# Light (anti)nuclei production in small systems with ALICE (Run 1+2)

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**[On behalf of the ALICE Collaboration]**

ALICE

# Light (anti)nuclei in high-energy collisions

- LHC provides optimal conditions for studying the antinuclei formation as it produces an equal amount of matter and antimatter
- We consider **light** nuclei if $Z \leq 2$

$$e.g.\ p + n \rightarrow d\ \&\ \overline{p} + \overline{n} \rightarrow \overline{d}$$

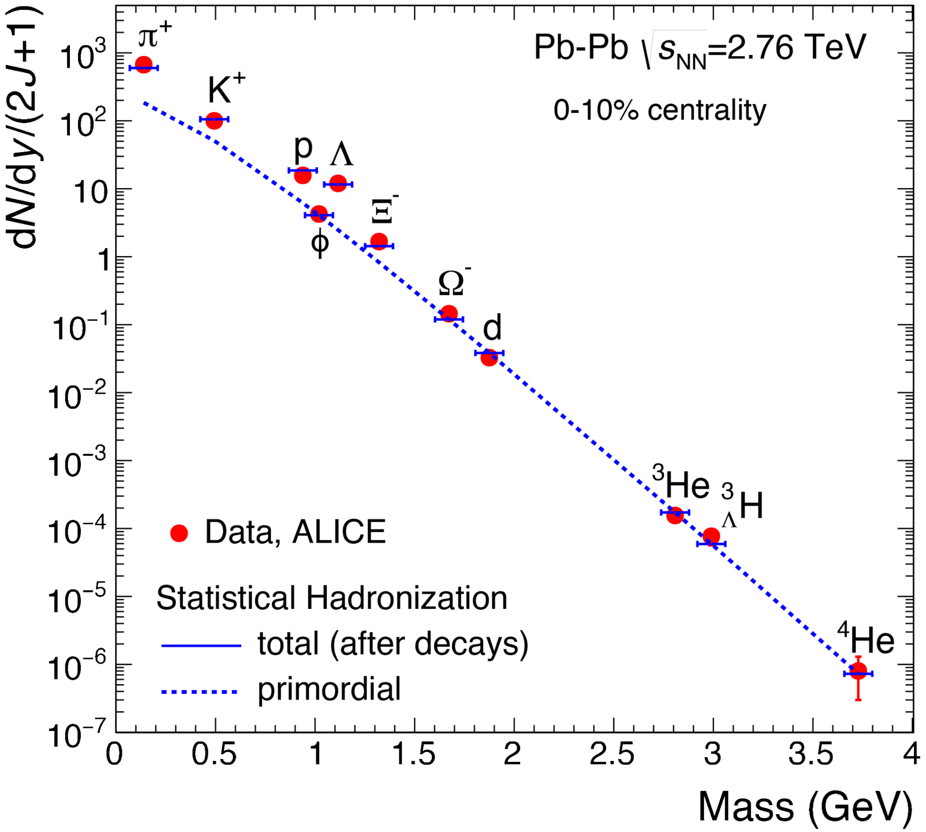
The study of light (anti)nuclei **formation** in **high-energy collisions** is fundamental for several reasons:

- **Astrophysics applications**: Measurements in the lab provide fundamental input to constrain cosmic ray background in indirect dark matter searches
- Their production mechanism needs to be understood using models like
  - **Statistical thermal models**
  - **Coalescence Models**

# Thermal Model

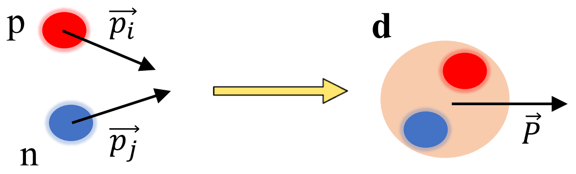
- Hadrons emitted from the interaction region at statistical equilibrium when fireball reaches limiting temperature
- Particle yield exhibits an exponential dependency → **yield** ∝ exp(-m/ $T_{chem}$)
- Nuclei abundance is highly sensitive to the selection of $T_{chem}$, due to their large mass m.

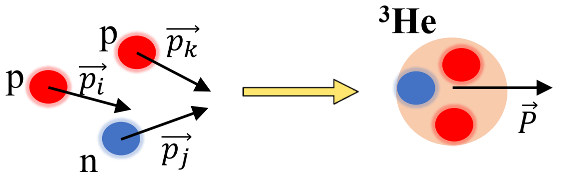
Andronic, A., Braun-Munzinger, P., Redlich, K. et al. Decoding the phase structure of QCD via particle production at high energy. Nature 561, 321–330 (2018)




Particle yields of light-flavour hadrons described over 9 orders of magnitude with a common $T_{chem} \approx 156$ MeV

# Coalescence model





[1] PRC 99 (2019) 024001
[2] PRL 123 (2019) 112002
[3] PRC 96 (2017) 064613

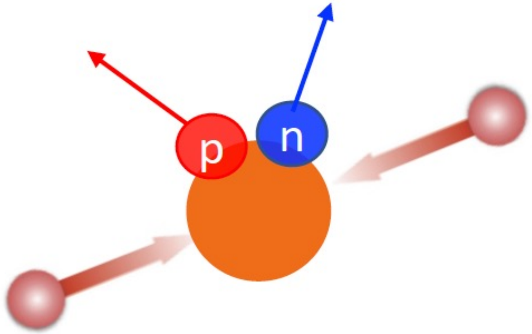

Nuclei formation probability is given by **overlap** of the nucleus Wigner density with the **phase-space distribution** of the nucleons → Probability is related to the coalescence parameter $\boldsymbol{B_{\mathrm{A}}}$

Coalescence parameter $\boldsymbol{B_{\mathrm{A}}}$ for a nucleus "i" with "A" nucleons is defined as

$$E_i \frac{\mathrm{d}^3 N_i}{\mathrm{d}p_i^3} = B_A \left( E_{\mathrm{p}} \frac{\mathrm{d}^3 N_{\mathrm{p}}}{\mathrm{d}p_{\mathrm{p}}^3} \right)^A \xrightarrow{\text{deuterons}} B_2 = \frac{E_{\mathrm{d}} \frac{\mathrm{d}^3 N_{\mathrm{d}}}{\mathrm{d}p_{\mathrm{p}}^3}}{\left( E_{\mathrm{p}} \frac{\mathrm{d}^3 N_{\mathrm{p}}}{\mathrm{d}p_{\mathrm{p}}^3} \right)^2}$$

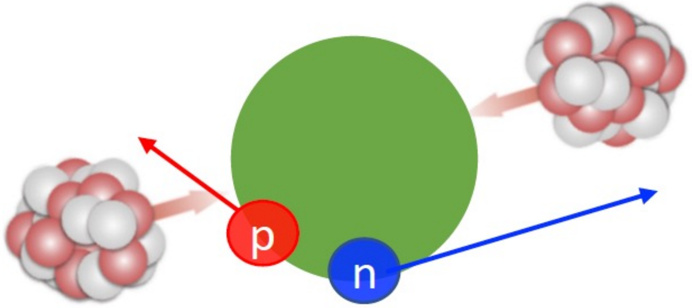
**Larger $\boldsymbol{B_{\mathrm{A}}}$ ⟺ Larger coalescence probability**

In state-of-the-art models, $\boldsymbol{B_{\mathrm{A}}}$ depends on $\boldsymbol{A}$, $\boldsymbol{p_{\mathrm{T}}}$, size of nucleus and **particle source**




**[1]pp, [2]p–Pb: $\mathbf{r_0}$ = 1–1.5 fm**

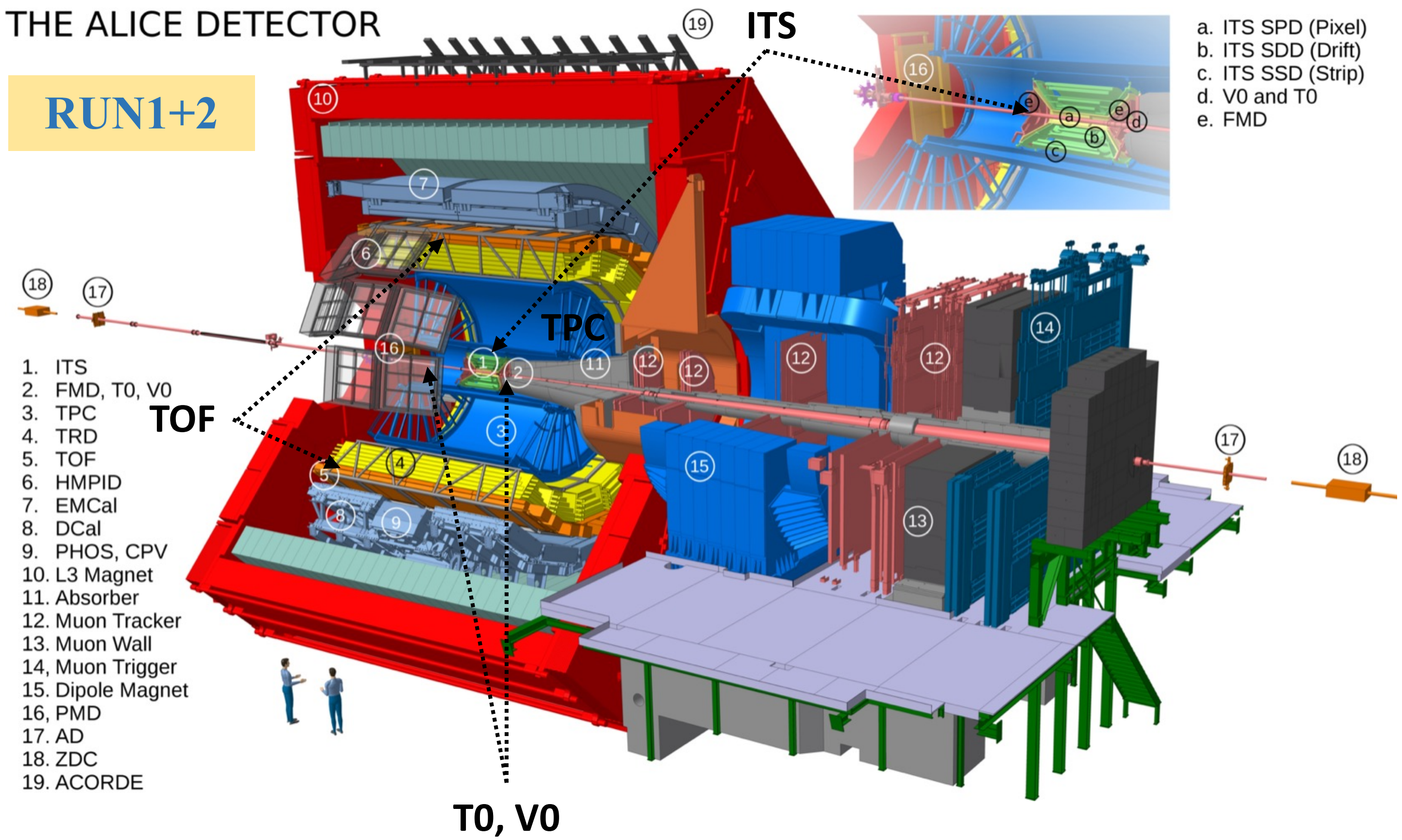
Small system
=
Small distance in space
(Only momentum correlations matter)
⟺ expect large $\boldsymbol{B_{\mathrm{A}}}$




**[3]Pb–Pb: $\mathbf{r_0}$ = 3–6 fm**

Large system
=
Large distance in space
(Both momentum and space correlations matter)
⟺ expect smaller $\boldsymbol{B_{\mathrm{A}}}$

# The ALICE Detector




JINST 3, S08002 (2008)

## ITS ($|\eta|<0.9$)

Trigger, vertex, tracking, PID ($dE/dx$)

## TPC ($|\eta|<0.9$)

Tracking and vertexing, PID ($dE/dx$)

$\sigma_{dE/dx} \sim$ 5.5% for pp

$\sigma_{dE/dx} \sim$ 7% for Pb–Pb

## TOF ($|\eta|<0.9$)

Multi-gap Resistive Plate Chambers

Time resolution ($\sigma_{TOF} \sim$ 80 ps) , PID (time-of-flight)

## V0 (A&C)

trigger, multiplicity estimators

(Minimum Bias: 0 – 100%, High Multiplicity: 0 – 0.1%)

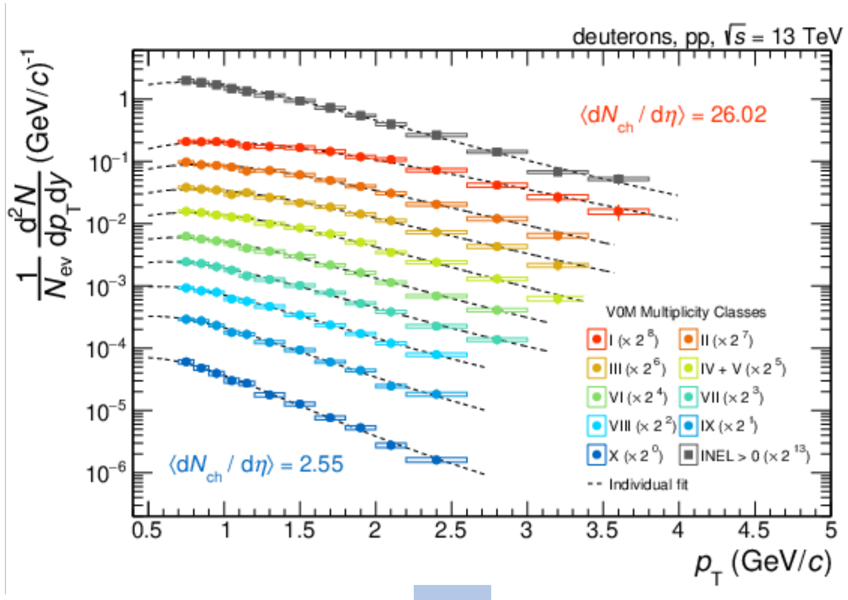
**ALICE is uniquely equipped for particle identification (PID)**

The most suitable detector for (anti)nuclei production study over a wide range of system sizes and energy

# Light (anti)nuclei production in pp and p–Pb collisions

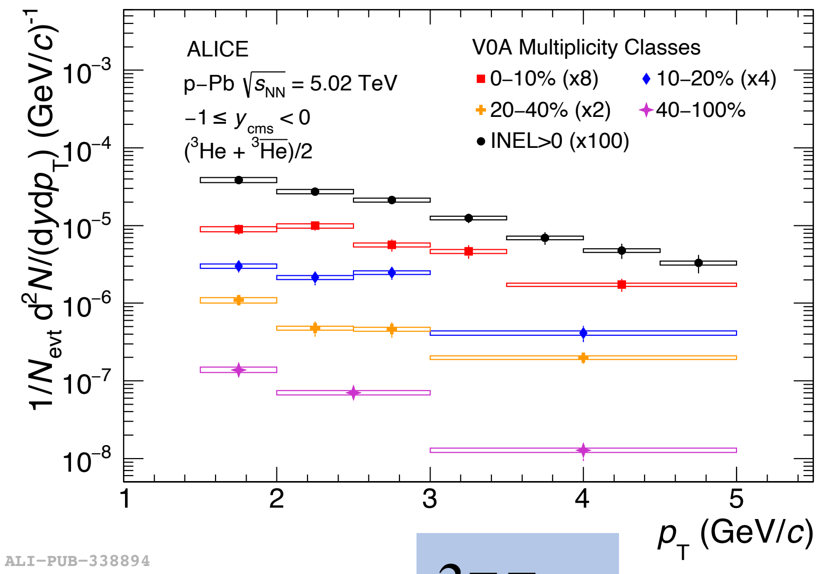
INFN Istituto Nazionale di Fisica Nucleare | ALICE

**pp @ 13 TeV** | **p–Pb @ 5.02 TeV** | **p–Pb @ 8.16 TeV**



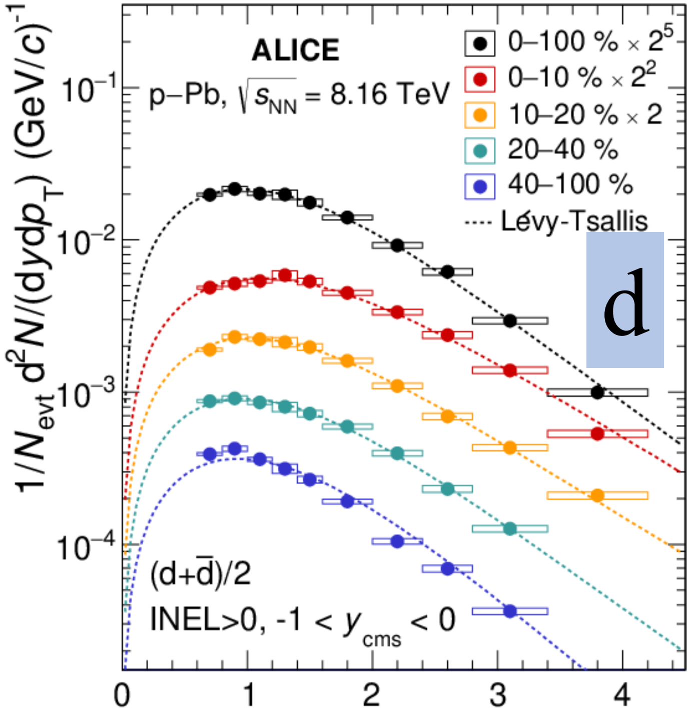

d

**Eur. Phys. J. C 80, 889 (2020)**




$^3$He

**PhysRevC.101.044906 (2020)**



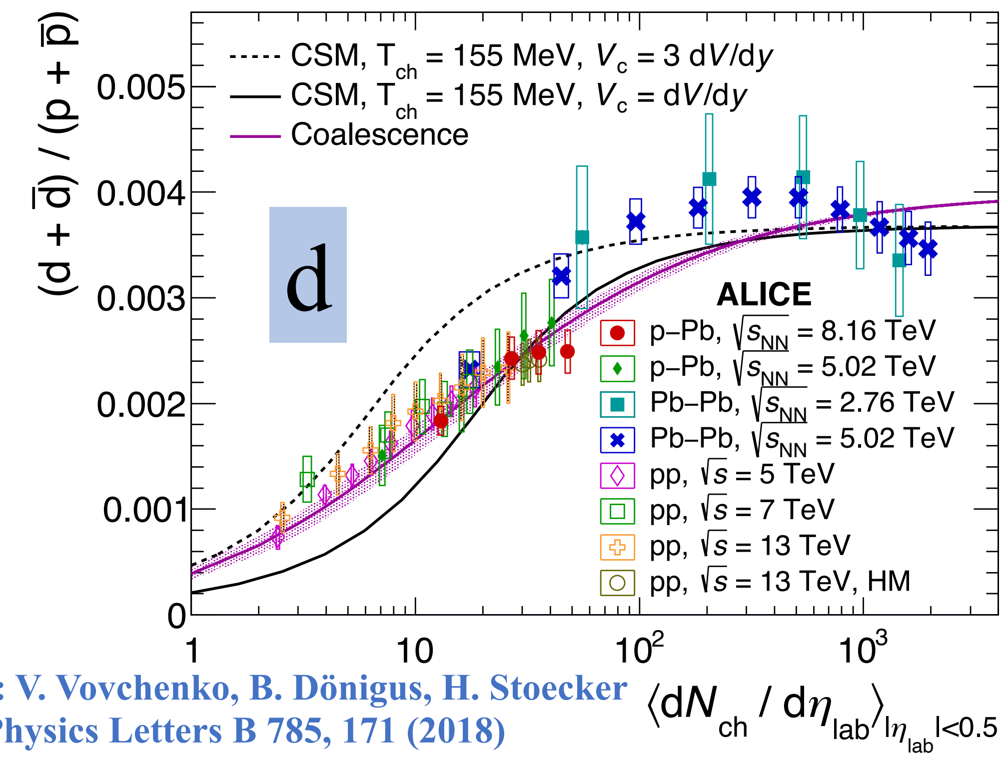

d

**[arXiv:2212.04777]** $p_T$ (GeV/$c$)

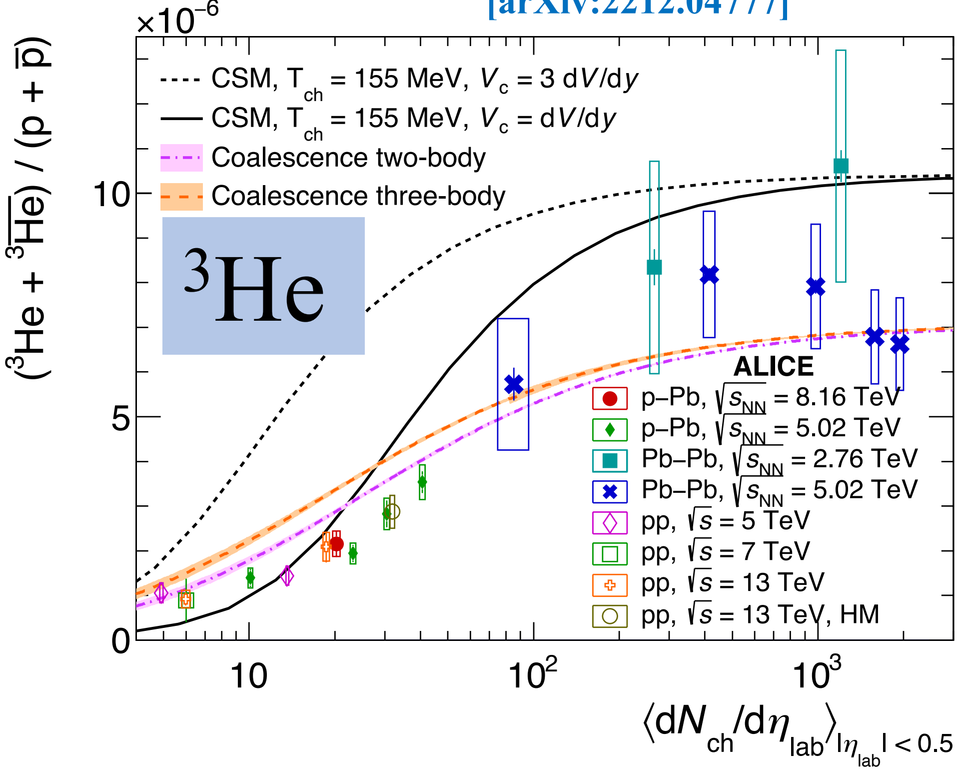
- $p_T$ spectra fitted with Lévy-Tsallis function → Extrapolation to unmeasured regions
- Similar behaviour was observed in pp and p–Pb systems such as hardening with increasing centrality → as seen for other light-flavour hadrons
- Light (anti)nuclei up to $^3$He have been measured in small systems

# Ratio to protons with model comparison

[arXiv:2212.04777]




[arXiv:2212.04777]



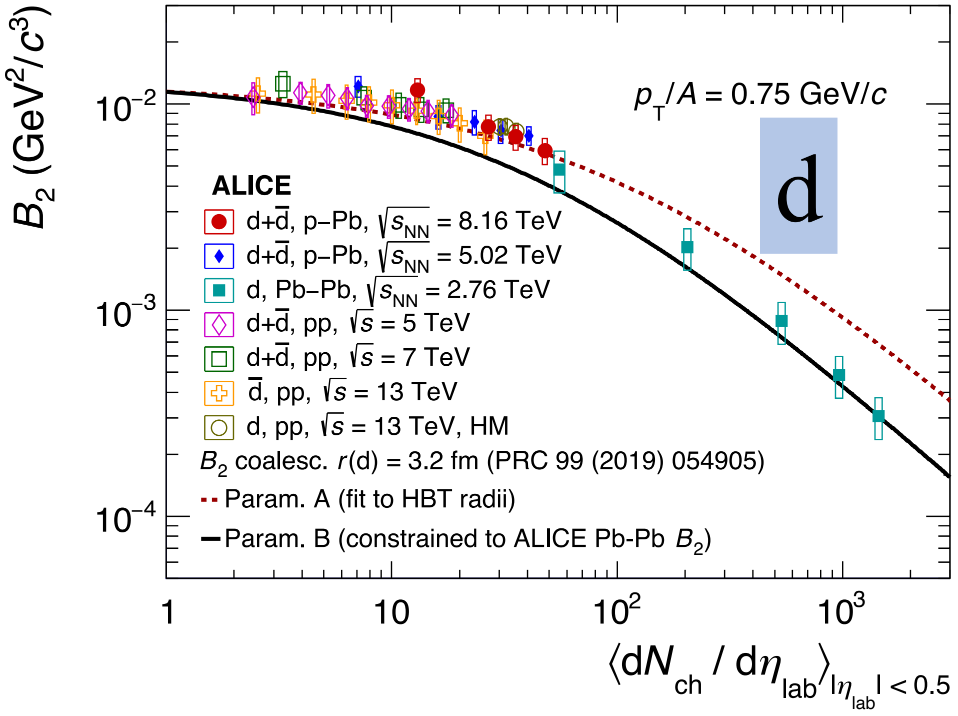

[1] CSM: V. Vovchenko, B. Dönigus, H. Stoecker
Physics Letters B 785, 171 (2018)

- **d/p** ratio evolves **smoothly** with **multiplicity** → dependence on the **system size**
- For **d/p** ratio both models describe the data:
  - [1]CSM (Canonical Statistical Model): canonical suppression
  - Coalescence model: interplay between source size and nuclear size

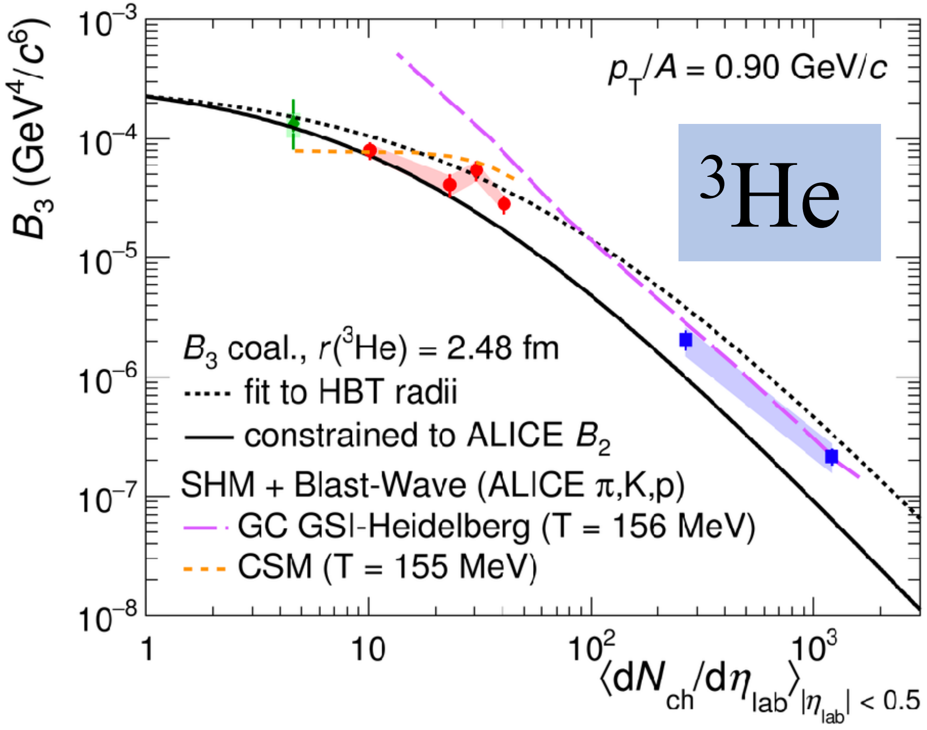
- **$^3$He/p** evolves **smoothly** with **multiplicity**
  - Coalescence seems to describe better the data as compared to CSM
- **d/p** increases by a factor of 4 from pp to mid-central Pb-Pb collision, but a hint of a small decrease in central **Pb–Pb** collision (not significant within the uncertainties)

# Coalescence parameter $B_A$

[arXiv:2212.04777]




PhysRevC.101.044906 (2020)




- Continuous evolution of $B_2$ with multiplicity → Smooth transition from small to large system size
- Similar conclusions apply also to $B_3$
- Advanced coalescence models taking into account the size of the nucleus and of the emitting source predict a similar trend

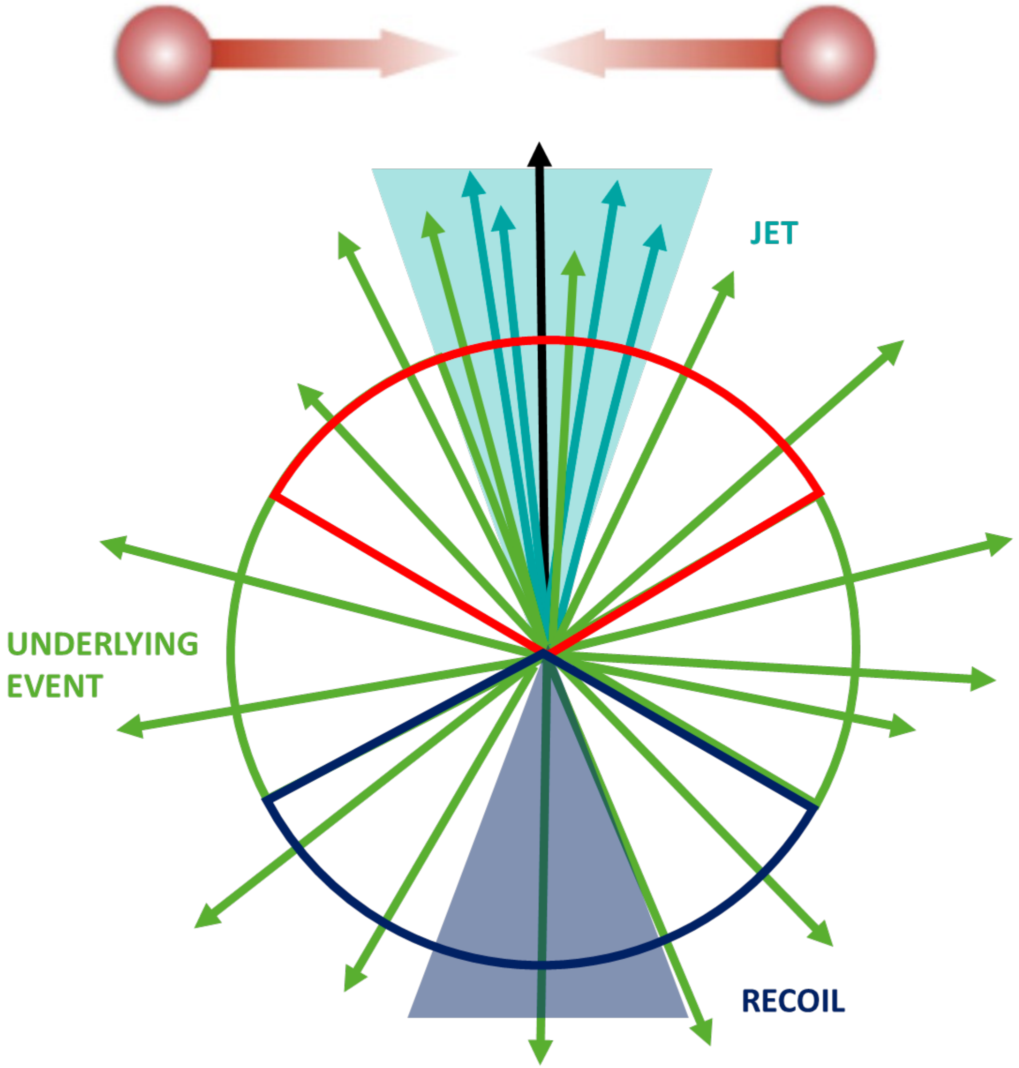
**The evolution with multiplicity is explained as an increase in the source size 'R' in coalescence models (e.g. Scheibl, Heinz PRC 59 (1999) 1585, F. Bellini and A. P. Kalweit, Phys. Rev. C 99, 054905)**

# In-jet and underlying event

- The study in small collision systems such as pp and p–Pb can also be explored using the underlying event (UE) activity
- The coalescence mechanism can be tested by comparing the deuteron production in jets, where nucleons are closer as compared to the underlying event
- Leading particle ($p_{T}^{\text{ lead}} > 5$ GeV/$c$) used as a proxy for the jet axis
- 3 regions in the transverse plane wrt leading track:

❑ Toward: Contains Jet and Underlying Event (UE)
❑ Transverse: Dominated by the UE
❑ Away: Contains recoil jet and UE

- Jet = Toward – Transverse (Jet+UE – UE)

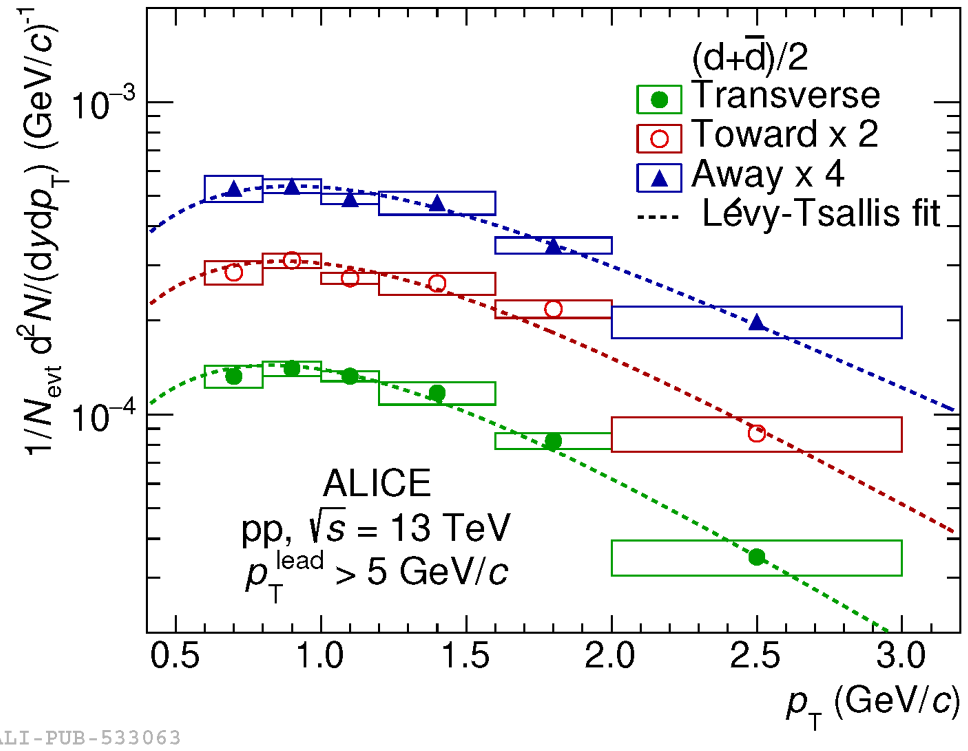


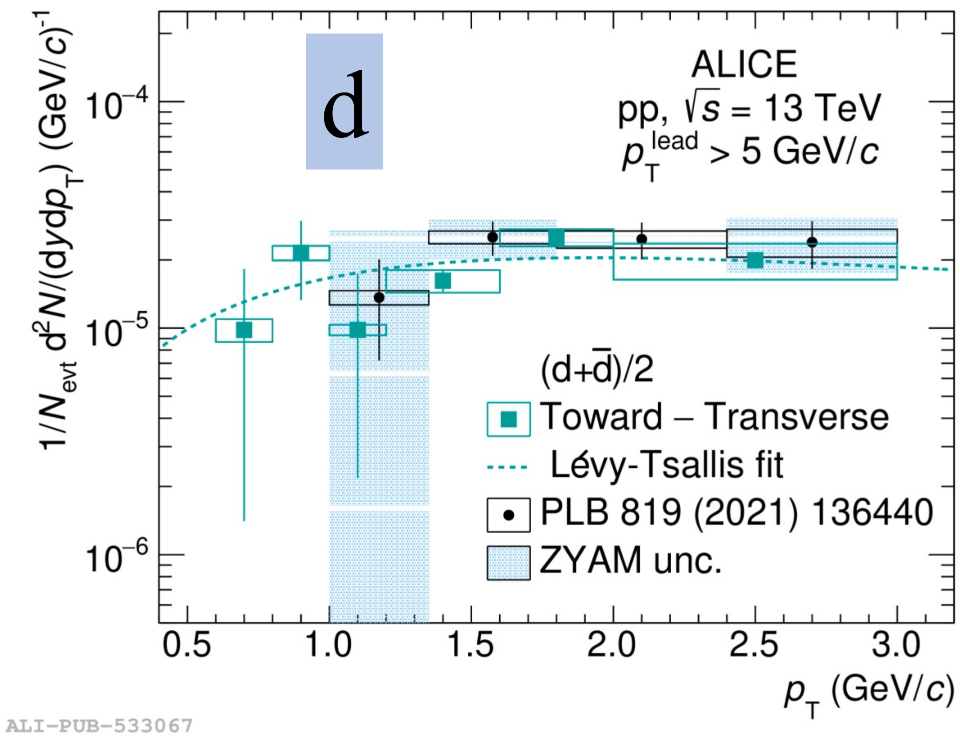

Martin, T., Skands, P. & Farrington, S.: Eur. Phys. J. C76, 299 (2016)

# In-jet and underlying event: (Anti)deuteron spectra

[arXiv:2211.15204v1]

**pp @ 13 TeV**




Deuteron production in events with $p_T^{lead} > 5$ GeV/$c$

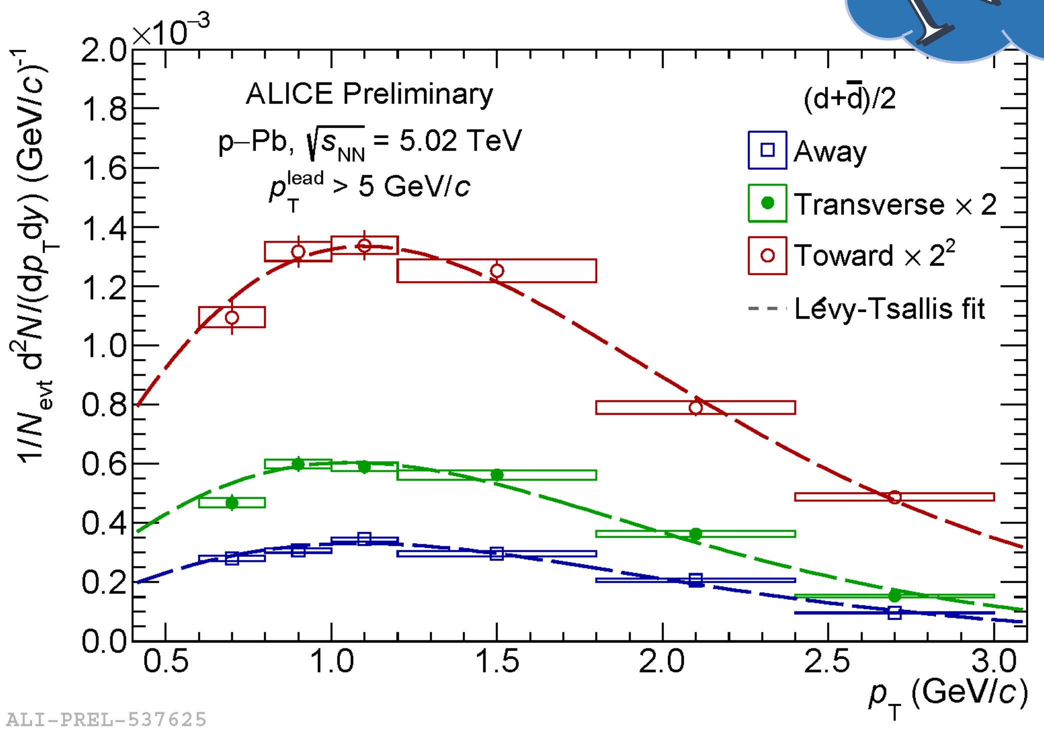
Jet = Toward – Transverse (Jet+UE – UE)

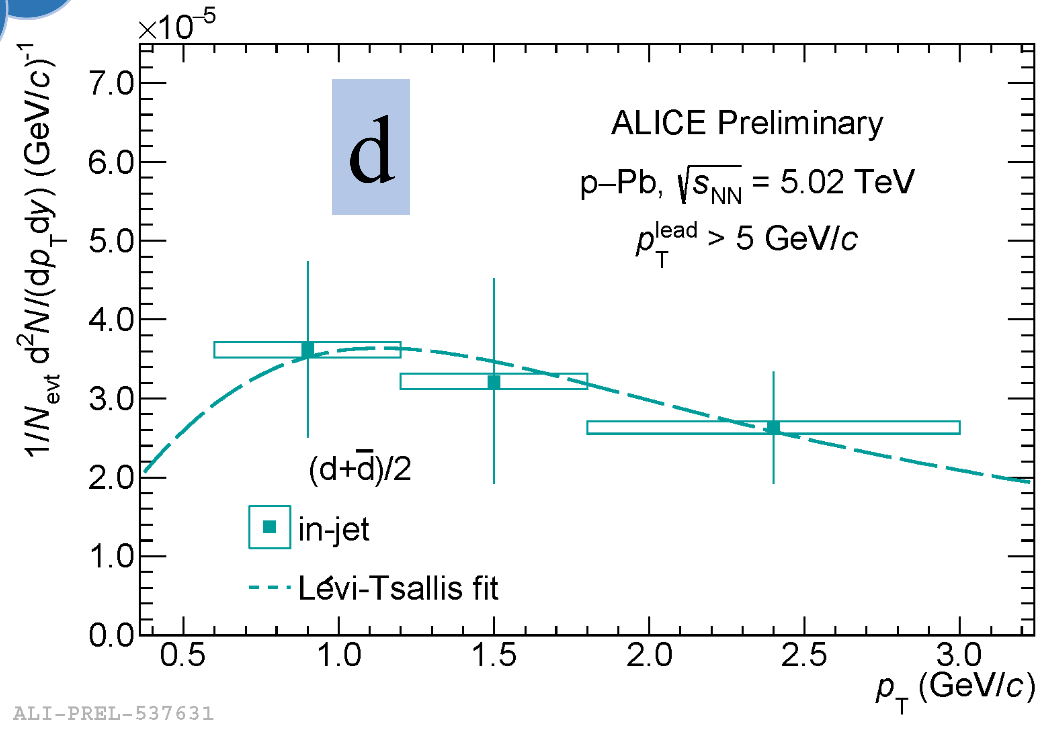
- The fraction of deuterons produced in the jet is ~ 10% wrt UE in pp
- The majority of the deuterons are produced in the underlying event

# In-jet and underlying event: (Anti)deuteron spectra

NEW

p–Pb @ 5.02 TeV

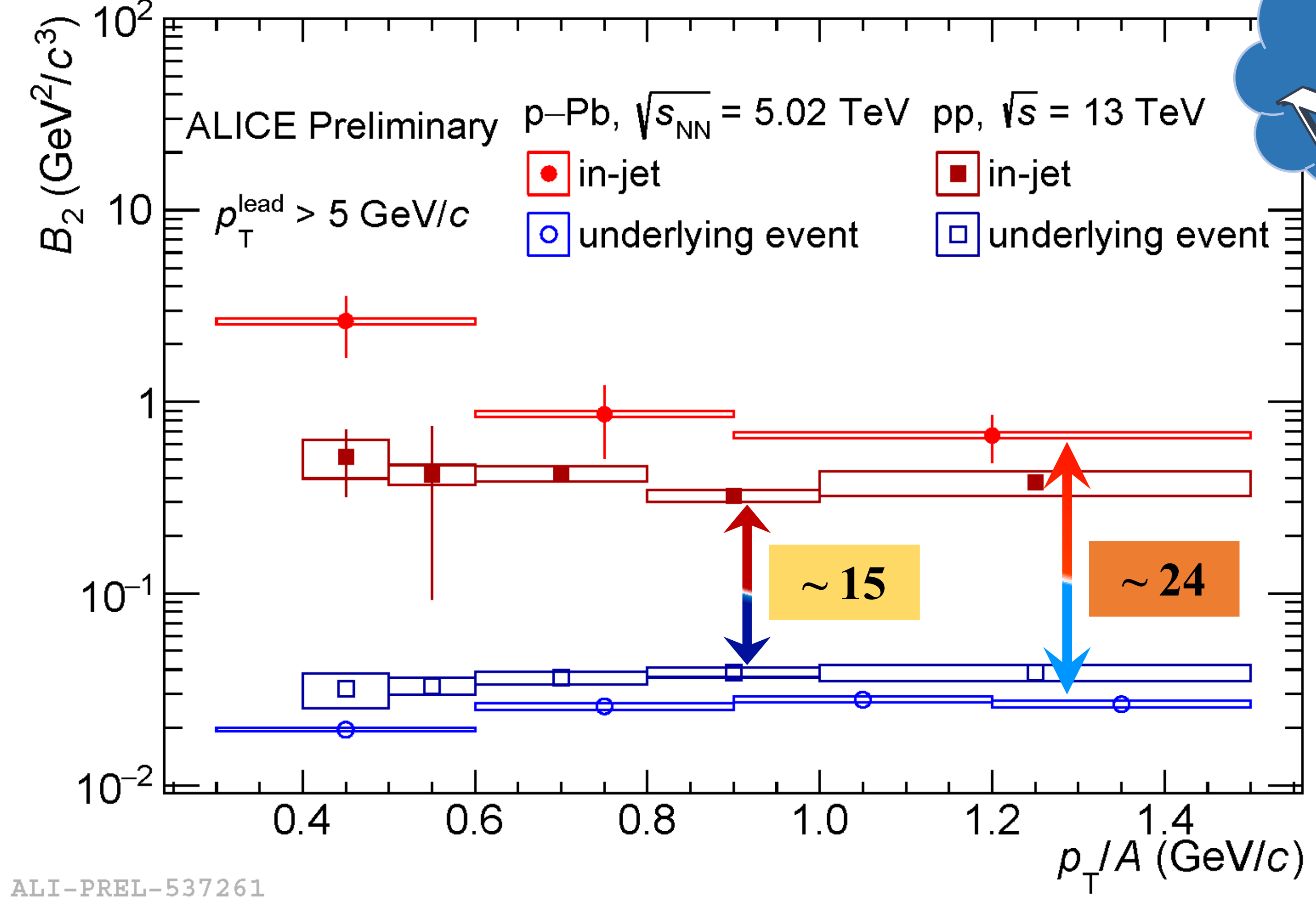



Deuteron production in events with $p_T^{lead} > 5$ GeV/$c$

Jet = Toward – Transverse (Jet+UE – UE)

# In-jet and underlying event: coalescence parameter $B_2$




- Enhancement of $B_2^{jet}$ wrt $B_2^{UE}$ in pp and p–Pb collisions
- Enhancement factor is larger in p–Pb wrt pp collisions

- Due to the reduced distance in phase space of hadrons in jets compared to those out of jets
  → favors coalescence

- $B_2^{jet}$(p–Pb) > $B_2^{jet}$(pp)
- $B_2^{UE}$(p–Pb) < $B_2^{UE}$(pp), since p–Pb source size is larger than pp source size

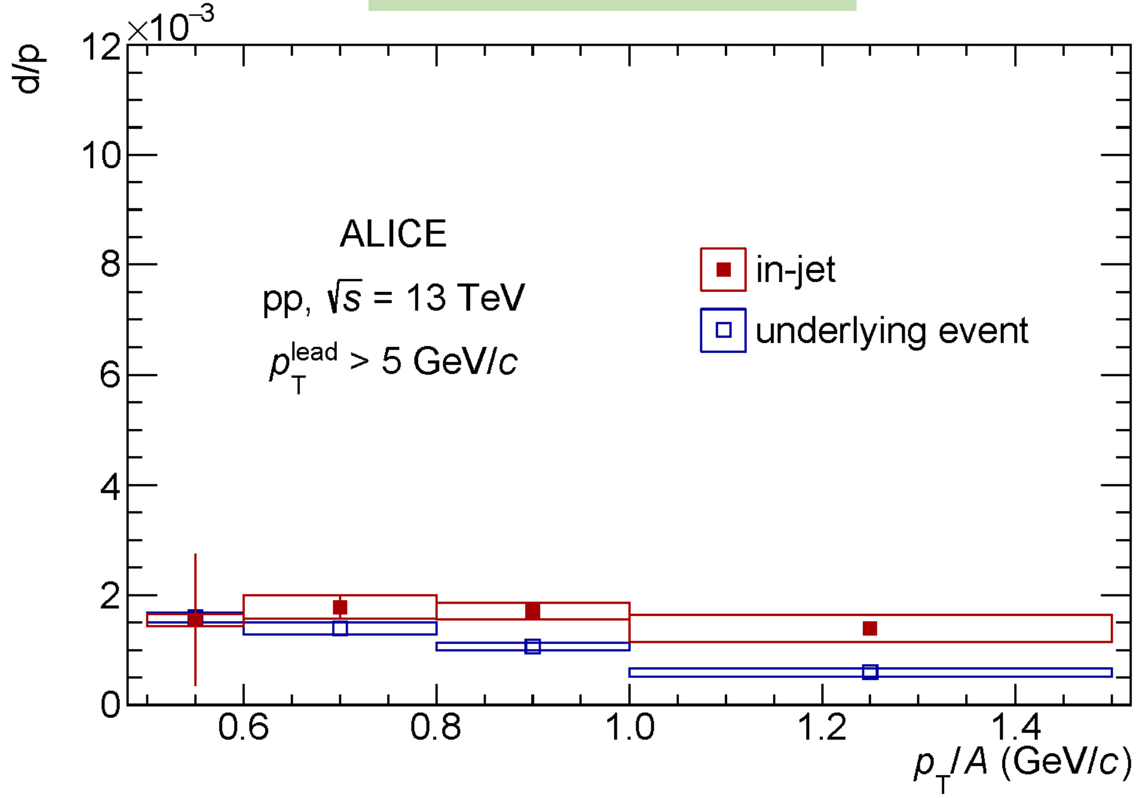
**Assuming same source size for nucleons in jet**
- **Might be more nucleons in p–Pb closer in phase space?**
- **Larger $B_2$ in p–Pb**

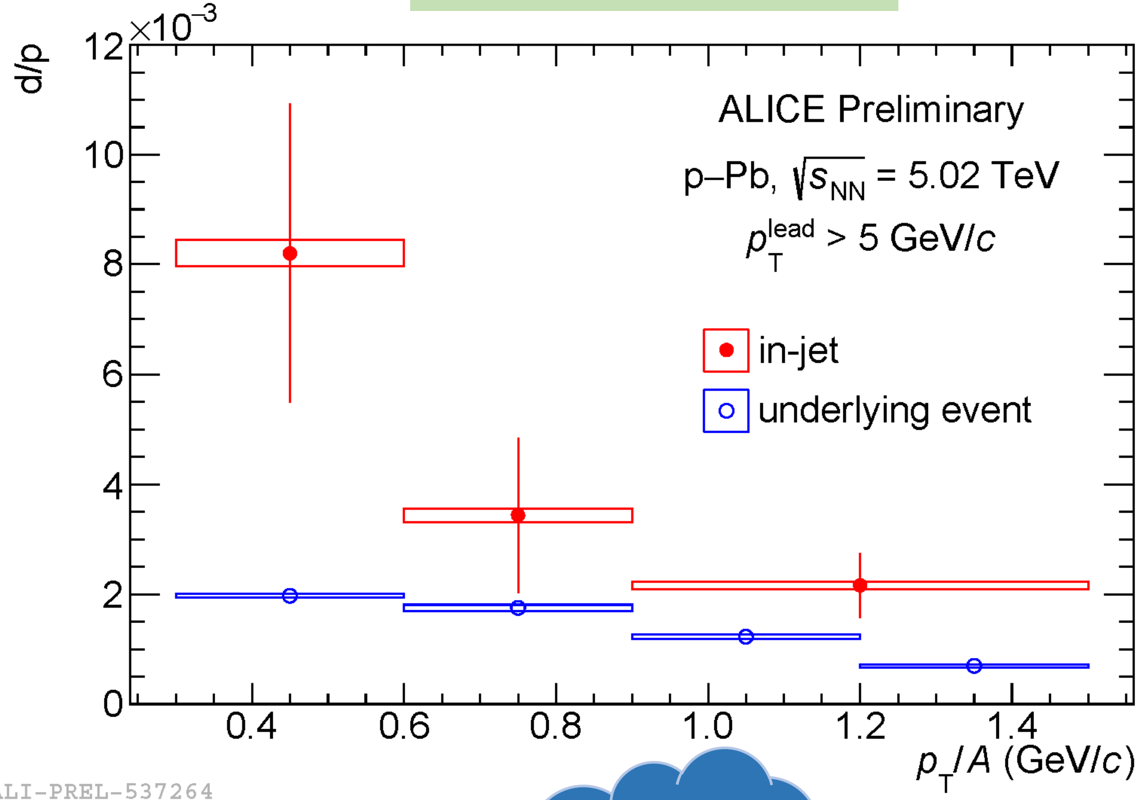
# In-jet and underlying event: d/p ratio

**pp @ 13 TeV**

[arXiv:2211.15204v1]

**p–Pb @ 5.02 TeV**



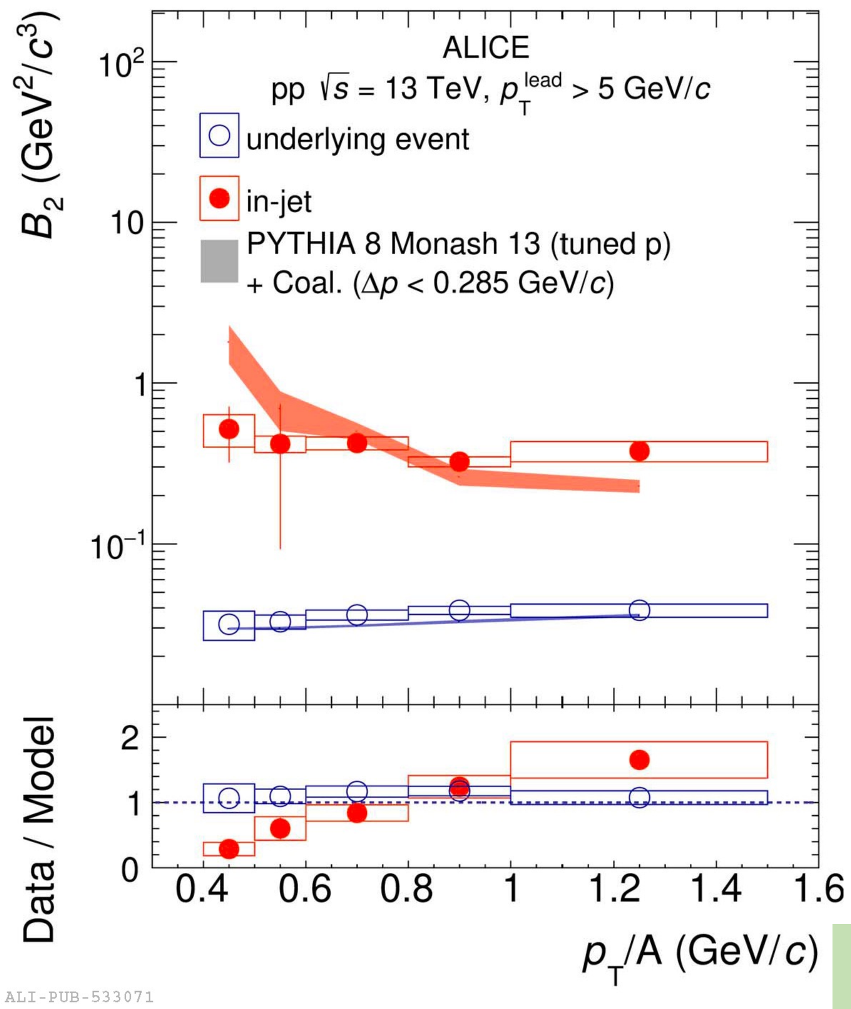

ALI-PREL-537264

- d/p calculated as a ratio of normalized spectra
- $d/p^{jet}$ is higher than $d/p^{UE}$
- Indication of higher $d/p^{jet}$ in p–Pb collisions wrt pp collisions

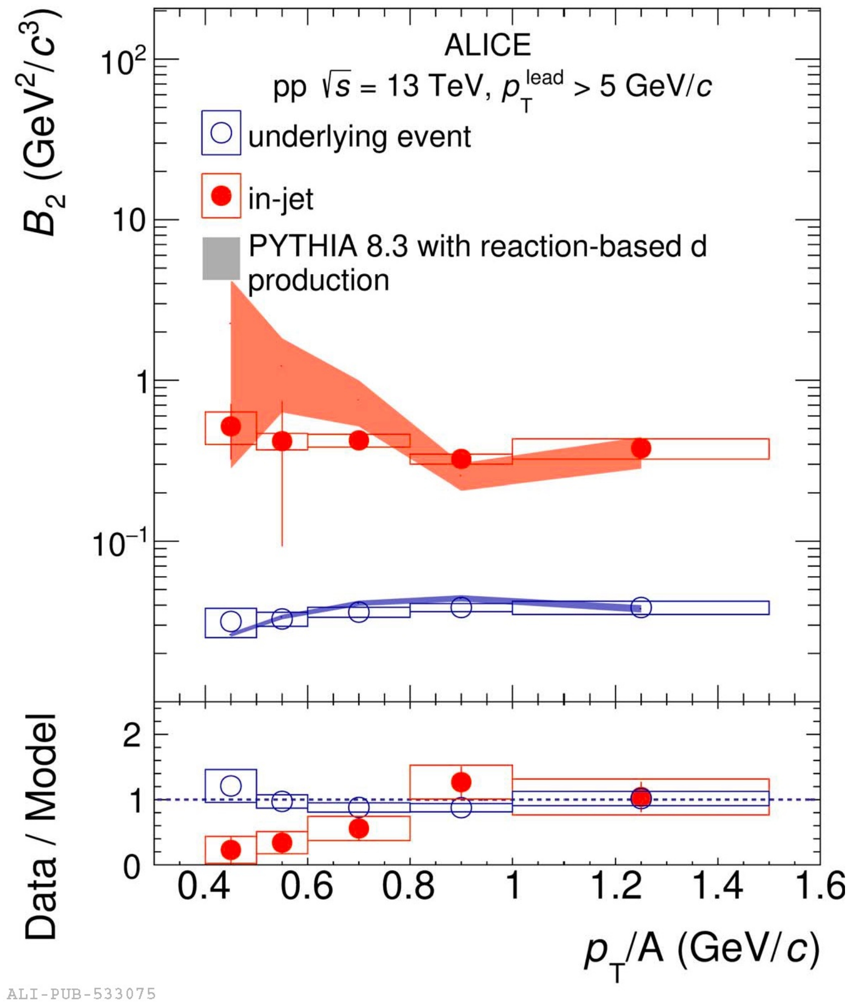
NEW

# $B_2$ in-jet and underlying event with model comparison

[1]PYTHIA 8 Monash 13 + Coalescence




[2]PYTHIA 8.3 with reaction based deuteron production




[arXiv:2211.15204v1]

- Both models qualitatively reproduce the data → large difference between $B_2^{jet}$ and $B_2^{UE}$
- **$B_2^{UE}$ in PYTHIA reproduces the trend of data**
- **$B_2^{jet}$ in PYTHIA is consistent within uncertainties**

**Further developments of models are needed**

[1] PYTHIA 8: Skands et al., EPJC 74 (2014) 8, 3024
[2] PYTHIA 8.3: Bierlich et al., arXiv:2203.11601

# Summary

- ✓ Light (anti)nuclei up to $^3$He have been measured in small systems
  - → Production of light nuclei evolves smoothly with the multiplicity
- ✓ Experimental results challenge the models for A=3 nuclei
- ✓ 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
- ✓ $B_2^{\mathrm{jet}}$ is larger than $B_2^{\mathrm{UE}}$ by an order of magnitude
  - → nucleons might be closer in phase space
- ✓ Models need to be improved for in-jet study
- ✓ Further investigation with high statistics RUN 3 data (**Stay tuned for new results**)

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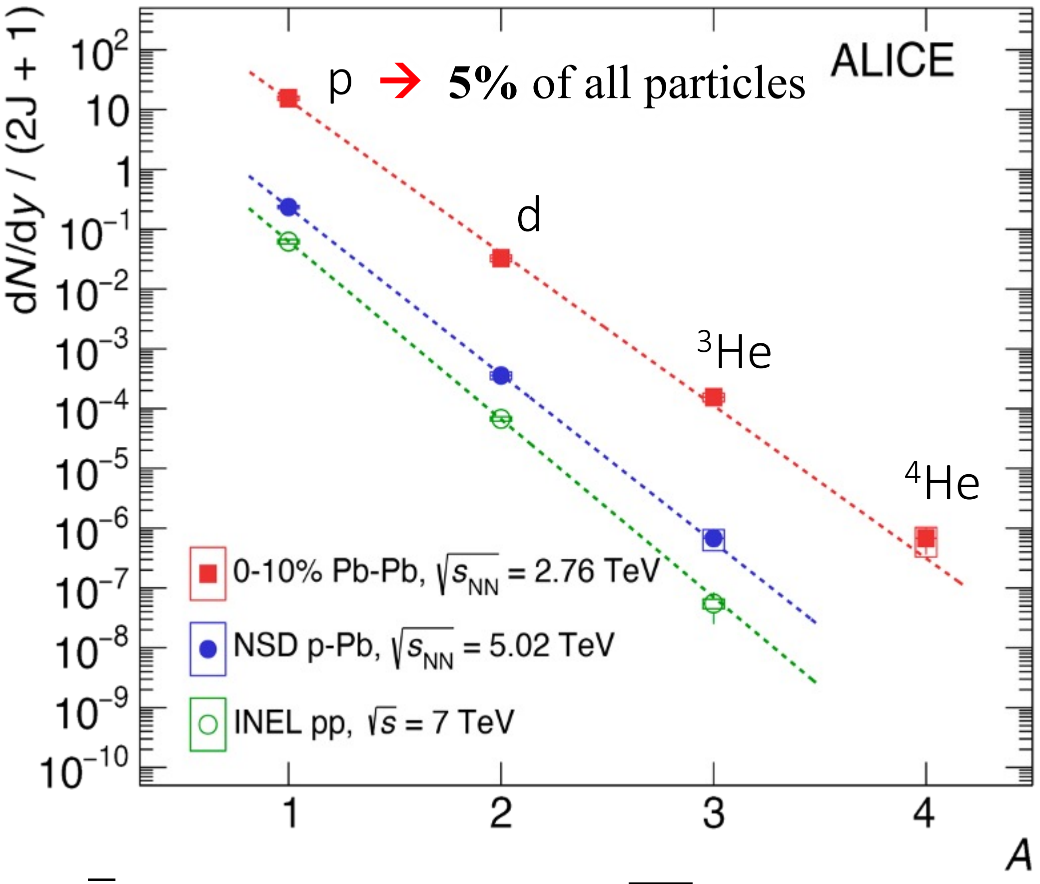
THANK YOU FOR YOUR ATTENTION...

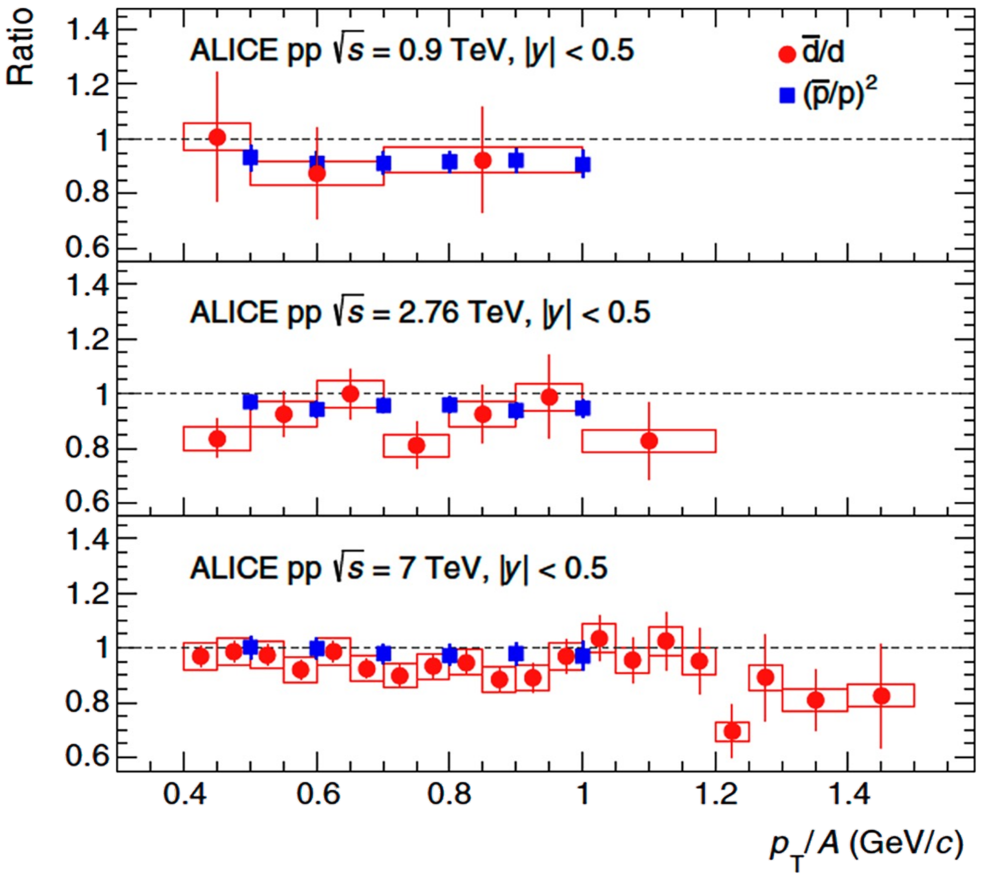
# BACK UP

# LHC is an antinucleus factory

S. Acharya *et al.* [ALICE], Phys. Lett. B **800**, 135043 (2020)




Physical Review C97, 024615 (2018)



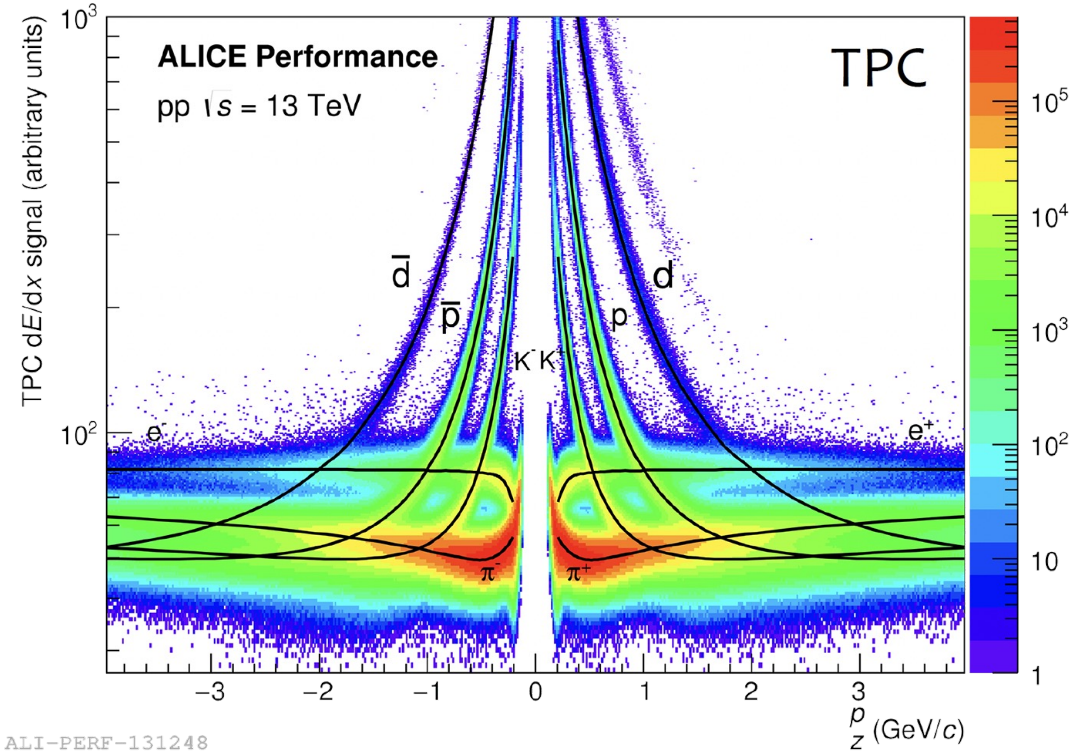

$\bar{d}/\bar{p}$ (Pb-Pb) ~ 1/300 $^{3}\overline{He}/\bar{p}$ (Pb-Pb) ~ $1/10^5$

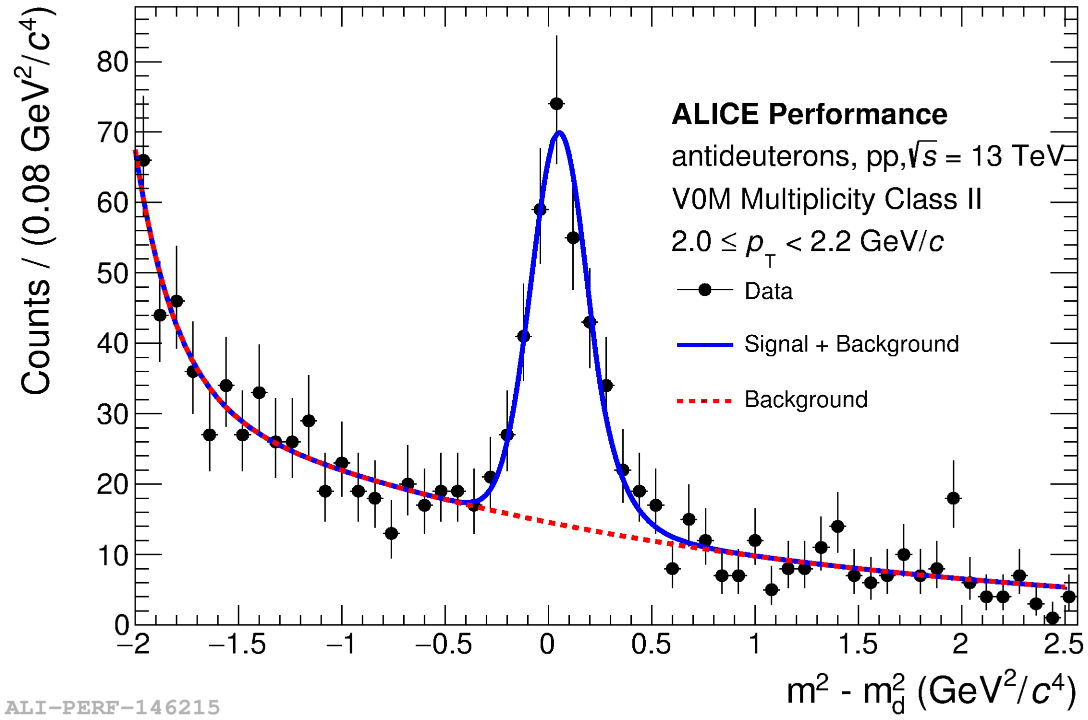
$\bar{d}/\bar{p}$ (pp) ~ 1/1000 $^{3}\overline{He}/\bar{p}$ (pp) ~ $1/10^6$

$$\frac{\text{antimatter}}{\text{matter}} \sim \mathbf{1}$$

LHC provides optimal conditions for studying the antinucleus formation

# Particle identification (PID) of (anti)nuclei




***Low momenta***

PID via specific ionization energy loss in TPC

$$\langle -\frac{dE}{dx} \rangle = K\, z^2 \frac{Z}{A} \frac{1}{\beta^2} \left[ \frac{1}{2} \ln 2 \frac{m_e c^2 \beta^2 \gamma^2 W_{max}}{I^2} - \beta^2 - \frac{\delta(\beta\gamma)}{2} \right]$$

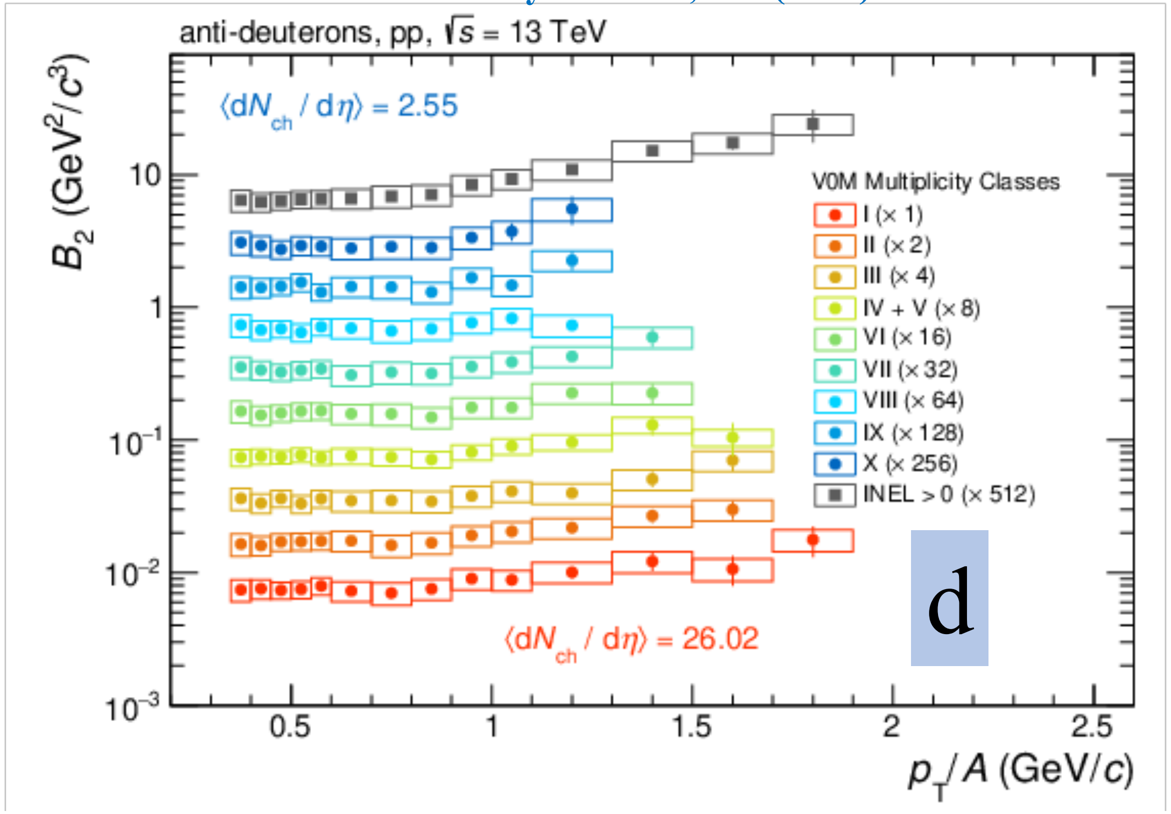
***Higher momenta***

PID via time-of-flight measurements in TOF

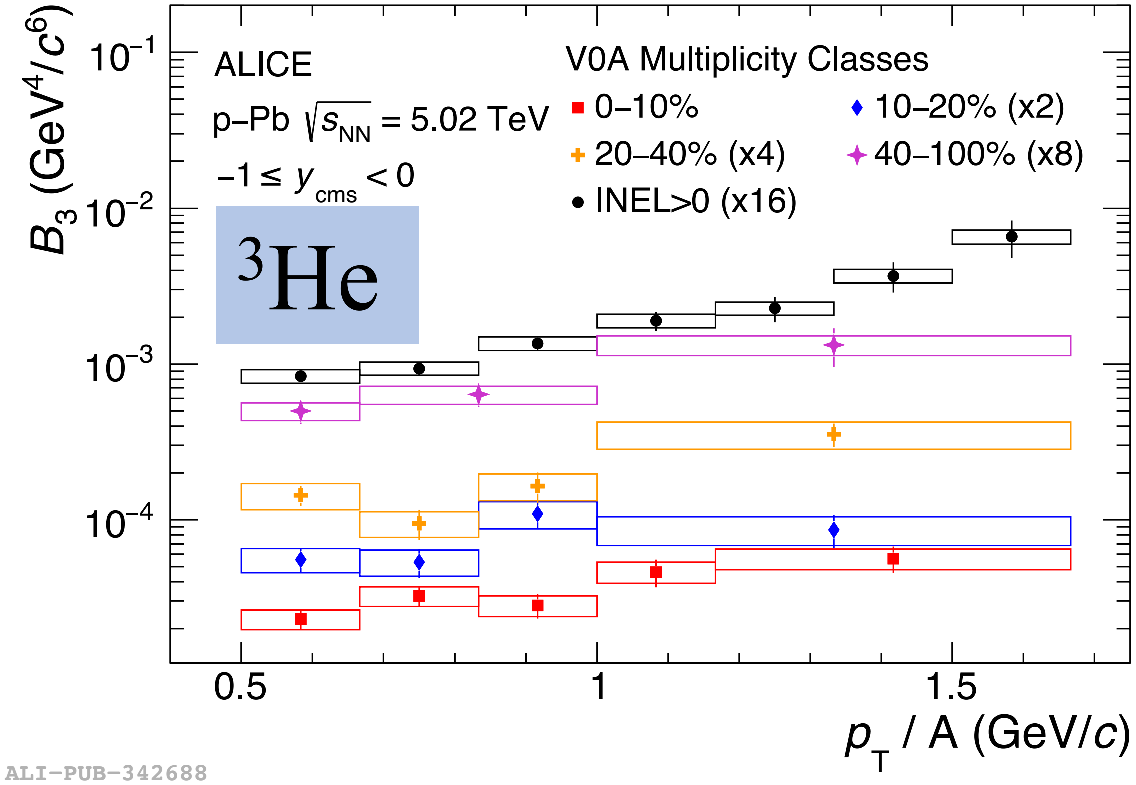
$$m^2 = \frac{p^2}{c^2} \cdot \left( \frac{c^2 t^2}{L^2} - 1 \right)$$

# Coalescence parameter $B_A$ Vs ($p_T$/A)

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




PhysRevC.101.044906 (2020)




ALI-PUB-342688

**pp @ 13 TeV**

**p–Pb @ 5.02 TeV**

**Coalescence parameter, $B_A$, is rather flat in multiplicity classes, but increases at high $p_T$/A in the MB class**