Recent results of light (hyper)nuclei production with RHIC-STAR experiment

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Feb. 13-17, 2023 @ Bologna, Italy

Outline

1. Introduction
2. STAR Experiment and BES-II Upgrades
3. Results and Discussions
   - Light Nuclei Production
   - Hypernuclei production
4. Summary and Outlook

Introduction

1. Light Nuclei

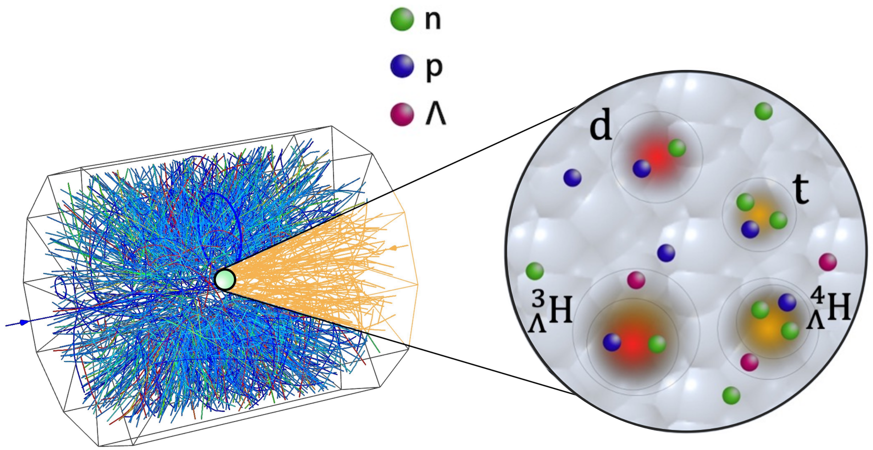
① **Light nuclei** carry information about local baryon density fluctuations

② Provides an effective probe to study first-order phase boundary and the QCD **C**ritical **P**oint

2. Hypernuclei

① **Hypernuclei** can provide access to the hyperon–nucleon interaction

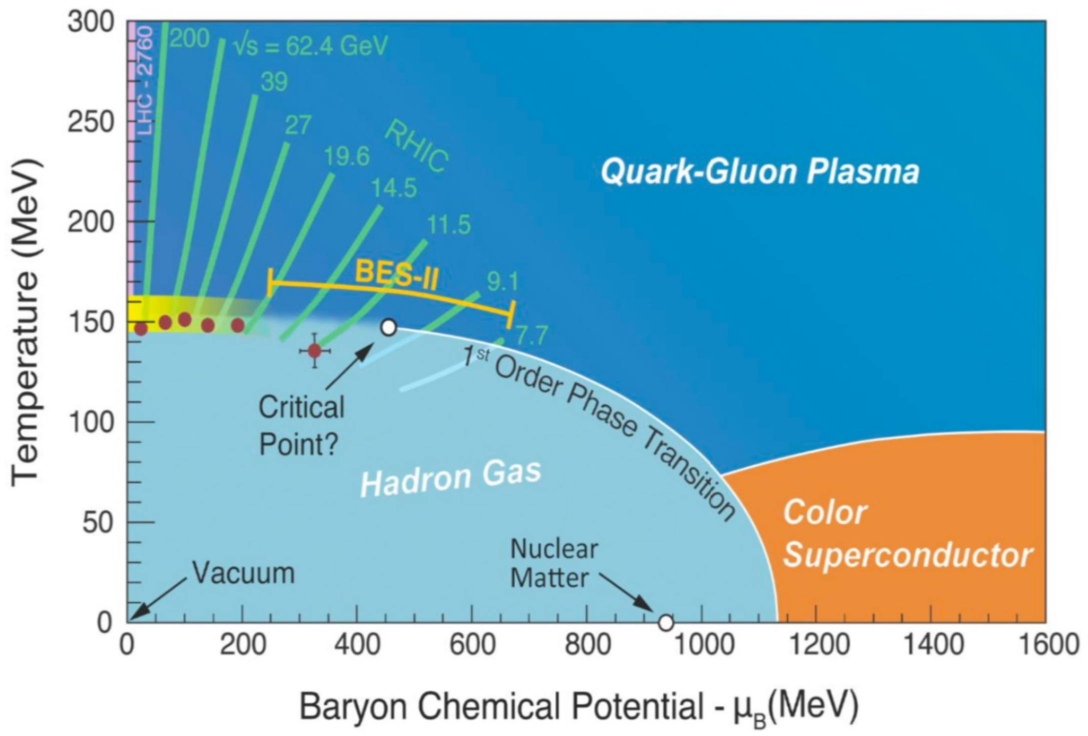
② To understand the formation of loosely bound states in heavy-ion collisions



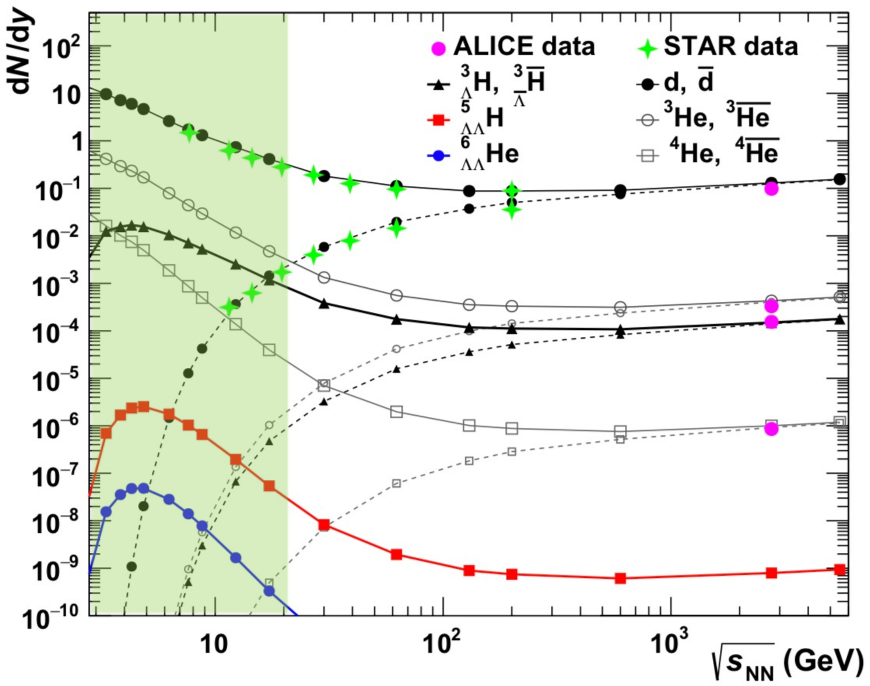
K. Sun et al. Phys.Lett.B 774 (2017) 103-107
E. Shuryak et al. Phys.Rev.C 101 (2020) 3, 034914
H. Agakishiev et al. [STAR Collaboration] Nature 473 (2011) 353

Introduction

- Light nuclei production in heavy-ion collisions at wide energy ranges have been extensively studied both experimentally and theoretically
- Hypernuclei measurements are scarce in heavy-ion experiments



BES-II



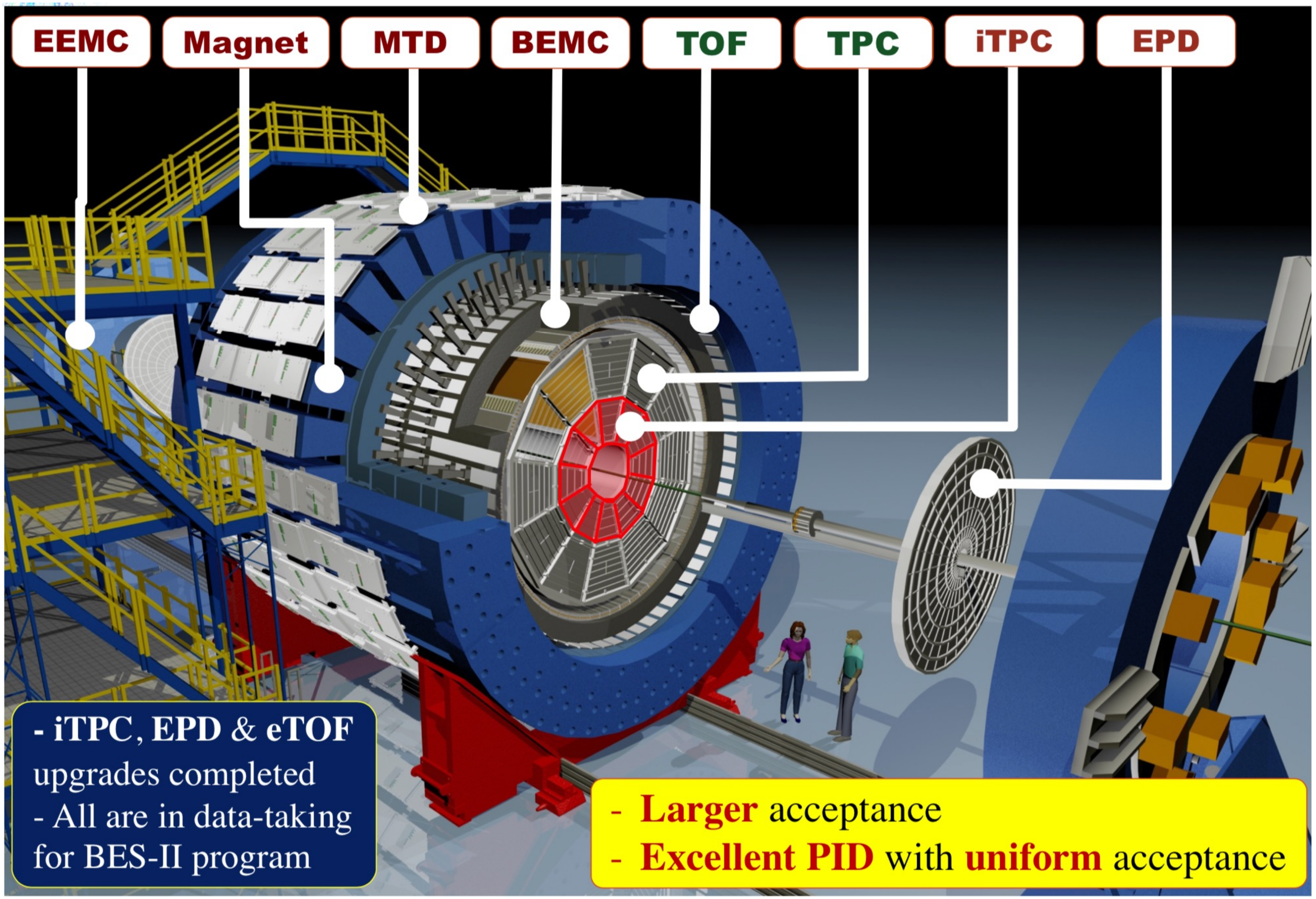
- At low energies, light (hyper)nuclei production is expected to be enhanced due to high baryon density

μ_B *up to 750 MeV at 3.0 GeV*

A. Andronic et al. Phys.Lett.B 697 (2011) 203-207
B. Dönigus, Eur.Phys.J.A 56 (2020) 11, 280

STAR Detector & BES-II Upgrades

The Solenoidal Tracker At RHIC



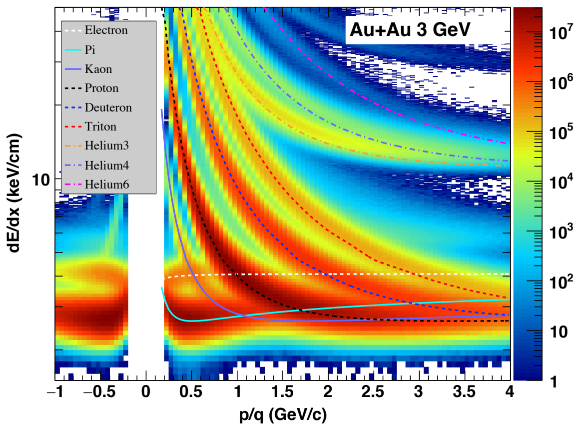
BES-II Upgrades

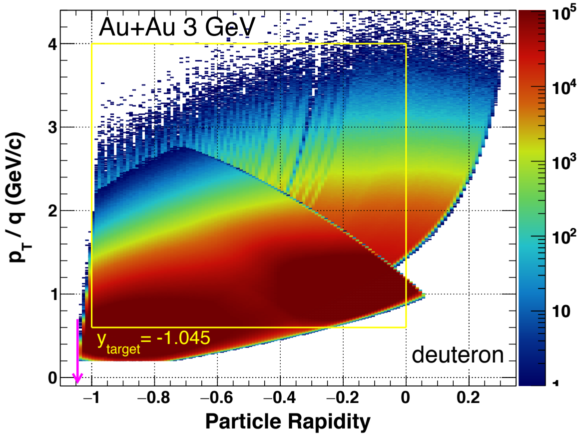
- iTPC (2019+)
  - Extended η acceptance and improved tracking and dE/dx resolution
- eTOF (2019+)
  - Extended PID coverage
- EPD (2018+)
  - Improved EP resolution

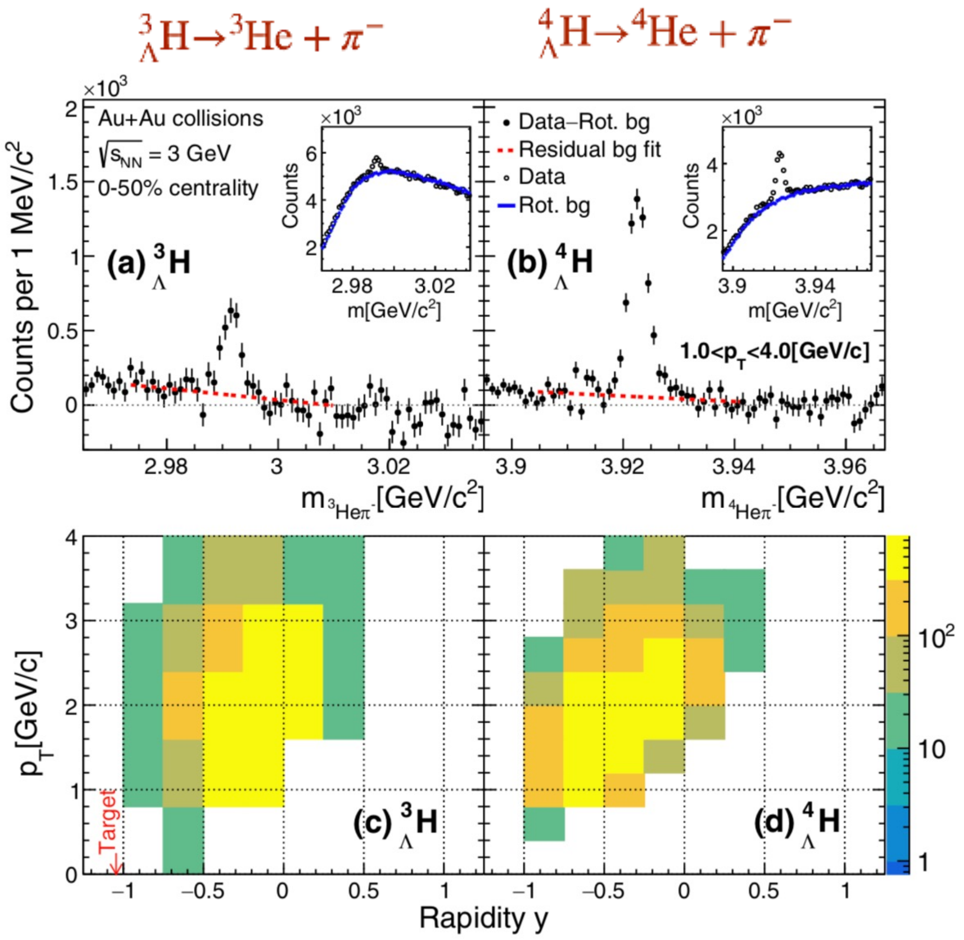
Particle Identification

- Good kinematic coverage in 3 GeV Au+Au collisions
- Particle identification using Time Projection Chamber (TPC) and Time of Flight (TOF)
- Combinatorial background estimated via rotating pion tracks or event mixing on hypernuclei reconstruction

Hypernuclei reconstruction via 2-body channel:



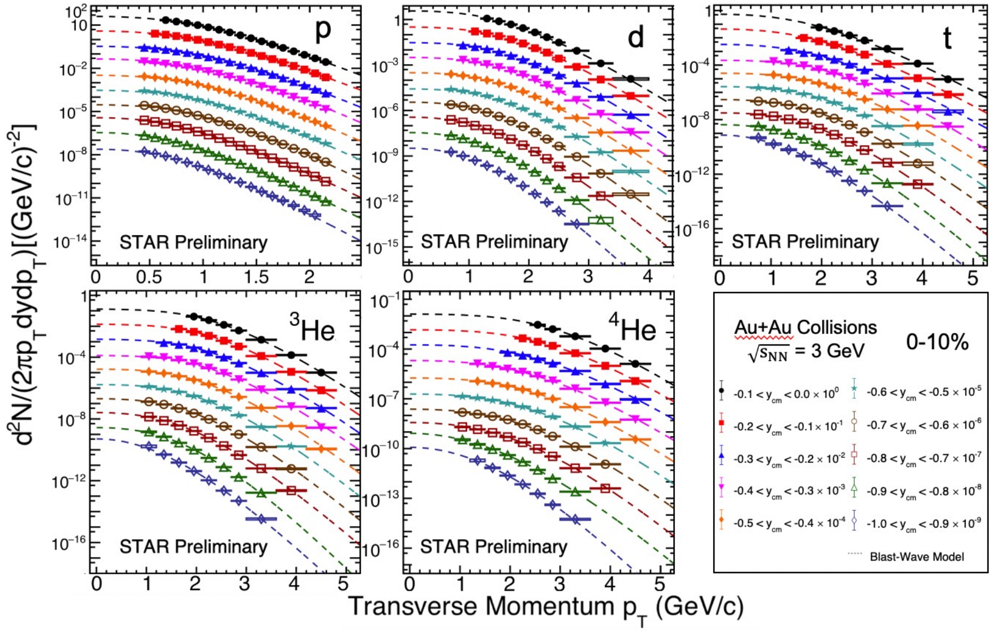




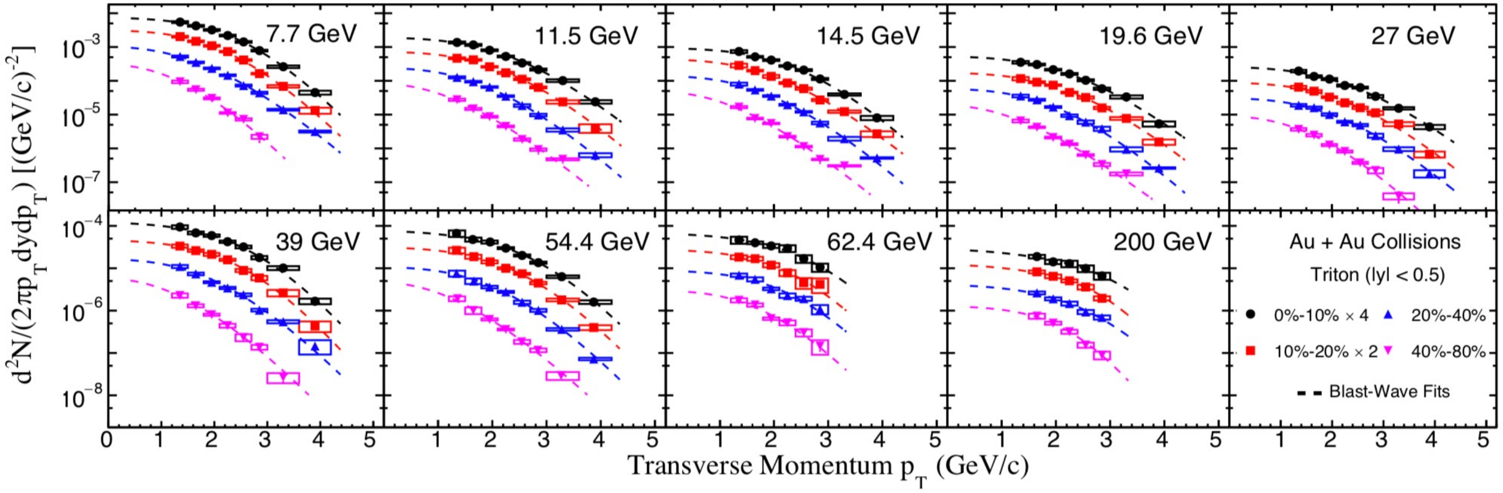
M. Abdallah et al. [STAR Collaboration] Phys.Rev.Lett. 128 (2022) 20, 202301

Measurements of light nuclei production in Au+Au collisions

Transverse Momentum Spectra



- Transverse momentum spectra of p, d, t, ^{3}He, and ^{4}He with rapidity slices in central (0-10%) Au+Au collisions at $\sqrt{s_{NN}}$ = 3 GeV (**BES-II**)
- Mid-rapidity (|y|<0.5) transverse momentum spectra of triton in Au+Au collisions at $\sqrt{s_{NN}}$ = 7.7 – 200 GeV (**BES-I**)



Blast-Wave Function:

$$\frac{1}{2\pi p_T}\frac{d^2N}{dp_T dy} \propto \int_0^R r dr m_T I_0\left(\frac{p_T \sinh\rho}{T_{kin}}\right) K_1\left(\frac{m_T \cosh\rho}{T_{kin}}\right)$$

$$\rho = \tanh^{-1}\beta_r, \quad \beta_r(r) = \beta_T\left(\frac{r}{R}\right)^n$$

Freeze-out parameters:

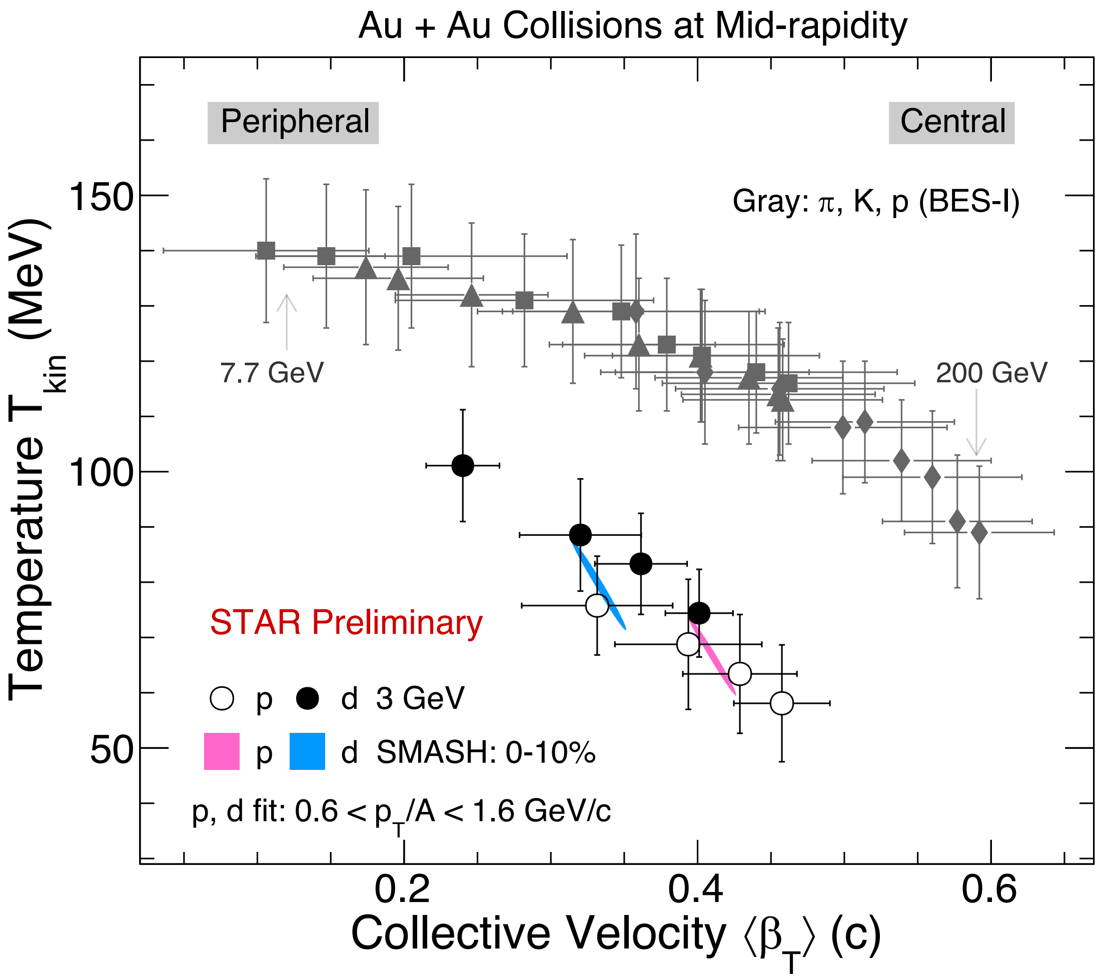
T_{kin} : kinetic freeze-out temperature

$\langle\beta_T\rangle$: average radial flow velocity

n : n=1 (I_0 and K_1 are from Bjorken Hydrodynamic assumption)

H. Liu, arxiv:2208.04650
[STAR Collaboration] arxiv:2209.08058

Freeze-out Parameters



- At 3 GeV Au+Au collisions, the freeze-out parameters (T_{kin}, $\langle\beta_T\rangle$) show different trend compared to that of higher energy collisions

Indicate a different equation of state (EoS)

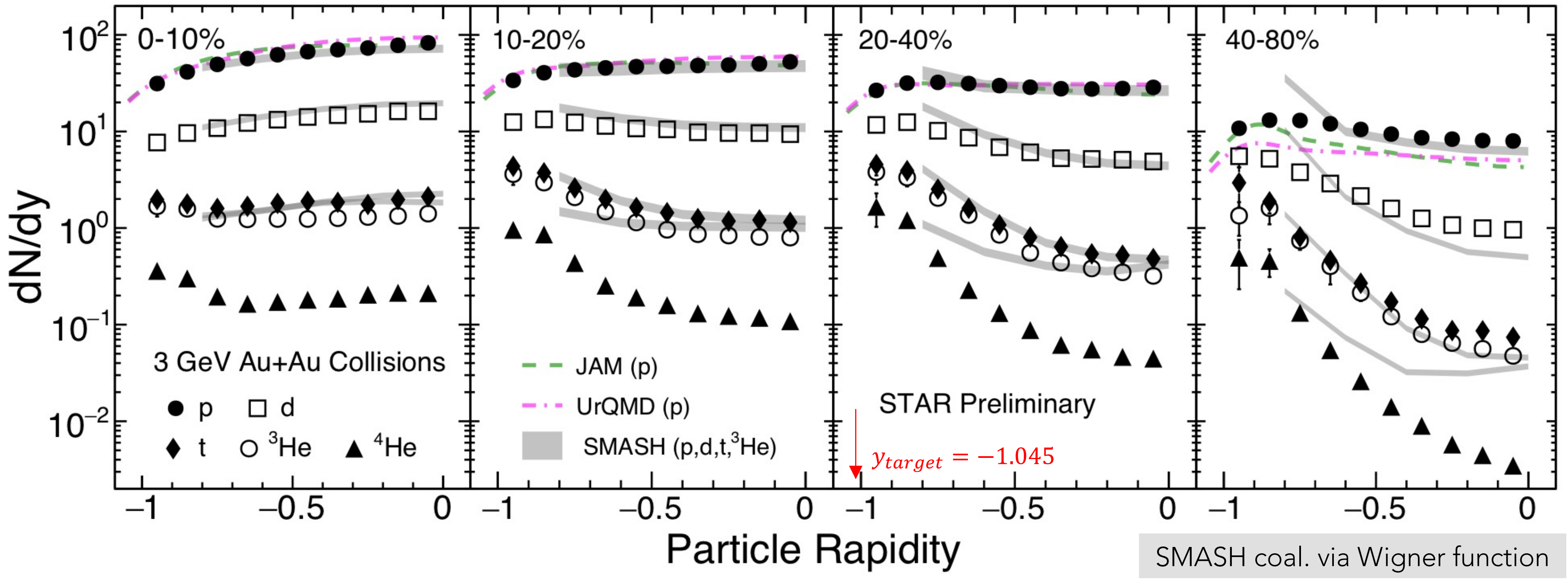
- The freeze-out parameter (T_{kin}) of d is systematically higher than that of p at 3 GeV, which is different from higher energies

Similar trend seen in SMASH Model
$T_d > T_p$

H. Liu, arxiv:2208.04650

B.I. Abelev et al. [STAR Collaboration] Phys.Rev.C 79 (2009) 034909
L. Adamczyk et al. [STAR Collaboration] Phys.Rev.C 96 (2017) 4, 044904

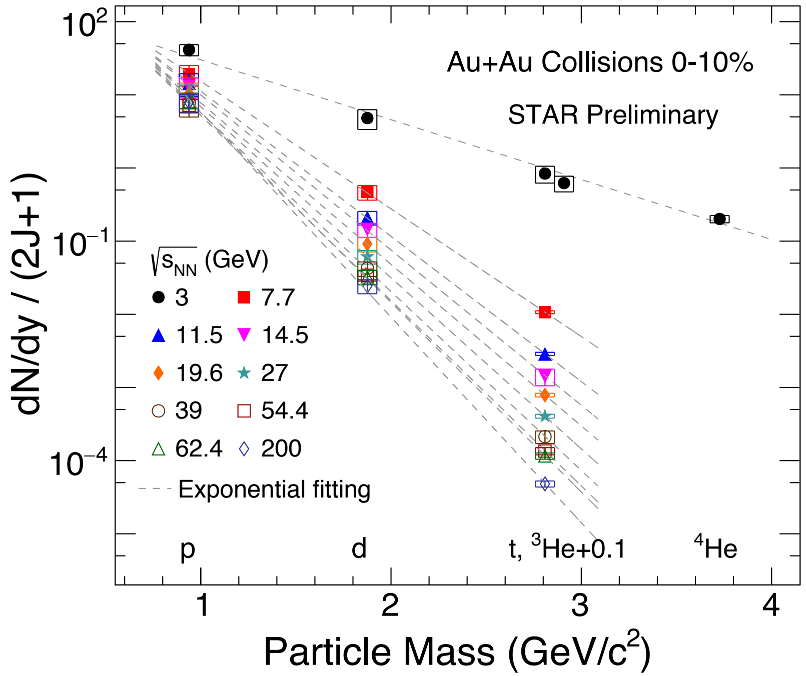
Rapidity Dependence of Yields at 3 GeV

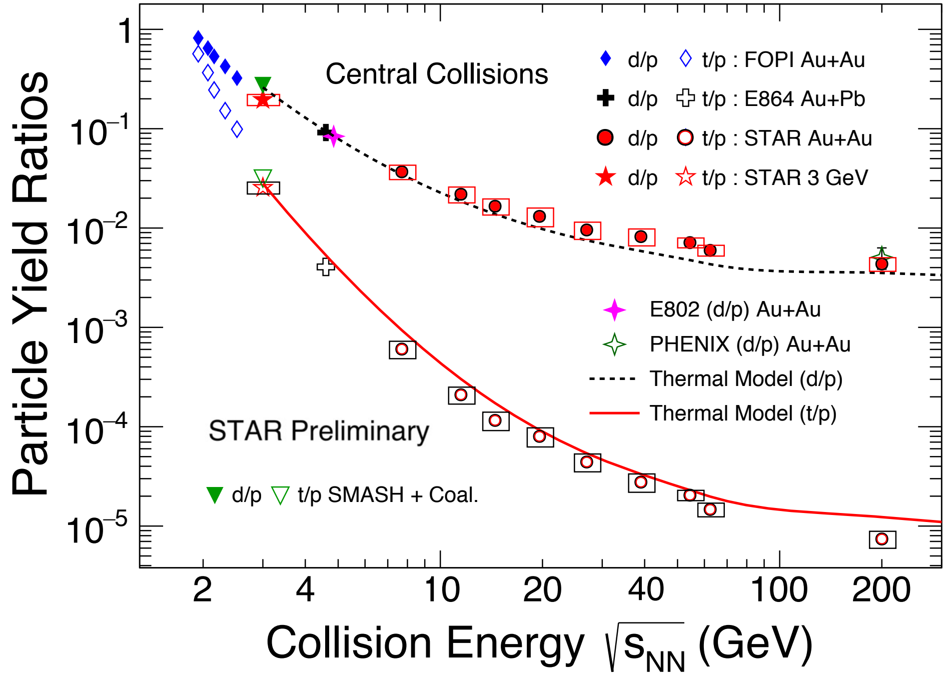


- dN/dy of protons and light nuclei show significant centrality and rapidity dependence at 3 GeV
- 3 GeV with good rapidity coverage provides the opportunity to calculate 4π yields accurately
- Transport model reproduces the trend of particle rapidity distribution in central and mid-central collisions

L. W. Chen et al. Phys.Rev.C 68 (2003) 017601; J. Weil et al. Phys.Rev.C 94 (2016) 5, 054905
W. Zhao et al. Phys.Rev.C 98 (2018) 5, 054905; H. Liu, arxiv:2208.04650

Energy Dependence of Yields

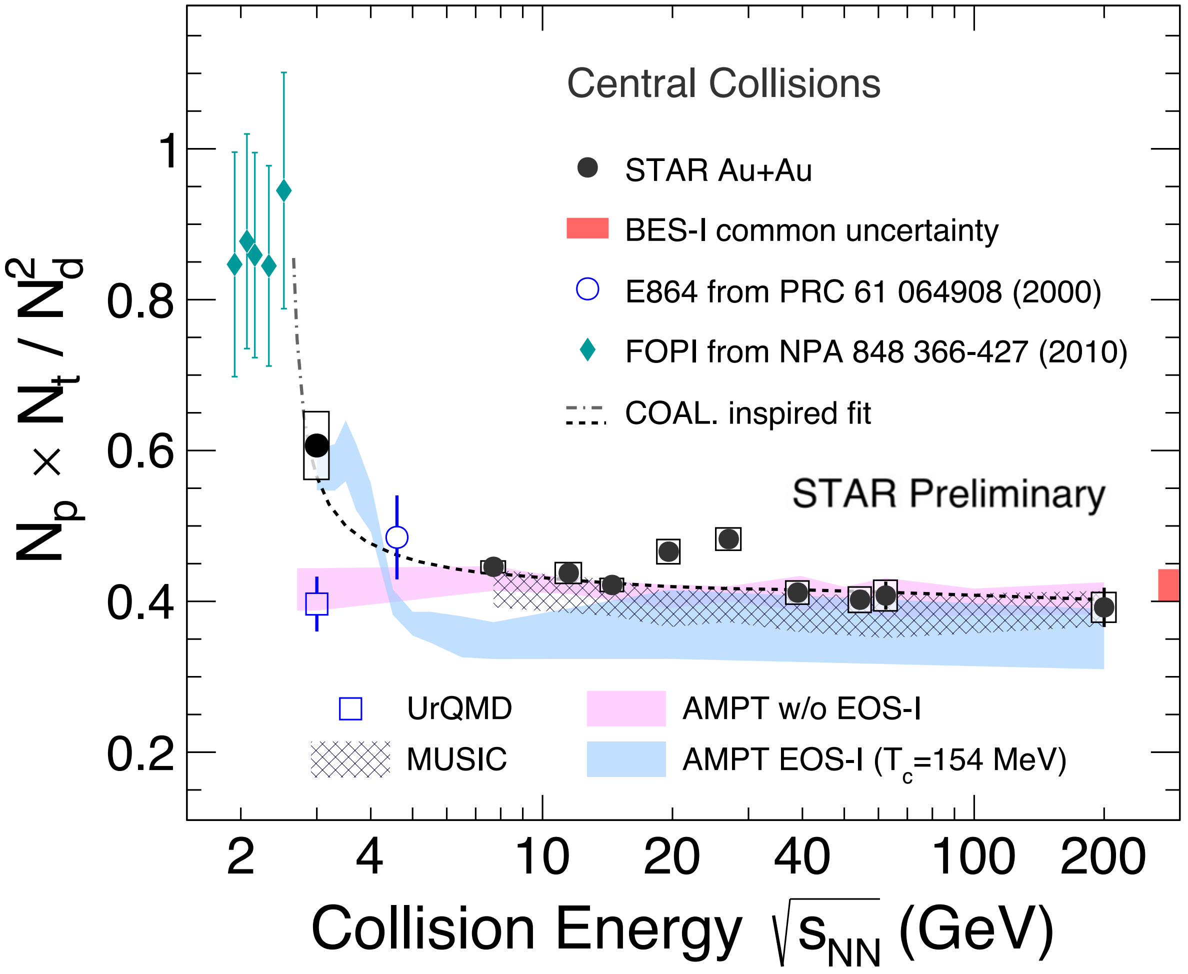




- Light nuclei yields decrease exponentially with increasing particle mass
- Slope decrease indicates that light nuclei are more easily formed at low energies
- Clear energy dependence is observed for both d/p and t/p ratios
- The trends of ratios can be described qualitatively by the Thermal model

V. Vovchenko, et al. Phys. Rev. C 93(2016) 6, 064906
L. Adamczyk et al. [STAR Collaboration] Phys.Rev.C 96 (2017) 4, 044904
J. Adam et al. [STAR Collaboration] Phys.Rev.C 99 (2019) 6, 064905
L. Ahle et al. [E802 Collaboration] Phys.Rev.C 60 (1999) 064901
T.A. Armstrong et al. [E864 Collaboration] Phys.Rev.C 61 (2000) 064908
W. Reisdorf et al. [FOPI Collaboration] Nucl.Phys.A 848 (2010) 366-427

Energy Dependence of Yield Ratios



- Non-monotonic behavior observed in 0-10% Au+Au collisions around 19.6 and 27 GeV
- The energy dependence trend can be well described by coalescence-inspired fit, and the enhancements at 19.6 and 27 GeV with a combined significance of 4.1**σ**

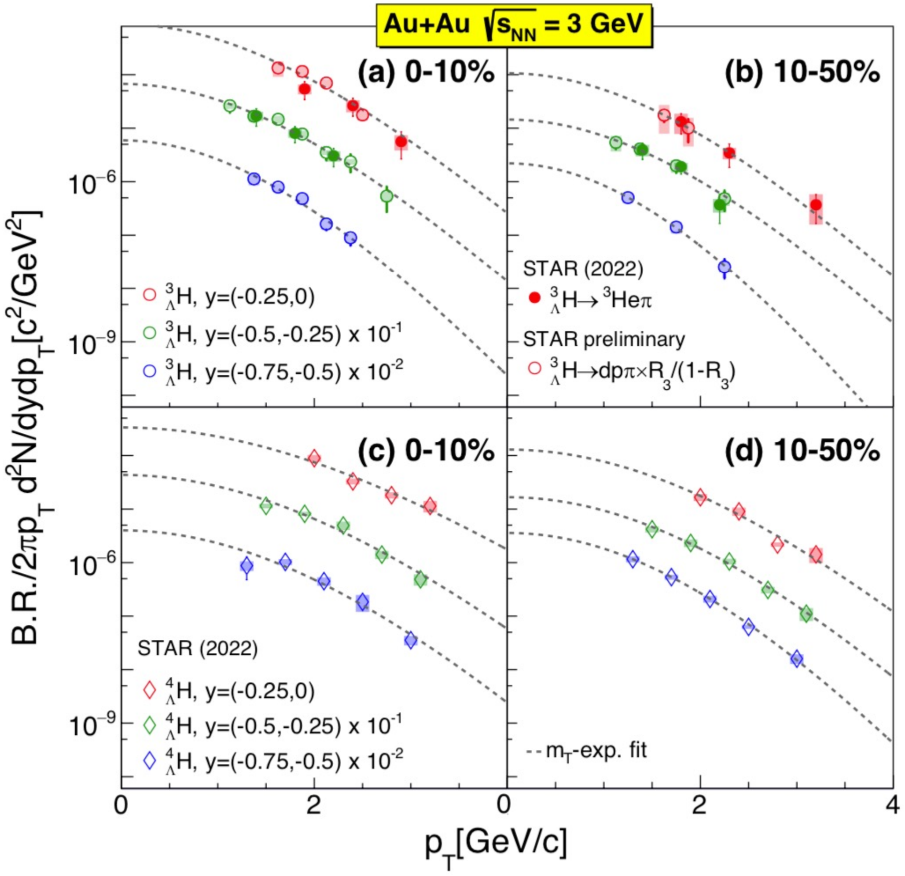
Coal. inspired fit: $\frac{N_p \times N_t}{N_d^2} \propto \left(\frac{R^2+\frac{2}{3}r_d^2}{R^2+\frac{1}{2}r_t^2}\right)^3, \quad R \propto (dN_{ch}/d\eta)^{1/3}$

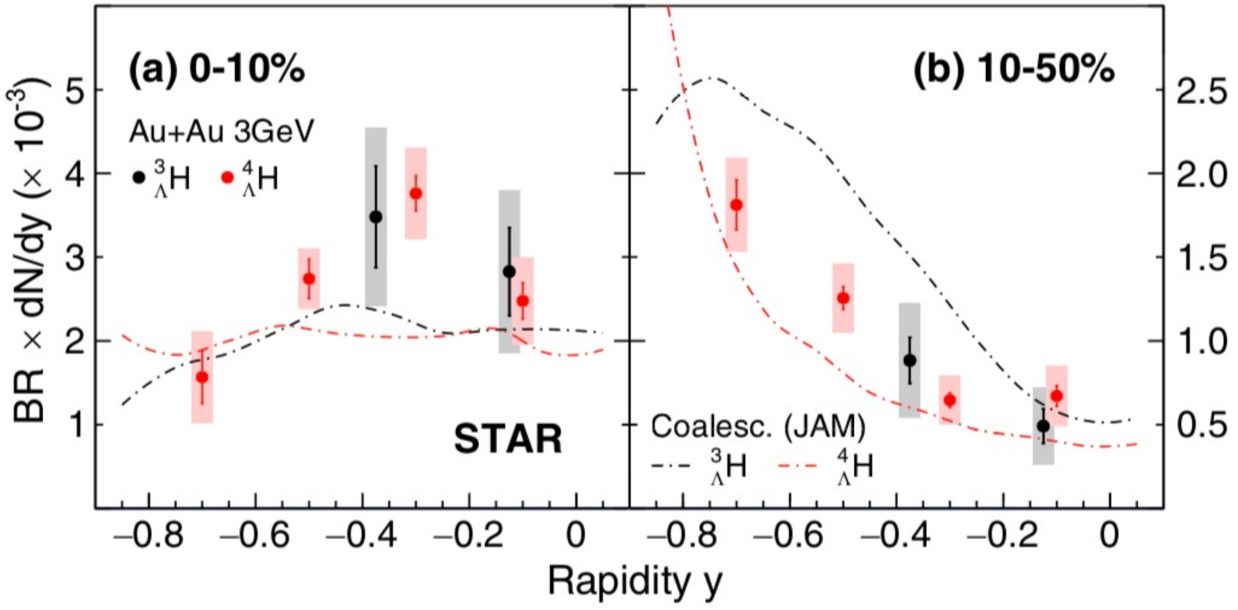
- The AMPT model calculations with a first-order phase transition can describe the increasing of the yield ratio at 3 GeV

[STAR Collaboration] arxiv:2209.08058
K. Sun et al. Phys.Lett.B 792 (2019) 132-137; arXiv: 2205.11010

Measurements of hypernuclei production in Au+Au collisions

p_T Spectra and Yields

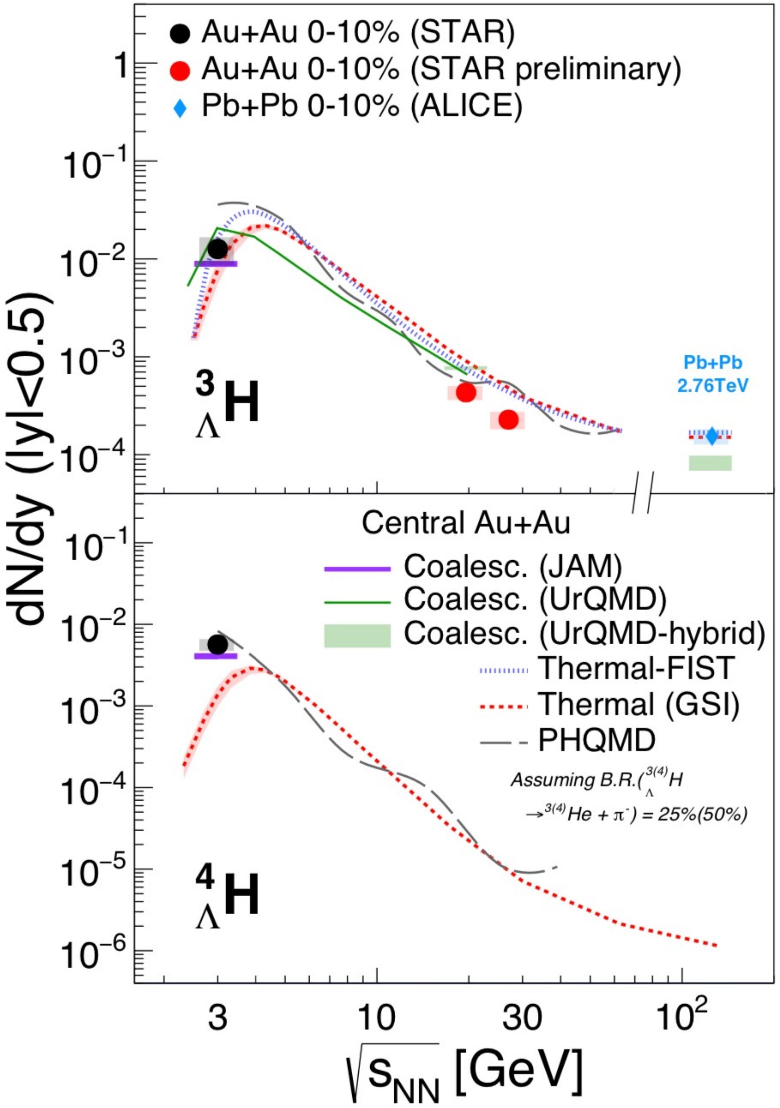




- First measurements on rapidity dependence of hypernuclei yields in heavy ion collisions
- Different trends in the $^4_\Lambda$H rapidity distribution in 0-10% and 10-50% centralities
- Coalescence model (JAM) with tuned parameters (r_c, p_c) qualitatively describe the trend of $^4_\Lambda$H yields versus rapidity

Y. Nara et al. Phys.Rev.C 61 (2000) 024901
H. Liu et al. Phys.Lett.B 805 (2020) 135452
M. Abdallah et al. [STAR Collaboration] Phys.Rev.Lett. 128 (2022) 20, 202301

Energy Dependence of Hypernuclei Production



- $^{3}_{\Lambda}H$ yield at mid-rapidity increases from 2.76 TeV to 3 GeV, likely driven by the increase in baryon density at low energies

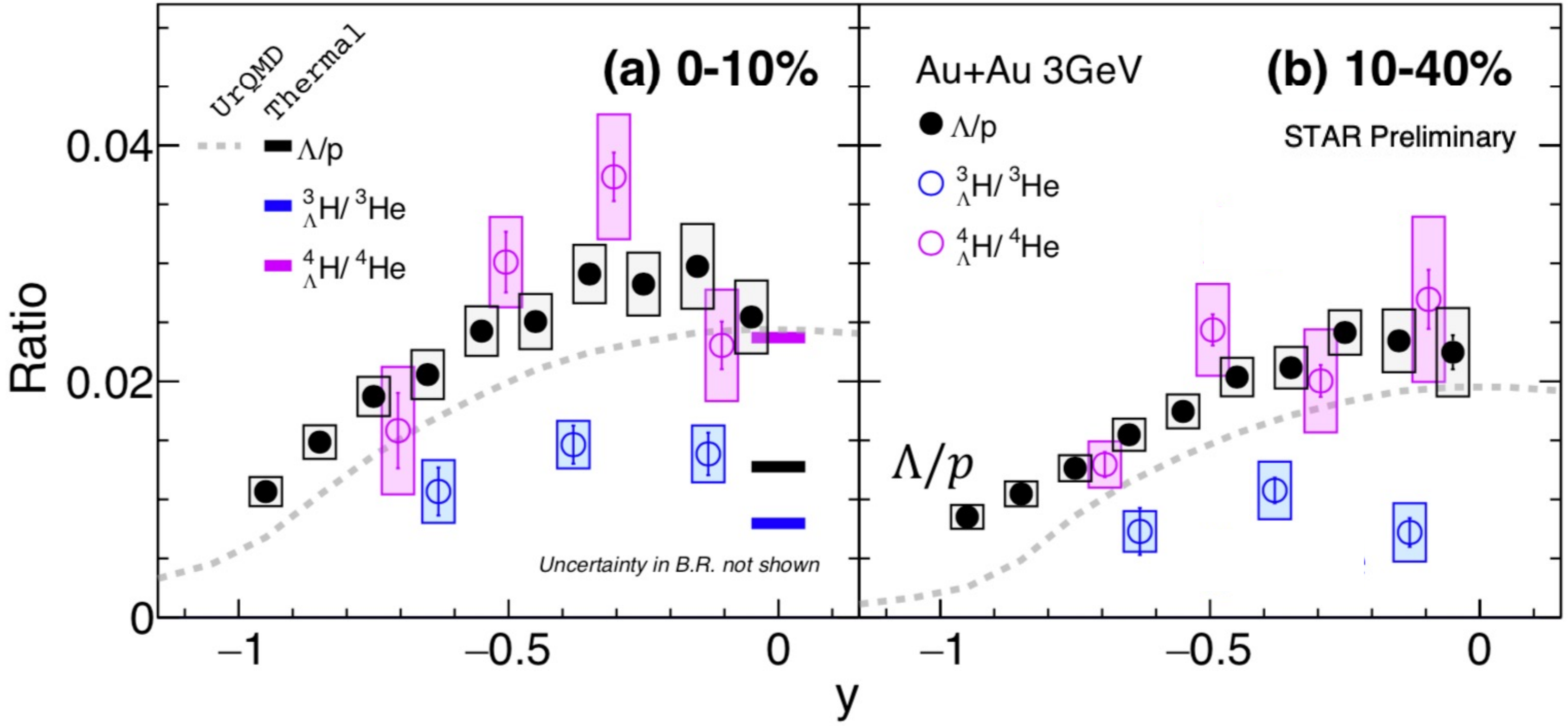
Low energy collision experiments as a promising tool to study exotic strange matter

- Thermal model predicts the trend while not quantitatively describe the yields
- For Au+ Au Collisions 3 GeV
  - Coalescence model (JAM) with tuned coalescence parameters can describe data
  - PHQMD describes $^{4}_{\Lambda}H$ yield while slightly overestimate $^{3}_{\Lambda}H$ yield

Provide first constraints for hypernuclei production models in the high baryon density region

Andronic et al, PLB 697 (2011)203
J. Steinheimer et al, PLB 714(2012),85
S. Glaßel et al, Phys.Rev.C 105 (2022) 1, 014908
J. Adam et al. [ALICE Collaboration] Phys.Lett.B 754 (2016) 360-372
M. Abdallah et al. [STAR Collaboration] Phys.Rev.Lett. 128 (2022) 20, 202301

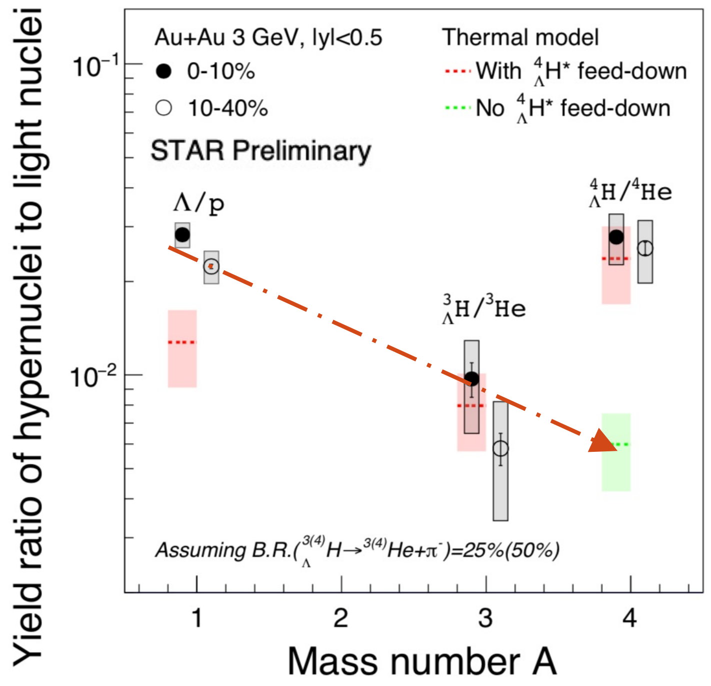
Hyper to Light Nuclei Ratios

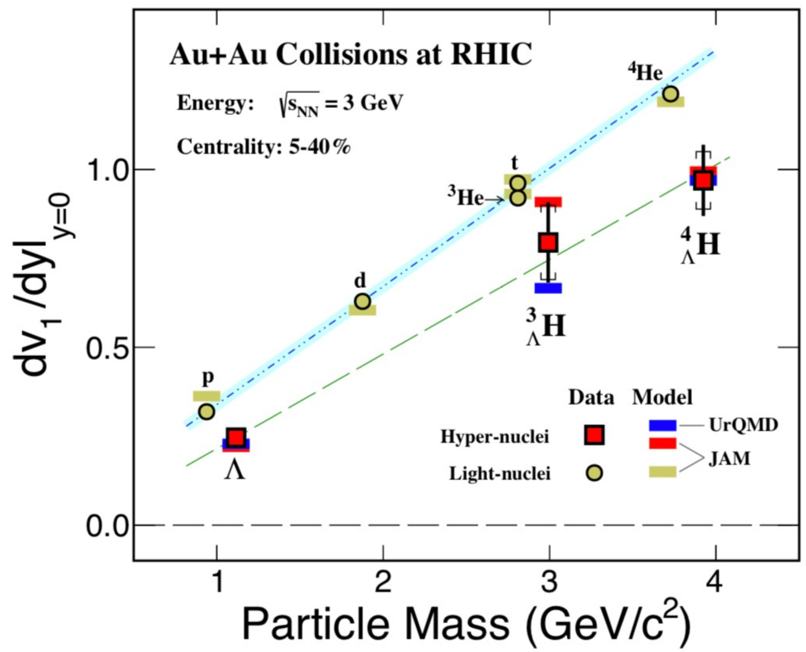


- Comparable the rapidity dependence of $^{3}_{\Lambda}\mathrm{H}/^{3}\mathrm{He}$ and $^{4}_{\Lambda}\mathrm{H}/^{4}\mathrm{He}$ ratios to that of Λ/p
- Suppression of $^{3}_{\Lambda}\mathrm{H}/^{3}\mathrm{He}$ ratios compared to that of Λ/p at both in central (0-10%) and mid-central (10-40%) Au+Au collisions at 3 GeV

A Andronic et al. Phys.Lett.B 697 (2011) 203-207

Mass Dependence of Hypernuclei Production





- $^4_\Lambda$H lies a factor of 6 above exponential fit to (Λ, $^3_\Lambda$H, and $^4_\Lambda$H)
- Thermal model indicate that this is possibly due to feed-down from excited state enhancing $^4_\Lambda$H production

$^4_\Lambda H^*(J^+ = 1) \rightarrow ^4_\Lambda H(J^+ = 0) + \gamma$

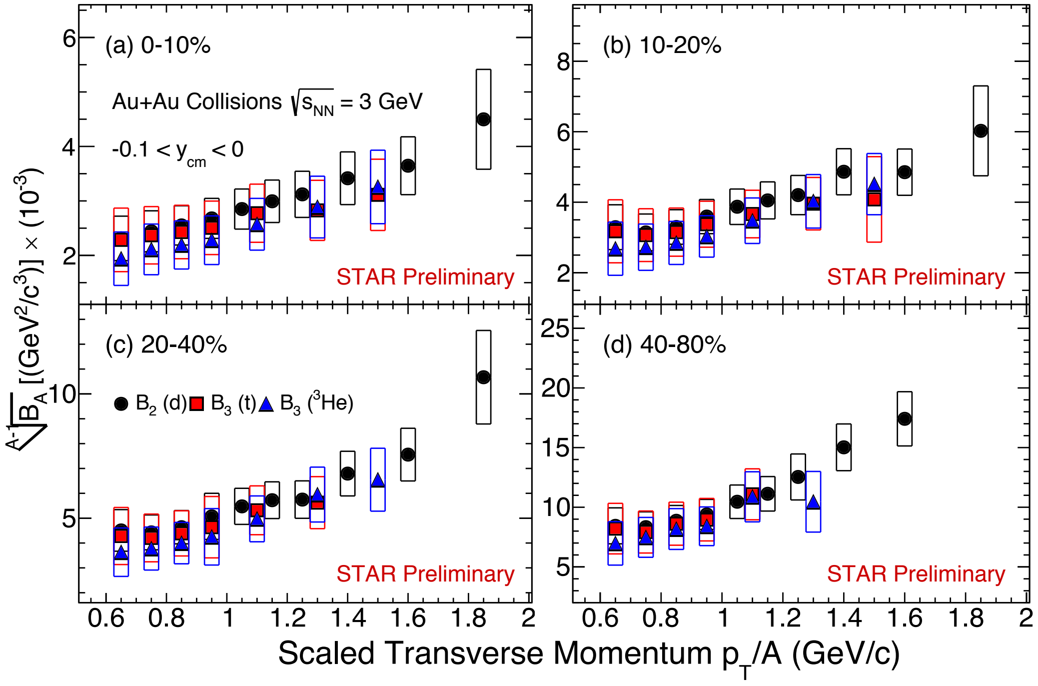
- v_1 slope both of light nuclei and hypernuclei follow mass number scaling in 5-40% Au+Au collisions
- Light and (hyper)nuclei are formed mainly via coalescence process

A Andronic et al. Phys.Lett.B 697 (2011) 203-207
[STAR Collaboration] arXiv:2211.16981

Coalescence Parameters & Strangeness Population Factors

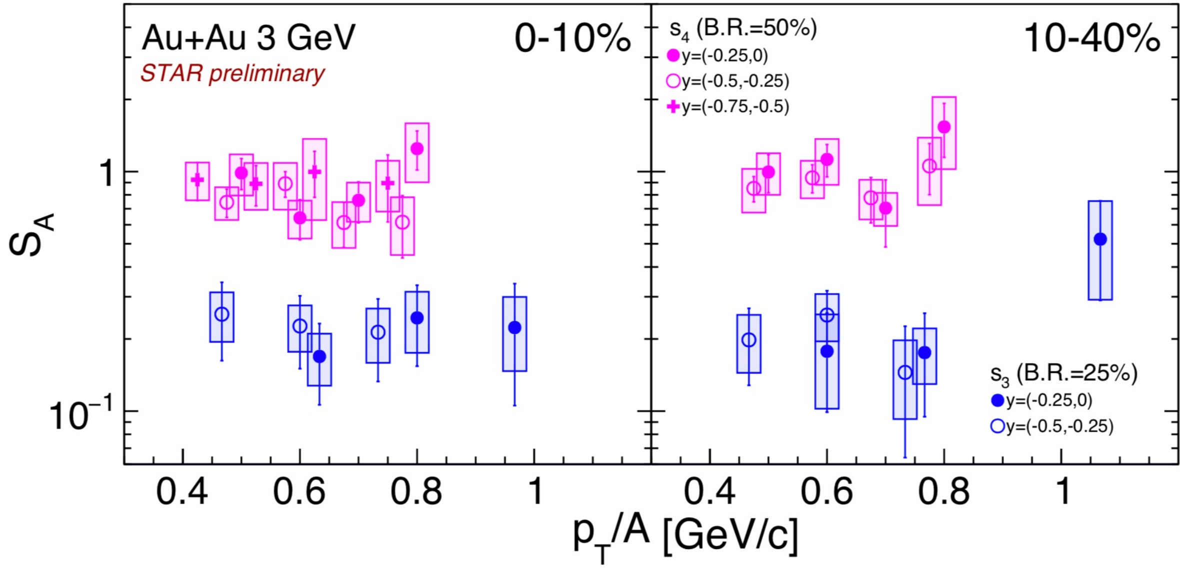
Coalescence parameter (B_A):

$$E_A \frac{d^3N_A}{dp_A^3} \approx B_A\left(E_p \frac{d^3N_p}{dp_p^3}\right)^A\Big|_{p_p=p_n=\frac{p_A}{A}}$$



Strangeness population factor (S_A):

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



R. Scheibl and U. Heinz Phys.Rev.C 59 (1999) 1585-1602
S. Zhang et al. Phys.Lett.B 684 (2010) 224-227
J. Adam et al. [STAR Collaboration] Phys.Rev.C 99 (2019) 6, 064905

- $B_A \propto (1/V)^{(A-1)}$ reflects the region of homogeneity and the freeze-out property
- No obvious p_T, rapidity, and centrality dependence of S_A observed at 3 GeV
- B_A of light nuclei and hypernuclei follow similar trends in p_T/rapidity/centrality

Summary and Outlook

1. Light Nuclei measurement

   → Strong centrality and rapidity dependences observed for p **and light nuclei at 3 GeV**

   → Enhancements of the yield ratios are observed in 0-10% most central collisions at 19.6 and 27 GeV with a combined significance of 4.1σ

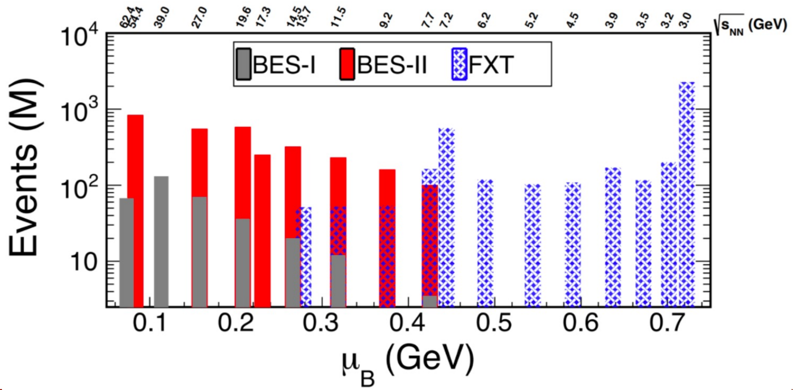
2. Hypernuclei measurement

   → First set of hypernuclei yield measurements in the high-baryon-density region with high statistical precision

   → Provide stronger constraints on hypernuclei internal structures

3. Collectivity behavior support the coalescence of light and (hyper)nuclei production

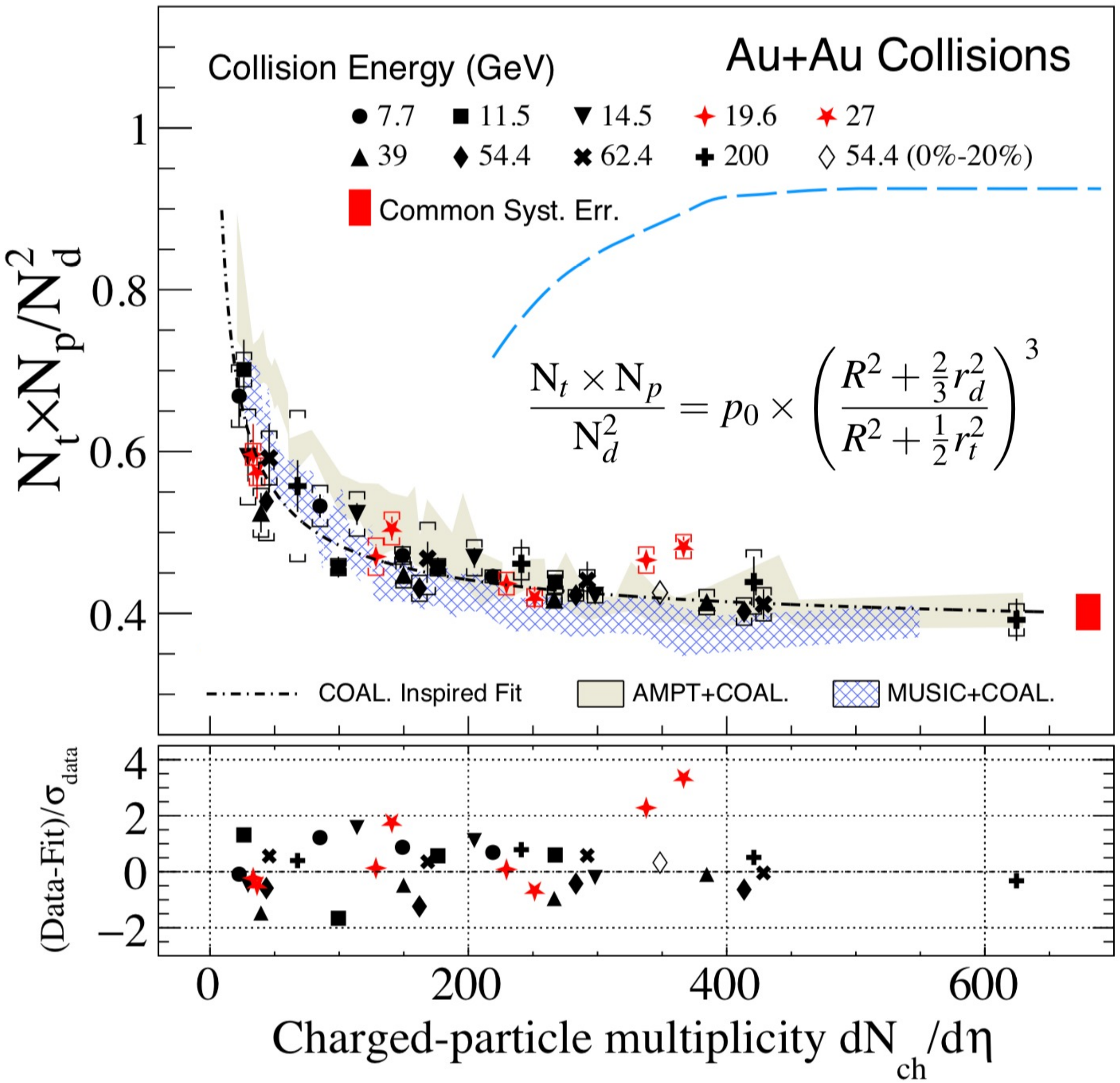
- High statistical data in STAR BES-II at $\sqrt{s_{NN}}$ = 3 – 19.6 GeV
- Deep understanding on light nuclei production mechanisms
- Precise measurements on hypernuclei intrinsic properties



Thanks for your attention!

Backup Slides

Energy Dependence of Yield Ratios

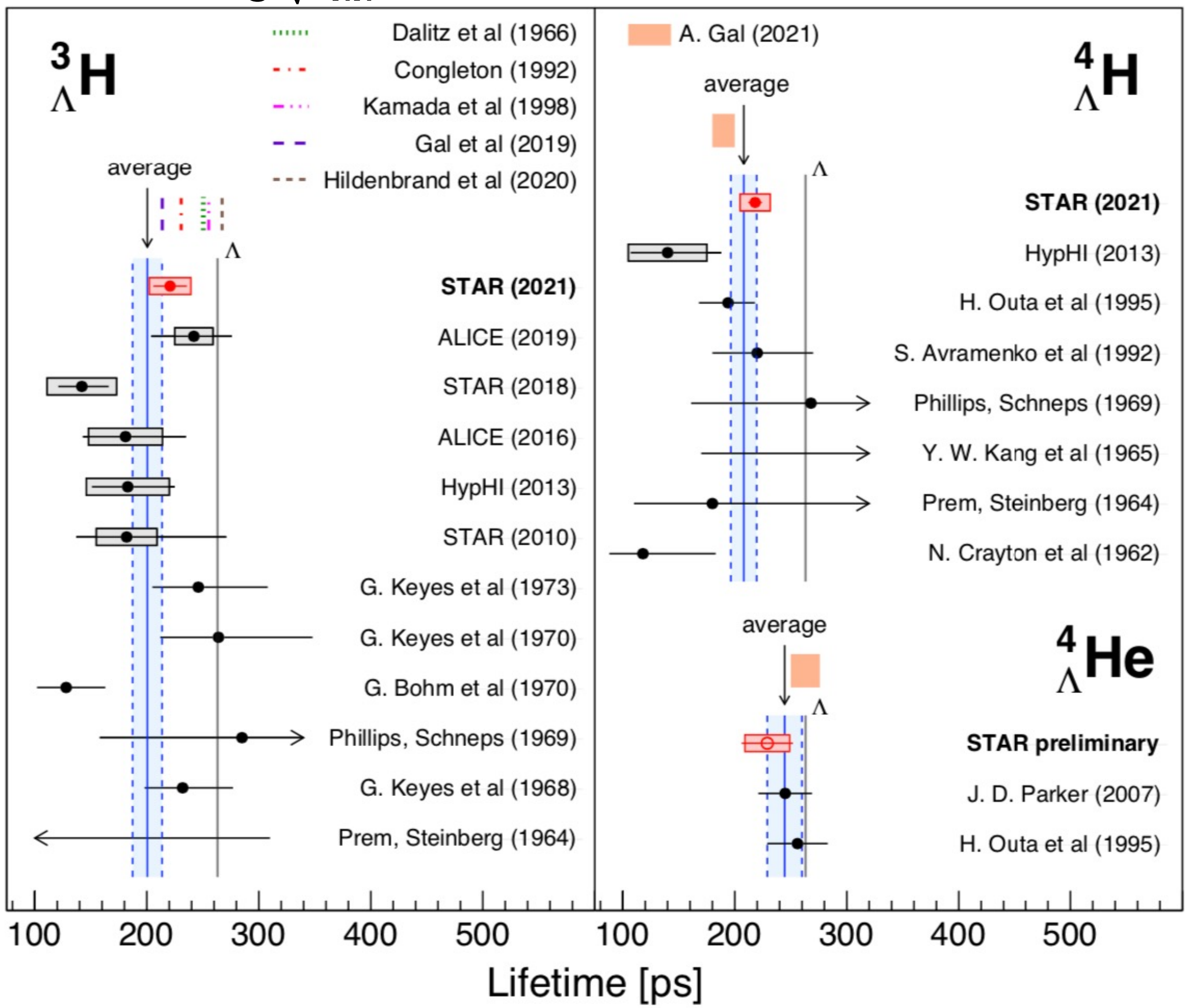


- The light nuclei yield ratio decreases monotonically with increasing $dN_{ch}/d\eta$ and exhibits a scaling behavior
- The ratio can be well described by the coalescence model
- Non-monotonic behavior observed in the energy dependence of the yield ratio in 0-10% Au+Au collisions around 19.6 and 27 GeV, the enhancements to the coalescence baseline with a significance of 2.3σ and 3.4σ, respectively

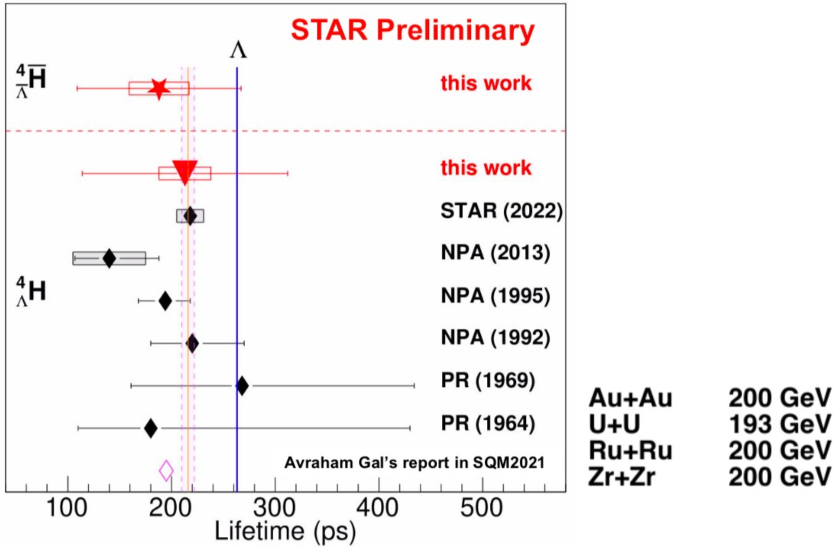
[STAR Collaboration] arxiv:2209.08058

Hypernuclei Lifetime

Unsing $\sqrt{s_{NN}}$ = 3.0 GeV and 7.2 GeV datasets



- Lifetimes of hypernuclei ($^3_\Lambda$H, $^4_\Lambda$H, and $^4_\Lambda$He) are shorter than that of free Λ (with 1.8σ, 3.0σ, and 1.1σ respectively)
- Consistent with former measurements



The first $^4_{\bar\Lambda}\bar{H}$ lifetime measurement in heavy ion collisions

M. Abdallah et al. [STAR Collaboration] Phys.Rev.Lett. 128 (2022) 20, 202301

J. Wu, sQM2022
Avraham Gal, EPJ Web Conf. 259 (2022) 08002