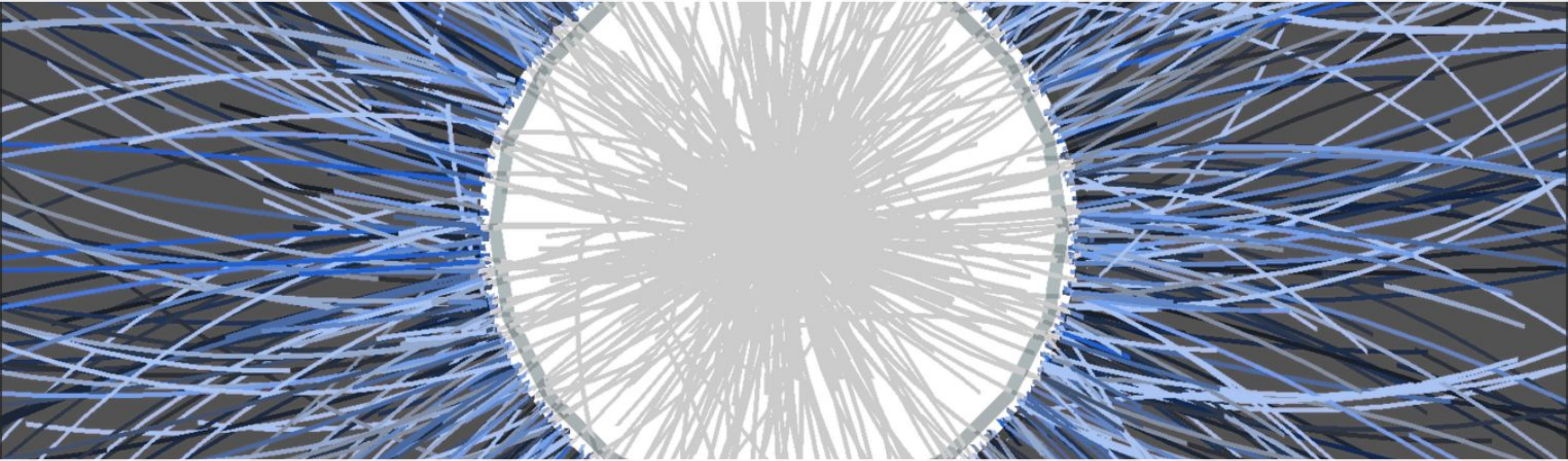
Beyond the average: higher moments of the (anti)deuteron multiplicity distribution with ALICE



Sourav Kundu
(for the ALICE Collaboration)

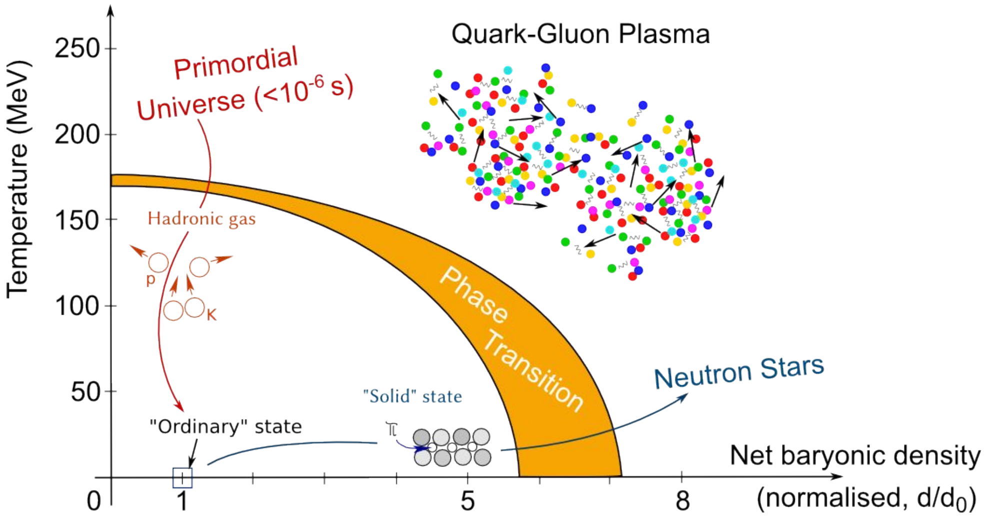
EP-LHC seminar: 02/08/2022
CERN

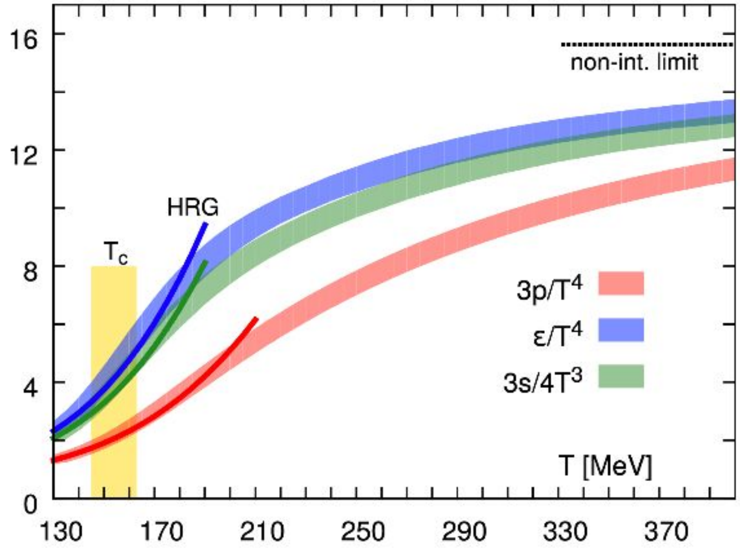
Outline

- Introduction to light nuclei production models
- Result
  – Deuteron production yields
  – First measurements of event-by-event antideuteron fluctuations in heavy-ion collisions

  (based on new ALICE measurements: *arXiv:2204.10166*)
- Future perspectives and summary

Why heavy-ion collisions?



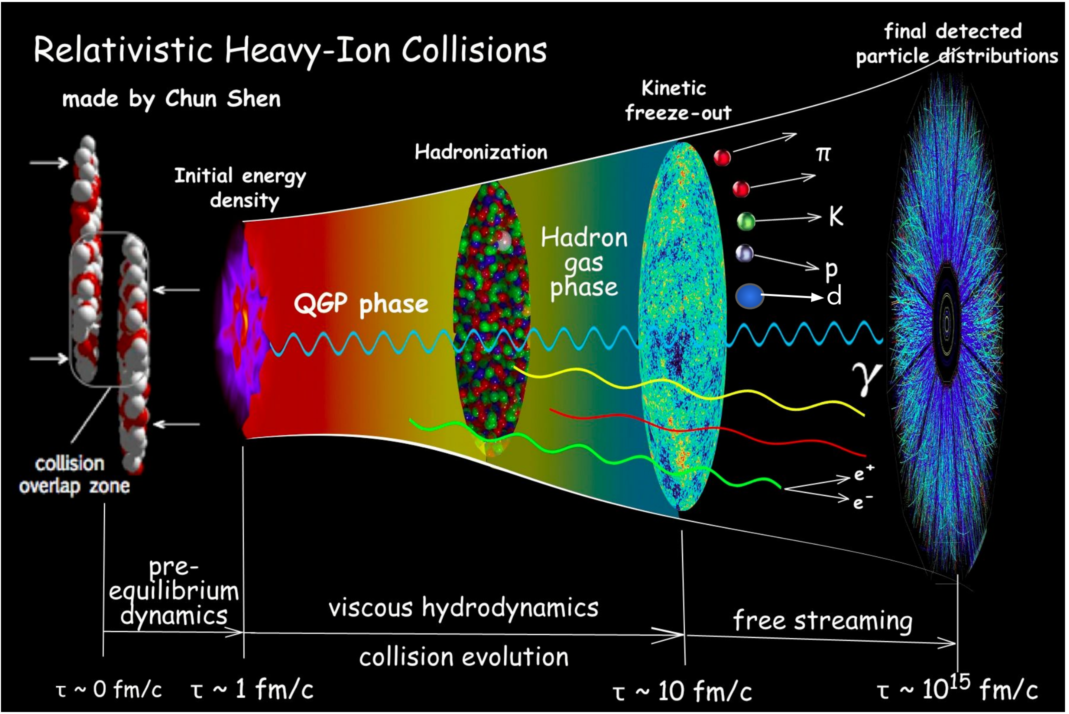


https://cds.cern.ch/record/2025215

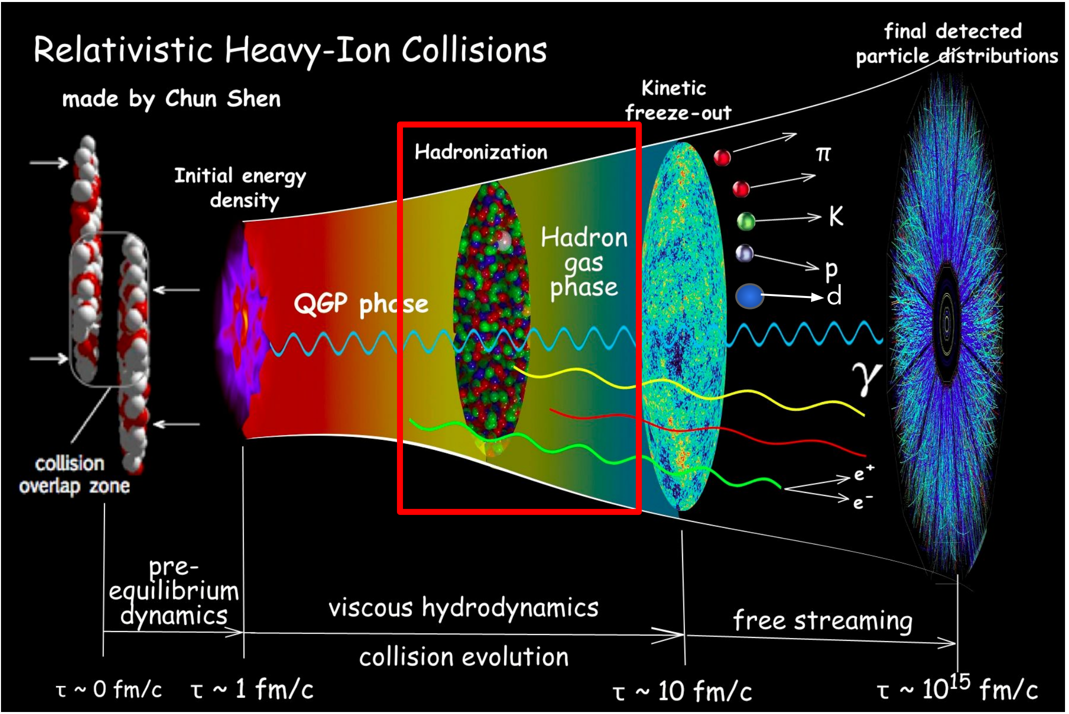
A. Bazavov et al. (HotQCD Collaboration) Phys. Rev. D 90 (2014) 094503

- One of the goals is to characterize the phase diagram of QCD matter
- Quark–gluon plasma: deconfined phase of quarks and gluons
- Phase transition at LHC (low baryonic density region)
  – smooth crossover: similar to early universe (~few μs after the Big Bang)

Time evolution of heavy-ion collision



Hadronization



- Hadronization process not well understood
  - in-vacuum fragmentation does not describe the hadronization in such high-partonic density environment
  - phenomenological models are used

Statistical hadronization model

- Hadron yields at chemical freeze-out (hadron abundances are fixed) calculated using the Grand Canonical partition function:

$$n_i = -\frac{T}{V}\frac{\partial\, ln(Z_i)}{\partial \mu} = \frac{g_i}{2\pi^2}\int_0^\infty \frac{dp\, p^2}{\exp[(E_i-\mu_i)/T]\pm 1}$$

- Assumptions:
  – Thermal equilibrium
  – Point-like hadrons
  – Conservation laws applied on average

- Primordial yields + feed-down from high-mass states

- Model parameters: T_{chem}, μ_B and V

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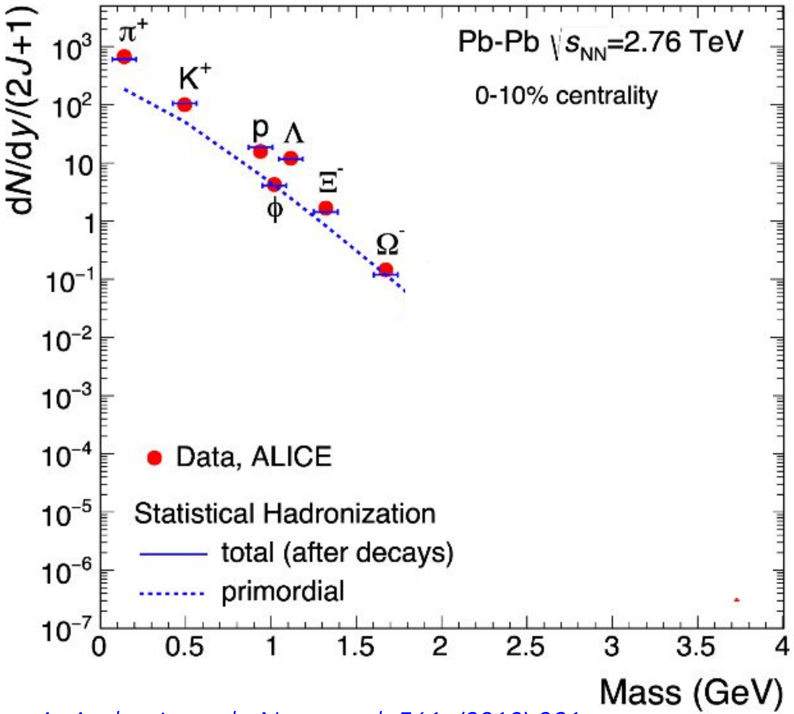
- Model parameters: T_{chem}, μ_B and V
- T_{chem} = 156.5 ± 1.5 MeV → $T_{chem} \approx T_{pc}$
- Chemical freeze-out close to phase boundary



A. Andronic et al., Nature vol. 561, (2018) 321
HotQCD Collaboration, Phys, Lett. B 795 (2019) 15

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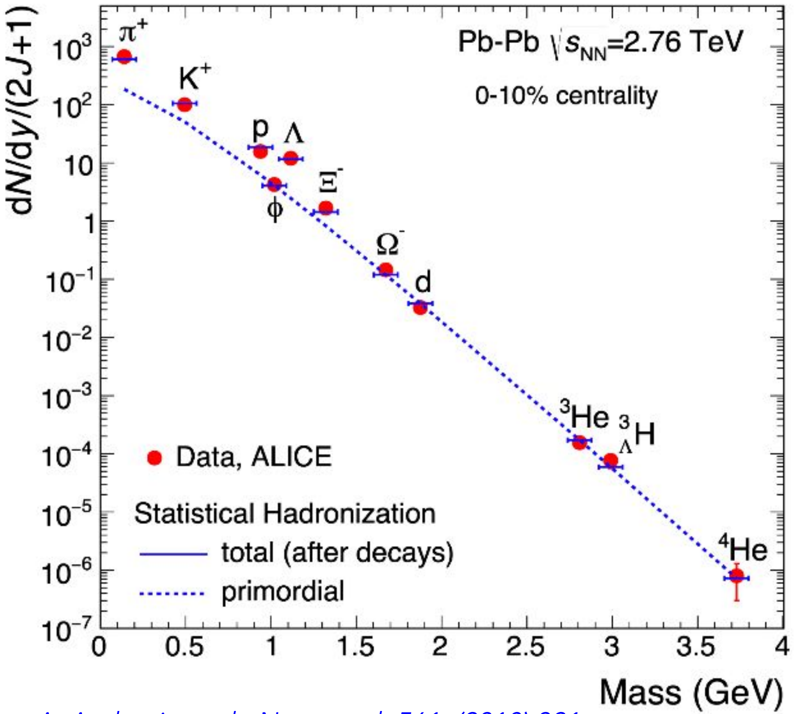
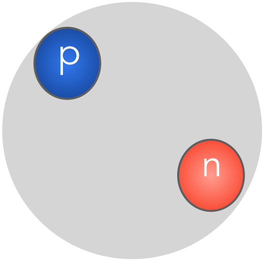


A. Andronic et al., Nature vol. 561, (2018) 321
HotQCD Collaboration, Phys, Lett. B 795 (2019) 15

Agreement with the nuclei yields is surprising!

Production of light (anti)nuclei

Hadronization for light nuclei is not well understood

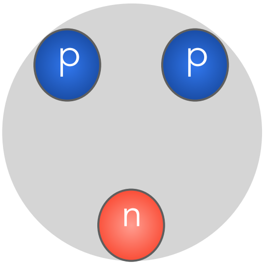


Deuteron

E_b = 2.22 MeV

$\sqrt{\langle R_c^2 \rangle}$ = 2.13 fm

P. J. Mohr et al., Rev. Mod. Phys. 88 (2016) 035009



^{3}He

E_b = 7.72 MeV

$\sqrt{\langle R_c^2 \rangle}$ = 1.96 fm

Nucl. Data Sheets 130, 1 (2015)

- Pseudocritical temperature (T_{pc}) is the average temperature at which phase transition occurs
- It is calculated from lattice QCD at vanishing baryo-chemical potential μ_B (matter = antimatter):

$$T_{pc} = 156.5 \pm 1.5 \text{ MeV}$$

HotQCD Collaboration, Phys, Lett. B 795 (2019) 15
S. Borsanyi et al., Phys. Rev. Lett. 125 (2020) 052001

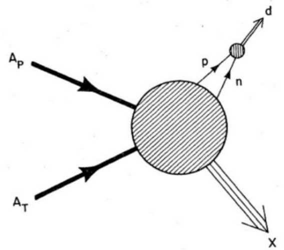
Are such loosely-bound states also produced at the phase transition with $T_{pc} \approx$ 156 MeV?

Coalescence model

- Bound states produced at phase boundary are destroyed by interactions in the hadron gas phase
- Nuclear clusters are formed at kinetic freeze-out by coalescence of nucleons (hyperons) if nucleons are close in phase space
- Simple Coalescence model: only momentum correlations are considered: $\Delta p_{ij} = 0$

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

Invariant yield of nuclei — Coalescence parameter — Invariant yield of nucleon



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

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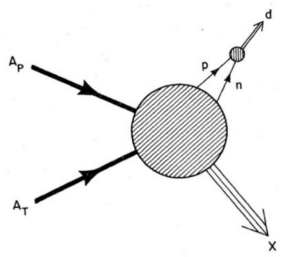


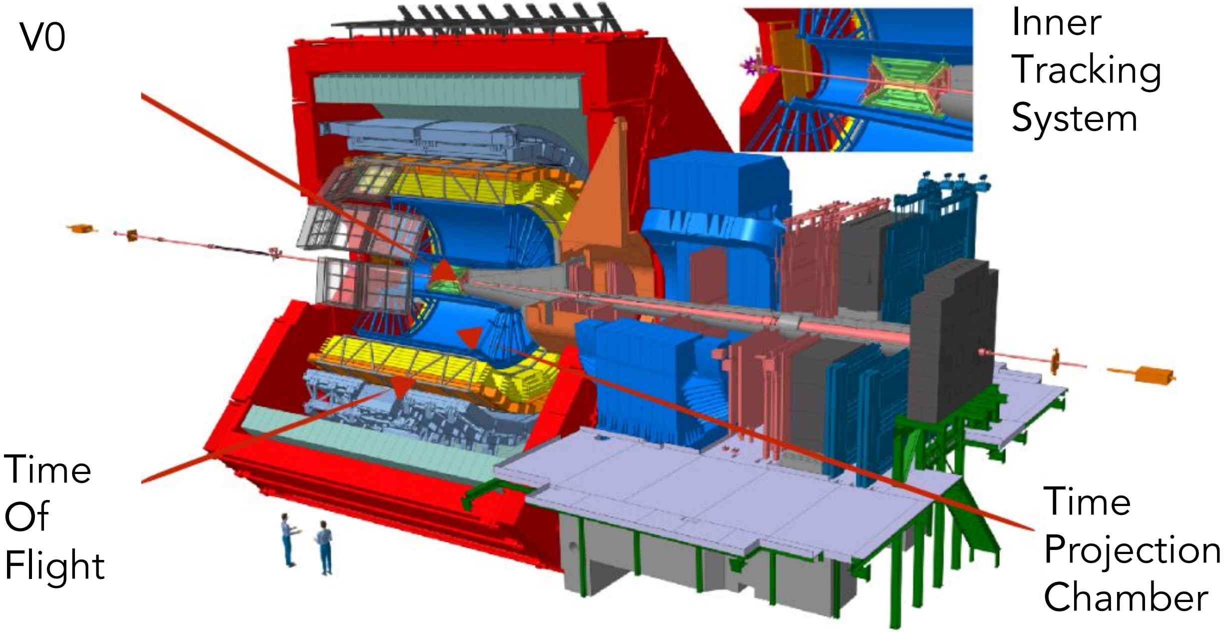
J. Kapusta, Phys. Rev. C 21 (1980) 1301

- Advanced Coalescence model: include source size *R* and finite size r_d of the cluster, and kinetic freeze-out temperature T_k

$$B = \frac{3}{4(mT_K R^2)^{3/2}} \frac{1}{\left(1 + \frac{1}{mT_K \sigma^2}\right)^{3/2}} \frac{1}{(1 + \frac{\sigma^2}{4R^2})^{3/2}} \qquad \sigma = \sqrt{8/3}\, r_d$$

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

The ALICE detector



Inner Tracking System (ITS)

- Tracking, vertexing

Time Projection Chamber (TPC)

- Tracking and particle identification via dE/dx in the TPC gas mixture

Time Of Flight (TOF)

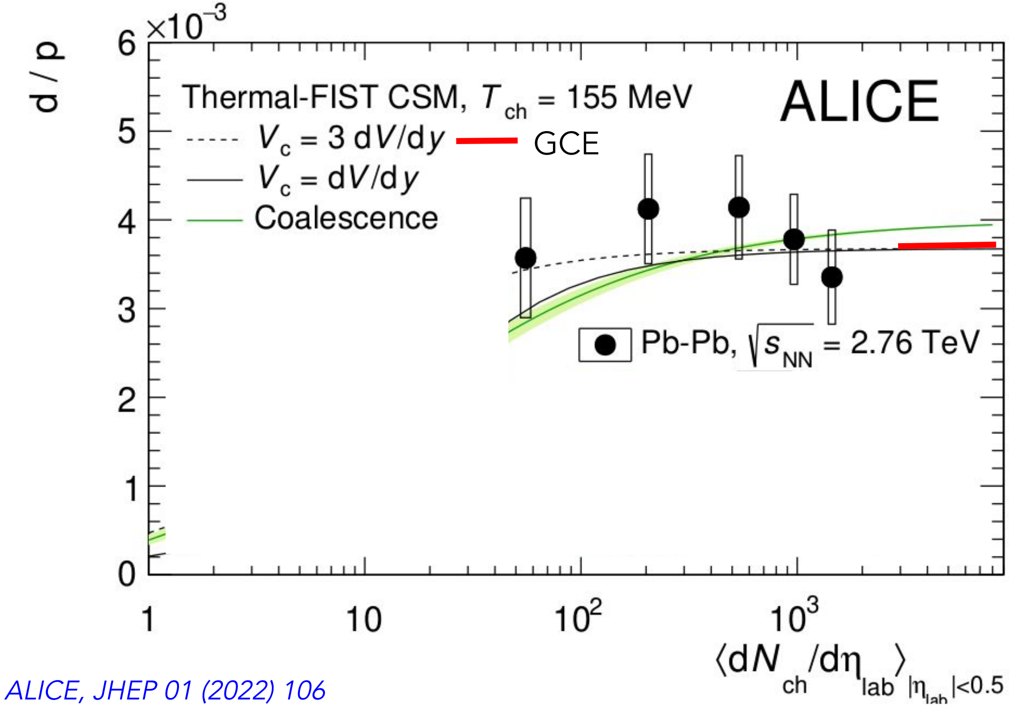
- particle identification via velocity measurement

V0 Scintillators

- Trigger and centrality estimation

- Low material budget, excellent tracking and particle identification over broad momentum range: unique detector for nuclei measurements!

Thermal vs. Coalescence: deuteron production yield



ALICE, JHEP 01 (2022) 106

AA collisions:

- Produced system size larger than the size of deuteron
- d/p ratio vs, multiplicity ~ flat and reaches GCE limit
- Less discrimination power in AA collisions

$V_c \rightarrow$ volume in which baryons are correlated due to baryon number conservation

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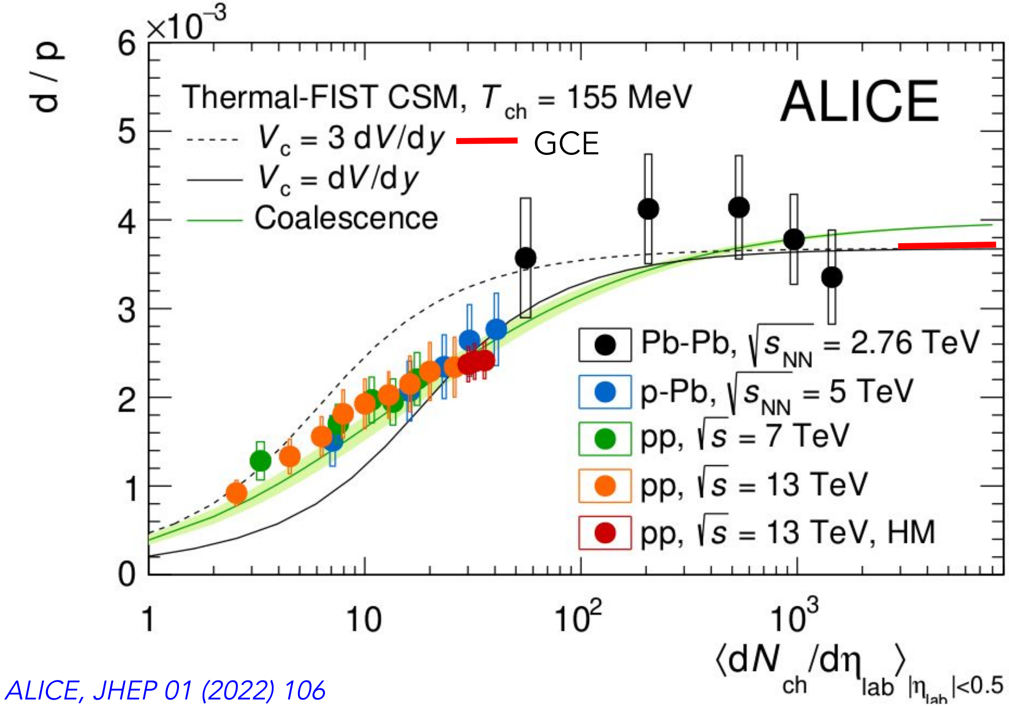


ALICE, JHEP 01 (2022) 106

Both models give similar value of deuteron production yield across all the collision systems

AA collisions:

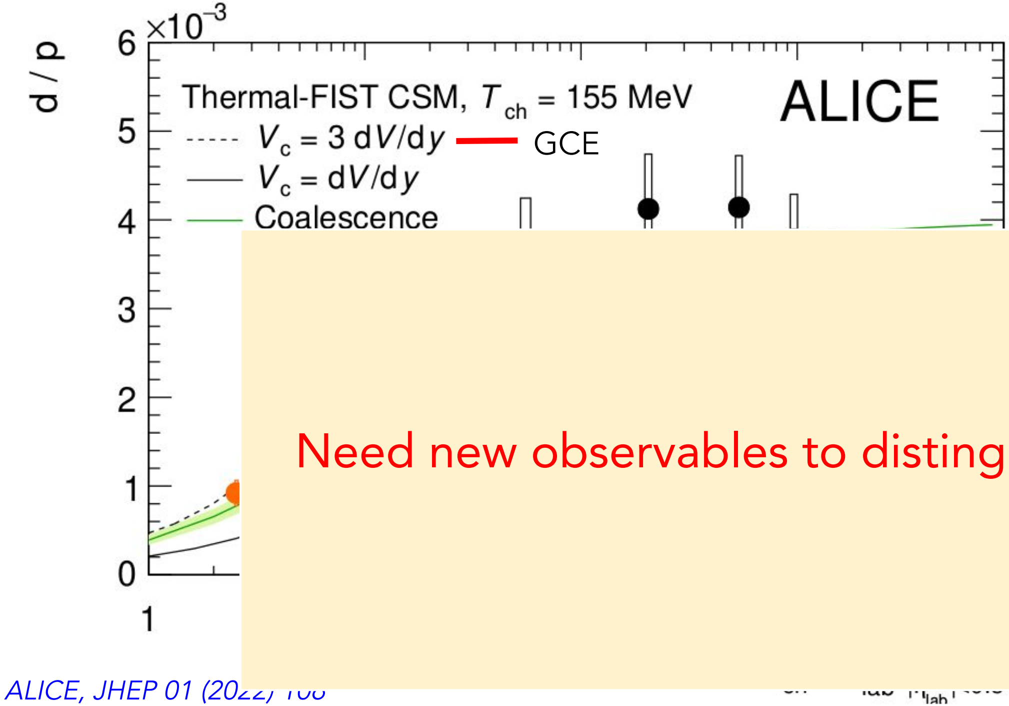
- Produced system size larger than the size of deuteron
- d/p ratio vs, multiplicity ~ flat and reaches GCE limit
- Less discrimination power in AA collisions

Small system:

- Produced system size comparable with the size of deuteron
- Smooth transition from pp to AA – single description for the nucleosynthesis?
- Suppression of d/p ratio at low multiplicity
  – Canonical Ensemble of SHM (CSM) → effect of baryon number conservation
  – Coalescence model → finite size effect of deuteron

$V_c \rightarrow$ volume in which baryons are correlated due to baryon number conservation

Thermal vs. Coalescence: deuteron production yield



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llisions

synthesis?

plicity

ation

– Coalescence model
→ finite size effect of deuteron

Need new observables to distinguish the nucleosynthesis model

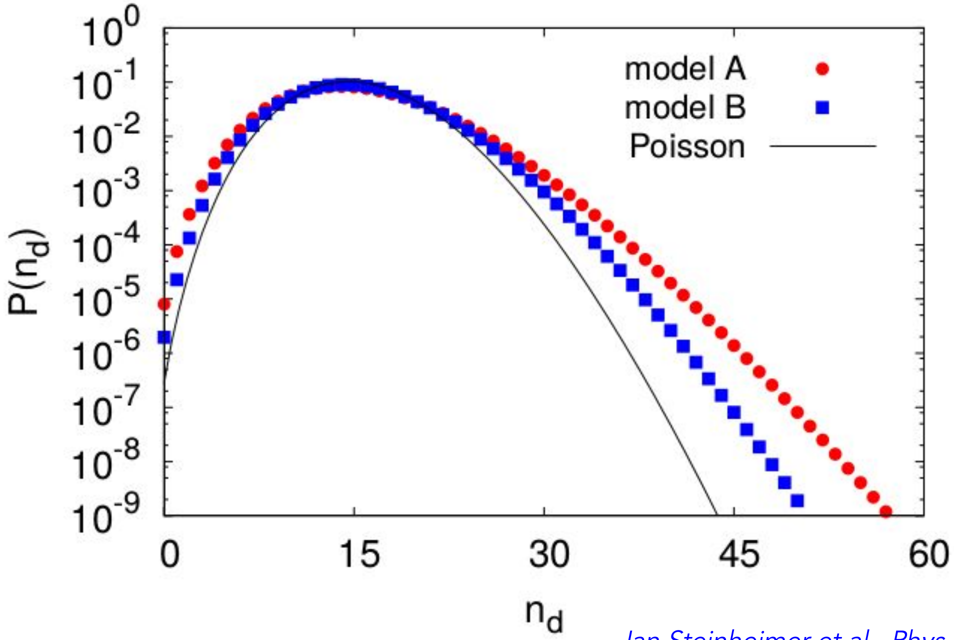
Both model give similar value of deuteron production yield across all the collision systems

V_c → volume in which baryons are correlated due to baryon number conservation

Fluctuation as a probe of deuteron synthesis

Event-by-event deuteron distribution:

- GCE of Thermal model: Poisson
- Coalescence model: convolution of two Poisson distribution → deviation from Poisson



Initial conditions in coalescence model:

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

Model parameters:

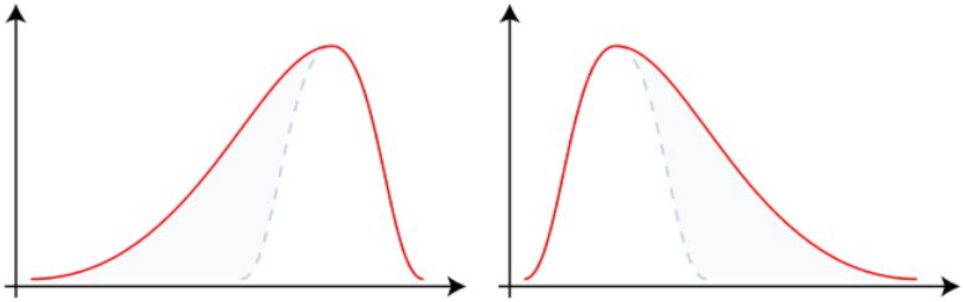
- Coalescence parameter B
- Average initial proton or neutron number

Jan Steinheimer et al., Phys. Rev. C 93 , (2016) 054906

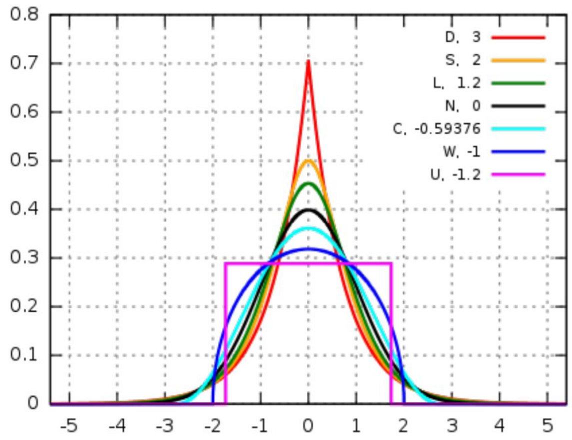
Higher-order fluctuation

- Moments and cumulants are mathematical measures of “shape” of a distribution, which probes fluctuations of an observable.

Skewness → asymmetry



Kurtosis → sharpness



Higher-order cumulants:

$\kappa_1 = \langle n \rangle$, $\kappa_2 = \langle (\delta n)^2 \rangle$ $\delta n = n - \langle n \rangle$

$\kappa_3 = \langle (\delta n)^3 \rangle$, $\kappa_4 = \langle (\delta n)^4 \rangle - 3\langle (\delta n)^2 \rangle^2$

Analysed observable:

$\kappa_2 / \kappa_1 \rightarrow 1$ for Poisson distribution

proton(p)-deuteron(d) correlation

$\rho_{pd} = \langle (n_p - \langle n_p \rangle)(n_d - \langle n_d \rangle) \rangle / \sqrt{(\kappa_{2p}\kappa_{2d})}$ → 0 for GCE

Experimental challenges: purity

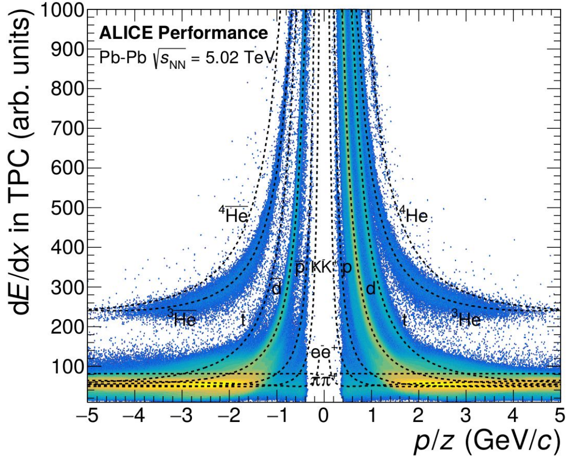
Choice of particle: Antiparticle instead of particle to avoid secondaries produced in detector material

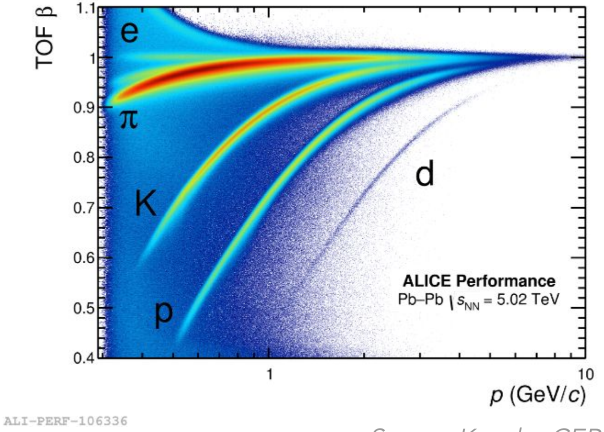
Particle identification:

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%
- Autocorrelation due to misidentification of antiproton as antideuteron is negligible due to separate p_T acceptance





Experimental challenges: efficiency correction

- Efficiency correction depends on the event-by-event efficiency distributions.
  – ~binomial distribution

- MC closure test is performed to validate the method

Binomial efficiency corrected cumulant:

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

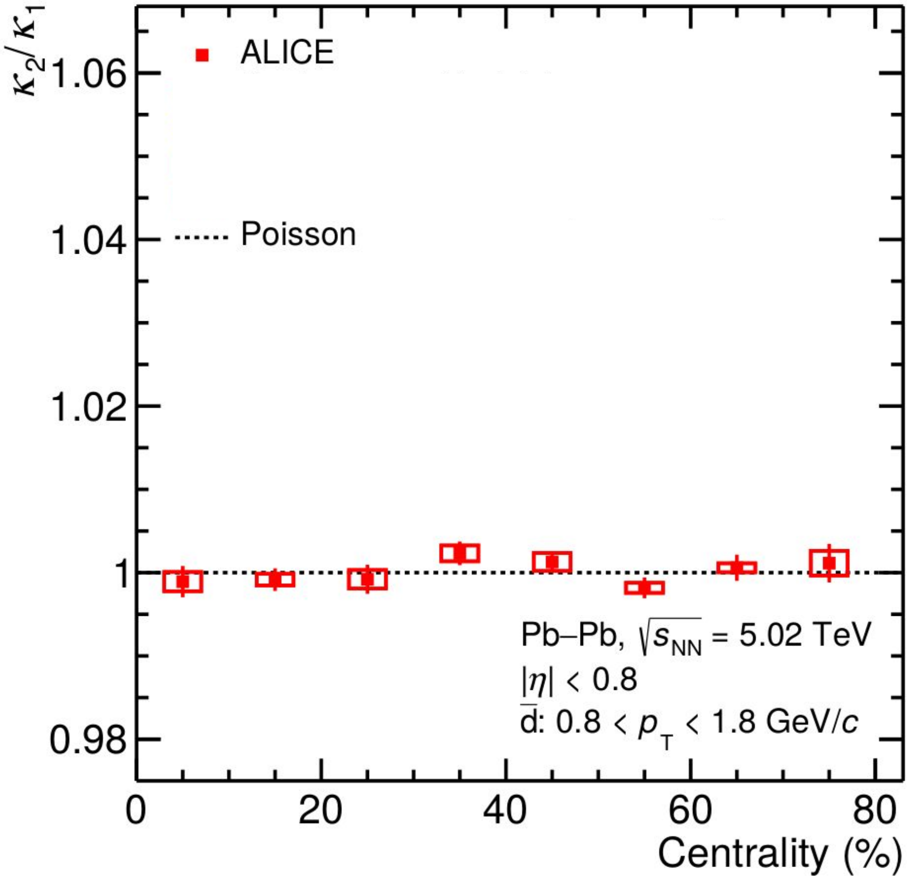
$$\rho = (\langle q_1^d q_1^p \rangle - \langle q_1^d \rangle \langle q_1^p \rangle) \,/\, \sqrt{(\kappa_2^d\, \kappa_2^p)}$$

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

M = number of p_T bins
ε = efficiency
n_i = raw counts in ith p_T bin

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

First antideuteron fluctuation measurement



- Consistent with Poisson baseline

Jan Steinheimer et al., Phys. Rev. C 93 , (2016) 054906
ALICE, arXiv:2204.10166

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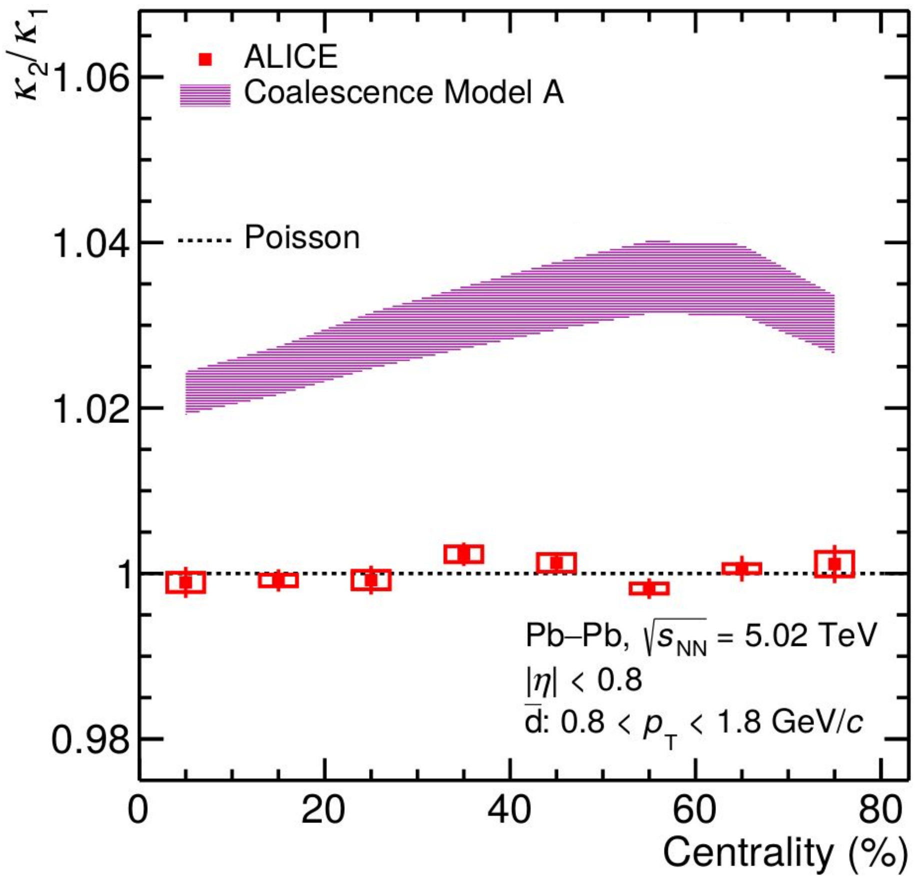

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- Simple Coalescence Model A (correlated nucleon distribution) over predicts data

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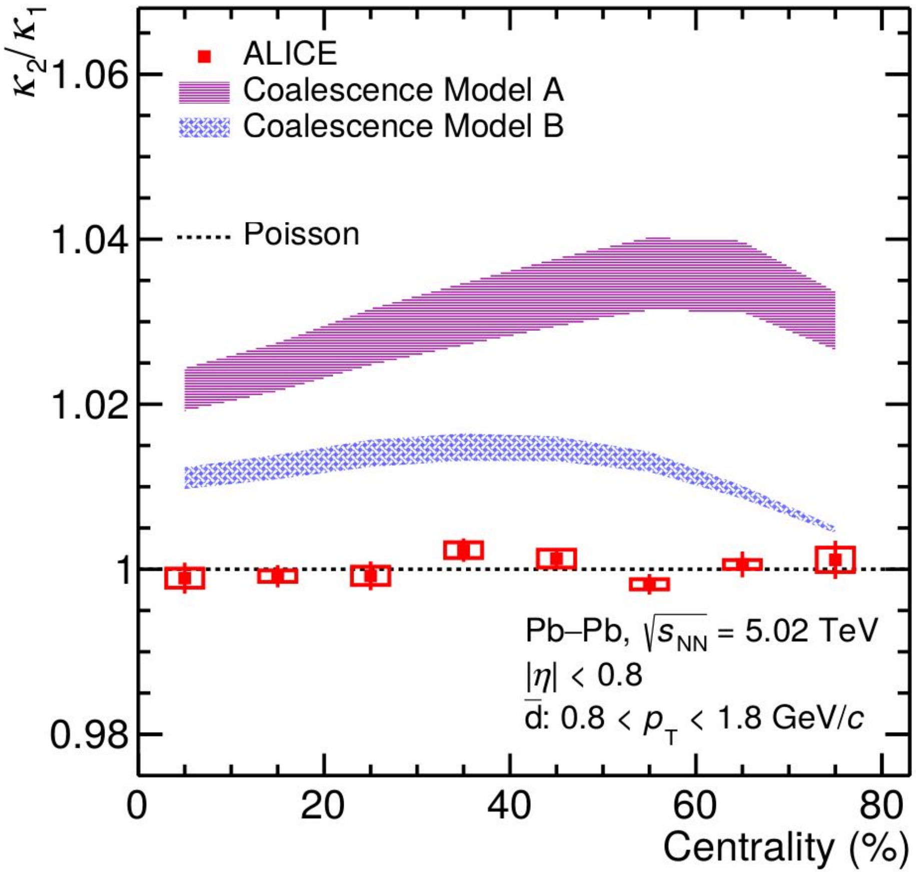

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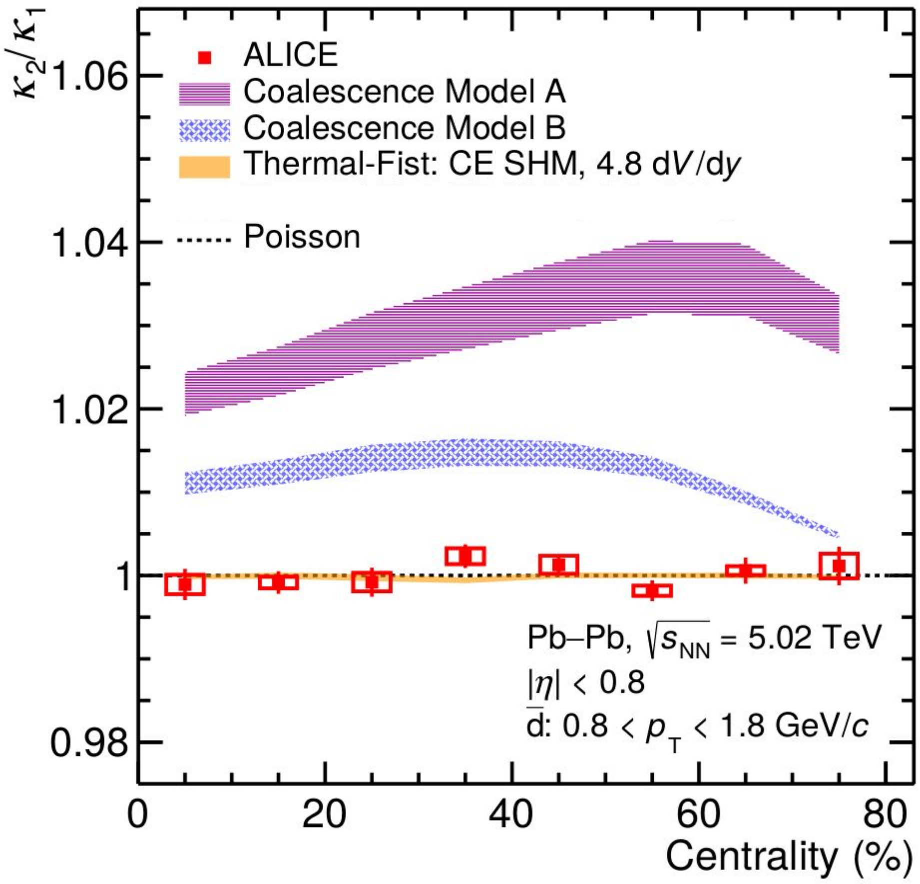
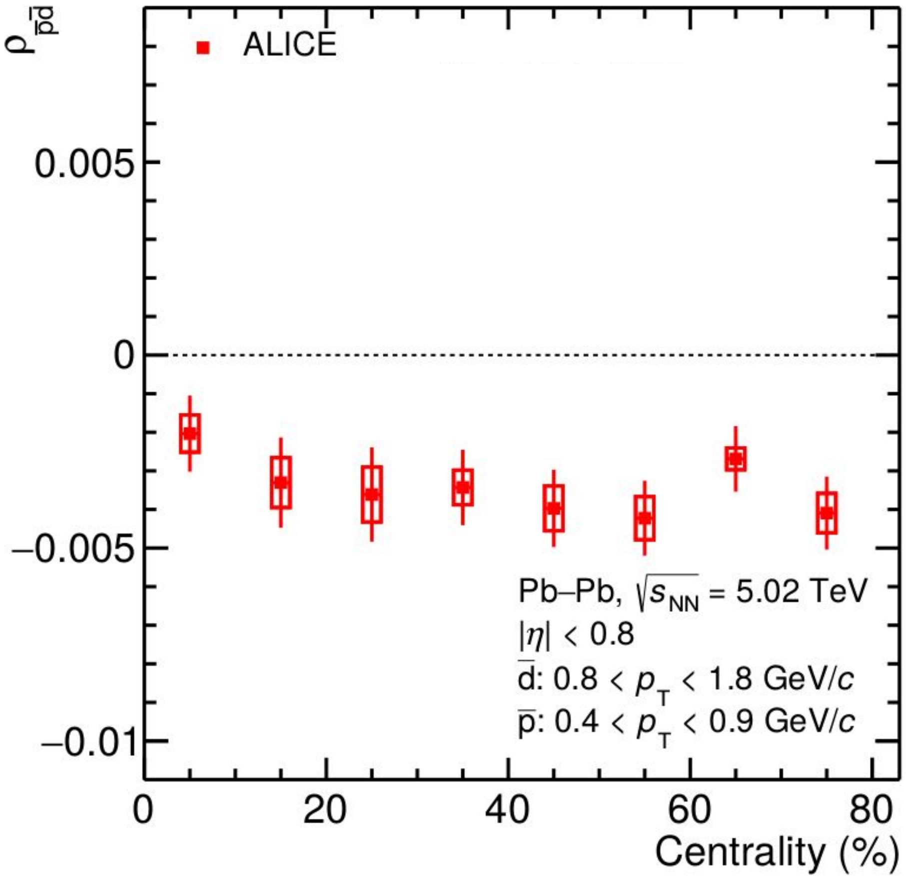


- Consistent with Poisson baseline
- Simple Coalescence Model A (correlated nucleon distribution) over predicts data
- Simple Coalescence Model B (independent nucleon distribution) over predicts data
- Canonical Ensemble (CE) SHM consistent with data, no significant effect of baryon number conservation on κ_2/κ_1 ratio

Jan Steinheimer et al., Phys. Rev. C 93 , (2016) 054906

ALICE, arXiv:2204.10166

Correlation between antideuteron and antiproton



- Evidence of small negative correlation – in events with at least one antideuteron, there are O(0.1%) less antiprotons than in an average event

$$\rho_{pd} = \langle (n_p - \langle n_p \rangle)(n_d - \langle n_d \rangle) \rangle / \sqrt{(\kappa_{2p}\kappa_{2d})}$$

Jan Steinheimer et al., Phys. Rev. C 93 , (2016) 054906

ALICE, arXiv:2204.10166

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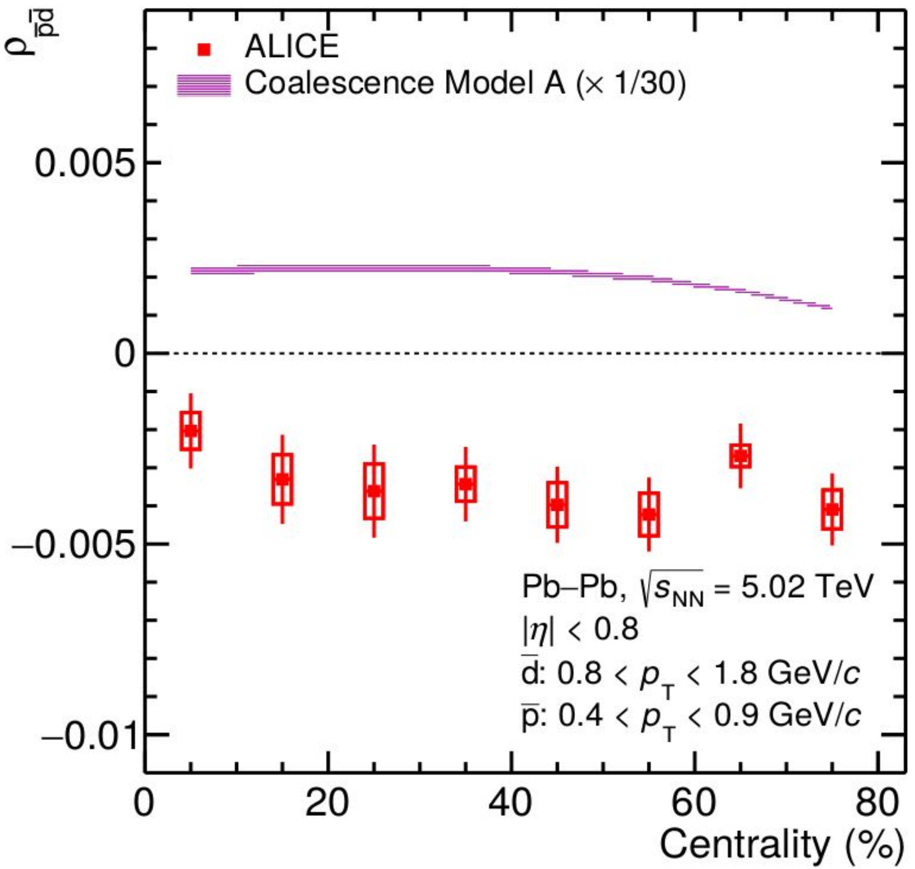

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- Rules out Coalescence model with correlated production of nucleons
  – isospin conservation in antiproton channel

Jan Steinheimer et al., Phys. Rev. C 93 , (2016) 054906

ALICE, arXiv:2204.10166

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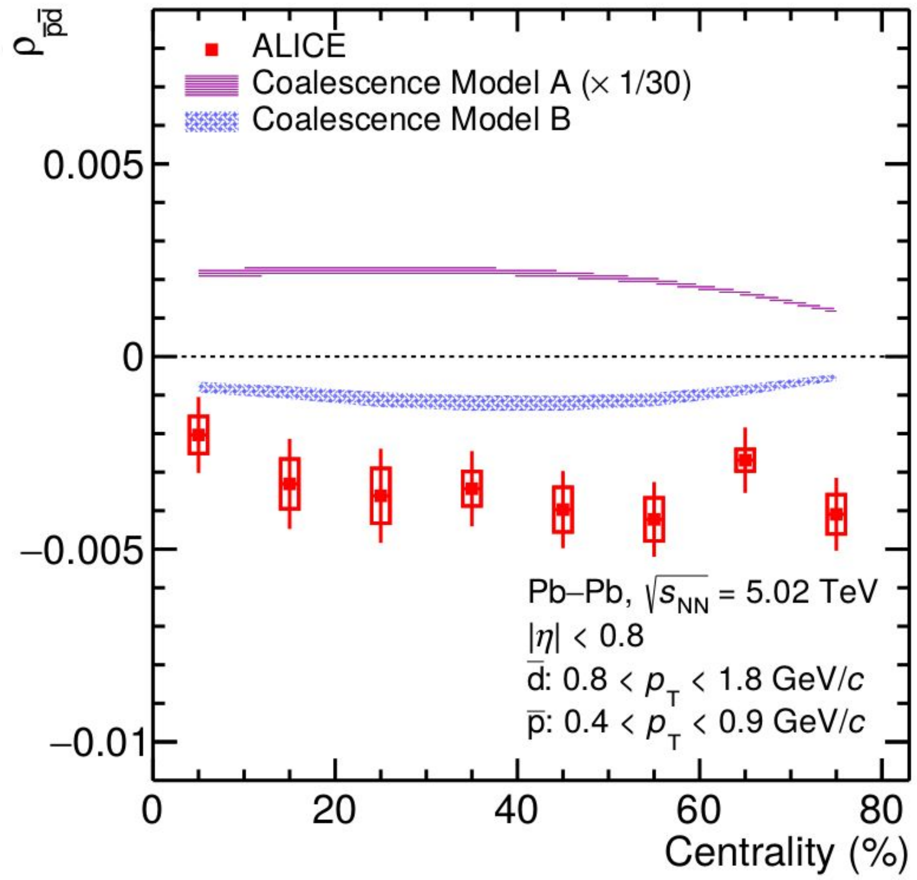

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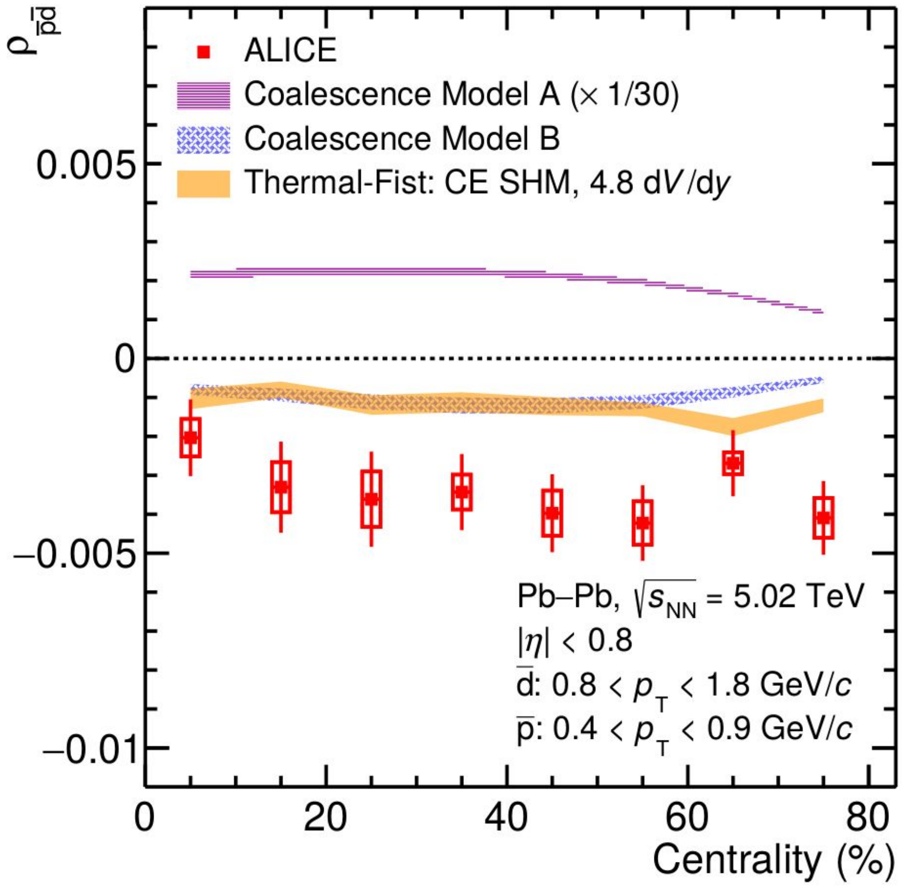

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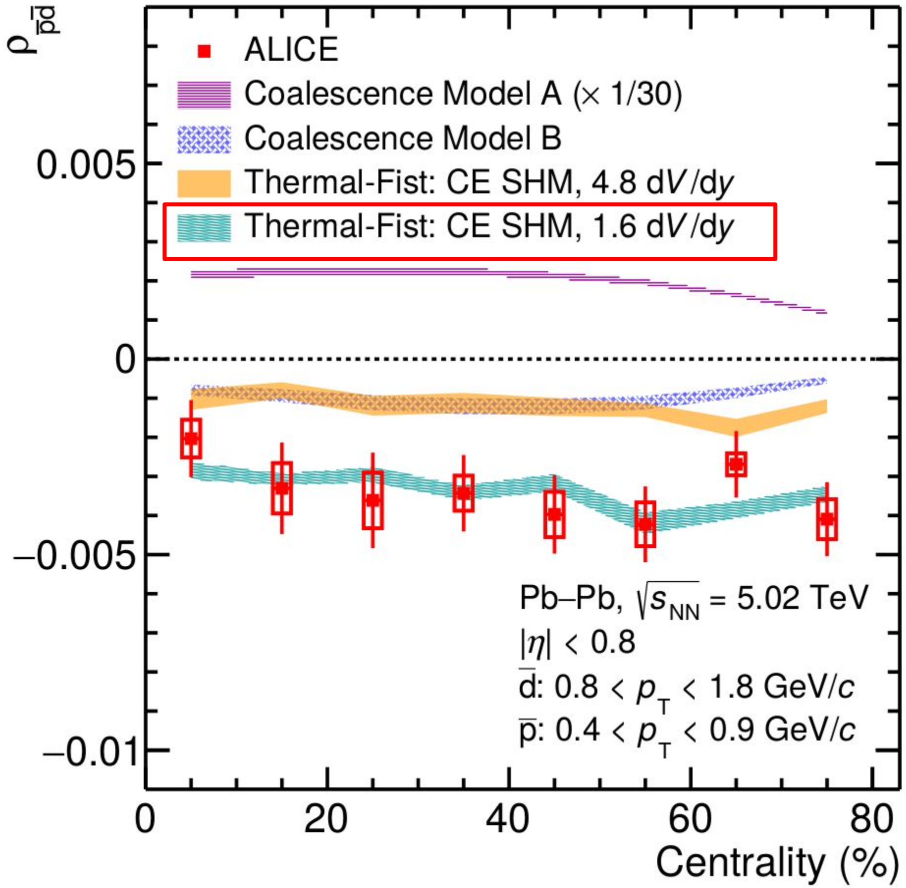
- Rules out Coalescence model with correlated production of nucleons
  – isospin conservation in antiproton channel
- Qualitatively explained by Coalescence model with independent fluctuation of nucleons
- Coalescence model B ≃ CE SHM with large correlation volume
- None of model configurations quantitatively explain the data

Jan Steinheimer et al., Phys. Rev. C 93 , (2016) 054906

ALICE, arXiv:2204.10166

Correlation length between nuclei and nucleon



- χ^2 minimization is performed by varying the correlation volume in the SHM model
- Correlation volume of 1.6 ± 0.3 d*V*/d*y* best describes the data

ALICE, arXiv:2204.10166

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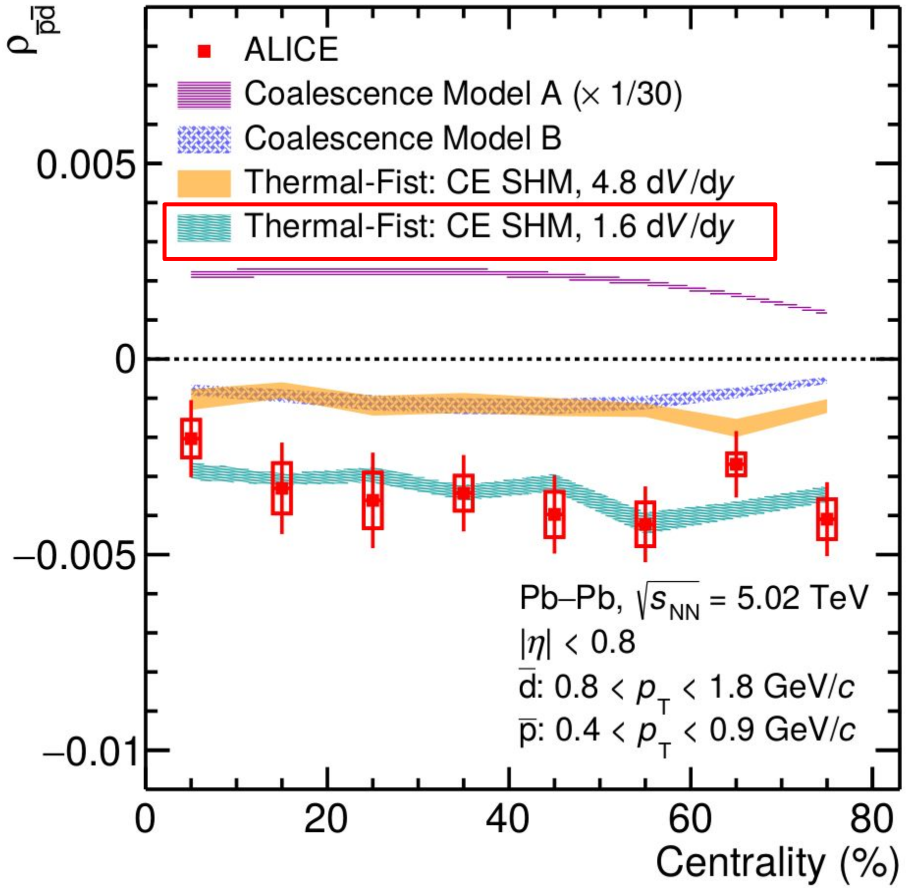

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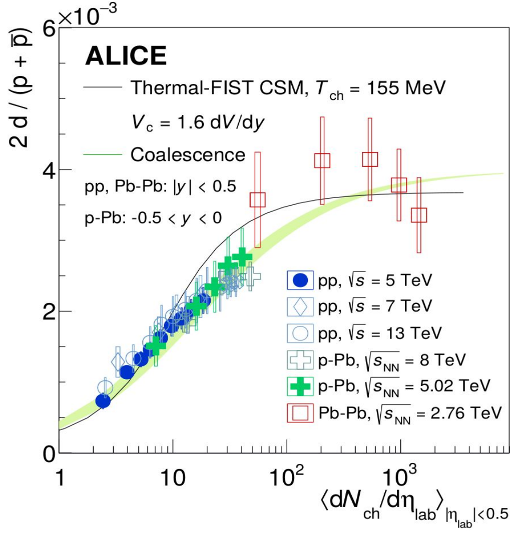
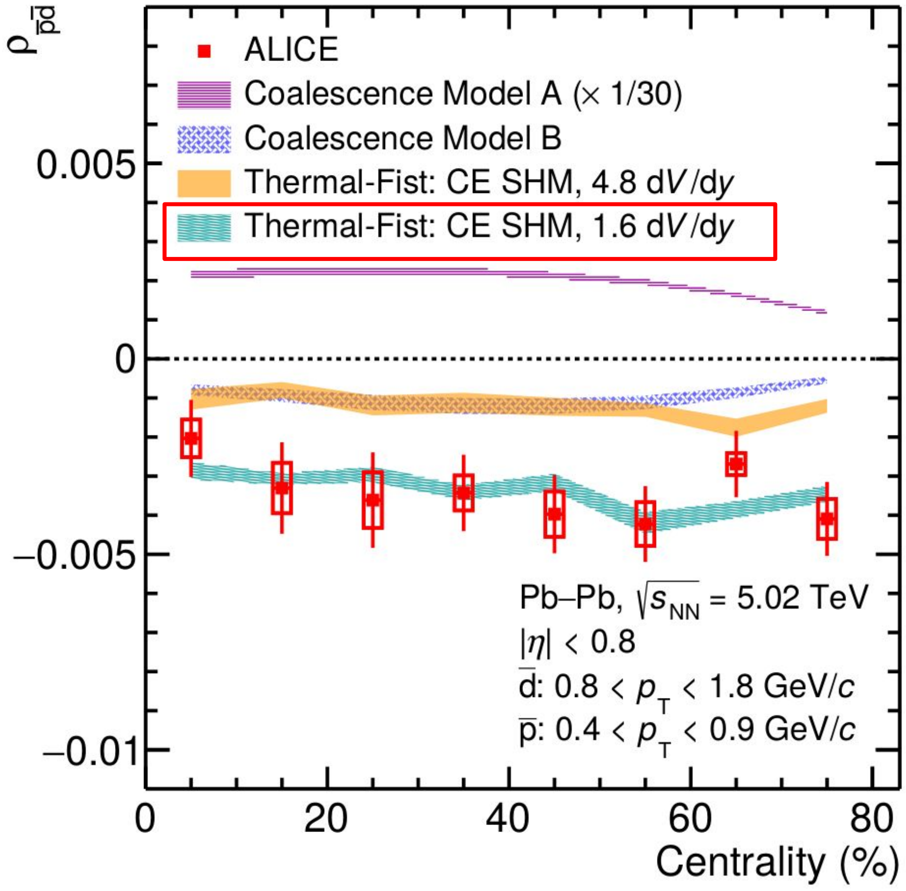
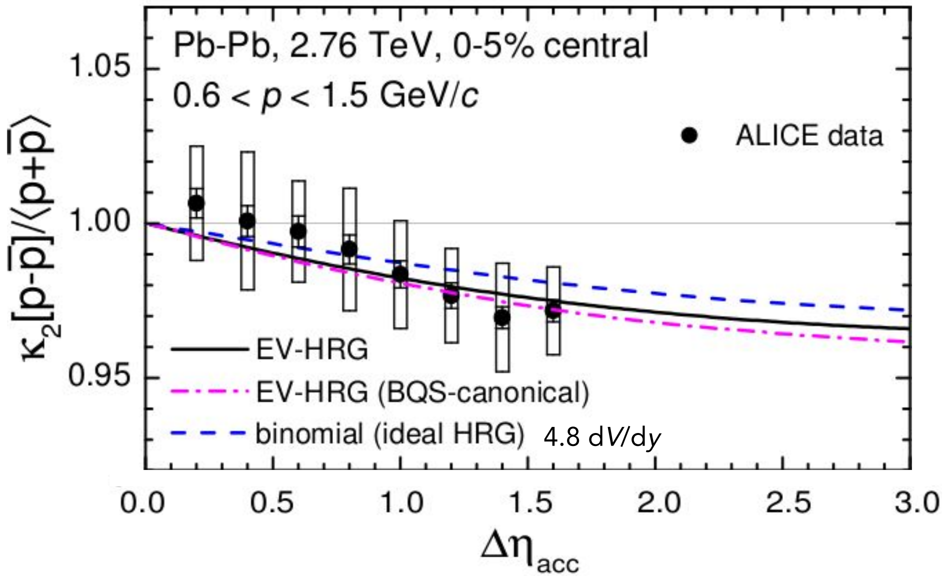


A small correlation volume describes well deuteron production yield across all collision systems

ALICE, arXiv:2204.10166

Comparison with net-proton fluctuation

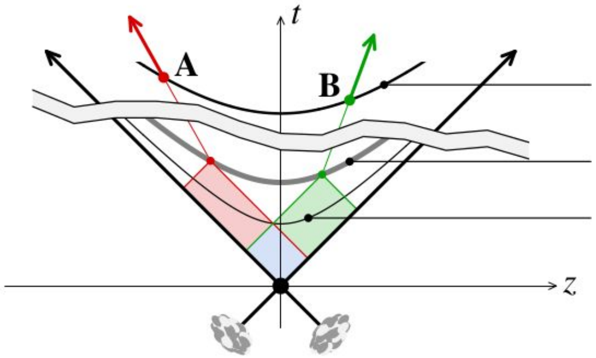




Smaller correlation length between antiproton and antideuteron compared to the correlation length between proton and antiproton

V. Vovchenko et al., Phys. Rev. C 103, (2021) 044903
ALICE, Phys. Lett. B 807 (2020) 135564
ALICE, arXiv:2204.10166

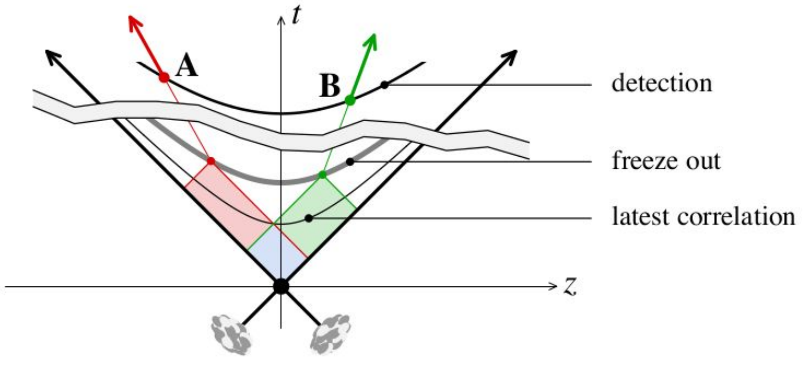
Correlation length



$$\tau \leq \tau_{\text{freeze out}}\, e^{-\frac{1}{2}|y_A - y_B|}$$

- Long range rapidity correlation → originates at early time
- Short range rapidity correlation → originates at later time

Correlation length



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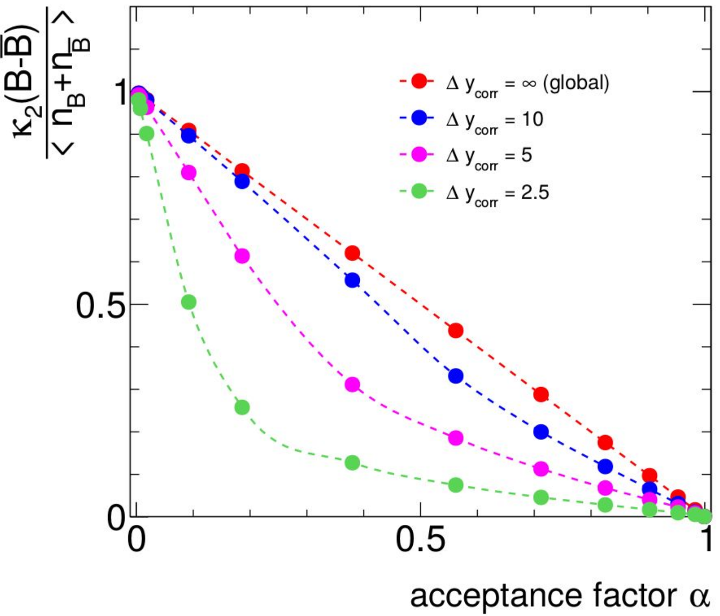
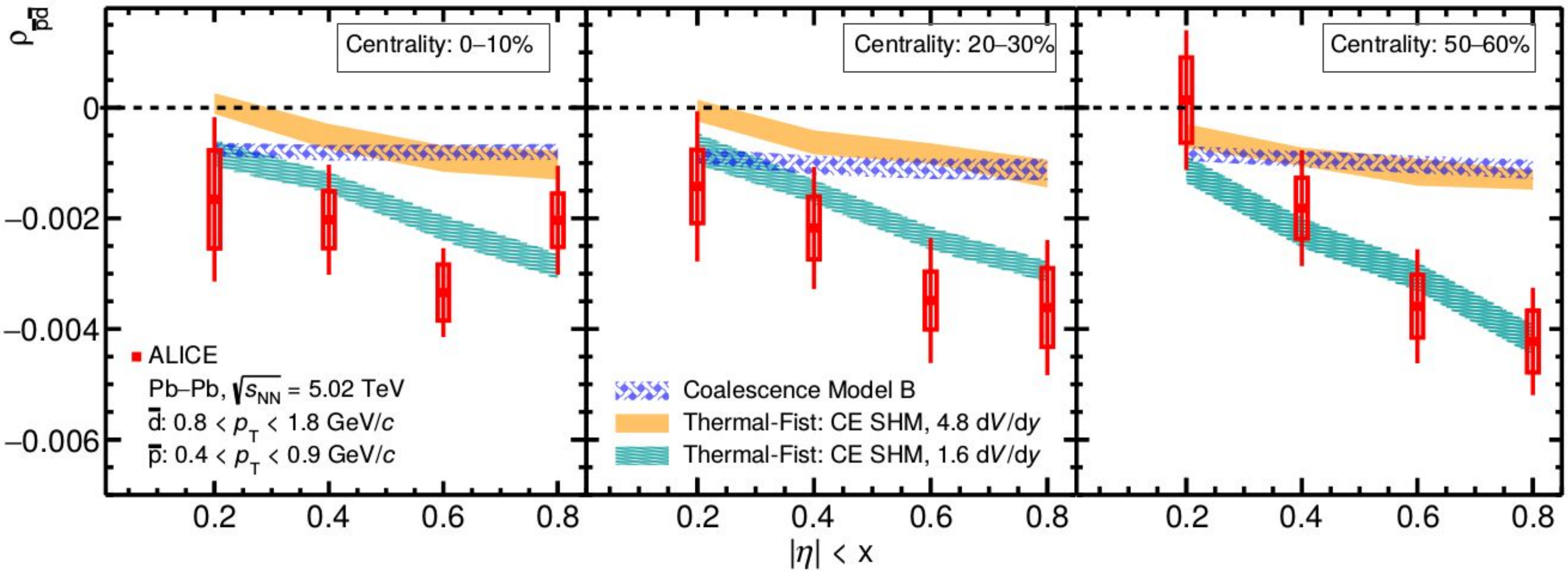


increase in **η** acceptance

- Long range rapidity correlation → originates at early time
- Short range rapidity correlation → originates at later time
- Shape of the correlation function changes with correlation length

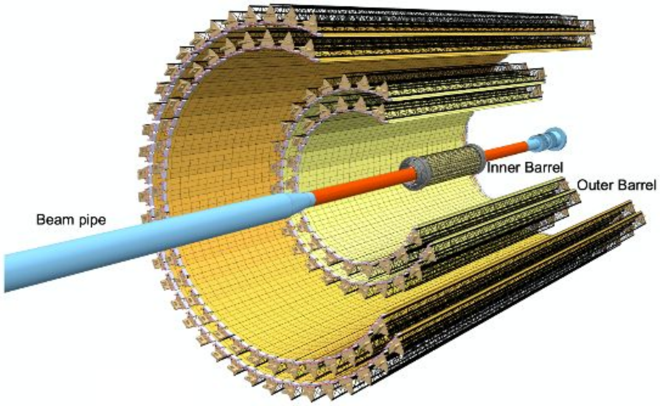
Acceptance dependence of correlation

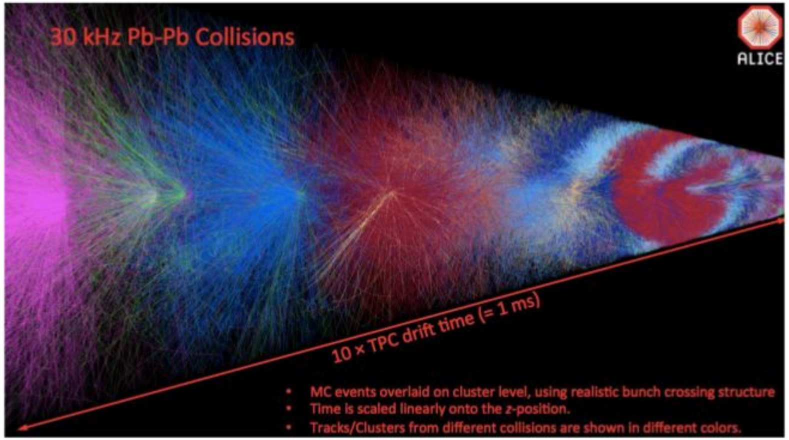


ALICE, arXiv:2204.10166

- 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

ALICE 2 and future perspectives (LHC Runs 3 – 4)





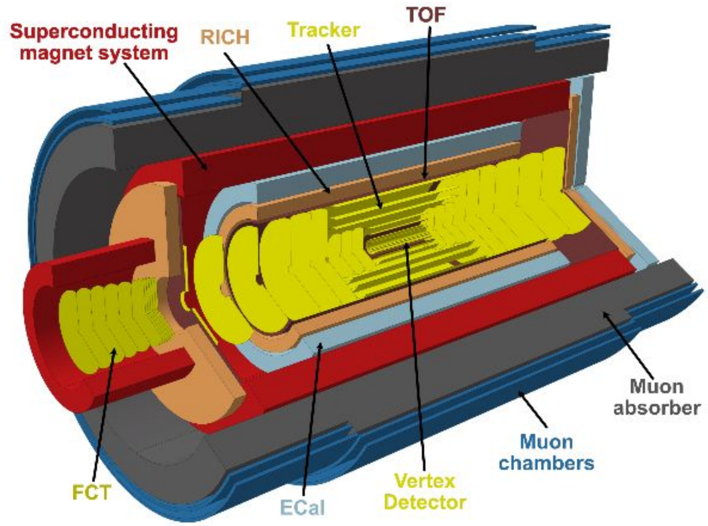
- New Inner Tracking System:
  improved tracking at low p_T and vertex resolution
  → high tracking efficiency at low p_T

- Continuous readout system of the TPC using GEMs:
  will provide a factor 50 more statistics in Pb–Pb
  → $O(10^9)$ Pb–Pb and $O(10^{11})$ pp events

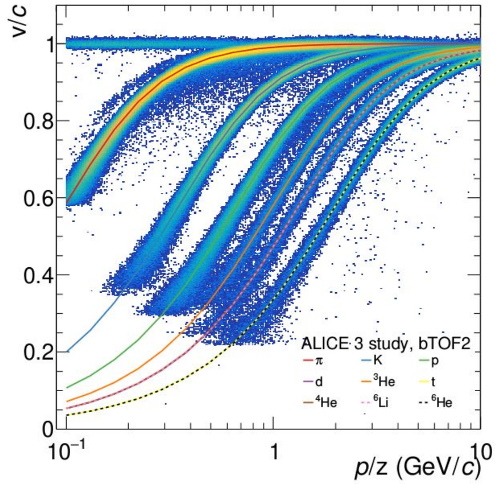
Improved statistics:

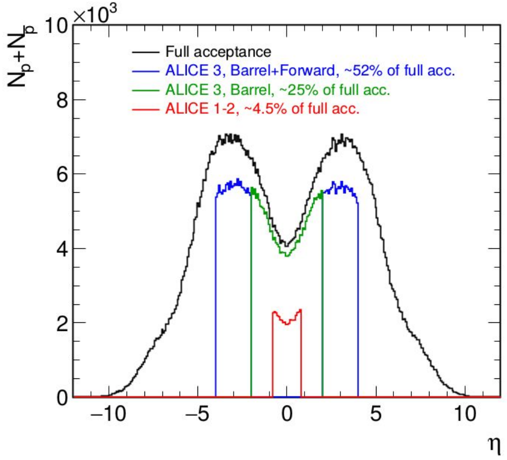
- Precise measurements of antideuteron fluctuation
- Higher-order correlations and cumulants
- A=3 nuclei and in measurements pp collisions

ALICE 3 and future perspectives (LHC Runs 5 – 6)



CERN-LHCC-2022-009





- High statistics: $O\,(10^9)$ Pb–Pb events
- Large acceptance → $|\eta| < 4$
- High PID purity

Allow precise mapping of correlation length between nuclei and nucleon

Summary

First measurement of event-by-event **nuclei fluctuation** and its correlation with nucleon in heavy-ion collisions gives additional testing ground for nucleosynthesis

SHM:

- Simultaneously describes the κ_2/κ_1 ratio of antideuteron and its correlation with antiproton but with a much smaller correlation volume
  → New theory developments are needed for resolving this conundrum between proton and deuteron
  – partial chemical equilibrium or the implementation of the interaction of hadrons through phase-shift

Coalescence:

- Available coalescence model calculations do not simultaneously describe the antideuteron fluctuations and its correlation with antiproton

- Observables show a great sensitivity to the initial correlation between the antiproton and the antineutron which can be used for further development of these models

Future

- ALICE2 and ALICE3 will provide an unique opportunity to extend these measurements to heavier antinuclei and to higher order correlation coefficients and cumulants

Summary

First measurement of event-by-event **nuclei fluctuation** and its correlation with nucleon in heavy-ion collisions gives additional testing ground for nucleosynthesis

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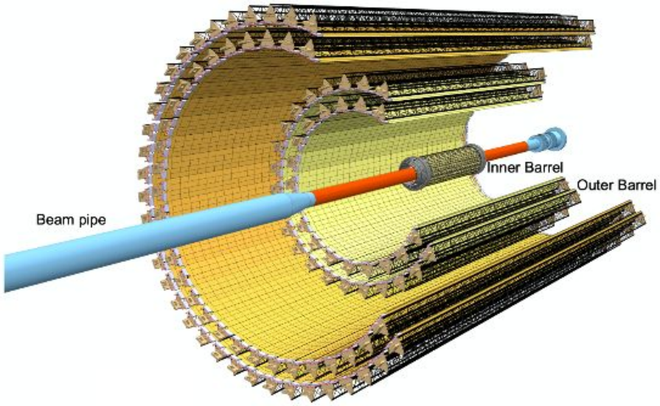
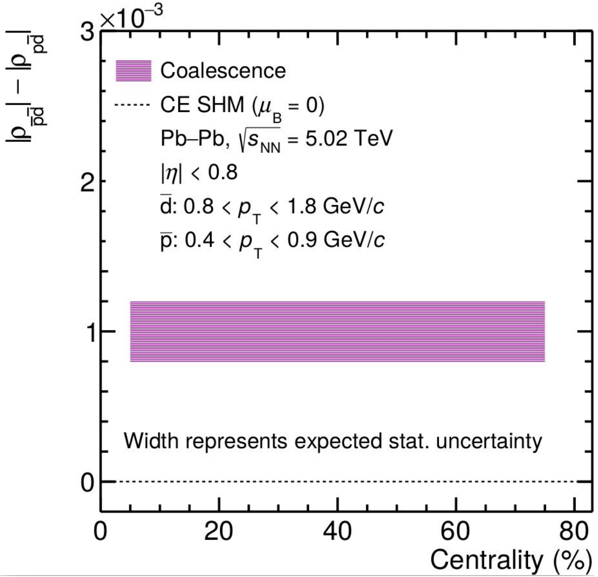
Thank you for your attention

Back up

ALICE 2 and future perspectives (2022-2030)





- New Inner Tracking System: improved tracking at low p_T and vertex resolution → high tracking efficiency at low p_T
- Continuous readout system of the TPC using GEMs: will provide a factor 50 more statistics in Pb–Pb → $O(10^9)$ Pb–Pb and $O(10^{11})$ pp events
- Light ITS: significantly reduced material budget → negligible contribution of p and d from spallation

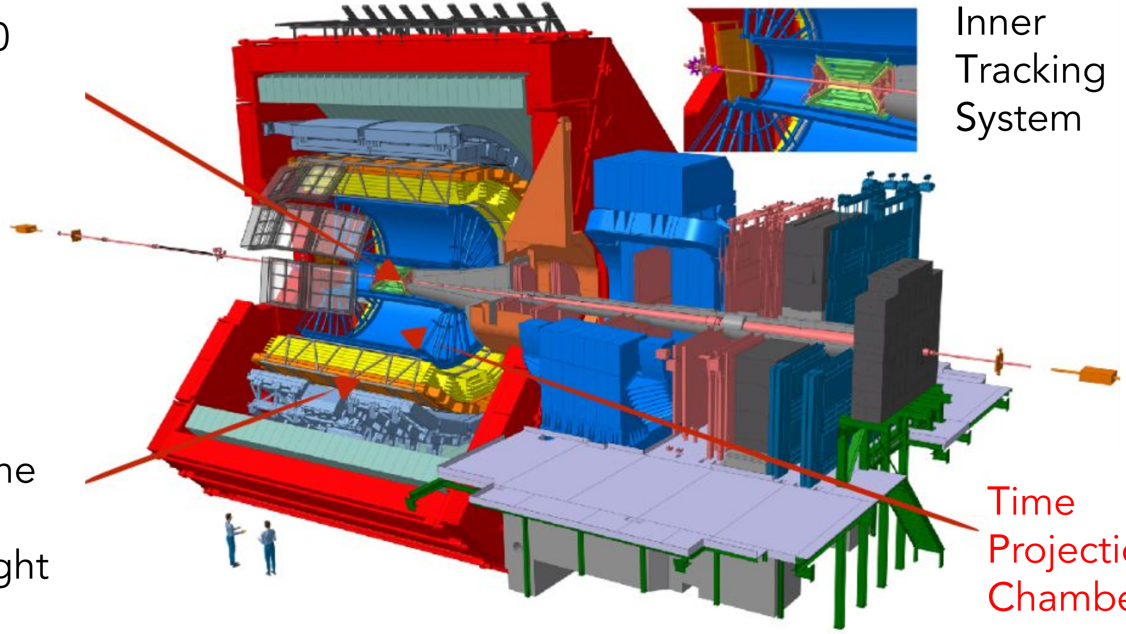
Source of correlation:

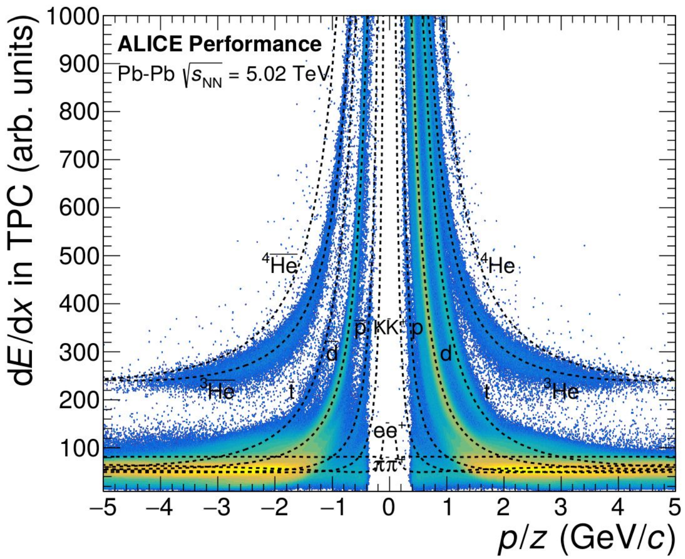
- antiproton-antideuteron: coalescence + conservation
- proton-antideuteron: conservation

Reduced material budget:

- Difference between antiproton-antideuteron and proton-antideuteron correlation

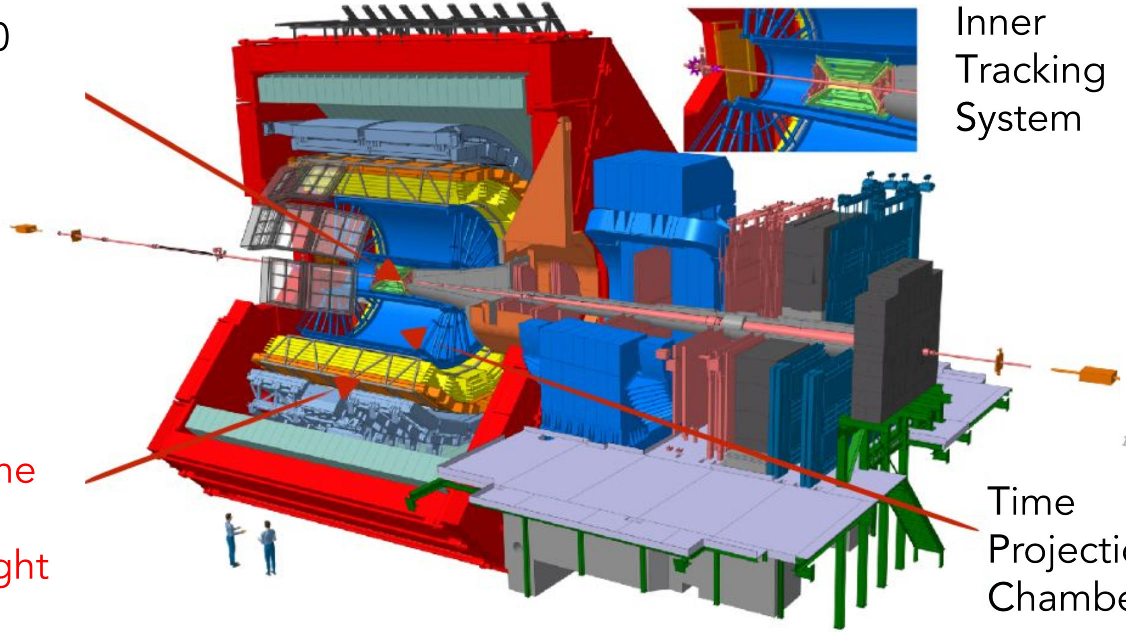
(Anti)Nuclei identification

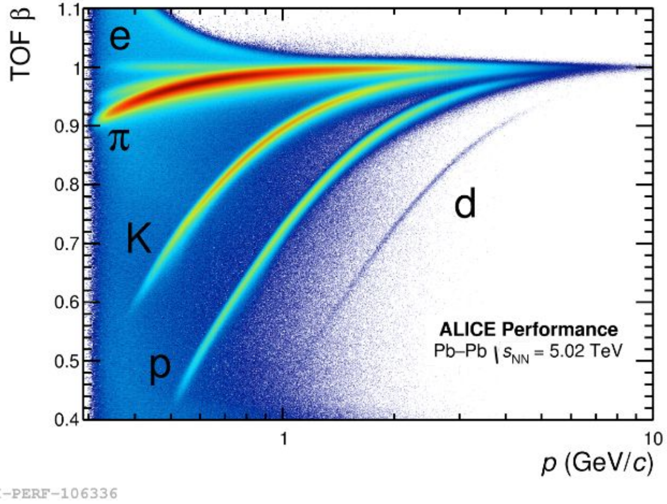




- At low momentum the specific energy loss measured by TPC provides excellent PID for deuterons → rel. σ dE/dx ~6.5% (in Pb–Pb collisions)

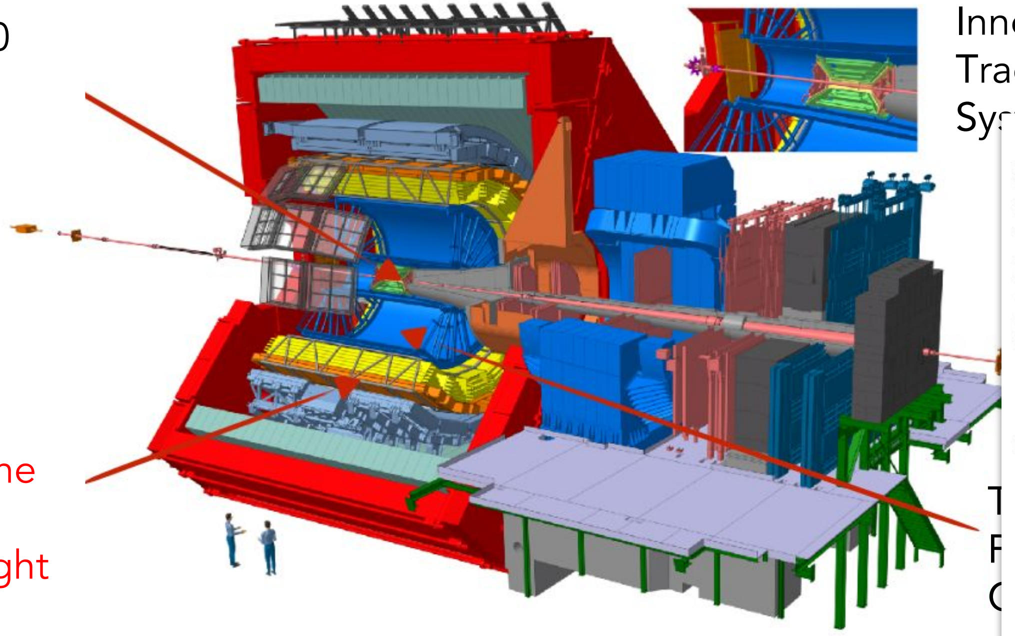
(Anti)Nuclei identification

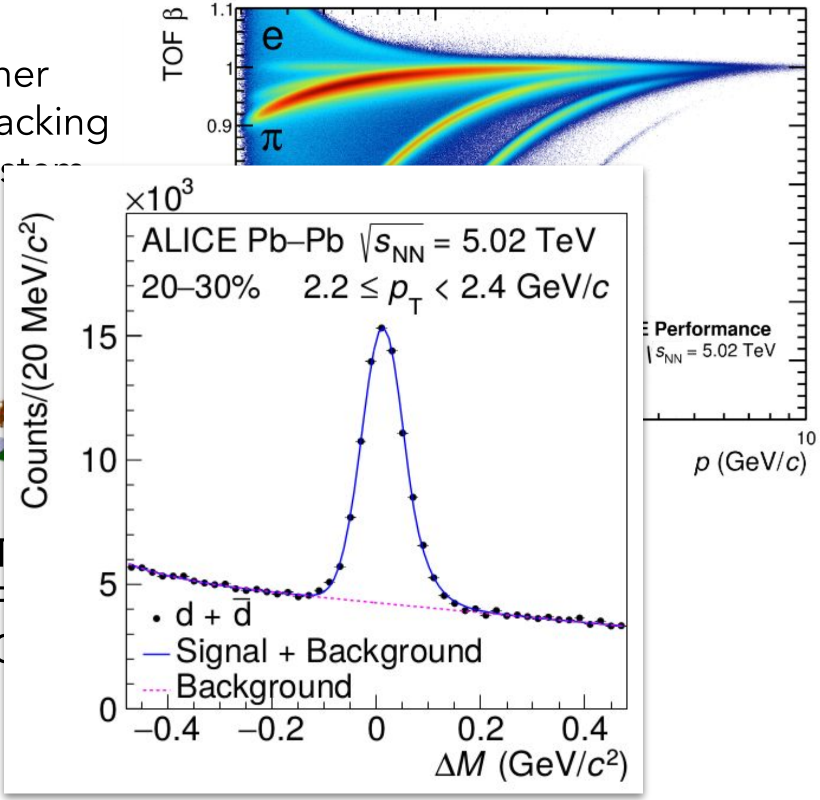




- At high momentum the PID is performed using TOF to measure the β hence the mass of the particle → rel. σ TOF-PID ~ 65 ps in Pb–Pb collisions

(Anti)Nuclei identification





ALICE , Phys. Rev. C 102 (2020) 055203

- At high momentum the PID is performed using TOF to measure the β hence the mass of the particle → rel. σ TOF-PID ~ 65 ps in Pb–Pb collisions

Fluctuation as a probe of deuteron synthesis

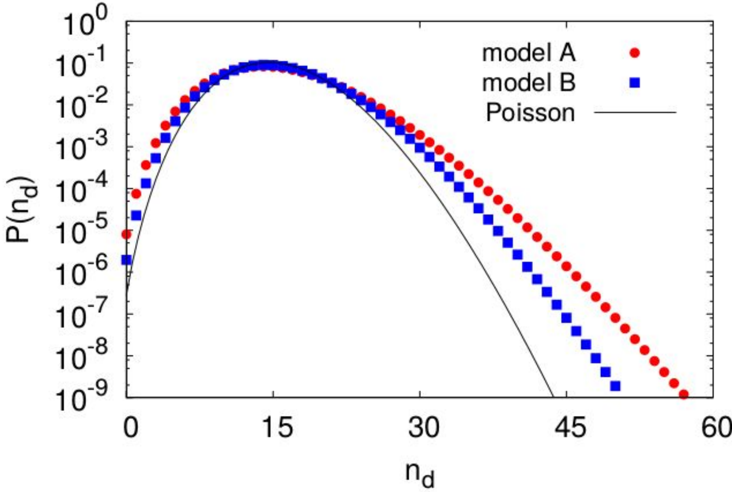
Event by event deuteron distribution:

- 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:

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

  - Final deuteron multiplicity distribution:

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



Jan Steinheimer et al., Phys. Rev. C 93 , (2016) 054906

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

Model parameters:

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

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

Coalescence model

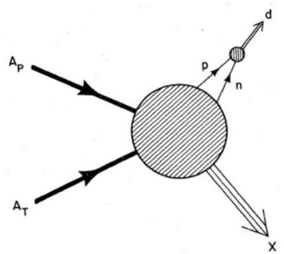
- Bound states produced at phase boundary are destroyed by interactions in the hadron gas phase
- Nuclear clusters are formed at kinetic freeze-out by coalescence of nucleons (hyperons) if nucleons are close in phase space
- Simple Coalescence model: only momentum correlations are considered: $\Delta p_{ij} = 0$

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

Invariant yield of nuclei

Coalescence parameter

Invariant yield of nucleon



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

- Advanced Coalescence model:

$$N_d = g_d \int d^3\mathbf{x}_1 \int d^3\mathbf{k}_1 \int d^3\mathbf{x}_2 \int d^3\mathbf{k}_2 f_n(\mathbf{x}_1, \mathbf{k}_1) f_p(\mathbf{x}_2, \mathbf{k}_2) W_d(\mathbf{x}_1 - \mathbf{x}_2, (\mathbf{k}_1 - \mathbf{k}_2)/2),$$

spin-isospin degeneracy factor

phase space distributions of nucleon

Wigner function of nuclei

$$N_d = \frac{3 N_n N_p}{4 (m T_K R^2)^{3/2}} \frac{1}{\left(1 + \frac{1}{m T_K \sigma^2}\right)^{3/2}} \frac{1}{(1 + \frac{\sigma^2}{4R^2})^{3/2}}$$

$$\sigma = \sqrt{8/3}\, r_d$$

Nuclei yield depends on source size R, finite size r_d of the cluster and kinetic freeze-out temperature T_k

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

Experimental challenges: efficiency correction

- Efficiency correction depends on the event-by-event efficiency distributions.
  - ~binomial distribution
  - MC closure test is performed to validate the method

Binomial efficiency corrected cumulant:

$\kappa_1 = <q_1>$

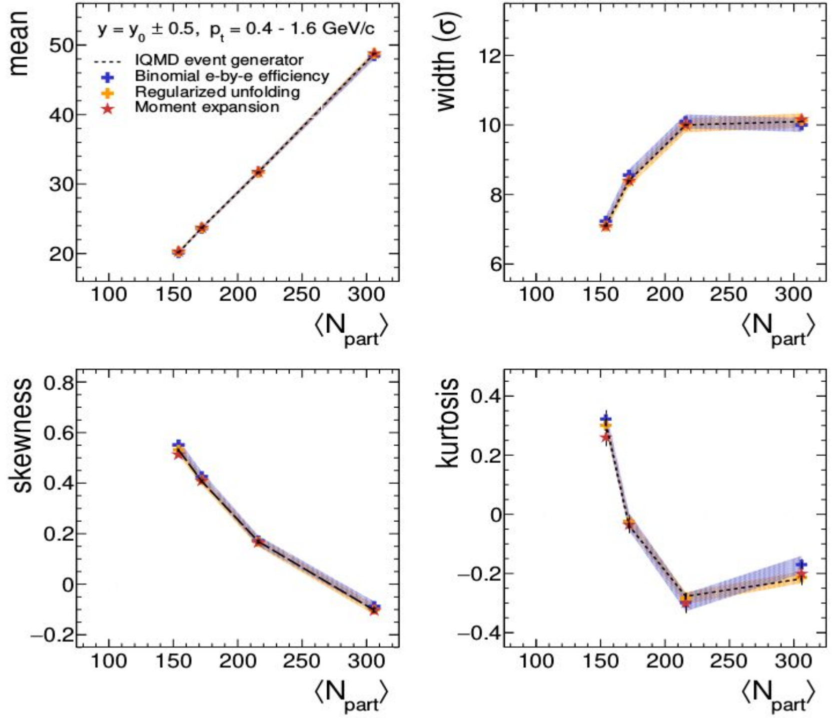
$\kappa_2 = <q_1^2> - <q_1>^2 + <q_1> - <q_2>$

$\kappa_{11} = <q_1^d q_1^p> - <q_1^d><q_1^p>$

$\rho = \kappa_{11} / \sqrt{(\kappa_2^d \kappa_2^p)}$ *T. Nonaka et al., Phys. Rev. C 95, (2017) 064912*

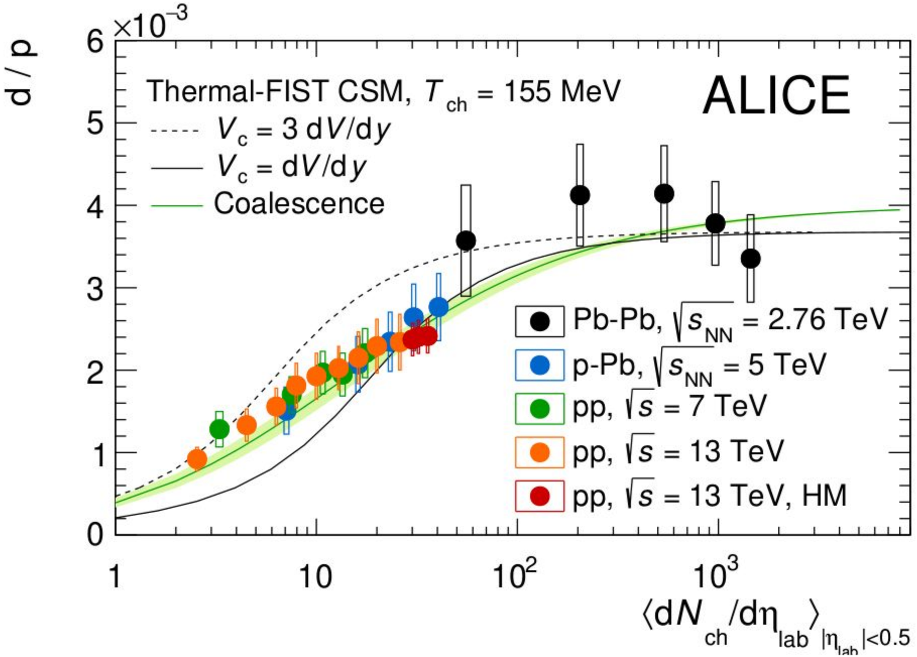
$q_n = \sum_{i=1}^{M} (n_i/\varepsilon_i^n)$

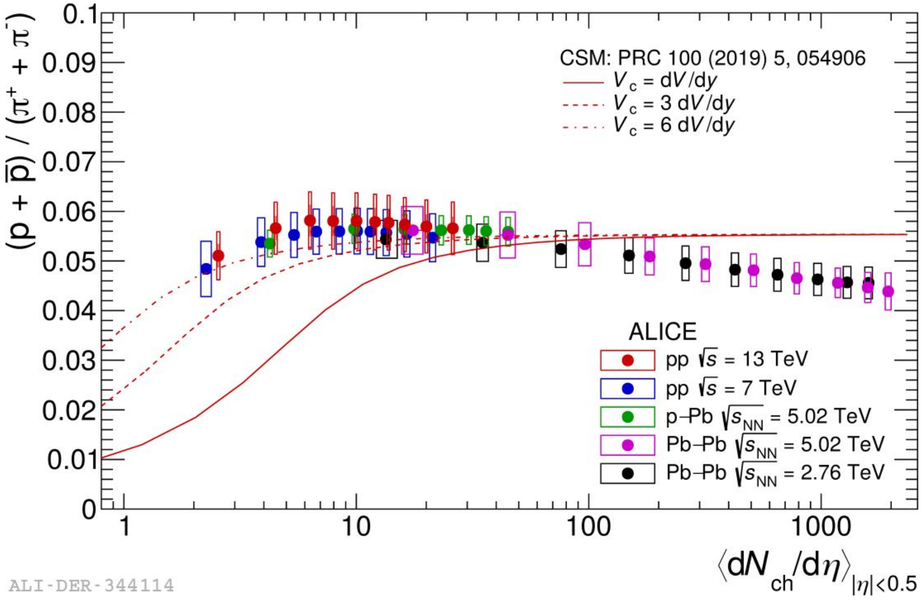
M = number of p_T bins
ε = efficiency
n_i = raw counts in i^th p_T bin



HADES, Phys. Rev. C 102, (2020) 024914

Thermal vs. Coalescence: A=2 nuclei



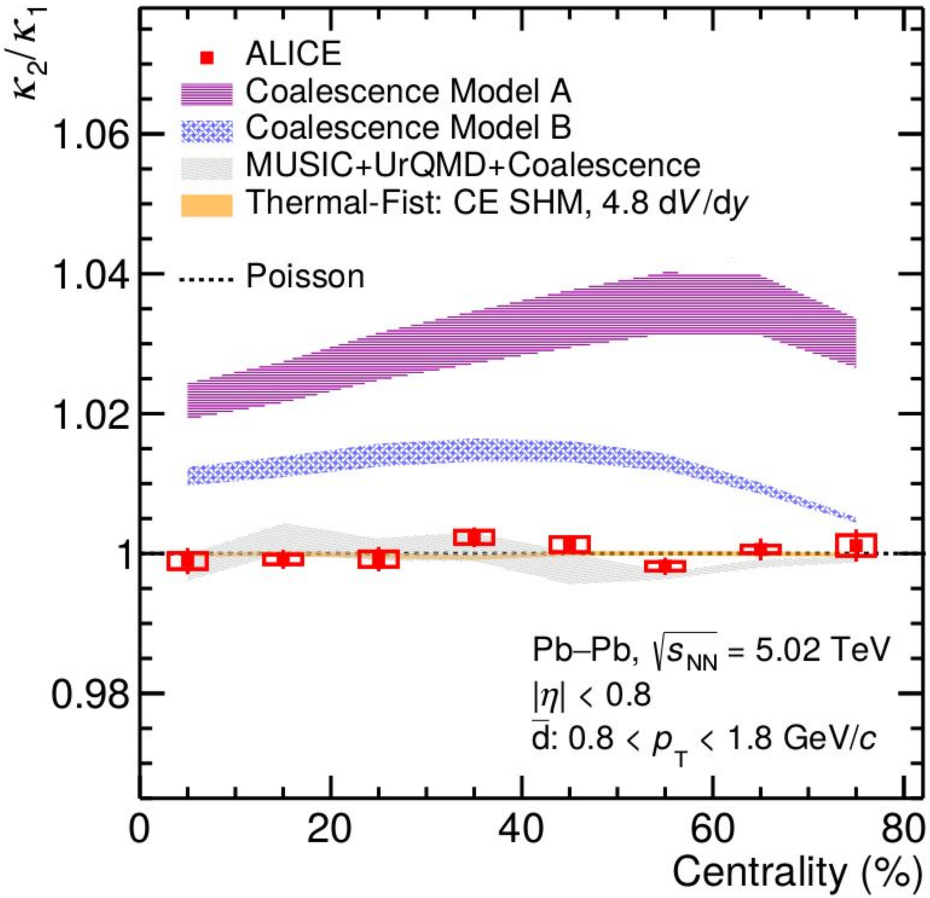


ALICE, JHEP 01 (2022) 106

- With the same correlation volume (V_c) proton over pion ratio is not reproduced at low multiplicity

$V_c \rightarrow$ volume in which baryons are correlated due to baryon number conservation

First antideuteron fluctuation measurement



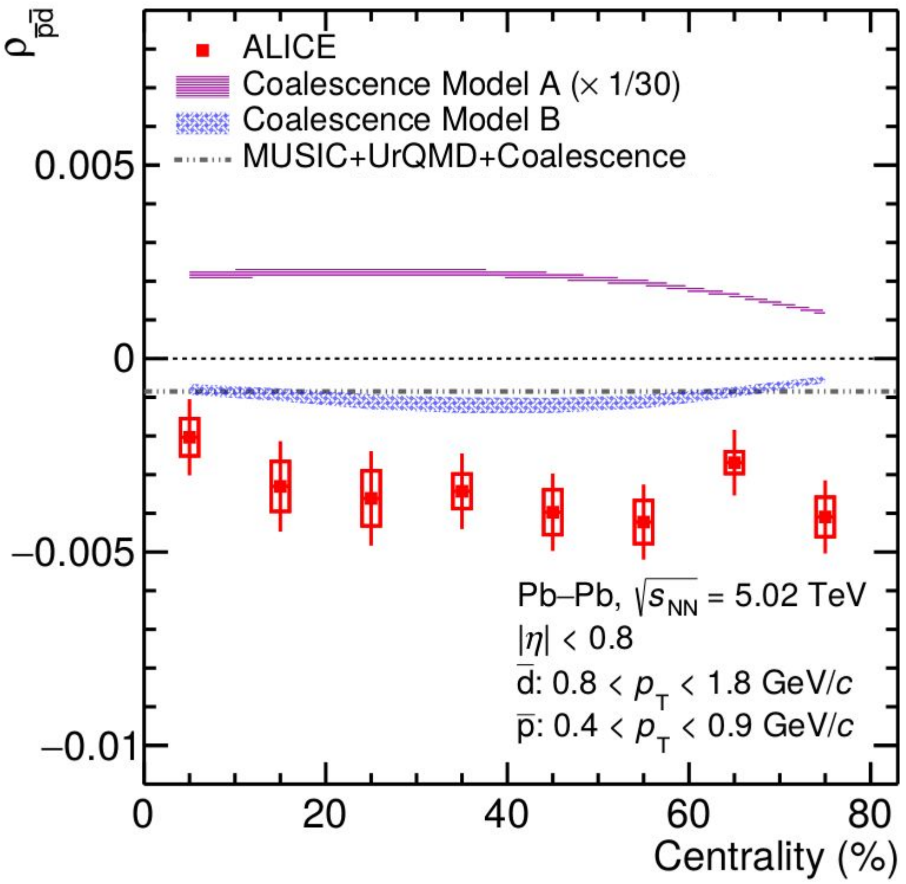
- MUSIC+UrQMD+Coalescence: coupling coalescence to a hydrodynamical model with hadronic interactions in the final state
- Consistent with the data
- Difference is due to the method of conservation

– Simple coalescence: perturbative approach of nuclei production

– MUSIC+UrQMD+Coalescence: sequential production of nuclei

K. -J. Sun et al., arXiv:2204.10879
ALICE, arXiv:2204.10166

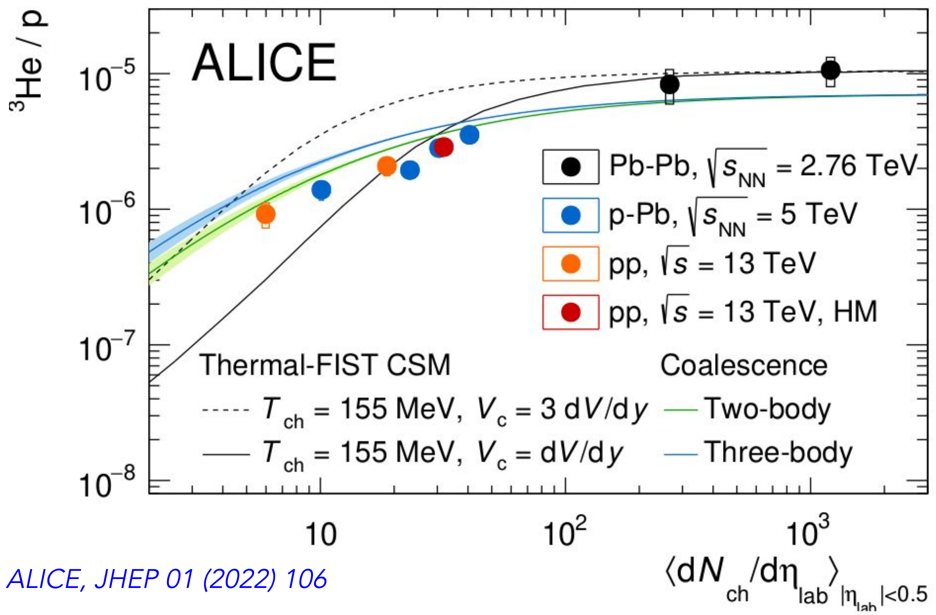
Correlation between antideuteron and antiproton



- Evidence of small negative correlation – in events with at least one antideuteron, there are $O(0.1\%)$ less antiproton than in an average event
- Rules out Coalescence model with correlated production of nucleons – isospin conservation in antiproton chanel
- Qualitatively explained by Coalescence model with independent fluctuation of nucleons
- MUSIC+UrQMD+Coalescence ≃ Coalescence model B

K. -J. Sun et al., arXiv:2204.10879
ALICE, arXiv:2204.10166

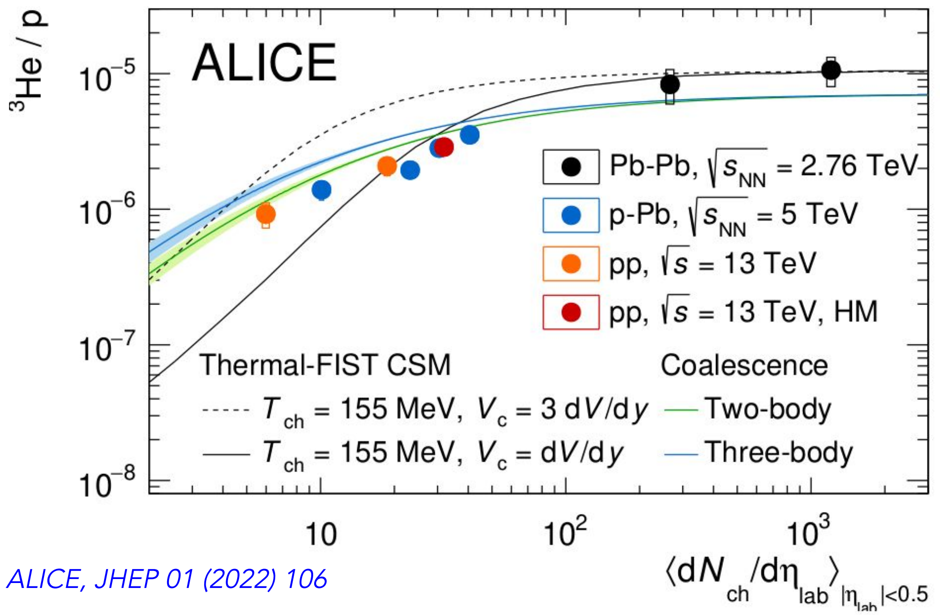
Thermal vs. Coalescence: A = 3 nuclei



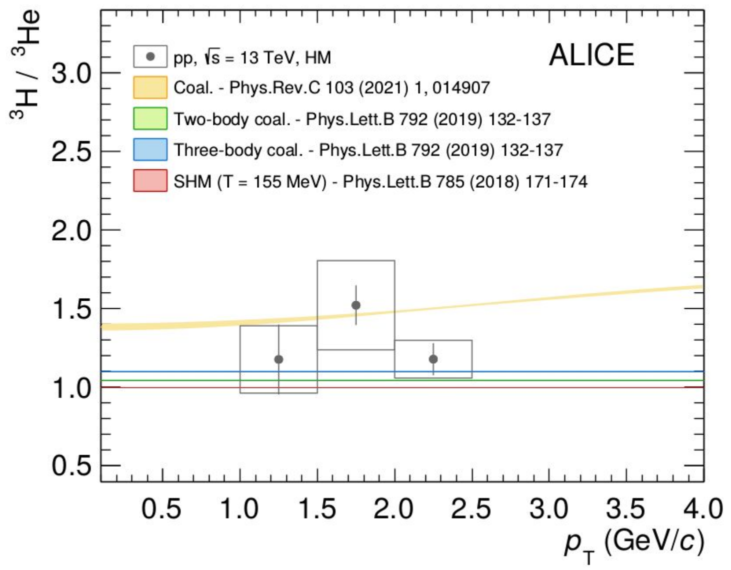
ALICE, JHEP 01 (2022) 106

- Qualitatively described by both models

Thermal vs. Coalescence: A = 3 nuclei



ALICE, JHEP 01 (2022) 106

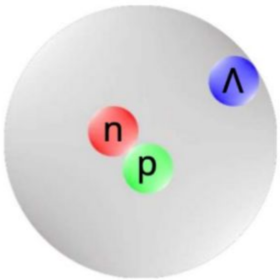


- Qualitatively described by both models

- SHM: $^{3}H/^{3}He \sim 1$ because of similar mass
- Coalescence: $^{3}H/^{3}He > 1$ as $r(^{3}H) / r(^{3}He) \sim 0.9$

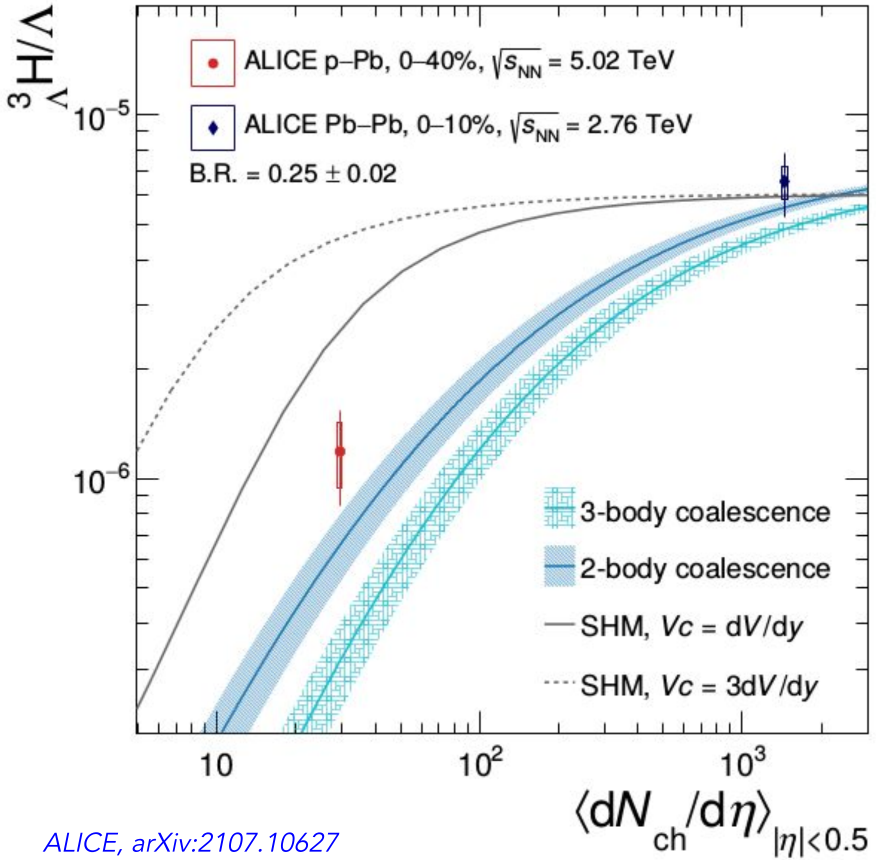
No conclusive evidence to distinguish between production mechanisms

Thermal vs. Coalescence: hypertriton



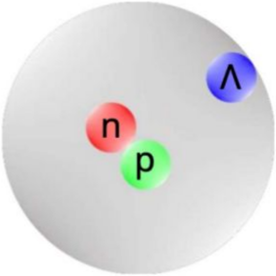
$\sqrt{\langle R_c^2 \rangle}$ = 4–5 fm

- 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 but not in AA collisions



ALICE, arXiv:2107.10627

Thermal vs. Coalescence: hypertriton



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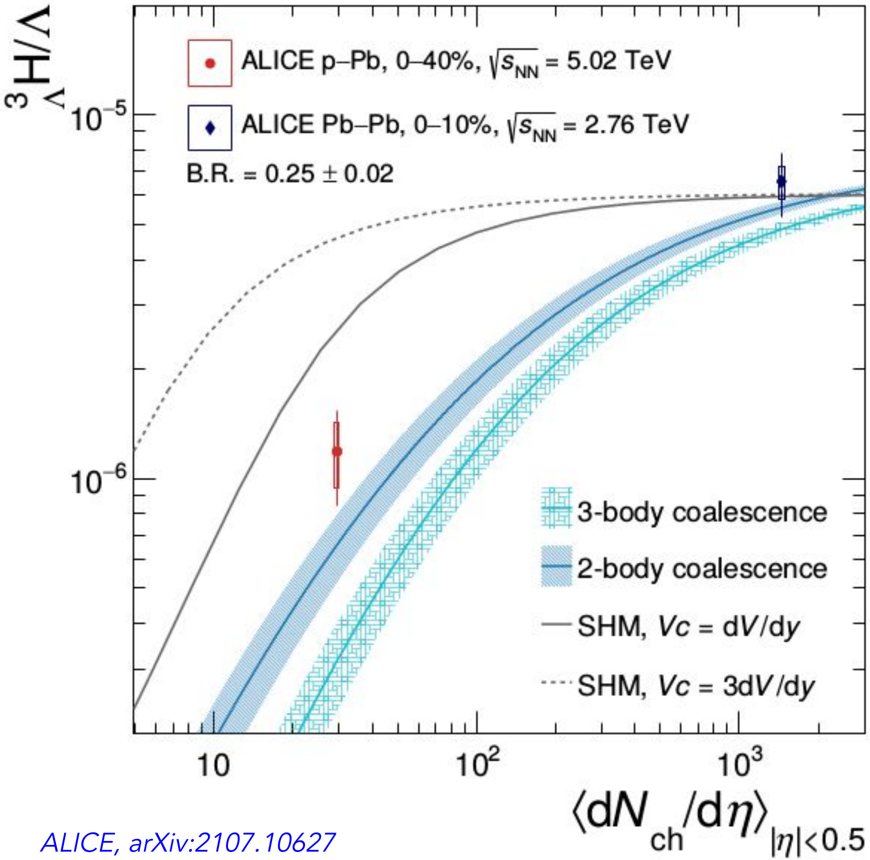
Open points in SHM:

- Hadrons are assumed as point-particle
- Large root-mean-square radius ~ 4–5 fm > system volume in pp / p-Pb collisions



ALICE, arXiv:2107.10627

Experimental challenges: purity

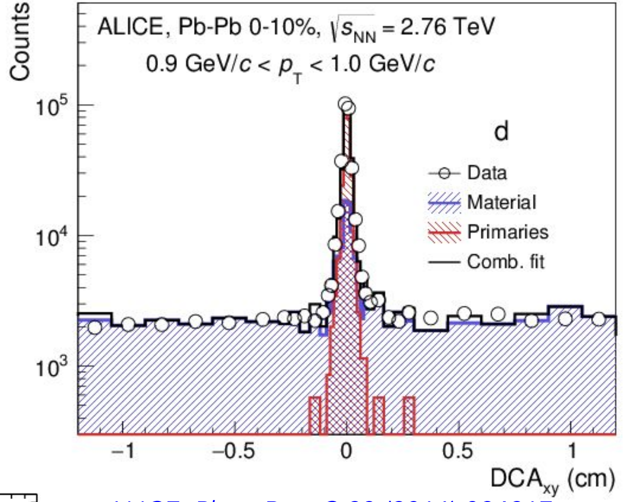
Choice of particle: Antiparticle instead of particle to remove secondaries produced in detector material

Particle identification:

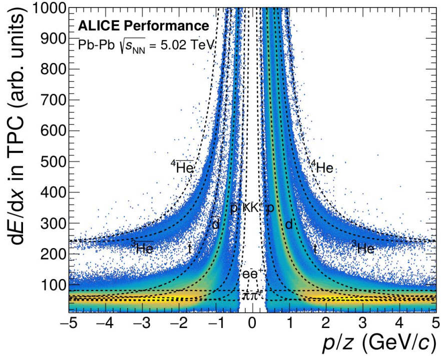
TPC: $0.8 < p_{\mathrm{T}} < 1.0$ GeV/c (antideuteron)
$0.4 < p_{\mathrm{T}} < 0.6$ GeV/c (antiproton)

TPC+TOF: $1.0 < p_{\mathrm{T}} < 1.8$ GeV/c (antideuteron)
$0.6 < p_{\mathrm{T}} < 0.9$ GeV/c (antiproton)

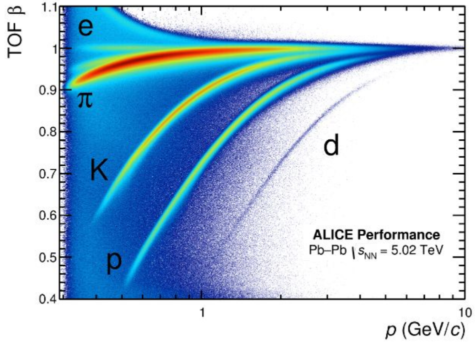
- Antideuteron purity > 90%, antiproton purity > 95%
- Autocorrelation due to misidentification of antiproton as antideuteron is negligible due to separate p_{T} acceptance



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

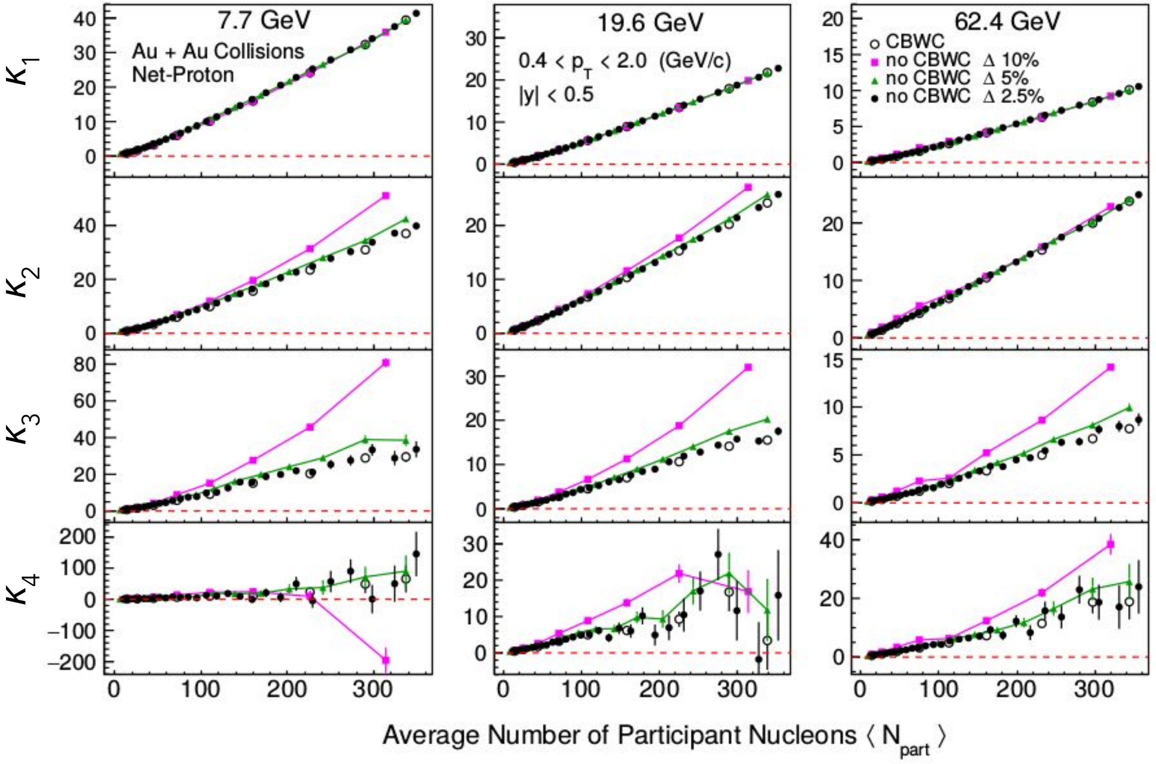


ALI-PERF-341664



ALI-PERF-106336

Experimental challenges: initial volume fluctuation

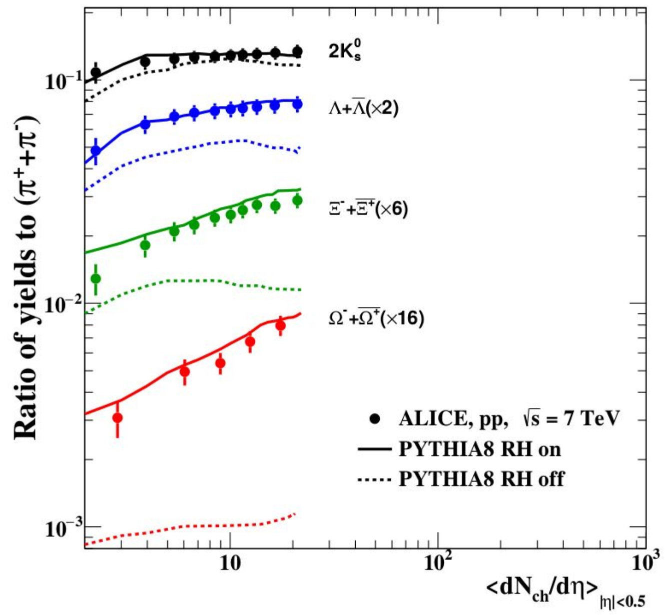


- Initial geometry and final-state multiplicity does not correspond one-to-one
- Volume fluctuations can be largely suppressed by centrality bin width correction (CBWC)

STAR, Phys. Rev. C 104, (2021) 024902

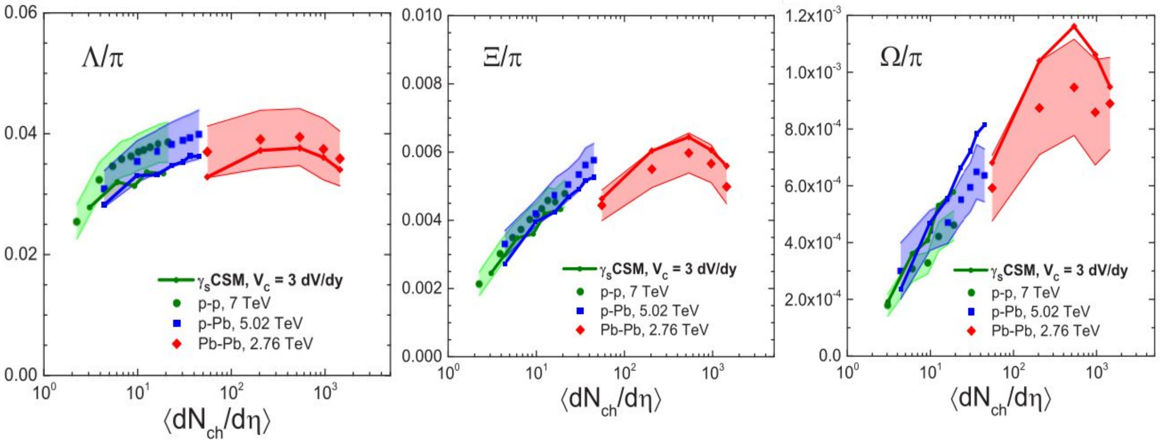
Perspectives for strangeness hadronization

PYTHIA



R. Nayak et al., Phys. Rev. D 100, (2019) 074023

Strange Canonical Ensemble of Thermal model



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

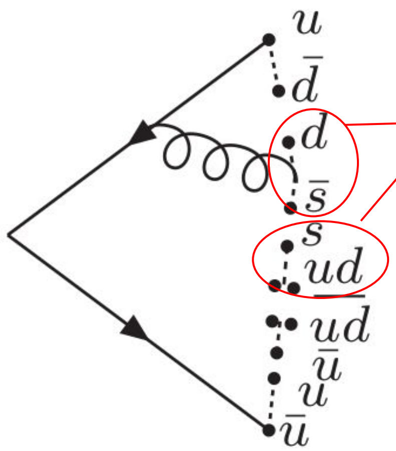
- Both PYTHIA and Thermal model explain strangeness production in small system

What is the underlying reason of strangeness enhancement in small system?

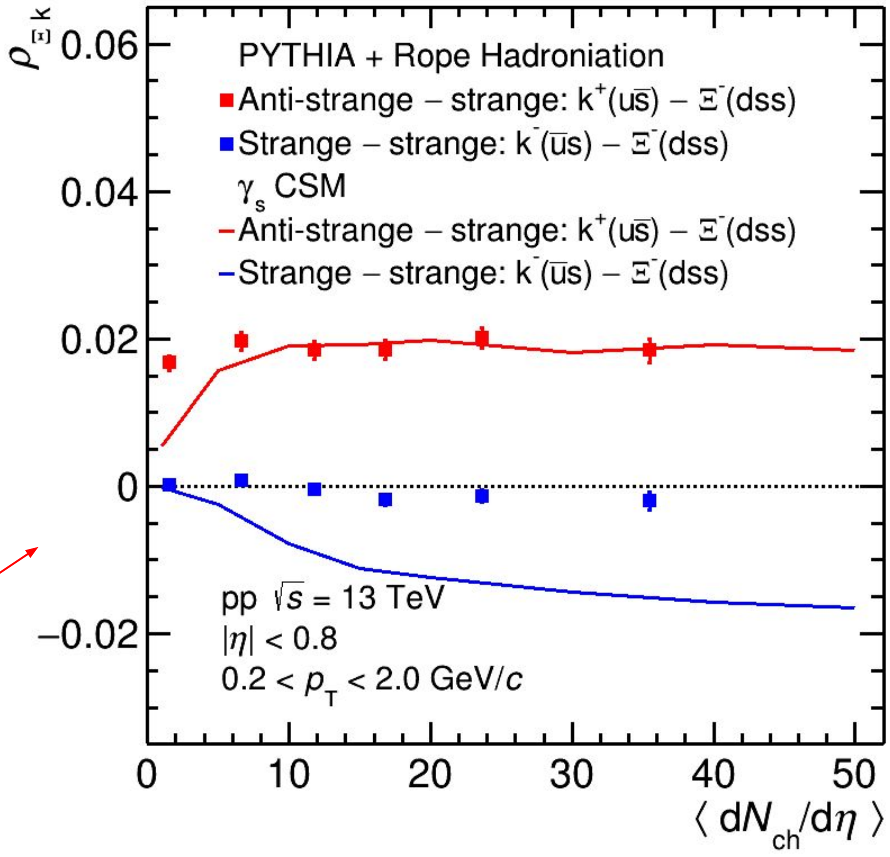
Canonical suppression of open strange hadrons / the inclusion of baryon junction in rope hadronization

Perspectives for strangeness hadronization

Lund string hadronization



- Production of strange hadrons is always associated with the production of antistrange hadron
- Negligible correlation between 2 strange or antistrange hadrons



Thermal model:

- Strangeness is conserved in a volume

Strangeness correlation can help to understand strange hadron production

Summary of nuclei production yield

Heavy-ion collisions: all models give similar predictions for light and hypernuclei yields

→ Need to go beyond the yield measurements

Small system: models can be discriminated using nuclei of larger radius

Survival of light nuclei in hadron gas

Hadron gas is a very hostile environment for light nuclei (reminder: binding energy ≈ few MeV)

- typical hadronic momentum transfer > 100 MeV/c

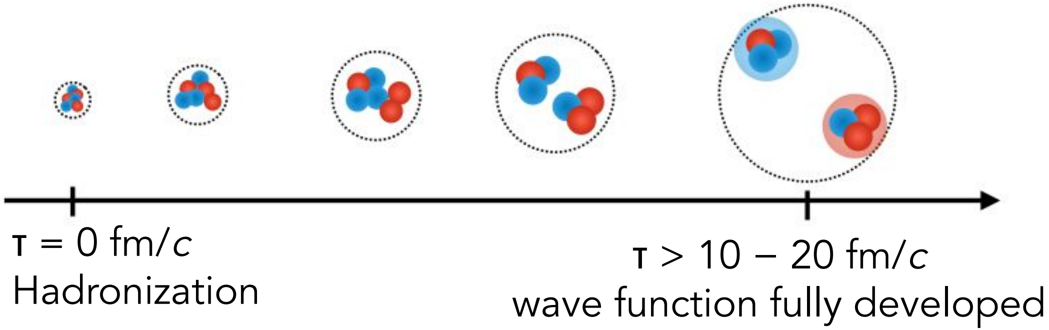
$$\sigma_{\pi d} > 100 \text{ mb} = 10 \text{ fm}^2$$

From SAID database

$$\lambda_d = \frac{1}{n\sigma} < \frac{1}{\frac{0.05}{\text{fm}^3} \times 10 \text{ fm}^2} = 2 \text{ fm}$$

Density at kinetic freeze-out
(when elastic interactions cease)

λ_d should exceed ≈ 10-15 fm for deuteron survival!



Assumptions:

- Light nuclei produced as compact (colorless) quark systems
  > Negligible interaction with hadrons
- Formation time > τ hadronic phase

Back up