Overview and new directions about light (anti)nuclei measurements with ALICE

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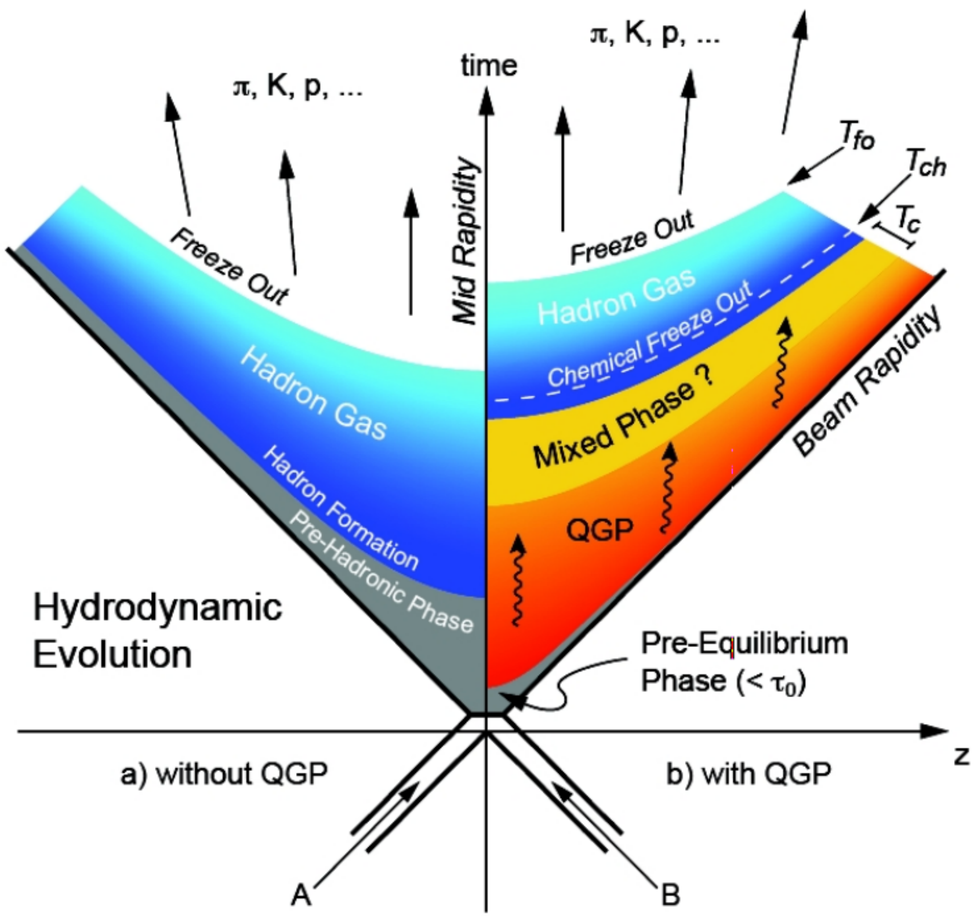
On behalf of the ALICE Collaboration

1. University and INFN of Catania

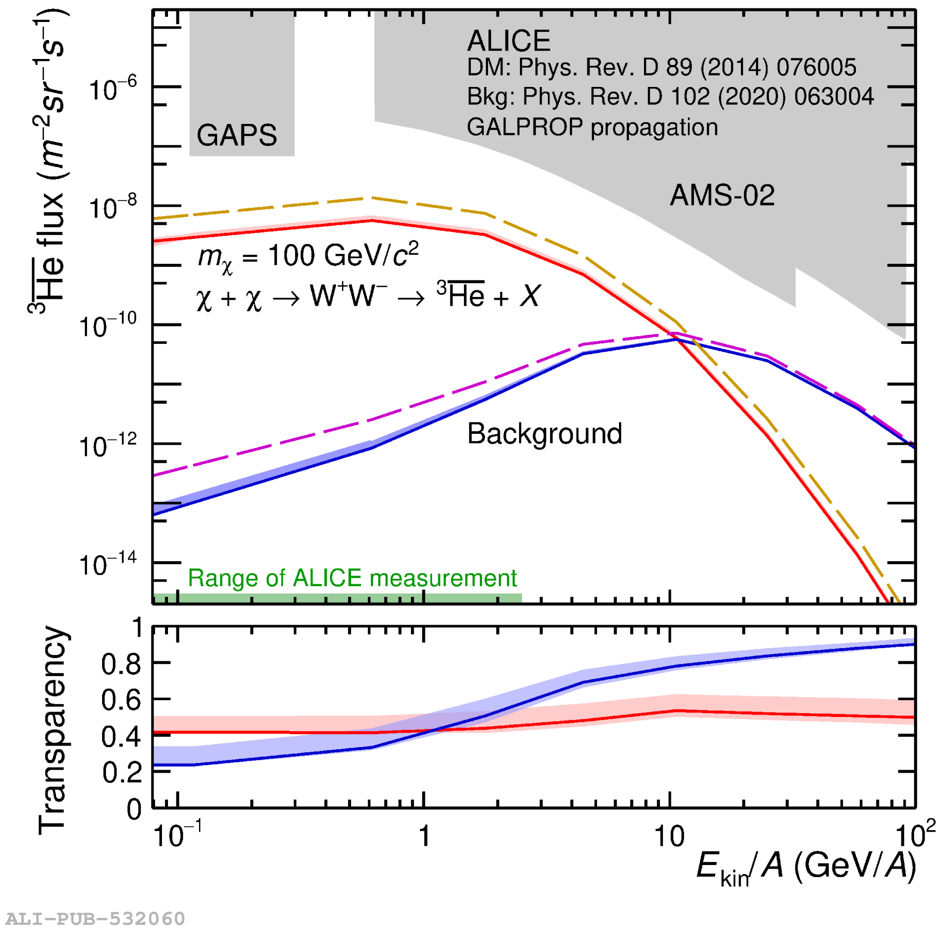
HADRON 2023

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 Model (SHM) and coalescence

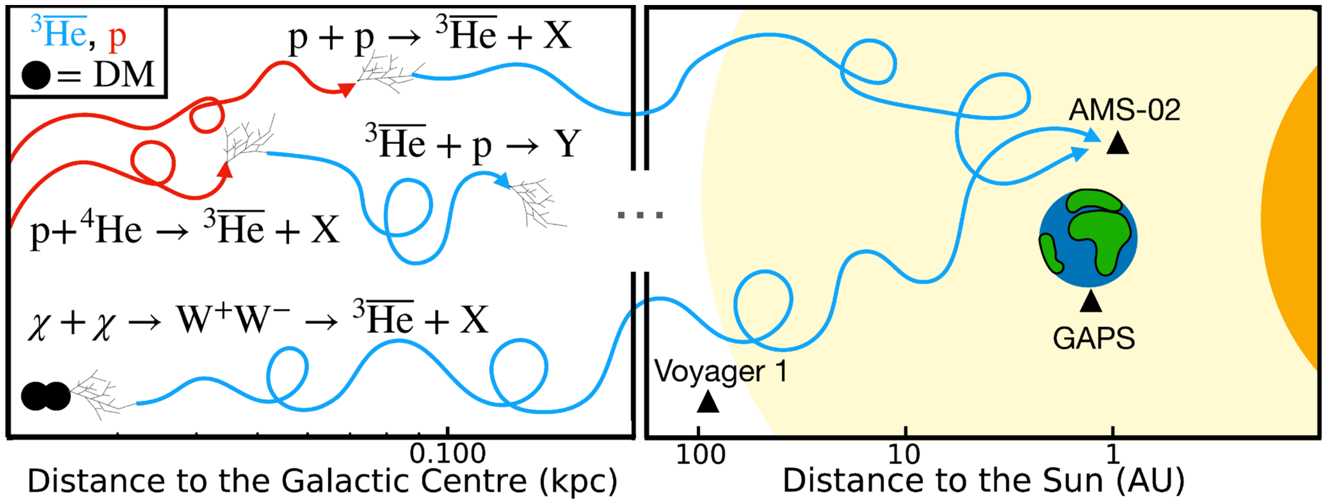
Why studying light (anti)nuclei?



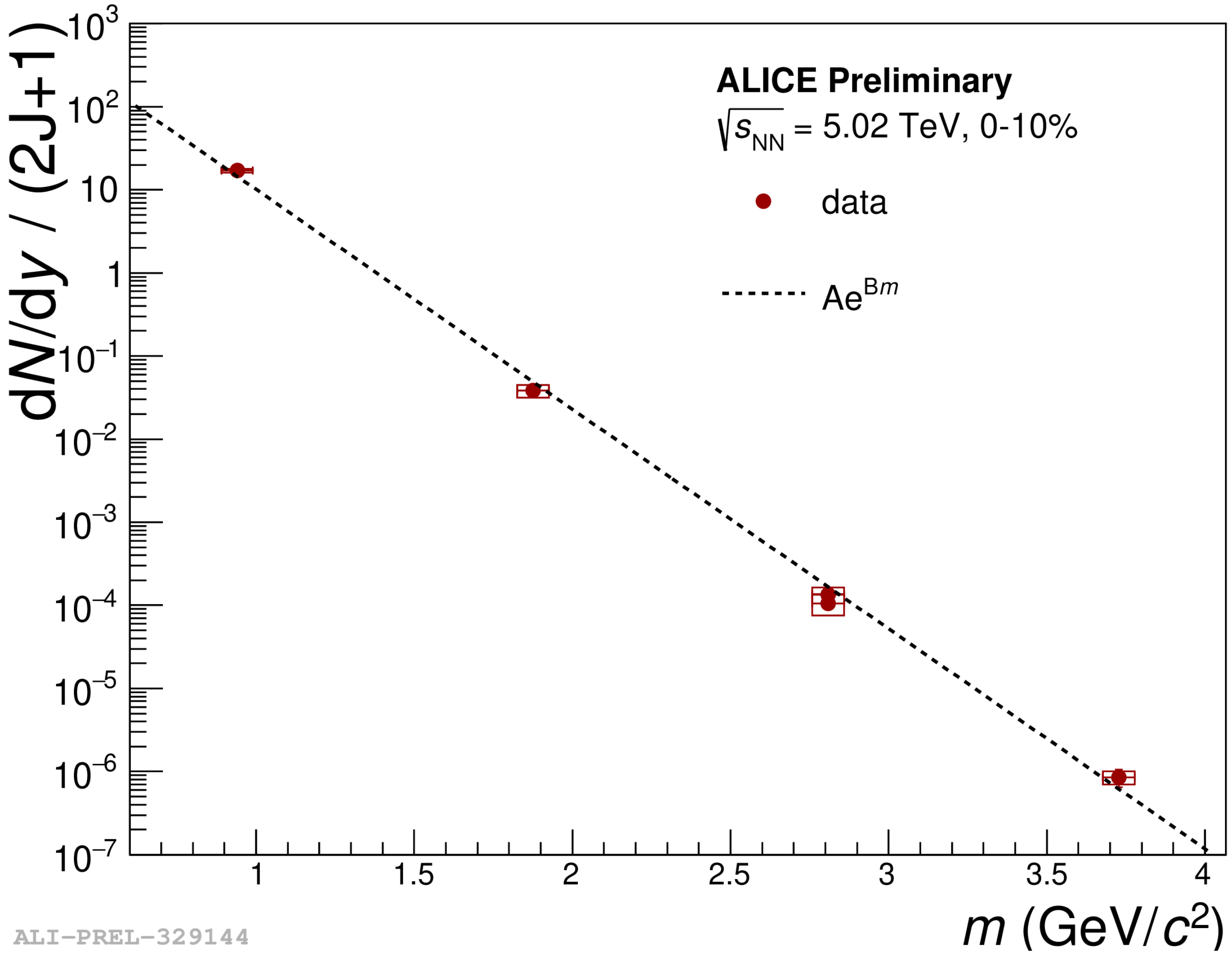
Nature Phys. 19 (2023) 1, 61-71

- 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 Model (SHM) and coalescence
- Astrophysical aspects: indirect detection of dark matter in space

Don't miss Giovanni's talk! 07/06, 17:50

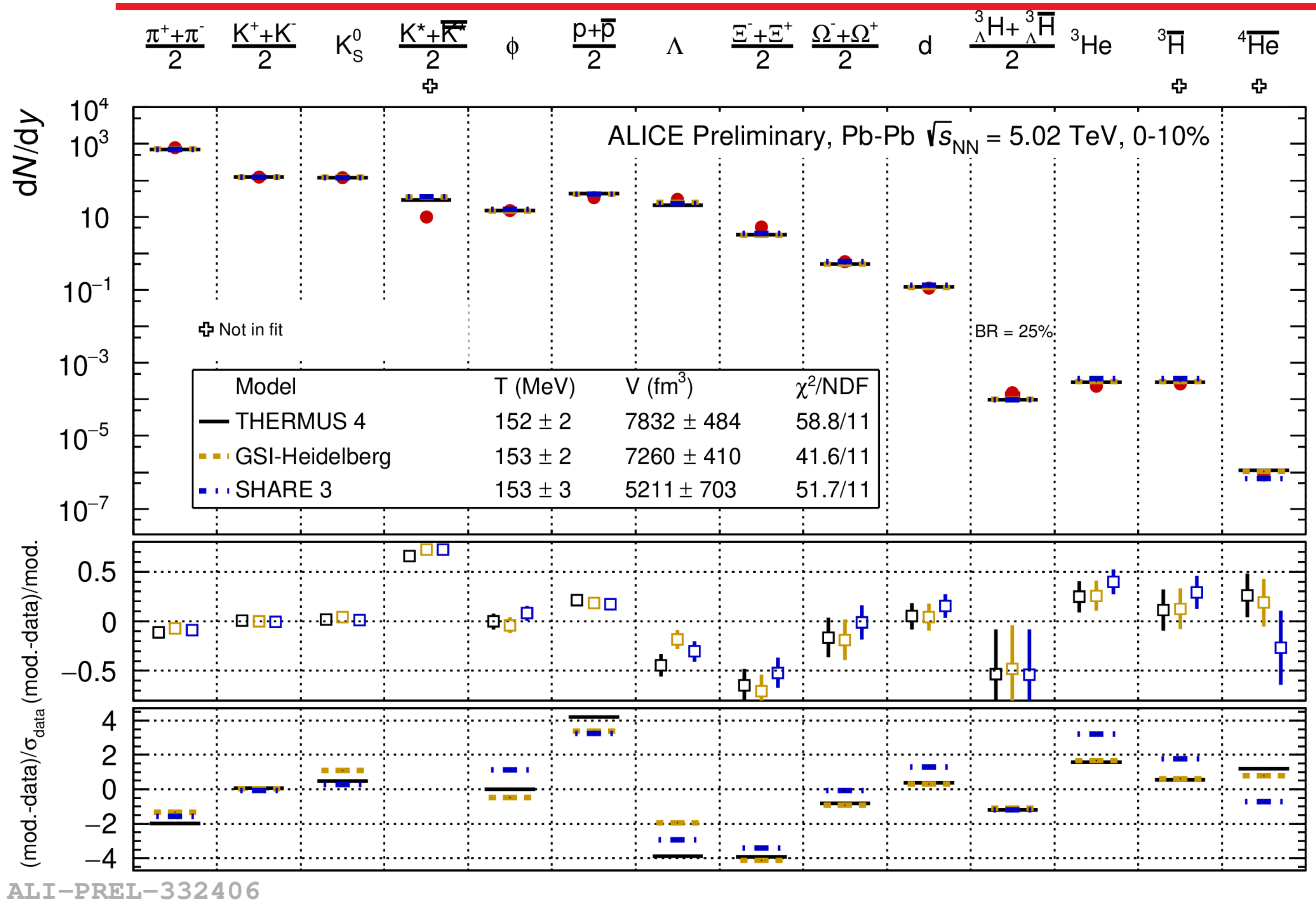


Statistical Hadronization Model



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

Statistical Hadronization Model

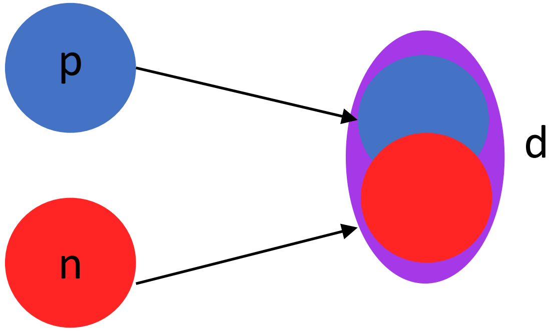


THERMUS 4: Comput.Phys.Commun. 180 (2009) 84-106
GSI-Heidelberg: Phys.Lett. B 673 (2009) 142
SHARE 3: Comput.Phys.Commun. 167 (2005) 229-251

- Hadrons emitted from a system in statistical and chemical equilibrium
- T_{chem} is the key parameter
- $dN/dy \propto \exp(-m/T_{chem})$ → 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?

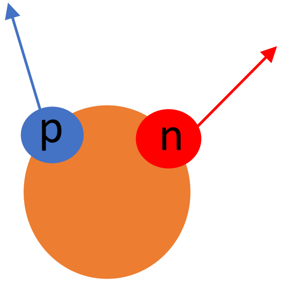
Simple coalescence model

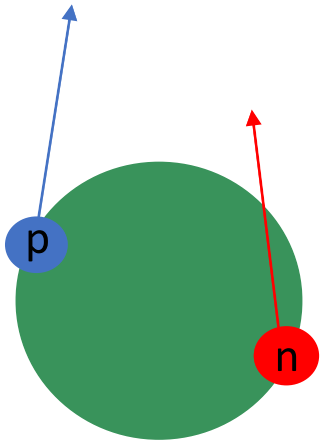
S. T. Butler et al., Phys. Rev. 129 (1963) 836



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

$$\underbrace{E_\mathrm{A}\frac{\mathrm{d}^3N_\mathrm{A}}{\mathrm{d}p_\mathrm{A}^3}}_{\text{Invariant yield of nucleus}} = \underbrace{B_\mathrm{A}}_{\text{Coalescence parameter}} \cdot \underbrace{\left(E_\mathrm{p}\frac{\mathrm{d}^3N_\mathrm{p}}{\mathrm{d}p_\mathrm{p}^3}\right)^\mathrm{A}}_{\text{Invariant yield of protons}} \qquad p_\mathrm{p} = p_\mathrm{A}/\mathrm{A}$$





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

Advanced coalescence model

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

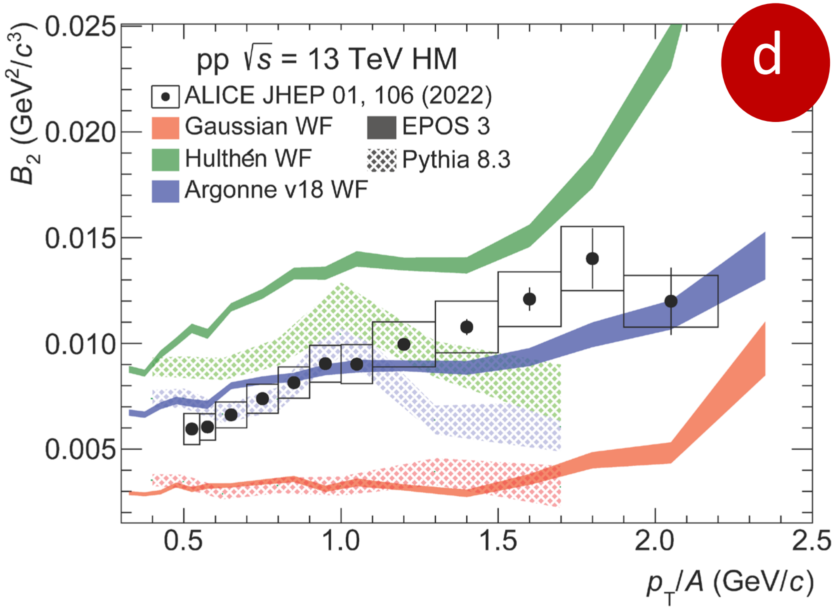
$$N_A = \underbrace{g_a}_{\text{spin-isospin degeneracy factor}} \cdot \int d^3x_1 \ldots d^3x_A \cdot d^3k_1 \ldots d^3k_A \cdot \underbrace{f_1(x_1,k_1) \ldots f_A(x_A,k_A)}_{\text{phase space distributions of nucleons}} \cdot \underbrace{W_A(x_1,\ldots,x_A,k_1,\ldots,k_A)}_{\text{Wigner density of the bound state}}$$

spin-isospin degeneracy factor

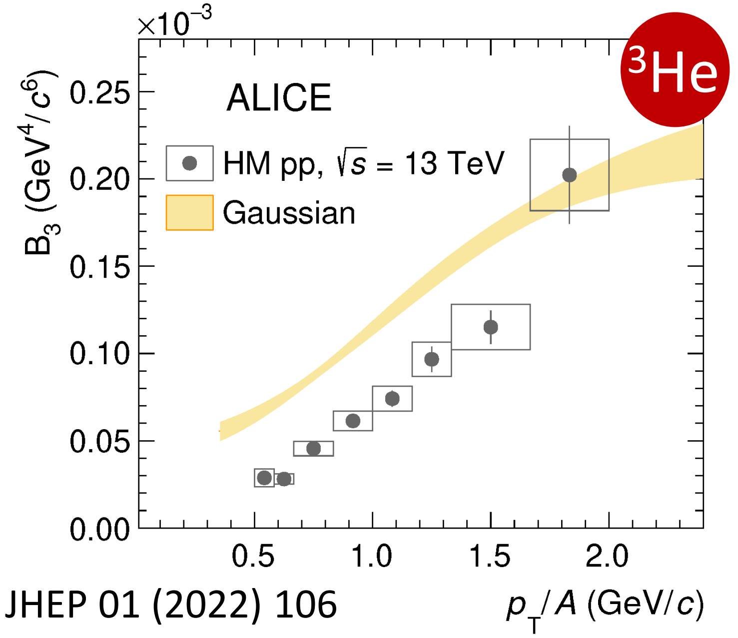
phase space distributions of nucleons → dependence on the source size

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

M. Mahlein et al., arXiv:2302.12696

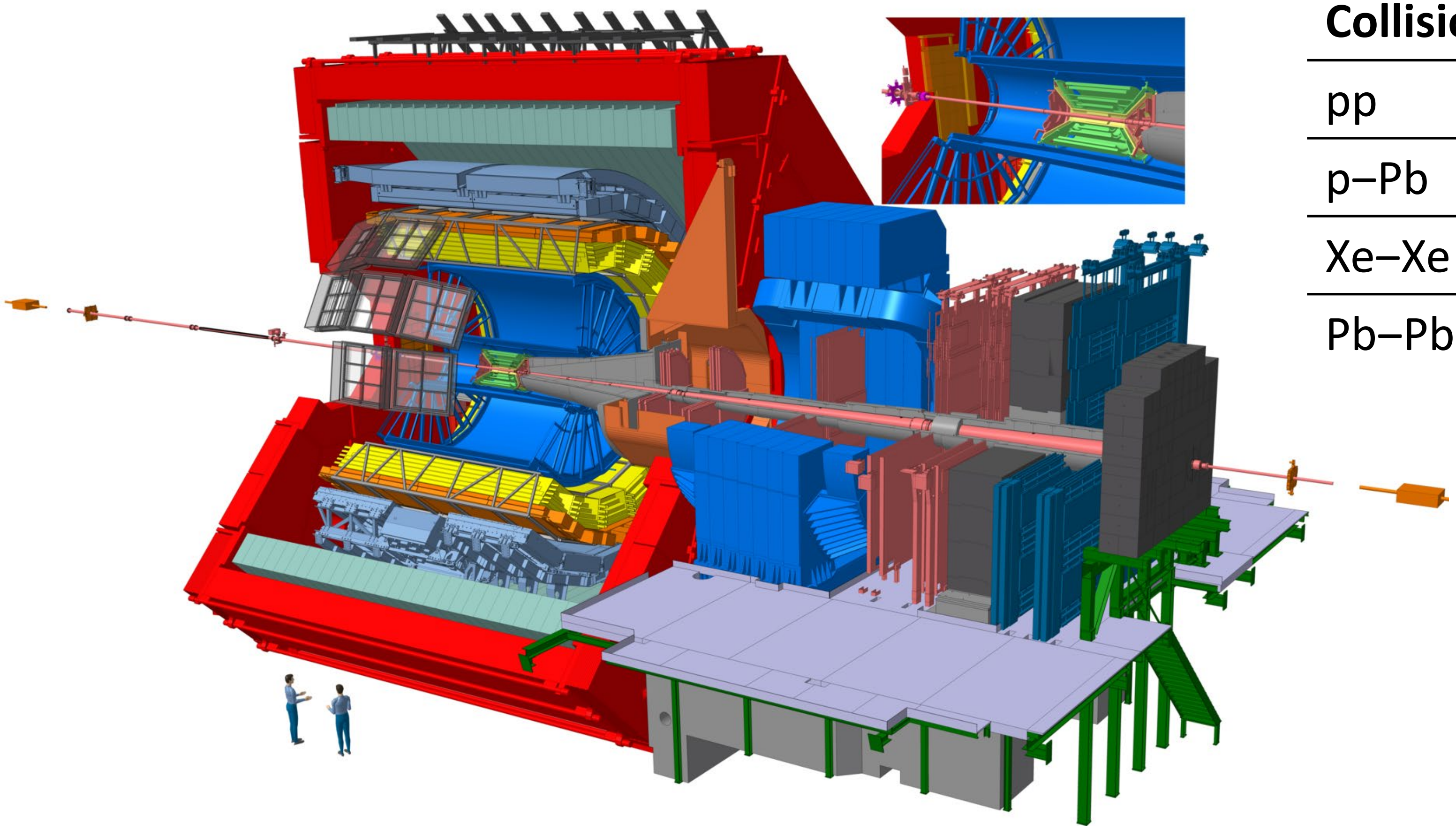


- The coalescence parameter is an observable sensitive to the wave function of the nucleus
- B_2 is in agreement with Argonne v_{18} wave function
- Both B_2 and B_3 are not in agreement with the Gaussian wave function (approx. in the calculus)



JHEP 01 (2022) 106

The ALICE detector in Run 1&2



Collisions system	$\sqrt{s_{NN}}$ (TeV)
pp	0.9, 2.76, 5.02, 7, 8, 13
p–Pb	5.02, 8.16
Xe–Xe	5.44
Pb–Pb	2.76, 5.02

- 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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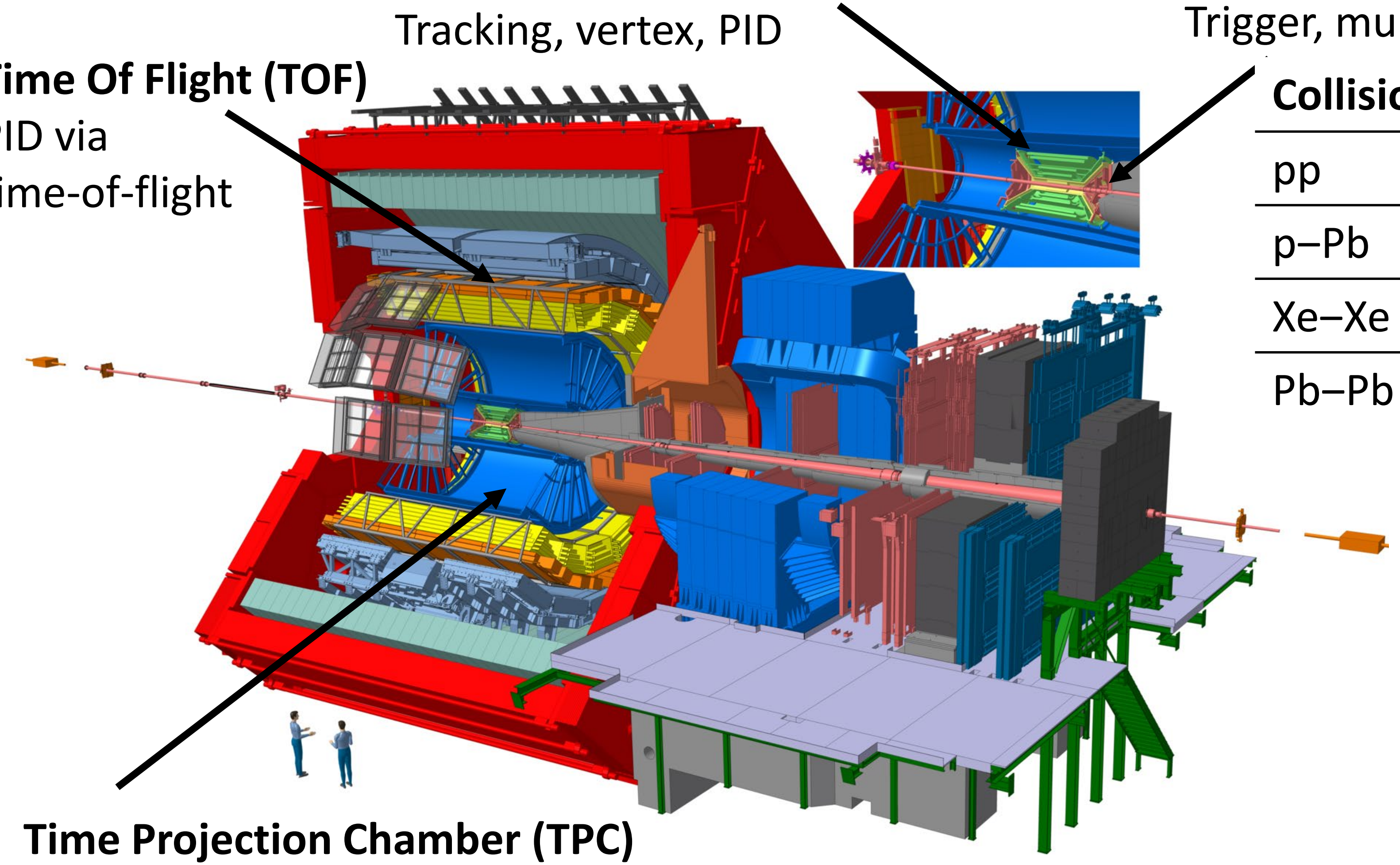

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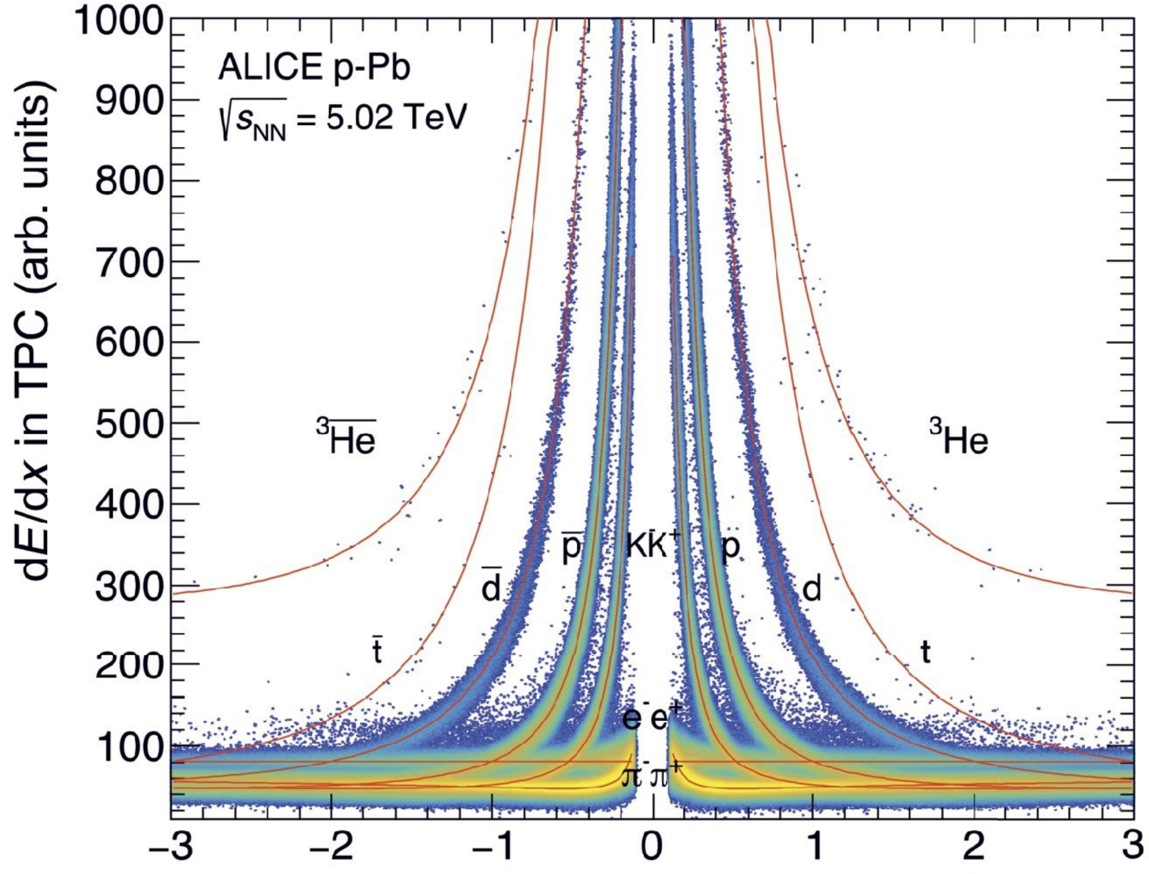
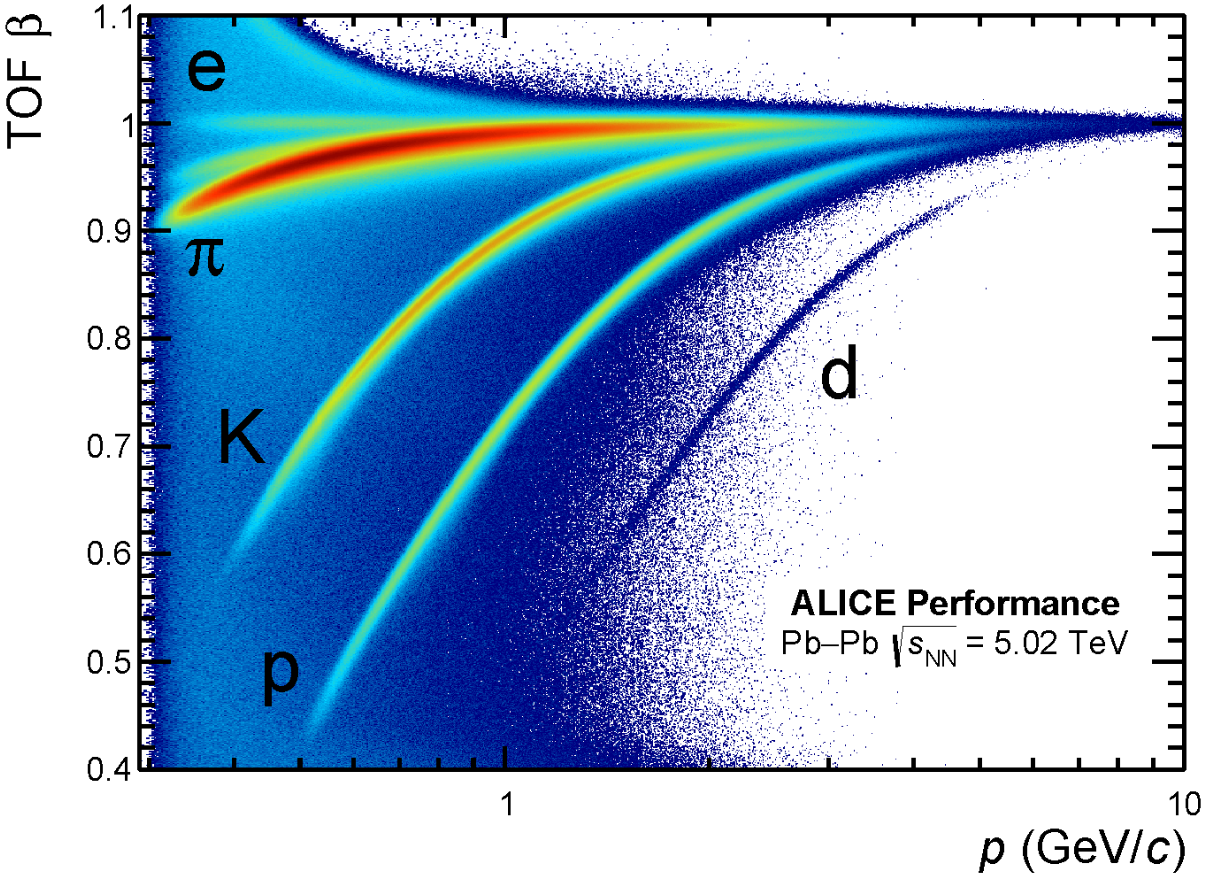
Light (anti)nuclei identification



Phys.Lett. B800 (2020) 135043



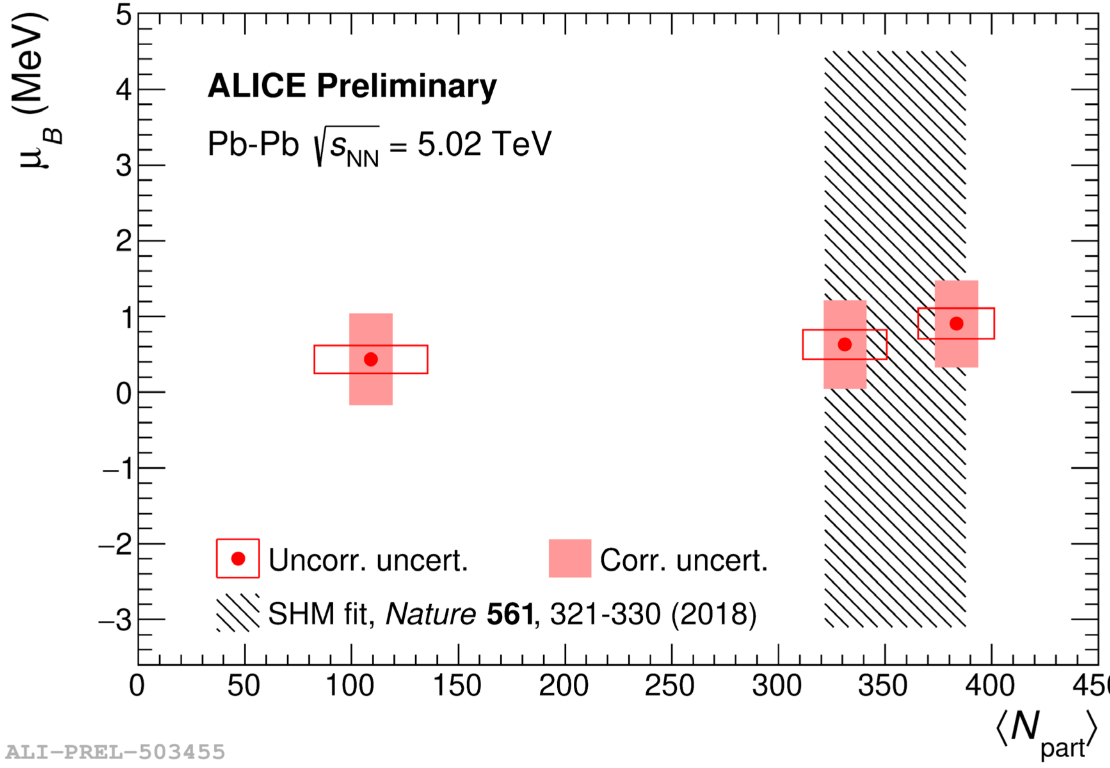
Low p_T region (below 1 GeV/c): PID via dE/dx
$\sigma_{dE/dx} \sim$ 5.5% in pp, ~ 7% in Pb–Pb

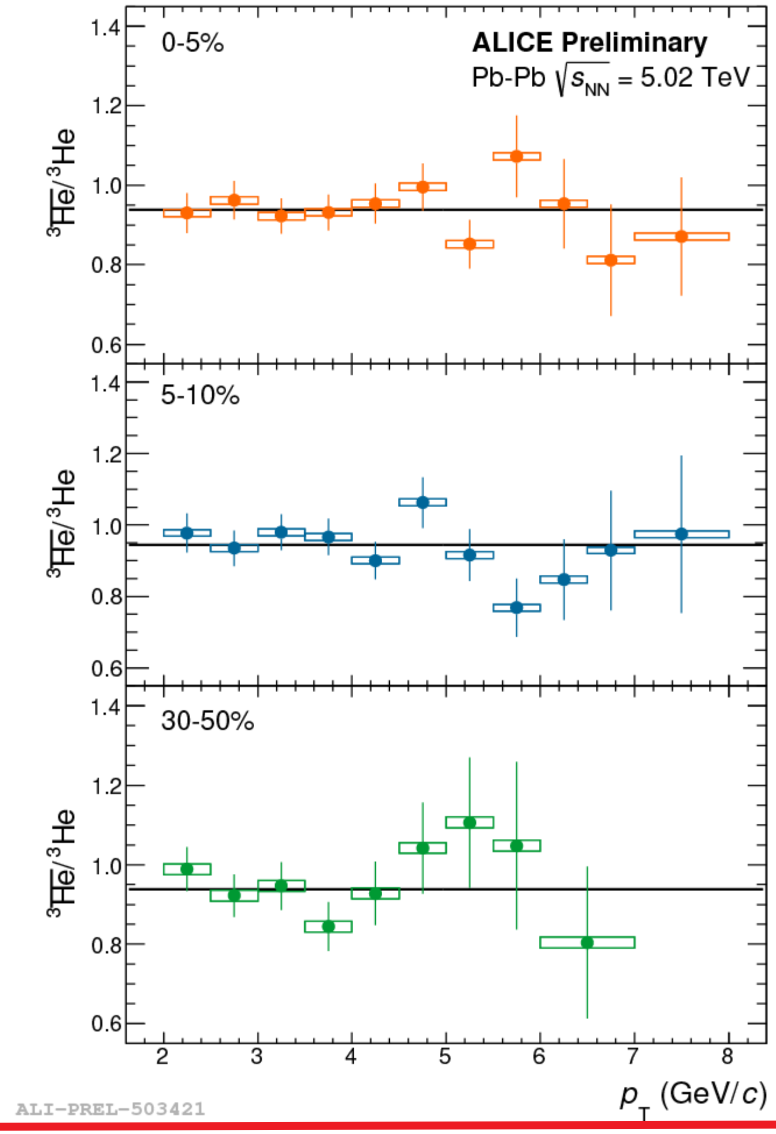
High p_T region (over 1 GeV/c): PID via time-of-flight $\sigma_{PID} \sim$ 70 ps for pp, ~ 60 ps for Pb–Pb

LHC: an (anti)nuclei factory

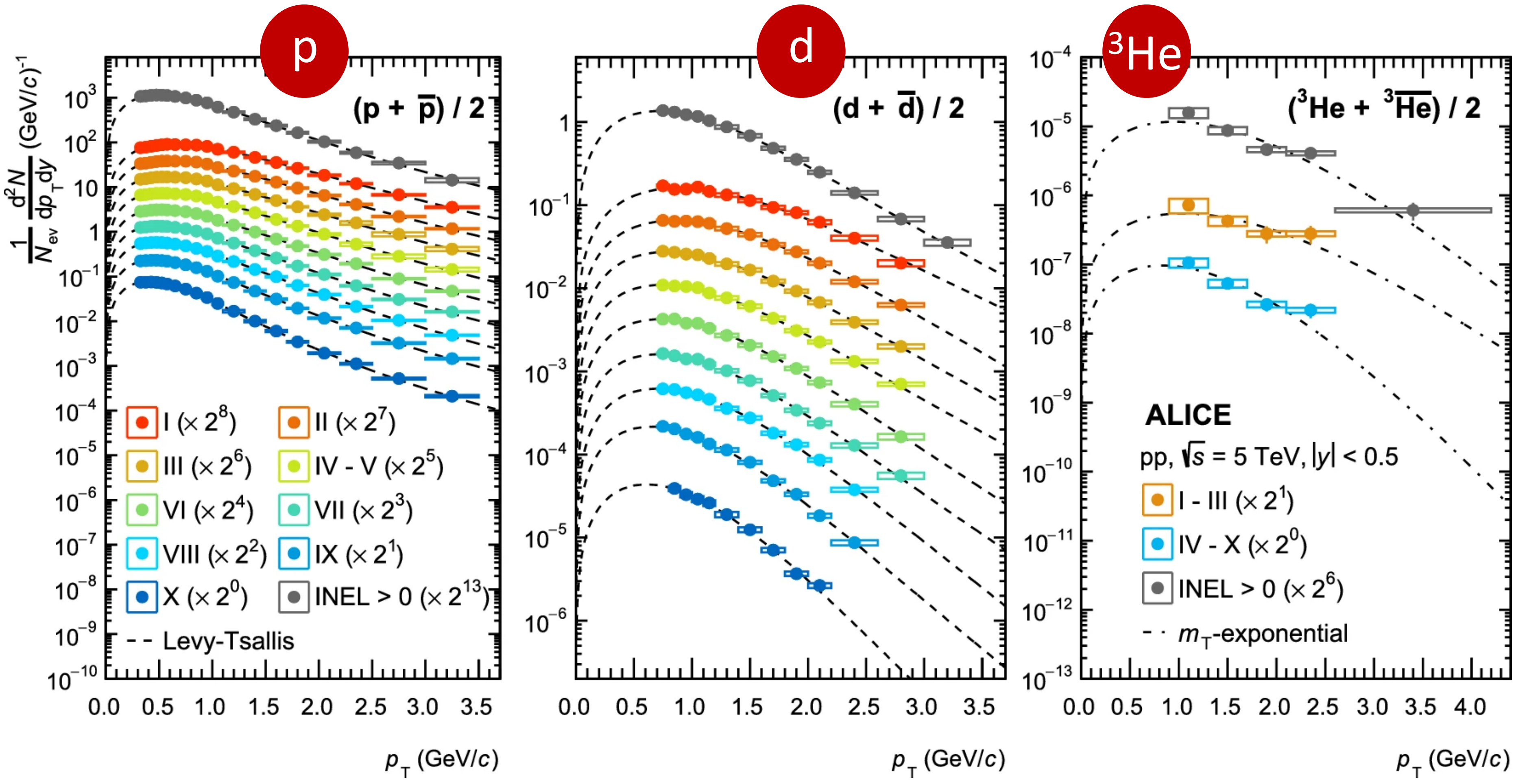
- At the LHC energies the same quantity of matter and antimatter are produced at midrapidity → baryochemical potential $\mu_B \approx 0$

- Antimatter-to-matter ratio consistent with unity





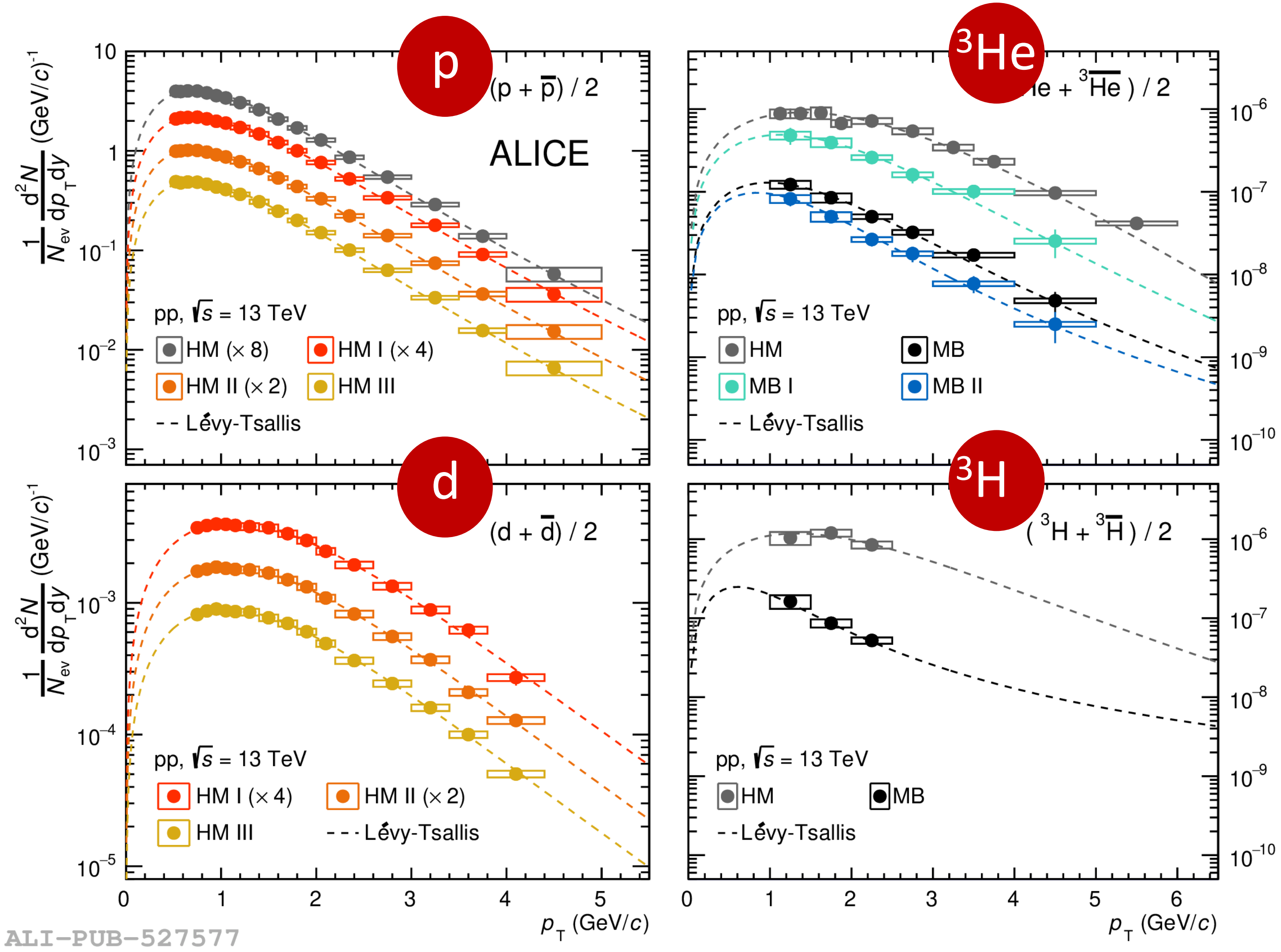
Light (anti)nuclei in pp collisions



- Nuclei production studied in different collisions systems and energies vs. multiplicity
- Identification of (anti)nuclei up to (anti)^{3}He
- Spectra fitted with Lévy - Tsallis or m_T-exponential → extrapolation at low and high p_T
- Spectra hardening with multiplicity

Eur. Phys. J. C 82, 289 (2022)

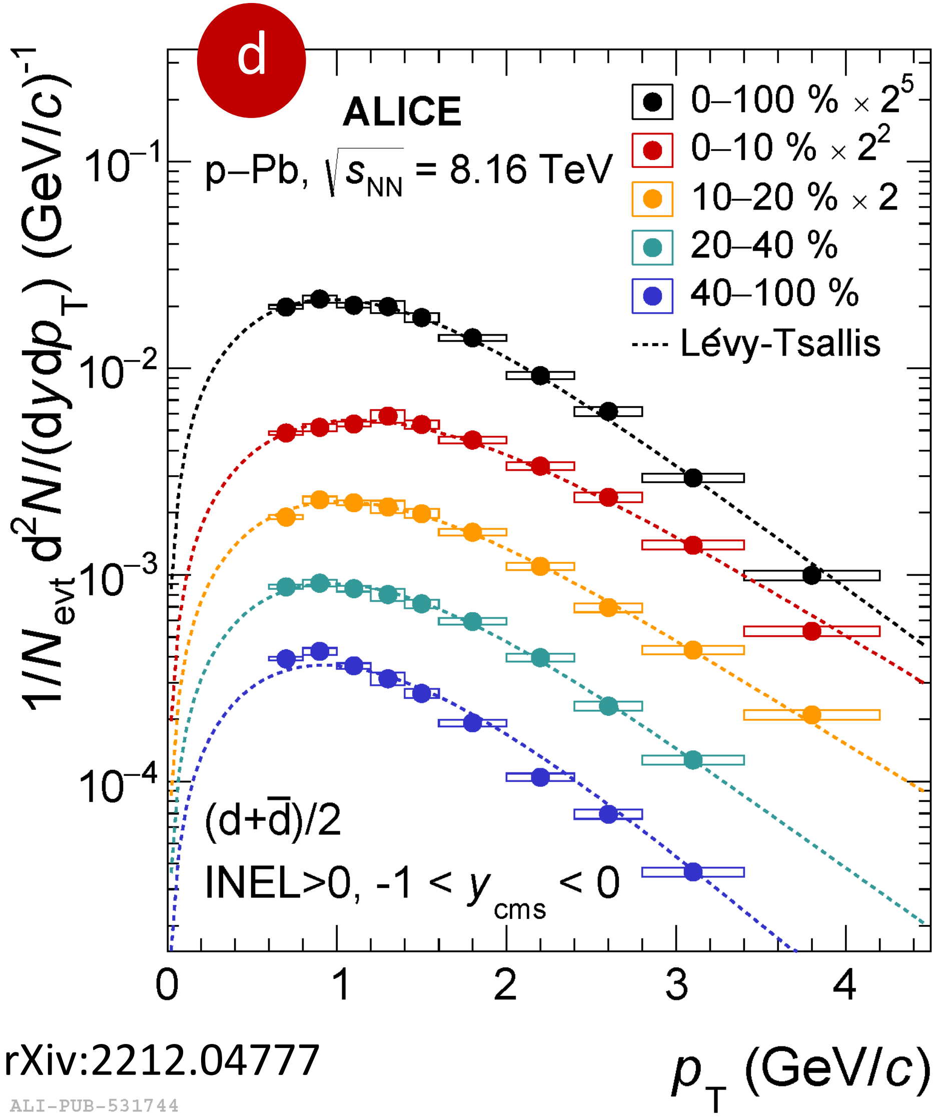
Light (anti)nuclei in pp collisions – HM



JHEP 01 (2022) 106

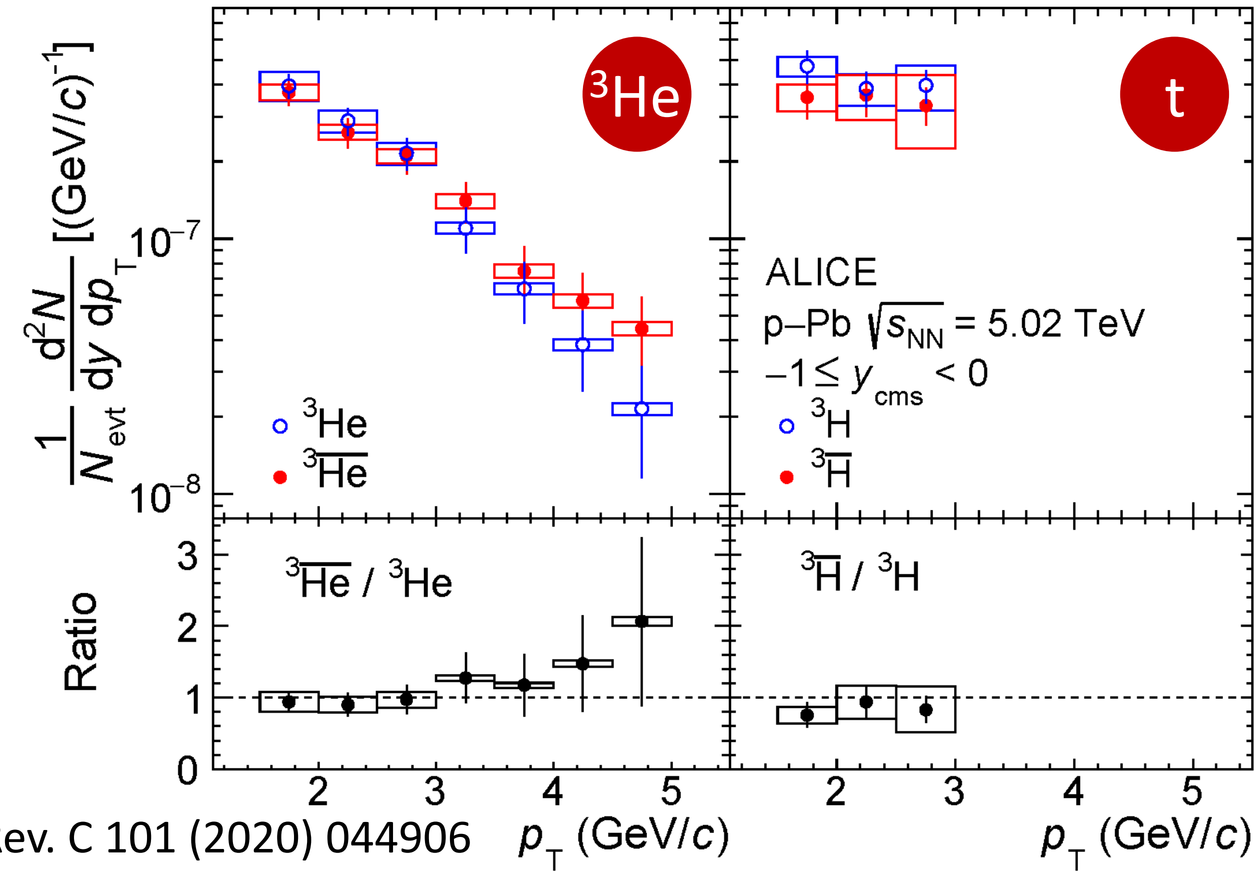
- Spectra and coalescence parameter evaluated in high multiplicity data sample
- High multiplicity → most central collisions (0 – 0.1% multiplicity classes)
- Precise measurement of the emission source size using femtoscopy is available
- Crucial masurements to test the coalescence model (B_2 and wave function parametrization, see slide 5)

Light (anti)nuclei in p–Pb collisions



arXiv:2212.04777

ALI-PUB-531744



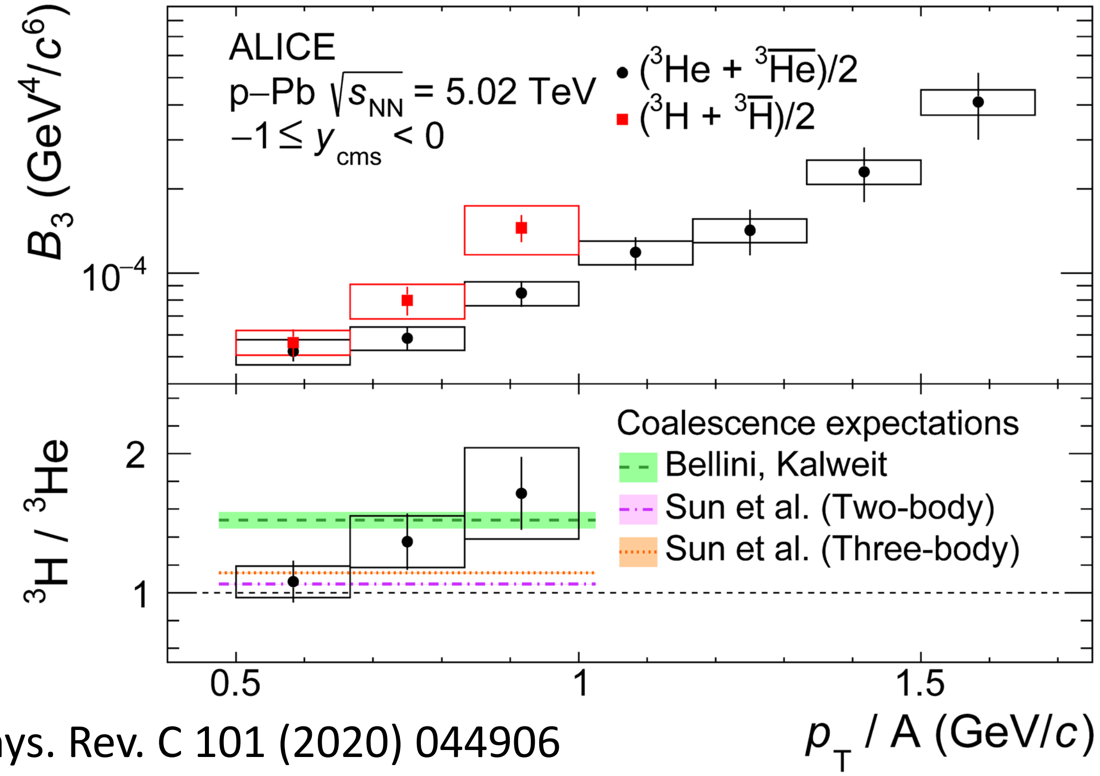
Phys. Rev. C 101 (2020) 044906

- Identification of (anti)nuclei up to (anti)^{3}He
- Similar behaviour of pp system, such as hardening of spectra

^{3}H/^{3}He in low multiplicity systems

- In the coalescence model ^{3}H/^{3}He is expected to be larger than unity since the different source size
- The models predict the largest ^{3}H and ^{3}He yields difference at low multiplicity
- Both pp HM and p-Pb data shows ^{3}H/^{3}He greater than unity

JHEP 01 (2022) 106



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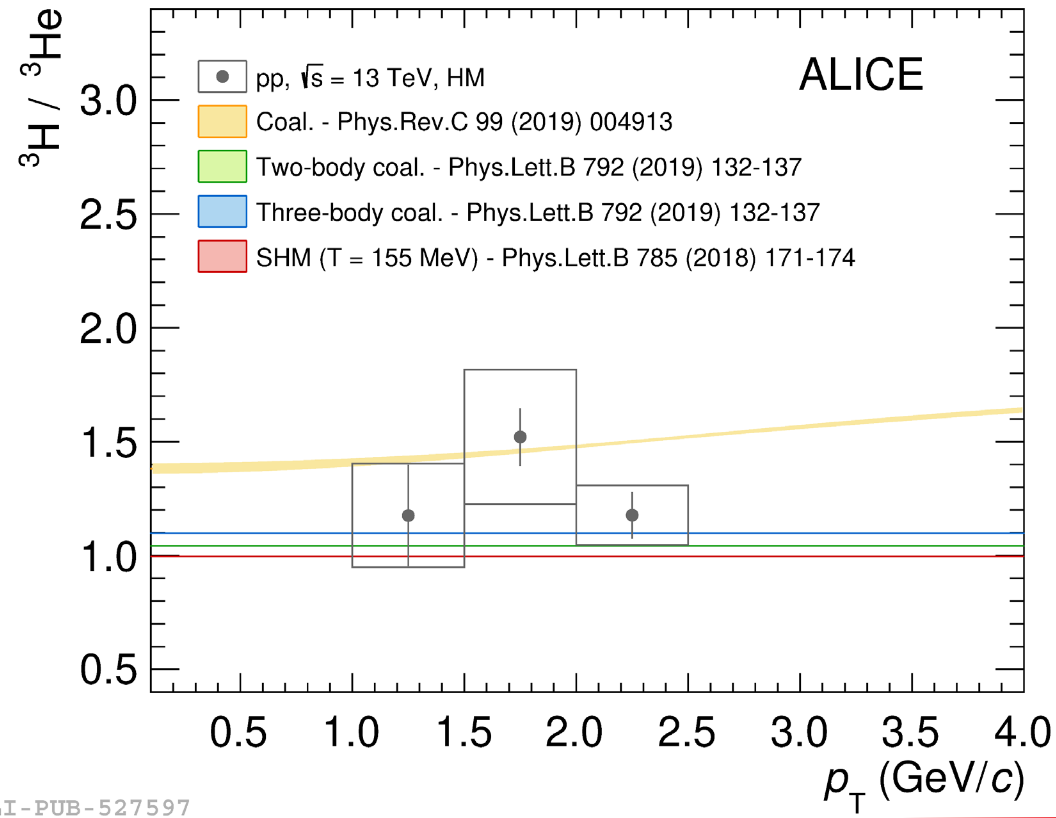
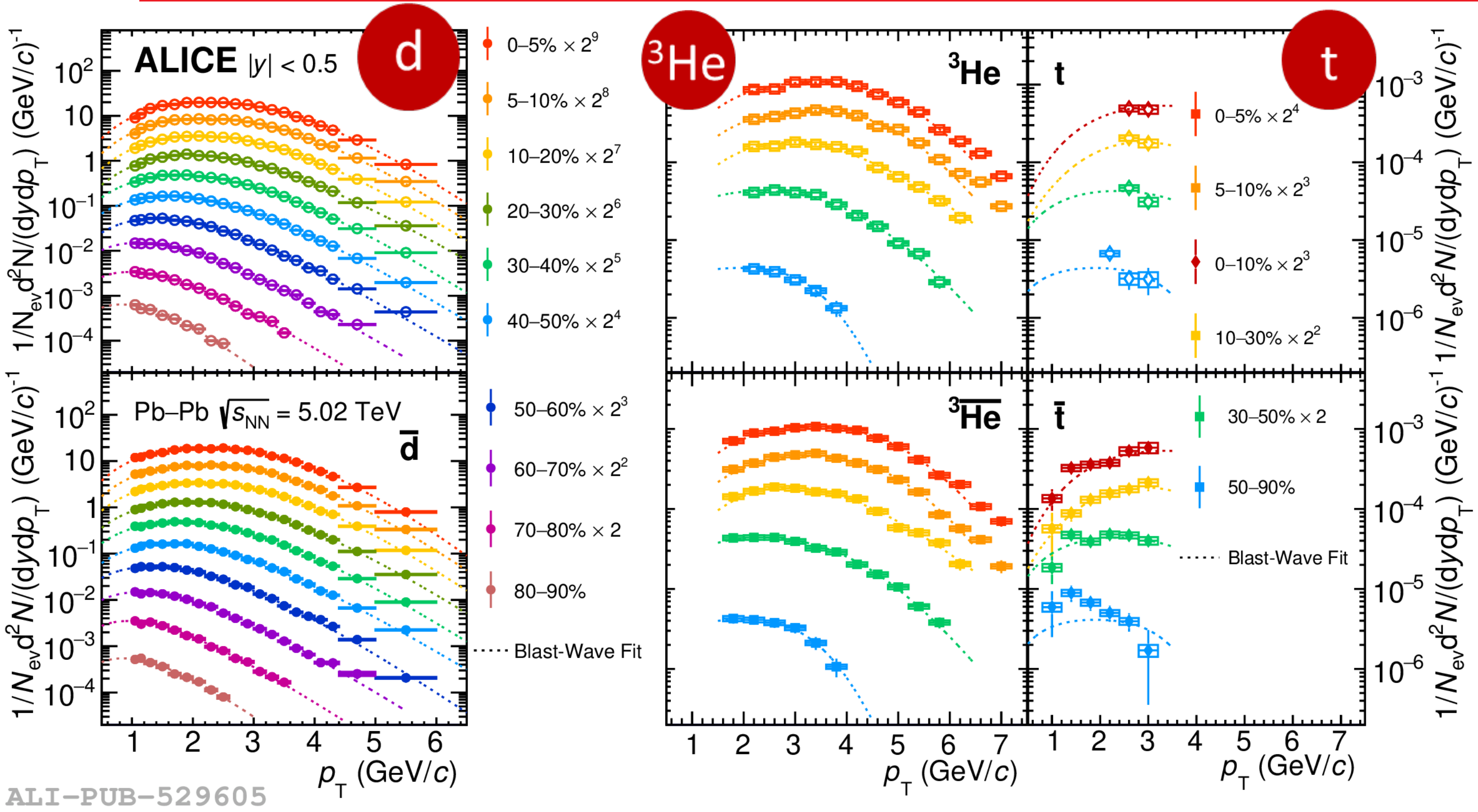


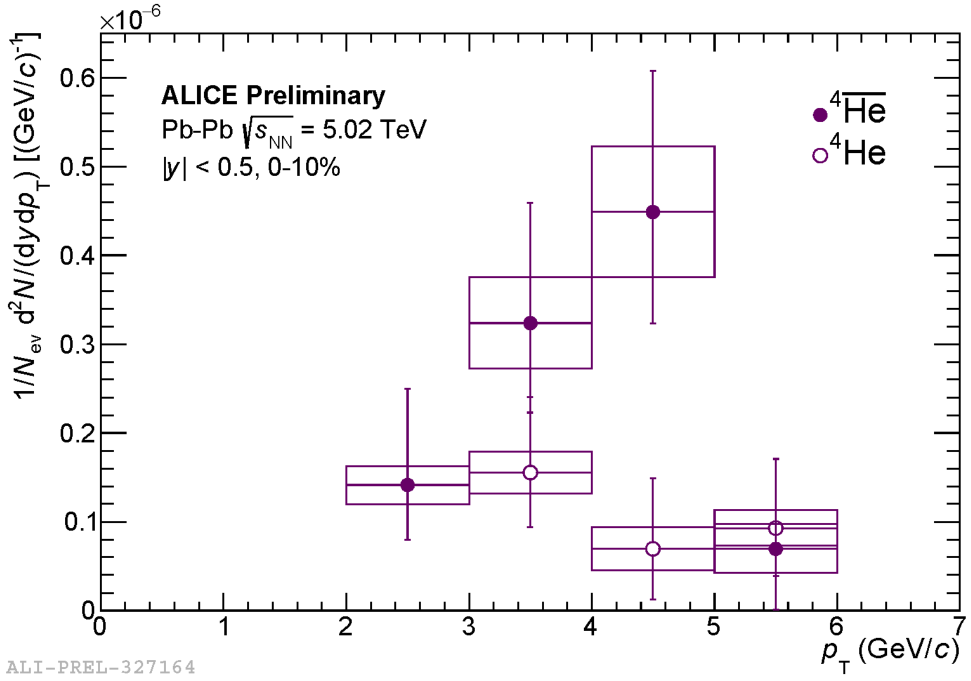
ALI-PUB-527597

Light (anti)nuclei in Pb–Pb collisions



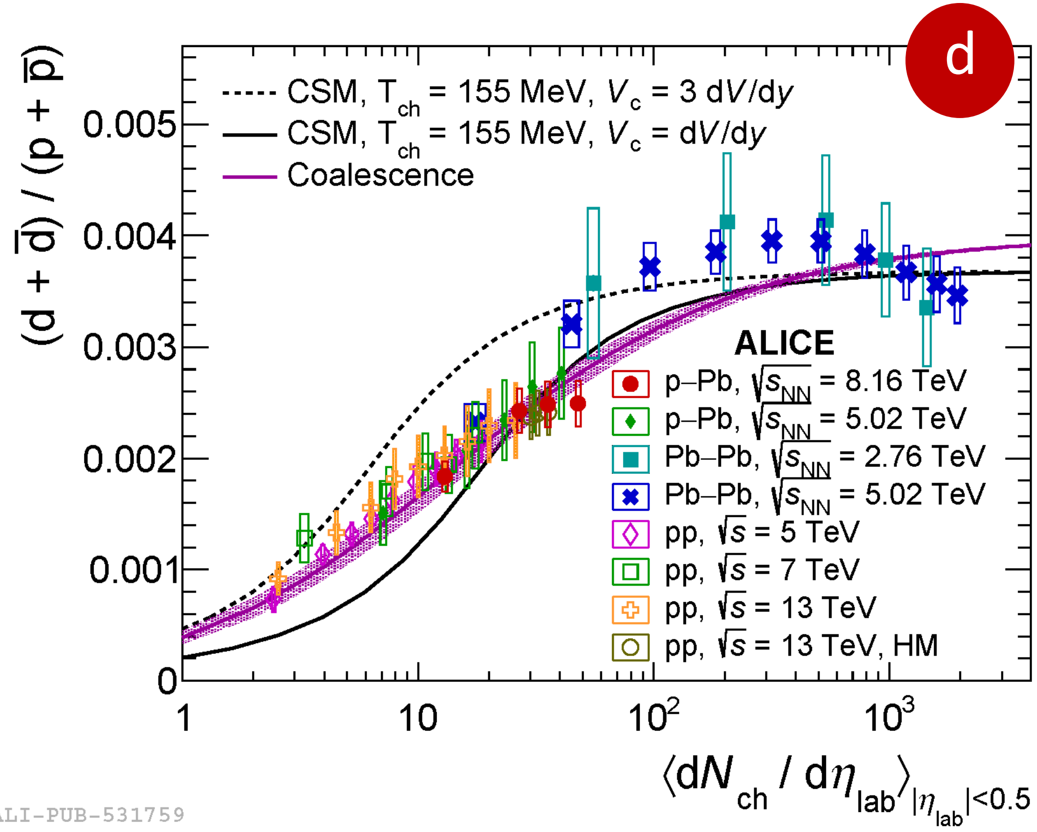
arXiv:2211.14015

- Only in Pb–Pb collisions (anti)^{4}He is observed and studied → preliminary results for the p_T spectra
- 2σ deviation in 4 GeV/c < p_T < 5 GeV/c

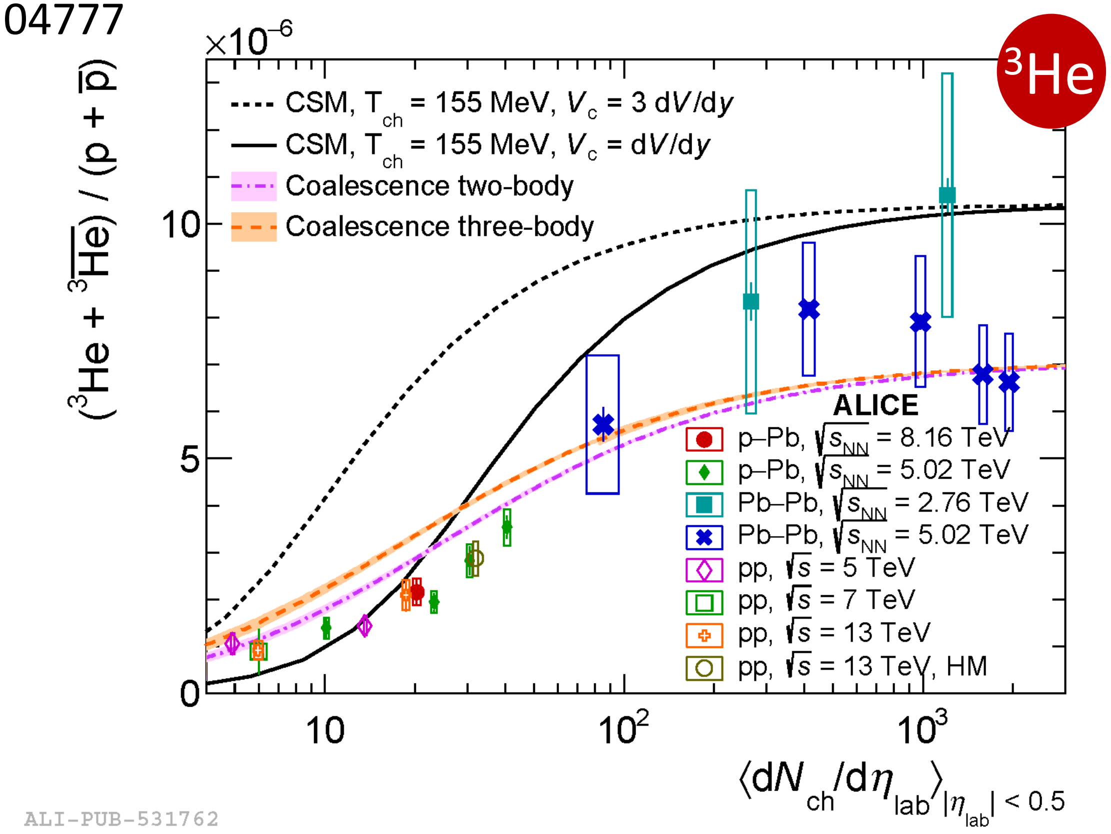


- With the higher statistics, observed light (anti)nuclei at higher values of p_T wrt small collision systems
- Crucial measurements for the comparison with the SHM

Comparison with models – ratio to protons



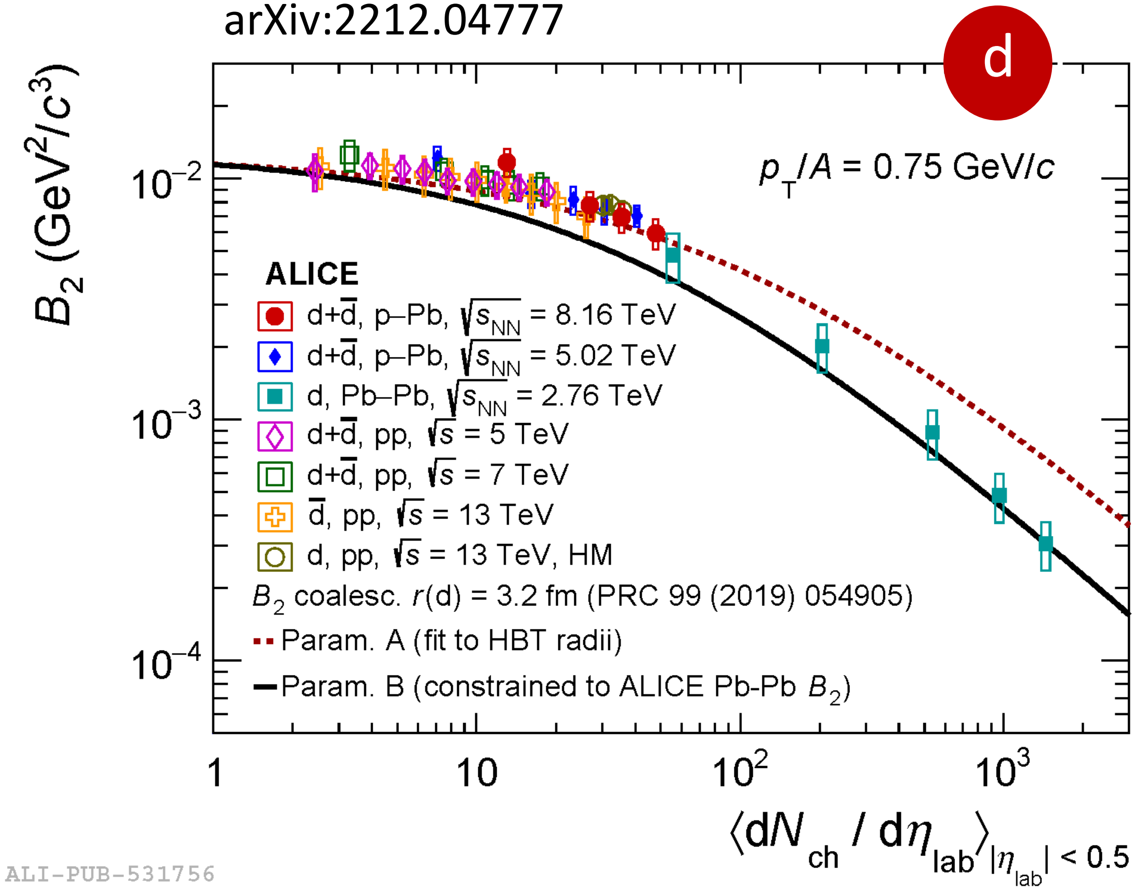
arXiv:2212.04777



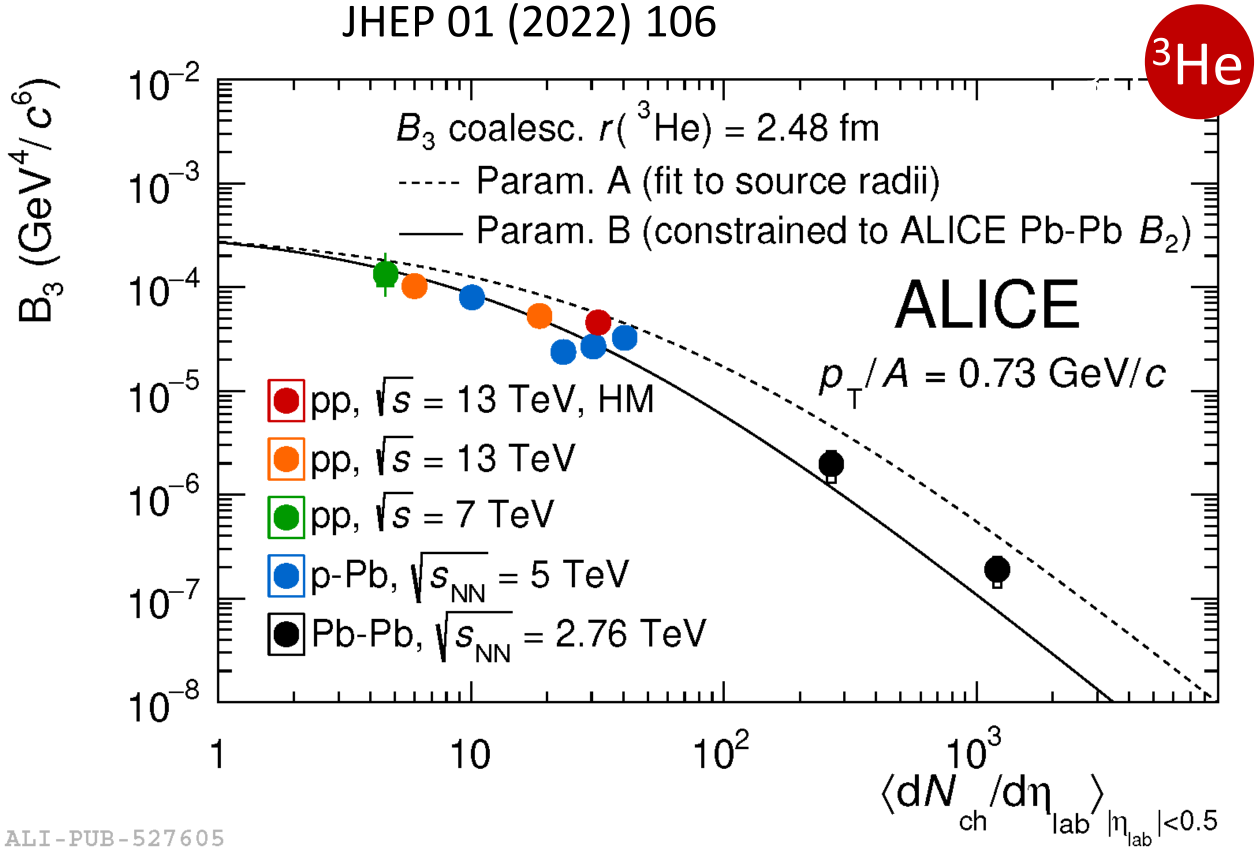
- d/p and He/p ratio evolves smoothly as a function of multiplicity → dependence on the system size
- Observed saturation at multiplicity that corresponds to Pb–Pb collisions
- Ratio compared to predictions from Thermal-FIST CSM and coalescence model
- SHM and coalescence give similar prediction for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

Comparison with models – coalescence

arXiv:2212.04777



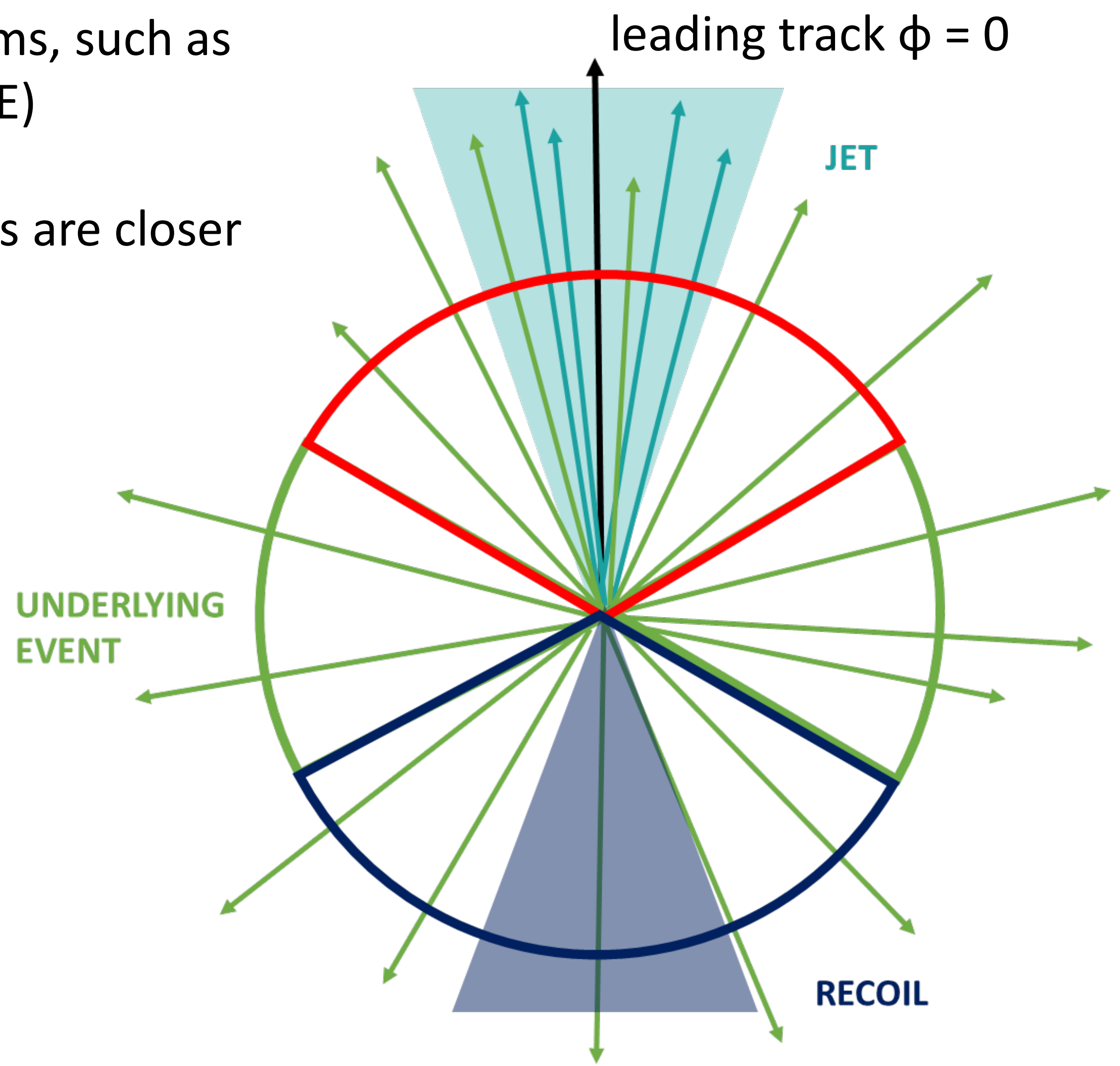
JHEP 01 (2022) 106



- 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!**

In-jet and underlying event

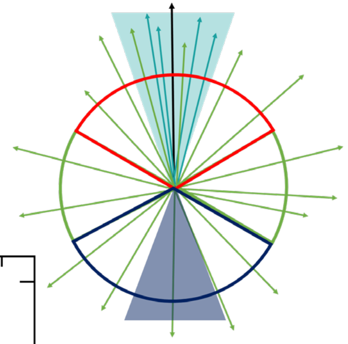
- The study of the nuclear production in small collisions systems, such as pp and p–Pb, can be explored using the underlying event (UE)
- Test of the coalescence model: the nucleons in small systems are closer in phase space wrt Pb–Pb
- Leading particle (highest p_T and $p_T > 5$ GeV/c) used as a proxy for the jet axis
- CDF technique used to find the three azimuthal regions
  - **Toward** ($|\Delta\phi| < 60°$) : contains JET and UE
  - **Transverse** ($60° < |\Delta\phi| < 120°$) : dominated by the Underlying Event (UE)
  - **Away** ($|\Delta\phi| > 120°$): contains RECOIL JET and UE
- **Jet**: **Toward** – **Transverse**

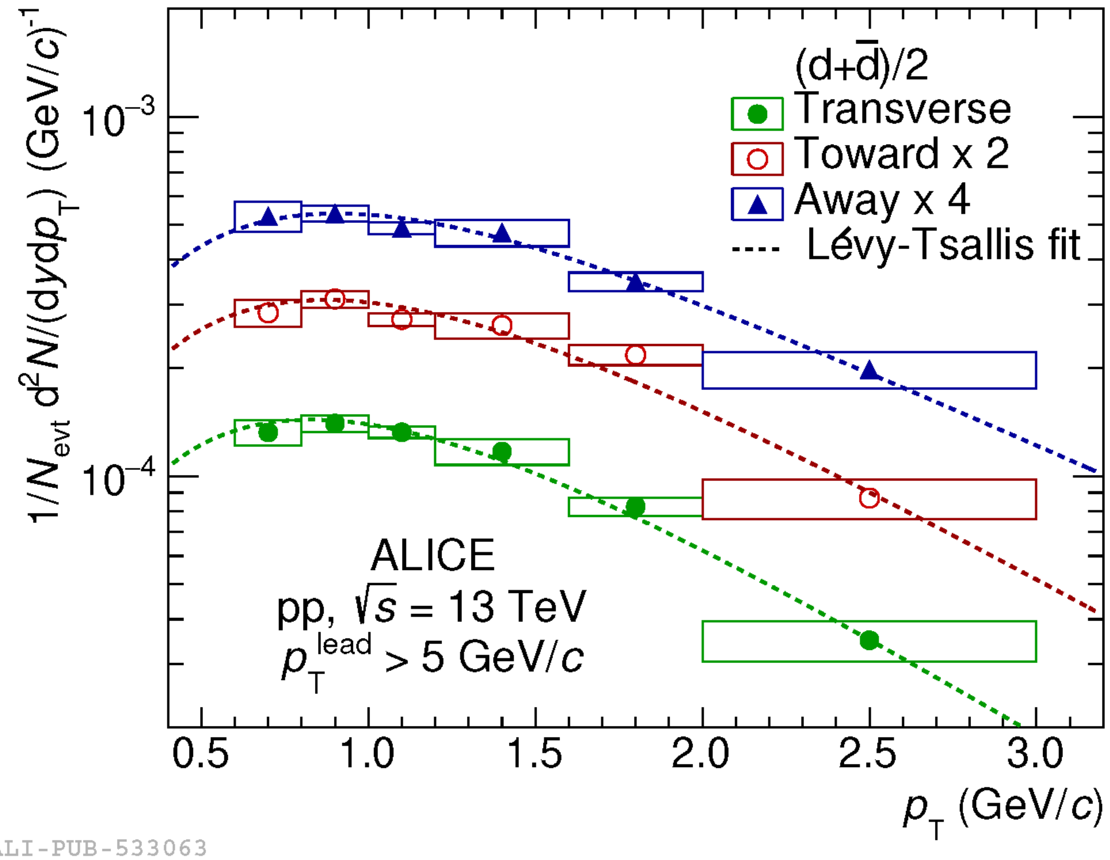


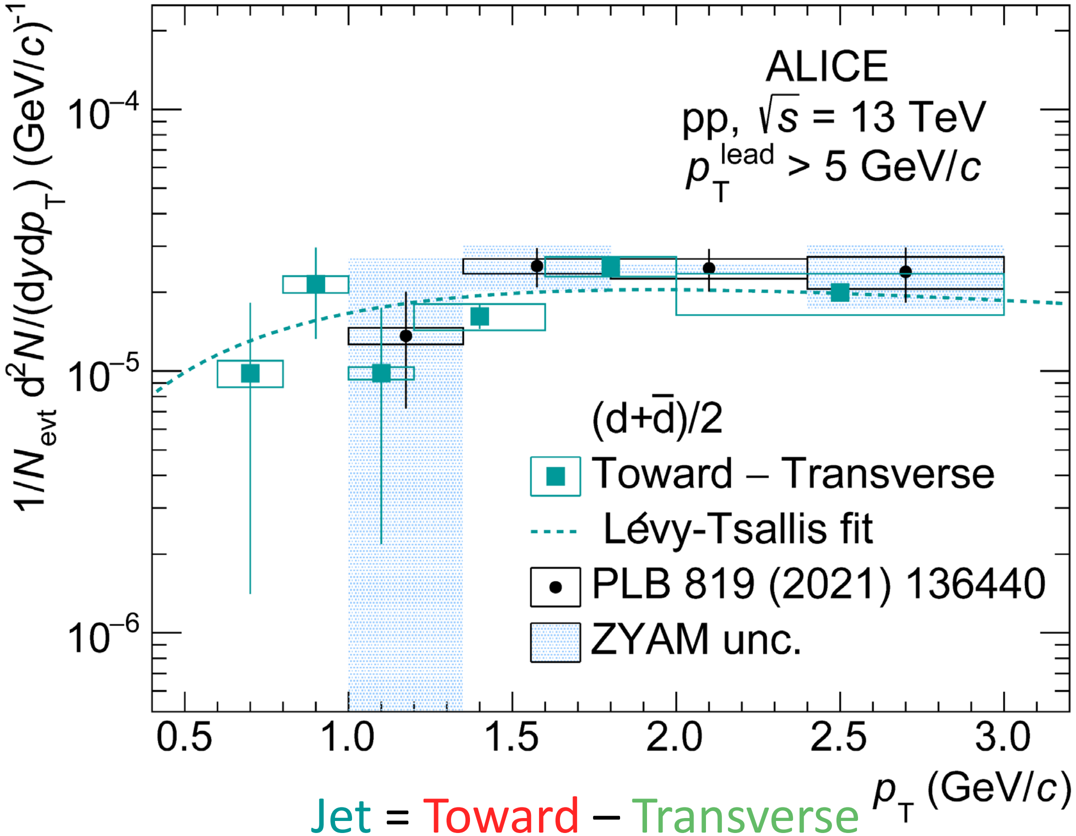
Martin, T., Skands, P. & Farrington, S. *Eur. Phys. J. C* **76**, 299 (2016)

In-jet and UE spectra

pp @ 13 TeV







Jet = Toward – Transverse

arXiv:2211.15204v1

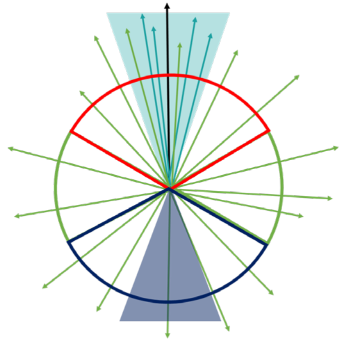
Deuteron production in events with p_T^{lead} > 5 GeV/c

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

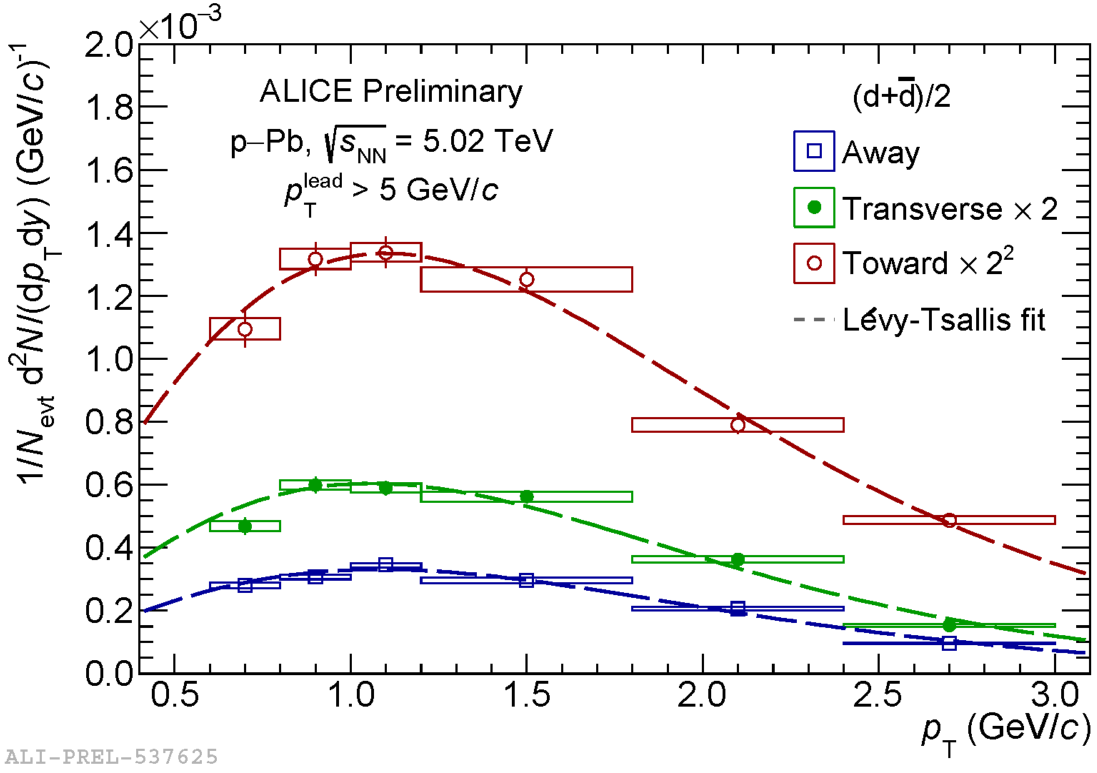
In-jet and UE spectra

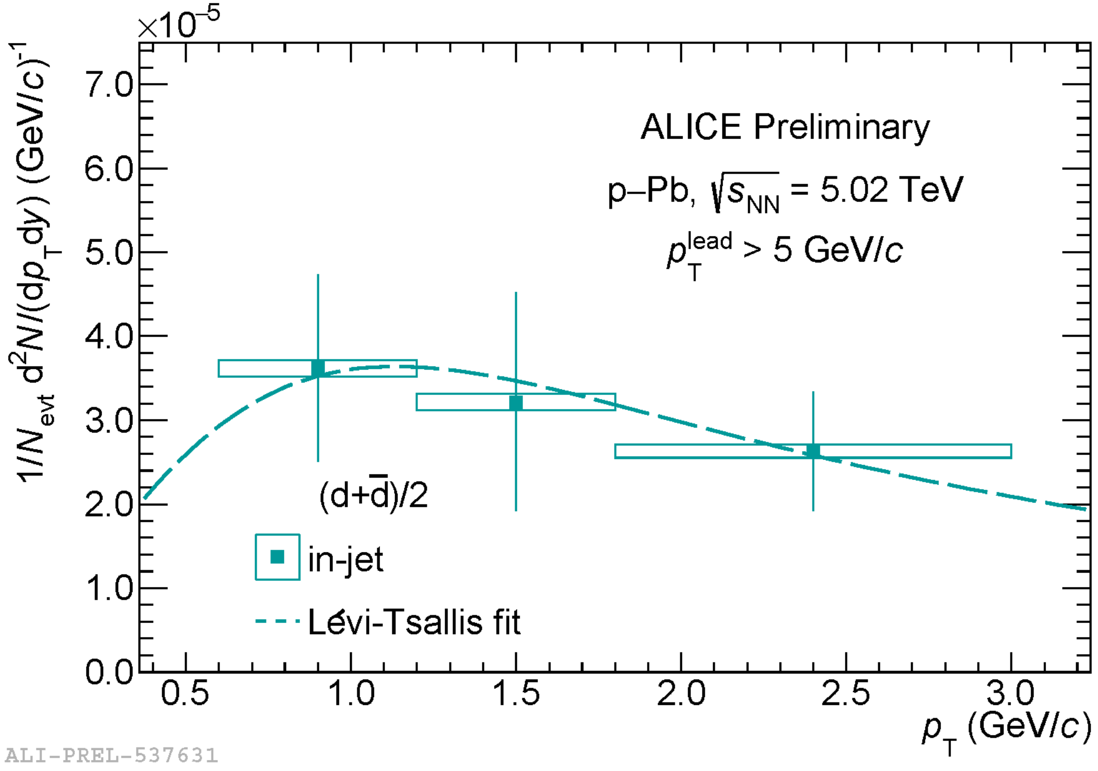
- What do we need for the coalescence parameter?

p-Pb@ 5.02 TeV



- **First ingredient**: (anti)deuteron spectra

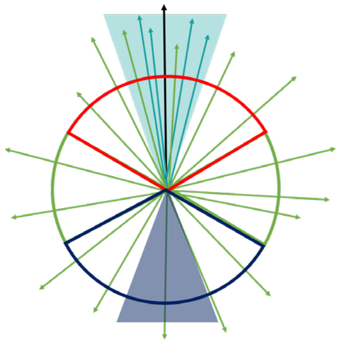




(Anti)Deuteron production in events with p_T^{lead} > 5 GeV/c

Jet = Toward - Transverse

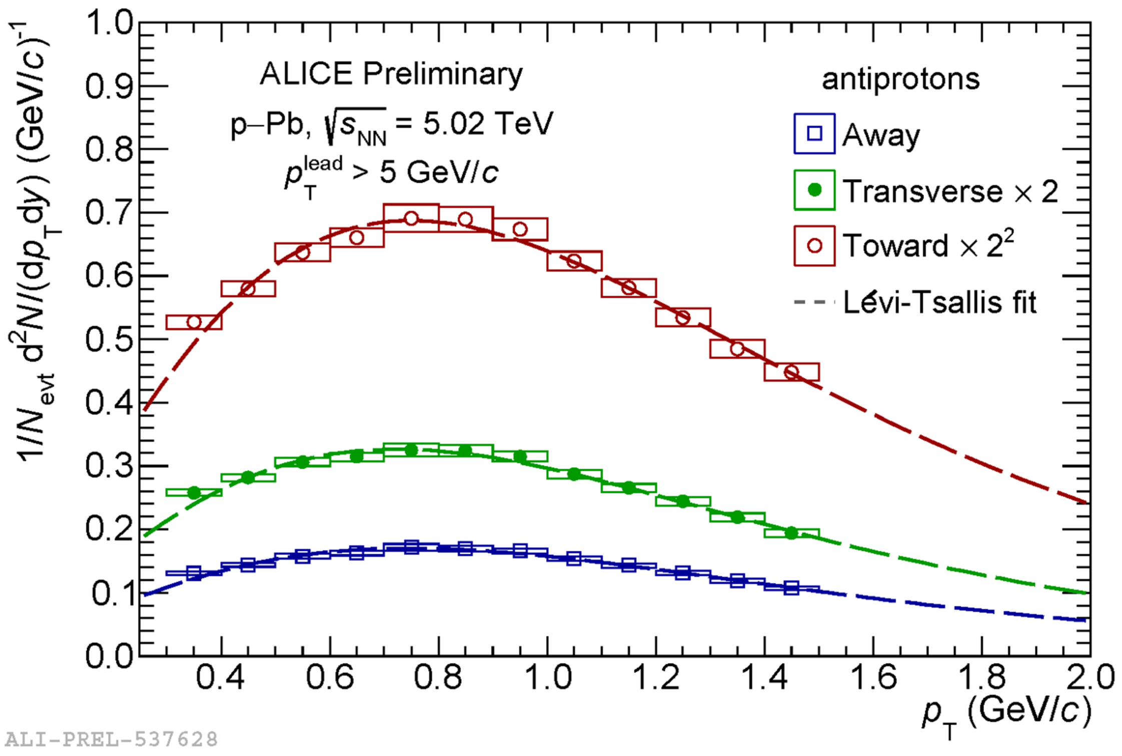
In-jet and UE spectra

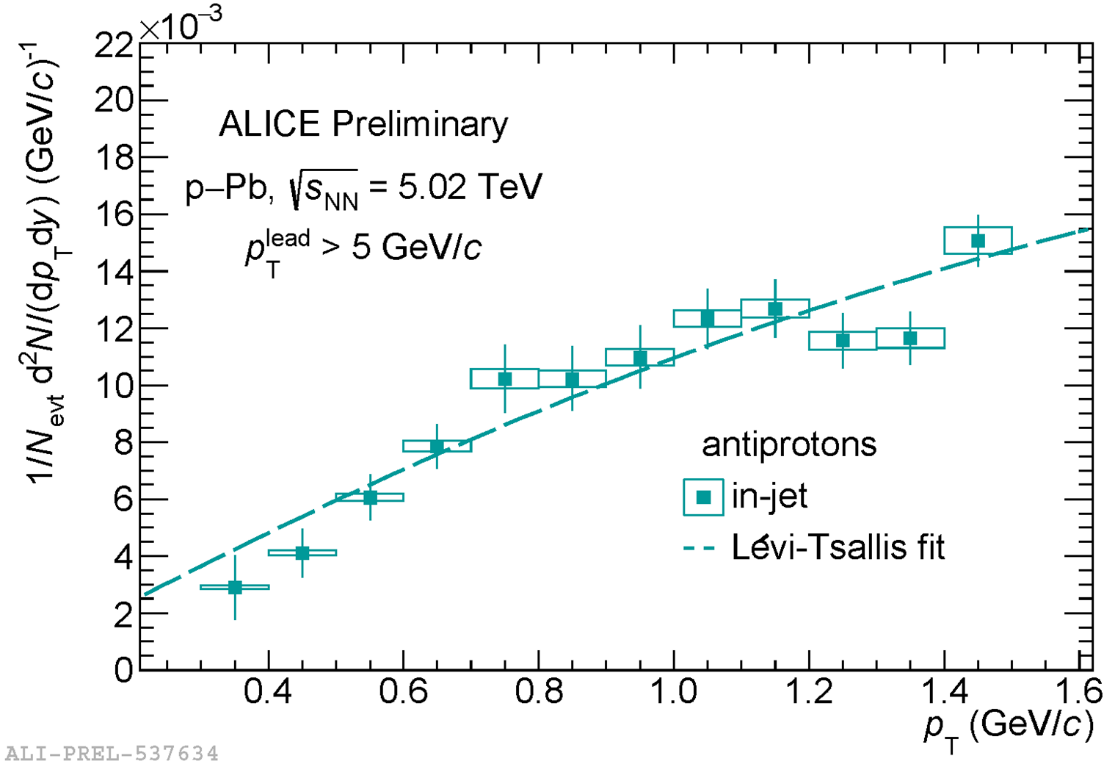


- What do we need for the coalescence parameter?

p-Pb@ 5.02 TeV

- **Second ingredient**: (anti)proton spectra

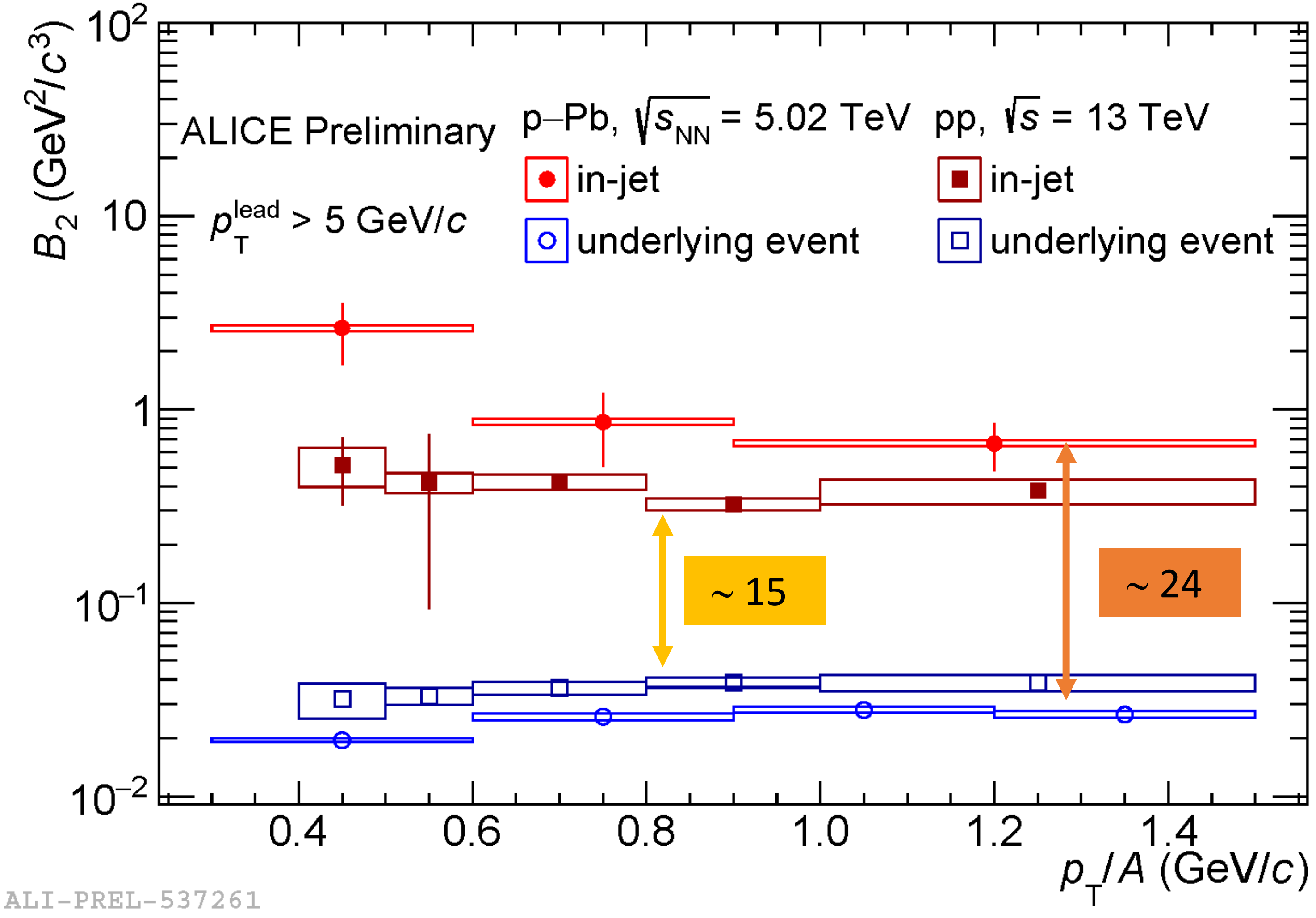


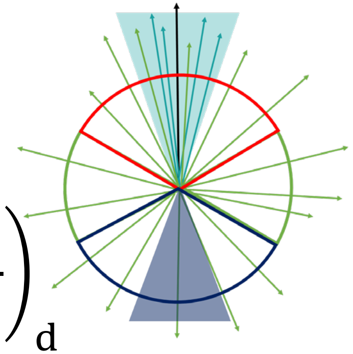


Antiproton production in events with p_T^{lead} > 5 GeV/c

Jet = Toward - Transverse

B_2 in jet and UE

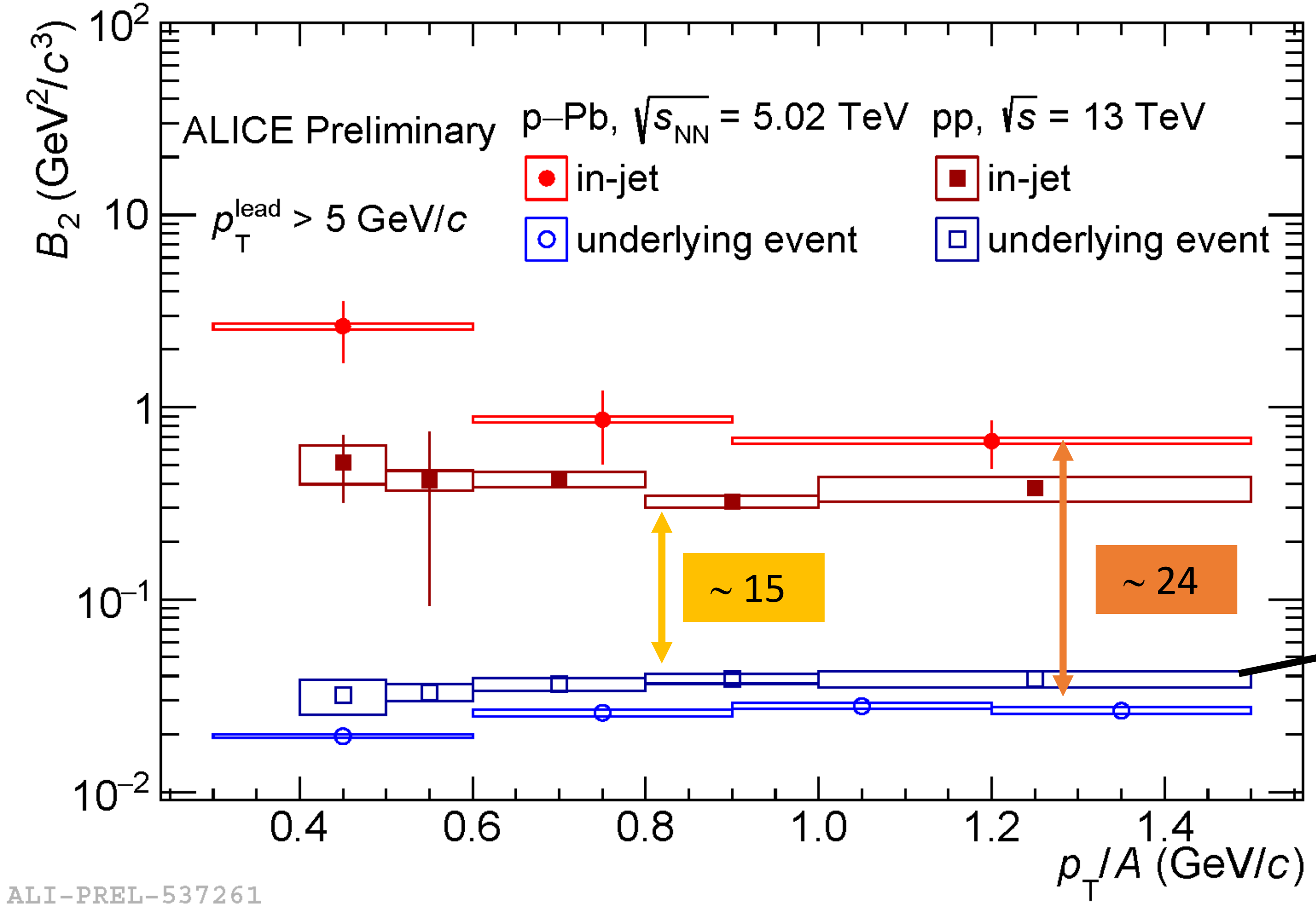


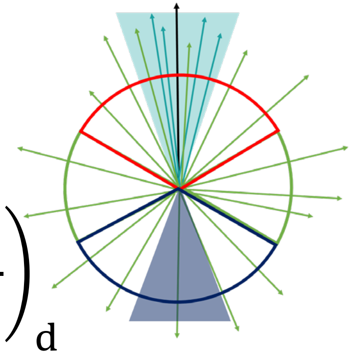


$$B_2 = \frac{\frac{1}{(2\pi/3)p_T^d}\left(\frac{d^2N}{dy dp_T}\right)_d}{\left(\frac{1}{(2\pi/3)p_T^p}\left(\frac{d^2N}{dy dp_T}\right)_p\right)^2}$$

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

B_2 in jet and UE





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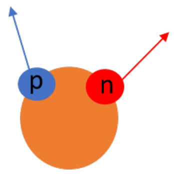
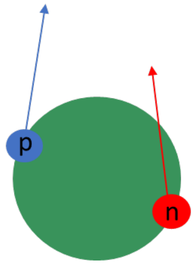
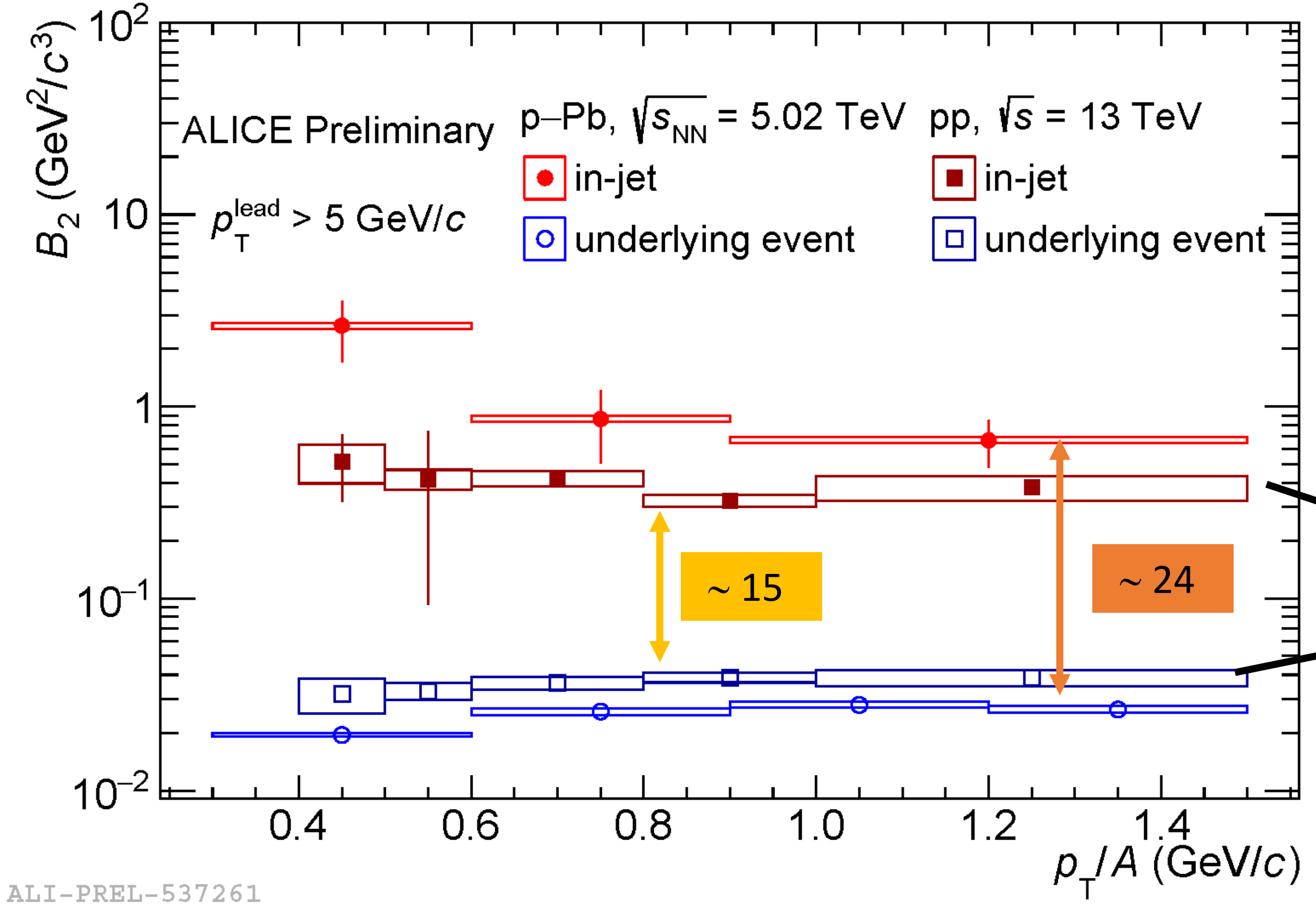
- Enhancement of B_2^{jet} wrt B_2^{UE} in pp collisions
- In p–Pb collision the enhancement factor is larger wrt pp collisions

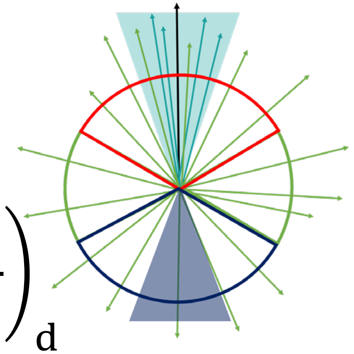
B_2^{UE}(p–Pb) < B_2^{UE}(pp) since p–Pb source size is larger than pp source size





B_2 in jet and UE





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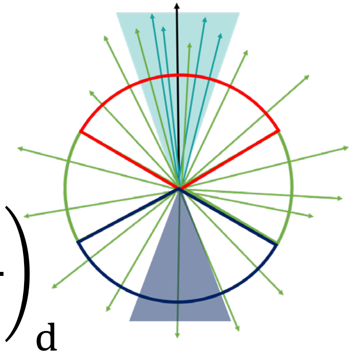
- Enhancement of B_2^{jet} wrt B_2^{UE} in pp collisions
- In p–Pb collision the enhancement factor is larger wrt pp collisions

***B_2^{jet}* (p–Pb) > *B_2^{jet}* (pp)**

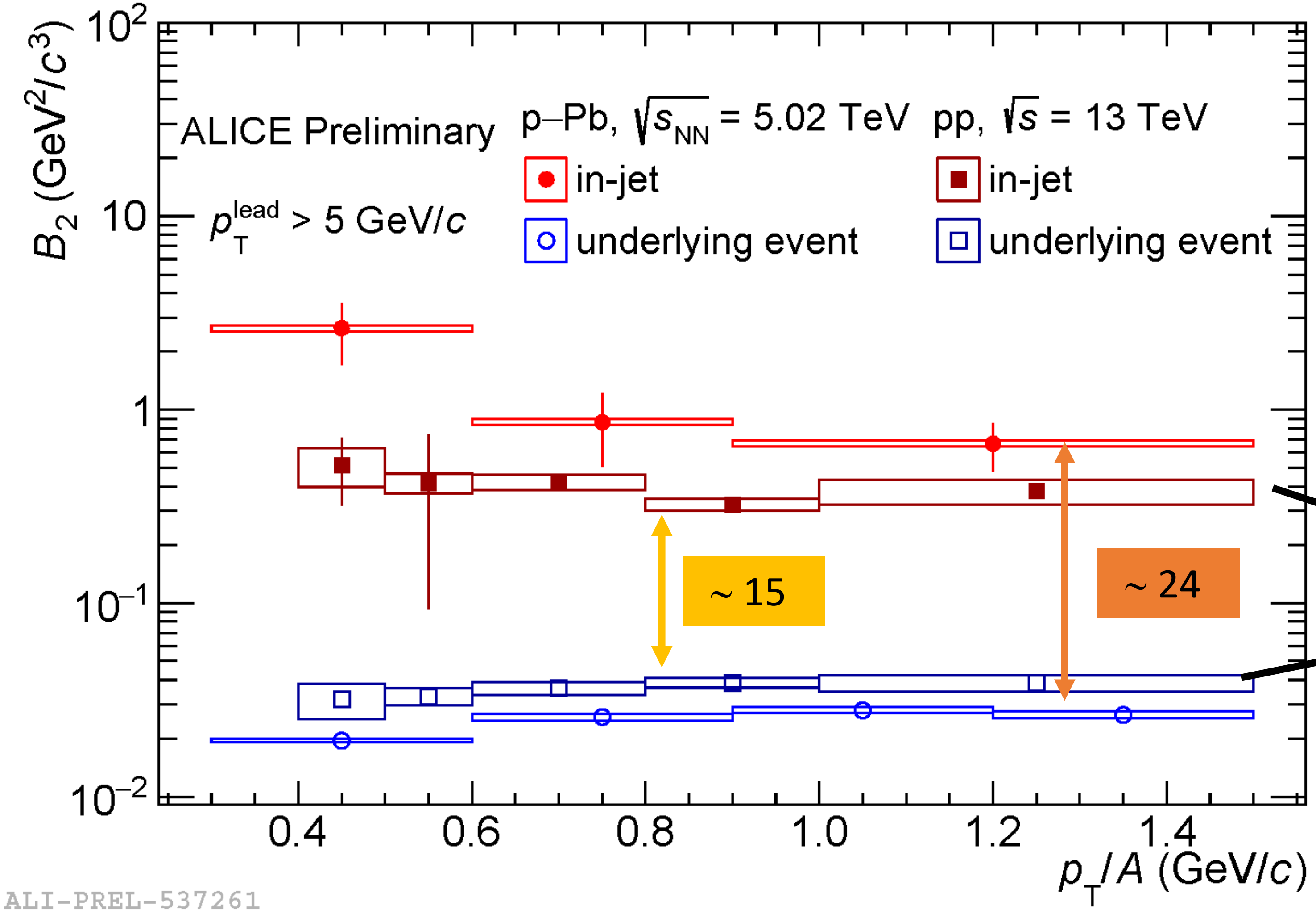
B_2^{UE} (p–Pb) < B_2^{UE}(pp) since p–Pb source size is larger than pp source size

Assuming the same source size for nucleons in jet, nucleons are probably closer in momentum space in p–Pb wrt pp

B_2 in jet and UE



$$B_2 = \frac{\frac{1}{(2\pi/3)p_T^d}\left(\frac{d^2N}{dy\,dp_T}\right)_d}{\left(\frac{1}{(2\pi/3)p_T^p}\left(\frac{d^2N}{dy\,dp_T}\right)_p\right)^2}$$



- Enhancement of B_2^{jet} wrt B_2^{UE} in pp collisions
- In p–Pb collision the enhancement factor is larger wrt pp collisions

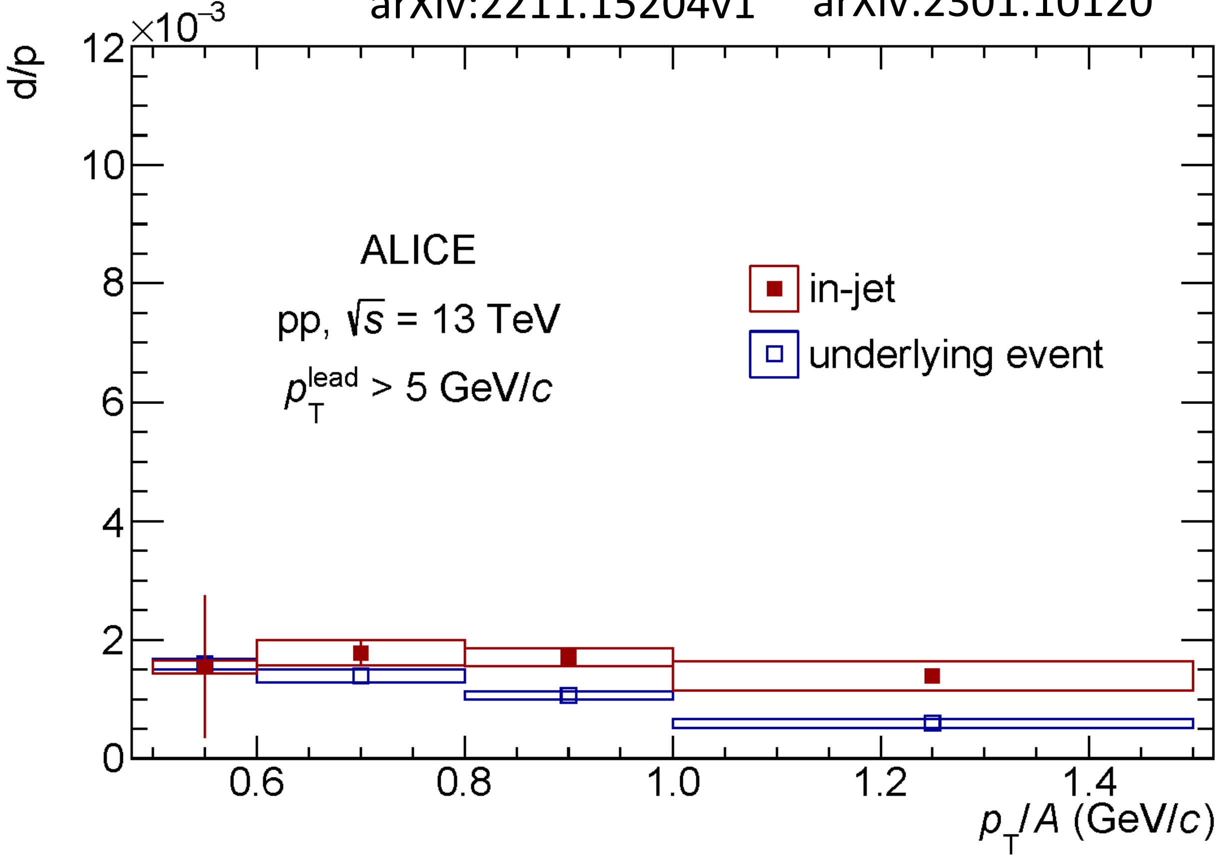
***B_2^{jet}* (p–Pb) > *B_2^{jet}* (pp)**

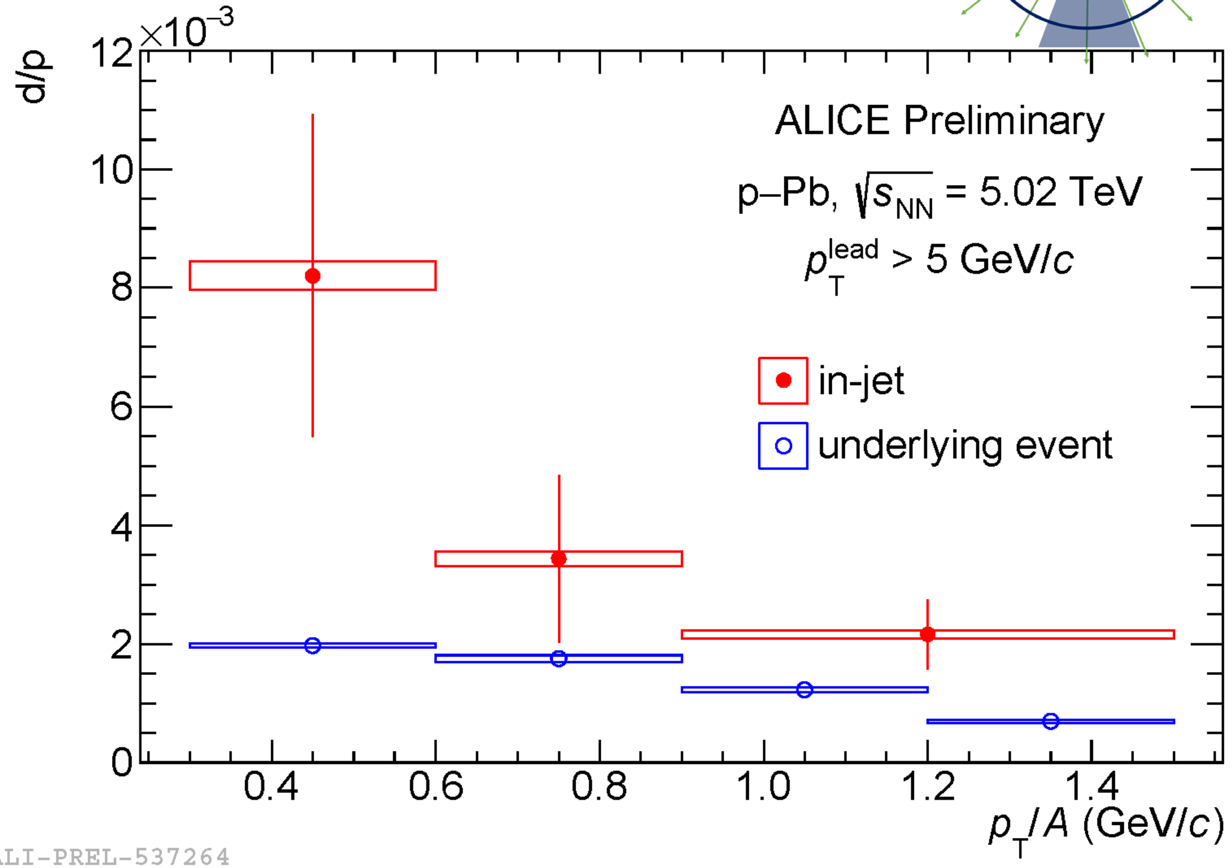
B_2^{UE} (p–Pb) < B_2^{UE}(pp) since p–Pb source size is larger than pp source size

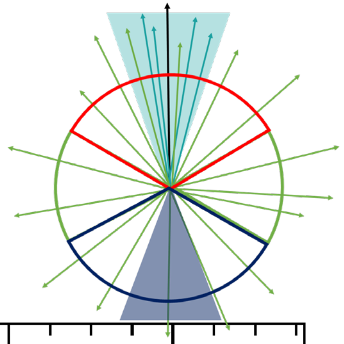
We see some differences between jets in pp and p–Pb collisions. Could be related to particle composition?

d/p in jet and UE

arXiv:2211.15204v1 arXiv:2301.10120

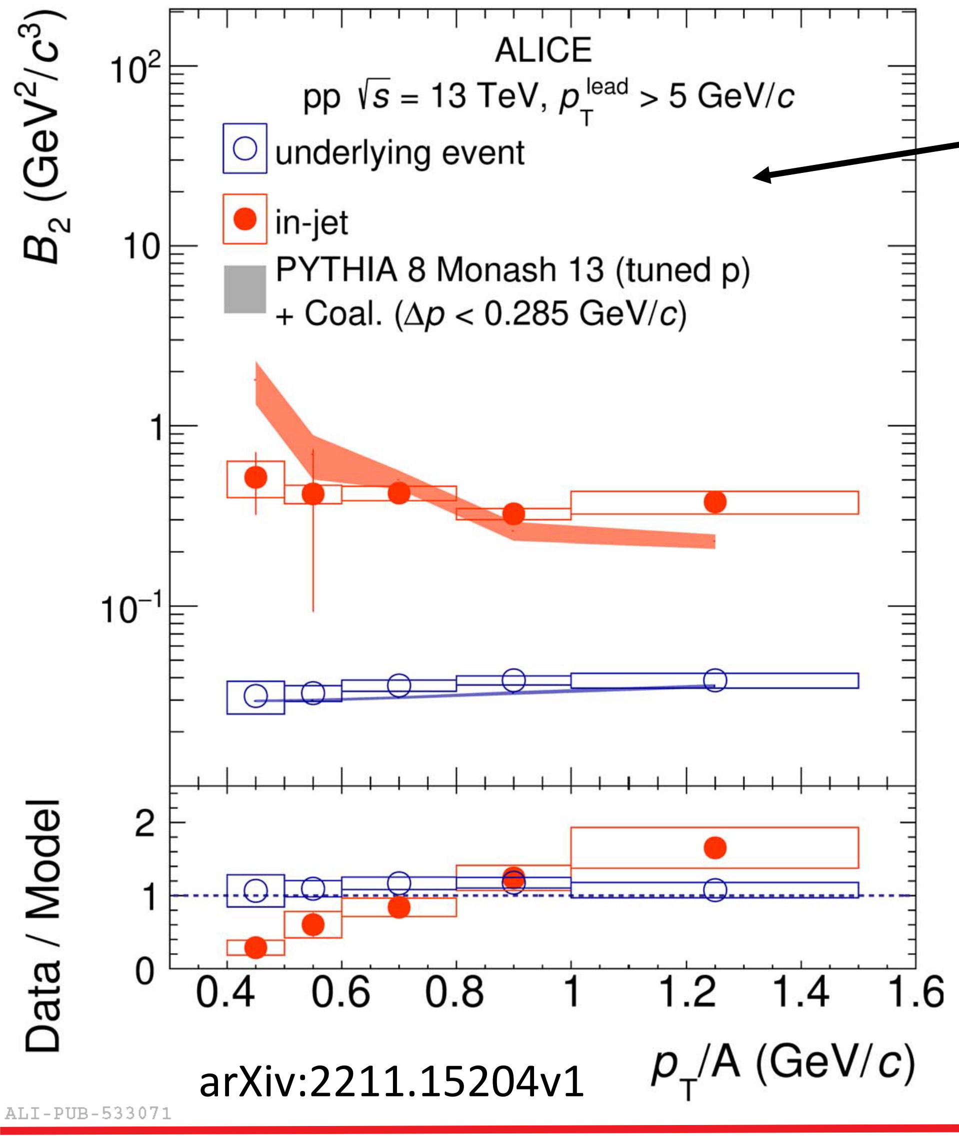






- d/p ^{jet} is higher than d/p ^{UE}
- **Higher d/p ^{jet} in p–Pb collisions wrt pp collisions**
- Different particle composition → could affect the coalescence probability

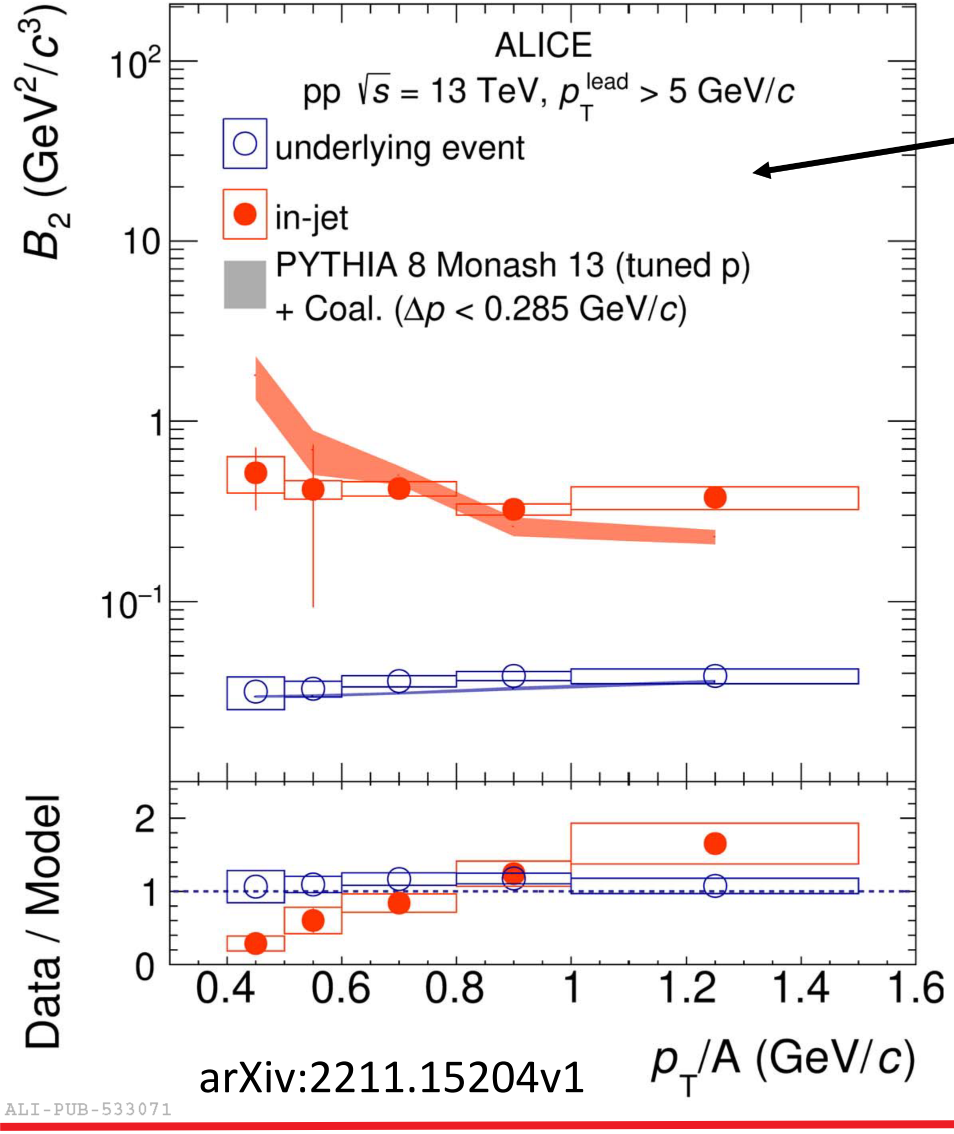
B_2 in jet and UE – model comparison



arXiv:2211.15204v1

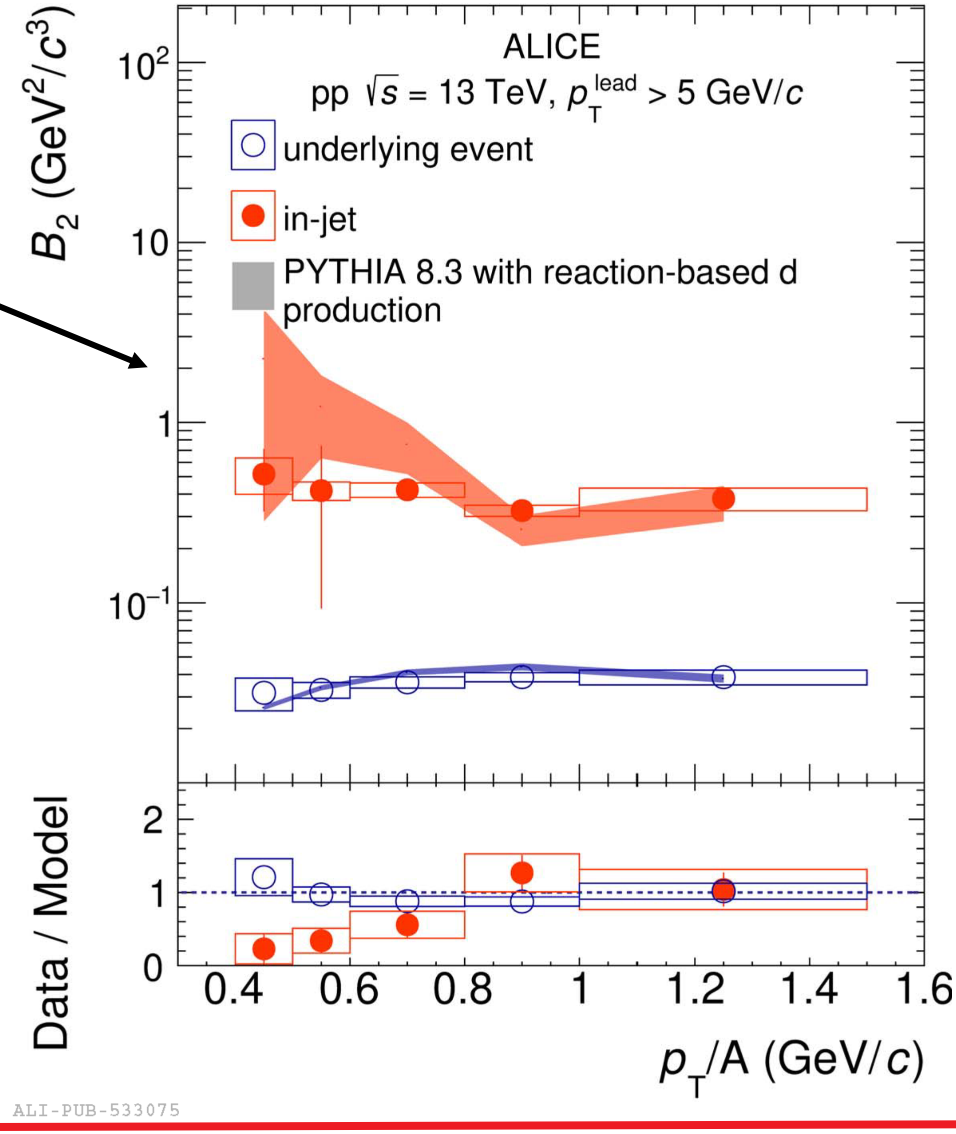
- Two different models:
  - PYTHIA 8 Monash 13 + simple coalescence

B_2 in jet and UE – model comparison

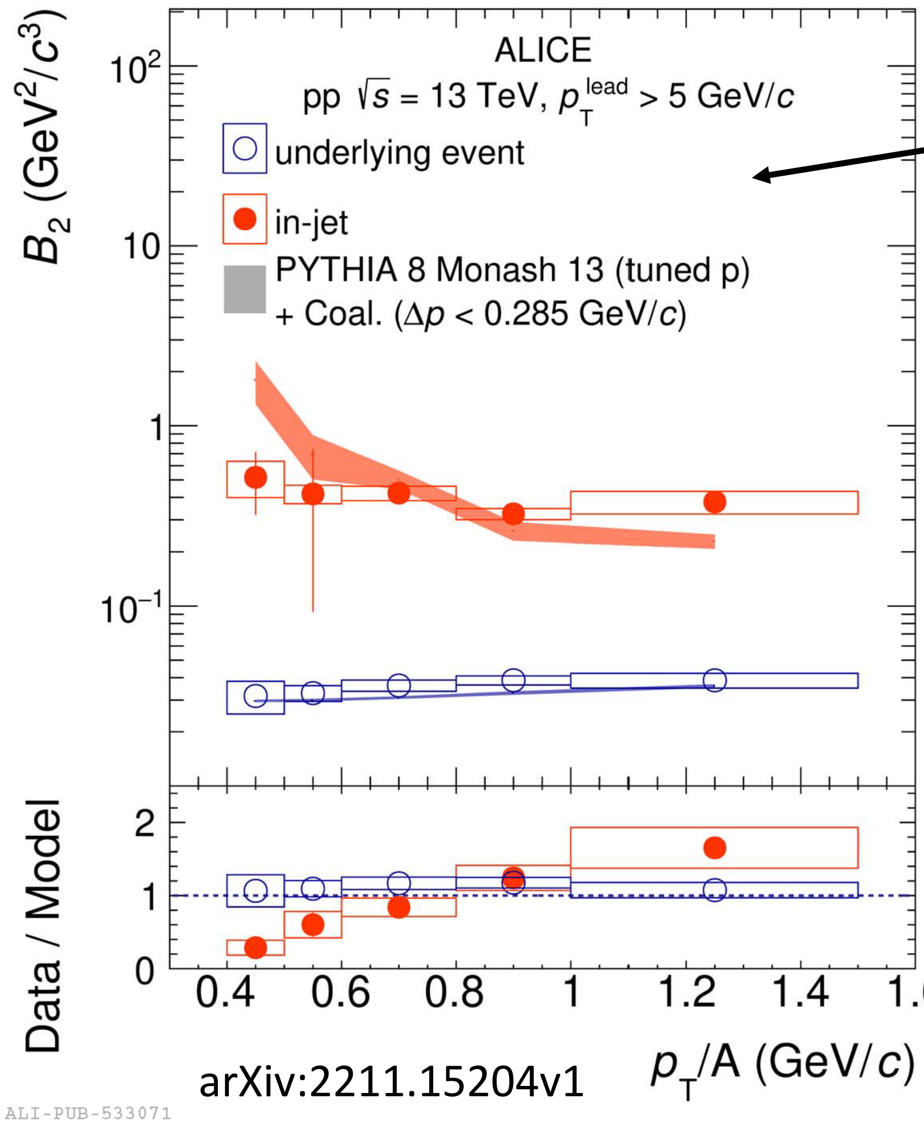


arXiv:2211.15204v1

- Two different models:
  - PYTHIA 8 Monash 13 + simple coalescence
  - PYTHIA 8.3 with reaction-based deuteron production (Bierlich et al., arXiv:2203.11601)

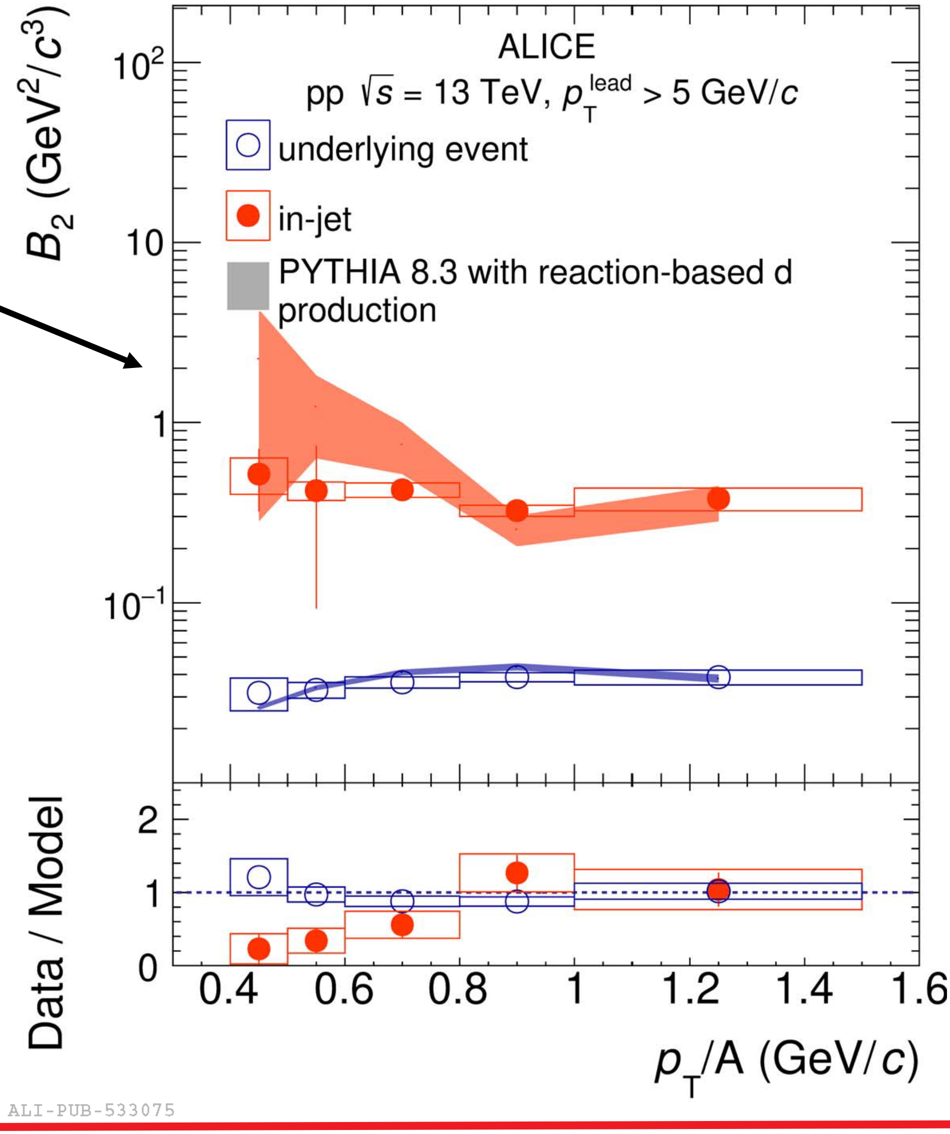


B_2 in jet and UE – model comparison

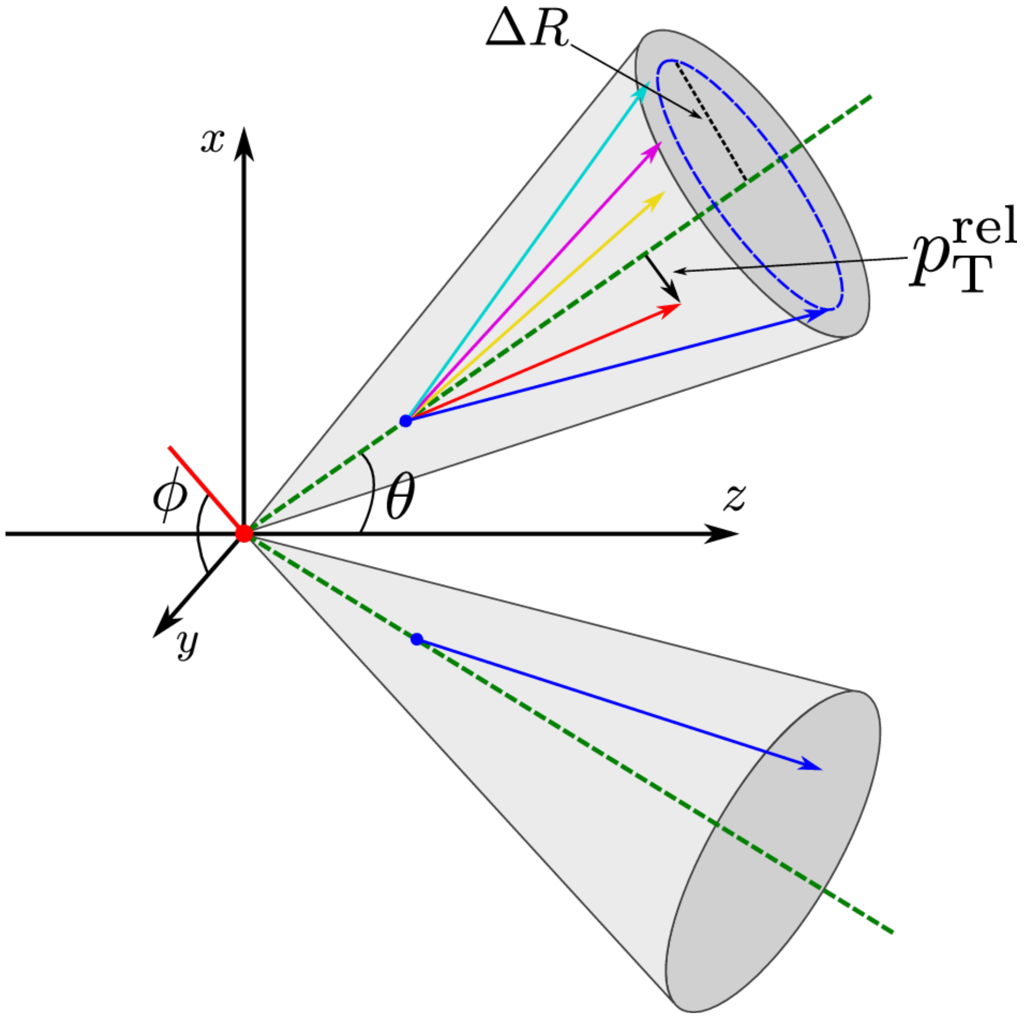


arXiv:2211.15204v1

- Two different models:
  - PYTHIA 8 Monash 13 + simple coalescence
  - PYTHIA 8.3 with reaction-based deuteron production (Bierlich et al., arXiv:2203.11601)
- Both models qualitatively reproduce the data and the large difference between B_2^{jet} and B_2^{UE}
- Further comparison with models



Light (anti)nuclei in jets: what's next?



- Run3 data taking is ongoing! How can we improve our measurements?
- Reconstruction of jets with jet finder algorithms
- Multi-differential measurements of light (anti)nuclei production (jet radii, $p_{\mathrm{T,\,lead}}$,etc …)

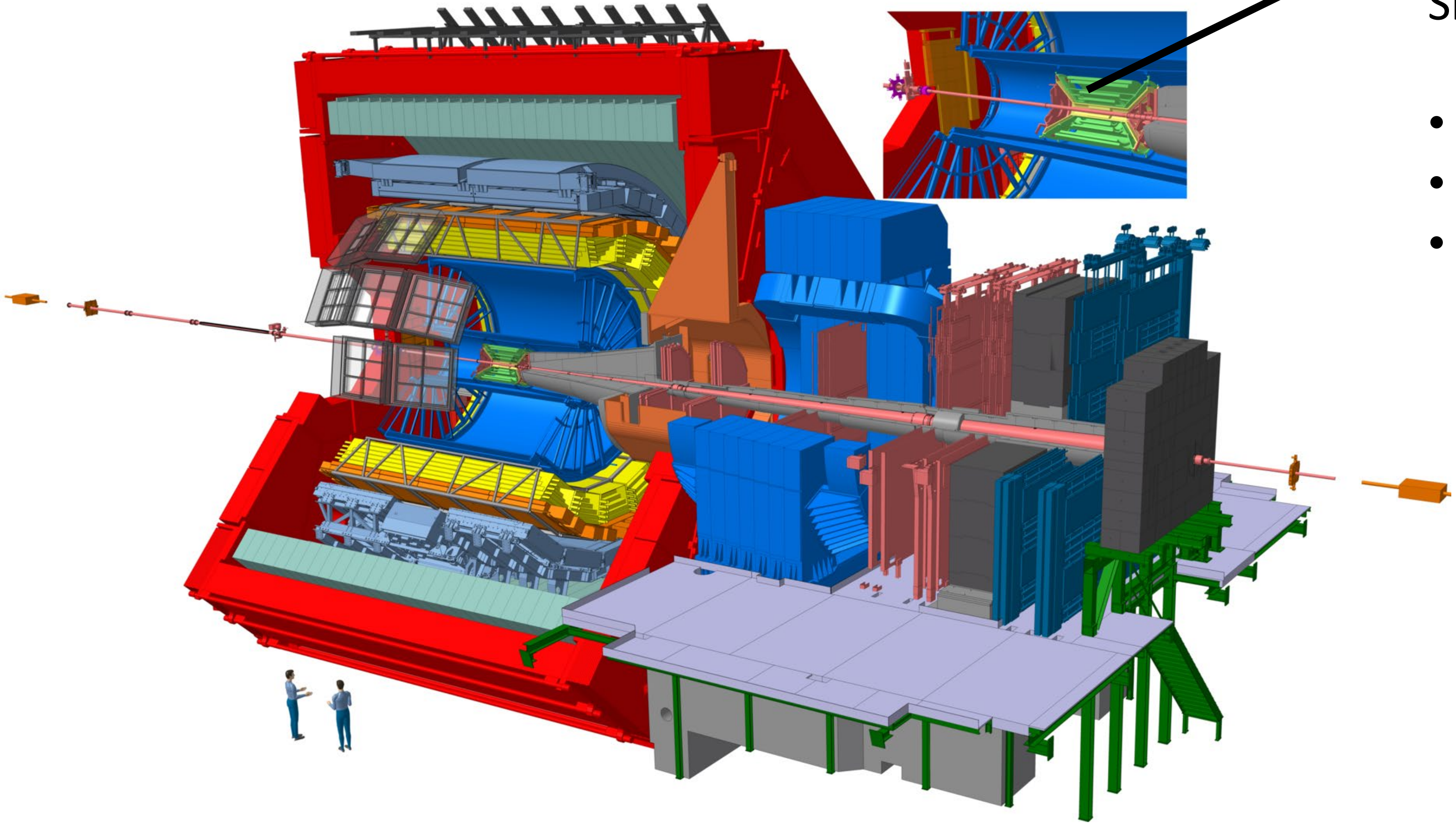
Conclusions

- Light (anti)nuclei production have been studied in depth by the ALICE experiment, obtaining results in different collision systems and energies
- Two main physical motivation: hadronization and dark matter searches
- The data have been compared to the hadronization theoretical models: SHM and coalescence
- In both cases, the models qualitatevely reproduce the data but there is not a definitive answer → **need for new observables!**
- Coalescence in jet: enhancement of B_2^{jet} wrt B_2^{UE} of a factor 15 (24) in pp (p–Pb) collisions
- New studies currently ongoing with Run3 data: **stay tuned for new results!**

Thank you for your attention!

Backup

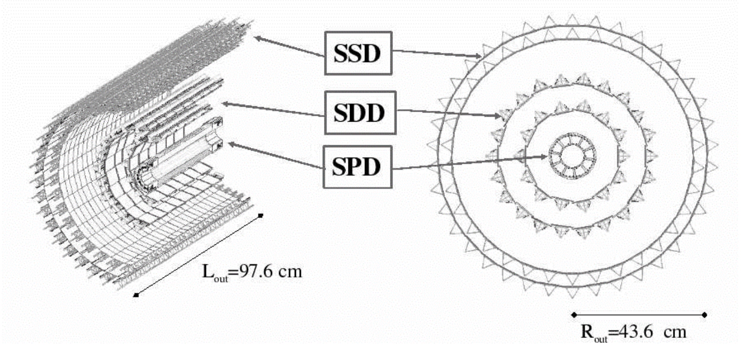
The ALICE detector in Run 1&2



Inner Tracking System (ITS)

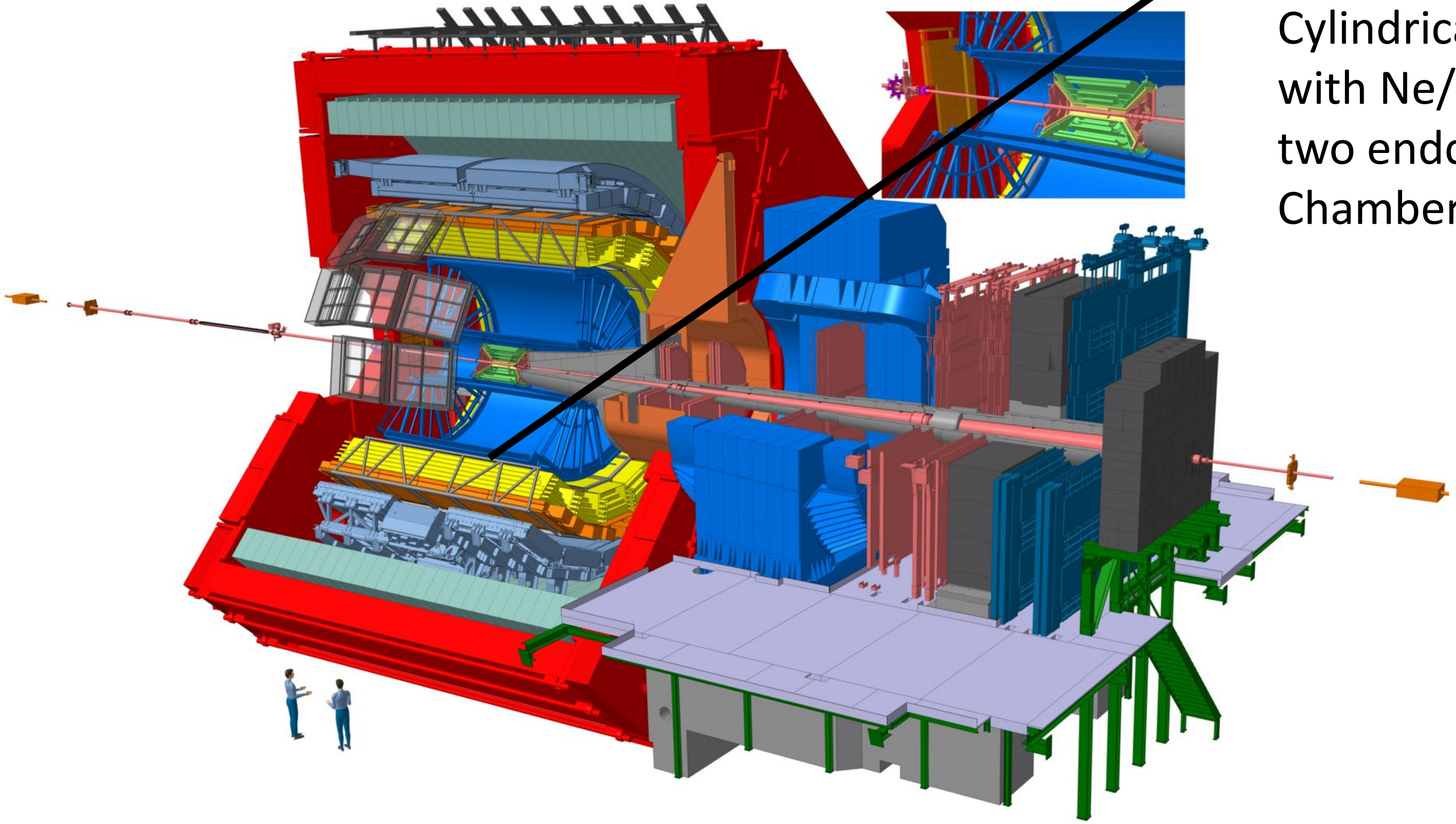
Six concentrical layer of silicon sensors:

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



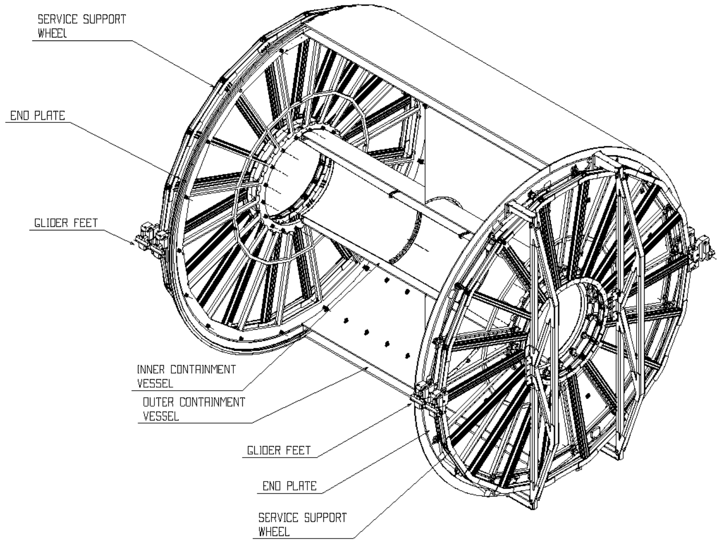
JINST 3 (2008) S08002
Int. J. Mod. Phys. A 29 (2014) 1430044

The ALICE detector in Run 1&2



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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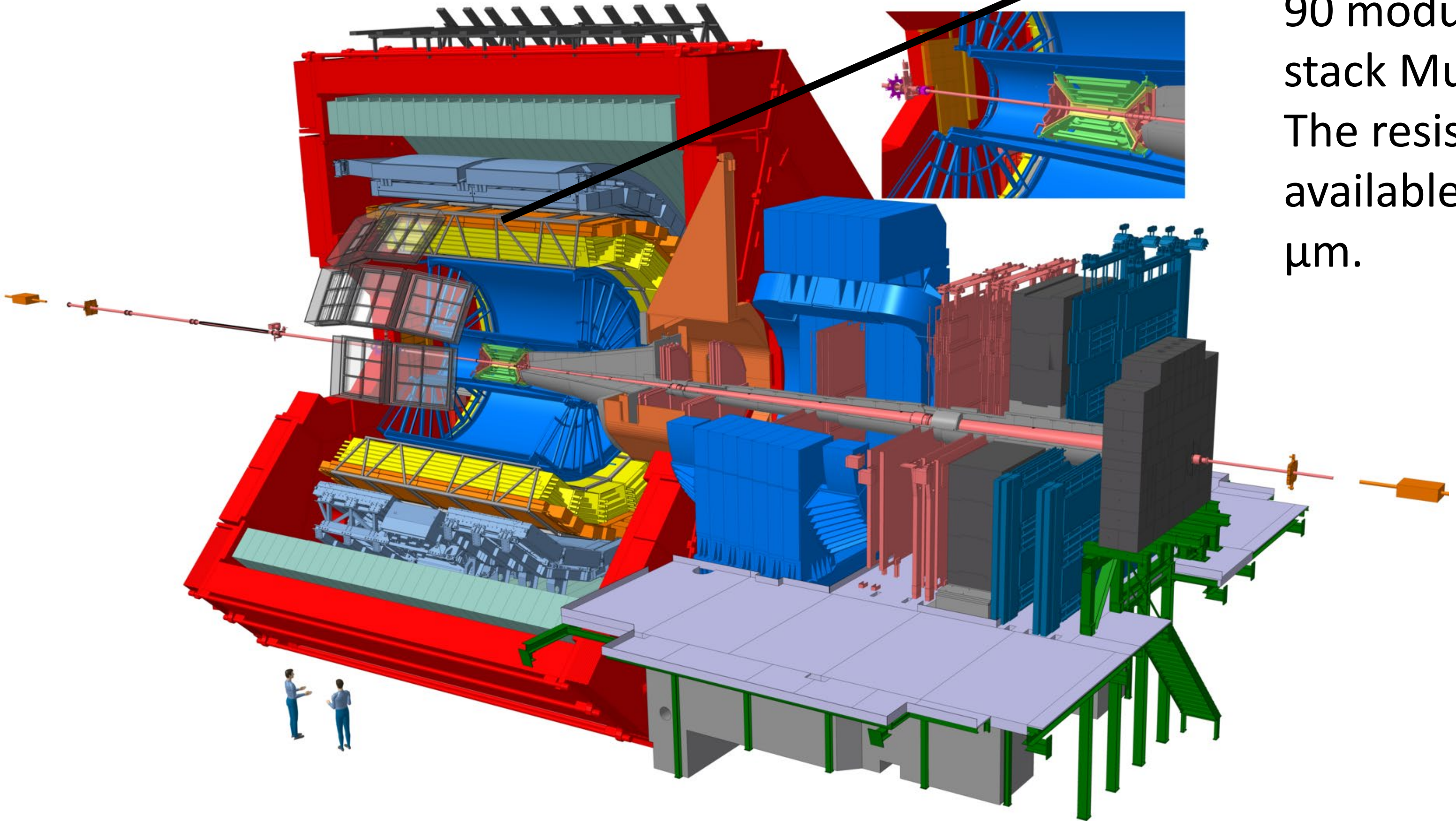
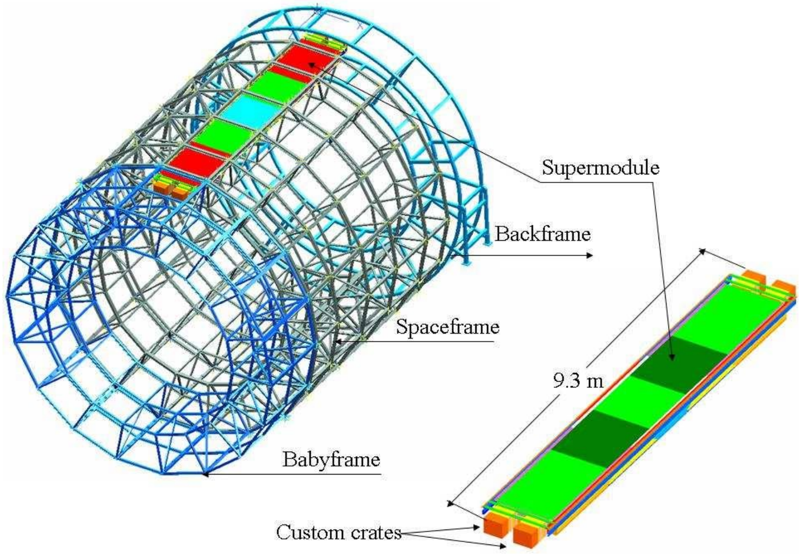
The ALICE detector in Run 1&2



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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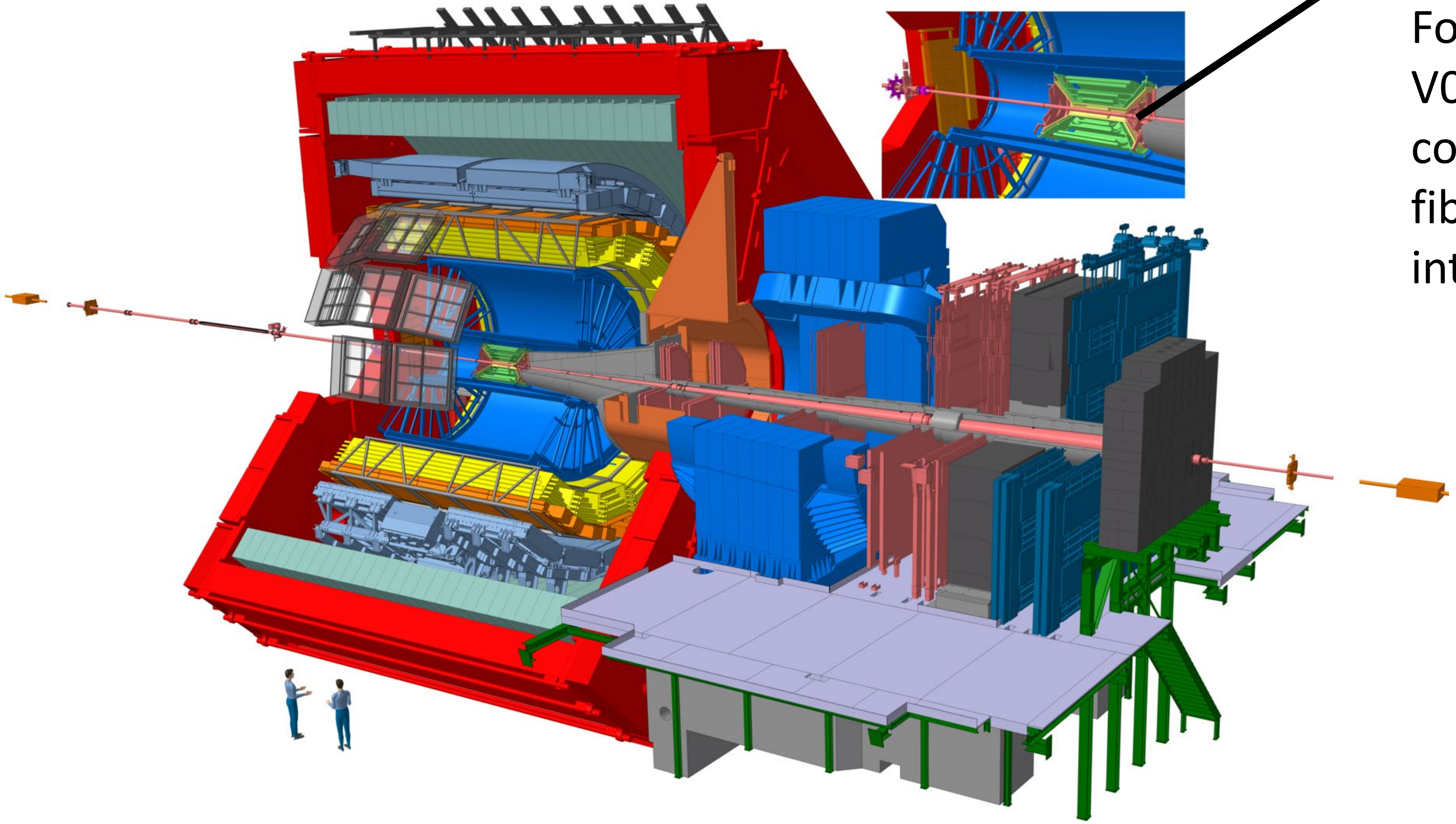
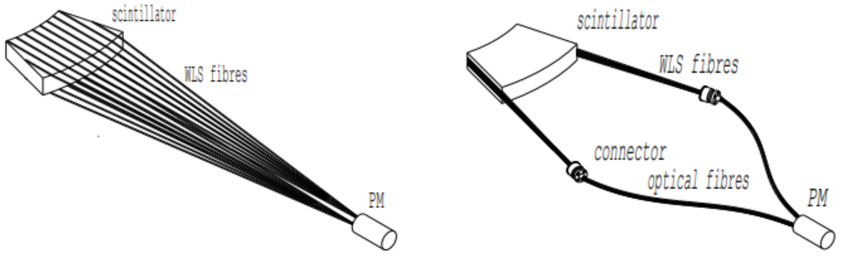
The ALICE detector in Run 1&2



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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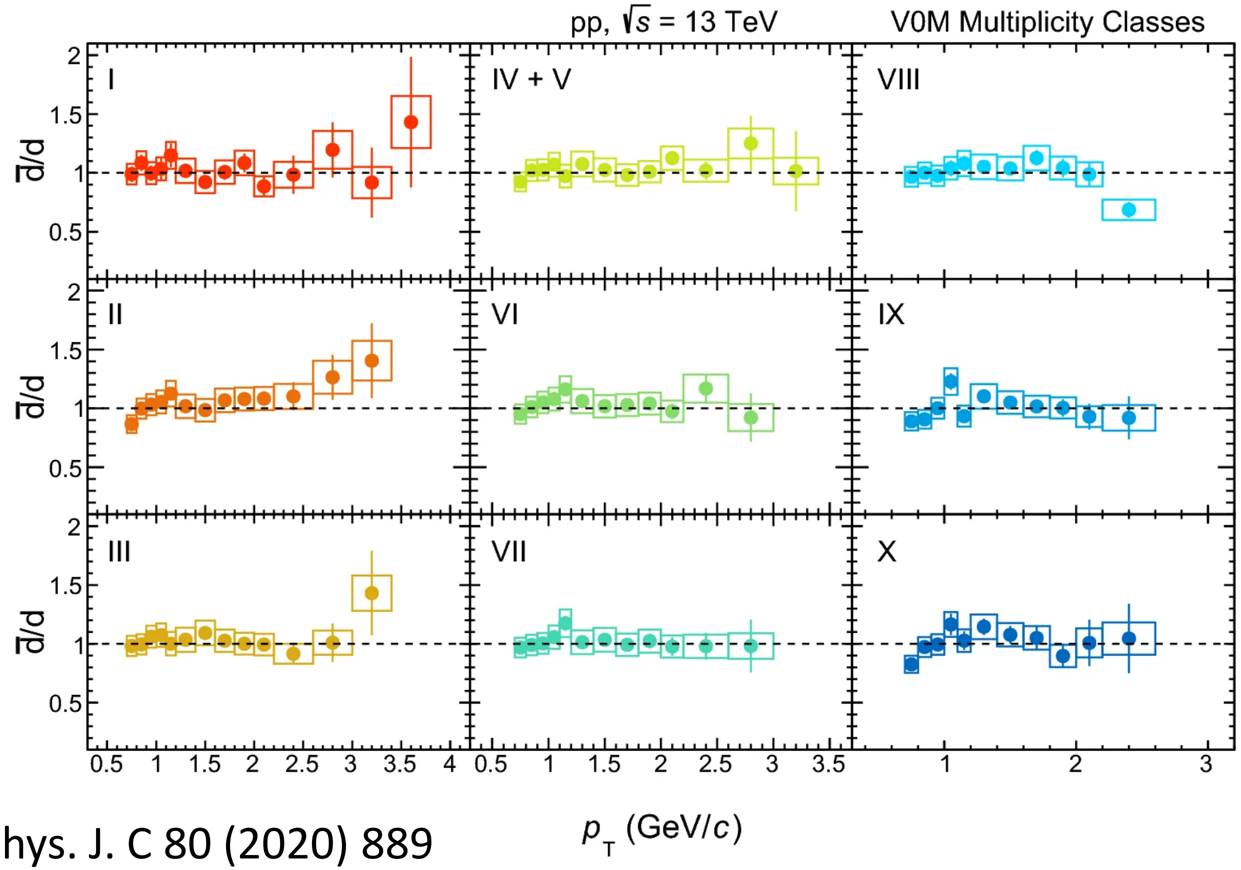
LHC: an (anti)nuclei factory

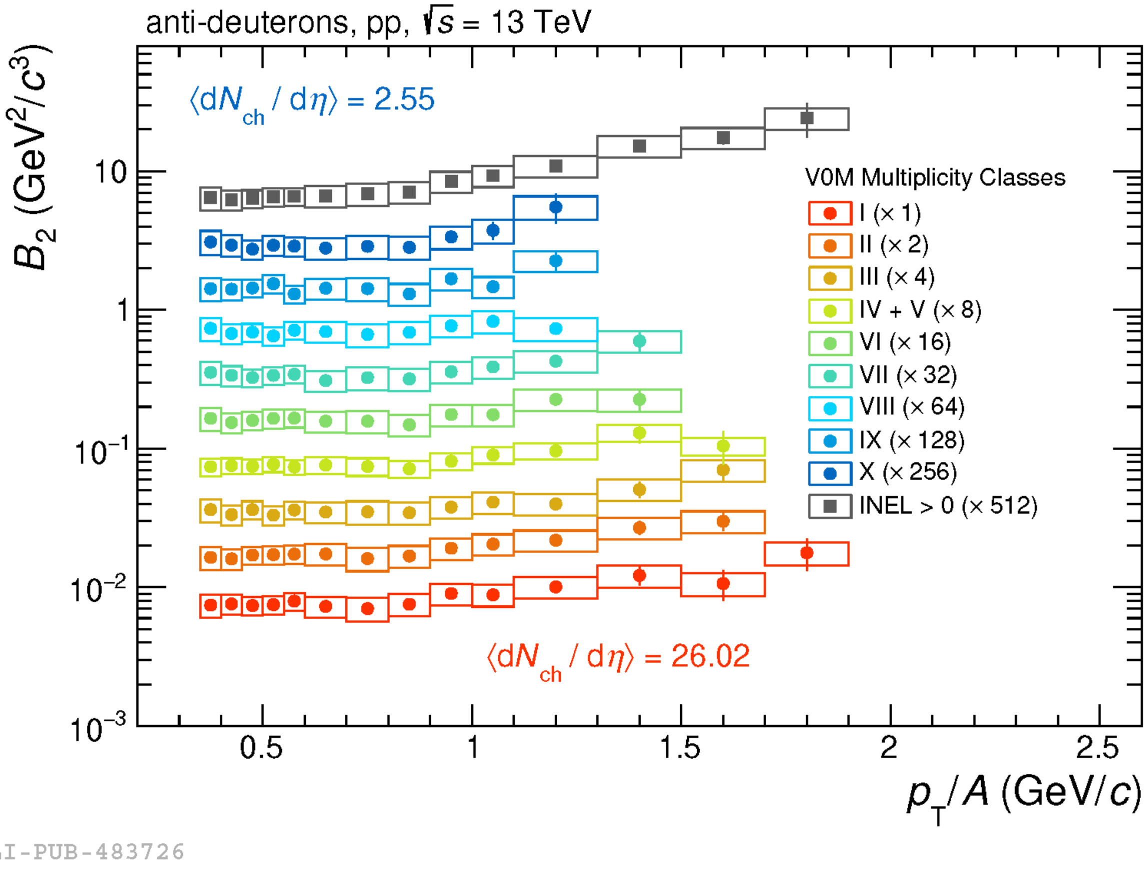
- At the LHC energies (almost) the same quantity of matter and antimatter are produced at midrapidity → baryochemical potential $\mu_B \approx 0$
- Antimatter-to-matter ratio consistent with unity



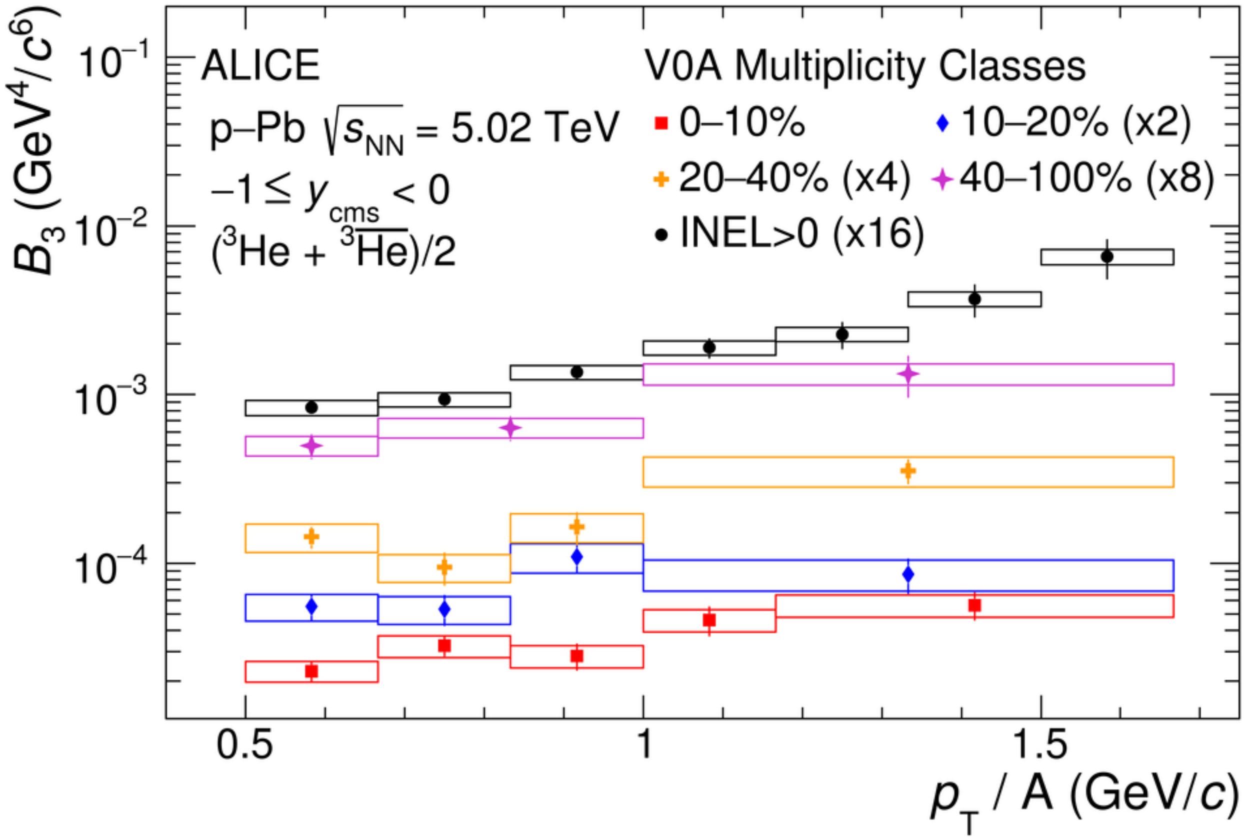
Eur. Phys. J. C 80 (2020) 889

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

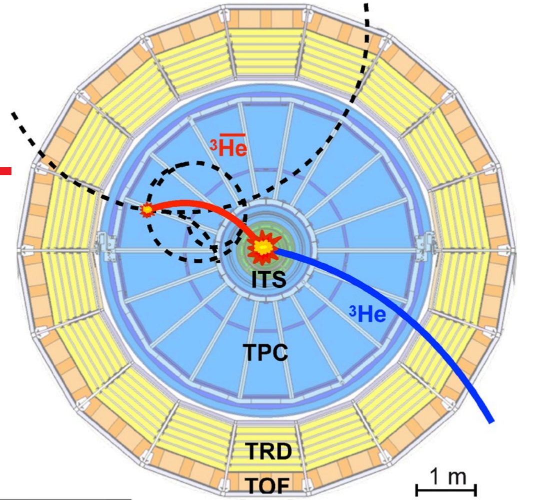
PYTHIA simulation details

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

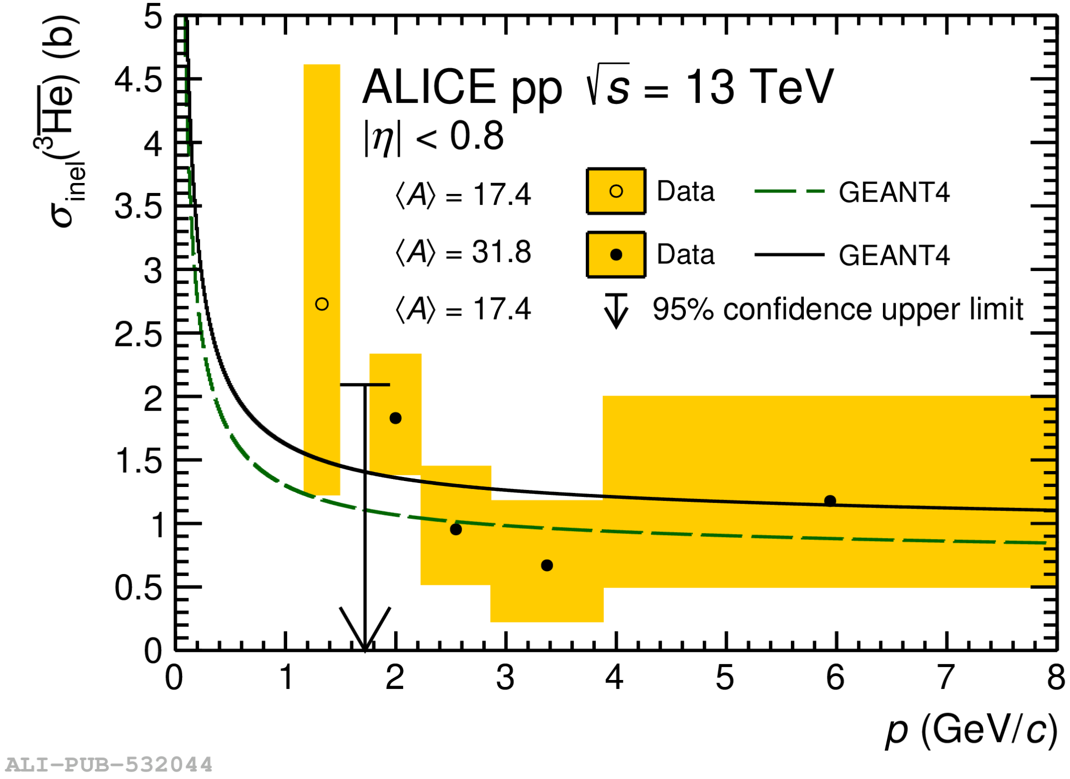
    $p + n \rightarrow \gamma + d$
    $p + n \rightarrow \pi^0 + d$
    $p + n \rightarrow \pi^0 + \pi^0 + d$
    $p + n \rightarrow \pi^+ + \pi^- + d$
    $p + p \rightarrow \pi^+ + d$
    $p + p \rightarrow \pi^+ + \pi^0 + d$
    $n + n \rightarrow \pi^- + d$
    $n + n \rightarrow \pi^- + \pi^0 + d$

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

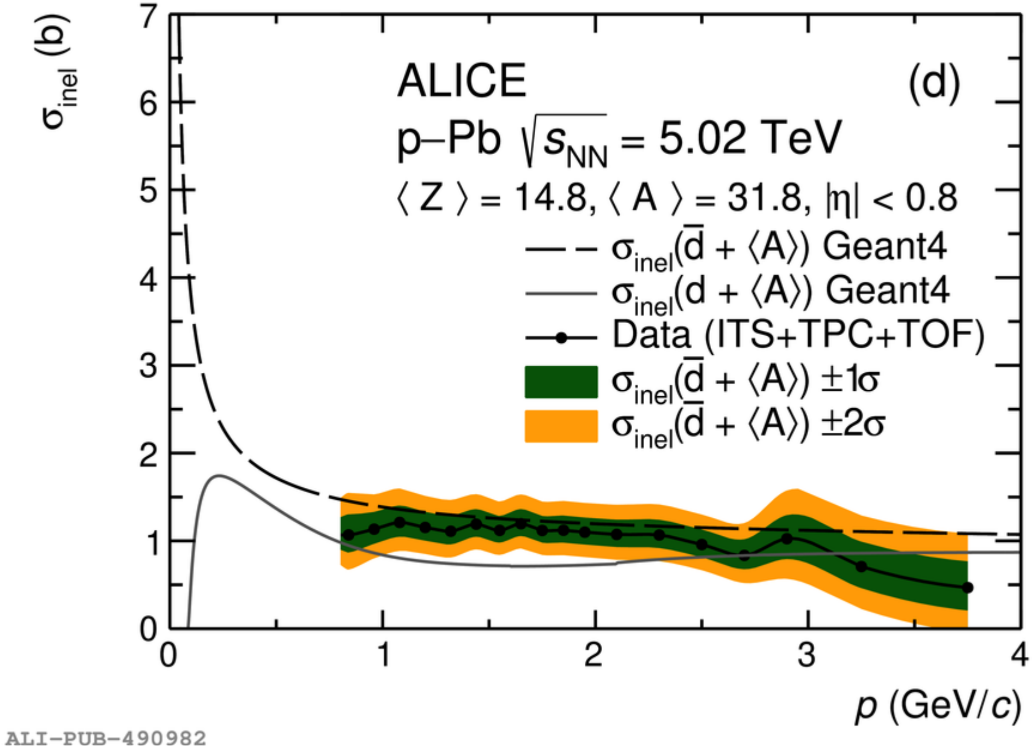
Light (anti)nuclei for DM detection



- Measurement of $\sigma_{inel}(^3\overline{\mathrm{He}})$ and $\sigma_{inel}(\bar{\mathrm{d}})$ using the detector as a passive absorber
- Obtained value used as input for dark matter or cosmic ray interaction modelling



Nature Phys. 19 (2023) 1, 61-71



Phys. Rev. Lett. 125 (2020) 162001