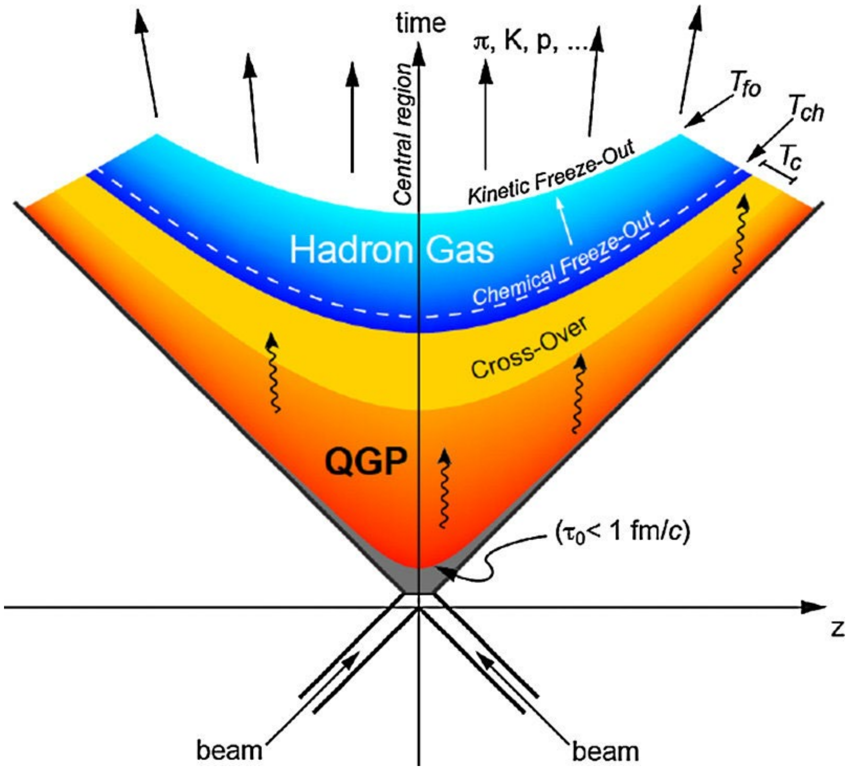
Constraining the light (anti)nuclei production in and out of jets in small systems with ALICE

Marika Rasà[1] on behalf of the ALICE Collaboration

1. University and INFN, Catania

Why studying light (anti)nuclei?



- Light (anti)nuclei are produced in high-energy hadronic collisions at the LHC
- Their production mechanism is still not understood
- Two phenomenological models:
  - Statistical hadronization
  - Coalescence

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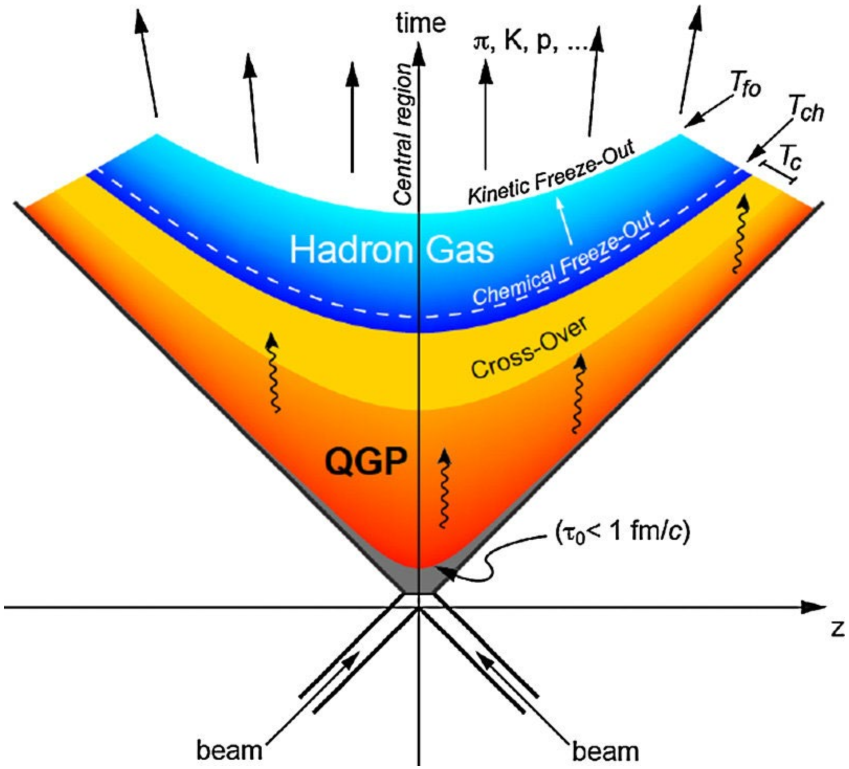

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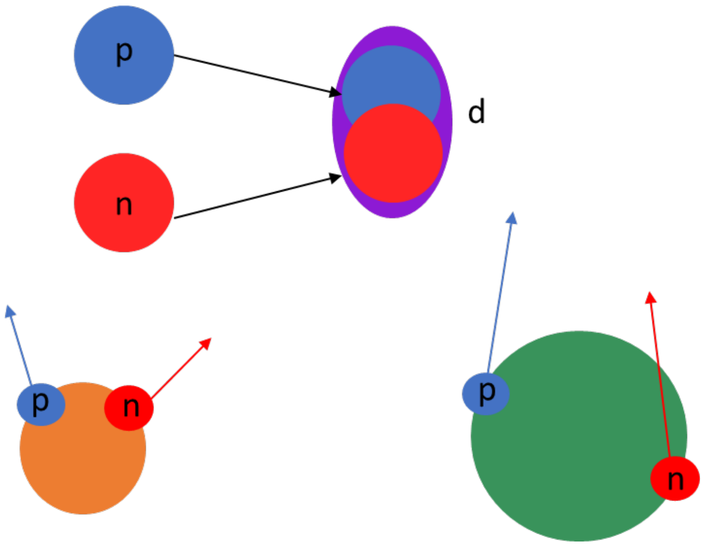
Focus on it

Simple coalescence model

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



- If (anti)nucleons are close in phase space and match the spin states, they can form an (anti)nucleus

- Coalescence parameter B_A is the key observable:

$$E_A \frac{d^3 N_A}{dp_A^3} = B_A \cdot \left(E_p \frac{d^3 N_p}{dp_p^3} \right)^A$$

Invariant yield of nucleus — Coalescence parameter — Invariant yield of protons

State of the art coalescence model

- Coalescence parameter depends on both the source size and radial extension of the nucleus wave function
- Wigner function formalism

$$N_A = g_a \cdot \int d^3x_1 \dots d^3x_A \cdot d^3k_1 \dots d^3k_A \cdot f_1(x_1, k_1) \dots f_A(x_A, k_A) \cdot W_A(x_1, \dots, x_A, k_1, \dots, k_A)$$

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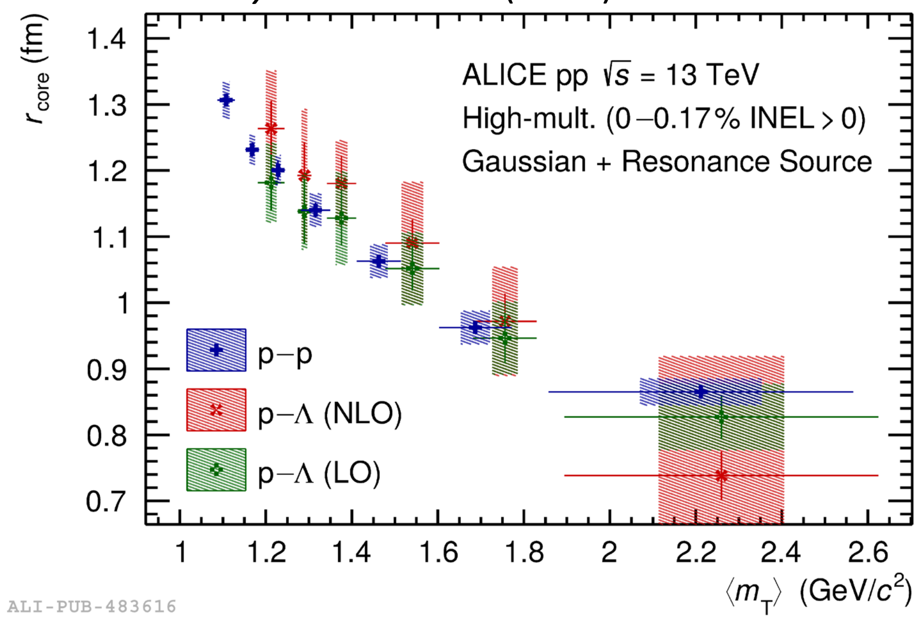
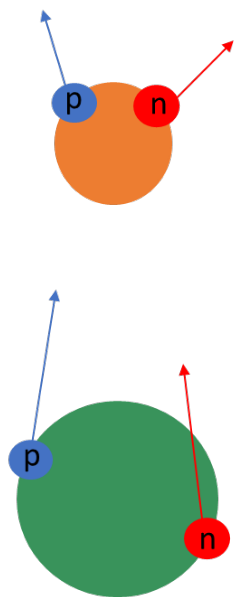
phase space distributions of nucleons → dependence on the source size

Phys. Lett. B 811 (2020) 135849



- Femtoscopy measurement to the source size available
- Dependence on the source size:
- Small source size → Large B_A (pp ~ 1 fm, p– Pb ~ 1.5 fm)
- Large source size → Small B_A (Pb–Pb ~ 3-6 fm)



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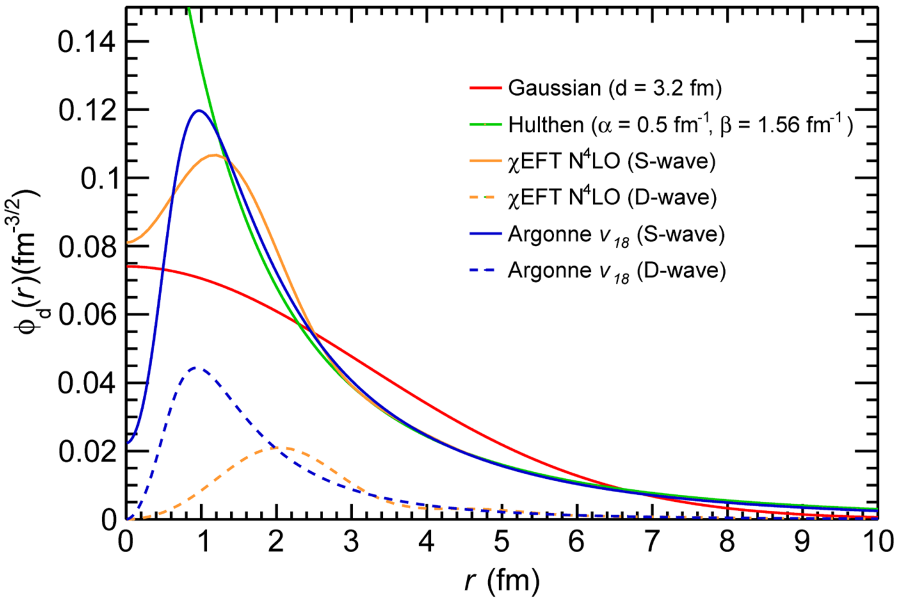
Wigner density of the bound state → dependence on the wave function

M. Mahlein et al., *Eur. Phys. J. C* 83 (2023) 804



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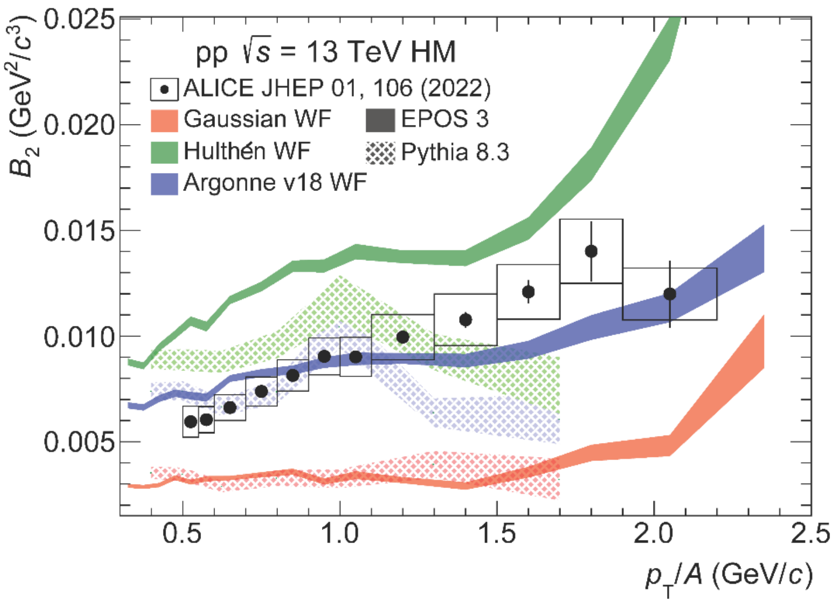


- Different wave functions available
- Best results for deuteron with Argonne v_{18}

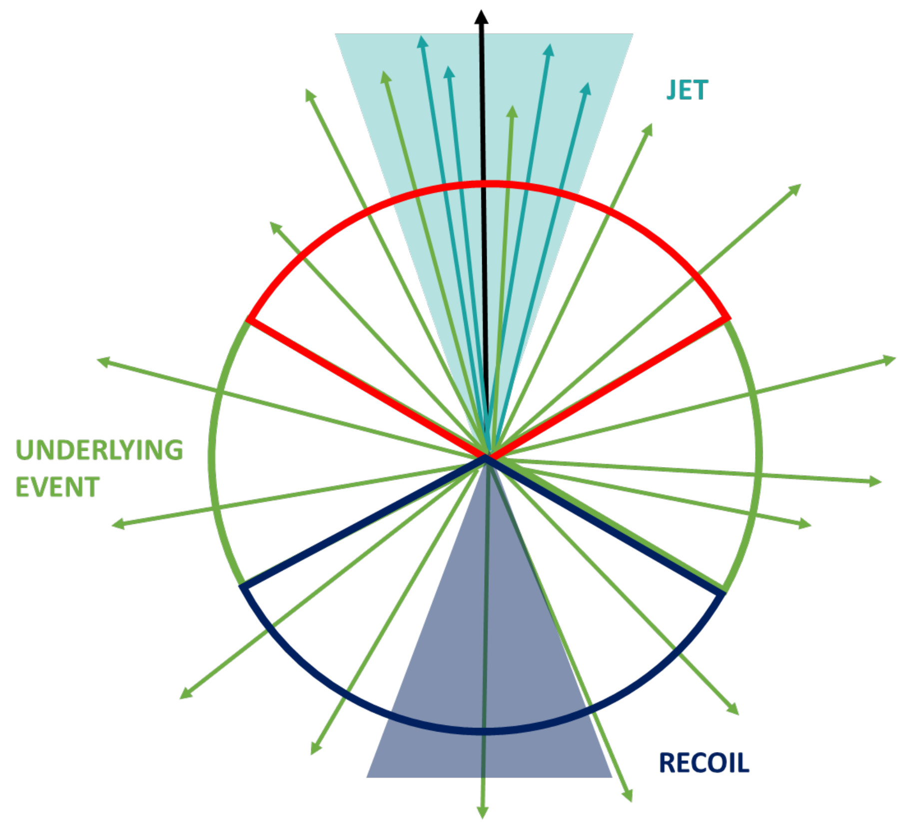
In-jet and underlying event

- Constraint of the coalescence model: study production of nuclei in and out of jets
  - nucleons in jets are closer in phase space → larger coalescence probability expected wrt UE

- CDF technique:
  - **Toward** (|Δϕ| < 60°) : contains JET and UE
  - **Transverse** (60° < |Δϕ| < 120°) : dominated by the Underlying Event (UE)
  - **Away** (|Δϕ| > 120°): contains RECOIL JET and UE

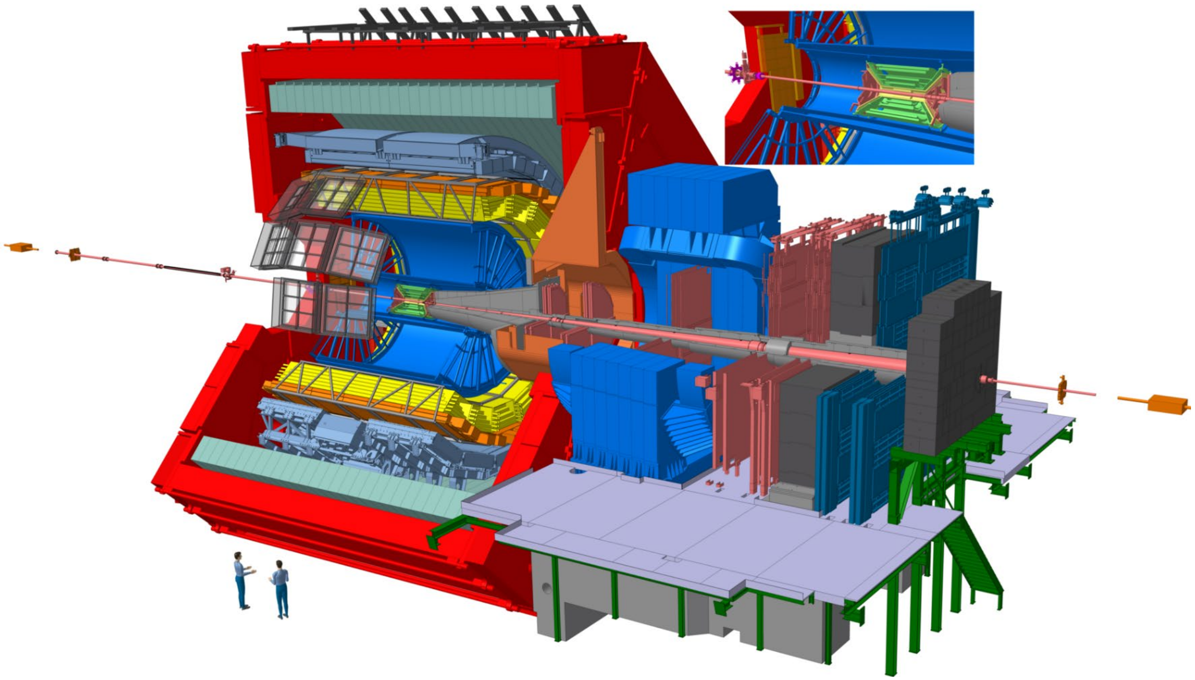
- **Jet**: **Toward** – **Transverse**

Leading particle (highest p_T and p_T > 5 GeV/*c*)



T. Martin et al, *Eur. Phys. J. C* **76**, 299 (2016)

The ALICE detector in Run1&2



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

JINST 3 (2008) S08002
Int. J. Mod. Phys. A 29 (2014) 1430044

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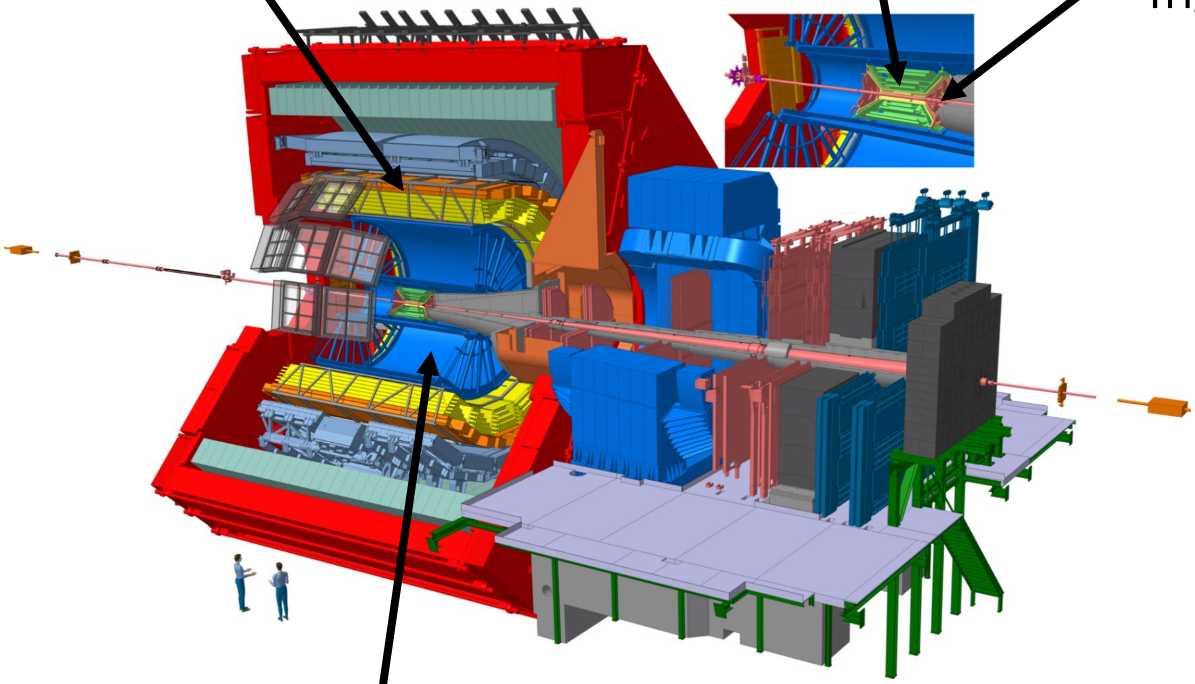

- Most suited LHC experiment to study light (anti)nuclei production
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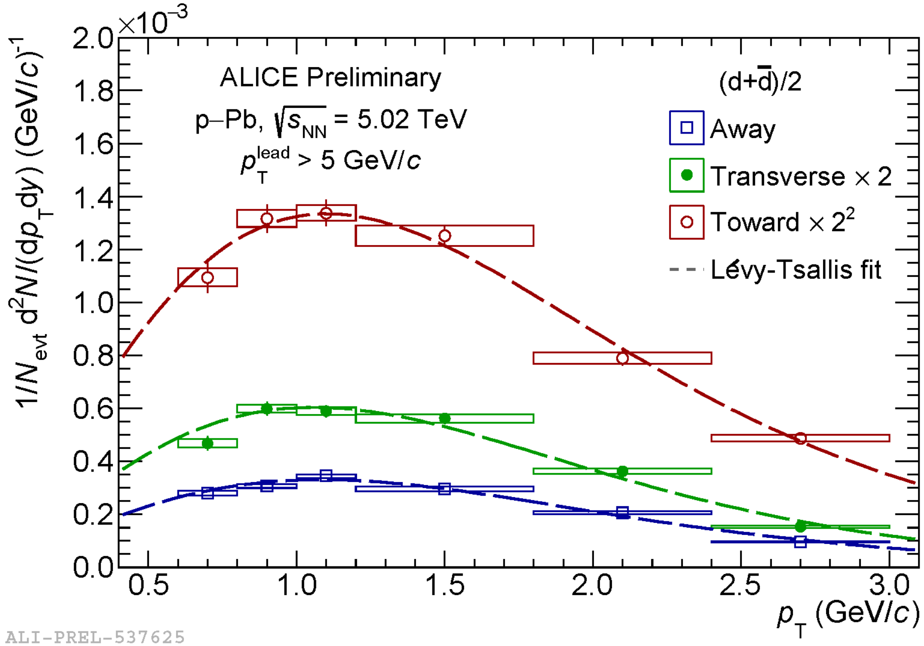
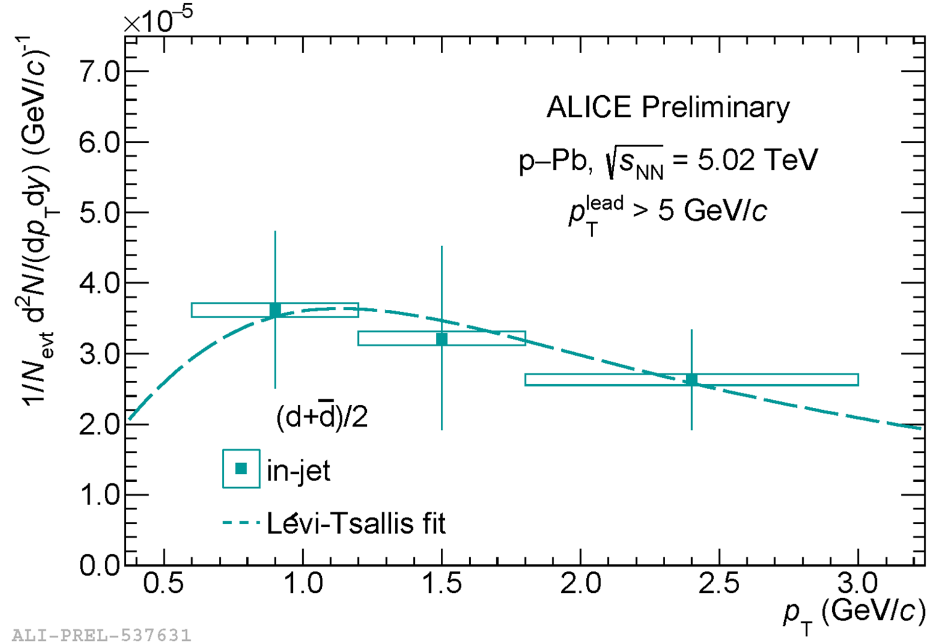
In-jet and UE spectra

- What do we need for the coalescence parameter?
- **First ingredient**: (anti)deuteron spectra

$$B_2 = \frac{\frac{1}{2\pi p_T^d}\left(\frac{d^2N}{dyd p_T}\right)_d}{\left(\frac{1}{2\pi p_T^p}\left(\frac{d^2N}{dyd p_T}\right)_p\right)^2}$$





Jet = Toward - Transverse

In-jet and UE spectra

- What do we need for the coalescence parameter?
- **Second ingredient**: (anti)proton spectra

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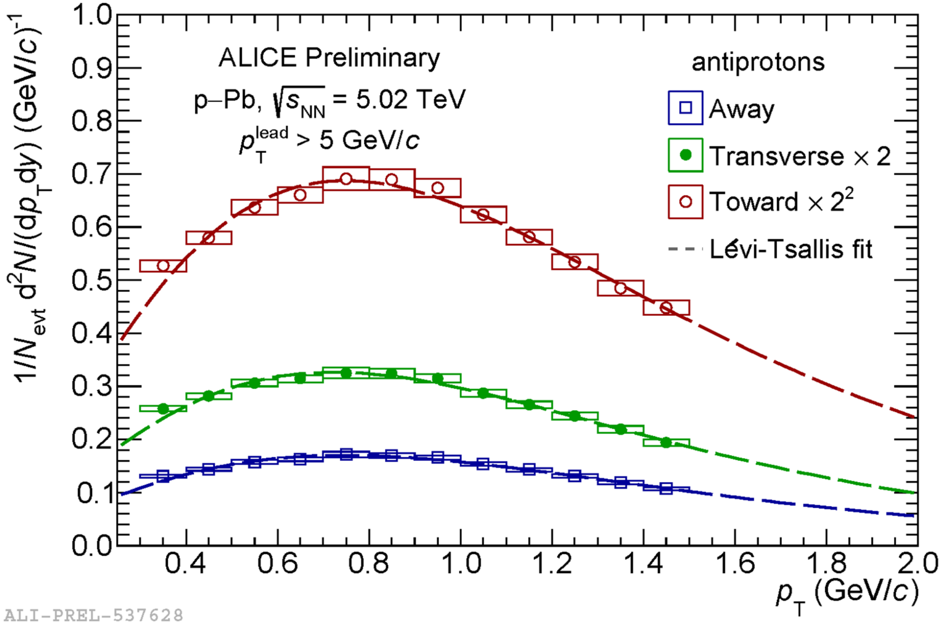
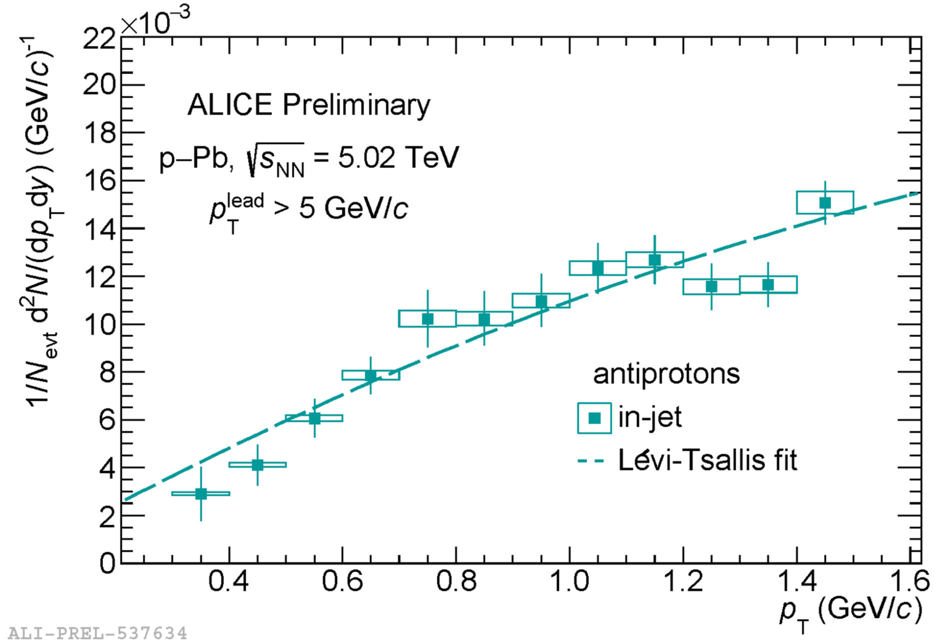
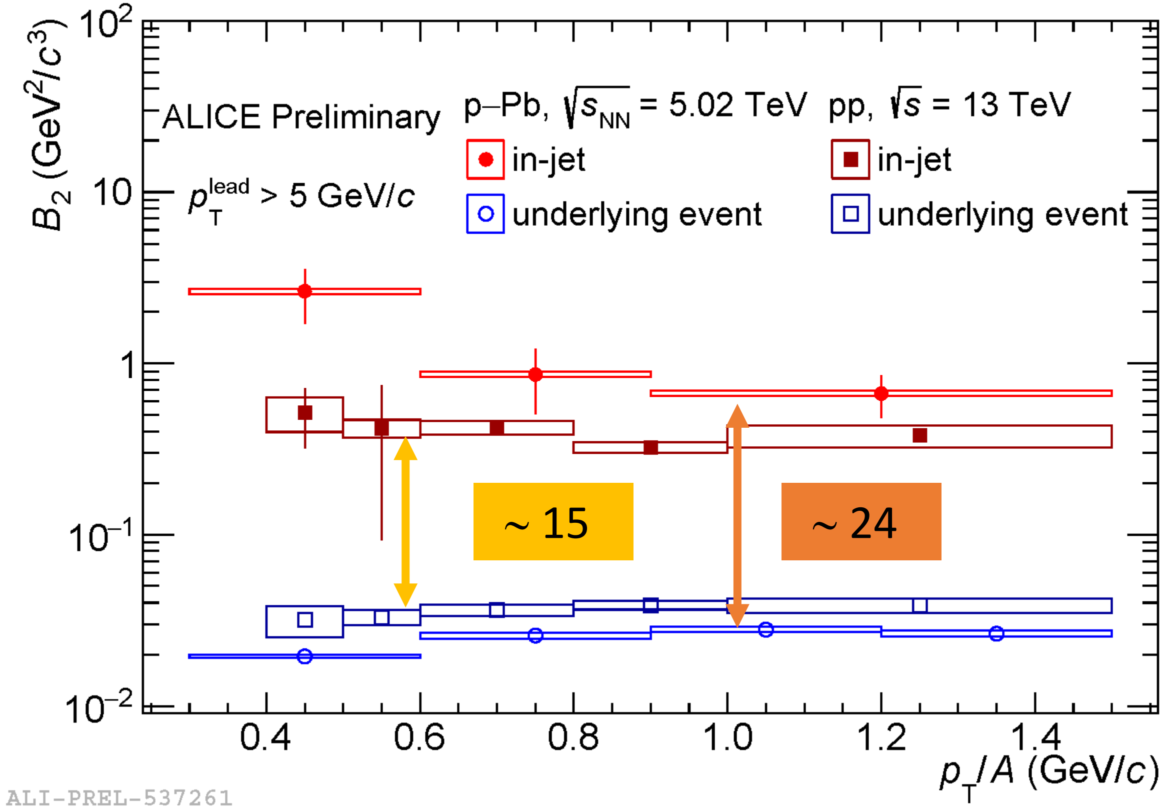




Jet = Toward - Transverse

B_2 in jet and UE

pp: *Phys. Rev. Lett. 131* (2023) 042301



- **Striking gap** between B_2^{jet} and B_2^{UE} → compatible with the coalescence picture
- **Larger gap** in p–Pb collision wrt pp collisions

B_2 in jet and UE

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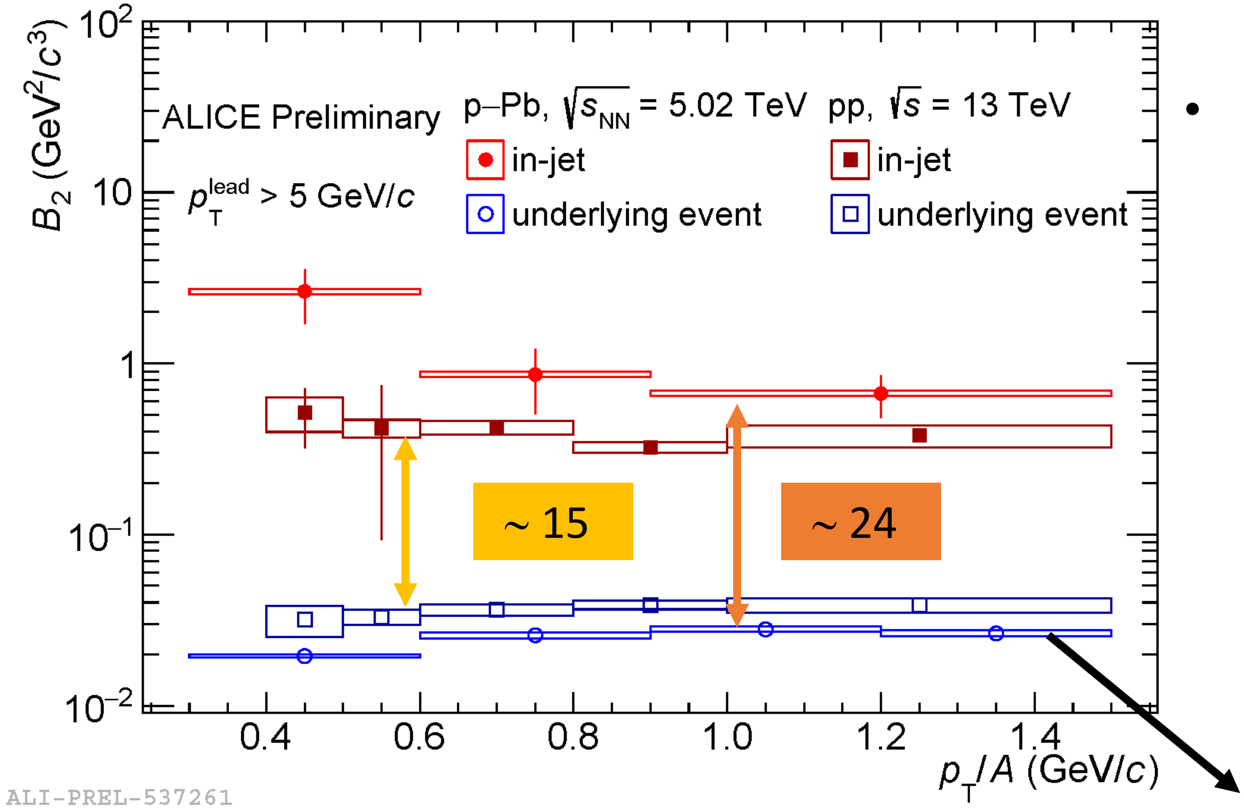

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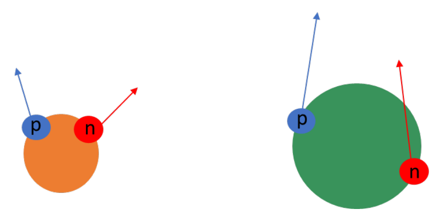

B_2^{UE}(p–Pb) < B_2^{UE}(pp) since p–Pb source size is larger than pp source size

B_2 in jet and UE

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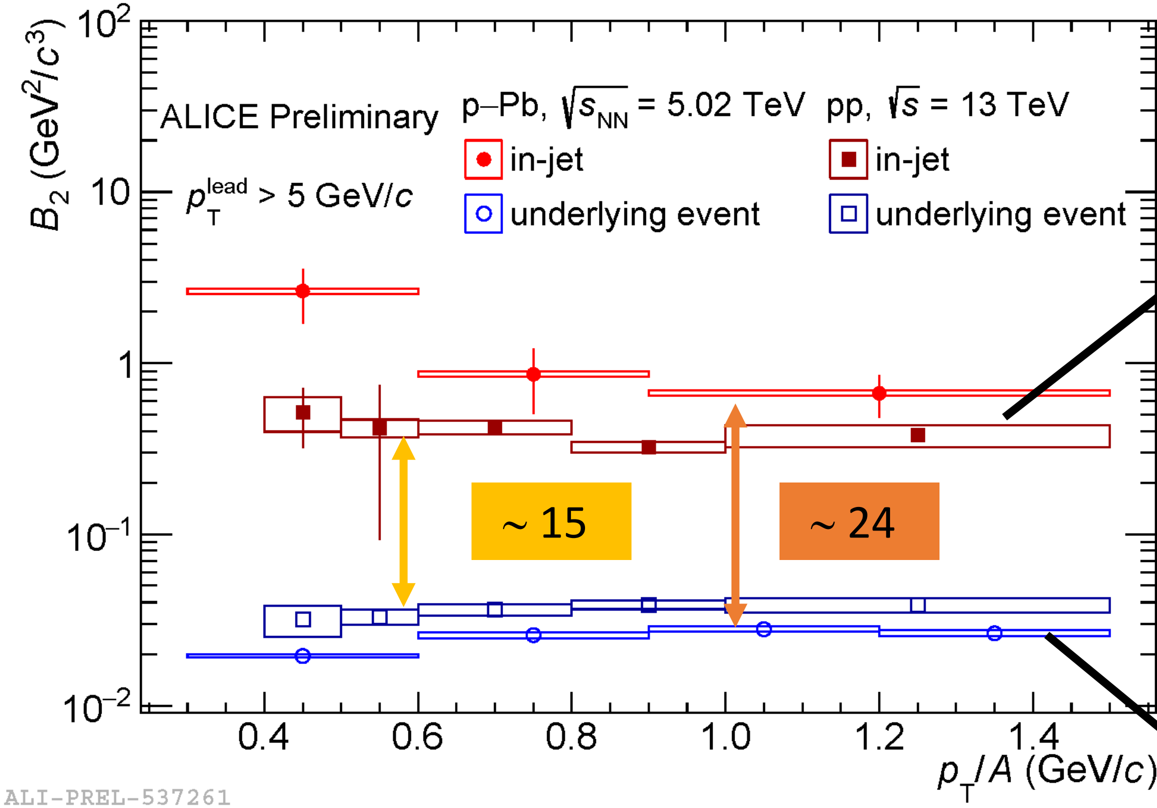


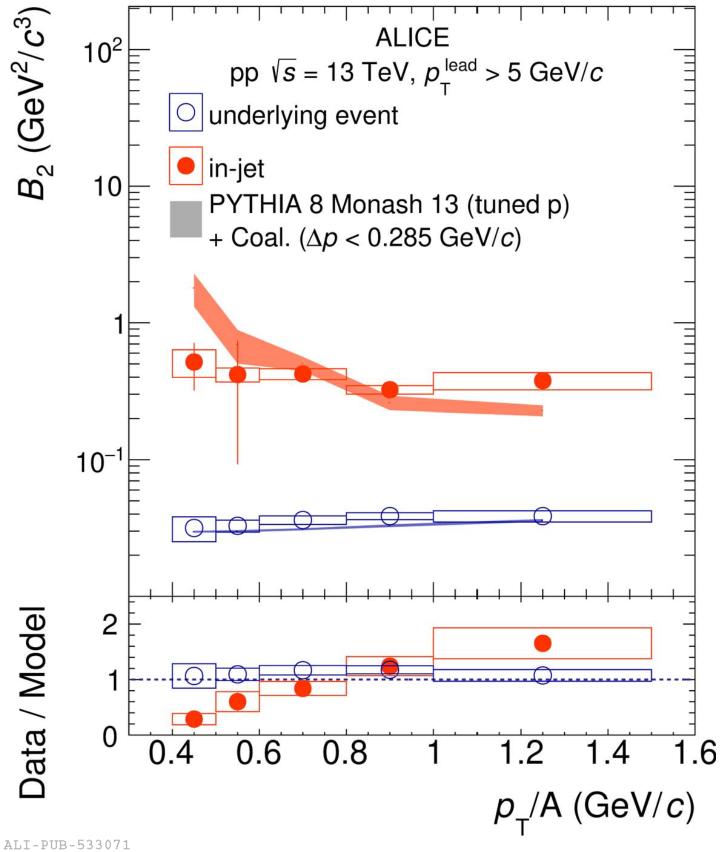
- **Striking gap** between B_2^{jet} and B_2^{UE} → compatible with the coalescence picture
- **Larger gap** in p–Pb collision wrt pp collisions

B_2^{jet} (p–Pb) > B_2^{jet} (pp)

- Different particle composition of jets in pp and p—Pb?
- Stronger momentum correlations between nucleons?

B_2^{UE} (p–Pb) < B_2^{UE}(pp) since p–Pb source size is larger than pp source size

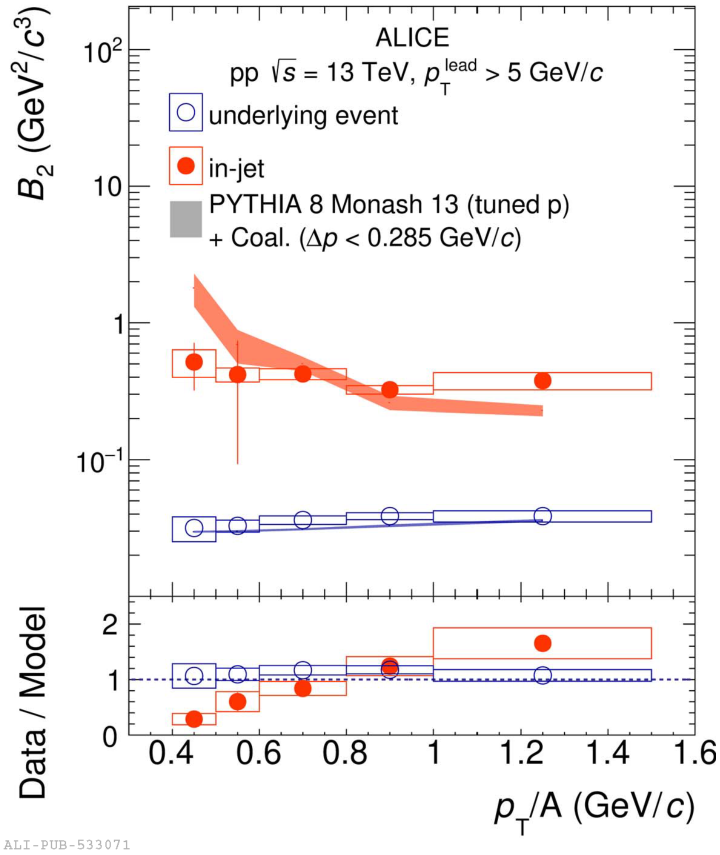
B_2 in jet and UE – model comparison



PYTHIA 8 Monash 13 +
simple coalescence

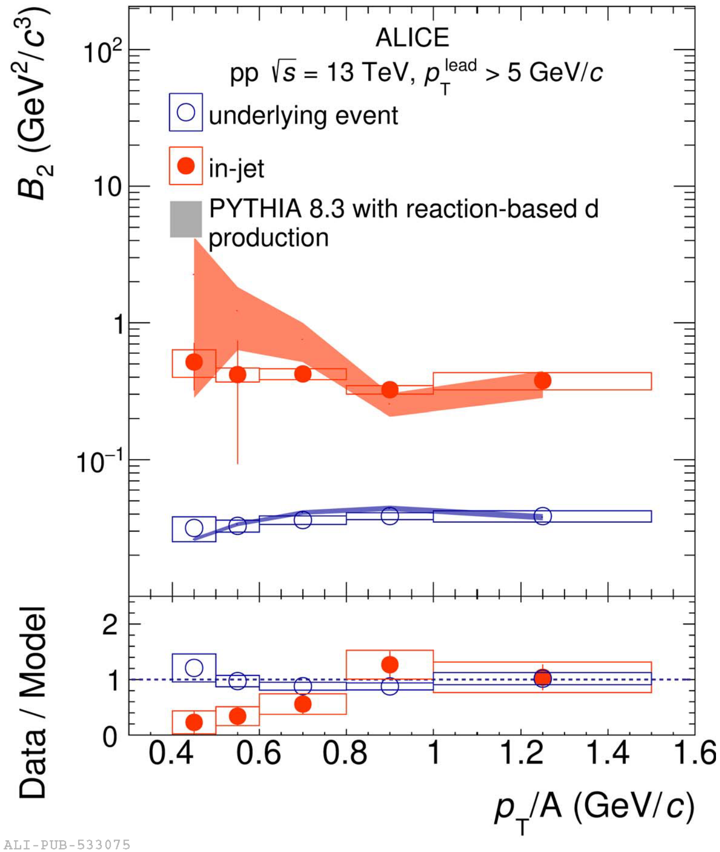
Phys. Rev. Lett. 131 (2023) 042301

B_2 in jet and UE – model comparison



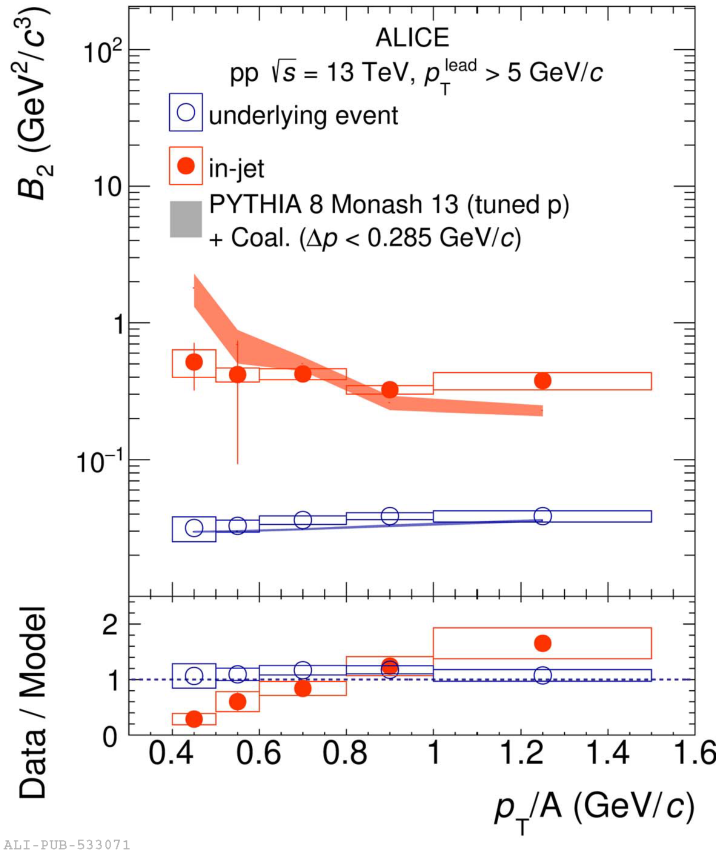
PYTHIA 8 Monash 13 + simple coalescence

PYTHIA 8.3 with reaction-based deuteron production (Bierlich et al., arXiv:2203.11601)



Phys. Rev. Lett. 131 (2023) 042301

B_2 in jet and UE – model comparison



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Both models qualitatively reproduce the data and the large difference between B_2^{jet} and B_2^{UE}

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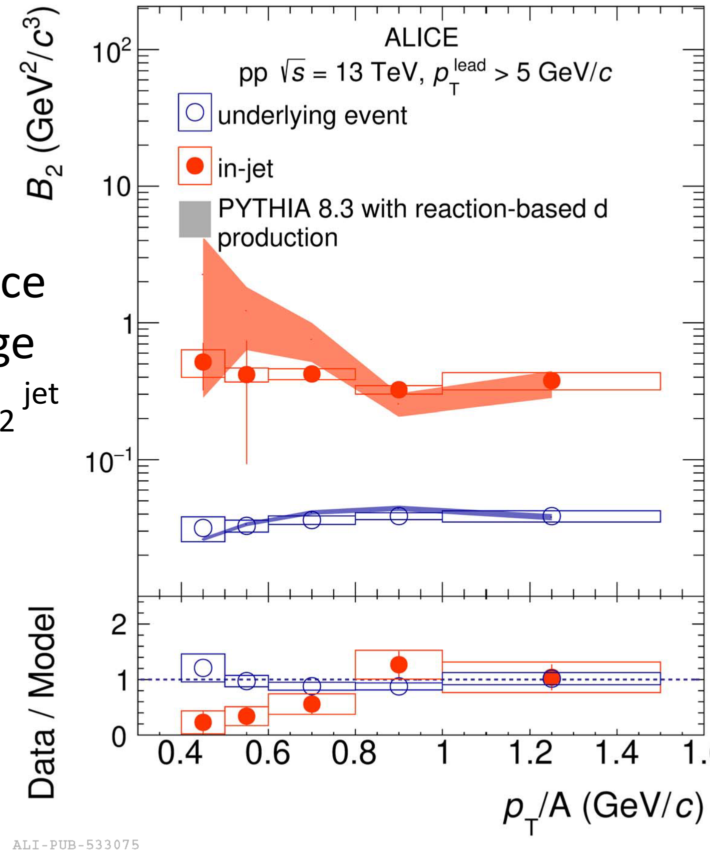
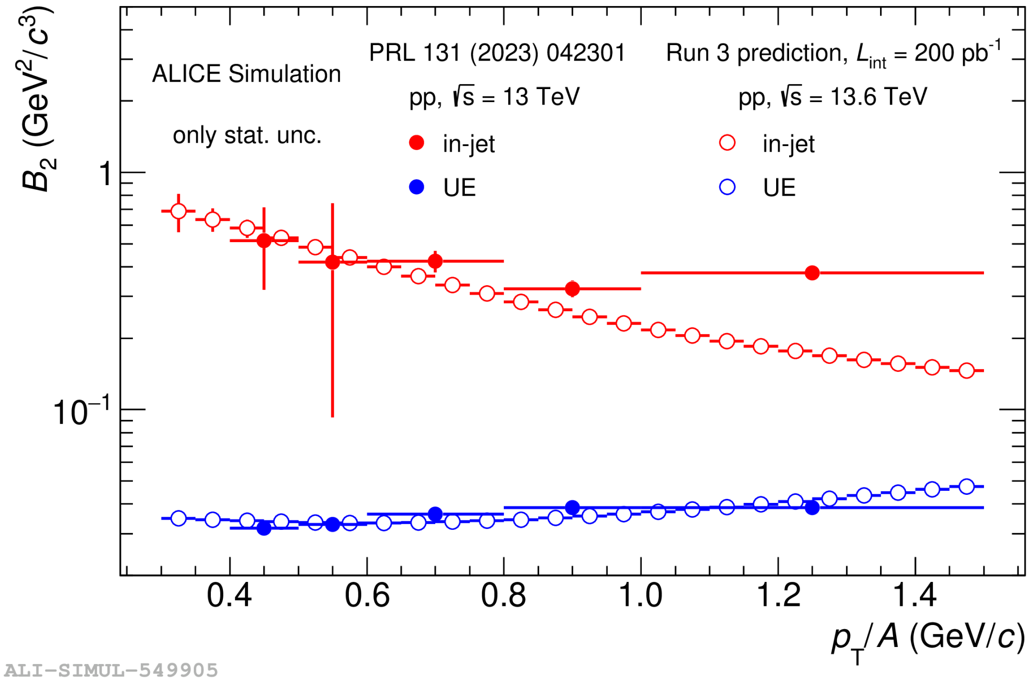


Phys. Rev. Lett. 131 (2023) 042301

Prospect for Run 3 measurements



- Simulation studies for Run 3 prospects
- The measured p_T spectra [1][2] are parametrized and used as inputs for the simulation
- Assumed same efficiency and σ_{inel}[3] of Run 2
- **Improvement of the statistical uncertainties:**
  - factor 4 for B_2^{jet}
  - factor 3 for B_2^{UE}
- **Promising results**, multi-differential measurements (e.g. vs multiplicity in the transverse region) could be performed

[1] *Phys. Rev. Lett.* 131 (2023) 042301
[2] *JHEP* 06 (2023) 027
[3] LHCb Collaboration, *JHEP* 06 (2018) 100

Conclusions

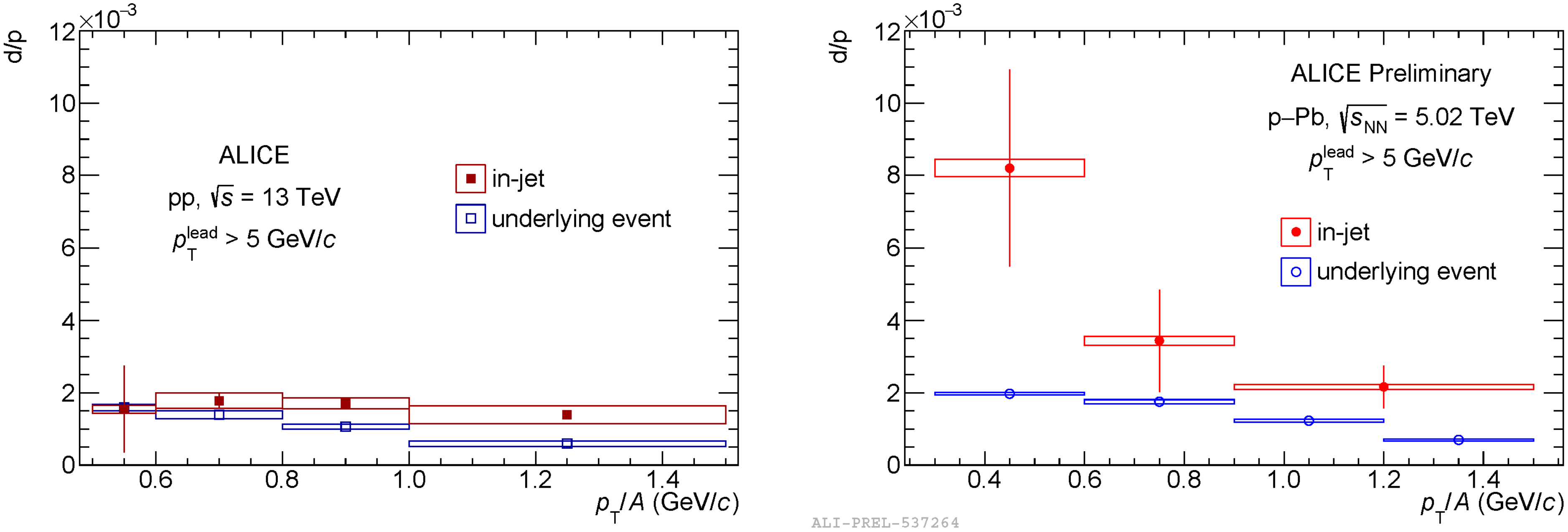
- Light (anti)nuclei production have been studied in depth by the ALICE experiment, in order to constraint their production mechanism
- State of the art coalescence model based on femtoscopy measurements and Wigner formalism
- The coalescence model can be tested looking at the light (anti)nuclei production in and out of jets
- **Striking gap between B_2^{jet} and B_2^{UE}** → compatible with the coalescence picture
- Good agreement with model comparison in pp collisions
- **New studies could be performed** thanks to the high integrated luminosity that will be collected at the end of Run 3

Thank you for your kind attention!

Backup

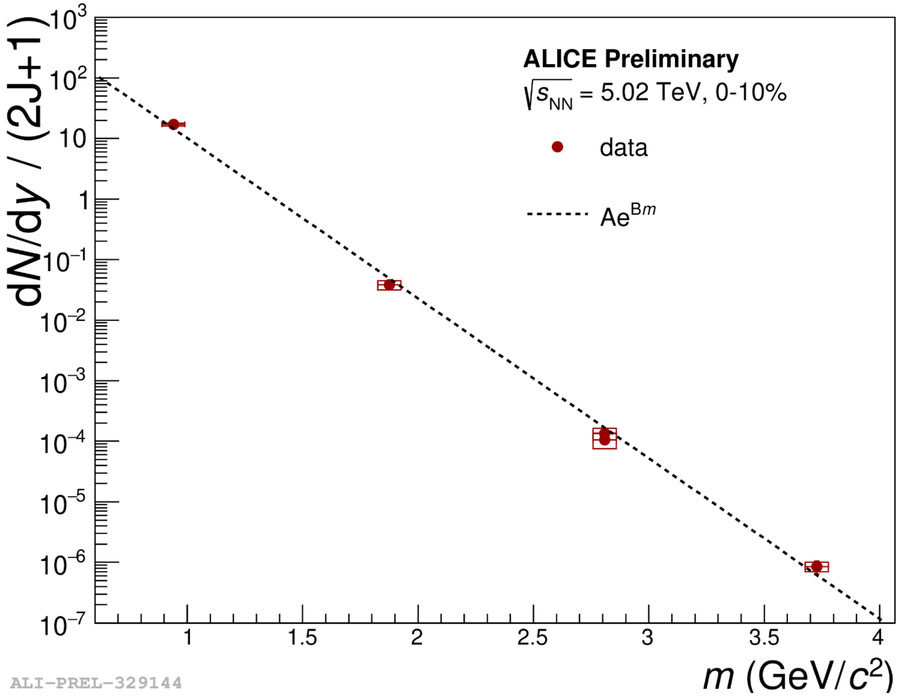
d/p injet and UE

d: *Phys. Rev. Lett.* 131 (2023) 042301   p: *JHEP* 06 (2023) 027



- d/p $^{\text{jet}}$ is higher than d/p $^{\text{UE}}$
- **Higher d/p $^{\text{jet}}$ in p–Pb collisions wrt pp collisions**
- Different particle composition → could affect the coalescence probability

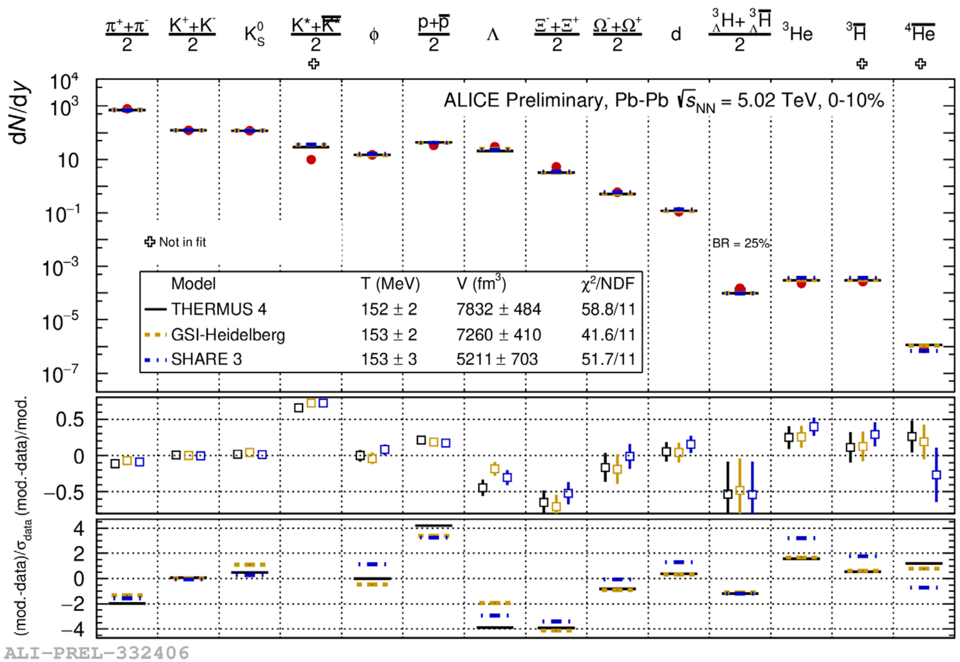
Statistical Hadronization Model



- Hadrons emitted from a system in statistical and chemical equilibrium
- T_{chem} is the key parameter
- dN/dy ∝ exp(-m/T_{chem}) → nuclei are sensitive to T_{chem} due their large mass
- Particle yield well described with a common T_{chem} of ~ 156 MeV

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

Statistical Hadronization Model



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- $dN/dy \propto \exp(-m/T_{chem})$ → nuclei are sensitive to T_{chem} due their large mass
- Particle yield well described with a common T_{chem} of ~ 156 MeV
- Comparison between measured and expected yield, evaluated with different SHM implementations
- Nuclei binding energy ~ few MeV → how can they survive?

THERMUS 4: *Comput.Phys.Commun*. 180 (2009) 84-106

GSI-Heidelberg: *Phys.Lett. B* 673 (2009) 142

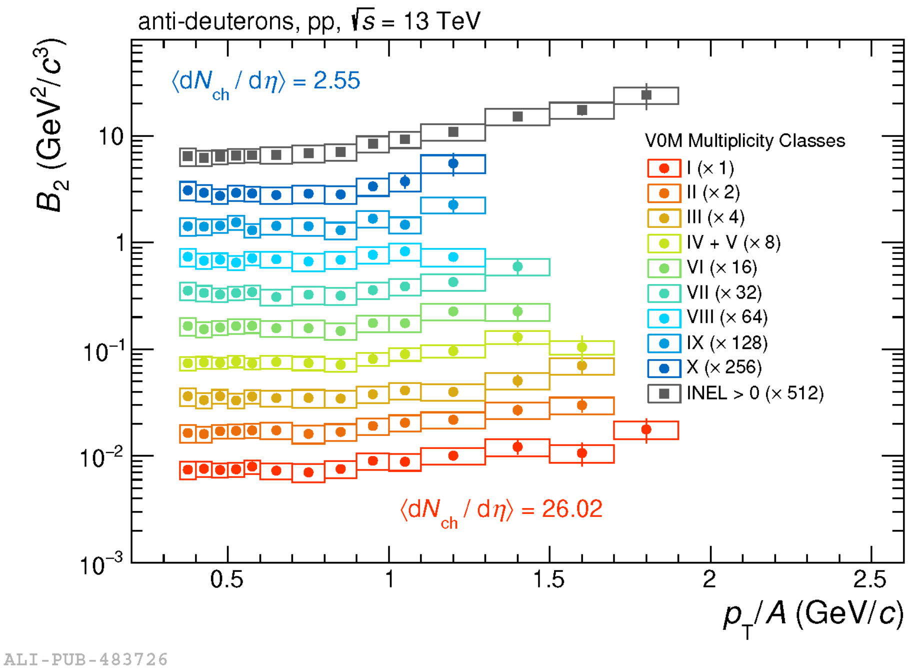
SHARE 3: *Comput.Phys.Commun.* 167 (2005) 229-251

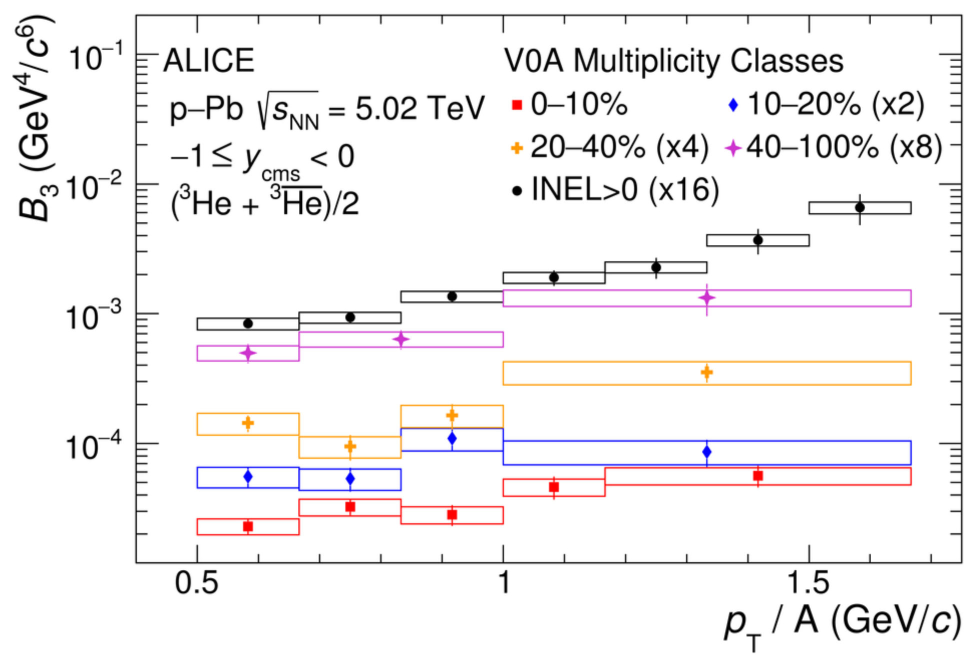
Andronic et al, *Nature* vol. 561 (2018) 321-330

Coalescence parameter

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

Phys. Rev. C 101 (2020) 044906

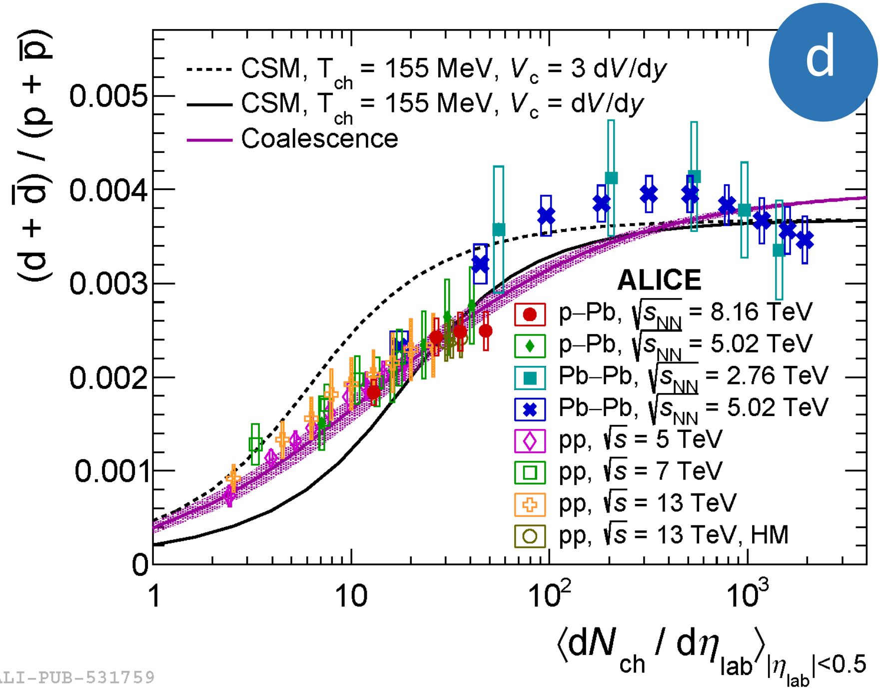


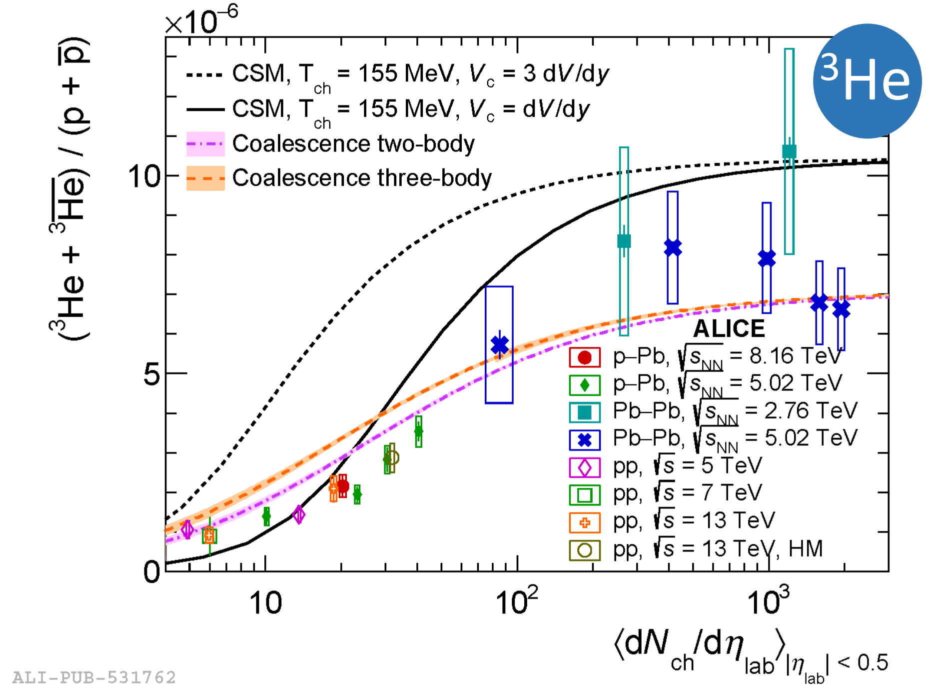


- B_A is rather flat in all multiplicity classes, but increase at high p_T/A in the MB class

Comparison with models – ratio to p

Phys. Lett. B 846 (2023) 137795

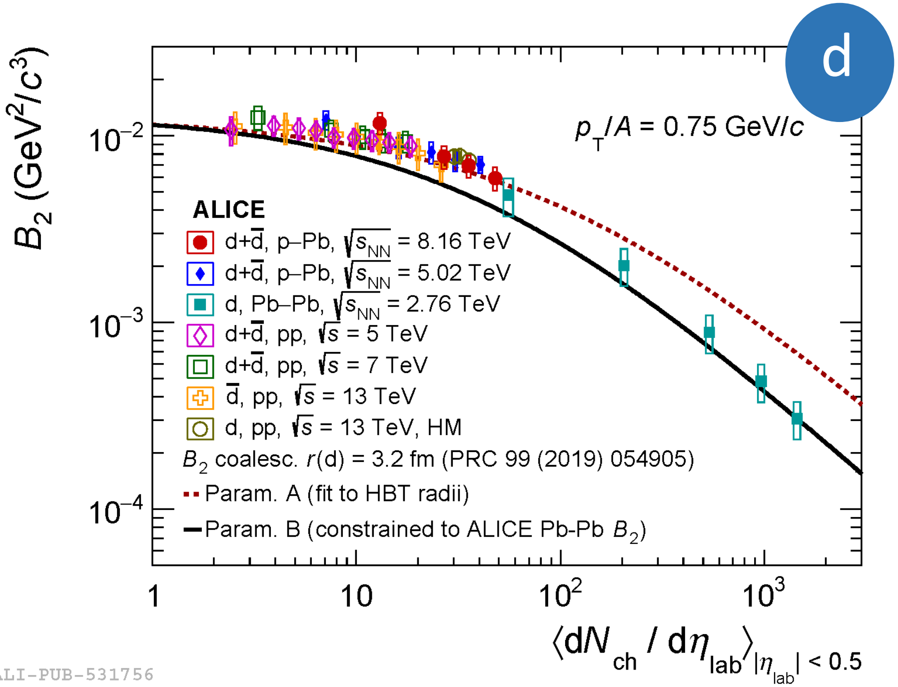




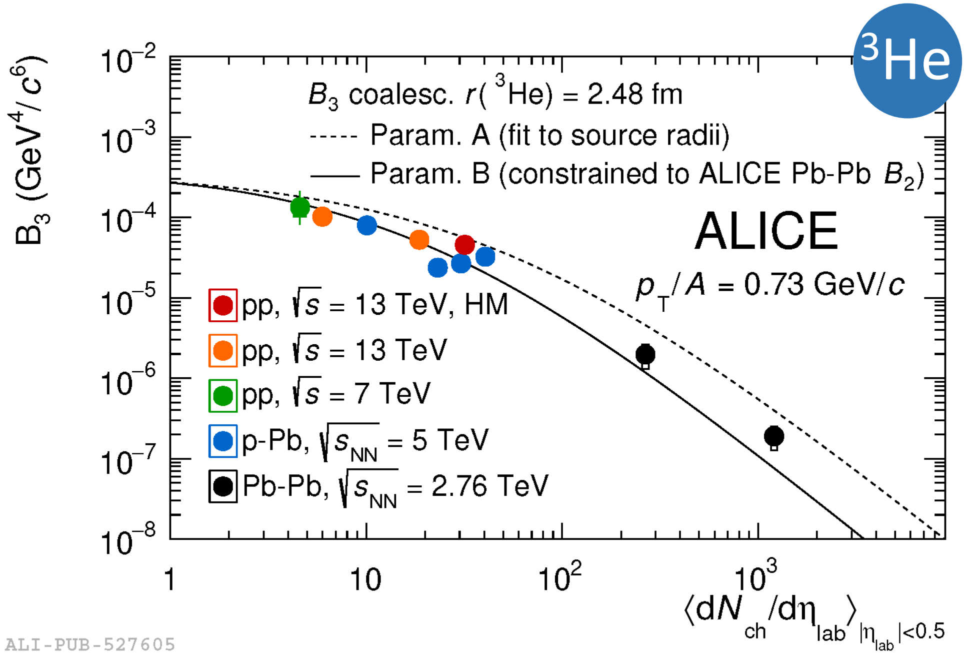
- d/p and He/p ratio evolves smoothly as a function of multiplicity → dependence on the system size
- Observed saturation at multiplicity that corresponds to Pb–Pb collisions
- Ratio compared to predictions from Thermal-FIST CSM and coalescence model
- SHM and coalescence give similar prediction for d, while they diverge for ^{3}He → **need new observables!**

Comparison with models – B_A

Phys. Lett. B 846 (2023) 137795

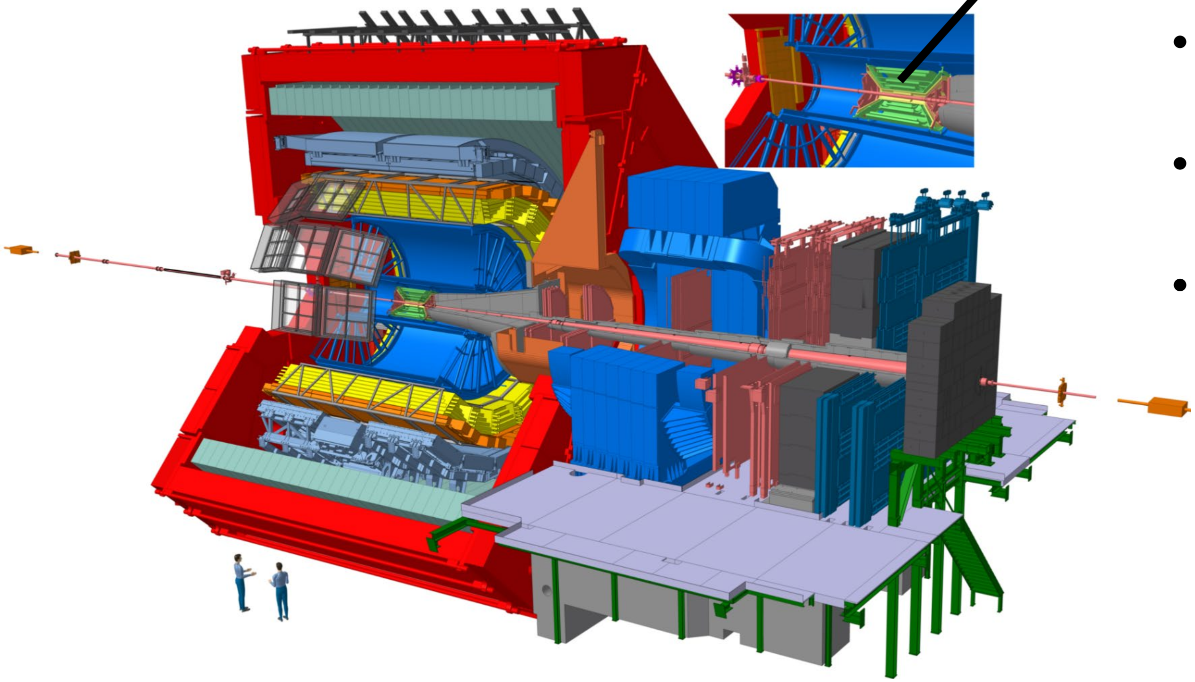


JHEP 01 (2022) 106



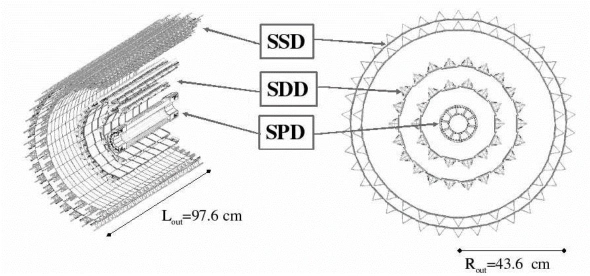
- Coalescence parameter evolves smoothly with multiplicity and decreases with source size
- Different parametrization of source size as a function of $dN_{ch}/d\eta$ available
- The parametrizations diverge at high multiplicity → ***B_A* is a good observable!**

The ALICE detector in Run 1&2



Inner Tracking System (ITS)
Six concentrical layer of silicon sensors:

- 2 layers of Silicon Pixel Detectors (SPD);
- 2 layers of Silicon Drift Detectors (SDD);
- 2 layers of Silicon micro-Strip Detectors (SSD).



JINST 3 (2008) S08002
Int. J. Mod. Phys. A 29 (2014) 1430044

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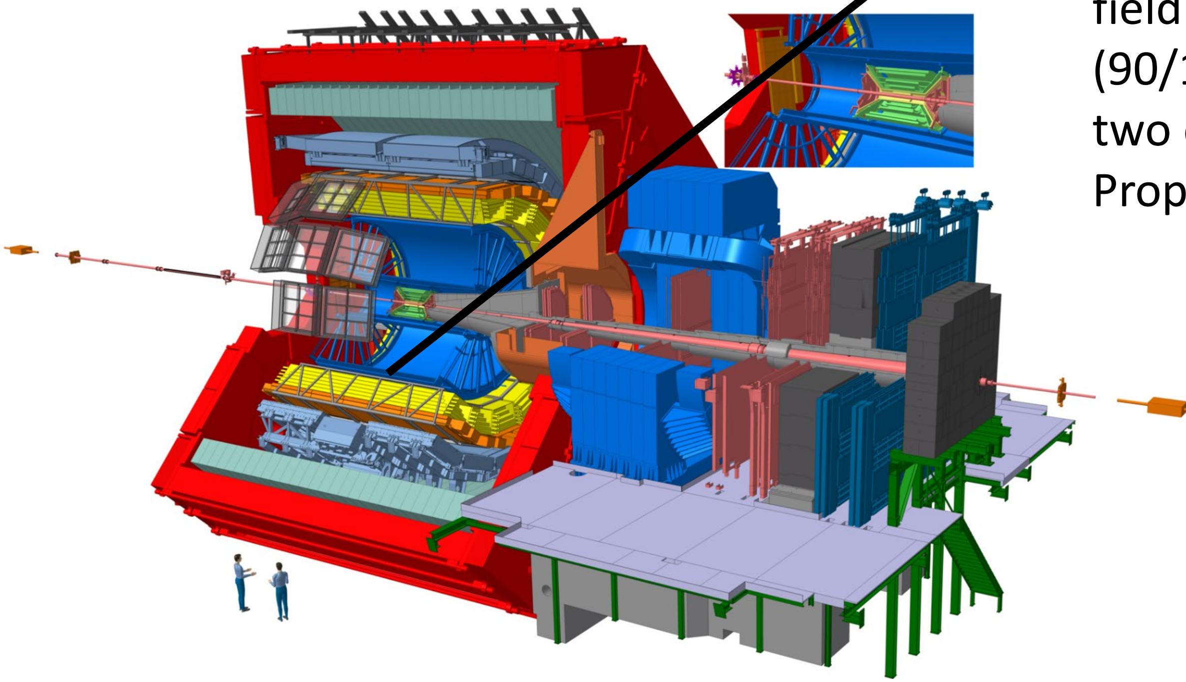
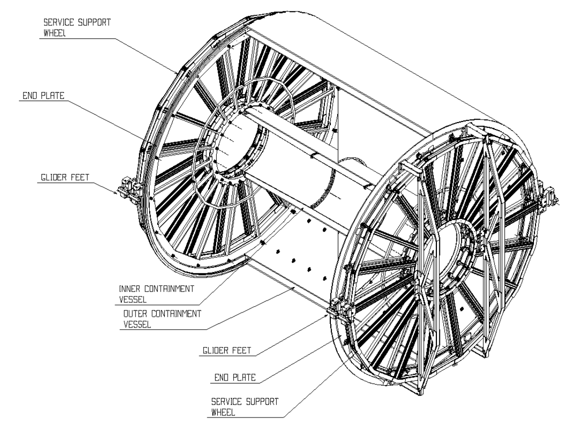


Time Projection Chamber (TPC)

Cylindrical gas detector, made by a field cage filled with $Ne/CO_2/N_2$ (90/10/5). The cage is closed with two endcaps made of Multi-Wire Proportional Chambers (MWPC).



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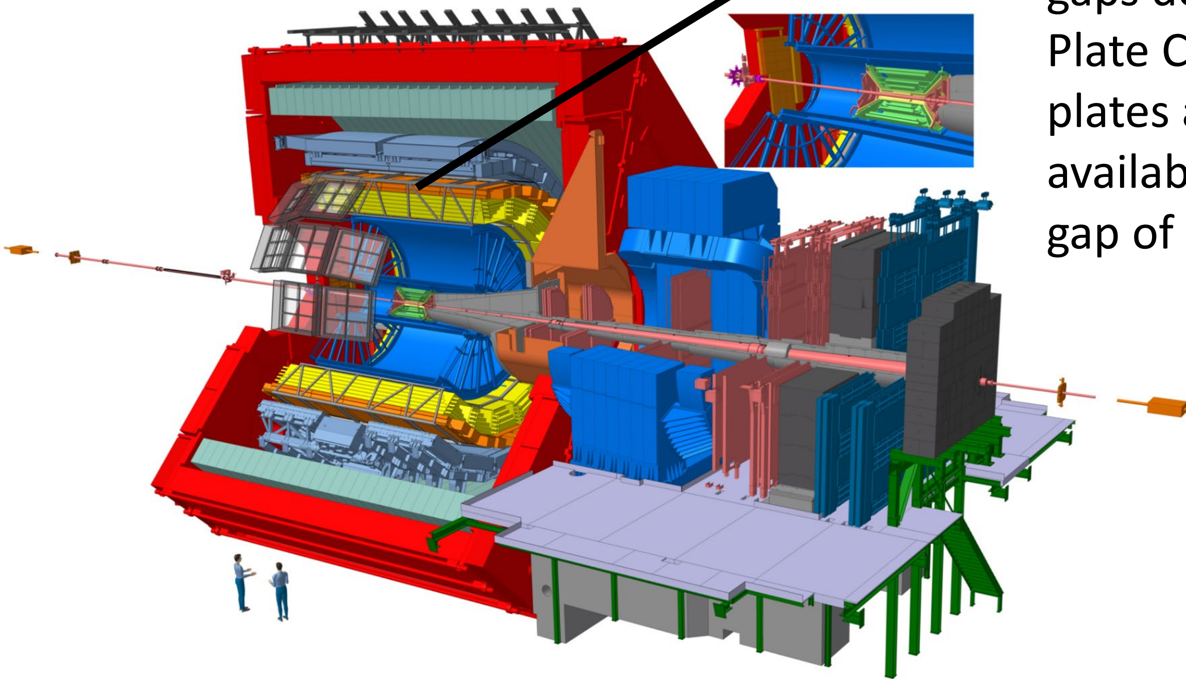
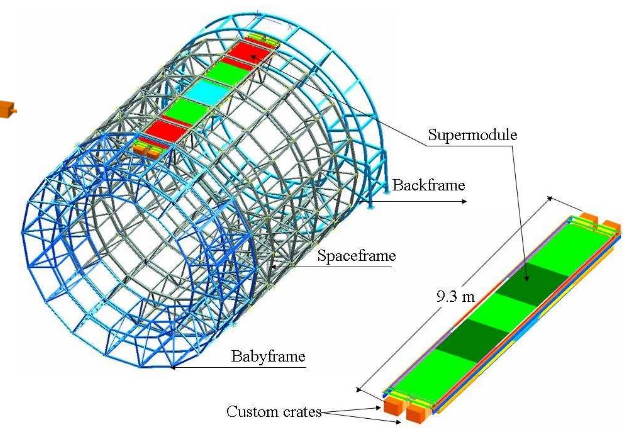


Time Of Flight (TOF)

90 modules formed by a system of 10 gaps double stack Multigap Resistive Plate Chambers (MRPC). The resistive plates are made with commercially available soda-lime glass sheets with a gap of 250 µm.



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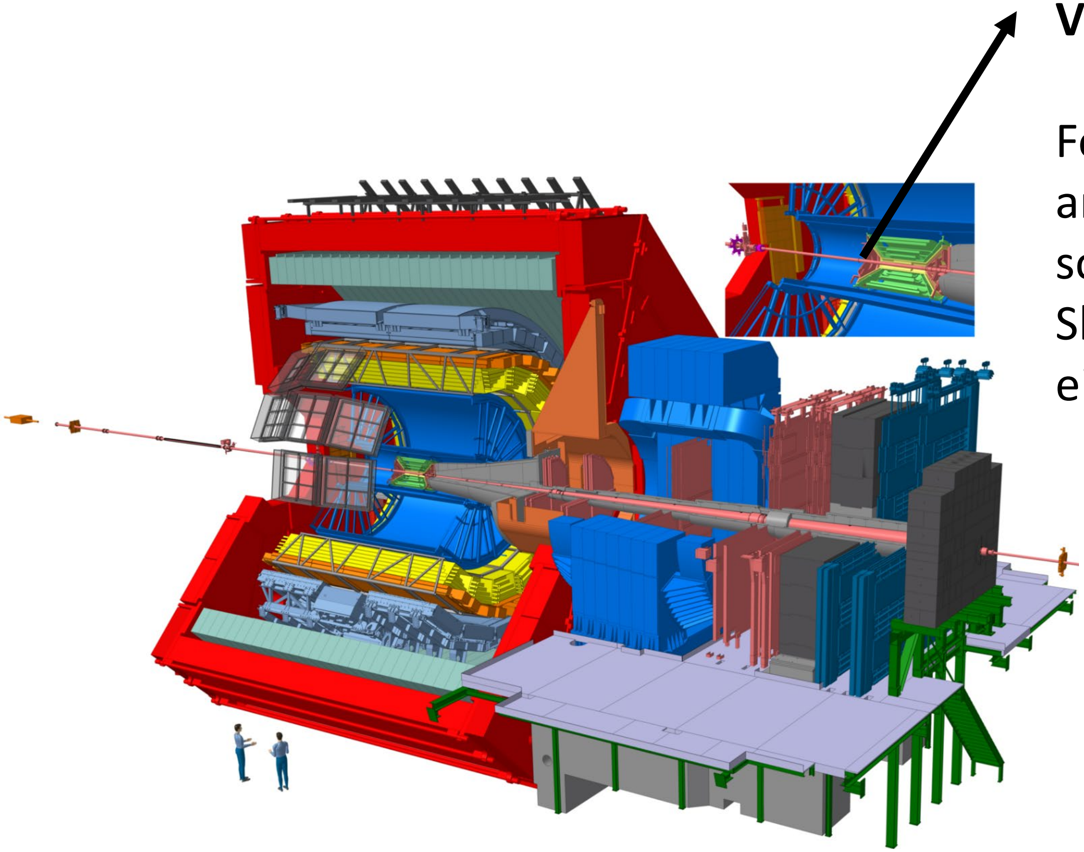
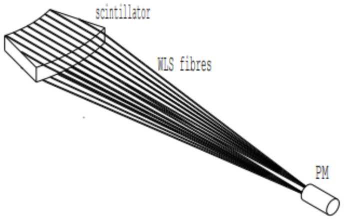
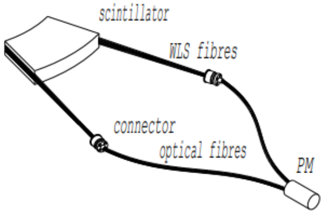


V0

Formed by two different modules, V0A and V0C, consisting of two arrays of scintillator counters and Wave-Length Shifting (WLS) fibres installed on either sides of the interaction point.



V0A



V0C

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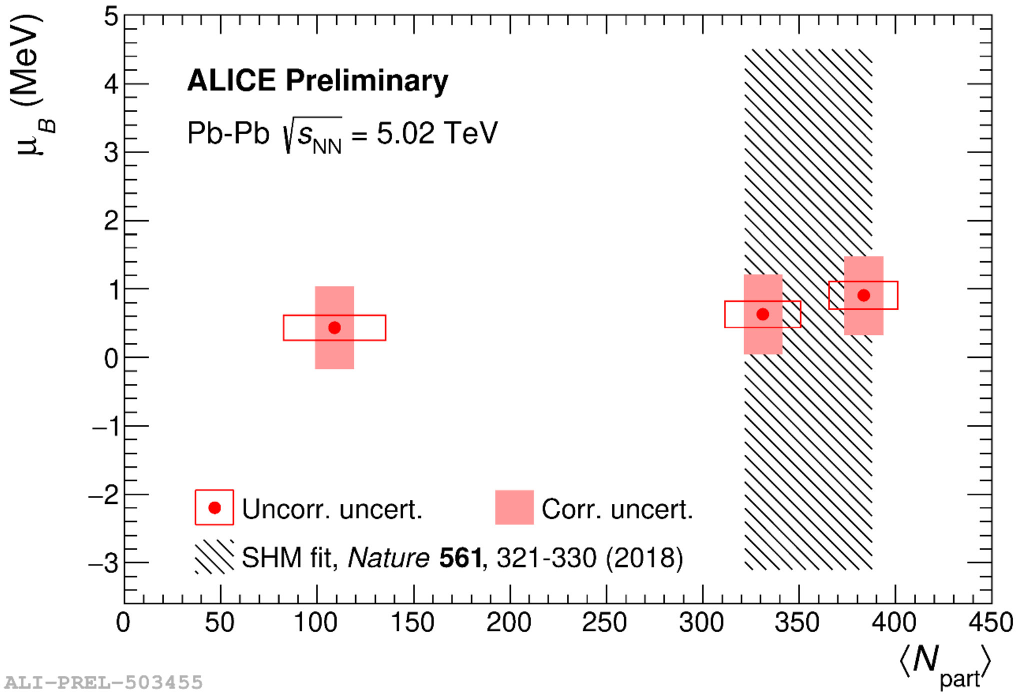
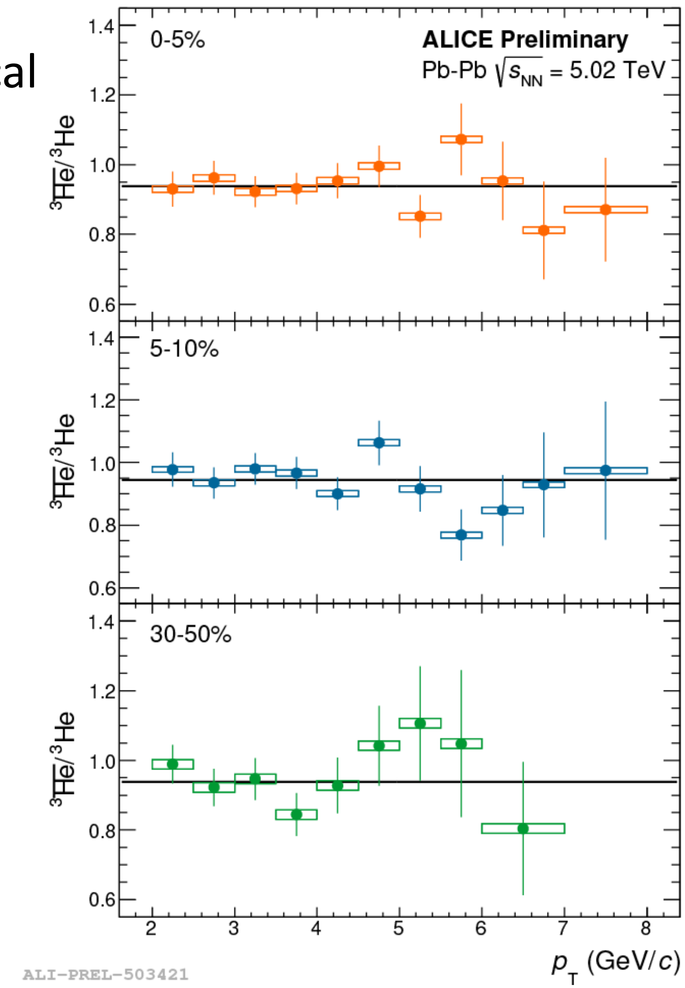
LHC: an (anti)nuclei factory

- At the LHC energies the same quantity of matter and antimatter are produced at midrapidity → baryochemical potential $\mu_B \approx 0$
- Antimatter-to-matter ratio consistent with unity





In-jet and UE spectra

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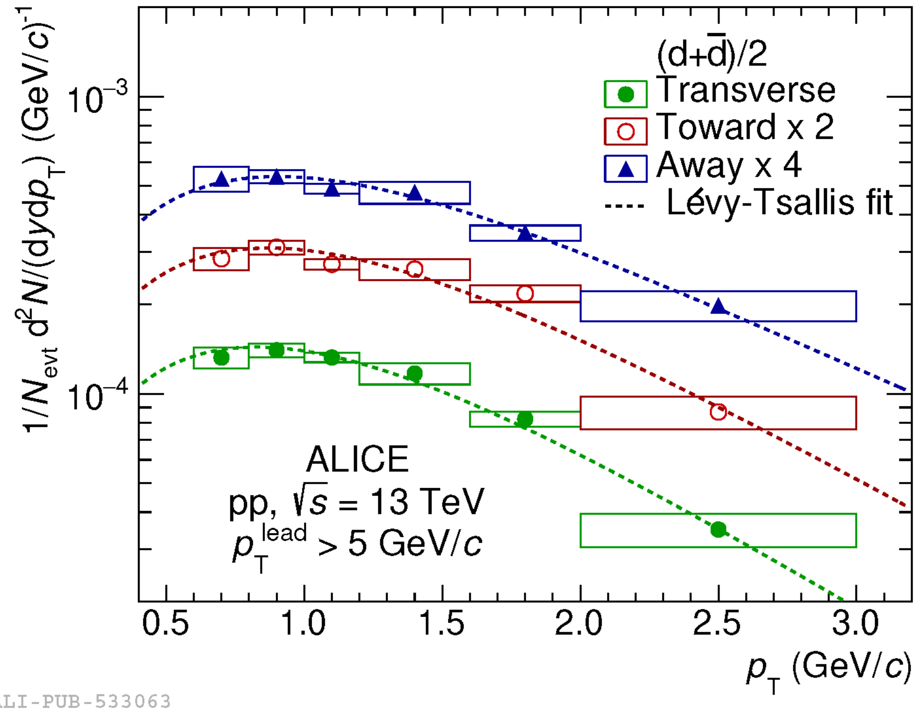
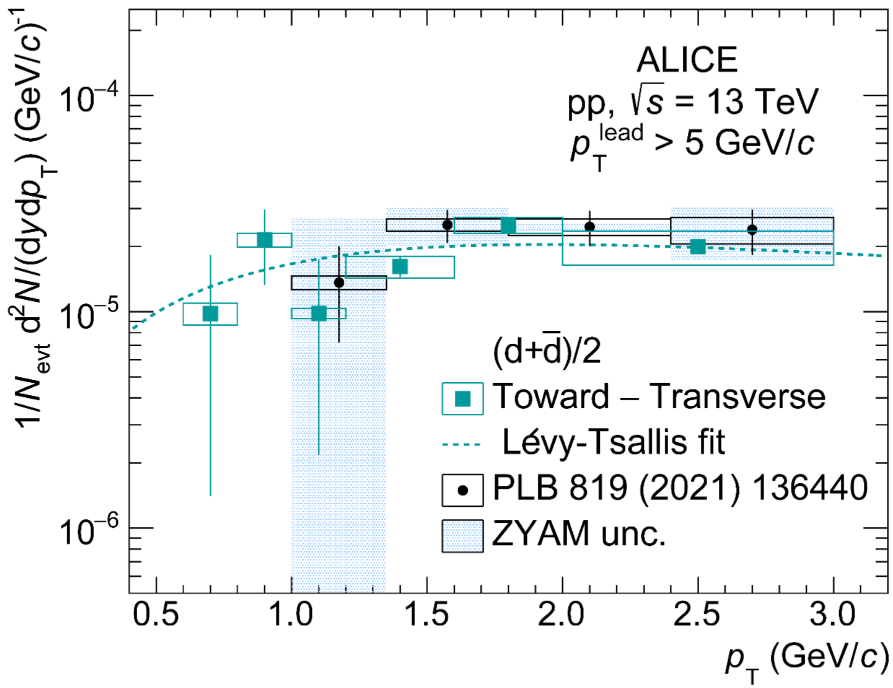
pp @ 13 TeV





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

Jet = Toward – Transverse

The results are consistent with those obtained using the two-particle correlation method

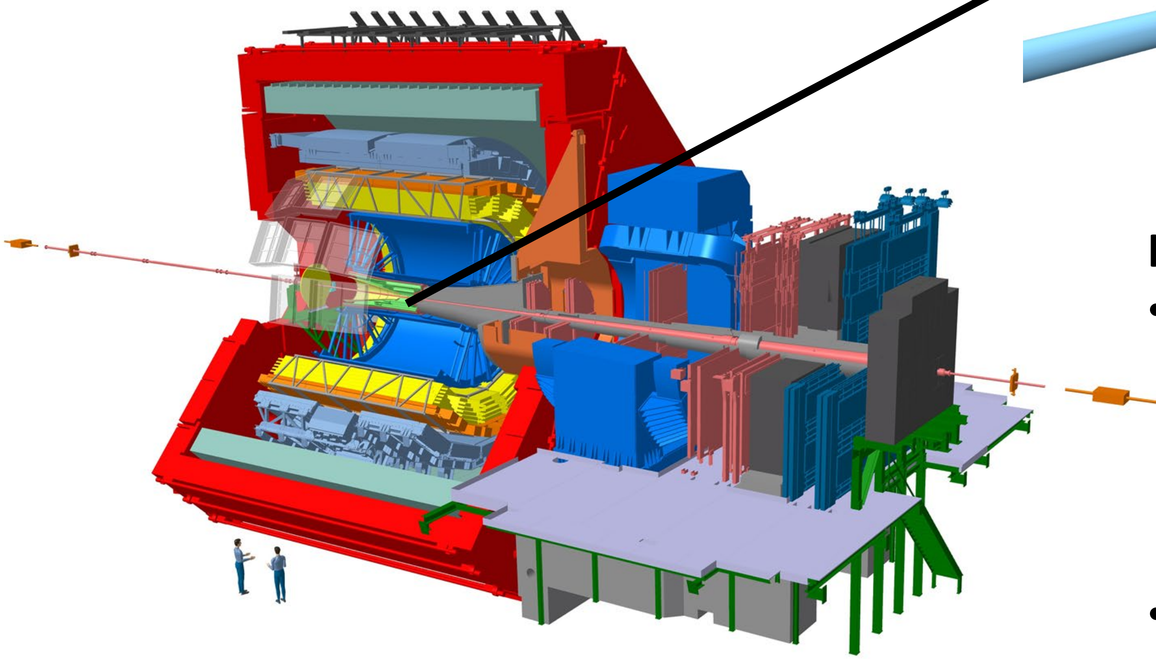
PYTHIA simulation details

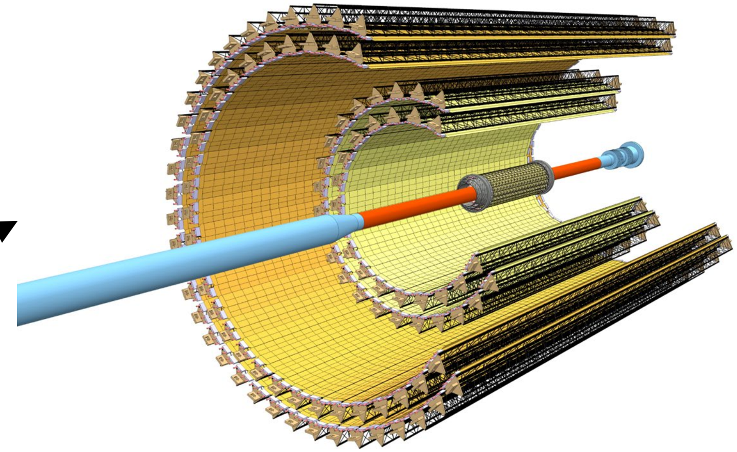
- PYTHIA 8.3:
  - d production via ordinary reactions
  - Energy dependent cross sections parametrized based on data
  - Reactions:

    $p + n \rightarrow \gamma + d$
    $p + n \rightarrow \pi^0 + d$
    $p + n \rightarrow \pi^0 + \pi^0 + d$
    $p + n \rightarrow \pi^+ + \pi^- + d$
    $p + p \rightarrow \pi^+ + d$
    $p + p \rightarrow \pi^+ + \pi^0 + d$
    $n + n \rightarrow \pi^- + d$
    $n + n \rightarrow \pi^- + \pi^0 + d$

- PYTHIA 8 Monash:
  - Simple coalescence
  - d is formed if $\Delta p < p_0$, with $p_0 = 285$ MeV/c

The new ALICE detector





ITS upgrade:

- 7 layers of silicon pixel detectors with low material budget (0.35% X_0 per layer for inner barrel)
- 1st layer closer to interaction point (22 mm) → improved pointing resolution (×3)

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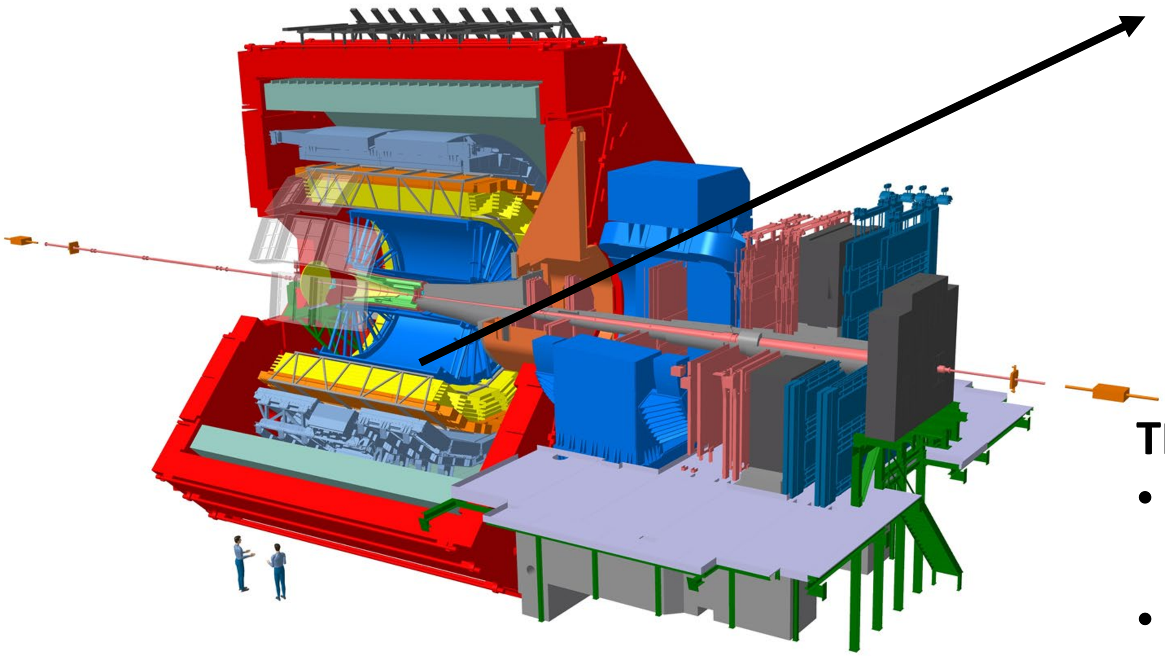
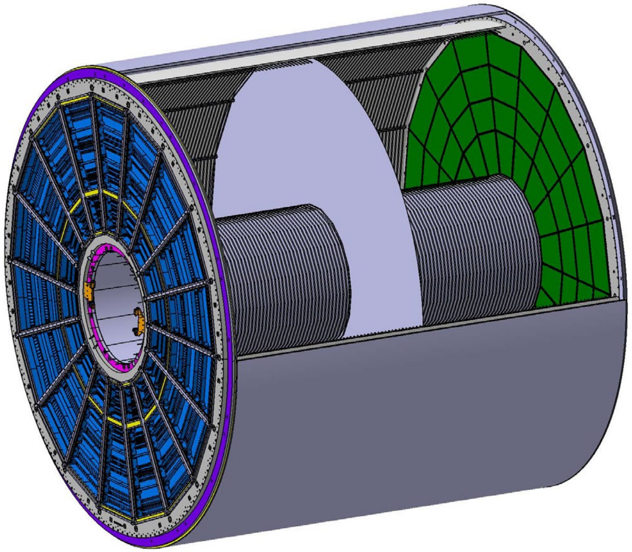
The new ALICE detector

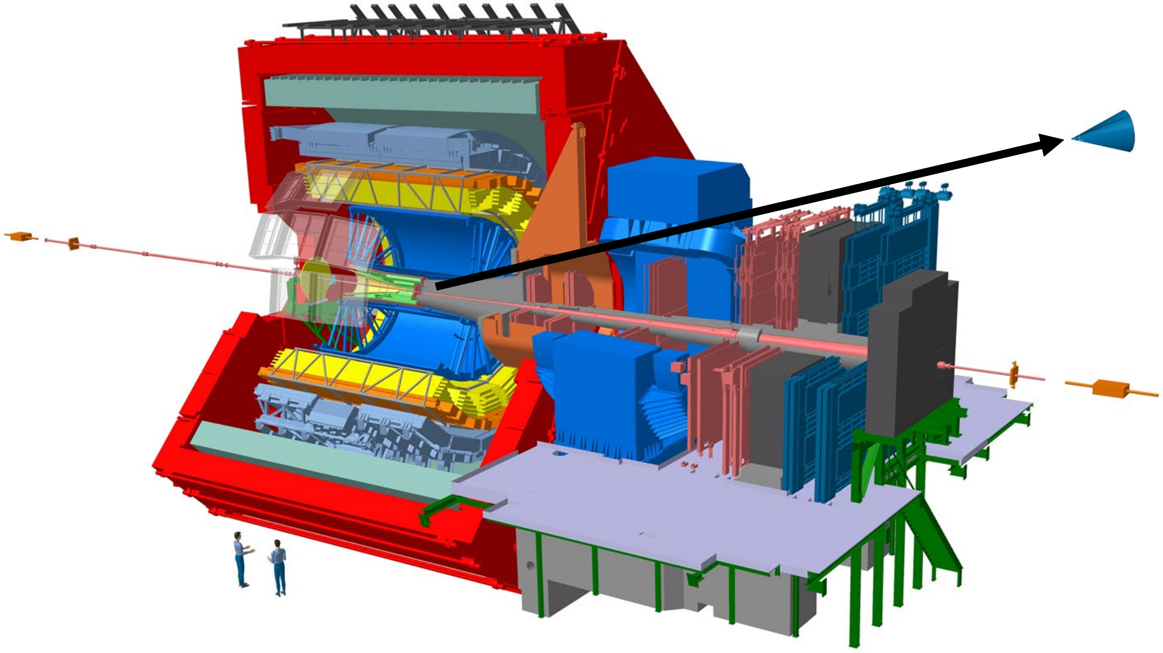


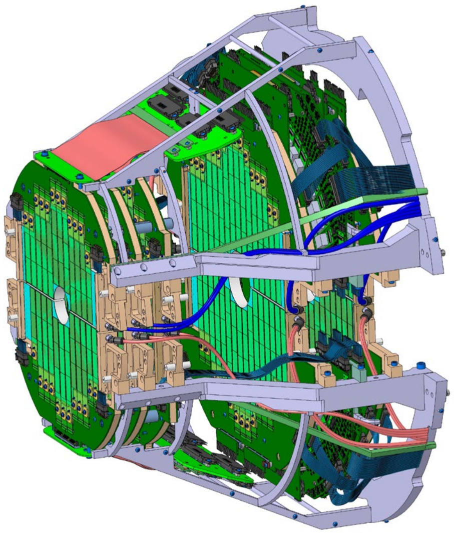


TPC upgrade:

- MWPCs replaced with GEMs
- continuous readout (up to 50 kHz in Pb-Pb collisions) → about x50 more events wrt Run 2 for Pb-Pb collisions

The new ALICE detector

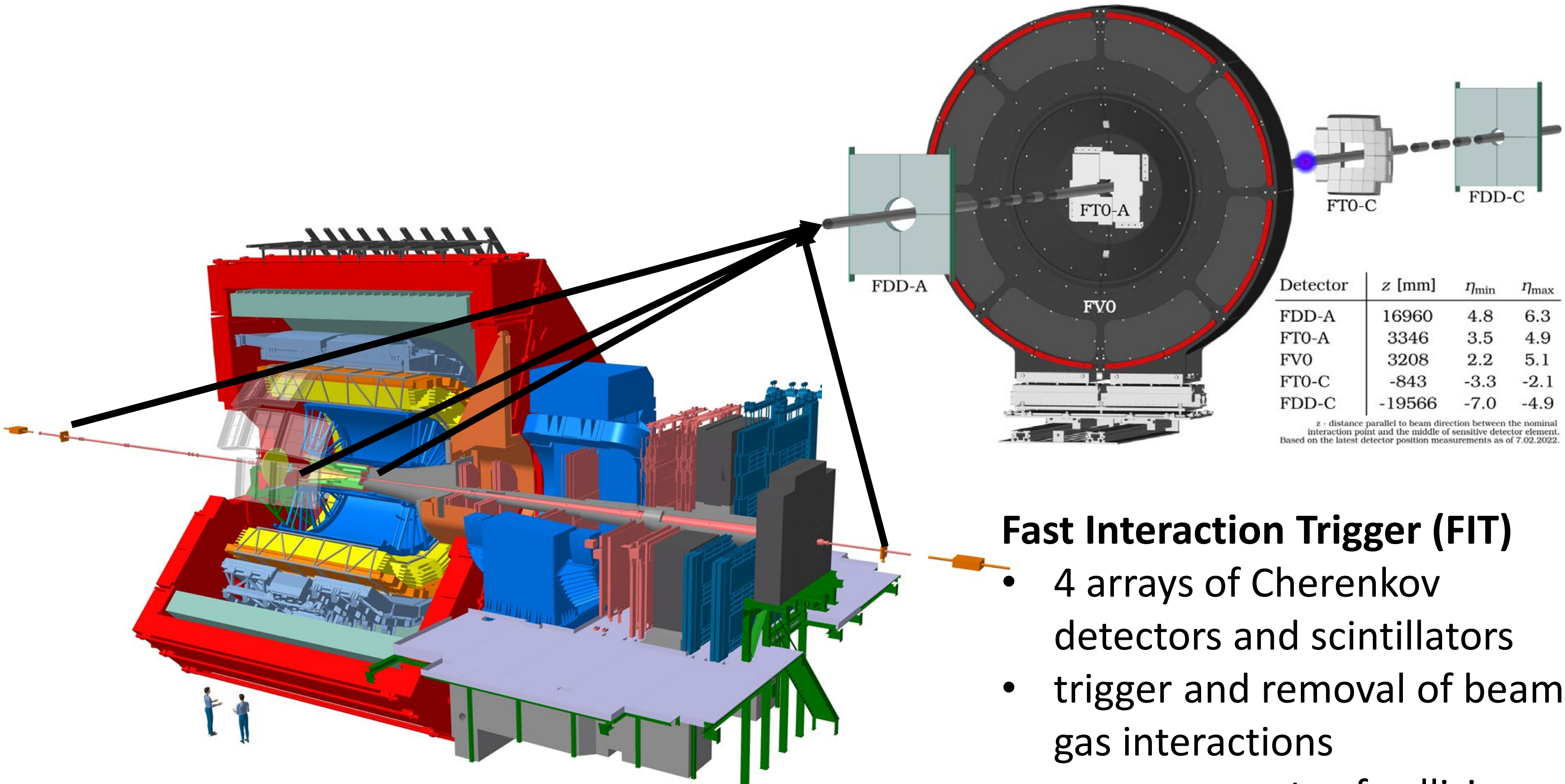




MFT (Muon Forward Tracker)

- High-resolution silicon tracker installed before the forward absorber
- Improve muon pointing and separation of prompt and non-prompt muons

The new ALICE detector



Detector	z [mm]	η_{min}	η_{max}
FDD-A	16960	4.8	6.3
FT0-A	3346	3.5	4.9
FV0	3208	2.2	5.1
FT0-C	-843	-3.3	-2.1
FDD-C	-19566	-7.0	-4.9

z - distance parallel to beam direction between the nominal interaction point and the middle of sensitive detector element. Based on the latest detector position measurements as of 7.02.2022.

Fast Interaction Trigger (FIT)

- 4 arrays of Cherenkov detectors and scintillators
- trigger and removal of beam-gas interactions
- measurements of collision time and geometry (centrality and event plane)