Light Nuclei Production in RHIC-STAR BES-II Program

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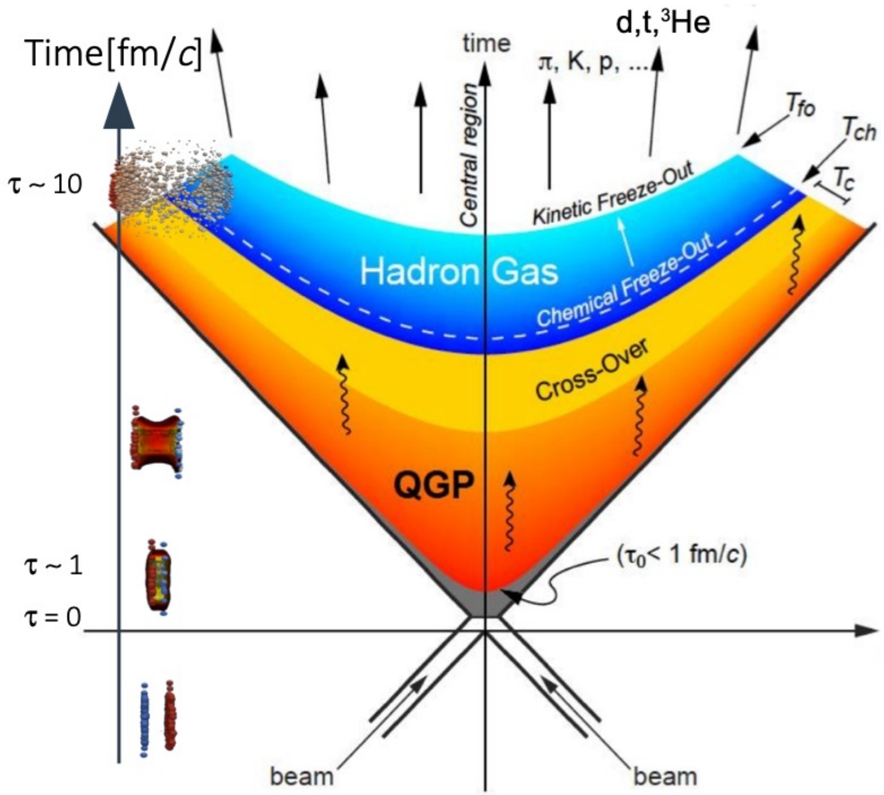
Outline

- 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

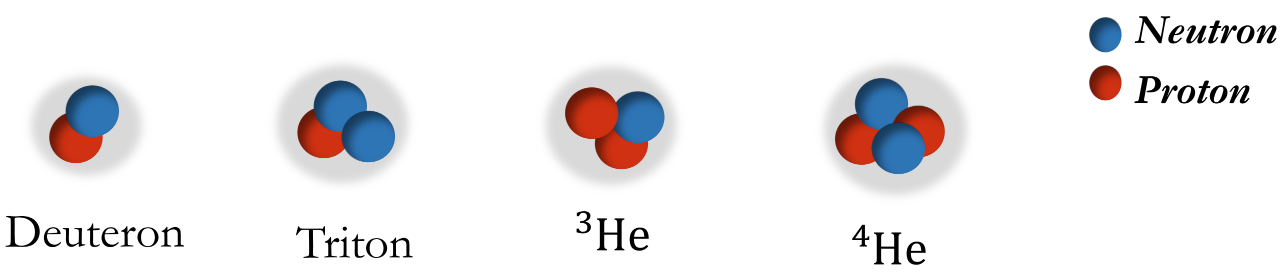


➢ Chemical Freeze-out

Hadron composition fixes.

➢ 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**

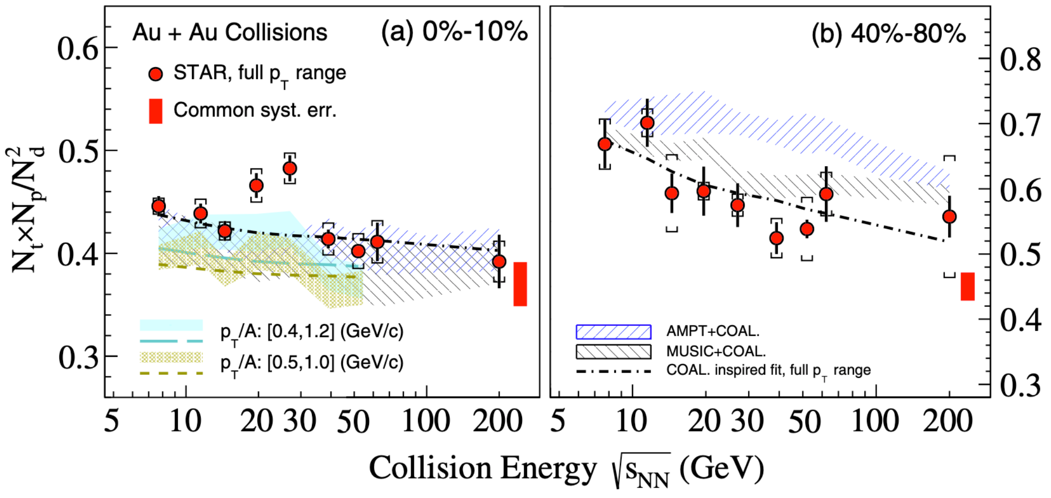
Assumes that light nuclei are produced by the coalescence of nucleons in the late-stage evolution of the hadron gas.

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

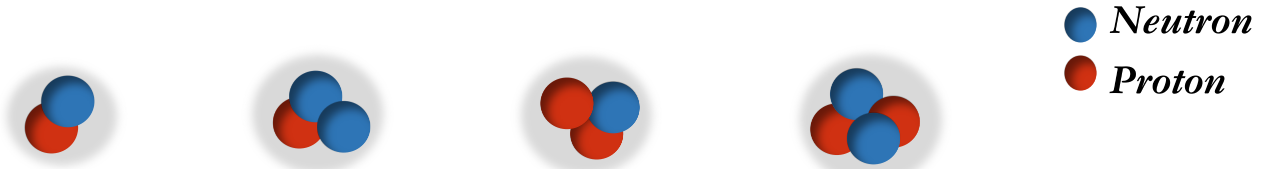
K. J. Sun et al., Phys. Lett. B 792, 132-137 (2019)

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.**



Deuteron Triton ^{3}He ^{4}He

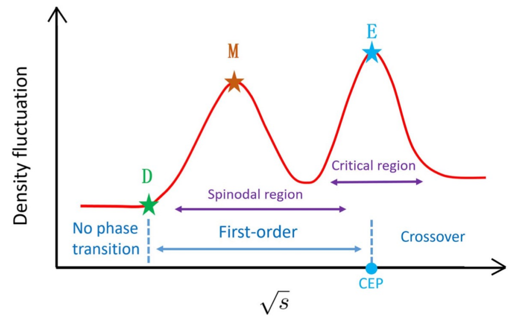
- **Light Nuclei Compound Yield Ratio**

Sensitive Observations for Searching Critical Point and 1st order boundary

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

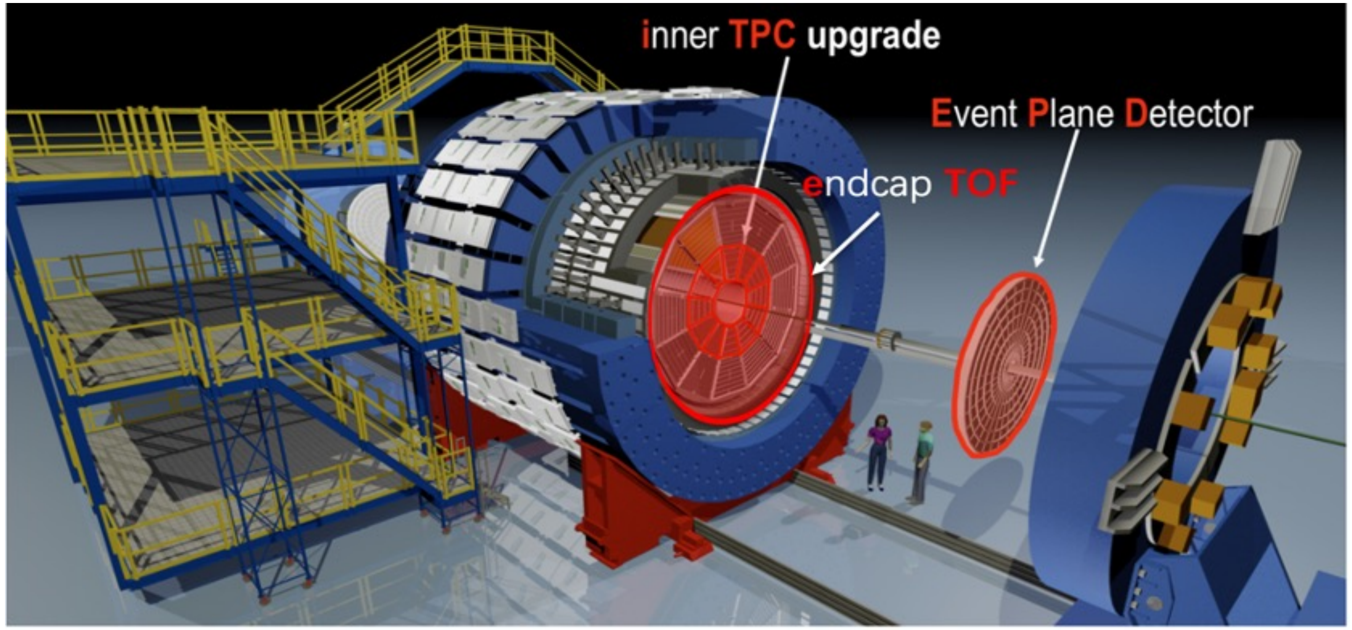
Δn: Neutron Density Fluctuation

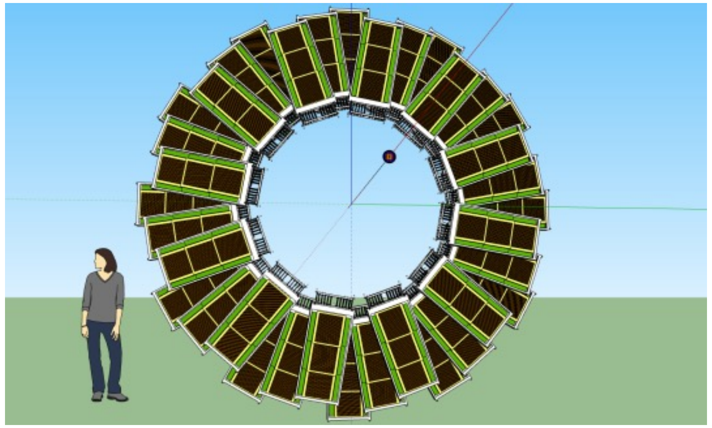
$G(\frac{\xi}{\sigma})$: Long-range Correlation



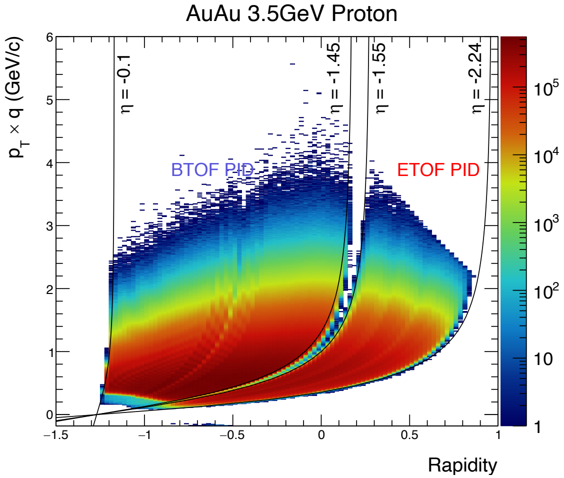
K.J. Sun et al, Phys.Lett.B 781 (2018) 499-504;
K.J. Sun et al, Phys.Lett.B 816 (2021) 136258

STAR Detector





Full ETOF wheel



Proton acceptance in BTOF/ETOF

➢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, $p_T > 60$ MeV/c.
- eTOF
  - at the east end of STAR, $-2.15 < \eta < -1.55$

➢ Fixed target mode

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

μ_B: 750-280 MeV

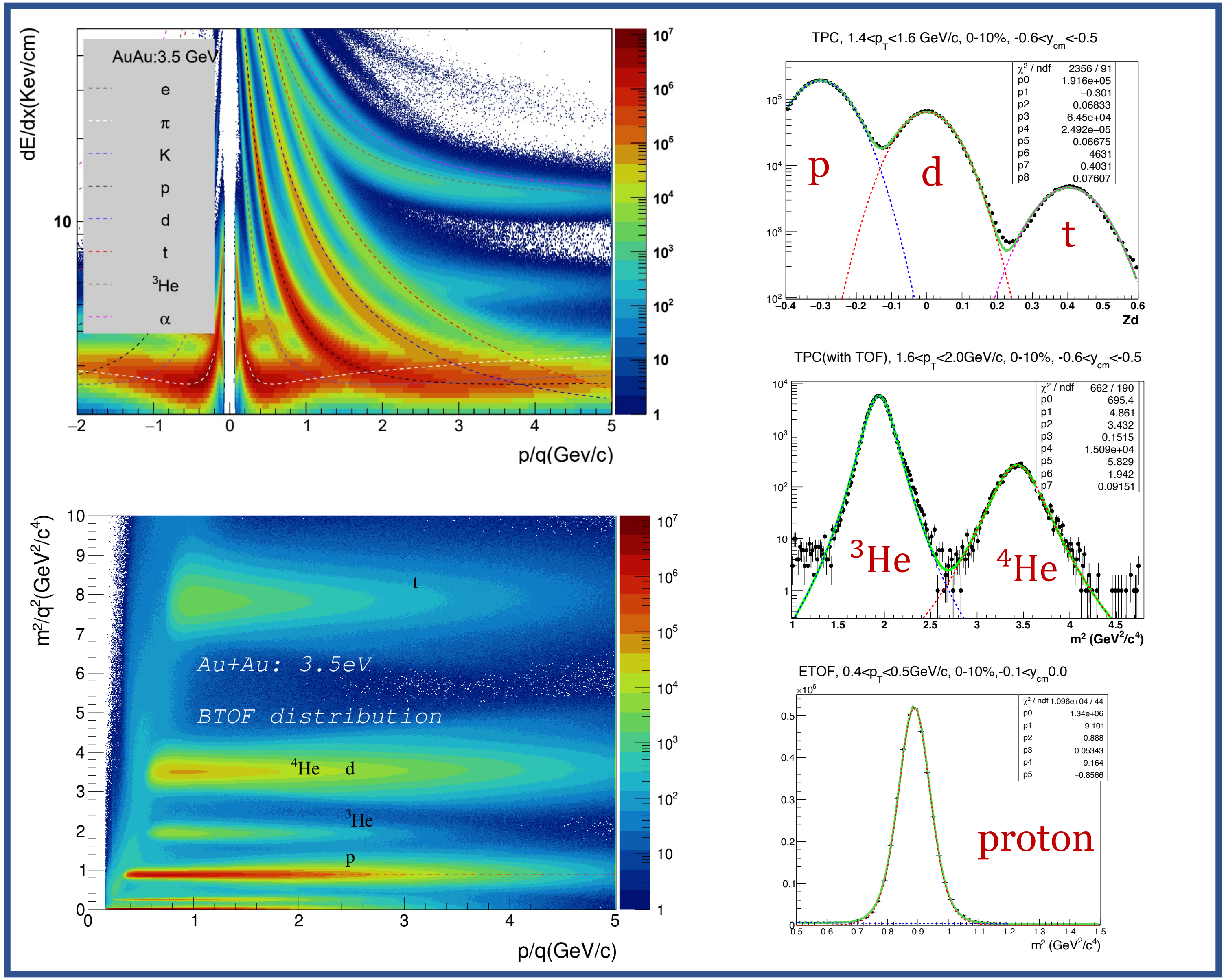
➢ Collider mode

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

μ_B: 420-156 MeV

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

Signal Extraction



- TPC(low p_T):
  - Signal(red/Magenta): Gaussian function

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

  - Background(blue): Gaussian

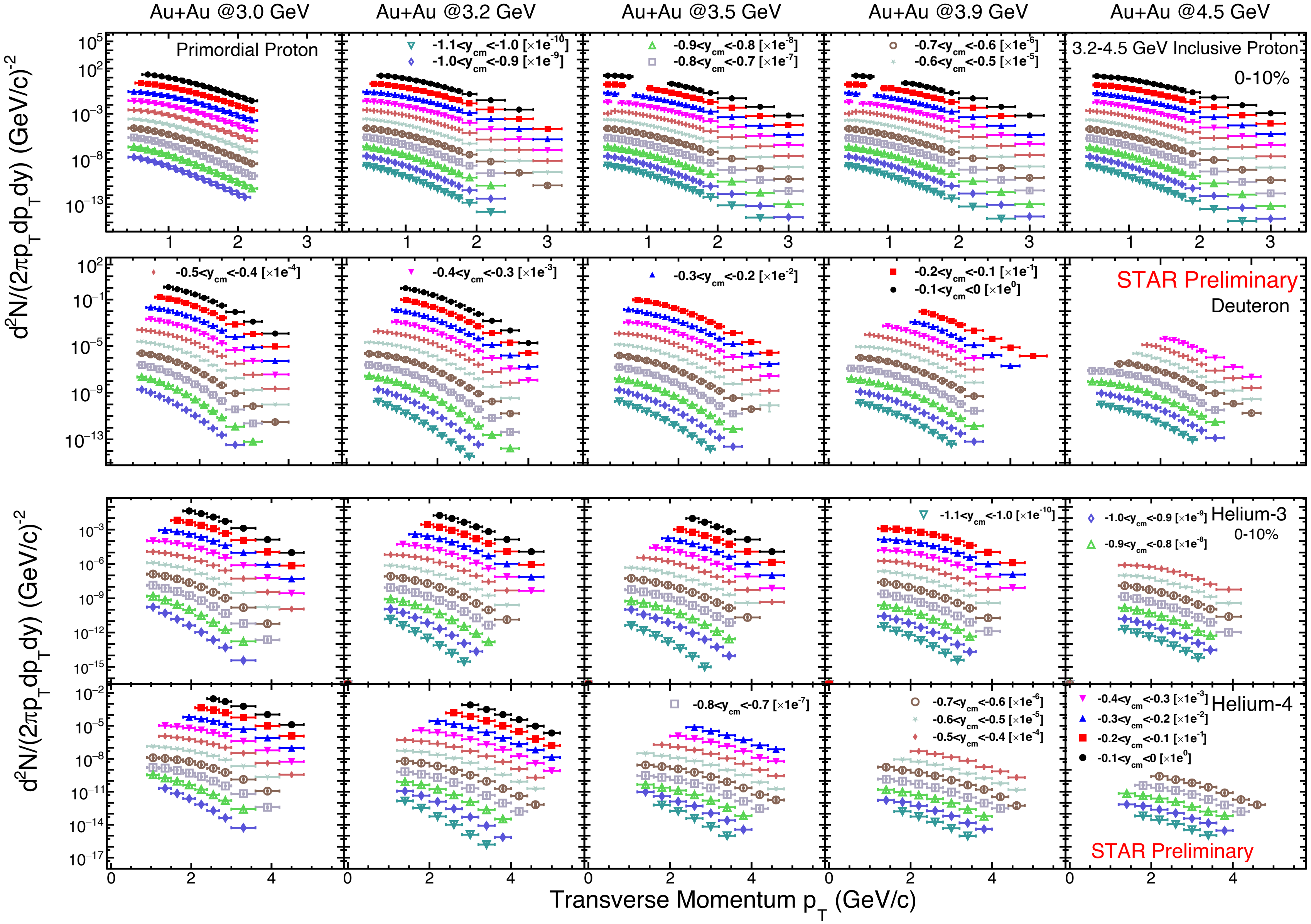
- TPC with TOF (high p_T):
  - Signal: Student-t function

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

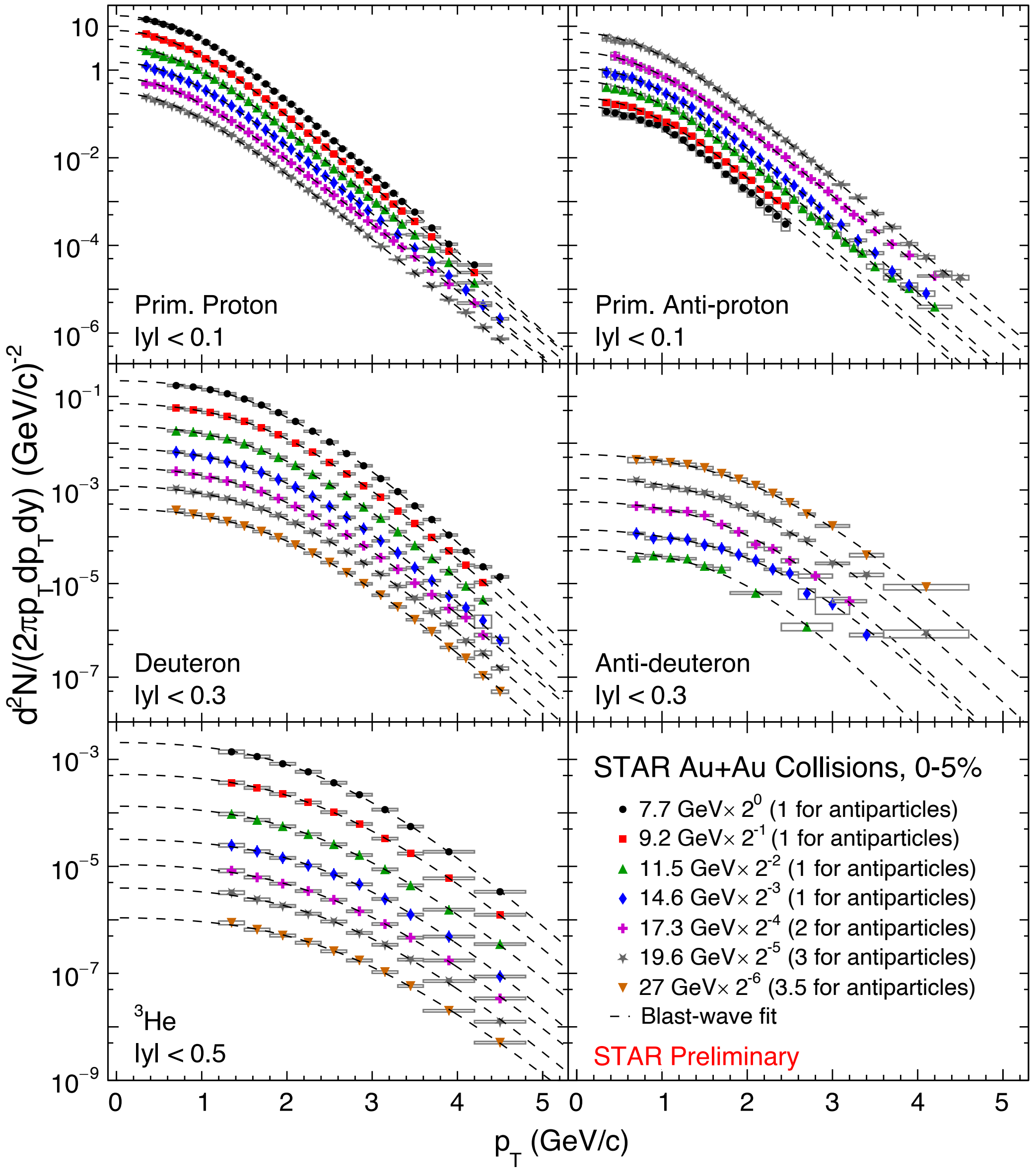
$$t = (\frac{m^2 - p_2}{p_3})^2$$

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

Transverse Momentum Spectra



Transverse Momentum Spectra



- Default fit function(Blastwave):

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

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

Kinetic Freeze-out Parameters:

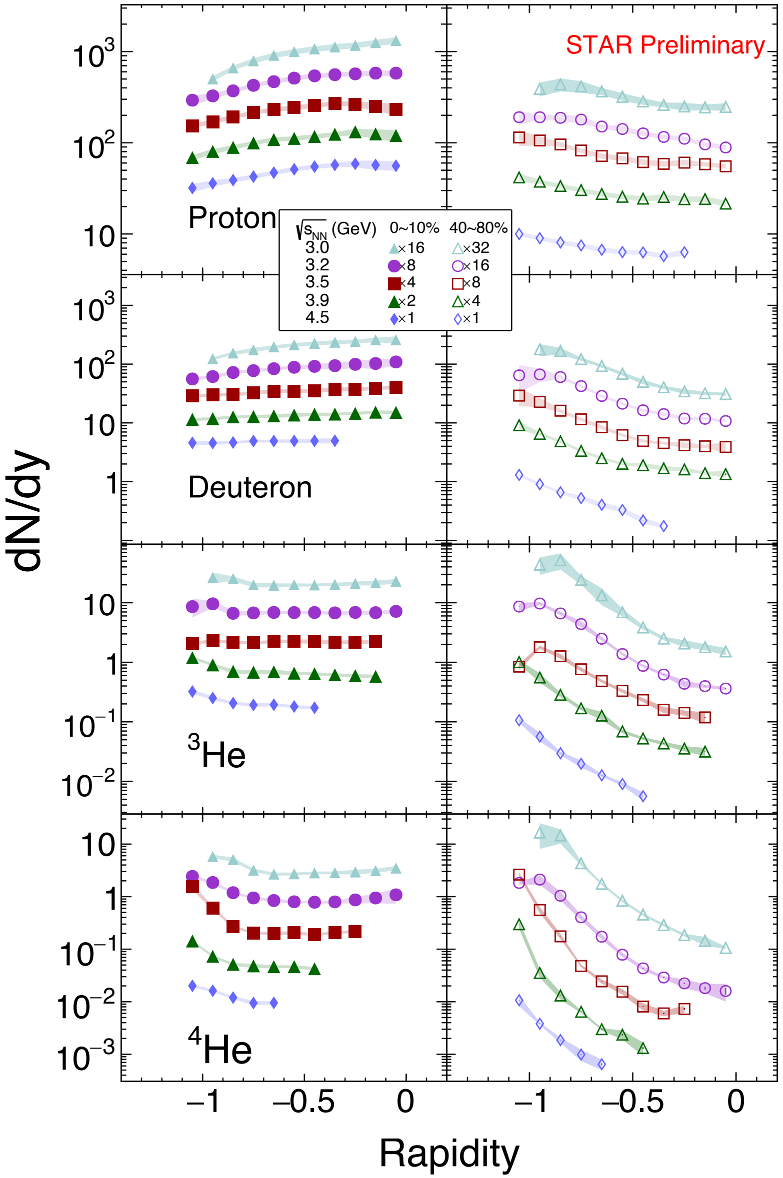
T_{kin} : kinetic freeze-out temperature
$\langle\beta_T\rangle$: average radial flow velocity

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

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

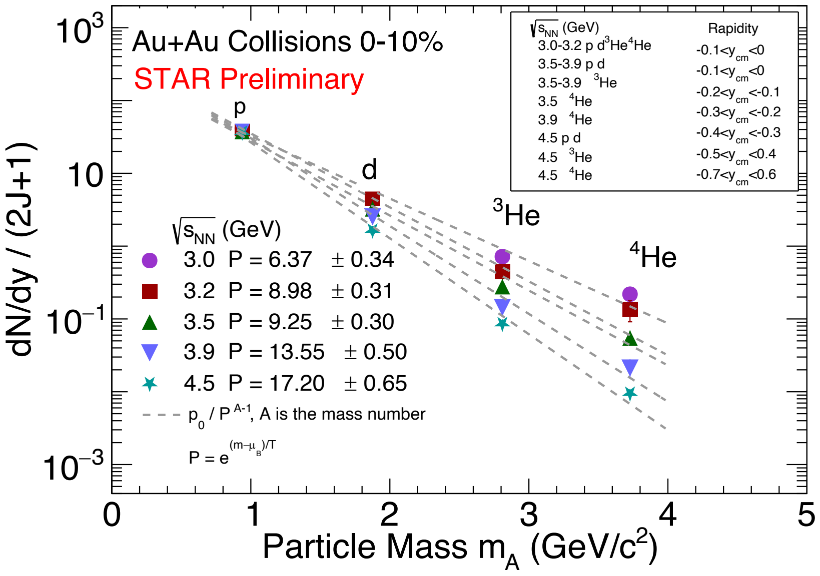
QM2025, Yixuan Jin

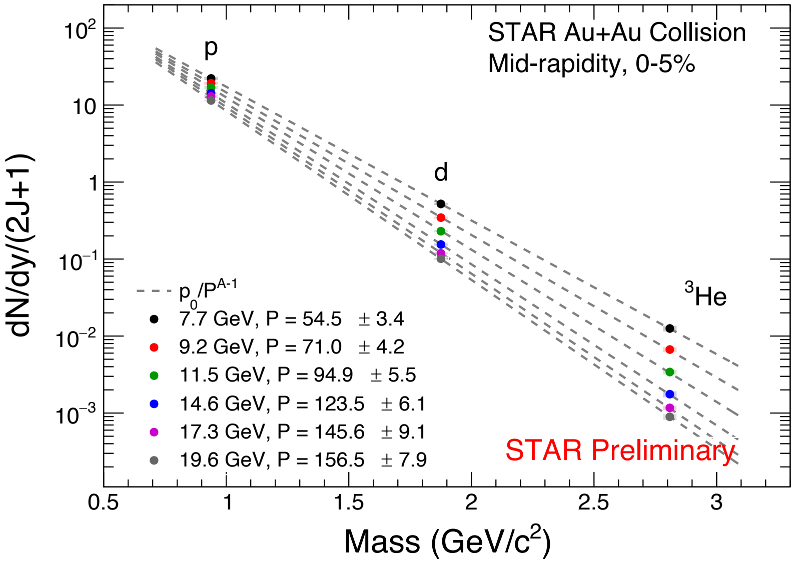
dN/dy distribution

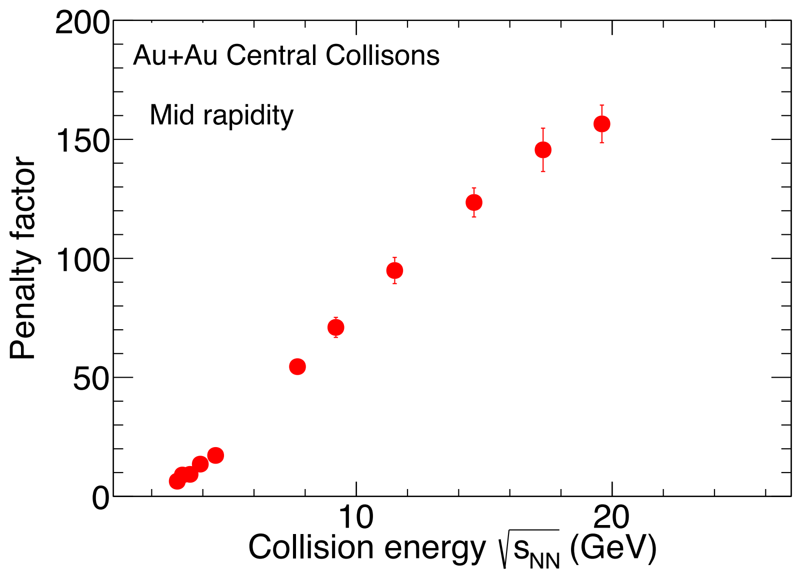


- dN/dy for proton, deuteron, triton, ^{3}He and ^{4}He in $\sqrt{s_{NN}}$ = 3-4.5 GeV with centrality and rapidity dependence.
- Light nuclei with larger mass numbers show higher dN/dy from target to mid-rapidity and central to peripheral collisions, suggesting fragment contributions to their production.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

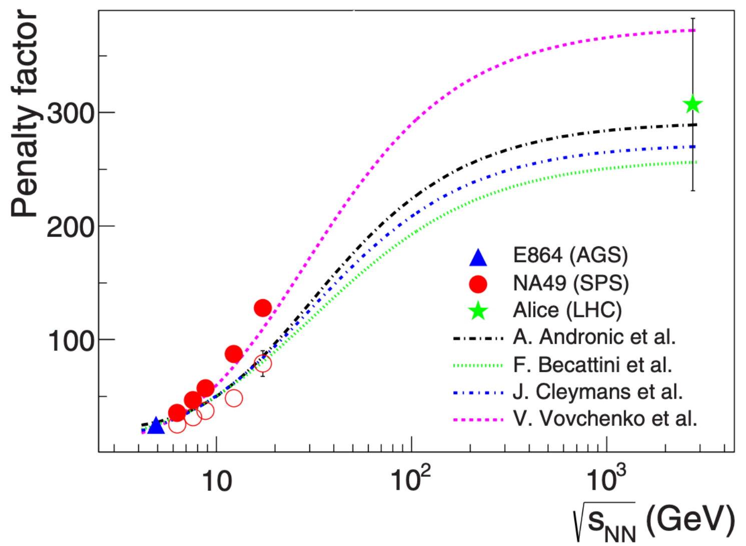
dN/dy distribution





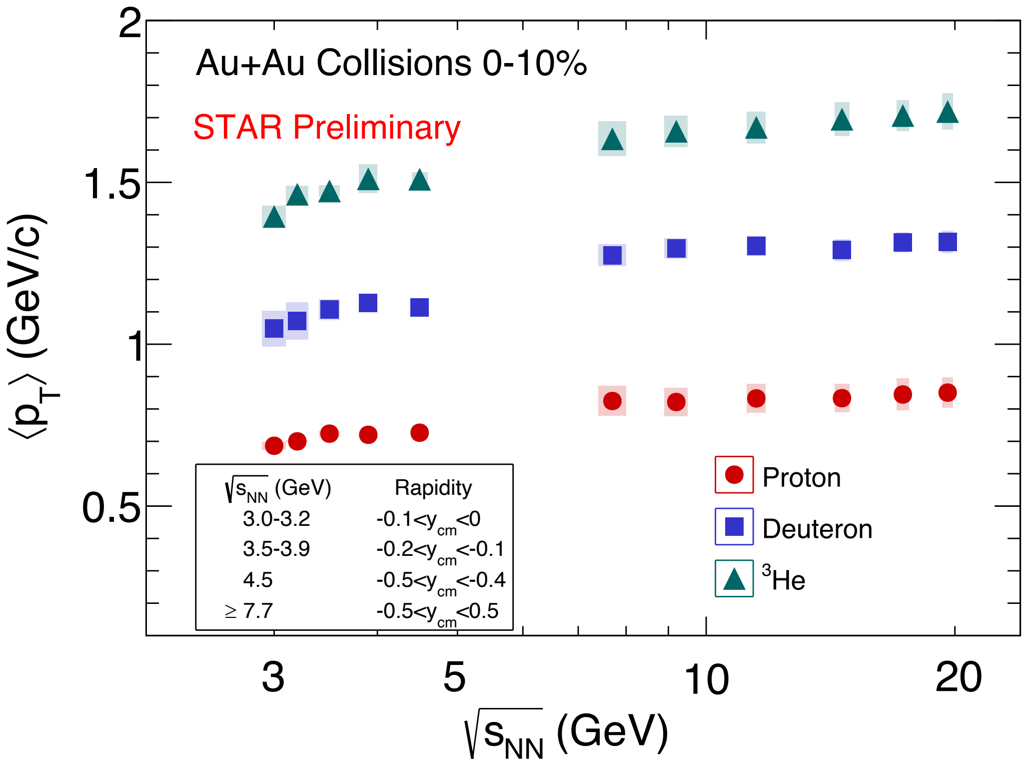


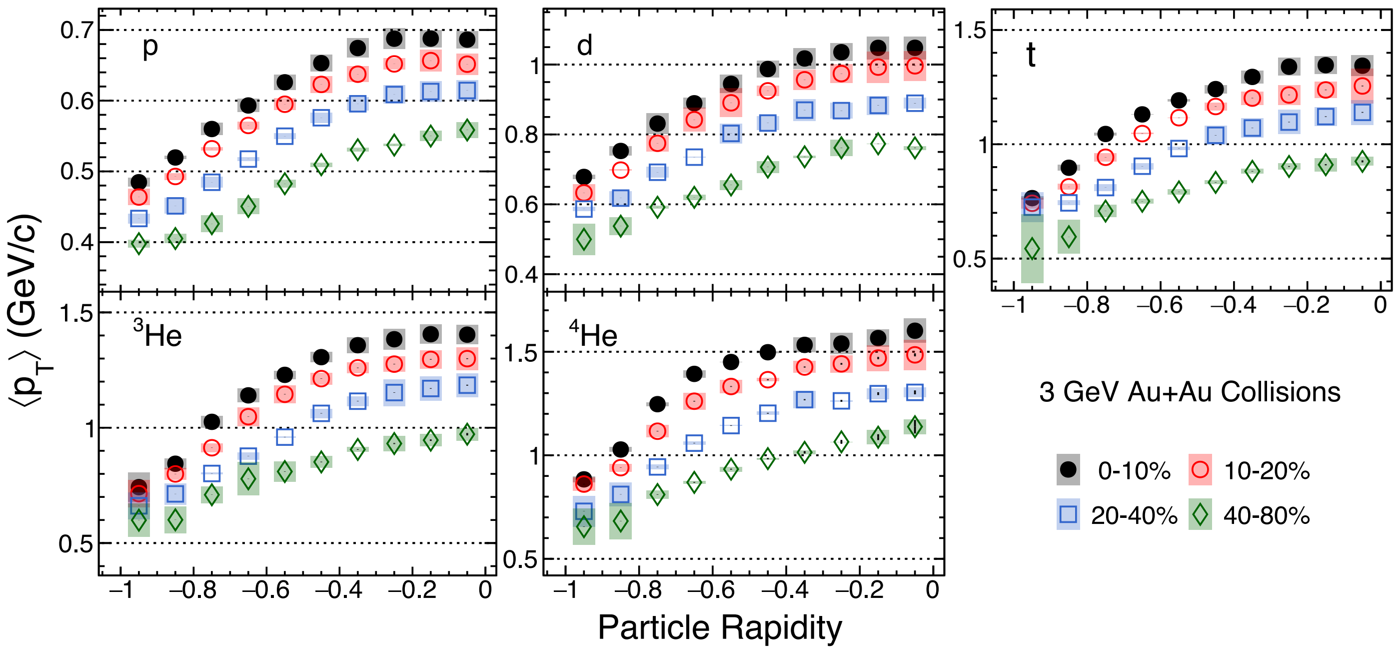
- ➢ dN/dy/(2J+1) was fit with $\frac{p_0}{P^{A-1}}$, where P is the penalty factor and determined by Boltzmann factor $e^{\frac{m-\mu_B}{T}}$. P value increases with increasing beam energy, indicating suppression formation of high-mass objects at higher energies.



[NA49 Collaboration]PHYSICAL REVIEW C 94, 044906 (2016)

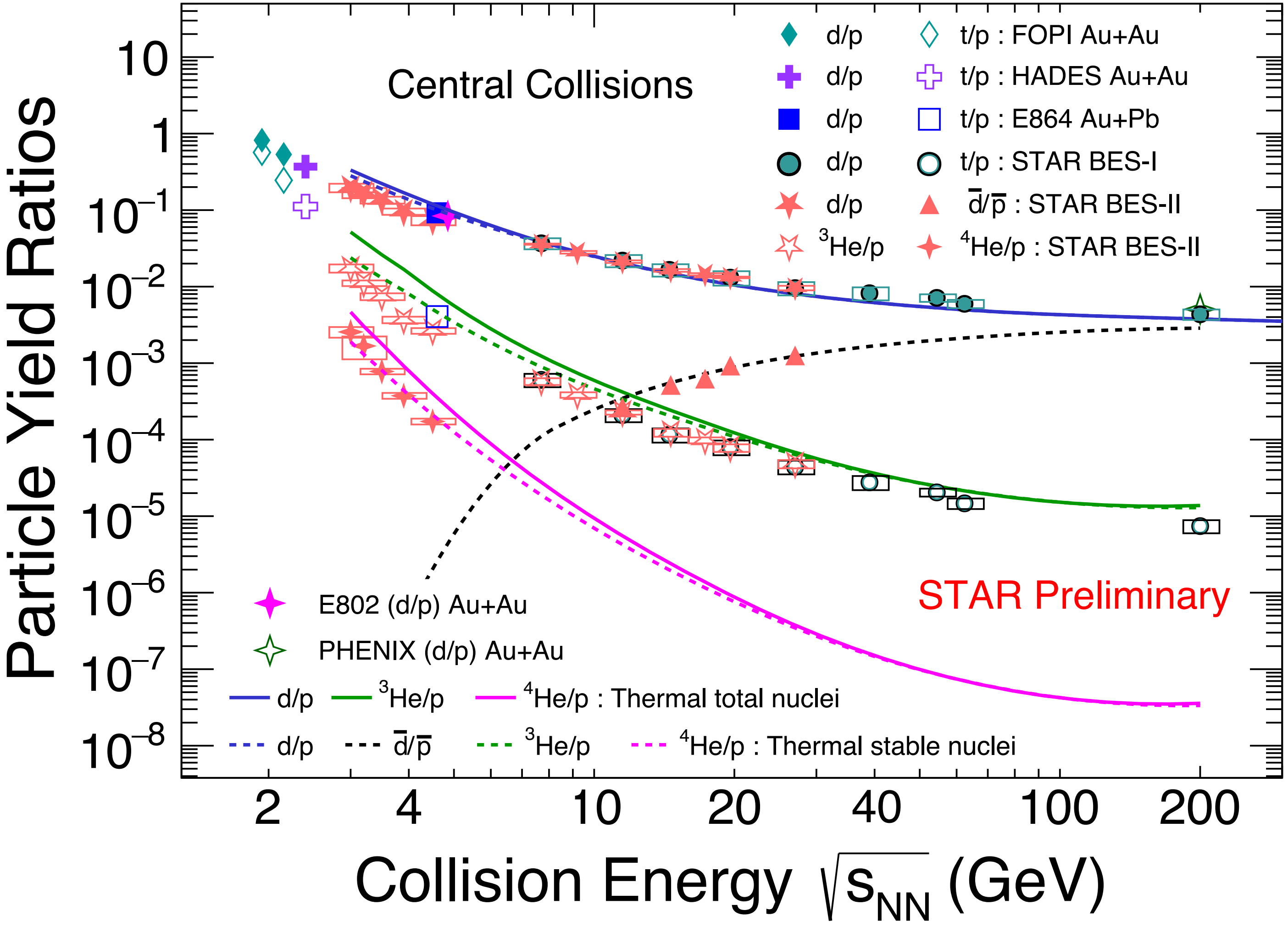
Averaged Transverse Momentum ⟨p_T⟩





- ➢ $\langle p_T \rangle$ 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 studied in 4.5 - 7.7 GeV in the future.

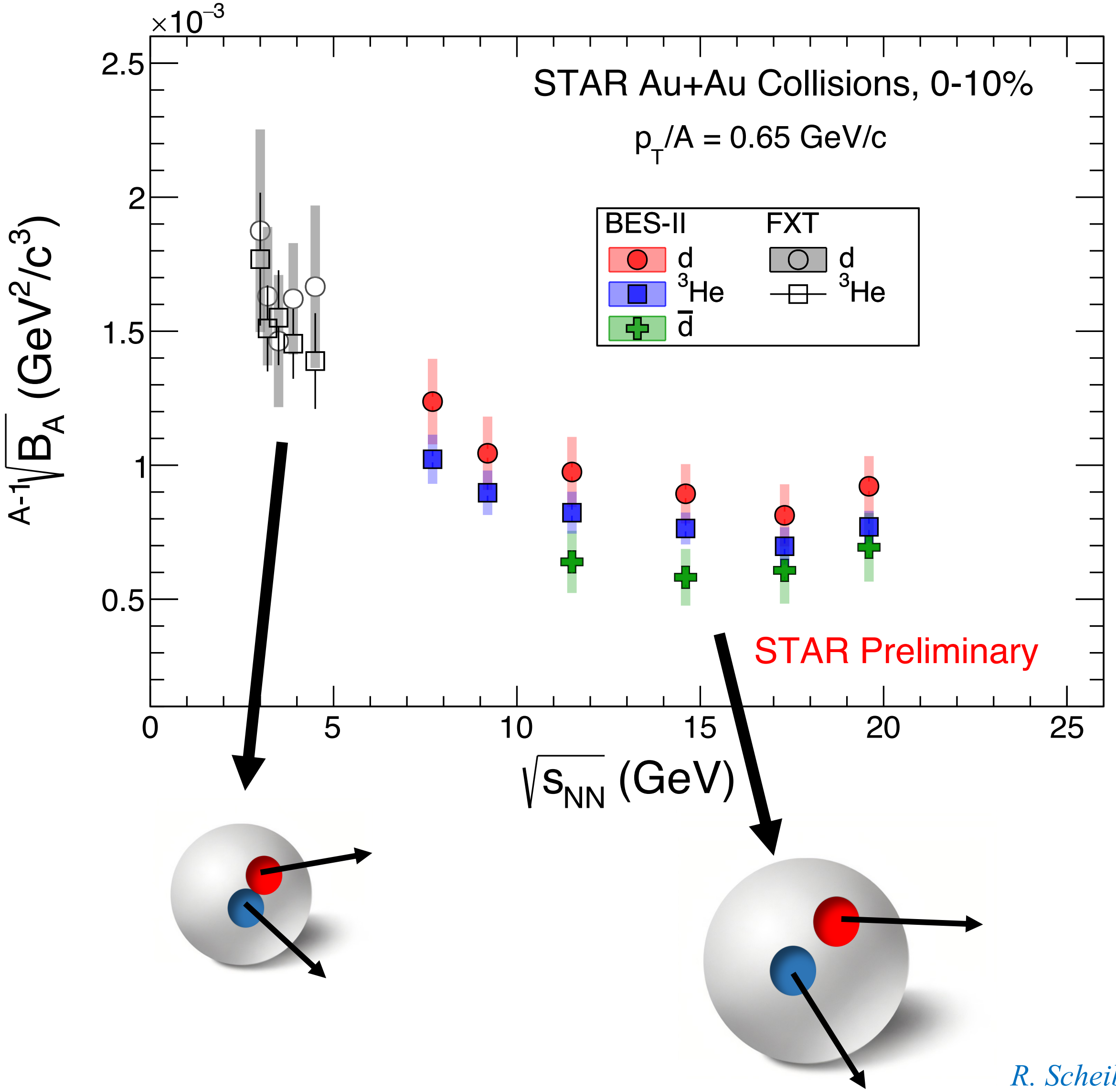
Particle Ratio

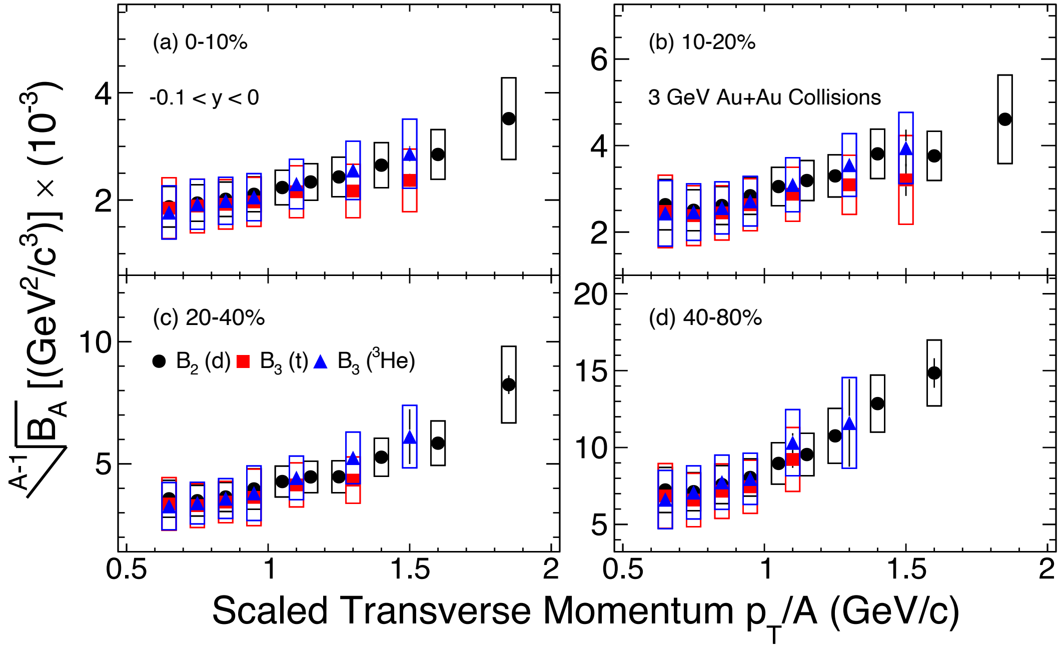


- Clear energy dependence is observed for both d/p, $\bar{d}/\bar{p}$, t/p, $^3\mathrm{He}/p$, and $^4\mathrm{He}/p$ ratios.
- The trends of ratios can be described qualitatively by the thermal model.
- $^3\mathrm{He}/p$ were overestimated by thermal model, possibly due to the hadronic re-scattering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





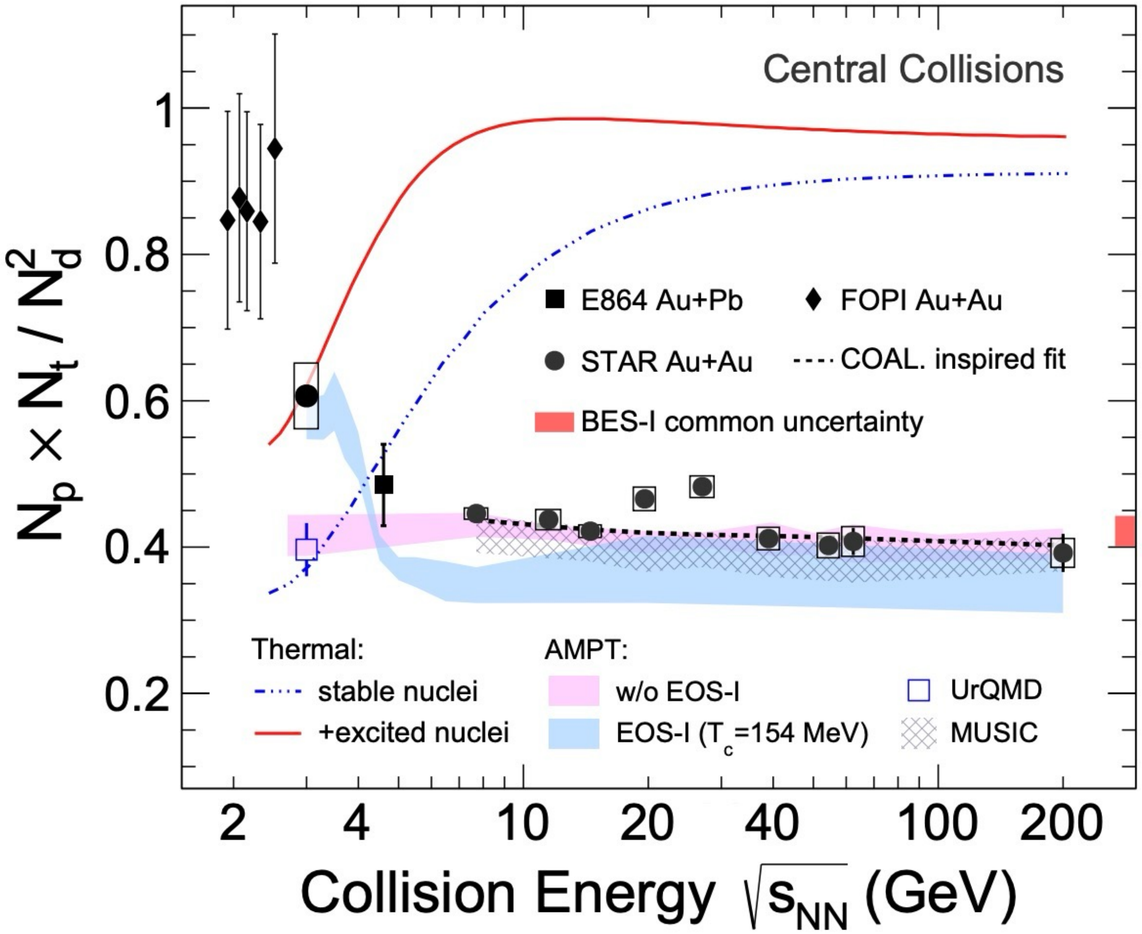
- $E_A \frac{d^3N_A}{d^3p_A} = B_A (E_p \frac{d^3N_p}{d^3p_p})^Z (E_n \frac{d^3N_n}{d^3p_n})^{A-Z} \approx B_A \left(E_p \frac{d^3N_p}{d^3p_p}\right)^A, B_A \propto \left(\frac{1}{V_{eff}}\right)^{(A-1)}$

  V_{eff} is the effective volume of a nucleon.

- As the energy and momentum increases, B_A becomes smaller, reflecting that the effective volume of the system becomes larger.
- $B_A \propto (1/V_{eff})^{(A-1)}$ reflects the region of homogeneity and the freeze-out property.
- Length of homogeneity becomes smaller in peripheral collisions and at higher p_T region.

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



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

Δn: Neutron Density Fluctuation

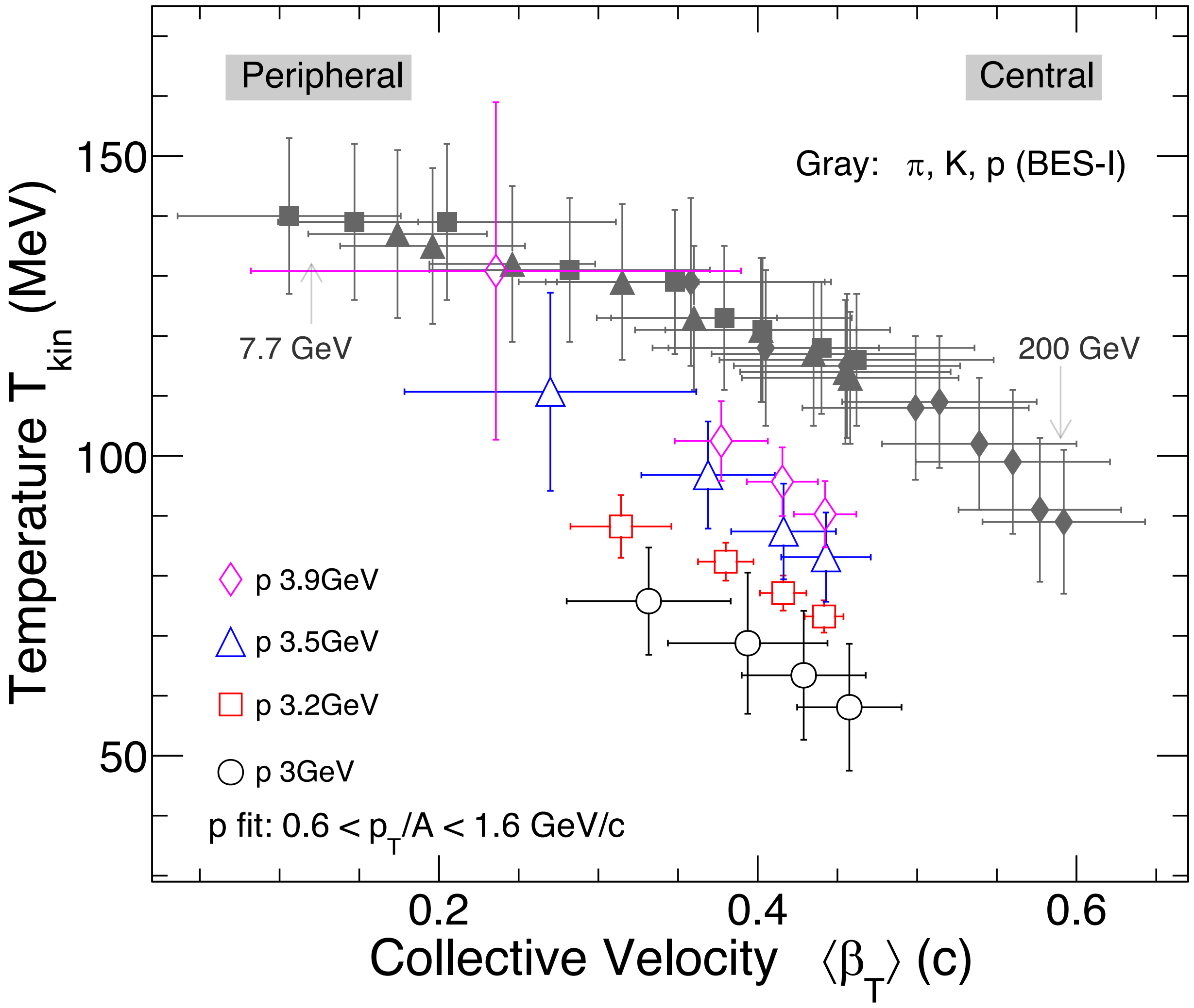
$G\left(\frac{\xi}{\sigma}\right)$: Long-range Correlation

- Energy dependence of $\frac{N_t \times N_p}{N_d^2}$ in most central Au+Au collisions.
- AMPT model with employing a first order phase transition by input the critical temperature of 154 MeV would reproduced 3 GeV yield ratio.
- $\sqrt{s_{NN}}$ = 3.2-27 GeV compound ratio is in progress.

K. Sun et al. Phys.Rev.C 103 (2021) 6, 064909
STAR Collaboration. Phys.Rev.C 110 (2024) 5, 054911

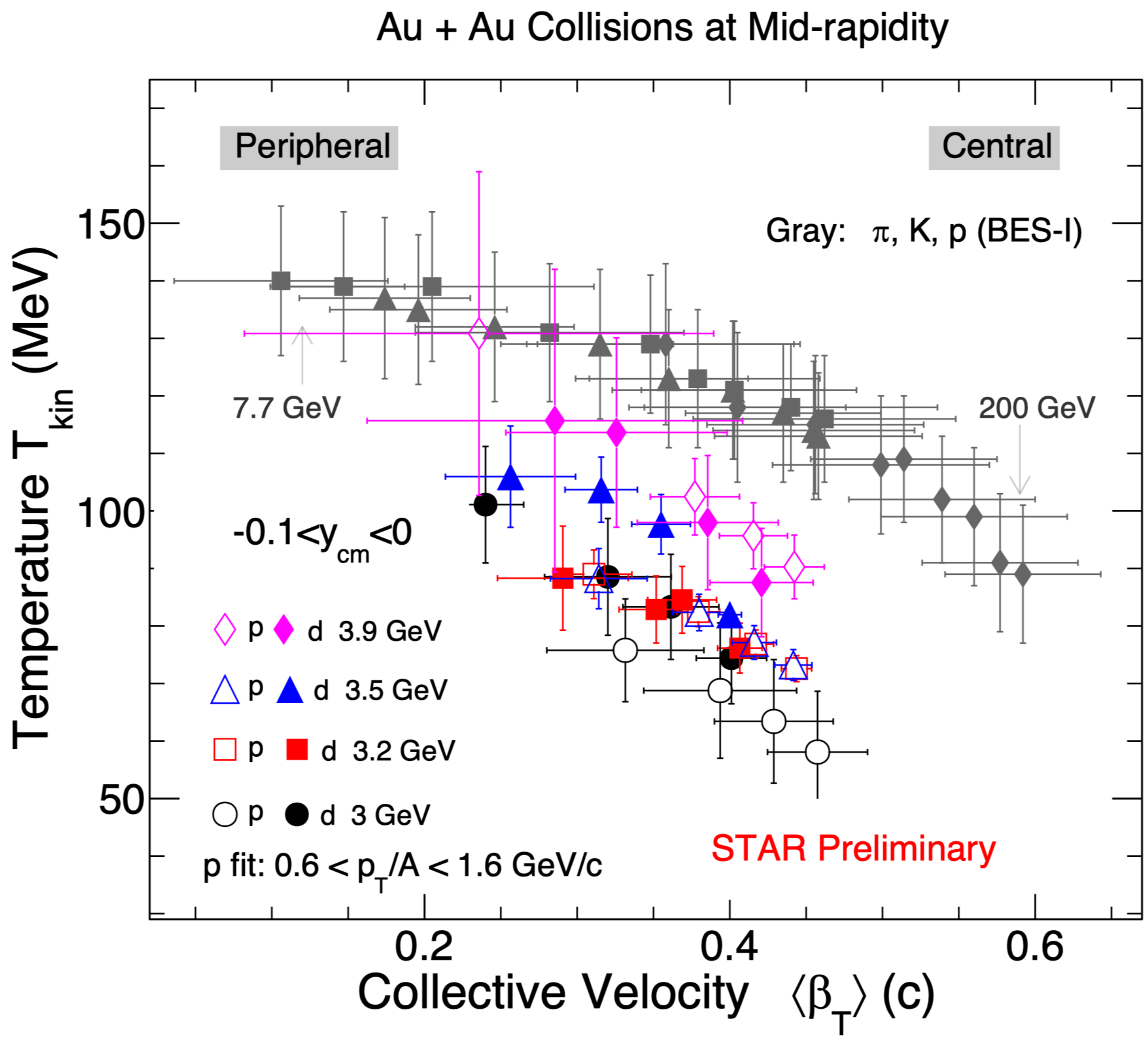
Kinetic Freeze-out Dynamics

Au + Au Collisions at Mid-rapidity



- 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 implying 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 light nuclei ratio d/p and ^3He /p, but 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:*

- Continue to calculate the compound ratio ($N_t \times N_p / N_d^2$) in Au+Au collisions at $\sqrt{s_{NN}}$=3.2-27 GeV.
- Update ^{4}He production in $\sqrt{s_{NN}} \geq 7.7$ GeV to study more about its production mechanism.

Thank you