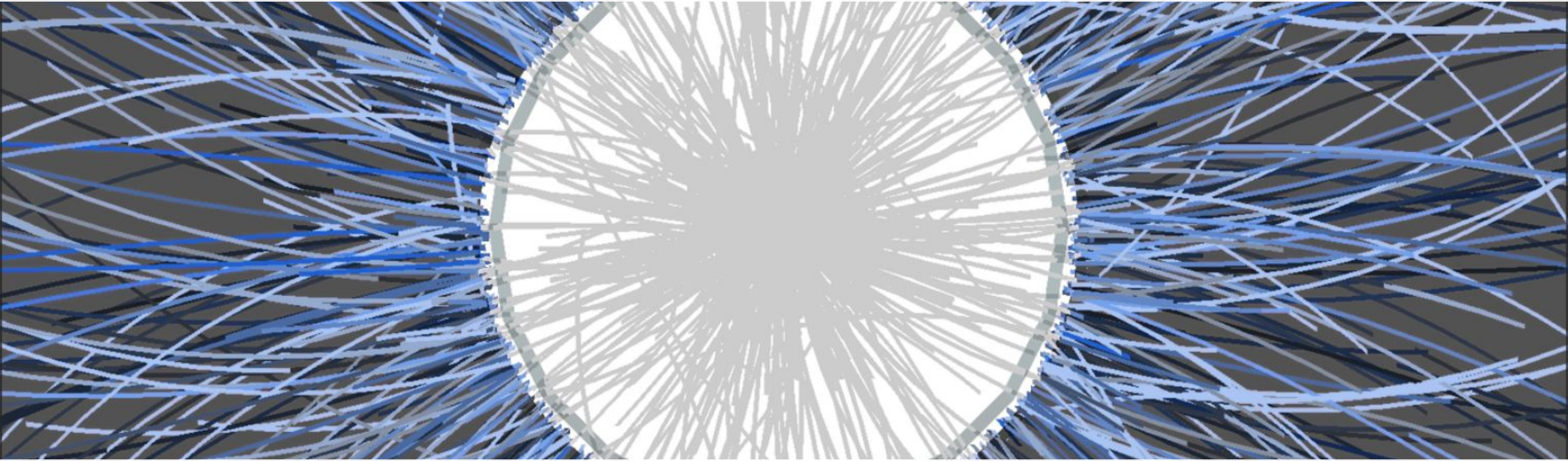
New experimental observables to probe (anti)nucleosynthesis at the LHC with ALICE

ALICE

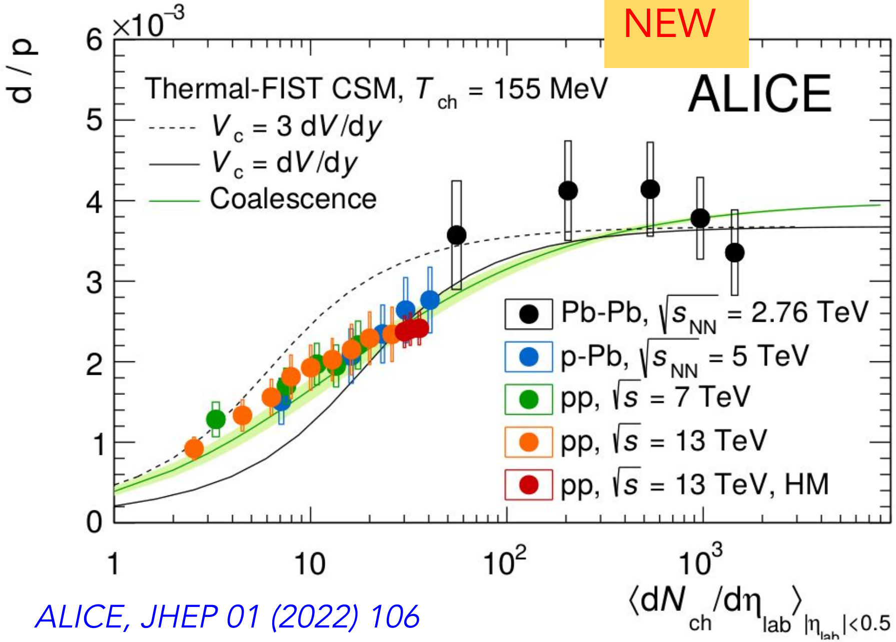


Sourav Kundu
(for the ALICE collaboration)

QUARK MATTER KRAKÓW 2022
29TH INTERNATIONAL CONFERENCE ON ULTRARELATIVISTIC NUCLEUS - NUCLEUS COLLISIONS
APRIL 4-10, 2022
KRAKÓW, POLAND

Deuteron synthesis: Thermal vs. Coalescence

NEW



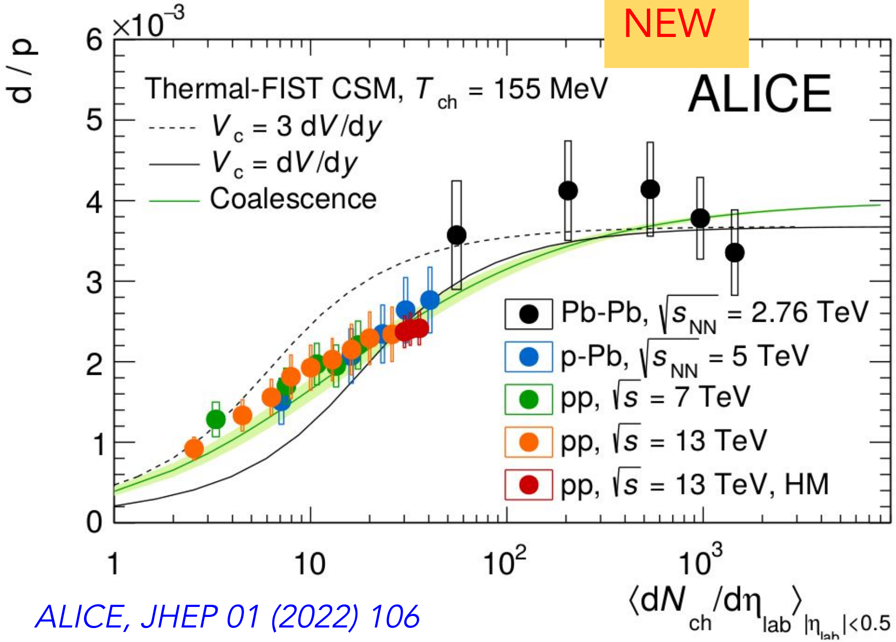
ALICE, JHEP 01 (2022) 106

- Nuclei synthesis models
  - Thermal *V. Vovchenko et al., Phys. Lett. B 785, (2018) 171*
  - Coalescence *K.-J. Sun et al., Phys. Lett. B 792, (2019) 132*

- Both models describe deuteron production
  - New observables to distinguish nuclei synthesis

Thermal model and baryon chemical potential (μ_B)

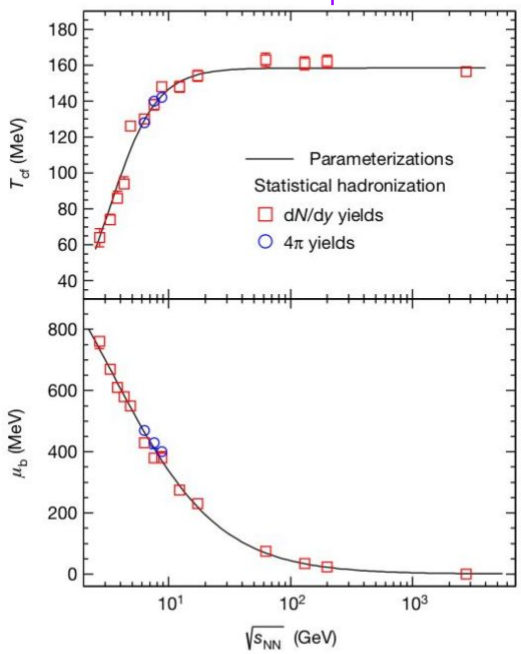
NEW



ALICE, JHEP 01 (2022) 106

Thermal model parameters

A. Andronic et al., Nature 561, (2018) 321



Obtained from thermal model fit of measured hadron yields

- Nuclei synthesis models
  - Thermal *V. Vovchenko et al., Phys. Lett. B 785, (2018) 171*
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- Both models describe deuteron production
  - New observables to distinguish nuclei synthesis

- $\mu_B \rightarrow$ measure of antimatter-matter imbalance
- $\mu_B = 0.7 \pm 3.8$ MeV (0-5% Pb-Pb, $\sqrt{s_{NN}} = 2.76$ TeV)
  - New measurements of antiparticle-to-particle ratios with reduced systematic uncertainties

Fluctuation as a probe of deuteron synthesis

Event by event deuteron distribution:

- Grand Canonical Ensemble (GCE) of Thermal model: Poisson
- Coalescence model: deviation from Poisson
  - Average deuteron multiplicity: $\lambda_d = B n_i n_j$
  - Multiplicity distribution for a given number of initial nucleons:

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

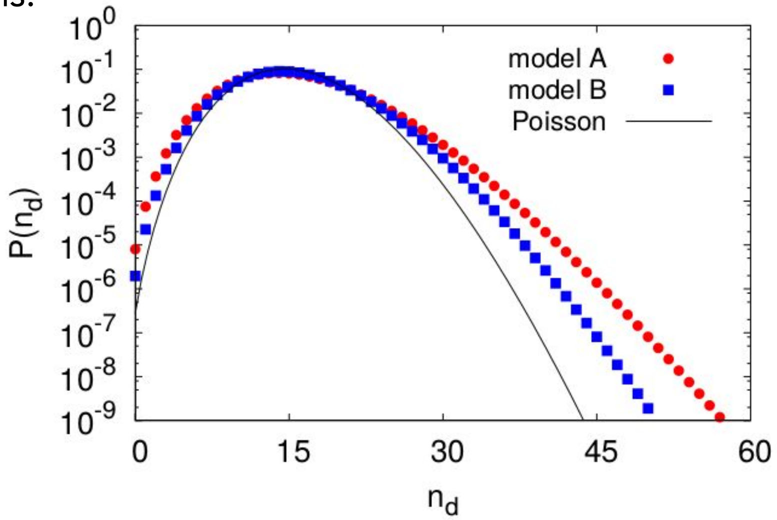
  - Final deuteron multiplicity distribution:

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

Model A: nucleons are correlated
Model B: nucleons fluctuate independently

Model parameters:

- Coalescence parameter B
- Average initial proton or neutron number $\langle n_i \rangle = \langle n_p \rangle + \langle n_d \rangle$



Jan Steinheimer et al., Phys. Rev. C 93 , (2016) 054906
F. Bellini et al., Phys. Rev. C 99(5), (2019) 054905

Observable and analysis details

Observable:

$$\kappa_1 = \langle n \rangle,$$

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

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

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Collision: Pb-Pb, $\sqrt{s_{NN}}$ = 5.02 TeV

Particle identification:

TPC: $0.8 < p_T < 1.0$ GeV/c (antideuteron)
$0.4 < p_T < 0.6$ GeV/c (antiproton)

TPC+TOF: $1.0 < p_T < 1.8$ GeV/c (antideuteron)
$0.6 < p_T < 0.9$ GeV/c (antiproton)

antideuteron purity > 90%, antiproton purity > 95%

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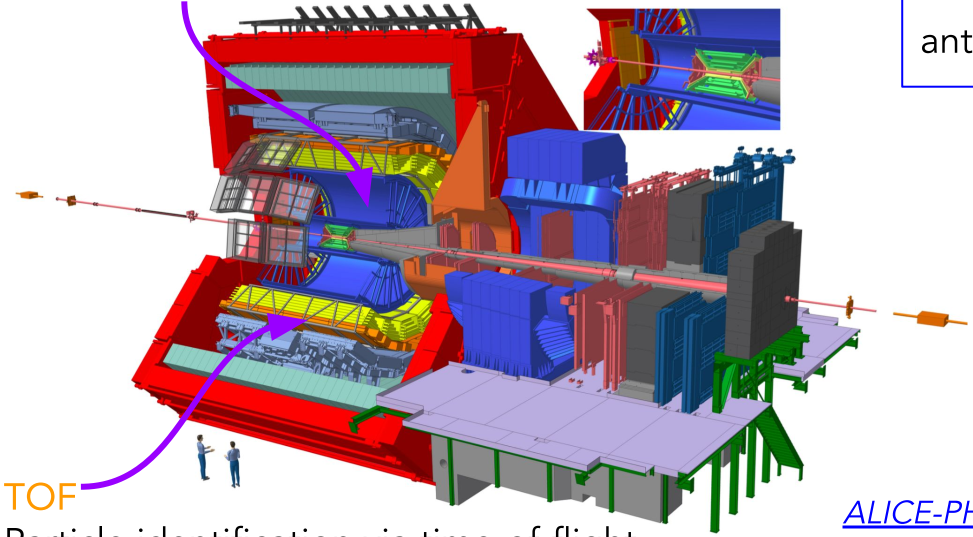
TPC
Particle identification via specific energy loss



TOF
Particle identification via time-of-flight

ALICE-PHO-SKE-2017-001

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Initial volume fluctuation:

Centrality Bin Width correction

X. Luo et al., J. Phys. G 40, (2013) 105104

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Binomial efficiency corrected cumulant:

$$\kappa_1 = \langle q_1 \rangle$$

$$\kappa_2 = \langle q_1^2 \rangle - \langle q_1 \rangle^2 + \langle q_1 \rangle - \langle q_2 \rangle$$

$$\kappa_{11} = \langle q_1^d q_1^p \rangle - \langle q_1^d \rangle \langle q_1^p \rangle$$

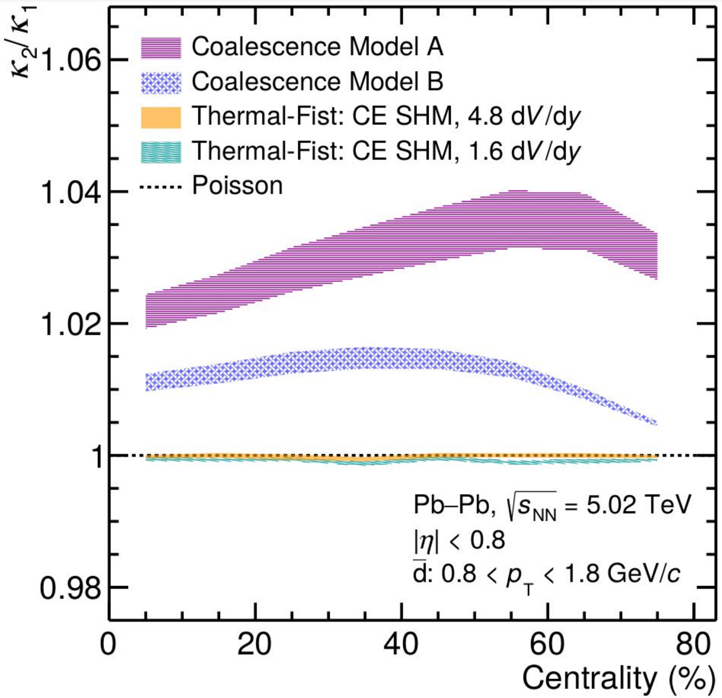
$$\rho = \kappa_{11} / \sqrt{(\kappa_2^d \kappa_2^p)}$$

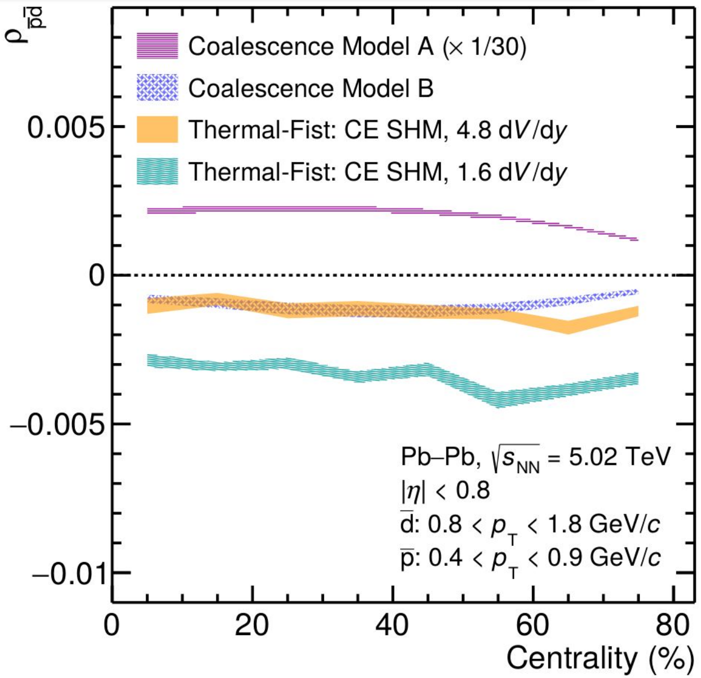
$$q_n = \sum_{i=1}^{M} (n_i / \varepsilon_i^n)$$

M = number of p_T bins
ε = efficiency
n_i = raw counts in i[th] p_T bin

T. Nonaka et al., Phys. Rev. C 95, (2017) 064912

Model expectation:coalescence vs. baryon conservation





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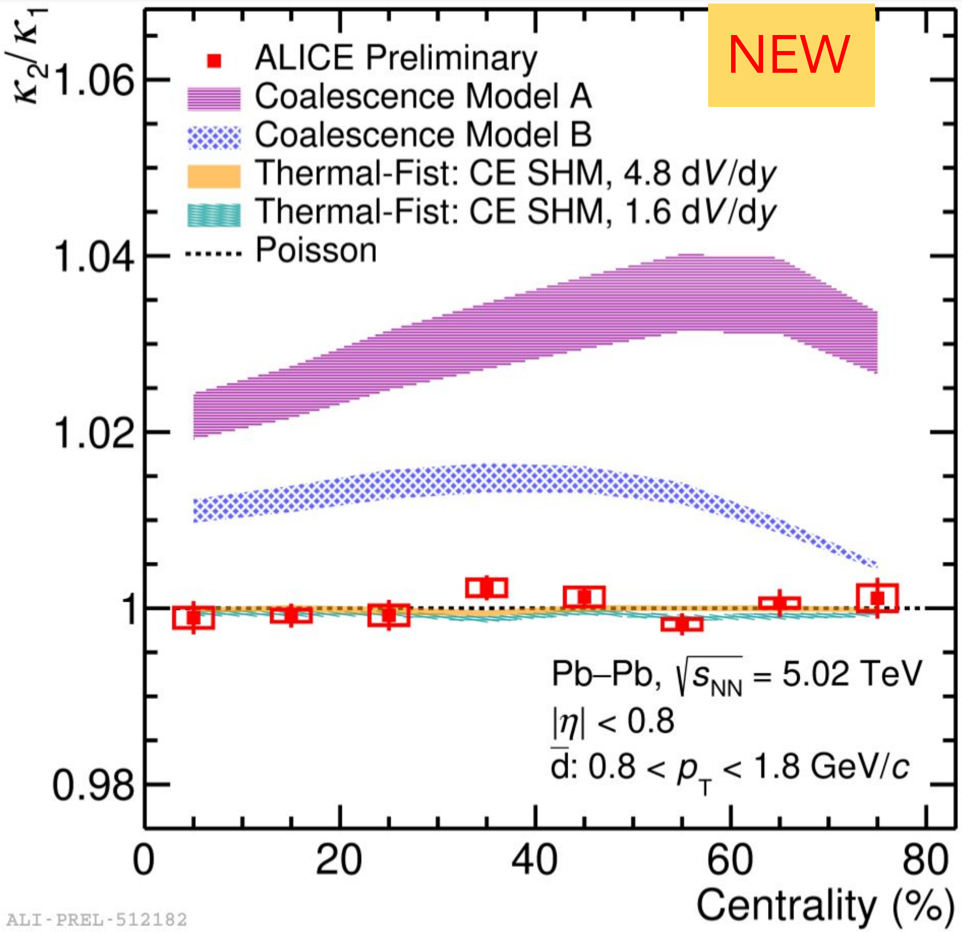
Coalescence model

- By definition negative correlation between antiproton and antideuteron
- Sensitive to initial correlation between antiproton and antineutron

Canonical ensemble (CE) of Thermal model

- Negative correlation can also appear from baryon number conservation in CE SHM
- Correlation observables are more sensitive to conservation compared to cumulant ratios

First antideuteron fluctuation measurement



- Consistent with Poisson baseline and SHM
- Overpredicted by Coalescence model

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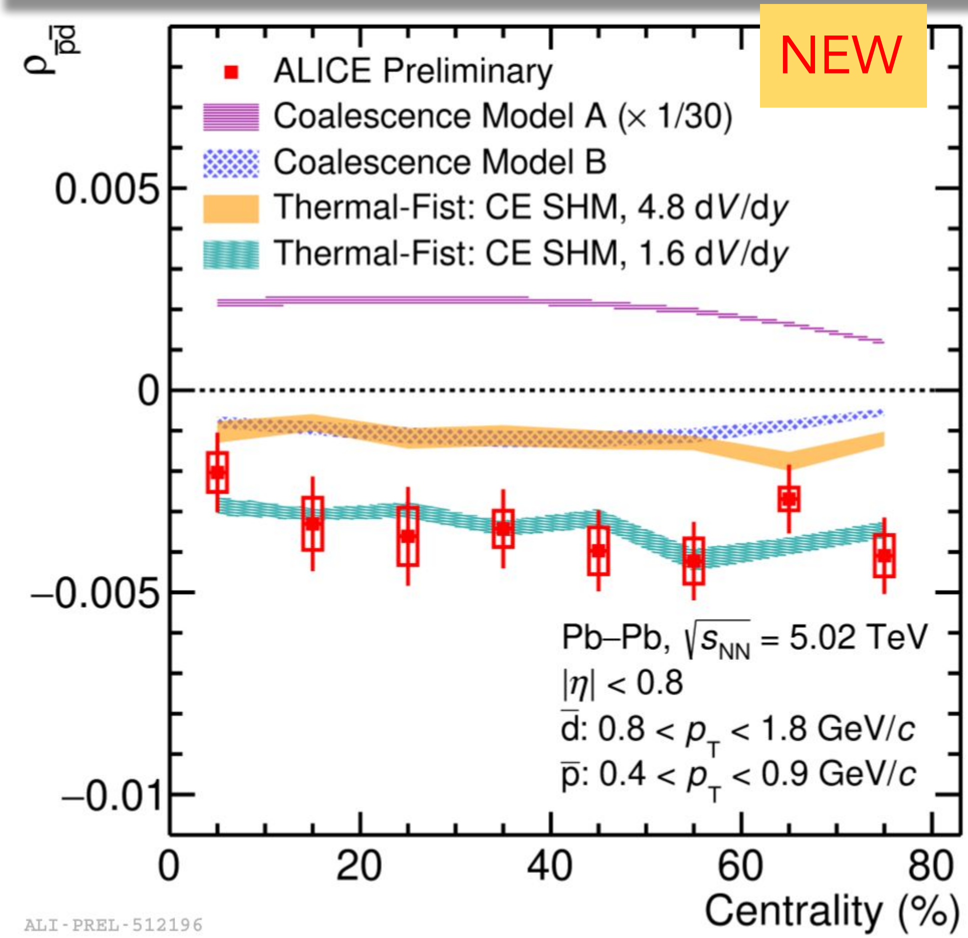
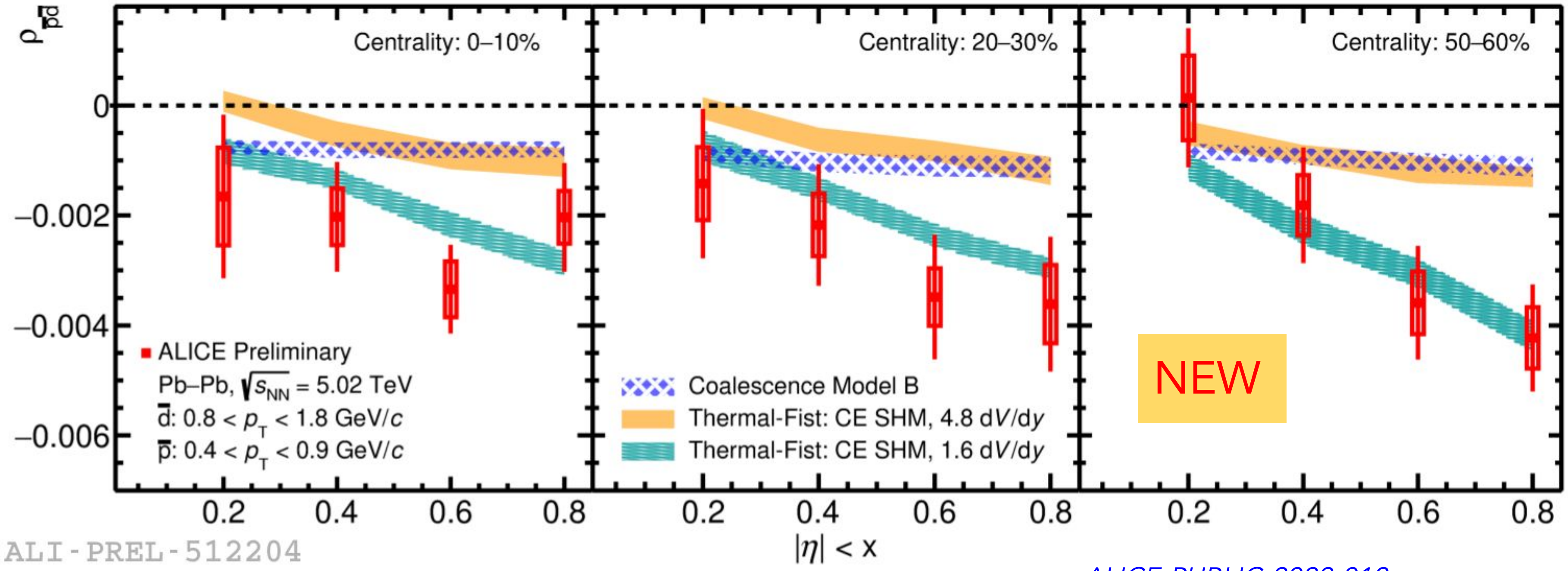
Correlation between antideuteron and antiproton



- Evidence of negative correlation
- Rules out Coalescence model with correlated production of nucleons
- Qualitatively explained by Coalescence model with independent fluctuation of nucleons
- Explained by CE SHM
  – smaller correlation volume compared to those describing κ_2/κ_1 of net-proton

[ALICE-PUBLIC-2022-012]

Correlation between antideuteron and antiproton



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- Data: strong acceptance dependence of correlation strength
- SHM: describes data, strength depends on fraction of baryons in acceptance out of total produced baryons
- Coalescence: ~flat with acceptance, strength depends on the nucleon phase space density or d/p ratio

Antiparticle over particle ratios and μ_B

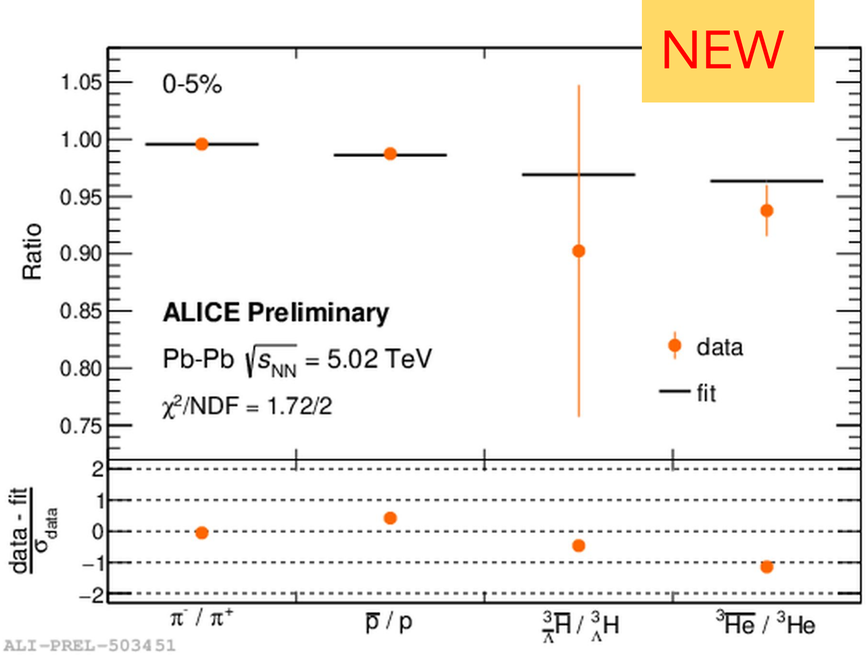
- Statistical Hadronization Model: $\bar{h}/h \propto \exp\left[-2 \cdot \frac{B_h\mu_B + S_h\mu_S + I_{3,h}\mu_{I_3}}{T}\right]$
- Strangeness neutrality: $\mu_B \sim 3\mu_S$
- Simplified expression: $\bar{h}/h \propto \exp\left[-2\left(B + \frac{S}{3}\right)\frac{\mu_B}{T} - 2I_3\frac{\mu_{I_3}}{T}\right]$

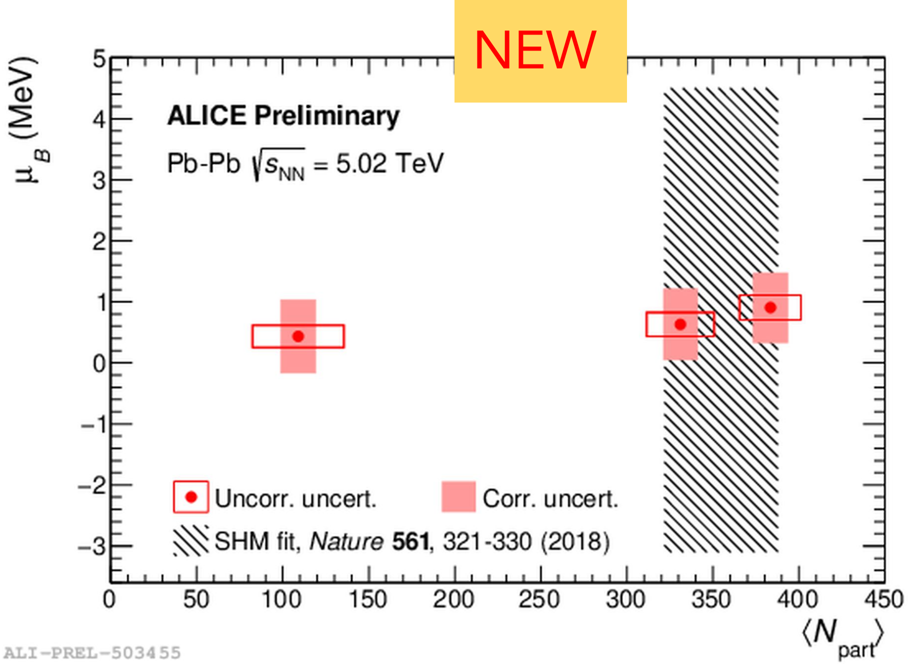
J. Cleymans et al., Phys. Rev. C 74, (2006) 034903

J. Cleymans and H. Satz., Z. Phys. C 57, (1993) 135–147

- Ratios of hadrons with high B+S/3 → sensitive to μ_B/T → light (anti)baryons, (anti)nuclei, and (anti)hypernuclei
  – proton, Λ, Ξ, Ω, ^{3}He, $^3_\Lambda$H
- Constraint on isospin chemical potential → π^-/π^+ ratio (B = S = 0)
- Ratios → reduce systematic uncertainties → precise μ_B measurement

Centrality-dependence of of μ_B at Pb-Pb 5.02 TeV





- T = 156.5 ± 1.5 MeV, fixed from SHM studies
  A. Andronic et al., Nature 561, (2018) 321
- μ_B and μ_{I3} as free fit parameters

- Most precise measurement in Pb-Pb at LHC – 6x improvement in precision with respect to Run 1 estimate
- Small but non-zero μ_B at LHC

See poster presentation by Mario Ciacco for more details

Summary and outlook

- EbyE fluctuation can be used as a probe of deuteron synthesis
  - ✓ SHM simultaneously describes fluctuation measurements but with a smaller correlation volume
  - ✓ Simple coalescence model does not simultaneously describe fluctuation measurements
- Most precise measurement of baryon chemical potential at LHC energy
  - ✓ Small but non-zero antibaryon-baryon imbalance at LHC

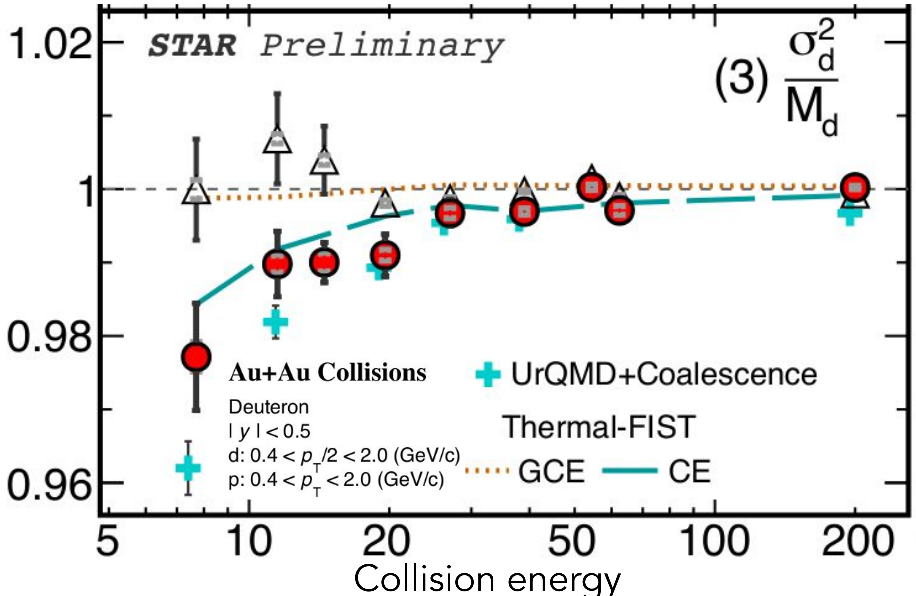
Outlook

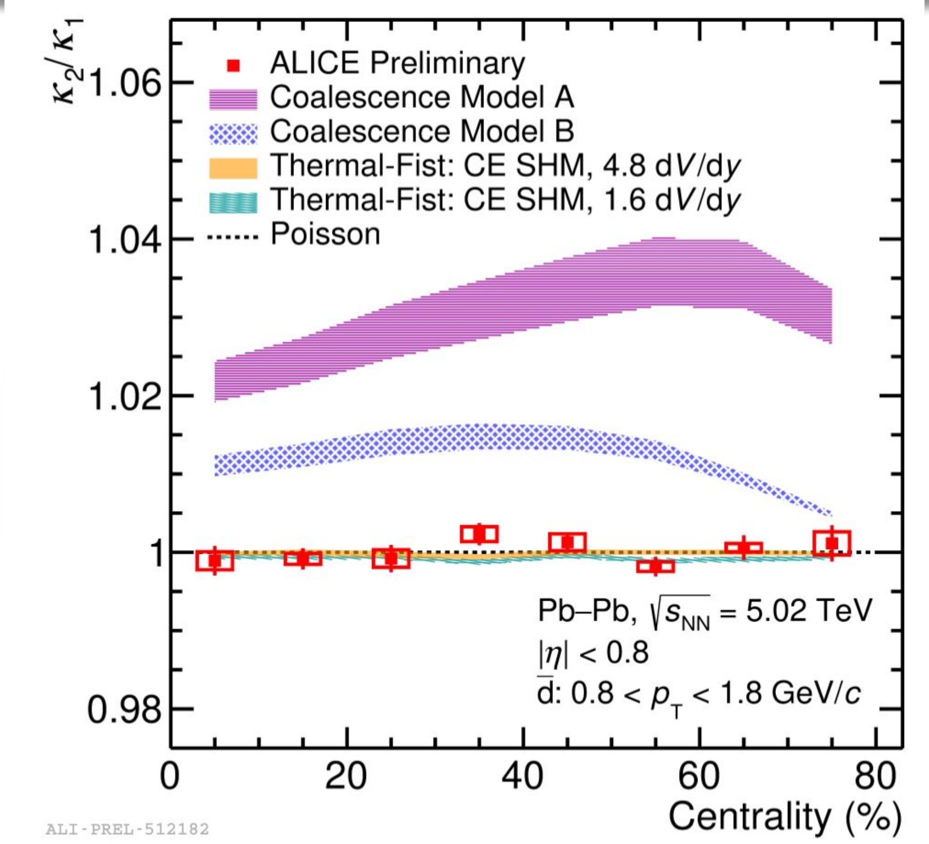
- **Experimental side:** precise measurements with upcoming high statistics Run 3 and Run 4 data
- **SHM:** partial chemical equilibrium, interaction of hadrons could resolve the conundrum between p and d
- **Coalescence:** sensitive to the initial correlation between nucleons, and fluctuation measurements can be used to tune the model

Additional slides

Comparison with STAR

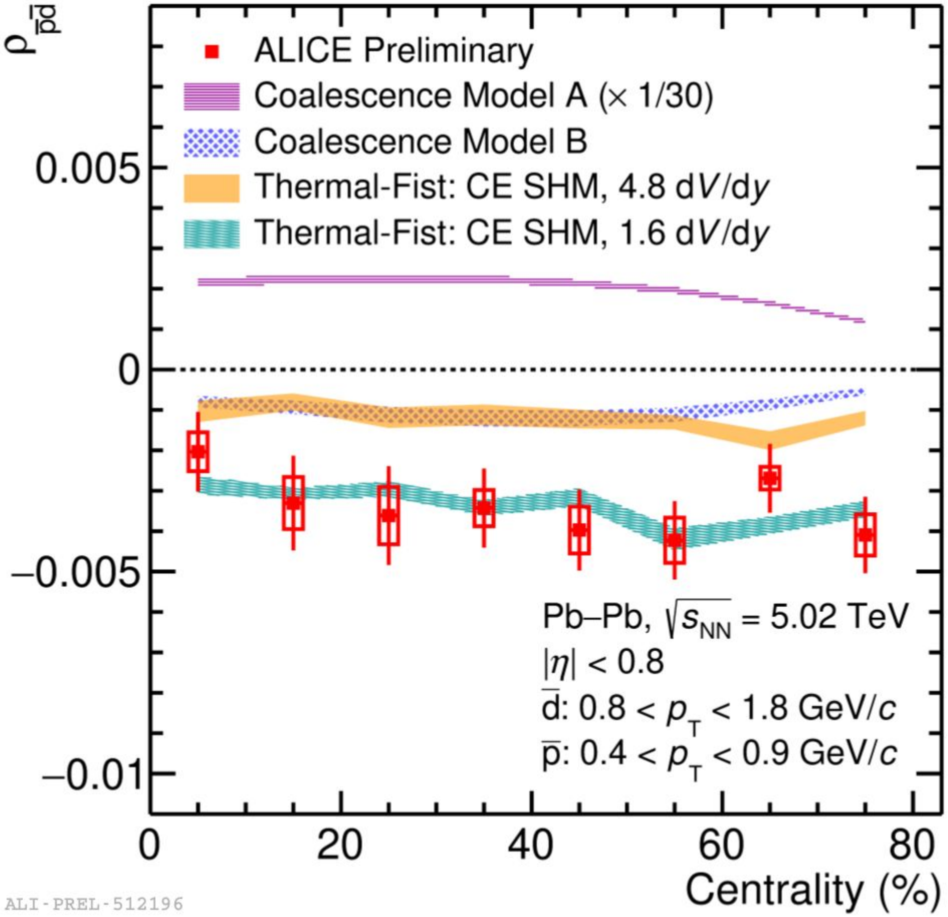
	STAR	ALICE
choice of particle	baryon	antibaryon
d selection	larger p_T acceptance	smaller p_T acceptance
p and d selection	have large overlapping p_T region	mostly separated

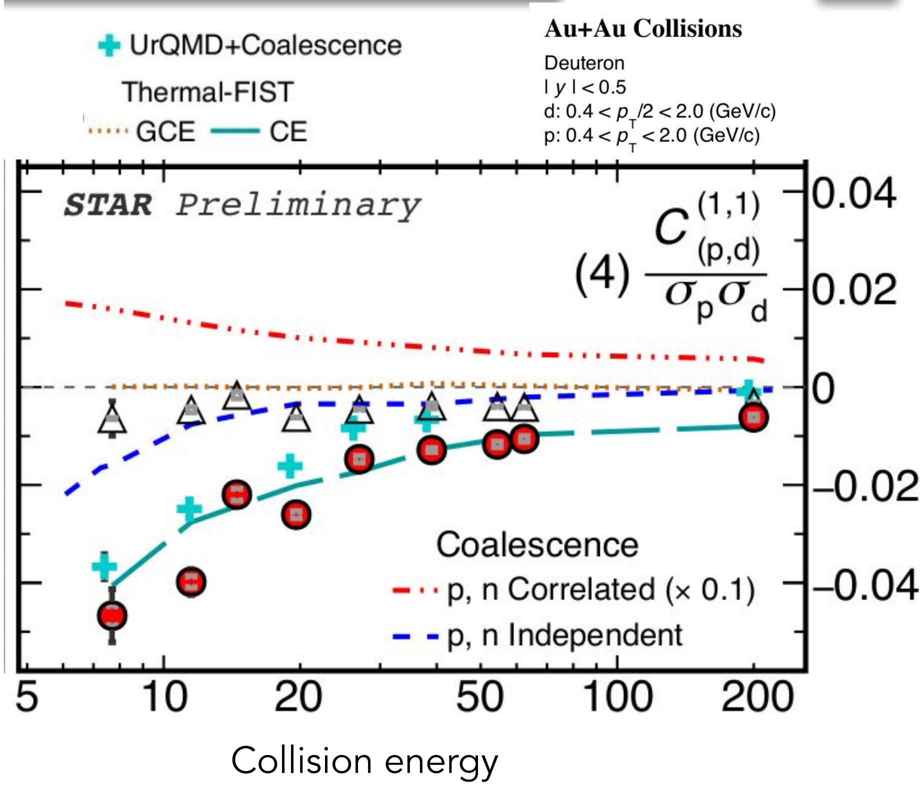




STAR results: by Debasish Mallick @ QM2022

Comparison with STAR





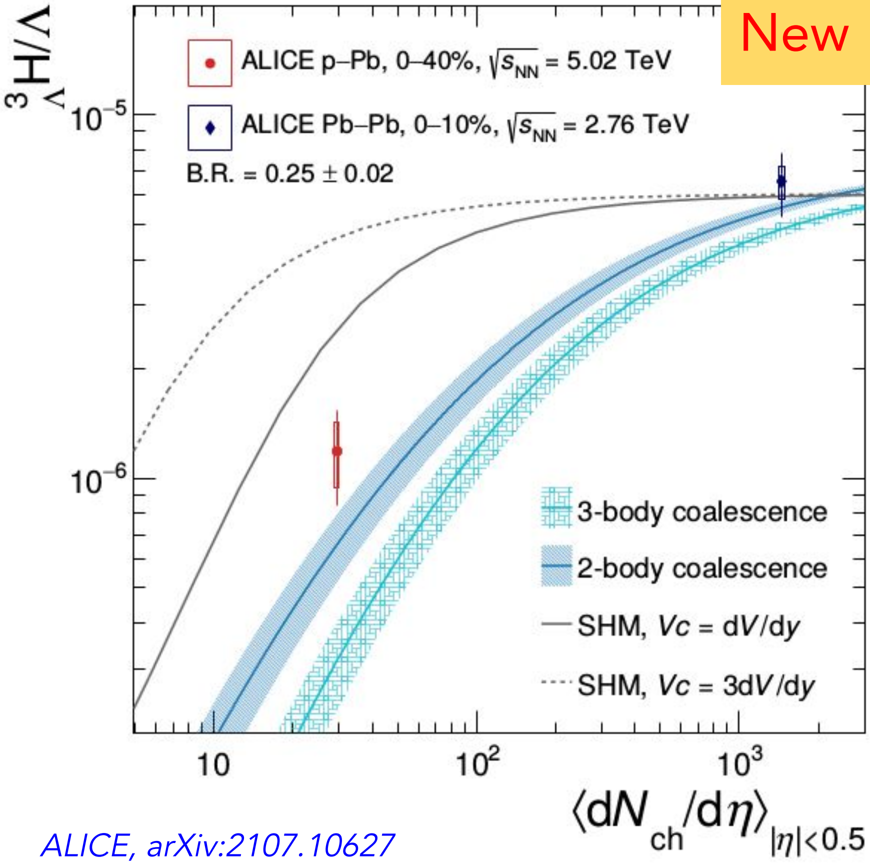
STAR results: by Debasish Mallick @ QM2022

Hypertriton synthesis

- Λ, p, n bound state
- Lightest known hypernucleus
- B_Λ is compatible with zero
- Loosely-bound nature confirmed
- Large radius of $^3_\Lambda$He in Coalescence model leads to a larger suppression in small system → good discriminating power between SHM and coalescence in small system

SHM	**d*V*/dy**	**3d*V*/dy**
Deviation (σ)	2.0	6.5
Coalescence	**2-body**	**3-body**
Deviation(σ)	1.2	1.5

New



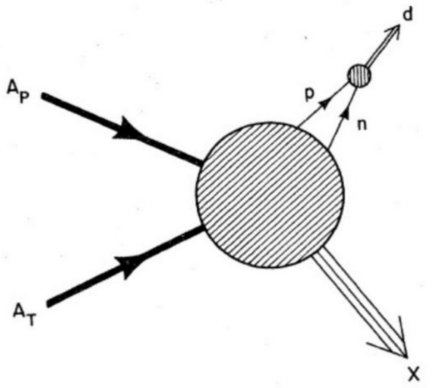
ALICE, arXiv:2107.10627

Nuclei synthesis: Coalescence model

- Nuclear clusters are formed at kinetic freeze-out if nucleons are close in phase space

- Coalescence into cluster A is determined by the momentum space density of n, p:

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



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

- State-of-the-art approaches include source size *R* and finite size r_d of the cluster, e.g. for deuterons:

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

F. Bellini et al., Phys. Rev. C 99 (2019) 054905
K.-J. Sun et al., Phys. Lett. B 792 (2019) 132

Thermal model: nuclei production

One, admittedly speculative, possibility is that such objects, at QGP hadronization, are produced as compact, colourless droplets of quark matter with quantum numbers of the final-state hadrons. The concept of possible excitations of nuclear matter into colourless quark droplets has already been considered. In the context of our work, these states should have a lifetime of 5 fm or longer, with excitation energies of 40 MeV or less, for evolution into the final-state hadrons that are measured in the detector. Since by construction they are initially compact, they would also survive a possible short-lived hadronic phase after hadronization. This would be a natural explanation for the striking observation of the thermal pattern for these nuclear bound states.

A Andronic et al., Nature 561 (2018) 321