Production of Light Nuclei in Au+Au Collisions with the STAR BES-II Program

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The STAR Collaboration

Introduction

Light Nuclei

- Loosely bound objects with small binding energies.
- Production mechanism: thermal model or coalescence model?

Light Nuclei Yield Ratio $(N_t \times N_p / N_d^2)$

- The yield ratio is proposed to be sensitive to neutron density fluctuations:

$$N_t \times N_p / N_d^2 \approx g(1 + \Delta n)$$

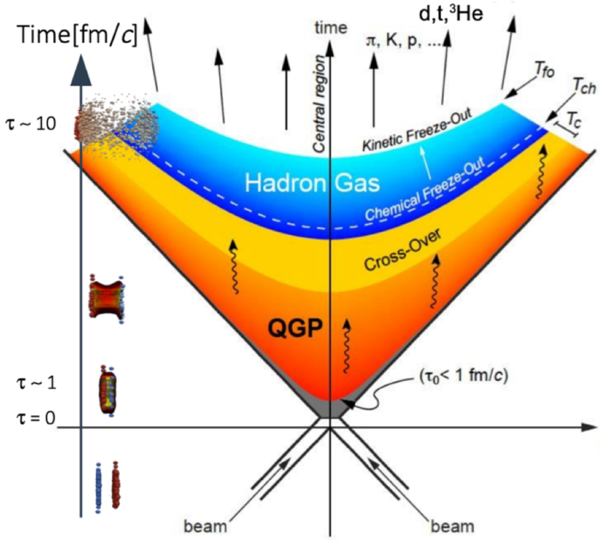
factor $g = \frac{1}{2\sqrt{3}}$ comes from thermal equilibrium assumption of nucleon abundances.

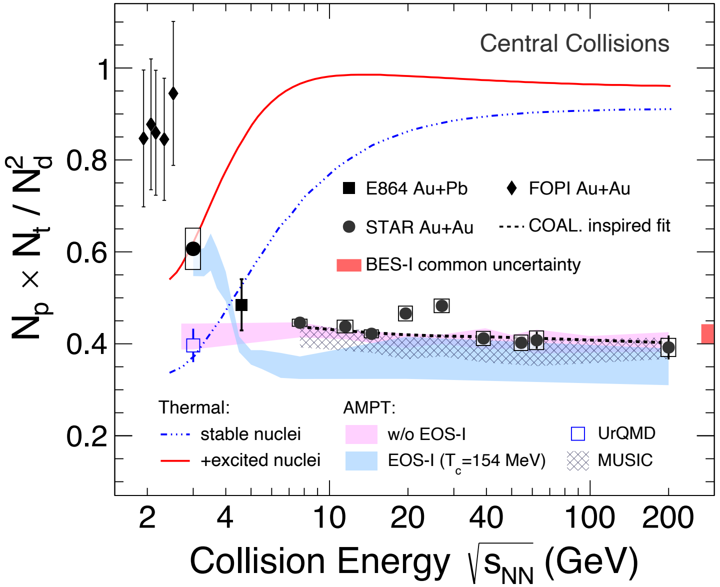
K. Sun et al. Phys.Lett.B 774 (2017) 103-107
E. Shuryak et al. Phys.Rev.C 101 (2020) 3, 034914

RHIC Beam Energy Scan Phase-II Program

- Collider energies ($\sqrt{s_{NN}} = 7.7 - 27$ GeV)
- FXT energies ($\sqrt{s_{NN}} = 3.0 - 13.7$ GeV)

STAR Note: https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

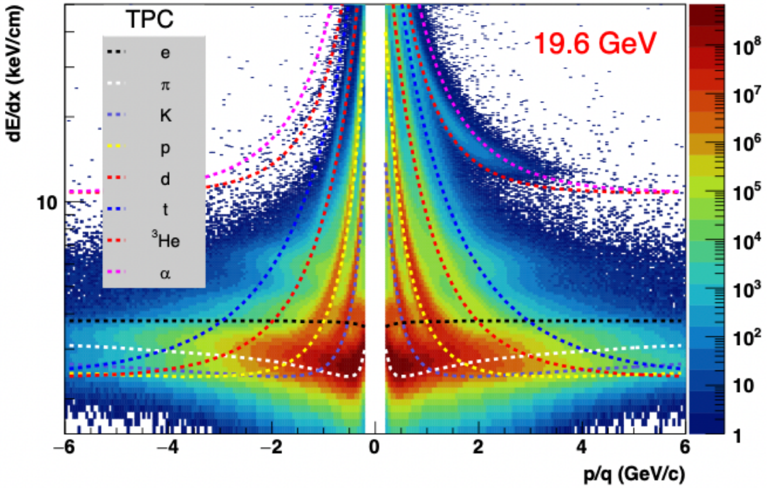




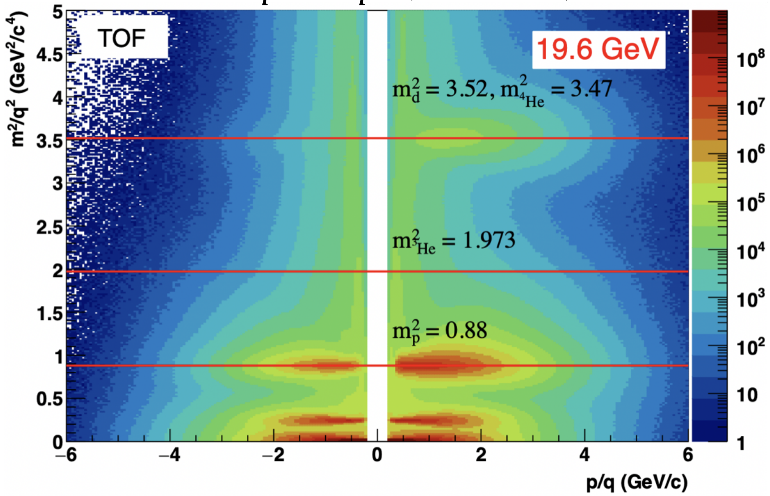
STAR Collaboration, Phys. Rev. Lett. 130 (2023) 202301.
STAR Collaboration, Phys. Rev. C 110, 054911 (2024).
K.J. Sun et al, Phys. Lett. B 833 (2022) 137329.

Particle Identification

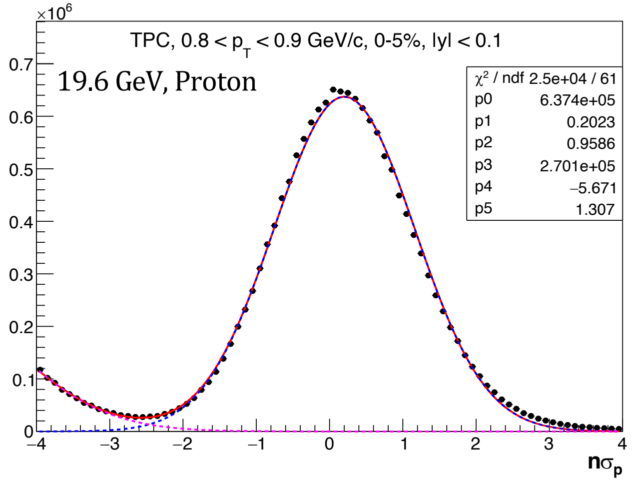
TPC: $z = \log\left(\frac{\langle dE/dx \rangle_{\text{measure}}}{\langle dE/dx \rangle_{\text{Bichsel}}}\right)$

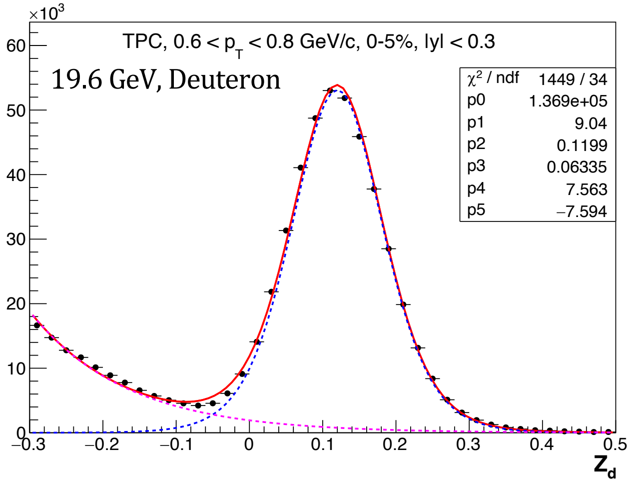


TOF: $\frac{m^2}{q^2} = \frac{p^2}{q^2}\left(\frac{c^2t^2}{L^2} - 1\right)$



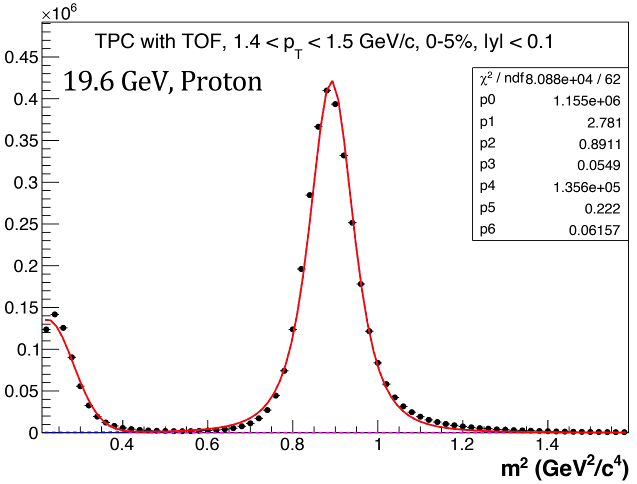
Signal Extraction (19.6 GeV, 0-5%)

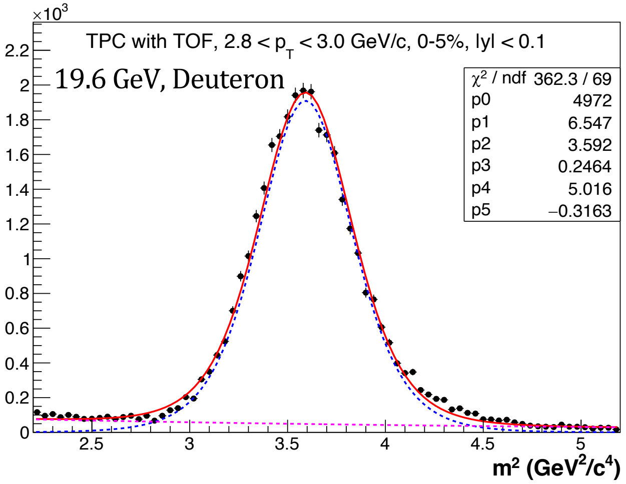




Low p_{T}: TPC

Signal: Gaussian (Blue)
BG: Gaussian (Magenta)
Total: (Red)

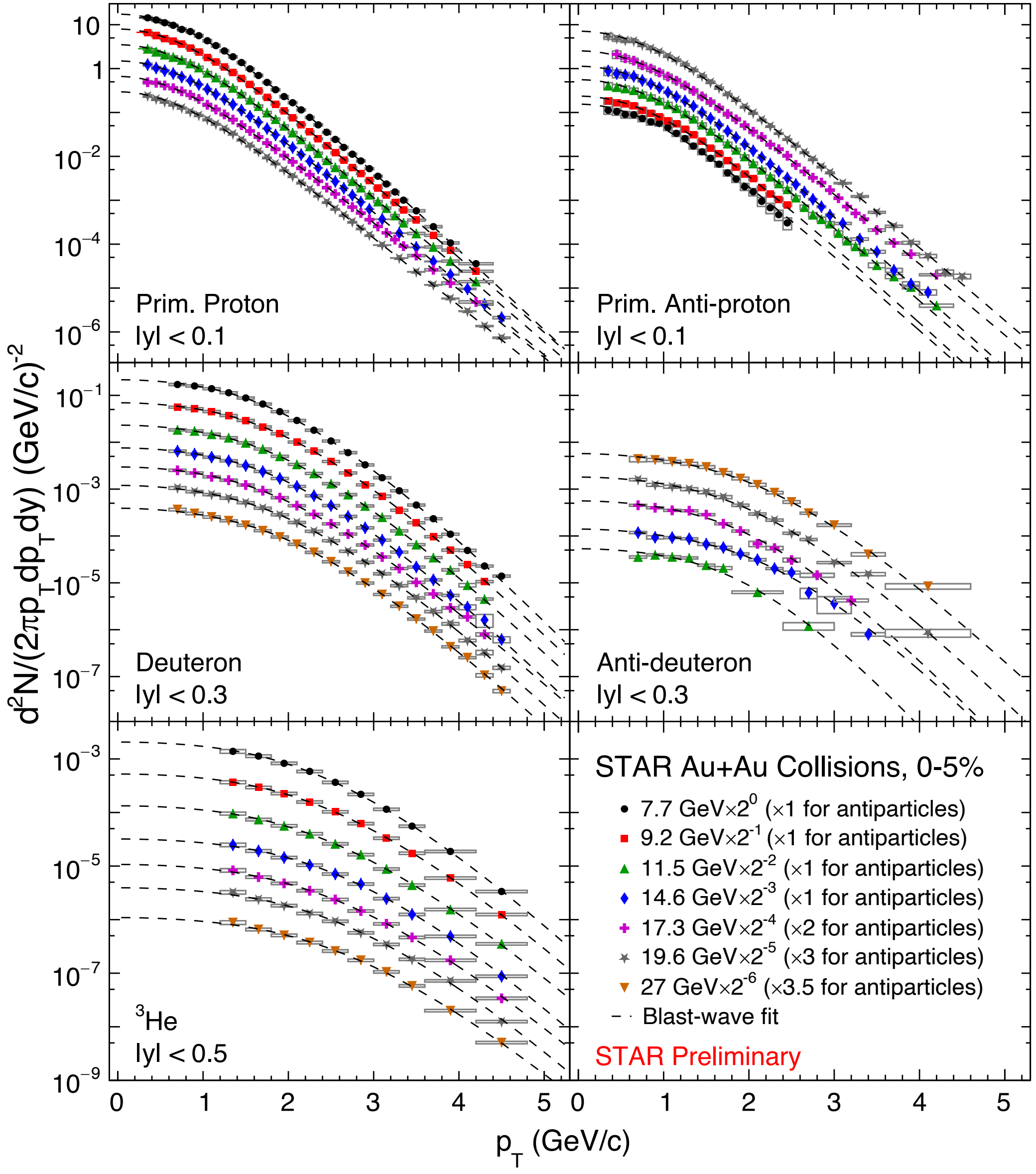




High p_{T}: TPC with TOF

Signal: Student-t (Blue)
BG: Gaussian (Magenta)
Total: (Red)

Transverse Momentum Spectra



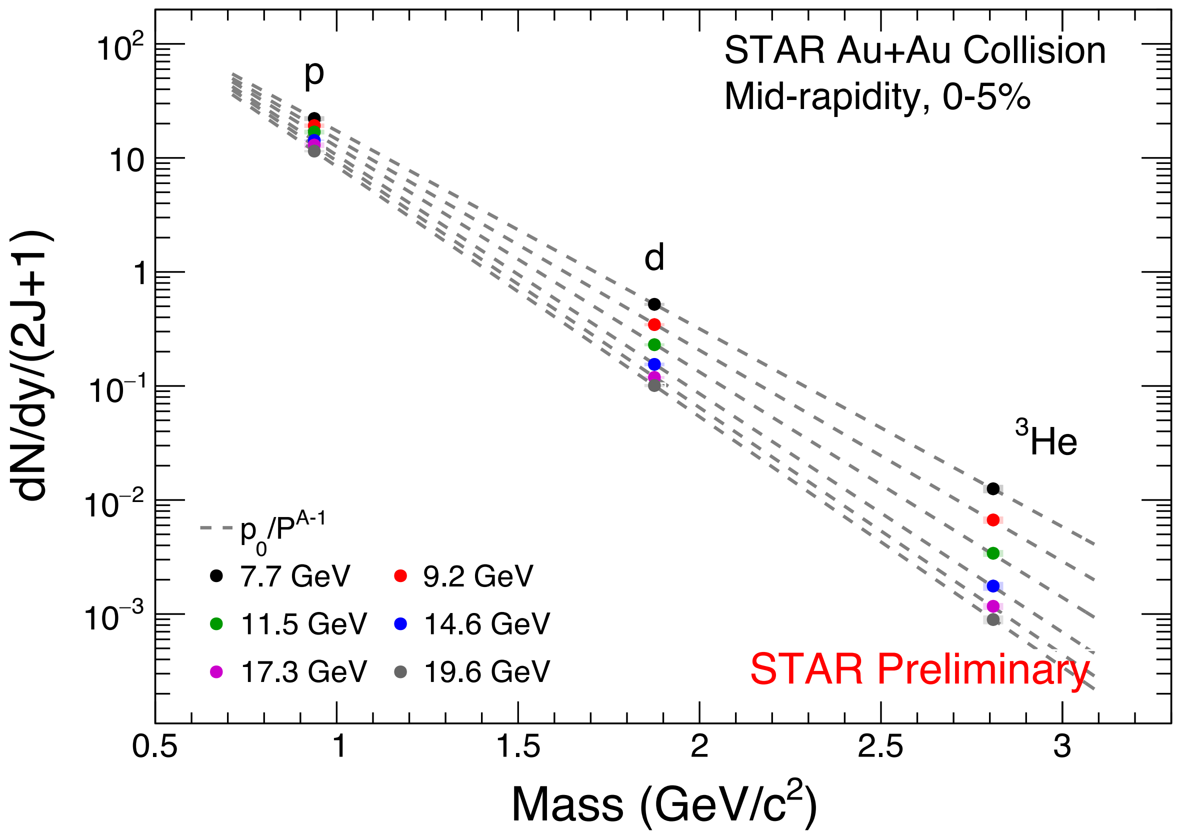
- Obtained spectra for p, d, $^{3}\mathrm{He}$, $\bar{\mathrm{p}}$ and $\bar{\mathrm{d}}$ as a function of p_{T} and centrality in Au+Au collisions at 7.7 – 27 GeV.
- p_{T}-integrated yields: Blast-wave function is used for low-p_{T} extrapolation

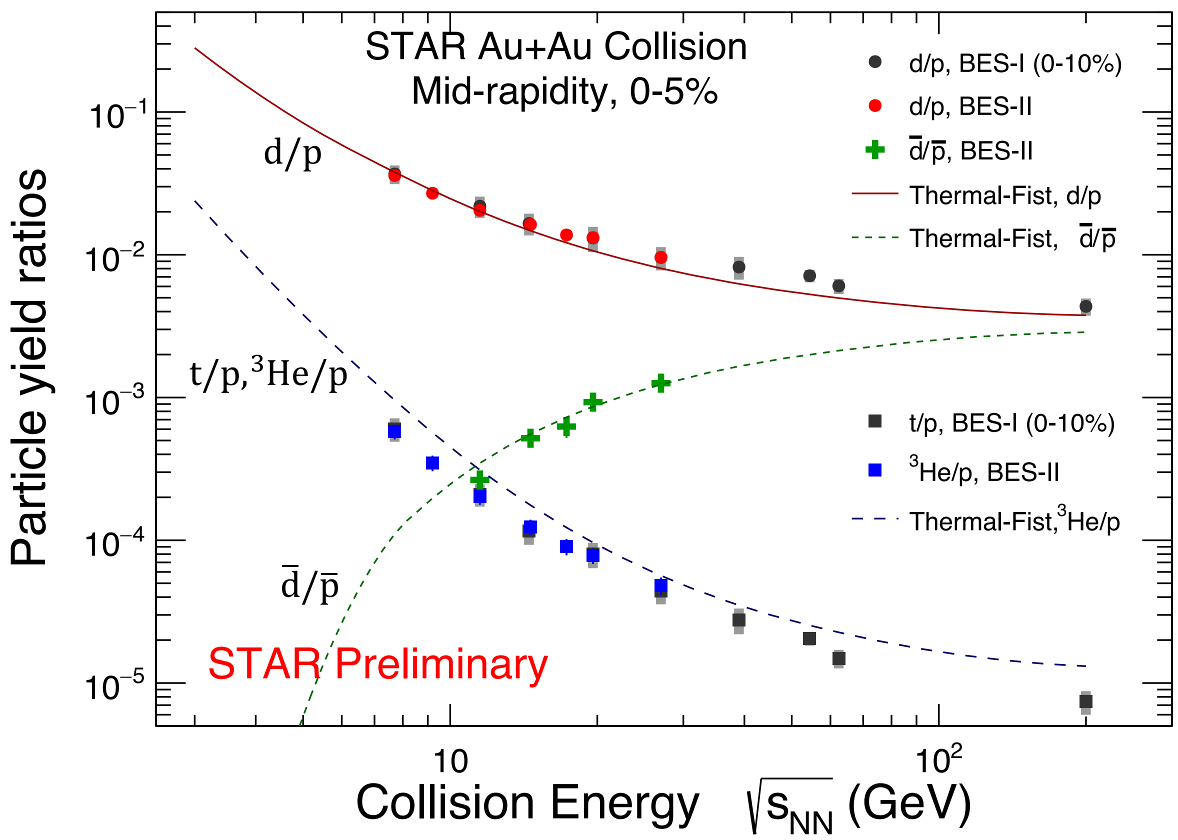
$$\frac{1}{2\pi p_{\mathrm{T}}}\frac{\mathrm{d}^2 N}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y} \propto \int_0^R r\mathrm{d}r m_{\mathrm{T}} I_0\left(\frac{p_{\mathrm{T}}\sinh\rho}{T}\right) K_1\left(\frac{m_{\mathrm{T}}\cosh\rho}{T}\right),$$

$$\text{where } \rho = \tanh^{-1}\beta_r = \tanh^{-1}\left[\beta_{\mathrm{T}}\left(\frac{r}{R}\right)^n\right].$$

- The low p_{T} reach is extended in BES-II, which leads to smaller systematic uncertainties in p_{T}-integrated yields.

Particle Yields and Ratios





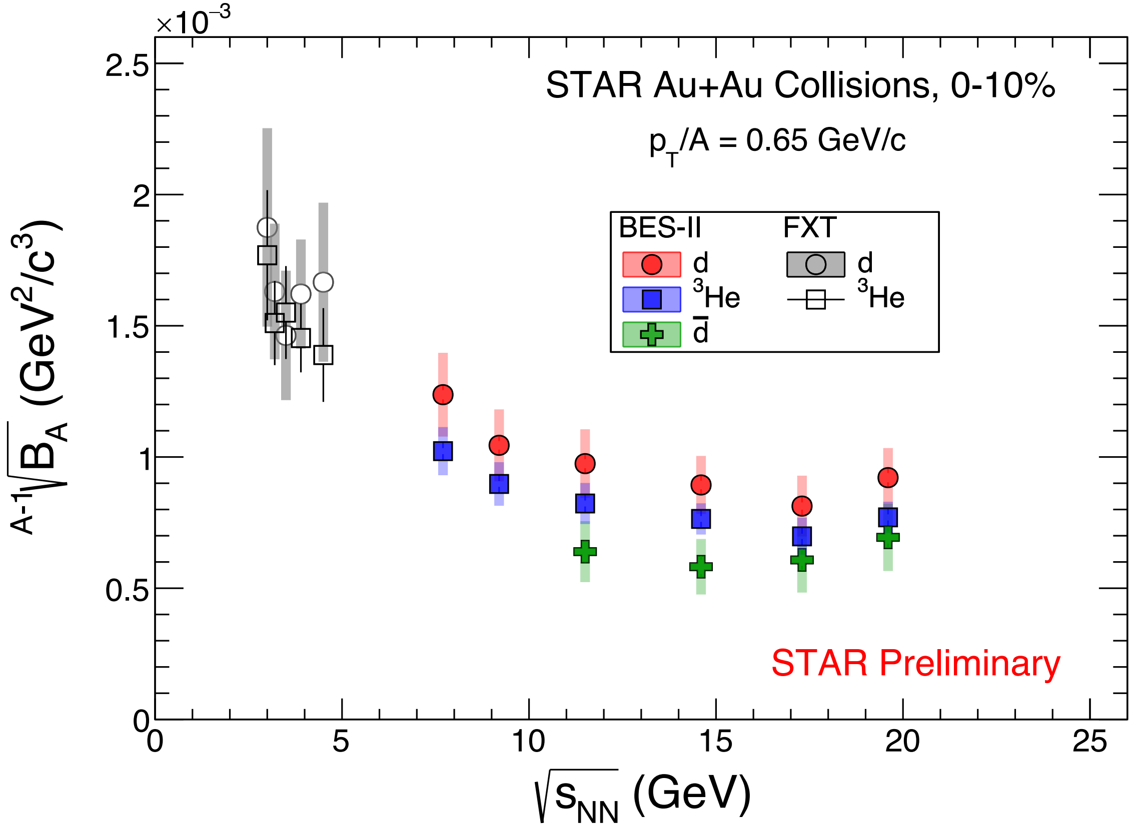
- The penalty factor is larger at higher collision energies, which reflects the increased difficulty to form high-mass objects.

E864 Collaboration, Phys.Rev.Lett. 83 (1999) 5431-5434
STAR Collaboration, Phys.Rev.Lett. 130 (2023) 202301

- The d/p and $\bar{d}/\bar{p}$ ratio can be well described by the thermal model while the t/p and ^{3}He/p ratios are overestimated.

V. Vovchenko, et al, Phys. Rev. C 93, 064906 (2016)
V. Vovchenko, et al, Phys. Lett. B, (2020) 135746
K.J. Sun, et al, Nature Commun, 15 (2024) 1, 1074

Coalescence Parameters



FXT results see poster by Liubing Chen, ID: 711

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

where *A* and *Z* are the mass and charge number of the nucleus. The coalescence parameters B_A reflect the probability of nucleon coalescence.

R. Scheibl and U. Heinz Phys.Rev.C 59 (1999) 1585-1602
STAR Collaboration, Phys.Rev.C 99 (2019) 6, 064905

- $\sqrt[A-1]{B_A}$ decrease with increasing energy, which indicates the effective volume (phase space region where nucleons can coalesce) increases with increasing energy.
- No significant differences were observed in the coalescence parameters for d, $\bar{\mathrm{d}}$, and $^3\mathrm{He}$.

Summary and Outlook

Summary:

- We report the light nuclei productions (p, d, $^{3}\mathrm{He}$, $\bar{\mathrm{p}}$ and $\bar{\mathrm{d}}$) in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 7.7 - 27$ GeV from RHIC STAR BES-II.
- Thermal model reproduces the d/p, $\bar{\mathrm{d}}/\bar{\mathrm{p}}$ ratios, but overestimates the $^{3}\mathrm{He}/\mathrm{p}$ ratio.
- Comparing with measurements from FXT energies (3 – 4.5 GeV), we observe that the coalescence parameters decrease with increasing energy, which indicates the effective volume increases with energy.

Outlook:

- Measure the compound ratio ($\mathrm{N_p} \times \mathrm{N_t}/\mathrm{N_d^2}$) using BES-II data.
- Extend measurements to heavier nuclei over a broad energy range from $\sqrt{s_{\mathrm{NN}}} = 3 - 27$ GeV.

Thank you for your attention!