



Light Nuclei Production in RHIC-STAR BES-II Program

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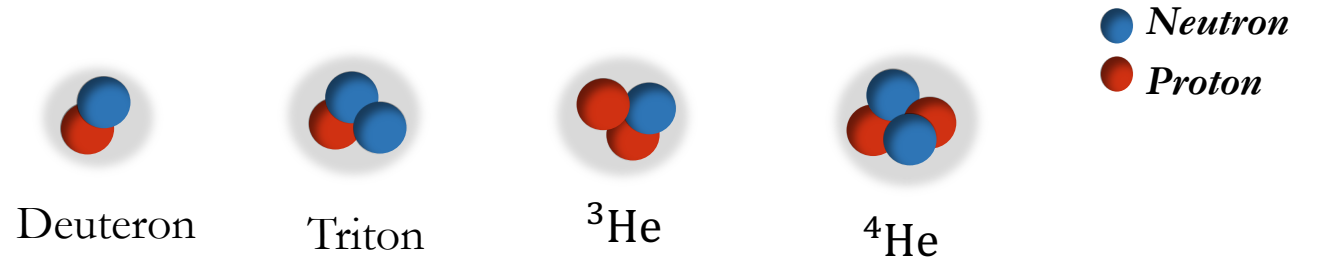
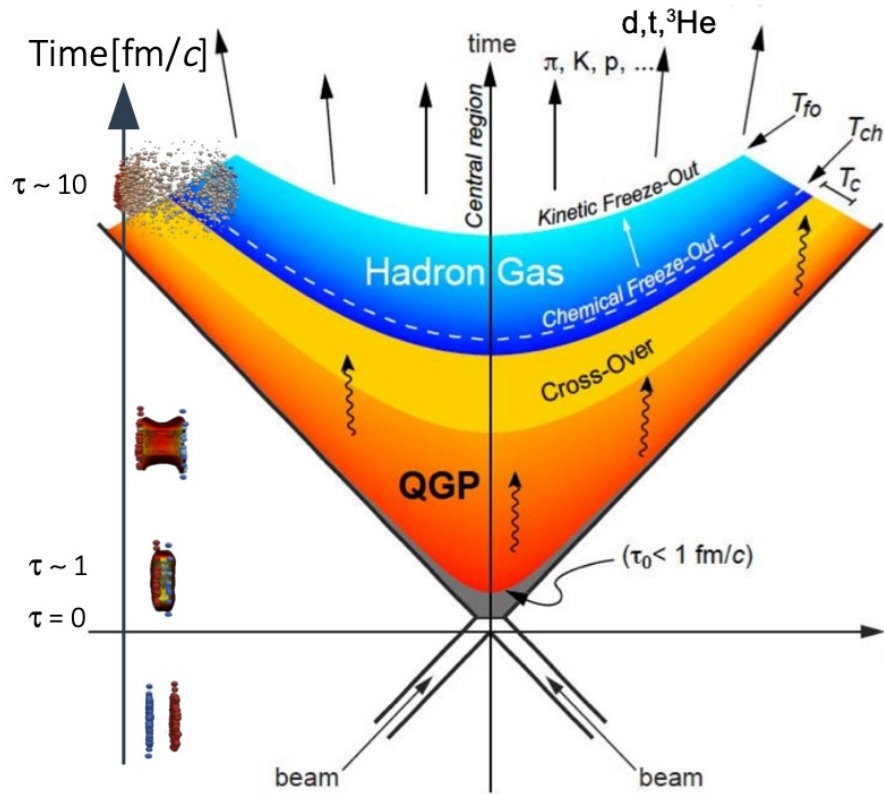


STAR collaboration

Outline

- Introduction
- Method
- Proton and light nuclei production
 - p_T spectra
 - dN/dy and $\langle p_T \rangle$
 - Yield ratios
 - B_A
 - Kinetic Freeze-out Dynamics
- Summary and Outlook

Introduction



➤ Light Nuclei Production Mechanism

- **Thermal approach**

Assumes that all particles, including light nuclei, have the same chemical freeze-out temperature and chemical potential.

- **Coalescence approach**

Assumes that light nuclei are produced by the coalescence of nucleons in the late-stage evolution of the hadron gas.

➤ Chemical Freeze-out

Hadron composition fixed.

➤ Kinetic Freeze-out

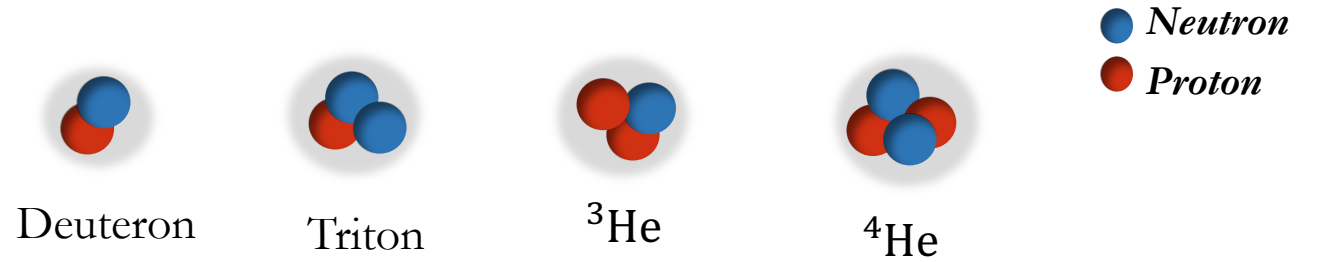
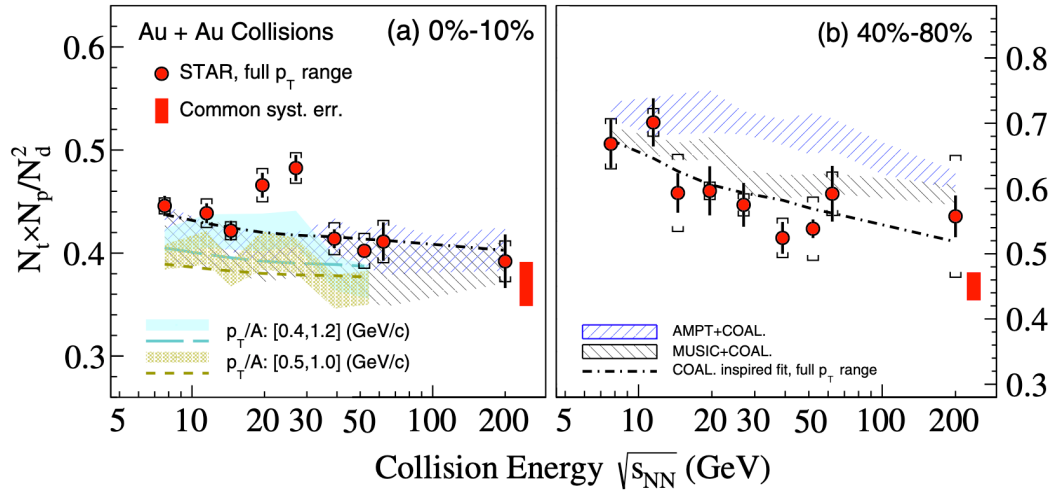
Particle momentum stop changing.

A. Andronic et al., Nature 561, 321-330 (2018)

K. J. Sun et al., Phys. Lett. B 792, 132-137 (2019)

Introduction

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



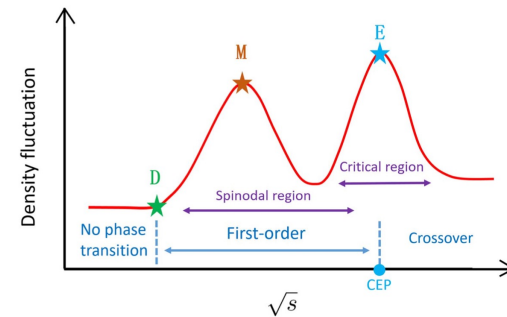
➤ Light Nuclei Compound Yield Ratio

Sensitive Observations for Searching Critical Point and 1st order boundary

$$\frac{N_t \times N_p}{N_d^2} = \frac{N(p_n) \times N(p)}{N(p_n) \times N(p_n)} \approx \frac{1}{2\sqrt{3}} \left[1 + \Delta n + \frac{\lambda}{\sigma} G\left(\frac{\xi}{\sigma}\right) \right]$$

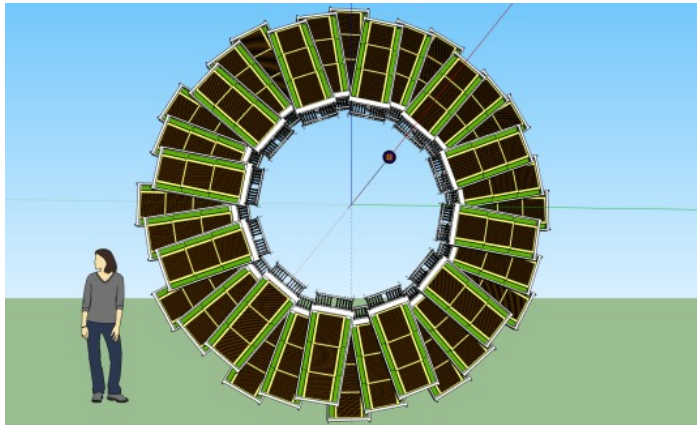
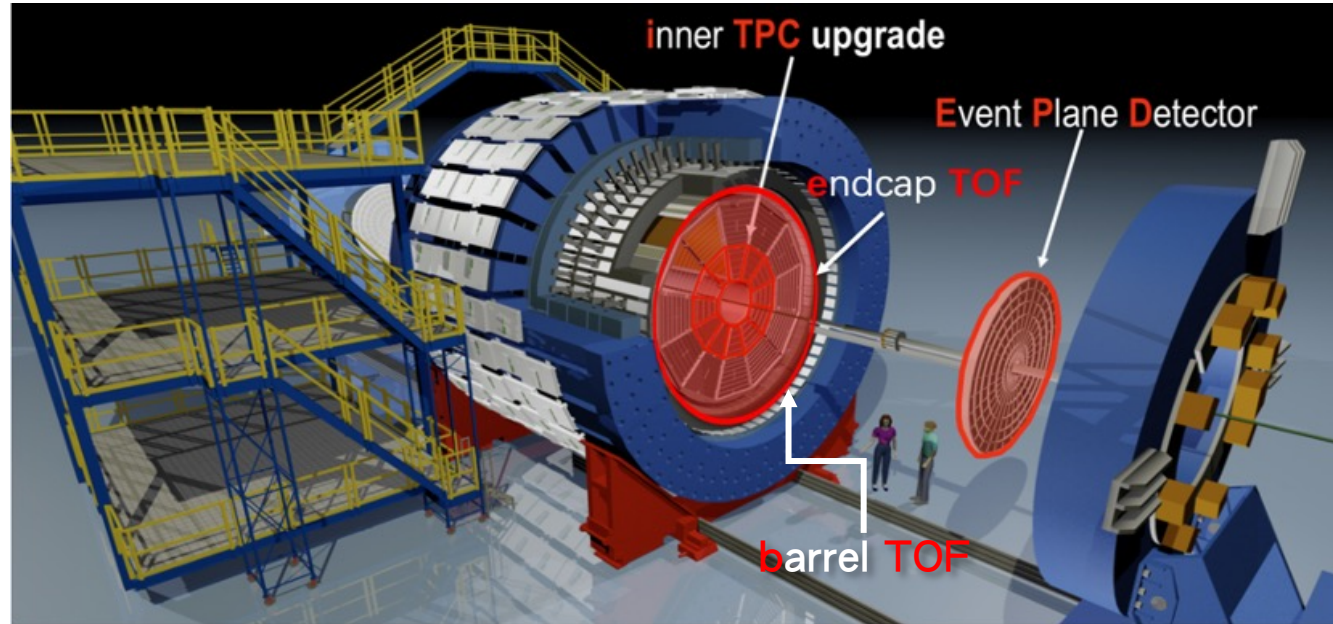
- Non-monotonic behavior of yield ratio vs. energy observed from 0-10% central Au+Au collisions of STAR experiment, possibly signaling a critical point and/or 1st order phase transition.

Δn : Neutron Density Fluctuation
 $G\left(\frac{\xi}{\sigma}\right)$: Long-range Correlation

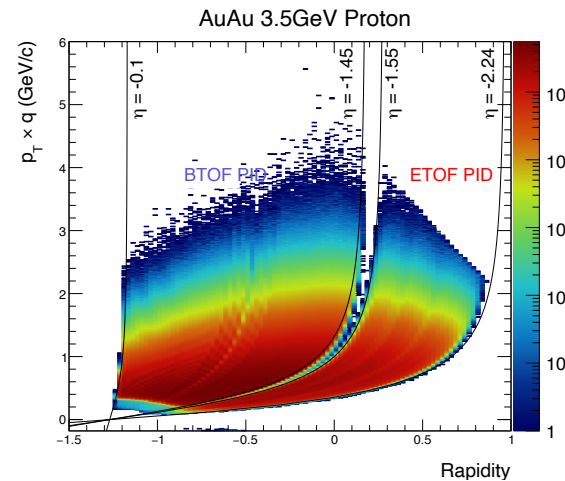


K.J. Sun et al, Phys.Lett.B 781 (2018) 499-504;
 K.J. Sun et al, Phys.Lett.B 816 (2021) 136258

STAR Detector



Full ETOF wheel



Proton acceptance in BTOF/ETOF

➤ Fixed target mode

$$\sqrt{s_{NN}} = 3.0-13.7 \text{ GeV}$$

$$\mu_B: 750-280 \text{ MeV}$$

➤ Collider mode

$$\sqrt{s_{NN}} = 7.7-27 \text{ GeV}$$

$$\mu_B: 420-156 \text{ MeV}$$

➤ BES-II detector upgrade

In Au+Au collisions at $\sqrt{s_{NN}} = 3.0, 3.2, 3.5, 3.9$ and 4.5 GeV

• iTPC

cover full area, $-2.4 < \eta < 0$

better dE/dx , $p_T > 60 \text{ MeV}/c$.

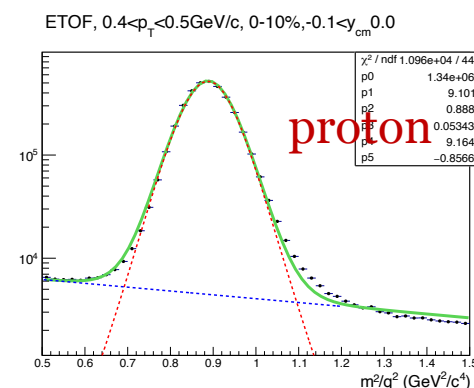
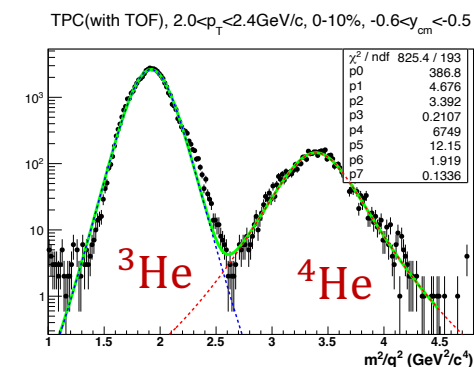
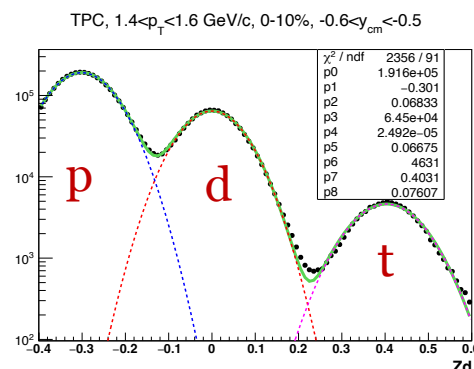
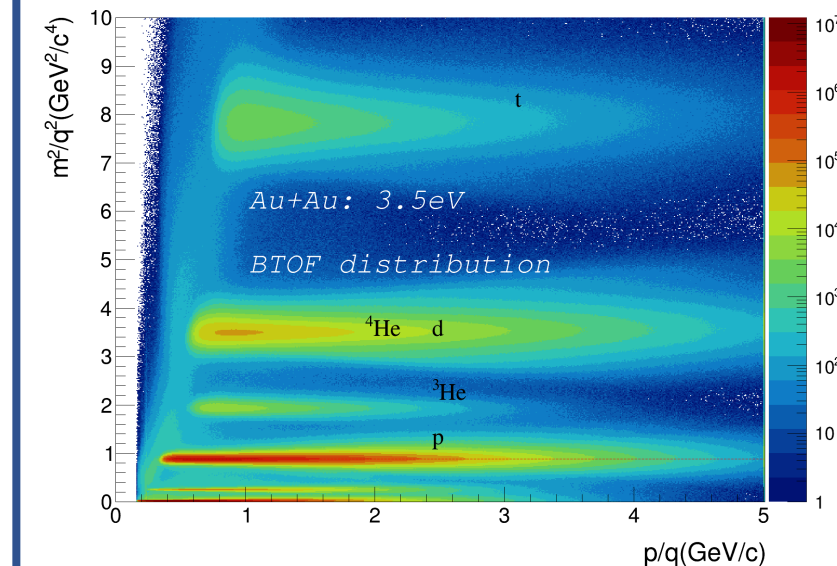
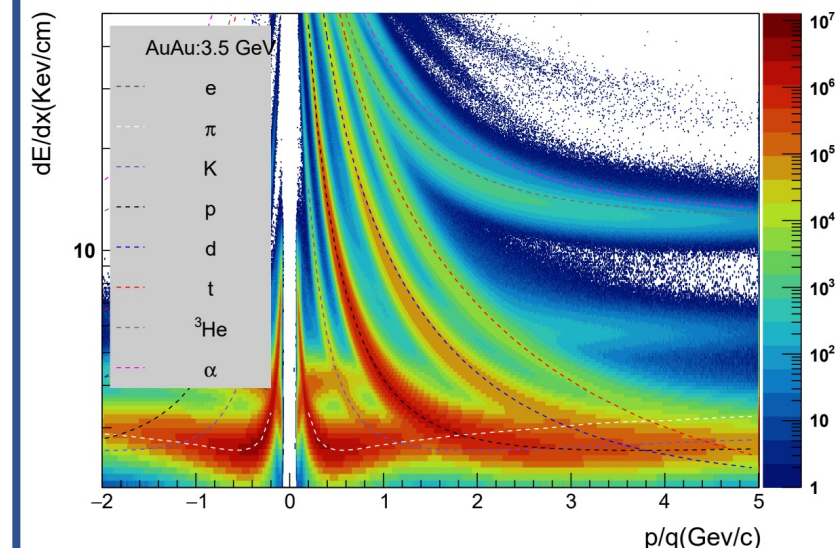
• eTOF

at the east end of STAR,

$-2.15 < \eta < -1.55$

➤ **ETOF** extends more acceptance in mid rapidity, and will be use for light nuclei production measurements in the future.

Signal Extraction



➤ TPC:

- Signal(**red**):

Gaussian function

$$f(p_T) = p_0 e^{-\frac{1}{2} \left(\frac{p_T - p_1}{p_2} \right)^2}$$

- Background(**blue/magenta**):

Gaussian

➤ TPC with TOF/ETOF:

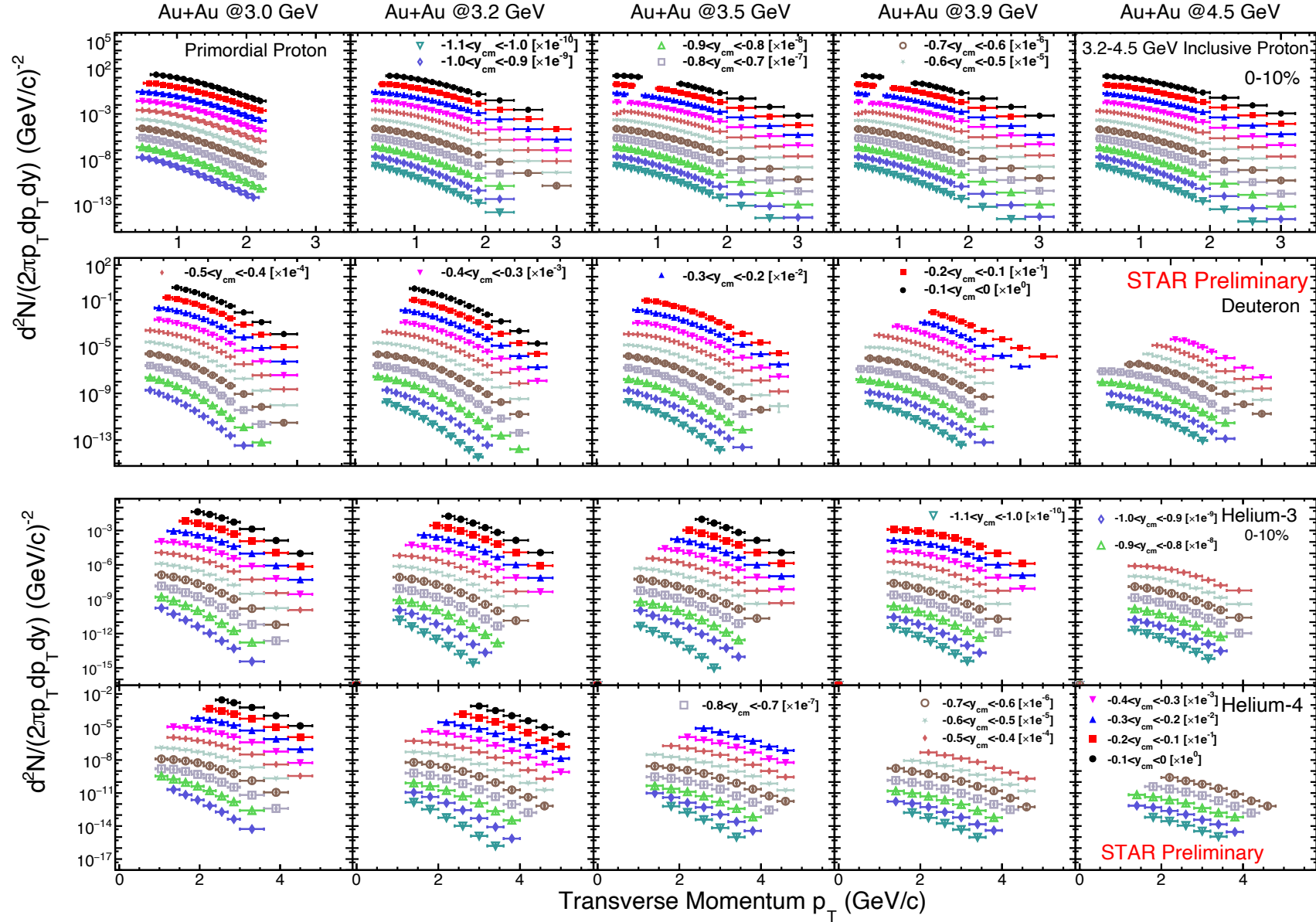
- Signal: **Student-t function**

$$f(x) = p_0 \frac{\Gamma(\frac{p_1 + 1}{2})}{p_1 \pi \Gamma(\frac{p_1}{2})} \times \left(1 + \frac{t^2}{p_1} \right)^{-\frac{p_1 + 1}{2}}$$

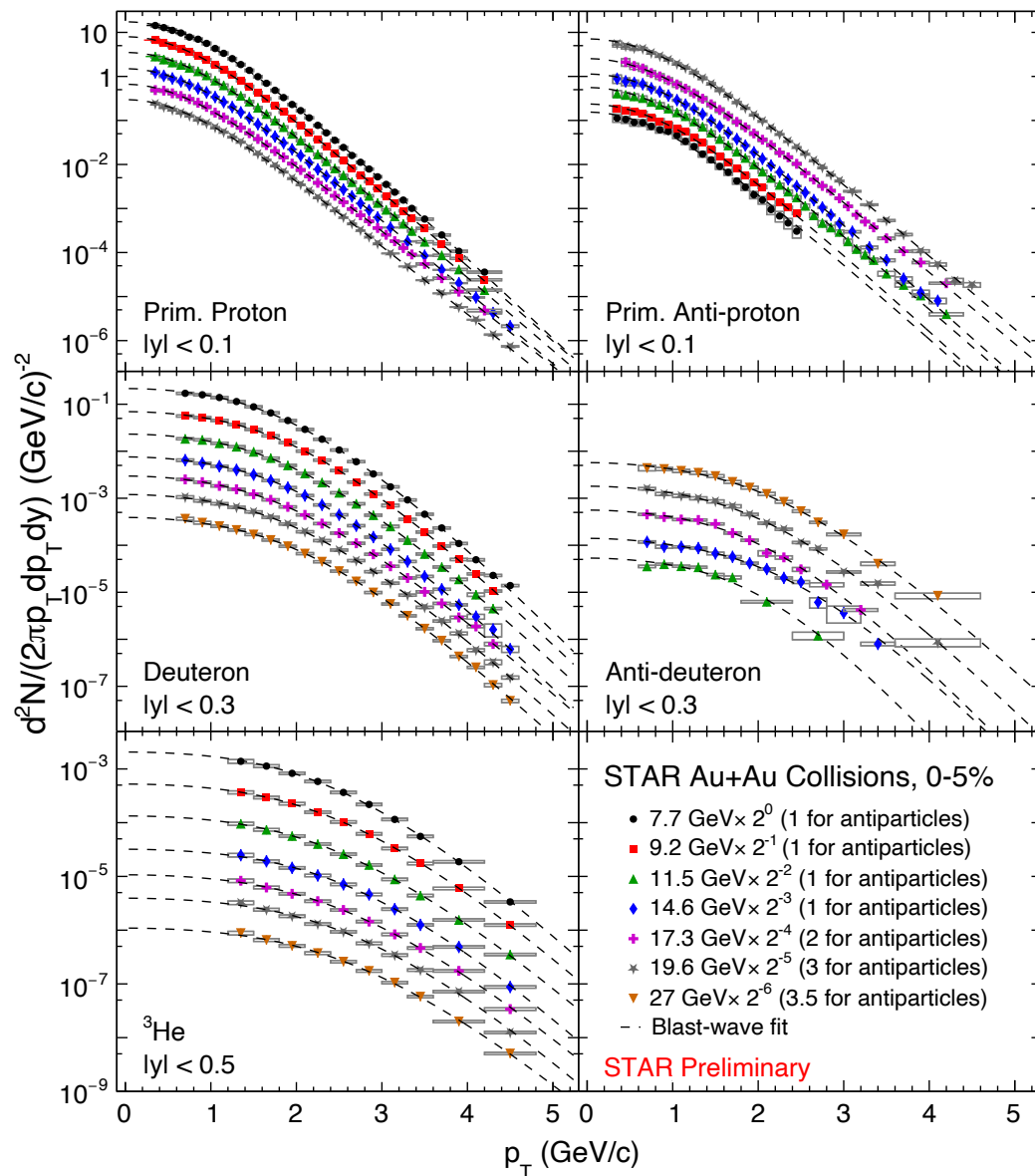
$$t = \left(\frac{m^2 - p_2}{p_3} \right)^2$$

- Background: **exponential, Student-t(³He, ⁴He)**

Transverse Momentum Spectra



Transverse Momentum Spectra



➤ Default fit function(**Blast-wave**):

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

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

Kinetic Freeze-out Parameters:

T_{kin} : kinetic freeze-out temperature

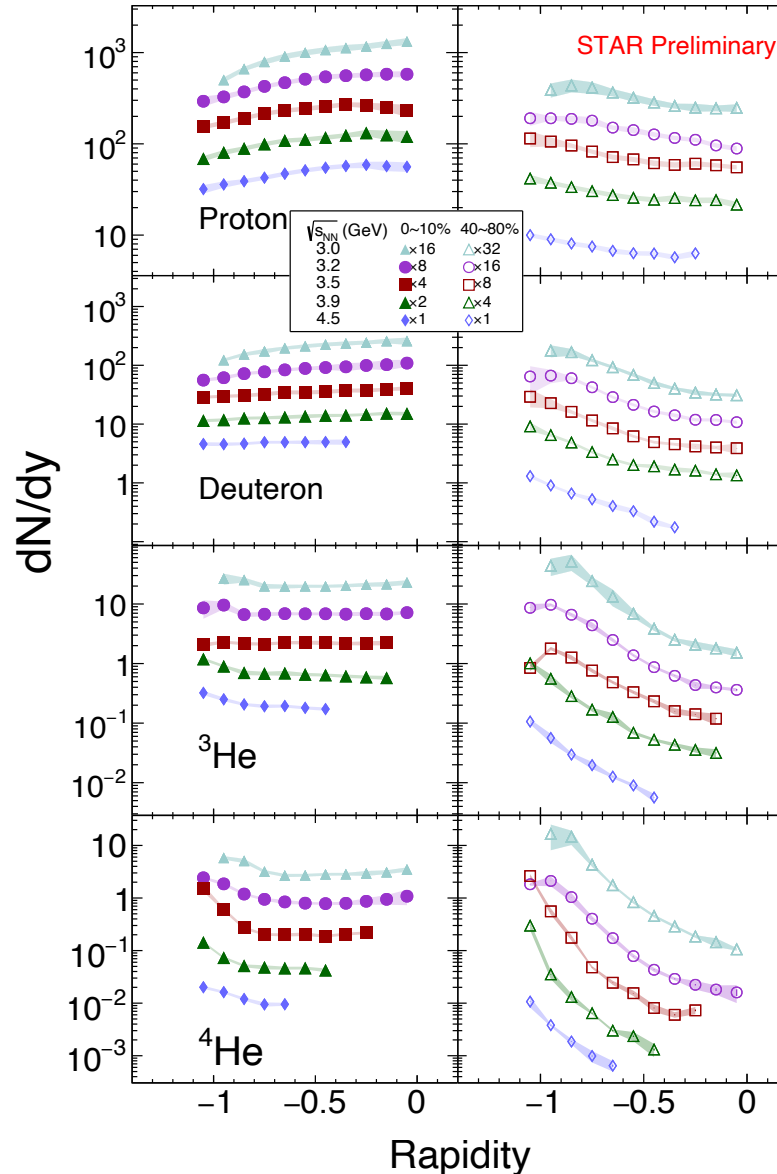
$\langle \beta_T \rangle$: average radial flow velocity

➤ Alternative fit function(**Double p_T^2 exp.**):

$$\frac{d^2N}{2\pi dp_T dy} \propto p_0 \exp\left(-\frac{p_T^2}{p_1^2}\right) + p_2 \exp\left(-\frac{p_T^2}{p_2^2}\right)$$

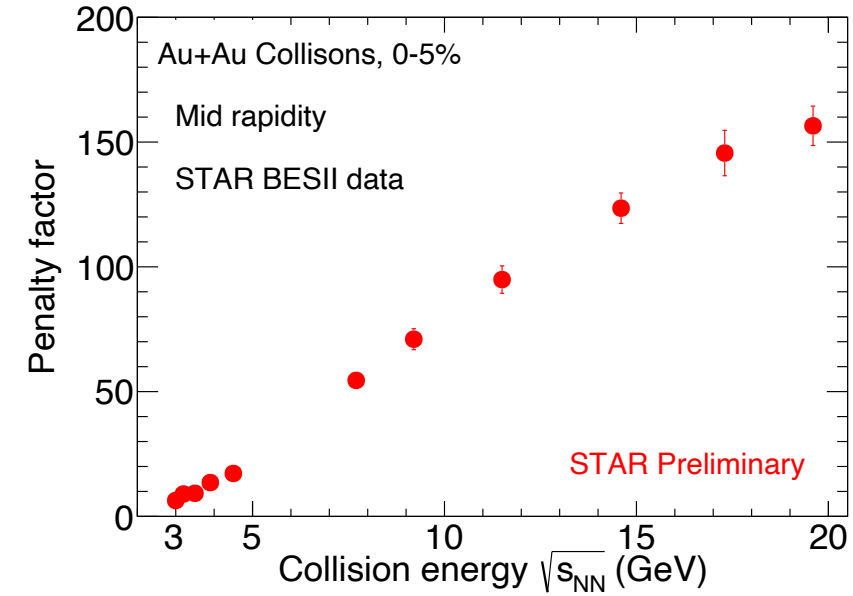
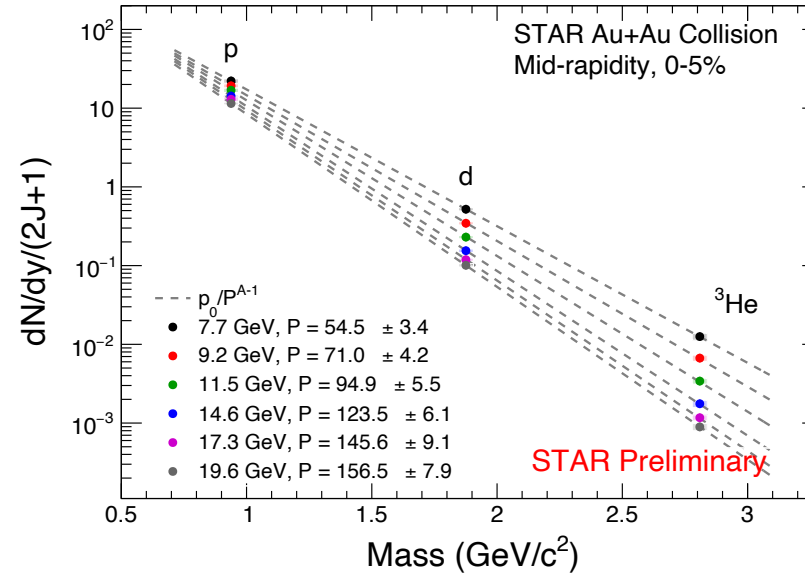
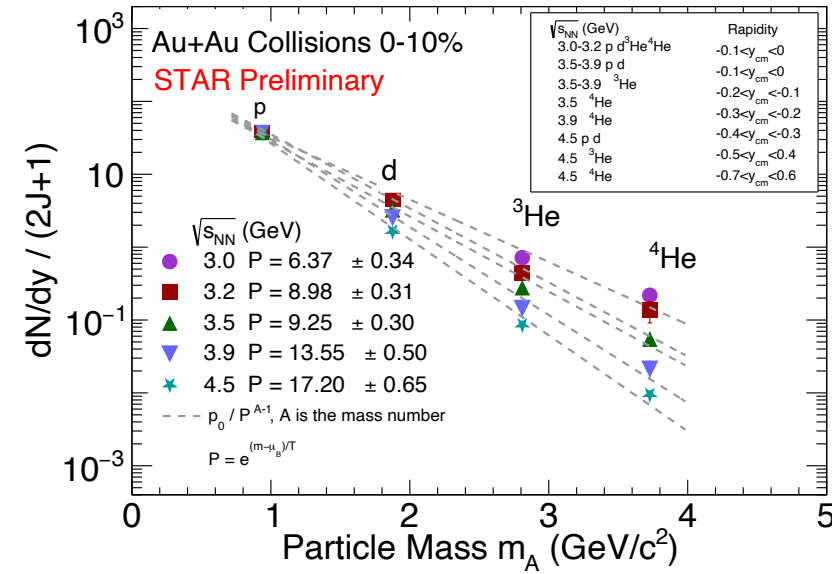
QM2025, Yixuan Jin

dN/dy distribution



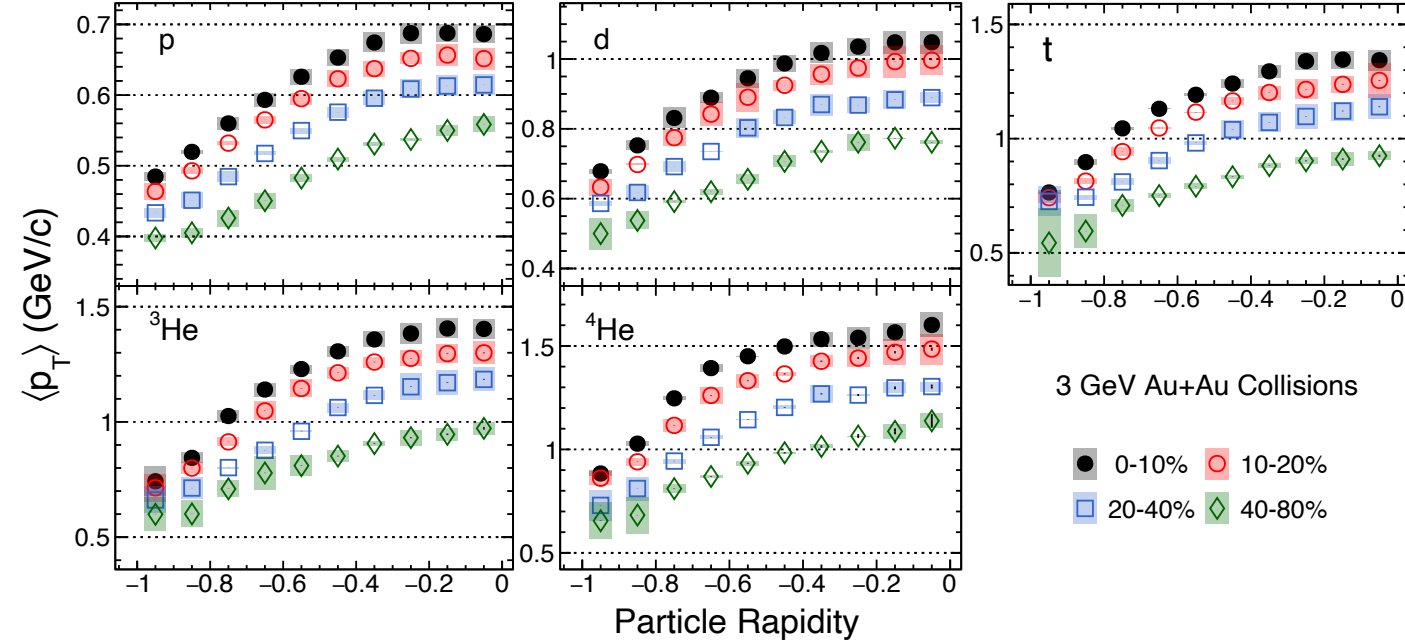
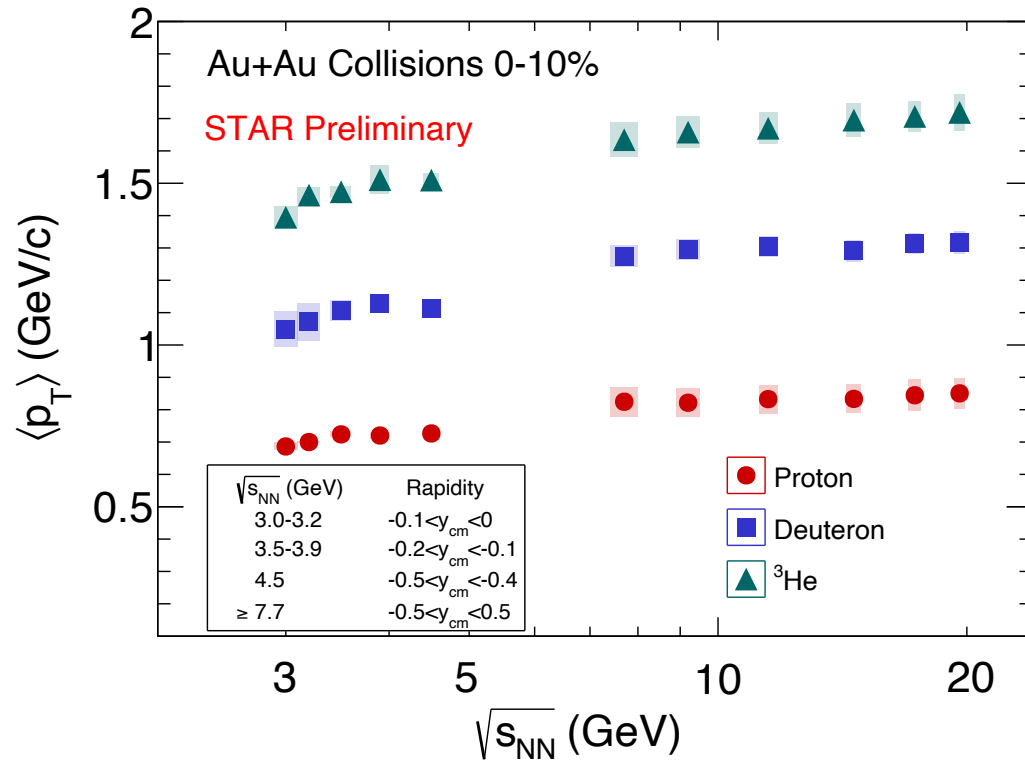
- dN/dy for proton, deuteron, triton, ^3He and ^4He in $\sqrt{s_{NN}} = 3\text{-}4.5$ GeV with centrality and rapidity dependence.
- Light nuclei with larger mass numbers show higher dN/dy from target to mid-rapidity and central to peripheral collisions, suggesting fragment contributions to their production.
- The band indicates systematical uncertainty.

dN/dy distribution



- $dN/dy/(2J+1)$ was fit with $\frac{p_0}{P^{A-1}}$, where P is the penalty factor and determined by Boltzmann factor $e^{\frac{m-\mu_B}{T}}$. P value increases with increasing beam energy, indicating suppressed formation of high-mass objects at higher energies.

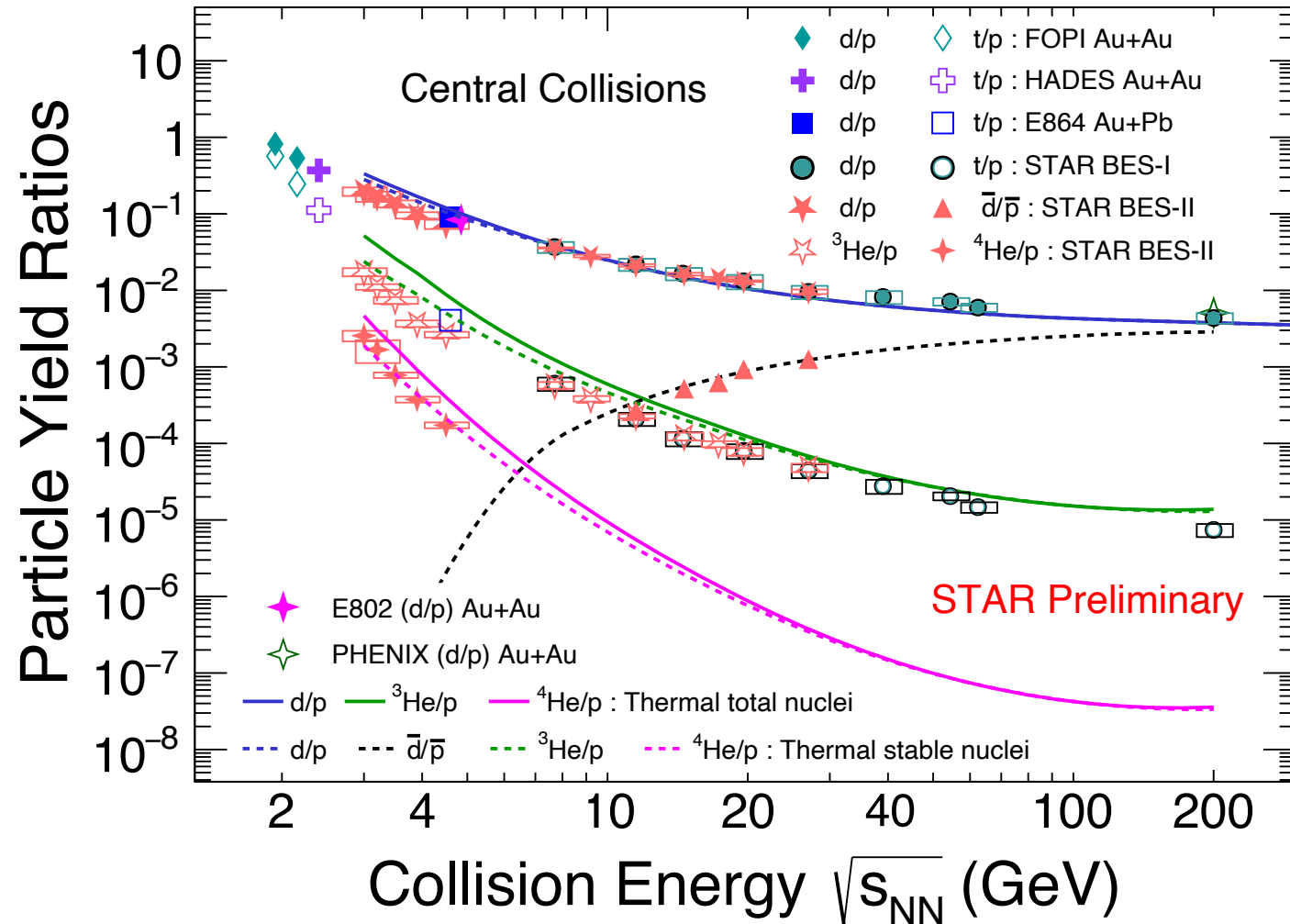
Averaged Transverse Momentum $\langle p_T \rangle$



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- $\langle p_T \rangle$ of protons and light nuclei as a function of centrality, rapidity, and collision energy.
- Hint of $\langle p_T \rangle$ increase with energy for 4.5 GeV and below, flat trend between 7.7 and 19.6 GeV. This behavior will be further studied in 4.5 - 7.7 GeV in the future.

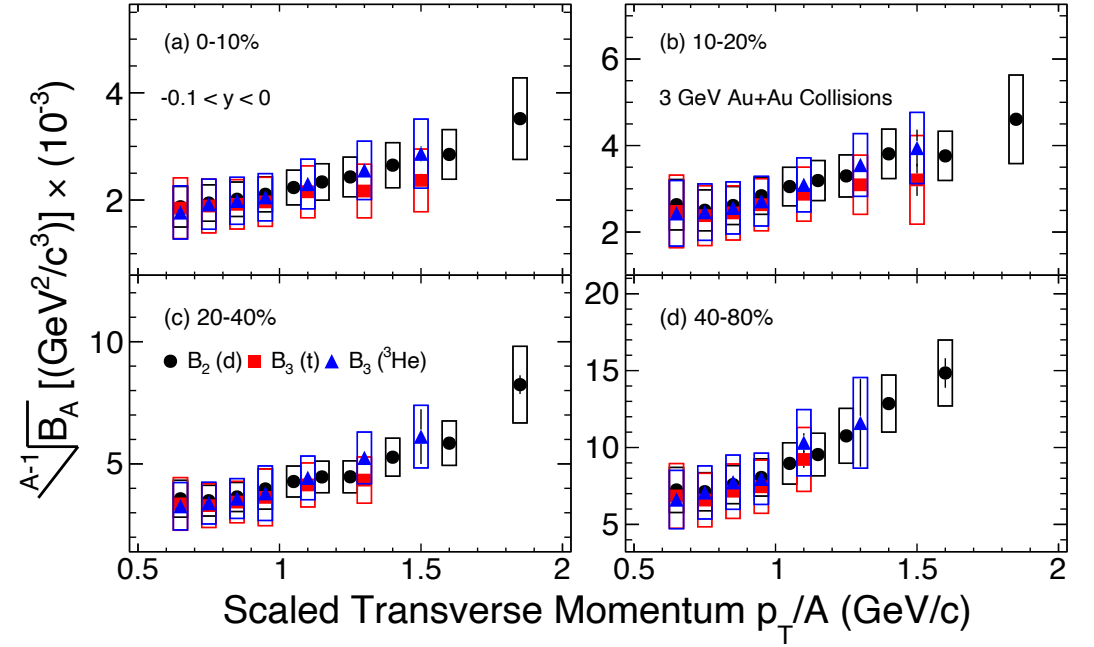
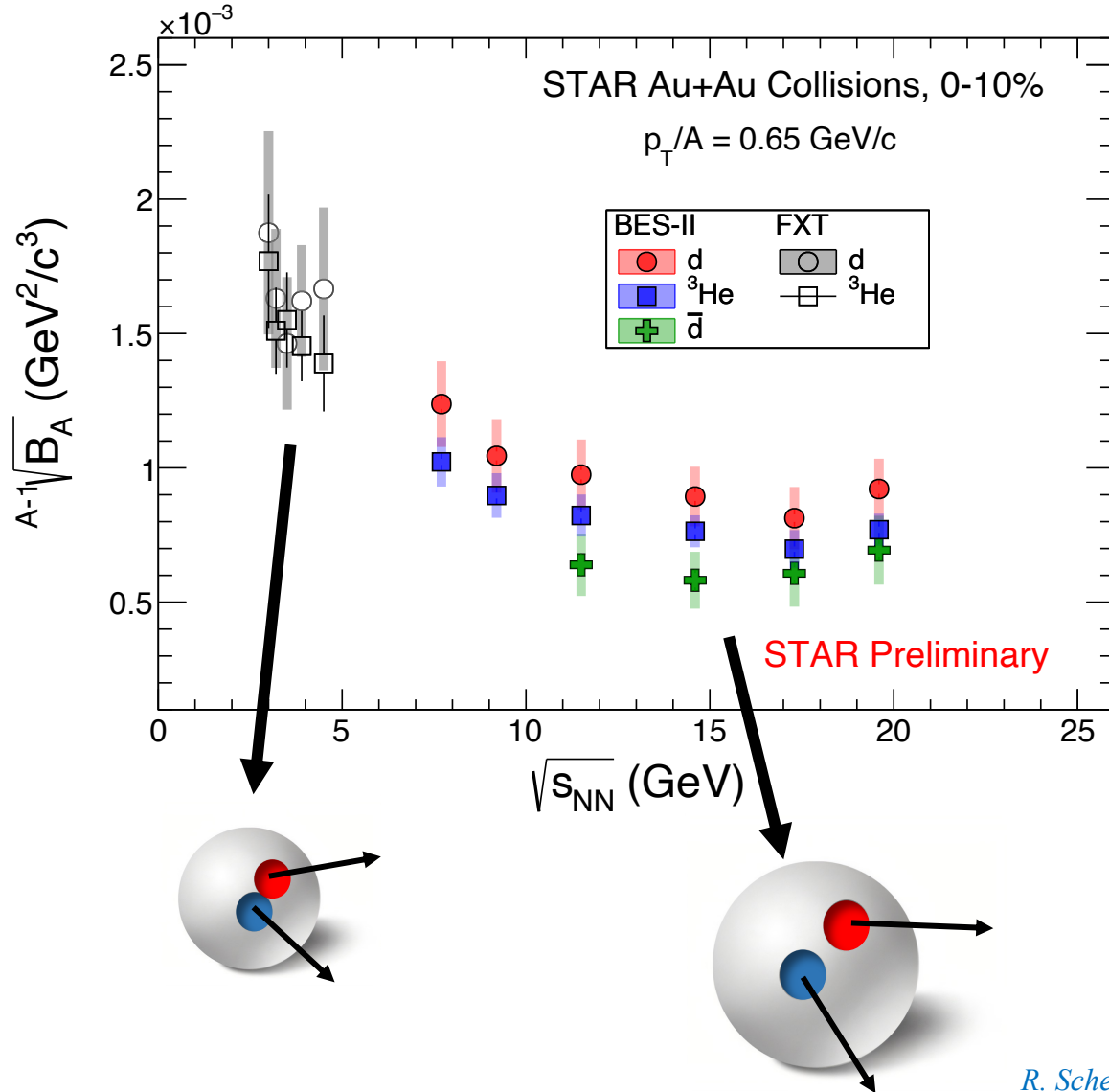
Particle Ratio



- Clear energy dependence is observed for both d/p , $\bar{d}/\bar{p}$, t/p , ${}^3\text{He}/p$, and ${}^4\text{He}/p$ ratios.
- The trends of ratios can be described qualitatively by the thermal model.
- ${}^3\text{He}/p$ is overestimated by thermal model, possibly due to the hadronic re-scattering effect.
- Considering only stable nuclei, ${}^4\text{He}/p$ from thermal model is consistent with the experiment data.

[STAR Collaboration] *Phys. Rev. C* 96, 044904 (2017); *Phys.Rev.Lett.* 130 (2023) 202301;
 [E802 Collaboration] *Phys.Rev.C* 60 (1999) 064901; [E864 Collaboration] *Phys.Rev.C* 61 (2000) 064908;
 [FOPI Collaboration] *Nucl.Phys.A* 848 (2010) 366-427; V. Vovchenko, et al. *Phys. Rev. C* 93(2016) 6, 064906;

Coalescence parameters B_A



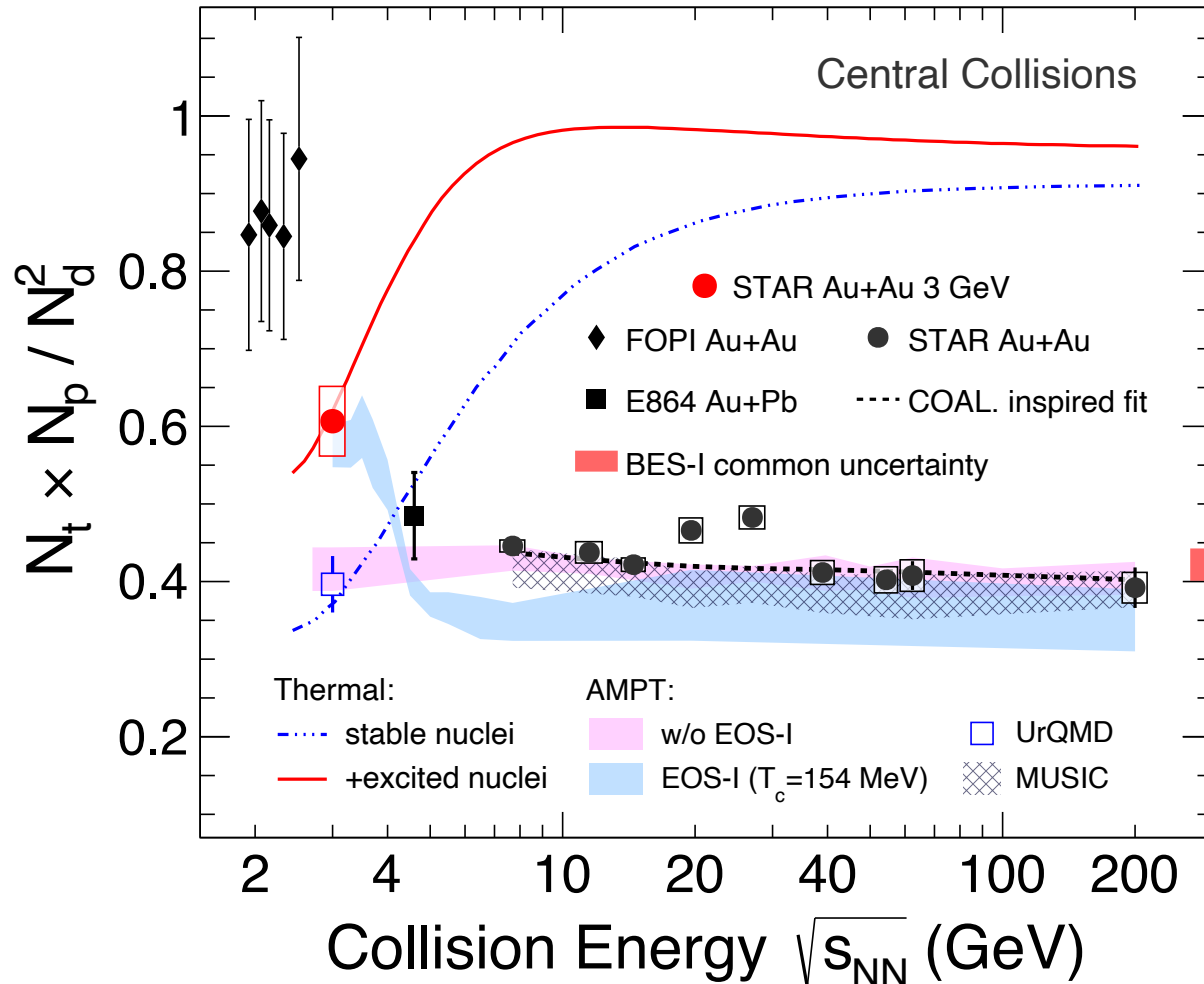
➤ $E_A \frac{d^3 N_A}{d^3 p_A} = B_A (E_p \frac{d^3 N_p}{d^3 p_p})^Z (E_n \frac{d^3 N_n}{d^3 p_n})^{A-Z} \approx B_A \left(E_p \frac{d^3 N_p}{d^3 p_p} \right)^A$, $B_A \propto \left(\frac{1}{V_{eff}} \right)^{(A-1)}$
 V_{eff} is the effective volume of the nucleon emission source.

- As the energy increases, B_A becomes smaller, indicating that the effective volume of the system becomes larger.
- Length of homogeneity becomes smaller in peripheral collisions and at higher p_T region.

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R. Scheibl and U. Heinz *Phys.Rev.C* 59 (1999) 1585-1602; S. Zhang et al. *Phys.Lett.B* 684 (2010) 224-227

Compound Ratio



$$\triangleright \frac{N_t \times N_p}{N_d^2} \approx \frac{1}{2\sqrt{3}} \left[1 + \Delta n + \frac{\lambda}{\sigma} G\left(\frac{\xi}{\sigma}\right) \right]$$

Δn : Neutron Density Fluctuation

$G(\frac{\xi}{\sigma})$: Long-range Correlation

$\triangleright$ Energy dependence of $\frac{N_t \times N_p}{N_d^2}$ in most central Au+Au collisions.

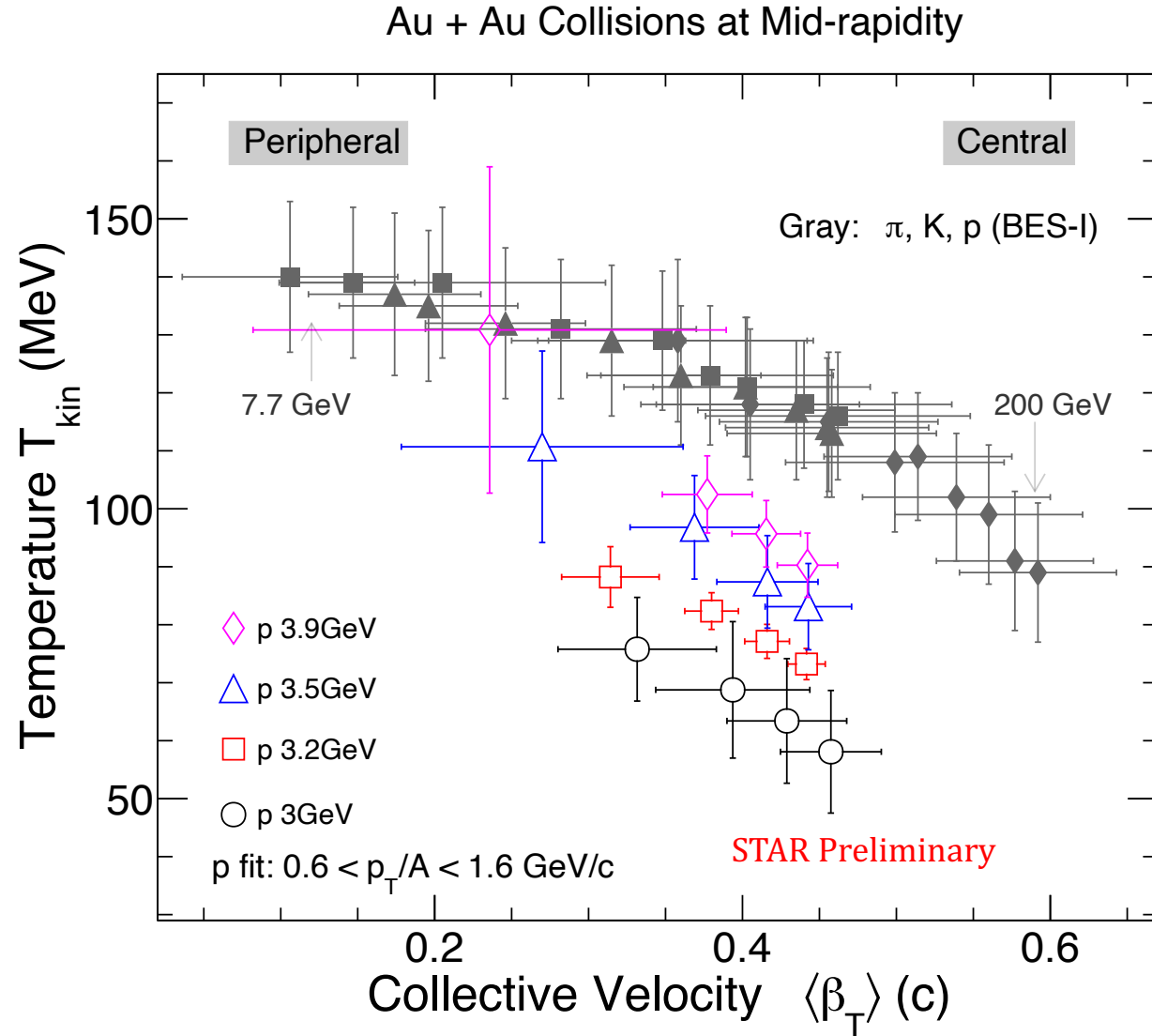
$\triangleright$ AMPT model employing a first order phase transition with input critical temperature of 154 MeV can reproduced 3 GeV yield ratio.

$\triangleright \sqrt{s_{NN}} = 3.2-27$ GeV compound ratio from STAR BES-II is in progress.

K. Sun et al. Phys.Rev.C 103 (2021) 6, 064909

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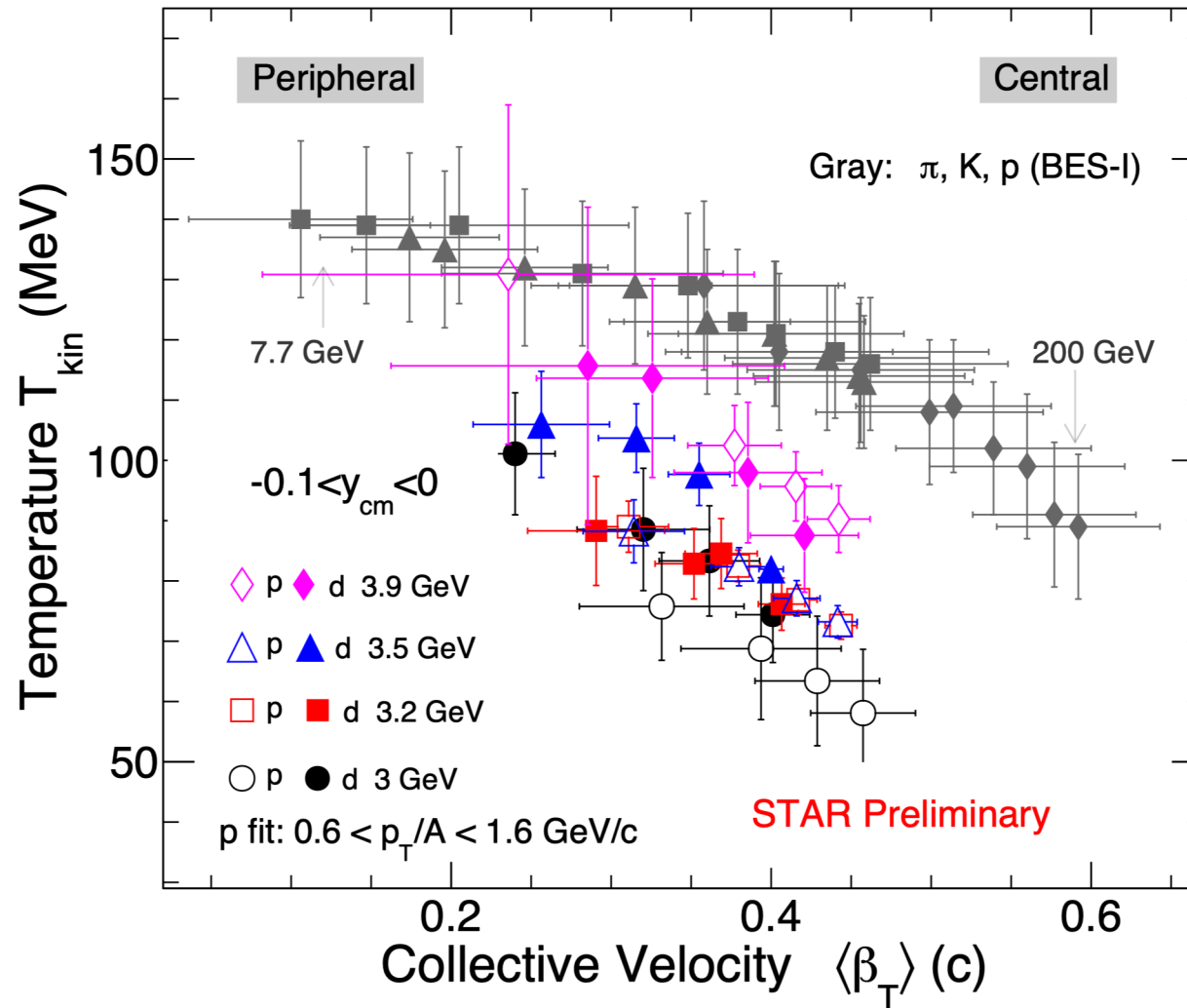
Kinetic Freeze-out Dynamics



➤ For $\sqrt{s_{NN}} = 3.0\text{-}3.9$ GeV, proton T_{kin} increases with energy while $\langle \beta_T \rangle$ stays approximately constant. This trend is different for $\sqrt{s_{NN}} \geq 7.7$ GeV, may imply a different medium equation of state (EoS).

Kinetic Freeze-out Dynamics

Au + Au Collisions at Mid-rapidity



- The differing trends in T_{kin} and $\langle \beta_T \rangle$ for protons and deuterons ($\sqrt{s_{NN}} = 3.0-3.9$ GeV) imply they have distinct kinetic freeze-out surfaces.
- T_{kin} versus $\langle \beta_T \rangle$ distribution shows a clear gap region between 3 GeV and energies above 7.7 GeV.
- The gap can be filled by collision energies $\sqrt{s_{NN}} = 3.0 - 3.9$ GeV, may imply a different medium equation of state (EoS).

Summary and Outlook

➤ **Summary:**

- ✓ We presented light nuclei production (p_T spectra, dN/dy , $\langle p_T \rangle$, particle ratio, and B_A) in Au+Au collisions at $\sqrt{s_{NN}} = 3.0-27$ GeV by STAR experiment, studying their rapidity and energy dependence.
- ✓ The thermal model overestimates d/p at low energies but describes it at higher collider energies, $^3\text{He}/p$ ratio is overestimated by the thermal model at all energies and $^4\text{He}/p$ is consistent with the thermal model only considering stable nuclei.
- ✓ The extracted kinetic freeze-out parameters (T_{kin} , $\langle \beta_T \rangle$) may imply that the equation of state describing the hot, dense nuclear matter at low collision energies ($\sqrt{s_{NN}} = 3.0-3.9$ GeV) differs from that observed at higher energies.

➤ **Outlook:**

- Measure the compound ratio ($N_t \times N_p / N_d^2$) using STAR BES-II data.
- Measure ^4He production in $\sqrt{s_{NN}} \geq 7.7$ GeV to gain more insight on $N_{^4\text{He}} \times N_p / (N_{^3\text{He}} \times N_d)$ and production mechanism.

Thank you