Production of light (hyper)nuclei in relativistic heavy-ion collisions

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Outline

- **Introduction**
- **Light Nuclei Production**
  - Coalescence Parameter
  - Yield Ratios
  - Nuclei Flow
- **Hypernuclei Production**
  - Lifetime
  - Strangeness Population Factor
  - Collectivity
- **Testing CPT Symmetry**
- **Discovery of Antimatter**
- **Summary & Outlook**

Introduction

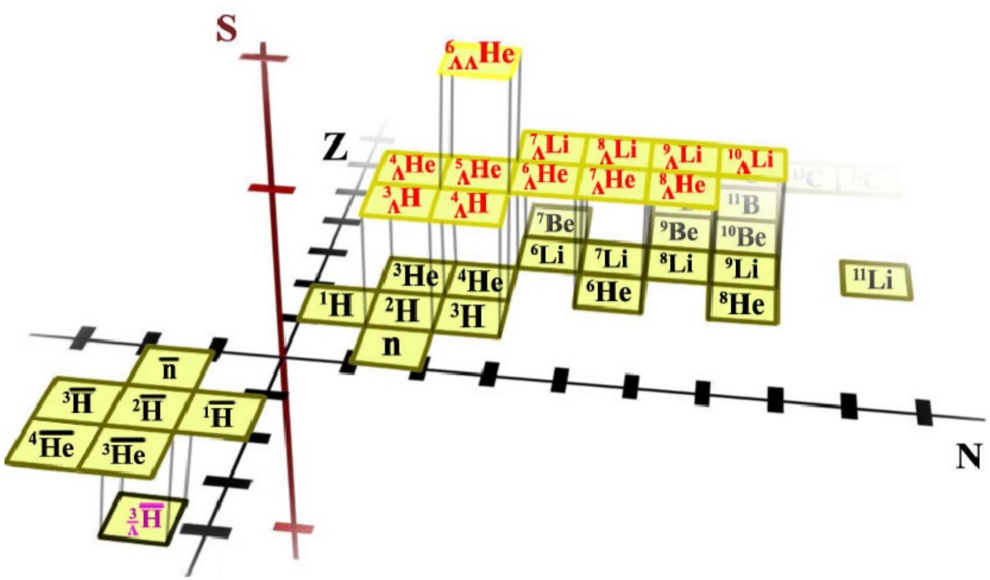
- Study of light **(hyper)nucleus formation in high-energy collisions** is fundamental for several reasons

- Their **production mechanism** is still not fully understood

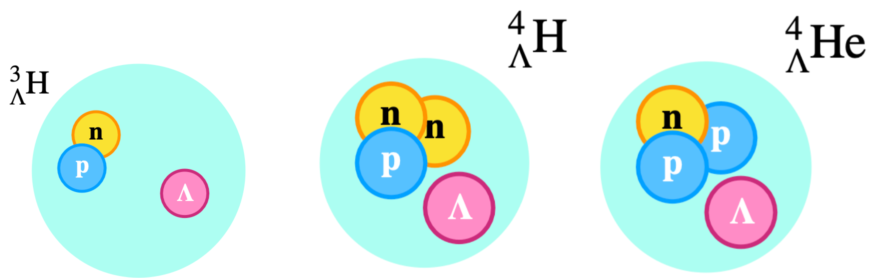
- **Low binding energy** (a few MeV) implies that light (anti)nucleus formation is strongly dependent on the chemical freeze-out conditions and the dynamics of the emitting source

- **Astrophysics applications**: measurements in controlled conditions constrain searches for **antimatter** from dark matter in cosmic rays

- **Hypernuclei** can be used as probes to
    - study the hyperon-nucleon (Y-N) interaction
    - Equation-of-State (EoS) of neutron star



STAR, Science 328 (2010) 58



Statistical Hadronisation Model (SHM)

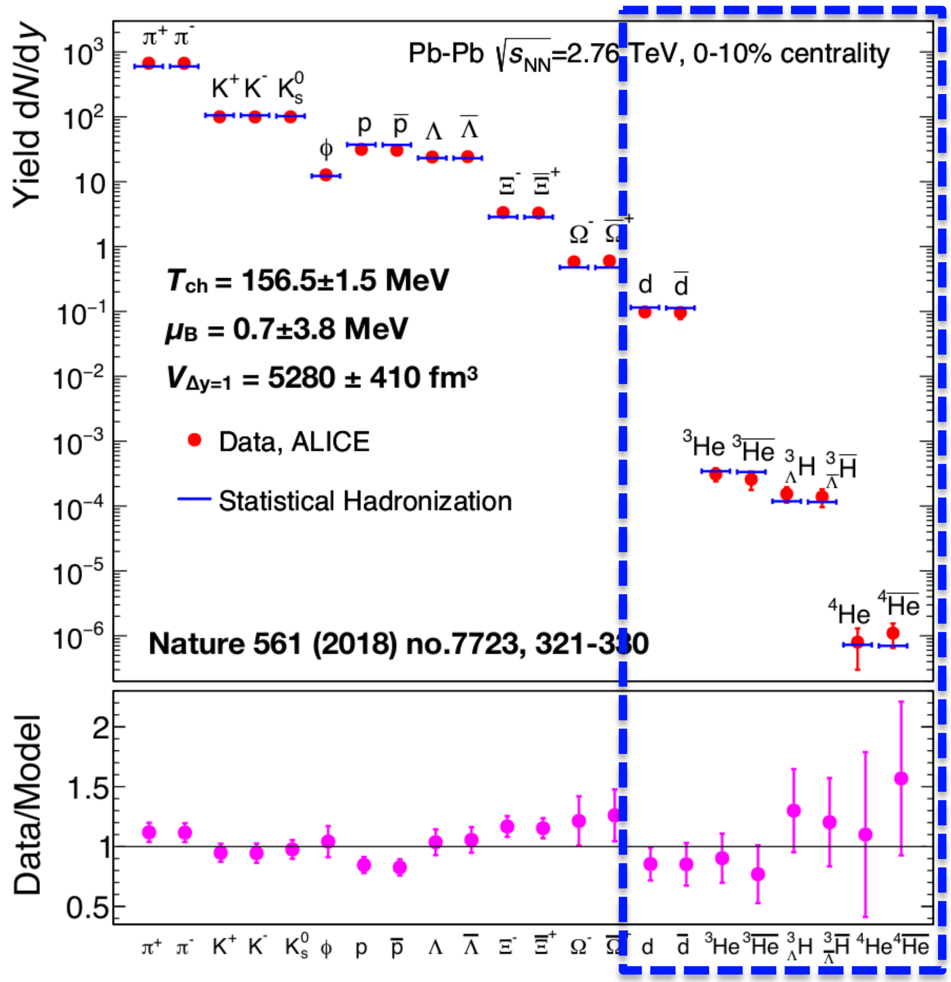
- It assumes hadron production from a system in **thermal** and **hadrochemical equilibrium** and that hadron abundances are fixed at **chemical freeze-out**

$$dN/dy \propto V \exp(-\frac{m}{T_{ch}})$$

- Large reaction volume (VT^3 >1) in Pb-Pb collisions
  - Grand Canonical Ensemble

- Production yields **d*N*/dy** in central Pb-Pb collisions described over a wide range of d*N*/dy (**9 orders of magnitude**), including light (hyper)nuclei

- In **small systems** (VT^3 < 1) a local conservation of quantum numbers (*S*, *Q* and *B*) is necessary
  - Canonical Ensemble (Canonical Statistical Model)



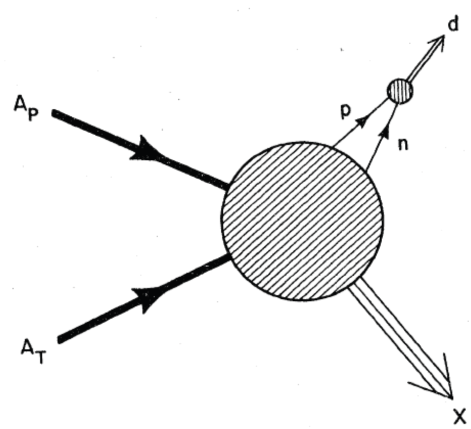
Andronic et al., Nature, 561 (2018) no. 7723, 321
V. Vovchenko et al., PLB 785 (2018) 171

Coalescence Model

- Nucleons that are **close in phase space** at the kinetic **freeze-out** can form a nucleus via **coalescence**

- The key concept is the overlap between the **nuclear wave-function** and the **phase space** distribution of the **nucleons**

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



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

Butler et al., Phys. Rev. 129 (1963) 836
J. Kapusta, Phys. Rev. C 21 (1980) 1301

B_A is related to the probability to form a nucleus via coalescence

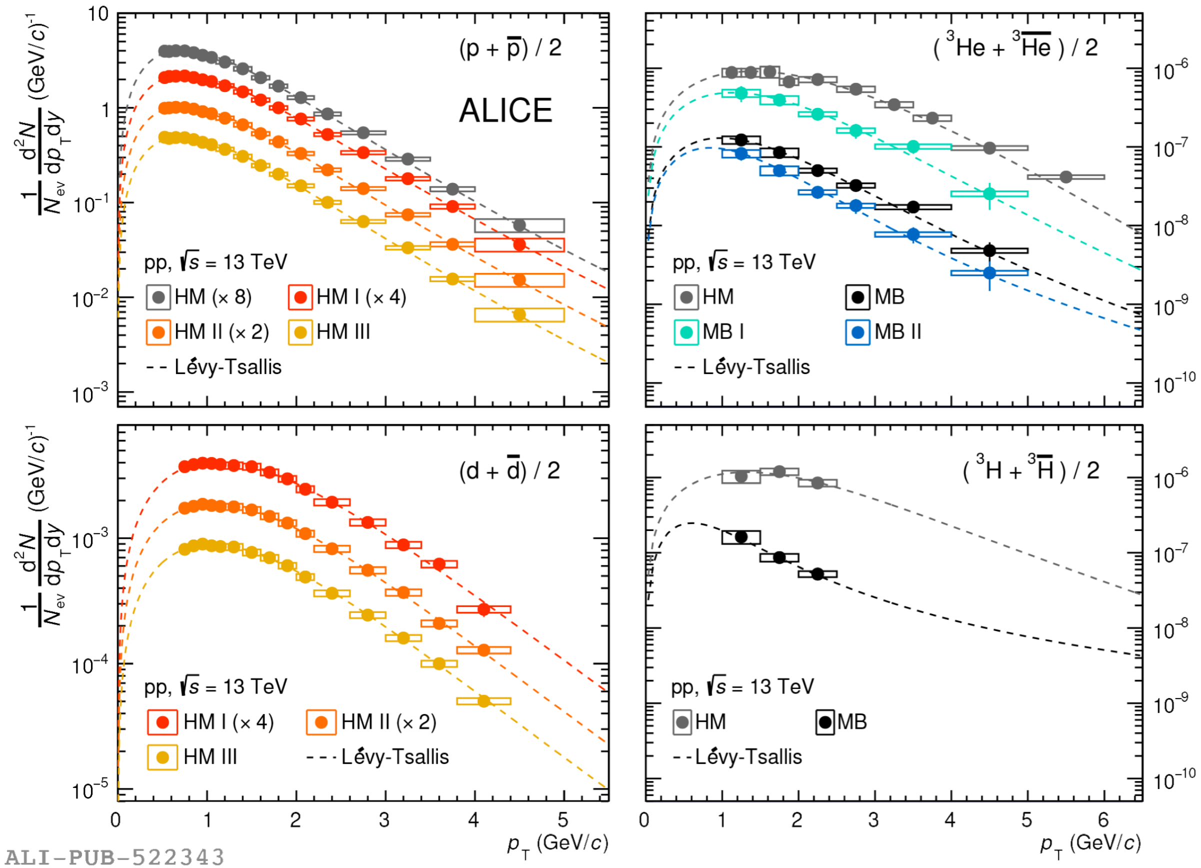
- State-of-the-art approaches include source size R and finite size r_d of the cluster, e.g. for deuterons:

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

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

Transverse Momentum Spectra

- Light nuclei p_T spectra measured for different multiplicity classes in small collision systems
- Similar behaviour for each nucleus species: Hardening of spectra with increasing multiplicity
- p_T spectra fitted with Lévy-Tsallis function to extrapolate in the unmeasured regions

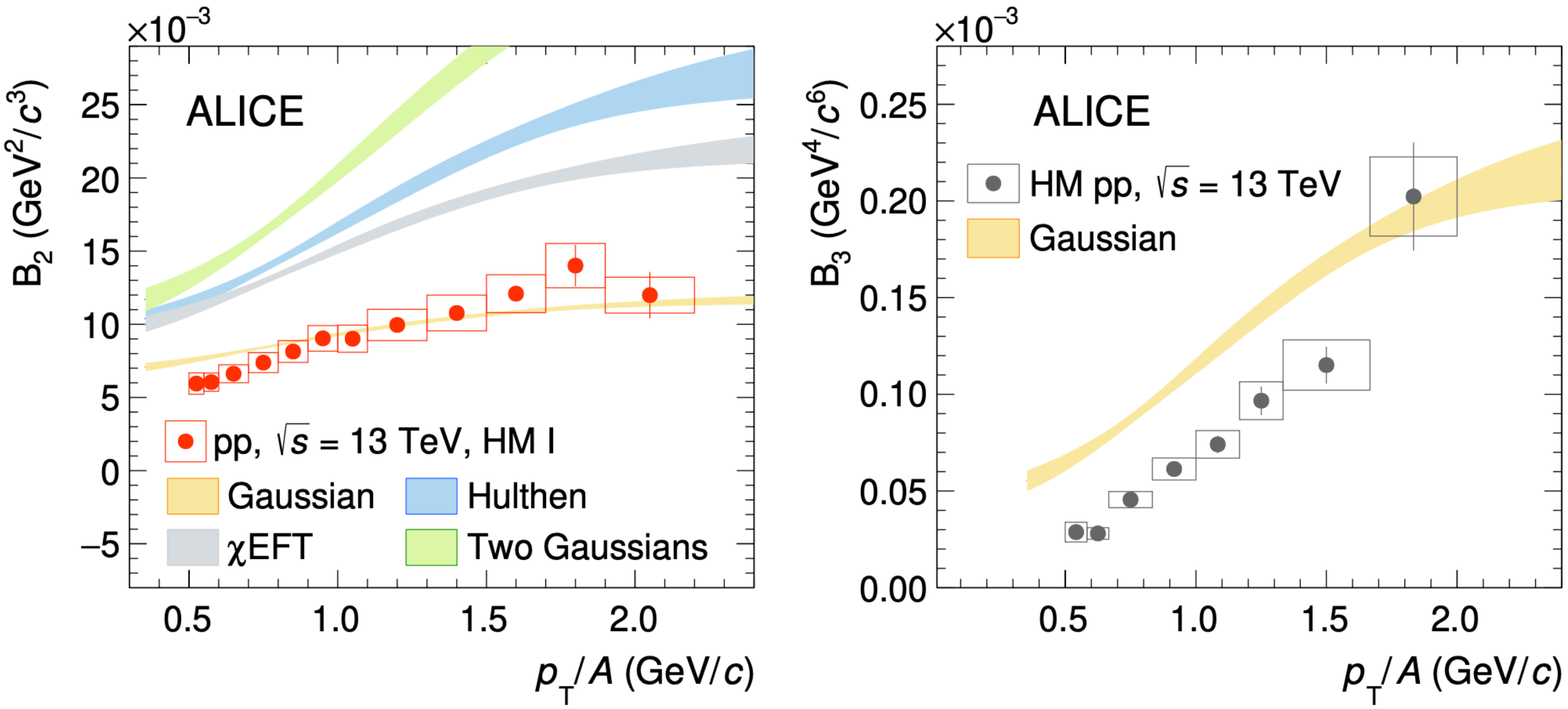


- The coalescence parameter B_A:

ALICE, JHEP 01 (2022) 106

$$B_A\left(p_{\mathrm{T}}^{\mathrm{p}}\right) = \frac{1}{2\pi p_{\mathrm{T}}^{\mathrm{A}}} \frac{\mathrm{d}^2 N_{\mathrm{A}}}{\mathrm{d}y \mathrm{d}p_{\mathrm{T}}^{\mathrm{A}}} \Bigg/ \left(\frac{1}{2\pi p_{\mathrm{T}}^{\mathrm{p}}} \frac{\mathrm{d}^2 N_{\mathrm{p}}}{\mathrm{d}y \mathrm{d}p_{\mathrm{T}}^{\mathrm{p}}}\right)^A, \text{ where } p_{\mathrm{T}}^{\mathrm{p}} = p_{\mathrm{T}}^{\mathrm{A}}/A$$

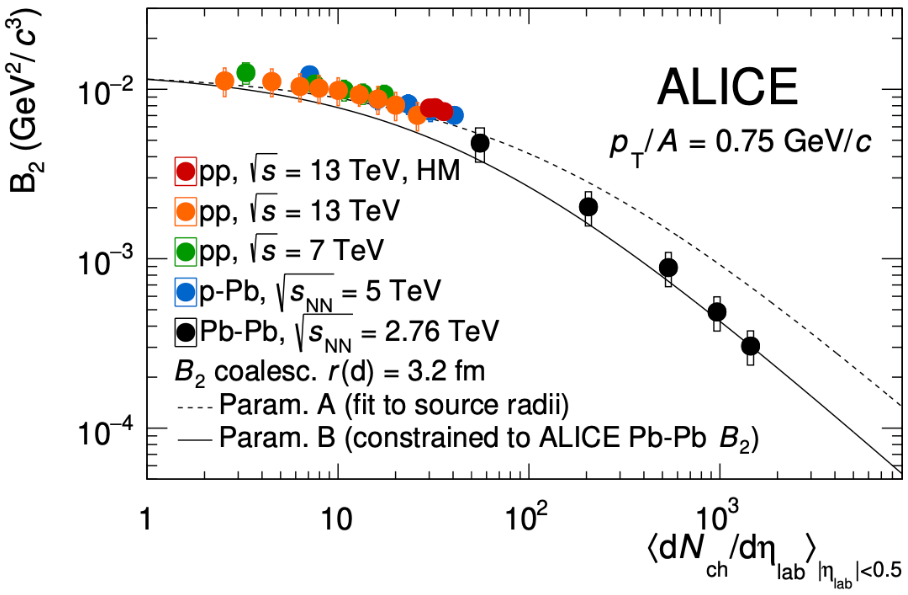
Testing Coalescence Model

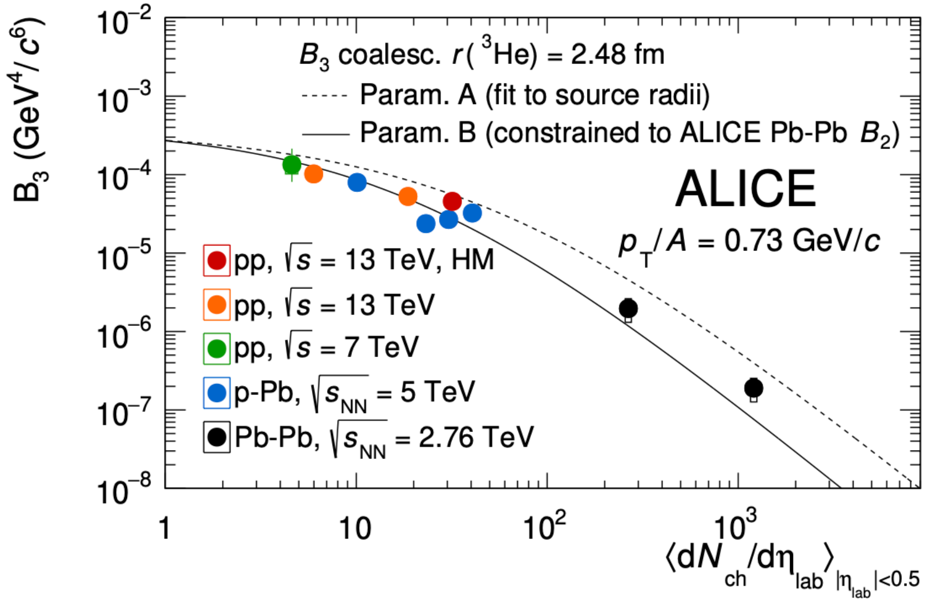


ALICE, JHEP 01 (2022) 106

- B_A measurements sensitive to the nuclear wave function
- **Gaussian wave function** gives best description of B_2

Multiplicity Dependence of B_A

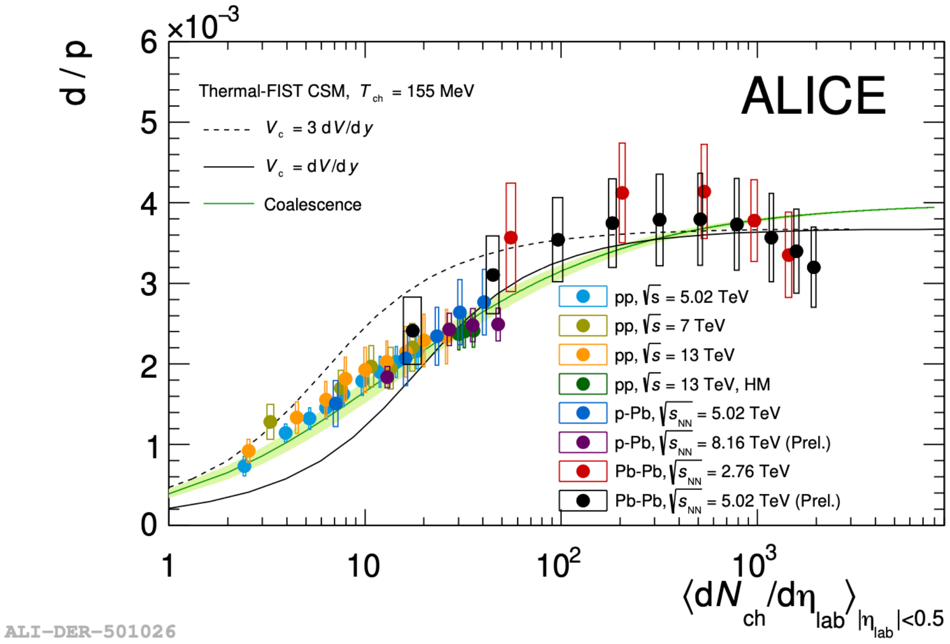


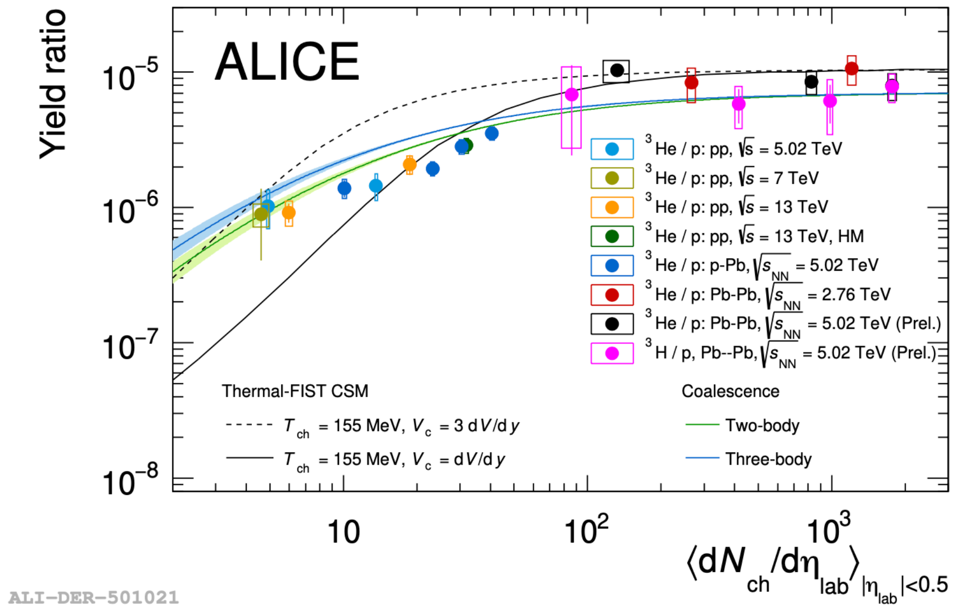


ALICE, JHEP 01 (2022) 106

- Smooth evolution of B_A with multiplicity
  - No dependence on the collision system and energy
- Coalescence probability depends on the system volume
- Coalescence model qualitatively describes the trend but fails in accurately describing the measurements in the whole multiplicity range

Nuclei Yield Ratios

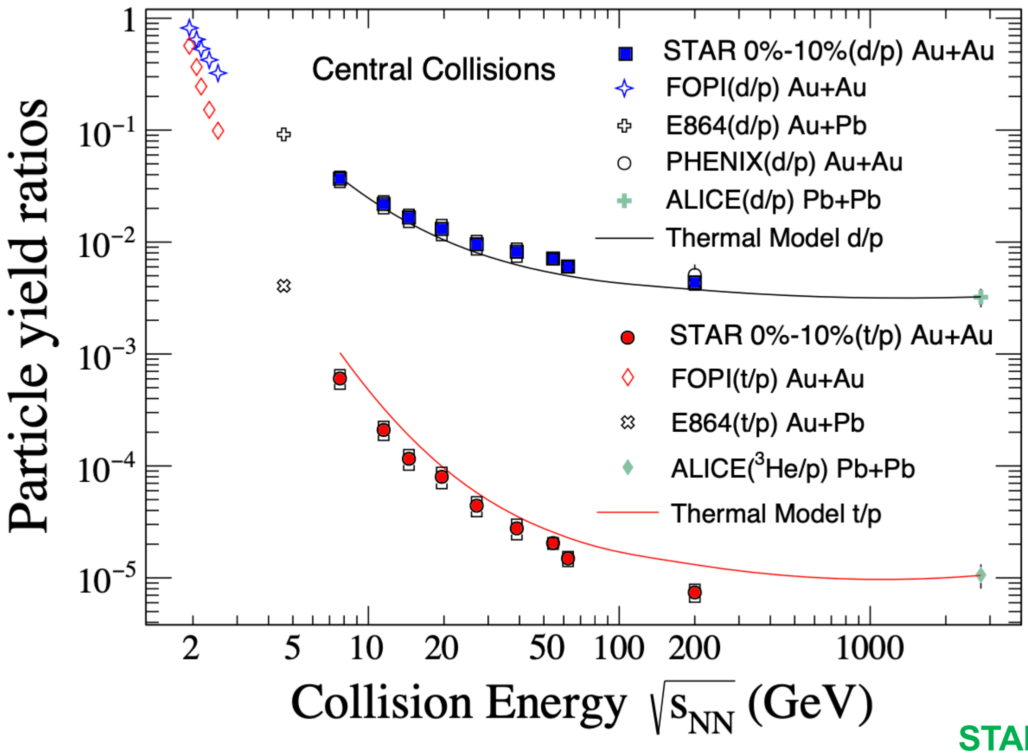




ALICE, JHEP 01 (2022) 106

- d/p, ^{3}H/p and ^{3}He/p ratios increase smoothly with multiplicity without any dependence on the collision system or energy
- Models can qualitatively describe nuclei ratios to protons, except for A > 2 in the intermediate multiplicity region

Nuclei Yield Ratios



STAR: arXiv:2209.08058

- d/p and t/p ratios increase monotonically with decreasing collision energy
- Differences between the ratios get smaller at lower collision energies
- Thermal model describes the d/p ratios well, but it systematically overestimates the t/p ratios except at the LHC energy

Compound Yield Ratio

- Near the critical point or the first order phase transition, density fluctuations become larger

  $$N_t \cdot N_p / N_d^2 = g(1 + \Delta n)$$

  Δn is the relative neutron density fluctuation

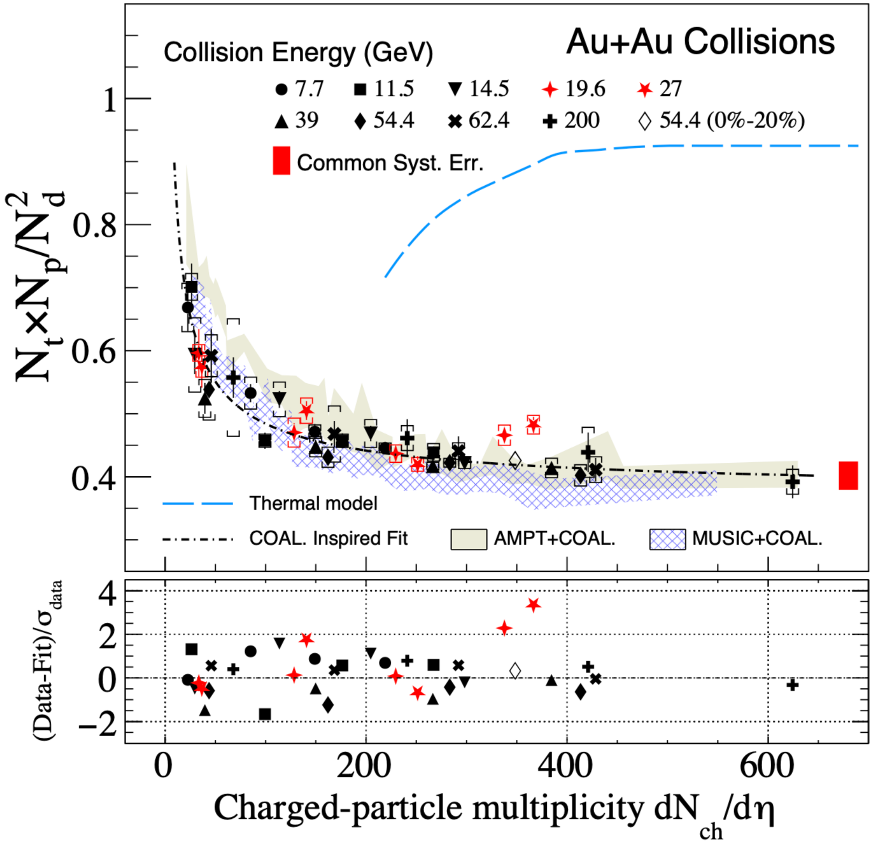
  K. J. Sun et al., Phys. Lett. B781, 499 (2018)

- Light nuclei yield ratio can be used to probe the QCD critical point or first order phase transition

- Ratio monotonically decreases with increasing multiplicity

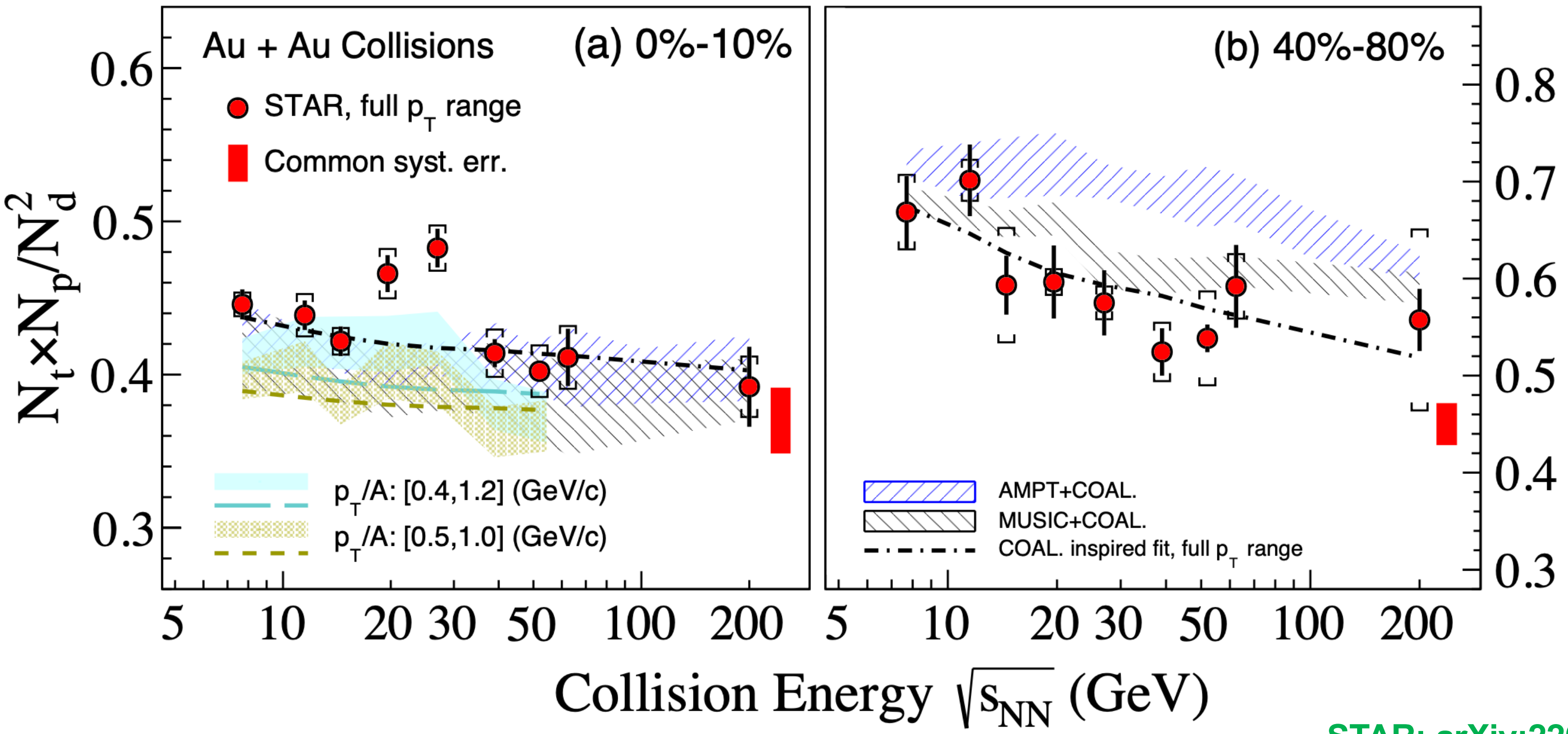
- The scaling behaviour is well described by the Coalescence Model, but overestimated by the Thermal Model.

- Ratios at 19.6 and 27 GeV from 0-10% centrality show enhancements to the coalescence baseline with a combined significance of 4.1σ



STAR: arXiv:2209.08058

Compound Yield Ratio

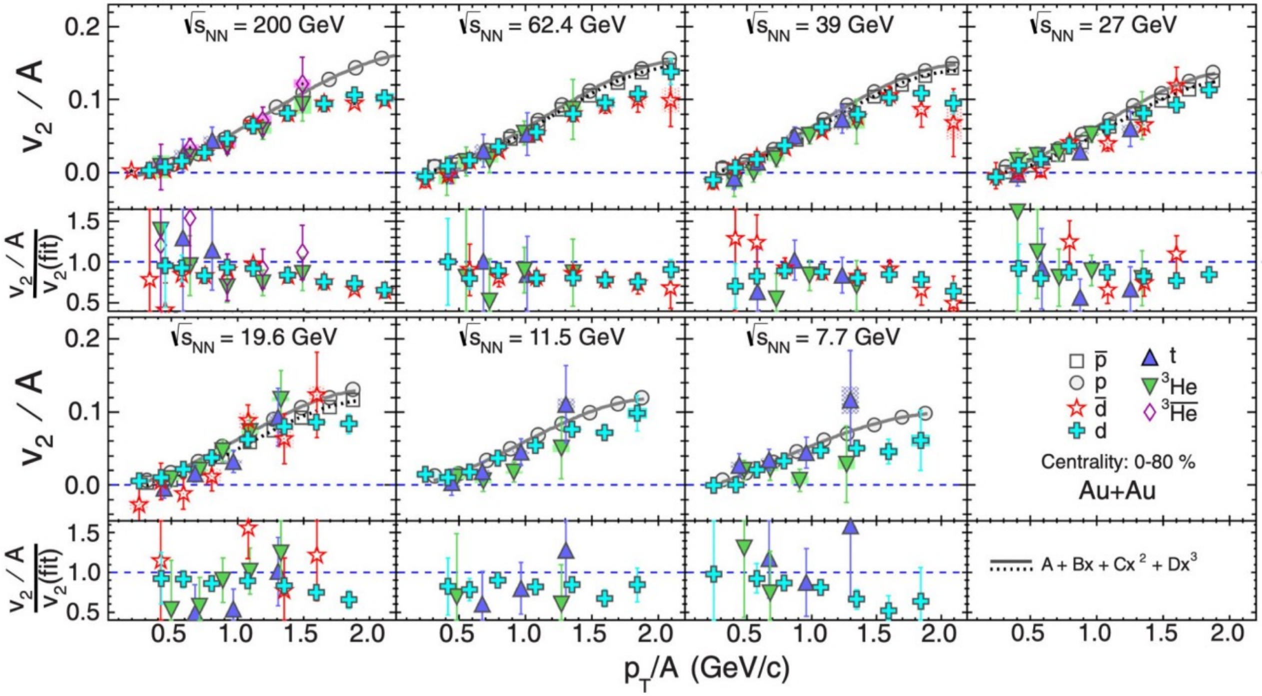


STAR: arXiv:2209.08058

R. Sharma's Talk, Fri, 3:40 pm, Coral Hall

- Non-monotonic behaviour observed in the energy dependence of the yield ratio from 0-10% central Au+Au collisions around 19.6 and 27 GeV
- Significance of the enhancements decreases with decreasing p_T acceptance in the region of interest

Light Nuclei Flow

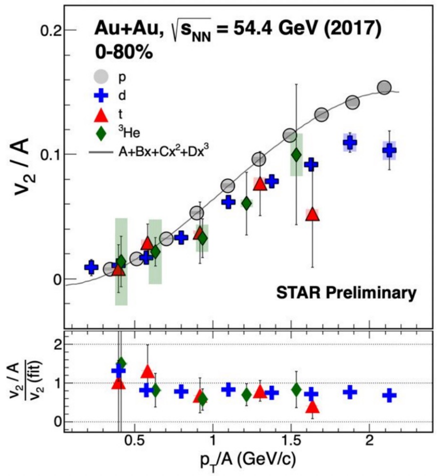


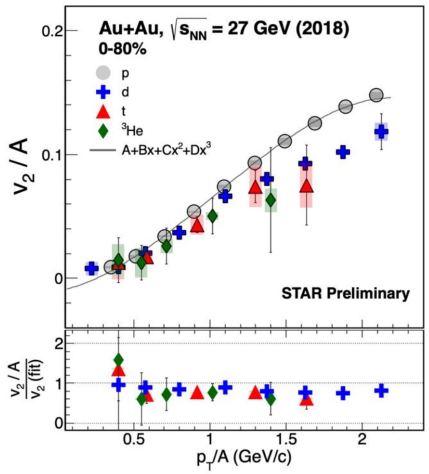
- v_2 /A of light nuclei was observed to be close to v_2 of protons for p_T /A < 1.5 GeV/c in BES-I data

STAR, Phys. Rev. C 94 3 (2016) 034908

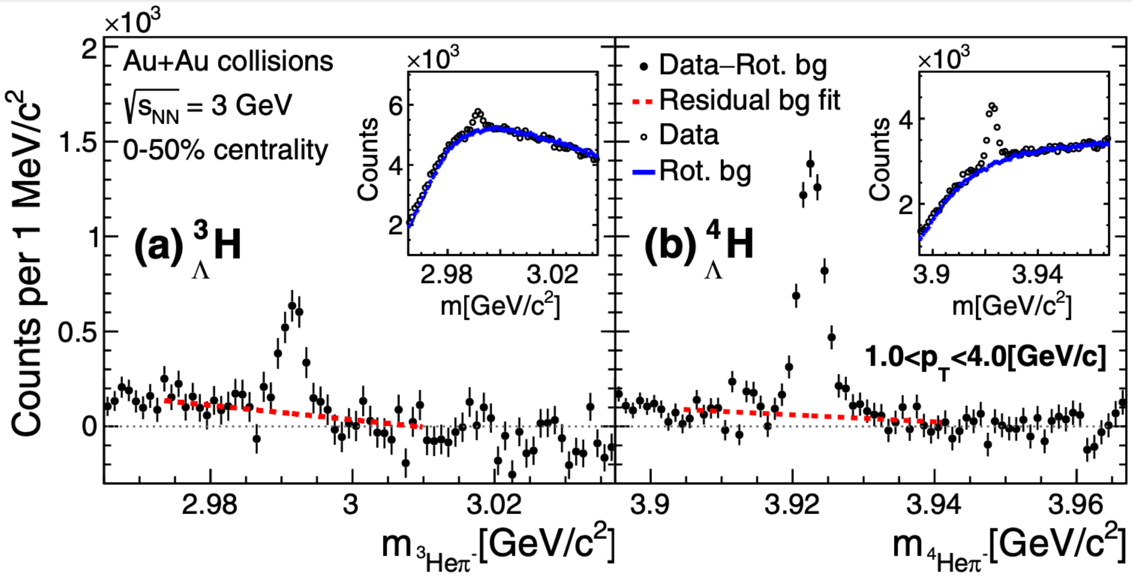
- A systematic deviation of around 10-20% from mass number scaling is observed for all light nuclei species

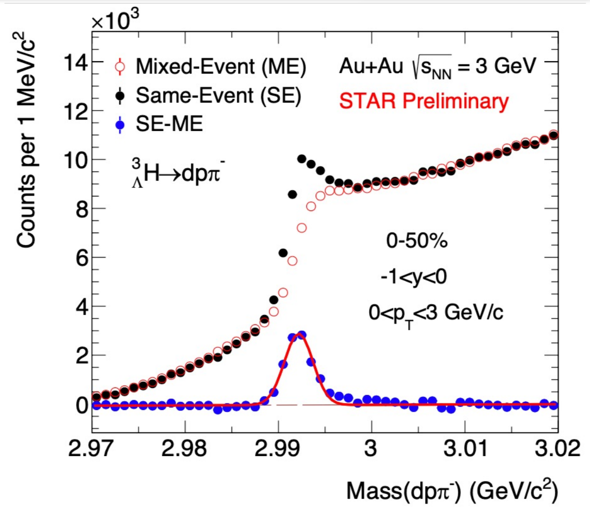
STAR: QM 2022

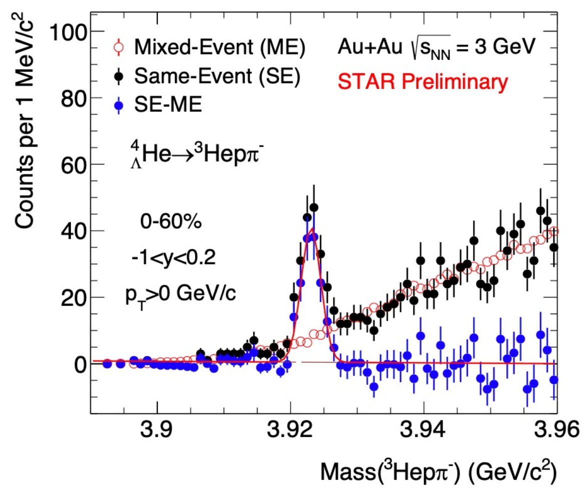




Hypernuclei Reconstruction







STAR, PRL 128, 202301(2022)
STAR: CPOD 2022

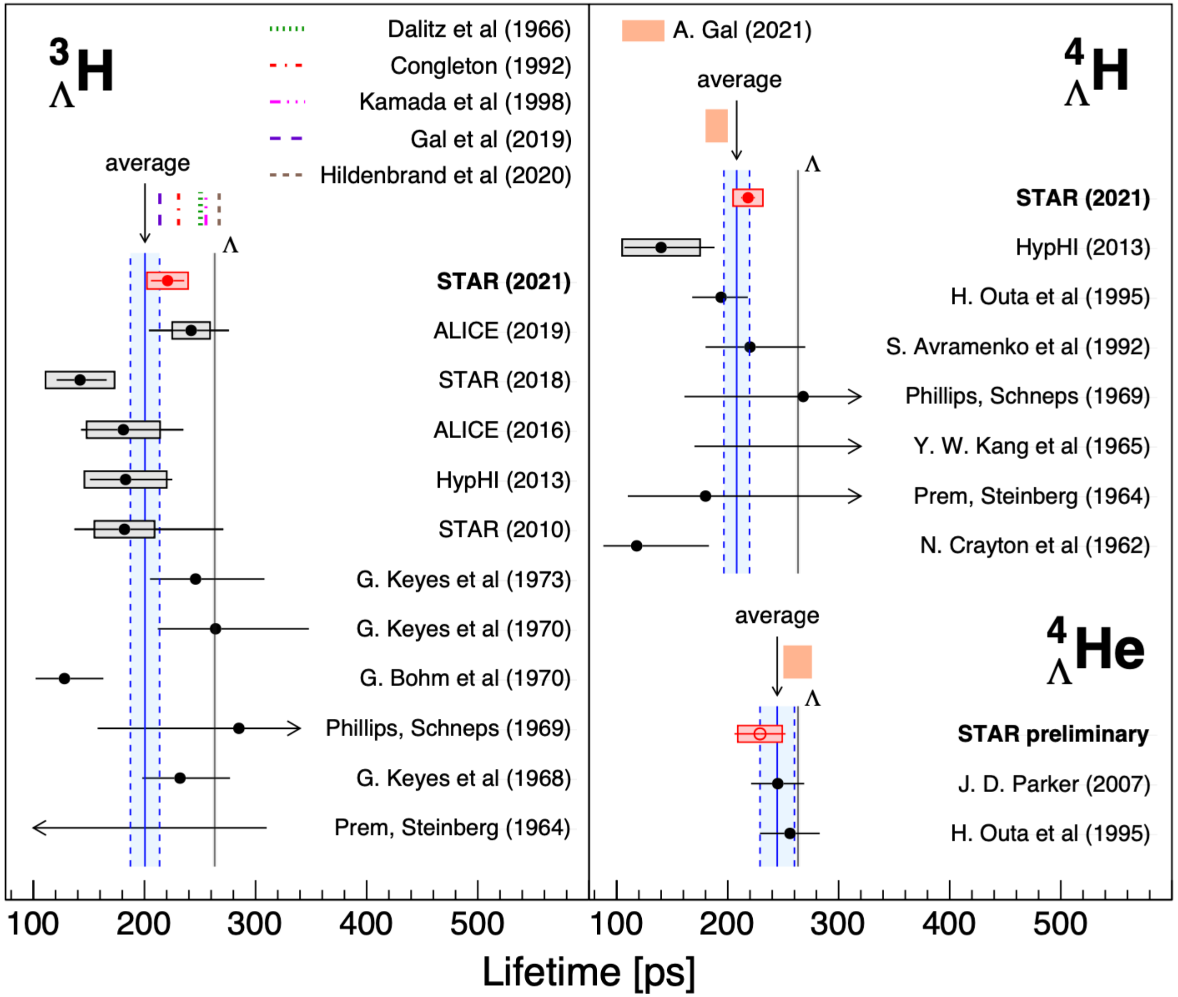
- Hypernuclei are reconstructed using the following decay channels:

$$^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^- \qquad ^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{p} + \pi^-$$

$$^{4}_{\Lambda}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \pi^- \qquad ^{4}_{\Lambda}\mathrm{He} \rightarrow {}^{3}\mathrm{He} + \mathrm{p} + \pi^-$$

- Combinatorial background estimated via:
  - Rotating pion tracks for 2-body decay channels
  - Event mixing for 3-body decay channels

Hypernuclei Lifetimes



STAR, Phys. Rev. Lett. 128 (2022) 20, 202301

- $^{3}_{\Lambda}\mathrm{H}$ and $^{4}_{\Lambda}\mathrm{H}$ lifetimes shorter than τ_{Λ} (with 1.8σ and 3.0σ respectively)
- Global average lifetime of $^{3}_{\Lambda}\mathrm{H}$ is (82 ± 5) % τ_{Λ}, shorter than lifetime of Λ (4.8σ)
- Consistent with theoretical calculations including pion FSI

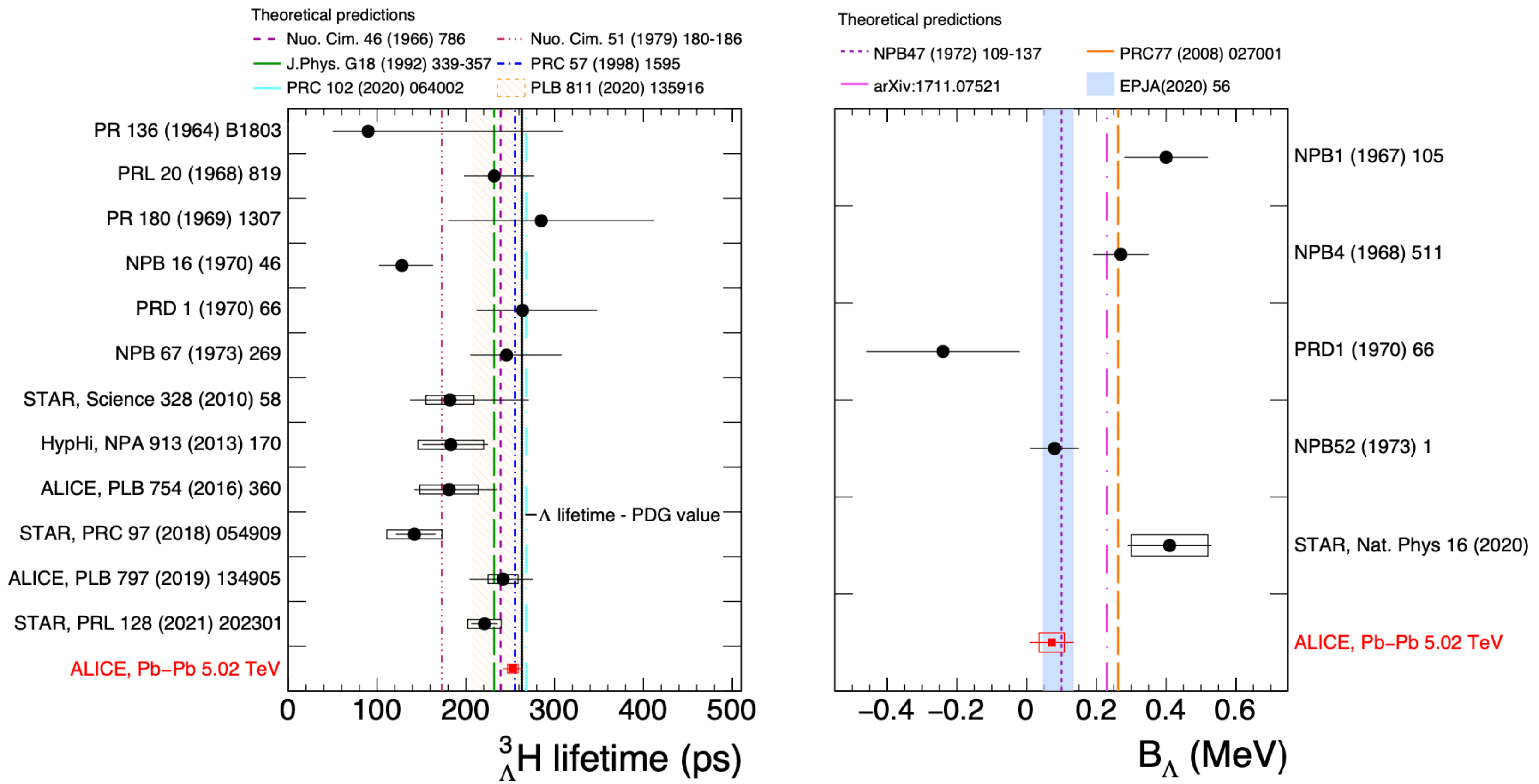
  A. Gal et al, Phys. Lett. B 791 (2019) 48

- $$\frac{\tau_{avg}(^{4}_{\Lambda}\mathrm{H})}{\tau_{avg}(^{4}_{\Lambda}\mathrm{He})} = 0.85 \pm 0.07$$

  consistent with theoretical expectation 0.74 ± 0.04

  A. Gal, EPJ Web Conf 259 (2022) 08002

Hypernuclei Lifetimes



ALICE, arXiv:2209.07360

Recent measurements in Run 2 Pb-Pb collisions at 5.02 TeV:

- Hypertriton lifetime is compatible with the free Λ lifetime within its uncertainties
  - Supports a very loosely-bound state
- Hypertriton binding energy is compatible with the latest theoretical predictions

Strangeness Population Factor

- Relative suppression of hypernuclei production compared to light nuclei production:

$$S_A = \frac{{}^{A}_{\Lambda}H}{{}^{A}He \times \frac{\Lambda}{p}} = \frac{B_A({}^{A}_{\Lambda}H)(p_T)}{B_A({}^{A}He)(p_T)}$$

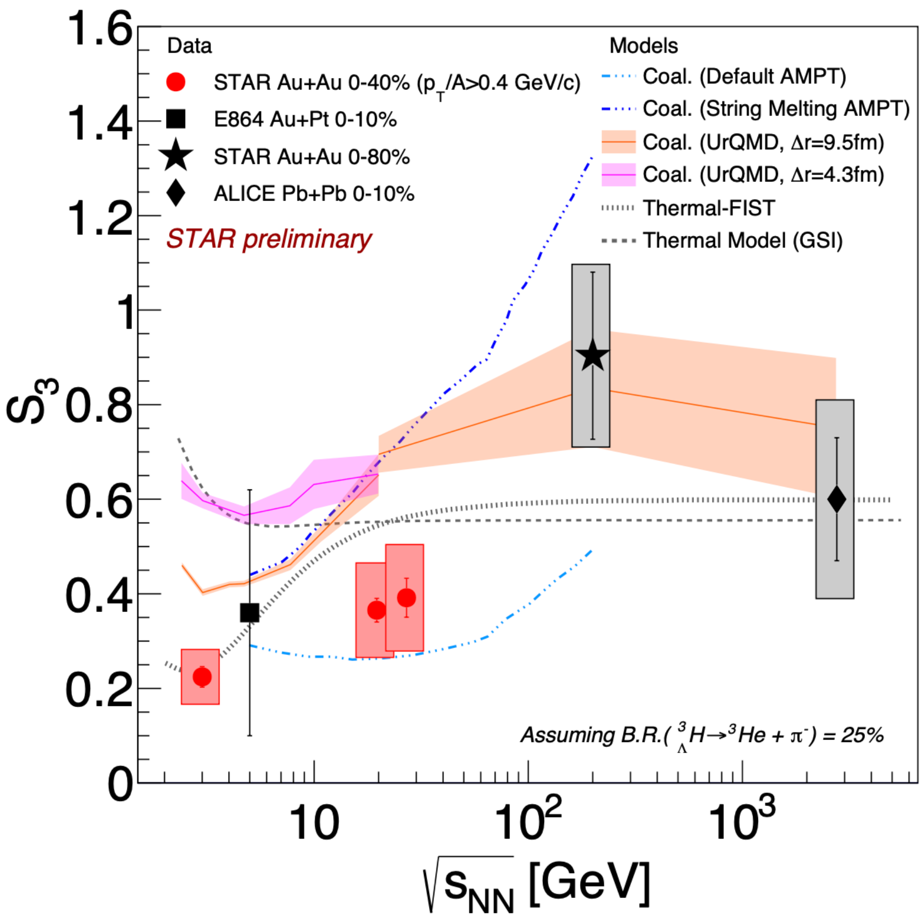
S. Zhang et al, PLB 684, 224 (2010)

If no suppression, $S_A \sim 1$ is expected

- $S_3 < 1 \rightarrow$ Relative suppression of ${}^{3}_{\Lambda}H$ to ${}^{3}He$

- A hint of an increasing trend of S_A from $\sqrt{s_{NN}}$ = 3.0 GeV to 2.76 TeV

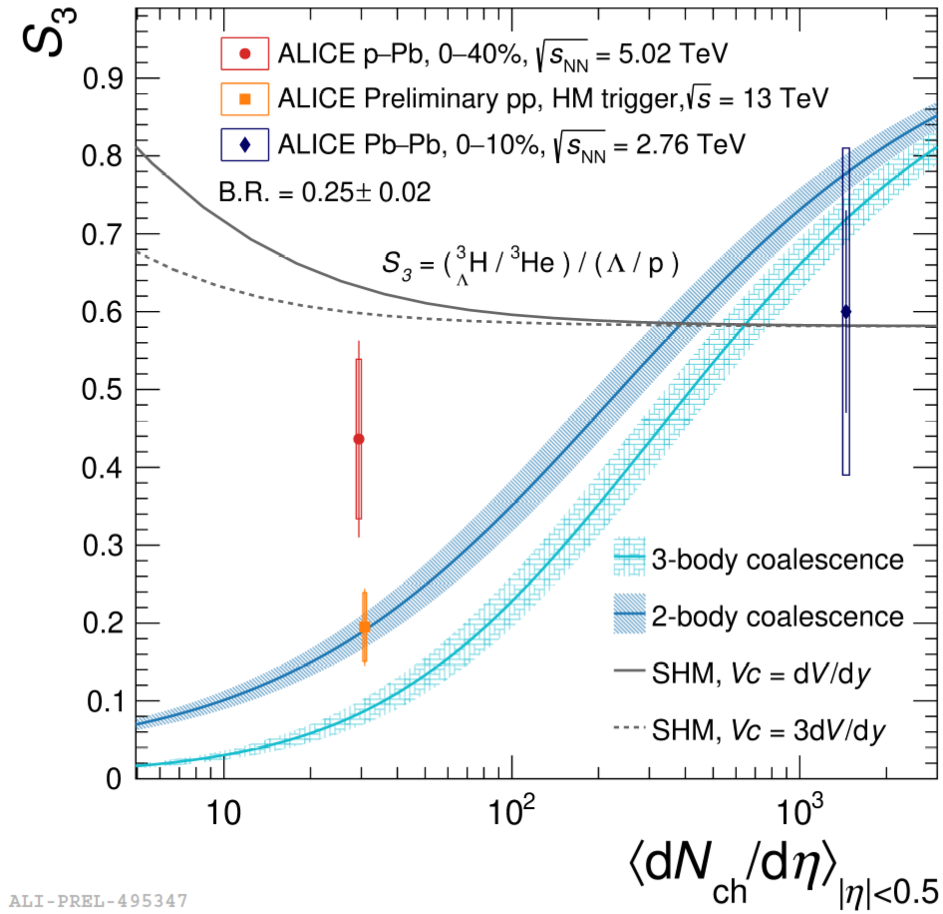
- Thermal-FIST describes the S_3 data reasonably well



STAR, Science 328 (2010) 58
ALICE, PLB 754 (2016) 360
E864, PRC 70 (2004) 024902
NA49, J.Phys.Conf.Ser.110 (2008) 032010
A. Andronic et al, PLB 697 (2011) 203 (Thermal (GSI))
S. Zhang, PLB 684(2010)224 (Coal.+AMPT)
T. Reichert et al, arXiv:2210.11876(2022) (UrQMD, Thermal-FIST)

Strangeness Population Factor

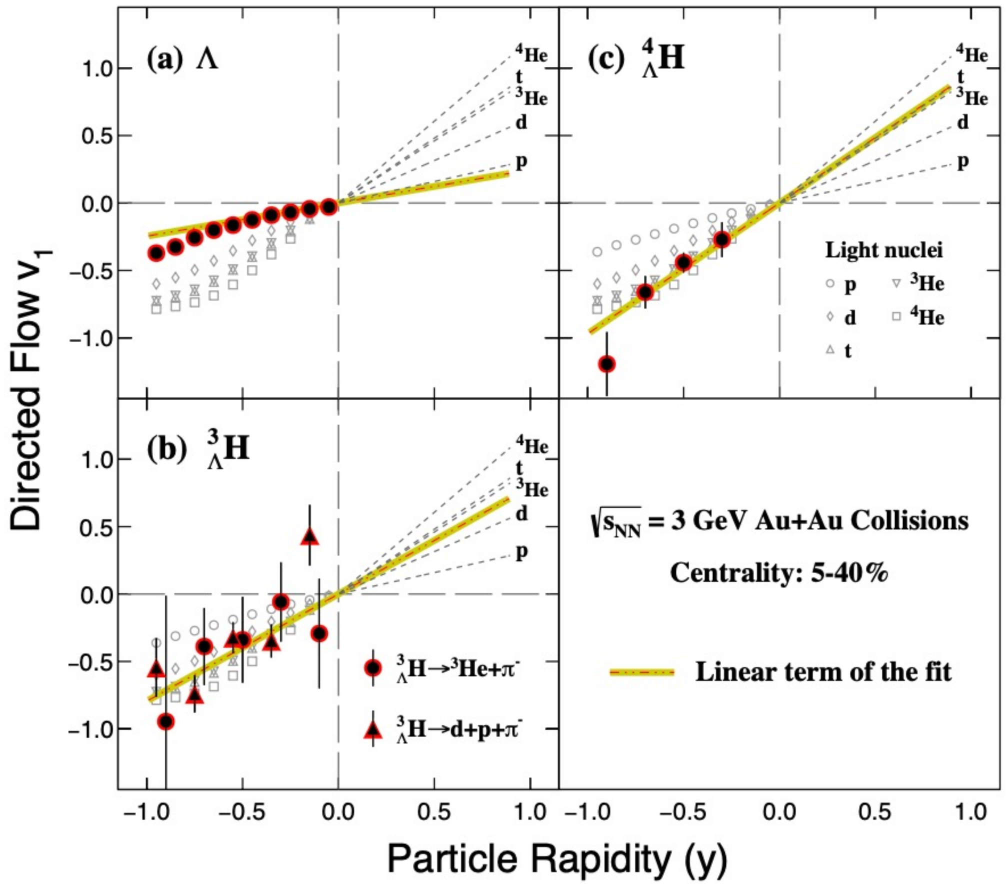
- New measurement of S_3 in pp and p-Pb collisions at the LHC
- Data slightly favours the two-body coalescence but do not exclude three-body coalescence

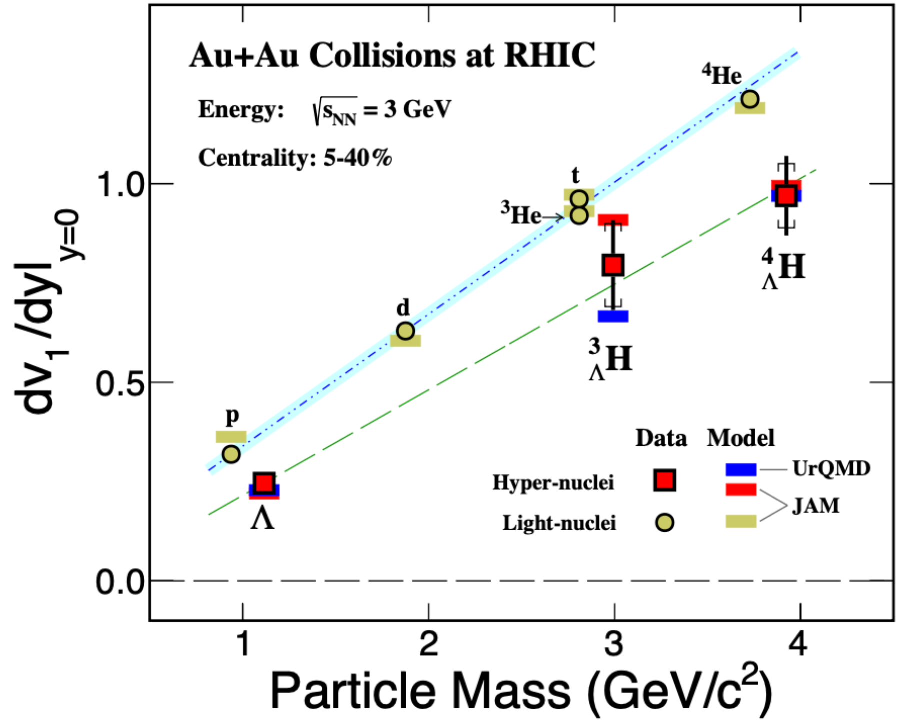


ALICE, Phys. Rev. Lett. 128 (2022) 252003

K.-J. Sun, C.-M. Ko and B. Dönigus, Phys. Lett. B 792 (2019)132
V. Vovchenko, B. Dönigus and H. Stoecker, Phys. Lett. B 785 (2018)171

Hypernuclei Collectivity

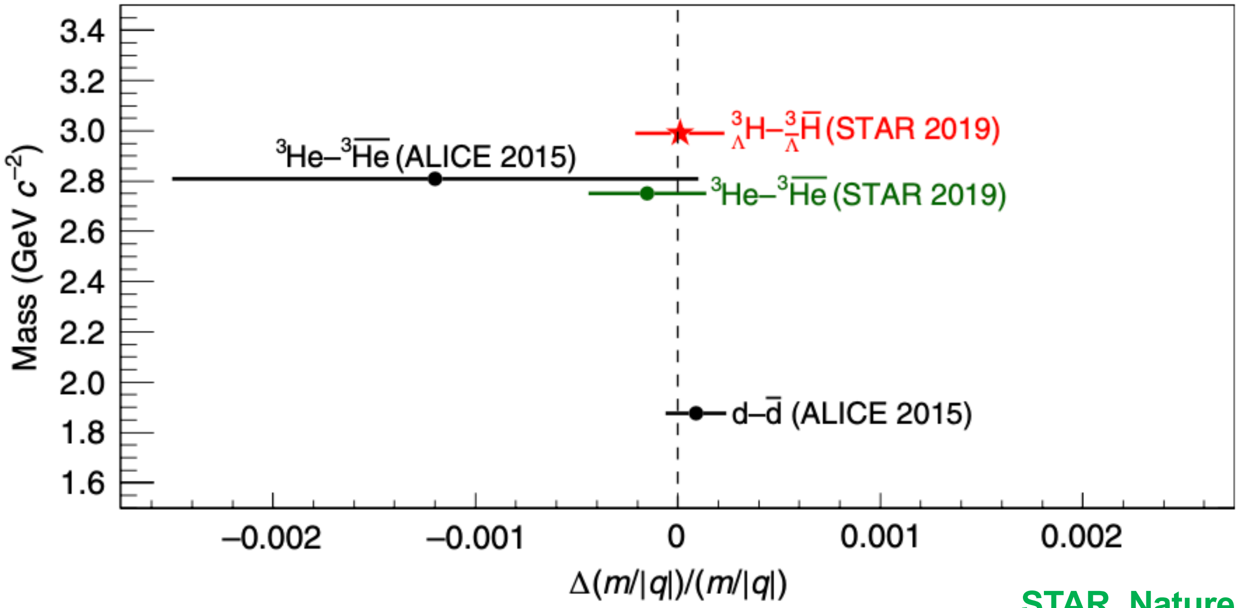




STAR, arXiv:2211.16981v1

- First measurements of $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H directed flow (v_1) in 5-40% central Au+Au collisions at $\sqrt{s_{NN}}$ = 3 GeV
- v_1 slopes of $^{3}_{\Lambda}$H and $^{4}_{\Lambda}$H follow mass number scaling, like light nuclei
  - Imply coalescence process to be the dominant formation mechanism for hypernuclei

Testing Fundamental Symmetry



STAR, Nature Phys. 16 (2020) 409
ALICE, Nature Phys 11 (2015) 811

$$m_{^3_\Lambda\mathrm{H}} = 2,990.95 \pm 0.13(\mathrm{stat.}) \pm 0.11(\mathrm{syst.})\ \mathrm{MeV}\ c^{-2}$$

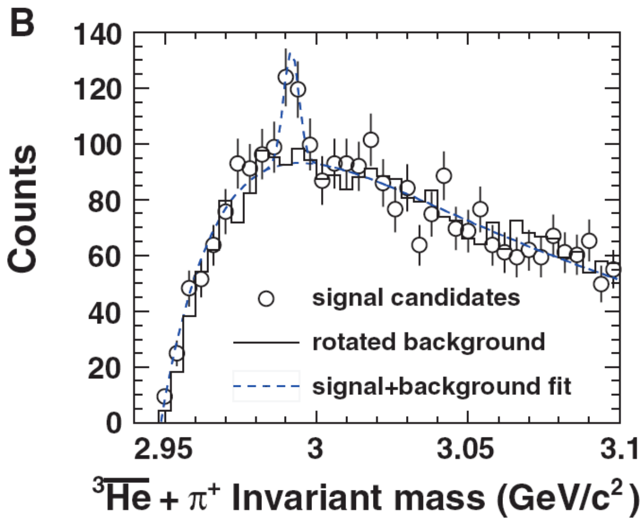
$$m_{^3_{\bar{\Lambda}}\overline{\mathrm{H}}} = 2,990.60 \pm 0.28(\mathrm{stat.}) \pm 0.11(\mathrm{syst.})\ \mathrm{MeV}\ c^{-2}$$

$$\boxed{\frac{\Delta m}{m} = \frac{m_{^3_\Lambda\mathrm{H}} - m_{^3_{\bar{\Lambda}}\overline{\mathrm{H}}}}{m} = (\ 0.1 \pm 2.0(\mathrm{stat.}) \pm 1.0(\mathrm{syst.})) \times 10^{-4}}$$

- ✓ CPT testing in hypernuclei sector for the first time
- ✓ No violation of CPT symmetry observed with high precision

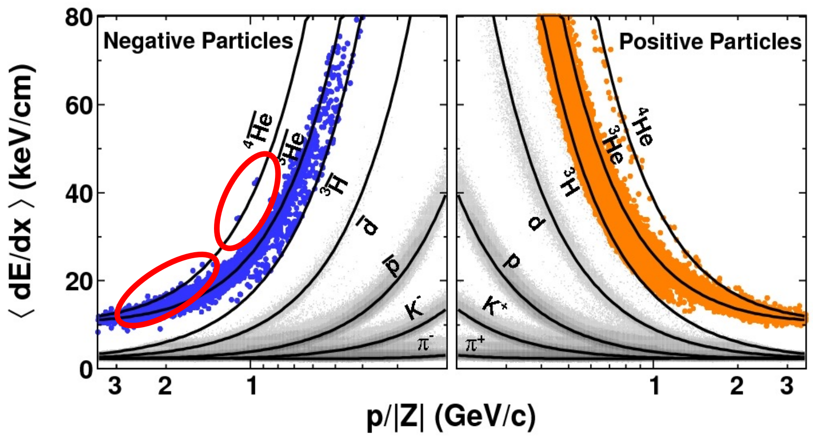
Discovery of Antimatter

Discovery of anti-hypertriton ($^{3}_{\bar{\Lambda}}\overline{H}$)



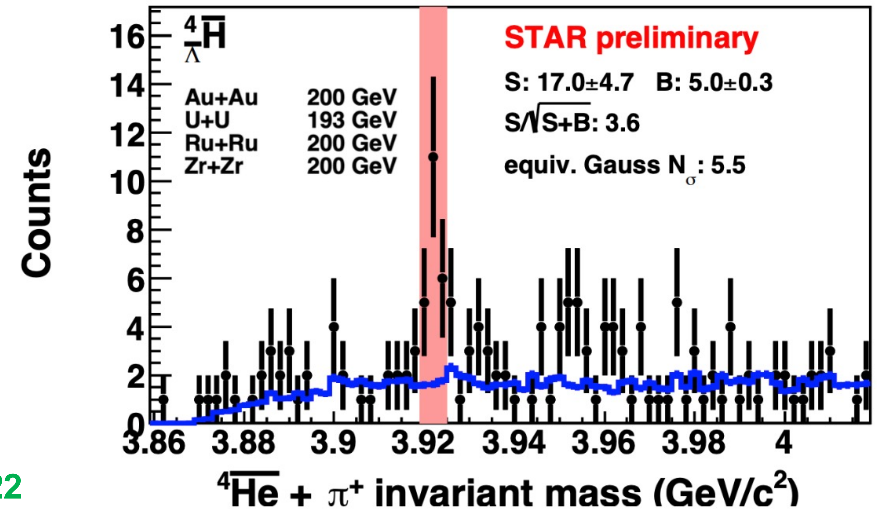
STAR, Science 328 (2010) 58

Discovery of anti-α ($^{4}\overline{He}$)



STAR, Nature 473, 353 (2011)

- The first observation of Anti-Hyper-Hydrogen-4 ($^{4}_{\bar{\Lambda}}\overline{H}$) with ~5$\sigma$ significance
  - Includes ~6.63B events from Au+Au, U+U, Ru+Ru and Zr+Zr collisions



STAR: QM 2022

Summary

- Extensive study to understand the light (hyper)nuclei production mechanism
  - ***B_A* vs multiplicity at LHC**: Coalescence model qualitatively describes the trend
  - **Yield ratios vs multiplicity at LHC**: Coalescence model and CSM describe d/p ratio but struggle to describe ^{3}He/p ratio
- Light nuclei yield ratio shows a non-monotonic dependence on collision energy
- Precise measurements of lifetimes of hypernuclei
- No violation of CPT symmetry observed with high precision in hypernuclei sector
- The first observation of Anti-Hyper-Hydrogen-4 ($^{4}_{\Lambda}\overline{H}$)

Outlook:

- Stay tuned for more exciting results from high statistics BES-II dataset and LHC Run3 with upgraded detectors

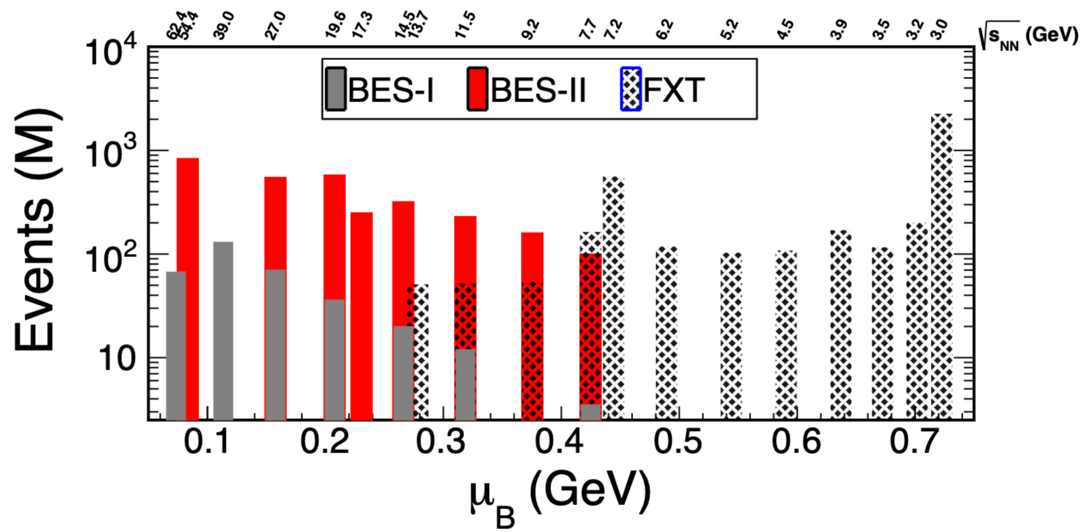
Thank You!

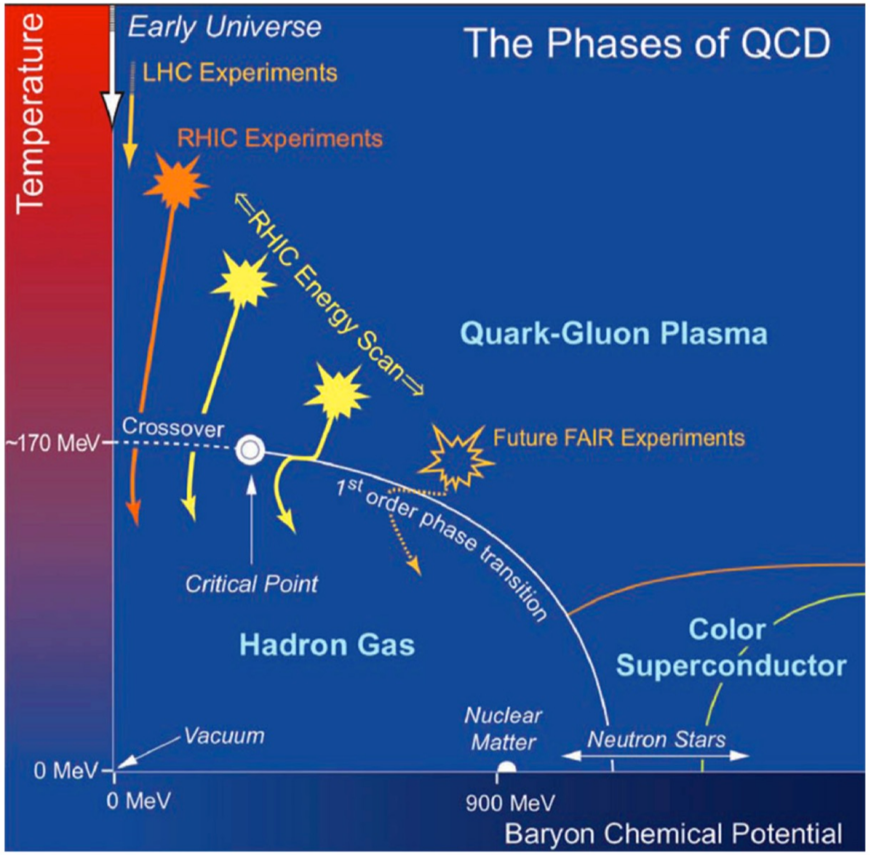
BES Program at RHIC

- RHIC provides a unique opportunity to explore the QCD phase diagram with different collision energies
  - ✓ Search for QCD critical point, 1st order phase transition, turn-off of QGP, etc.

- **BES-I** (2010 – 2011, 2014, 2017):
  $\sqrt{s_{NN}}$ = 7.7, 11.5, 14.5, 19.6, 27, 39, 54.4, 62.4 GeV

- **BES-II** (2018, 2019 – 2021):
- **Collider mode:**
  $\sqrt{s_{NN}}$ = 7.7, 9.2, 11.5, 14.6, 17.3, 19.6, 27 GeV
- **Fixed-Target mode:**
  $\sqrt{s_{NN}}$ = 3.0, 3.2, 3.5, 3.9, 4.5, 5.2, 6.2, 7.2 7.7 GeV





STAR: arXiv: 1007.2613
BES-II white paper: https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

Light Nuclei Production

- Production of light nuclei with small binding energy, formed via final state coalescence, are sensitive to the local nucleon density.

$$E_A \frac{d^3N_A}{d^3p_A} = B_A \left(E_p \frac{d^3N_p}{d^3p_p}\right)^Z \left(E_n \frac{d^3N_n}{d^3p_n}\right)^{A-Z} \approx B_A \left(E_p \frac{d^3N_p}{d^3p_p}\right)^A \qquad B_A \propto V_f^{1-A}$$

- The coalescence parameter, B_A, reflects the local nucleon density.

A.Z. Mekjian, Phys. Rev. C 17, 1051 (1978).

- In the vicinity of the critical point or the first order phase transition, density fluctuations become larger

$$N_d = \frac{3}{2^{1/2}} \left(\frac{2\pi}{m_0 T_{eff}}\right)^{3/2} N_p \langle n \rangle (1 + C_{np})$$

$$N_t = \frac{3^{\frac{3}{2}}}{4} \left(\frac{2\pi}{m_0 T_{eff}}\right)^{3} N_p \langle n \rangle^2 (1 + \Delta n + 2C_{np})$$

K. J. Sun et al., Phys. Lett. B781, 499 (2018)

C_{np} characterizes the neutron and proton density correlation.

Δn is the relative neutron density fluctuation

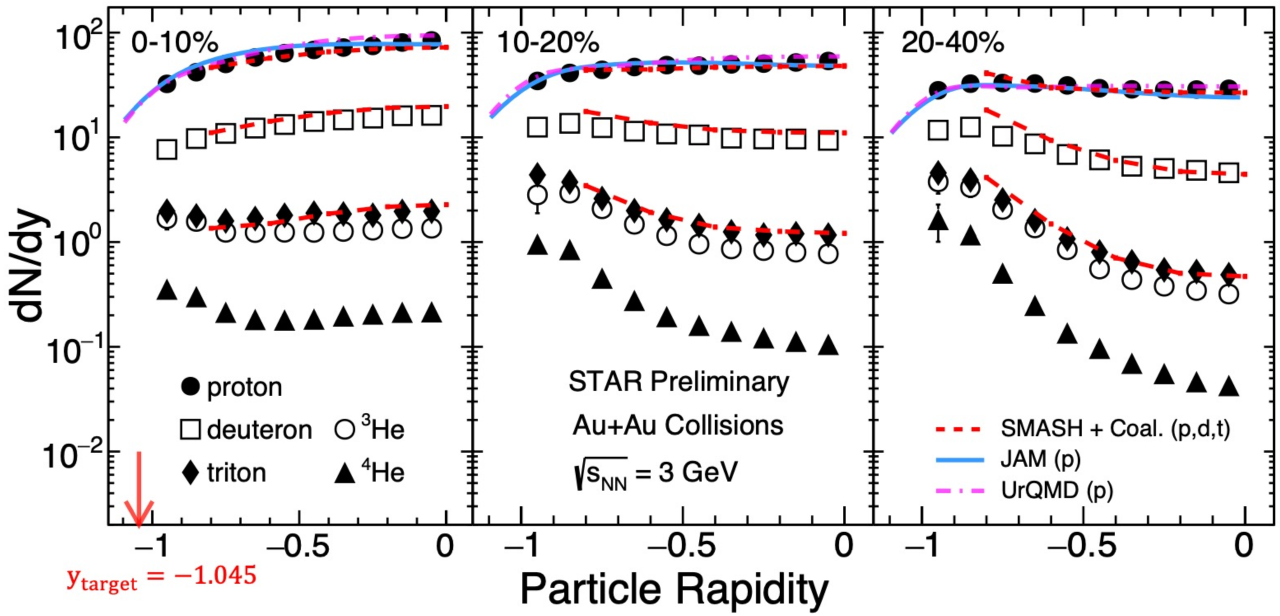
$$\boldsymbol{N_t \cdot N_p / N_d^2 = g(1 + \Delta n)}$$

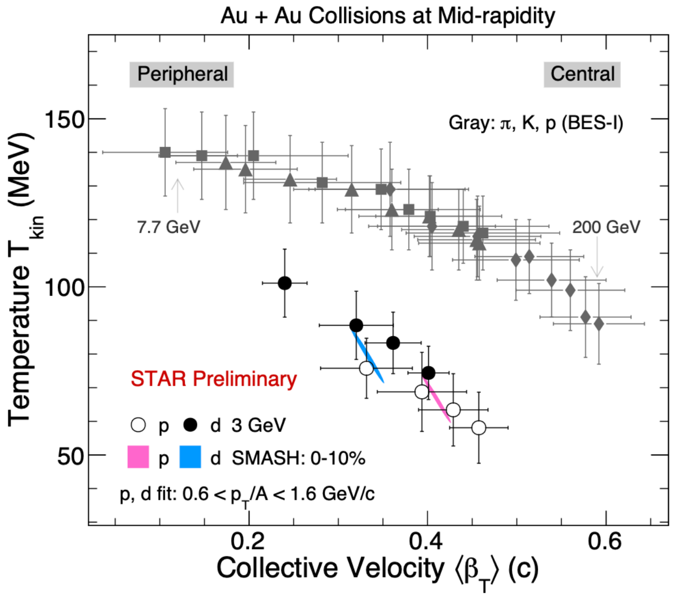
- Light nuclei yield ratio can be used to probe the QCD critical point or first order phase transition.

Kinetic freeze-out of light nuclei

- dN/dy of protons and light nuclei show significant centrality and rapidity dependence
- Yields of proton & light nuclei well described by models

STAR: QM 2022

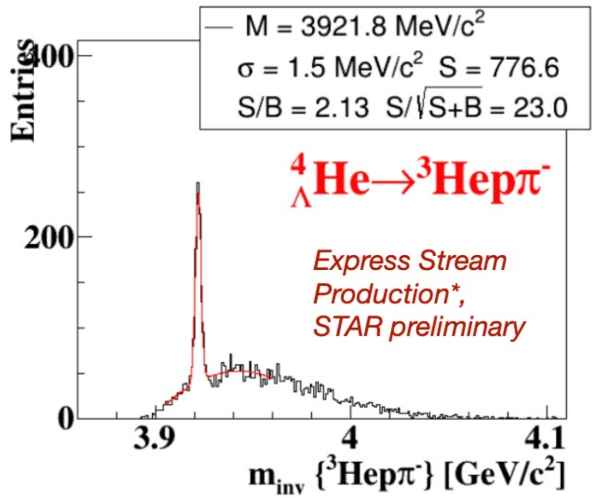


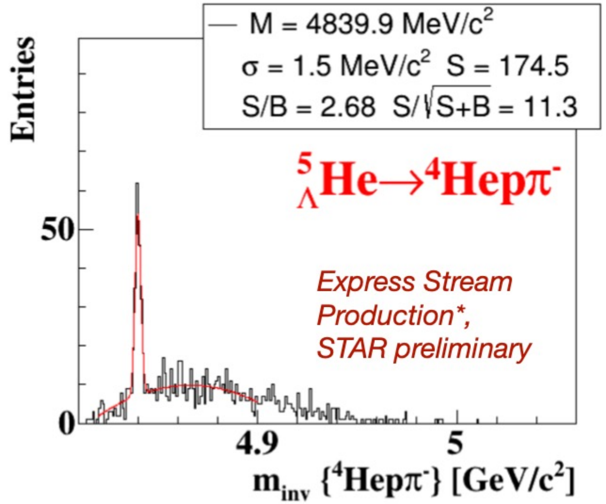


- Effective average kinetic freeze out parameters extracted using cylindrical blast wave fits
- At $\sqrt{s_{NN}}$ = 3 GeV, the freeze-out parameters (T_{kin}, β_T) show different trend compared to higher energies
  - ✓ Indicate a different equation of state (EoS)
- Similar trend seen in SMASH Model
  T_{kin} (d) > T_{kin} (p)

New (Anti-)Hypernuclei

- STAR provides opportunity to study yields, lifetimes and binding energies of ${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H, ${}^{4}_{\Lambda}$He, and ${}^{5}_{\Lambda}$He.





STAR: QM 2022

- The first observation of Anti-Hyper-Hydrogen-4 (${}^{4}_{\Lambda}\overline{H}$)
  - Includes data from Au+Au, U+U, Ru+Ru and Zr+Zr collisions