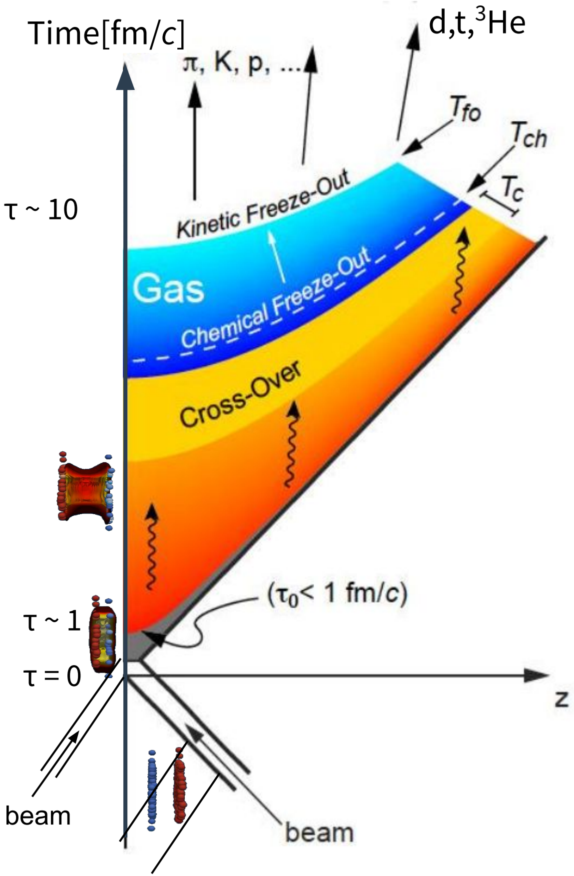
Production of light (anti)nuclei at the LHC

Ramona Lea
University of Brescia and INFN Pavia

ramona.lea@cern.ch

PHENOmenal Workshop

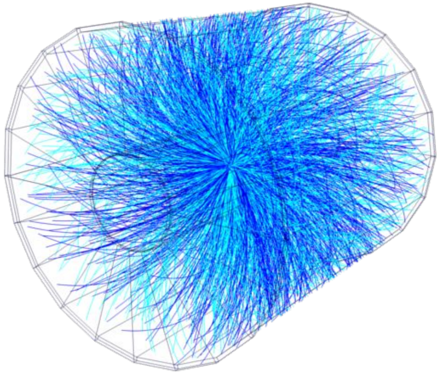
(Anti)(hyper)nuclei production

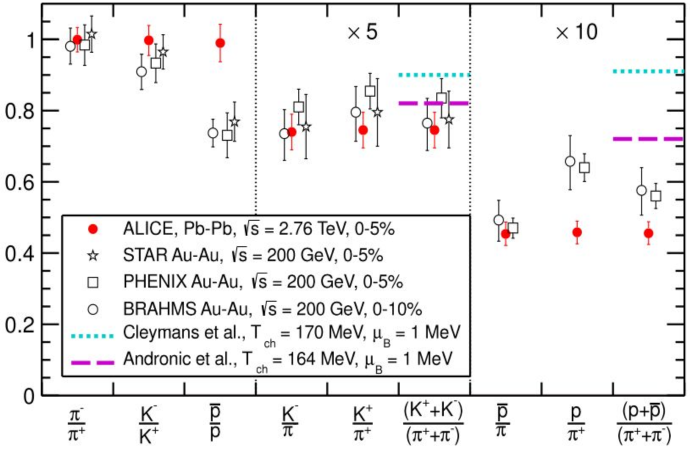


- (Anti)(hyper)nuclei measurement studies are crucial
  - Light nuclei measurements in high energy physics can be used to estimate the background of secondary anti-nuclei in dark matter searches
  - baseline for searches for exotic bound states
  - microscopic **production mechanism**
    - How/when do they form?
      - “early” at chemical freeze-out (thermal production)
      - or “late” at kinetic freeze-out (coalescence)?
    - Do they suffer for dissociation by rescattering?
  - Low binding energy (few MeV): nuclei formation is very sensitive to chemical freeze-out conditions and to the dynamics of the emitting source

Particle production at LHC

- Particle production in pp, p-Pb, and Pb-Pb collisions shows an **equal abundance** of matter and anti-matter in the central rapidity region
- A large number of particles is produced: $dN_{ch}/d\eta \approx 2000$ (central Pb-Pb collisions)





ALICE Collaboration Phys. Rev. Lett.109, 252301

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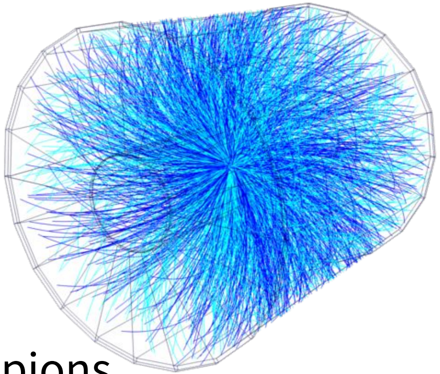

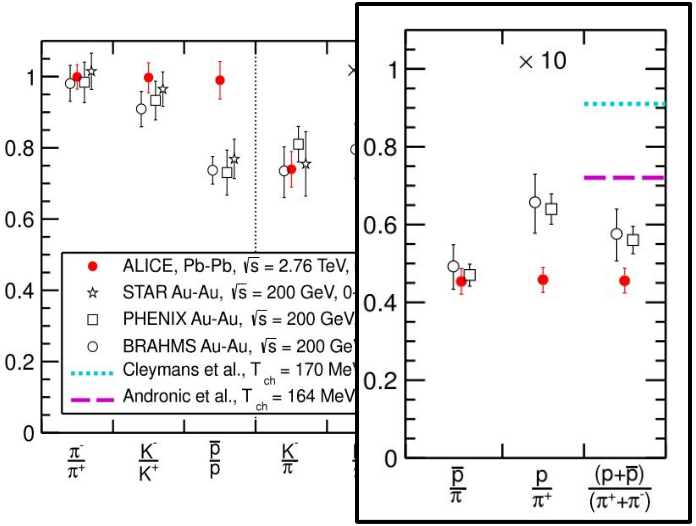

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≈ 5% of all charged particles are protons

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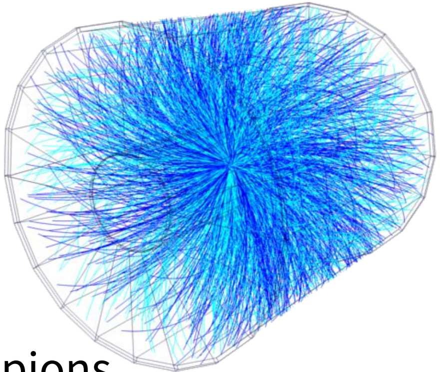

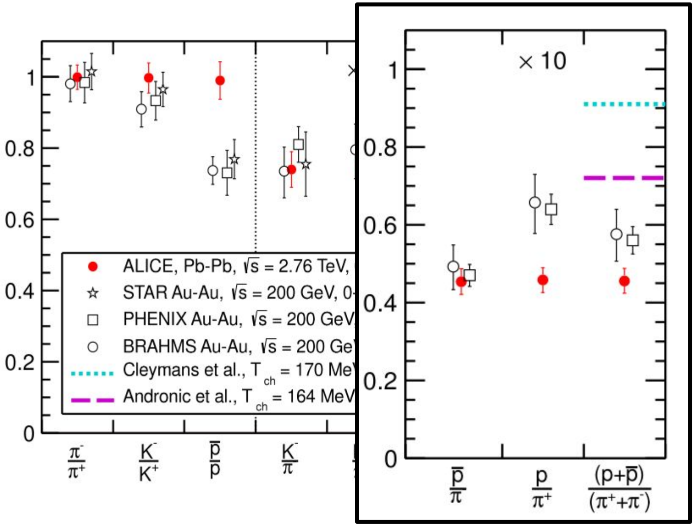

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≈ 80% of all charged particles are pions
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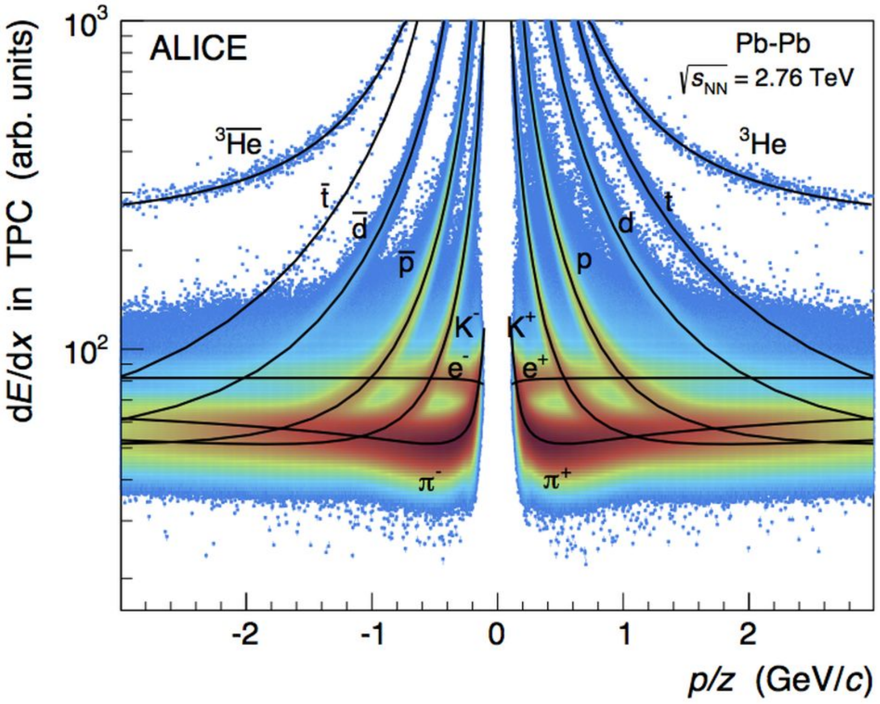
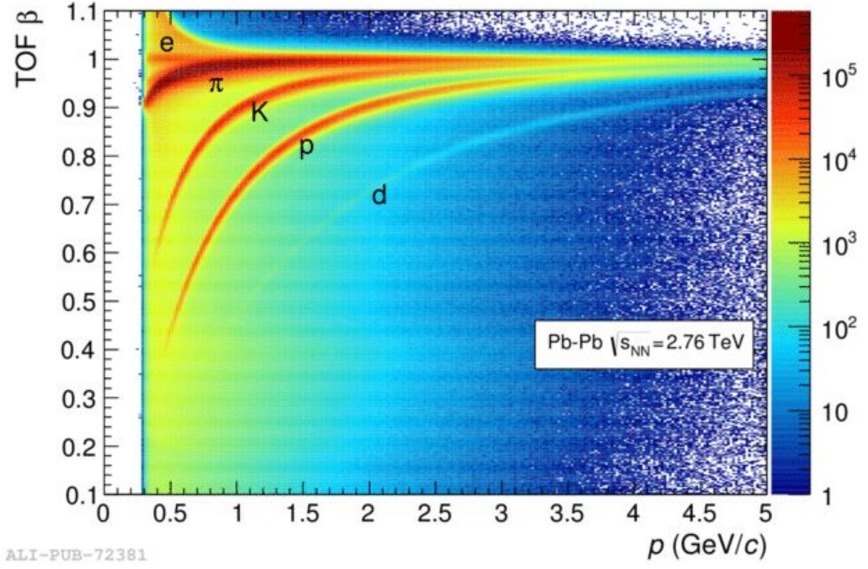
- Even in heavy ion collisions, light (anti-)nuclei are rarely produced:
  - (Anti-)nuclei up to A = 4 are within reach
  - For each additional nucleon the production yield at LHC decreases by a factor of about 350!

Nuclei identification

- ALICE measured production spectra of nuclei in pp, p-Pb and Pb-Pb collisions
    - excellent PID

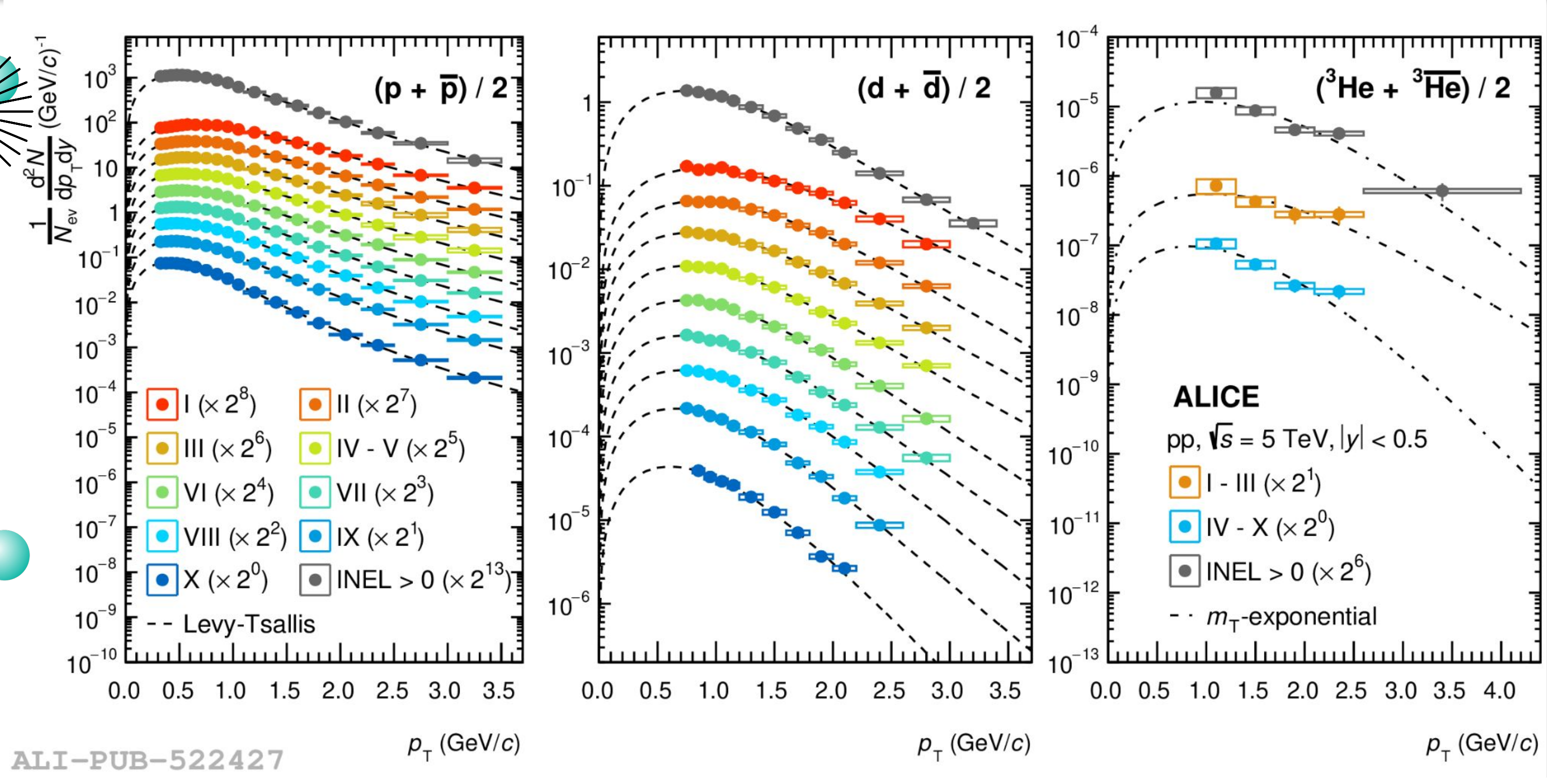




ALICE Collaboration,Phys. Rev. C 93, 024917 (2016)

ALICE Collaboration, Int. J. Mod. Phys. A 29 (2014) 1430044

Production spectra of nuclei with ALICE



ALICE Collaboration,EPJ C, 82, (2022) 289

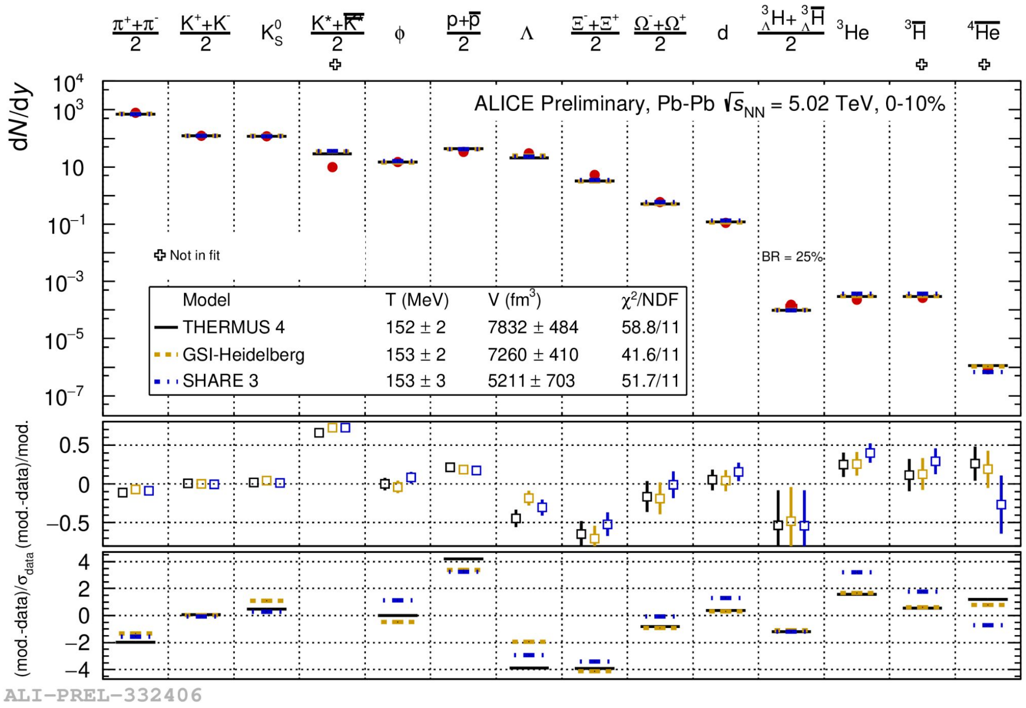
- p_T spectra fitted with Lévy-Tsallis / m_T-exponential function ⇒ extrapolation to unmeasured regions
- Measurements in classes of multiplicity: studies as a function of system size

The Statistical Hadronisation Model (SHM)

- It assumes hadron production from a system in thermal and hadrochemical equilibrium and that hadron abundances are fixed at chemical freeze-out

$$\mathrm{d}N/\mathrm{d}y \propto V \exp\left(-\frac{m}{T_{\mathrm{ch}}}\right)$$

- Large reaction volume ($VT^3 > 1$) in Pb-Pb collisions
    - ○ **grand canonical ensemble**
- Production yields d*N*/d*y* in central Pb-Pb collisions described over a wide range of d*N*/d*y* (9 orders of magnitude), **including nuclei**
- In small systems ($VT^3 < 1$) a local conservation of quantum numbers (S, Q and B) is necessary
    - ○ **canonical ensemble (CSM)**



[THERMUS 4: Comput.Phys.Commun. 180 (2009) 84-106](#)
[GSI-Heidelberg: Nucl.Phys.A 772 (2006) 167-199 V](#)
[SHARE 3: Comput.Phys.Commun. 167 (2005) 229-251](#)

[Vovchenko et al., PLB 785 (2018) 171-174](#)

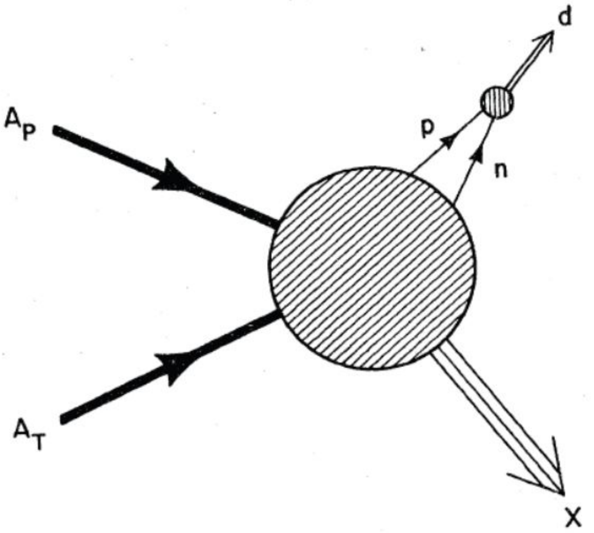
The coalescence model

- Nucleons that are close in phase space at the freeze-out can form a nucleus via coalescence
- The key concept is the overlap between the nuclear wavefunction and the phase space distribution of the nucleons
- The main parameter of the model is the 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
  - ○ $p_\mathrm{p} = p_\mathrm{A}$ / A

➢ B_A is related to the probability to form a nucleus via coalescence



J.I. Kapusta, PRC 21 (1980) 1301

Francesca Bellini, et al, Phys. Rev. C **103**, 014907

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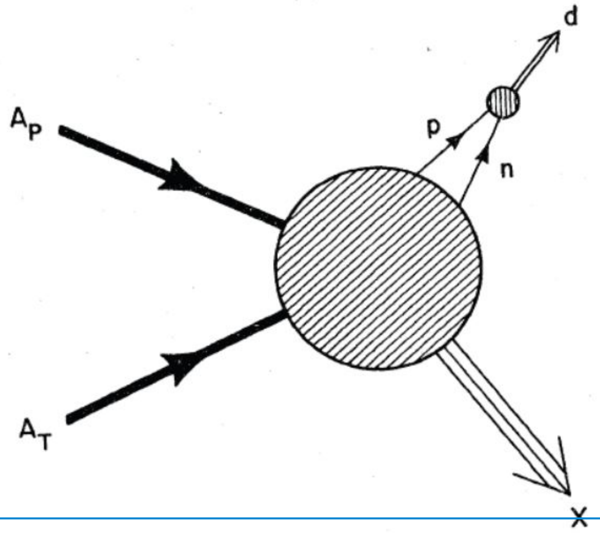
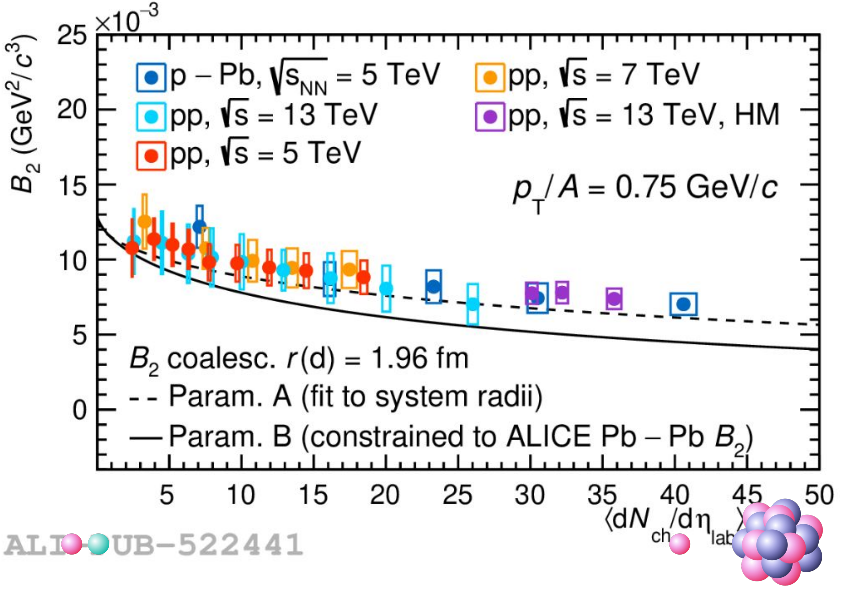


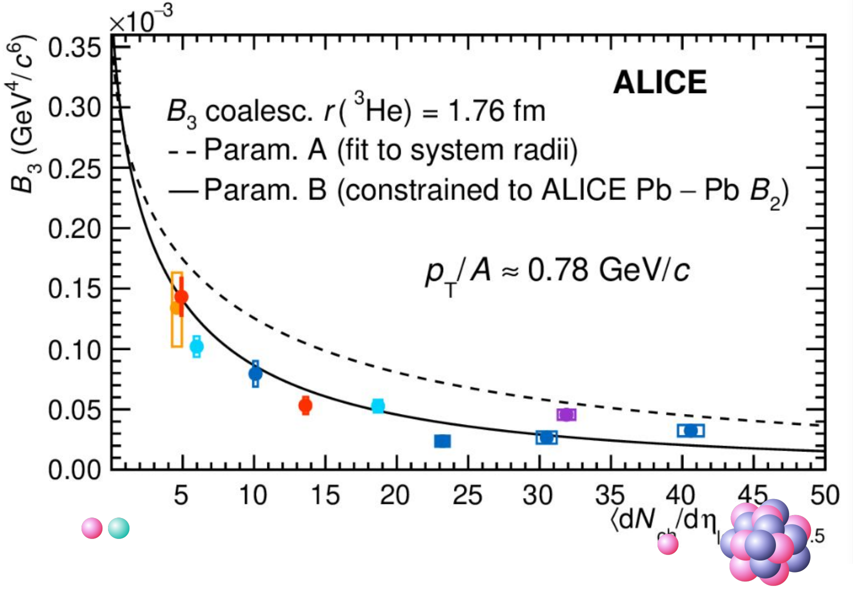
J.I. Kapusta, PRC 21 (1980) 1301

Francesca Bellini, et al, Phys. Rev. C **103**, 014907

- Small collision systems as pp are particularly interesting:
  - system created in the collision has a size similar to that of the nucleus
  - allows for the study of coalescence since nucleons are created close to each other
  - for small systems model predictions are quite different

Coalescence parameter B_A





ALICE Collaboration, EPJC 82, 289 (2022)

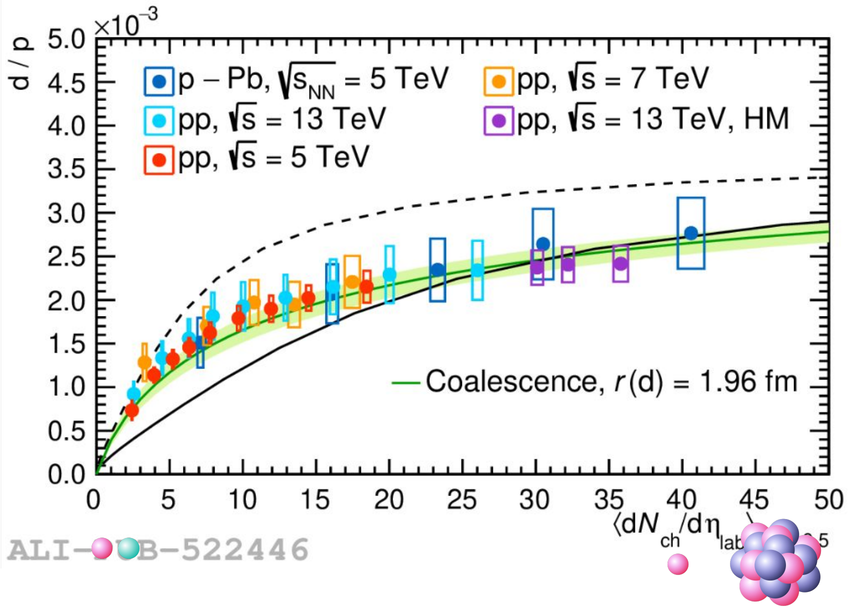
- B_A evolves smoothly with multiplicity
  - dependence on the system size
- Comparison with theory:

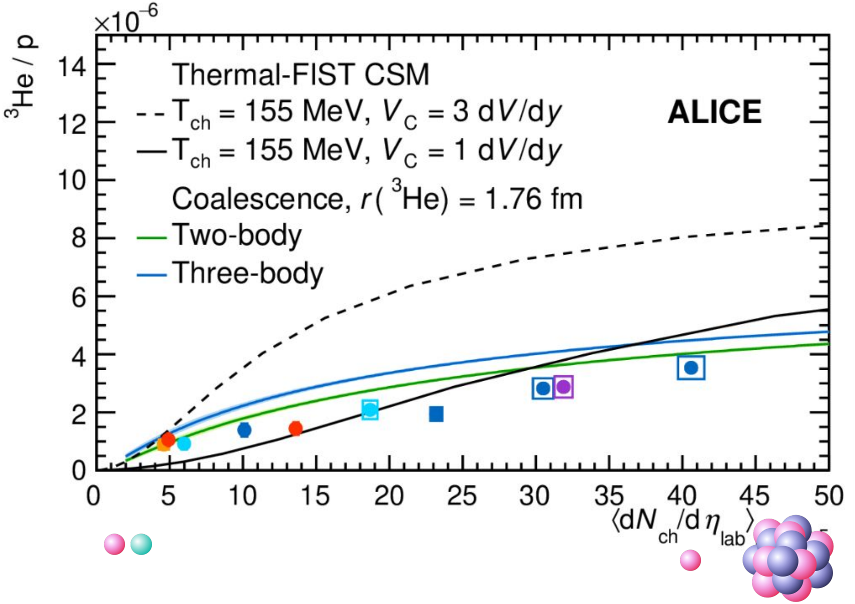
$$B_A = \frac{2J_A+1}{2\sqrt[A]{A}}\frac{1}{m^{A-1}}\left[\frac{2\pi}{R^2(m_T)+(R_A/2)^2}\right]^{\frac{3}{2}(A-1)}$$

- Two different parameterisations for dN/dη vs R
  - None of them can describe simultaneously B_2 and B_3

Yield ratios

- Particle ratio evolves smoothly with multiplicity: dependence on the system size





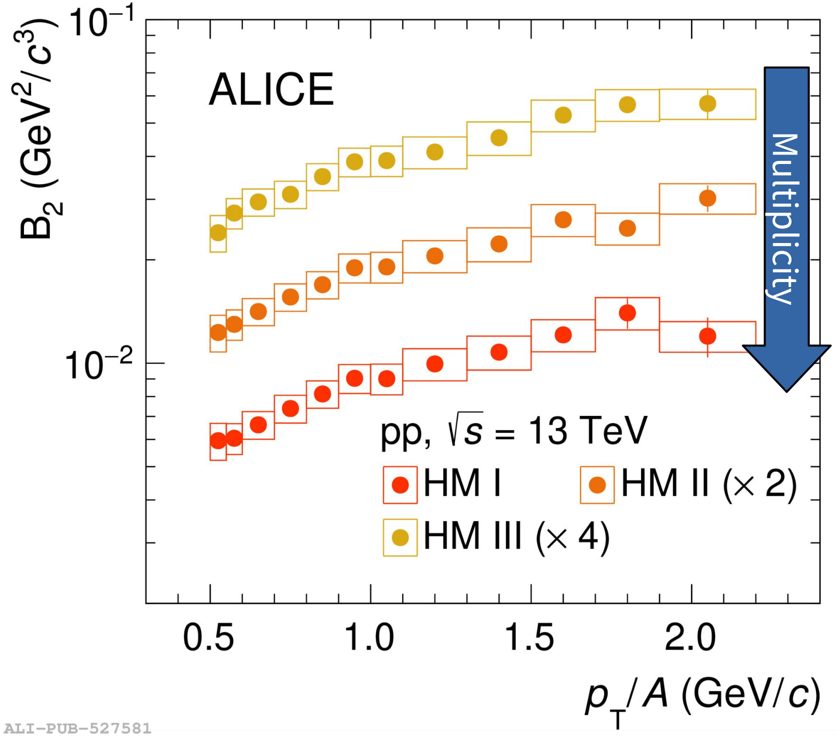
ALICE Collaboration, EPJC 82, 289 (2022)

- For d/p ratio both the models describe the data:
  - CSM: canonical suppression
  - Coalescence model: interplay between source size and nuclear size

- For ^{3}He/p there are more tensions between data and models
  - ⇒ Not possible to discriminate between the two models

B_A vs p_T in HM pp collisions

- B_2 and B_3 have been measured in HM pp collisions
- In the same data sample also the source size has been measured with femtoscopy
  - ⇒ comparison with theoretical predictions[1] is possible



[1]K. Blum et al, Phys.Rev.C 99 (2019) 4, 044913

ALICE Collaboration JHEP (2022) 206

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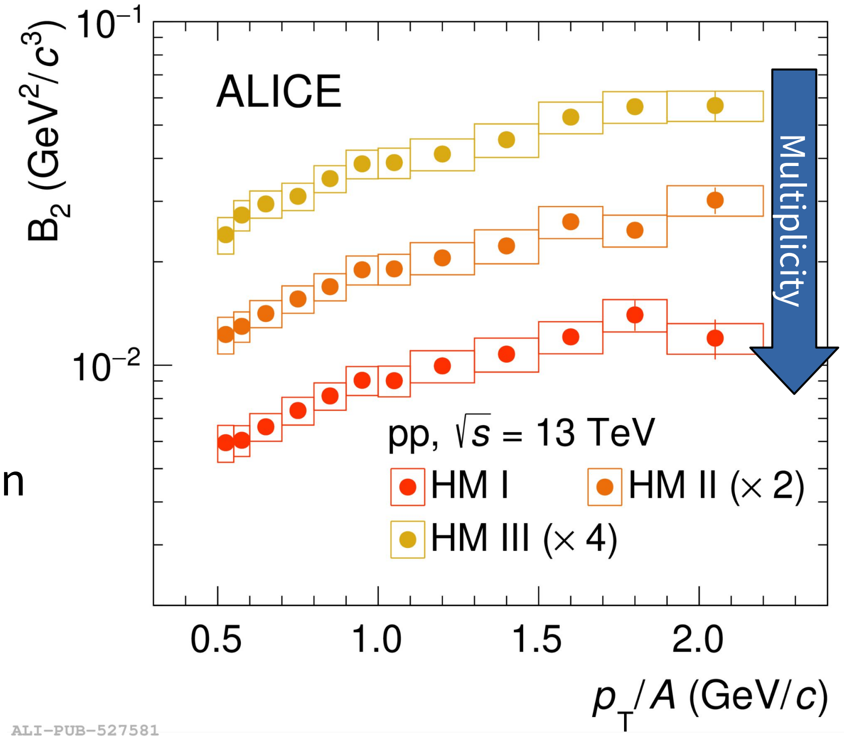
$$B_2(p_\mathrm{T}) \approx \frac{3}{2m}\int \mathrm{d}^3 q D(\vec{q}) e^{-R(p_\mathrm{T})^2 q^2}$$

- The source size R is a function of the deuteron p_T
- $D(\vec{q}) = \int \mathrm{d}^3 r |\phi_d(\vec{r})|^2 e^{-i\vec{q}\cdot\vec{r}}$ is the deuteron density
- $\phi_d(\vec{r})$ is the deuteron wave function



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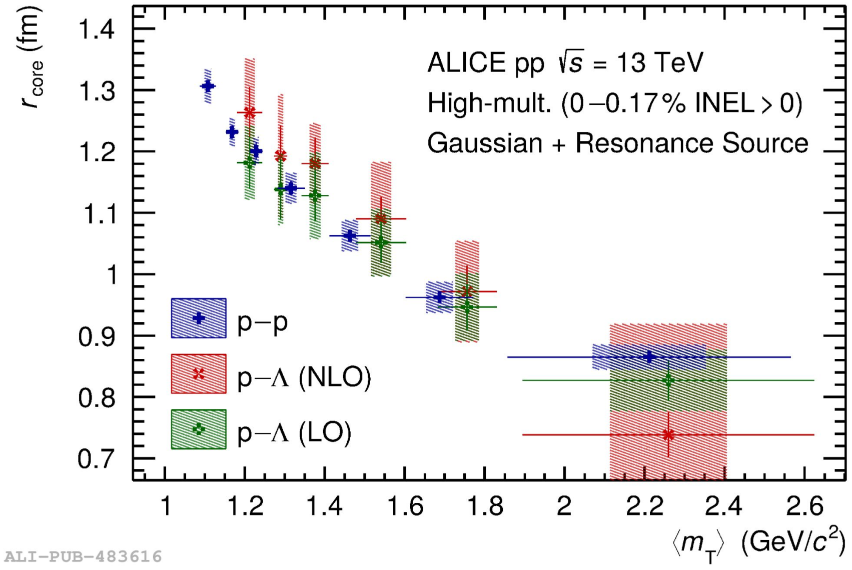
B_2 vs p_T/A

Different ingredients:

$$B_2(p_\mathrm{T}) \approx \frac{3}{2m}\int \mathrm{d}^3 q D(\vec{q}) e^{-R(p_\mathrm{T})^2 q^2}$$

- The source:
    - From two particle momentum correlation measurement: We have the precise measurement of the source size



ALICE Collaboration, PLB 811, 10 (2020), 135849

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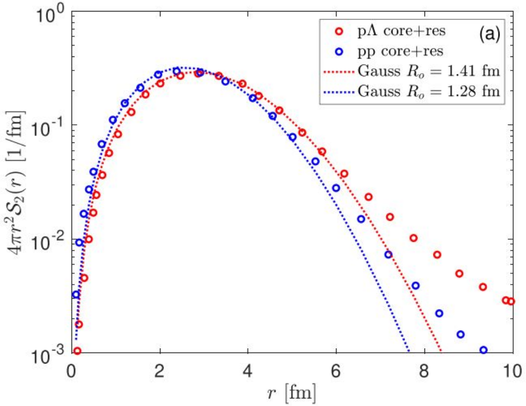
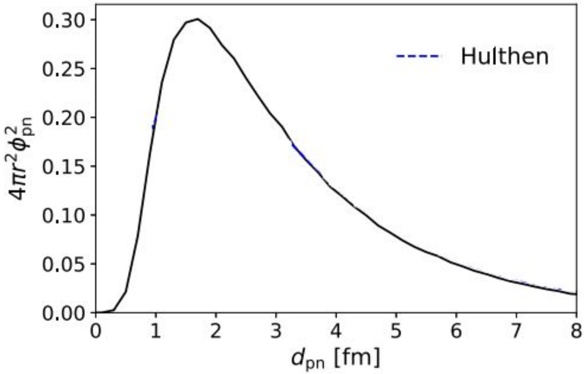
$$D(\vec{q}) = \int \mathrm{d}^3 r |\phi_d(\vec{r})|^2 e^{-i\vec{q}\cdot\vec{r}}$$

- It is possible to test different wave functions: Gaussian, Hulten, χEFT, Double Gaussian
- No free parameters!





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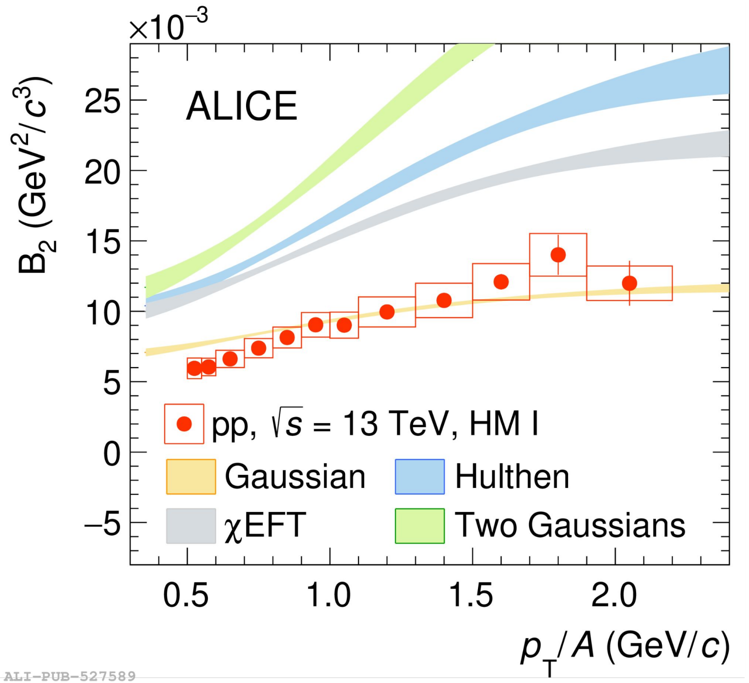


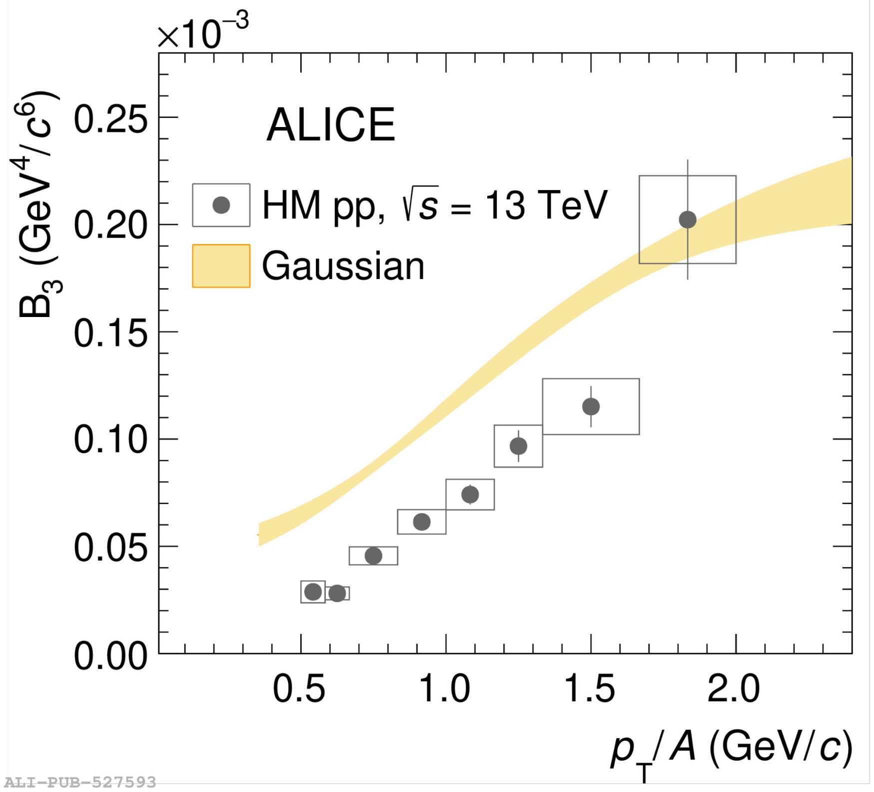
ALI-PUB-527589

- B_2 in agreement with Gaussian wave function (d = 3.2 fm)
  - From low-scattering experiment Hulthen is expected to provide the best description

$B3$ vs p_T/A

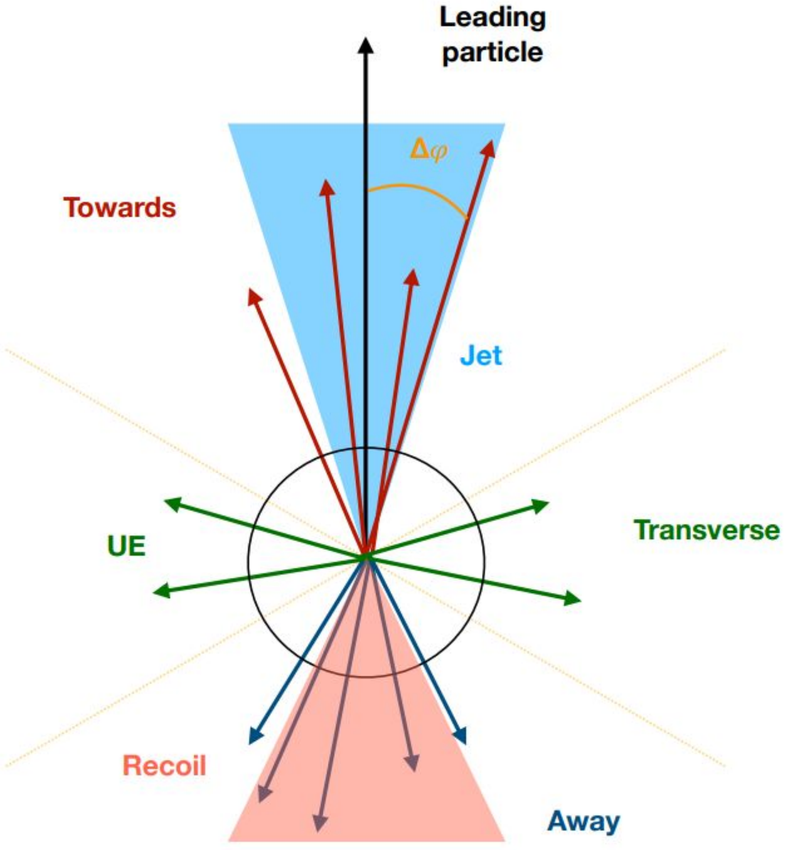
- B_3 is compared with prediction based on a Gaussian wave function
  - reasonable description, but worse with respect to B_2
- Very sensitive to nucleus radius d:

$$B_3 = \frac{\frac{2\pi^3}{\sqrt{3}m_p^3}}{\left[R^2 + \left(\frac{\mathrm{d}}{2}\right)^2\right]^3}$$



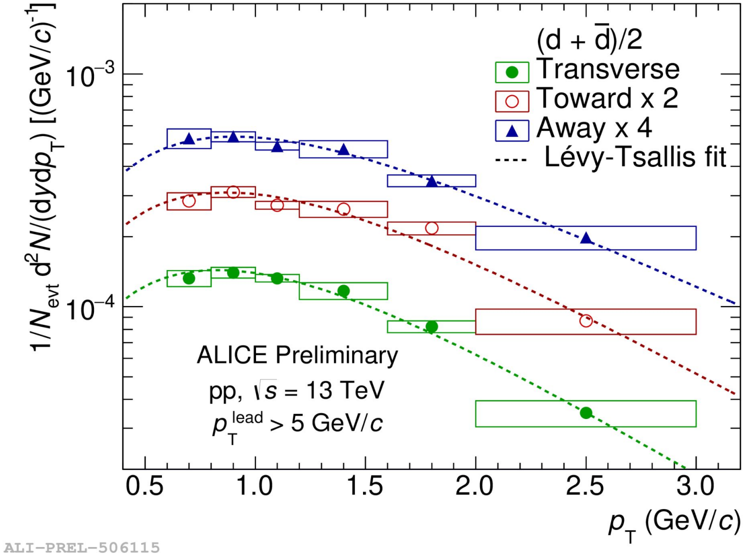
In and out of jet deuteron production

- Dependence of nuclear production on the activity of the event?
- Comparison between in-jet production and production in the underlying event (UE)
    - jets are collimated emissions of hadrons → coalescence probability should be enhanced
    - The leading particle (highest p_T, $p_T > 5$ GeV/c) is used as jet-proxy
- Three regions are distinguished wrt the leading particle
    - Toward: $|\Delta\varphi| < 60°$ → Jet + UE
    - Transverse: $60° < |\Delta\varphi| < 120°$ → UE
    - Away: $|\Delta\varphi| > 120°$ → Recoil + UE



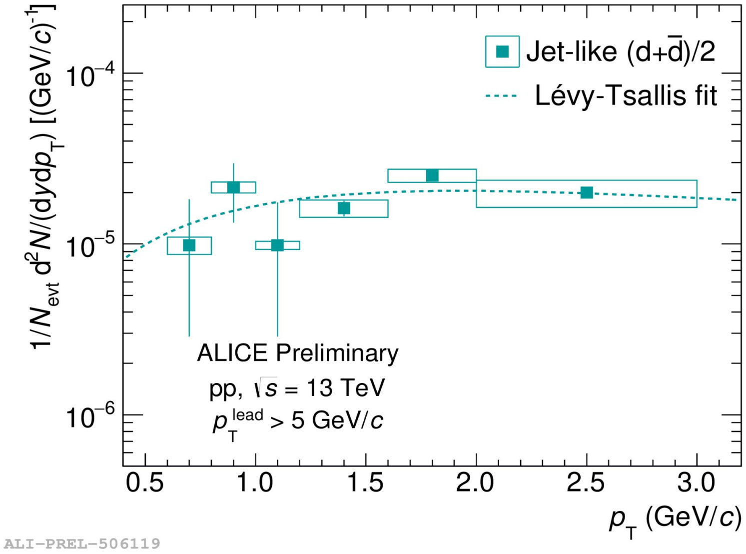
In and out of jet deuteron production

- Deuteron spectra are measured in the azimuthal regions:
    - towards, transverse and away



In and out of jet deuteron production

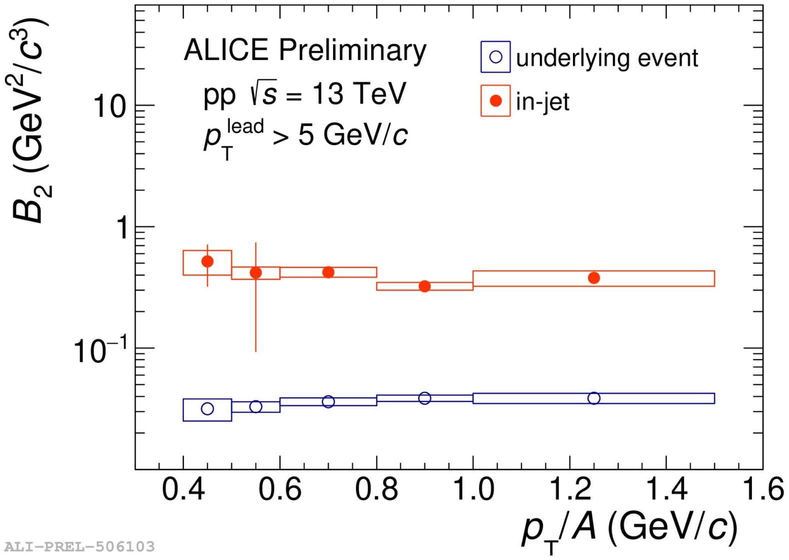
- Deuteron spectra are measured in the azimuthal regions:
    - towards, transverse and away
- The transverse region is considered a good estimate of the UE
- In-jet spectrum = towards - transverse



➢ Jet: ~ 10% of total production

In and out of jet deuteron production

- Deuteron spectra are measured in the azimuthal regions:
  - towards, transverse and away
- The transverse region is considered a good estimate of the UE
- In-jet spectrum = towards - transverse
- B_2 can be measured in-jet and in the underlying event
- B_2 parameter flat vs p_T/A → in agreement with simple coalescence
- B_2 in-jet ~ 15 times larger than B_2 in UE!

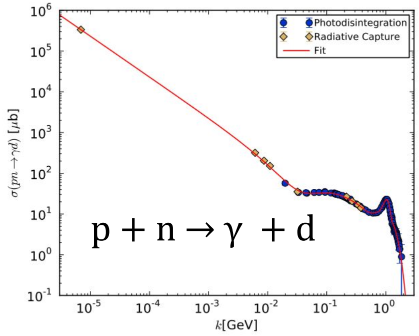


Comparison with Pythia simulations

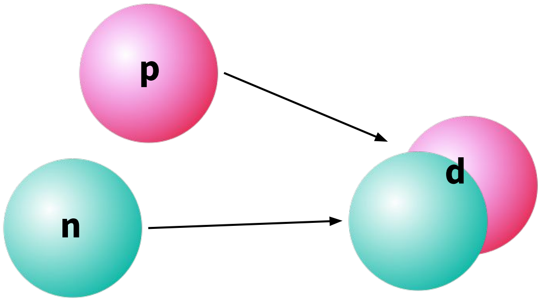
1. Pythia 8.3 [1]
   a. including d production via ordinary reactions, with energy dependent cross sections parametrized based on data [2]

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

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



2. Pythia 8.1 Monash [2] + simple coalescence
   a. $\Delta p < p_0$



[1] C. Bierlich et al., arxiv: 2203.11601
[2] L. A. Dal, A. R. Raklev arxiv: 1504.07242
[3] P. Skands et al., Eur.Phys.J.C 74 (2014) 8, 3024

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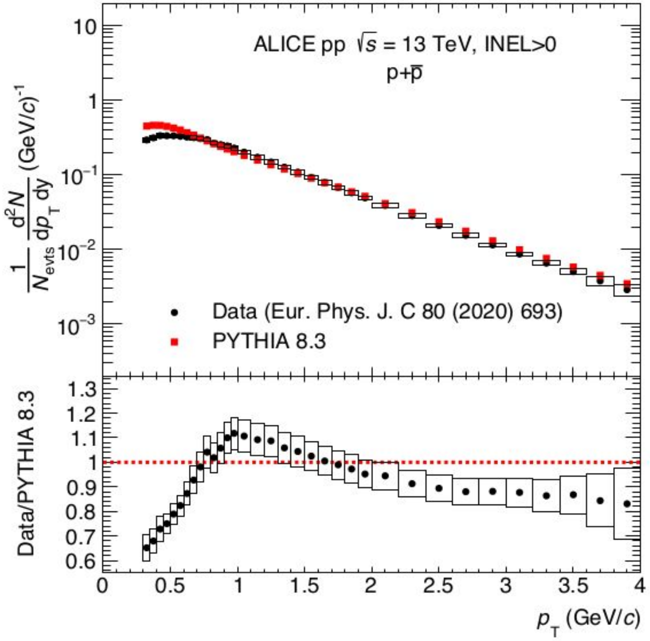
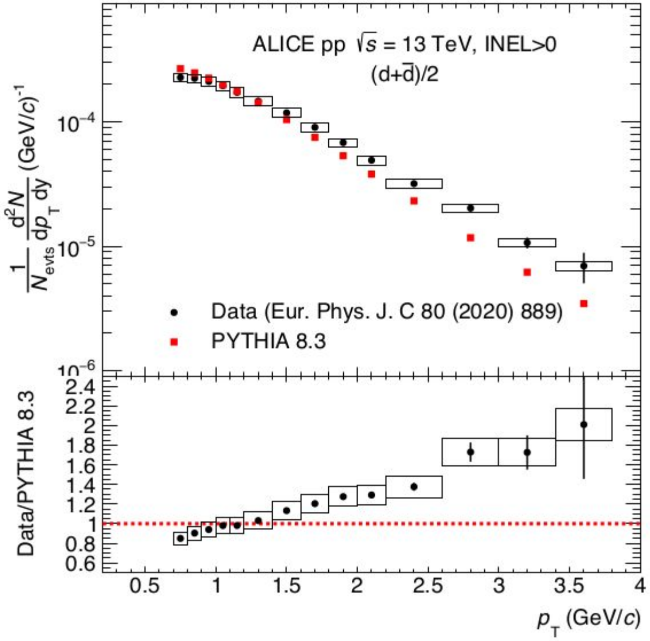
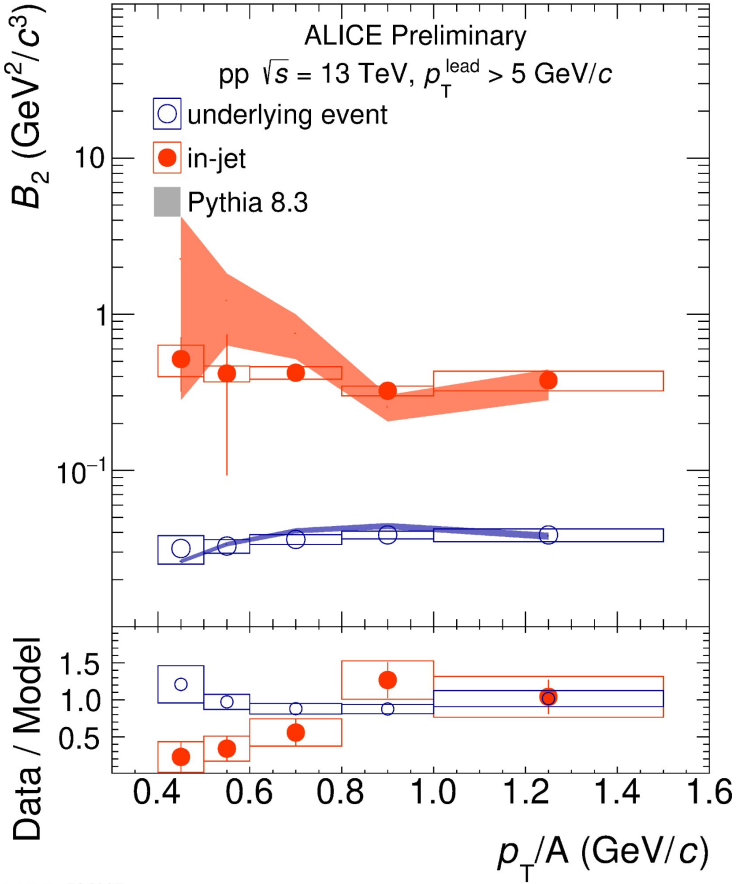




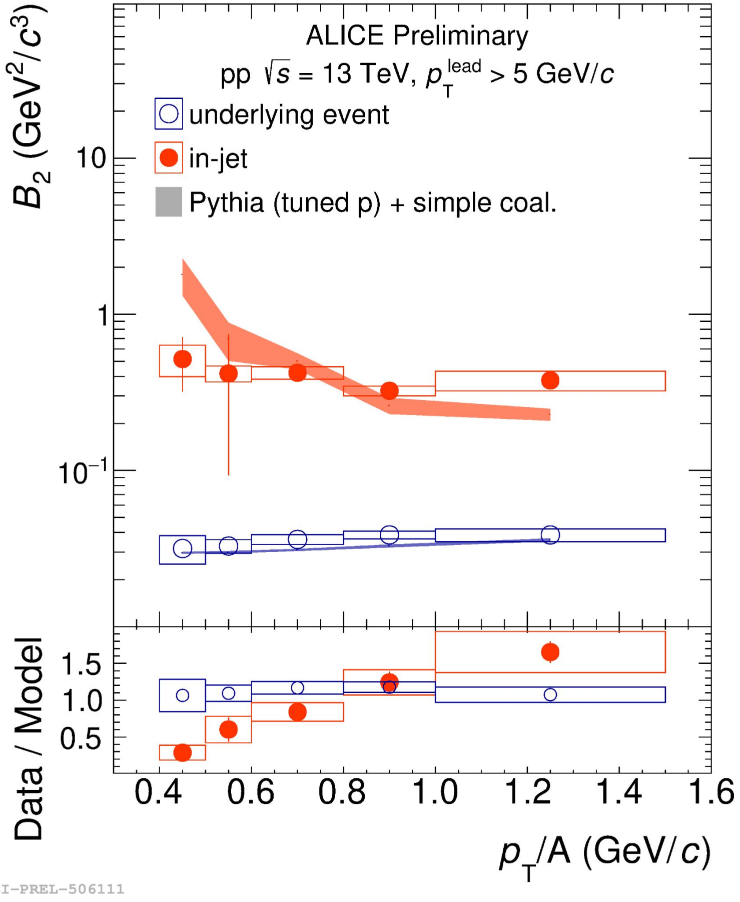
- Proton excess at low p_T in PYTHIA (known "feature")
    - Deuteron excess at low p_T by about 20%
- Deuteron spectrum at high p_T underestimated by PYTHIA despite proton excess also at high p_T
    - probably due to different momentum correlations between nucleons

Comparison with Pythia 8.3



- Enhanced production rate in simulations
  - normalization needed
- Protons not tuned on data
  - B_2 UE Pythia describes the trend of data
- B_2 in-jet Pythia reproduces difference between UE and jet

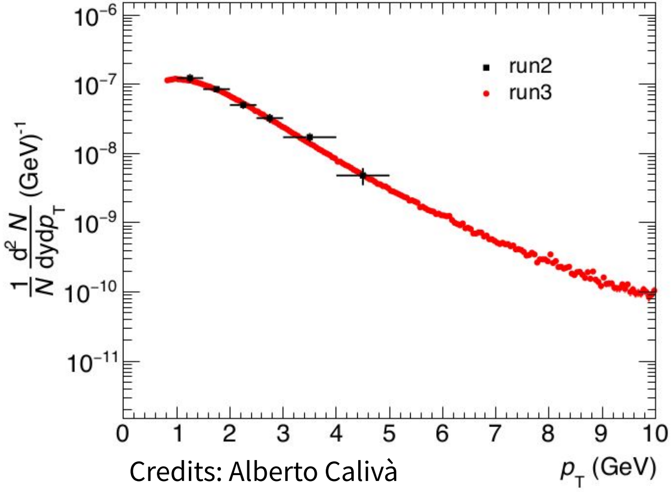
Comparison with Pythia 8.1 + simple coalescence



- Pythia 8 + simple Coalescence
  - ○ ($\Delta p < 0.285$ GeV/c)
- B_2 UE is fairly well reproduced by the model
- B_2 in-jet coalescence model gives a decreasing trend vs p_T not observed in data

Expectations for ^{3}He

- N_{evts} (LHC Run2) = 2.6×10^9 (minimum bias)
  - dN/dy = $(2.4 \pm 0.3 \pm 0.4) \times 10^{-7}$ [1]
  - Efficiency between: 0.3 (low p_T) and 0.8 (high p_T)
  - N^{raw} (run2) ≈ 230
- N_{evts} (run3) = 1.2×10^{13} (200 pb^{-1})
  - Assuming the same efficiency as in Run 2
  - N^{raw} (run3) ≈ 1.5×10^6



Credits: Alberto Calivà

- Considering that only about 1% of all events contain a trigger particle (p_T > 5 GeV/c)
  - N^{raw} (p_T > 5 GeV/c) ≈ 1.5×10^4
  - ⇒ R_T-differential analysis will be possible for ^{3}He!
- Work in progress with Alberto Calivà and Valentina Zaccolo to implement ^{3}He production in PYTHIA using
  - $p + D \rightarrow {}^3He + \pi^0$

[1]https://arxiv.org/abs/2109.13026

Conclusions

- Light nuclei measurements can are an ideal tool to test particle production mechanisms. Different quantities can be used as benchmark:

⇒ Yield ratios vs multiplicity:

- d/p: good description by coalescence model and CSM
- ^{3}He/p: models struggle in describing the data

⇒ B_A vs multiplicity

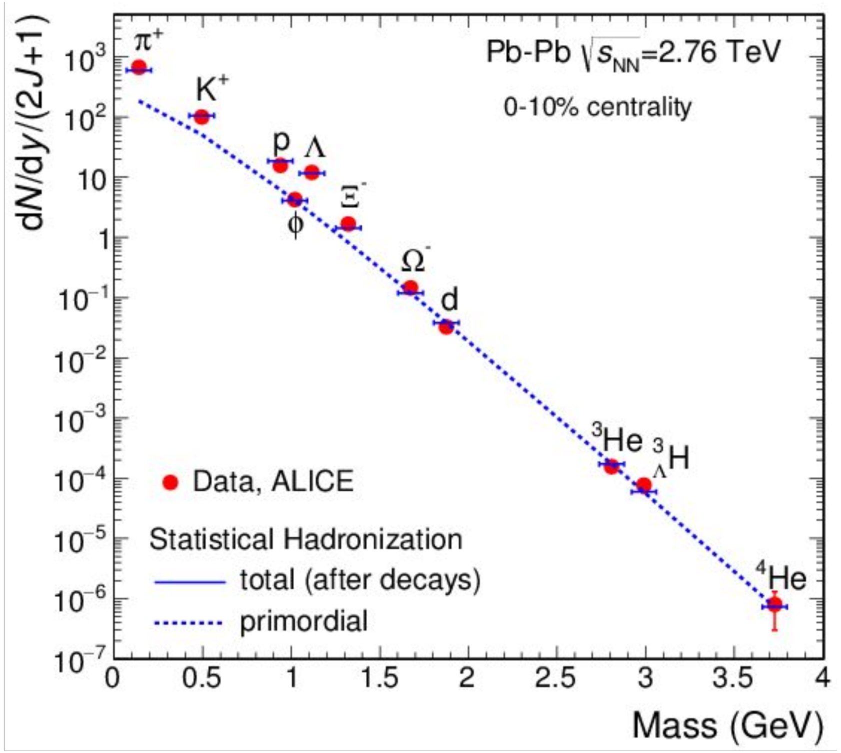
- B_2 and B_3 are described by the model
- Two different parameterisations needed

⇒ $B_A(p_T)$

- Coalescence model reproduces data within a factor of 2
- without free parameters
- In-jet B2 is increased with respect to B2 in the underlying event

Backup

Thermal model



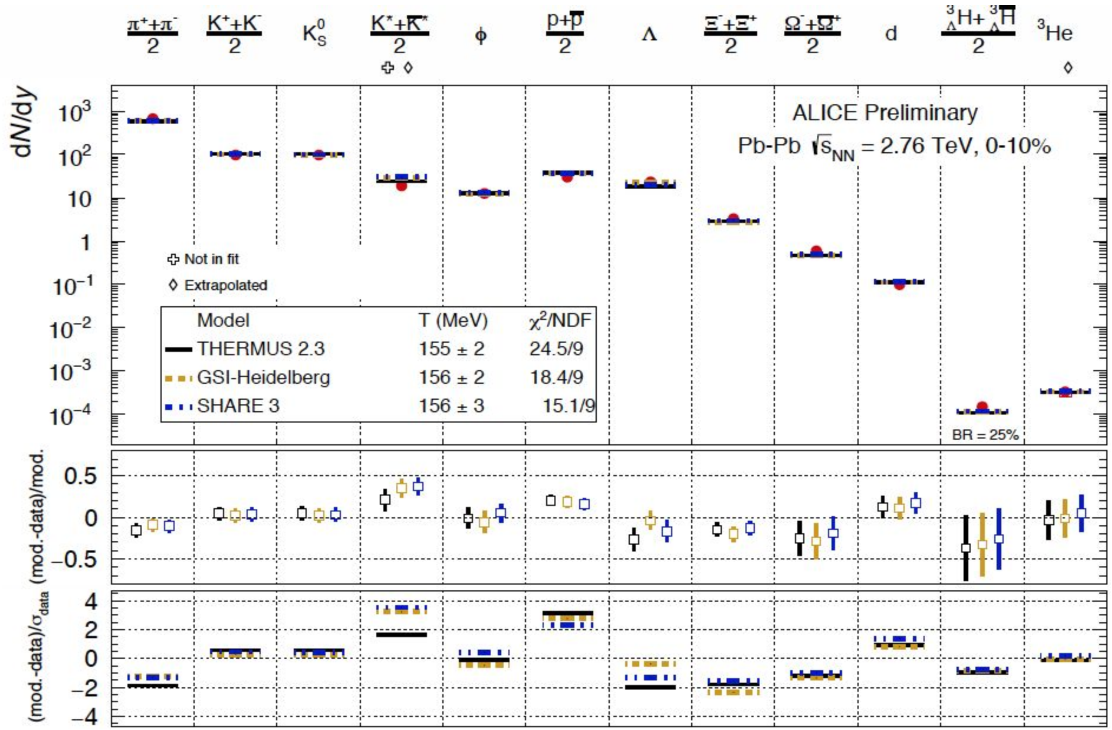
Nature 561 (2018) no.7723, 321-330 arXiv:1710.09425 [nucl-th]

- Statistical hadronization model: thermal emission from equilibrated source
- Particle abundances fixed at chemical freeze-out

$$N_i = \frac{g_i V}{2\pi^2}\int_0^{+\infty}\frac{p^2 dp}{\exp\left[-\left(\frac{E-\mu_B}{T_{\rm chem}}\right)\right]\pm 1}$$

- Primordial yields modified by hadron decays:
  - Contribution obtained from calculations based on known hadron spectrum
  - Excellent agreement with data with only 2 free parameters: T_{chem} , V

Thermal model fit to ALICE data



THERMUS: S. Wheaton, et al., CPC 180, 84 (2009)
GSI-Heidelberg: A. Andronic, et al., PLB 697, 203 (2011); PLB 673, 142 (2009) 142
SHARE3: G. Torrieri, et al., CPC 167, 229 (2005); CPC 175, 635 (2006); CPC 185, 2056 (2014)

K* not included in the fit

- The p_T-integrated yields and ratios can be interpreted in terms of statistical (thermal) models
- Particle yields of light flavor hadrons (including nuclei) are described with a common chemical freeze-out temperature (T_{chem} = 156 ± 2 MeV)

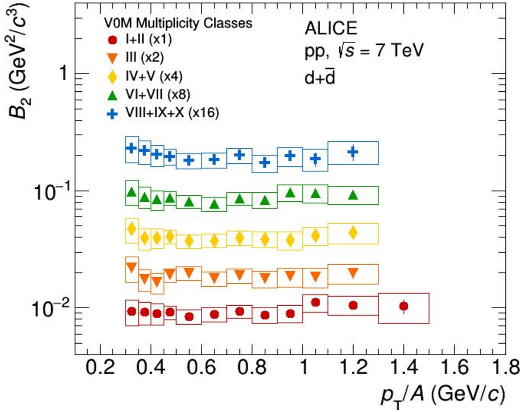
Coalescence model

- If baryons at freeze-out are close enough in phase space and match spin state a (anti-)nucleus can be formed
- Usually, since the nucleus is larger w.r.t. the source, the phase space is reduced to the momentum space
- Assuming that p an n have the same mass and have the same pT spectra, the yield of any nucleus can be determined as

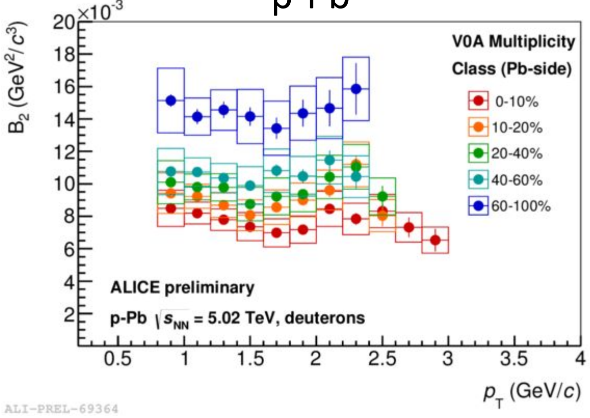
$$E_A \frac{\mathrm{d}^3 N_A}{\mathrm{d}p_A^3} = B_A \left(E_\mathrm{p} \frac{\mathrm{d}^3 N_\mathrm{p}}{\mathrm{d}p_\mathrm{p}^3} \right)^A$$

$$\boxed{B_A = \left(\frac{4\pi}{3} p_0^3 \right)^{(A-1)} \frac{1}{A!} \frac{M}{m^A}}$$

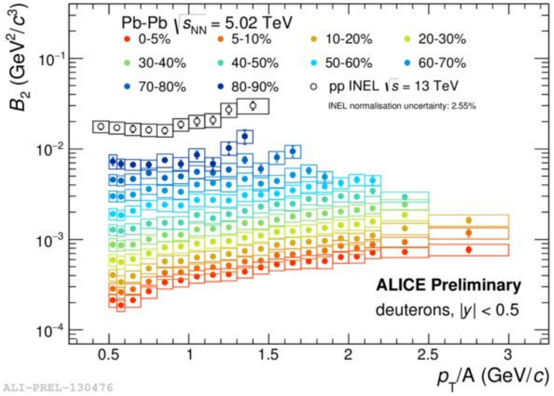
pp



p-Pb



Pb-Pb



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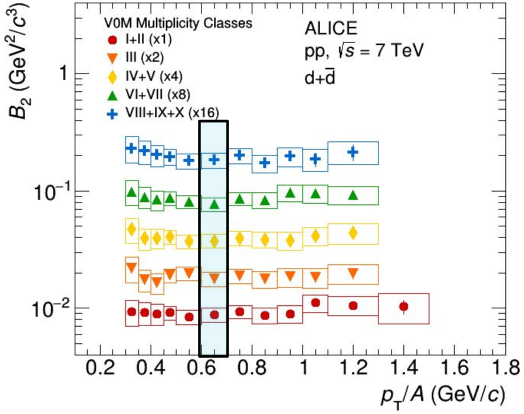
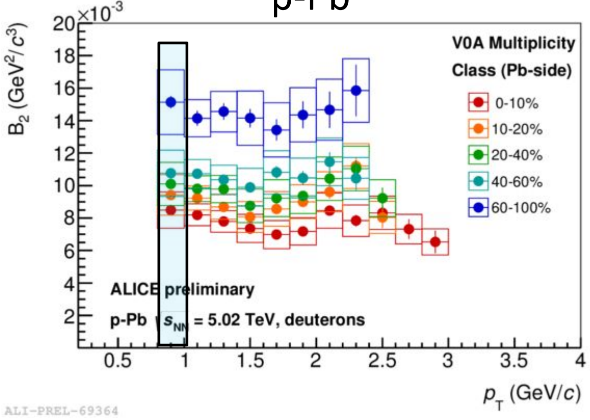
$\boxed{p_T/A = 0.75\ \mathrm{GeV}/c}$

pp



p-Pb



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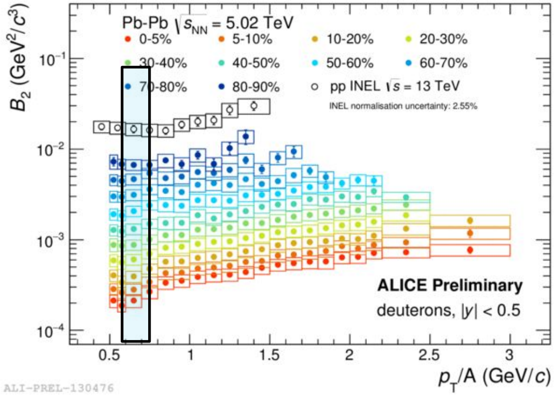
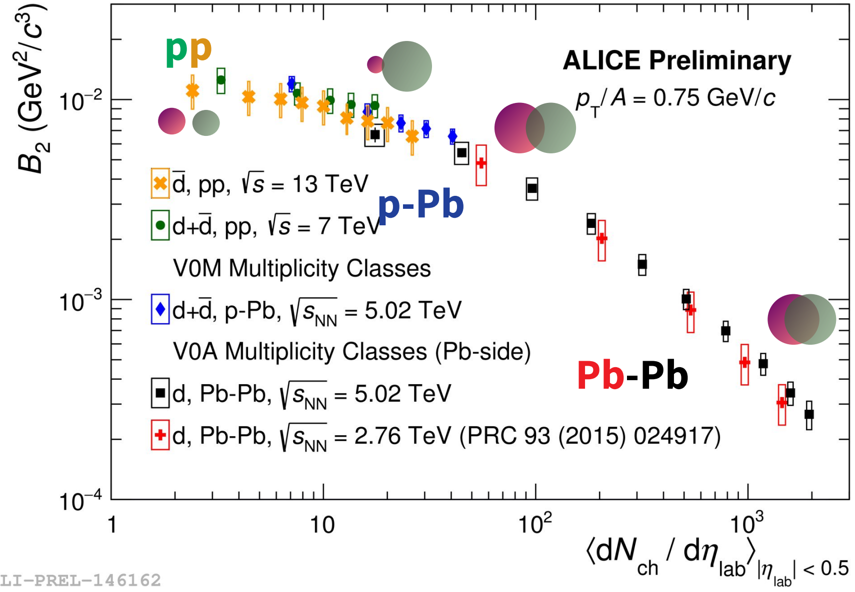


Coalescence parameter B_2



ALI−PREL−146162

F.Bellini and A. P.Kalweit, arXiv:1807.05894 [hep-ph].
R. Scheibl, U. Heinz, PRC 59 (1999) 1585-1602
K. Blum et al., PRD 96 (2017) 103021

Simple coalescence model

- Flat B_2 vs p_T and no dependence on multiplicity/centrality
  - ✔ Observed in "small systems": pp, p -Pb and peripheral Pb-Pb

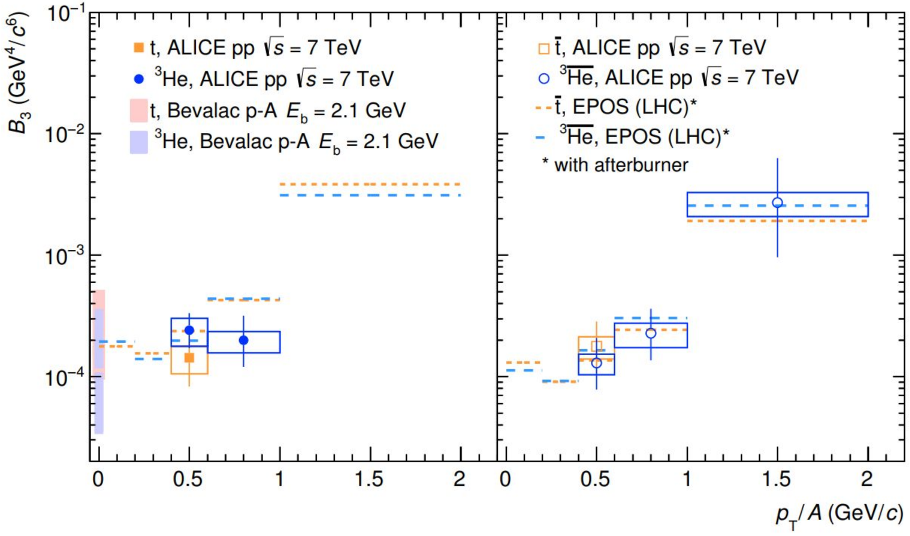
- **More elaborate** coalescence model takes into account the volume of the source:

$$\boxed{B_2 = \frac{3\pi^{3/2}\langle C_d \rangle}{2m_T R^3(m_T)}}$$

- B_2 scales like HBT radii (R)
  - ○ decrease with centrality in Pb-Pb is explained as an increase in the source volume
  - ○ increase with p_T in central Pb-Pb reflects the k_T-dependence of the homogeneity volume (i.e. volume with similar flow properties) in HBT
  - ✔ Qualitative agreement in central Pb-Pb collisions

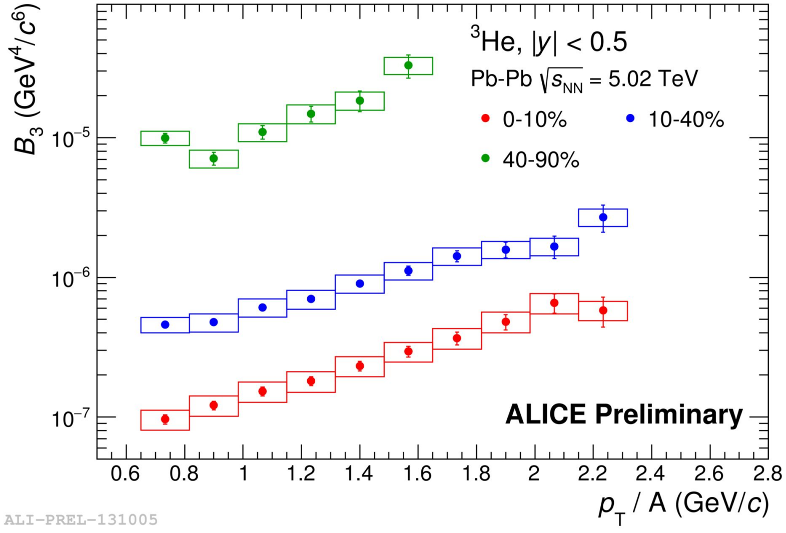
Coalescence parameter B_3

pp



ALICE Collaboration, arXiv:1709.08522

Pb-Pb



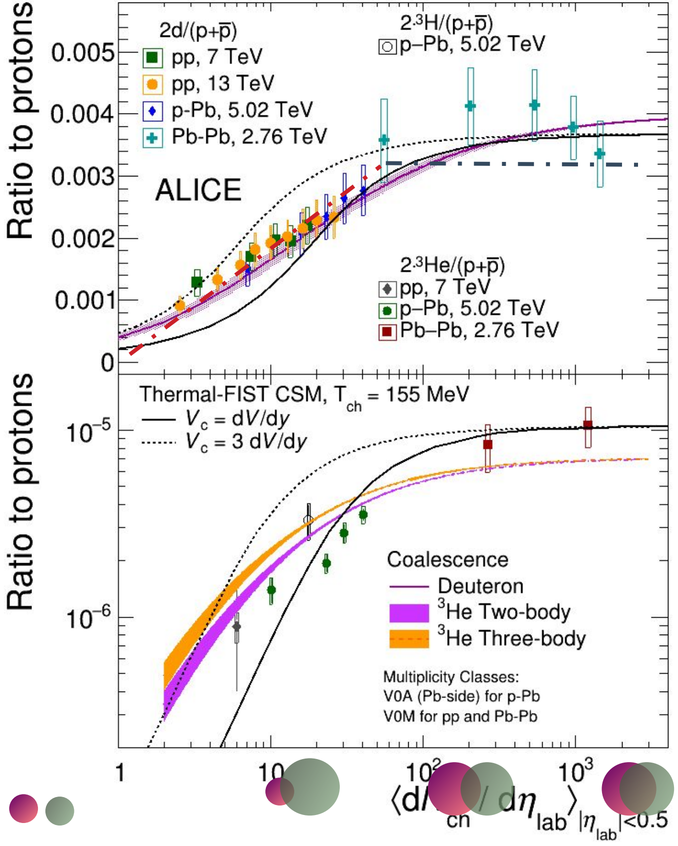
ALICE-PUBLIC-2017-006

B_3 of ($\bar{t}$)t and ($^3\overline{He}$)^{3}He measured in pp and Pb-Pb collisions

First ever measurements of the B_3 of t and ^{3}He in pp collisions

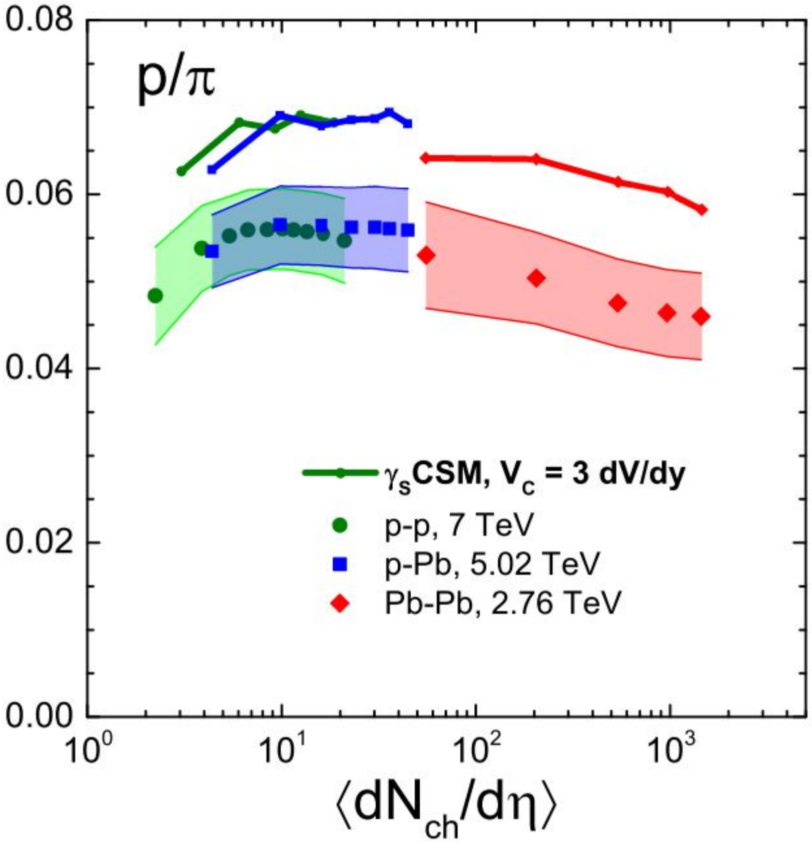
Increasing trend with p_T and centrality observed in Pb-Pb collision

Light nuclei production: Nuclei to proton ratio



- Nuclei/proton ratio increases with multiplicity going from pp to peripheral Pb-Pb : consistent with simple coalescence (d ∝ p^2)
- No significant centrality dependence in Pb-Pb : consistent with thermal model (yield fixed by T_{chem})
  - Smooth transition: is there a single particle production mechanism?

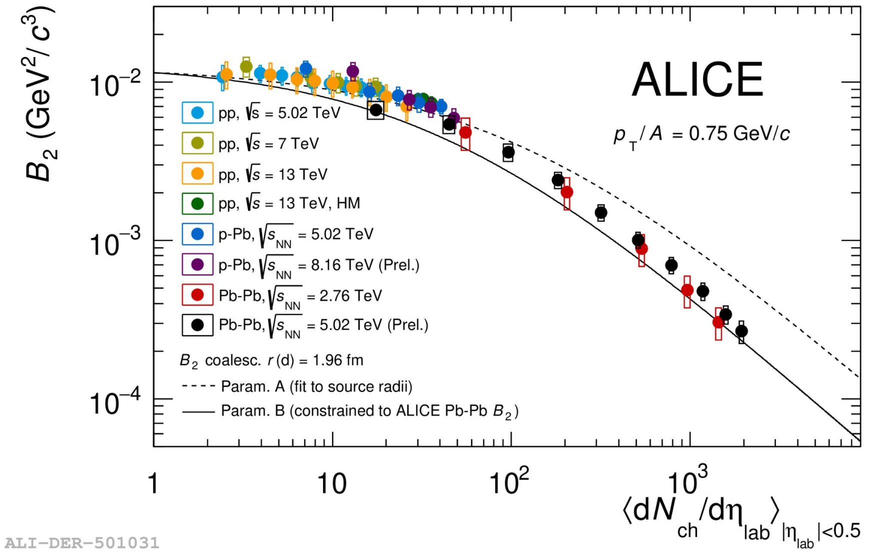
Yield ratios

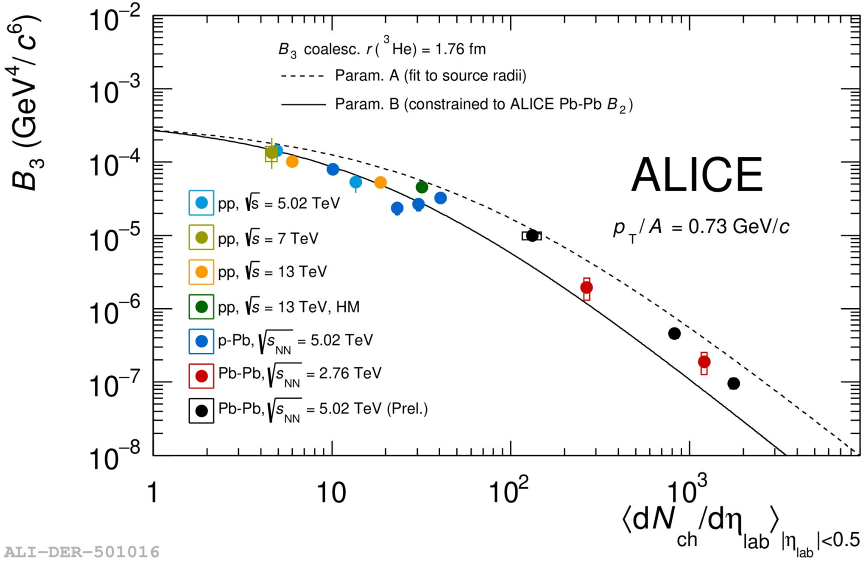


http://dx.doi.org/10.1103/PhysRevC.100.054906

- CSM cannot describe p/π with the same correlation volume used for d/p

Coalescence parameter B_A



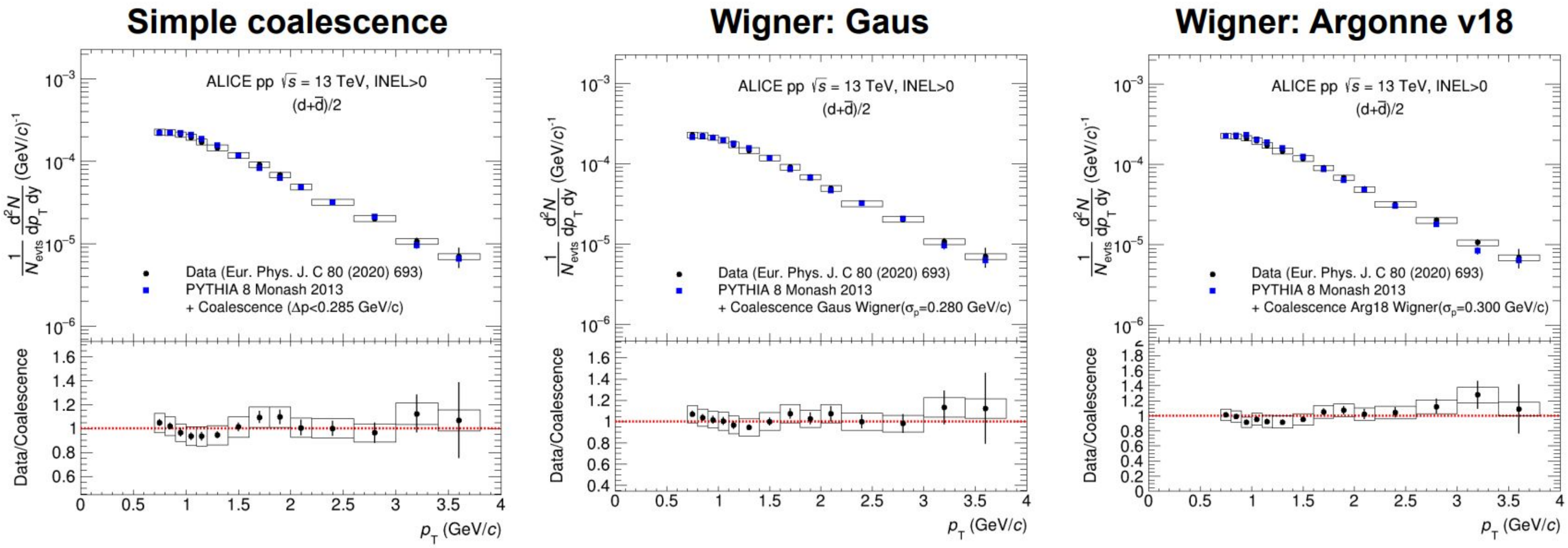


- B_A evolves smoothly with multiplicity
  - dependence on the system size
- Comparison with theory:

$$B_A = \frac{2J_A+1}{2\sqrt[A]{A}}\frac{1}{m^{A-1}}\left[\frac{2\pi}{R^2(m_T)+(R_A/2)^2}\right]^{\frac{3}{2}(A-1)}$$

- Two different parameterisations for dN/dη vs R
  - None of them can describe simultaneously B_2 and B_3

Different coalescence approach



Simple and “advanced” coalescence give similar results (also similar p_0)

> probably in pp collisions correlations in space coordinates play a minor role