STAR

HOT QUARKS 2025
HEFEI, CHINA

CENTRAL CHINA NORMAL UNIVERSITY

Light Nuclei Production in RHIC-STAR BES-II Program

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HOT QUARKS 2025, Hefei

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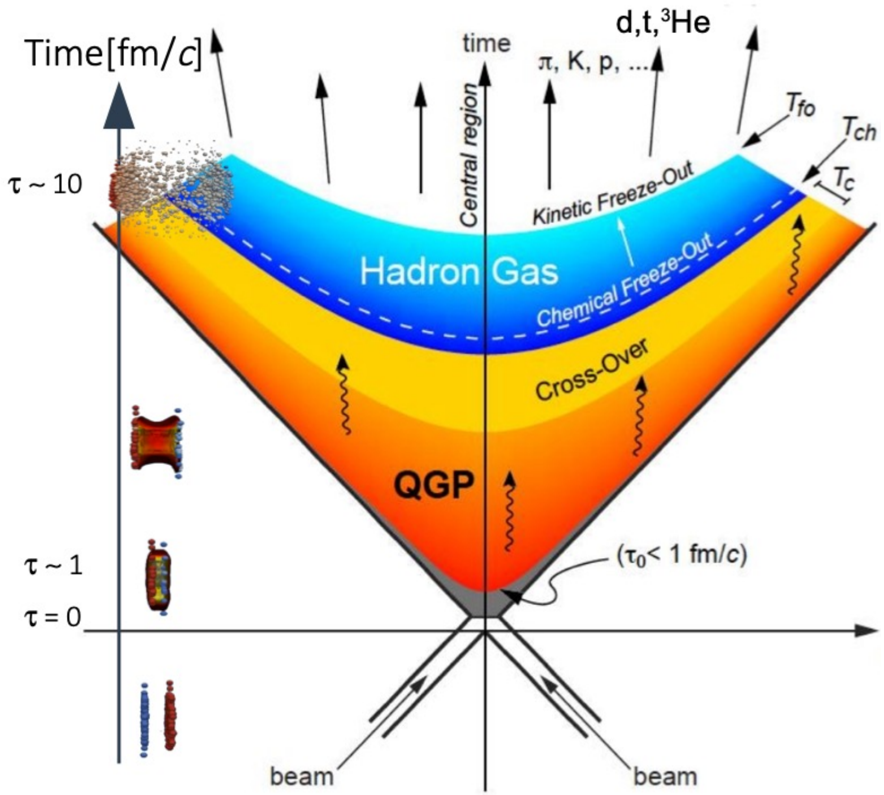
STAR collaboration

Outline

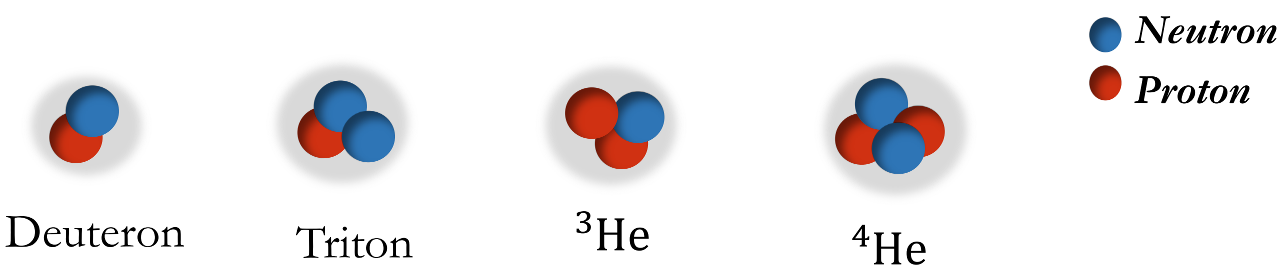
- Introduction
- Method
- Proton and light nuclei production
  - p_T spectra
  - dN/dy and $< p_T >$
  - Yield ratios
  - B_A
  - Kinetic Freeze-out Dynamics
- Summary and Outlook

Introduction



- **Chemical Freeze-out**
  Hadron composition fixed.

- **Kinetic Freeze-out**
  Particle momentum stop changing.



- **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**

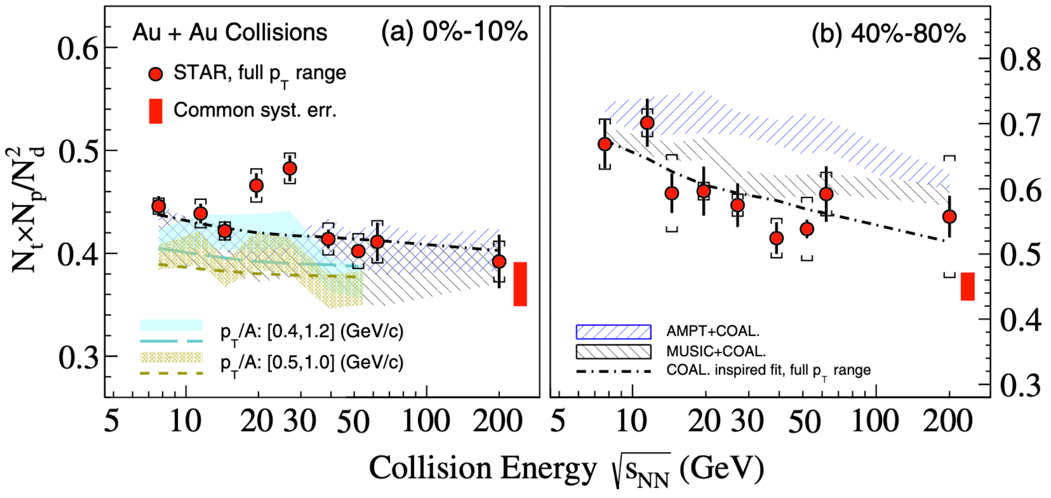
Assumes that light nuclei are produced by the coalescence of nucleons in the late-stage evolution of the hadron gas.

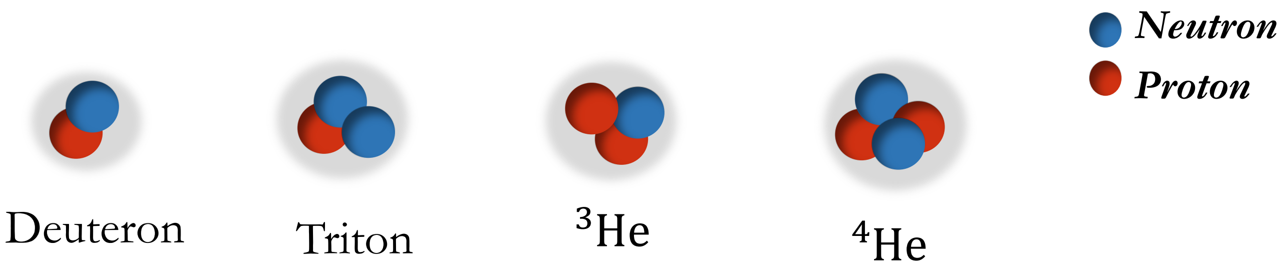
A. Andronic et al., Nature 561, 321-330 (2018)

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

Introduction

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





- **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.**

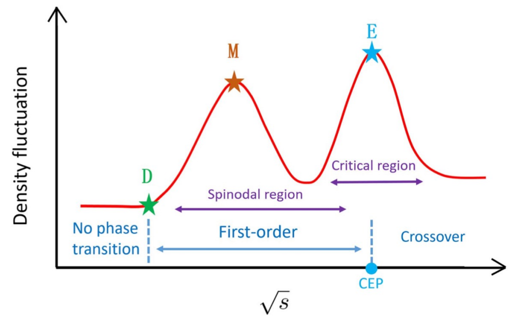
- **Light Nuclei Compound Yield Ratio**

Sensitive Observations for Searching Critical Point and 1st order boundary

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

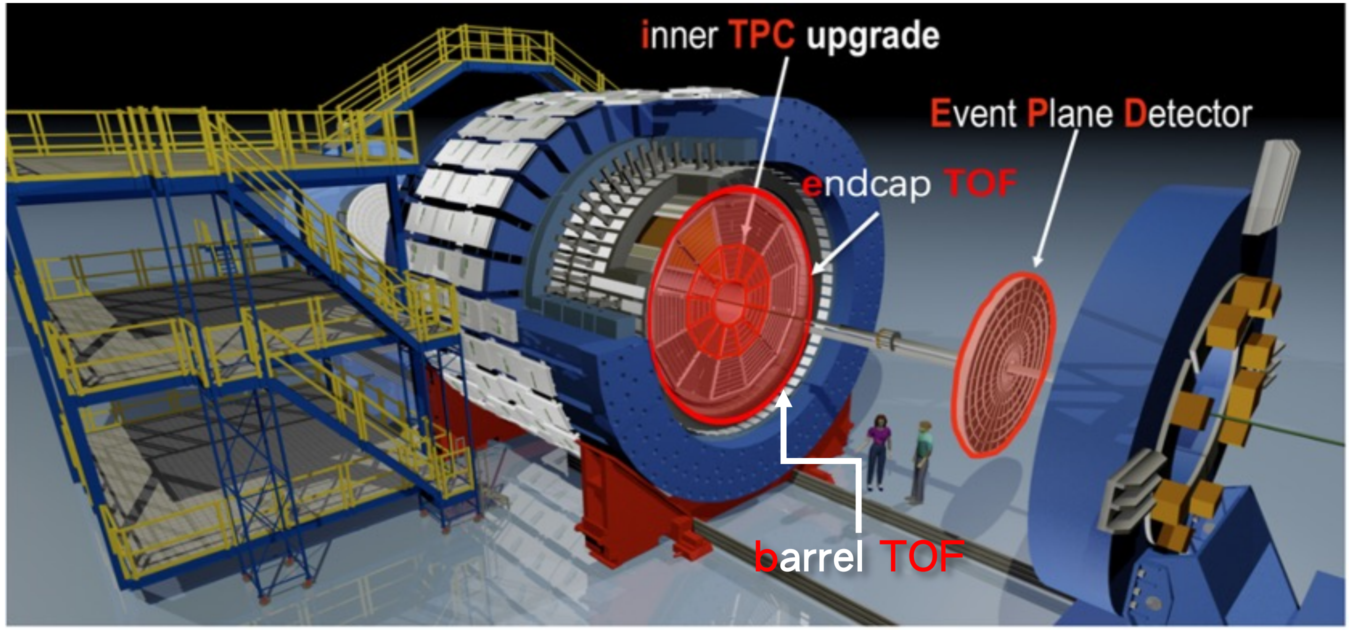
Δn: Neutron Density Fluctuation

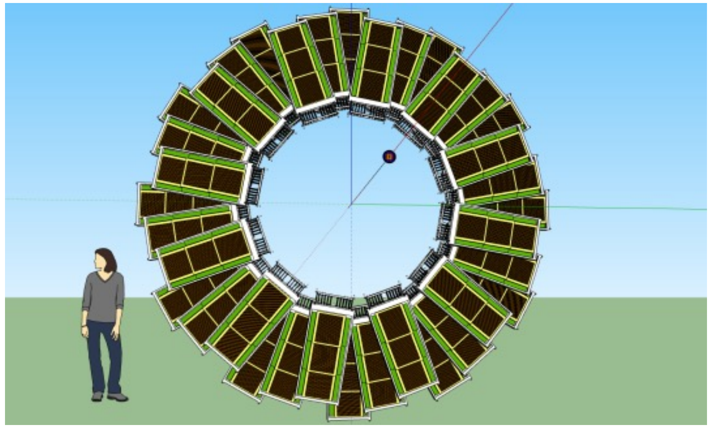
$G(\frac{\xi}{\sigma})$: Long-range Correlation



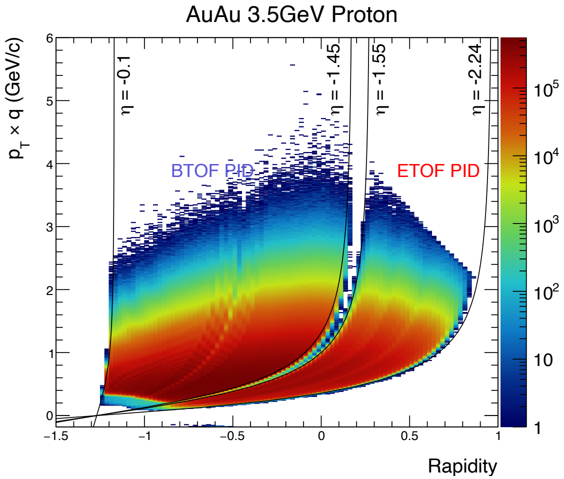
K.J. Sun et al, Phys.Lett.B 781 (2018) 499-504;
K.J. Sun et al, Phys.Lett.B 816 (2021) 136258

STAR Detector





Full ETOF wheel



Proton acceptance in BTOF/ETOF

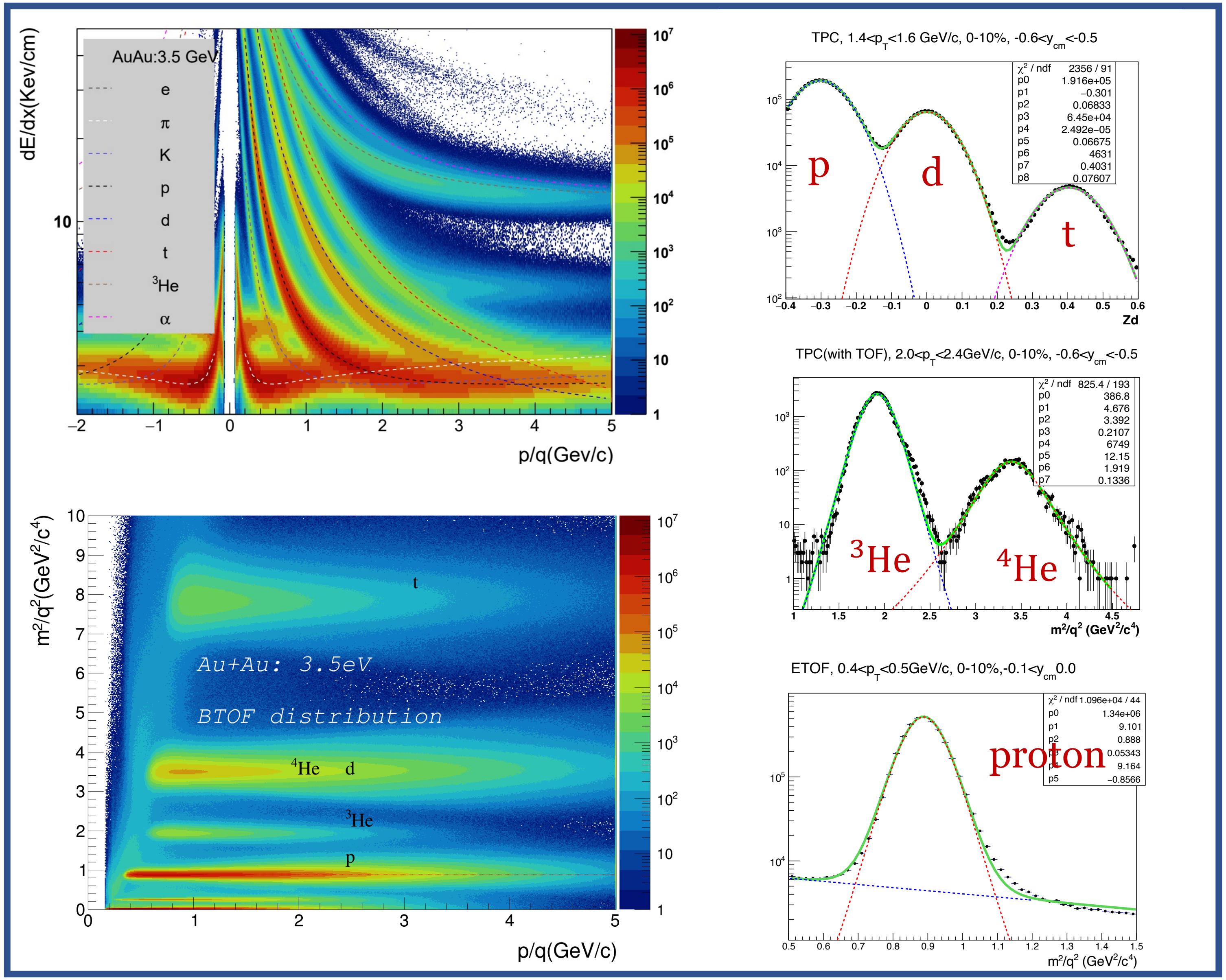
- **Fixed target mode**
  $\sqrt{s_{NN}}$=3.0-13.7 GeV
  μ_B: 750-280 MeV
- **Collider mode**
  $\sqrt{s_{NN}}$=7.7-27 GeV
  μ_B: 420-156 MeV
- **BES-II detector upgrade**

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 < η < 0
  better dE/dx, p_T > 60 MeV/c.
- eTOF
  at the east end of STAR,
  -2.15< η <-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

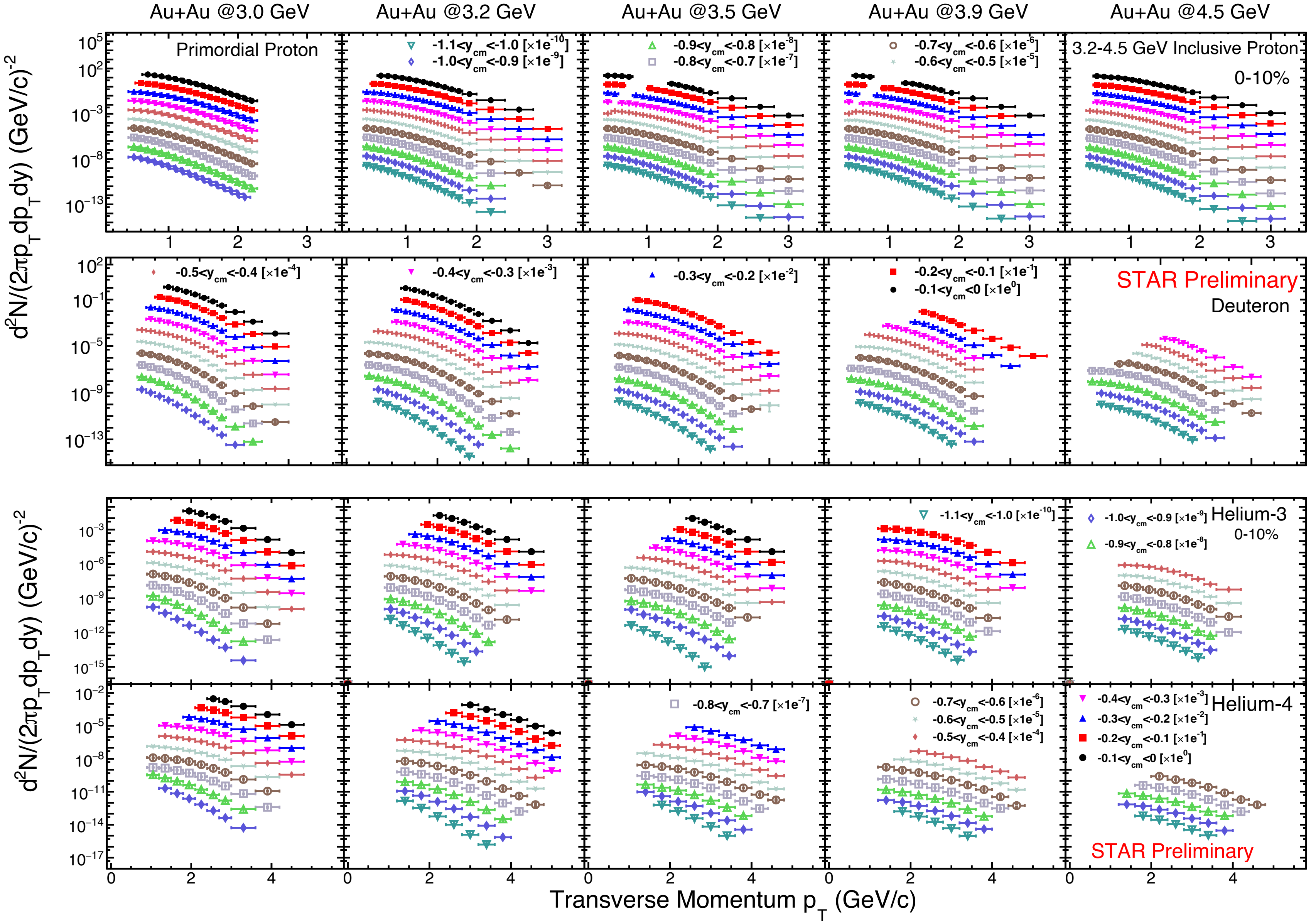
- ➢ TPC with TOF/ETOF:
  - Signal: Student-t function

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

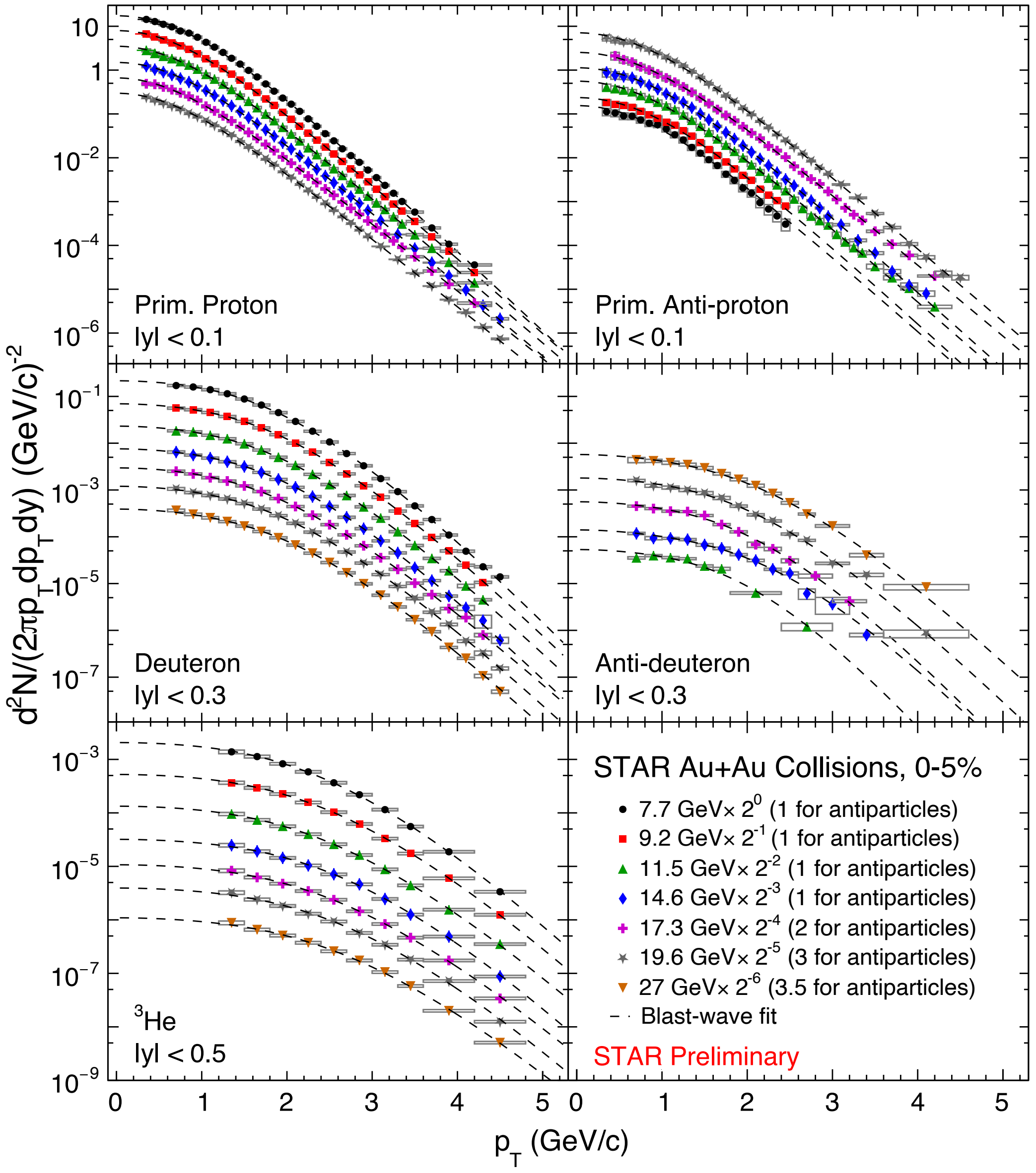
$$t = \left(\frac{m^2 - p_2}{p_3}\right)^2$$

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

Transverse Momentum Spectra



Transverse Momentum Spectra



- Default fit function(Blast-wave):

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

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

Kinetic Freeze-out Parameters:

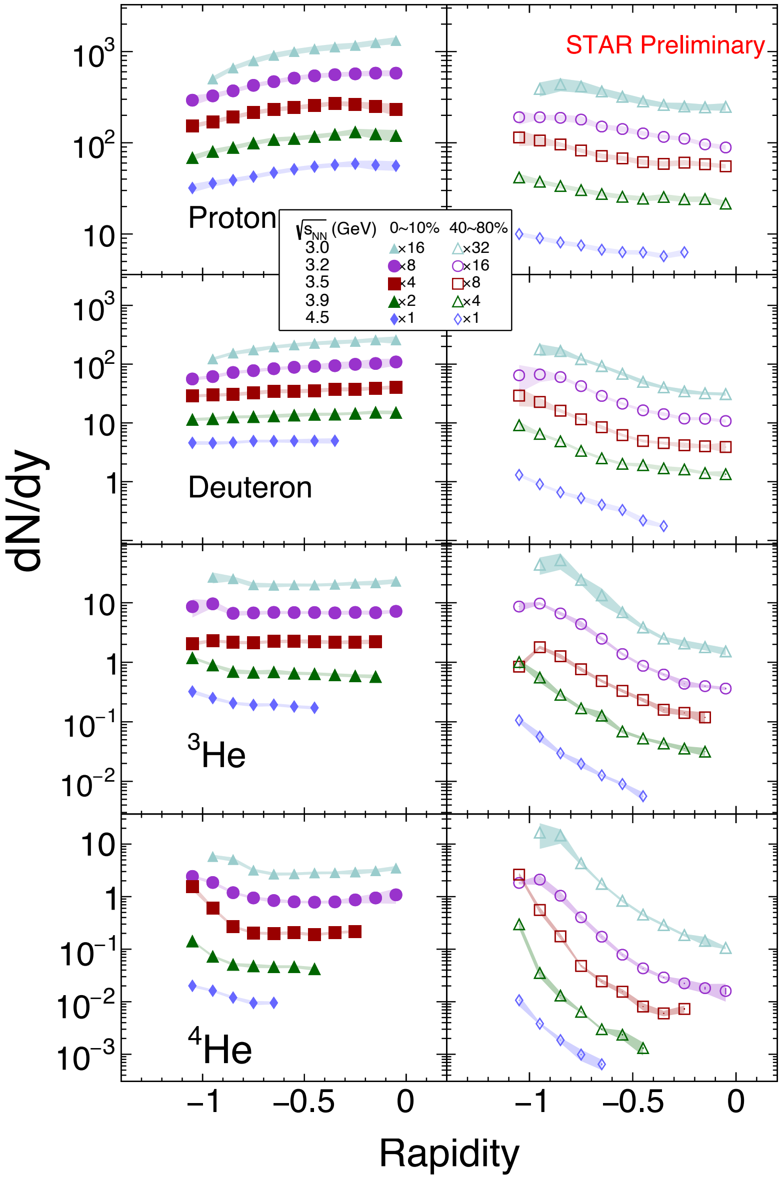
T_{kin} : kinetic freeze-out temperature
$\langle\beta_T\rangle$: average radial flow velocity

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

$$\frac{d^2N}{2\pi dp_T dy} \propto p_0 \exp\left(-\frac{p_T^2}{p_1^2}\right) + p_2 \exp\left(-\frac{p_T^2}{p_3^2}\right)$$

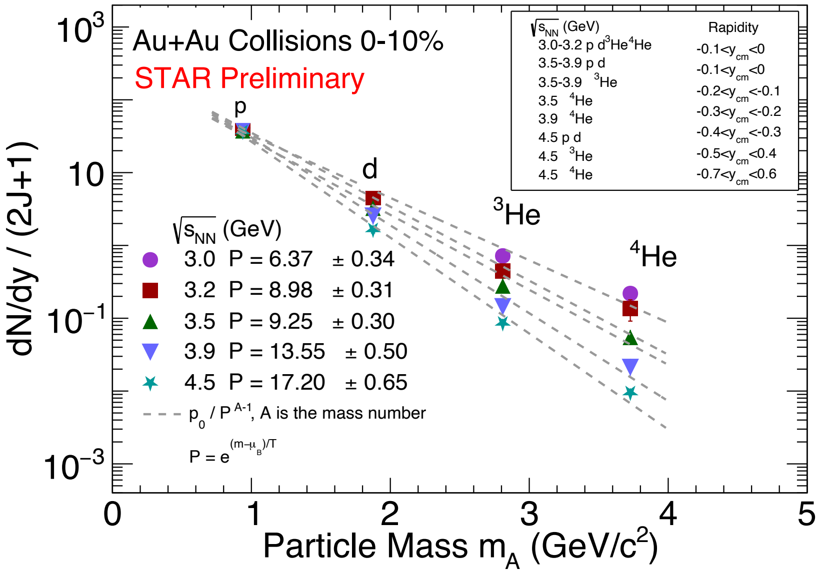
QM2025, Yixuan Jin

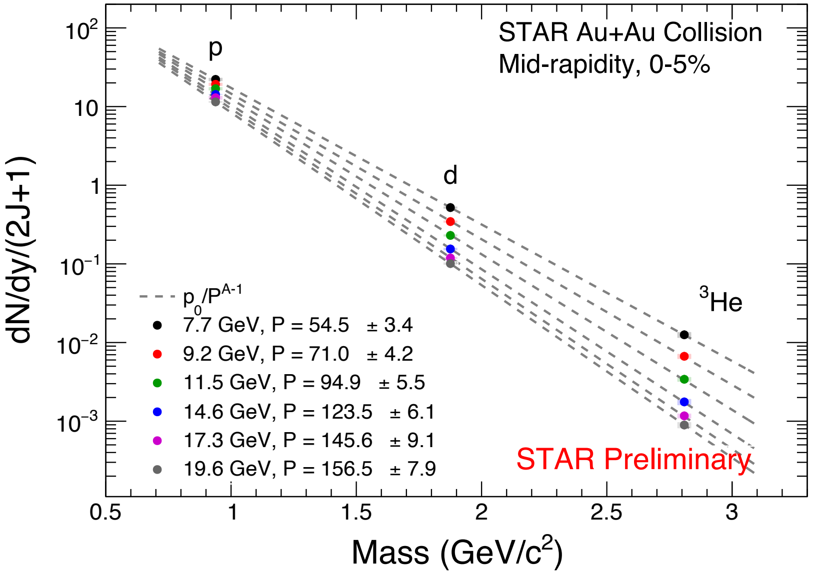
dN/dy distribution

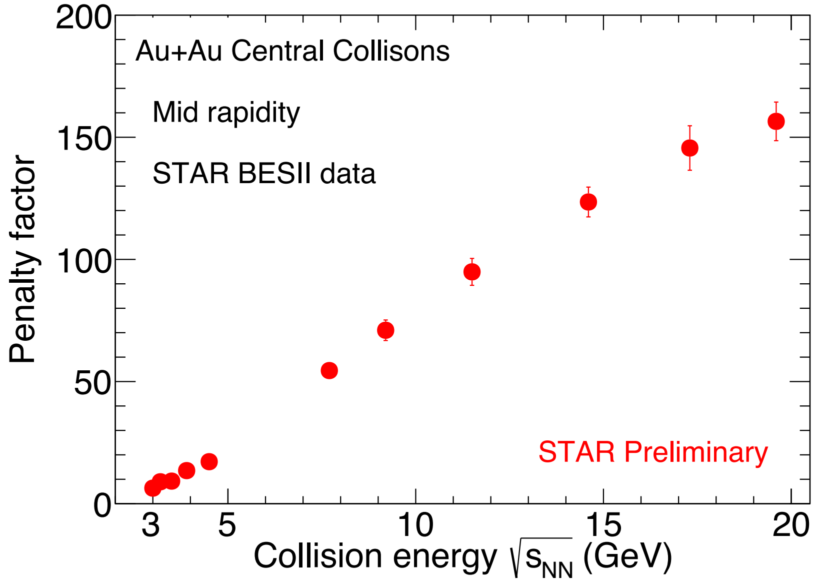


- dN/dy for proton, deuteron, triton, ^{3}He and ^{4}He in $\sqrt{s_{NN}}$ = 3-4.5 GeV with centrality and rapidity dependence.
- Light nuclei with larger mass numbers show higher dN/dy from target to mid-rapidity and central to peripheral collisions, suggesting fragment contributions to their production.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

dN/dy distribution

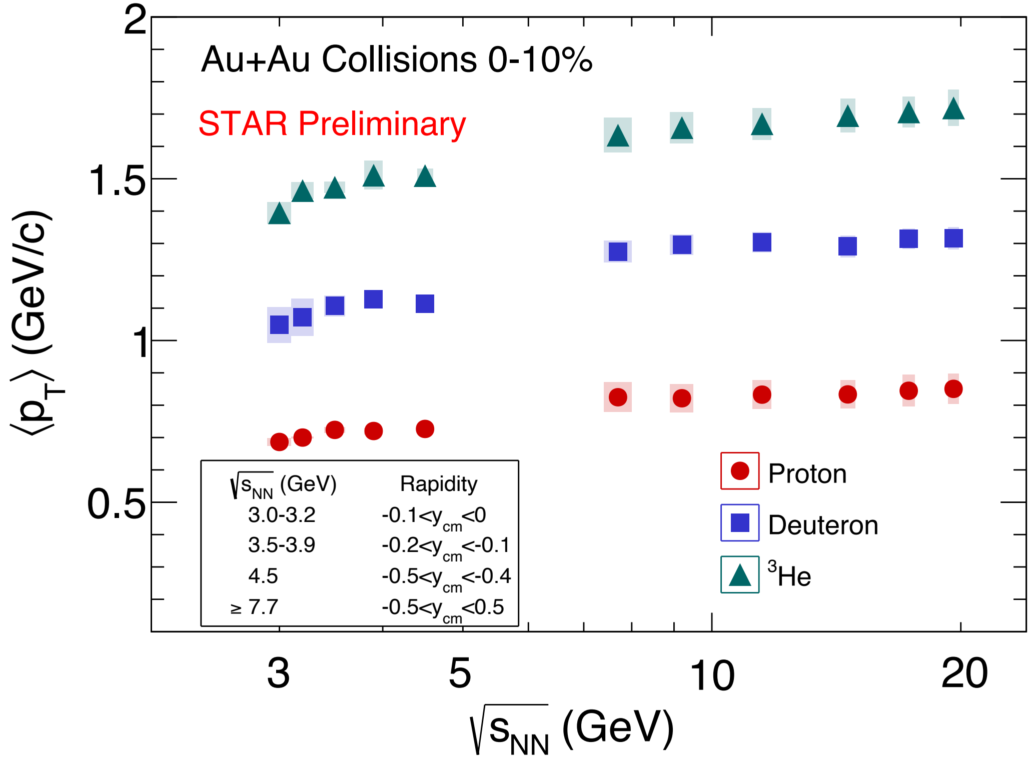


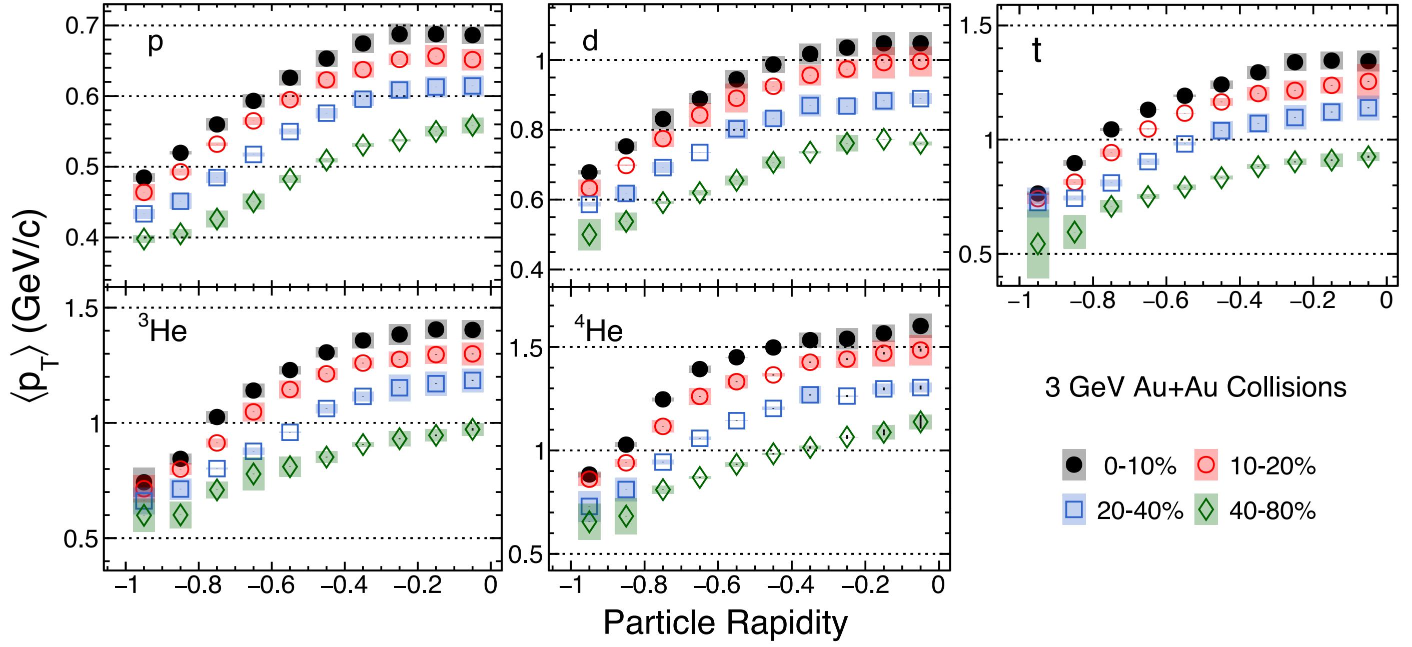




- dN/dy/(2J+1) was fit with $\frac{p_0}{P^{A-1}}$, where P is the penalty factor and determined by Boltzmann factor $e^{\frac{m-\mu_B}{T}}$. P value increases with increasing beam energy, indicating suppressed formation of high-mass objects at higher energies.

Averaged Transverse Momentum $\langle p_T \rangle$

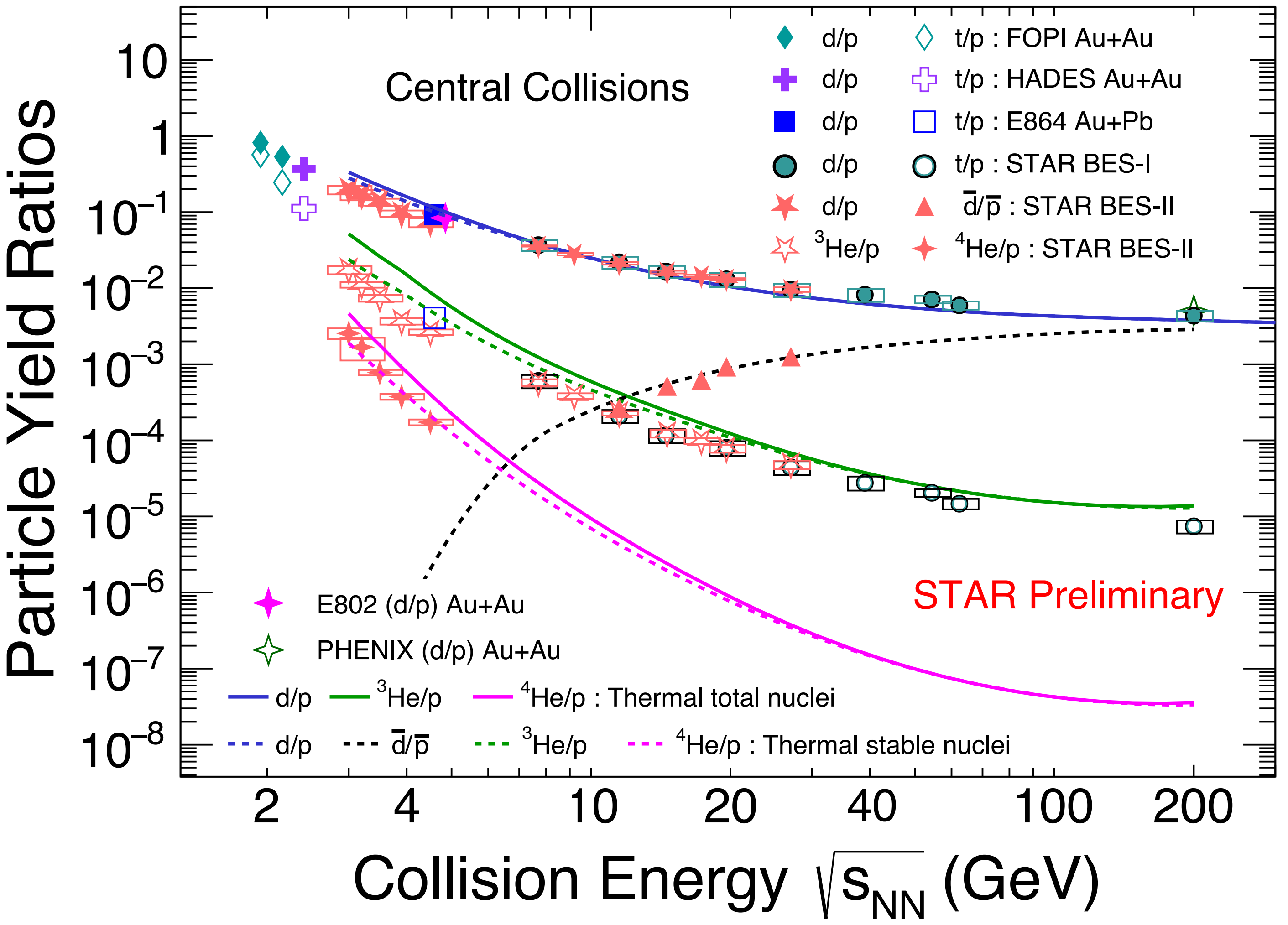




STAR Collaboration. Phys.Rev.C 110 (2024) 5, 054911

- $\langle p_T \rangle$ 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.

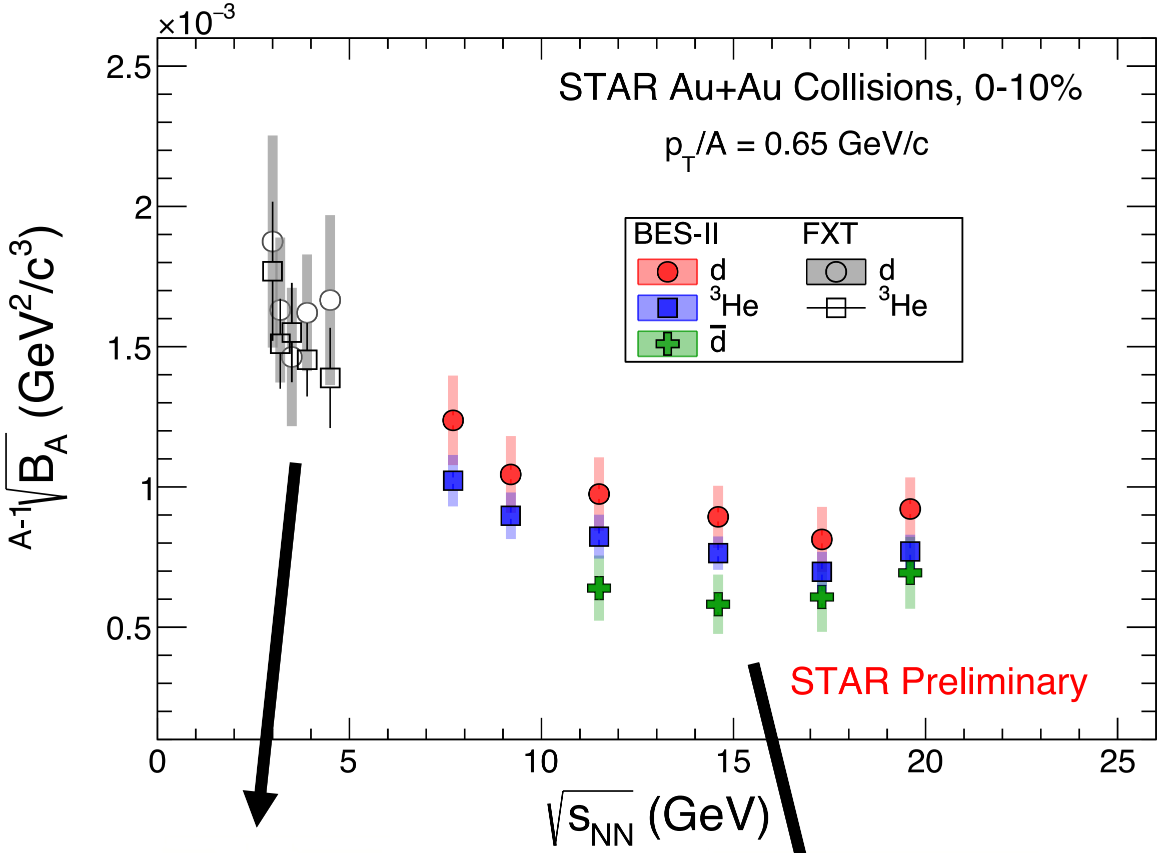
Particle Ratio

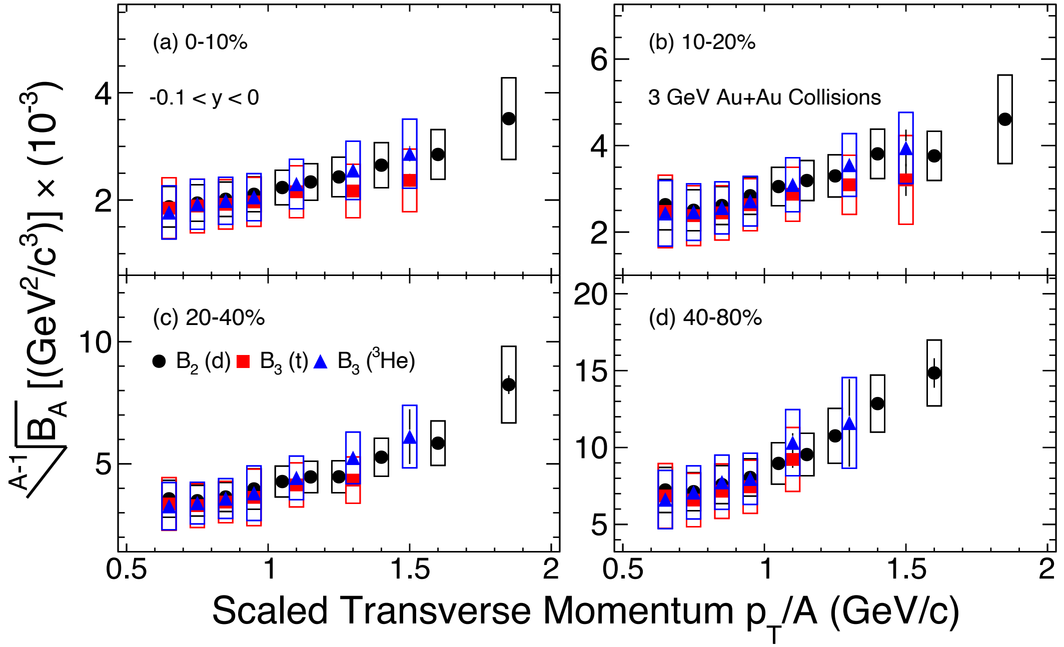


- Clear energy dependence is observed for both d/p, $\bar{d}/\bar{p}$, t/p, ^{3}He$/p$, and ^{4}He$/p$ ratios.
- The trends of ratios can be described qualitatively by the thermal model.
- ^{3}He$/p$ is overestimated by thermal model, possibly due to the hadronic re-scattering effect.
- Considering only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





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

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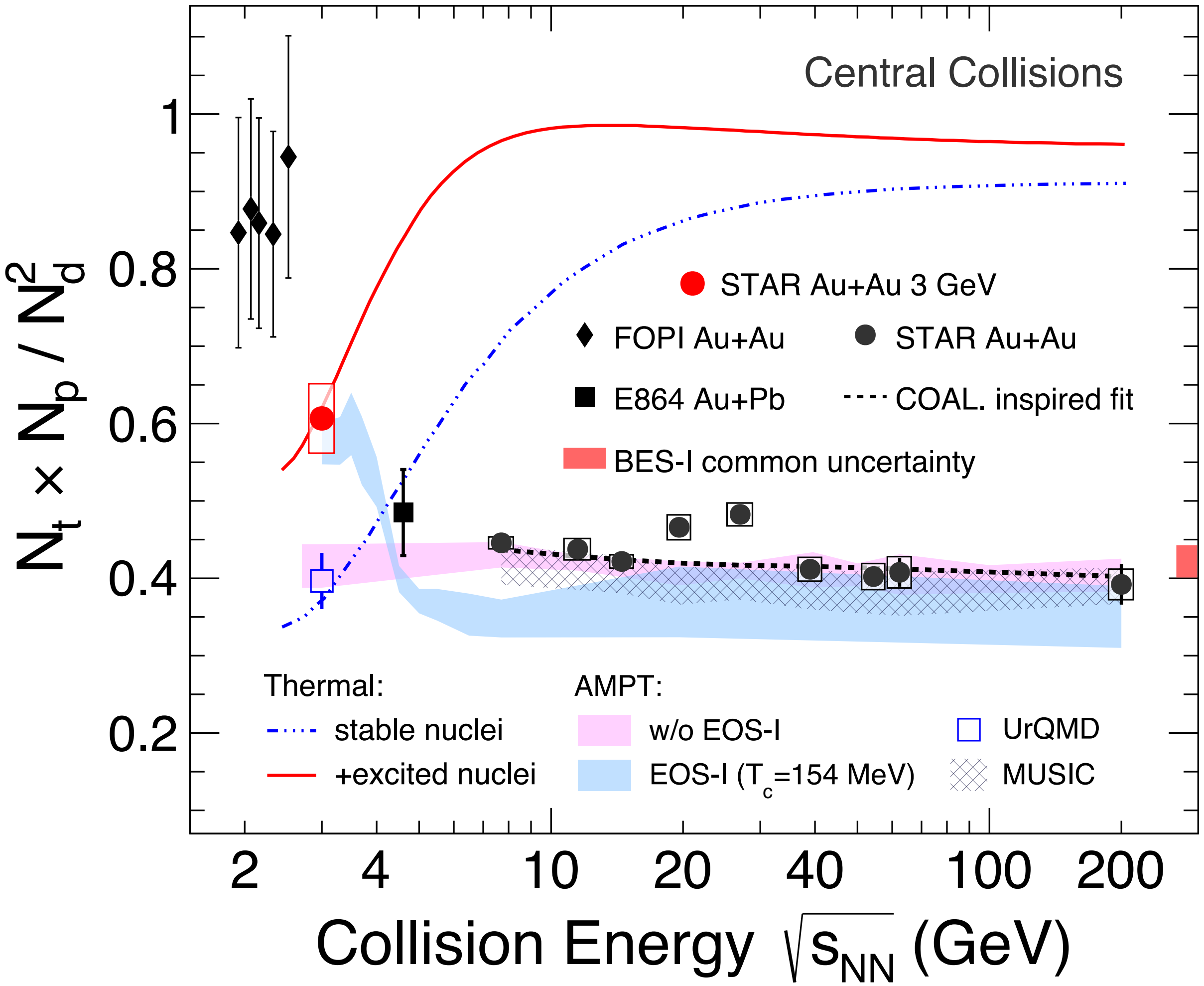
R. Scheibl and U. Heinz Phys.Rev.C 59 (1999) 1585-1602; S. Zhang et al. Phys.Lett.B 684 (2010) 224-227

Compound Ratio



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

Δn: Neutron Density Fluctuation

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

- Energy dependence of $\frac{N_t \times N_p}{N_d^2}$ in most central Au+Au collisions.
- AMPT model employing a first order phase transition with input critical temperature of 154 MeV can reproduced 3 GeV yield ratio.
- $\sqrt{s_{NN}}$ = 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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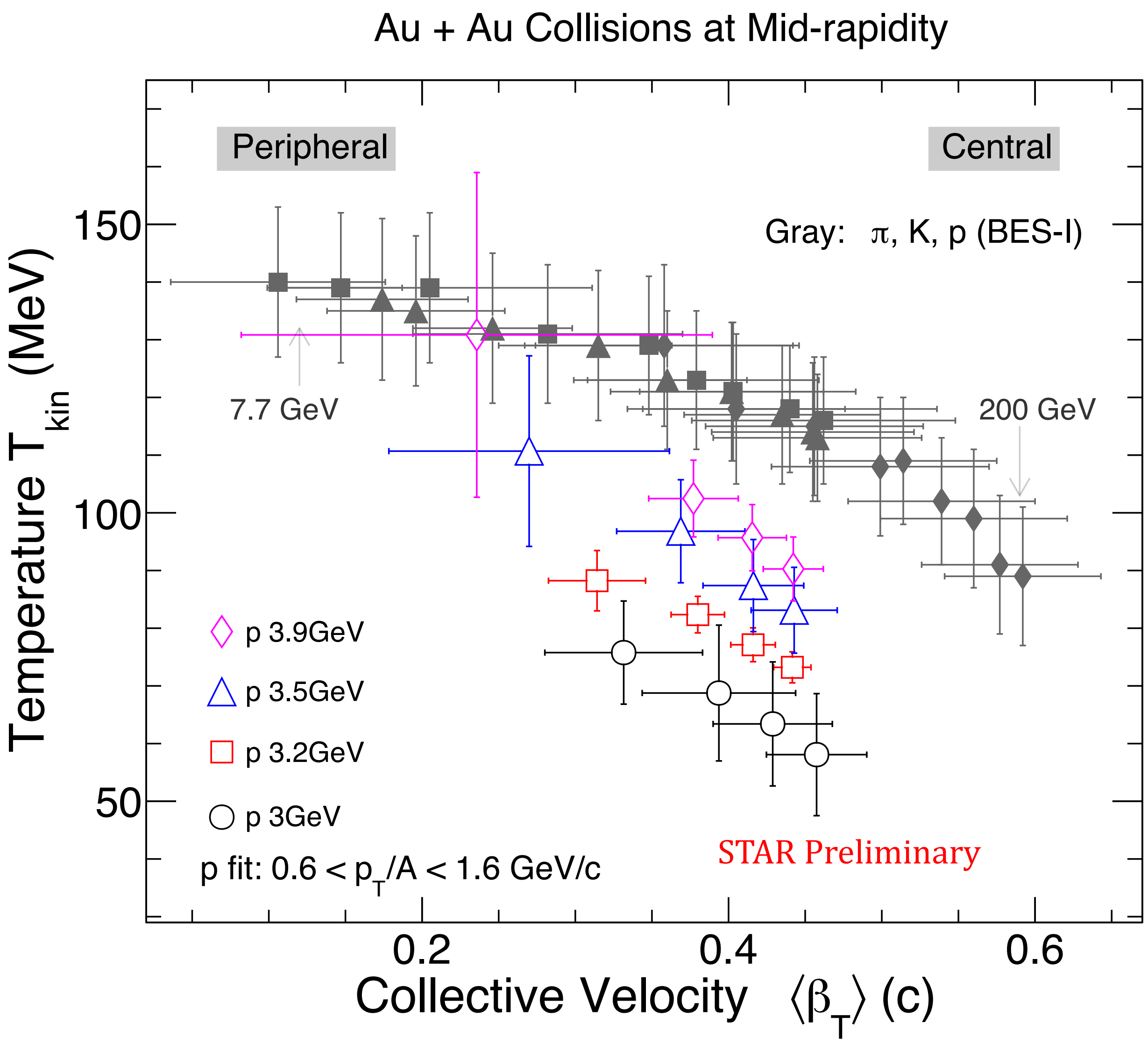
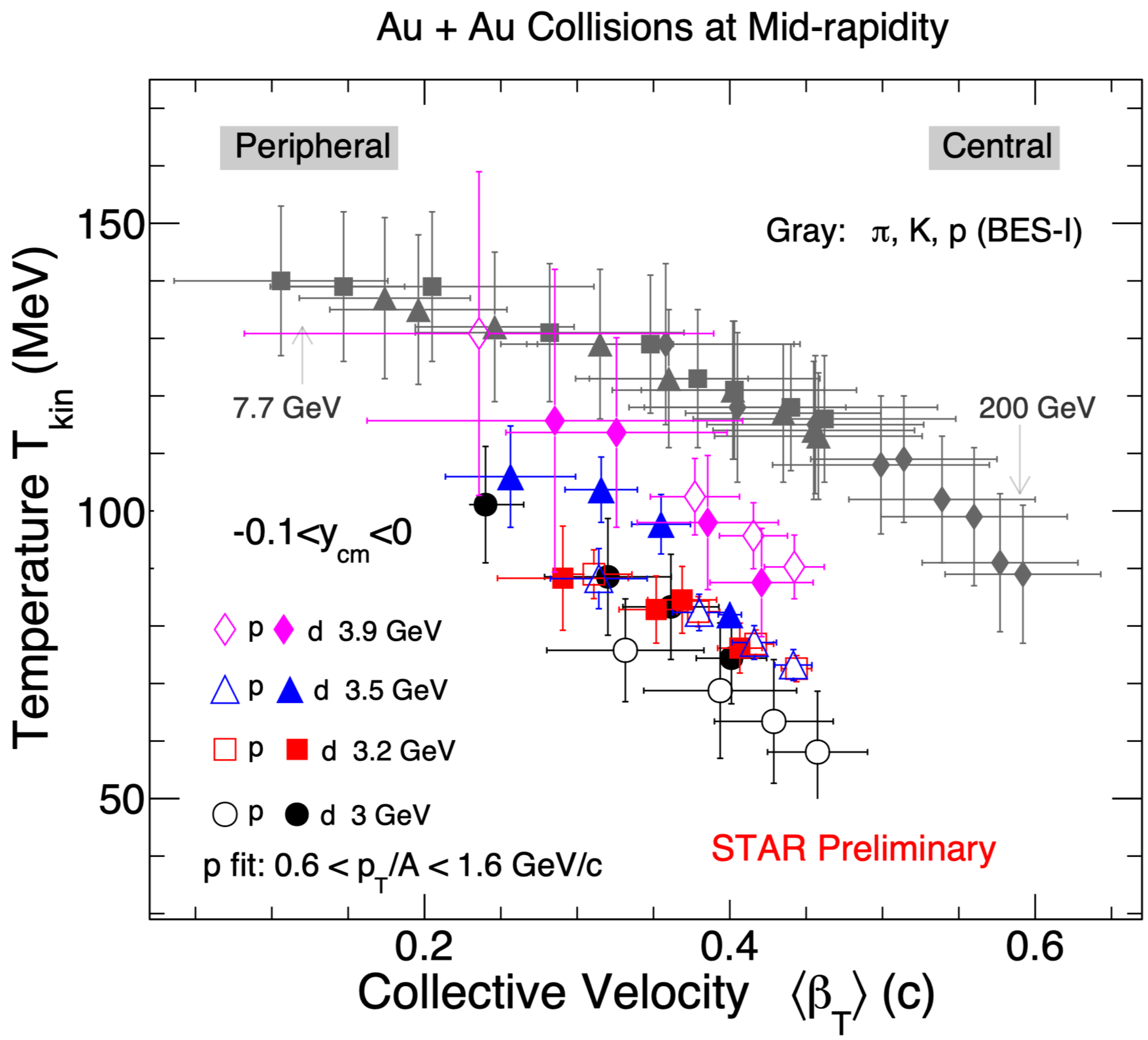
Kinetic Freeze-out Dynamics



➢For $\sqrt{s_{NN}}$ = 3.0-3.9 GeV, proton T_{kin} increases with energy while $<\beta_T>$ 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



- 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, $< p_T >$, 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, while ^3He/p ratio is overestimated at all energies and is consistent with ^4He/p only considering stable nuclei .

✓ The extracted kinetic freeze-out parameters (T_{kin}, $< \beta_T >$) 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 ^{4}He production in $\sqrt{s_{NN}} \geq 7.7$ GeV to gain more insight on $N_{^4\mathrm{He}} \times N_p / (N_{^3\mathrm{He}} \times N_d)$ and production mechanism.

Thank you