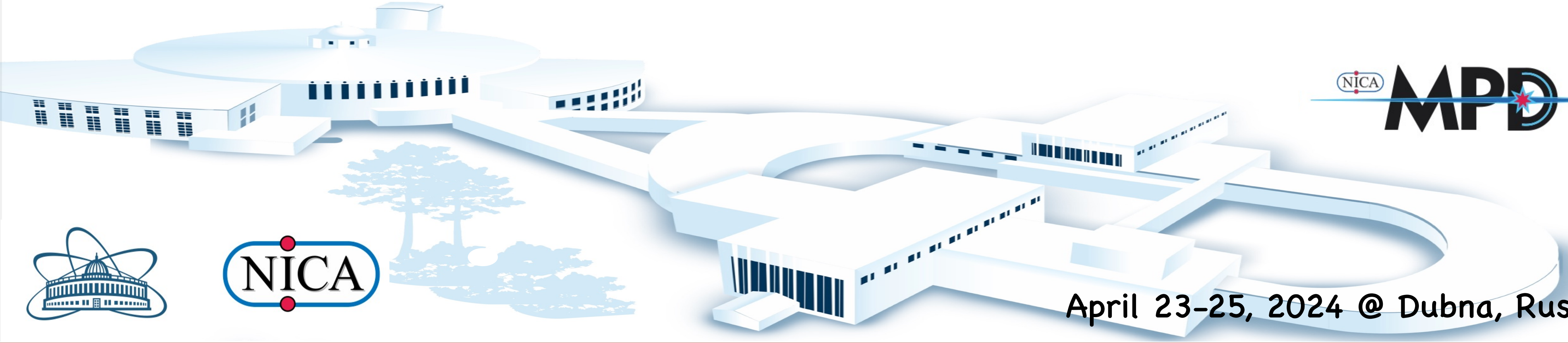
Light hadron and (hyper)nuclei production by RHIC-STAR

Hui Liu

Central China Normal University



April 23-25, 2024 @ Dubna, Russia

Outline

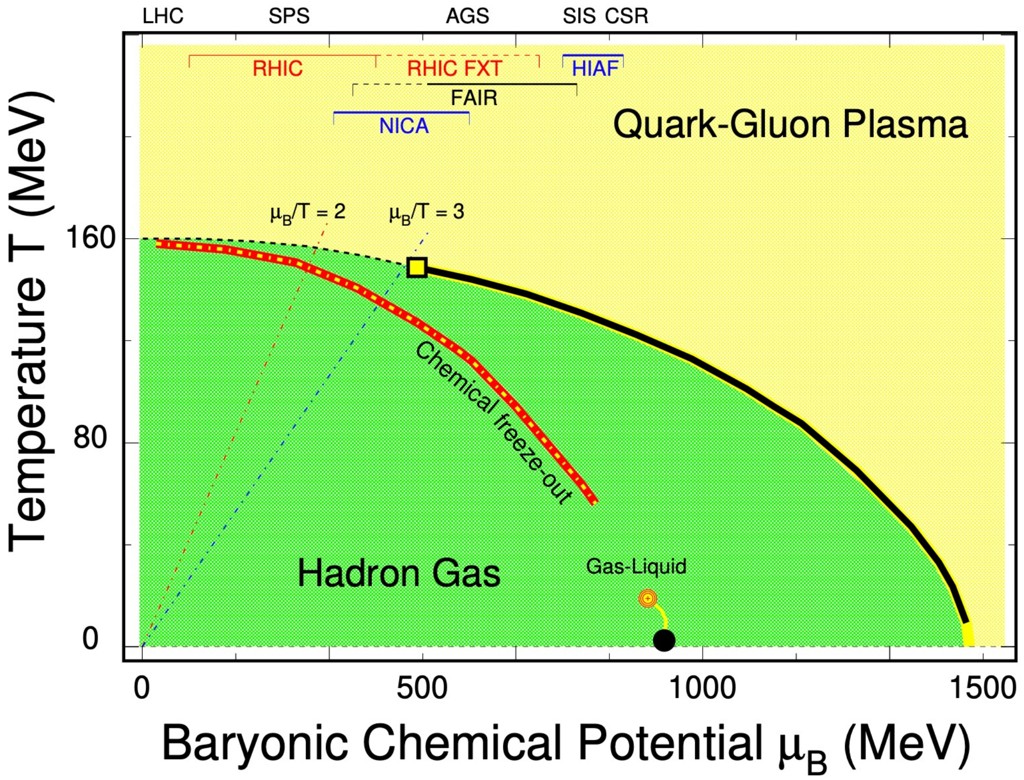
1. Introduction
2. RHIC-STAR Experiment
3. Results and Discussions
    - Proton and Light Nuclei Production
    - Hypernuclei production
4. Summary and Outlook

Introduction

Water

Ice

Water vapor

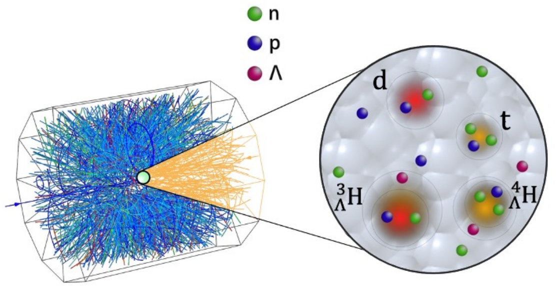


- **QCD Phase Transition**
  - High Temperature (T):
    - QGP properties
  - High Baryon Chemical Potential (μ_B):
    - Critical Point (CP)
    - 1^{st} phase boundary
- **Chemical Freeze-Out**
  - Inelastic collisions
  - Hadronization stage
  - Particle abundance is in equilibrium
- **Kinetic Freeze-Out**
  - Elastic collisions
  - Hadronic substance
  - The momentum distribution and kinetic energy of the particles are stabilized

Introduction

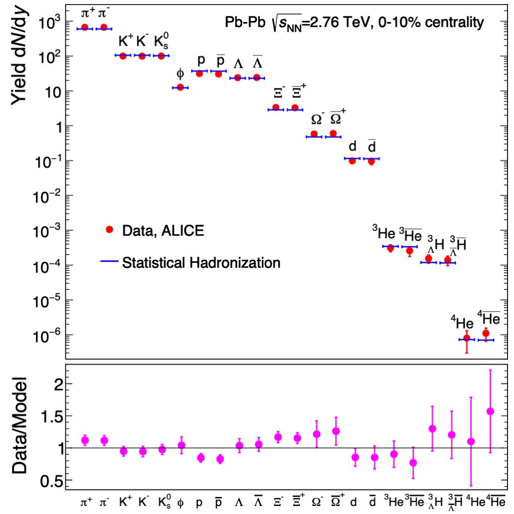
1. Light Nuclei

- Light nuclei carry information about local baryon density fluctuations
- Provides an effective probe to study first-order phase boundary and the QCD Critical Point



2. Hypernuclei

- Hypernuclei can provide access to the hyperon–nucleon interaction
- The structure of the hypernuclei reflect the loosely-bound state nature



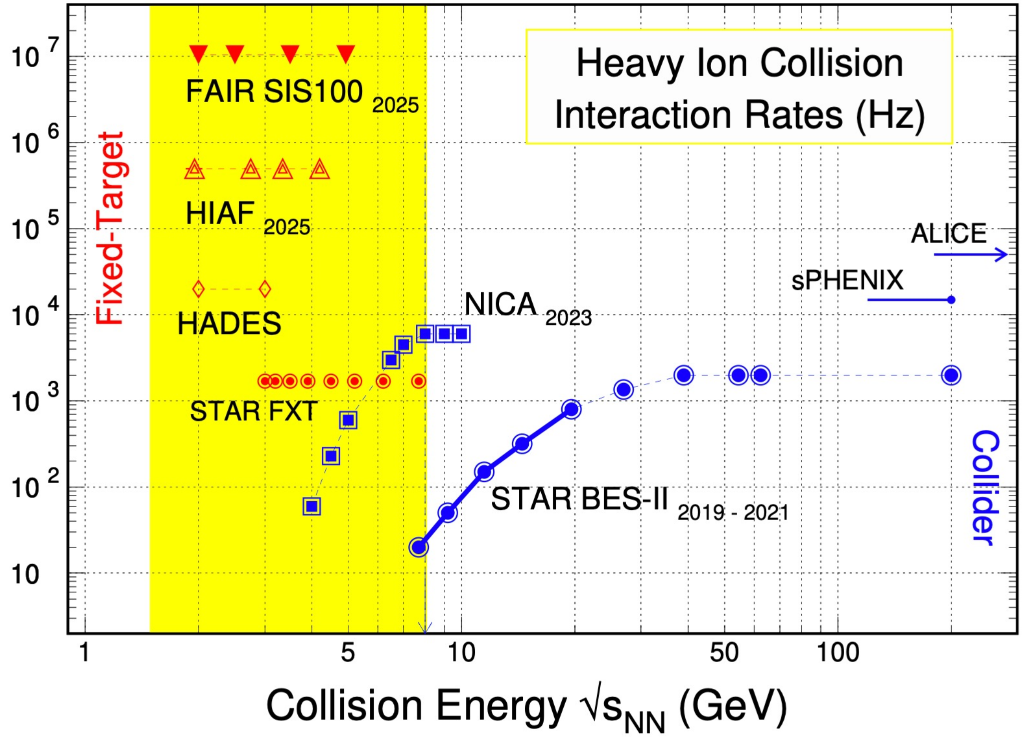
3. Production Mechanism

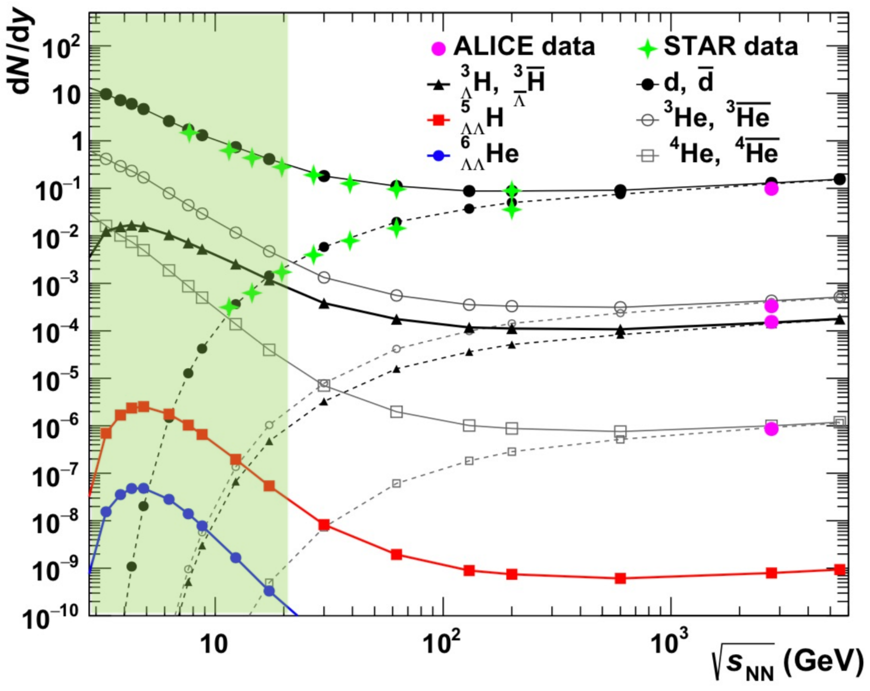
- **Statistical thermal:** Light (hyper)nuclei are produced directly during the evolution of the system
- **Coalescence:** After the kinetic freeze-out of the system, nucleons come together and coalesce to form a composite particle

K.J. Sun et al, Phys.Lett.B 792 (2019) 132-137;
A. Andronic et al, Nature 561 (2018) 7723, 321-330
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



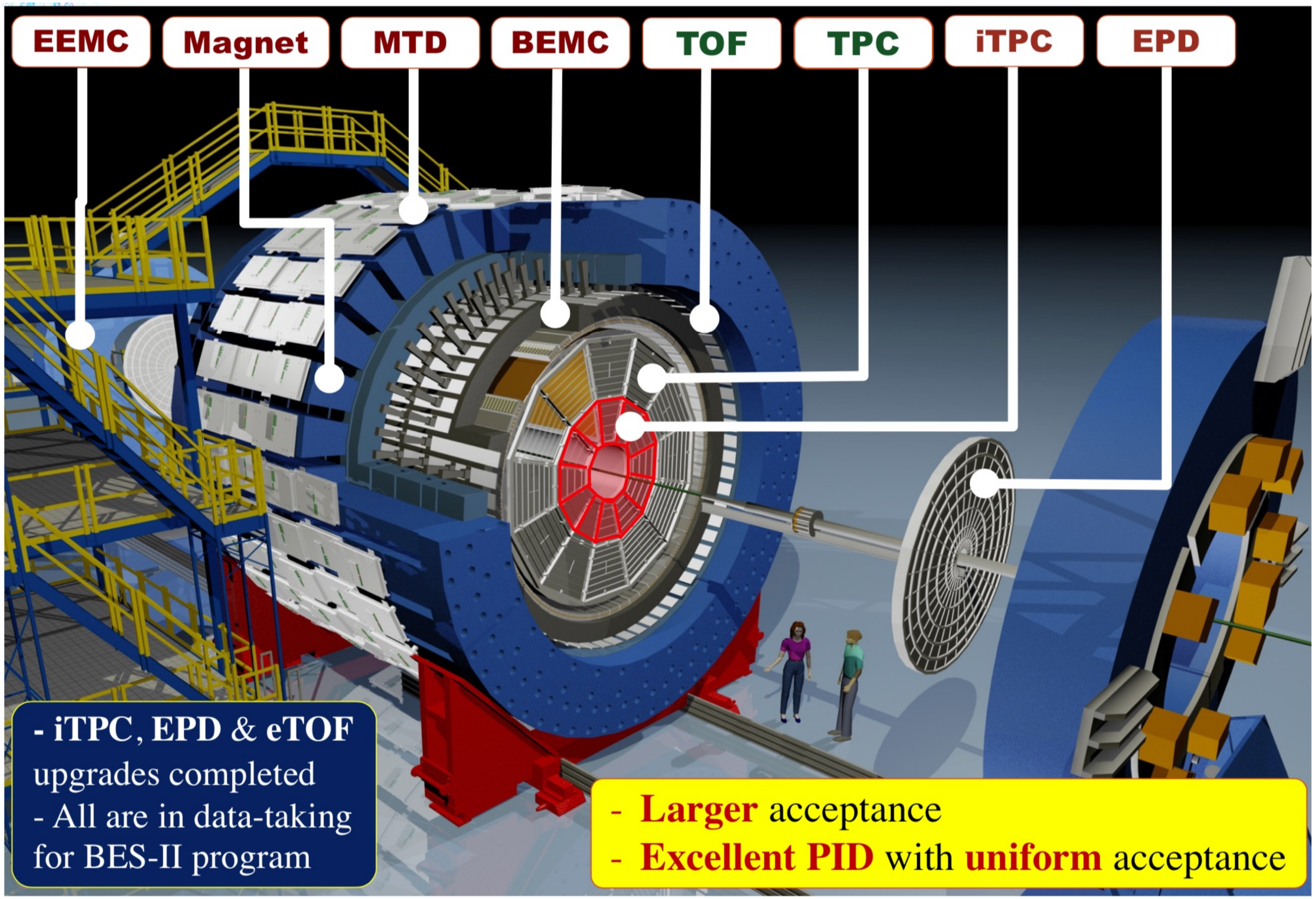


- At low energies, light (hyper)nuclei production is expected to be enhanced due to high baryon density

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

STAR Detector

The Solenoidal Tracker At RHIC



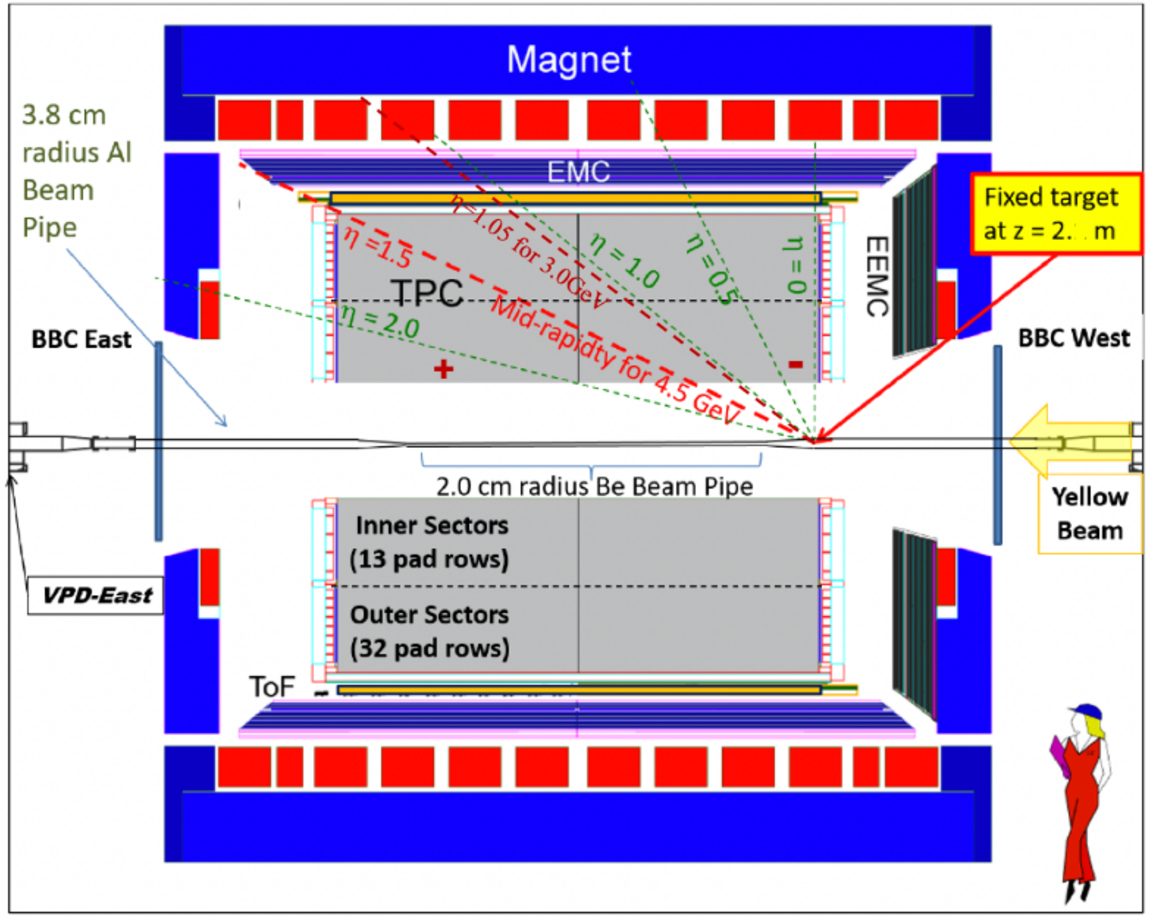
Main sub-detectors for PID

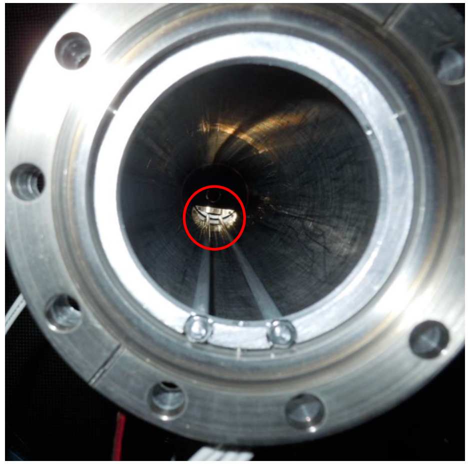
- Time Projection Chamber (TPC)
  - Ionization energy loss (dE/dx)
- Time of Flight (TOF)
  - $m^2 = p^2(c^2t^2/L^2 - 1)$

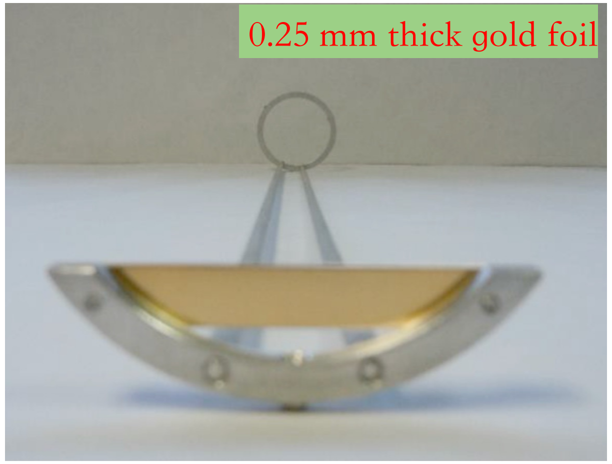
BES-II Upgrades

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

Fixed-Target Experiment



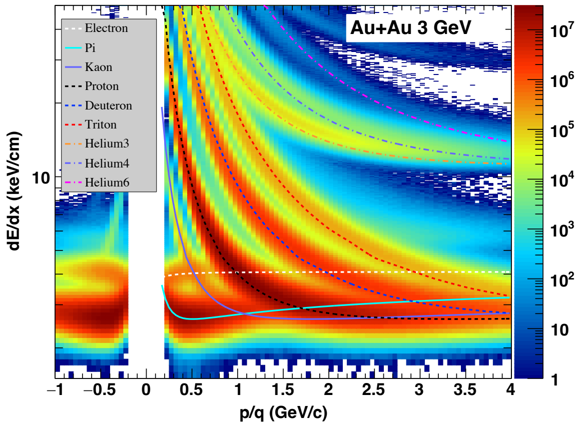


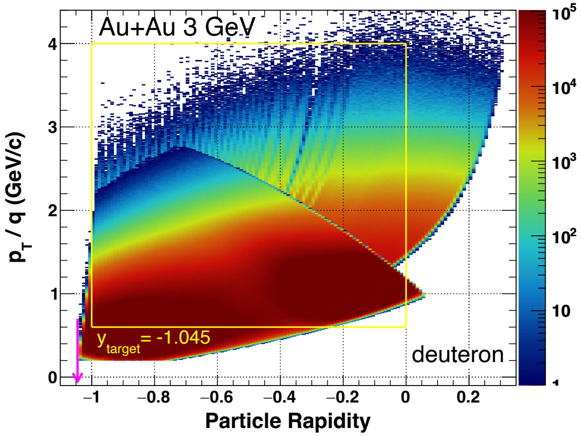


- Target is a 0.25 mm thick gold foil
- Target located at $z = 200.7$ cm
- Target is held 2 cm below center of beam axis
- FXT extends energy reach down to 3 GeV

Particle Identification

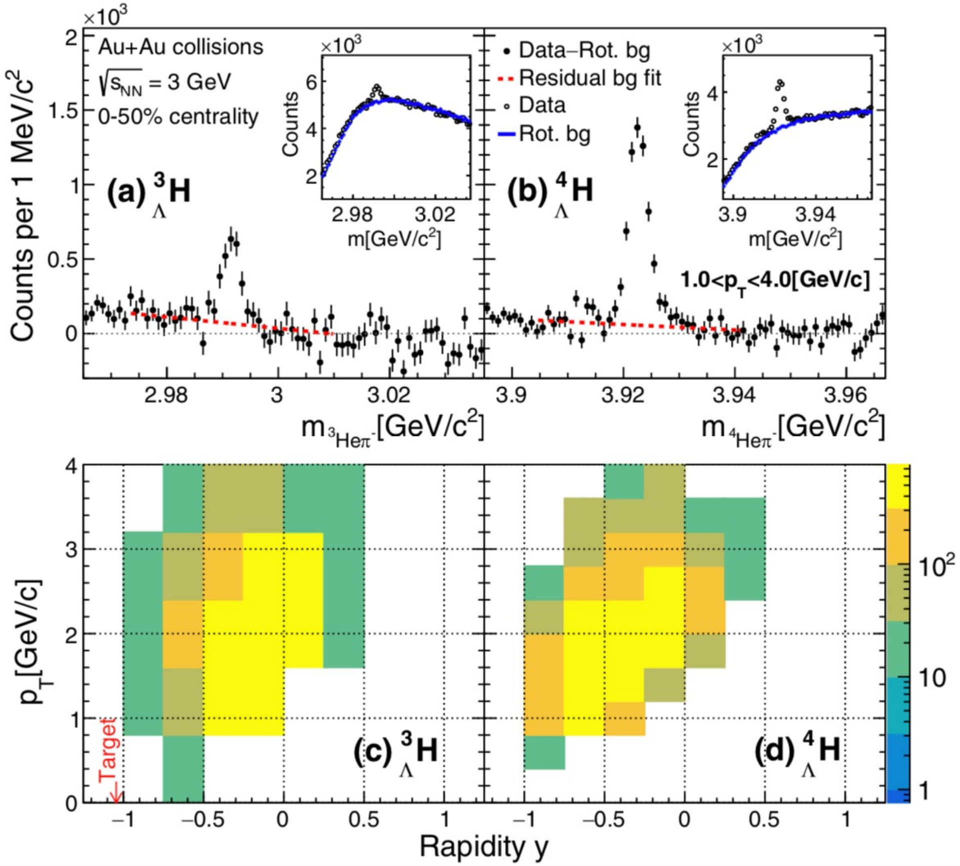
- Good kinematic coverage in 3 GeV Au+Au collisions
- Particle identification using Time Projection Chamber (TPC) and Time of Flight (TOF)
- Combinatorial background estimated via rotating pion tracks or event mixing on hypernuclei reconstruction





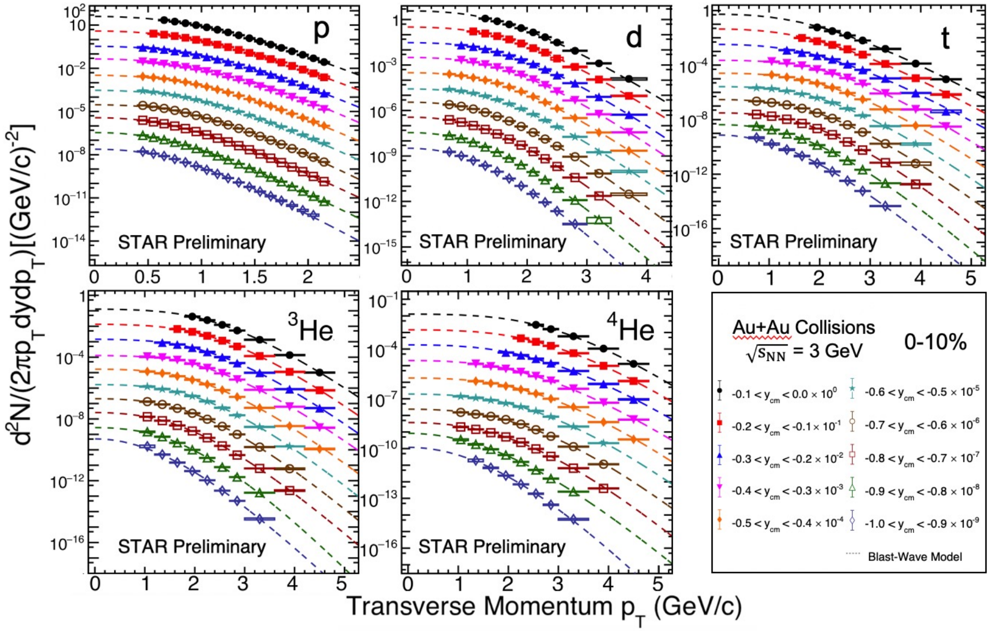
Hypernuclei reconstruction via 2-body channel:

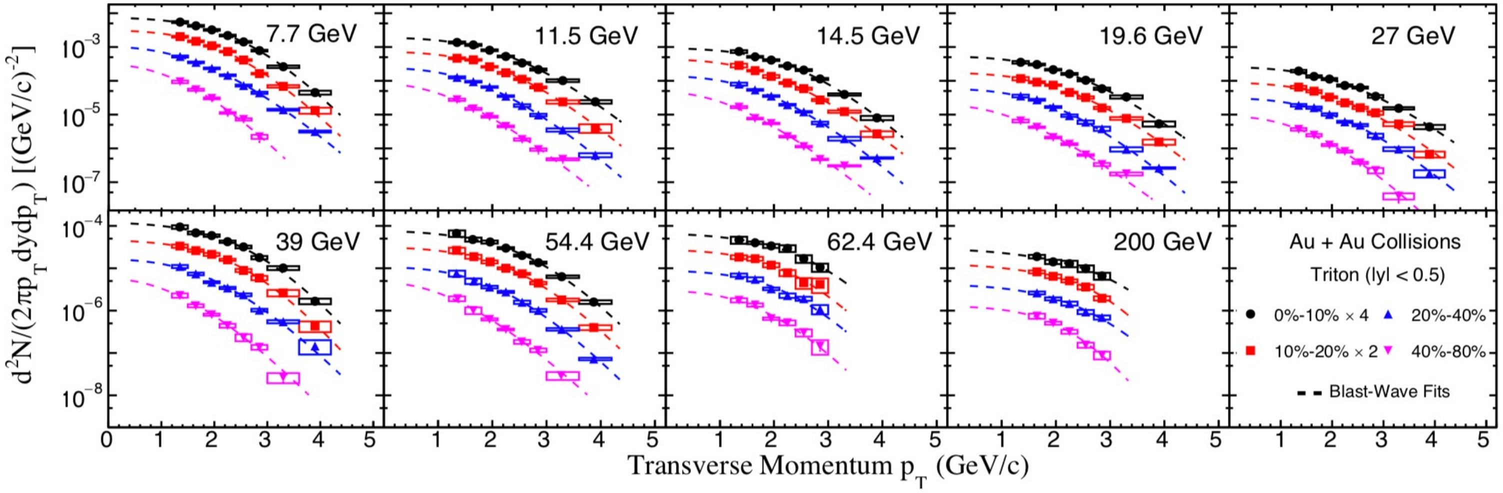
$^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$ $\quad$ $^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi^{-}$



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

Transverse Momentum Spectra





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

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:

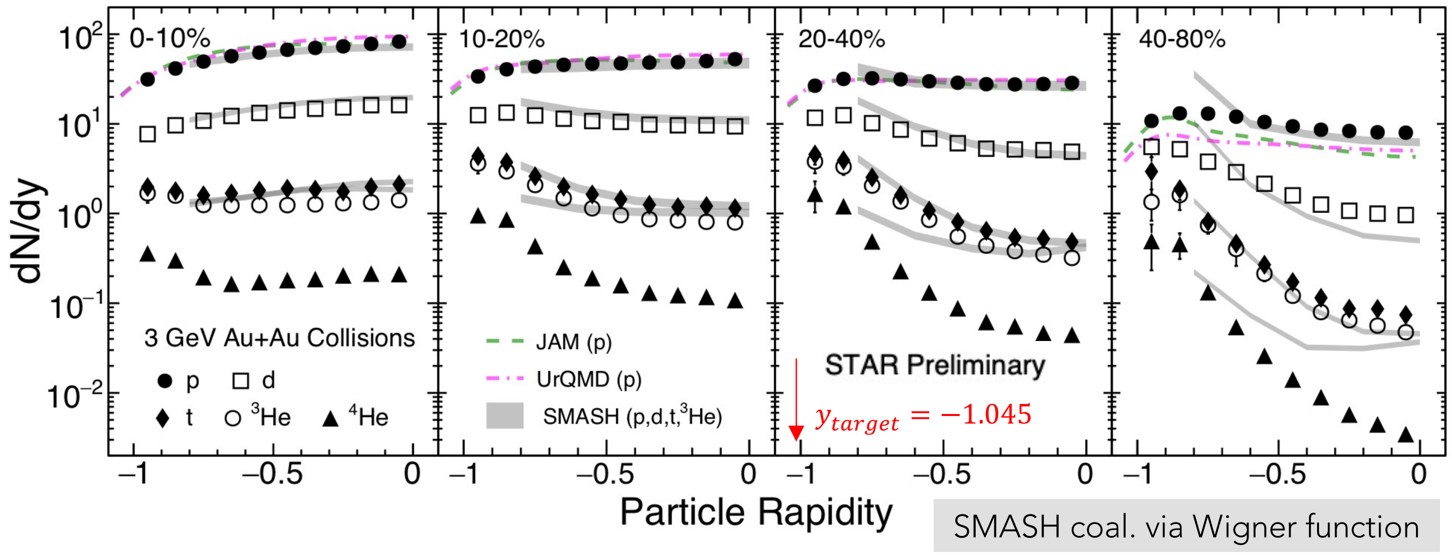
T_{kin} : kinetic freeze-out temperature

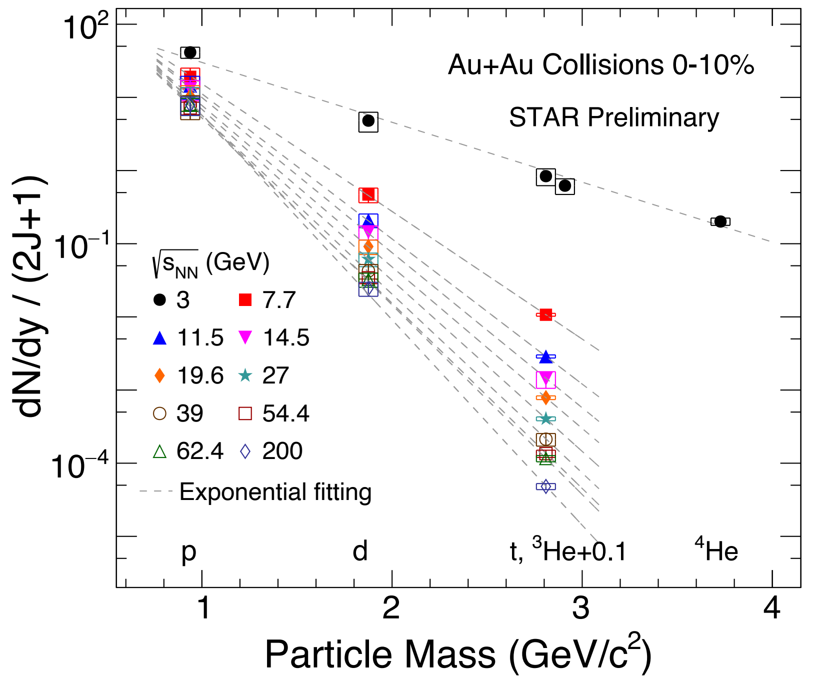
$\langle\beta_T\rangle$: average radial flow velocity

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

H. Liu [STAR Collaboration] arXiv:2311.11020
[STAR Collaboration] Phys. Rev. Lett. 130, 202301 (2023)

Yields of Light Nuclei





- 3 GeV with good rapidity coverage provides the opportunity to calculate proton and light nuclei 4π yields accurately
- Transport model reproduces the trend of particle rapidity distribution in central and mid-central collisions

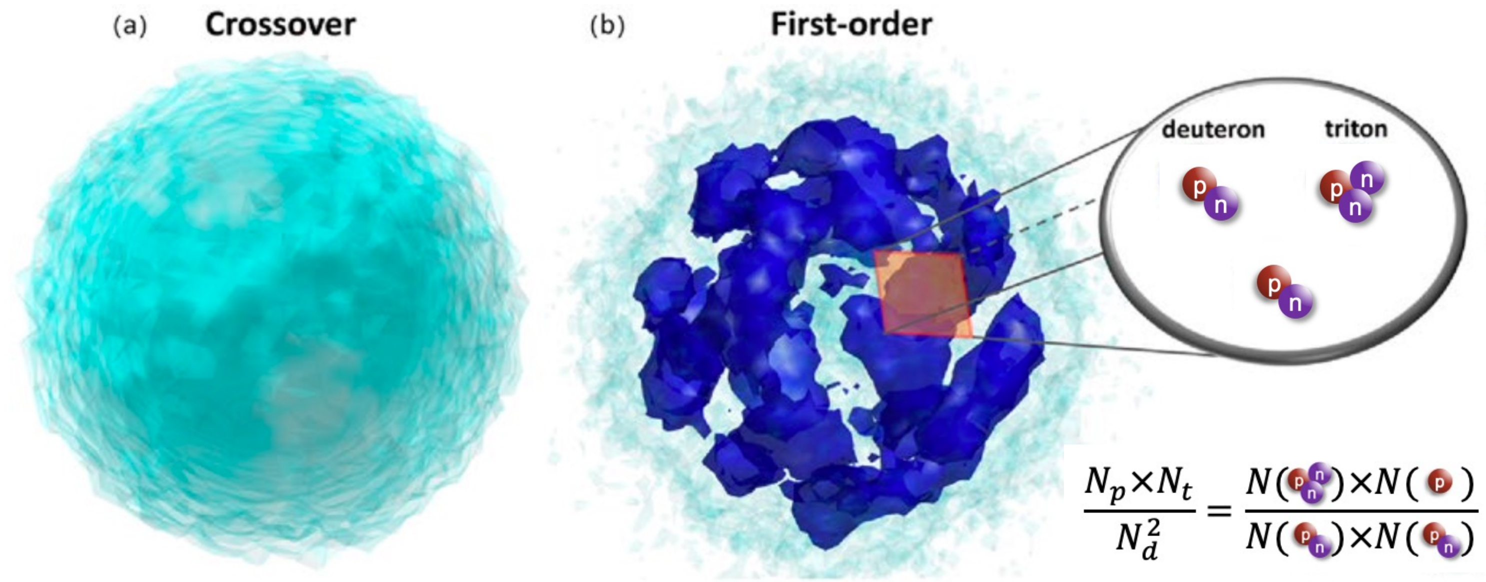
- Light nuclei yields decrease exponentially with increasing particle mass
- Slope decrease indicates that light nuclei are more easily formed at low energies

L. W. Chen et al. Phys.Rev.C 68 (2003) 017601;
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

Observations of Density Fluctuations

Compound Yield Ratio

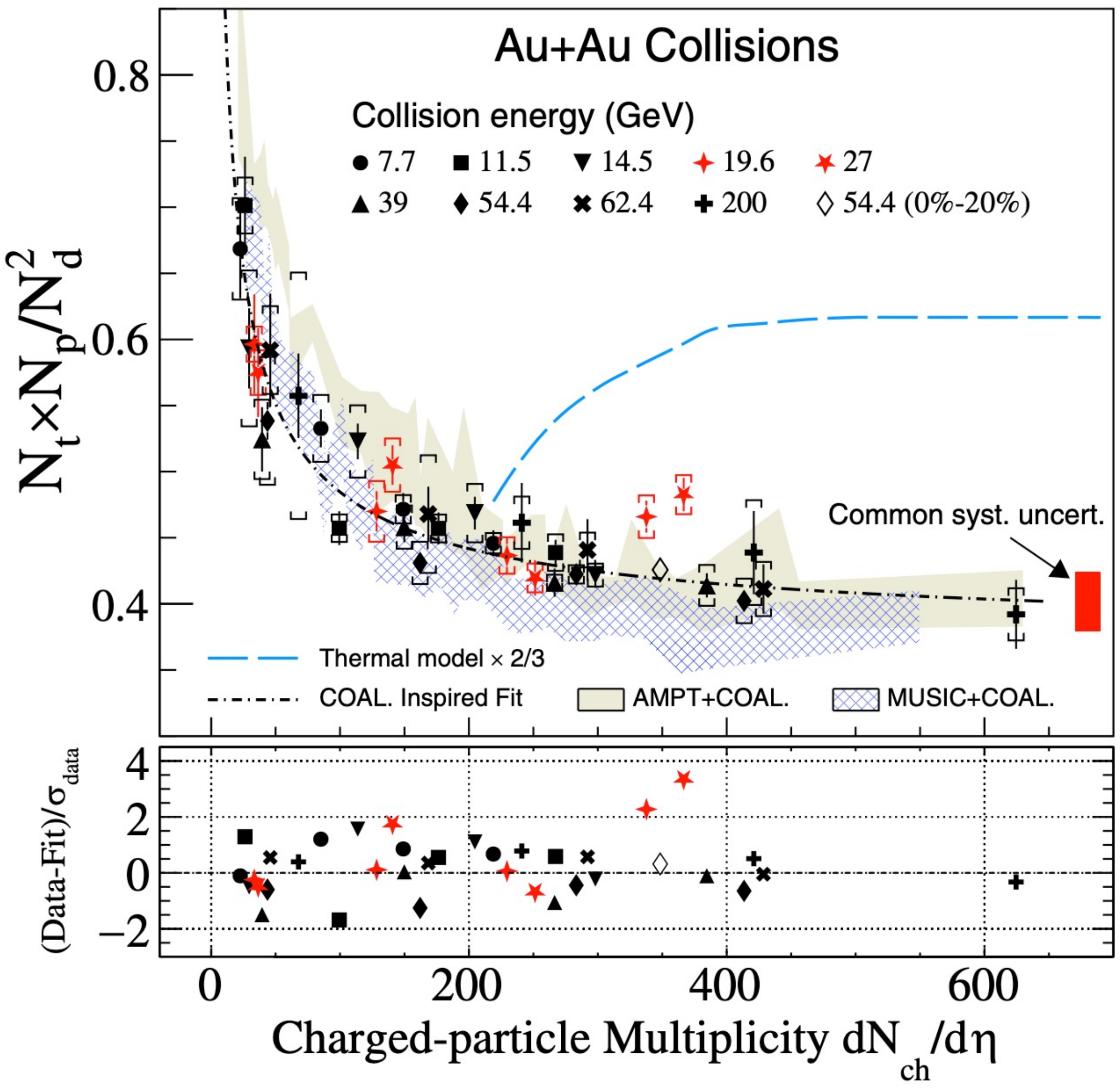
Sensitive Observations for Searching Critical Point and 1st order boundary



First-order phase transition → Amplification of the density inhomogeneity → Large density fluctuations → Enhance the production of composite particles

C.M. Ko, Searching for QCD critical point with light nuclei. NUCL SCI TECH 34, 80 (2023)

Charge-particle Dependence of Compound Yield Ratios



- The yield ratio $N_t \times N_p / N_d^2$ as a function of charged-particle multiplicity $dN_{ch}/d\eta$ ($|\eta| < 0.5$)
- It is observed that the yield ratio $N_t \times N_p / N_d^2$ exhibits scaling, regardless of collision energy and centrality

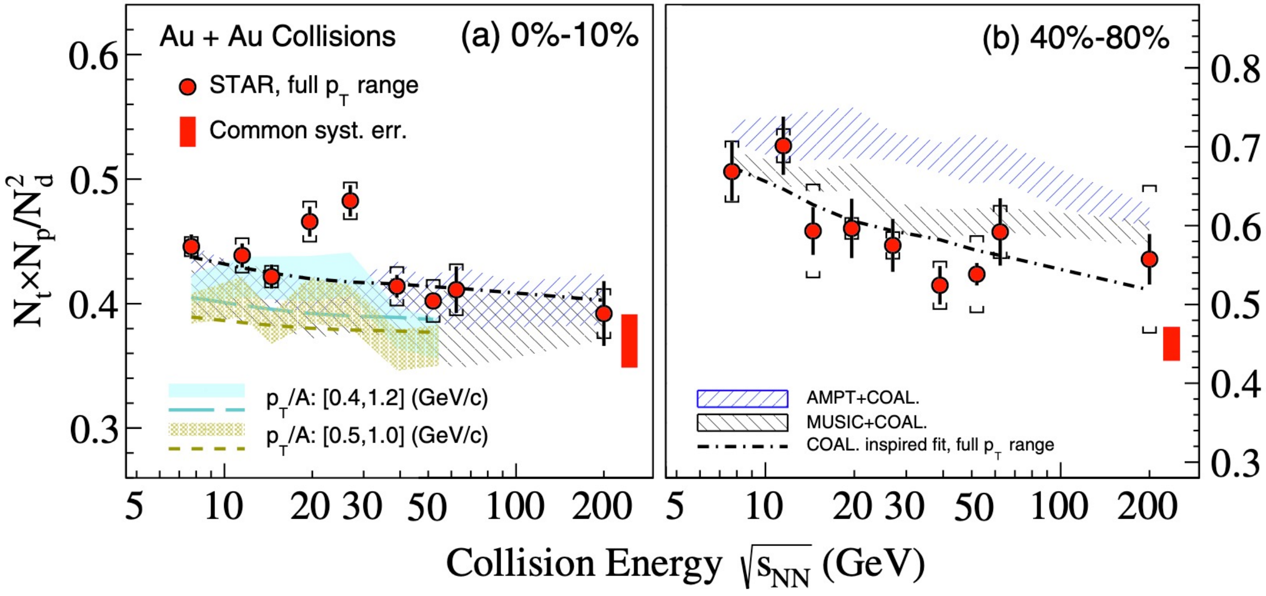
Coal. inspired fit: $\frac{N_t \times N_p}{N_d^2} \propto \left(\frac{R^2 + \frac{2}{3} r_d^2}{R^2 + \frac{1}{2} r_t^2}\right)^3$

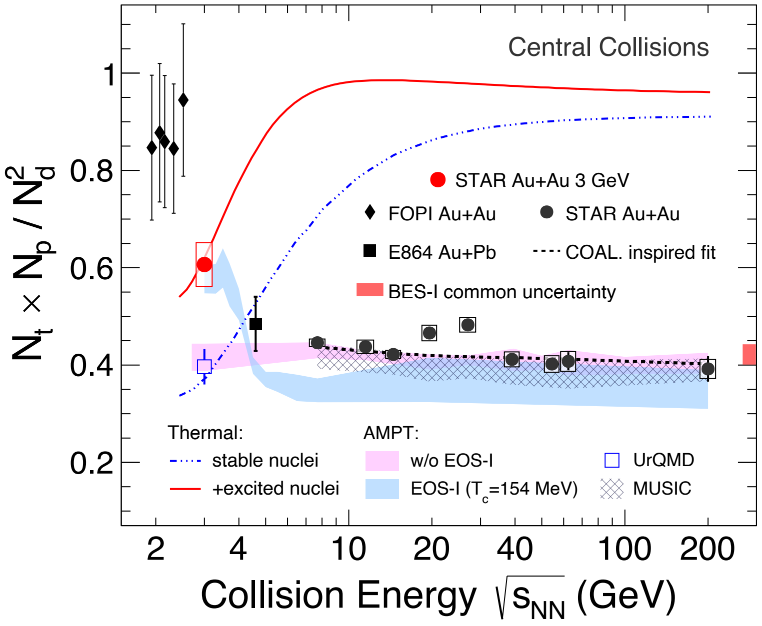
$R \propto (dN_{ch}/d\eta)^{1/3}$, $r_d = 1.96$ fm, $r_t = 1.59$ fm

- An enhancement with a significance of 4.1σ is observed at 19.6 and 27 GeV, while no enhancement is observed at 54.4 GeV for the same $dN_{ch}/d\eta$ value

[STAR Collaboration] Phys.Rev.Lett. 130 (2023) 202301

Energy Dependence of Compound Yield Ratios

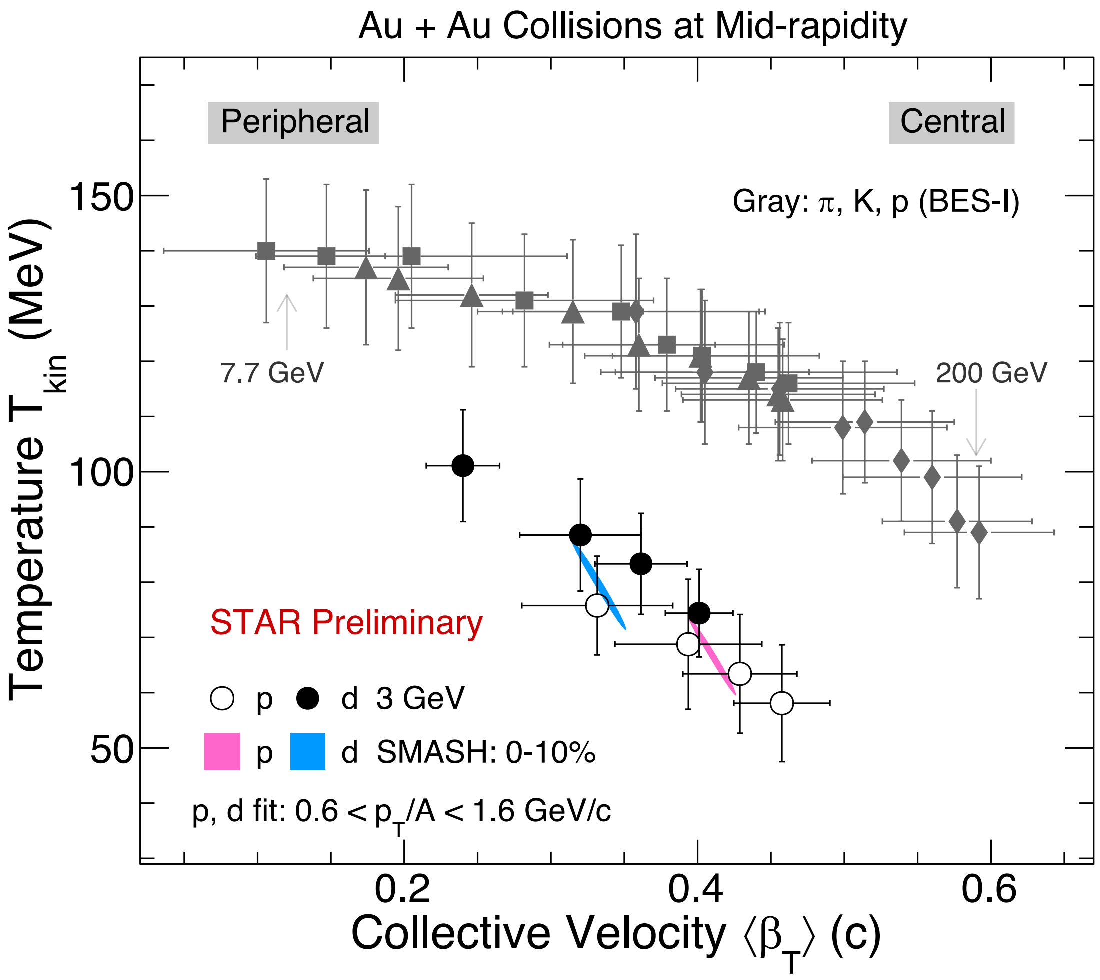




- Non-monotonic behavior of yield ratio vs. energy observed from 0-10% central collisions possibly signaling a critical point and/or 1st order phase transition
- 3 GeV 0-10% Au+Au collisions follow the world trend of the energy dependence and monotonically increase with decreasing energies
- The thermal model shows the energy-dependent trend contrary to experiments
- The yield ratio can be reproduced by the AMPT model when employing a first-order phase transition by input the critical temperature of 154 MeV

K. Sun et al. arXiv: 2205.11010

Kinetic Freeze-out Dynamic



- 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)

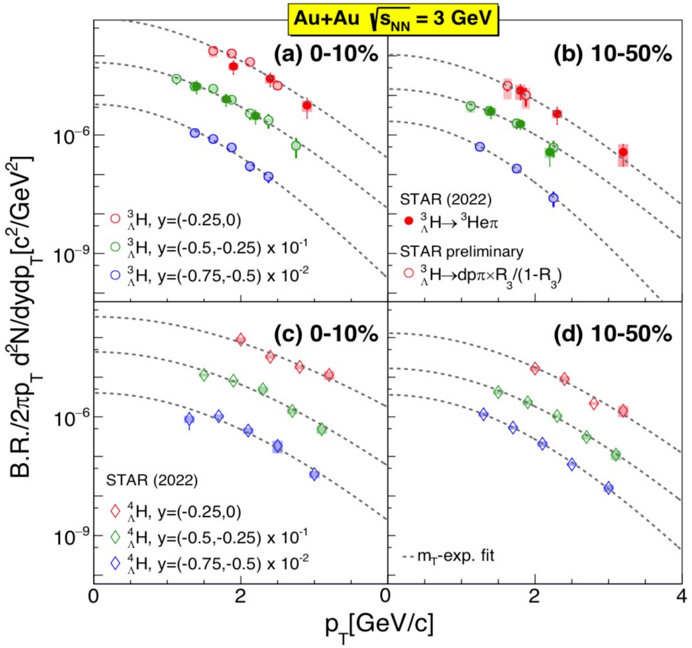
- The freeze-out parameter (T_{kin}) of d is systematically higher than that of p at 3 GeV, which is different from higher energies, similar trend seen in SMASH Model

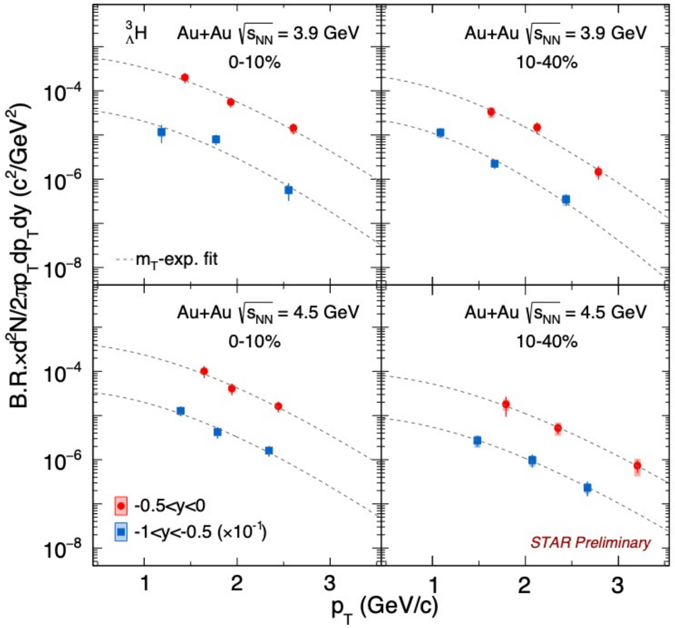
The heavier the particle, the earlier freeze-out?

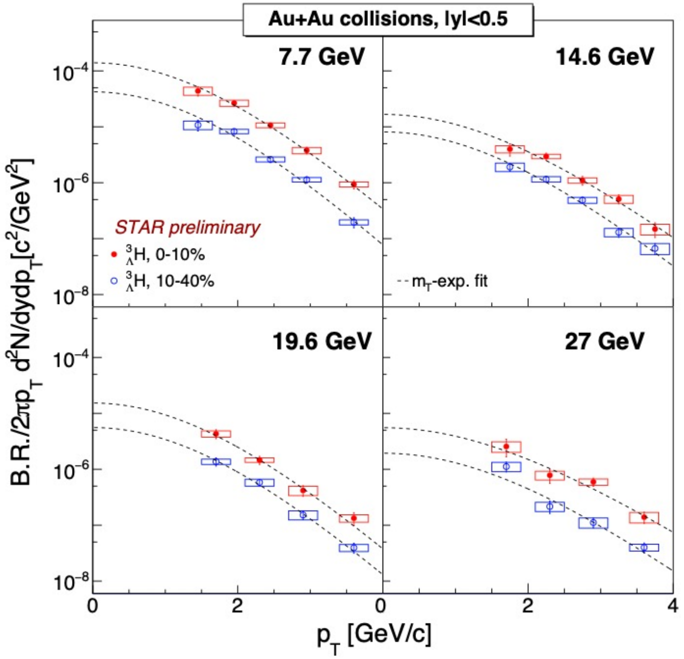
H. Liu, arxiv:2208.04650

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

Transverse Momentum Spectra







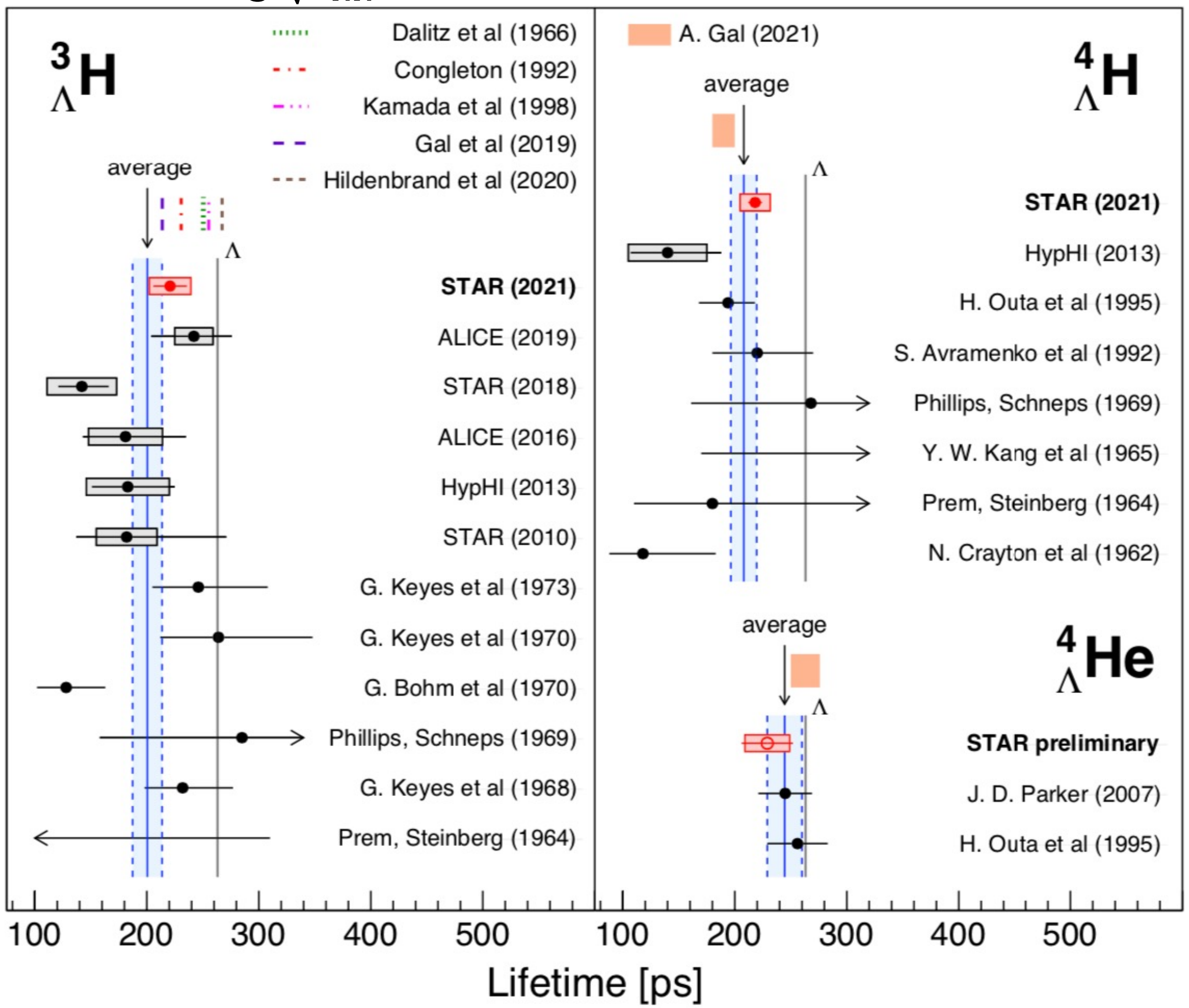
- Transverse momentum spectra of ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$ with rapidity slices in Au+Au collisions at $\sqrt{s_{NN}}$ = 3 (published), 3.9 – 27 GeV (BES-II Preliminary)

- m_T exponential: $\frac{1}{2\pi m_T}\frac{d^2N}{dm_T dy} \propto \exp(-m_T/T)$

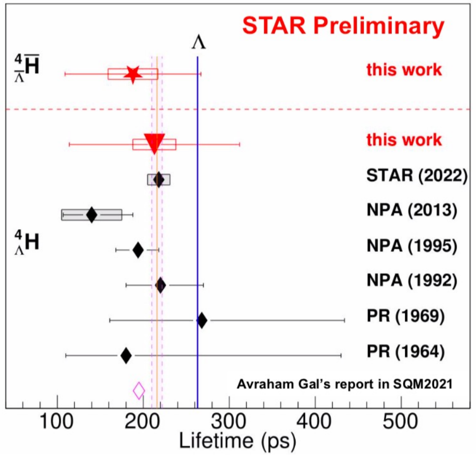
Y. Ji [STAR Collaboration] arXiv: 2312.15768
[STAR Collaboration] Phys.Rev.Lett. 128 (2022) 20, 202301
Yue Hang Leung, CBM Collaboration Meeting 20230925

Lifetime of Hypernuclei

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 new measurement greatly reduces the uncertainties



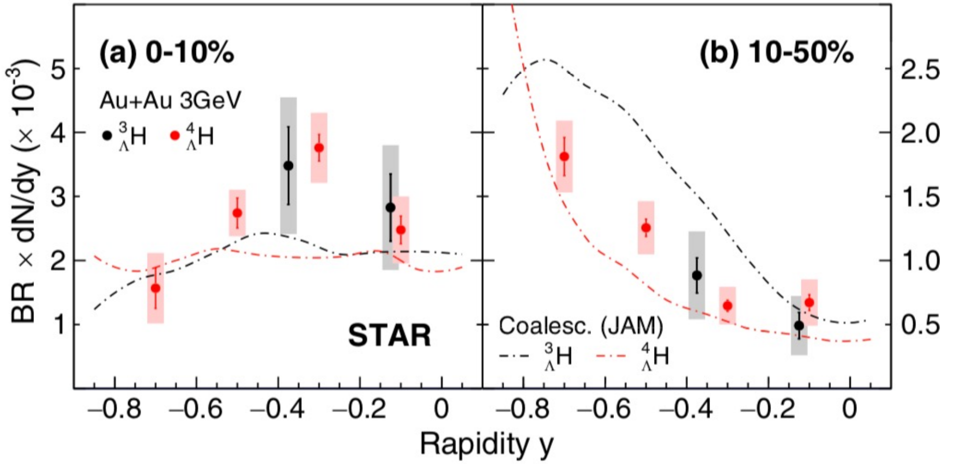
Au+Au	200 GeV
U+U	193 GeV
Ru+Ru	200 GeV
Zr+Zr	200 GeV

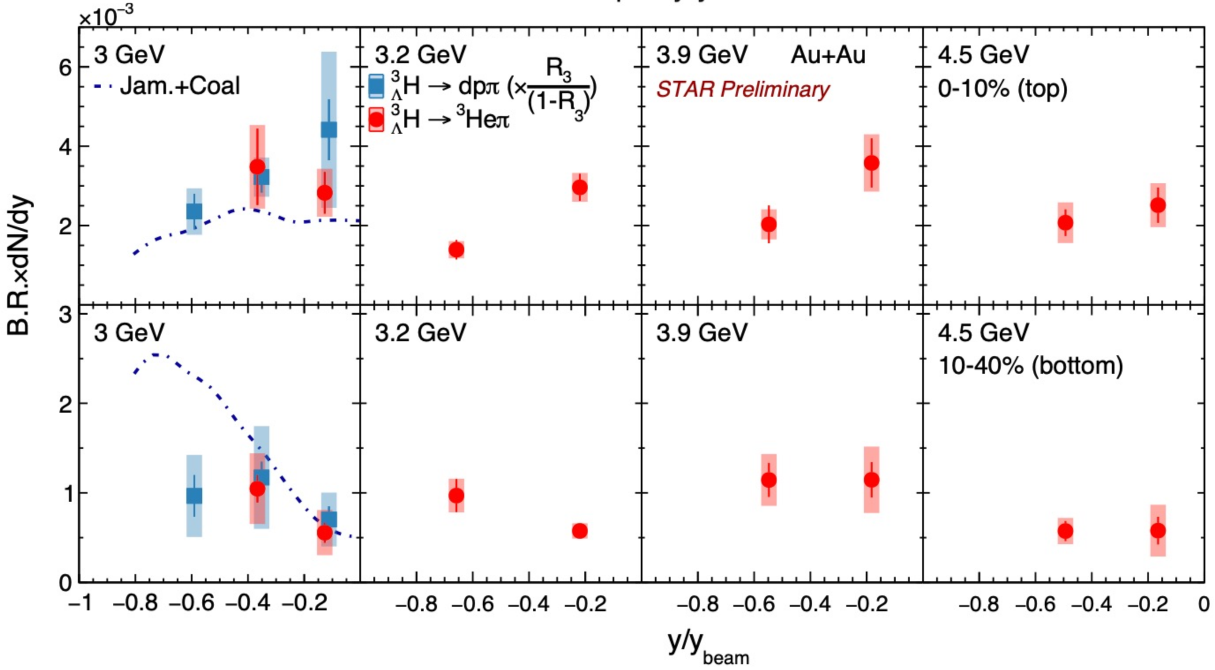
The first $^{4}_{\Lambda}\overline{H}$ lifetime measurement in heavy ion collisions

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

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

Yields of Hypernuclei



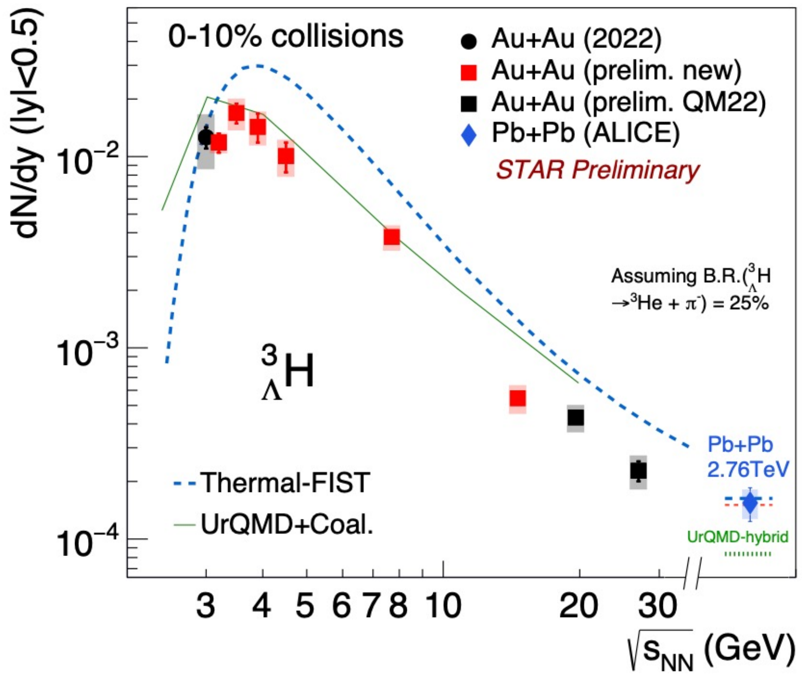


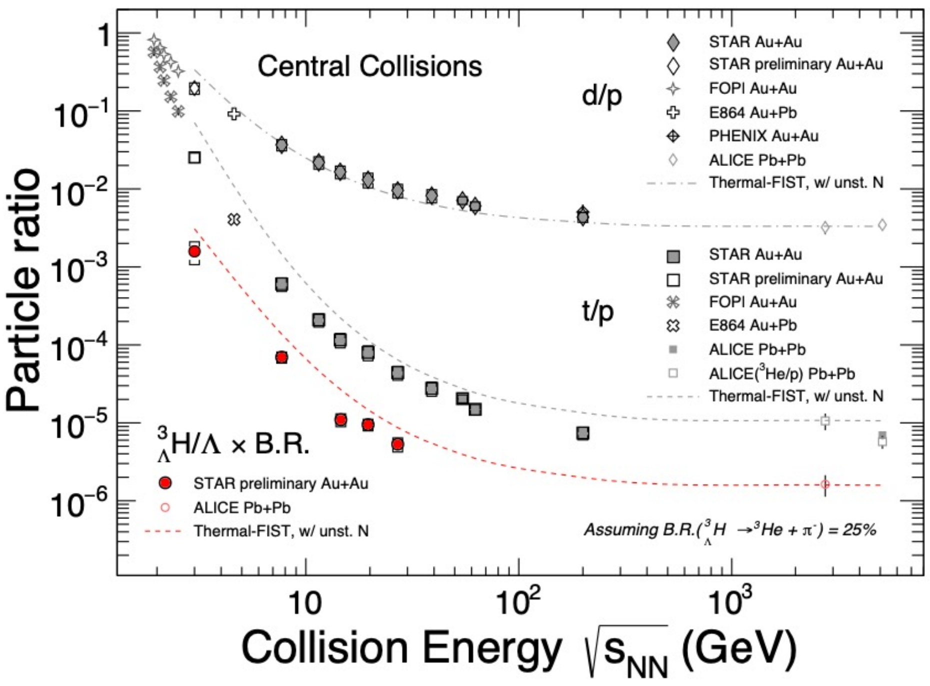
- First measurements on rapidity dependence of hypernuclei yields in heavy ion collisions
- JAM + Coalescence qualitatively describe the rapidity dependence of ${}^{3}_{\Lambda}\mathrm{H}$ yields at $\sqrt{s_{NN}}$ = 3 GeV in 0-10% collisions, while fail to describe the trend in non-central collisions
- JAM + Coal. qualitatively describe the trend of ${}^{4}_{\Lambda}\mathrm{H}$ yields versus rapidity
- Provide first constraints for hypernuclei production models in the high baryon density region

JAM coal. via with tuned parameters (r_c, p_c)

Y. Nara et al. Phys.Rev.C 61 (2000) 024901
H. Liu et al. Phys.Lett.B 805 (2020) 135452
Y. Ji [STAR Collaboration] arXiv: 2312.15768
[STAR Collaboration] Phys.Rev.Lett. 128 (2022) 20, 202301

Energy Dependence of Yields

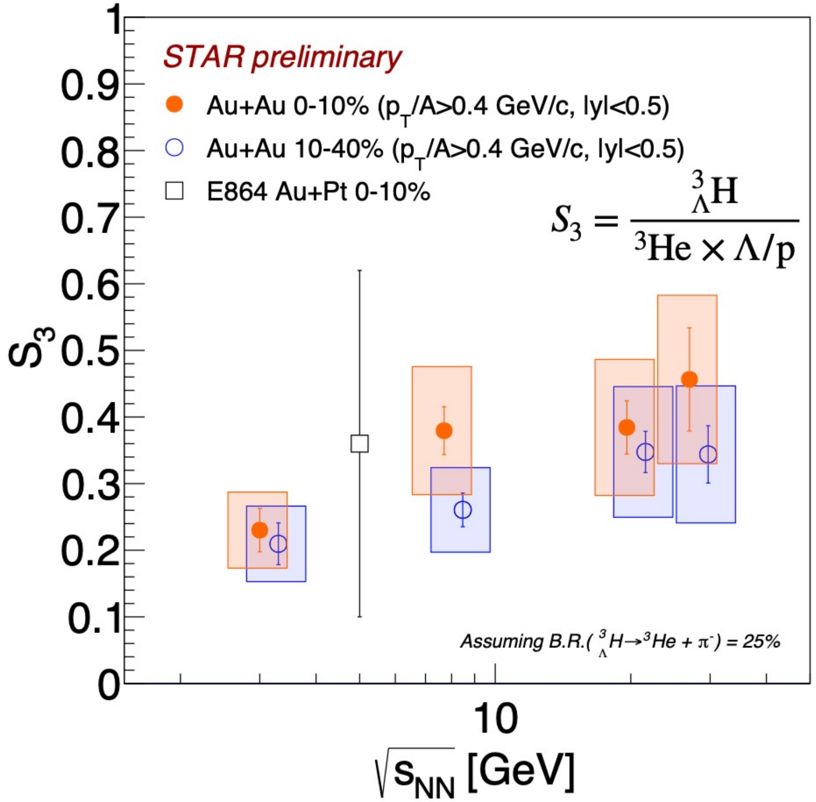


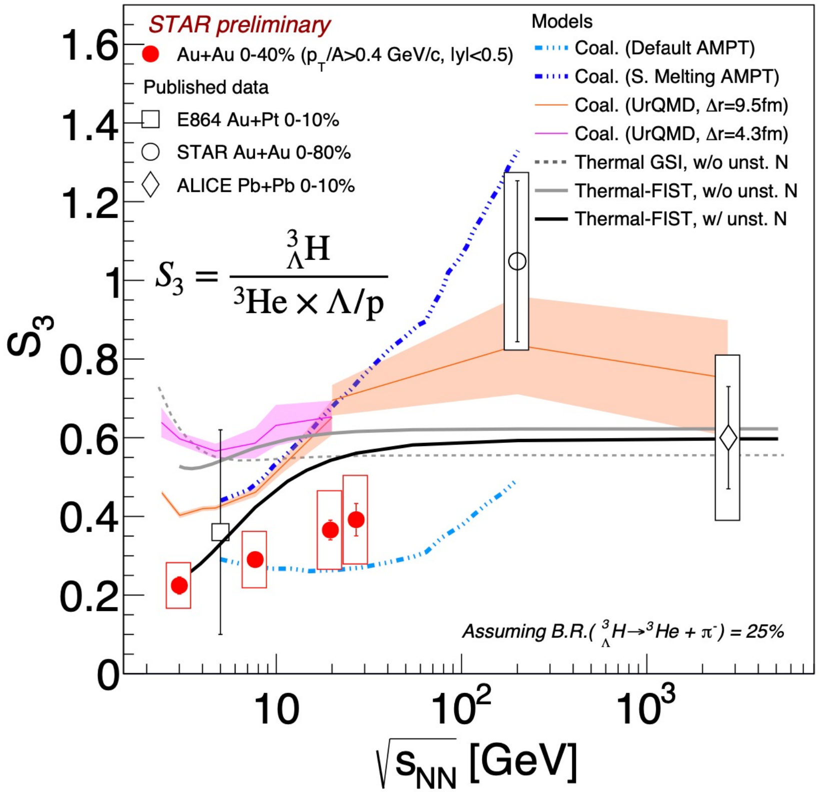


- $^{3}_{\Lambda}\mathrm{H}$ yield at mid-rapidity increases from 2.76 TeV to 3 GeV, peak at around 3-4 GeV
- Energy dependence qualitatively explained by the increase in baryon density and stronger strangeness canonical suppression at low energies

- Clear energy dependence is observed for $\mathrm{d/p}$, $\mathrm{t/p}$, and $^{3}_{\Lambda}\mathrm{H}/\Lambda$ ratios
- Thermal model predicts the trend while not quantitatively describe the yields, it indicate that hypertriton and triton yields might not reach equilibrium at chemical freeze-out

Energy Dependence of S_3

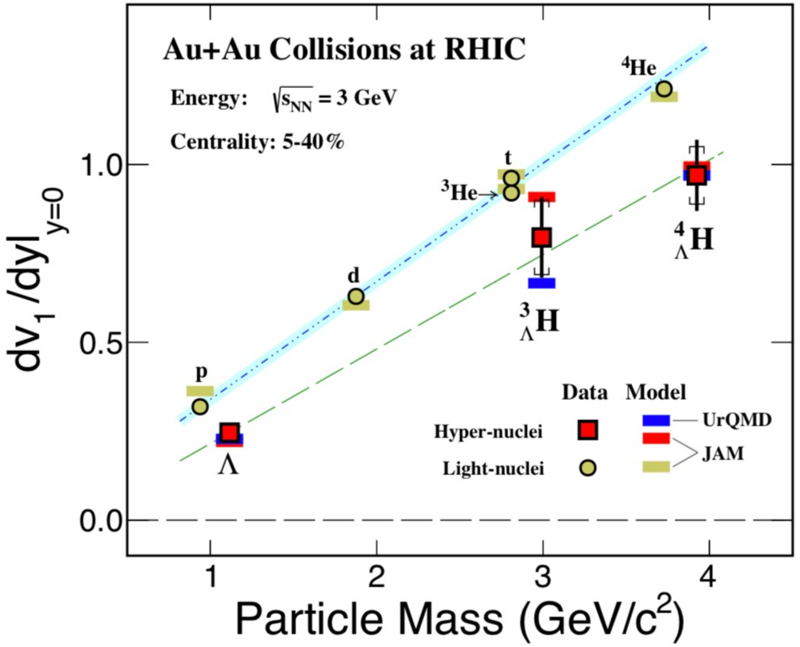


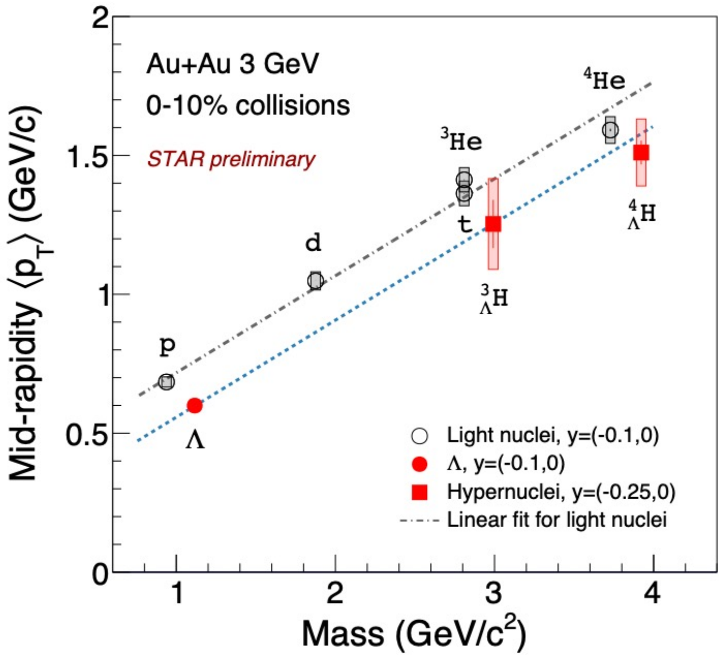


- The centrality dependence of S3 could reveal information on its production mechanism
- S_3 indicates an increasing trend with increasing collision energy
- The drop of S_3 at lower beam energies is due to the large source size of the hypernuclei
- Both of coalescence and thermal-FIST suggest increasing trend

T. Reichert et al, Phys.Rev.C 107 (2023) 1, 014912

Mass Dependence of dv_1/dy and $\langle p_T \rangle$





Collective behavior

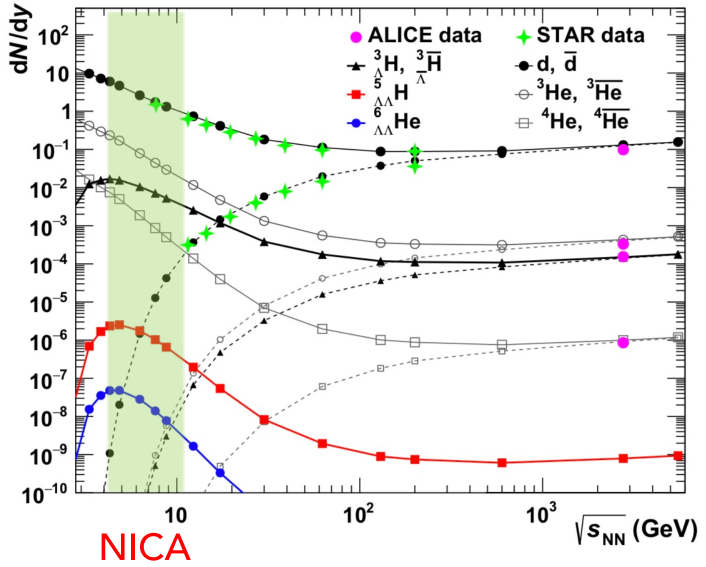
- v_1 slope (5-40%) and $\langle p_T \rangle$ (0-10%) of light and (hyper)nuclei follow mass number scaling in 3 GeV Au+Au collisions within uncertainties
- The linear trend of particle mass scaling behaviors of light and (hyper)nuclei indicate that they are formed mainly via coalescence process

A Andronic et al. Phys.Lett.B 697 (2011) 203-207
[STAR Collaboration] Phys.Rev.Lett. 130 (2023) 21, 212301;arXiv:2211.16981

Summary and Outlook

1. Light Nuclei measurement
   - ➜ Enhancements of the yield ratios are observed in 0-10% most central collisions at 19.6 and 27 GeV with a combined significance of 4.1**σ**
   - ➜ Hot and dense medium created in the 3 GeV collisions seems different from that of high energy collisions
2. Hypernuclei measurement
   - ➜ The hypertriton yield reaches a maximum at around 3-4 GeV
3. Collectivity behavior support the coalescence of light and (hyper)nuclei production

- ❑ High statistical data in STAR BES-II at $\sqrt{s_{\mathrm{NN}}}$ = 3 – 19.6 GeV
- ❑ Deep understanding on light and (hyper)nuclei production mechanisms
- ❑ The NICA experiment covers collision energies of $4.0<\sqrt{s_{\mathrm{NN}}}<11$ GeV, providing very favorable conditions for exploring the production of nuclei and (hyper)nuclei in the low-energy region.



Thanks for your attention!