# Light Nuclei Production in Au+Au Collisions at Fixed Target $\sqrt{s_{NN}}$ = 3 GeV from STAR

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quarks Q2C cosmos

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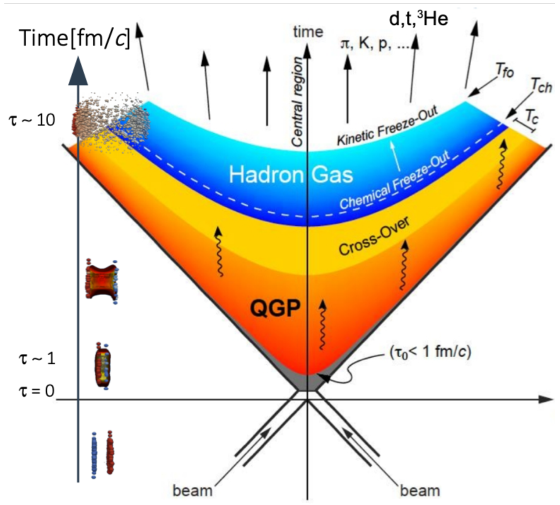
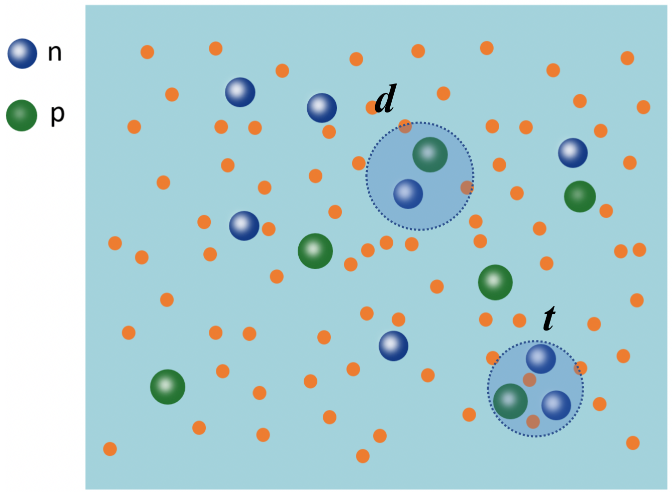
# Outline

- Motivation
- STAR Fixed Target and Data Sets
- Analysis Details and Results
- Summary and Outlook

# Motivation




## ➢ Heavy-ion Collisions

- **Chemical freeze-out:** Inelastic collisions ceases, chemical composition of particle yield get fixed
- **Kinetic freeze-out:** Elastic collisions ceases, momentum distributions of particles get fixed

## ➢ Why Light Nuclei ?

- Light nuclei are formed in a restricted volume of phase space, they carry information about local baryon density fluctuations
- Coalescence model:

$$N_d \approx \frac{3}{2^{1/2}}\left(\frac{2\pi}{m_T}\right)^{3/2}\frac{N_n N_p}{V},\ N_t \approx \frac{3^{3/2}}{4}\left(\frac{2\pi}{m_T}\right)^{3}\frac{N_n^2 N_p}{V^2}$$

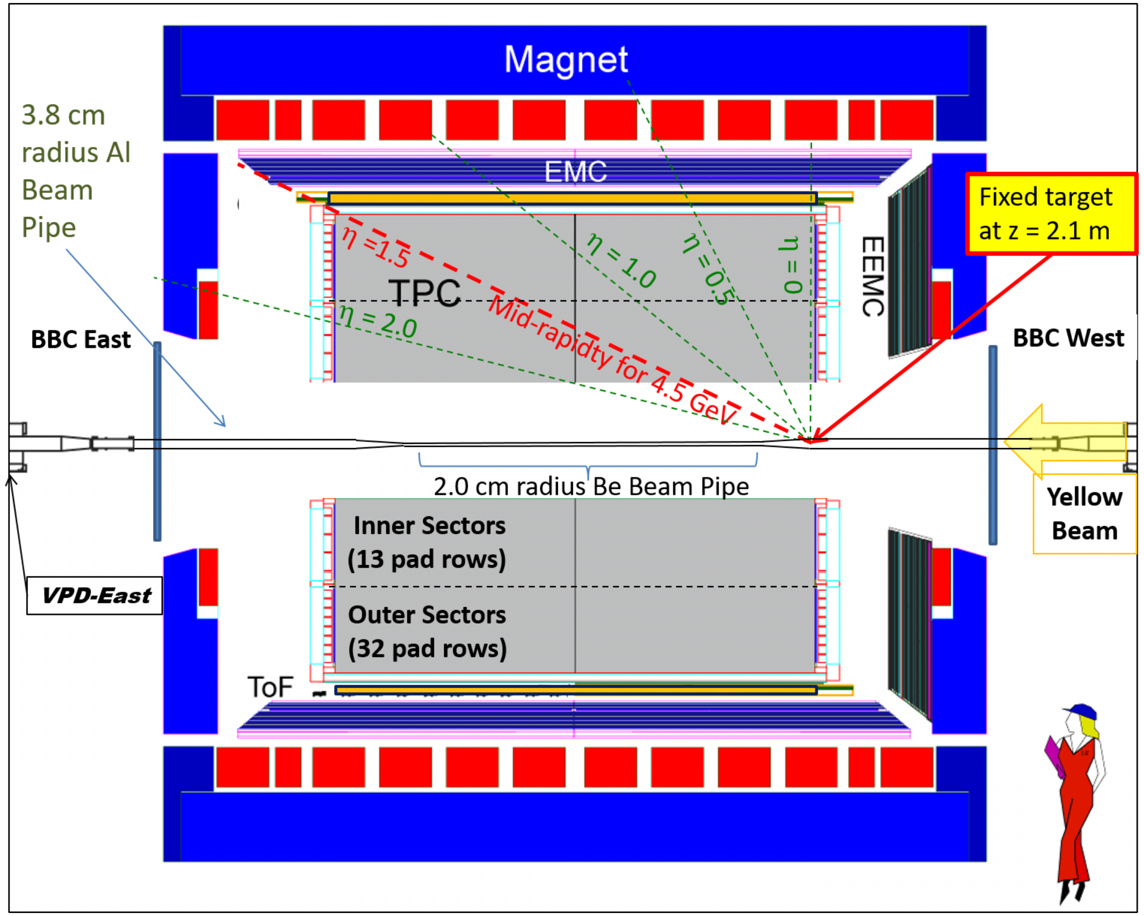
- Expectation:

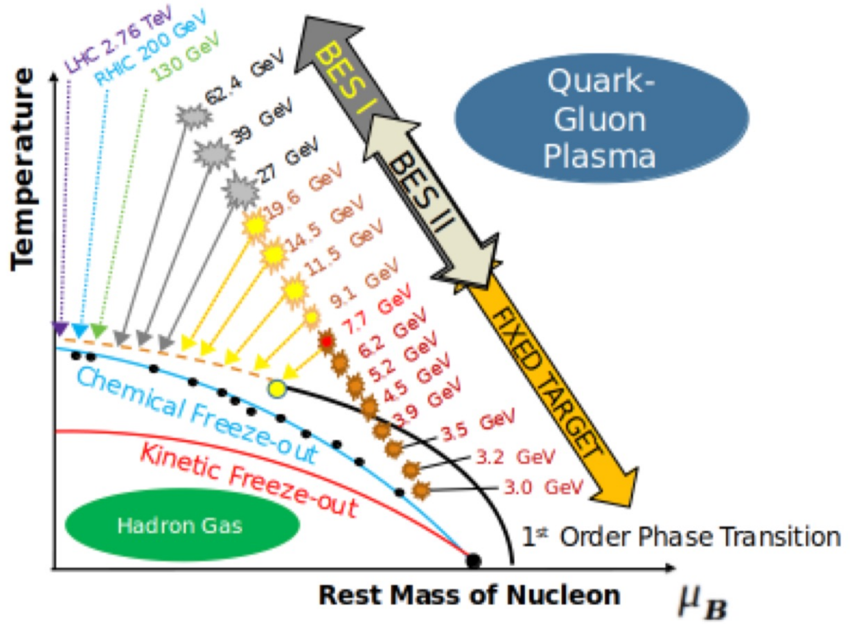
$$N_p \times N_t / N_d^2 = g(1+\Delta n),\ g=0.29$$

$\Delta n$: neutron density fluctuation

Phys. Lett. B 774, 103 (2017)
Phys. Lett. B 781, 499 (2018)

# STAR Fixed Target and Data Sets

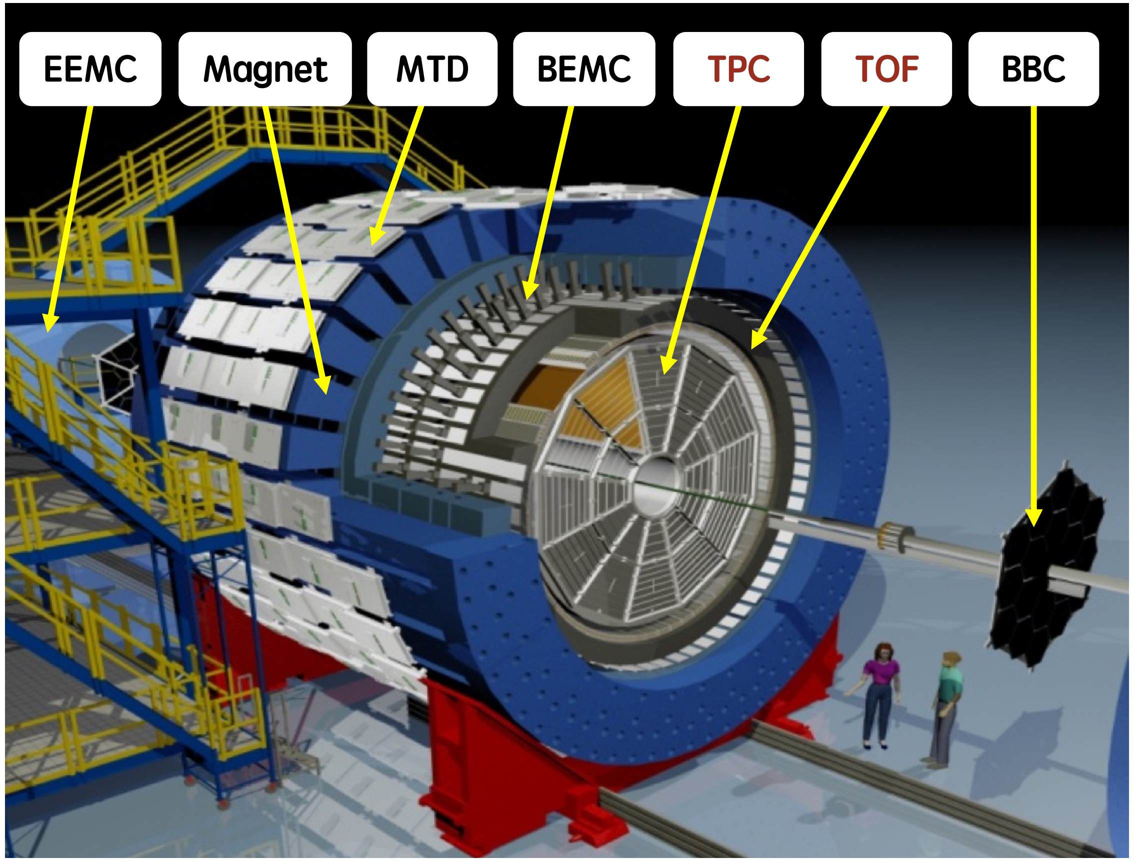


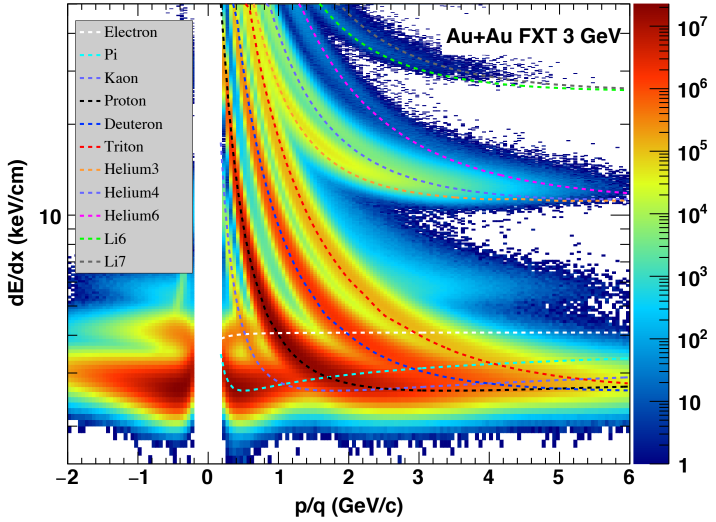




- Fixed Target (FXT) covers the collision energy $\sqrt{s_{NN}}$ = 3 - 7.7 GeV
- This study is based on the FXT $\sqrt{s_{NN}}$ = 3 GeV

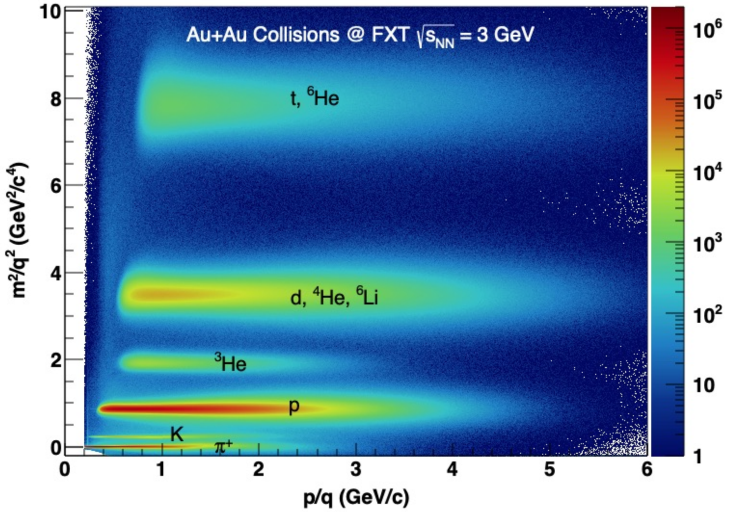
  Total events about 260M

# Analysis Details --- STAR Detector & Particle Identification



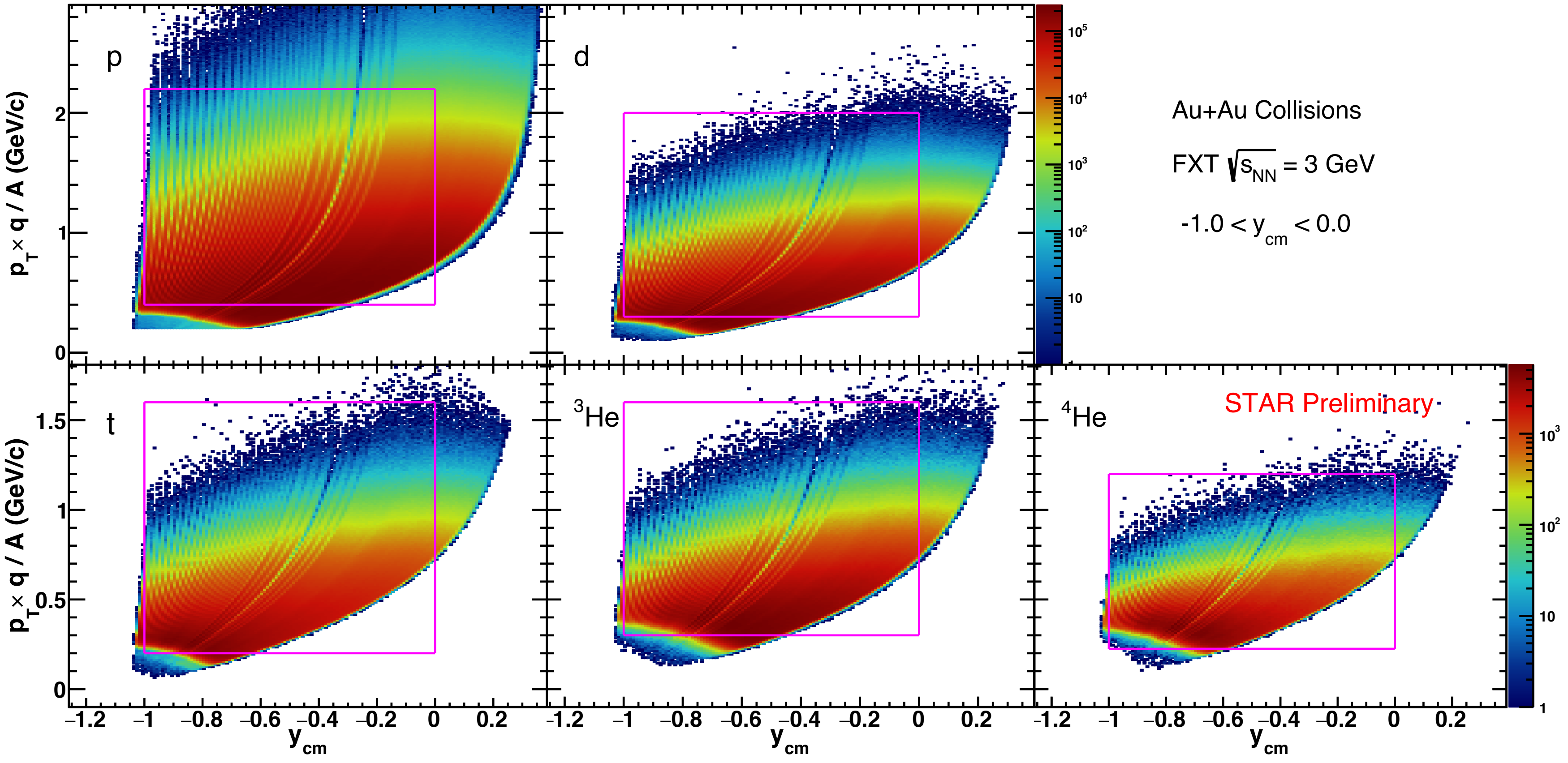

Low $p_T$: TPC




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

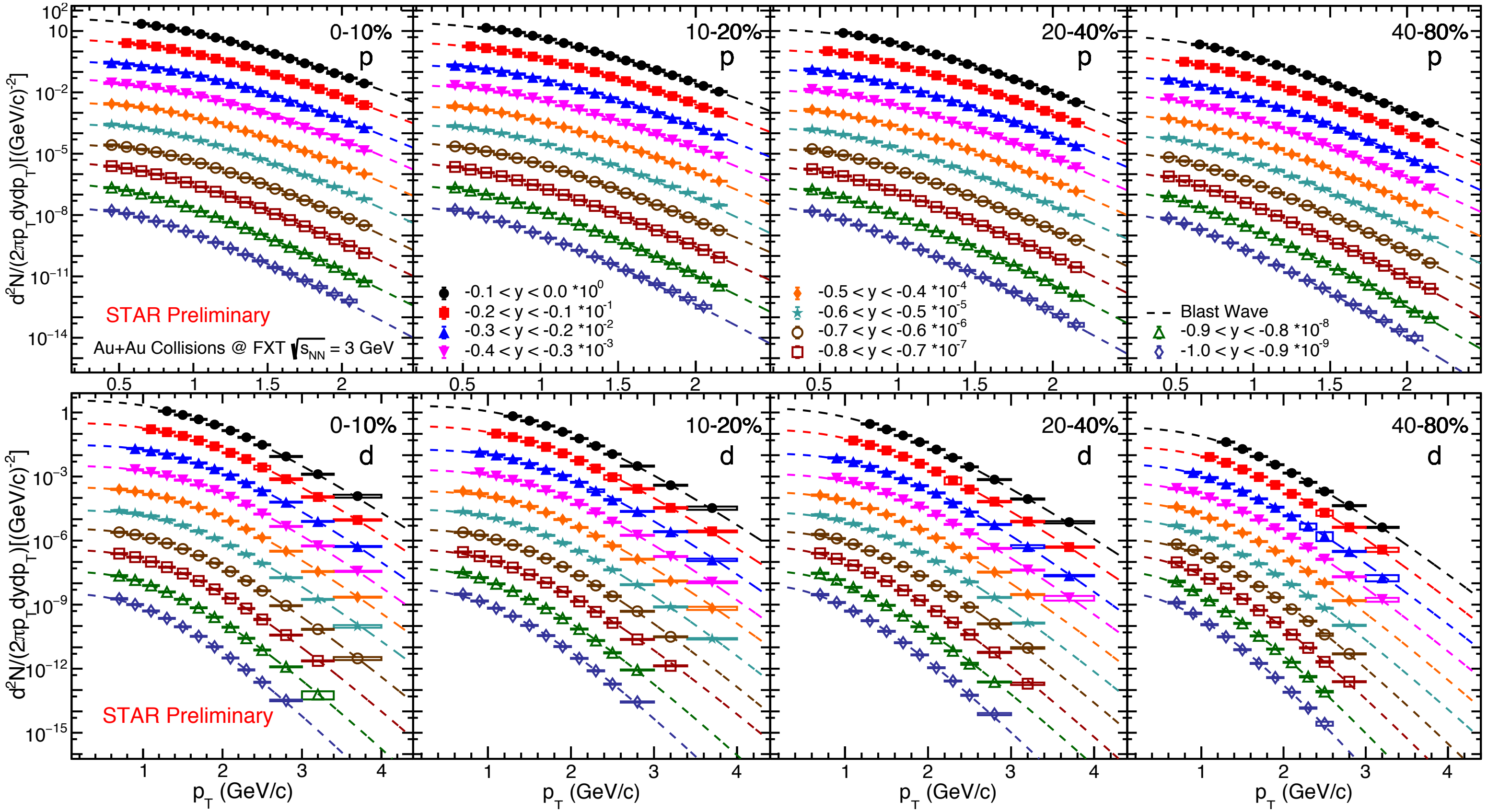
High $p_T$: TPC+TOF

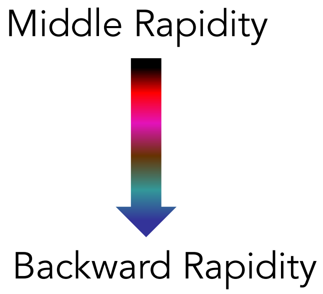
# Analysis Details --- Phase Space of Particles




- Mid-rapidity of FXT 3 GeV at $y_{mid}$ = -1.045, $y_{cm} = -(y_{lab} - y_{mid})$
- The purple boxes in the figure indicate the $p_T$ and rapidity ranges of the analysis

# Analysis Details --- Transverse Momentum Spectra




- $p_T$ spectra of inclusive protons and deuterons at different rapidity windows are scaled by different factors

- --- Blast-Wave Function

$$\frac{1}{2\pi p_T}\frac{d^2N}{dp_T dy} \propto \int_0^R r dr m_T I_0\left(\frac{p_T \sinh\rho}{T}\right) K_1\left(\frac{m_T \cosh\rho}{T}\right)$$

$$\rho = \tanh^{-1}\beta_r$$

$$\beta_r(r) = \beta\left(\frac{r}{R}\right)^n$$

$T$ : kinetic freeze-out temperature

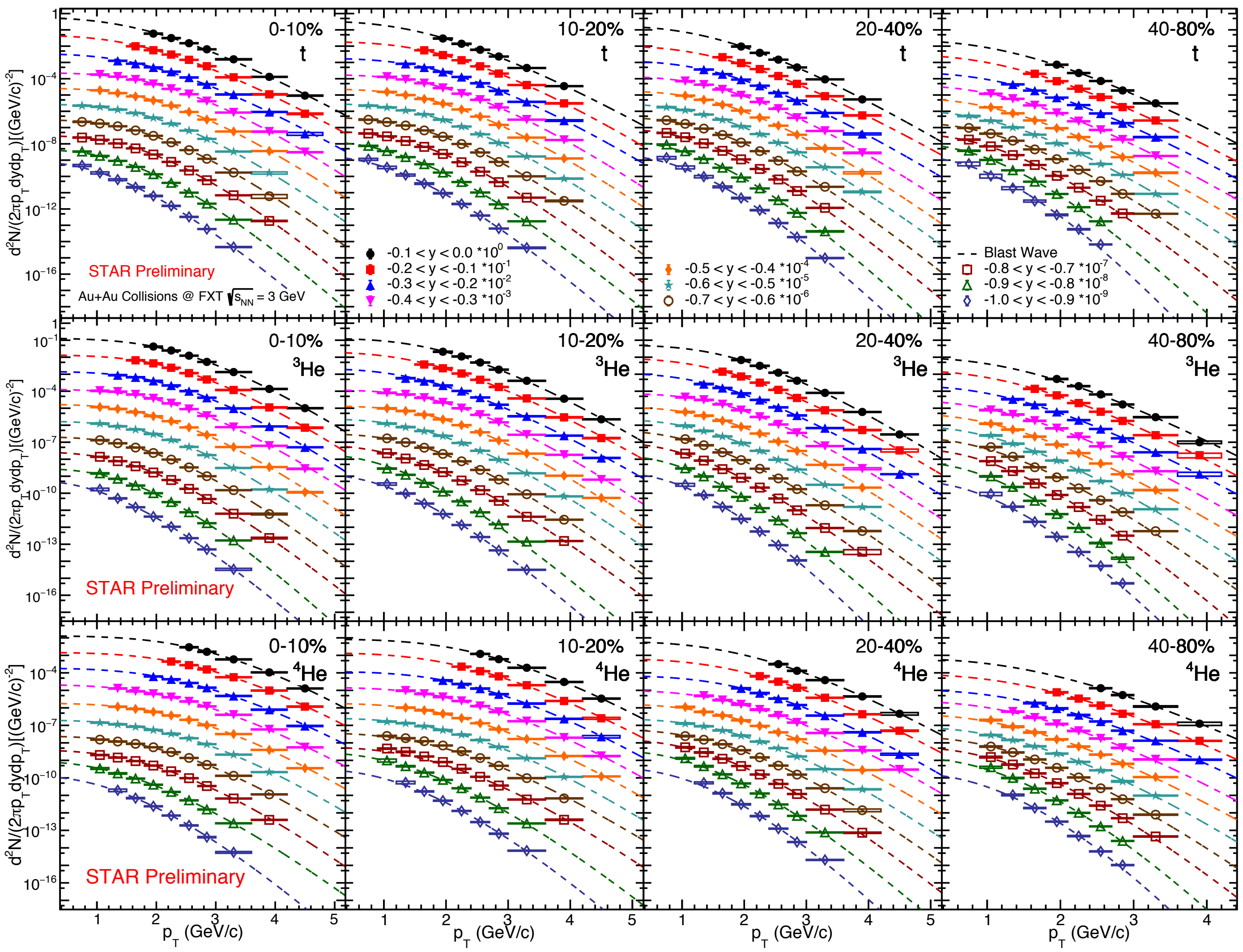
$<\beta>$ : average radial flow velocity

# Analysis Details --- Transverse Momentum Spectra

Triton

$^3$He

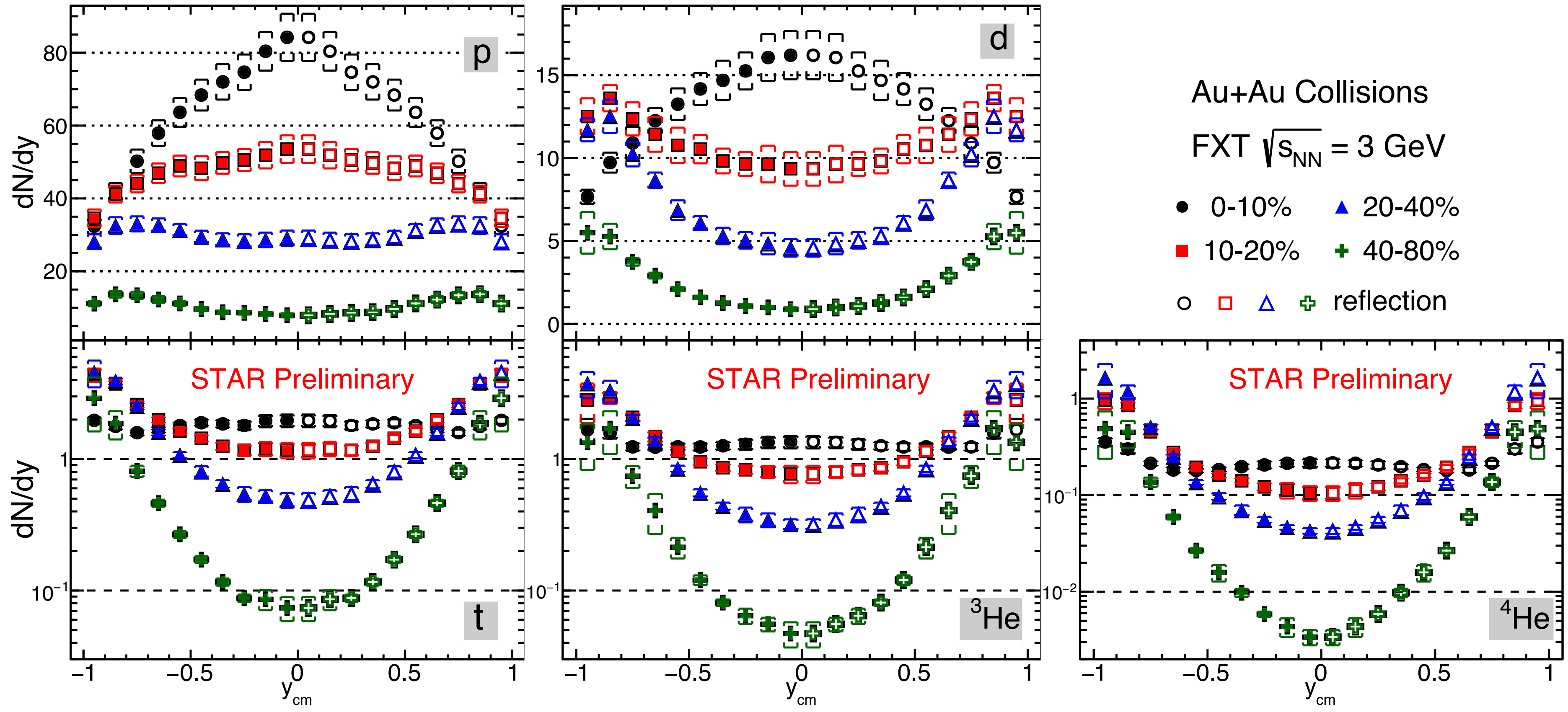
$^4$He




Middle Rapidity

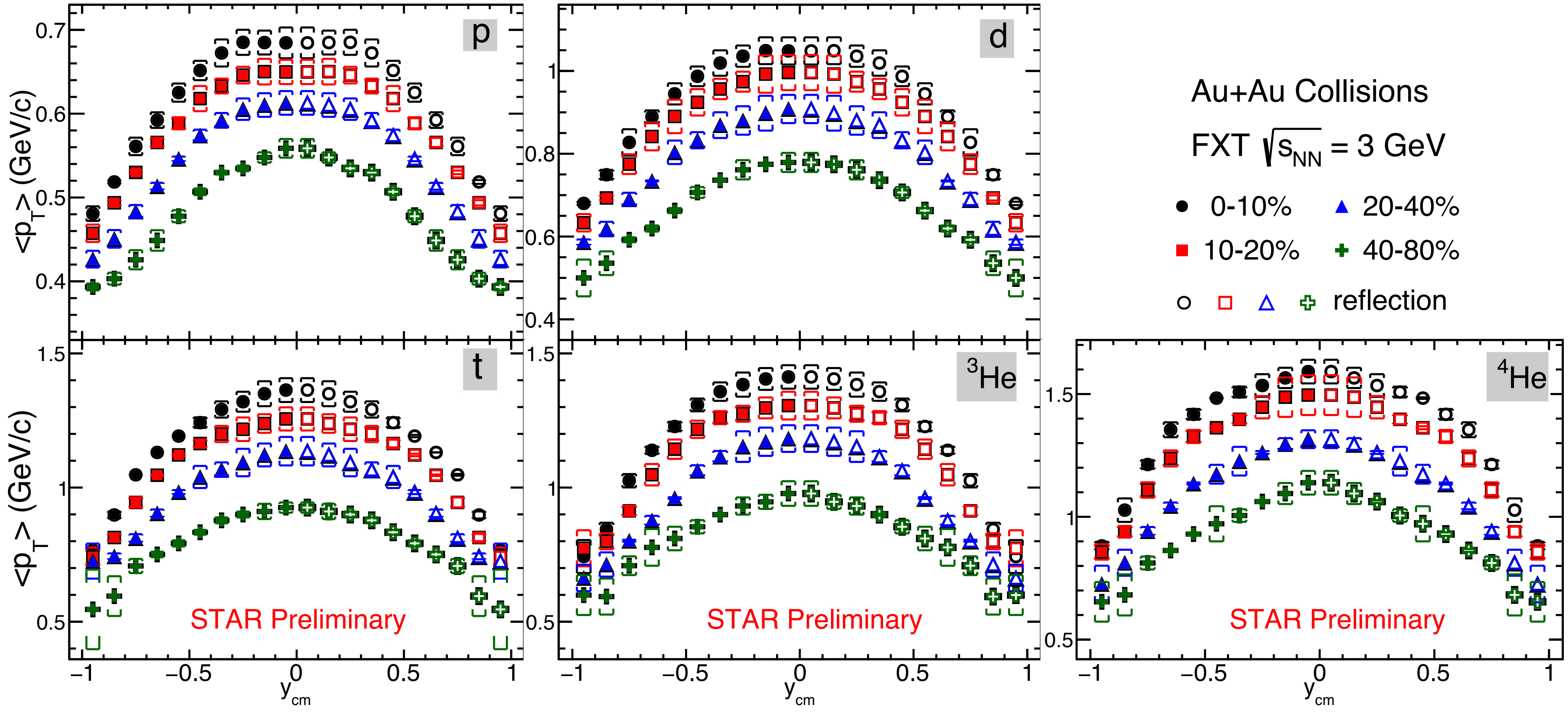
Backward Rapidity

# Results --- dN/dy of Particles



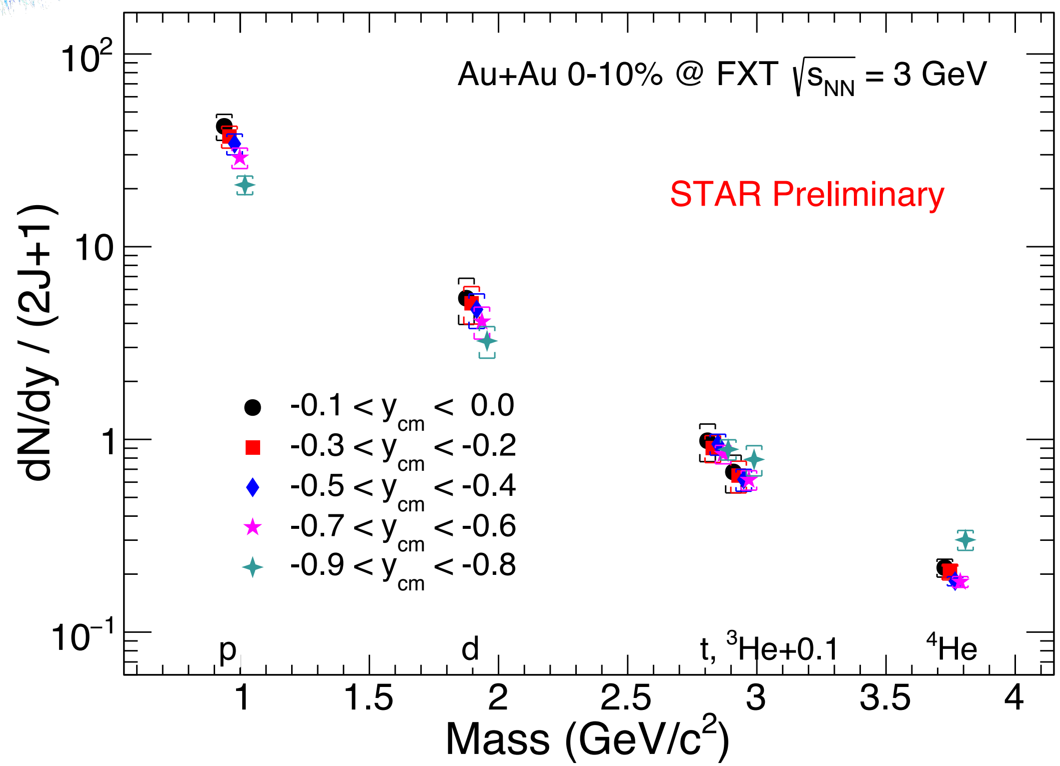

- $-1 < y_{\rm cm} < 0$: obtained by $p_T$ spectra; $0 < y_{\rm cm} < 1$: reflection by measured range
- Systematic uncertainties are evaluated by various track cuts and different fit functions
- dN/dy of particles shows strong rapidity and centrality dependence

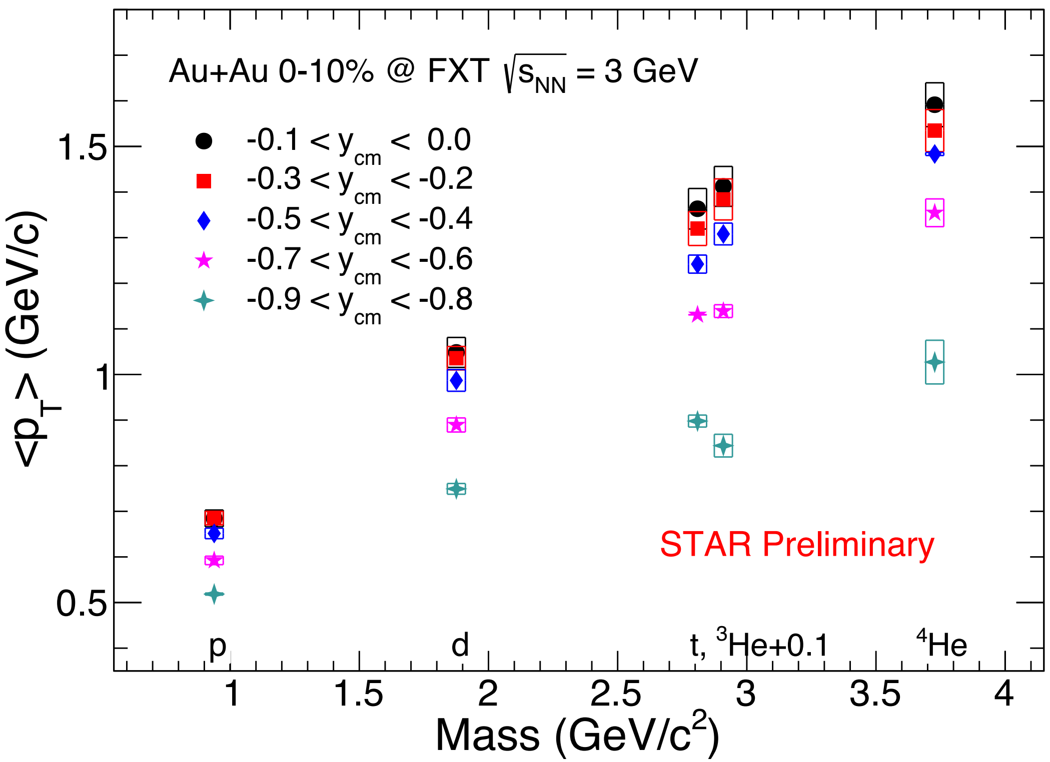
# Results --- $< p_T >$ of Particles




- $-1 < y_{cm} < 0$: obtained by $p_T$ spectra; $0 < y_{cm} < 1$: reflection by measured range
- Systematic uncertainties of $< p_T >$ are evaluated by different fit functions
- $< p_T >$ of all particles decreases from mid-rapidity $(y_{cm} = 0)$ to backward rapidity $(y_{cm} < 0)$ in all centralities

# Results --- dN/dy and $< p_T >$ vs. Particle Mass



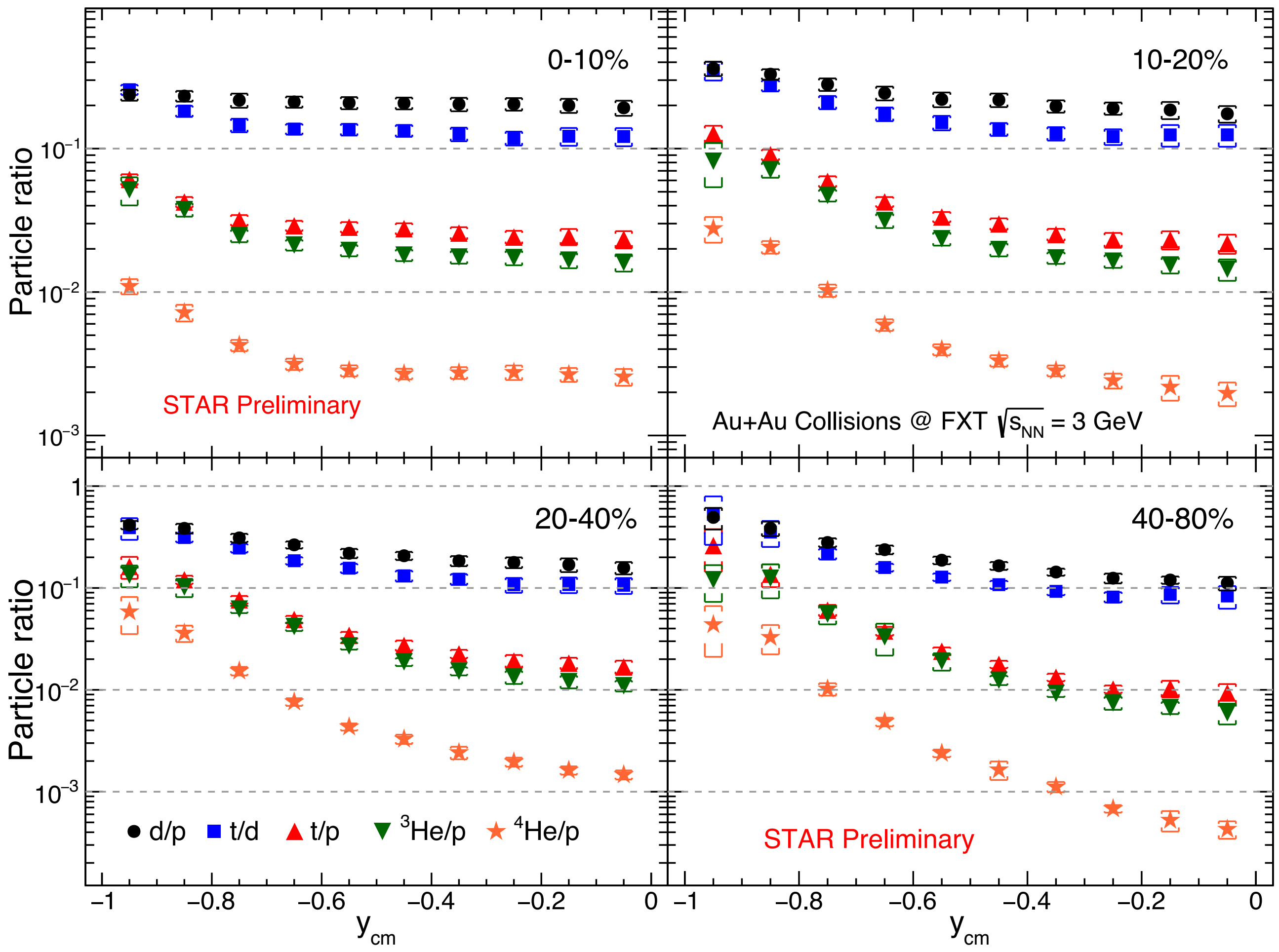

Mass of particles with a small shift at different rapidity ranges

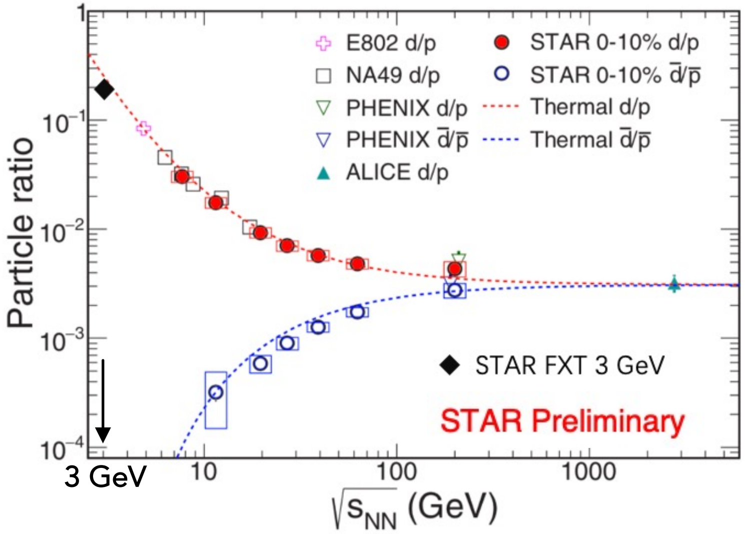
Nuclear Physics A 772 (2006) 167–199

Phys. Rev. Lett. 83, 5431 (1999)

- dN/dy decreases exponentially as a function of particle mass, 2J+1 is the spin degeneracy factor .
- $< p_T >$ increases linearly as a function of particle mass: collective motion of light nuclei !

# Results --- Particle Ratios



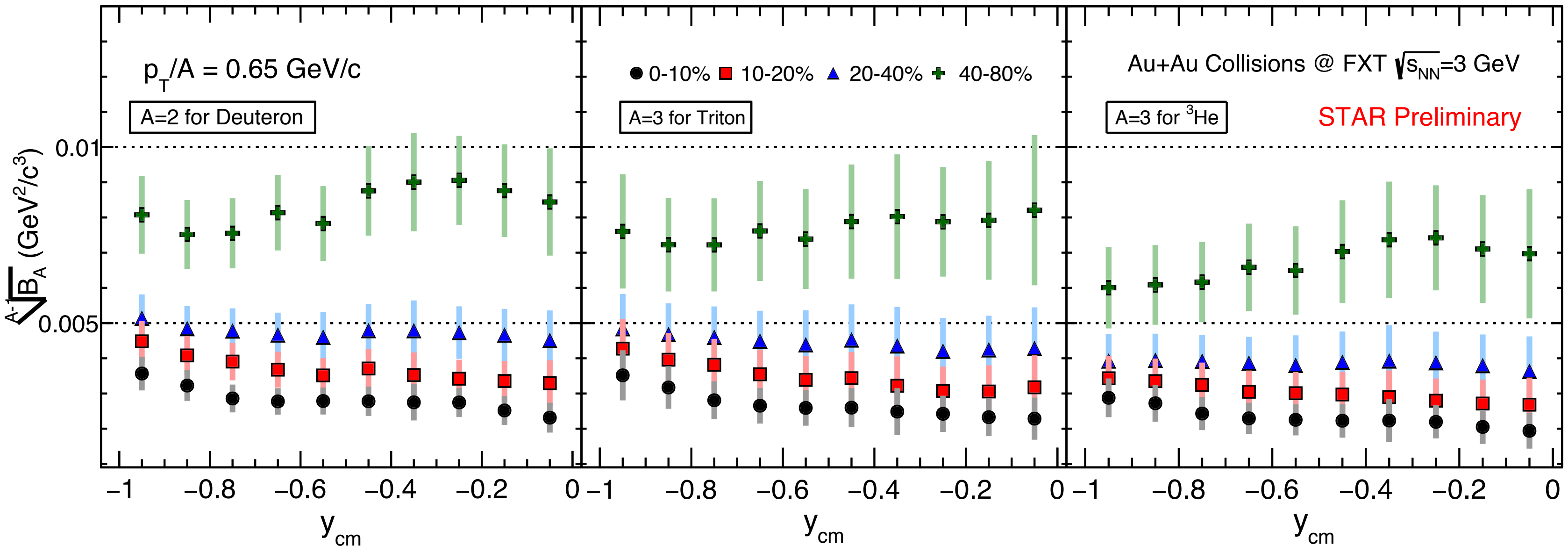



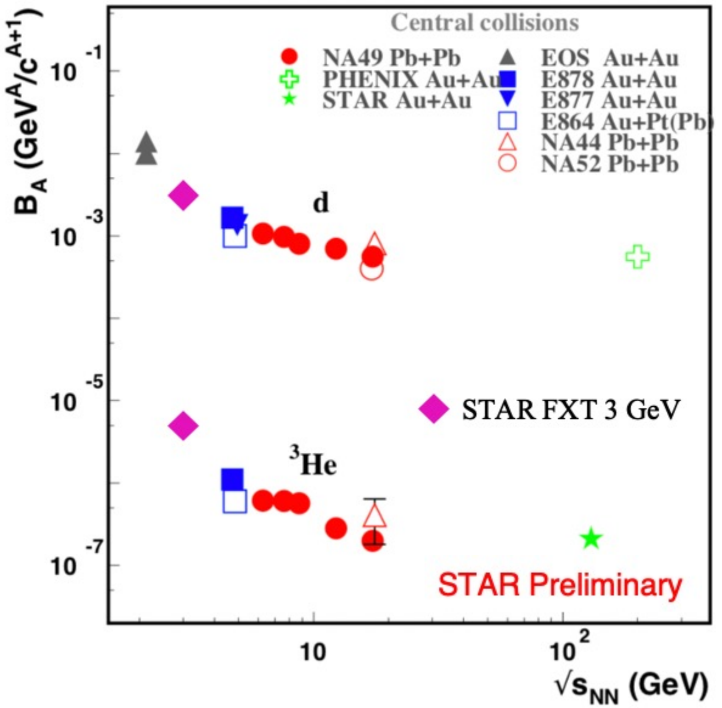

Physical Review C 99, 064905 (2019)

- Particle ratios show increasing trend from mid-rapidity to backward rapidity at each centrality
- d/p ratio follows the energy dependence trend as observed in BES-I and can be described well by statistical thermal model

# Results --- Coalescence Parameter $B_A$

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



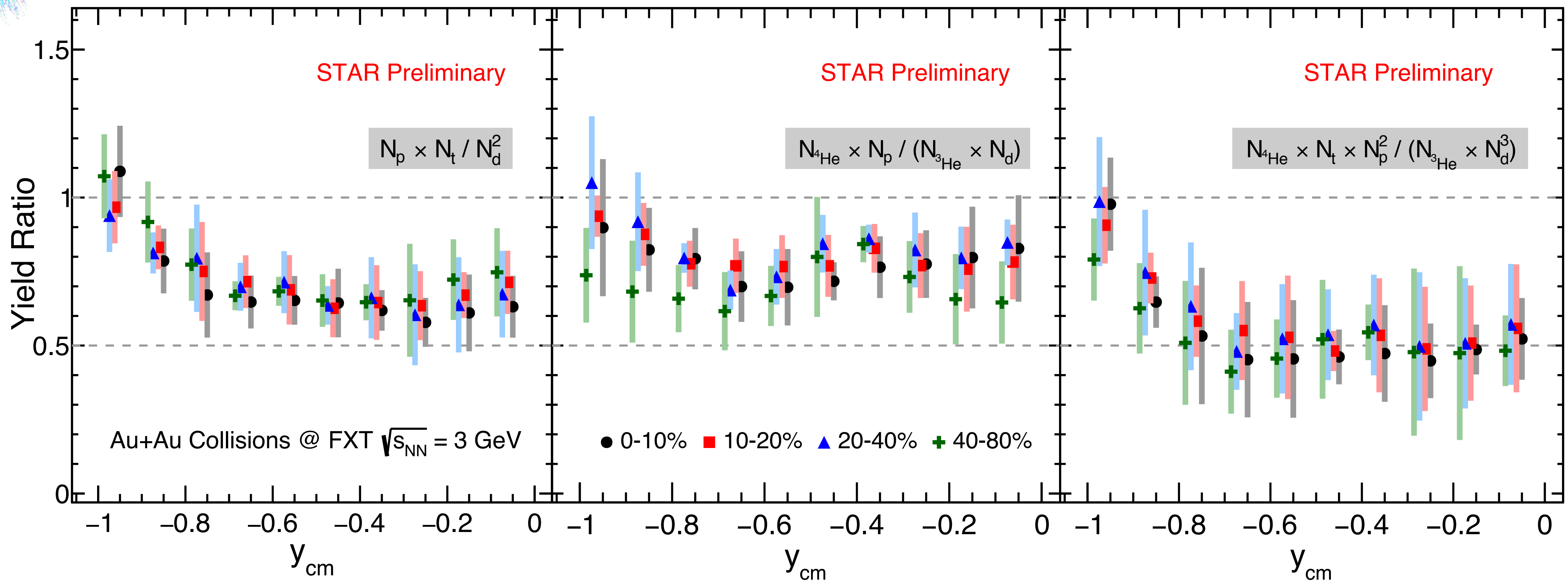





Phys. Rev. C 94 (2016) 4, 044906
Phys. Rev. C 61 (2000) 064908
Phys. Lett. B 417, 202 (1998)
Eur. Phys. J. C 23, 237 (2002)
Phys. Rev. Lett. 87, 262301 (2001)
Phys. Rev. Lett. 94, 122302 (2005)
Phys. Rev. C 83 (2011) 044906


- Coalescence parameter $B_A \propto (1/V)^{(A-1)}$ reflects freeze-out property
- $\sqrt[A-1]{B_A}$ of d, t and $^3$He shows an increasing trend from central to peripheral collisions, no significant rapidity dependence
- $B_A$ follows the world trend, and shows energy dependence

# Results --- Yield Ratios




- Systematic errors are obtained from different fit functions
- $N_p \times N_t / N_d^2$ and $N_{^4He} \times N_t \times N_p^2 / (N_{^3He} \times N_d^3)$ show rapidity dependence, no obvious centrality dependence
- $N_{^4He} \times N_p / (N_{^3He} \times N_d)$ has no significant rapidity and centrality dependence within the uncertainty

# Summary and Outlook

- We report the first measurement of light nuclei (d, t, $^{3}\mathrm{He}$ and $^{4}\mathrm{He}$) production in Au + Au collisions at FXT $\sqrt{s_{NN}}$ = 3 GeV from STAR
- $\mathrm{p_T}$ spectra, dN/dy and $< \mathrm{p_T} >$ of particles from mid-rapidity to backward rapidity have been presented
- Coalescence parameters and particle ratios follow the energy dependence trend as observed in Beam Energy Scan
- Measure the yield ratios as a function of rapidity at each centrality. In addition, we measured $^{4}\mathrm{He}$ production and include it into yield ratio calculation

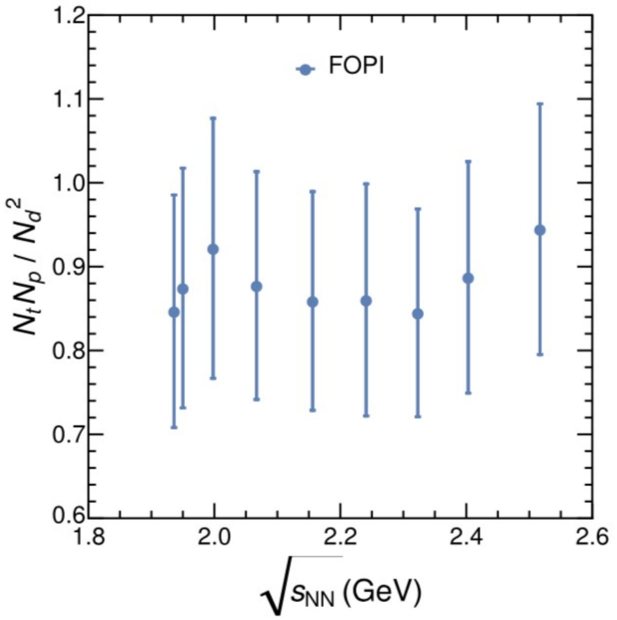
- Light nuclei production from STAR BES II and more FXT data

**Thank you for your attention!**

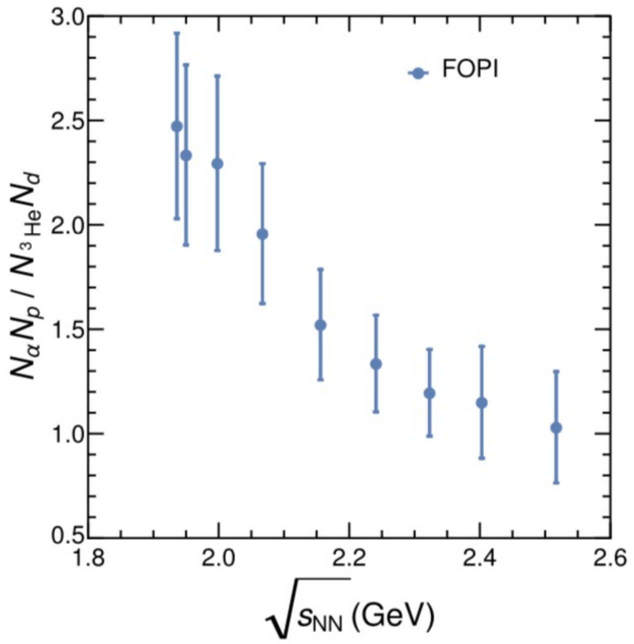
# Back up

## Yield Ratios

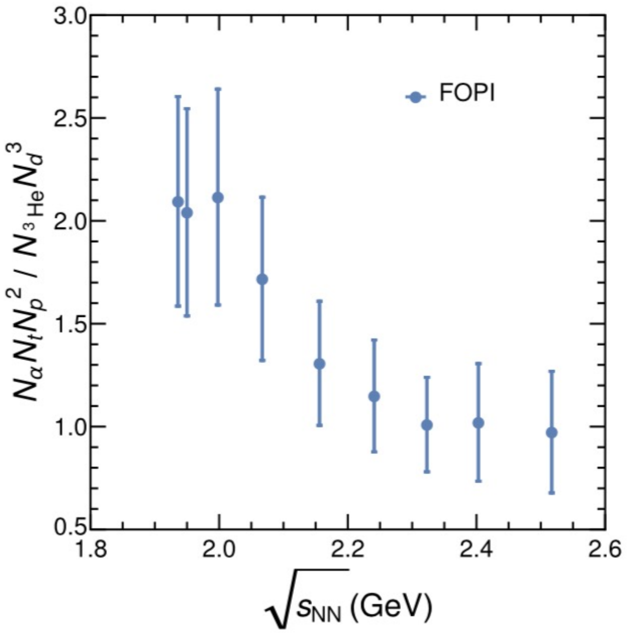
$$\mathcal{O}_{tpd} \simeq 0.29 \frac{\langle e^{-3V(r)/T}\rangle}{\langle e^{-V(r)/T}\rangle^2},$$




$$\mathcal{O}_{\alpha p ^3\mathrm{He} d} \equiv \frac{N_\alpha N_p}{N_{^3\mathrm{He}} N_d} \simeq 0.18 \frac{\langle e^{-6V(r)/T}\rangle}{\langle e^{-3V(r)/T}\rangle \langle e^{-V(r)/T}\rangle},$$




$$\mathcal{O}_{\alpha t p ^3\mathrm{He} d} \equiv \frac{N_\alpha N_t N_p^2}{N_{^3\mathrm{He}} N_d^3} \simeq 0.05 \frac{\langle e^{-6V(r)/T}\rangle}{\langle e^{-V(r)/T}\rangle^3},$$




- Ratio formed from FOPI multiplicity results at low energies

Eur. Phys. J. A 56 (2020) 9, 241