Insights into light nuclei production from pp to Pb-Pb collisions with ALICE

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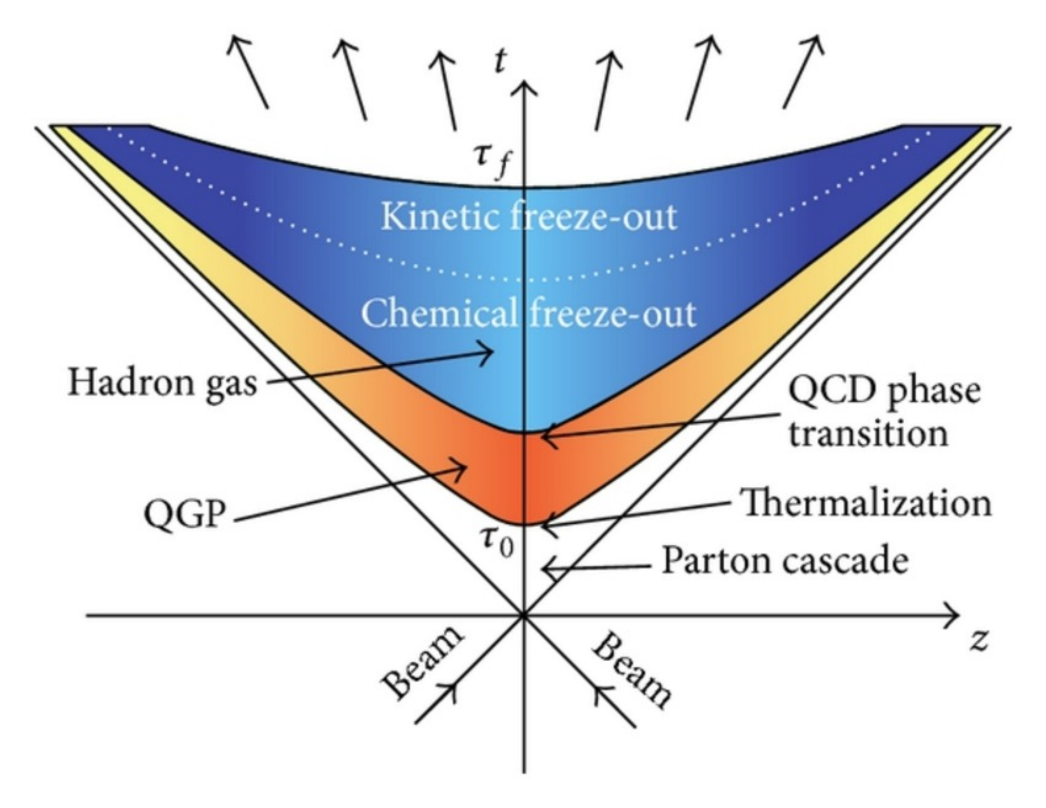
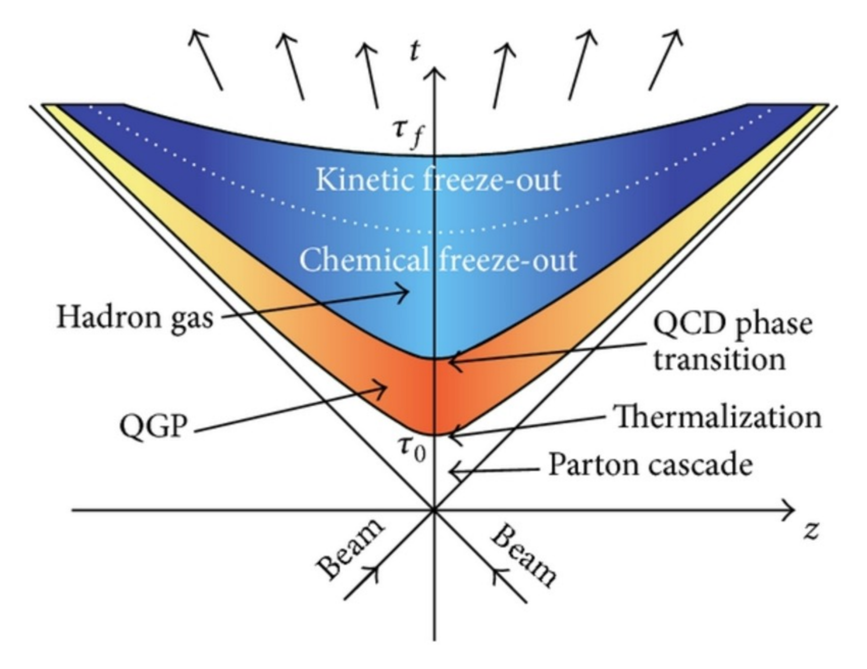
ON BEHALF OF THE ALICE COLLABORATION

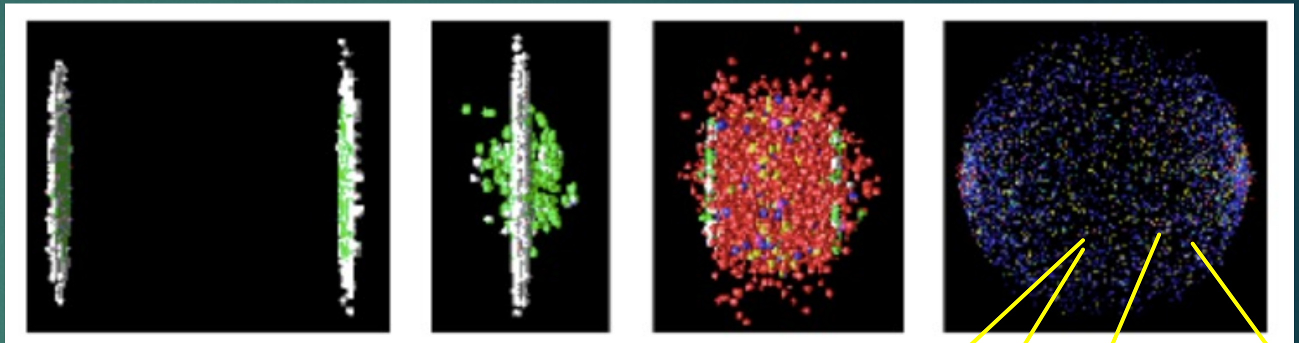
Heavy ion collision evolution

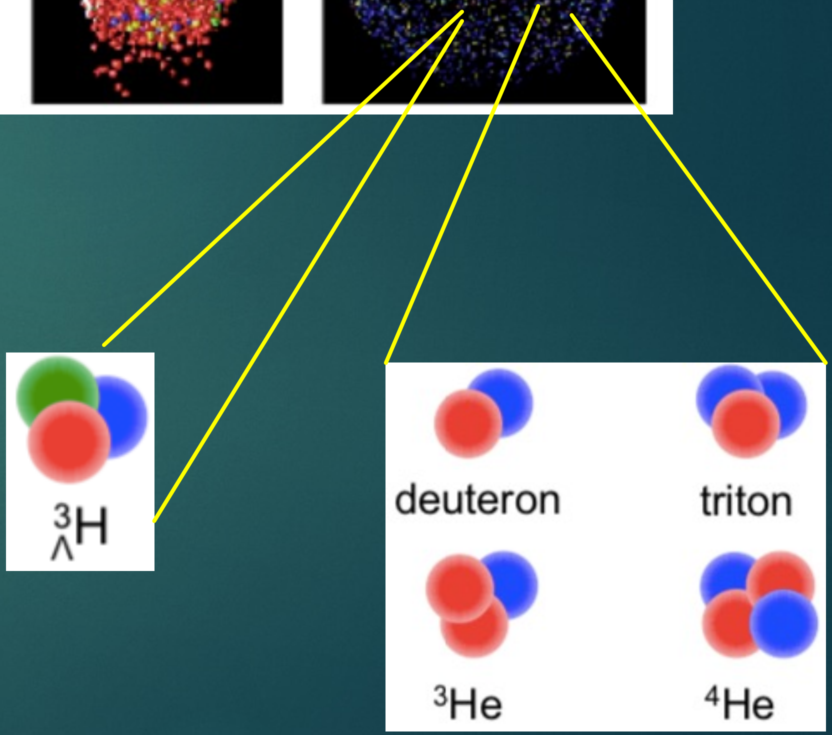


- After a thermalization time τ_0 ≈1 fm/c, a deconfined phase of quarks and gluon is created: Quark-gluon plasma (QGP)
- The system expands and cools down reaching the temperature at which hadronization takes place (T_C≈154±9 MeV) https://doi.org/10.1103/PhysRevD.90.094503
- A gas of interacting hadrons and resonances interacts up to a chemical freeze-out temperature T_{ch} (~156.5± 1.5 MeV) where inelastic interactions stop and hadron yields are fixed https://www.nature.com/articles/s41586-018-0491-6
- The last elastic interactions stop at the kinetic freeze-out temperature T_{kin} (~110 MeV) 10.1103/PhysRevC.101.044907

Heavy ion collision evolution





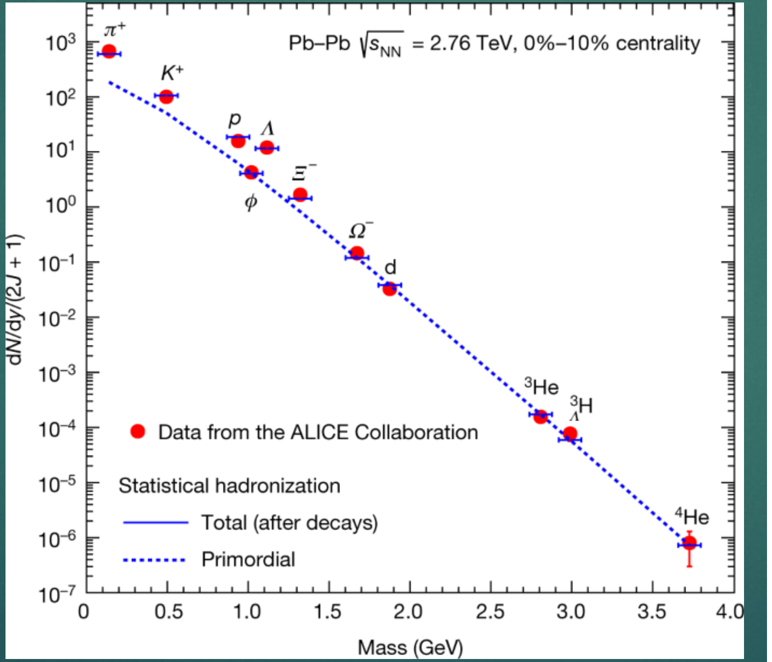


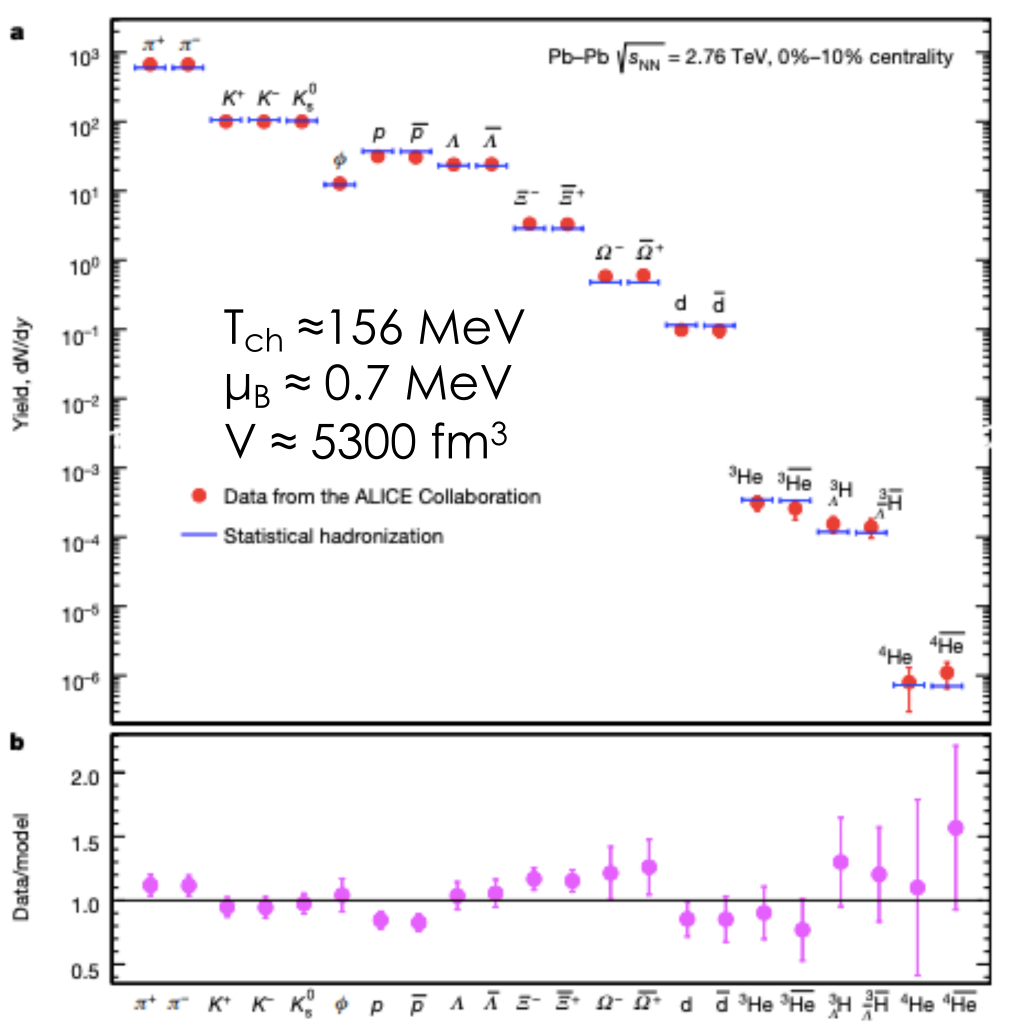
Nuclei production can be described by two models:

- Statistical Hadronization Model (SHM)
- Nucleon coalescence

Statistical Hadronization Model

- Hadrons produced in Pb–Pb collisions are well described by a grand canonical ensemble with three free parameters (μ_B, V and T_{ch})
- ALICE Pb–Pb data agree very well with Statistical Hadronization Model predictions.
  - Yields ~ exp(-m/T_{ch})





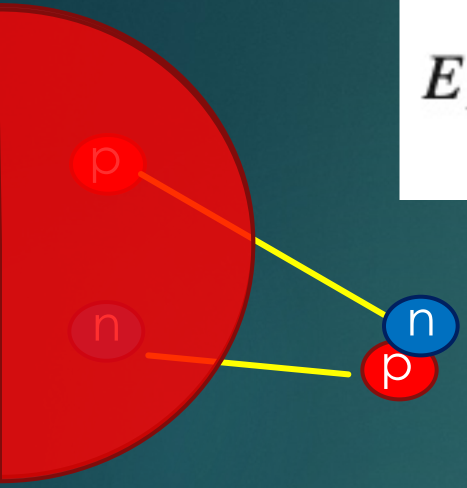
In small systems a canonical ensemble has to be considered (->free parameters N, V, T_{ch})

▶A. Andronic, P. Braun-Munzinger, K. Redlich, J.Stachel, *Nature 561 (2018) 32*

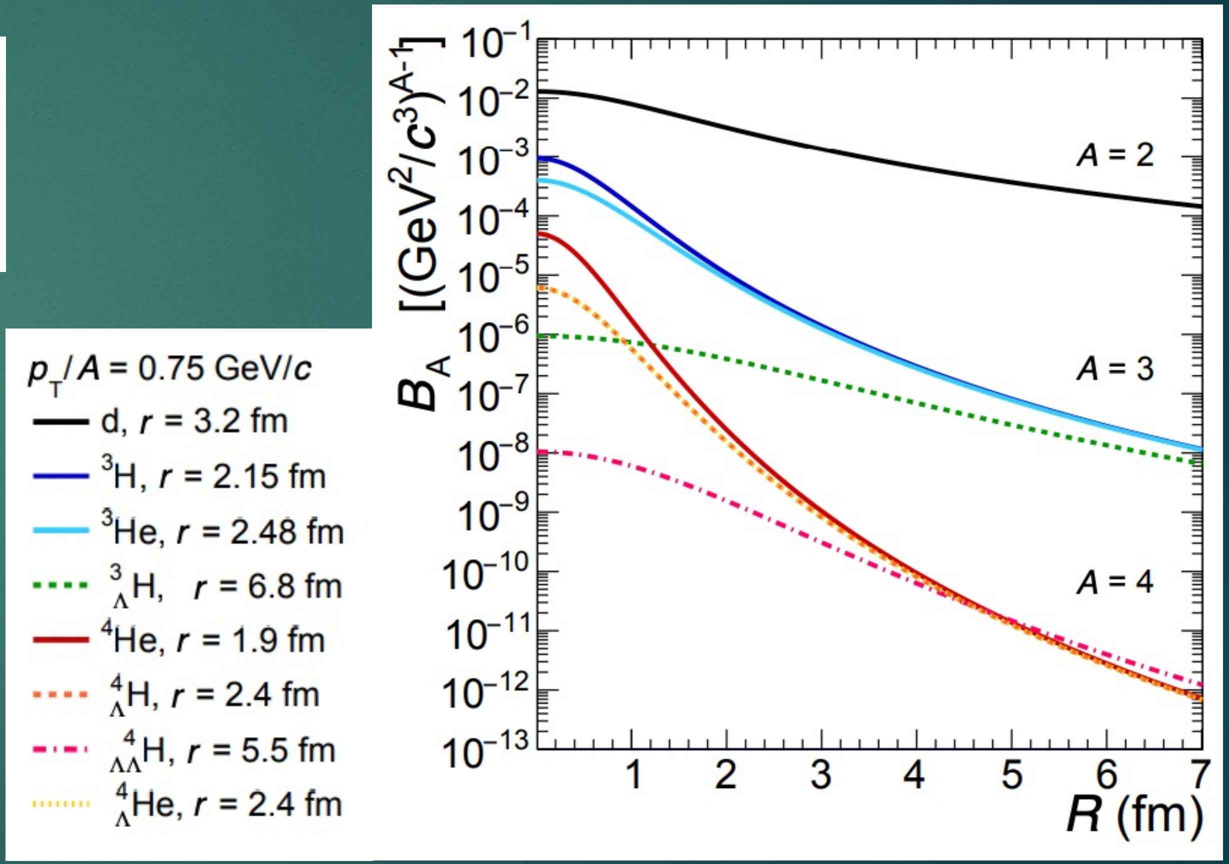
Coalescence Model

- Nuclei are formed by protons and neutrons close in phase space at the kinetic freeze-out
  At a given nucleon mass number A $p_p = p_A/A$

$$E_A \frac{d^3 N_A}{d^3 p_A} = B_A \left(E_p \frac{d^3 N_p}{d^3 p_p} \right)^A$$

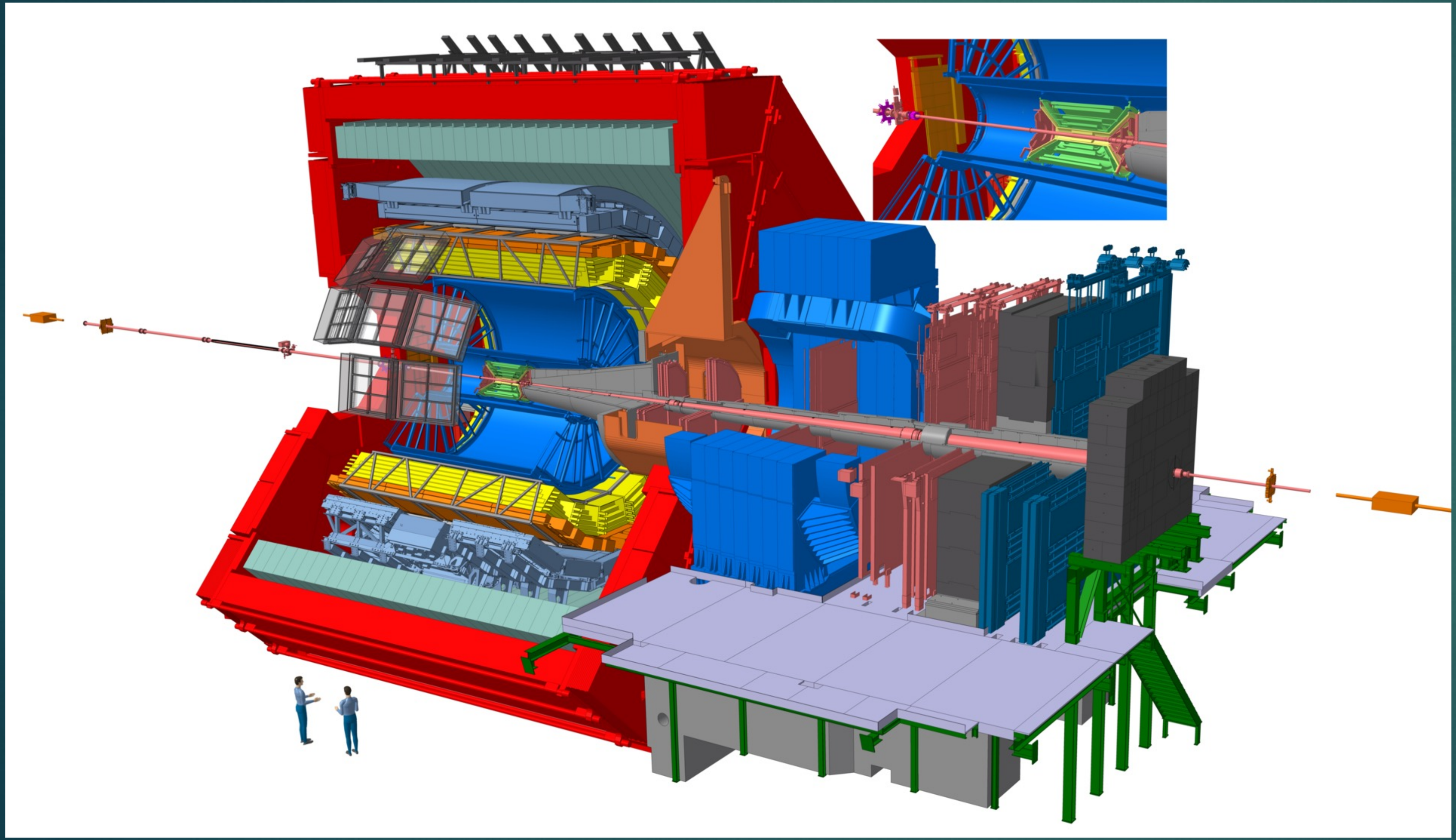


- Coalescence parameter B_A is the crucial parameter
  - simple coalescence scenario foresees it is not dependent on p_T and muliplicity



F. Bellini, and A. Kalweit, Acta Phys. Pol. B 50 (2019)

The ALICE Detector



Inner Tracking System (ITS):
- Tracking & Vertexing
  - $\sigma_{DCAxy} < 100\ \mu m$

Time Projection Chamber (TPC):
- Tracking & Vertexing
- PID via dE/dx (≈6%)

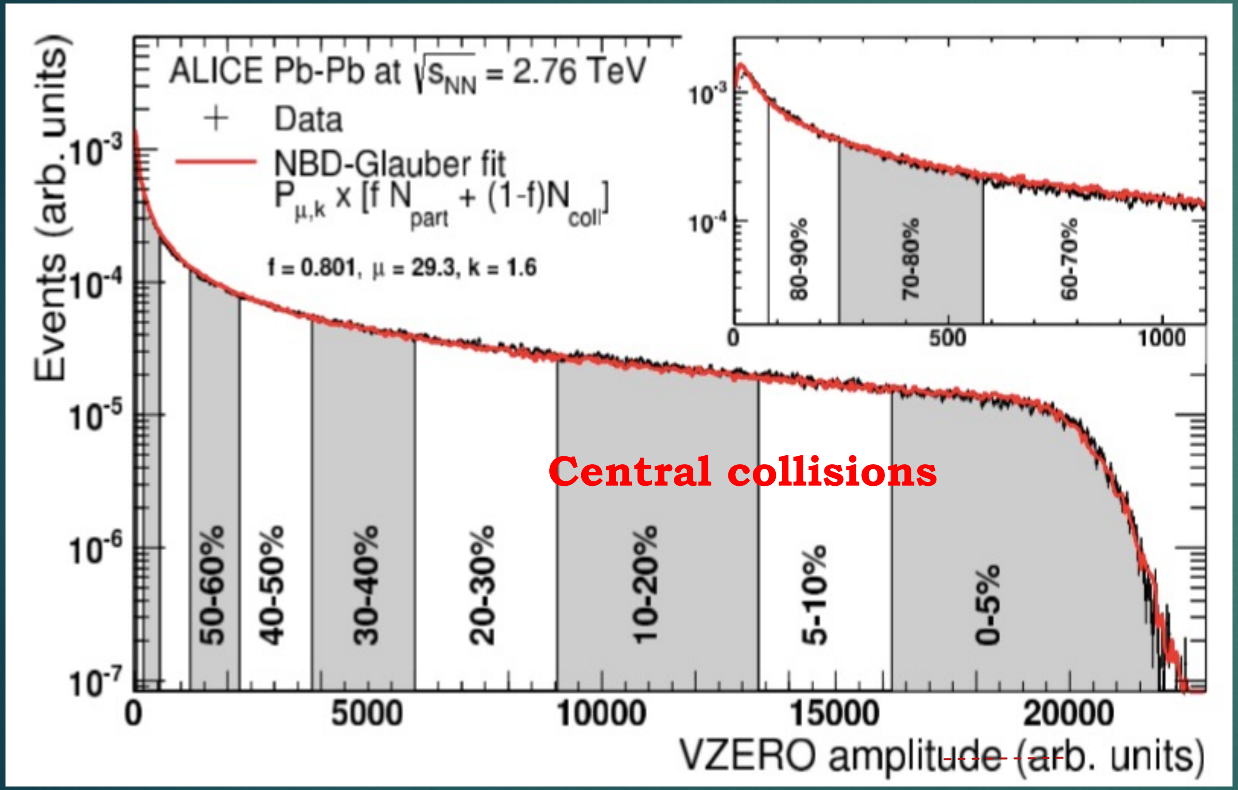
Time-of-Flight (TOF)
- PID $\sigma_{TOF} \approx 60$ ps

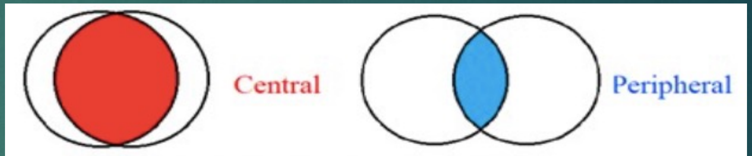
V0 :
- Centrality/multiplicity determination

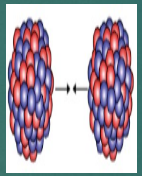
Centrality

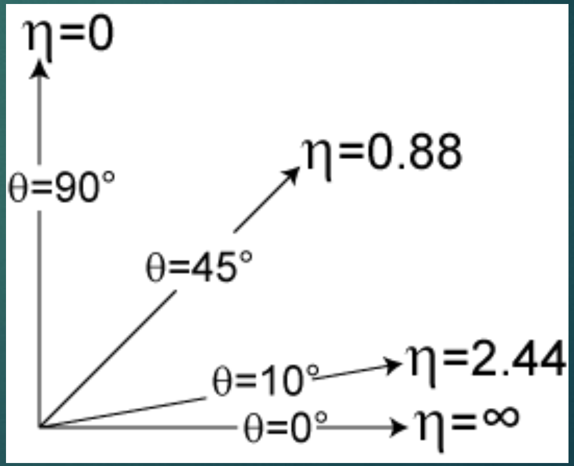
- The number of produced particles at midrapidity increases with centrality

10.1103/PhysRevC.88.044909





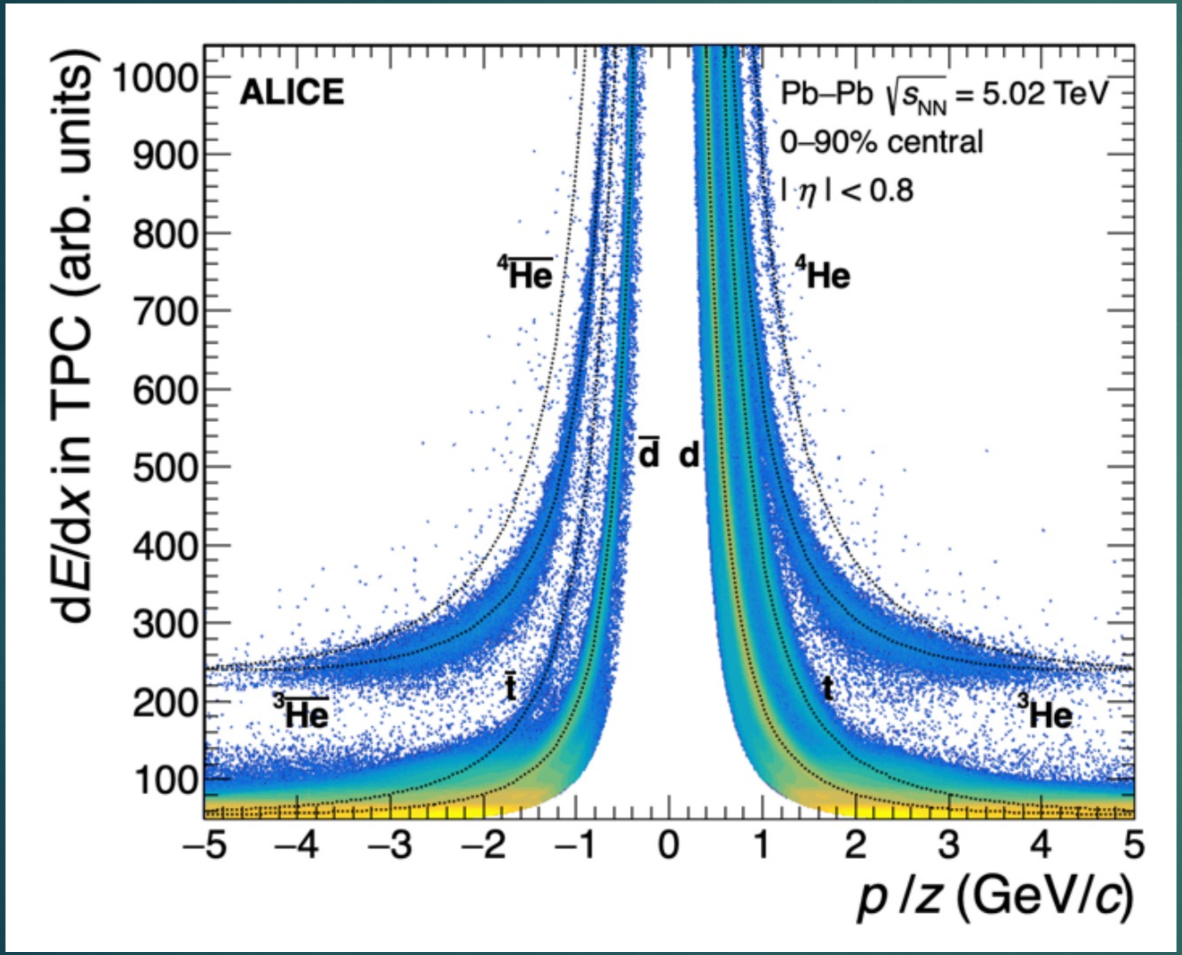




TPC/TOF

V0

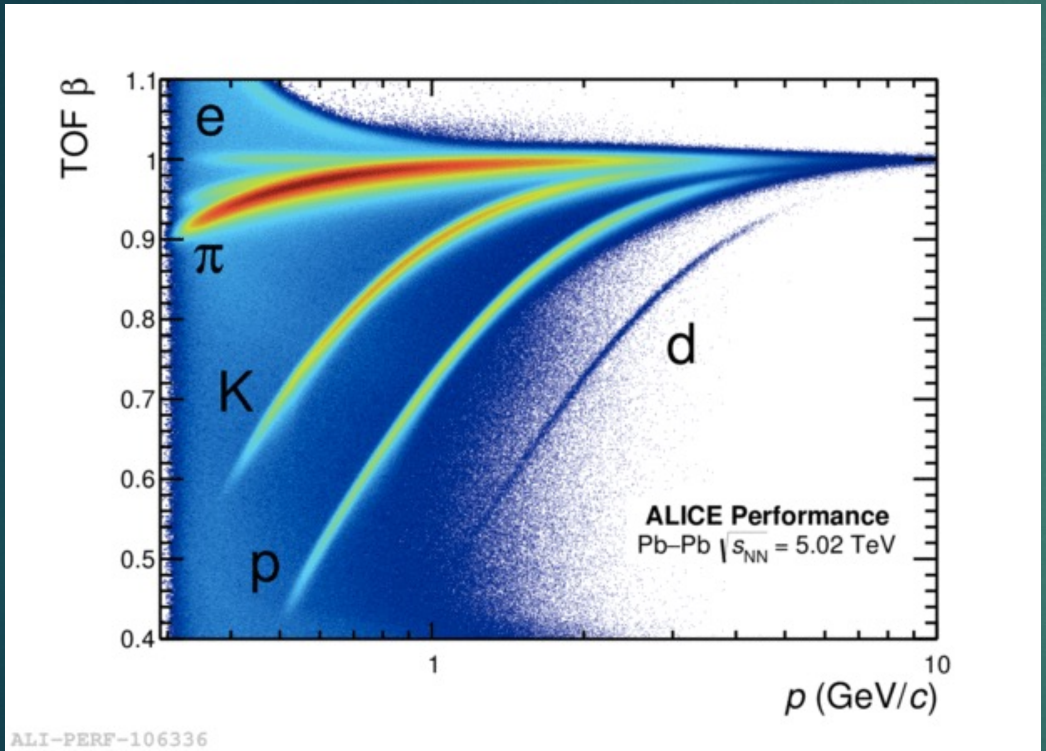
Nuclei identification via dE/dx



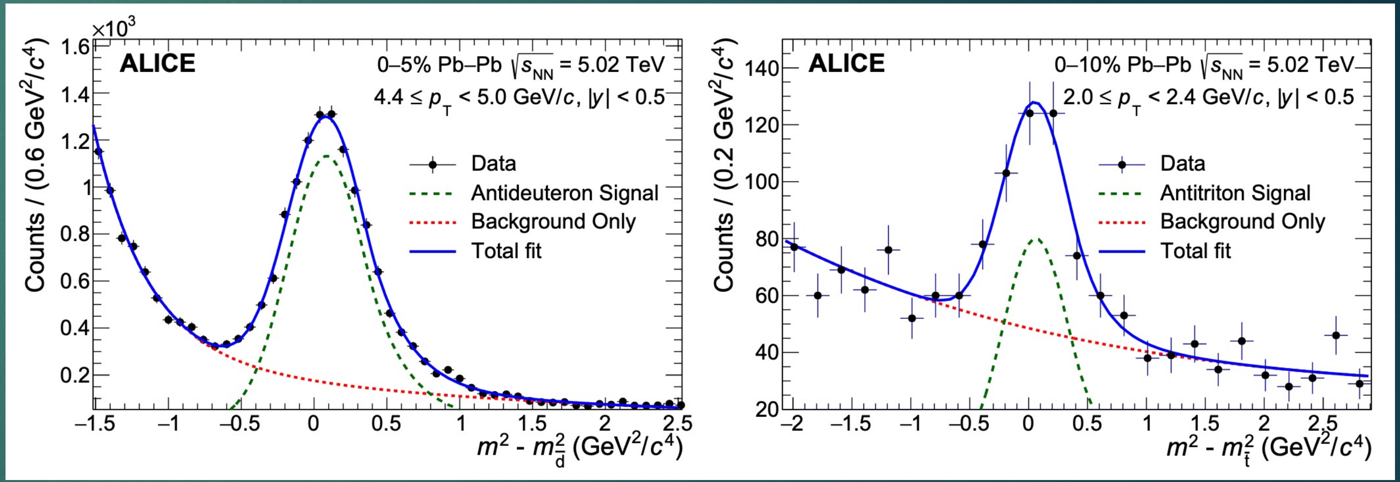
https://doi.org/10.1103/PhysRevC.107.064904

A=2, A=3 and A=4 nuclei and antinuclei can be identified via dE/dx from the TPC

Nuclei identification via TOF



- $m^2 = \frac{(1-\beta^2)}{\beta^2} p^2$ and $\beta = \frac{L}{t_{TOF} c}$



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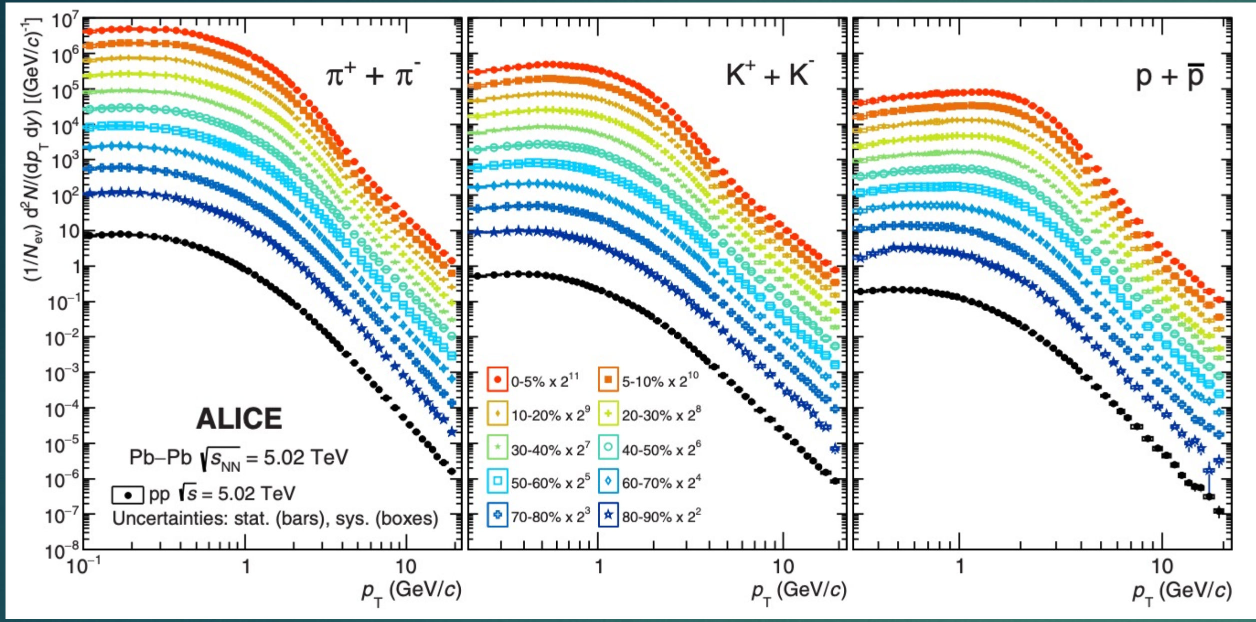
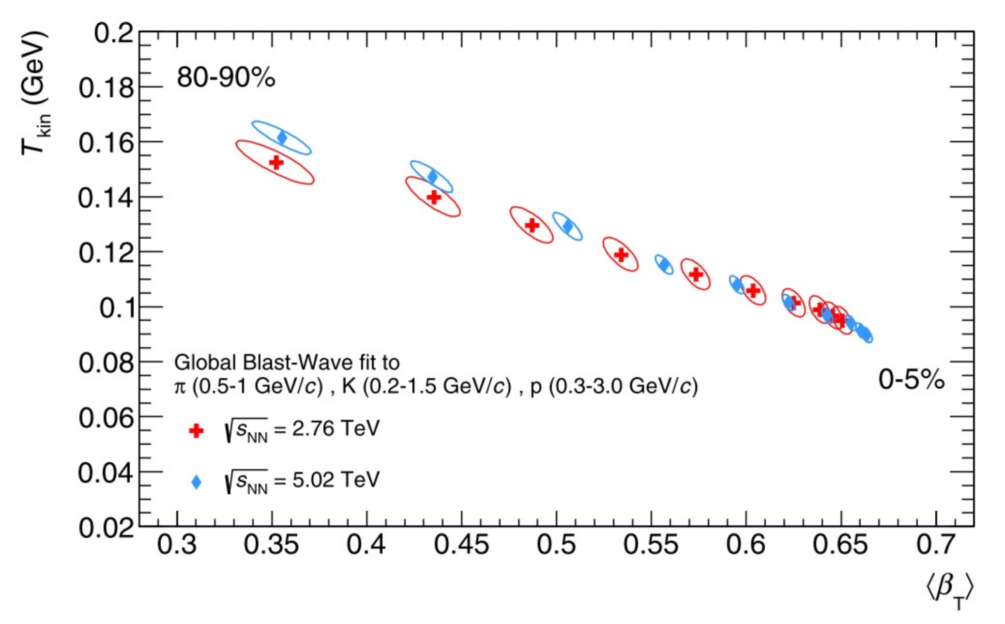
Light hadron spectra



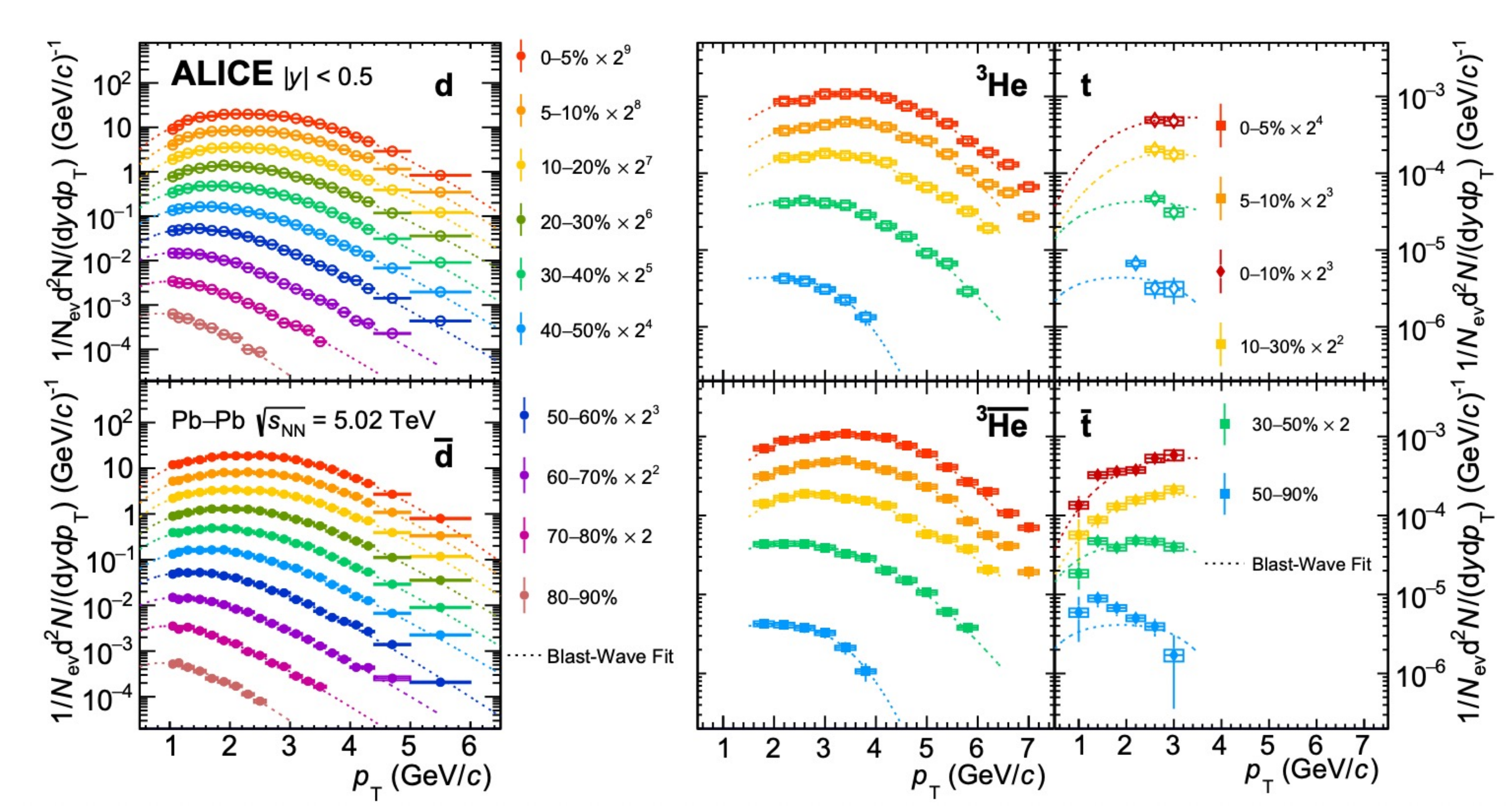


10.1103/PhysRevC.101.044907

Blast wave model: light hadrons are emitted by an expanding source at a temperature T_{kin} and show a collective motion given by a radial flow $<\beta_T>$
$\Rightarrow$ Hardening of the spectra with the centrality

Nuclei spectra

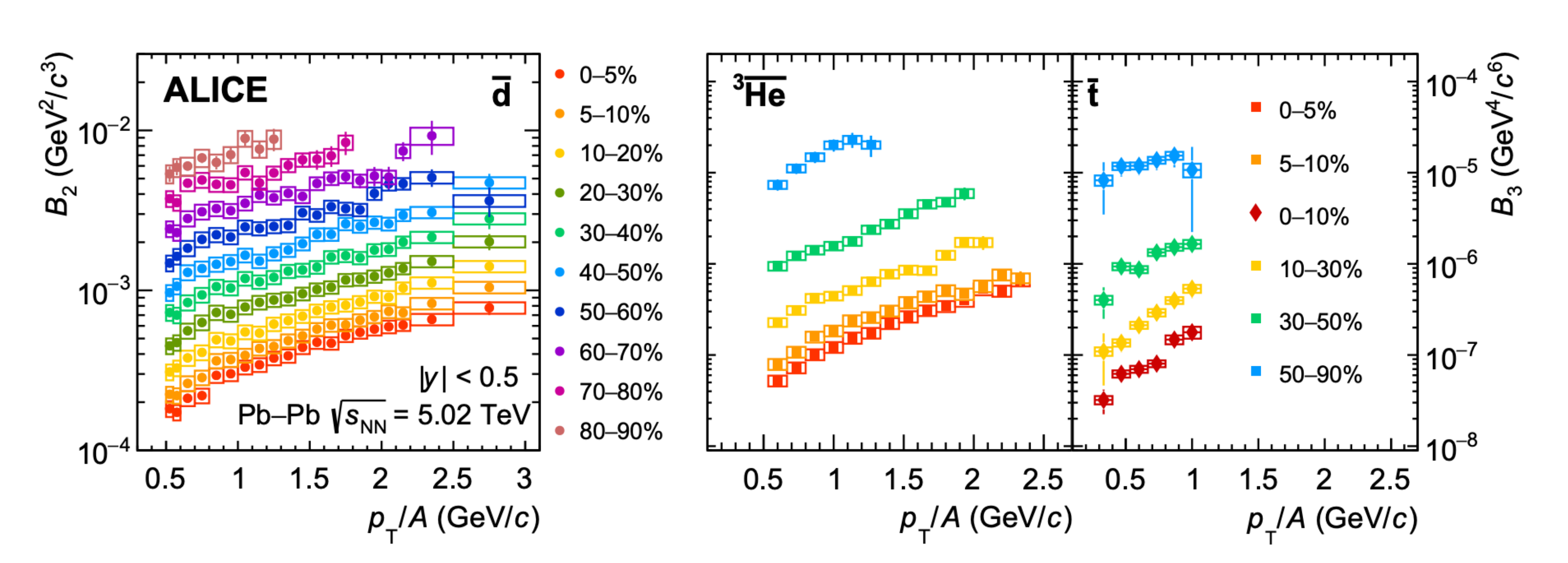
https://doi.org/10.1103/PhysRevC.107.064904



- Results from A=2 and A=3 (anti)nuclei measured in Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5 TeV at different centralities
- Expected increase of the slope at most central collisions
- From peripheral to most central Pb–Pb collisions average p_T almost doubles
- A shift in the peak position towards higher p_T for increasing multiplicity

Dashed lines → Blast-Wave model of light hadrons from a thermal production from an expanding source

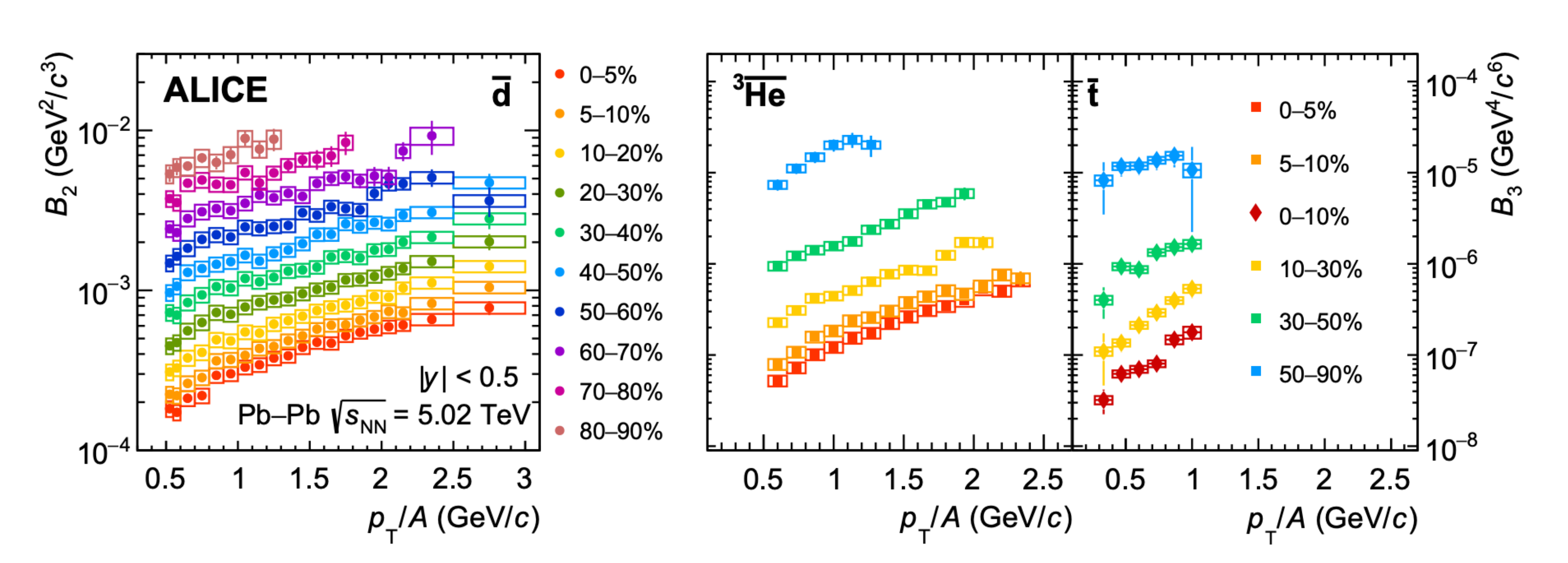
Coalescence parameters : A=2 and A=3



$$B_A = \frac{E_A \frac{d^3N_A}{d^3p_A}}{\left(E_p \frac{d^3N_p}{d^3p_p}\right)^A}$$

- Ordering of the coalescence parameters with collision centrality: [10.1103/PhysRevC.101.044907]
  - *B_A decreases if centrality increases*
  - If centrality increases, then also the R of the source increases (peripheral to central events)
  - Bigger R implies a larger separation between nucleons => in the coalescence scenario this environment reduces coalescence probability

Coalescence parameters : A=2 and A=3

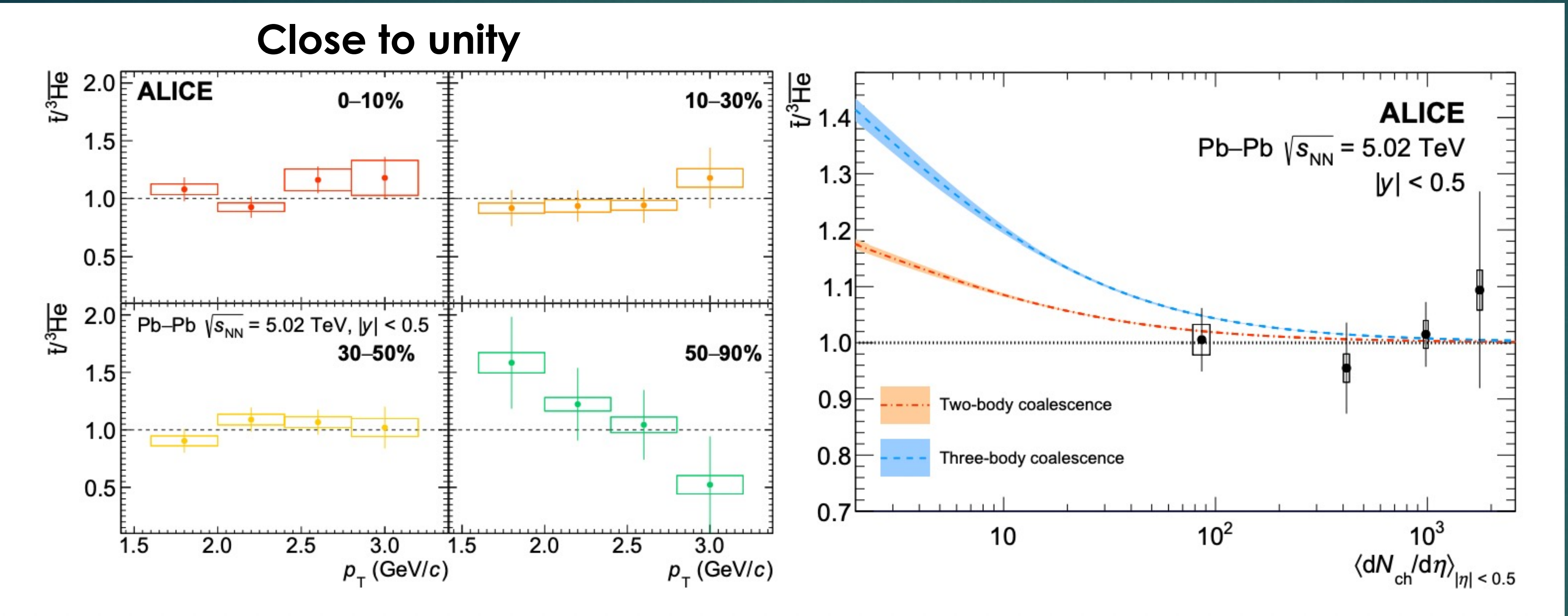


$$B_A = \frac{E_A \frac{d^3N_A}{d^3p_A}}{\left(E_p \frac{d^3N_p}{d^3p_p}\right)^A}$$

10.1103/PhysRevC.101.044907

- B_A raises with p_T
  - It points to the fact that high p_T particles originate from a smaller region of the source

Coalescence model: further test

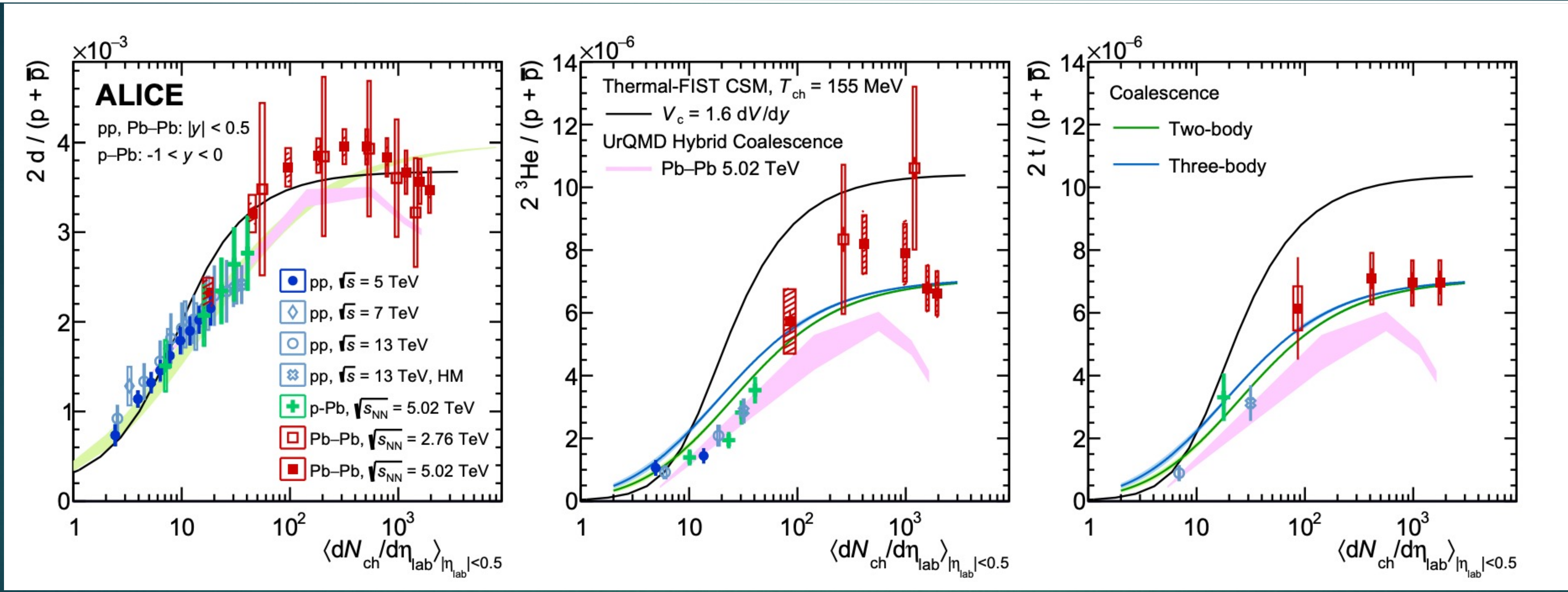


10.1103/PhysRevC.101.044907

- SHM expectation for this ratio is very close to 1
- Coalescence model predictions deviate from unity
- Different results in the 2-body vs 3-body coalescence
  - Different wave function of the two nuclei in the two cases

- Two predictions for the formation of the A = 3 nuclei
  - three nucleons (called three-body coalescence)
  - formation of the nucleus from a deuteron and a nucleon (two-body coalescence).

Light nuclei / proton from pp to Pb-Pb

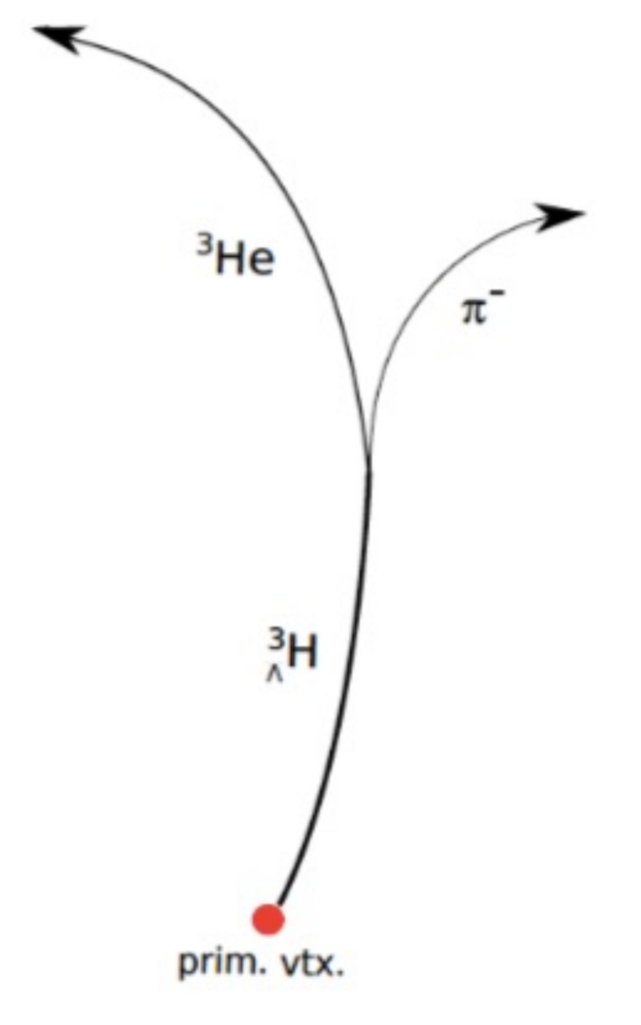


Increasing trend from pp to p–Pb and saturation in Pb–Pb collisions (Grand Canonical limit)

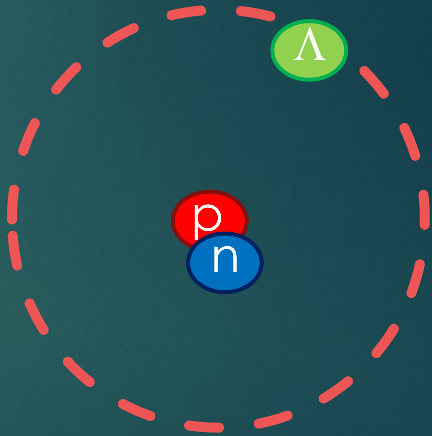
- For deuterons all models describe well the data.
- For A=3 the models describe qualitatively the trend with multiplicity

10.1103/PhysRevC.101.044907

Hypertriton



- m = 2.991 GeV/c^2
- B_Λ = 130 keV
- Radius for the hypertriton wave function $r_{\Lambda\text{-}d} \approx$ 10 fm https://arxiv.org/abs/1904.05818
- Fragile object



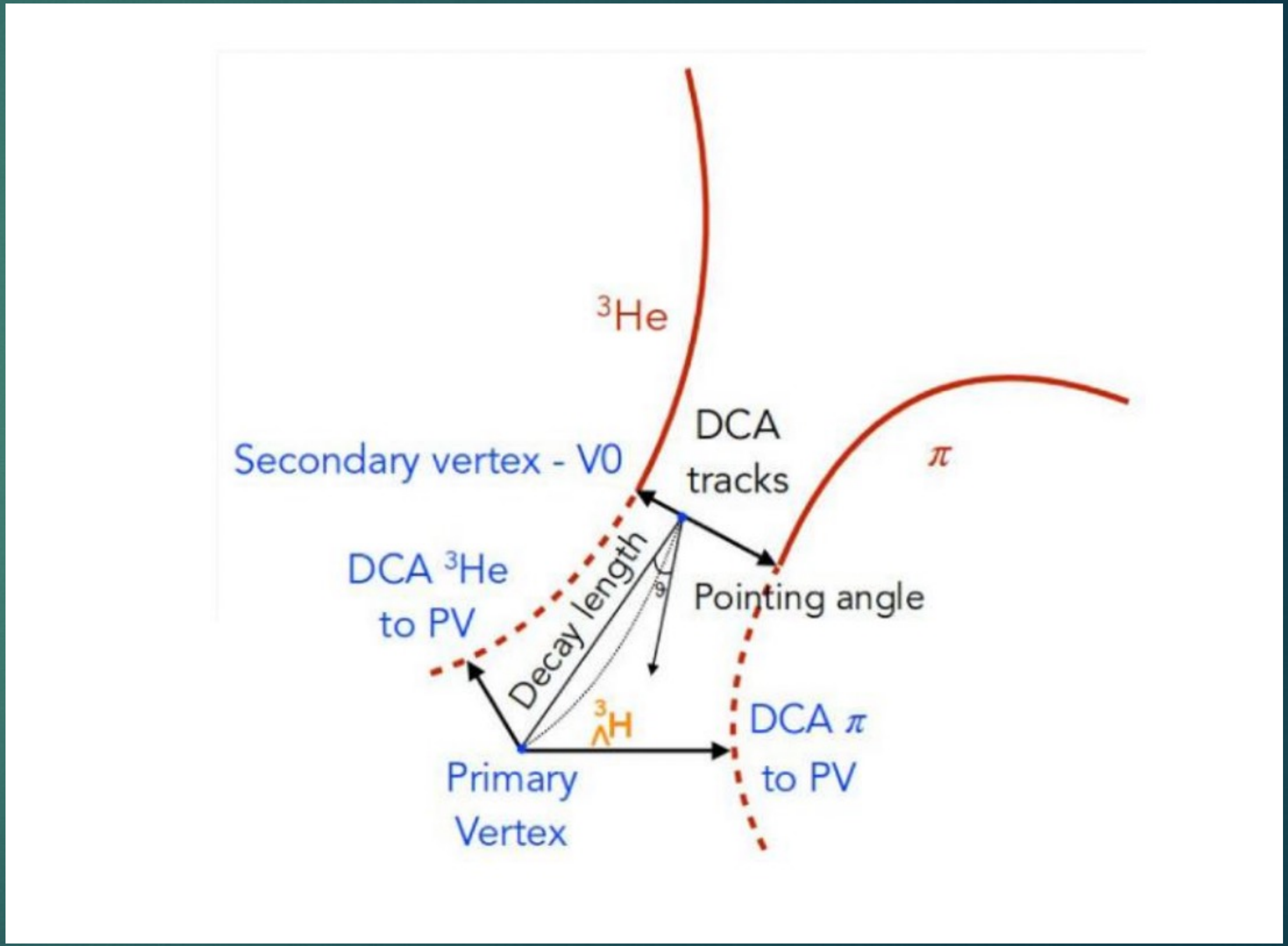
Decay channels

$$^3_\Lambda\mathrm{H} \rightarrow {}^3\mathrm{He} + \pi^-$$
$$^3_\Lambda\mathrm{H} \rightarrow {}^3\mathrm{H} + \pi^0$$
$$^3_\Lambda\mathrm{H} \rightarrow \mathrm{d} + \mathrm{p} + \pi^-$$
$$^3_\Lambda\mathrm{H} \rightarrow \mathrm{d} + \mathrm{n} + \pi^0$$

+ charge coniugates

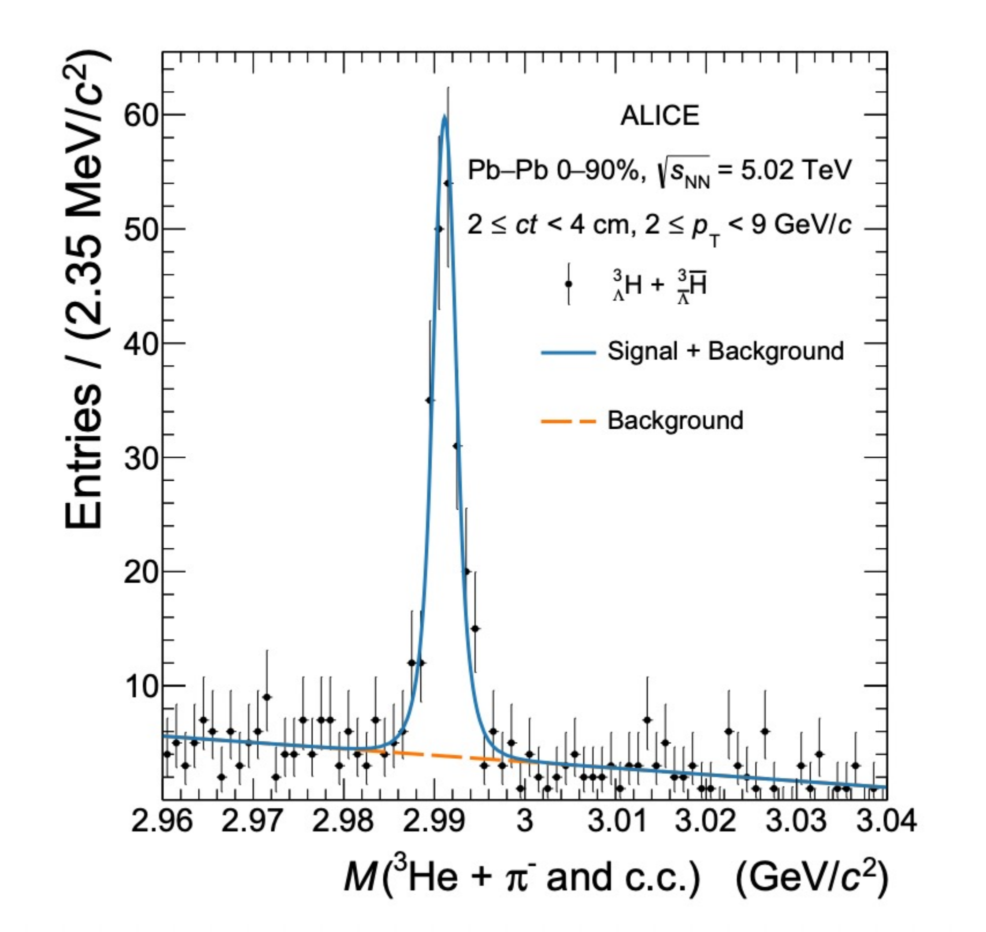
Hypertriton

- Measurement performed in one decay channel $^3He + \pi$
- Huge combinatorial background
- PID, topological cuts and and Machine Learning (ML) techniques applied

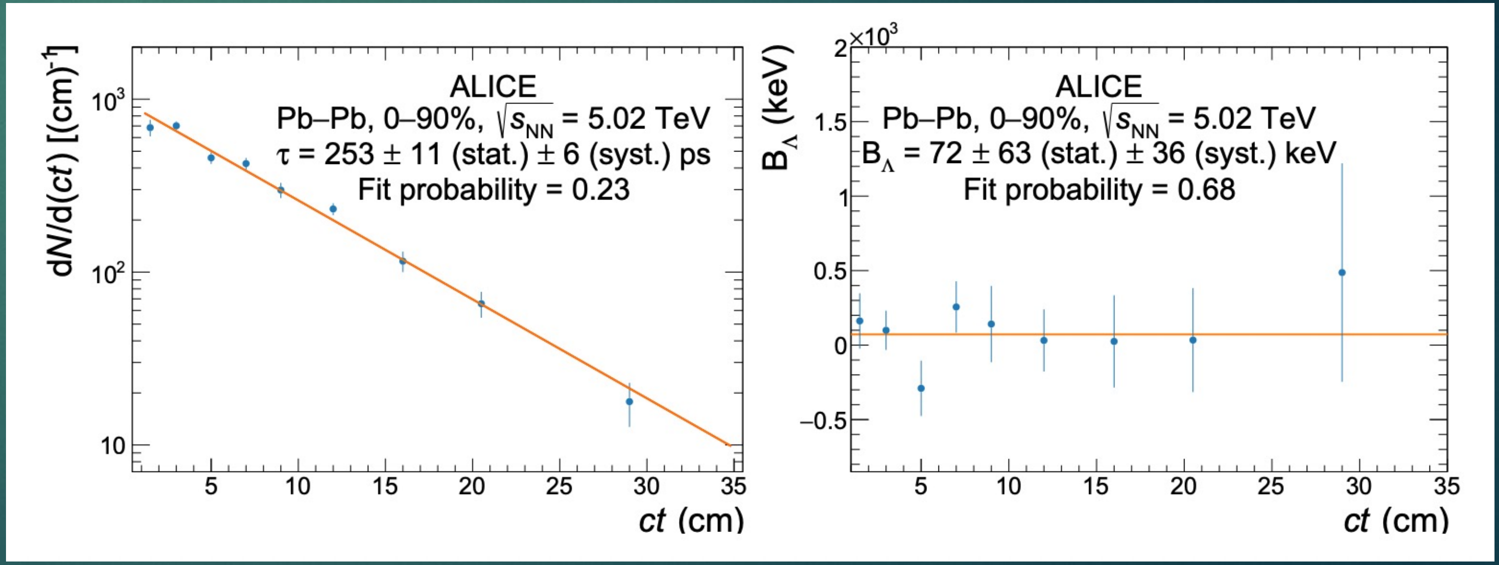


Hypertriton measurements in Pb-Pb

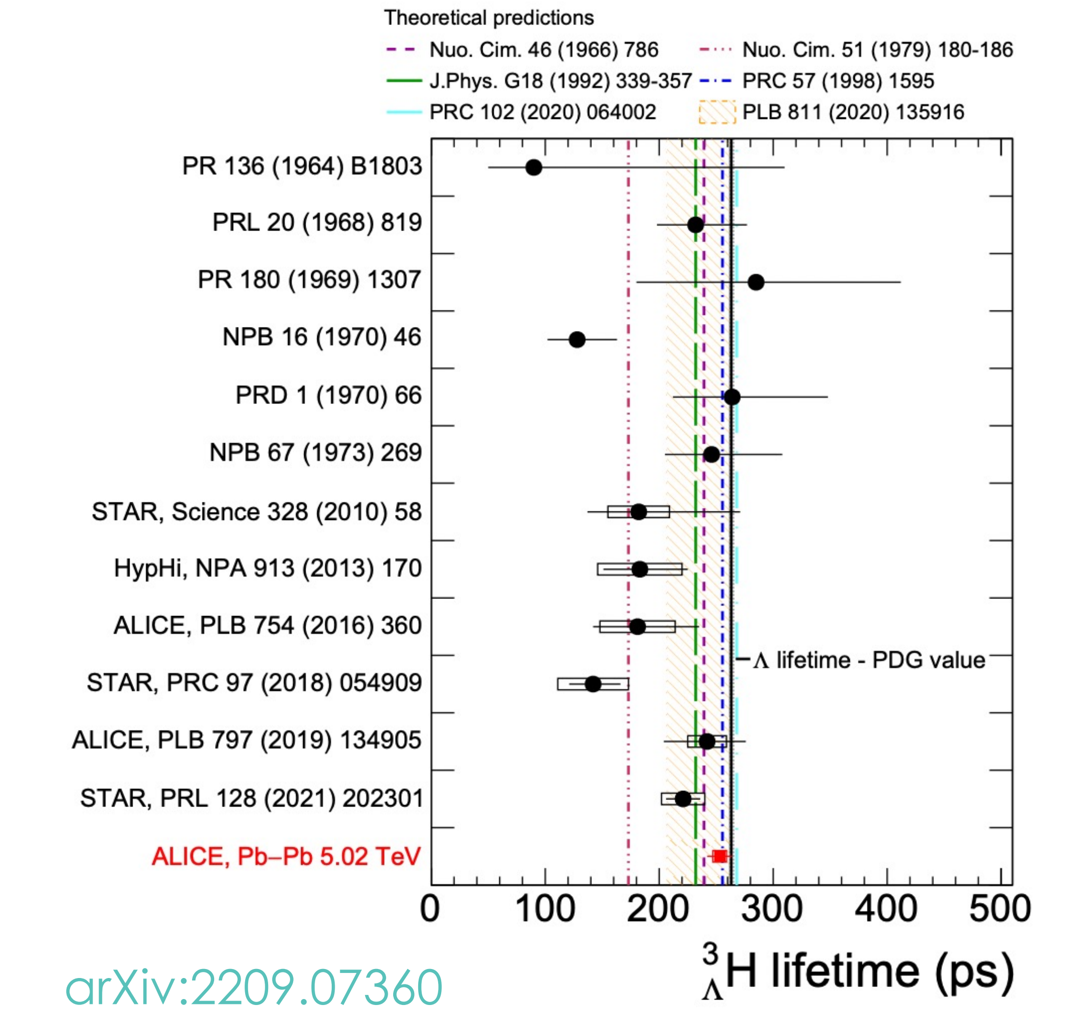
arXiv:2209.07360



The most precise measurements to date of the $^3{}_\Lambda H$ lifetime τ and Λ separation energy B_Λ are obtained using the data sample of Pb–Pb collisions at $\sqrt{s_{NN}}$ = 5.02 TeV collected by ALICE at the LHC.



Hypertiton Lifetime measurements

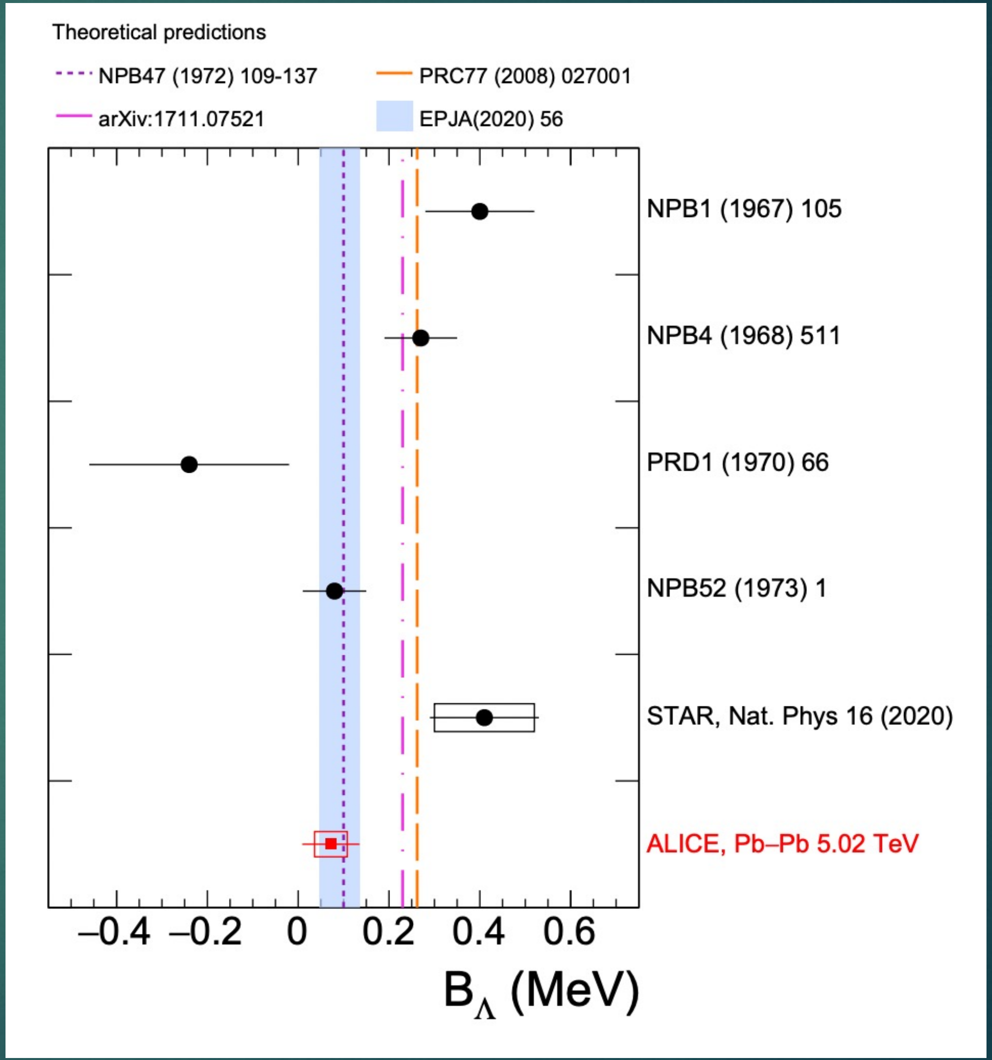


arXiv:2209.07360

- Theoretical expectations are close to the free Λ lifetime but previous experimental results were well below the theoretical values
- Hypertriton lifetime measured by ALICE is compatible with the free Λ lifetime within its uncertainhes
- It confirms it is a very loosely-bound state

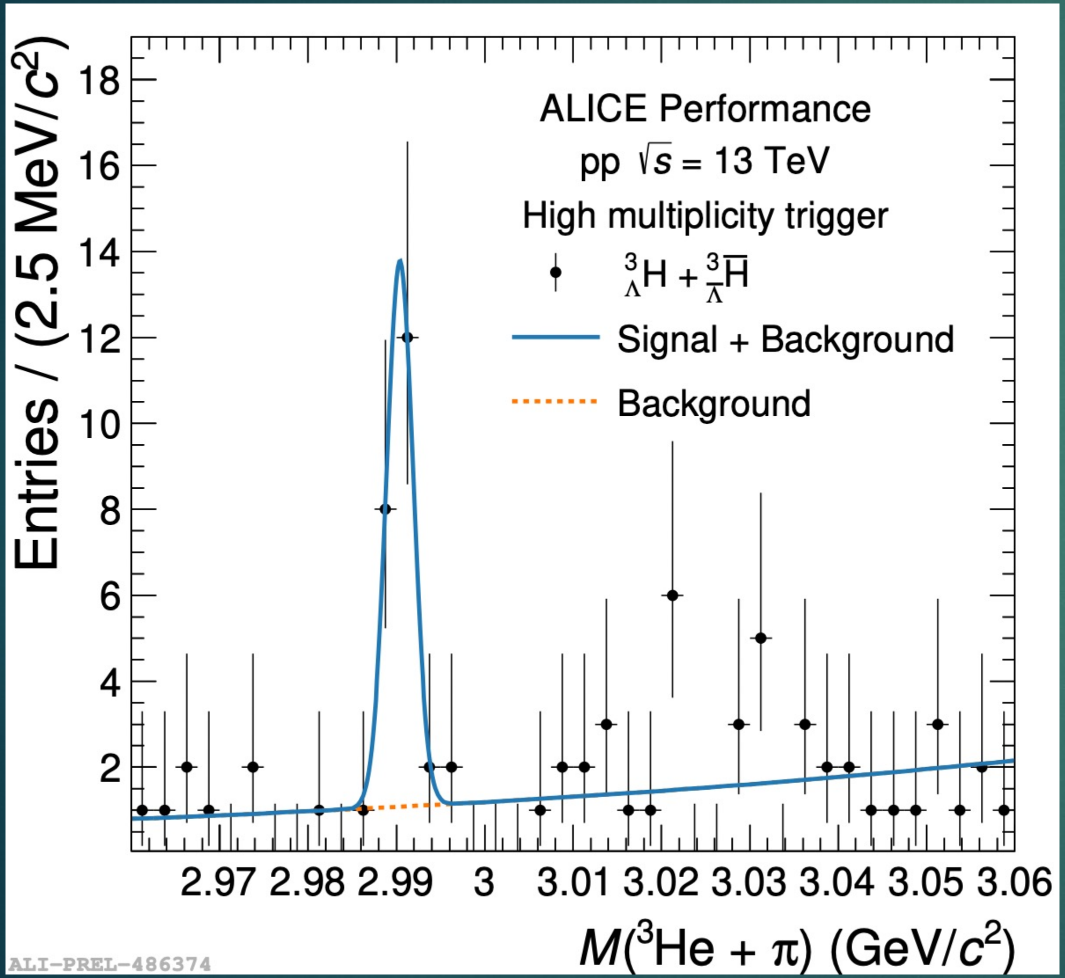
Hypertriton binding energy

- ALICE measurement of the hypertriton binding energy is in agreement with the latest theoretical predictions
- Results confirm it is a very loosely-bound state

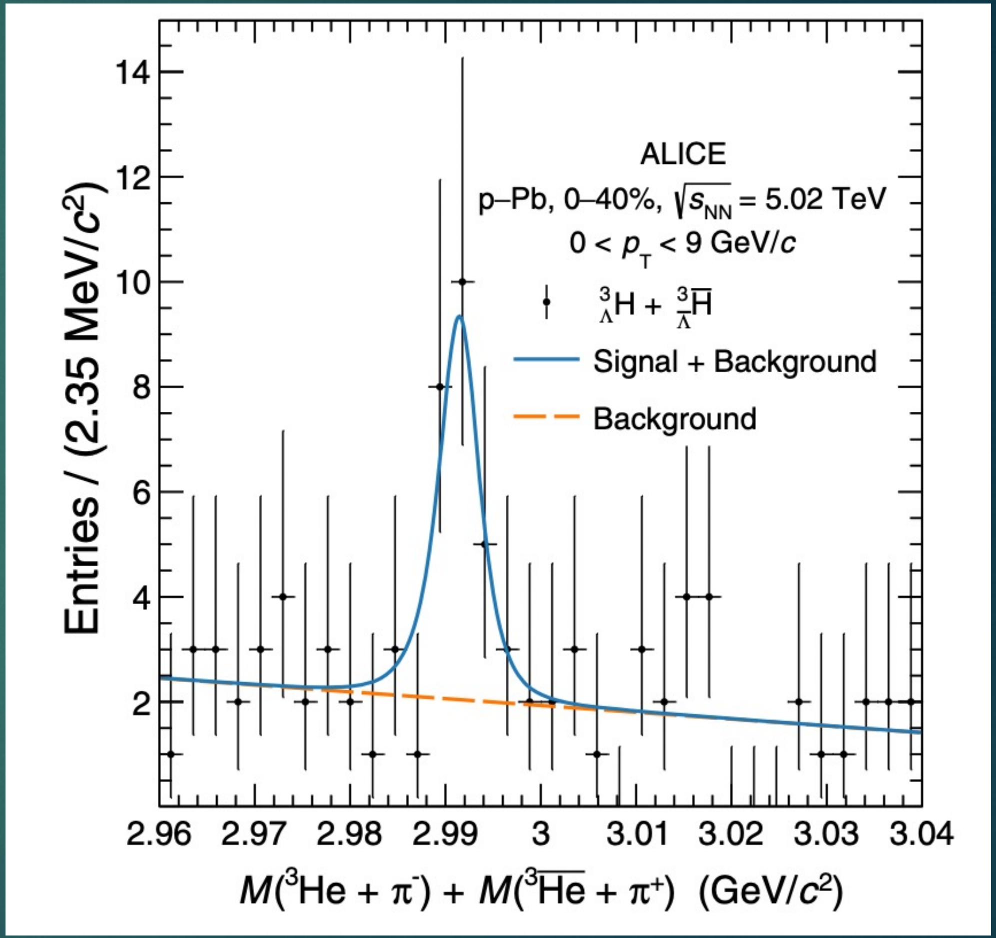


Hypertriton measurements in small systems

measurement of the hypertriton in pp (13 TeV) and p-Pb (5.02 TeV) collisions



- pp collisions : trigger on high multiplicity events
- Significance > 4σ

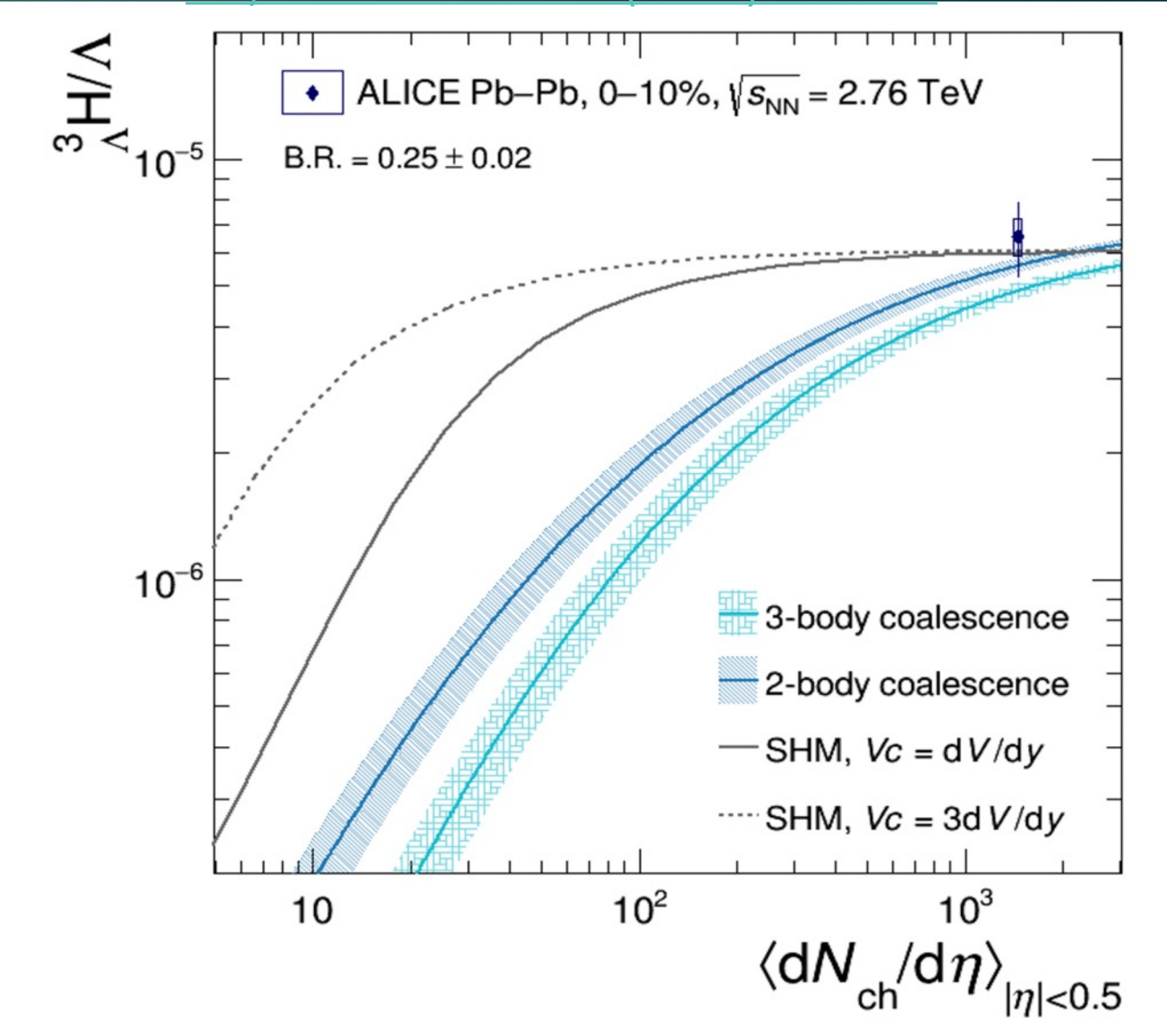


Phys. Rev. Lett.128 (2022) 252003

${}^{3}_{\Lambda}H$ / Λ ratio vs multiplicity

- Coalescence and statistical hadronization model predictions converge at heavy ion collision multiplicities
- Ratio is sensitive to the nuclei production mechanism at low multiplicities
- In statistical hadronization models the volume size is not relevant
- In a coalescence picture the production in small systems is suppressed expected due to the limited volume

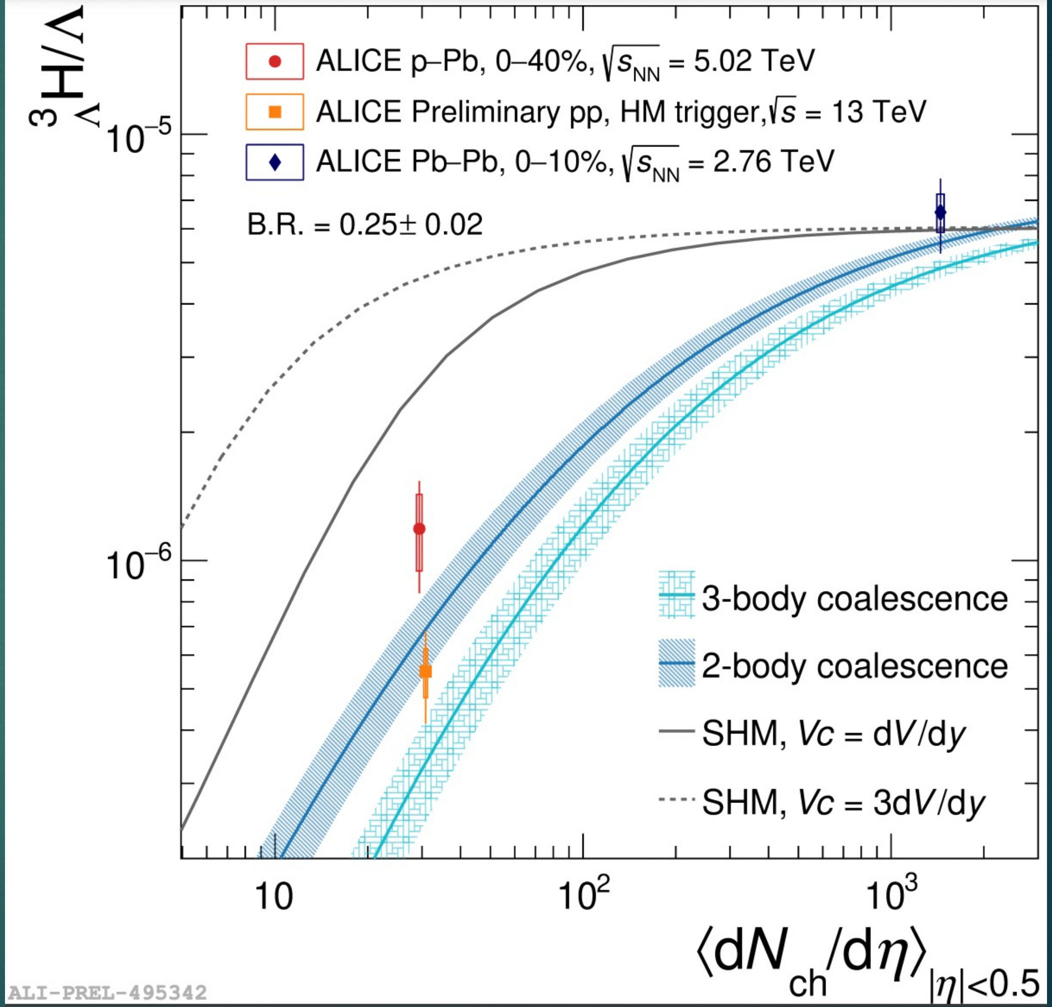
Phys. Rev. Lett.128 (2022) 252003



$^{3}_{\Lambda}H$ / Λ ratio vs multiplicity

Phys. Rev. Lett.128 (2022) 252003

- New measurements at two small multiplicities! where there is a large separation between models
- Measurements at different multiplicities indicate that two-body coalescence seems to get closer to the data
- SHM model with V_C = 3 dV/dy excluded by more than 6 σ



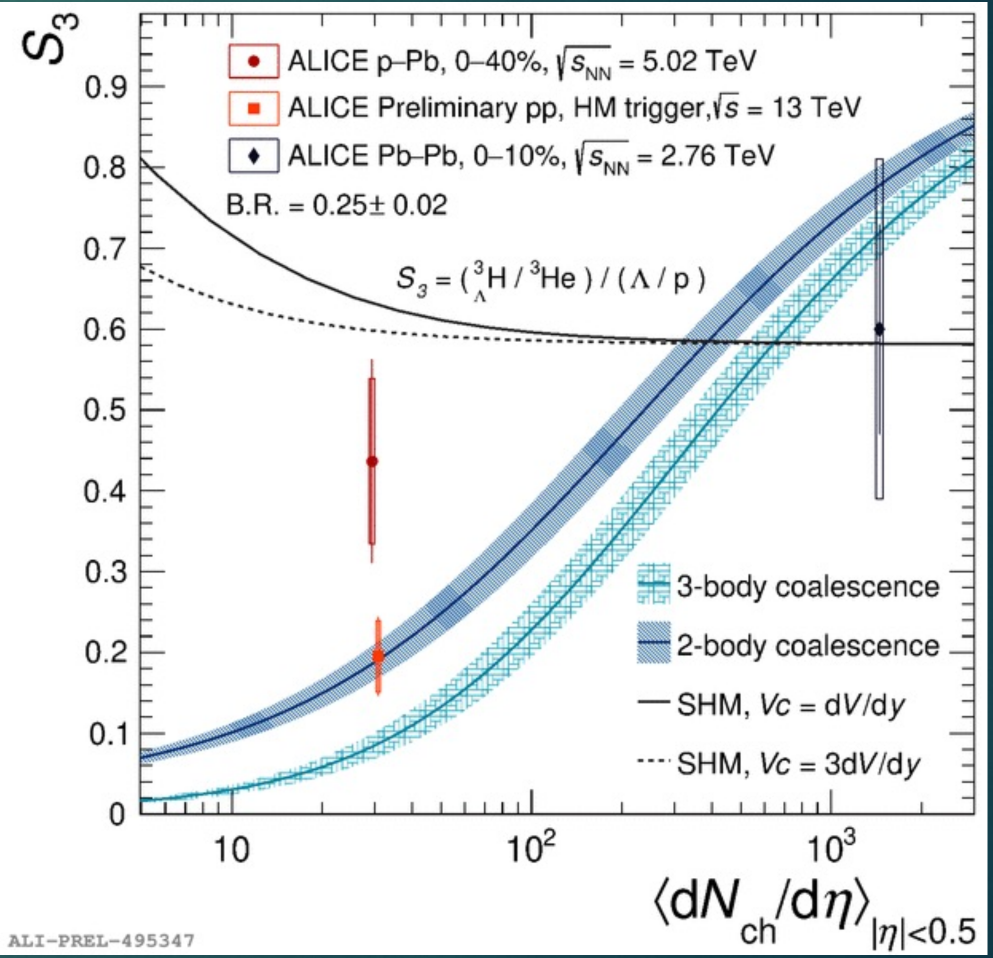
S_3. strangeness population factor

- Strangeness population factor is a measurement of baryon-strangeness correlations

$$S_3 = \frac{{}^{3}_{\Lambda}H / {}^{3}He}{\Lambda / p}$$

- mass difference drops out and size effects can be studied
- Measurements at different multiplicities indicate that two-body coalescence seems to get closer to the data
- agreement with the measurement of the ${}^{3}_{\Lambda}H / \Lambda$ ratio (lower sensitivity)

Phys. Rev. Lett.128 (2022) 252003



Summary

- The ALICE experiment has performed several measurements in Pb-Pb, p-Pb and pp collisions, thus providing a wider look to the production mechanism of light (anti)(hyper)nuclei

- Even though the measurements are more precise than previous data, they still do not allow for a final conclusion on the dominant production mechanism

- Most precise determination of the hypertriton lifetime and binding energy has been done and it confirms than $^{3}_{\Lambda}H$ is a very loosely bound state

- The ongoing Run 3 and the future Run 4 will add more statistics and thanks to high precision data there will be the possibility to improve our understanding in nuclei production mechanisms from cold to hot nulclear matter

Thank you