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Production of light nuclei in small collision systems with ALICE

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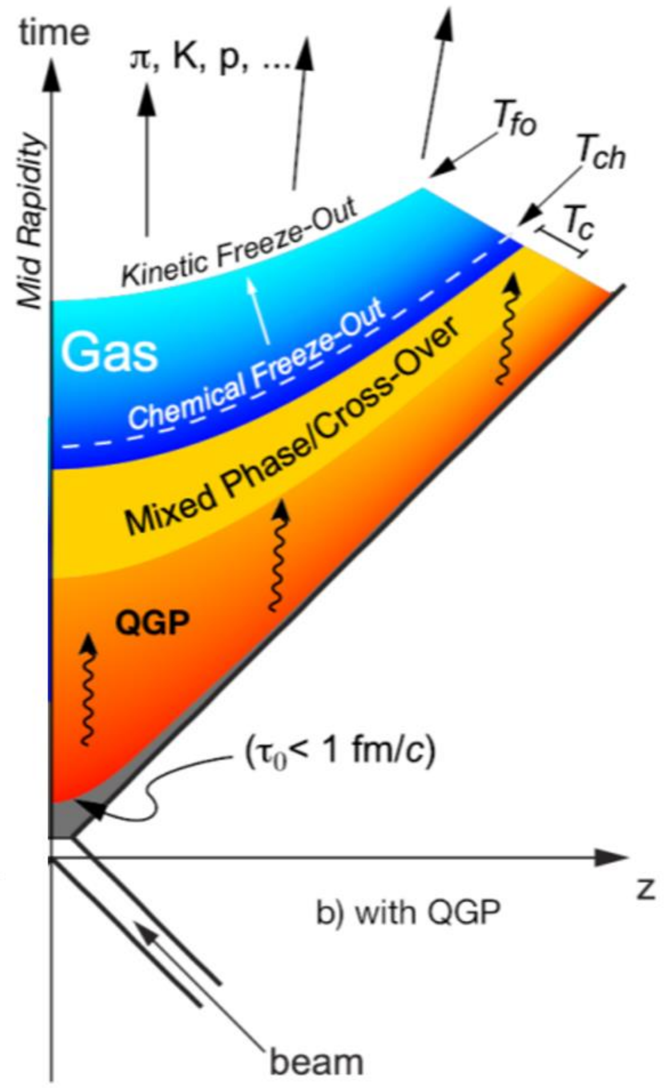
on behalf of the ALICE Collaboration

UNIVERSITÀ degli STUDI di CATANIA

INFN Catania Istituto Nazionale di Fisica Nucleare

ALICE

Physics motivation



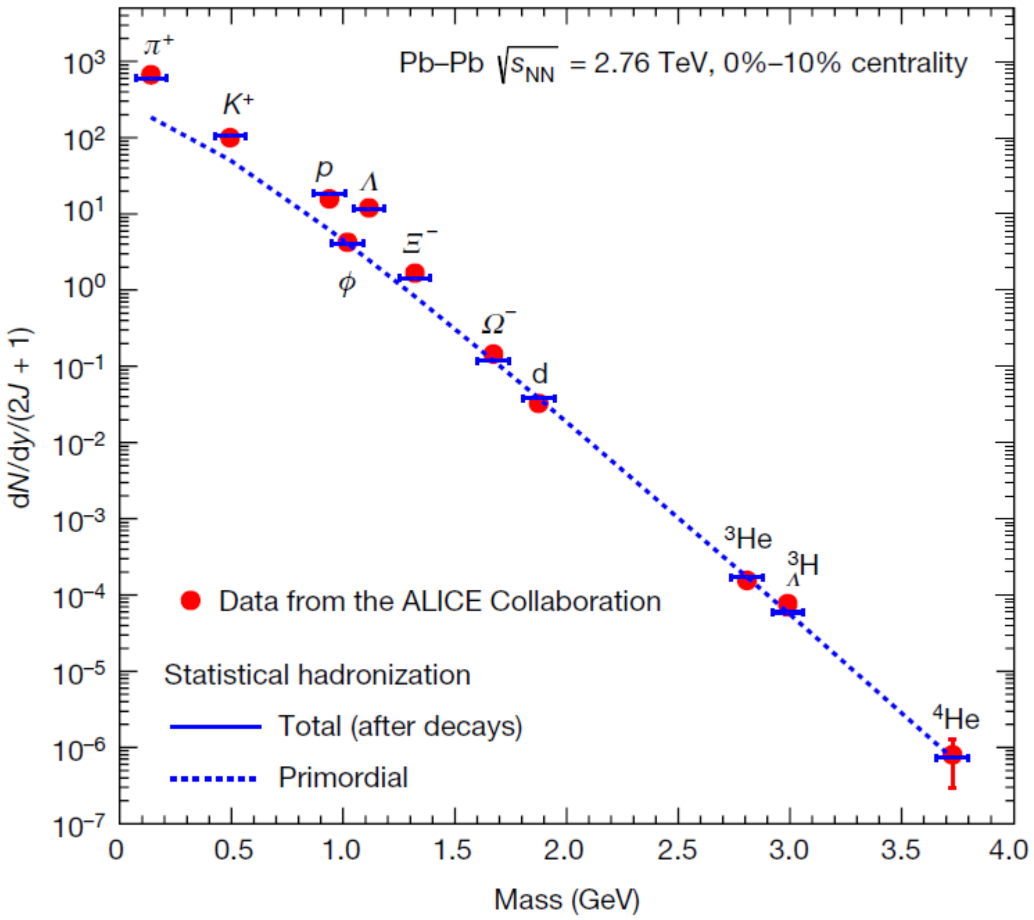
- Multi-baryon states are produced in high energy hadronic collisions at the LHC
- Their production mechanism is still under debate
- Two classes of phenomenological models:
  - Statistical hadronisation
  - Coalescence

Statistical models

- Hadrons emitted from a system in statistical and chemical equilibrium
- dN/dy ∝ exp(-m/T_{chem})

  ⇒ Nuclei (large m): large sensitivity to T_{chem}
- Light nuclei are produced during phase transition (as other hadrons)
- Typical binding energy of nuclei ~ few MeV (*E_B ~ 2 MeV for d*)

⇒ how can they survive the hadronic phase environment (T_{chem} ~ 156 MeV)?

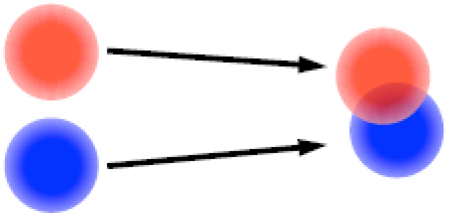


Andronic et al., Nature vol. 561, 321–330 (2018)

→ In Pb-Pb collisions, particle yields of light flavor hadrons are described over 9 orders of magnitude with a common chemical freeze-out temperature of T_{chem} ≈ 156 MeV.

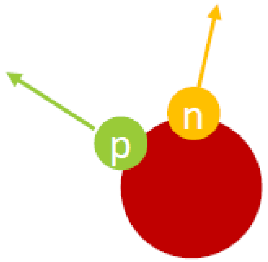
Coalescence models

S. T. Butler et al., Phys. Rev. 129 (1963) 836



- If (anti)baryons are close in phase space and match the spin state, they can form a (anti)nucleus
- Coalescence parameter B_A is the key parameter

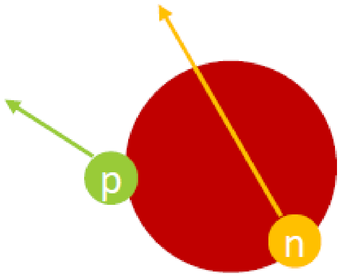
$$E_A \frac{d^3 N_A}{dp_A^3} = B_A \left(E_p \frac{d^3 N_p}{dp_p^3} \right)^A \Bigg|_{\vec{p}_p = \vec{p}_A / A}$$



- Experimental parameter tightly connected to the coalescence probability

Larger B_A ⟺ Larger coalescence probability

- Coalescence probability depends on the system size

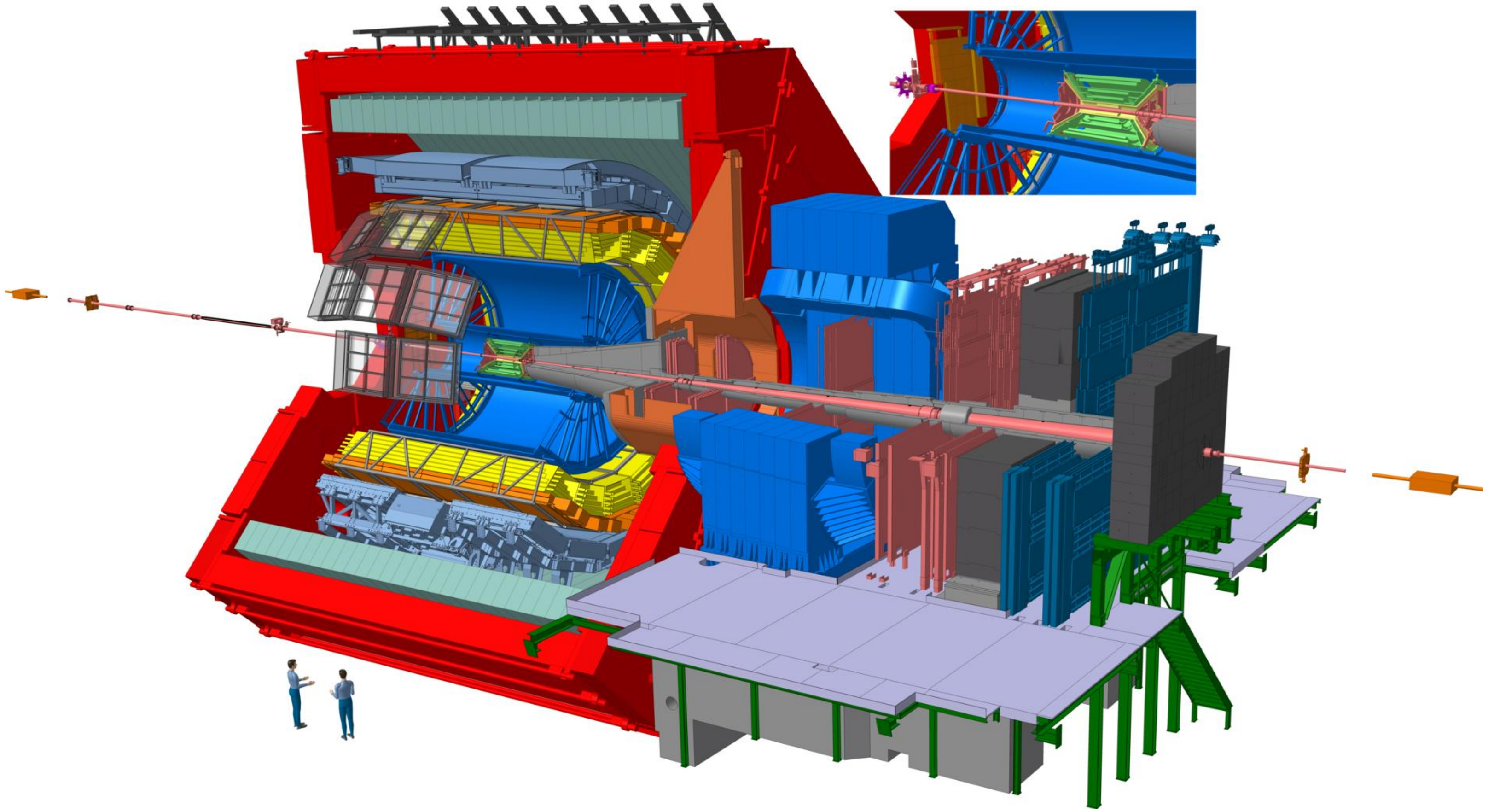


Small distance in space
(Only momentum correlations matter)
⟺ large B_A

Large distance in space
(Both momentum and space correlations matter)
⟺ small B_A

- More sophisticated coalescence models are available, with quantum mechanical properties considered

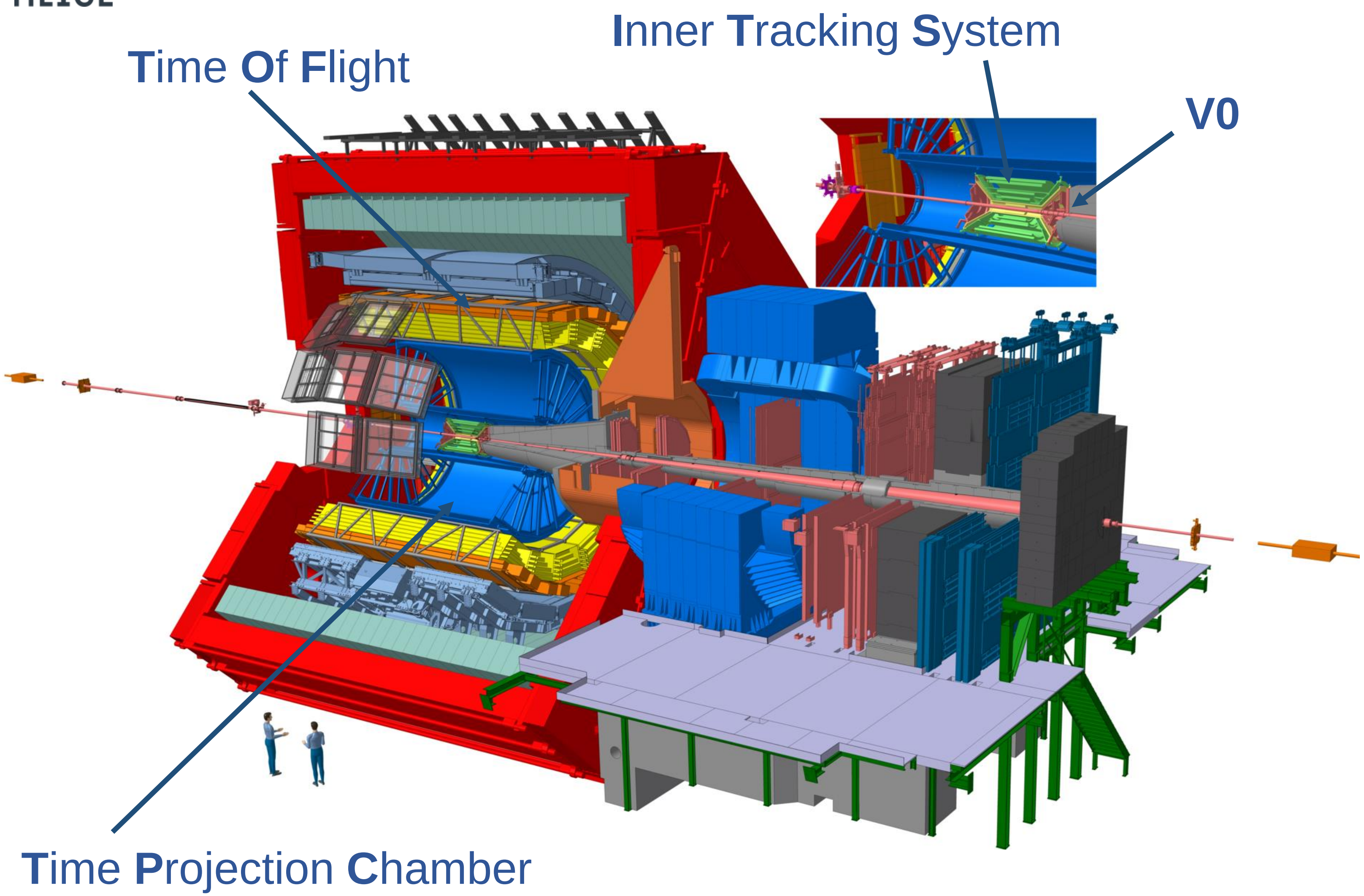
The ALICE detector



- General purpose experiment
- Excellent tracking and PID capabilities over a broad momentum range
- Low material budget

→ Most suited detector at the LHC for the study of (anti)nuclei produced in HE collisions

The ALICE detector



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- Excellent tracking and PID capabilities over a broad momentum range
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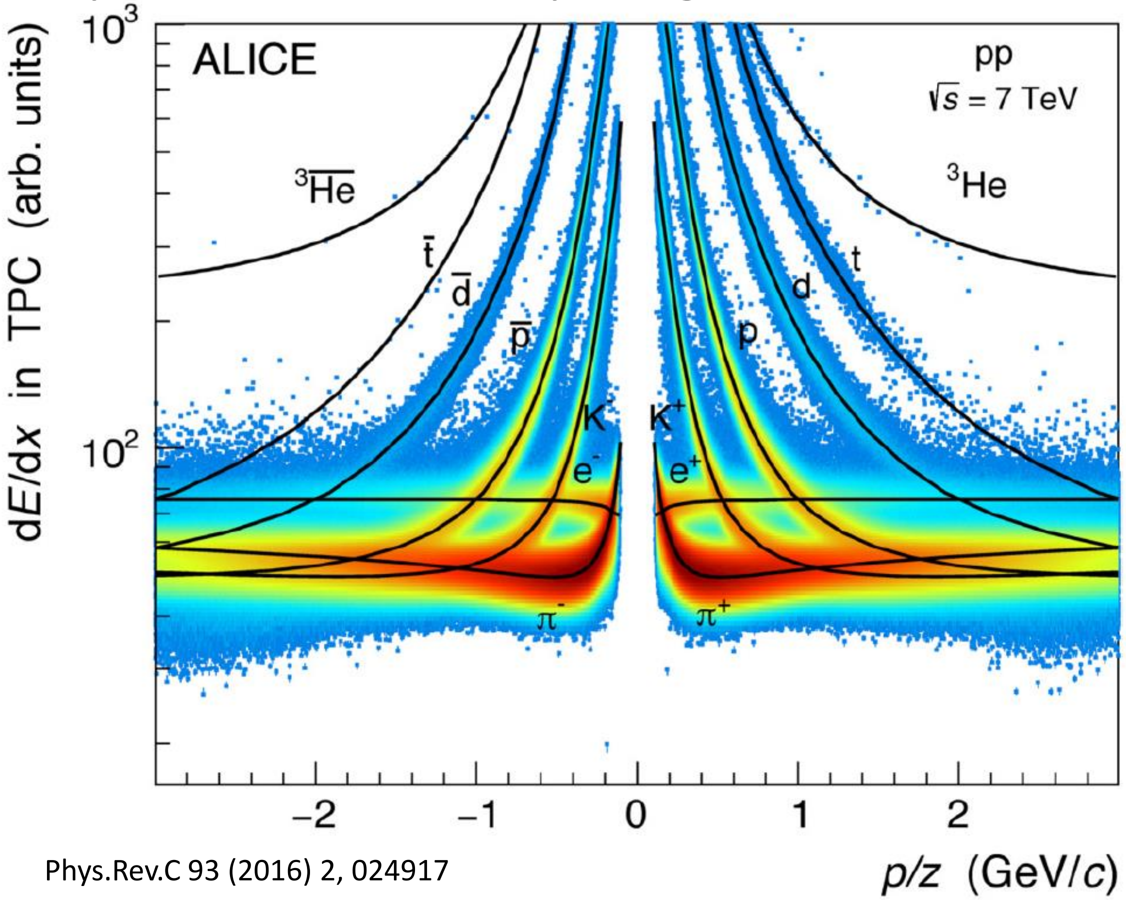
→ Most suited detector at the LHC for the study of (anti)nuclei produced in HE collisions

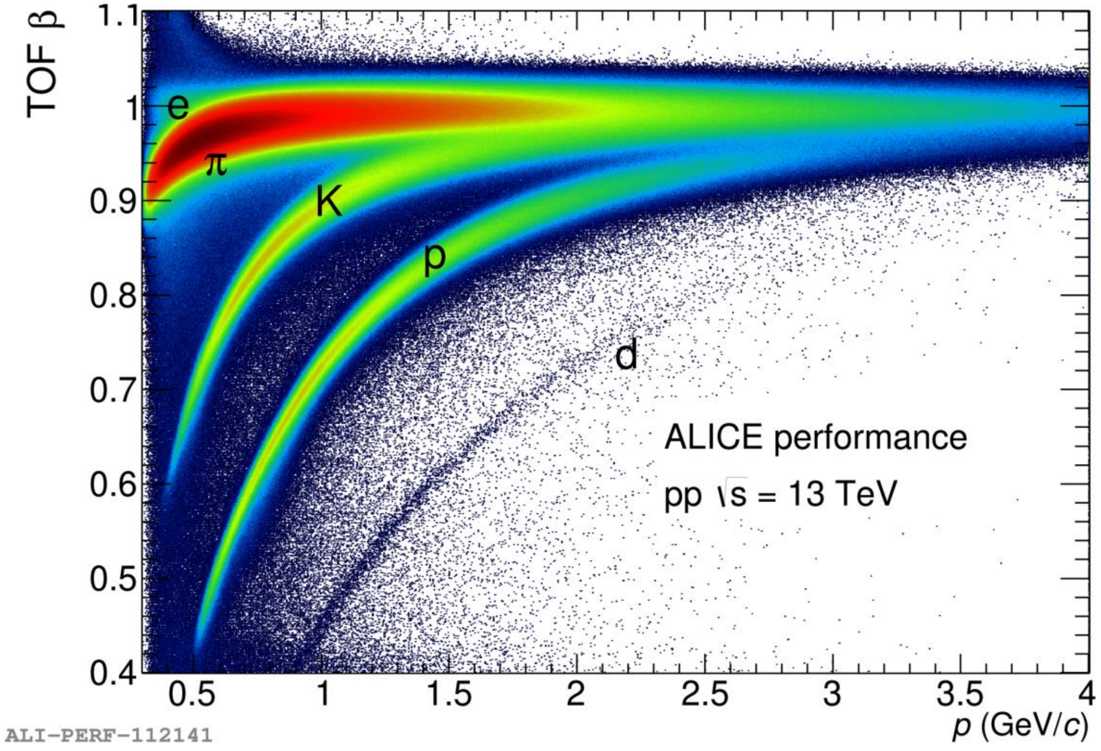
Nuclei identification

Low p region (below 1 GeV/c) → PID via dE/dx measurements in TPC

- (anti)^{3}He well separated from the other particle species over the full p range



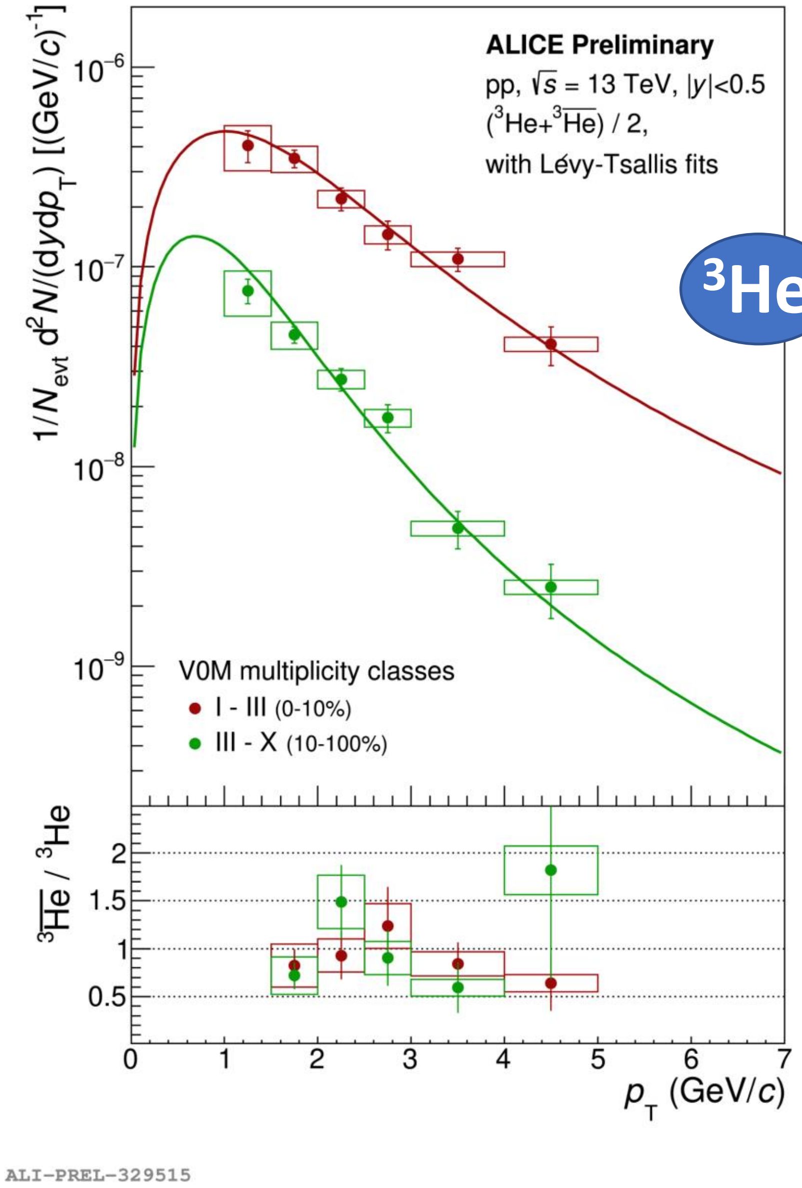
Phys.Rev.C 93 (2016) 2, 024917

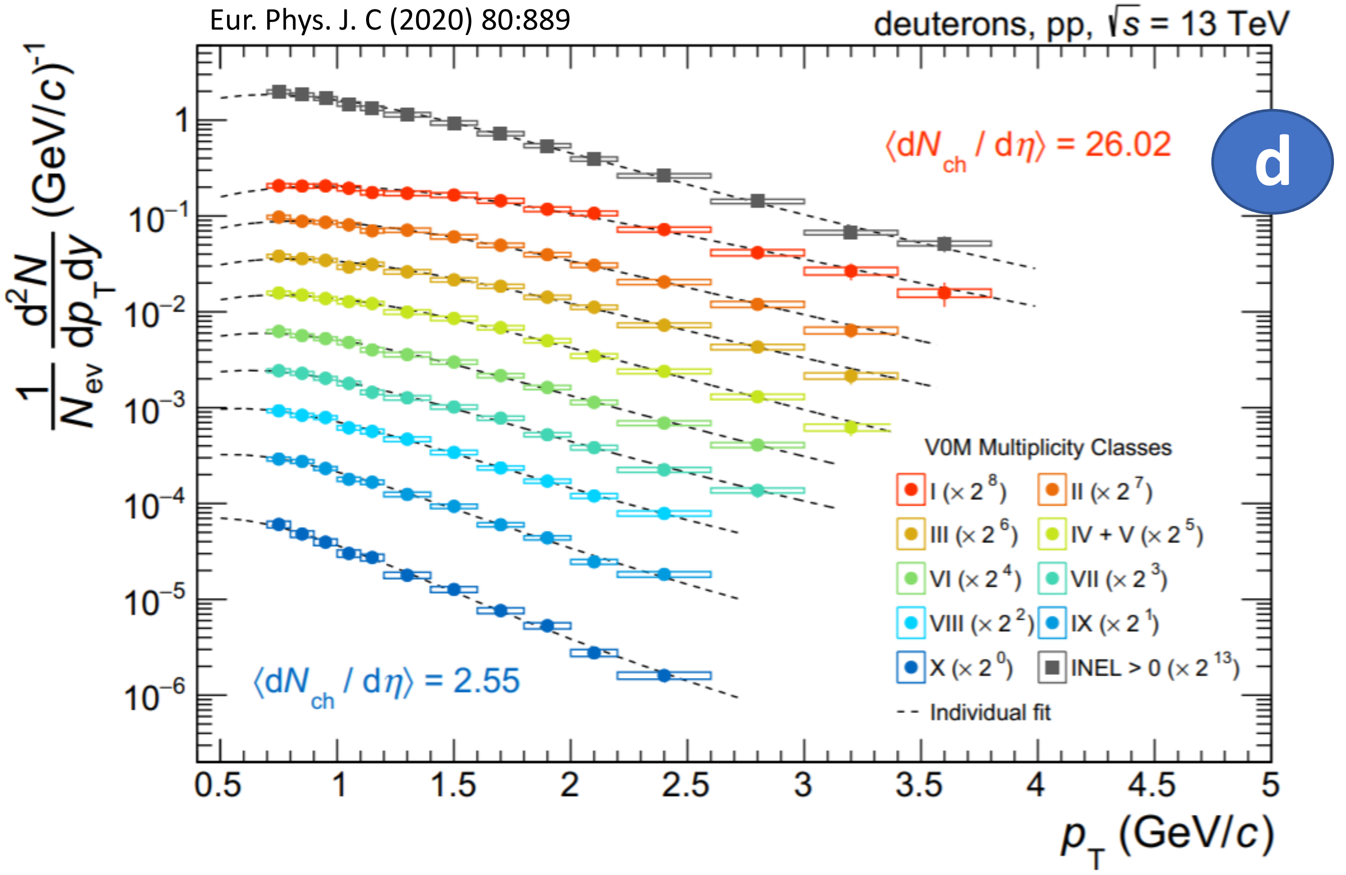


Higher p region (above 1 GeV/c) → PID via velocity β measurements in TOF

Light (anti)nuclei in pp

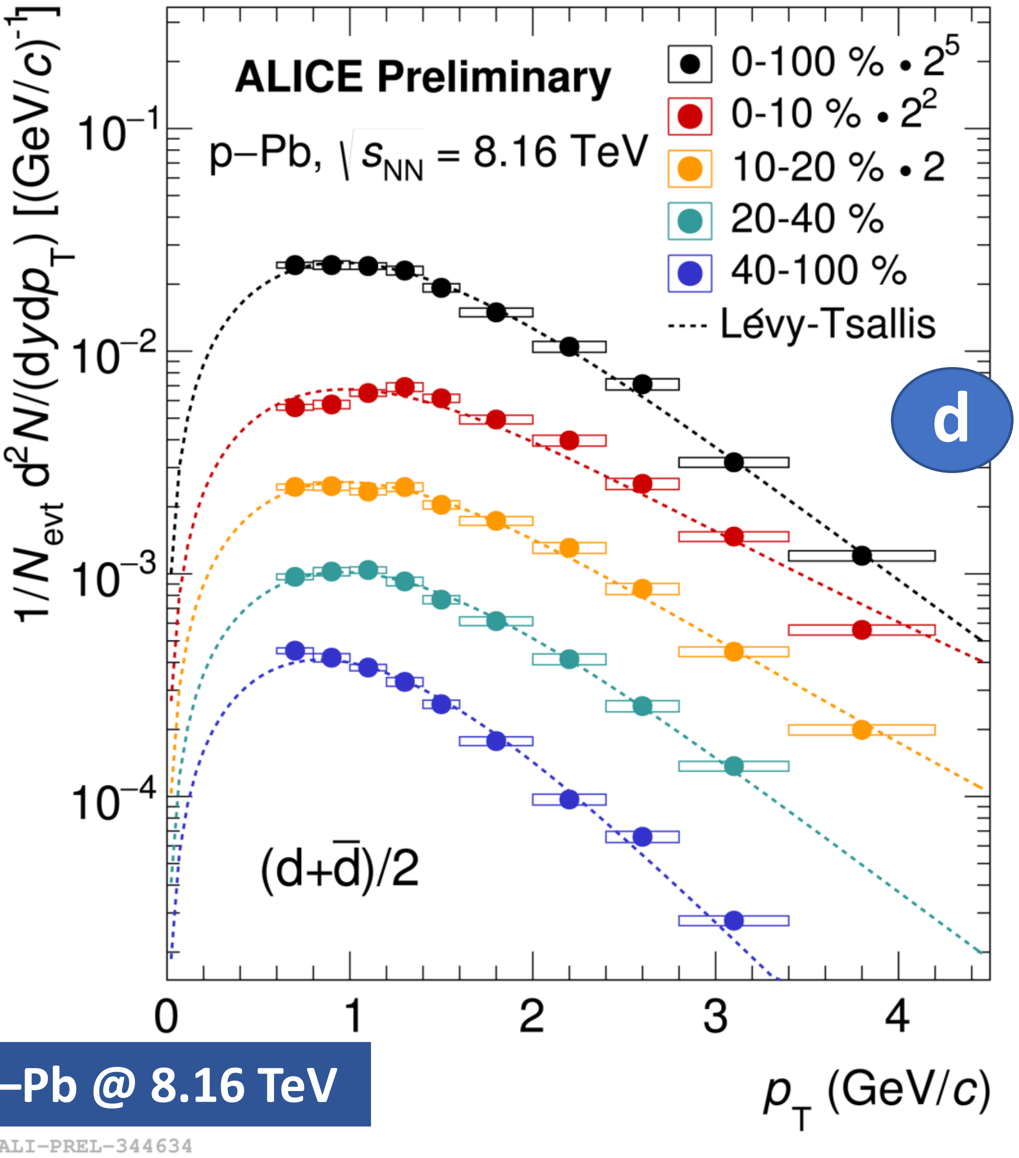
pp @ 13 TeV





- p_{T} spectra fitted with Lévy-Tsallis function ⇒ Extrapolation to unmeasured regions
- Hardening with increasing centrality – as seen for other light-flavour hadrons

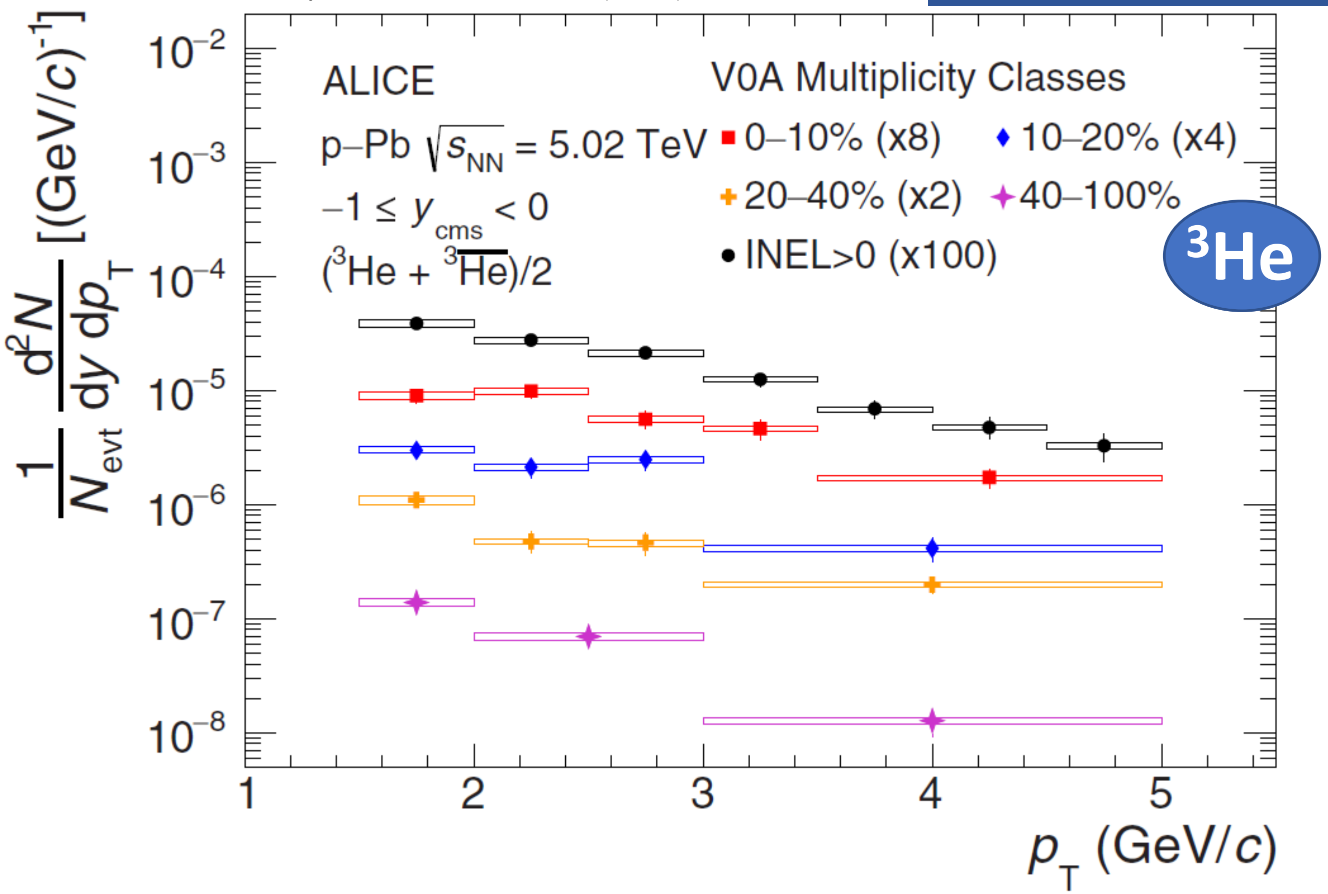
Light (anti)nuclei in p–Pb



p–Pb @ 8.16 TeV

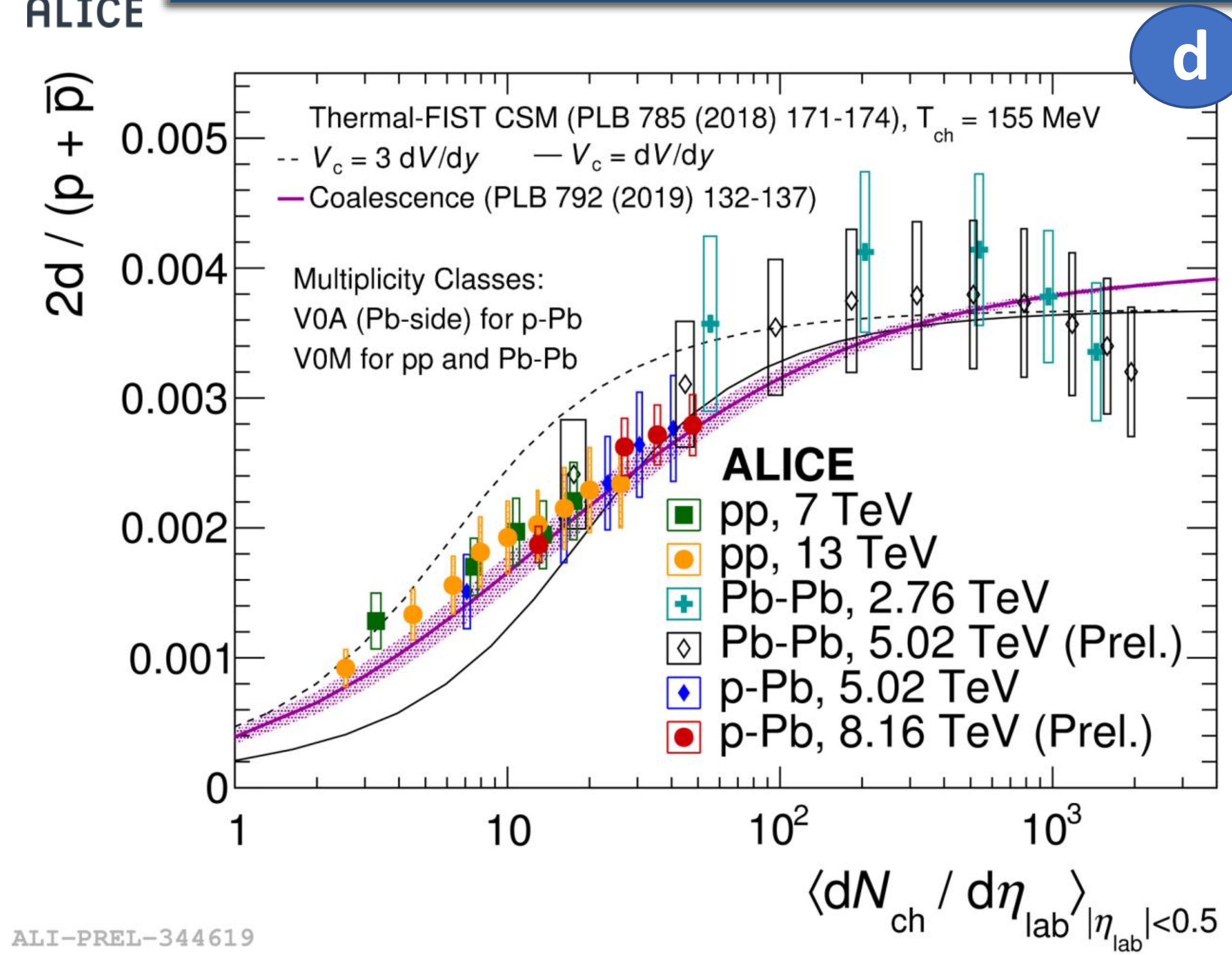
p–Pb @ 5.02 TeV

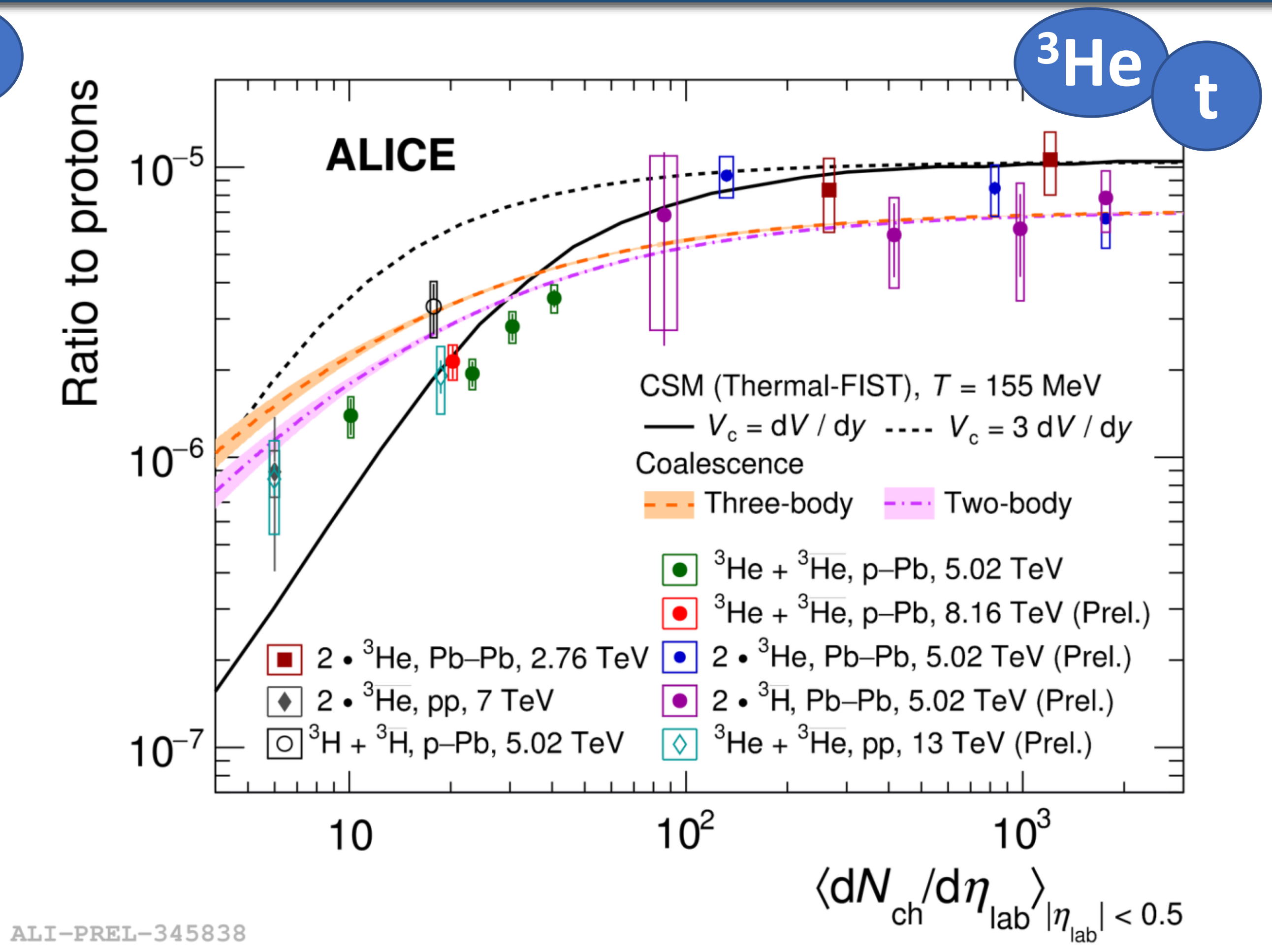
Phys. Rev. C 101, 044906 (2020)



- Similar behaviour observed also in p–Pb
- Light (anti)nuclei up to ^{3}He have been measured in small systems

Ratio to protons – models comparison

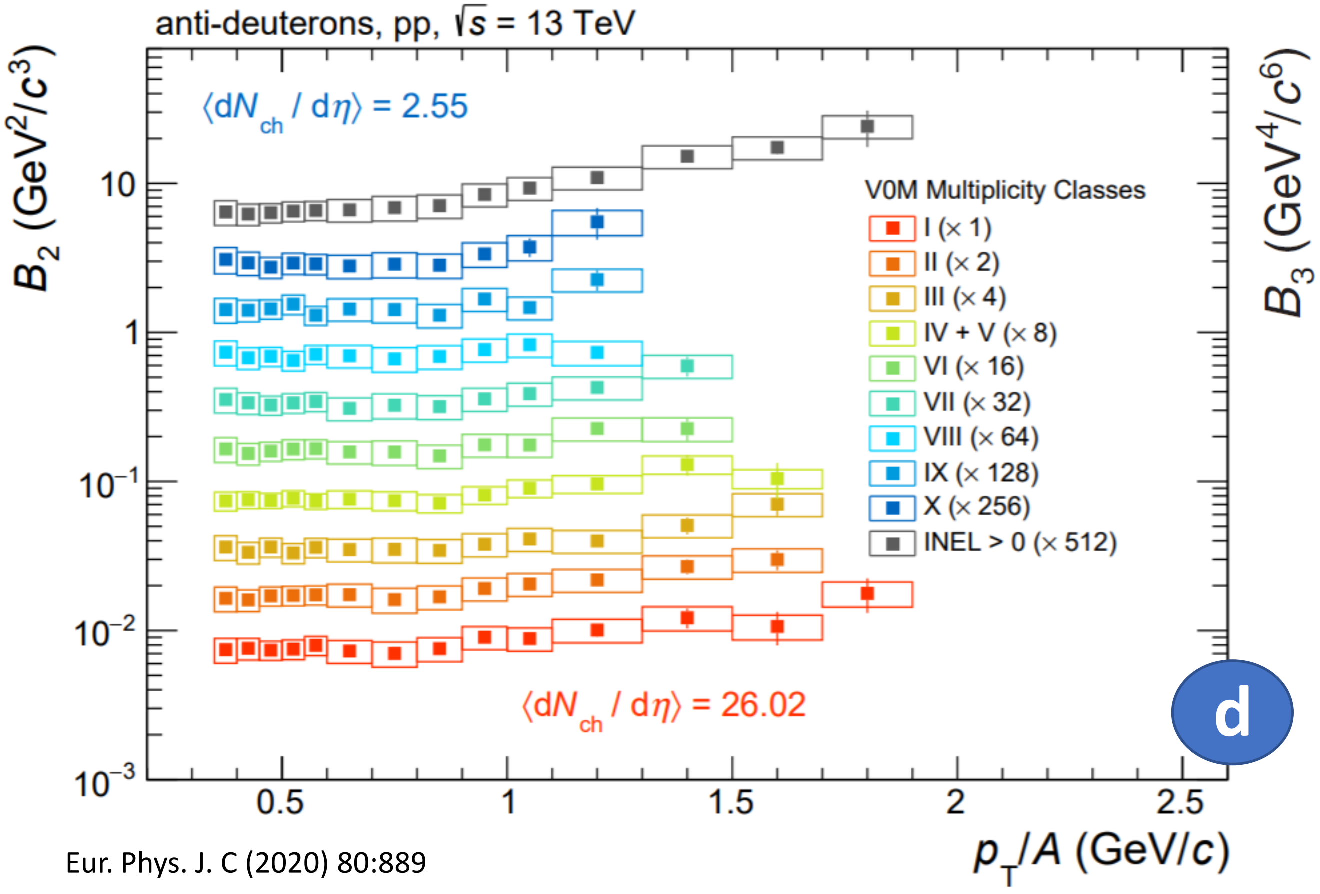




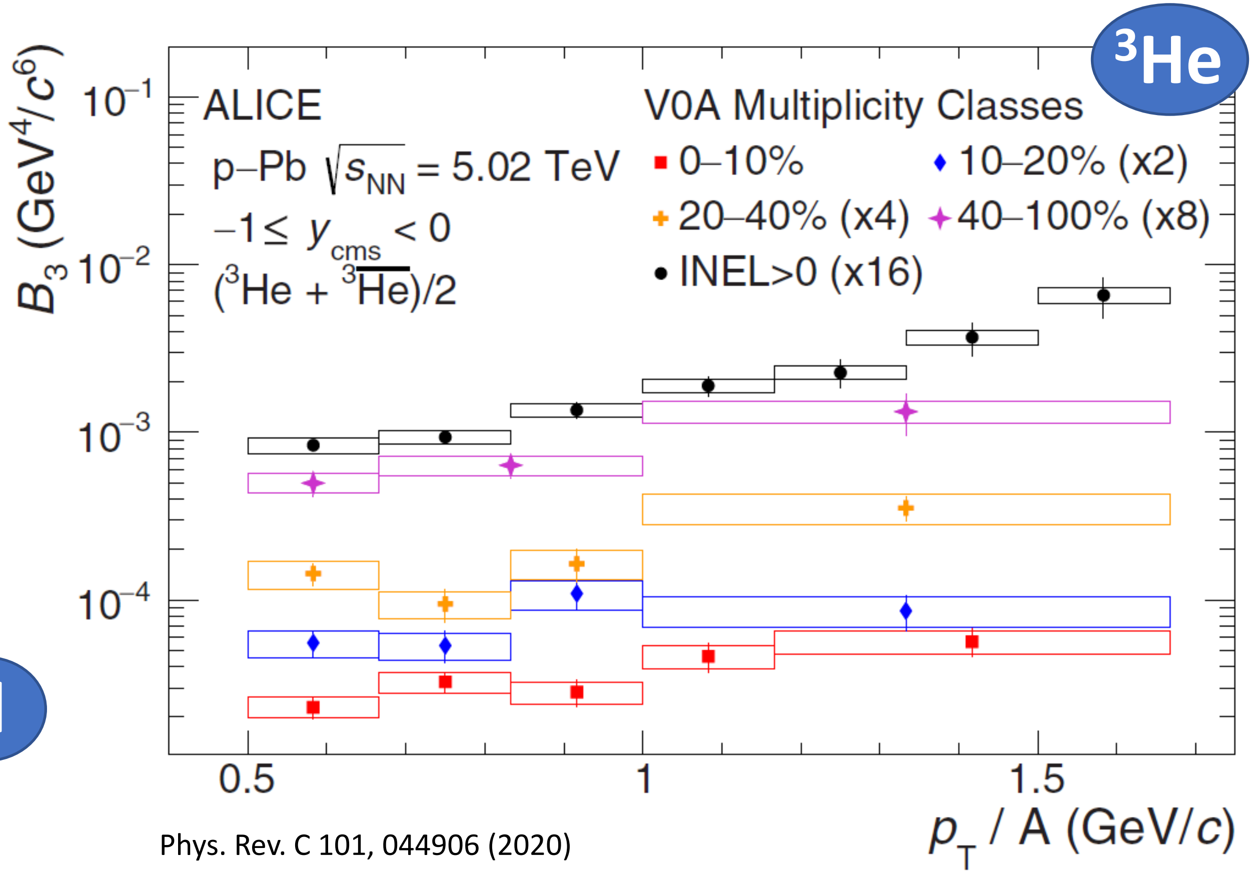
- Smooth transition across different collision systems and energies
- Light nuclei production seems to depend only on multiplicity
- Results challenge the models for A=3 nuclei

Coalescence parameters VS p_T/A

- B_A is rather flat in multiplicity classes, but increases at high p_T/A in the MB class



Eur. Phys. J. C (2020) 80:889

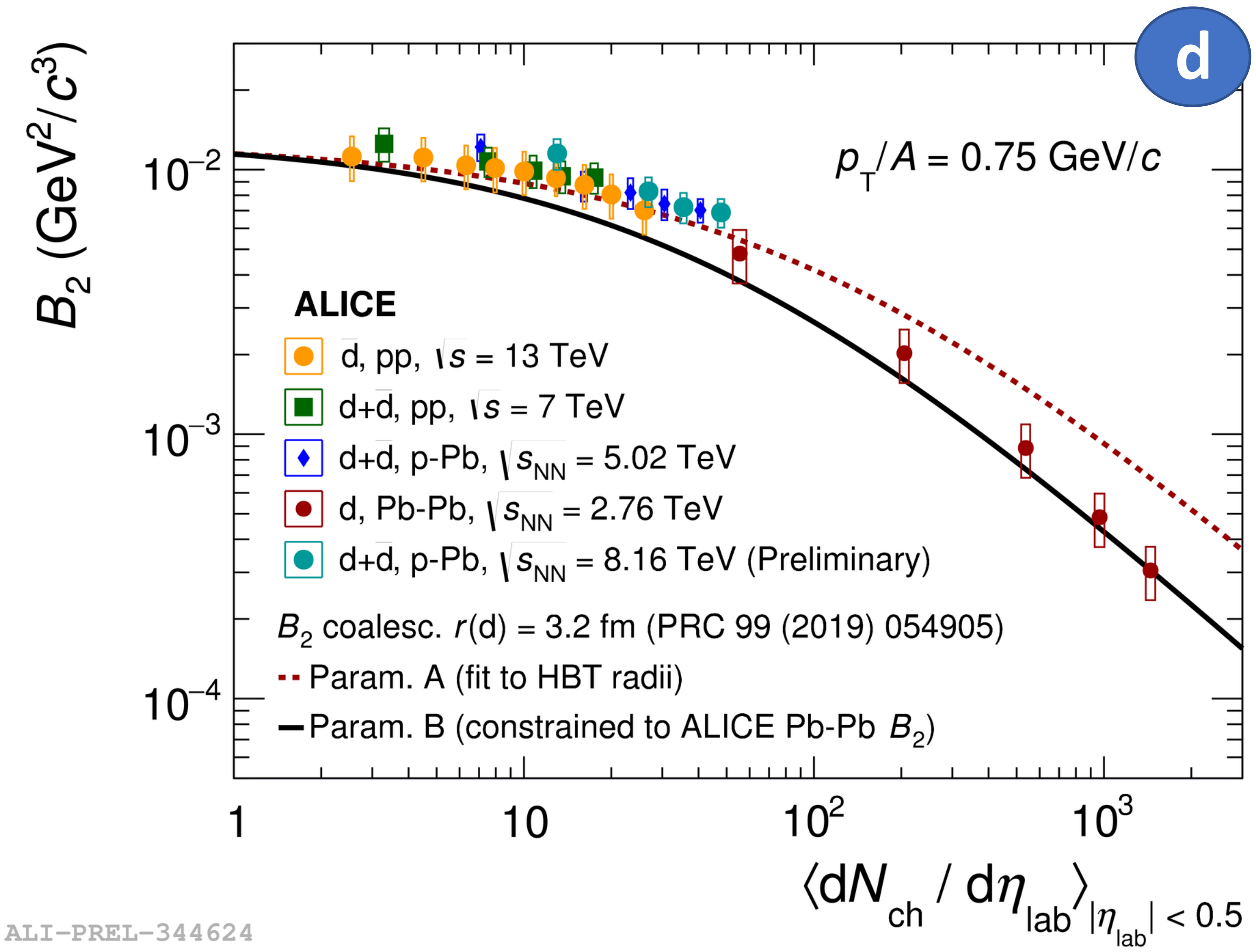


Phys. Rev. C 101, 044906 (2020)

pp @ 13 TeV

p–Pb @ 5.02 TeV

Coalescence parameter B_2



Strong dependence of B_2 on collision system size

Continuous evolution of B_2 with multiplicity

- Smooth transition from small to large system size
- Single underlying production mechanism?

Similar conclusions apply also for B_3

Advanced coalescence models taking into account the size of the nucleus and of the emitting source predict similar trend

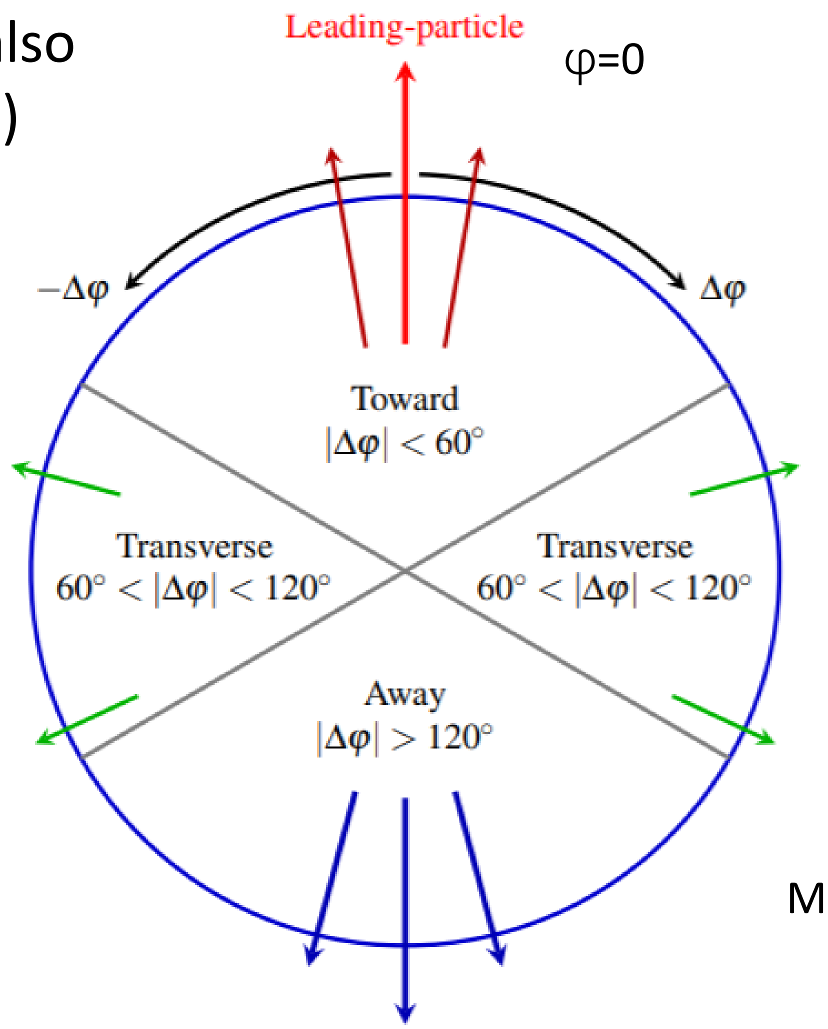
The evolution with multiplicity is explained as an increase in the source size R in coalescence models (e.g. *Scheibl, Heinz PRC 59 (1999) 1585*)

Transverse plane activity

Production in small collision systems is also explored using the underlying event (UE) activity

UE activity quantified by the self-normalized charged particle multiplicity:

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



TOWARDS region
Multiplicity dominated by hard trigger (jet)

TRANSVERSE region
Useful observable definition of the Underlying Event (UE)

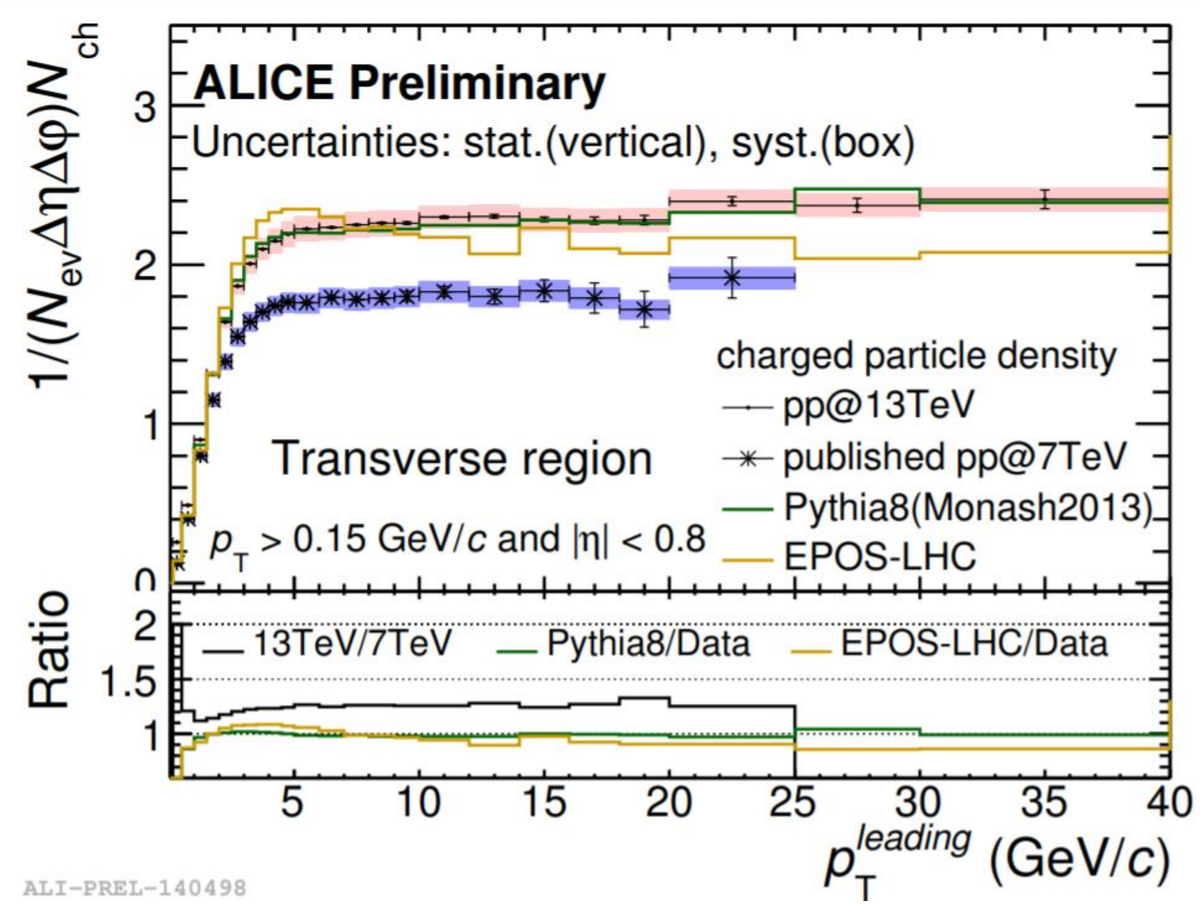
AWAY region
Momentum conservation
→ contains recoil jet

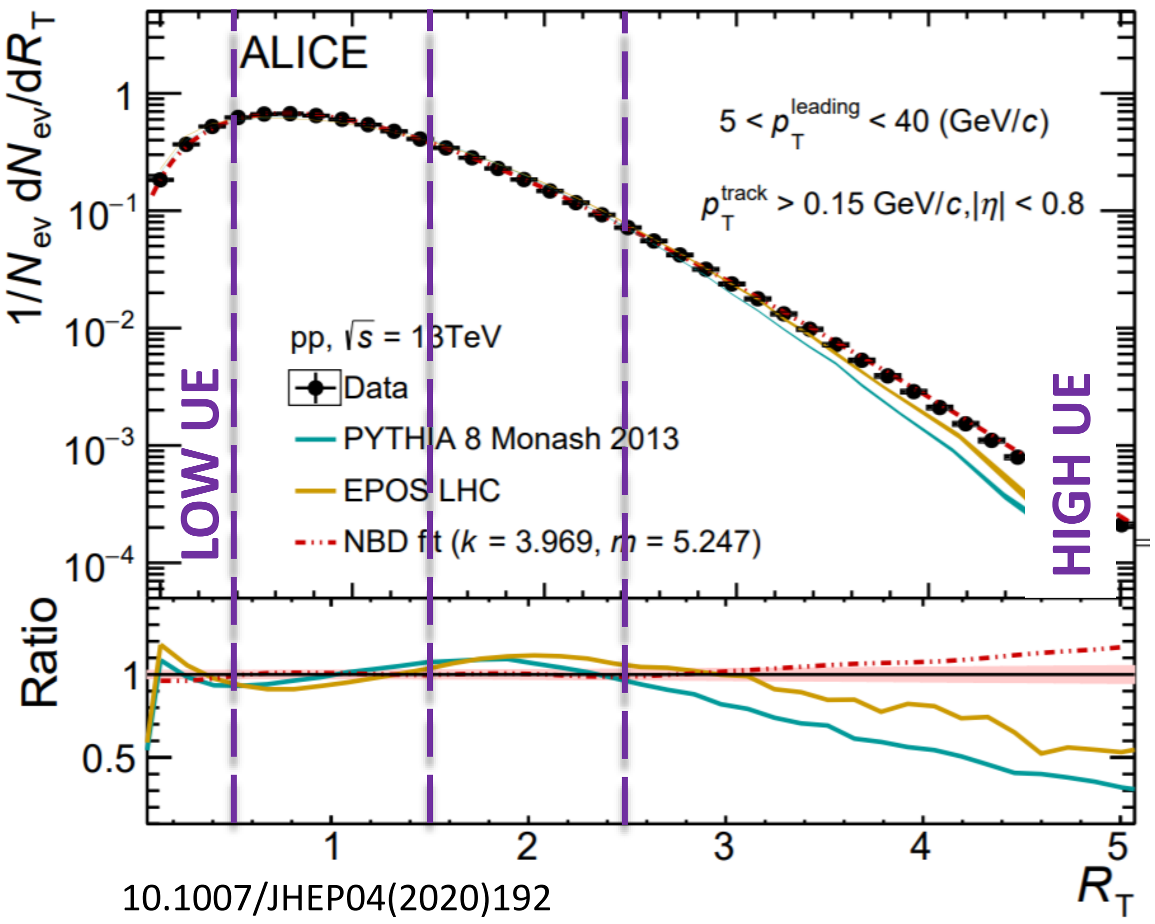
10.1140/epjc/s10052-016-4135-4

Characterize the UE

- Plateau region (jet pedestal): $5 < p_{T}^{leading} < 40$ GeV/c

- Several intervals of R_T are selected in order to distinguish between low and high UE activity



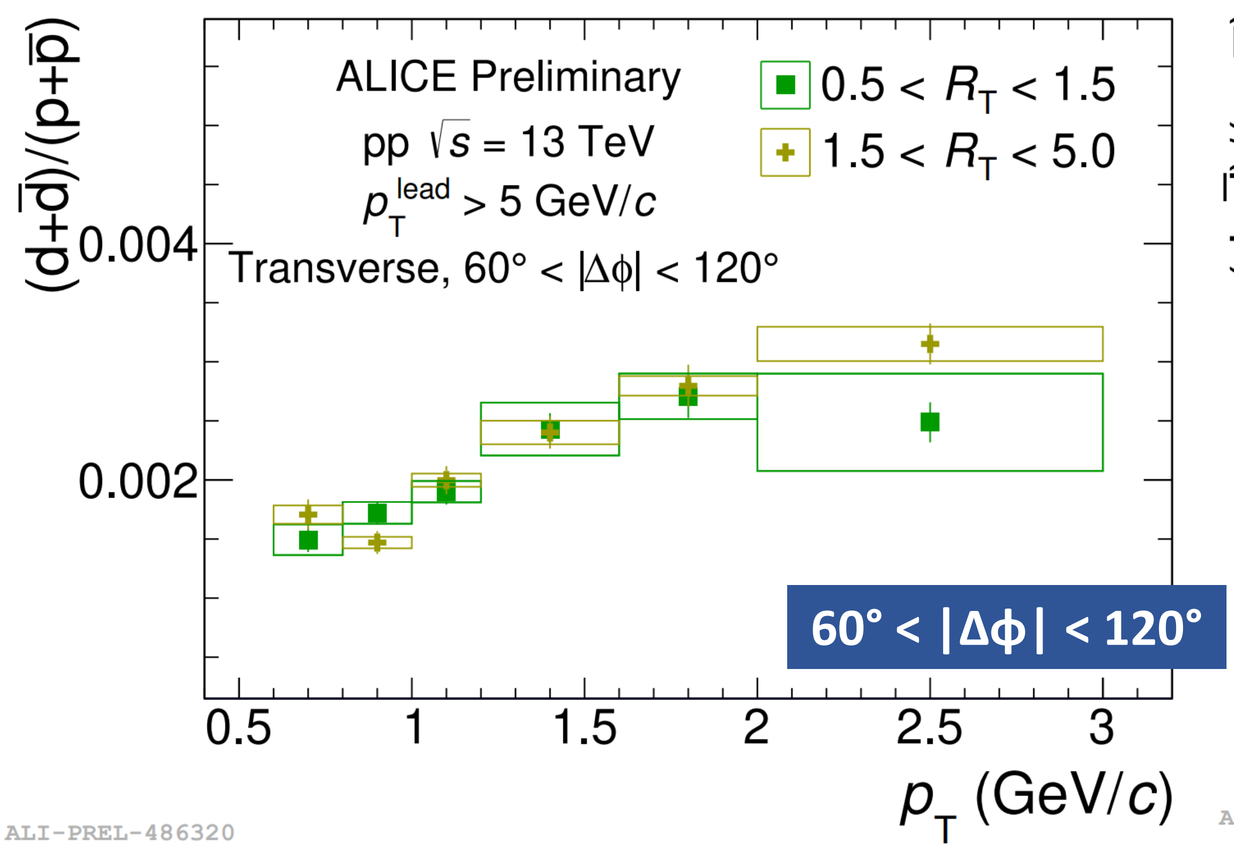


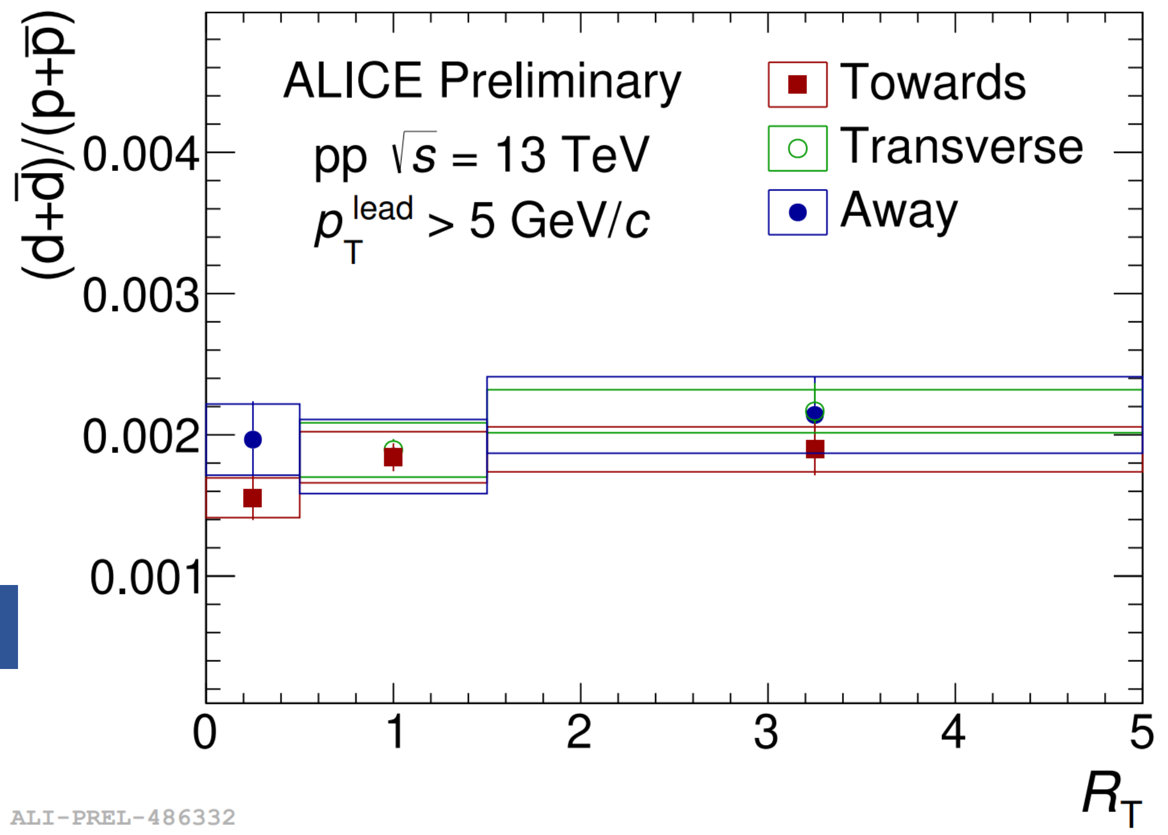
10.1007/JHEP04(2020)192

deuteron production vs R_T

pp @ 13 TeV

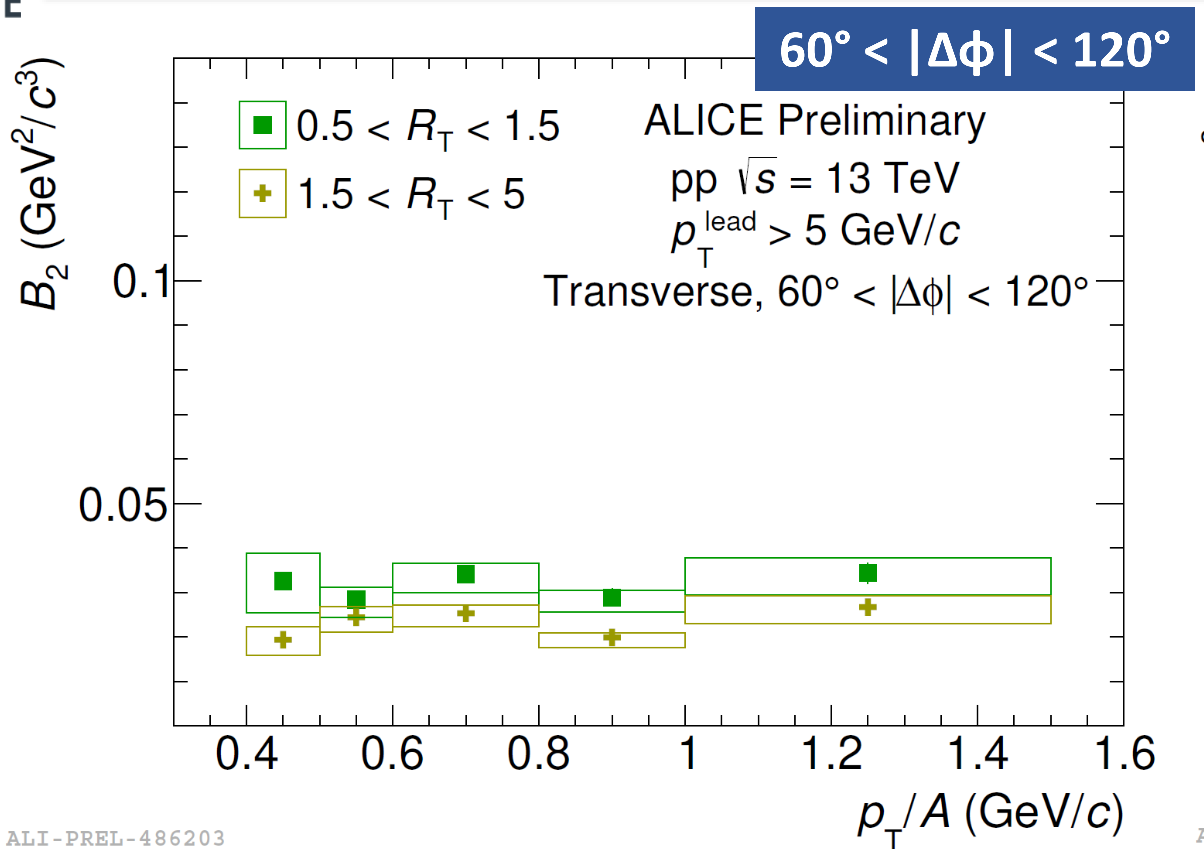
- First measurements of (anti)deuteron production in several R_T classes
- d-to-p integrated yields ratio does not depend on R_T

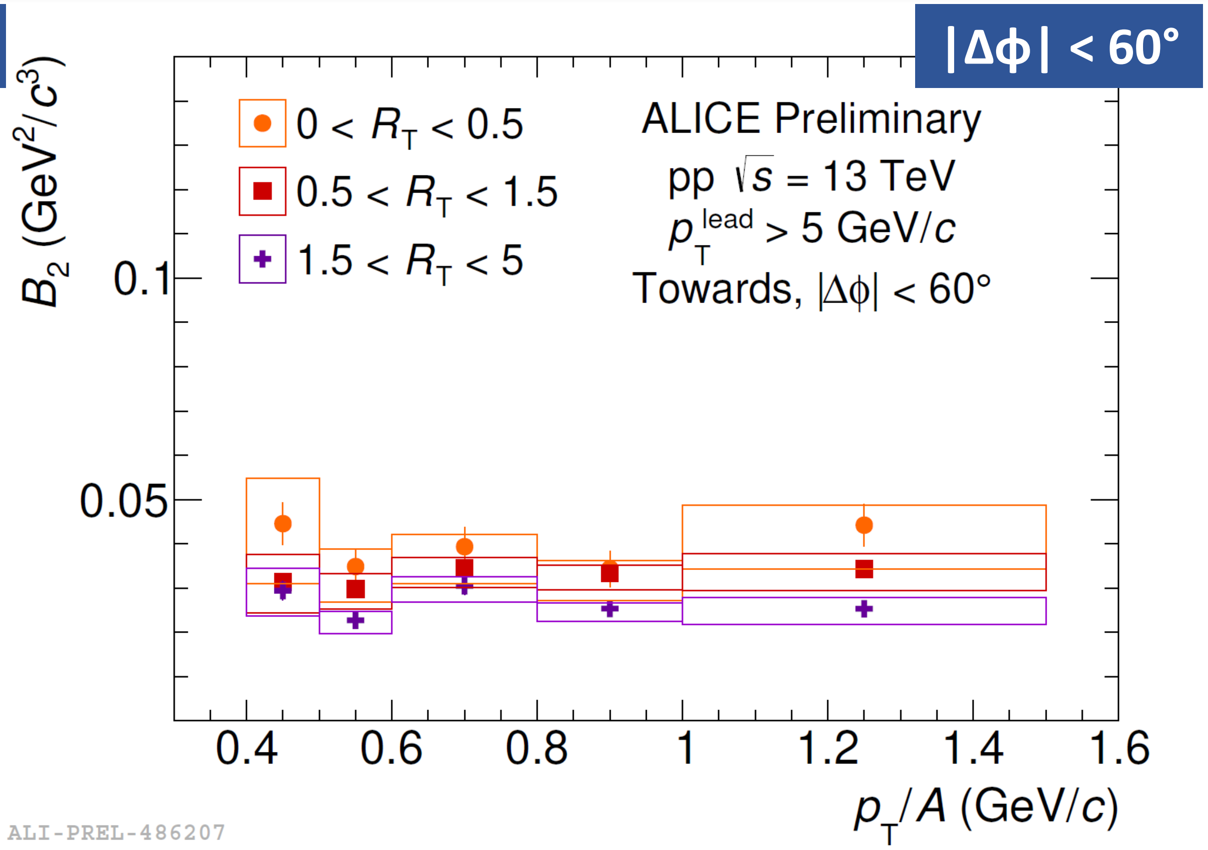




B_2 vs R_T

New!





- B_2 parameter flat vs p_T/A → in agreement with simple coalescence
- Similar values of B_2 for Towards & Transverse regions → against naive expectations

pp @ 13 TeV

B_2 vs R_T

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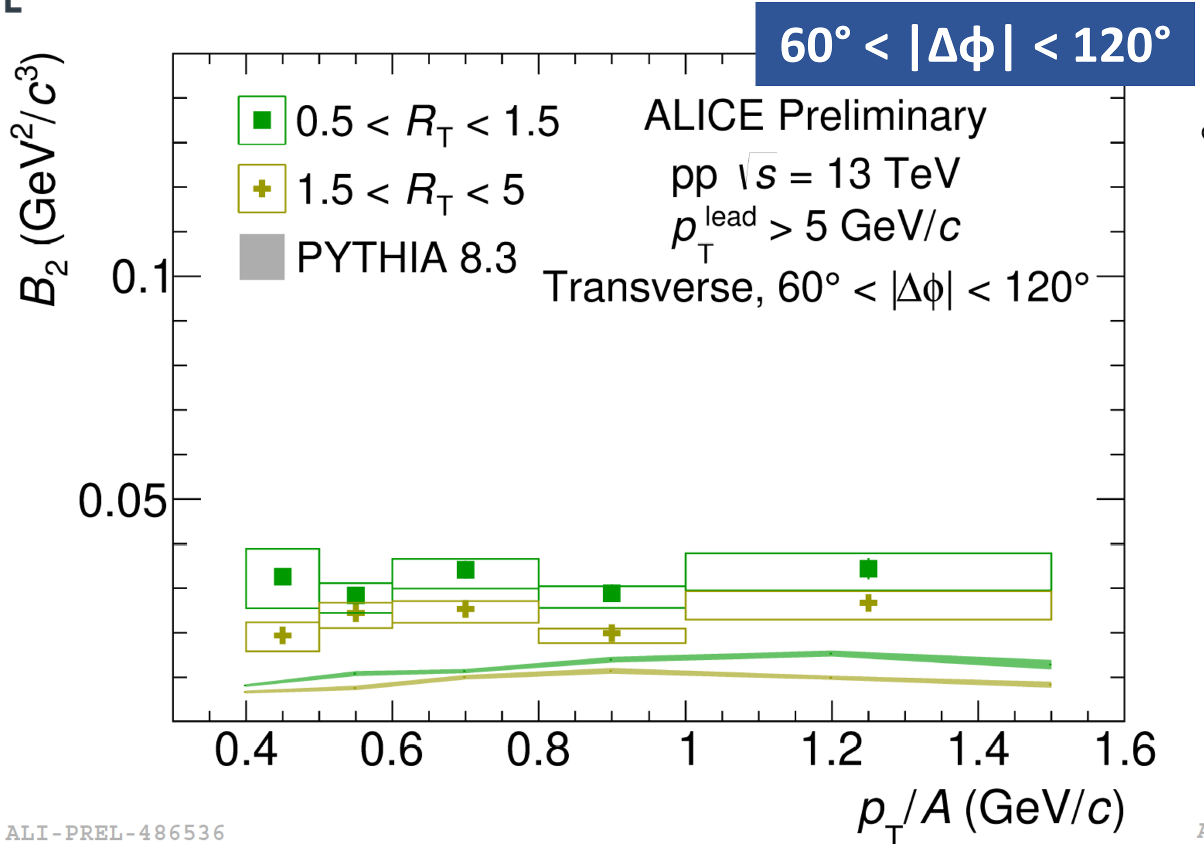

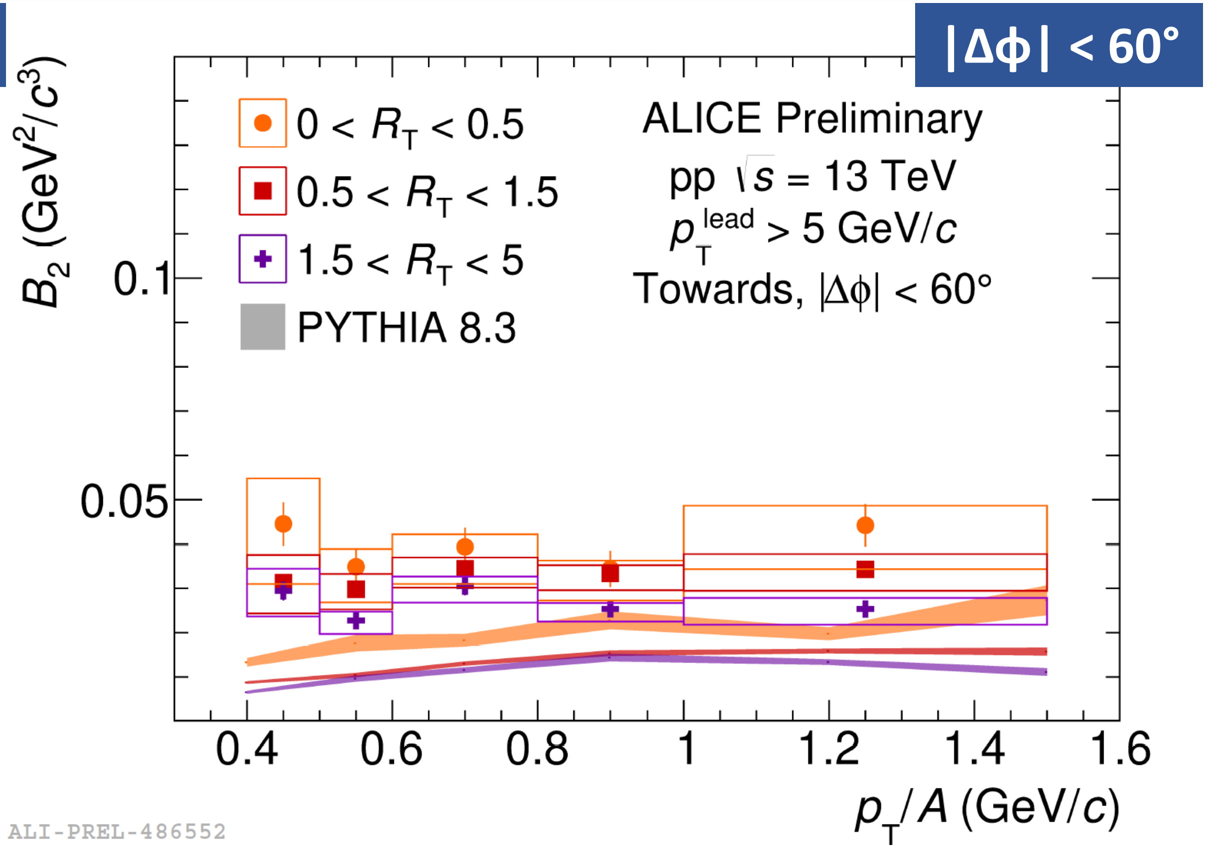

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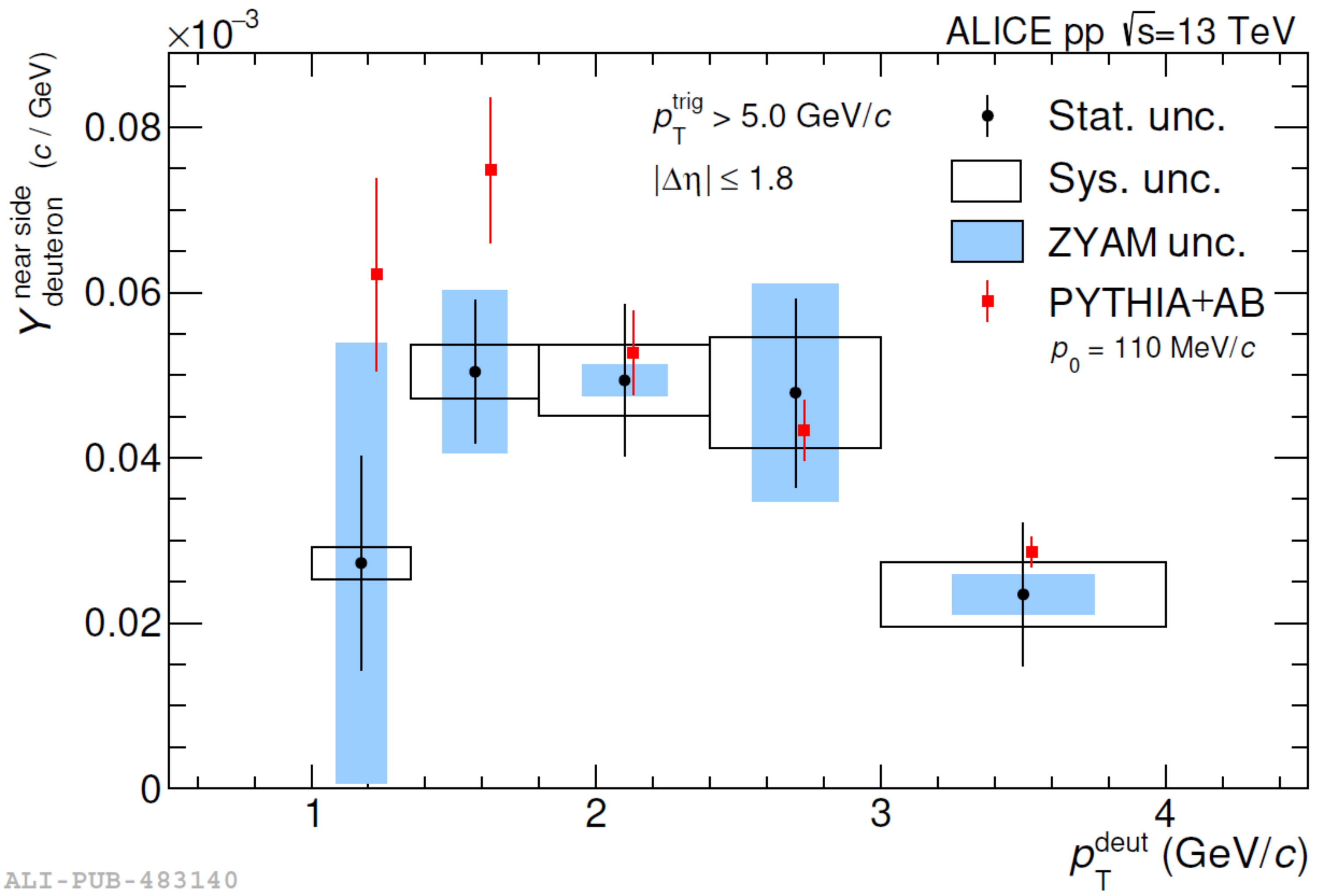
L.A. Dal, A.R. Raklev, Phys.Rev.D 91 (2015) 12

pp @ 13 TeV

d production in jets

- Deuteron production from hard processes: $p_T^{lead} > 5$ GeV/c
- Fraction of deuterons produced in the jet is ~ 8–15%, increasing with increasing p_T
- The majority of the deuterons are produced in the underlying event



pp @ 13 TeV

arXiv:2011.05898 [nucl-ex]

Summary

- Production of light nuclei evolves smoothly with multiplicity
- Experimental results challenge the models
- Production in small collision systems is also explored using the underlying event (UE) activity
- The majority of the deuterons are produced in the underlying event

Thank you for the attention!

Backup

Simple coalescence models (I)

- ***B*$_A$** is related to the **probability** to form a nucleus via coalescence
- **Different implementations** of coalescence model

<u>SIMPLEST COALESCENCE</u>

Considers an emitting source of nucleons randomly distributed like a gas of nucleons in thermal and chemical equilibrium

Hypotheses:

- Neutron spectrum = proton spectrum (**isospin invariance**)
- **No space-time** distribution of the nucleons considered
- Nucleons with similar momentum ($\Delta p < p_0$ [=coalescence momentum]) can form a nucleus

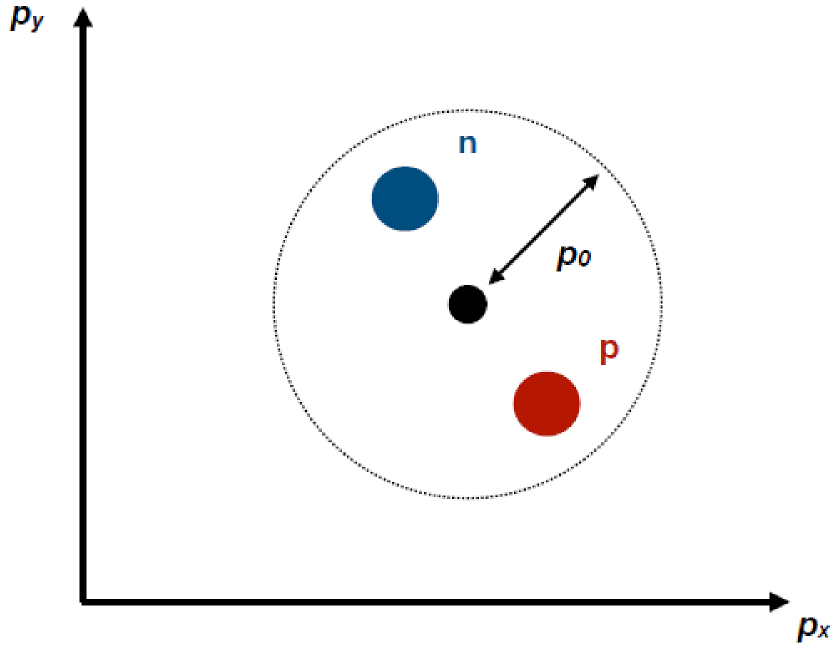
$$B_A = \left(\frac{4\pi}{3}p_0^3\right)^{A-1} \frac{m_A}{m_p^A}$$

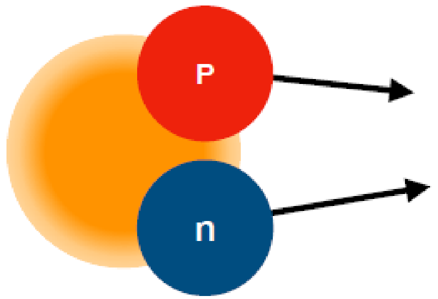
Consequences:

- B_A vs p_T is **flat**

Applications:

- **pp collisions**: small volume (comparable with nucleus size) → nucleons are always close to each other

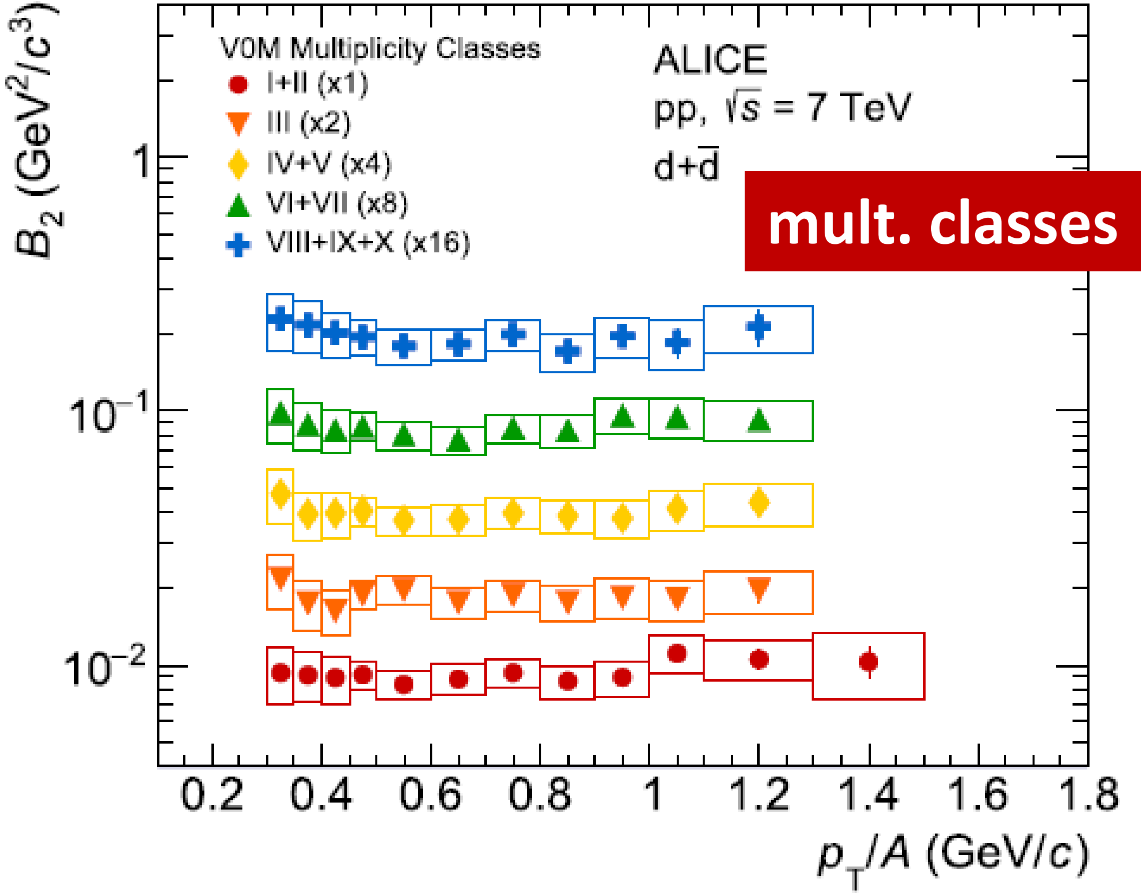




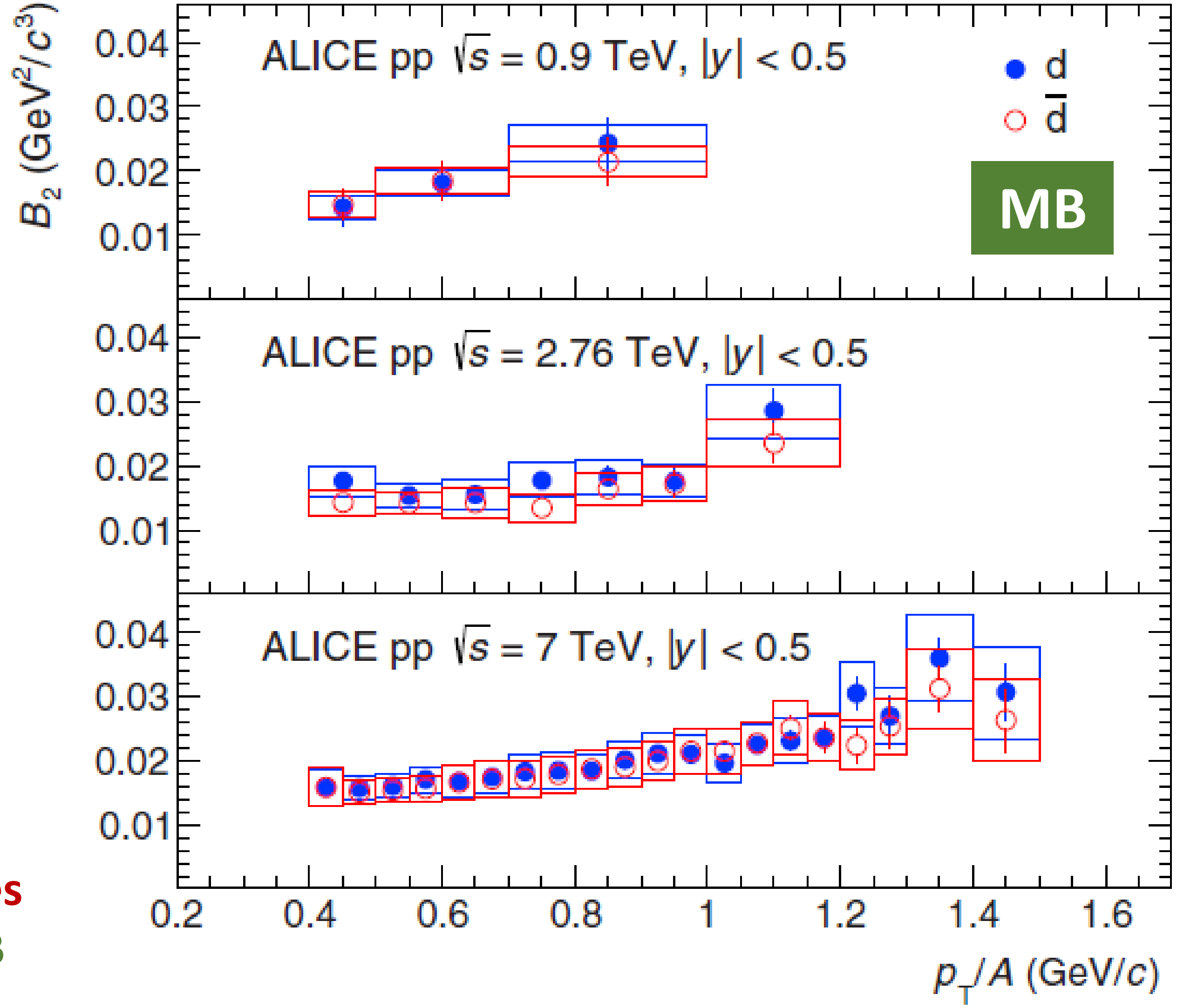
Simple coalescence models (II)

pp collisions

Phys. Lett. B 794 (2019) 50–63



Phys. Rev. C 97, 024615 (2018)



- B_A vs p_T is **flat** in small systems as pp → **in mult. classes**
- B_A vs p_T is **increasing** with increasing *p*T in pp → **in MB**

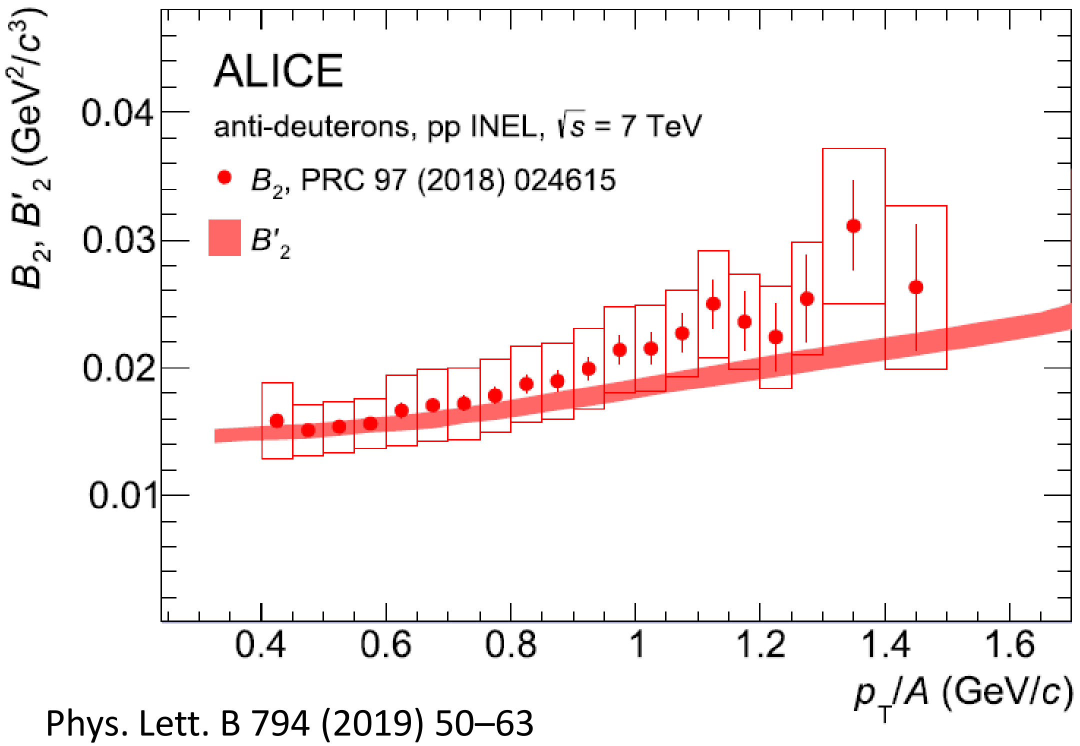
Simple coalescence models (III)

pp collisions

An **increasing B'_2** for the integrated-multiplicity class can be obtained from a **flat B_2** in each **multiplicity** class with

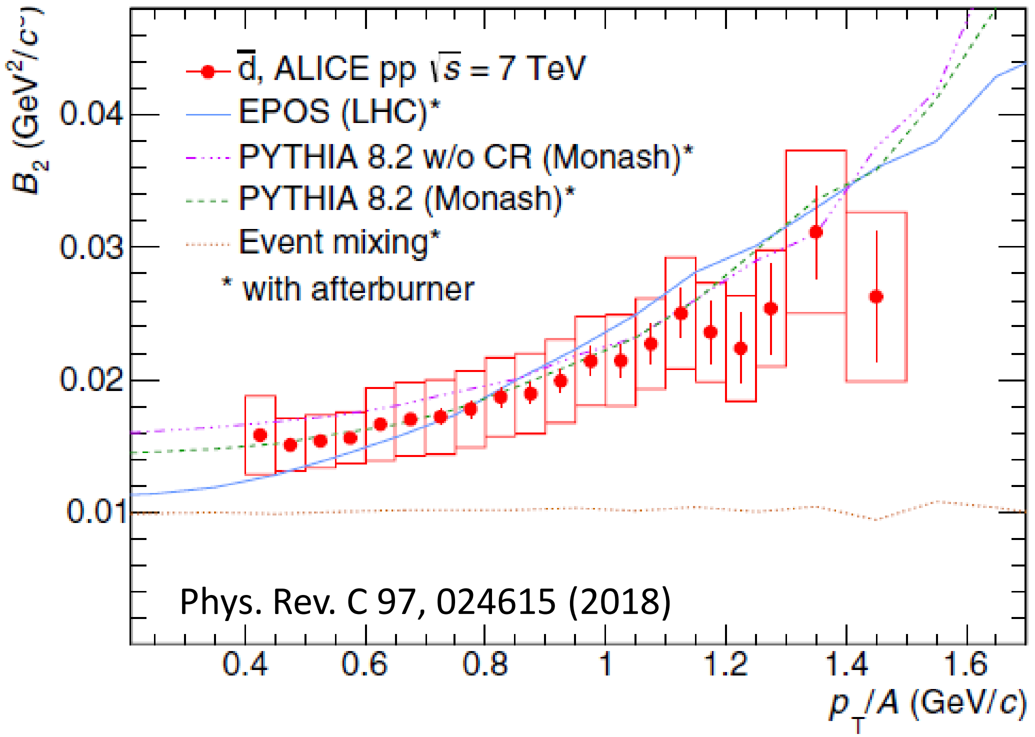
$$B'_2 = B_2 \frac{\sum_{i=0}^{n} (N_i/N)\, S_{p,i}^2}{\left[\sum_{i=0}^{n} (N_i/N)\, S_{p,i}\right]^2} \qquad \text{with } S_{d,i} = B_2 S_{p,i}^2$$

Rise of B_2 : consequence of the **hardening** of the **proton spectra** with increasing multiplicity + hard scattering effect (high p_T)



Phys. Lett. B 794 (2019) 50–63

Rising trend with p_T reproduced by QCD-inspired models coupled to coalescence-based afterburner > only momentum correlations between nucleons are considered ($\Delta p < p_0$)



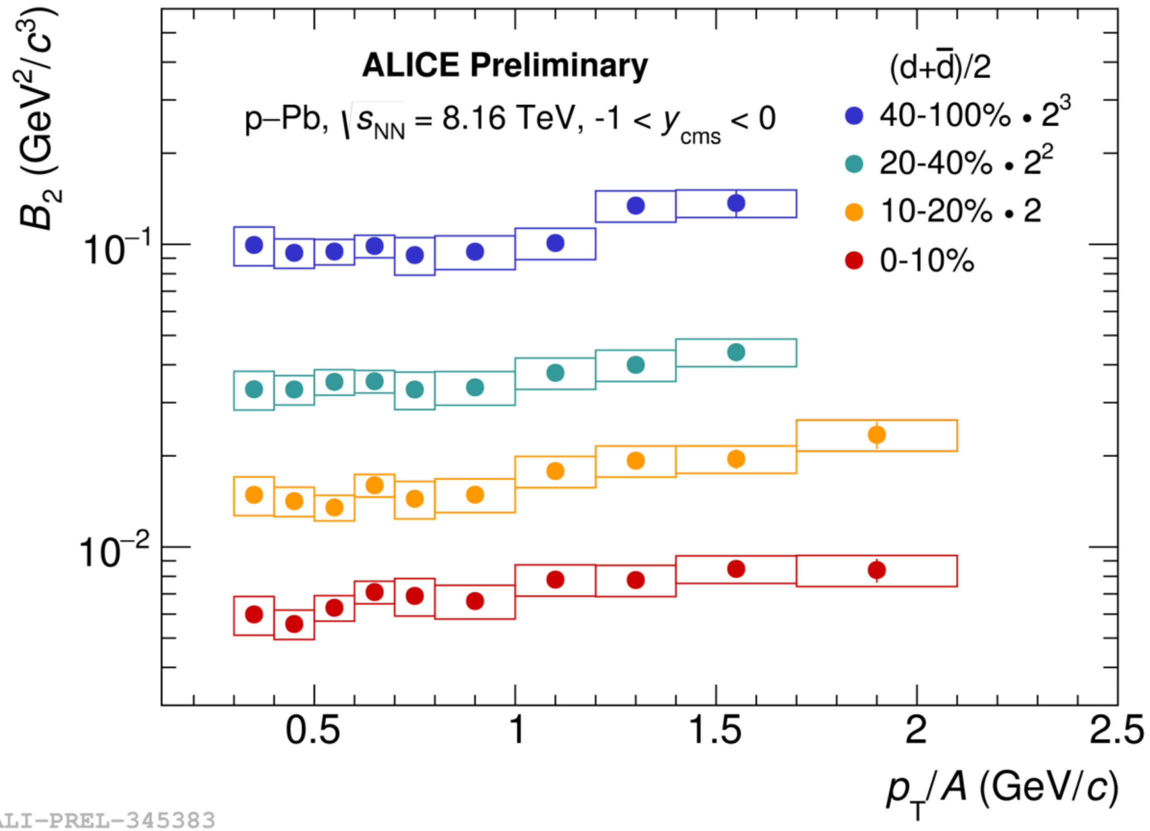
- B_2 is flat only in event mixing: uncorrelated pairs of nucleons
- Rising trend with p_T : hard scattering effect vs AA collisions where related to collective flow

SIMPLE COALESCENCE IS A GOOD APPROXIMATION FOR d IN pp

Simple coalescence models (IV)

p–Pb collisions

B_2 weakly rising with p_T/A also in p–Pb collisions in mult. classes
> trend of B_2 in MB most probably explained by kinematic effect



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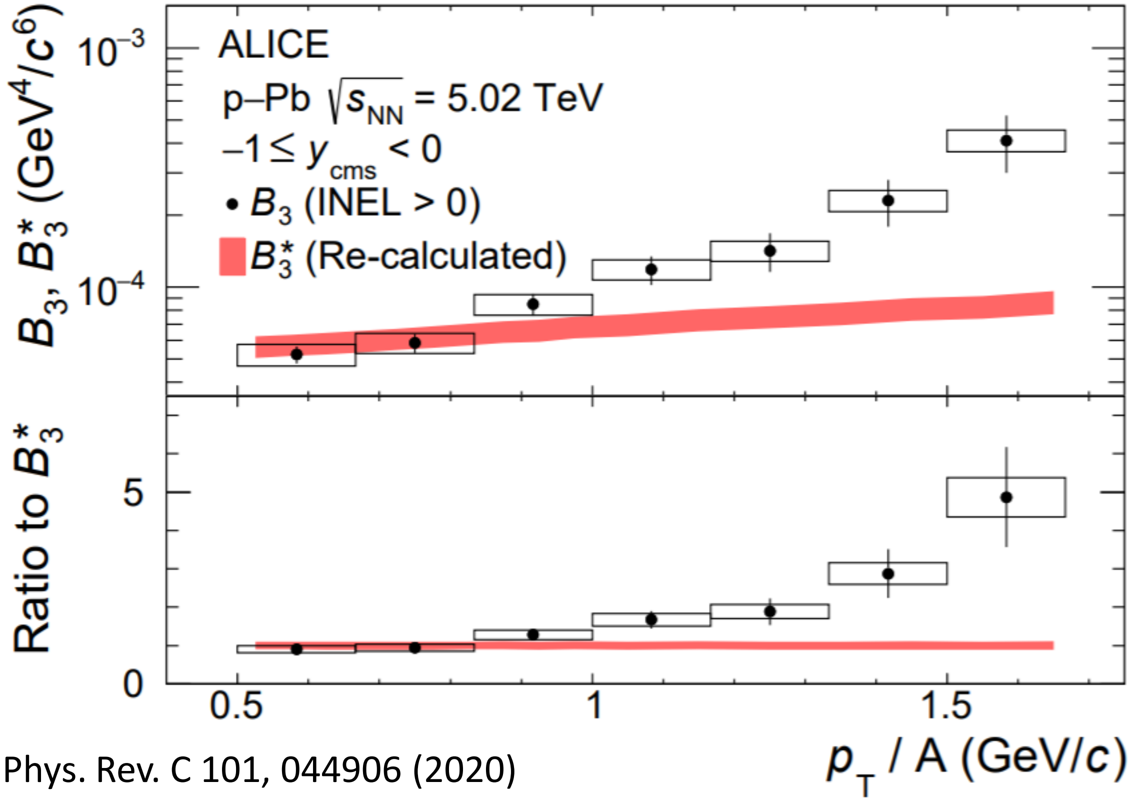


Phys. Rev. C 101, 044906 (2020)

Rising trend of B_3 with p_T/A cannot be explained by simple coalescence hypothesis

MORE SOPHISTICATED COALESCENCE IS NEEDED FOR A=3 NUCLEI, CONSIDERING VOLUME DEPENDENCE

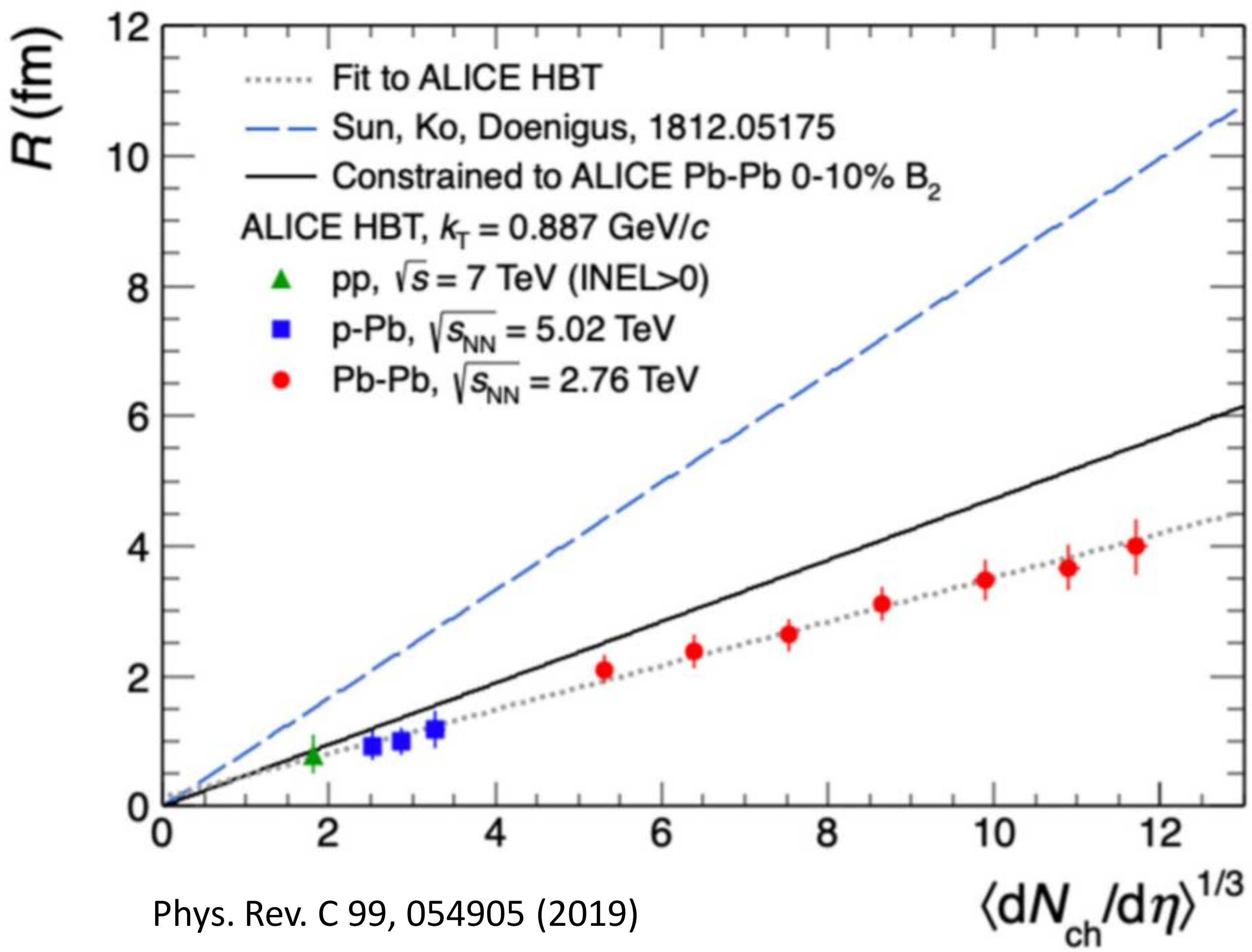
Advanced coalescence models

- **Space-time** distribution considered
- Coalescence probability given by **overlap** between **nucleus wave-function** (Wigner formalism) and **nucleon phase-space distribution**

  [Sun et al., Phys Lett B 792 (2019) 132-137]

- System size: **HBT radius R**
- R vs multiplicity: $R = a \langle dN/d\eta \rangle^{1/3} + b$

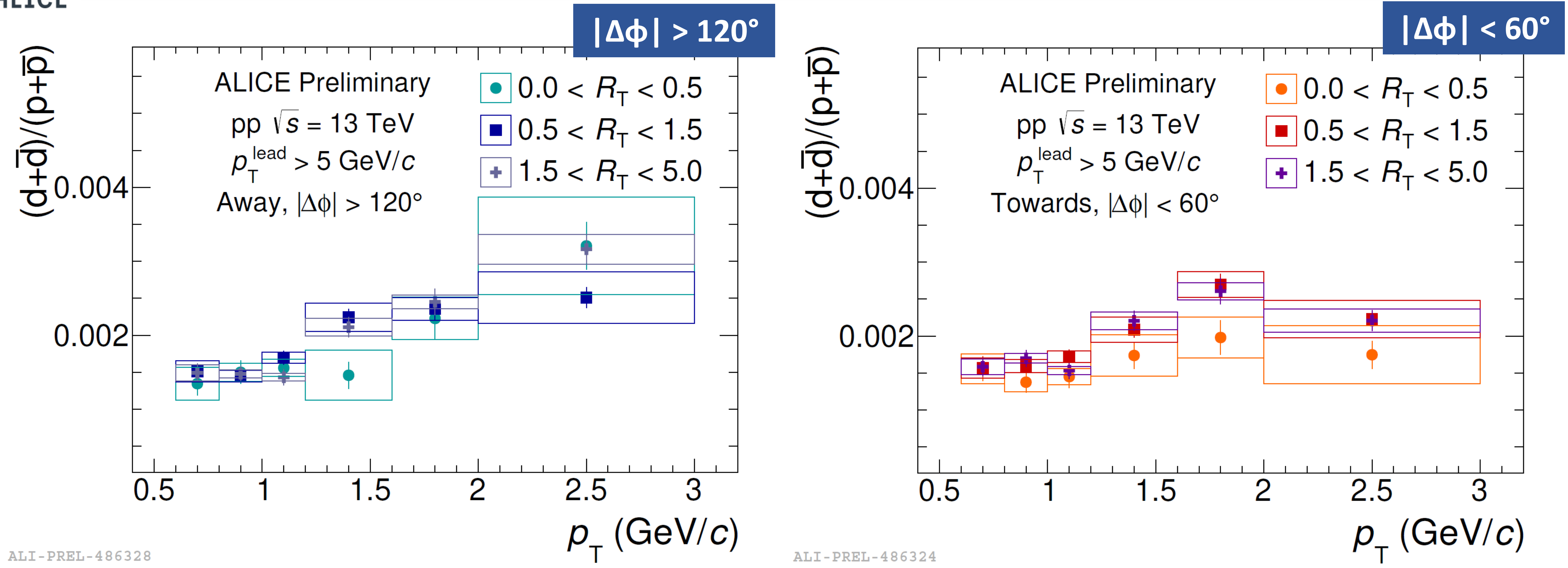
- When looking at B_A vs mult. the parameterization of R plays a crucial role in the predictions



Phys. Rev. C 99, 054905 (2019)

d/p ratios vs R_T

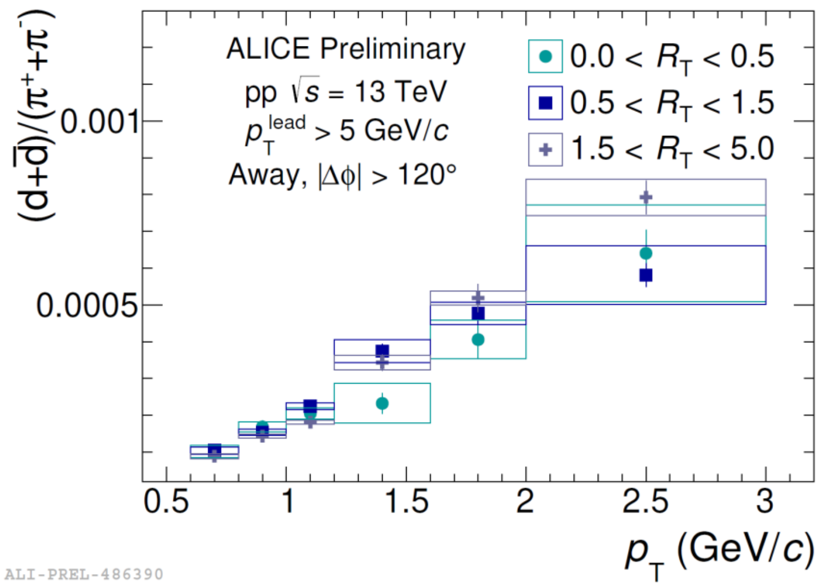
New!

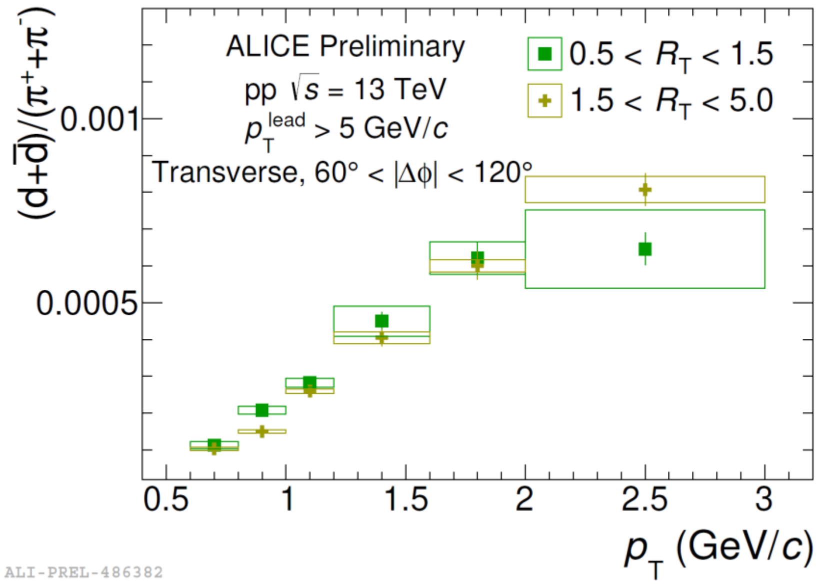


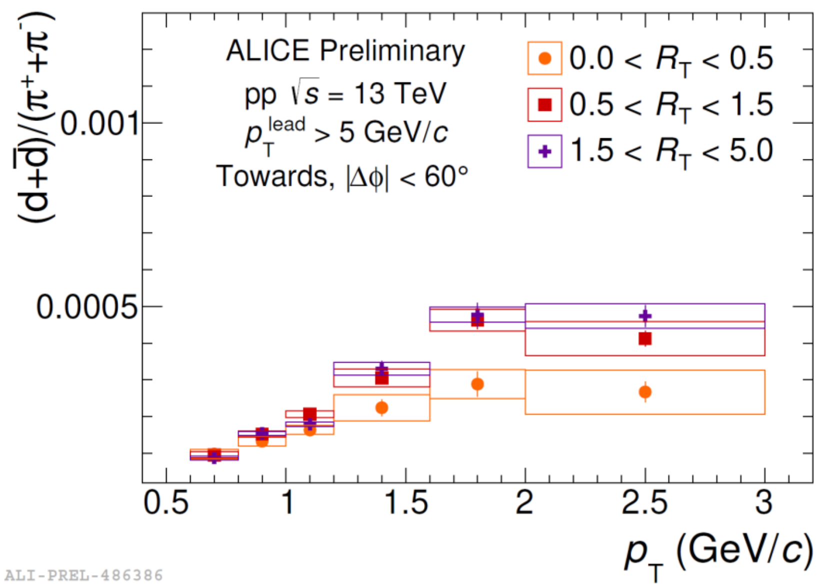
- d-to-p ratios vs p_T show weak dependence on R_T for all azimuthal regions

pp @ 13 TeV

d/π ratios vs R_T







|Δϕ| > 120°

60°<|Δϕ|< 120°

|Δϕ| < 60°

- d-to-π ratios vs p_T show mild dependence on R_T in all azimuthal regions

pp @ 13 TeV

d production in PYTHIA 8.3 simulations

Simulation details: http://home.thep.lu.se/~torbjorn/pythia82html/DeuteronProduction.html

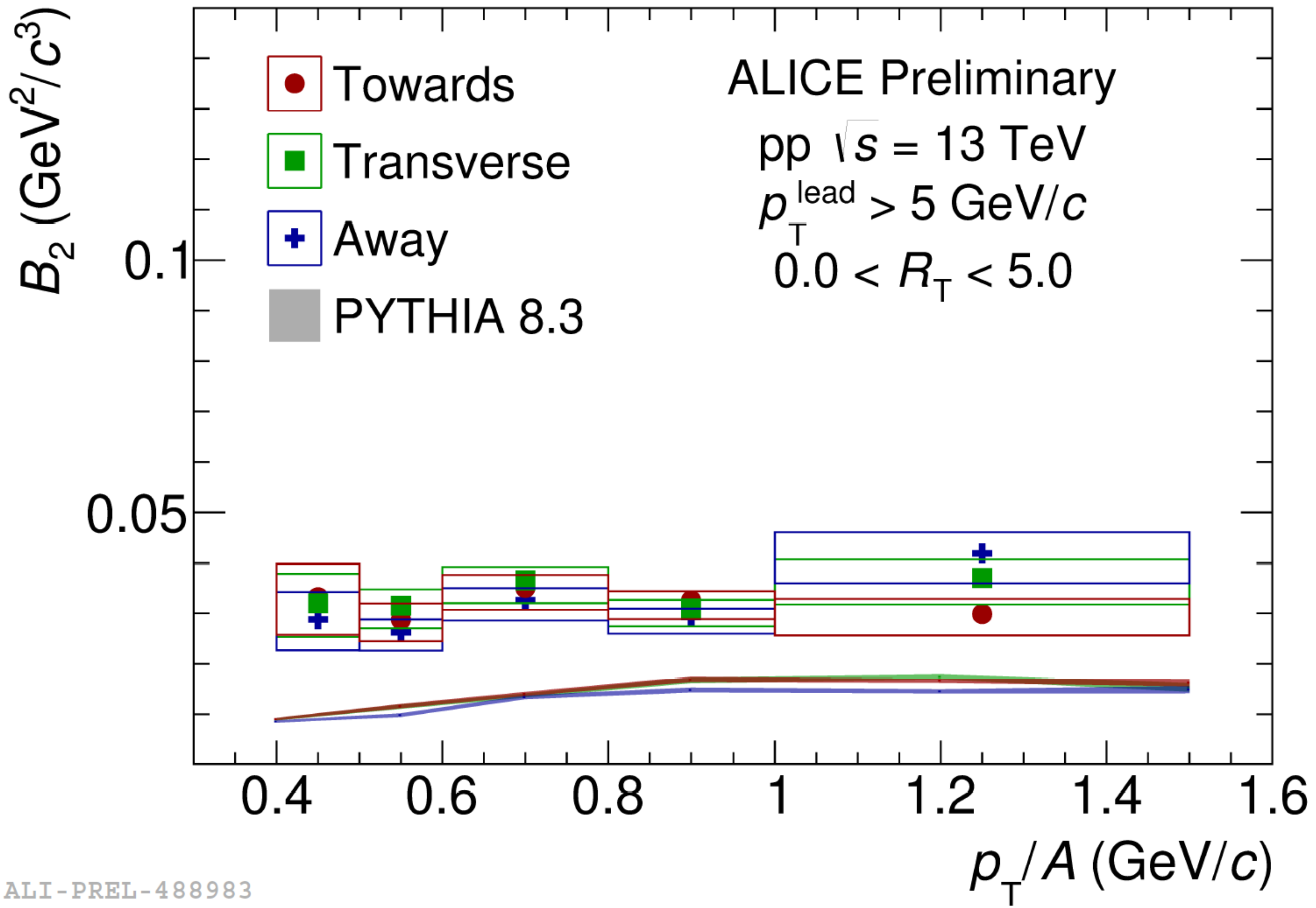
- After the final state particles of an event are produced, protons and neutrons are selected and combined into pairs which may form deuterons
- To ensure conservation of ***p*** and ***E***, the final state for each deuteron production channel is required to have at least two final products, where one product is a deuteron → **vs traditional coalescence**
- Default deuteron production setup with 8 production channels:

p+ n0 → gamma 2H
p+ n0 → pi0 2H
p+ n0 → pi0 pi0 2H
p+ n0 → pi+ pi- 2H
p+ p+ → pi+ 2H
p+ p+ → pi+ pi0 2H
n0 n0 → pi- 2H
n0 n0 → pi- pi0 2H

- Deuteron production:
  1. building all valid two-particle combinations
  2. determining whether the combinations bind
  3. performing an isotropic decay of the bound state into the specified final state

B_2 in the R_T–integrated case

New!

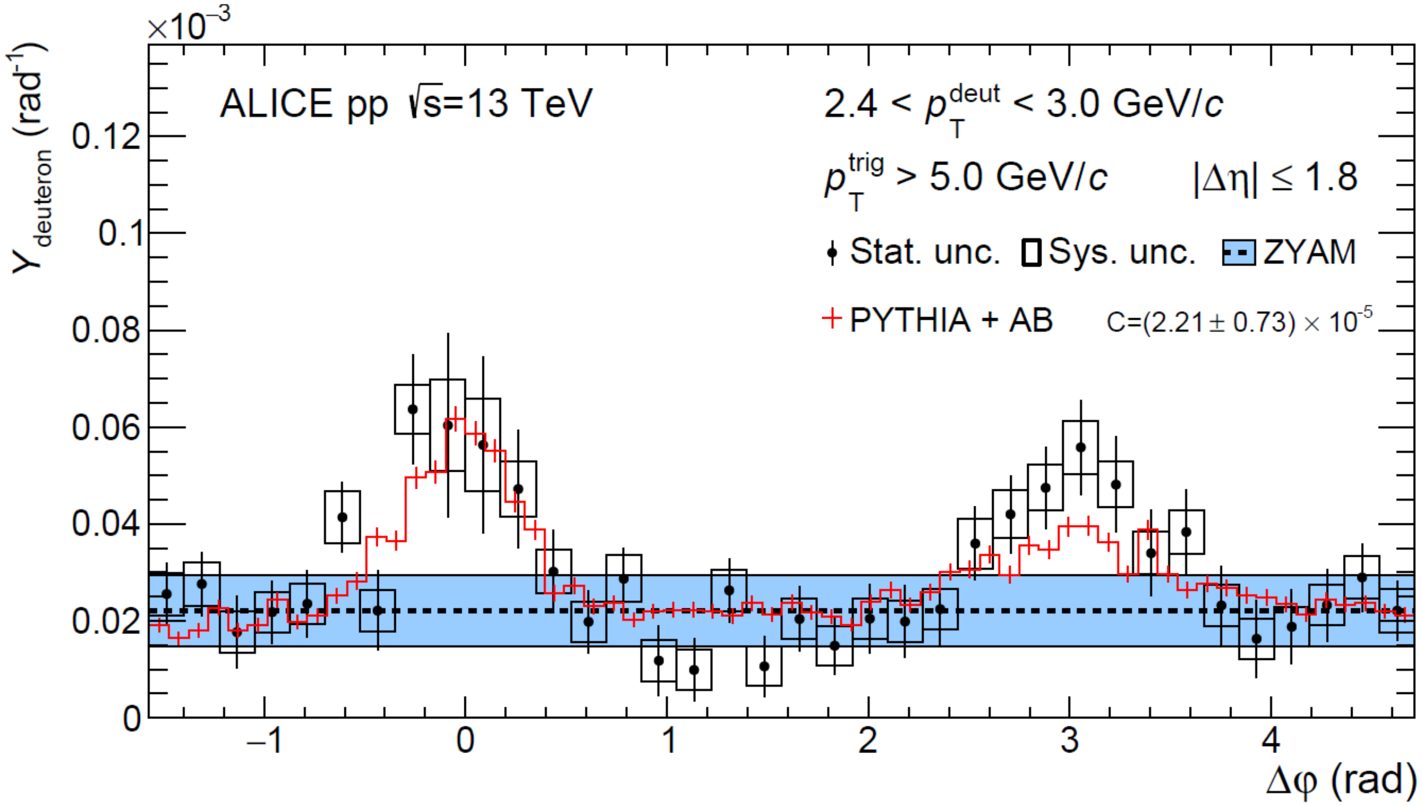


- B_2 parameter flat vs p_T/A → in agreement with simple coalescence
- Similar values of B_2 for Towards & Transverse regions → against naive expectations
- Comparison with Pythia 8.3 (including d production via coalescence and reactions)
- p_T-dependence & ordering are reproduced by simulations, but not the magnitude

pp @ 13 TeV

d production in jets (II)

- Insight on (anti)d production in smaller phase space available in jet fragmentation
- High-p_T (> 5 GeV/c) trigger particle used as jet proxy
- Measurement of (anti)d yields within $|\Delta\phi| < 0.7$ rad
  - Uncorrelated contribution subtracted with ZYAM (zero yield at minimum)
- (Anti)d yields is found to be 2.4–4.8 standard deviations above uncorrelated background ($p_T^d > 1.35$ GeV/c)
- Good agreement with PYTHIA calculation + coalescence afterburner



pp @ 13 TeV

arXiv:2011.05898 [nucl-ex]