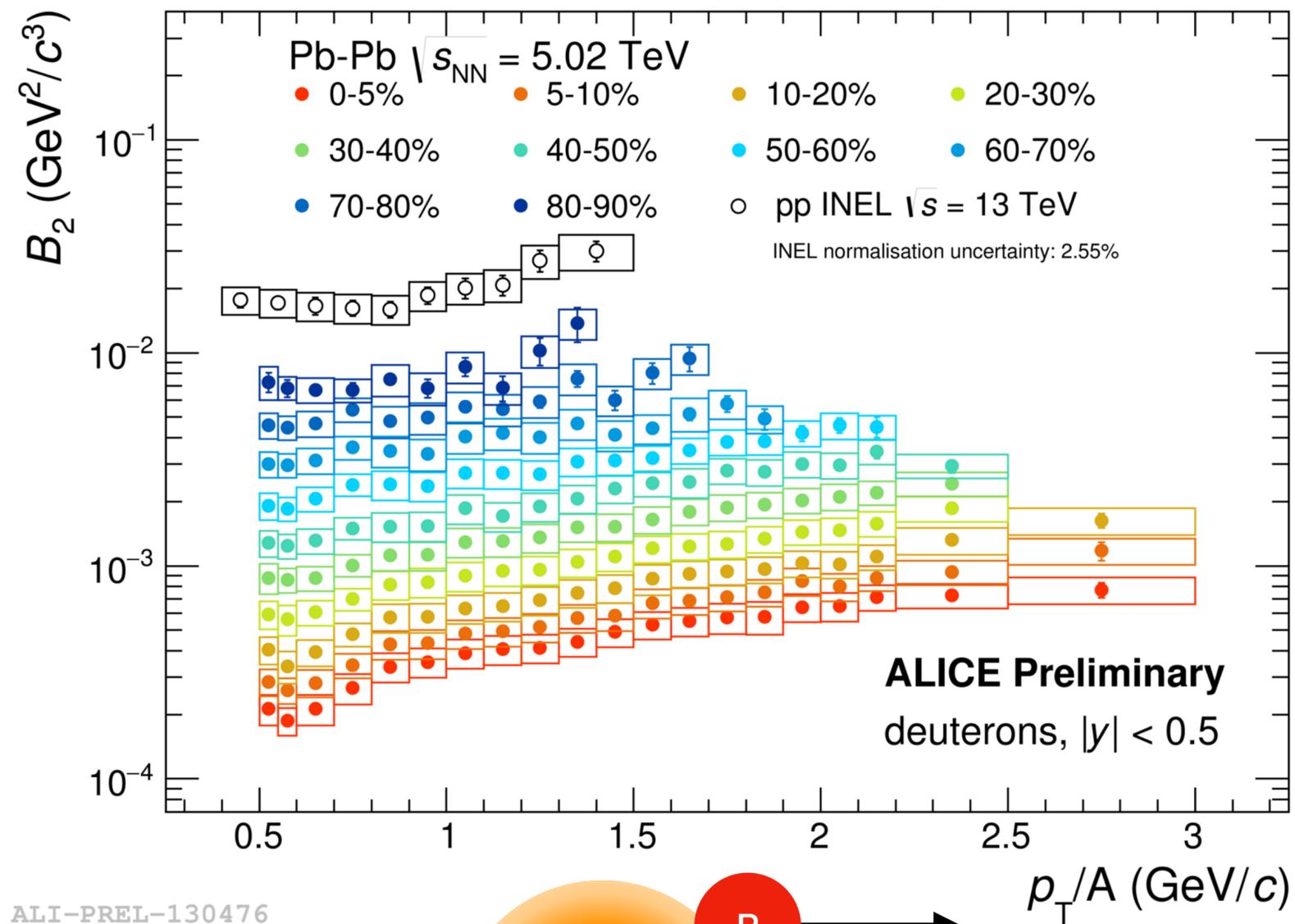


ALI-PUB-483726



The coalescence parameter B_A

- For pp collisions, B_A is **weakly dependent on p_T**
 - the system size is comparable with the nucleus size
- Moving to larger systems B_A **rises with p_T**
 - the system size is larger than the nucleus size
 - system size is inversely proportional to m_T



The coalescence parameter B_A

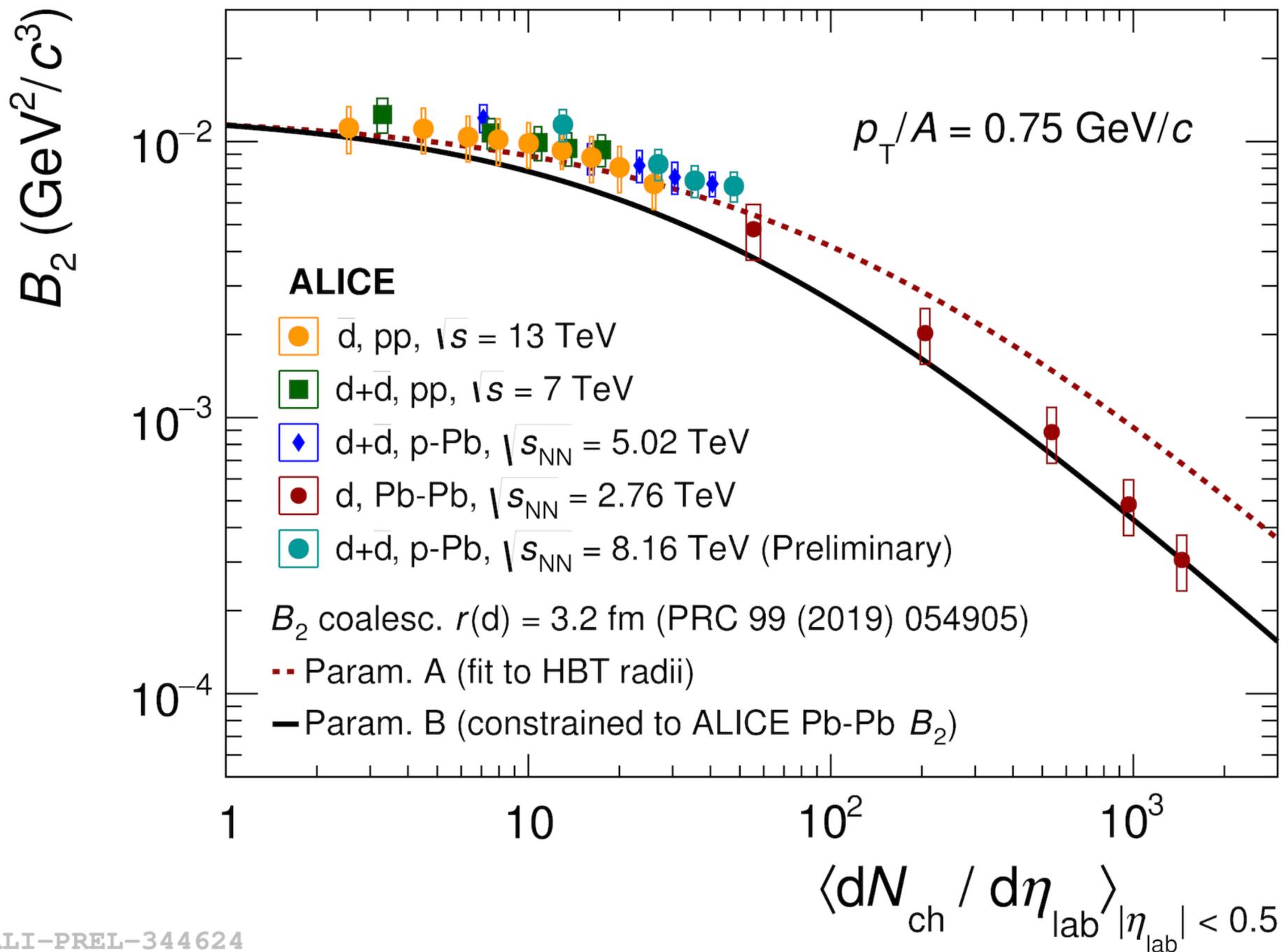
- Measuring B_A as a function of $dN_{ch}/d\eta$ at fixed p_T it is possible to study the dependence on the **system volume**.

▶ $V \propto dN_{ch}/d\eta$

- B_A evolves **smoothly** with **multiplicity**

- ▶ **production mechanism depends only on the system size**

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



ALI-PREL-344624

The coalescence parameter B_A

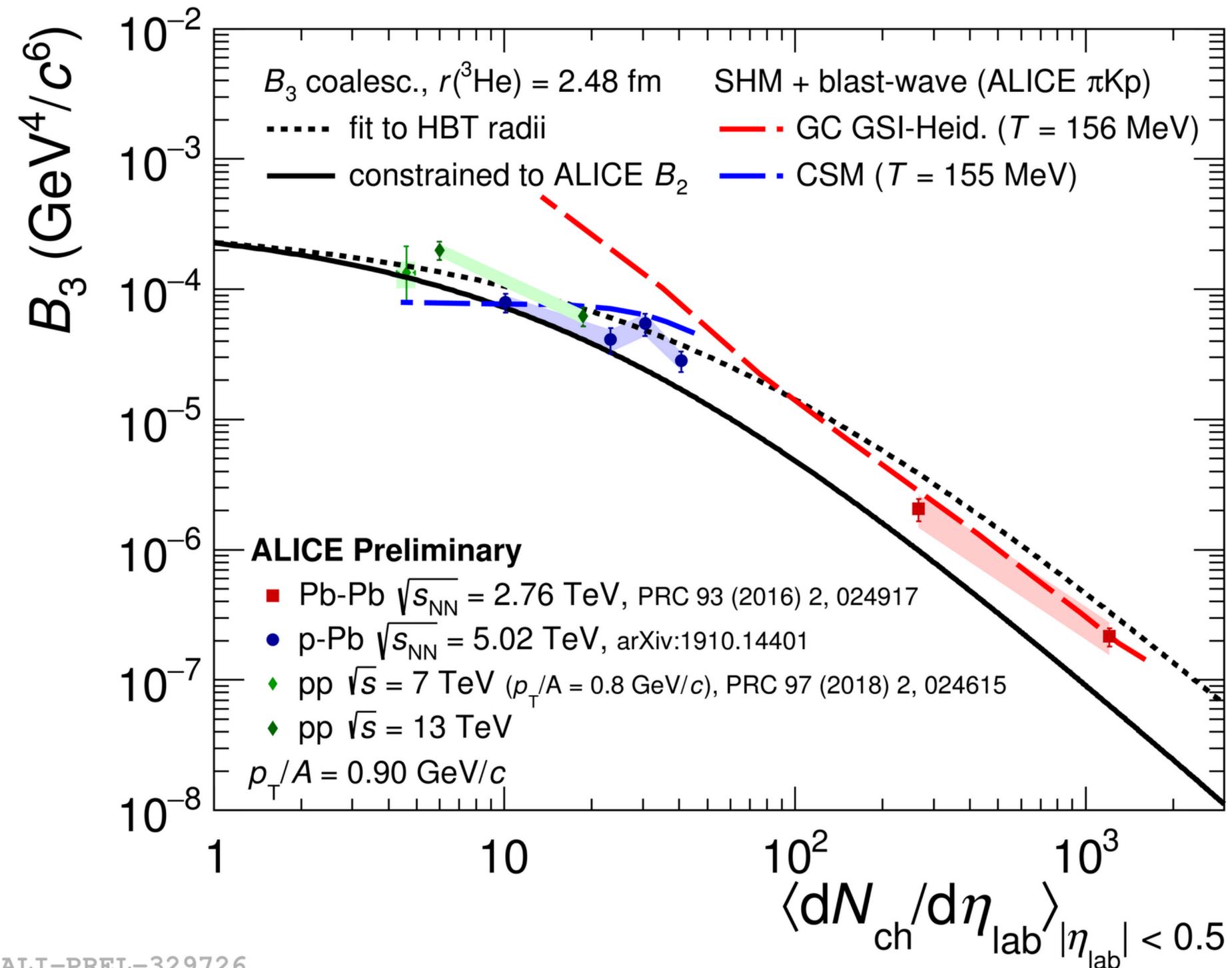
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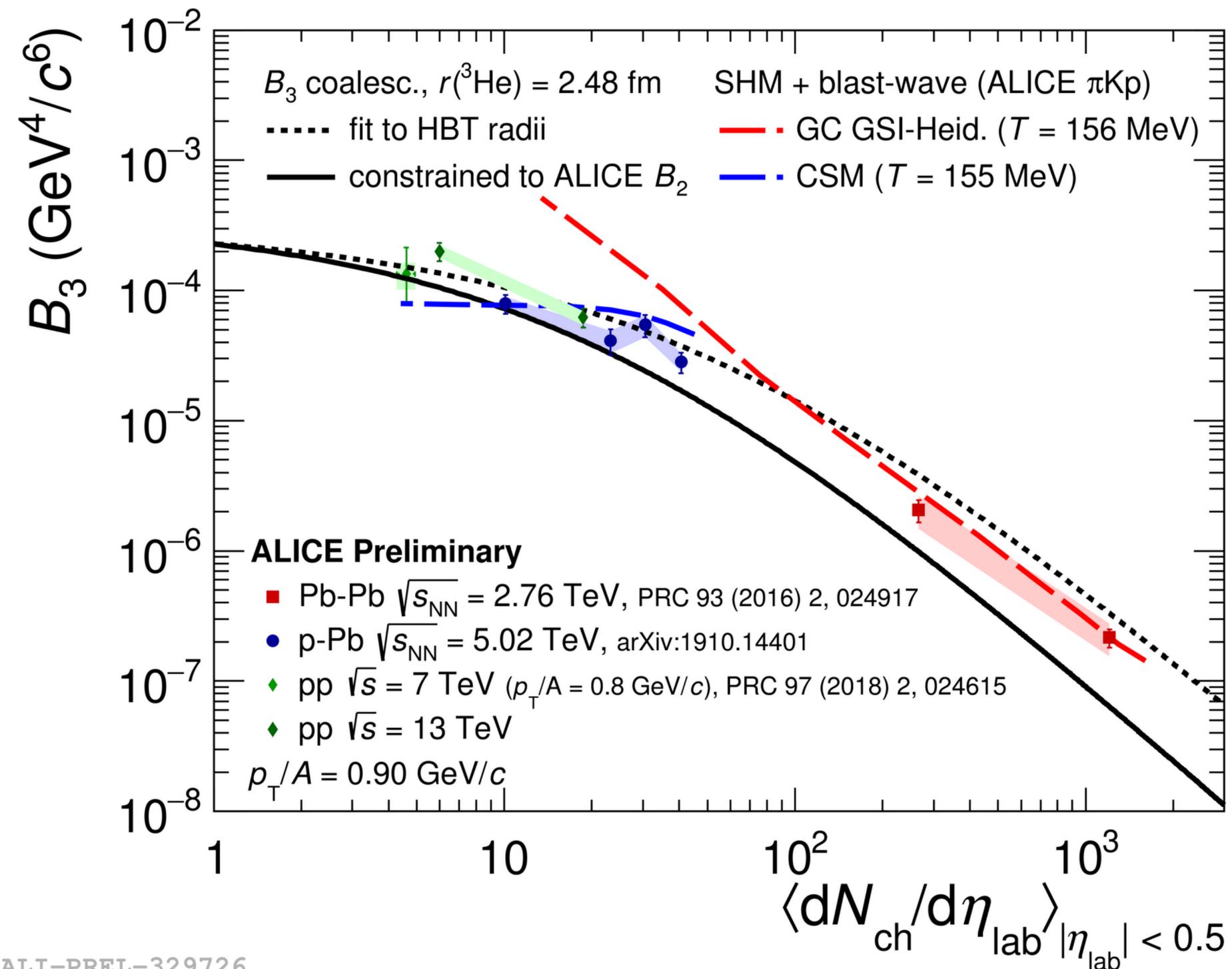
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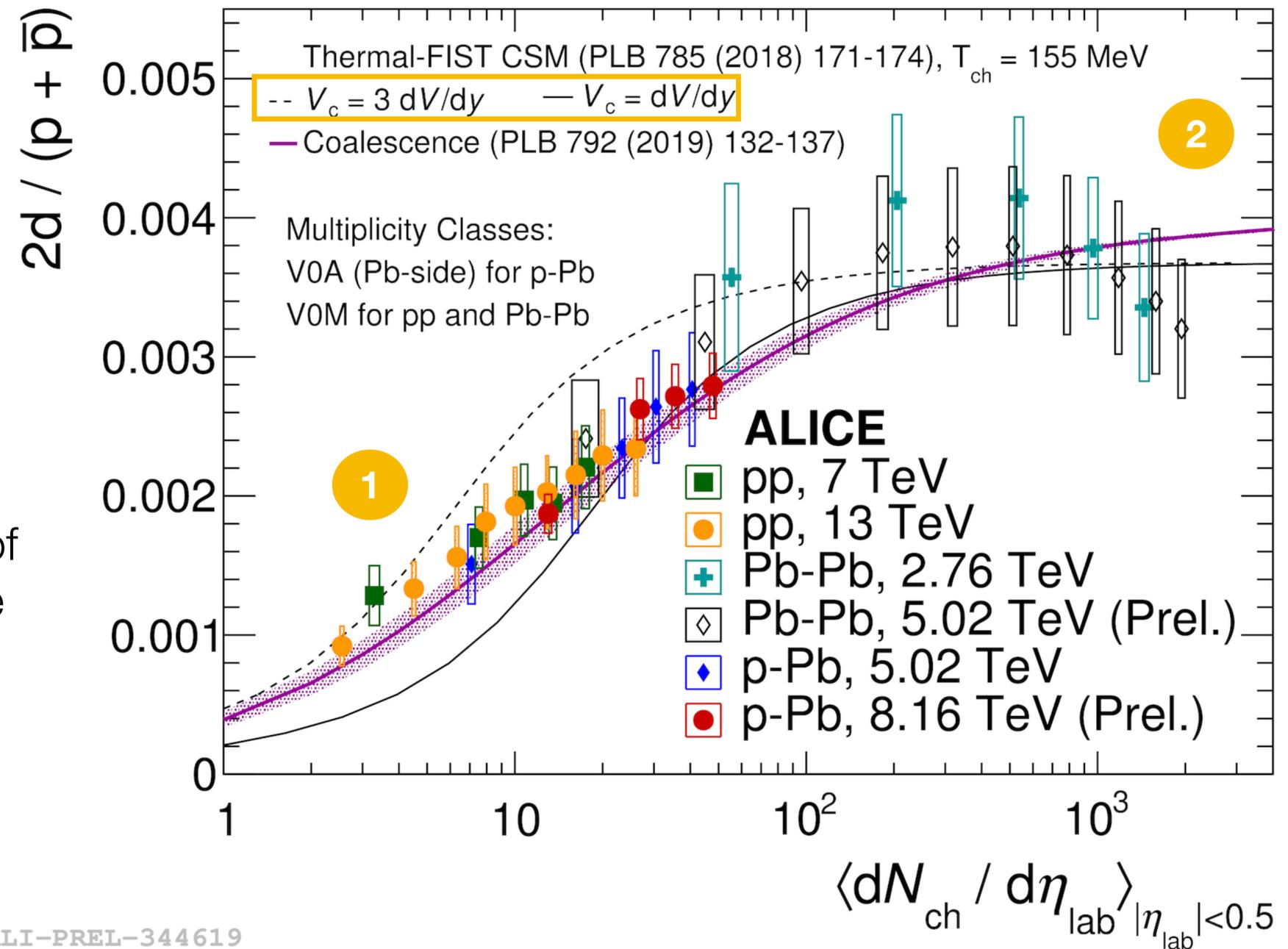
- B_A is sensitive to the nuclear radius

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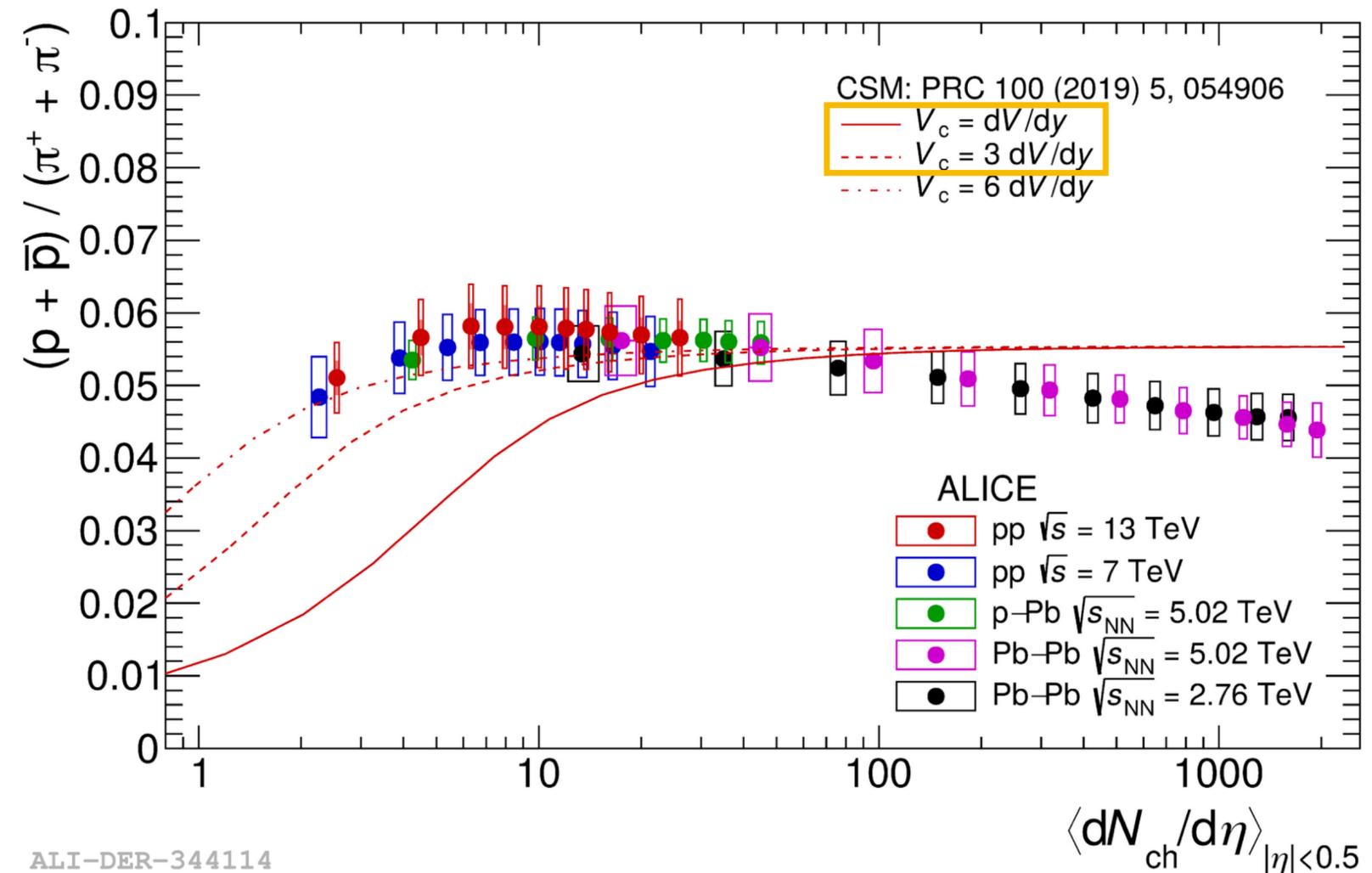
Yield ratios

- **d/p** ratio evolves **smoothly** with **multiplicity**, regardless of the collision system:
 - ▶ **production mechanism depends only on the system size**
- Two different regimes:
 - 1. increasing:**
 - Thermal model: **canonical suppression**
 - Coalescence: **interplay** between **system** and **nucleus size**
 - 2. flat:** at high multiplicity there is no dependence of the ratio on the multiplicity, in agreement with the predictions of the **thermal model** and **coalescence**



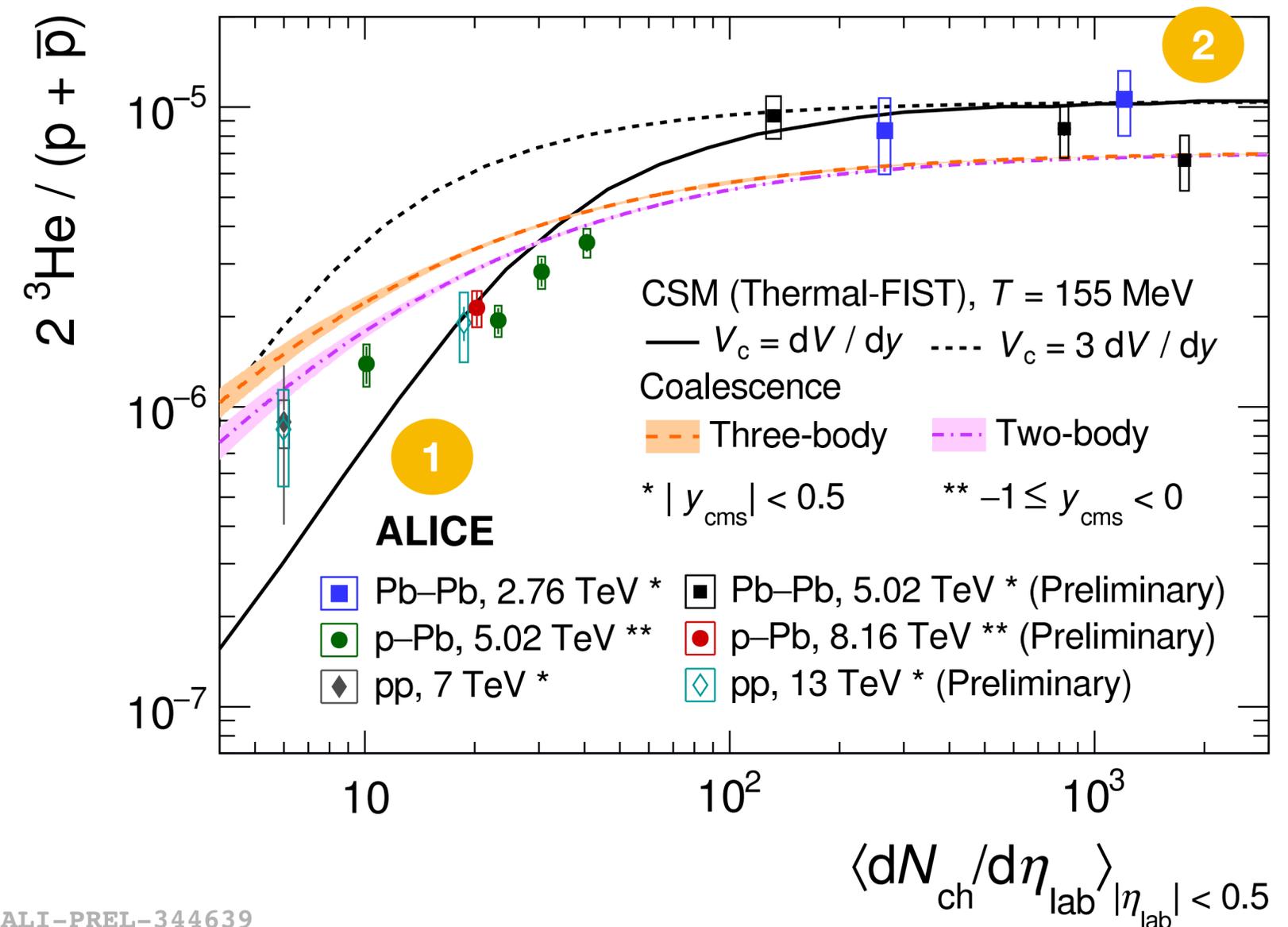
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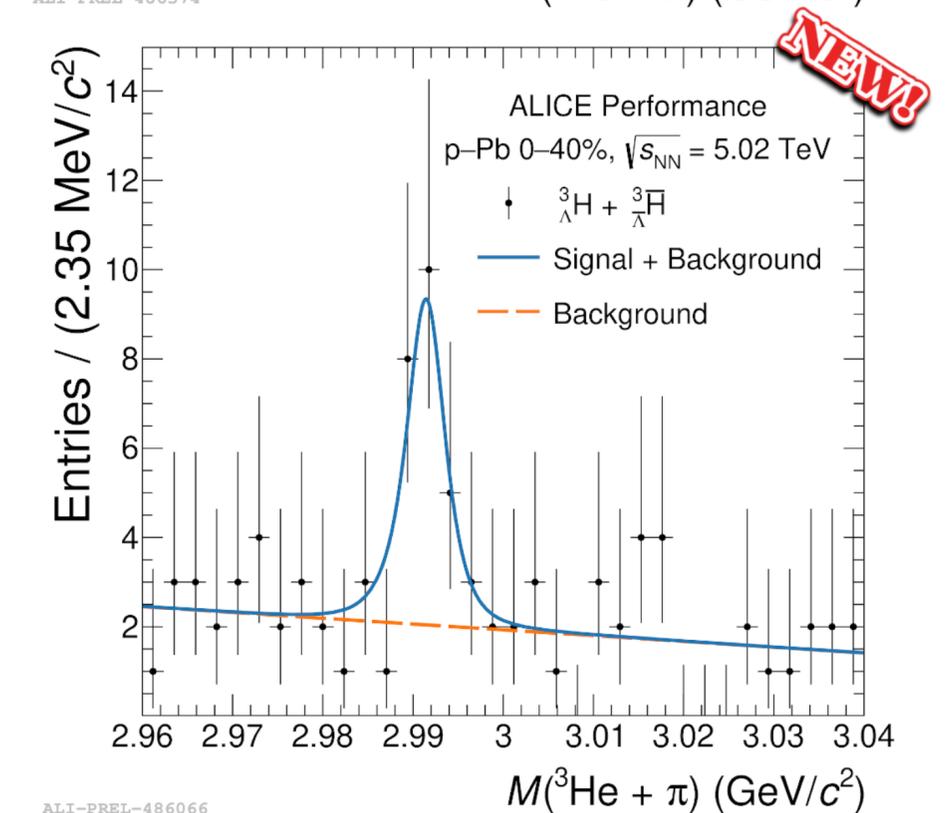
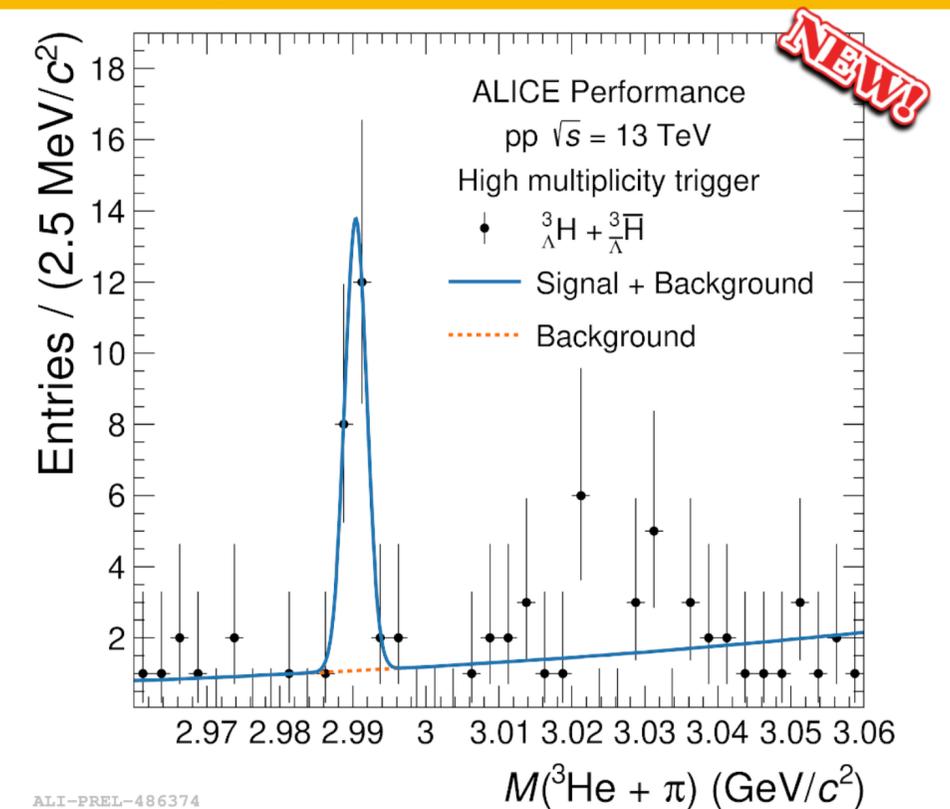
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- **CSM cannot describe p/π** with the same correlation volume used for d/p
- Larger tensions with models for **³He/p**
 - ▶ new SHM predictions soon available



Hypertriton production in small systems

- For the first time, ${}^3_{\Lambda}\text{H}$ has been observed in small systems
 - in **pp** collisions at 13 TeV with **High Multiplicity trigger**
 - in **p-Pb** collisions at 5 TeV
- ${}^3_{\Lambda}\text{H}$ has a large radius:
 - $r({}^3_{\Lambda}\text{H}) = 10.79 \text{ fm}^{(1)}$, $r({}^3\text{He}) = 2.58 \text{ fm}$, $r(\text{d}) = 3.2 \text{ fm}$
 - ${}^3_{\Lambda}\text{H}$ 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⁾

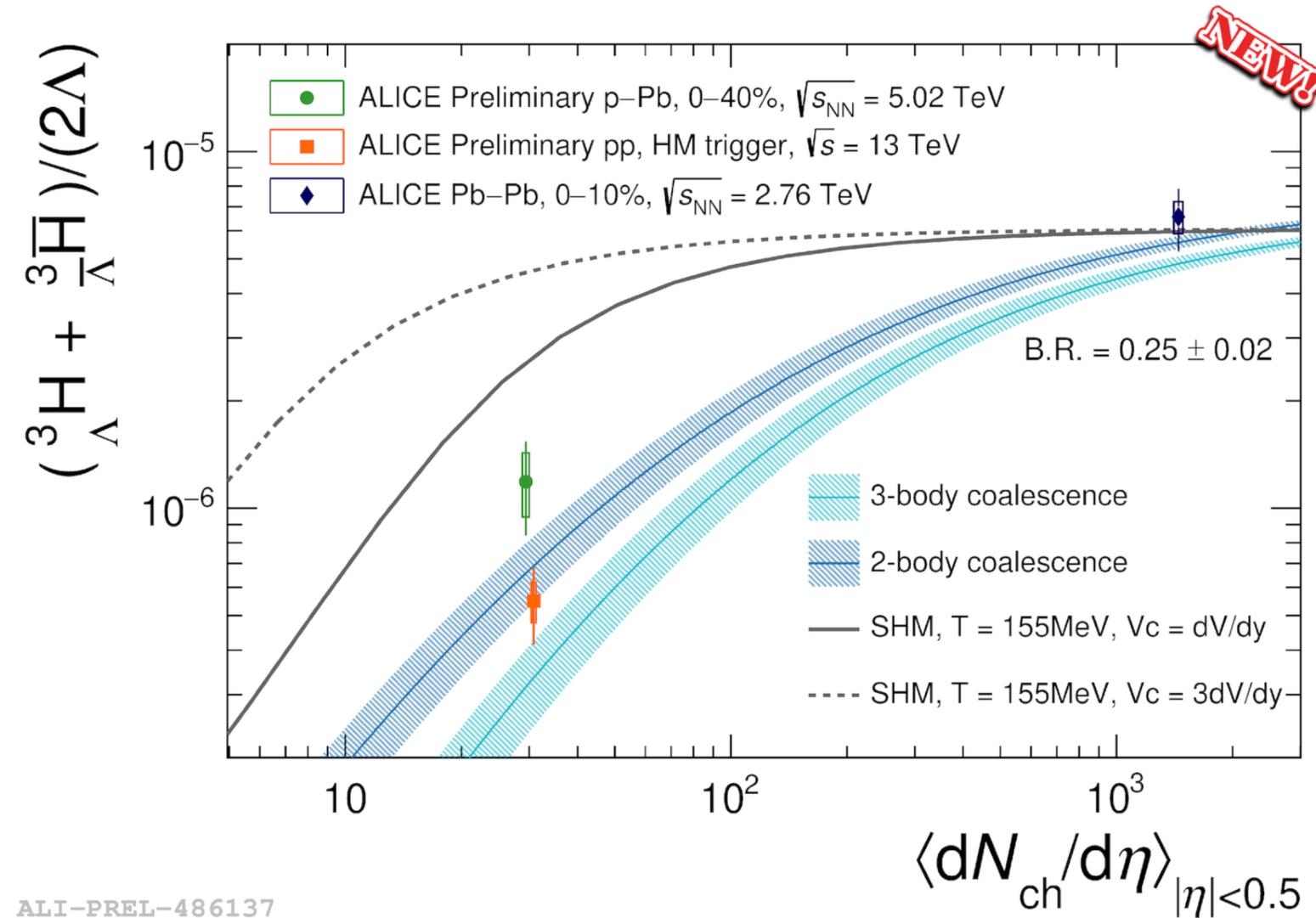


⁽¹⁾ [F. Hildenbrand and H.-W. Hammer, Phys. Rev. C 100, 034002](#)

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

Hypertriton production in small systems

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



Hypertriton production in small systems

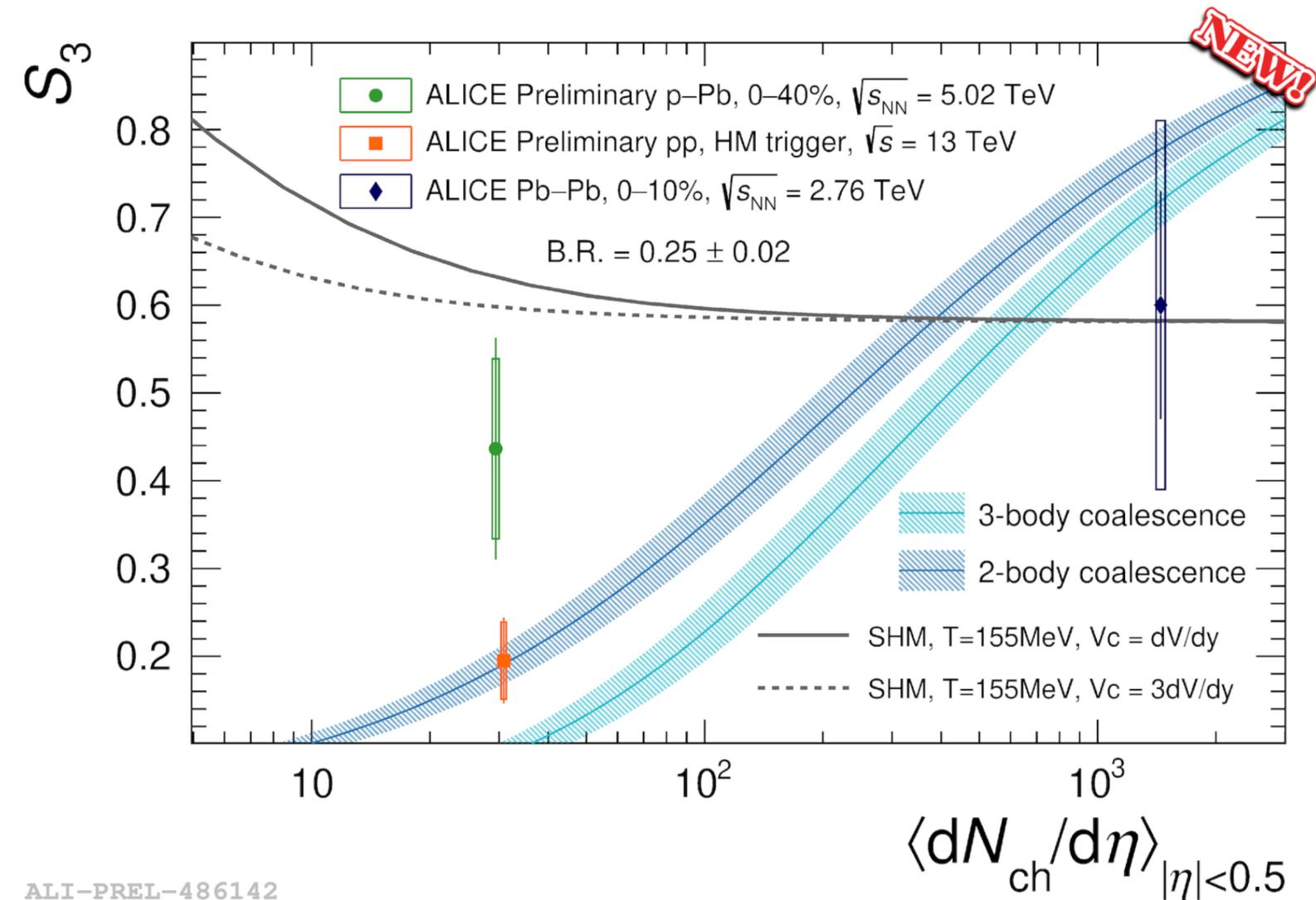
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- ▶ **Two-body coalescence** model provides the best description of data

- Also $S_3 = \frac{{}^3_{\Lambda}\text{H}/{}^3\text{He}}{\Lambda/p}$ is a valuable observable to

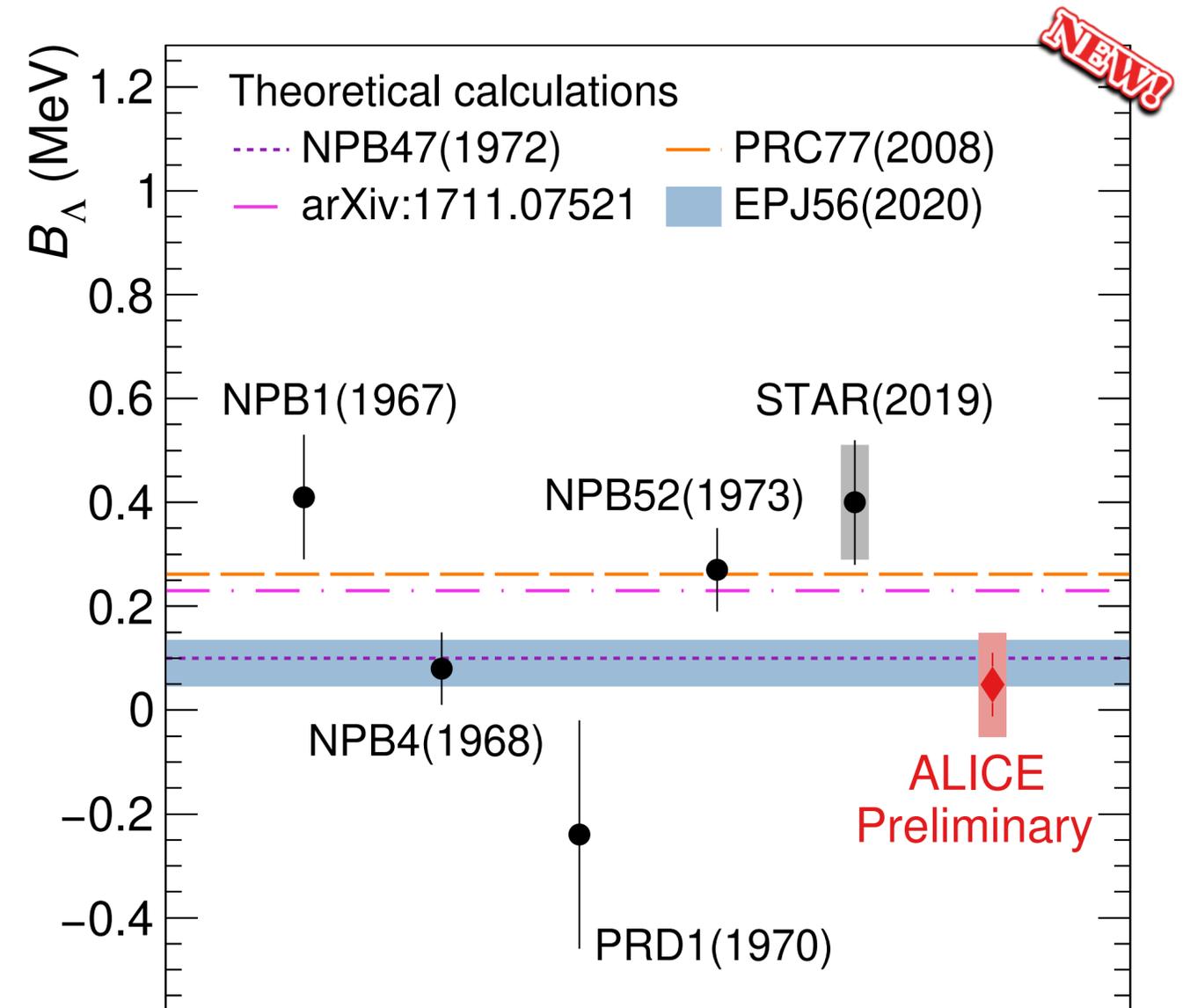
discriminate between production mechanisms

- ▶ Also in this case **coalescence** is favoured, even though with less sensitivity



Λ separation energy

- B_Λ has been measured with a **high precision**
- B_Λ is compatible with **zero** and with χ **EFT** and **Dalitz's** predictions
 - ▶ Hypertriton is a **loosely bound** object
- **1.9 σ** difference w.r.t. last **STAR** results
- **Lifetime** compatible with that of the **free Λ**



ALI-PREL-486370

Summary

- ALICE has measured the production of light (anti)(hyper)nuclei in different collision systems and at different energies.
- The coalescence model provides a good description of \mathbf{B}_Λ , $\mathbf{d/p}$ and ${}^3\mathbf{He/p}$ as a function of multiplicity
- **CSM** can describe the evolution of $\mathbf{d/p}$ and ${}^3\mathbf{He/p}$ with multiplicity, but **fails** in describing $\mathbf{p/\pi}$ with the same correlation volume.
- The measurements of ${}^3_\Lambda\mathbf{H/\Lambda}$ and \mathbf{S}_3 in pp and p-Pb collisions **favour two-body coalescence** w.r.t. CSM
- The precise measurement of \mathbf{B}_Λ confirms that hypertriton is a loosely bound state
- With Run 3 will be extremely important to address the problem of (hyper)nuclei production, due to the increased luminosity and the improved tracking precision

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Thank you for your attention!

Backup

The ALICE experiment

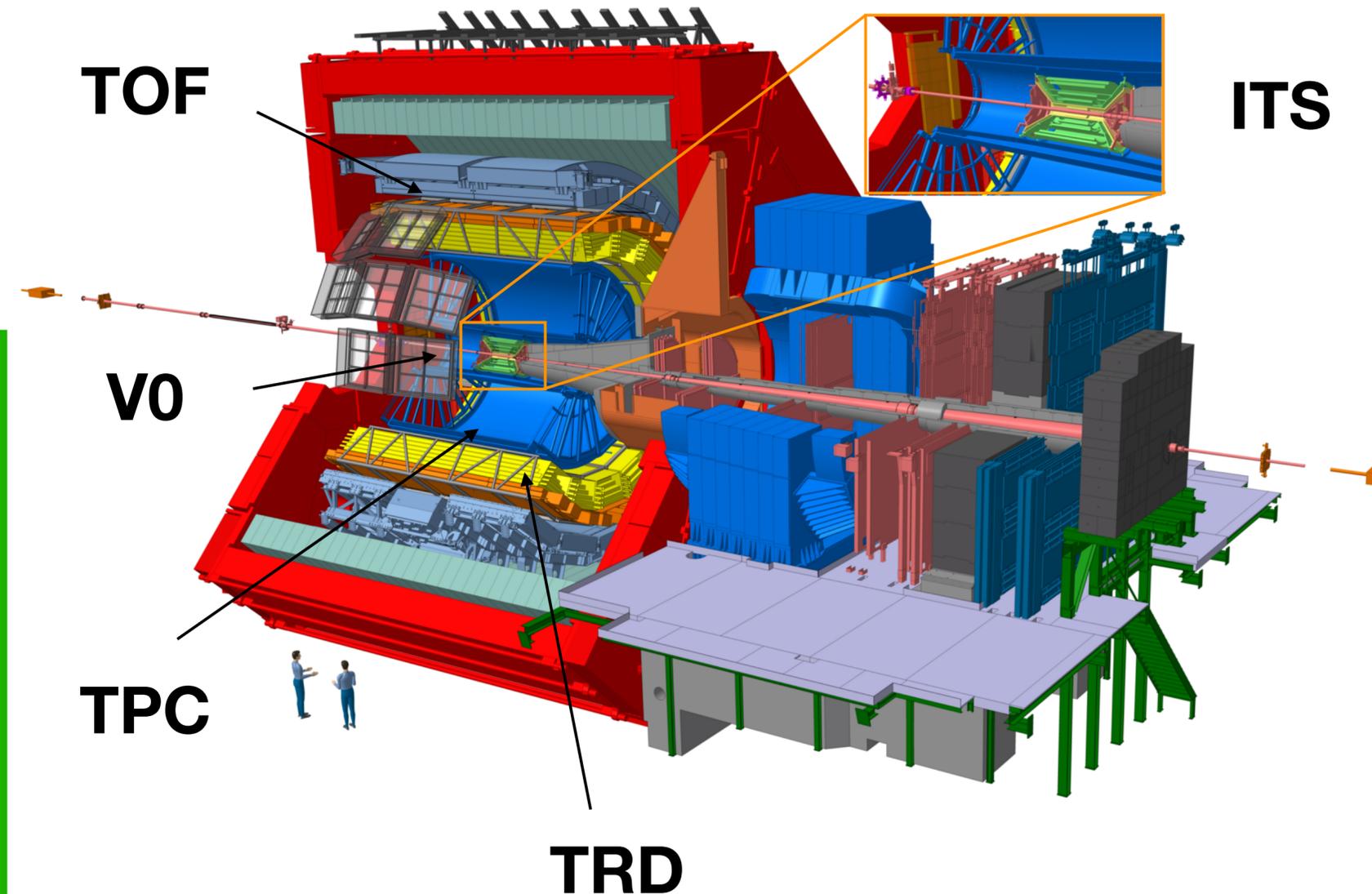
- General purpose heavy-ion experiment
 - ▶ 19 different sub-systems
 - ▶ Excellent particle identification (**PID**)
 - ▶ Most suited LHC experiment for studying the production of nuclei

Inner Tracking System

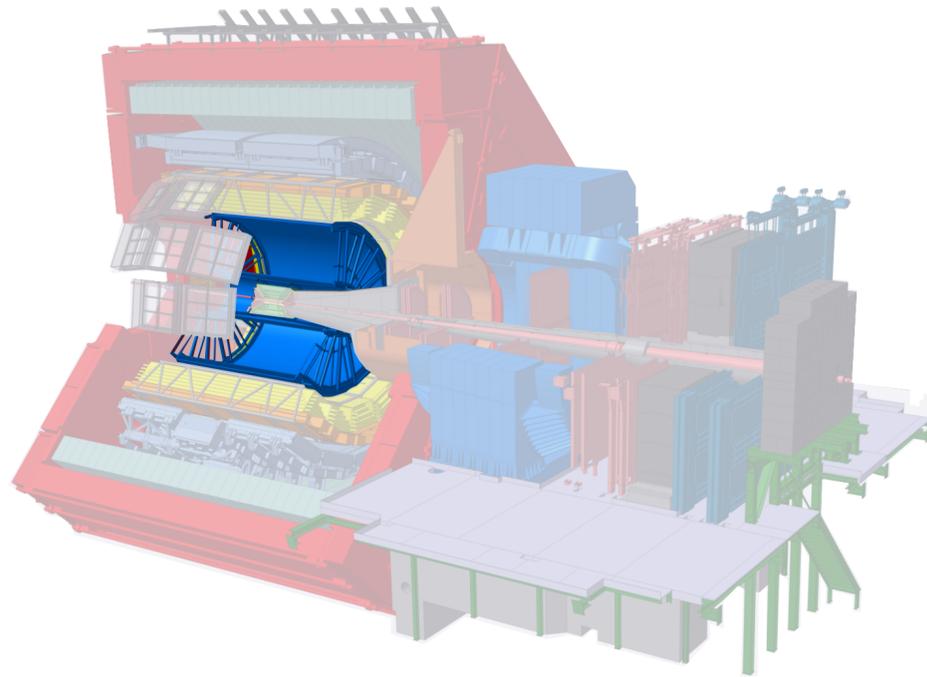
- **Tracking** and **Vertex** reconstruction
- $\sigma_{DCA_{xy}} < 100 \mu\text{m}$ for $p_T > 0.5 \text{ GeV}/c$ in Pb-Pb
- Separation of **primary** and **secondary nuclei** (coming from material knock-out)
- Separation of **primary** and **secondary vertices**

V0

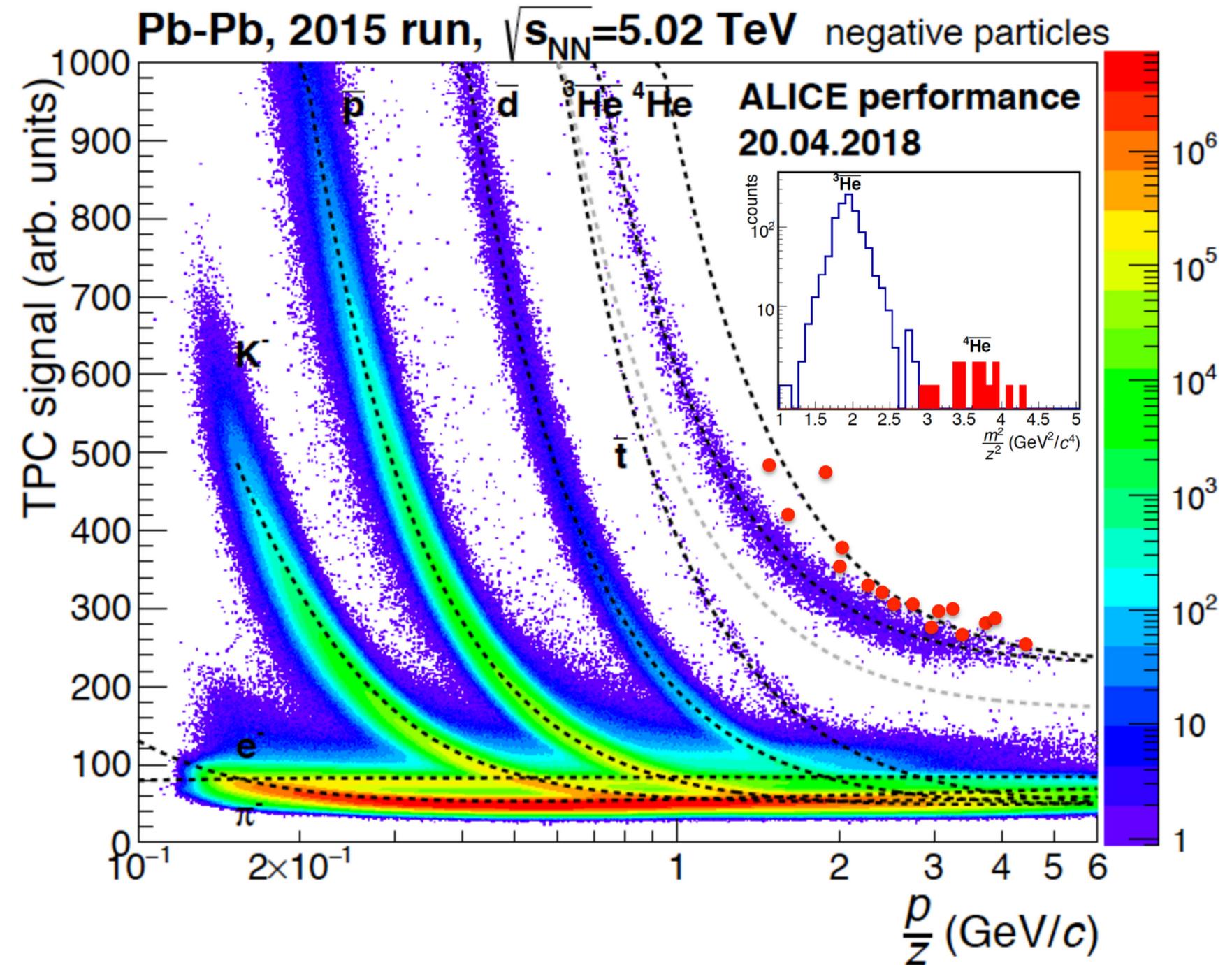
- **Multiplicity/centrality** determination



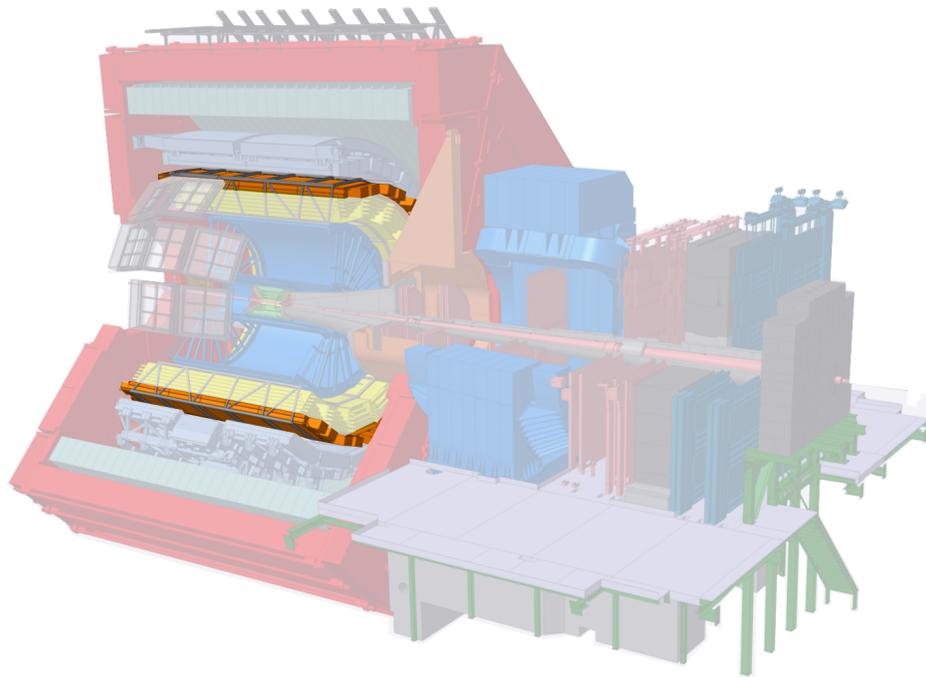
PID with the Time Projection Chamber



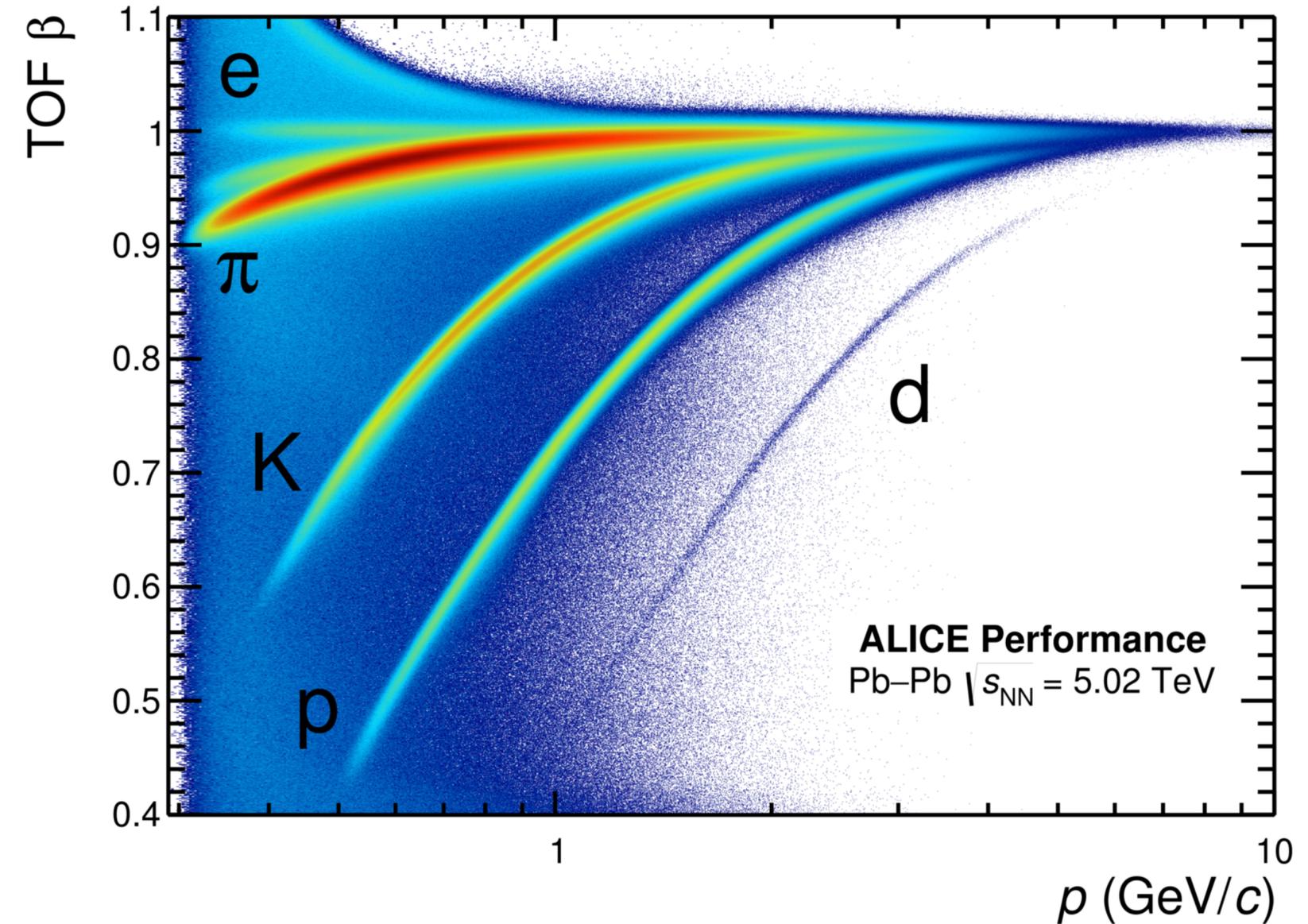
- **Tracking**
- **PID** via dE/dx measurement
 - ▶ $\sigma_{dE/dx} \sim 5.5\%$ (in pp collisions)
 - ▶ $\sigma_{dE/dx} \sim 7\%$ (in Pb-Pb collisions)
- ^3He and ^4He well separated



PID with the Time Of Flight



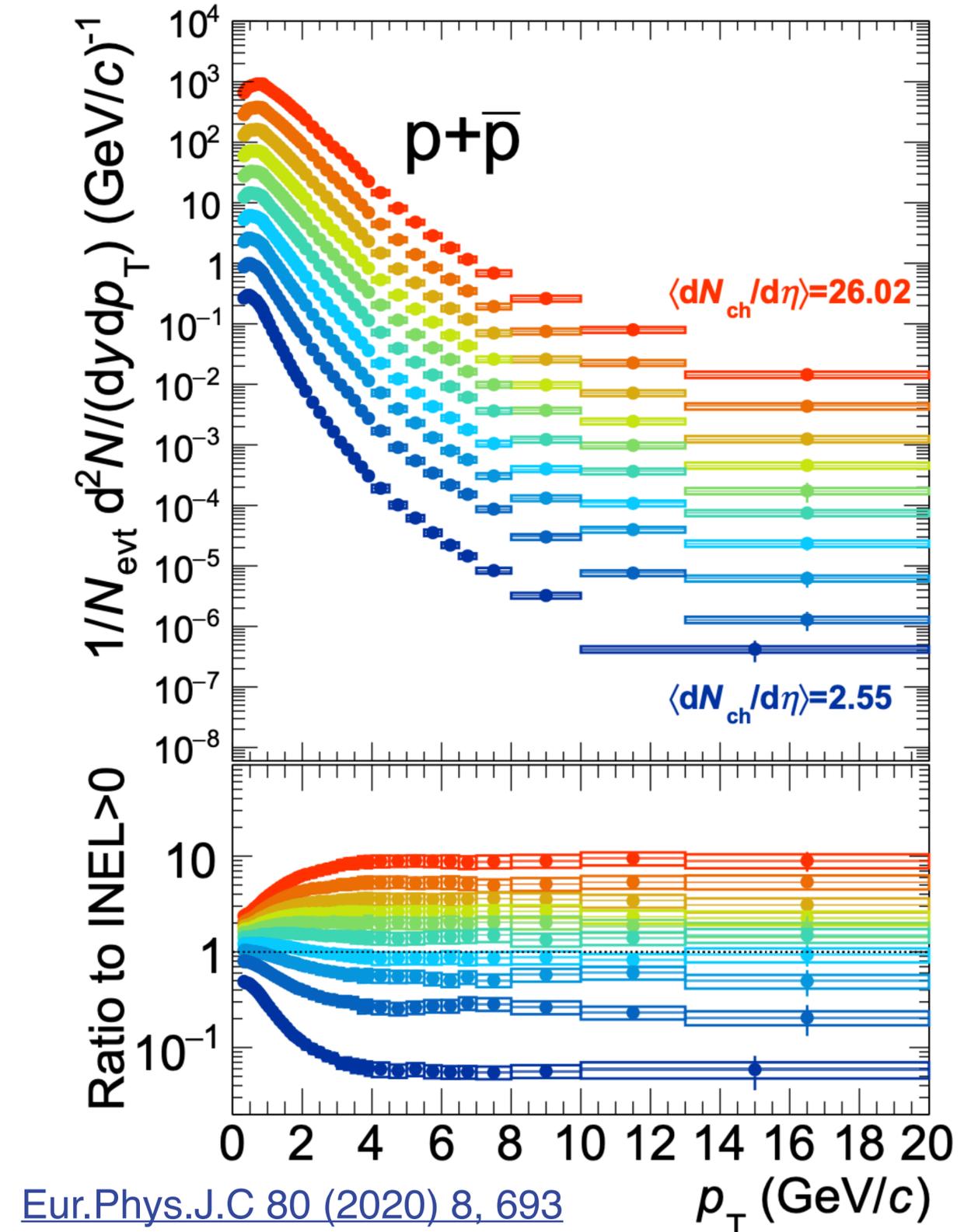
- **PID** via β measurement
 - ▶ $\sigma_{\text{TOF-PID}} \sim 60 \text{ ps}$ in **Pb-Pb** collisions
 - ▶ $\sigma_{\text{TOF-PID}} \sim 70 \text{ ps}$ in **pp** collisions
(lower precision on event collision time)



ALI-PERF-106336

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](#)

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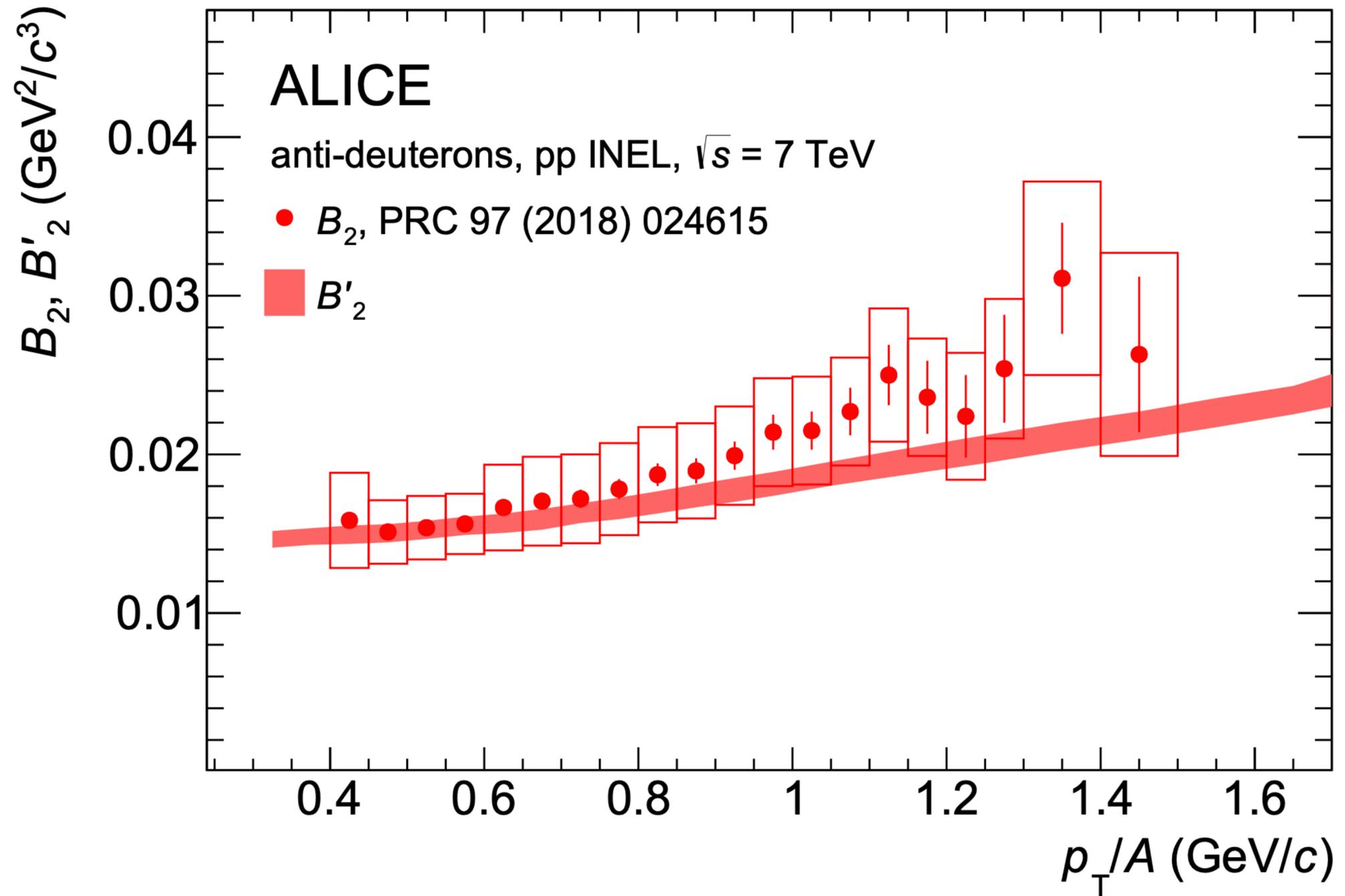
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[Phys.Lett.B 794 \(2019\) 50-63](#)

Charged particle multiplicity

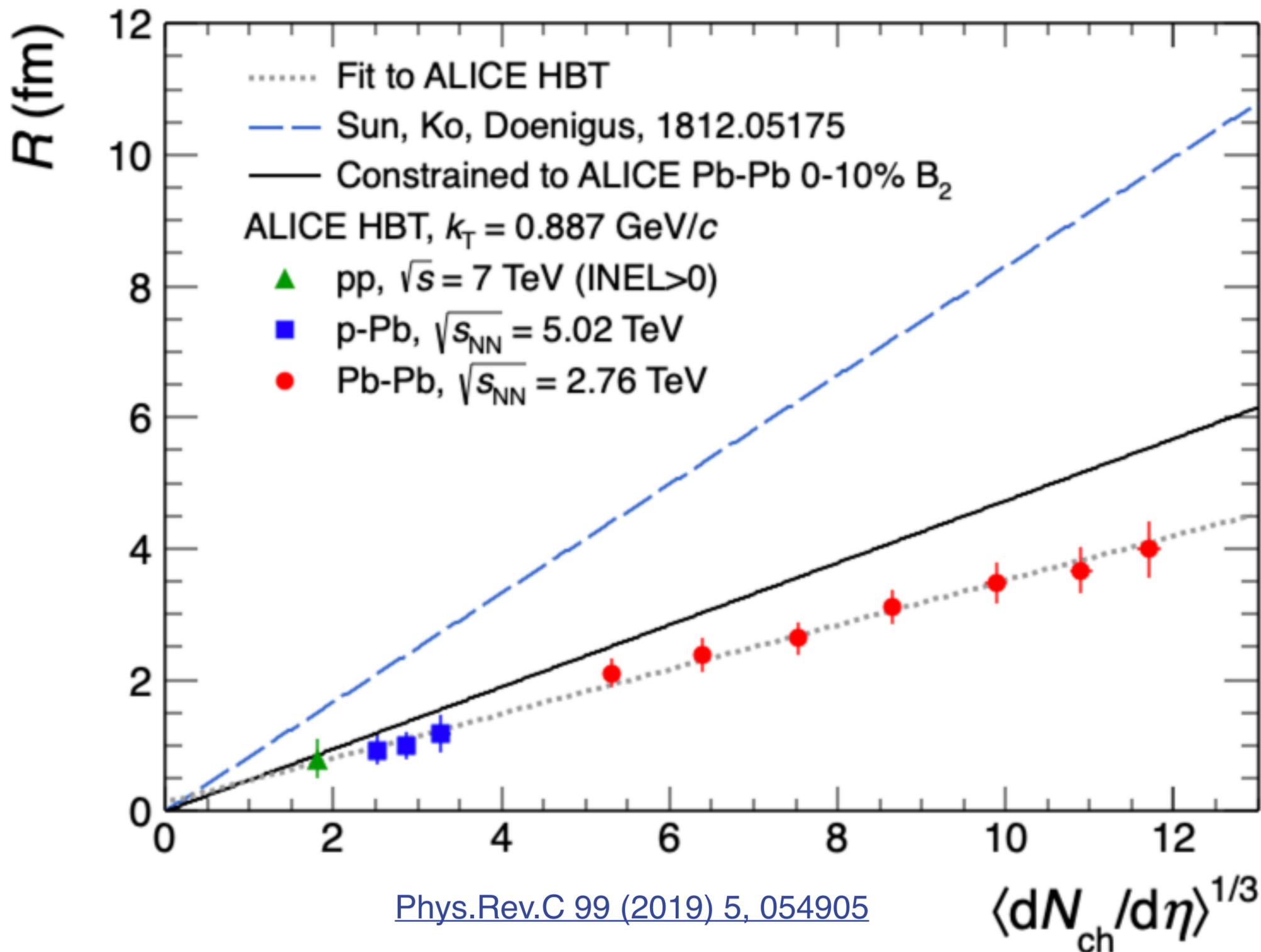
- Measurements are carried out vs multiplicity

- $\langle dN_{ch}/d\eta \rangle \leftrightarrow$ **system size**

- System size: **HBT radius R**

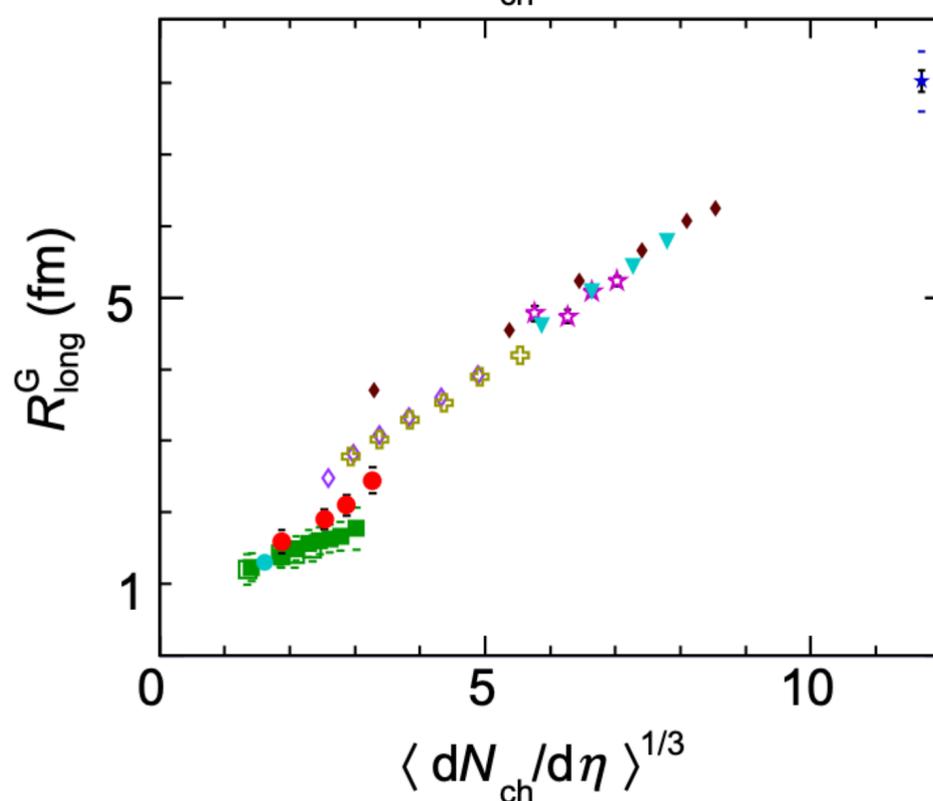
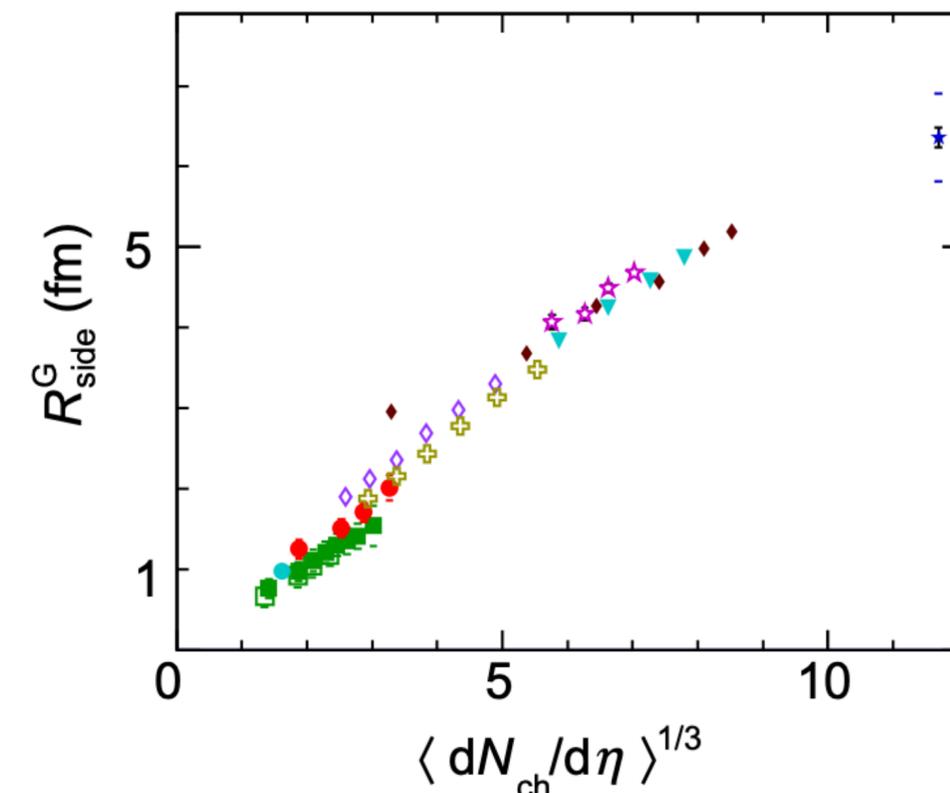
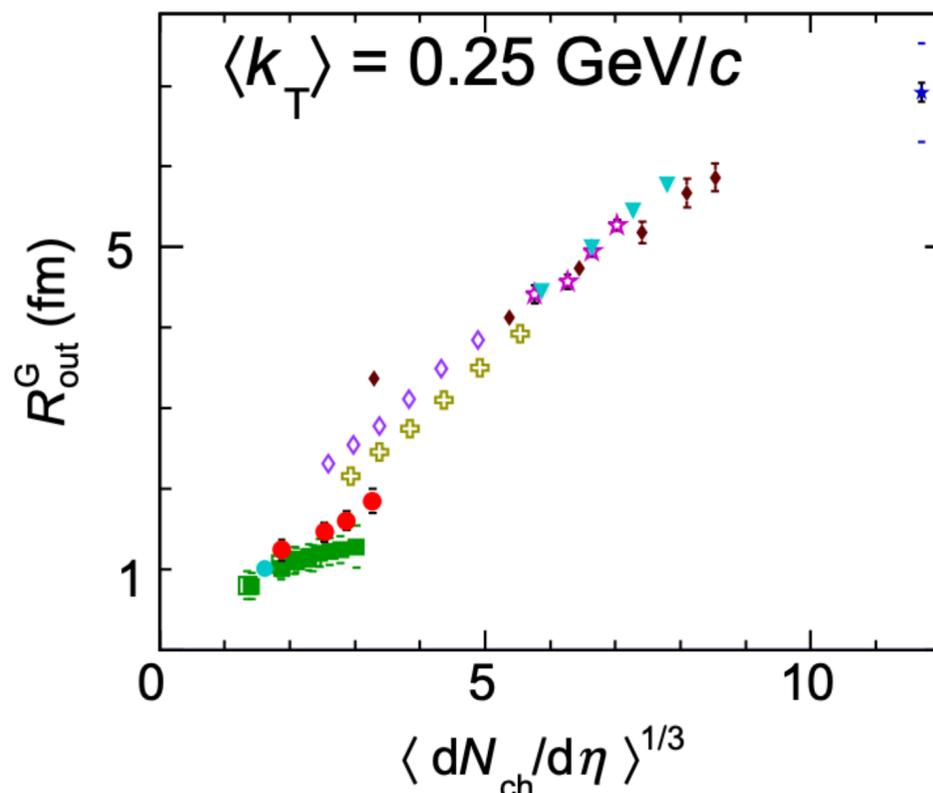
- ▶ R vs multiplicity:

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



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



- ◆ STAR Au-Au $\sqrt{s_{NN}} = 200 \text{ GeV}$
- ⊕ STAR Cu-Cu $\sqrt{s_{NN}} = 200 \text{ GeV}$
- ▼ STAR Au-Au $\sqrt{s_{NN}} = 62 \text{ GeV}$
- ◇ STAR Cu-Cu $\sqrt{s_{NN}} = 62 \text{ GeV}$
- ☆ CERES Pb-Au $\sqrt{s_{NN}} = 17.2 \text{ GeV}$
- ★ ALICE Pb-Pb $\sqrt{s_{NN}} = 2760 \text{ GeV}$
- ALICE pp $\sqrt{s} = 7000 \text{ GeV}$
- ALICE pp $\sqrt{s} = 900 \text{ GeV}$
- STAR pp $\sqrt{s} = 200 \text{ GeV}$
- ALICE p-Pb $\sqrt{s_{NN}} = 5020 \text{ GeV}$

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

Hypertriton reconstruction

- **Hypertriton** is reconstructed through its **two-body** mesonic decay (B.R. 25%):

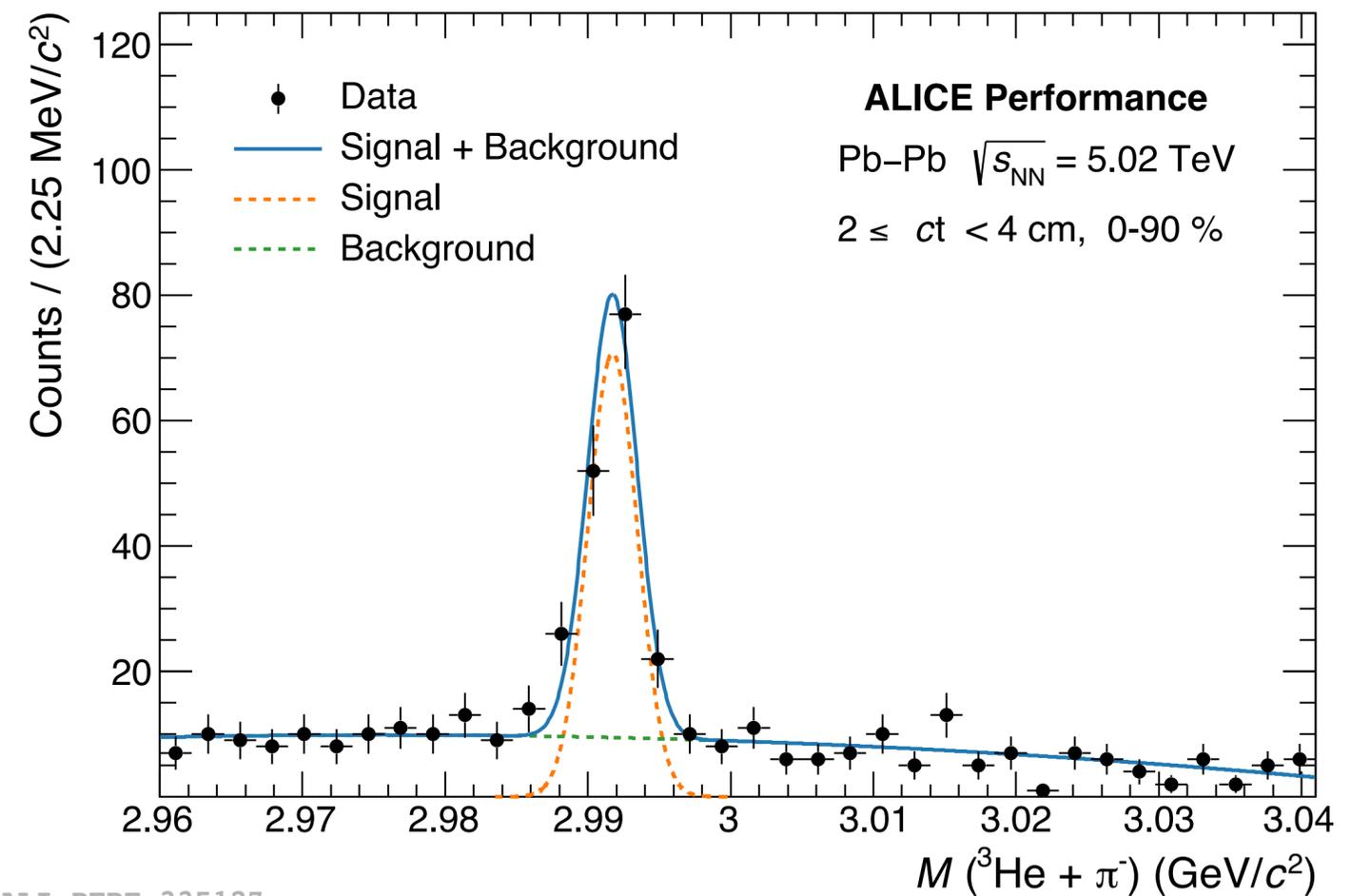
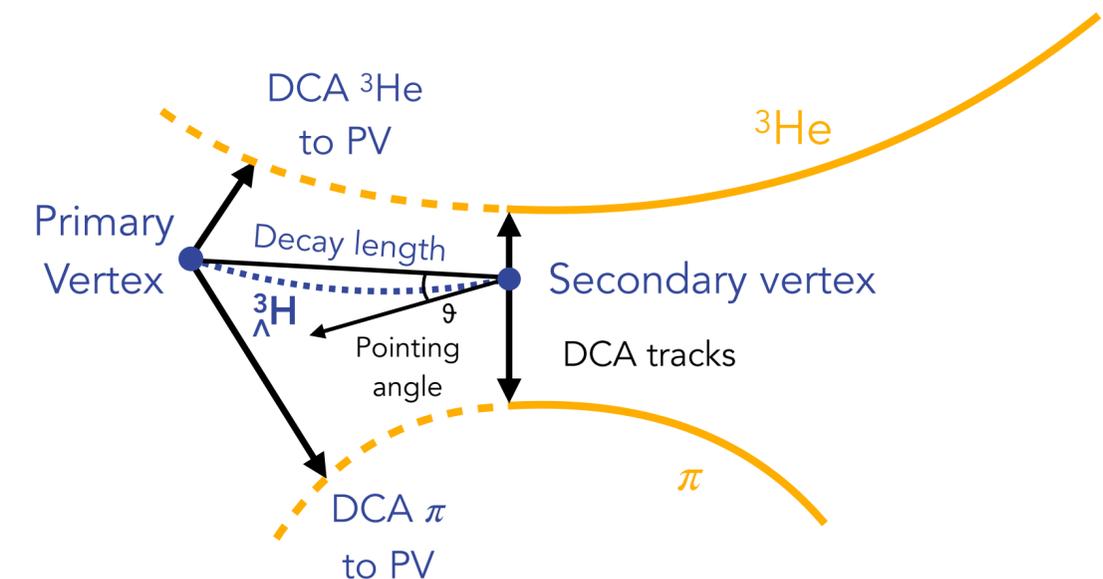
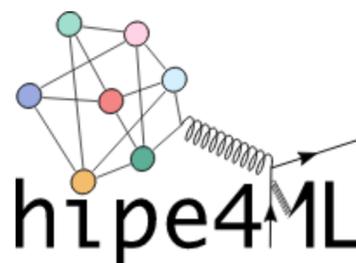


- Candidates are selected with:

- ▶ Standard selections on **single-track** and **topological** variables
- ▶ **Boosted Decisions Trees** (BDT) models, trained on dedicated MC samples used to discriminate signal and background

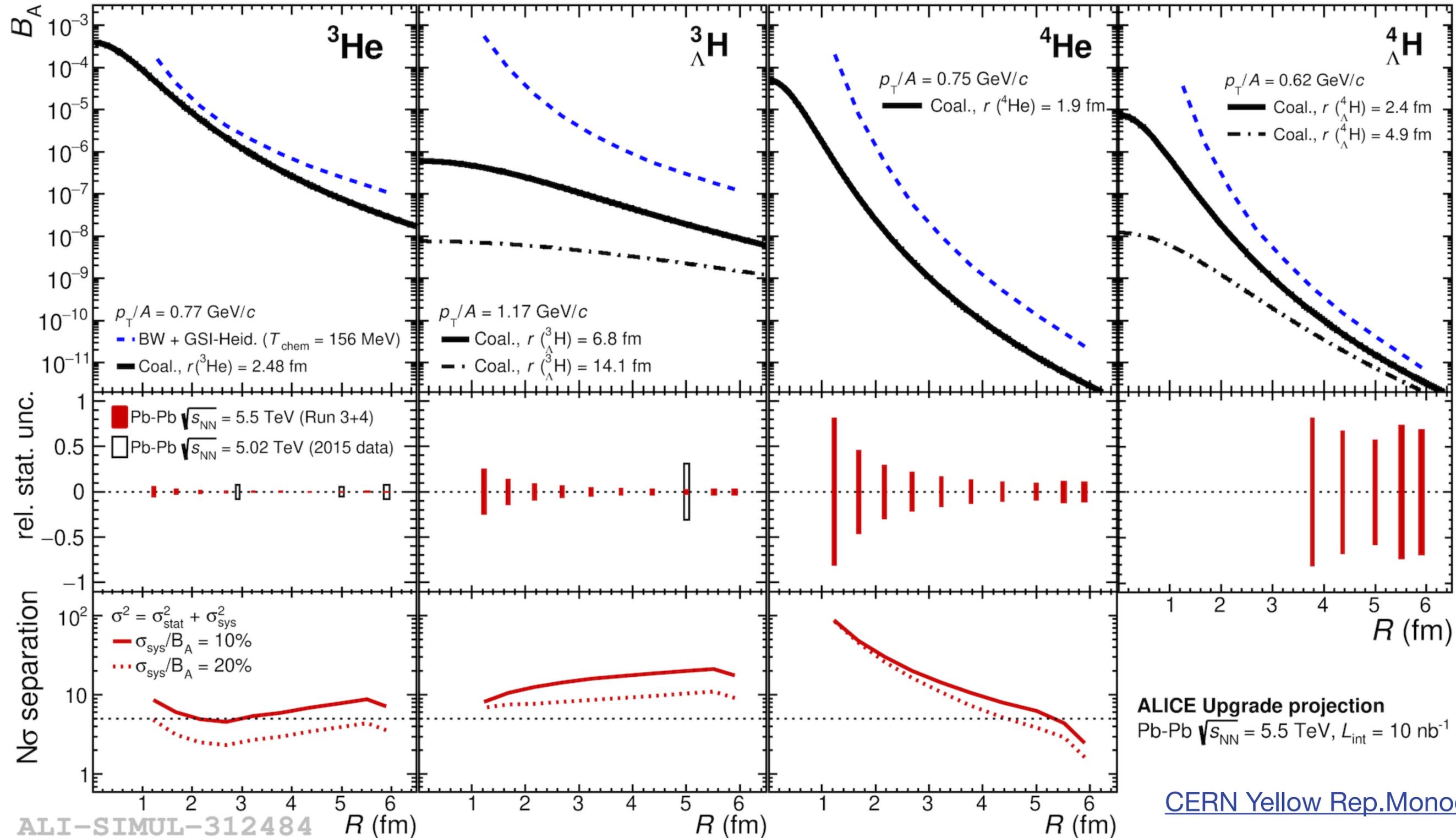
- BDT selections are optimised to **improve** the **significance** of the signal

- Use of the package hipe4ML



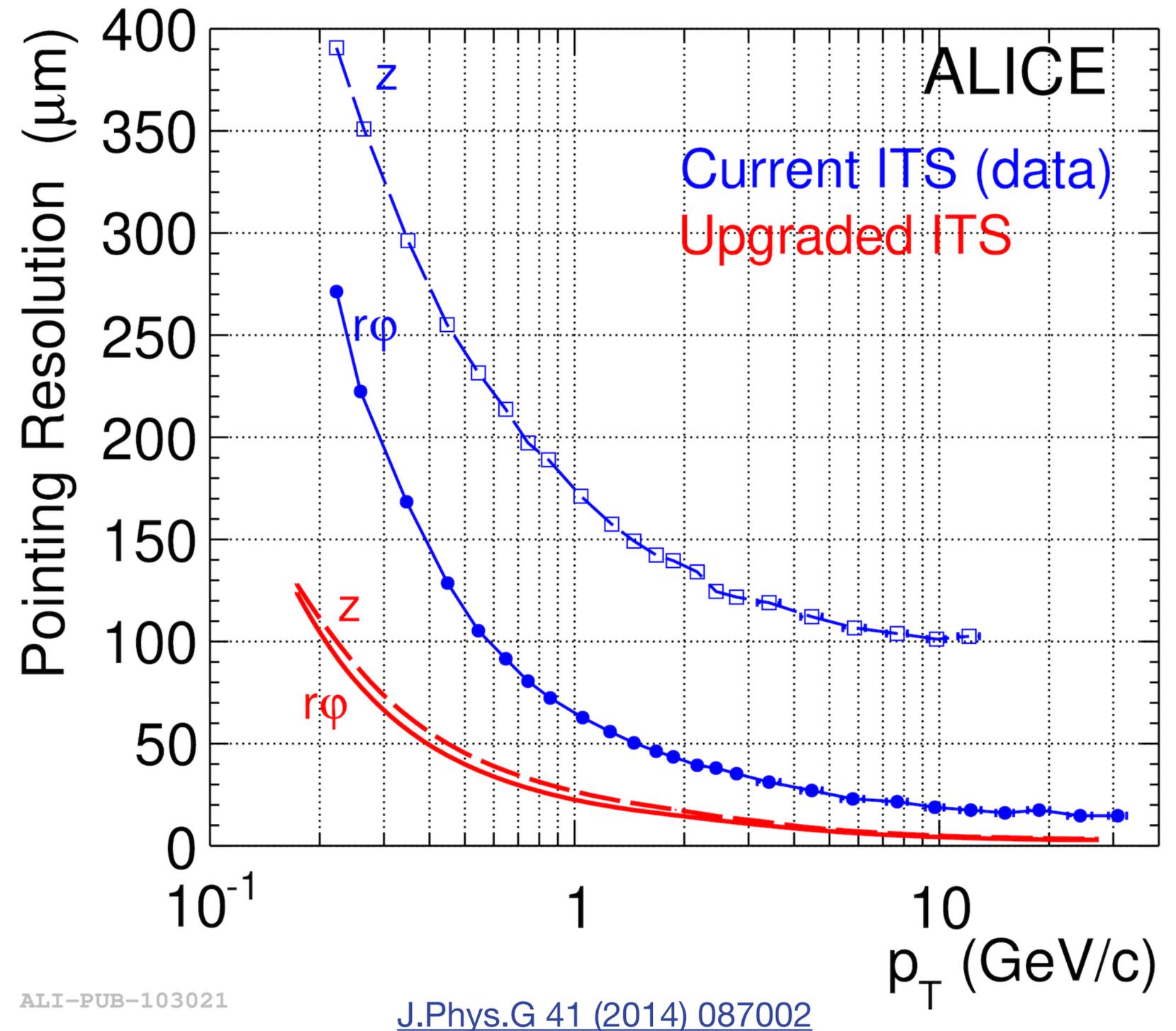
ALI-PERF-335127

(Hyper)nuclei in Pb-Pb collisions



Upgrade of the ITS

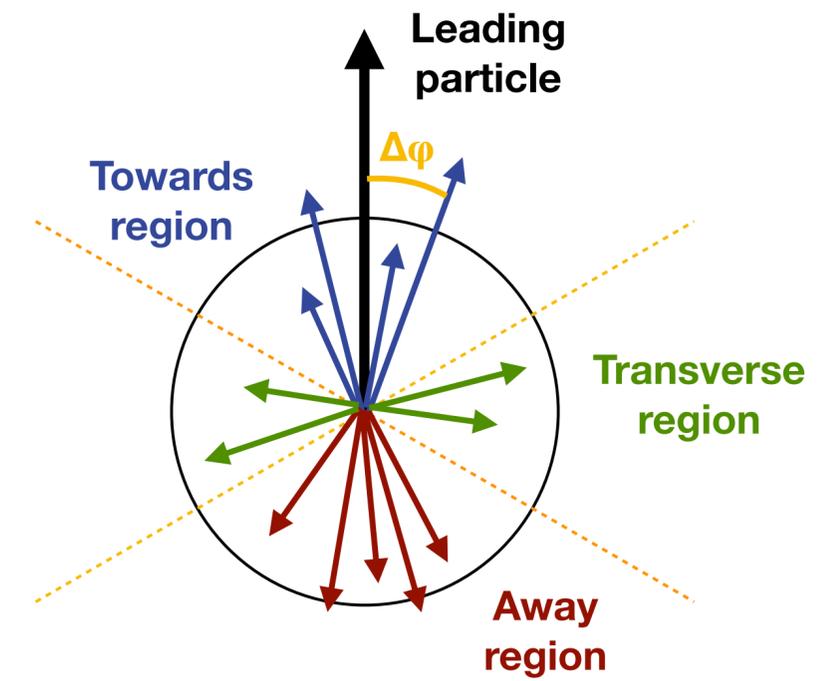
- **Seven cylindrical layers** of silicon pixel sensors
 - Inner barrel: 3 layers with turbo geometry
 - Outer barrel: 4 layers with overlapping edges
- **Low material budget:**
 - 0.3% X0 for the I.B.
 - 1% X0 for the O.B.
- **Improved tracking precision**



Nuclear production vs R_T

- **Dependence** of nuclear production on the multiplicity of the **underlying event** (UE)?
- We define R_T as:

$$R_T = \frac{N_{\text{transverse}}}{\langle N_{\text{transverse}} \rangle}$$



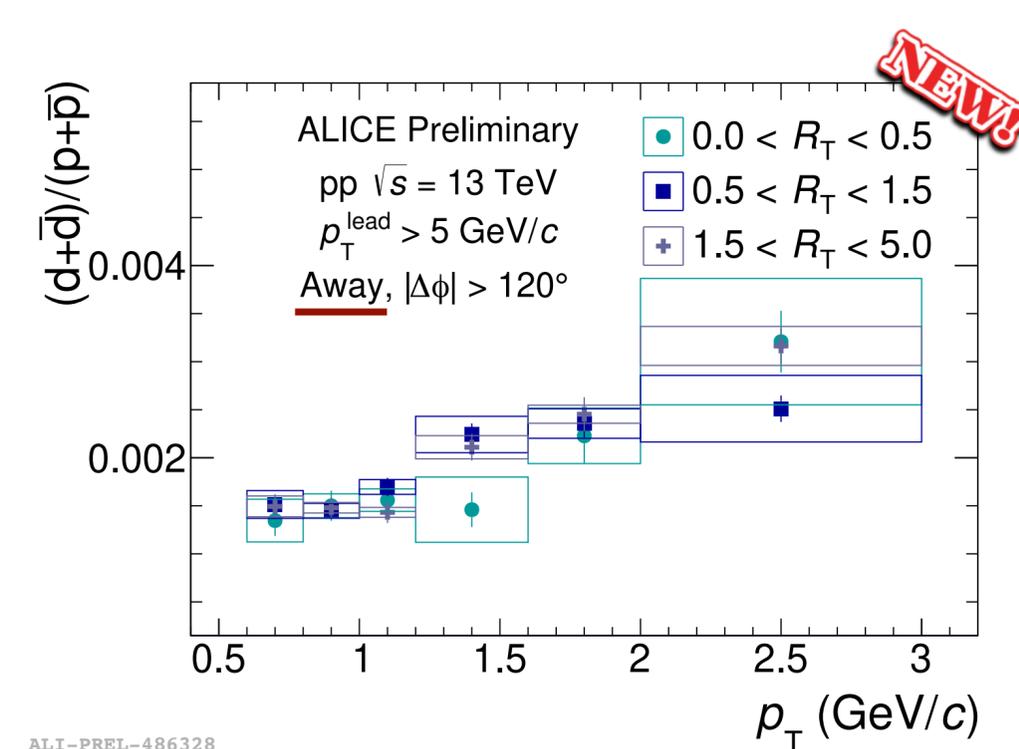
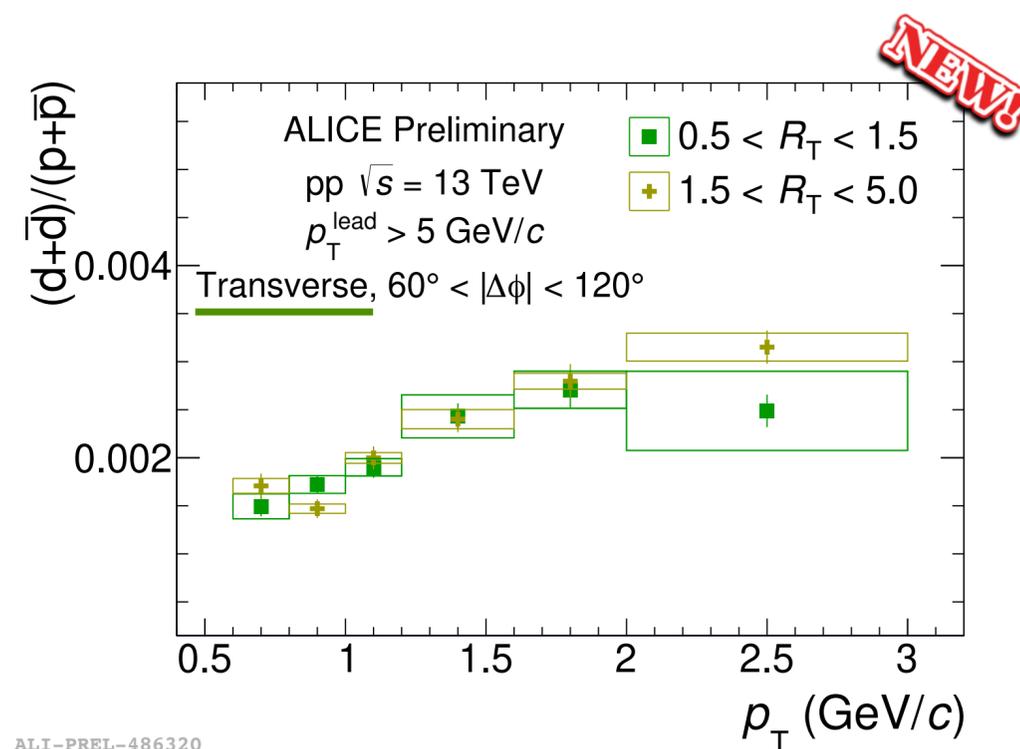
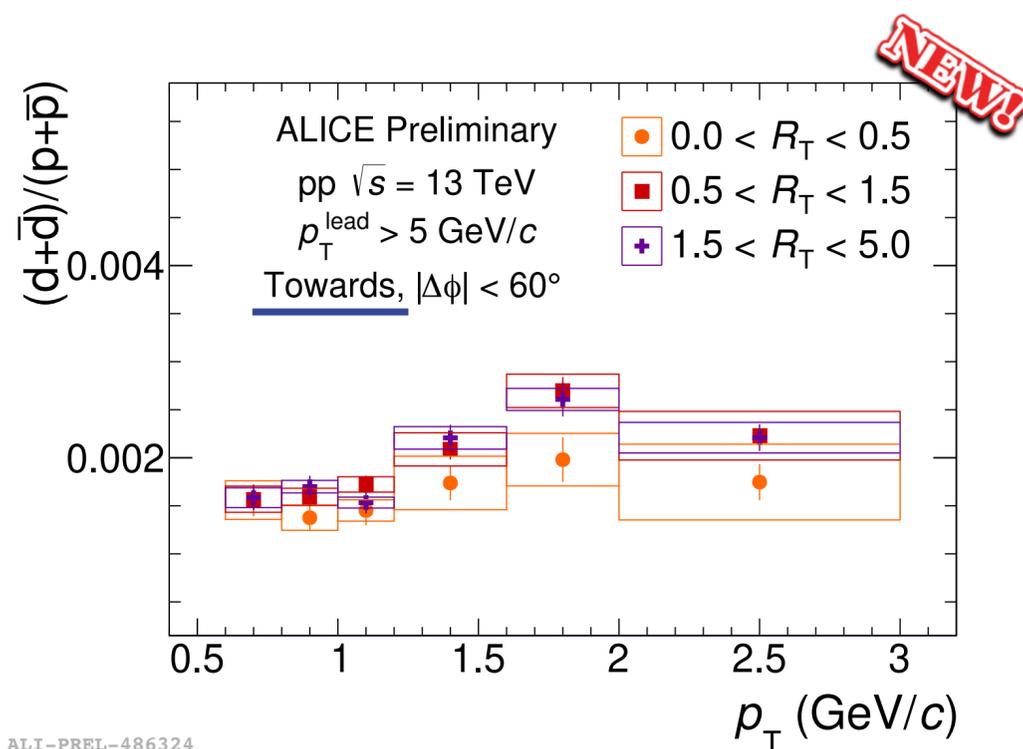
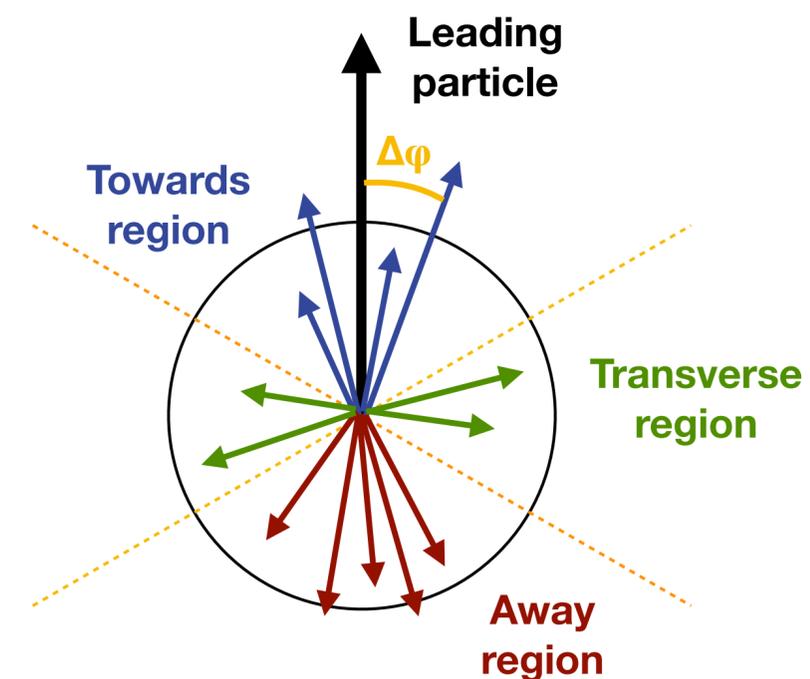
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- d/p does **not strongly depend** on the **UE**



ALI-PREL-486324

ALI-PREL-486320

ALI-PREL-486328

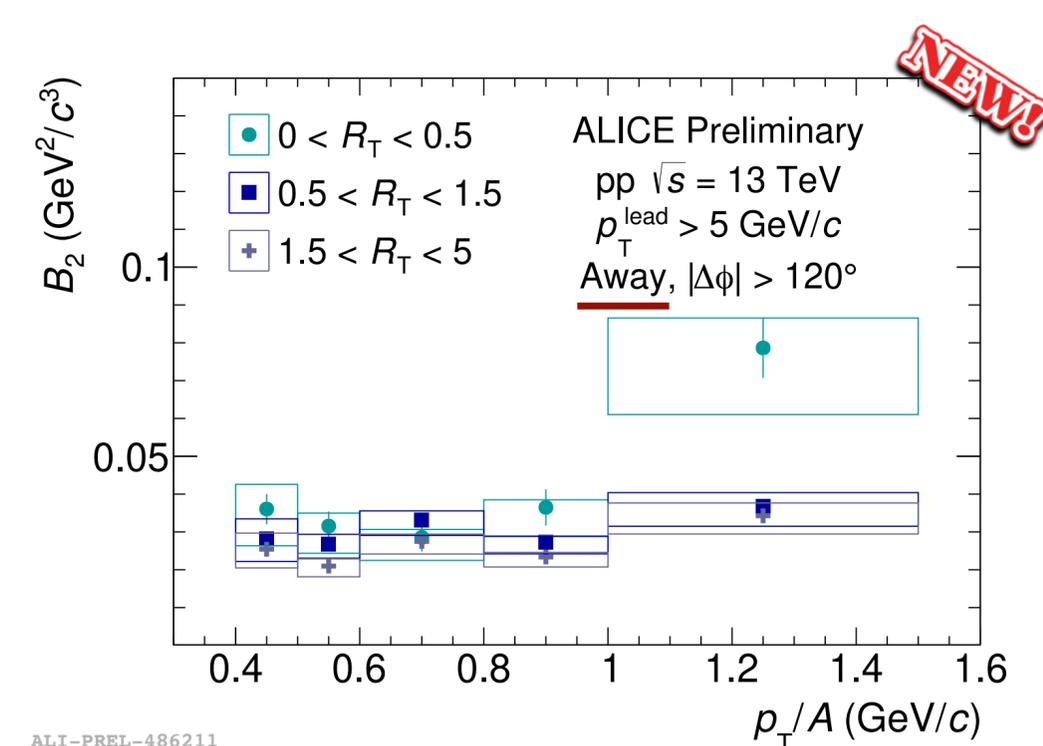
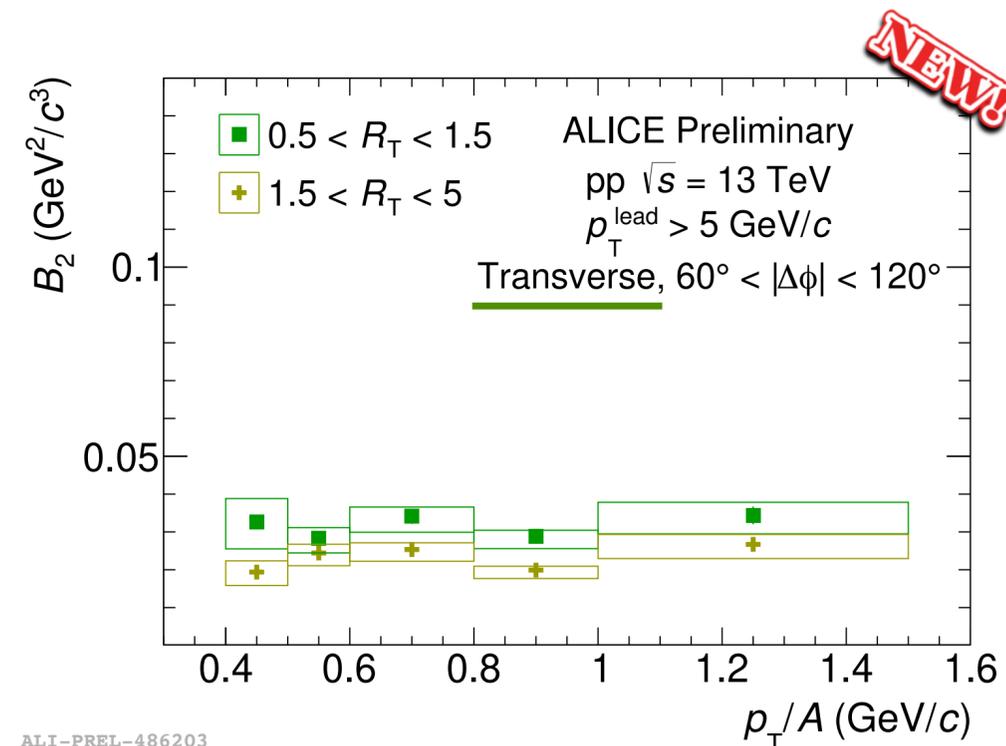
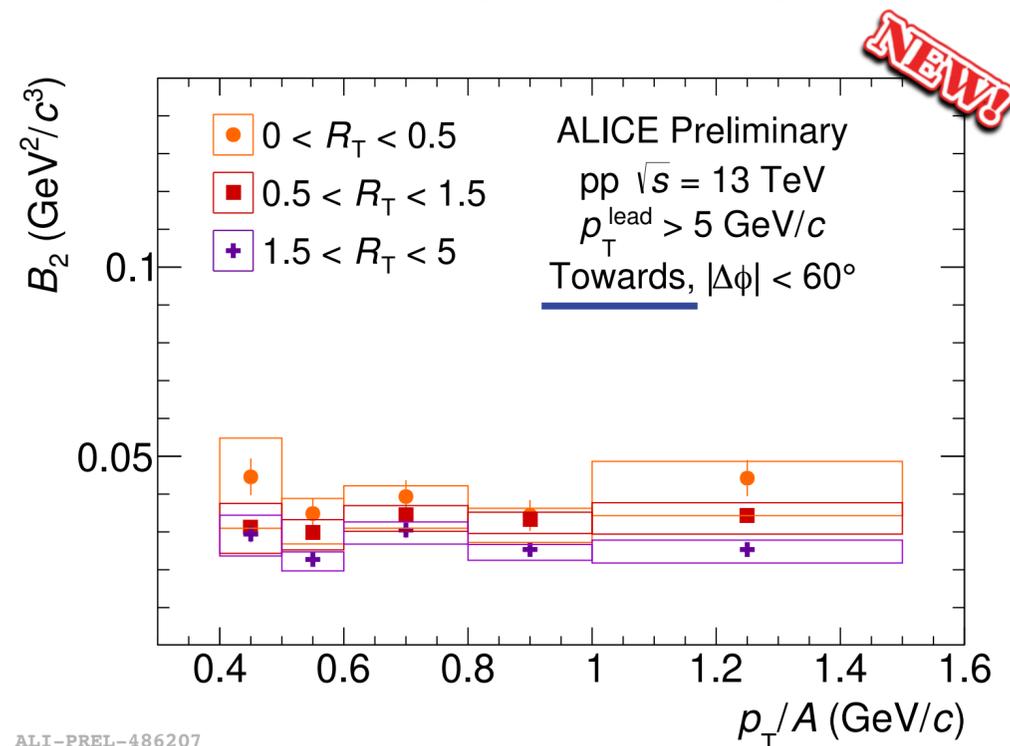
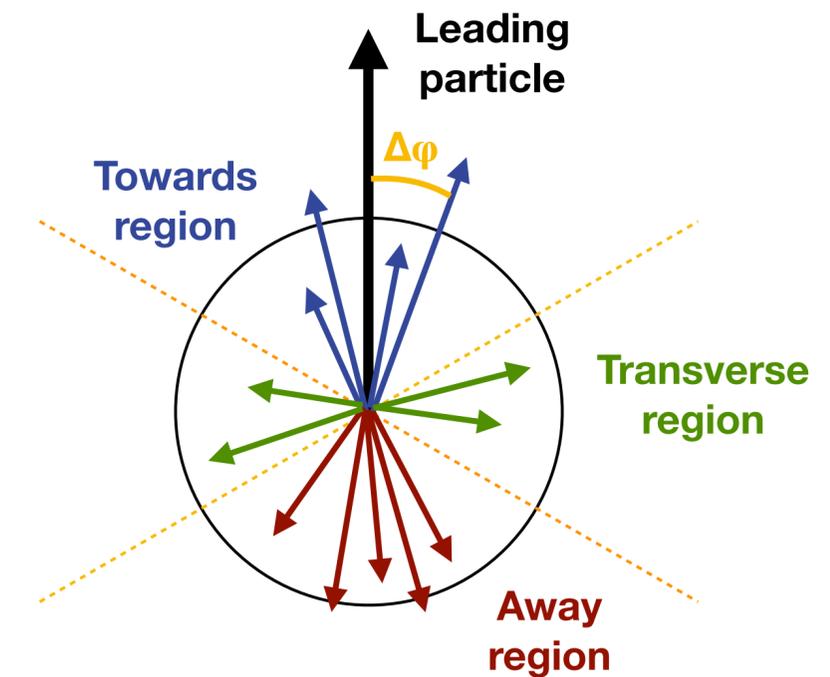
Nuclear production vs R_T

- **Dependence** of nuclear production on the multiplicity of the **underlying event (UE)**?

- We define R_T as:

$$R_T = \frac{N_{\text{transverse}}}{\langle N_{\text{transverse}} \rangle}$$

- **d/p** does **not strongly depend** on the **UE**
- B_2 shows a **very mild dependence** on R_T



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