(Anti)nucleosynthesis in heavy-ion collisions and (anti)nuclei as "baryonmeter" of the collision

Mario Ciacco
on behalf of the ALICE Collaboration

(Anti)deuteron production in heavy-ion collisions

Light nuclei in heavy-ion collisions

- Low binding energy w.r.t.fireball temperature at chemical freeze-out

Synthesis models

- Thermal Model

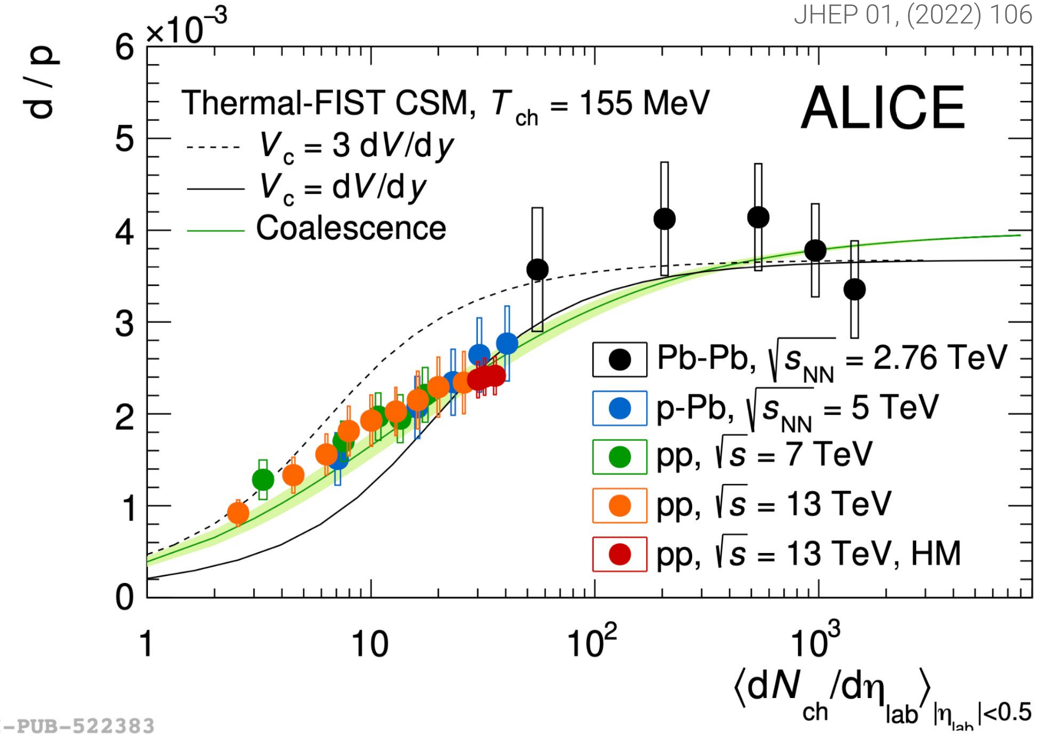
[1] V. Vovchenko *et al.*, Phys. Lett. B 785, (2018) 171

- Coalescence model

[2] K.-J. Sun *et al.*, Phys. Lett. B 792, (2019) 132

→ event-by-event antideuteron fluctuations to study production mechanism

JHEP 01, (2022) 106



ALI-PUB-522383

(Anti)nuclei and the Statistical Hadronisation Model

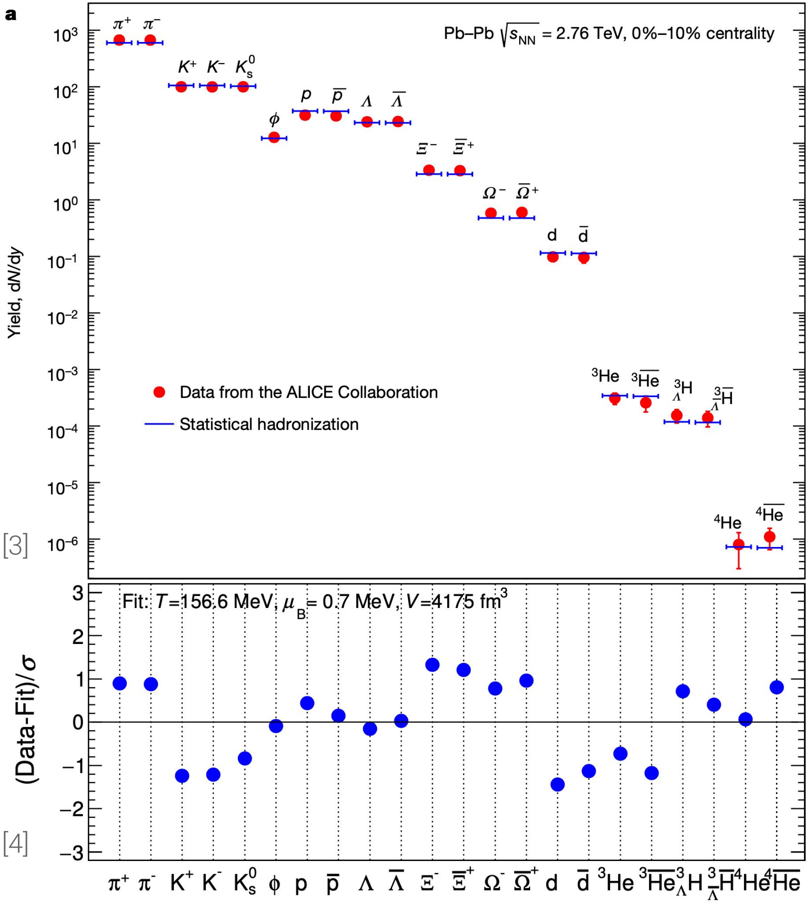
Statistical Hadronisation Model (SHM)

- fireball at chemical freeze-out → hadron resonance gas
- fit model to particle yield data → successful description over 9 orders of magnitude

Baryon chemical potential μ_B

- antimatter-matter balance
- Last measurement in Pb–Pb at LHC → μ_B = 0.7 ± 3.8 MeV [3]

→ new precise measurement based on antiparticle-to-particle ratios



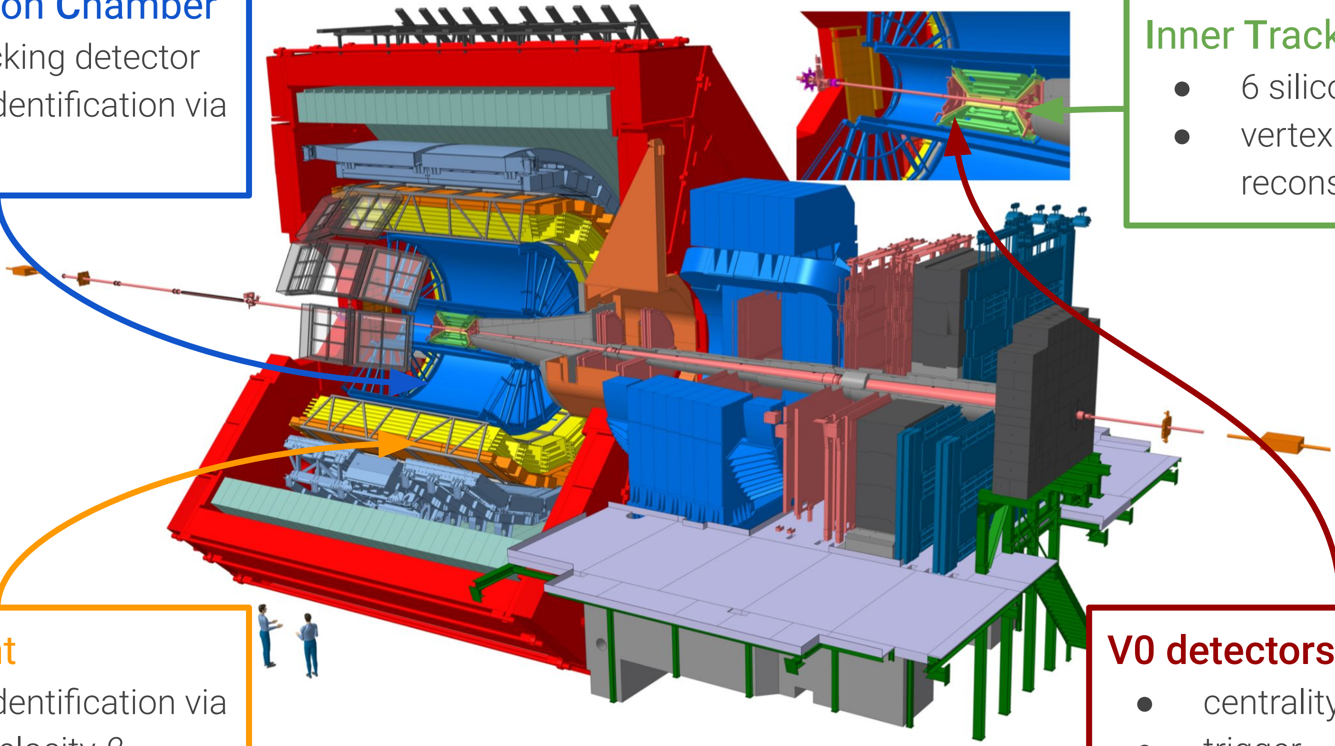
[3] A. Andronic *et al.*, Nature 561, (2018) 321

[4] A. Andronic *et al.*, (2018) arXiv:1808.03102 [hep-ph]

The ALICE apparatus

Time Projection Chamber
- main tracking detector
- particle identification via dE/dx

Time-Of-Flight
- particle identification via particle velocity β
- event time



ALICE-PHO-SKE-2017-001

Inner Tracking System
- 6 silicon layers
- vertex and track reconstruction

V0 detectors
- centrality estimation
- trigger

Antideuteron multiplicity distribution

Grand Canonical Ensemble (GCE) Thermal Model

- Poisson

Coalescence model → deviations from Poisson

- **Model A:** correlated nucleons
- **Model B:** independent nucleons

Average deuteron multiplicity

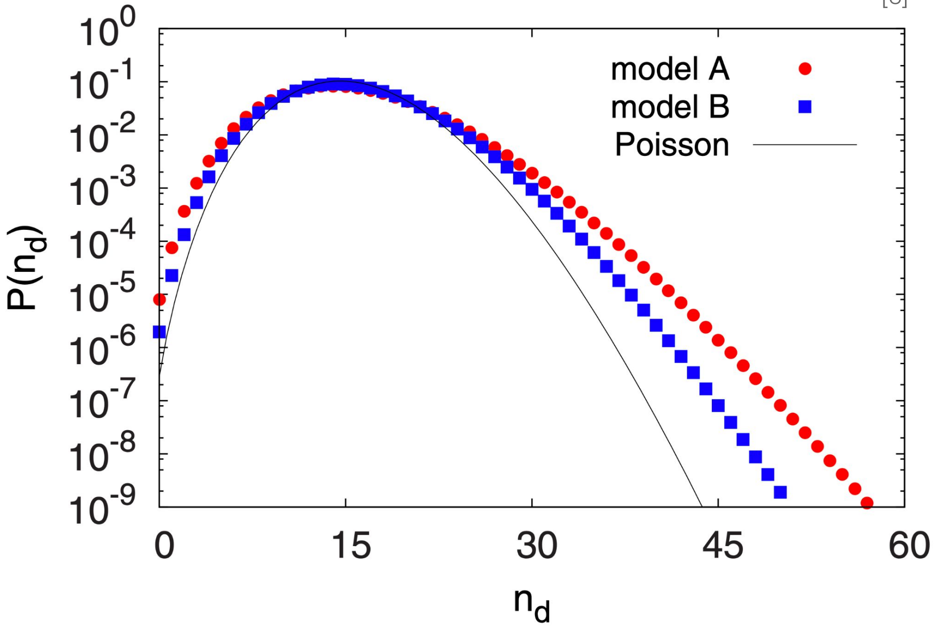
$$\lambda_d = B\, n_i\, n_j$$

coalescence parameter (B)

initial nucleon number (n_j)

i = protons, j = neutrons

[5]



[5] Jan Steinheimer *et al.*, Phys. Rev. C 93 , (2016)

[6] F. Bellini *et al.*, Phys. Rev. C 99(5), (2019) 054905

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ALICE

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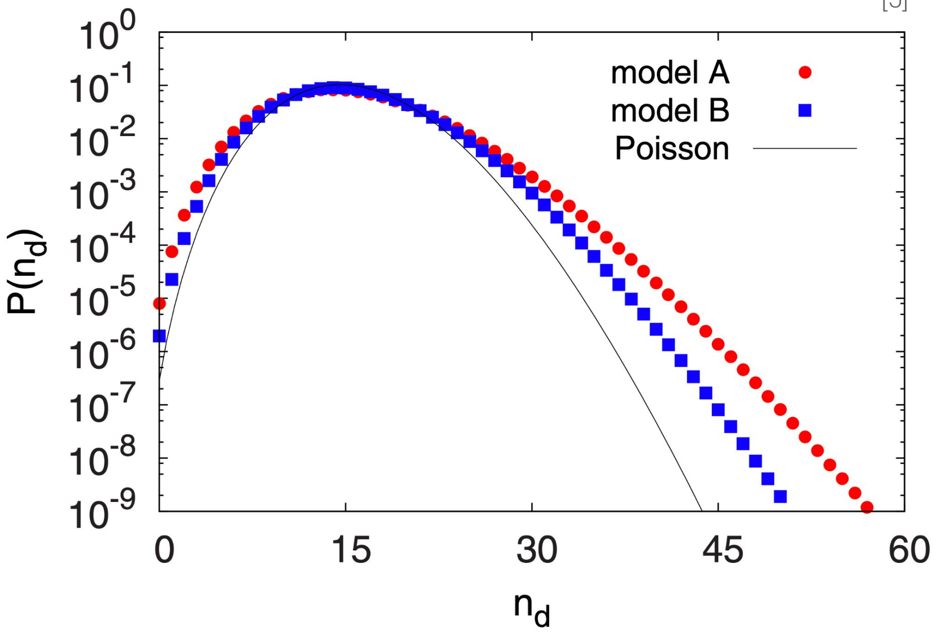
Multiplicity distribution given initial nucleon number

$$P_d(n_d|n_i,n_j) = \lambda_d^{n_d}\frac{e^{-\lambda_d}}{n_d!} = (Bn_in_j)^{n_d}\frac{e^{-Bn_in_j}}{n_d!}$$

Final multiplicity distribution

$$P_d(n_d) = \sum_{n_i,n_j\geq n_d} P_d(n_d|n_i,n_j)P(n_i)P(n_j)$$

[5]



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Results: κ_2/κ_1

Cumulants

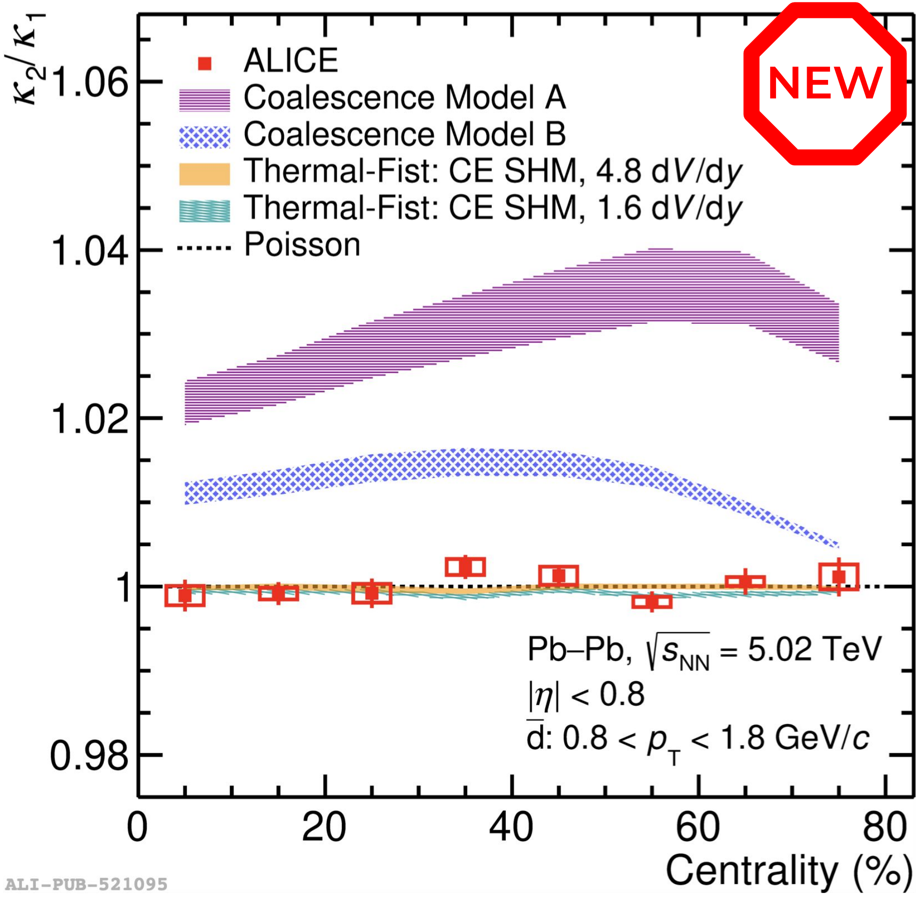
$$\kappa_1 = \langle n \rangle$$
$$\kappa_m = \langle (n - \langle n \rangle)^m \rangle,\ m = 2, 3$$

- Poisson → $\kappa_1 = \kappa_2 = \kappa_3$

κ_2/κ_1 cumulant ratio consistent with unity

- described by Grand Canonical SHM (Poisson)
- overpredicted by coalescence
- limited sensitivity to baryon number conservation of Canonical Ensemble

(2022) arXiv:2204.10166v1 [nucl-ex]



Results: antiproton-antideuteron correlation

Pearson correlation

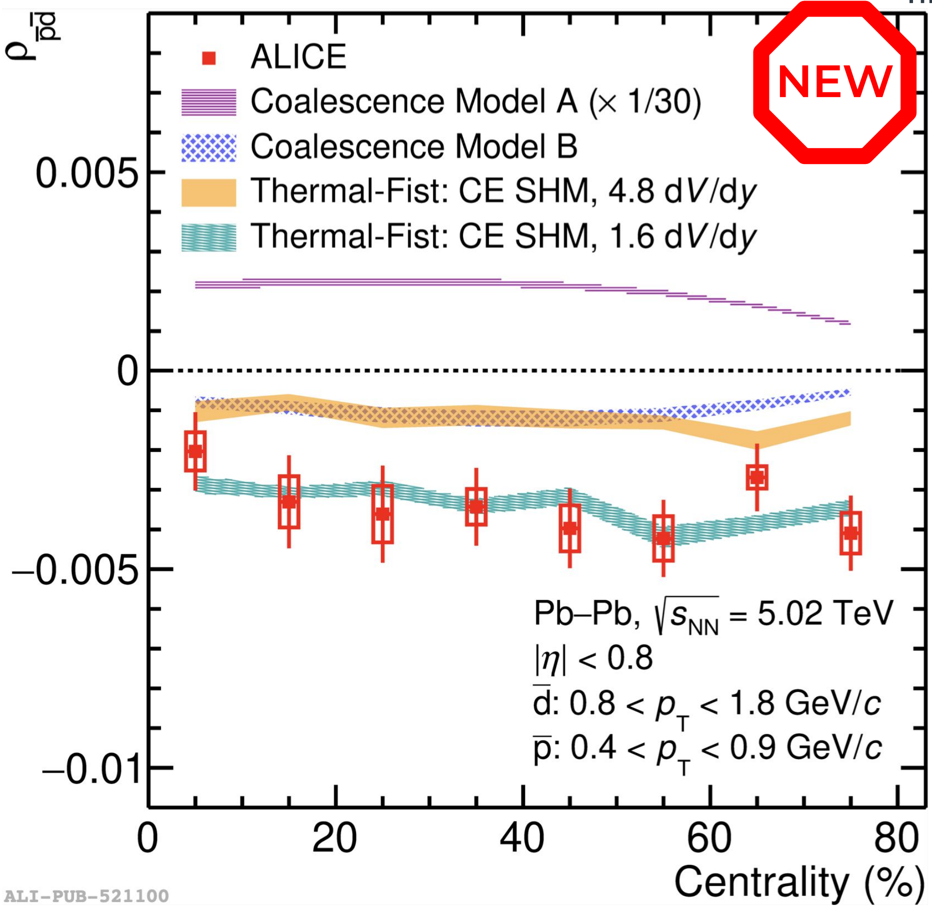
$$\rho_{ab} = \frac{\langle (n_a - \langle n_a \rangle) \rangle \langle (n_b - \langle n_b \rangle) \rangle}{\sqrt{\kappa_{2a}\kappa_{2b}}}$$

Negative correlation between antiprotons and antideuterons

- predicted by Canonical Ensemble thermal model with V_C = 1.6 dV/dy
  - *smaller correlation volume than for cumulant measurements of protons*

  M. Arslandok - 15/06/2022, 11:30

- qualitatively described by Model B
- Model A ruled out



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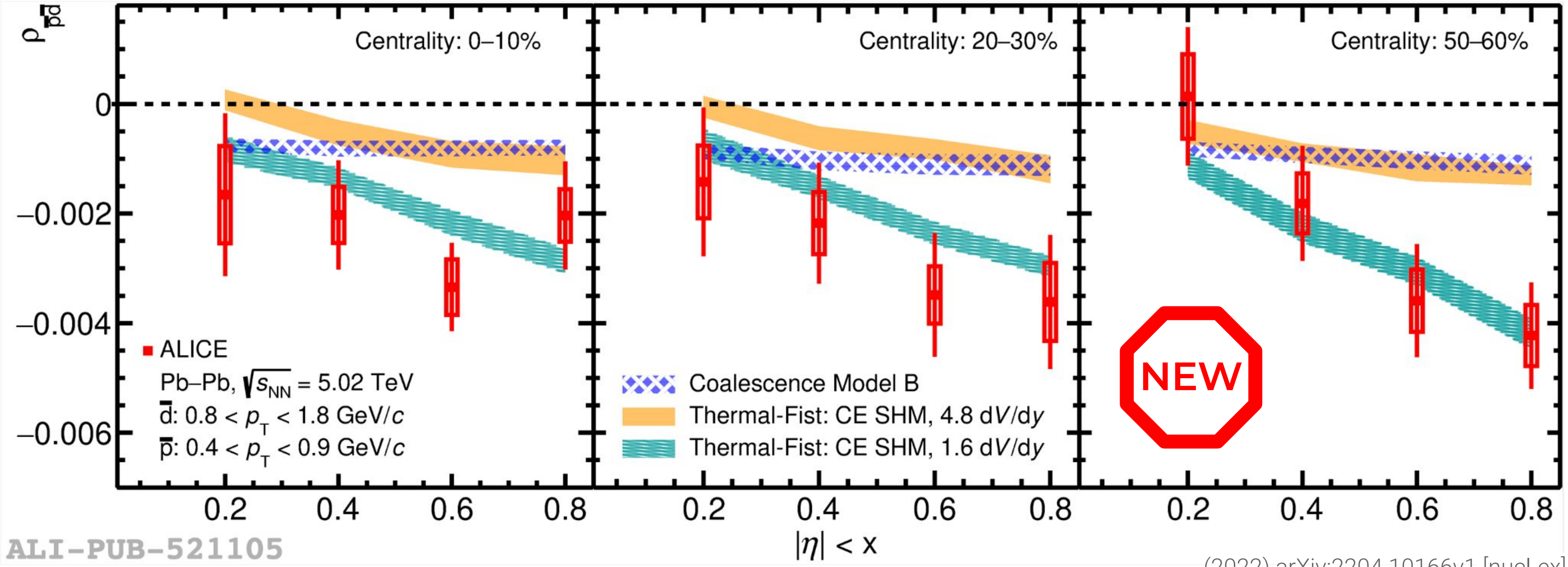

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Correlation dependence from acceptance

- SHM → correlation depends on fraction of baryons in acceptance out of total → acceptance dependence
- Coalescence → no significant acceptance dependence

Antiparticle to particle ratios and μ_B

Grand Canonical Ensemble SHM

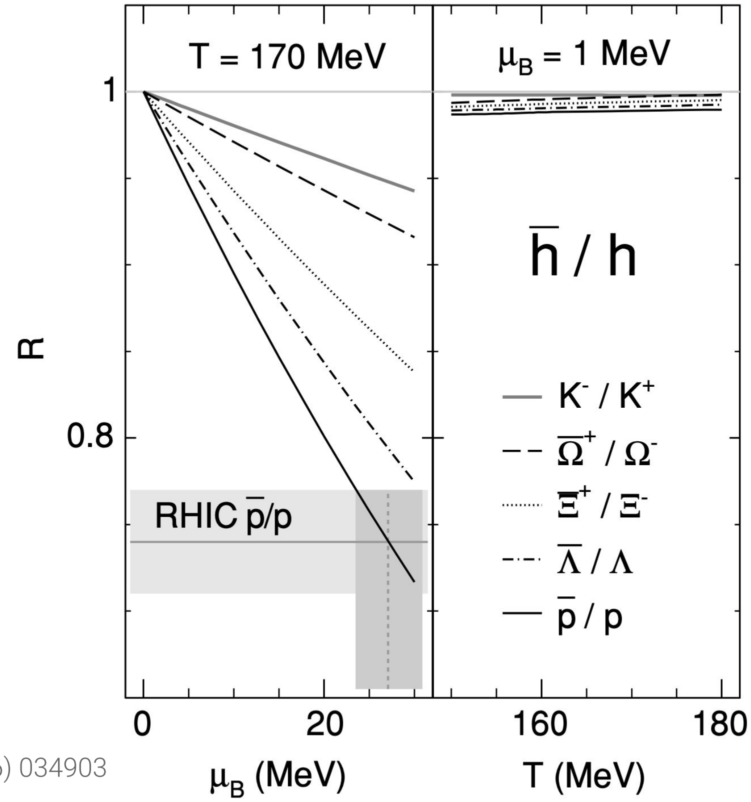
$$\bar{h}/h \propto \exp\left[-2\cdot\frac{B_h\mu_B + S_h\mu_S + I_{3,h}\mu_{I_3}}{T}\right]$$

baryon number — strangeness — 3rd isospin component

Strangeness neutrality $\rightarrow \mu_B \sim 3\mu_S$

$$\bar{h}/h \propto \exp\left[-2\left(B+\frac{S}{3}\right)\frac{\mu_B}{T} - 2I_3\frac{\mu_{I_3}}{T}\right]$$

[7]



[3] A. Andronic *et al.*, Nature 561, (2018) 321
[7] J. Cleymans *et al.*, Phys. Rev. C 74, (2006) 034903
[8] J. Cleymans and H. Satz, Z. Phys. C 57, (1993) 135-147

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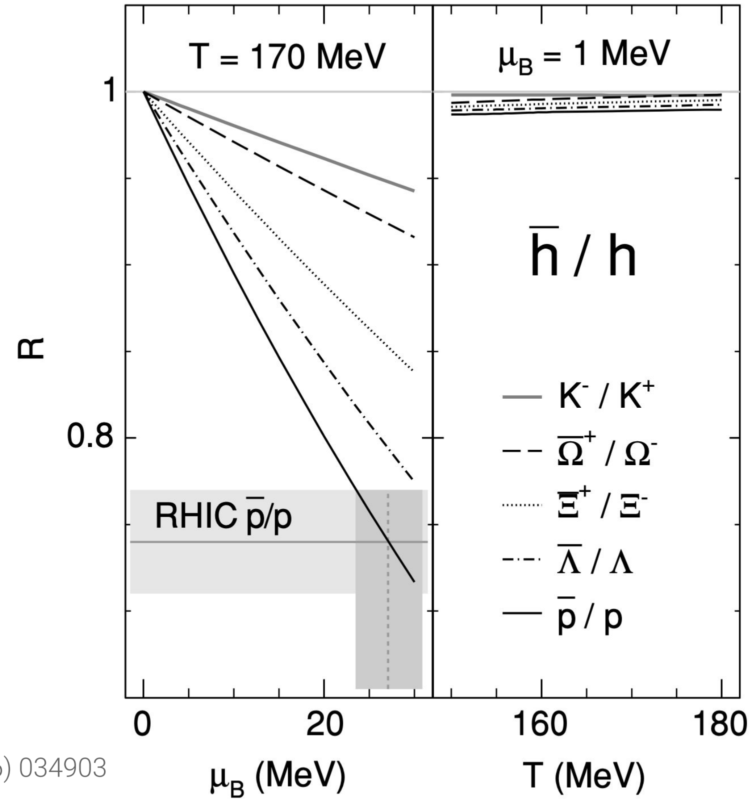
- Large $B + S/3$ → high sensitivity to μ_B → (anti)p, ^{3}He, $^3_\Lambda$H
- $\pi^\pm$ (B = S = 0) to constrain μ_{I3}
- small dependence on temperature T → fixed from SHM fit [3]

  T = 156.2 ± 1.5 MeV
- sensitivity to strangeness content

[7]



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Analysis of ratios

Data sample

- Pb–Pb at $\sqrt{s_{NN}}$ = 5.02 TeV
- centrality intervals: 0-5%, 5-10%, 30-50%

Pions, protons and helium

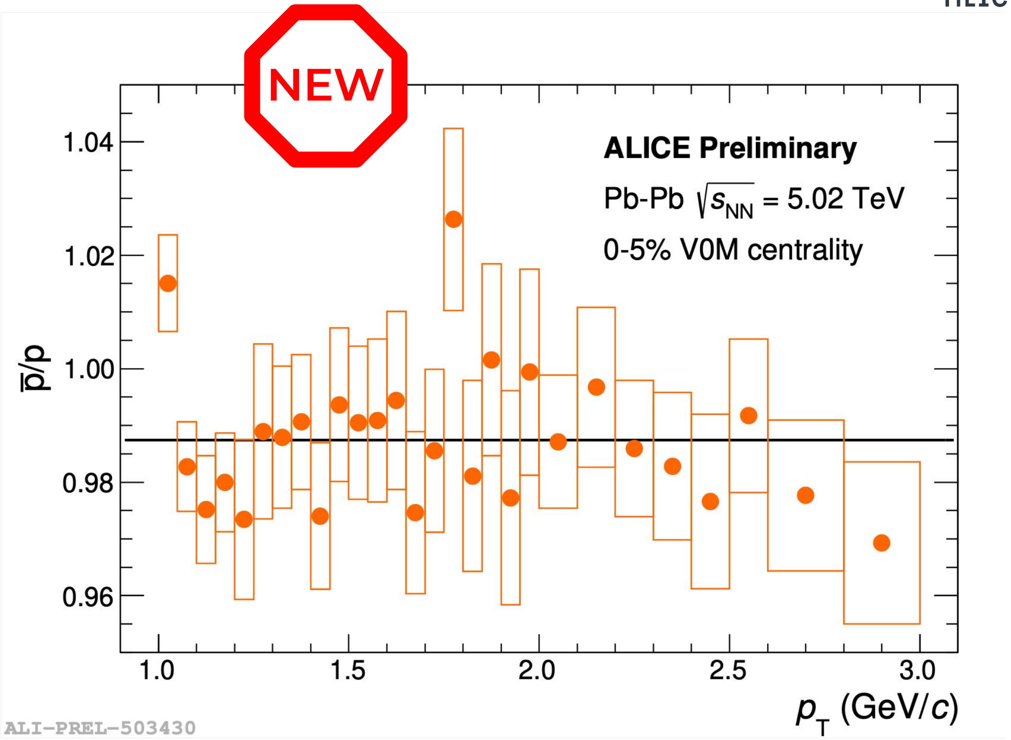
- particle identification via TPC+TOF (pions and protons) and TPC (^{3}He)
- subtract contribution from weak decays and spallation

Hypertriton

- reconstructed via 2-body mesonic decay

$$^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-} (+\ \mathrm{c.c.})$$

- candidate selection via XGBoost Boosted Decision Tree [9, 10]



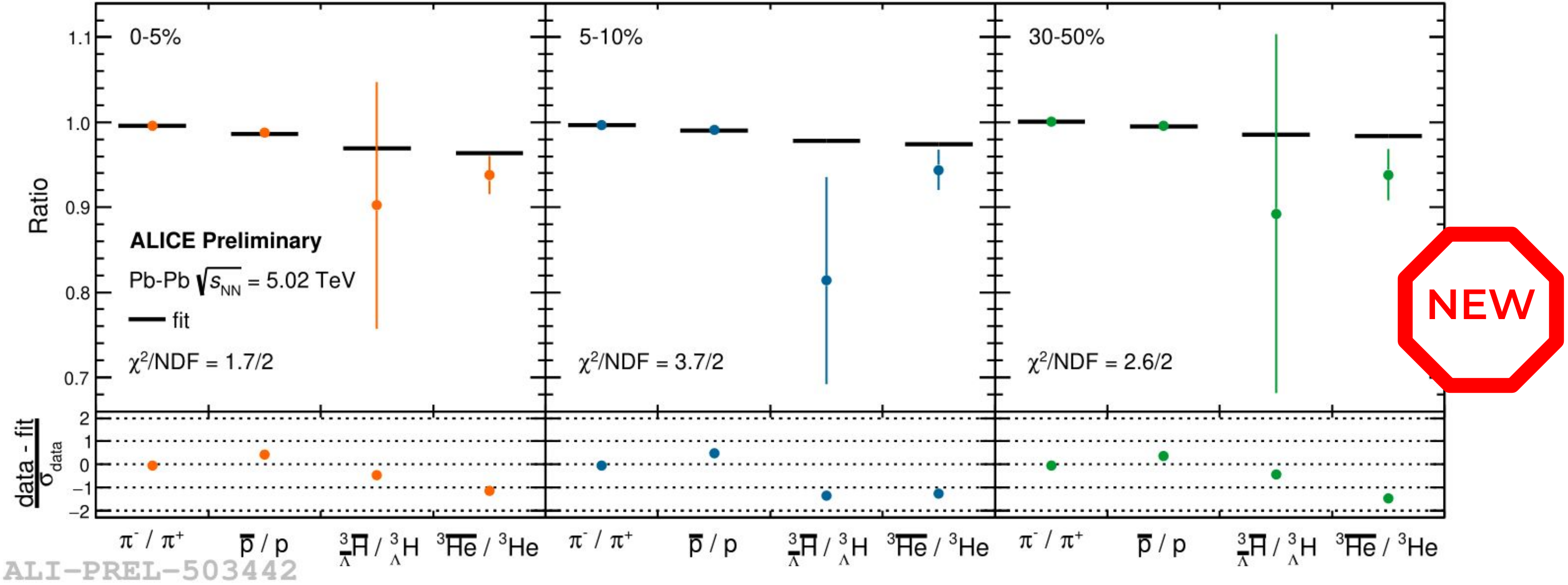
No significant p_T dependence → weighted average

[9] Chen *et al.*, (2016) arXiv:1603.02754 [cs.LG]

[10] (2021) arXiv:2107.10627v1 [nucl-ex]

C. Pinto - 14/06/2022, 9:20

Fits to ratios



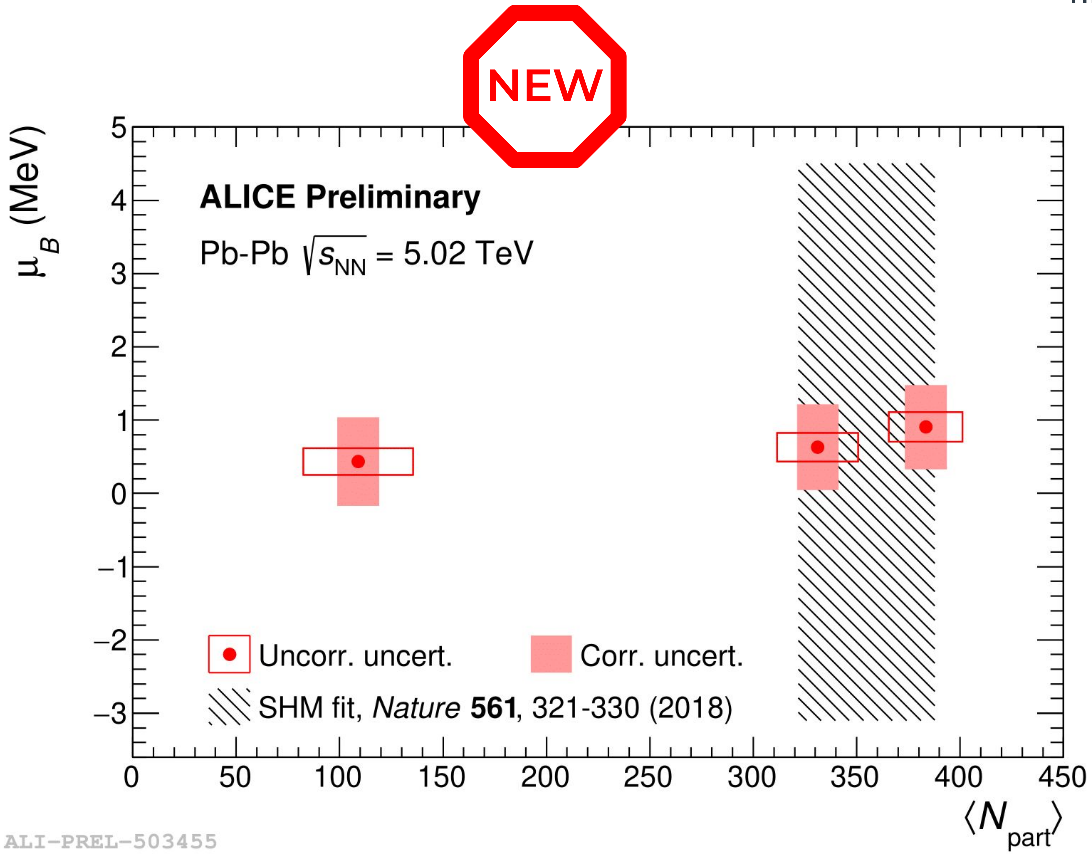
Fit to ratios

- Statistical and uncorrelated systematic uncertainties added in quadrature
- SHM equation → $\bar{h}/h \propto \exp\left[-2\left(B+\frac{S}{3}\right)\frac{\mu_B}{T} - 2I_3\frac{\mu_{I_3}}{T}\right]$ → μ_B and μ_{I3} fit parameters
- Hierarchy with baryon number

	π^+	p	^{3}He	${}^{3}_{\Lambda}H$
B+S/3	0	1	3	8/9
I_3	1	1/2	1/2	0

Results

- **Agreement** with previous studies
- *O*(10) improvement in precision from previous studies → most precise measurement in Pb−Pb at TeV scale
- Centrality dependence → decreasing μ_B from central to semicentral collisions due to different baryon stopping → not observed

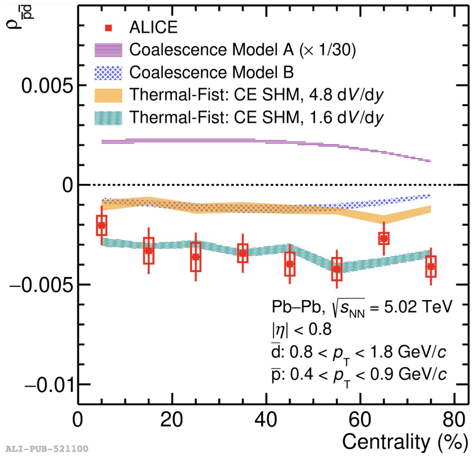


Summary and outlook

Antideuteron cumulant ratio and antideuteron-antiproton correlation

- new probe of deuteron synthesis in heavy-ion collisions
- good discriminating power between coalescence and thermal model

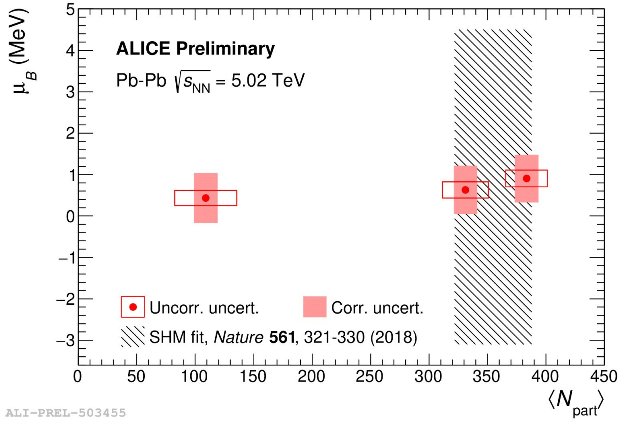
→ **precision studies** of **(anti)nucleosynthesis** using **Run 3** and **Run 4** data



Baryon chemical potential μ_B

- significant improvement from previous studies
- no evidence of centrality dependence

→ further test **strangeness** and **isospin dependence** of ratios via Λ, Ω and ^{3}H



Additional slides

Coalescence model

ALICE

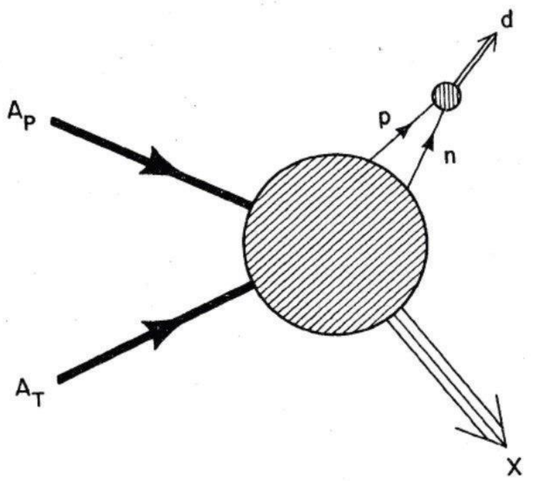
- Nuclei formed at kinetic freeze-out from nucleons close in phase space
- Coalescence probability → coalescence parameter B_A

- At LHC energies, neutron ~ proton production

$$E_A \frac{d^3 N_A}{dp_A^3} = B_A \left(E_{p,n} \frac{d^3 N_p}{dp_p^3} \right)_{\vec{p}_p = \vec{p}_n = \frac{\vec{p}_A}{A}}$$

- State-of-the-art coalescence includes momentum, source size R and cluster size r dependence

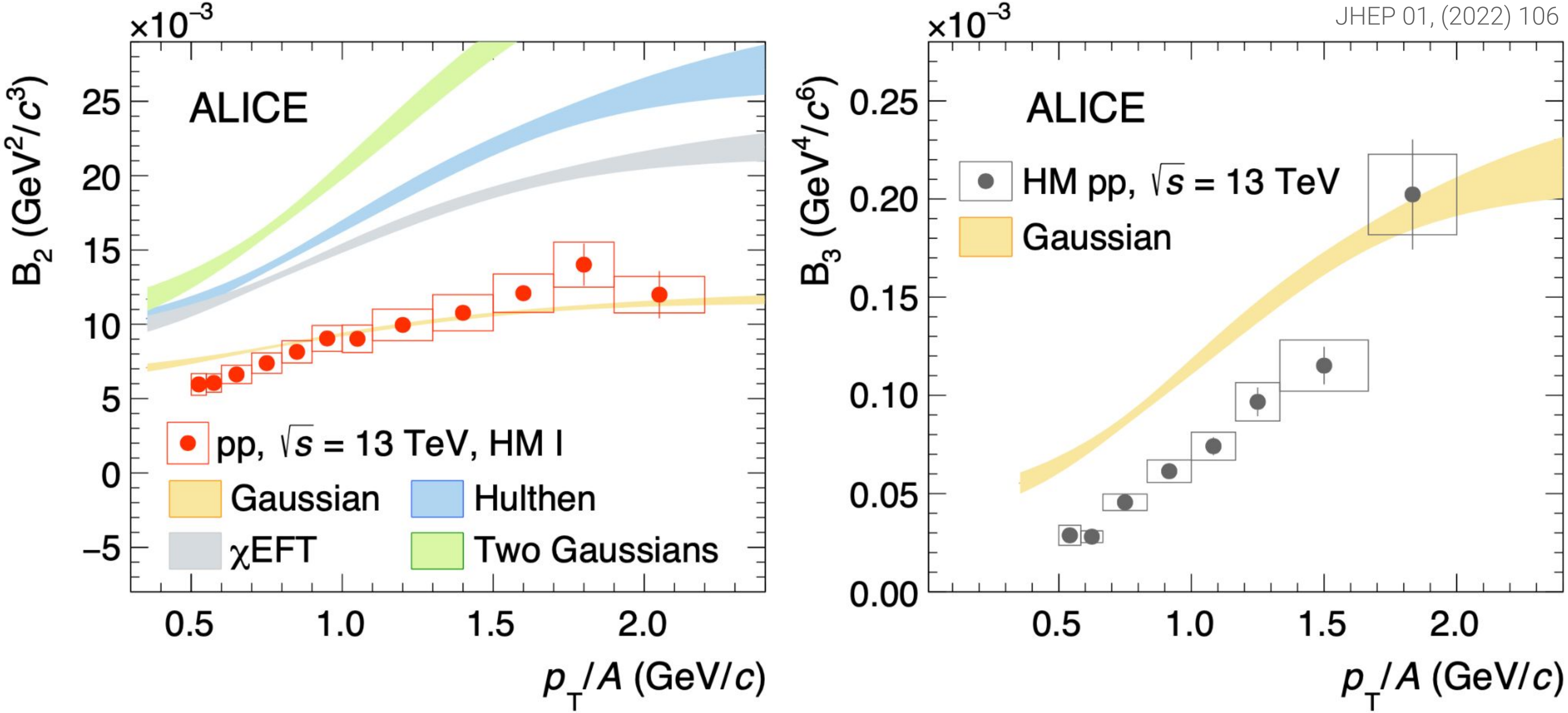
$$B_2 \approx \frac{3\pi^{3/2}\langle C_d \rangle}{2m_\mathrm{T} R^3(m_\mathrm{T})} \qquad \langle C_d \rangle \approx \left[1 + \left(\frac{r_d}{2R(m_\mathrm{T})}\right)^2\right]^{-3/2}$$



J. Kapusta, Phys. Rev. C 21, (1980) 1301

[6] F. Bellini *et al.*, Phys. Rev. C 99(5), (2019) 054905

Coalescence model



- Coalescence predictions using various wave functions for nuclei + source size

[11] F. Bellini *et al.*, Phys. Rev. C 103, (2021) 014907

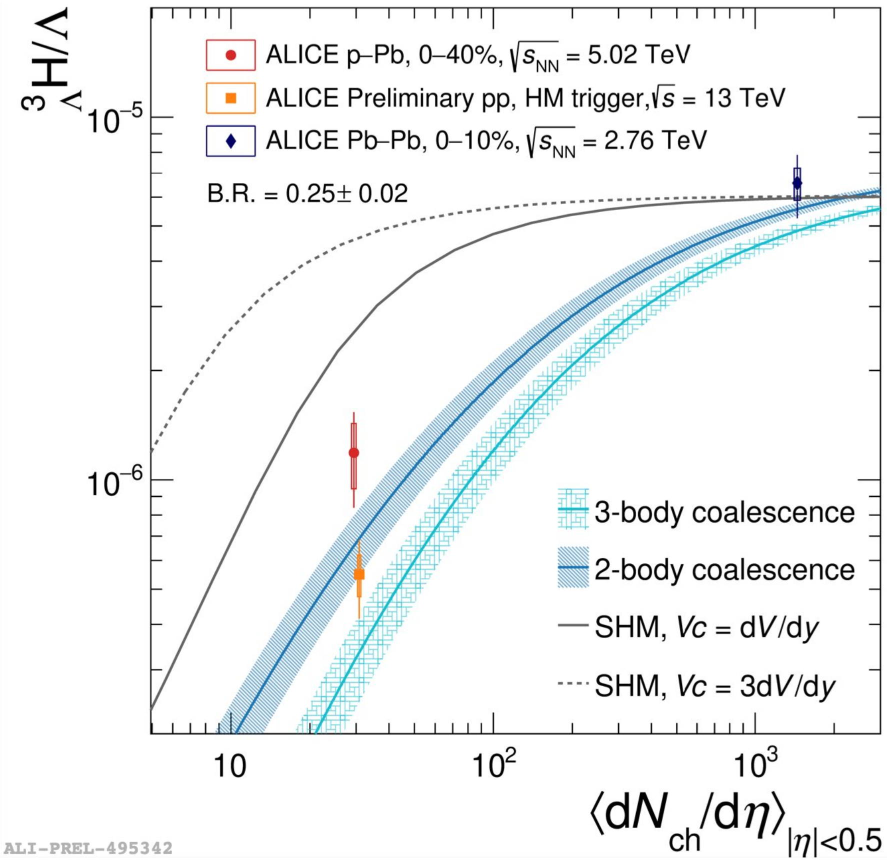
Hypertriton production

Lightest known hypernucleus

- Λ, p, n bound state
- lifetime and B_Λ close to free Λ

Loosely-bound state

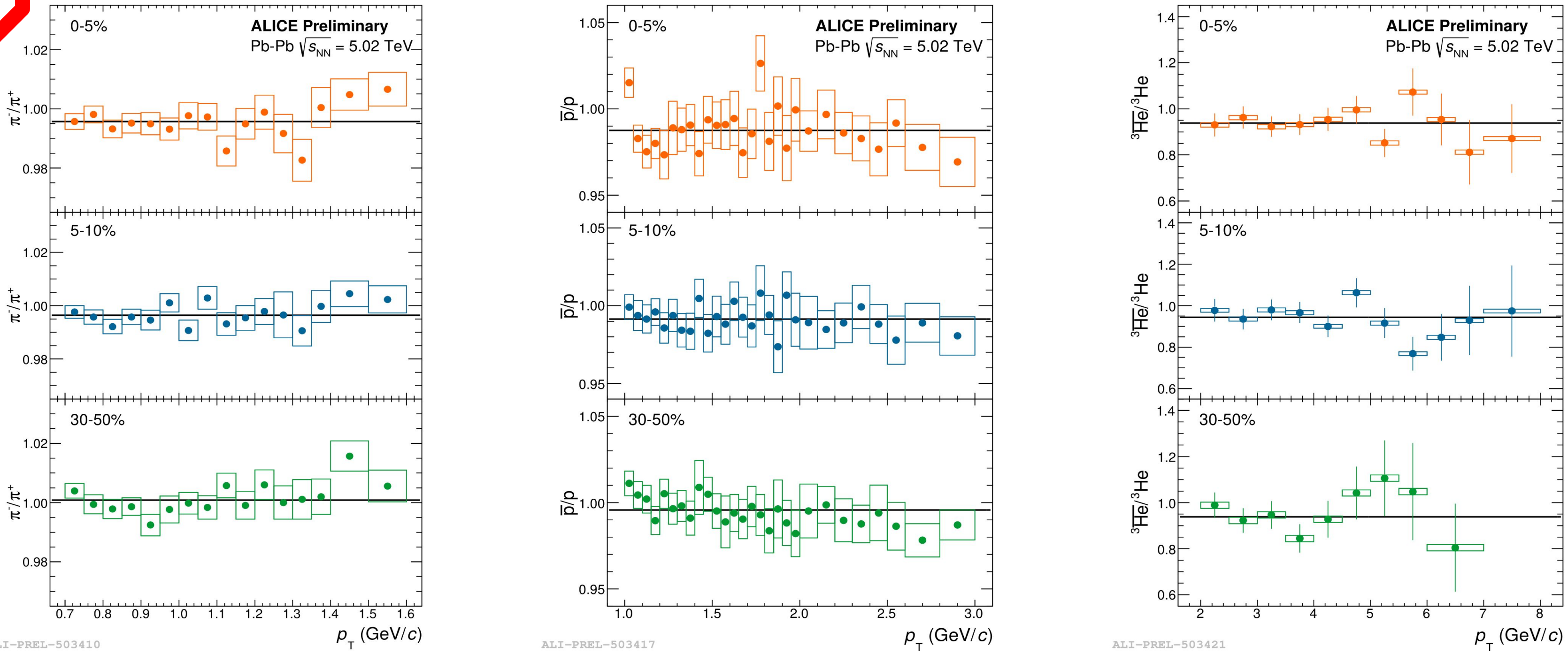
- good discriminating power between coalescence and SHM
- large deviation (~6σ) from SHM with $V_C = 3dV/dy$
- results compatible with 2 and 3 body coalescence



[10] (2021) arXiv:2107.10627v1 [nucl-ex]

Analysis of ratios: pions, protons and helium

NEW

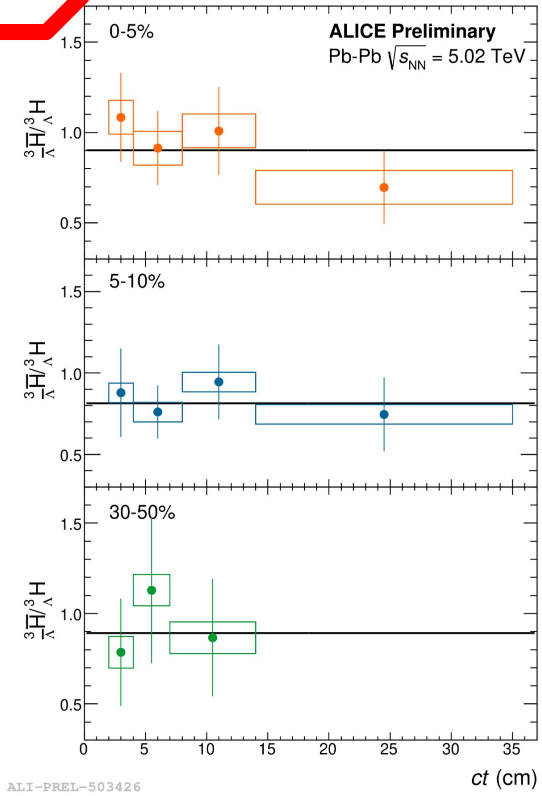


- vertical bars → statistical uncertainty
- boxes → systematic uncertainties

Analysis of ratios: hypertriton

NEW

$^{3}_{\Lambda}H$



Boosted Decision Tree selection

- pion yield ~10^6x ^3He yield → **large combinatorial background**
- training features: secondary vertex and daughter track variables
- selection threshold optimisation via maximisation of expected significance