New experimental observables to probe (anti)nucleosynthesis with ALICE

Francesco Mazzaschi on behalf of the ALICE Collaboration
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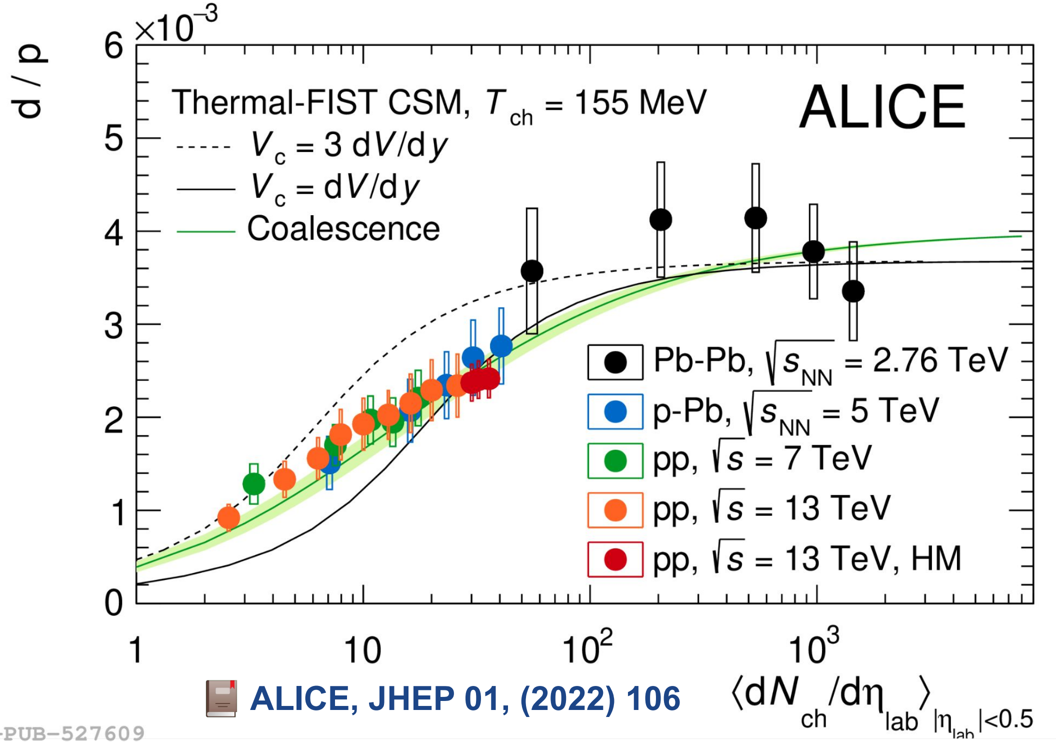
Nuclei production at LHC: Thermal vs. Coalescence

- Nuclei production measurements in high-energy collisions
  - from low (pp,p–Pb) to high (central Pb–Pb) charged-particle multiplicity

- Two successful models describe deuteron production
  - Thermal: V. Vovchenko et al., Phys. Lett. B 785, (2018) 171
  - Coalescence: K.-J. Sun et al., Phys. Lett. B 792, (2019) 132



- New observables required to investigate the nuclei synthesis mechanisms

Thermal model and baryon chemical potential (μ_B)

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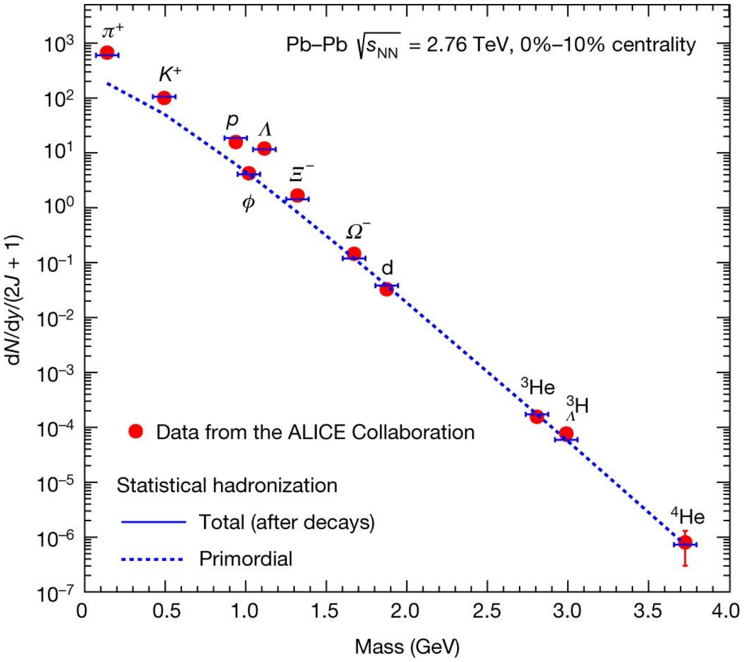
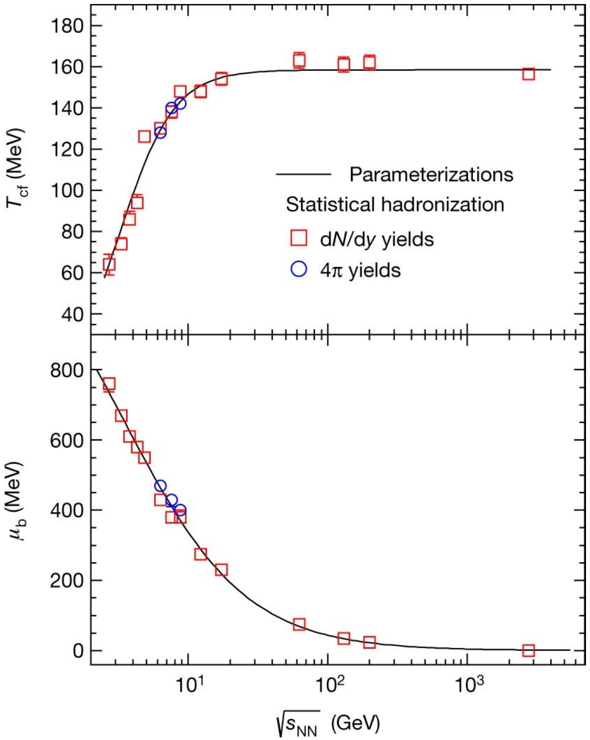
- thermal model fit of measured hadron yields in Pb–Pb collisions
  - $\mu_B \rightarrow$ measure of antimatter-matter imbalance
  - $\mu_B = 0.7 \pm 3.8$ MeV (0–5% Pb–Pb, $\sqrt{s_{NN}} = 2.76$ TeV)

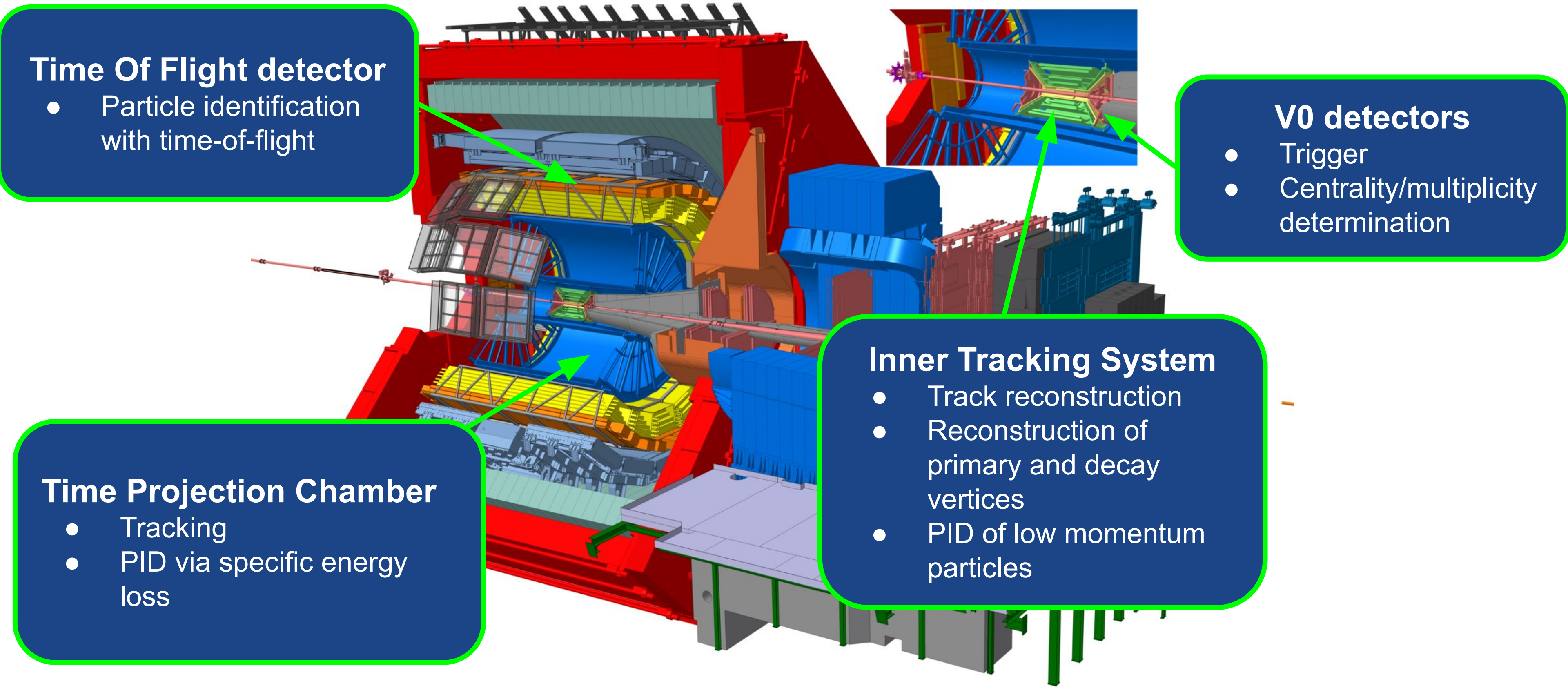




New measurements of antiparticle-to-particle ratios with reduced statistical and systematic uncertainties

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

The ALICE Run 2 detector



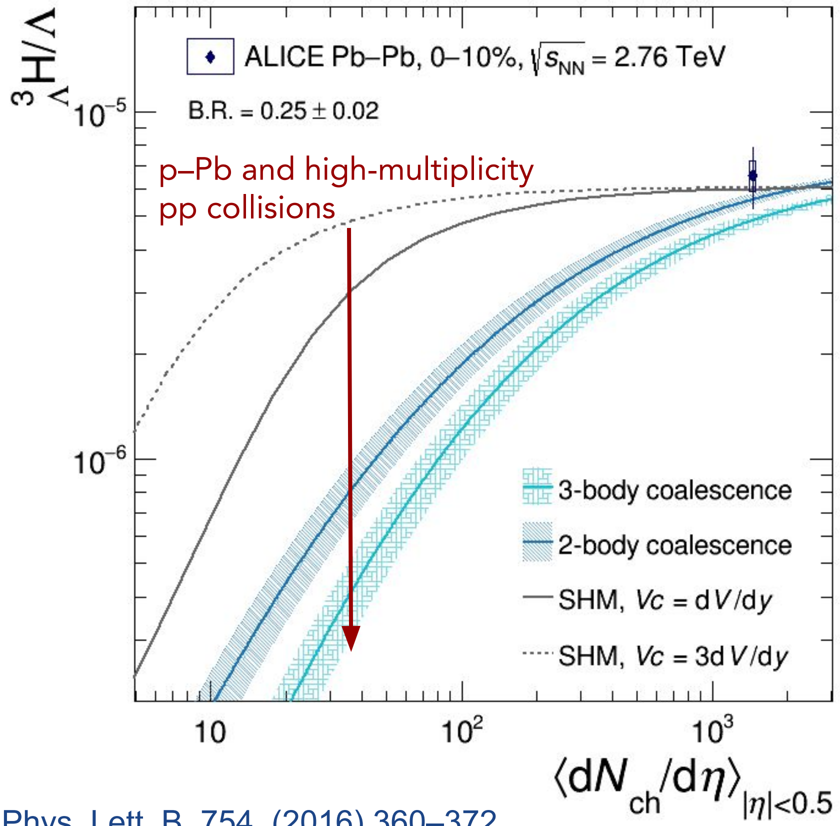
LHC Run 3: ITS and TPC upgrades

Small systems

First measurements of ${}^{3}_{\Lambda}H$ production in pp and p–Pb collisions

Small collision systems: $^{3}_{\Lambda}H$ synthesis

- Hypertriton ($^{3}_{\Lambda}H$):bound state of a neutron, a proton and a Λ
- Extreme weakly bound state (B_{Λ} ~ 100 keV)
  - $^{3}_{\Lambda}H$ / Λ → large separation between SHM and coalescence predictions at low charged-particle multiplicity density → coalescence relies on the radius of the particle relative to the system size while SHM does not
- $^{3}_{\Lambda}H$ production in pp and p–Pb: a key to understand the nuclear production mechanism at LHC

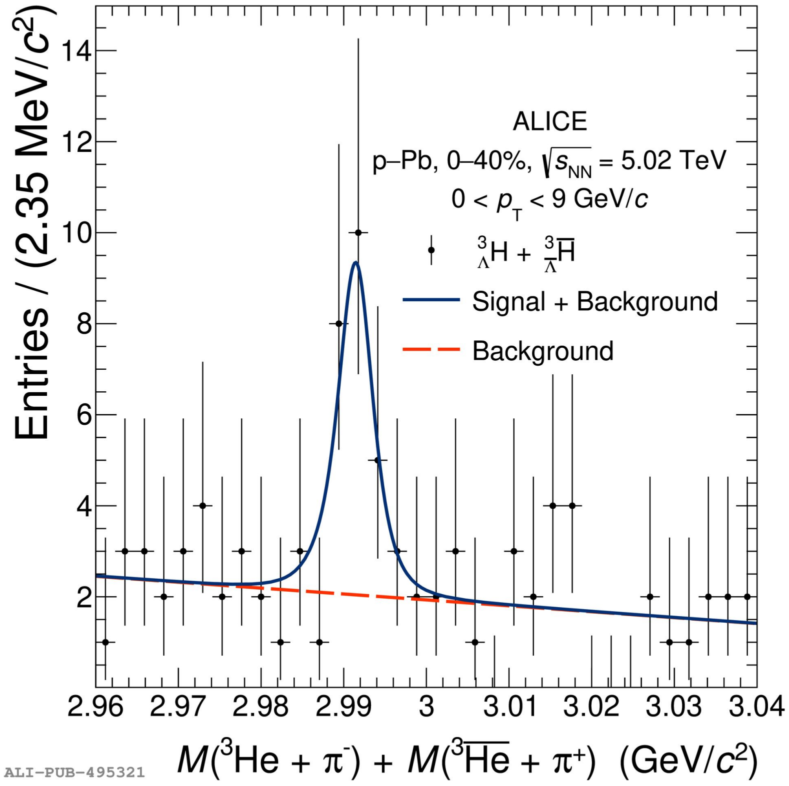


ALICE, Phys. Lett. B, 754, (2016) 360–372

$^{3}_{\Lambda}$H selection in pp and p–Pb collisions

- Data samples:
  - pp at $\sqrt{s}$ = 13 TeV and p–Pb at $\sqrt{s_{NN}}$ = 5.02 TeV collisions collected during Run 2
- $^{3}_{\Lambda}$H selection in pp: trigger on high multiplicity events using V0 detectors + topological cuts on triggered events
- $^{3}_{\Lambda}$H selection in p–Pb: 40% most central collisions + BDT Classifier
- Significance > 4σ both in pp and p–Pb

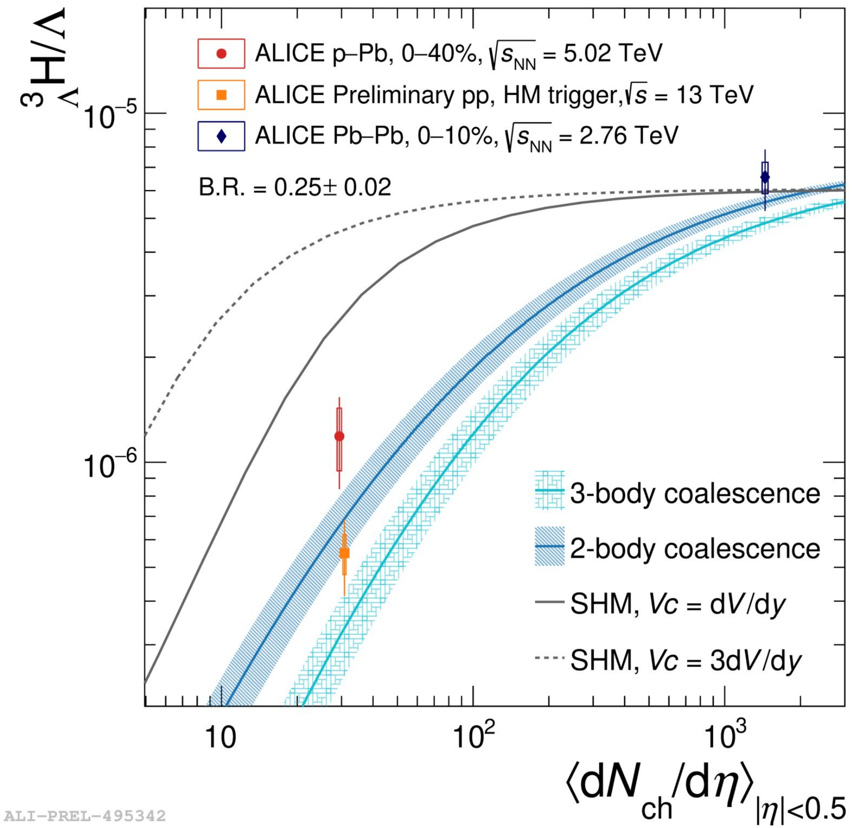
ALICE, Phys. Rev. Lett. 128, (2022), 252003



${}^{3}_{\Lambda}H$ / Λ in pp and p–Pb collisions

- First measurements of ${}^{3}_{\Lambda}H$ production in pp and p–Pb collisions
  - good agreement with 2-body coalescence [2]
  - tension with SHM at low charged-particle multiplicity density
    - $V_C = 3dV/dy$ excluded at a level of more than 6σ
    - First constraint to SHM possible configurations
- Coalescence quantitatively describes the ${}^{3}_{\Lambda}H$ suppression in small systems

ALICE, Phys. Rev. Lett. 128, (2022) 252003



Large systems

First measurement of antideuteron number fluctuations in Pb–Pb collisions

Precision measurement of baryon chemical potential μ_B in Pb–Pb collisions

Fluctuation as a probe of synthesis

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Event-by-event deuteron distribution

- Grand Canonical Ensemble (GCE) thermal model
  - Poisson
- Coalescence model: deviation from Poisson
  - Average deuteron multiplicity:

$$\lambda_d = B n_i n_j$$

coalescence parameter

protons

neutrons

  - Final deuteron multiplicity distribution:

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

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

Fluctuation as a probe of synthesis

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  - Poisson
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  - Average deuteron multiplicity:

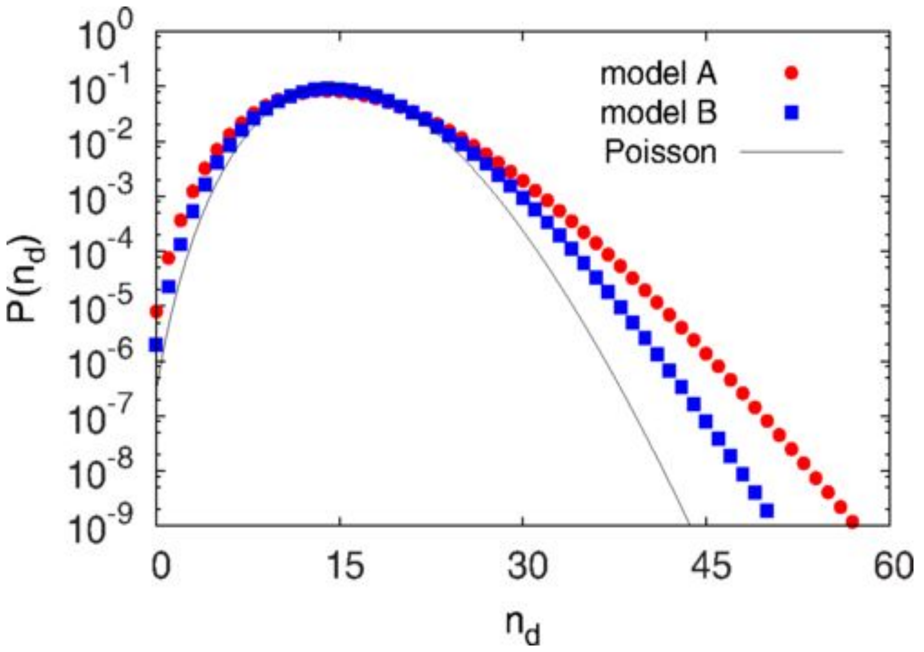
$$\lambda_d = B n_i n_j$$

coalescence parameter — # protons — # neutrons

  - 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

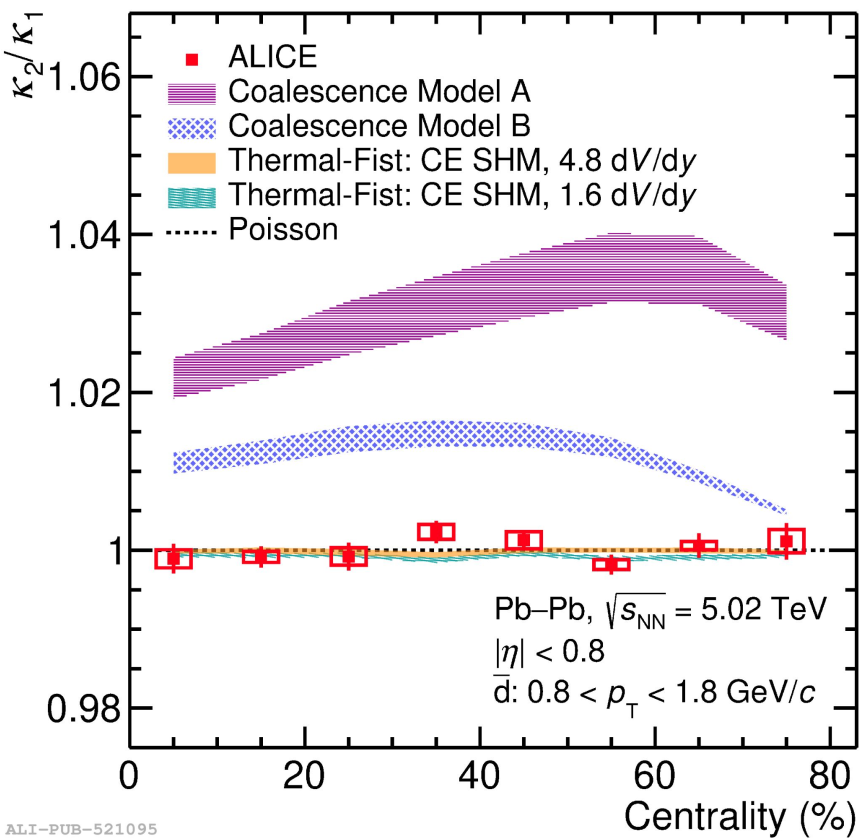


Jan Steinheimer et al., Phys. Rev. C 93 , (2016) 054906

Results: κ_2 / κ_1

- Cumulants:
  - $k_1 = < n >$
  - $k_m = < (n - <n>)^m >$, m = 2, 3
  - Poisson: $k_1 = k_2 = k_3$
- 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

arXiv:2204.10166



ALI-PUB-521095

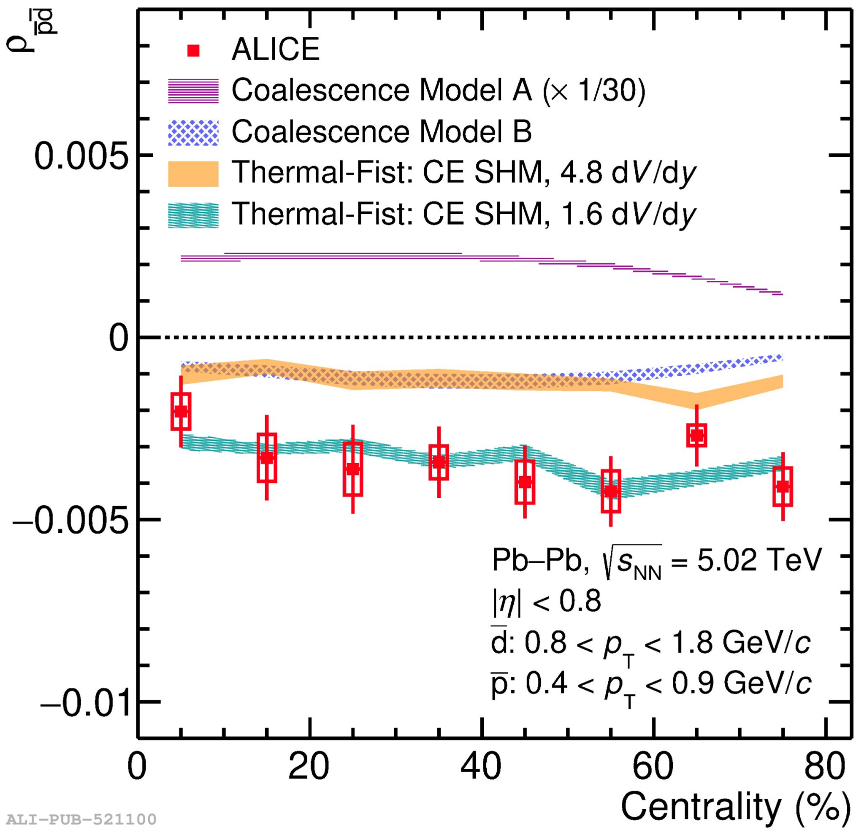
Results: Pearson correlation

- Pearson correlation:

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

- Negative correlation between antiprotons and antideuterons
  - predicted by Canonical Ensemble thermal model with V_C = 1.6 d*V*/d*y*
  - smaller correlation volume than for cumulant measurements of protons
  - qualitatively described by Model B
  - Model A ruled out

arXiv:2204.10166



Antiparticle-to-particle ratios and μ_B

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Grand Canonical Ensemble SHM [1]

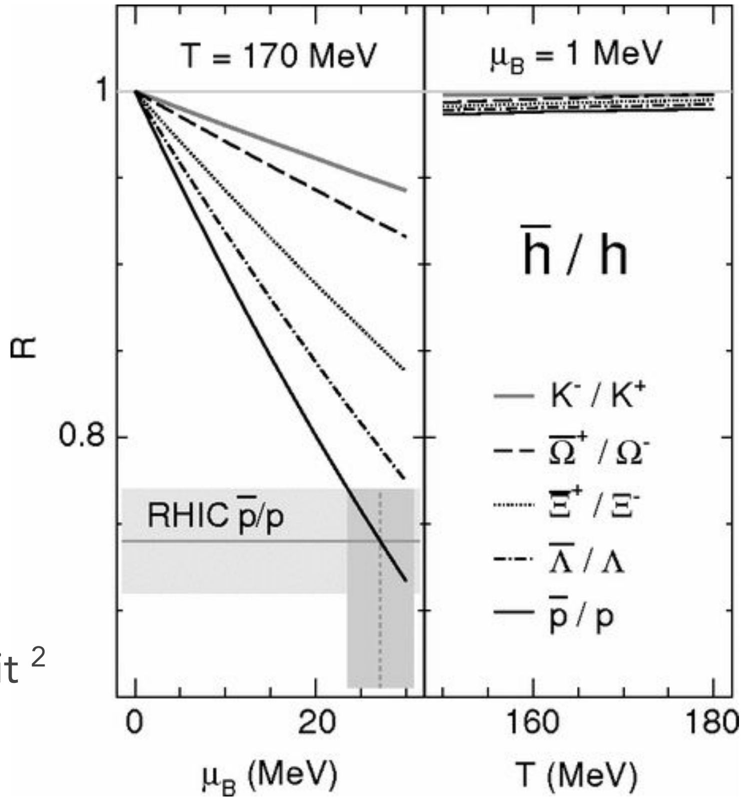
$$\bar{h}/h \propto exp[-2\frac{B_h\mu_b+S_h\mu_s+I_{3,h}\mu_{I_3}}{T}]$$

baryon number — strangeness — 3rd isospin component

Strangeness neutrality: $\mu_B \sim 3\mu_s$

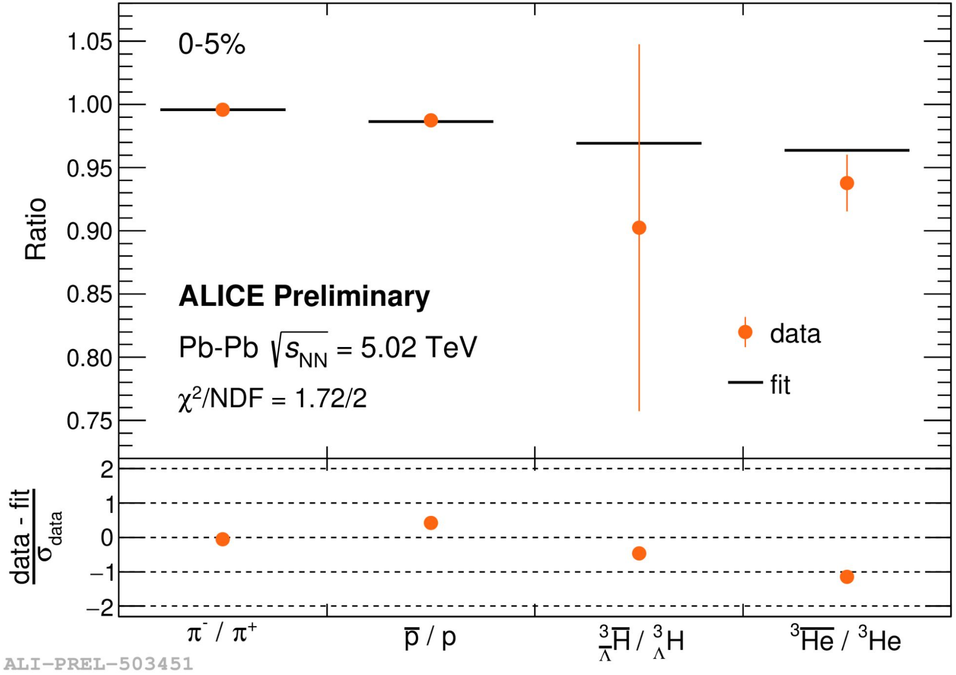
$$\bar{h}/h \propto exp[-2\frac{(B_h+S_h/3)\mu_B+I_{3,h}\mu_{I_3}}{T}]$$

- (anti)p, ^{3}He, $^{3}_{\Lambda}$H
- π ± (B = S = 0) to constrain μ_{I3}
- small dependence on temperature
  - fixed at T = 156.2 ± 1.5 MeV from SHM fit [2]
- sensitivity to strangeness content



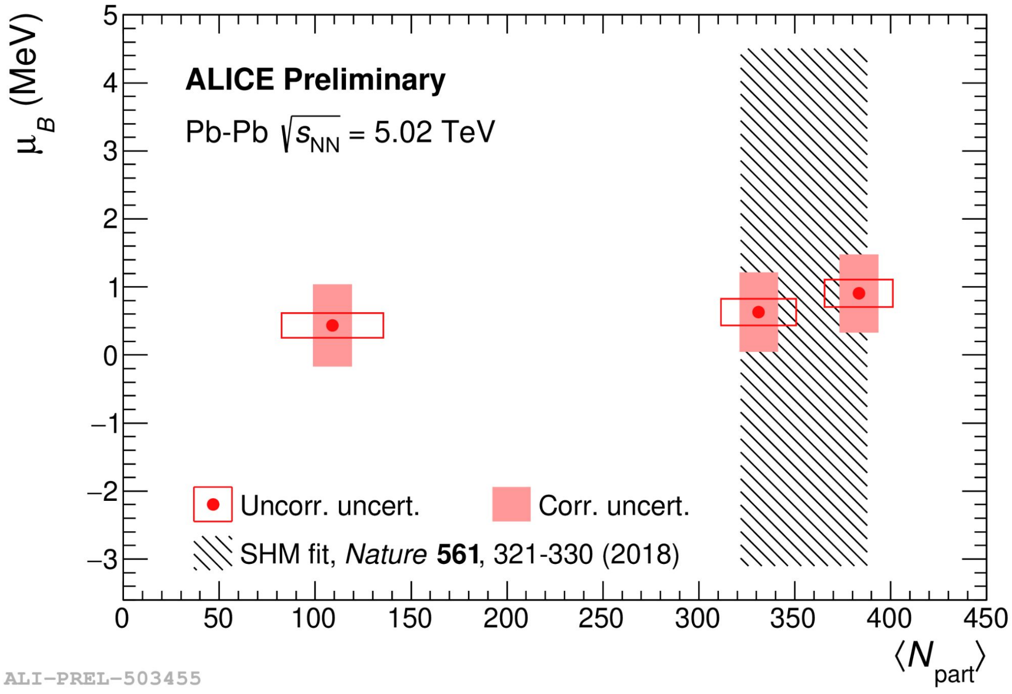
Antiparticle-to-particle ratios and μ_B

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



μ_B and centrality dependence

- 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



Conclusions

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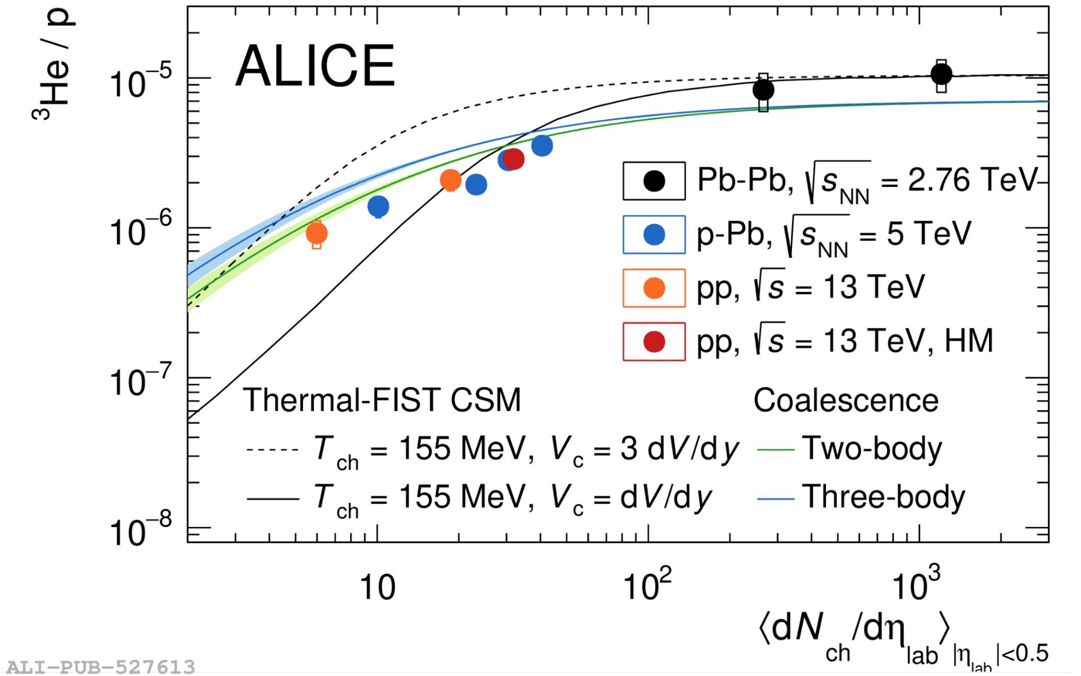
- New measurements performed by ALICE for probing the nucleosynthesis mechanisms in hadronic collisions
    - small systems: $^{3}_{\Lambda}$H / Λ ratio in pp and p–Pb favours coalescence expectation
    - large systems: antideuteron event-by-event fluctuations described by a simple Poissonian → SHM predictions
    - large systems: precision measurements of μ_B: no evidence of centrality dependence
- precision studies of (anti)nucleosynthesis using Run 3 and Run 4 data will strongly constrain the existing models with more measurements with increased precision in all collision systems

Backup slides

^{3}He production at LHC: Thermal vs. Coalescence

- ^{3}He/p vs multiplicity trend well described by coalescence
- ^{3}He/p ratio shows hint of deviation from both SHM and coalescence at intermediate multiplicity
  - coalescence is sensitive to the different source sizes parametrisation



ALICE, JHEP 01 (2022) 106

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