Studying (anti)nucleosynthesis via event-by-event fluctuations at the LHC with ALICE

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Politecnico di Torino, INFN

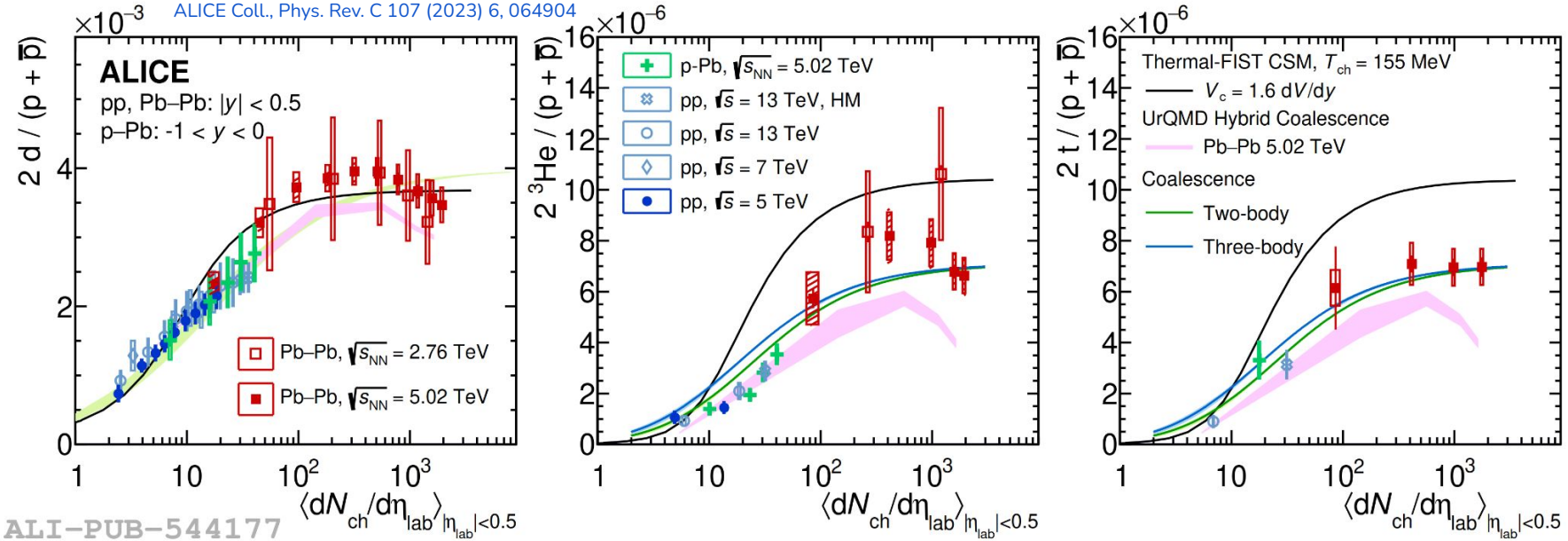
SQM 2024

(Anti)nuclei at the LHC

- (Anti)(hyper)nuclei production in heavy-ion collisions
  - How do composite objects survive in the environment created in Pb–Pb collisions?
- System-size scan of light-nuclei-to-proton yield ratio
  - Smooth evolution across different colliding systems
  - Reproduced in different phenomenological models

Y. Wang - June 5th, h. 8.50

ALICE Coll., Phys. Rev. C 107 (2023) 6, 064904

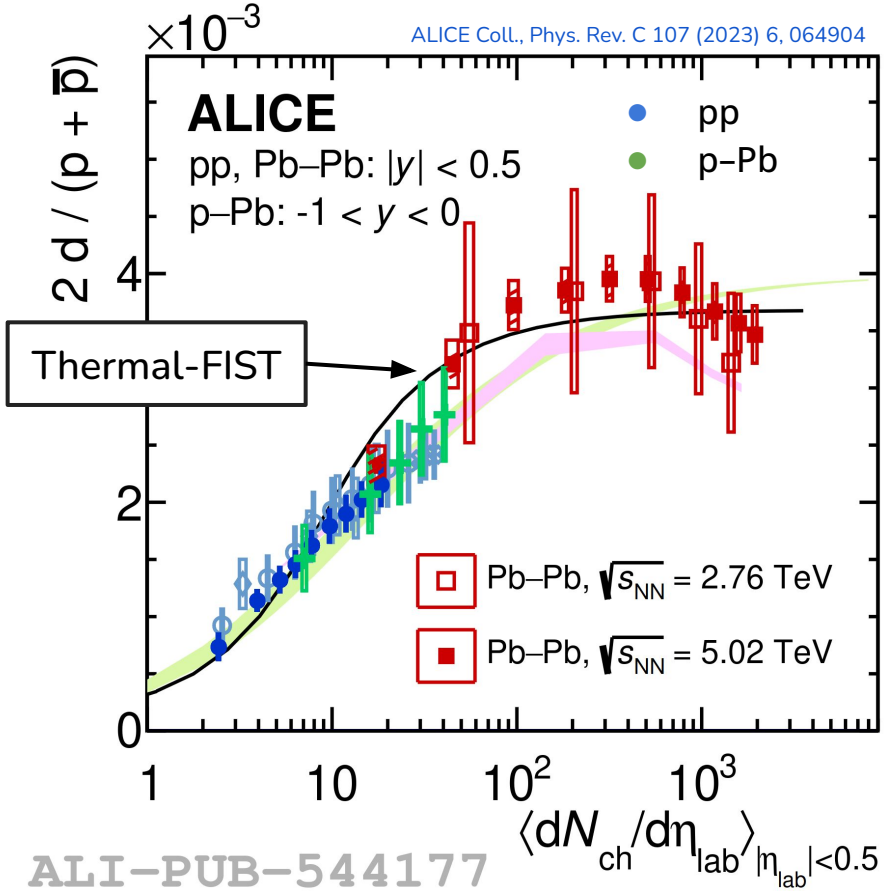


ALI-PUB-544177

(Anti)nucleosynthesis models

- Statistical hadronization model
  - Statistical-mechanical description of light-flavour hadron yields from a few parameters (T_{ch}, V, μ_B)
  - Canonical ensemble → exact conservation of quantum numbers over correlation volume, V_C

V. Vovchenko et al., Phys. Lett. B 785, 171 (2018)



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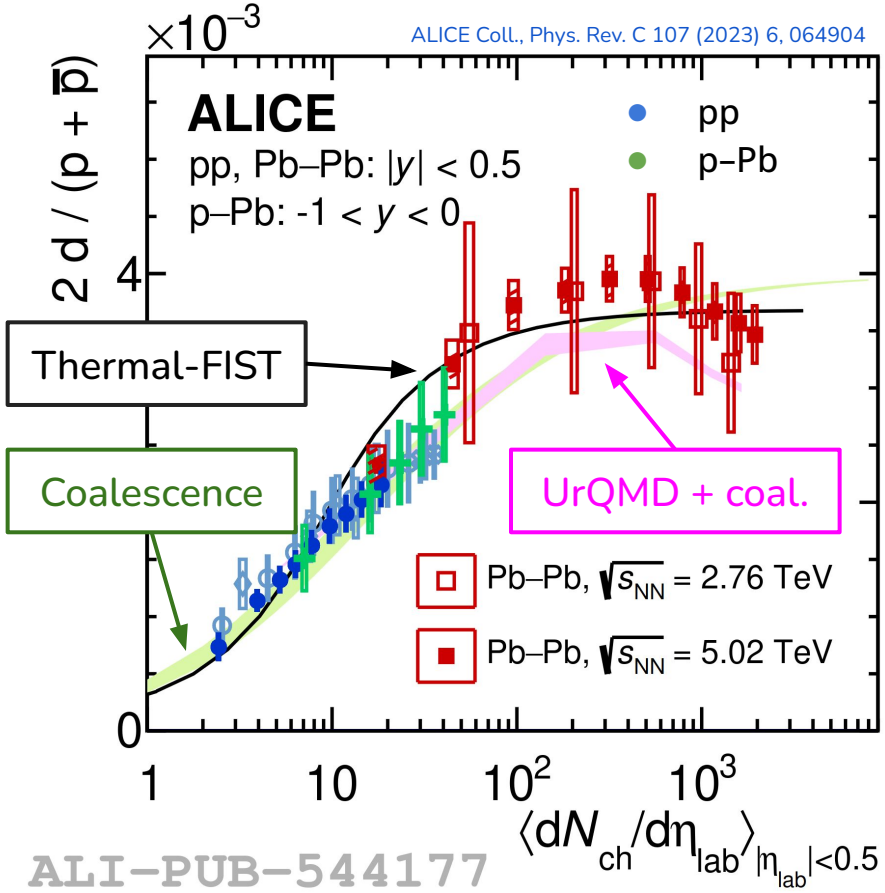
- Nuclear coalescence model
  - Nuclei are formed by nucleons emitted by a freeze-out hypersurface
  - System-size dependence of source size compared to fixed deuteron size

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

    F. Bellini and A. P. Kalweit, Phys. Rev. C 99 (2019) 5, 054905



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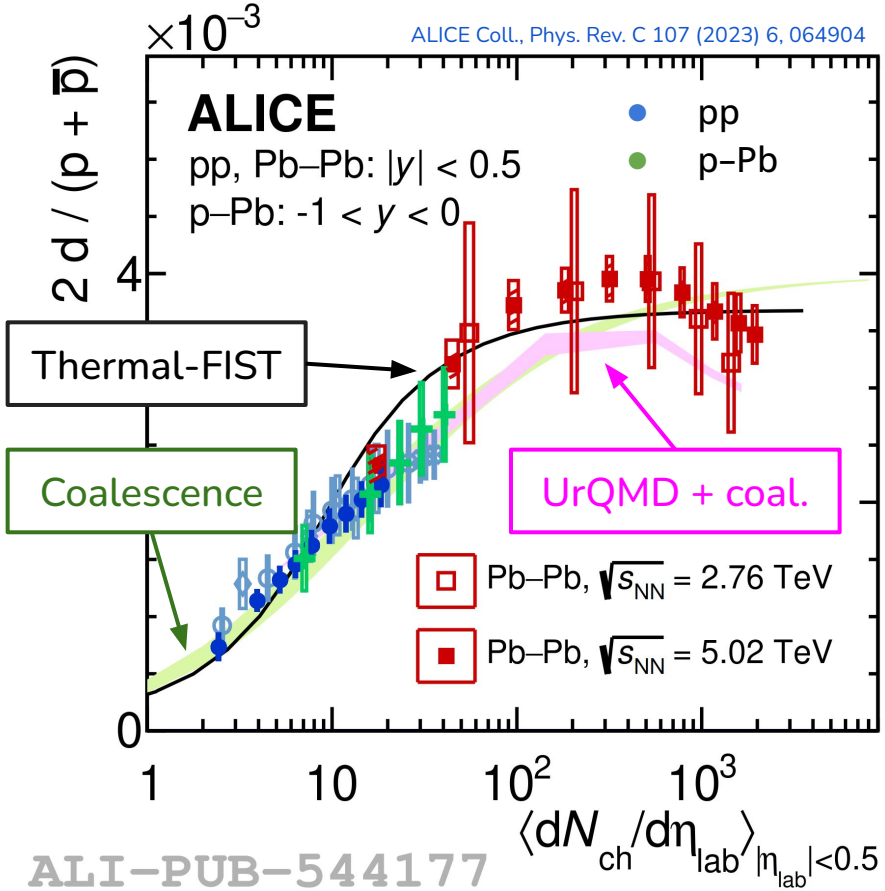
F. Bellini and A. P. Kalweit, Phys. Rev. C 99 (2019) 5, 054905

→ Can we say more going to higher-order moments?

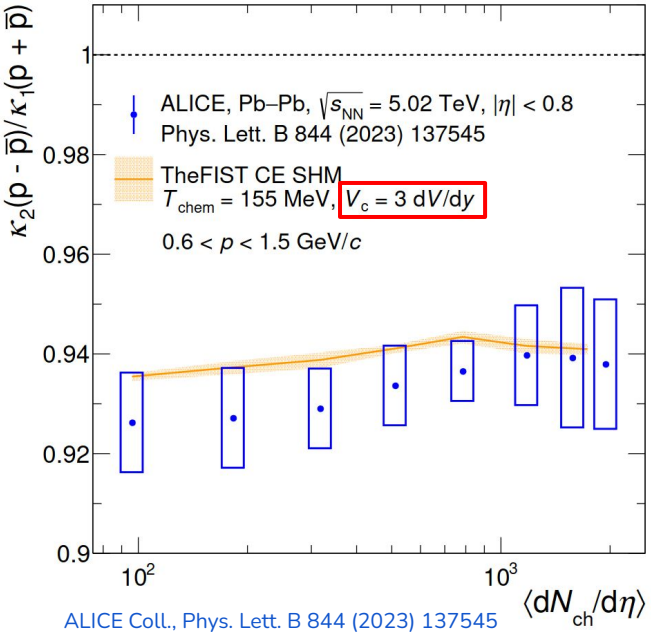


Event-by-event observables and charge conservation

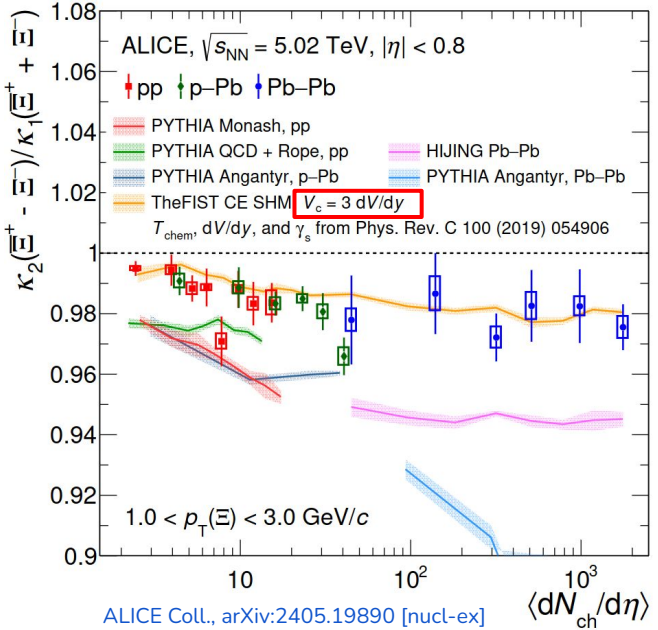
- Net-particle fluctuations at the LHC
  - Net-proton → $V_C \sim 3\ dV/dy$
  - Net-Ξ → $V_C \sim 3\ dV/dy$

S. Saha - June 4th, h. 17.10

- Large correlation volume for baryon and strangeness conservation
  - Exact V_C value depends on the different model implementations



ALICE Coll., Phys. Lett. B 844 (2023) 137545

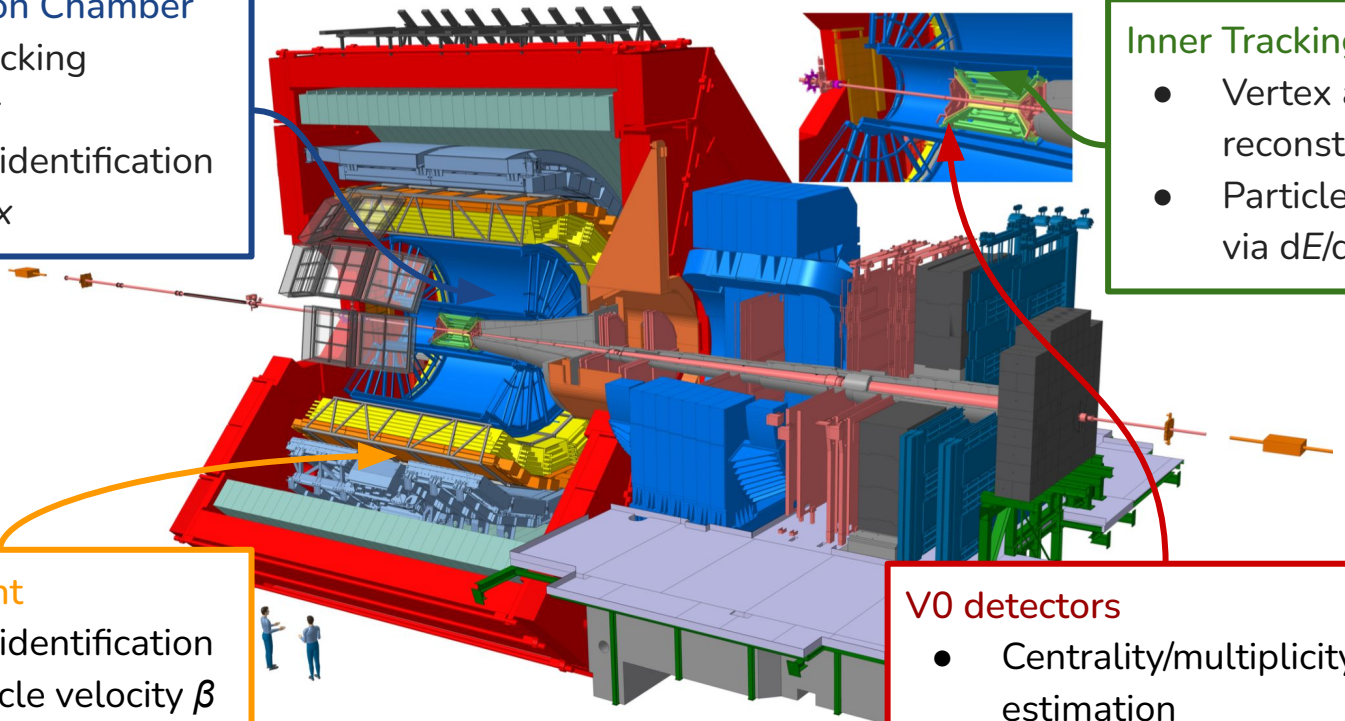


ALICE Coll., arXiv:2405.19890 [nucl-ex]

The ALICE detector during the LHC Run 2

Time Projection Chamber
- Main tracking detector
- Particle identification via d*E*/dx

Inner Tracking System
- Vertex and track reconstruction
- Particle identification via d*E*/dx



Time-Of-Flight
- Particle identification via particle velocity β

V0 detectors
- Centrality/multiplicity estimation
- Trigger

Observables

- Antideuteron–net-Λ number correlation
  - Probe charge conservation in the processes underlying nuclear formation
    - Λs are not present inside antideuterons

- Antideuteron–antiproton number correlation
  - Probe the *effective* V_C of baryon-number conservation in the (anti)nucleosynthesis process
    - Antimatter → no contamination from spallation reactions in the detector material

Definitions

$\kappa_1 = \langle n \rangle$	Mean value
$\kappa_2 = \langle (n - \langle n \rangle)^2 \rangle$	Variance
$\kappa_{11}(n,m) = \langle (n - \langle n \rangle)(m - \langle m \rangle) \rangle$	Covariance
$\rho(n,m) = \frac{\kappa_{11}(n,m)}{\sqrt{\kappa_2(n)\kappa_2(m)}}$	Pearson correlation coefficient

Analysis methods

- Antideuteron and antiproton
  - Particle identification (PID) using:
    - Low p_T → TPC dE/dx
    - Intermediate p_T → TPC + TOF β
  - Negligible cross-contamination in overlapping momentum region
    - Purity > 99%

- (Anti)Λ
  - Two-body decay topology
    $\Lambda \rightarrow p + \pi^-$
  - High-purity (> 93%) sample obtained via:
    - Topological selections
    - TPC PID of the decay product

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Efficiency correction

- $\kappa_1 = \langle q_1 \rangle$
- $\kappa_2 = \langle q_1^2 \rangle - \langle q_1 \rangle^2 + \langle q_1 \rangle - \langle q_2 \rangle$
- $\kappa_{11}(A, B) = \langle q_{1,A} q_{1,B} \rangle - \langle q_{1,A} \rangle \langle q_{1,B} \rangle$

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

M = number of p_T bins
ε_i = efficiency in i-th p_T bin
N_i = raw counts in i-th p_T bin

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

Volume fluctuations

- Antideuteron–antiproton → centrality bin-width correction (CBWC)
- Net-particles → suppressed at $\mu_B \sim 0$

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

ALICE Collaboration, arXiv:2311.13332 [nucl-ex]

Antideuteron–net-Λ correlation

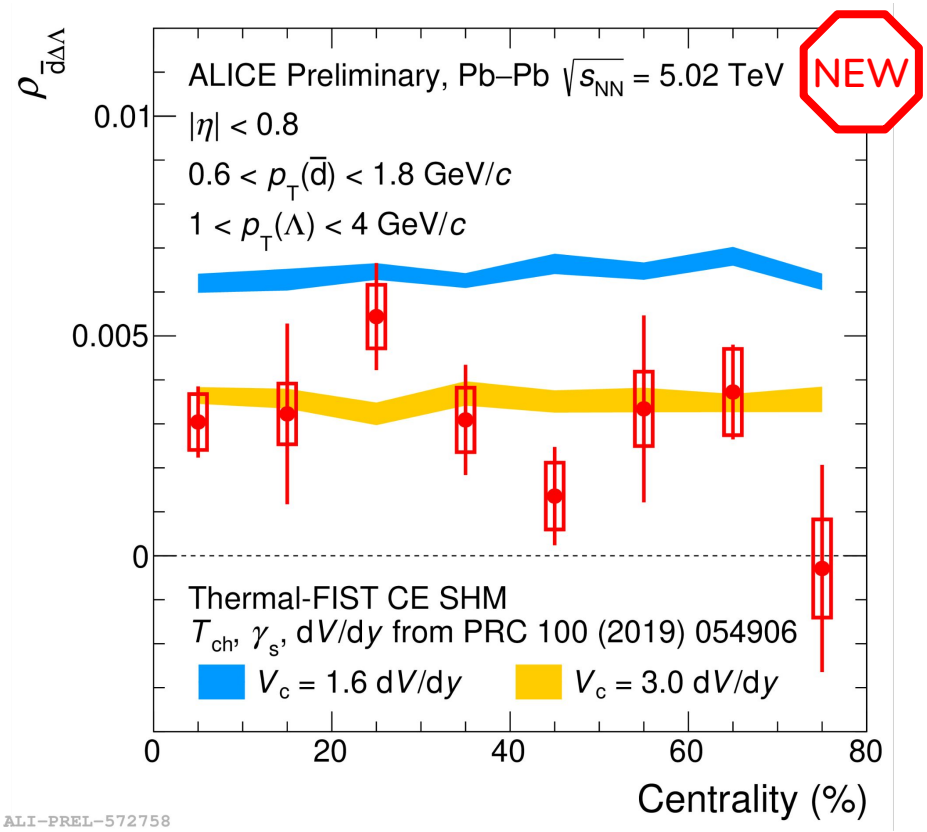
A positive correlation is observed

- Expected from baryon-number conservation in canonical ensemble (CE) SHM
  - Thermal-FIST model

V. Vovchenko et al., Comput. Phys. Commun. 244 (2019) 295-310

  - Parameters from published fits

V. Vovchenko et al., Phys. Rev. C 100 (2019) 5, 054906



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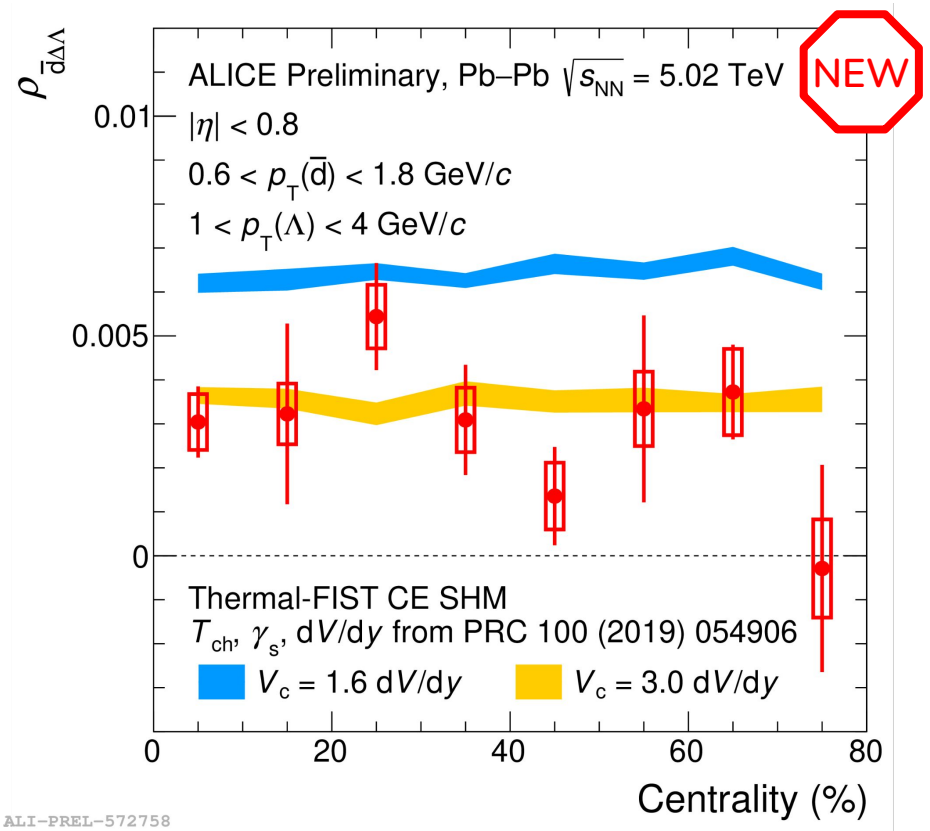
- Consistent with V_C = 3 dV/dy
  - Baryon-number conservation in the underlying processes is consistent with previous observations
- Tension with V_C = 1.6 dV/dy
  - Extracted from observables pairing deuterons with protons (e.g. d/p, ρ_{dp})



Net-Λ normalized second-order cumulant

Negative κ_2/κ_1 for net-Λ

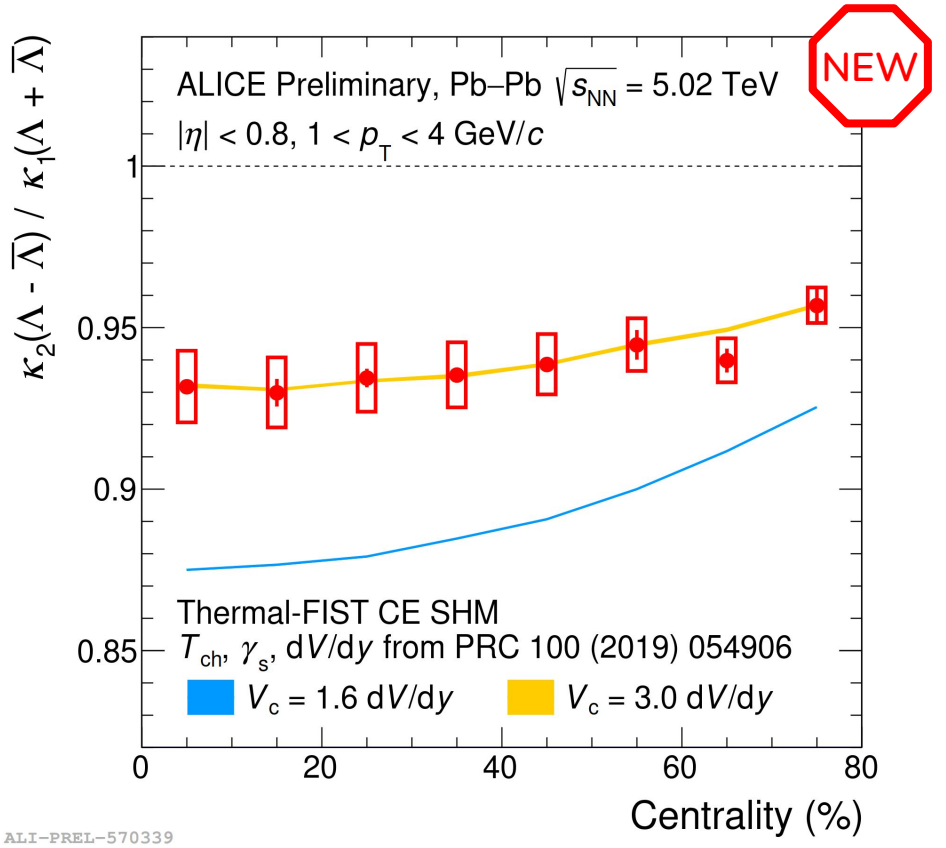
- Expected from baryon-number conservation in Canonical ensemble (CE) SHM
  - Thermal-FIST model

V. Vovchenko et al., Comput. Phys. Commun. 244 (2019) 295-310

  - Parameters from published fits

V. Vovchenko et al., Phys. Rev. C 100 (2019) 5, 054906

- Consistent with V_C = 3 dV/dy
  - Consistent with the previous observations in the baryon and strangeness sectors
  - Large correlation volume in Pb–Pb collisions



Probing (anti)nucleosynthesis mechanisms

Models

- Simple coalescence → convolution of proton and neutron distributions
  - Model A: correlated nucleons
  - Model B: independent nucleons

  Z. Fecková et al., Phys. Rev. C 93, 054906 (2016)

- Improved coalescence
  - MUSIC+UrQMD+Coalescence
  - No initial correlation between protons and neutrons

  K.-J. Sun et al., Phys. Lett. B, 840, 137864 (2023)

- Canonical Statistical Model
  - Correlation depends on the baryon number conservation volume, V_C

  V. Vovchenko et al., Phys. Lett. B 785, (2018) 171

Antideuteron–antiproton correlation

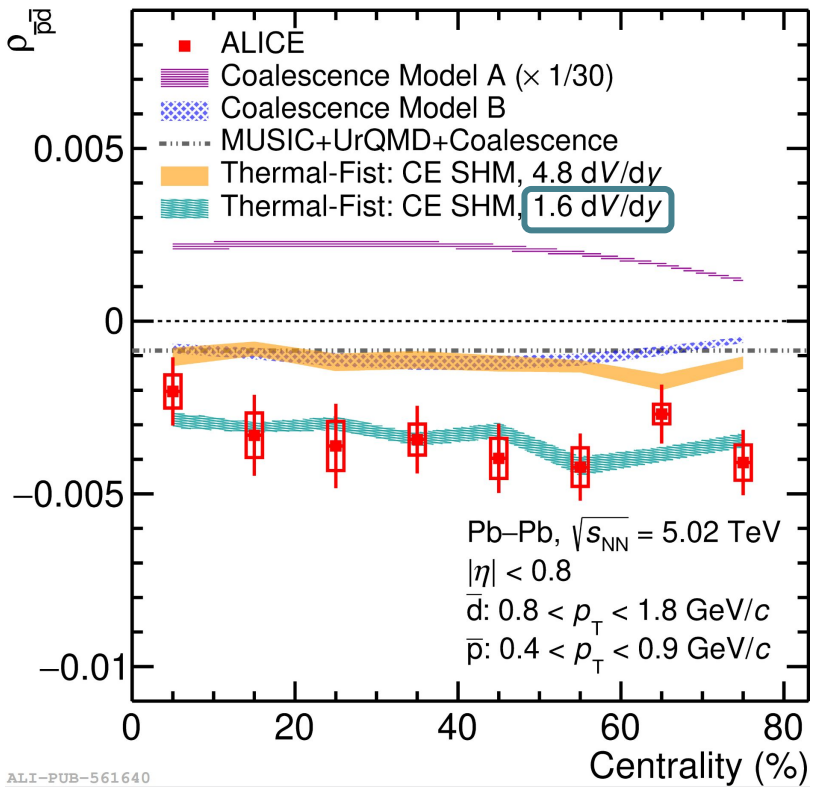
Significant anticorrelation is observed

- Baryon number conservation → strength of the correlation → probe of the (anti)nucleosynthesis mechanism

Models

- Simple coalescence
  - Anticorrelation qualitatively described
- MUSIC+UrQMD+Coalescence
  - Anticorrelation qualitatively described
- Canonical Statistical Model
  - Smaller V_C than other light-flavor hadrons

ALICE Coll., Phys. Rev. Lett. 131, 041901 (2023)

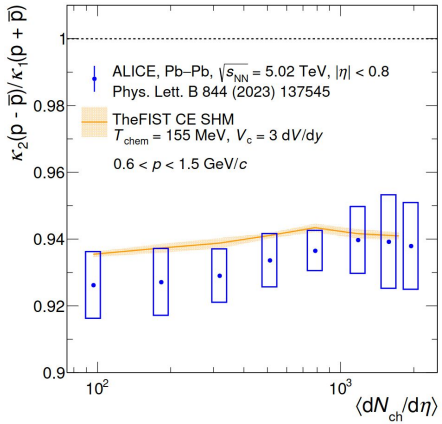


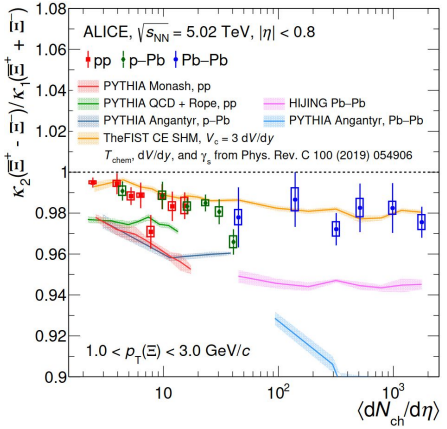
Event-by-event fluctuations: the full picture at LHC

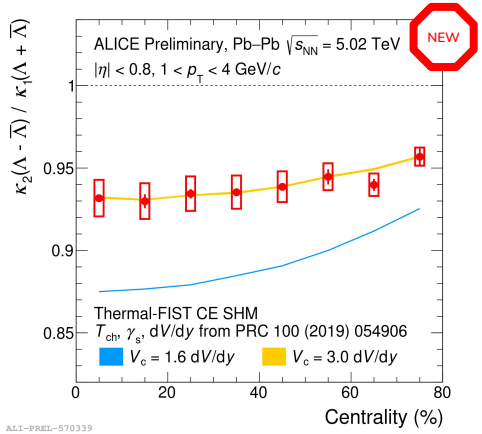
Net-proton	$V_C \sim 3\ dV/dy$
Net-Ξ and net-Ξ–net-K correlation	$V_C \sim 3\ dV/dy$
Net-Λ	$V_C \sim 3\ dV/dy$
Antideuteron–net-Λ correlation	$V_C \sim 3\ dV/dy$
Antideuteron–antiproton correlation	$V_C \sim 1.6\ dV/dy$

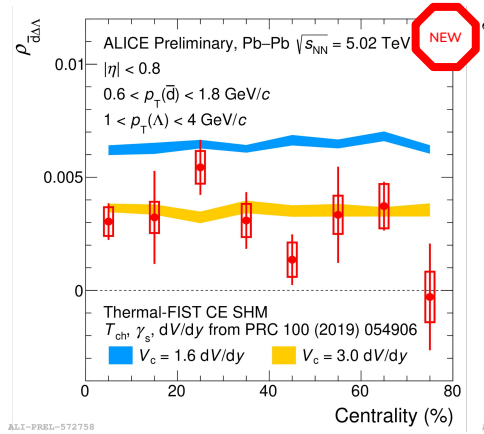
Smaller effective volume
→ stronger correlation between antideuteron and antiproton
→ the correlation strength is enhanced by the (anti)nucleosynthesis mechanism

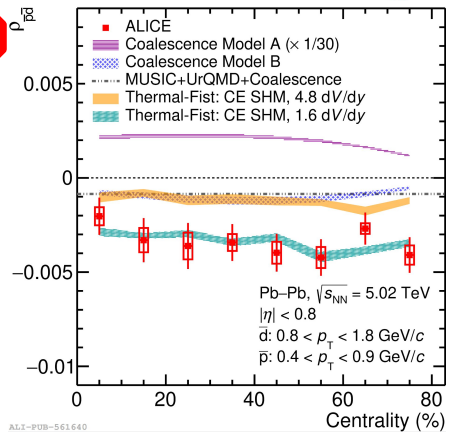
ALICE Coll., Phys. Lett. B 844 (2023) 137545









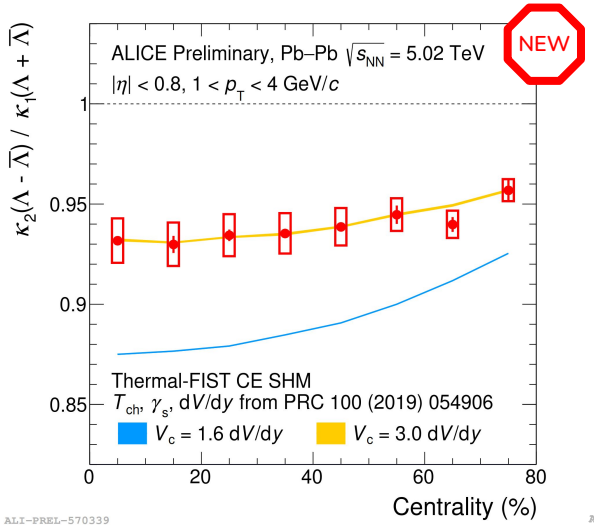


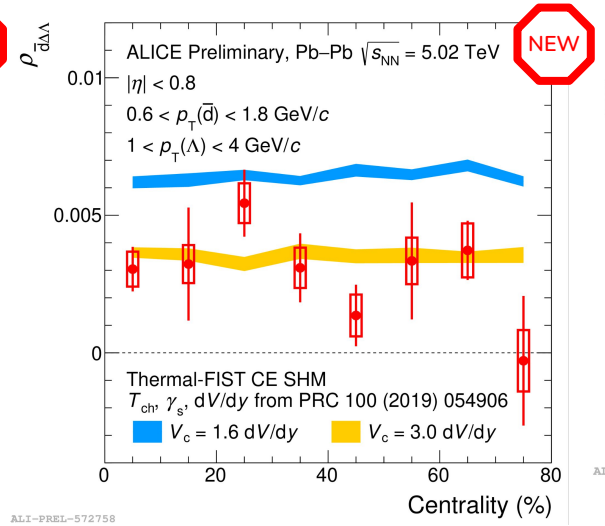
ALICE Coll., arXiv:2405.19890 [nucl-ex]

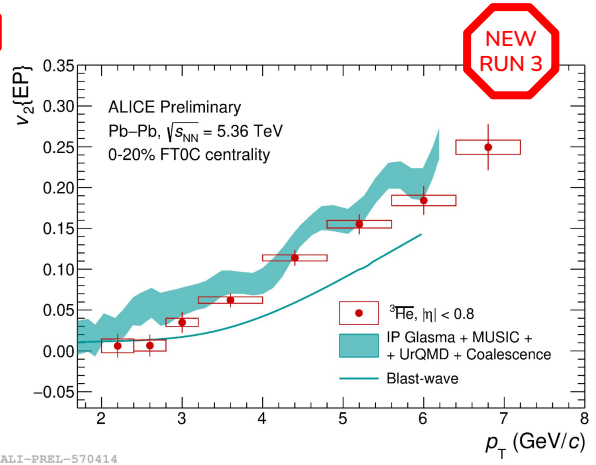
ALICE Coll., Phys. Rev. Lett. 131, 041901 (2023)

Summary and outlook

- Event-by-event observables are sensitive probes of nuclear formation mechanisms
  - Antideuteron–net-Λ correlation → observed correlation volume for quantum-number conservation is consistent with net-[p, Λ, Ξ]
  - Antideuteron–antiproton correlation → (anti)nucleosynthesis processes correlate baryon number over a smaller effective volume
- Full system-size scan and heavier nuclei (^{3}He) using Run 3 data sample







Additional slides

Antideuteron normalized second-order cumulant

κ_2/κ_1 cumulant ratio is consistent with unity

- Antideuterons carry a small fraction of the total (anti)baryon number in Pb–Pb collisions
  → Negligible effect of baryon number conservation

Models

- Simple coalescence
  - Overestimation of antideuteron fluctuations
- MUSIC+UrQMD+Coalescence
  - Consistent with Poissonian baseline
- Canonical Statistical Model
  - Limited sensitivity to the size of V_C

ALICE Coll., Phys. Rev. Lett. 131, 041901 (2023)