ALICE

Measurement of light (anti)nuclei production with ALICE

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on behalf of the ALICE Collaboration

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1859

chimica
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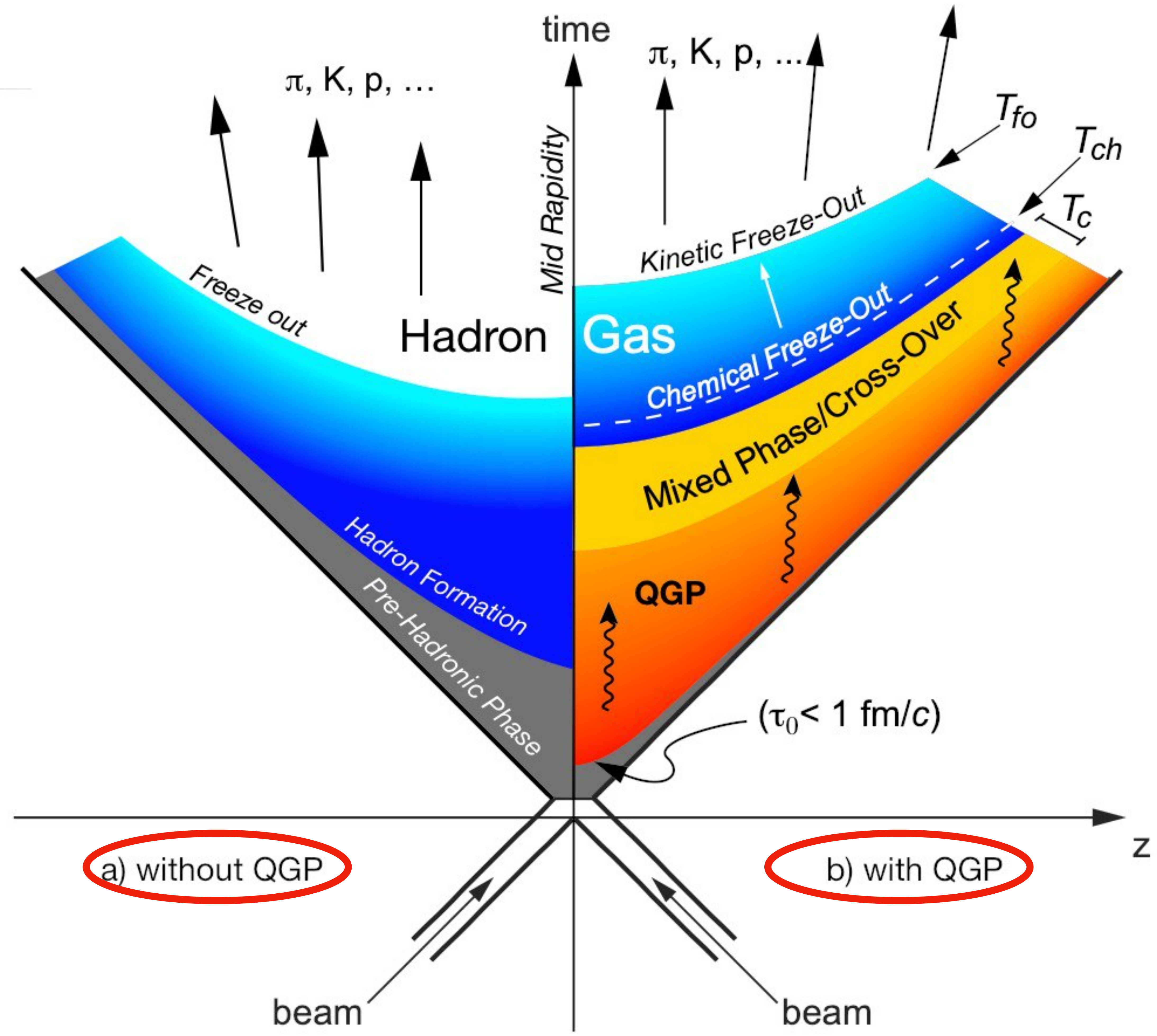
Nuclear matter production

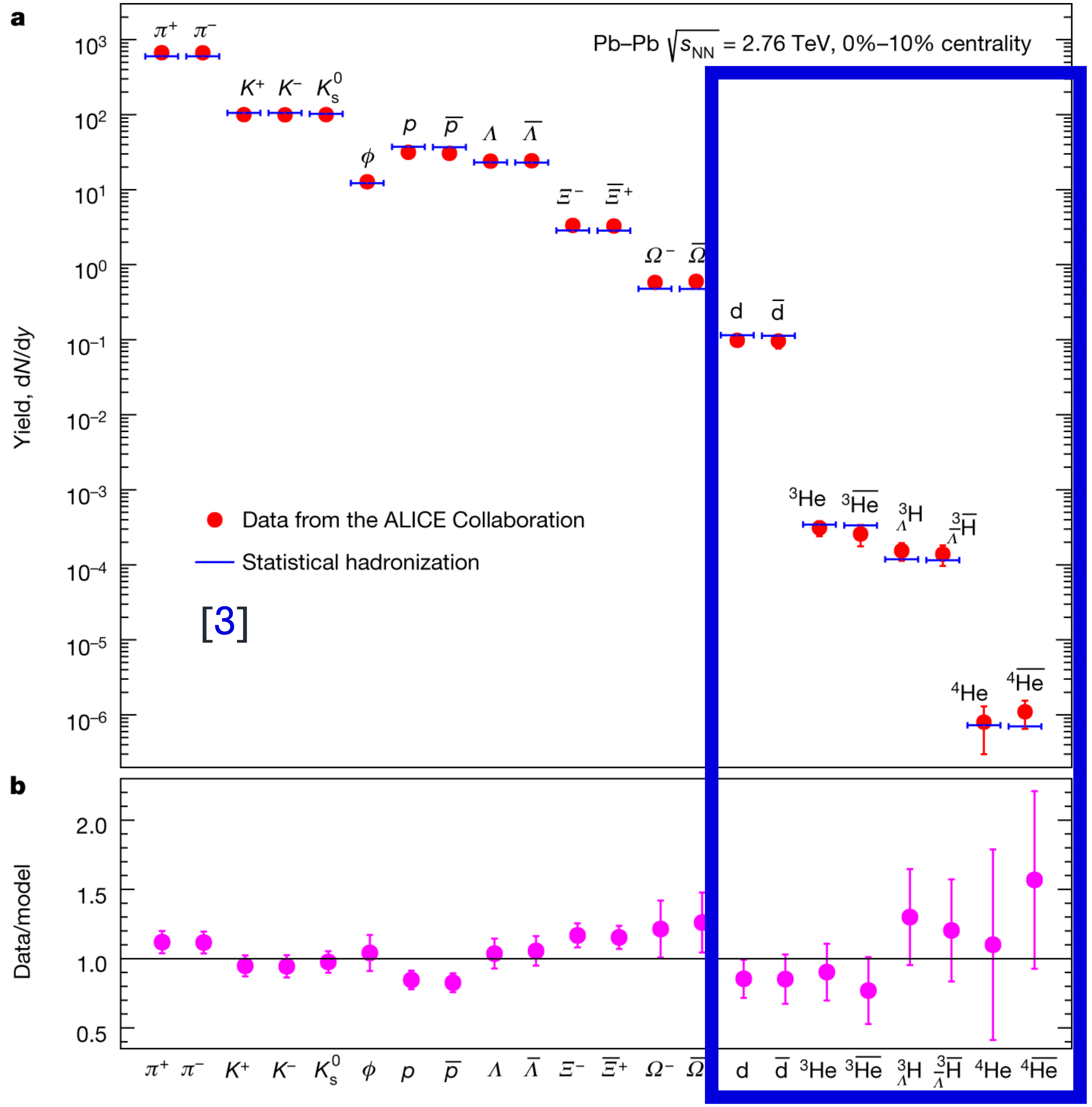
pp collisions **Pb—Pb collisions**



- Lattice QCD [1] predicts a new state of matter in Pb—Pb collisions: quark—gluon plasma (QGP)
- QGP time evolution:
  - chemical freeze-out ($T_{\mathrm{ch}} \sim 150$ MeV)
  - kinetic freeze-out ($T_{\mathrm{kin}} \sim 110$ MeV)
- Nuclei are produced in the latest stages of the collision and can be used as powerful tools to study hadronization

[1] C. Ratti, *Rep. Prog. Phys.* **81**, 084301 (2018)

Statistical Hadronization Model (SHM) [2]



- Hadron abundances are fixed at the chemical freeze-out assuming statistical equilibrium
- Expected production yields:

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

  where $T_{\rm ch}$ is the chemical freeze-out temperature

  ➡ large sensitivity to $T_{\rm ch}$ for nuclei (large m)
- Pb—Pb collisions:
  large reaction volume, global conservation of quantum numbers

  ➡ grand canonical ensemble
- Small systems (pp, p—Pb collisions):
  local conservation of quantum numbers

  ➡ canonical ensemble

[2] A. Andronic et al., *Phys. Lett. B* **697**, 203 (2011)
[3] A. Andronic et al., *Nature* **561**, 321-330 (2018)

Coalescence model [4]

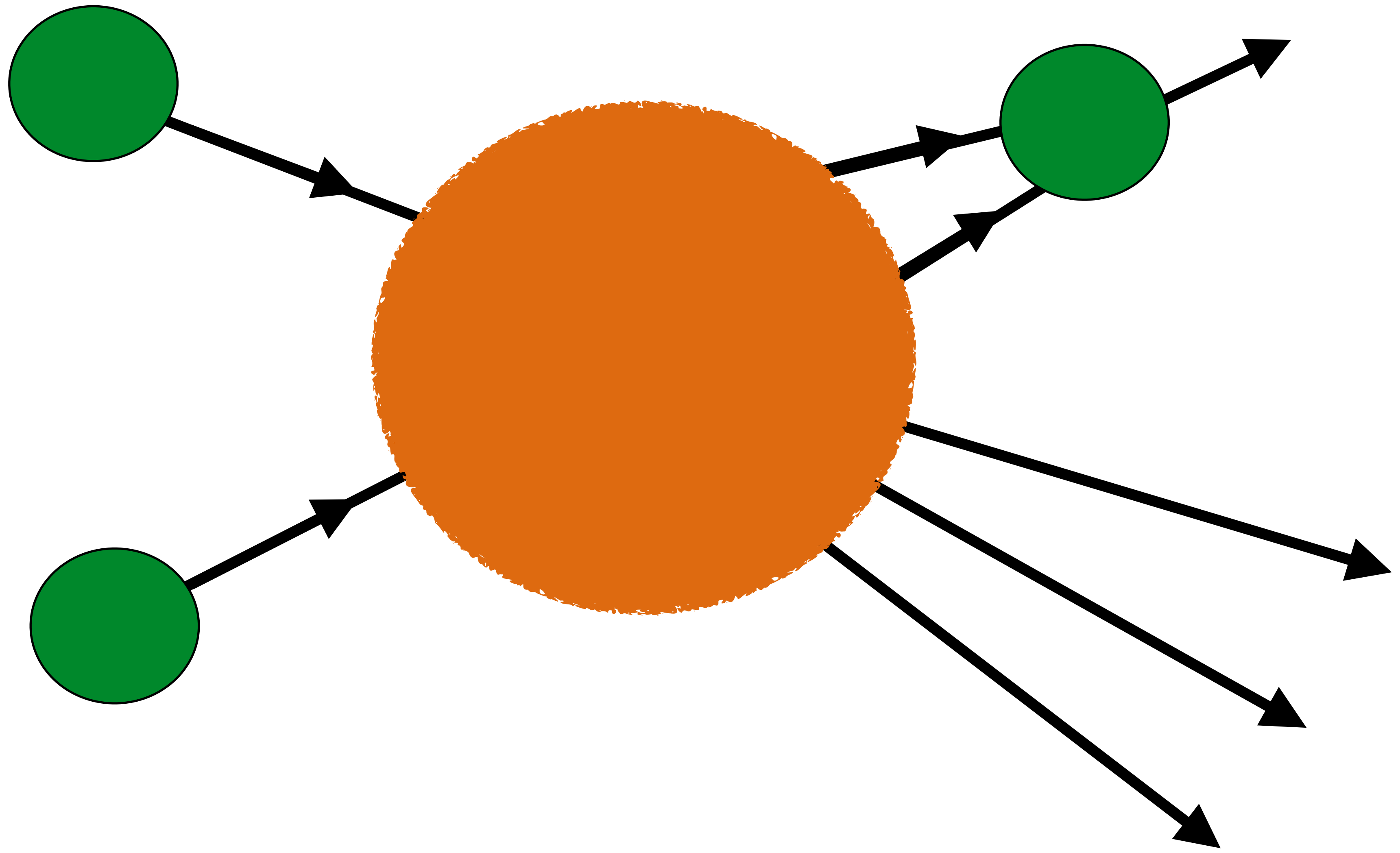
- (Anti)nucleons which are close in phase space at the freeze-out can form an (anti)nucleus via coalescence
- Key parameter: coalescence parameter B_A

$$B_\mathrm{A} = \frac{E_\mathrm{A}\frac{\mathrm{d}^3N_\mathrm{A}}{\mathrm{d}^3p_\mathrm{A}}}{\left(E_\mathrm{p}\frac{\mathrm{d}^3N_\mathrm{p}}{\mathrm{d}^3p_\mathrm{p}}\right)^A}$$

where A is the mass number of the nucleus

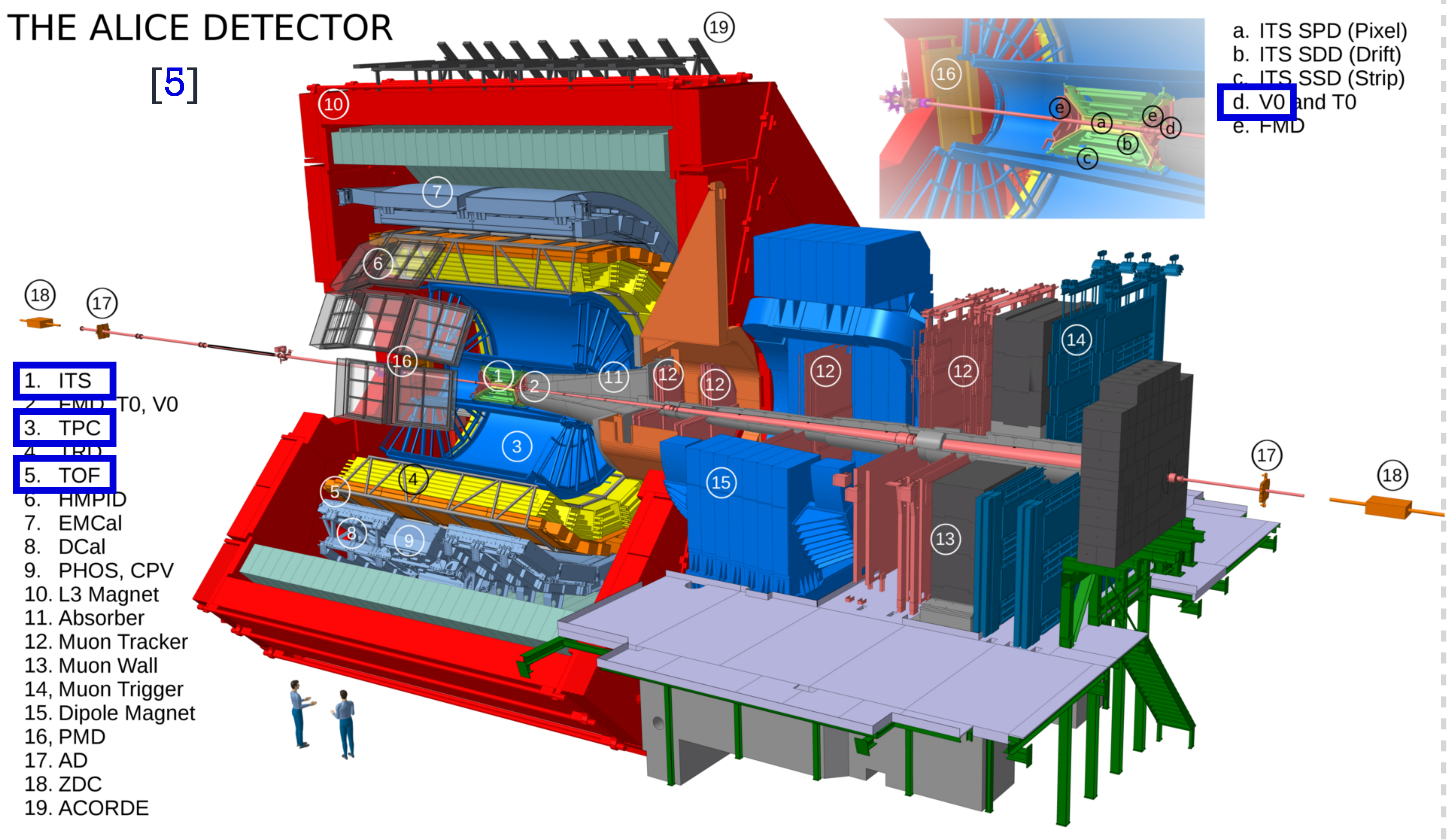
and $p_\mathrm{p} = p_\mathrm{A}/A$

- Coalescence probability is directly related to B_A
- Coalescence probability depends on the system size
  - ➡ small system size ↔ large B_A
  - ➡ large system size ↔ small B_A



[4] S. T. Butler, C. A. Pearson. *Phys. Rev.* **129**, 836 (1963)

The ALICE experiment



- Excellent particle identification (PID)
- Most suited LHC experiment to study light (anti)nuclei production

Inner Tracking System (**ITS**)

- Tracking and vertex reconstruction
- Low momentum PID

Time Projection Chamber (**TPC**)

- Tracking
- PID via energy loss measurement
  - $\sigma_{\mathrm{d}E/\mathrm{d}x} \sim 5.5\,\%$ in pp collisions
  - $\sigma_{\mathrm{d}E/\mathrm{d}x} \sim 7\,\%$ in Pb—Pb collisions

Time Of Flight (**TOF**)

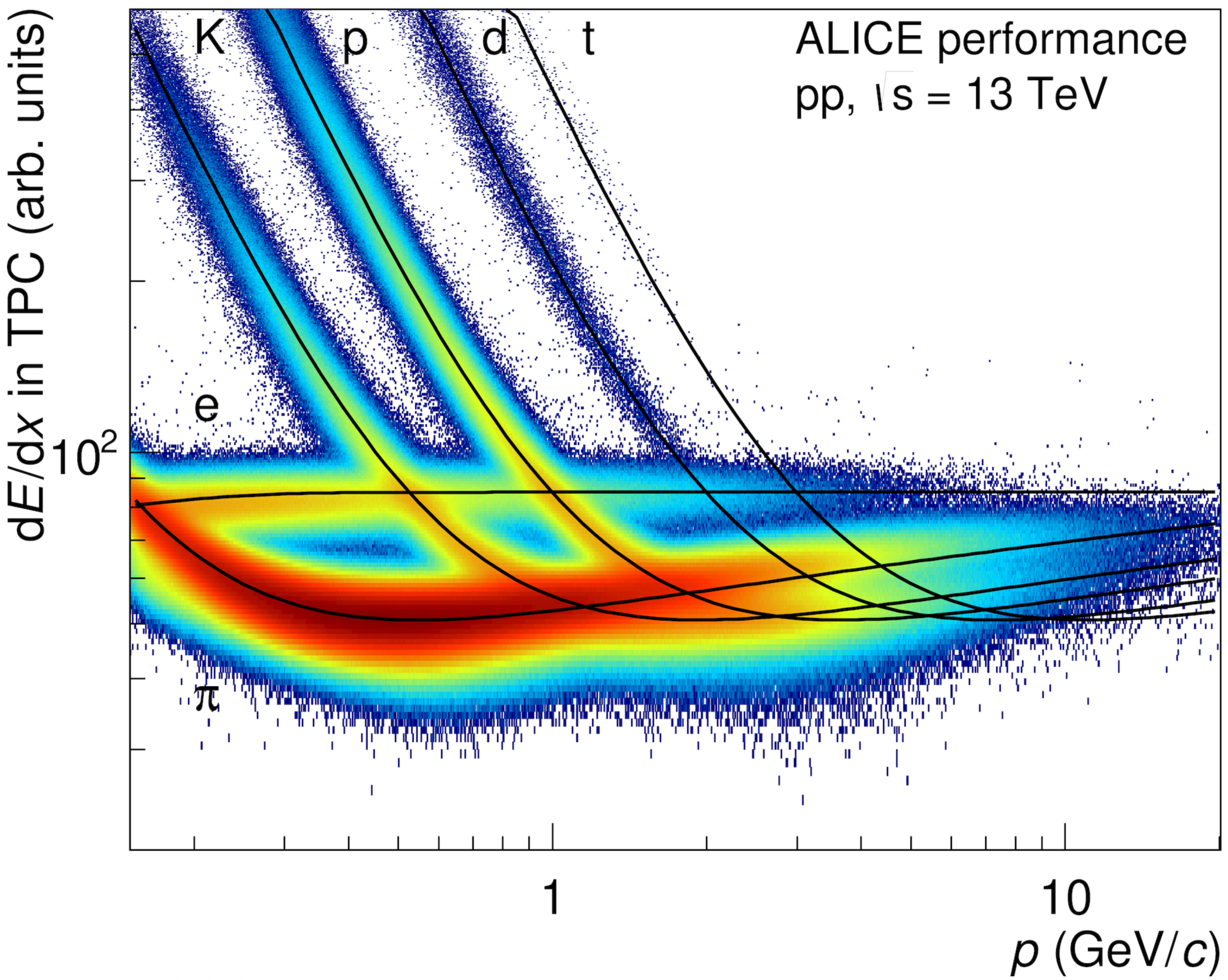
- PID via β measurement
  - $\sigma_{\mathrm{TOF}} \sim 70$ ps in pp collisions
  - $\sigma_{\mathrm{TOF}} \sim 60$ ps in Pb—Pb collisions

V0

- Trigger
- Multiplicity/centrality determination

[5] ALICE Collaboration, *J. Instrum.* **3**, 08 (2008)

Nuclei identification



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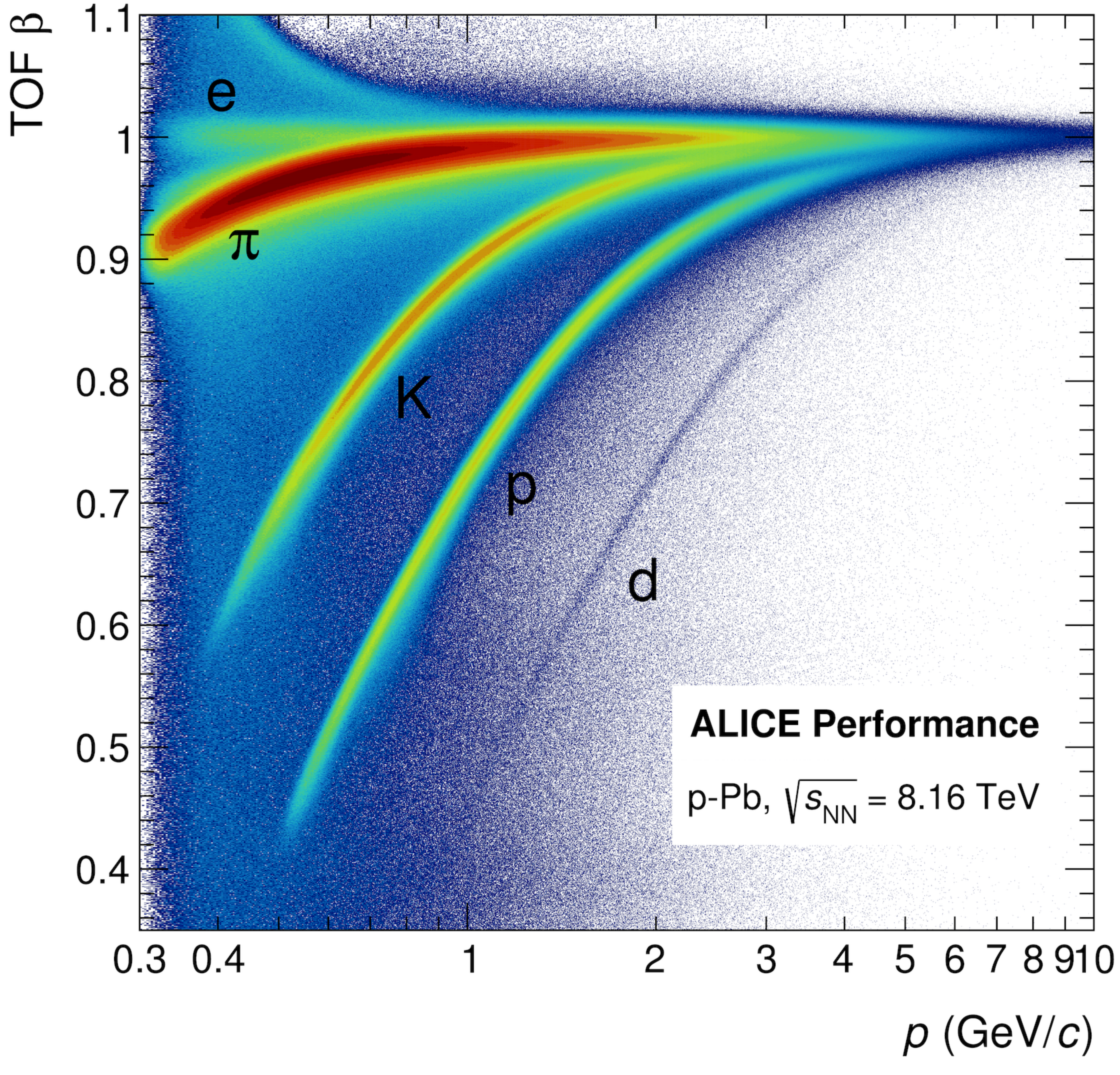
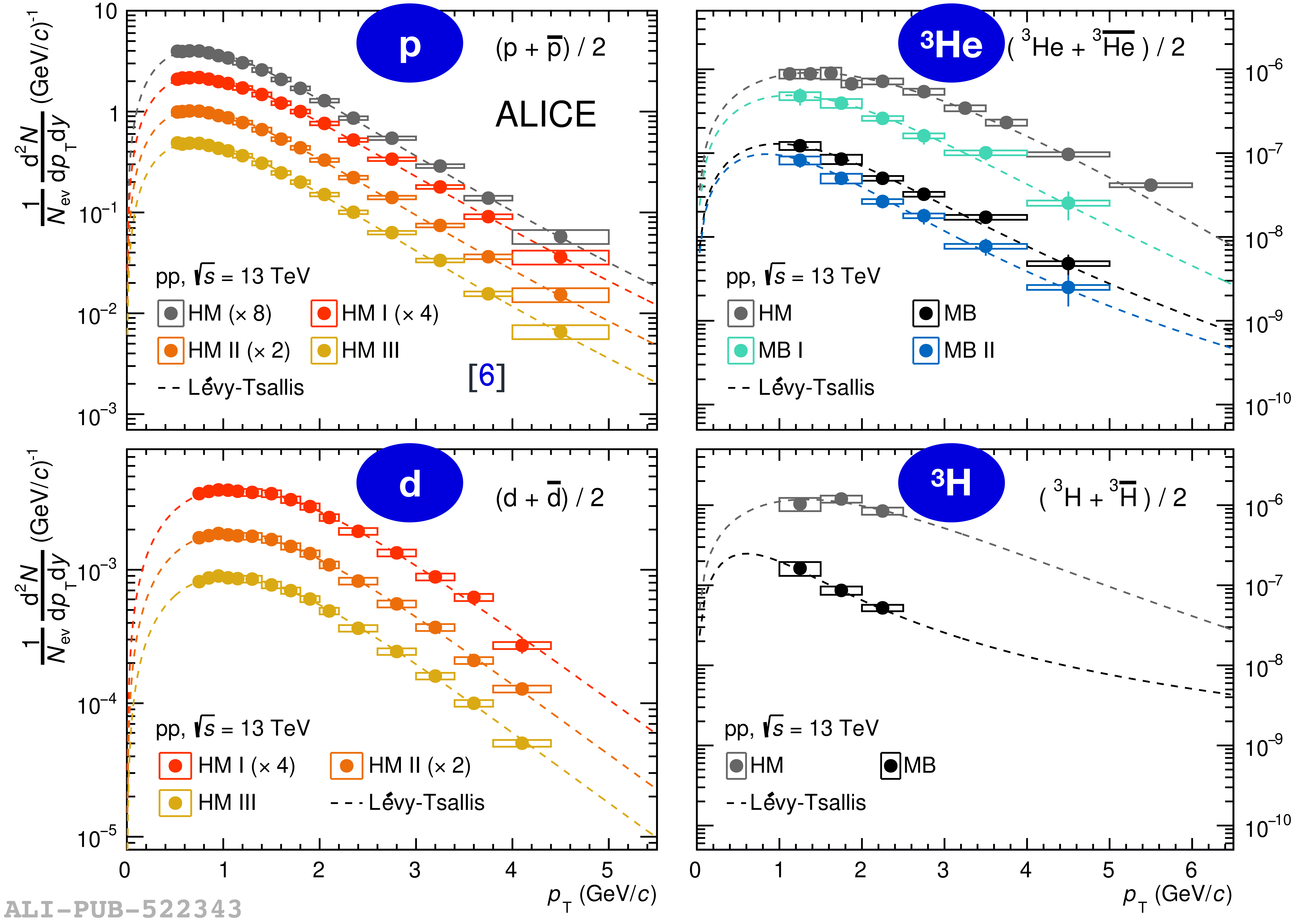
- **High-p_T region**: identification via β measurement using time-of-flight information



ALI-PERF-337022

- **Low-p_T region**: identification via dE/dx measurement in TPC
- Excellent separation of different nuclei species depending on the nuclear charge

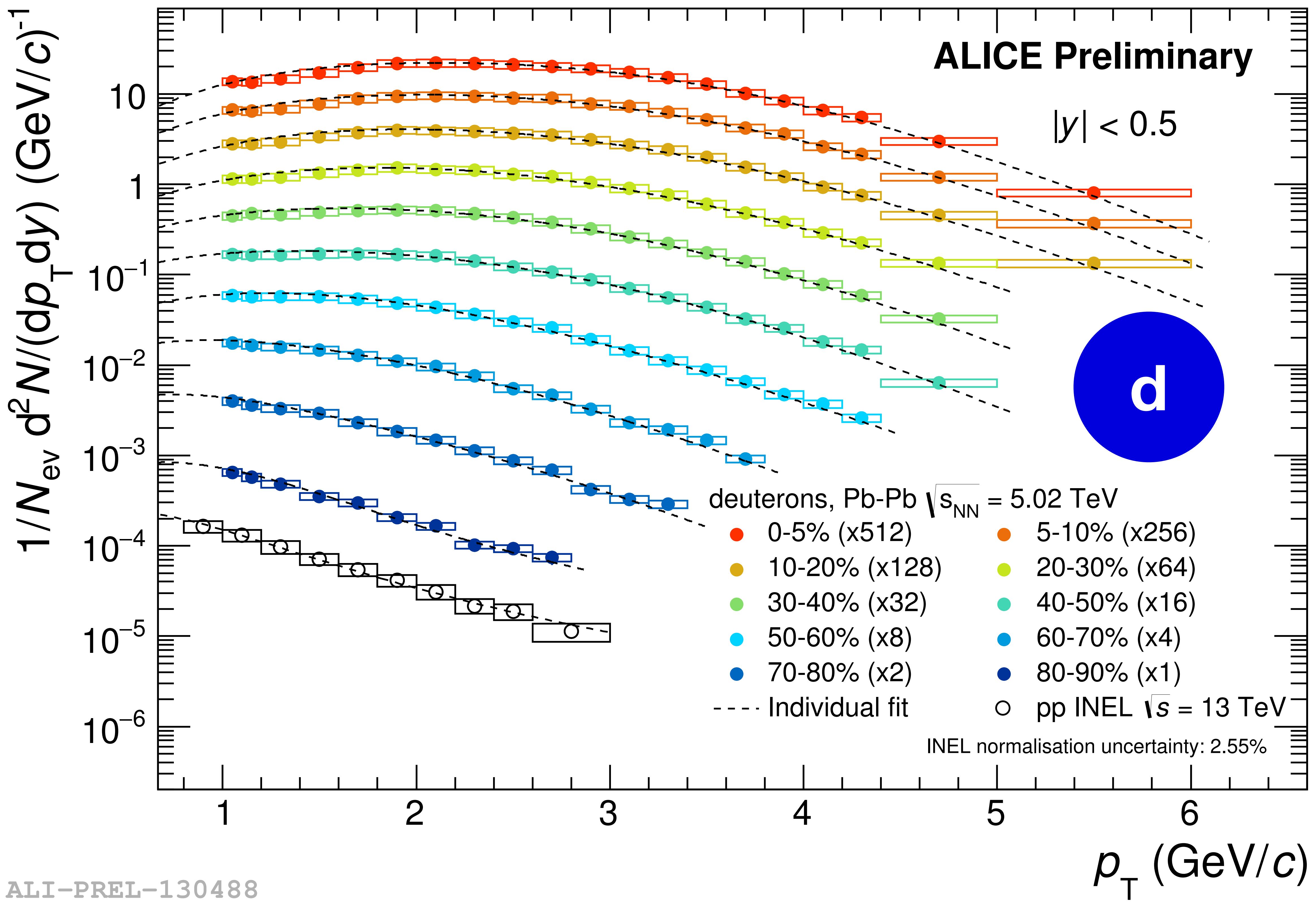
Light nuclei p_T spectra in pp collisions

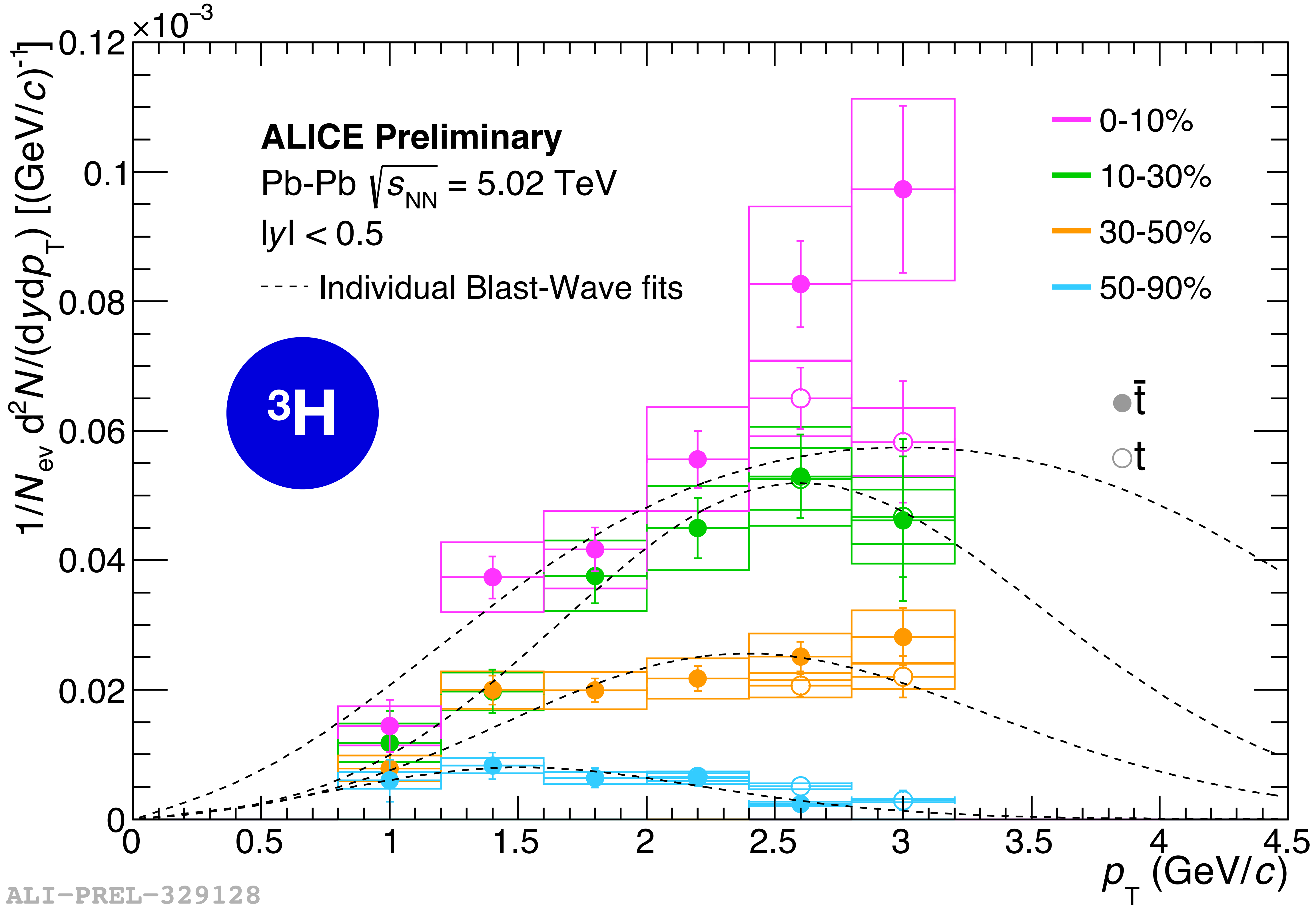


[6] ALICE Collaboration, *JHEP* **01**, 106 (2022)

- Light nuclei p_T spectra measured for different multiplicity classes in small collision systems
- Same behaviour for each nucleus species: spectra hardening with increasing multiplicity
- p_T spectra fitted with Lévy-Tsallis function to extrapolate in the unmeasured regions

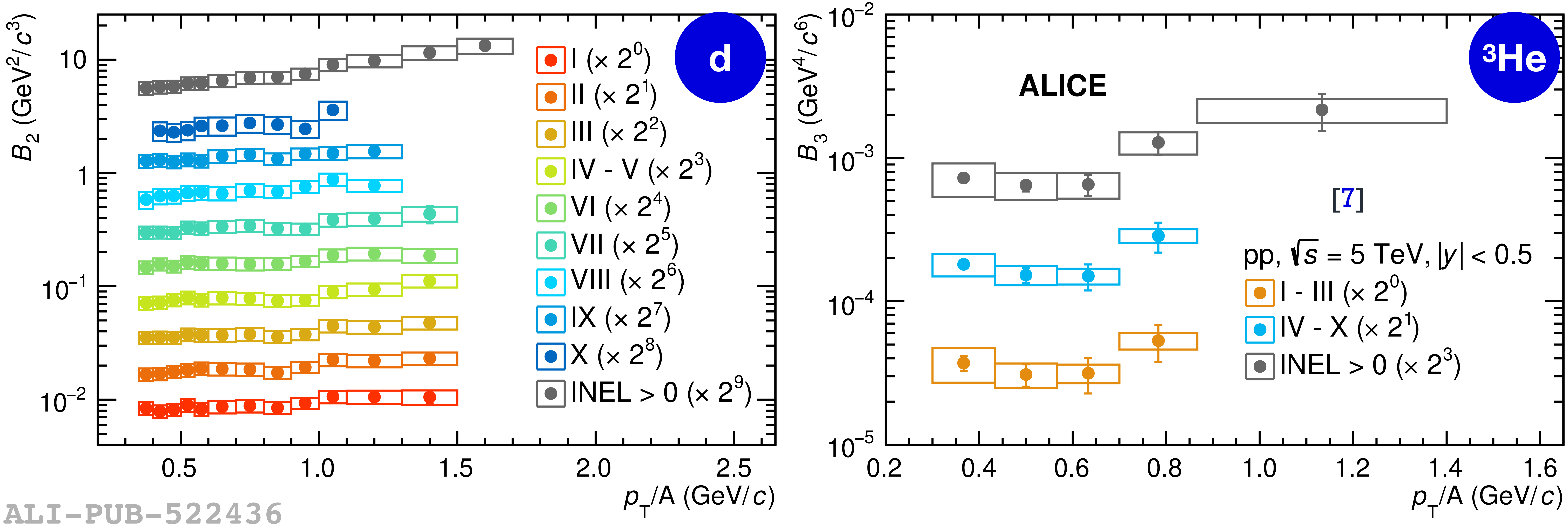
Light nuclei p_T spectra in Pb—Pb collisions





- Even more evident in Pb—Pb collisions: spectra hardening with increasing centrality
- Effect of collective motion (radial flow) also observed for other light-flavour hadrons

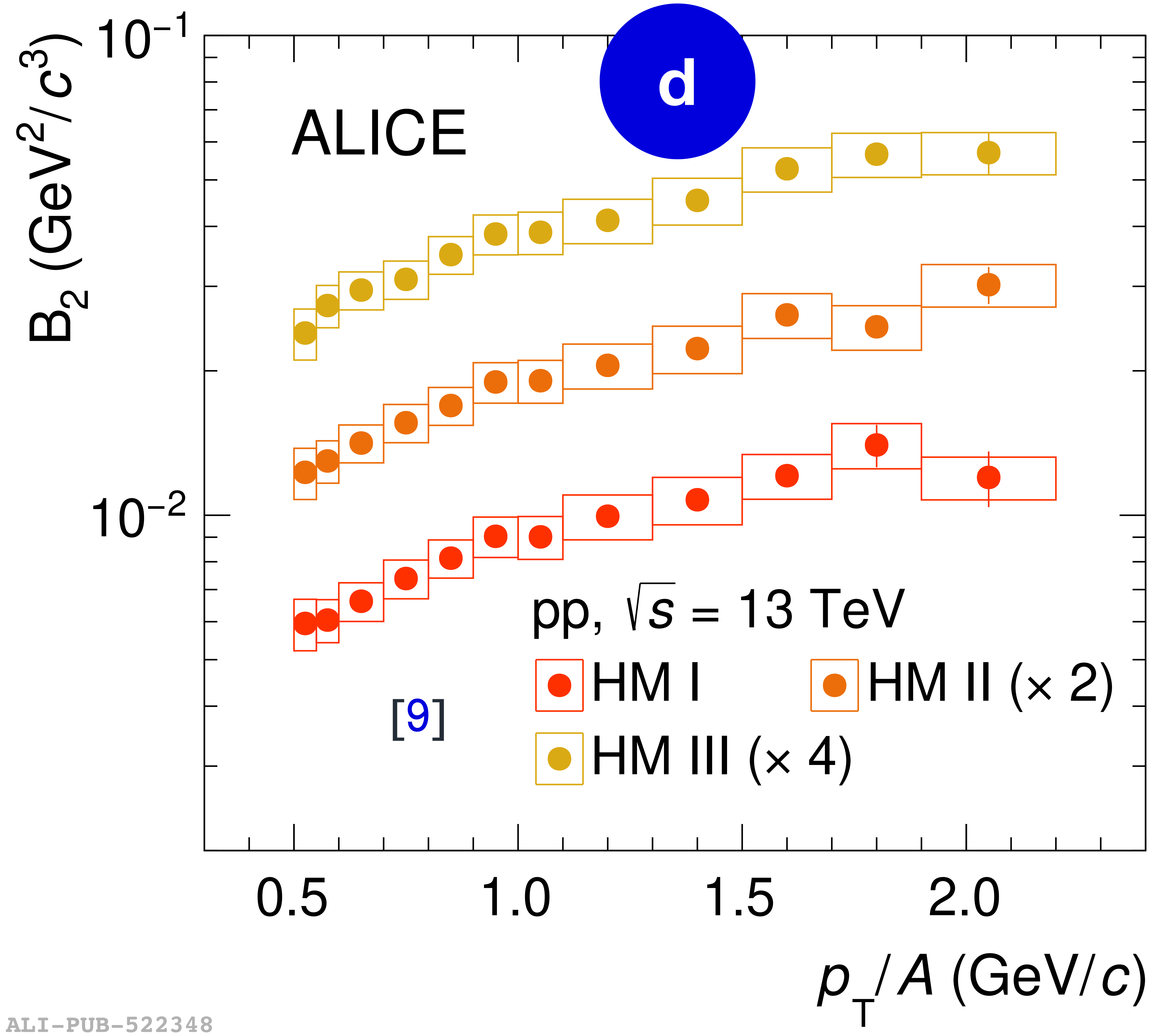
The coalescence parameter B_A in pp collisions



- Almost flat B_2 in narrow multiplicity intervals (in agreement with simple coalescence)
- B_3 rises significantly with p_T/A: predicted by state-of-the-art coalescence model [8] (size of particle-emitting source decreases with p_T)

[7] ALICE Collaboration, *Eur.* Phys. *J. C* **82**, 289 (2022)
[8] M. Gyulassy et al., *Nucl.* Phys. *A* **402**, 596-611 (1983)

The coalescence parameter B_A in pp collisions



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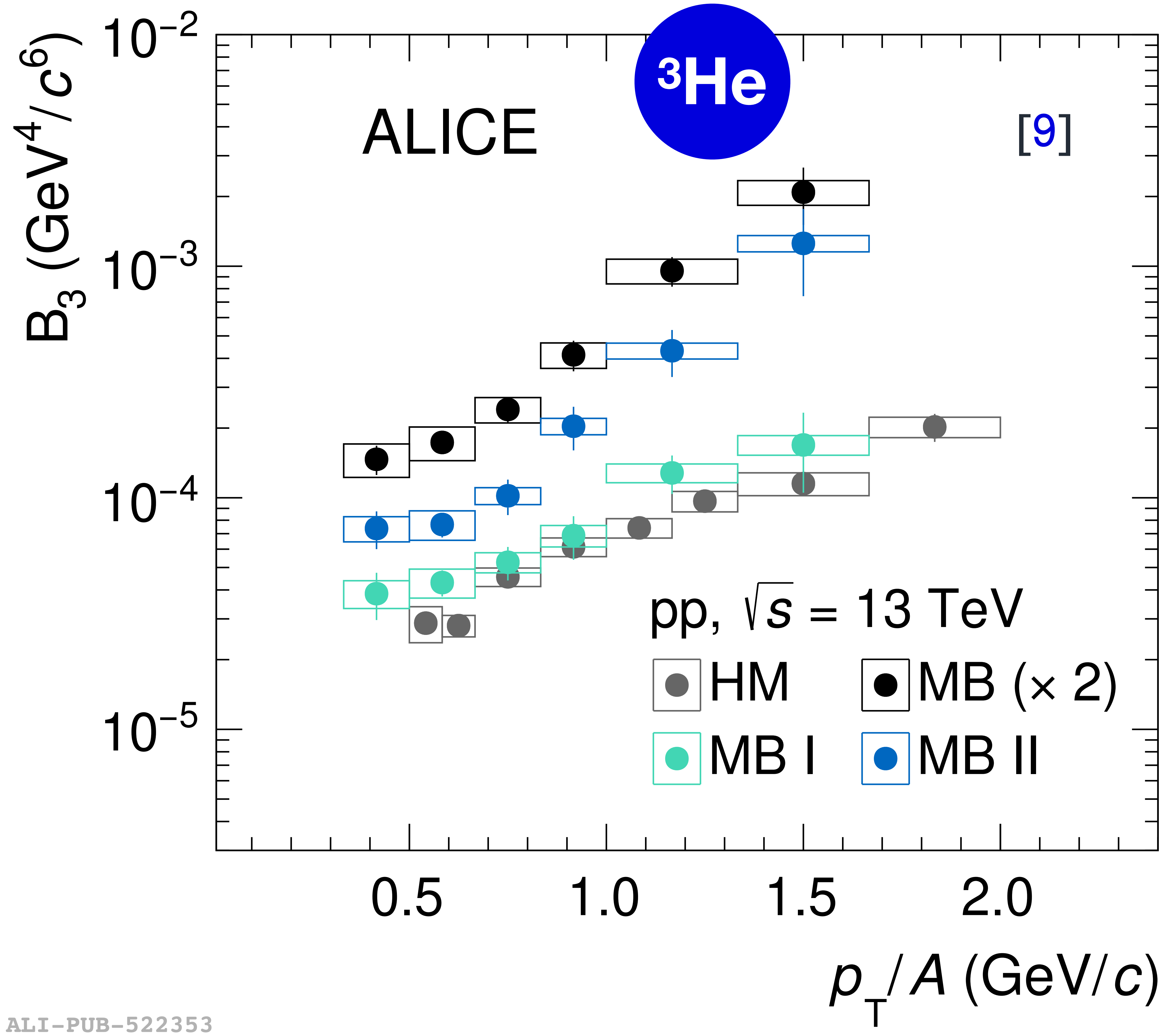
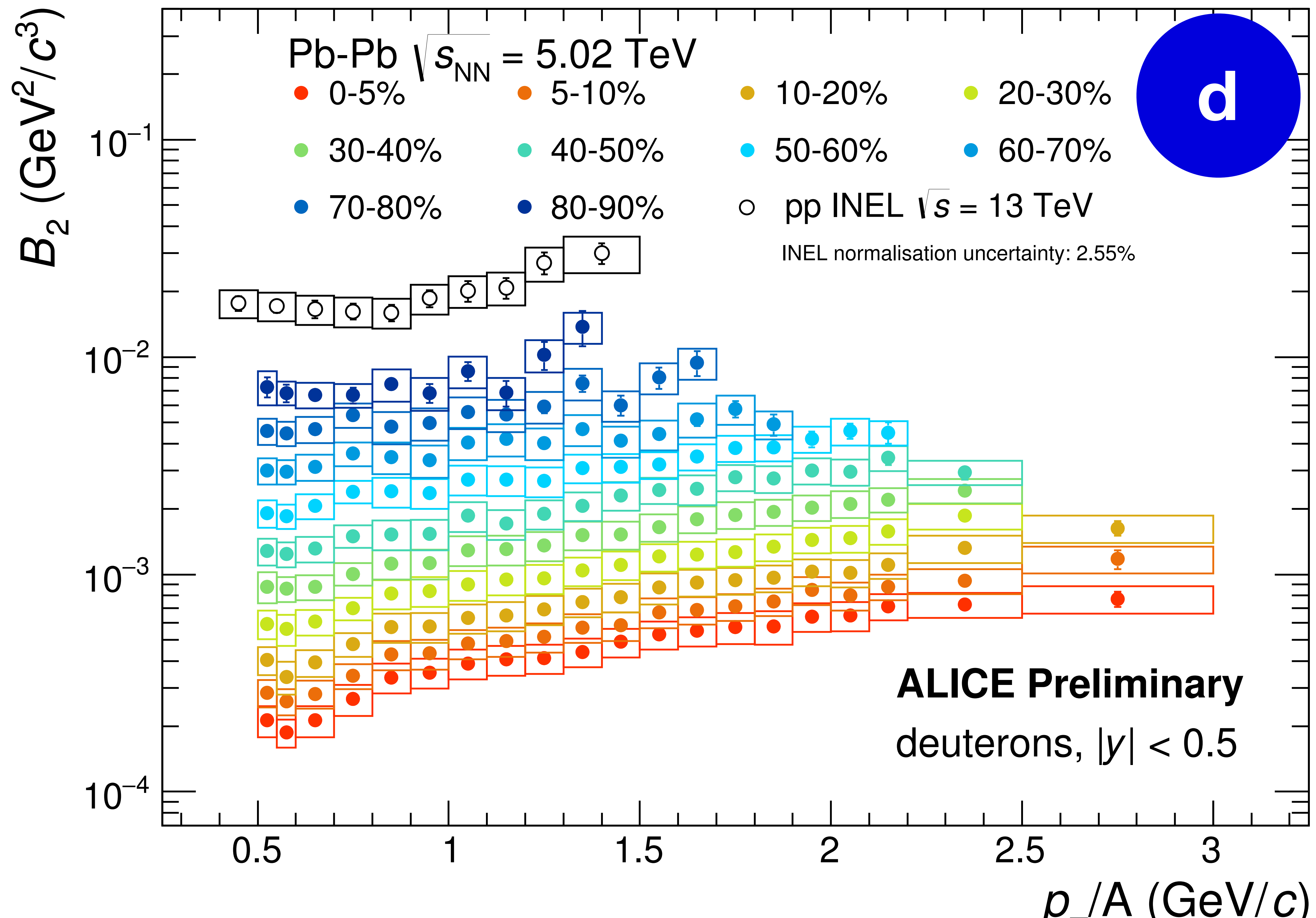


ALI-PUB-522353

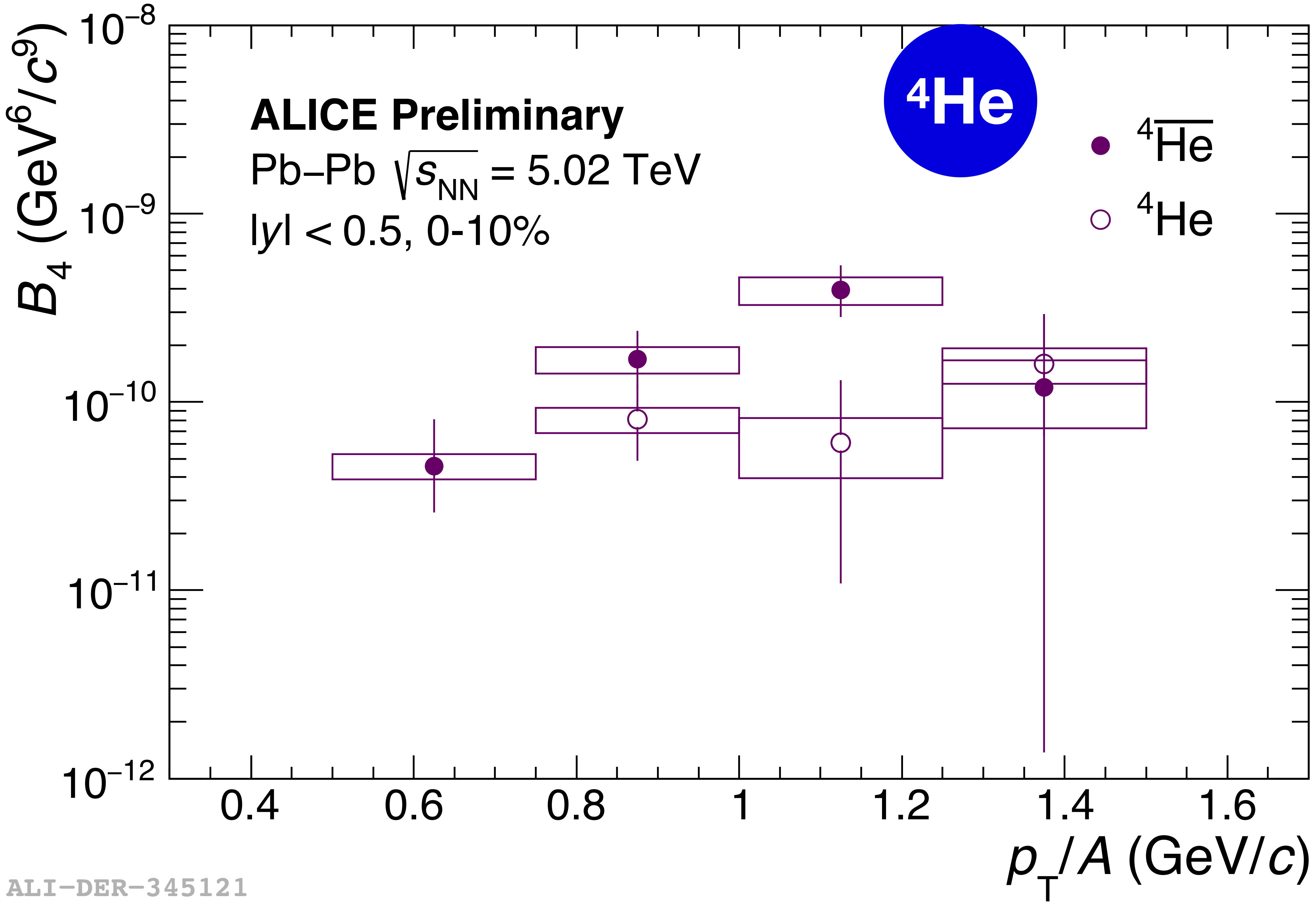
- B_A rises significantly with increasing p_T/A and with decreasing multiplicity in **high-multiplicity pp collisions**: predicted by state-of-the-art coalescence model [8]

[8] M. Gyulassy et al., *Nucl*. Phys. *A* **402**, 596-611 (1983)
[9] ALICE Collaboration, *JHEP* **01**, 106 (2022)

The coalescence parameter B_A in Pb—Pb collisions



ALI-PREL-130476

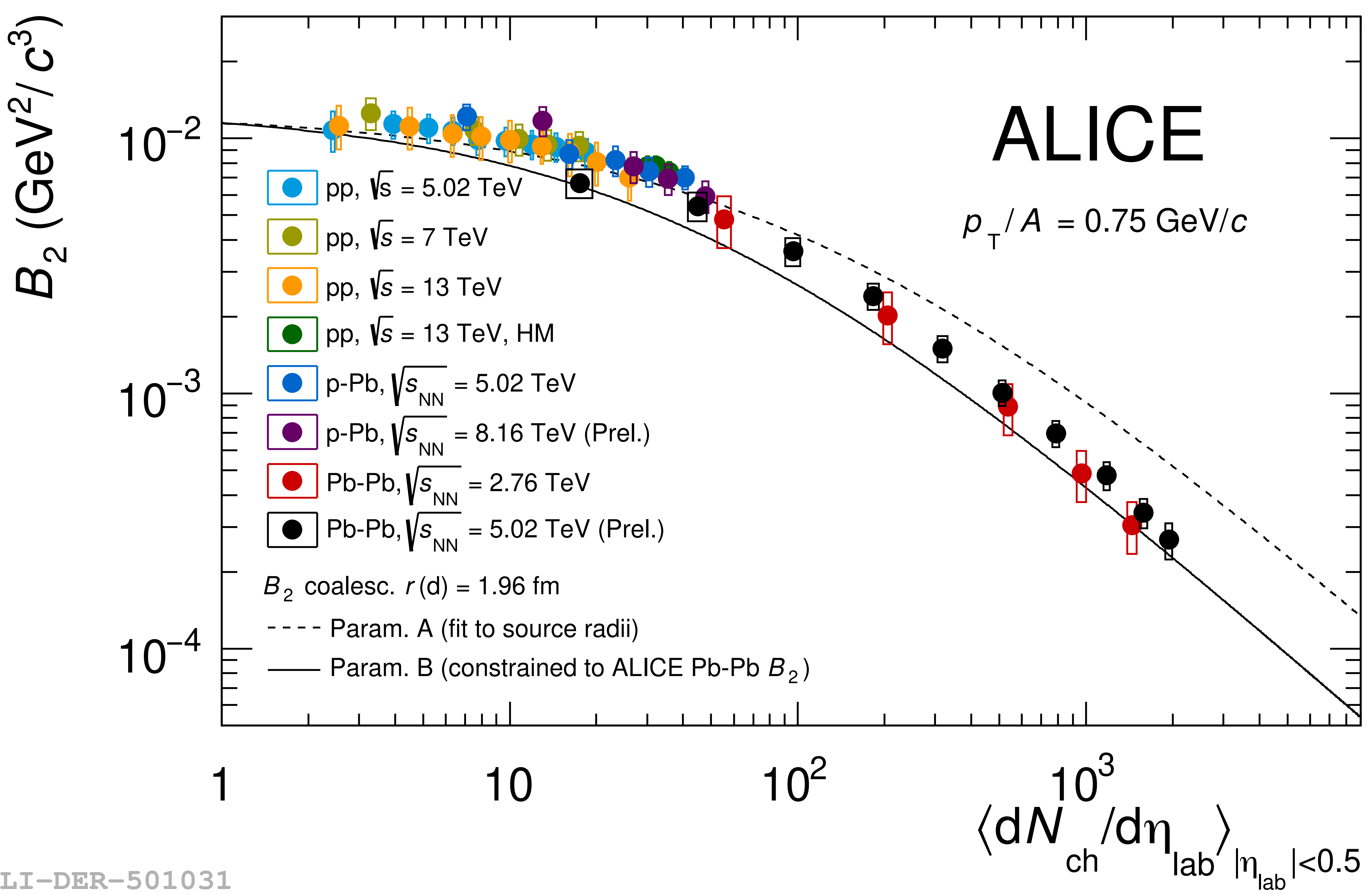


ALI-DER-345121

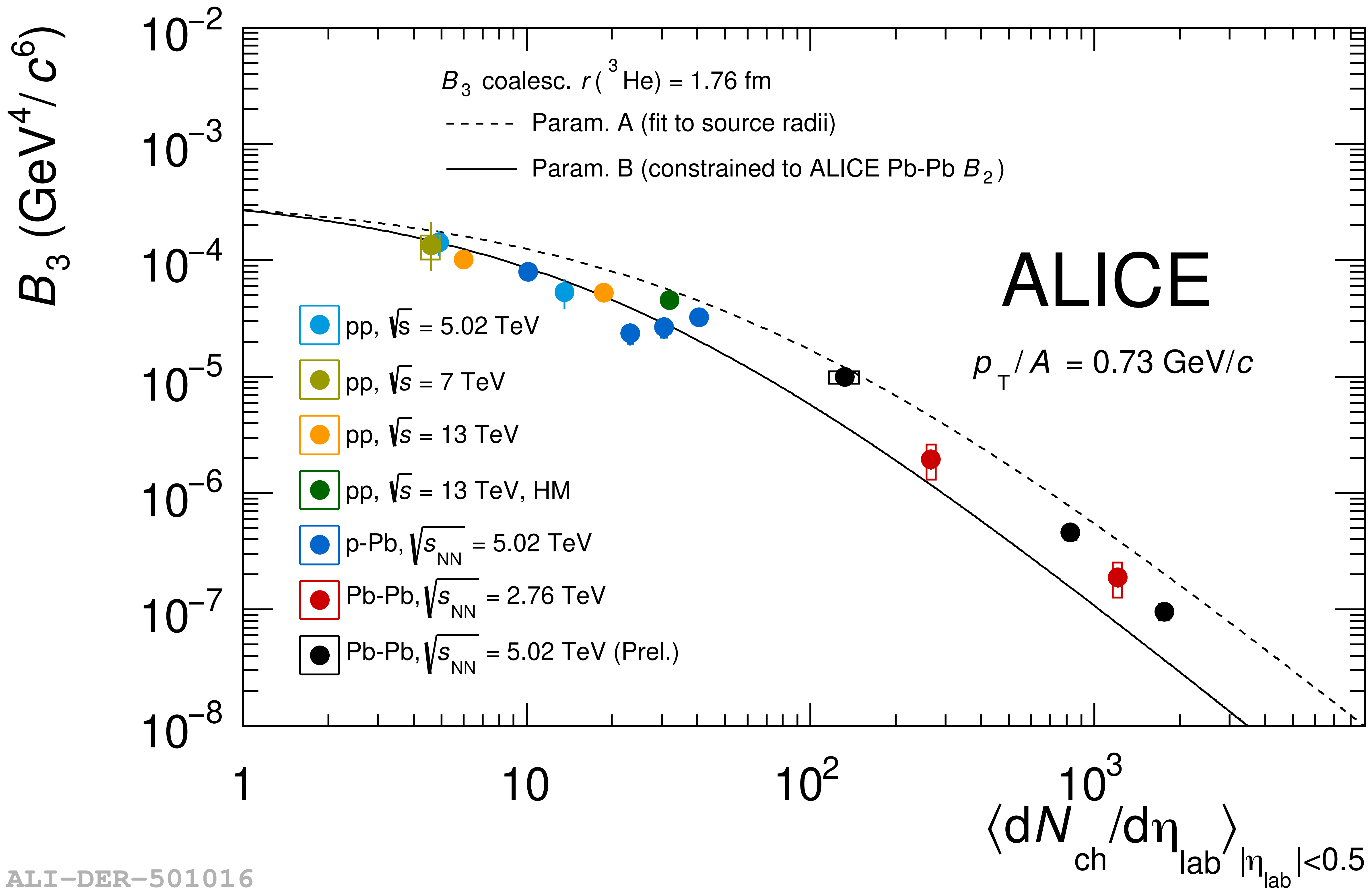
- B_A rises significantly with increasing p_T/A and with decreasing centrality in Pb—Pb collisions: predicted by state-of-the-art coalescence model [8]
- Challenging measurement for heavier light nuclei is possible: B_4 in Pb—Pb collisions

[8] M. Gyulassy et al., *Nucl*. Phys. *A* **402**, 596-611 (1983)

Multiplicity dependence of B_A



ALI−DER−501031



ALI−DER−501016

- Smooth evolution of B_A with multiplicity: no dependence on the collision system
- Two regimes observed:
  - almost flat for low multiplicity
  - decreasing for large system size

→ coalescence probability depends on the system volume

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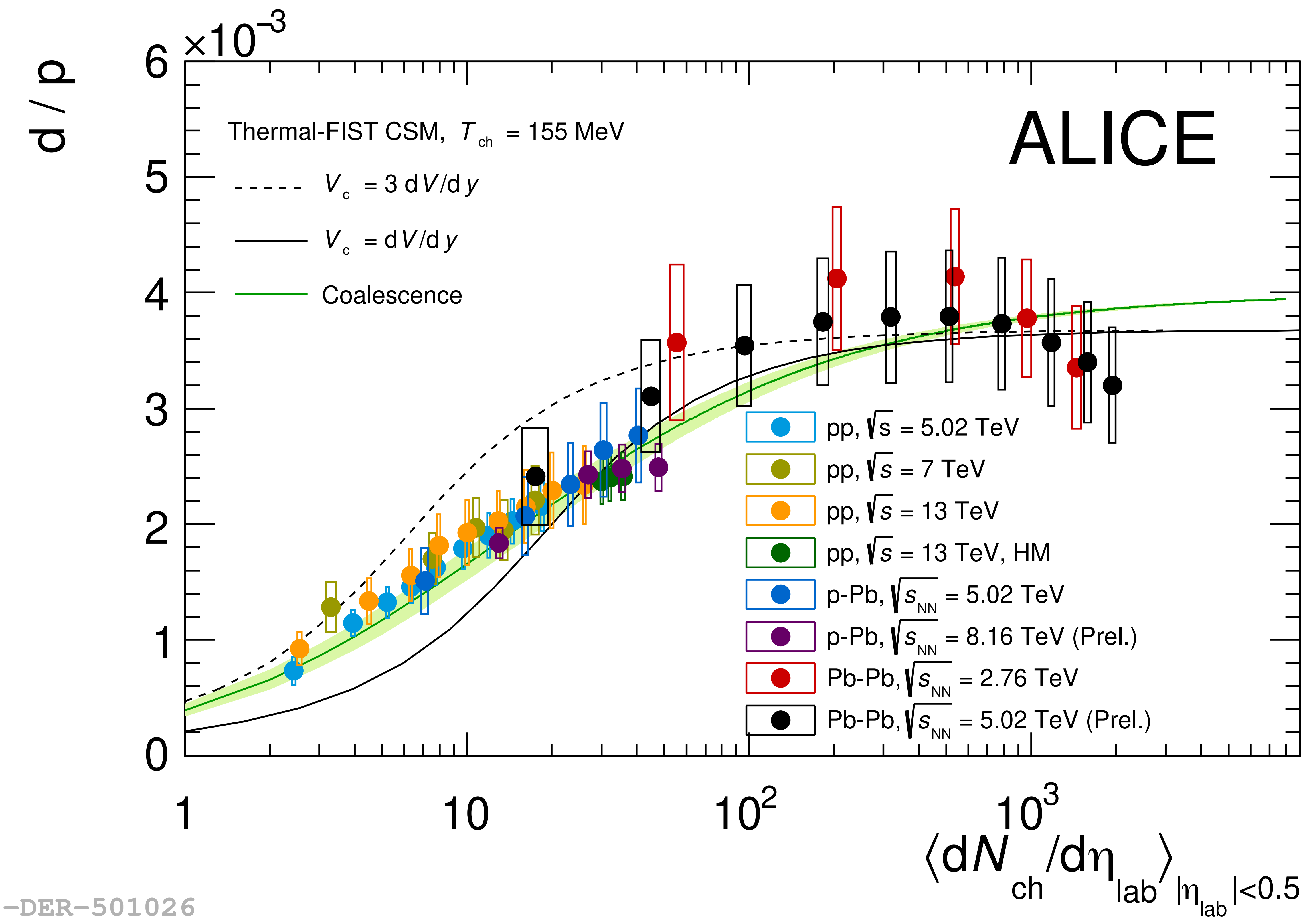
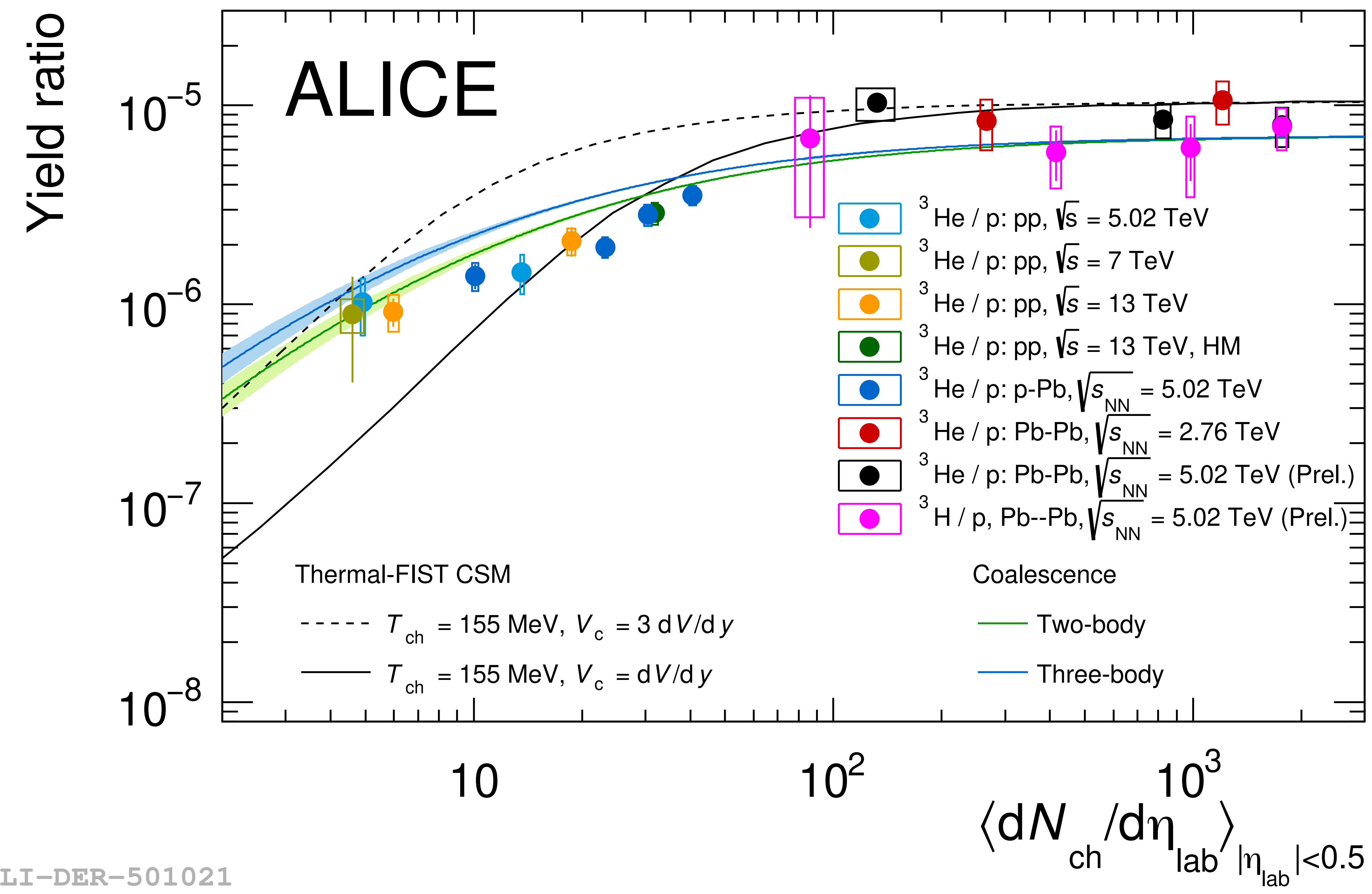
Yield ratios



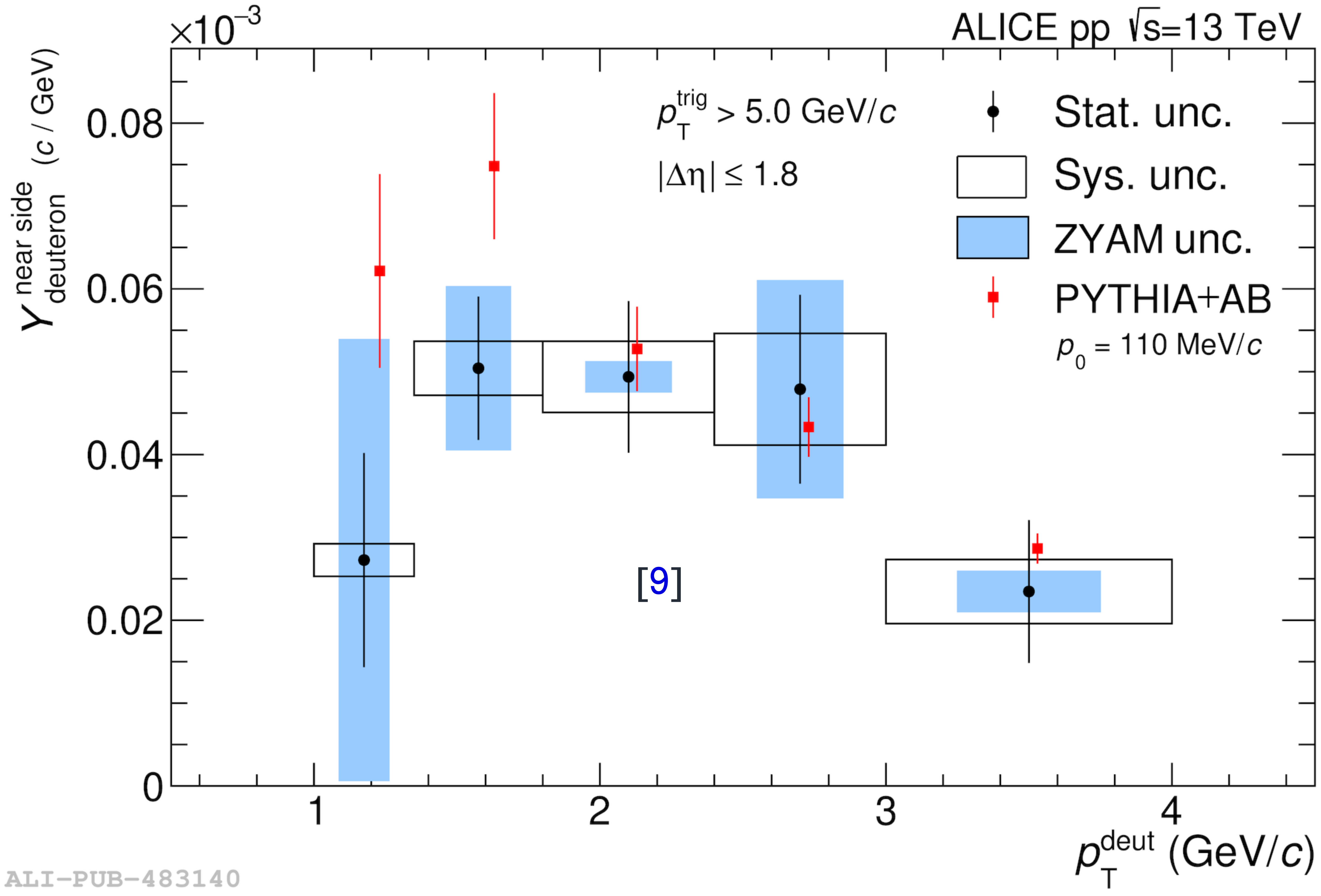
ALI-DER-501026



ALI-DER-501021

- d/p, ^{3}H/p and ^{3}He/p ratios increase smoothly with multiplicity without any dependence on the collision system or energy
- Models can qualitatively describe nuclei ratios to protons, except for $A > 2$ in the intermediate multiplicity region

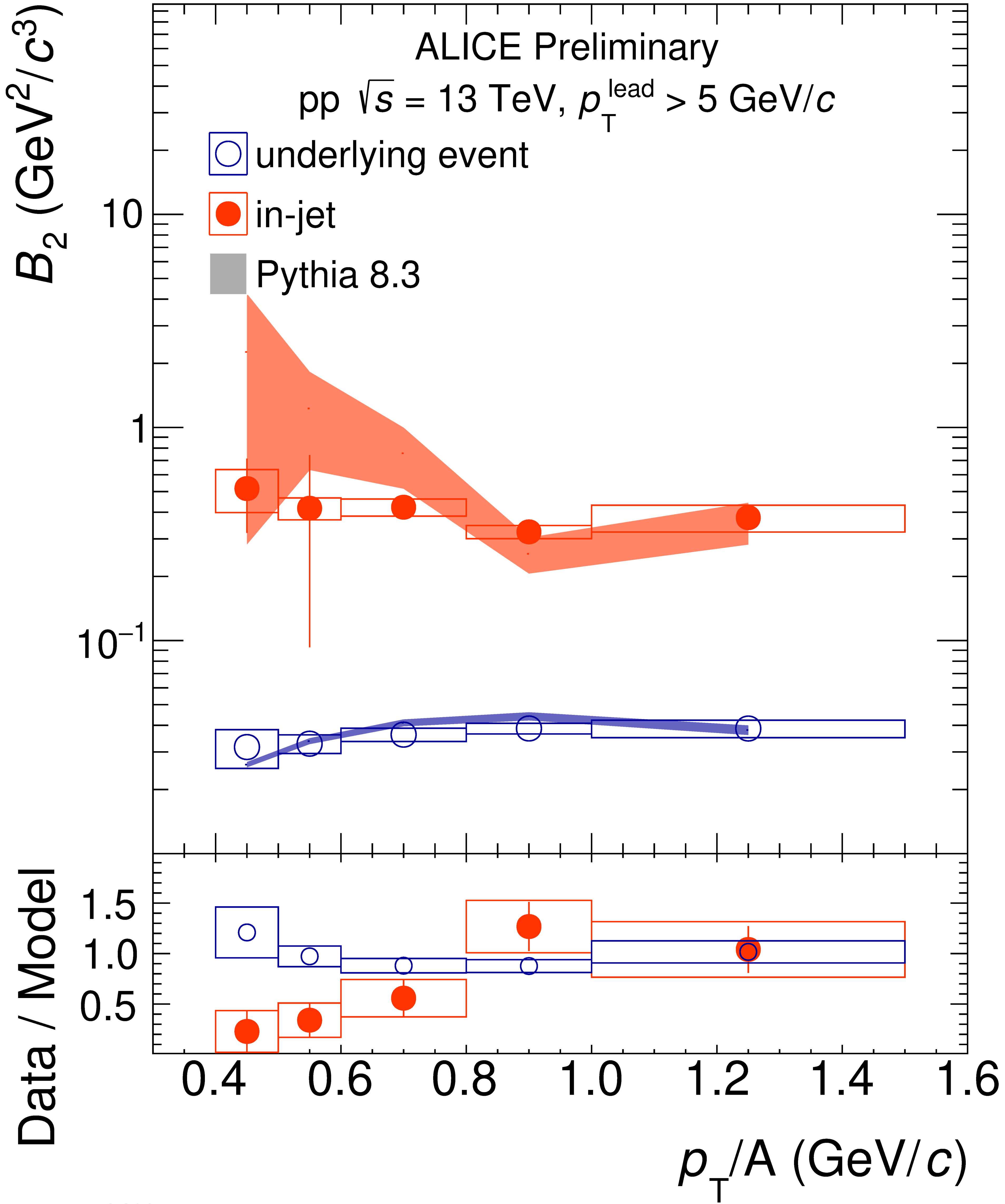
Deuteron production in jets



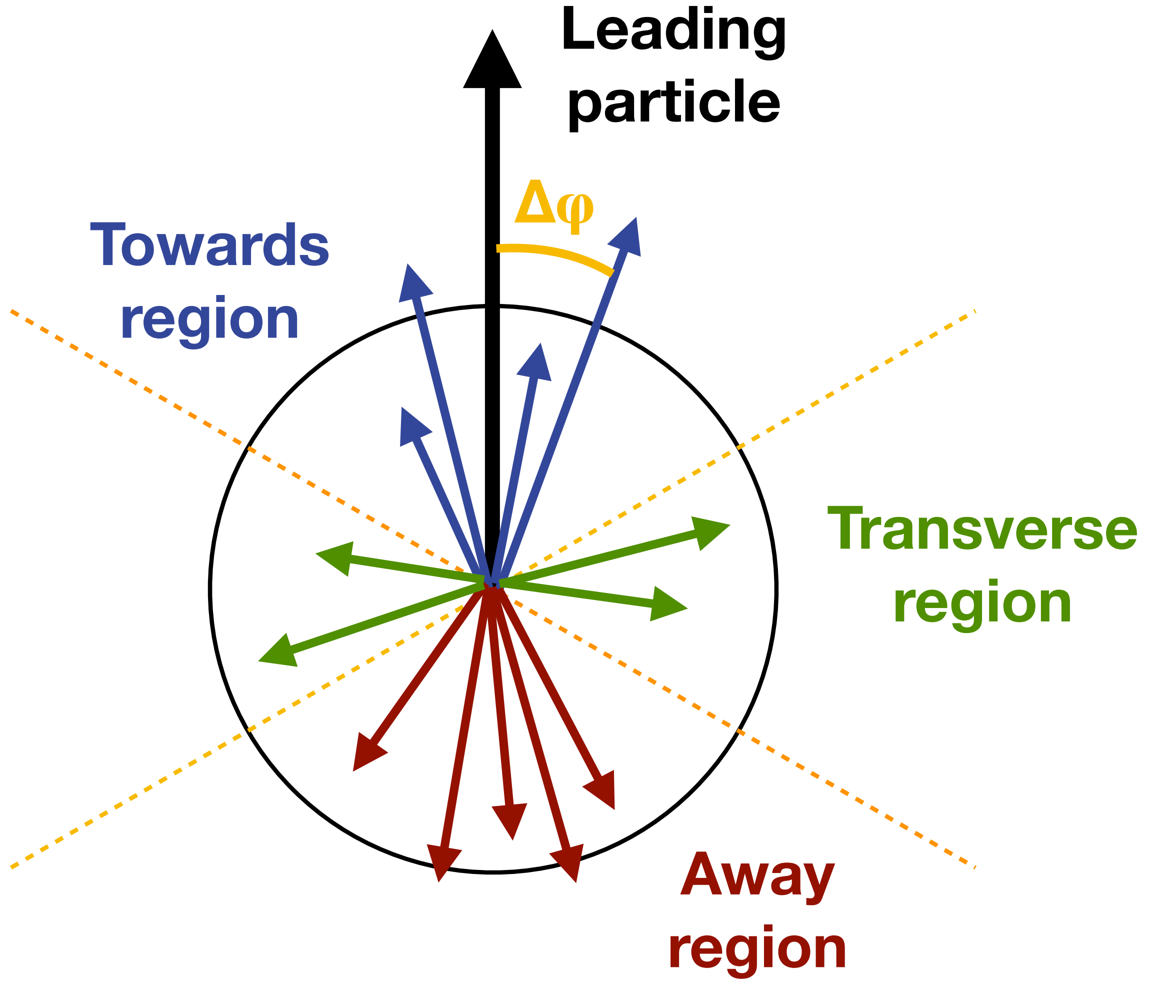
- d production from hard processes as a function of p_T
- Leading particles with $p_T^{lead} > 5$ GeV/c are used as proxies for jets
- The number of deuterons produced in-jet is ~ 10% of the one in the underlying event, increasing with p_T
- The model calculation (PYTHIA8 + coalescence afterburner) can describe the data

[10] ALICE Collaboration, *Phys*. Lett. *B* ***819***, 136440 (2021)

B_2 in jets



ALI-PREL-506107



- The **in-jet** yield is evaluated as the difference between the yields in the **towards** and in the **transverse** regions
- In-jet B_2 is ~ 10/15 times larger than B_2 in the underlying event
- PYTHIA8.3 (reaction-based deuteron production) can properly describe the B_2 behaviour in-jet and in the underlying event within the model uncertainties

Conclusions

- The ALICE experiment has measured light nuclei production in small and large collision systems at different energies
- B_{A}, d/p, ^{3}He/p and ^{3}H/p: no dependence on the collision system but only on the system size at freeze-out
- Deuteron production in jets: significant difference between B_2 in-jet and in the underlying event
- Light nuclei production mechanism: more data (LHC Run 3 is approaching) and more precise theoretical model predictions are needed

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