Production of Light Nuclei in Heavy-ion Collisions Measured by RHIC-STAR

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QUARK MATTER KRAKÓW 2022

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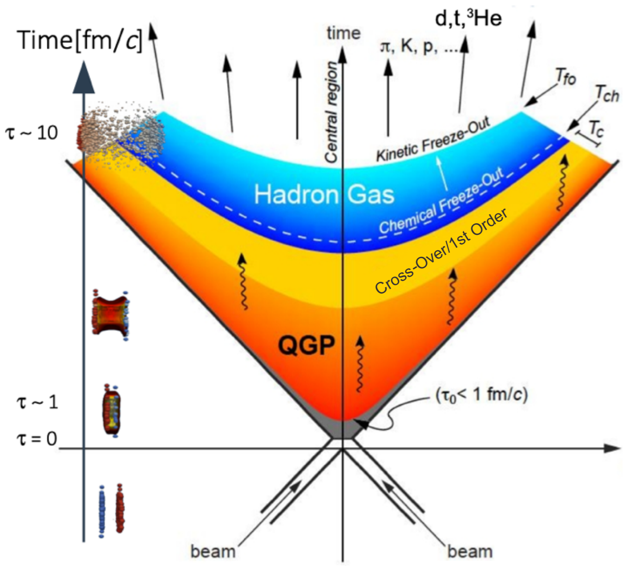
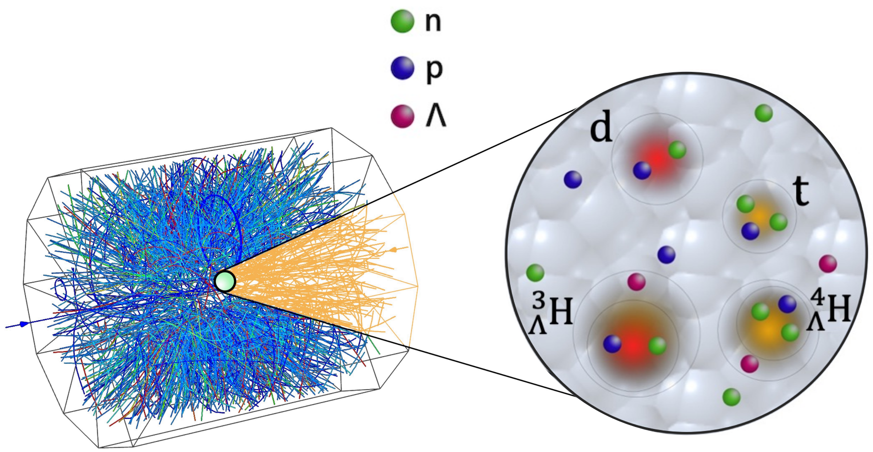
The XXIXth International Conference on Ultra-relativistic Nucleus-Nucleus Collisions

Outline

1. Introduction
2. STAR Experiment and Data Sets
3. Analysis Method
4. Results and Discussions
5. Summary and Outlook

Introduction





1. Heavy-ion Collisions

① Creating medium of hot and dense nuclear matter allows us to study the QCD structure under controlled conditions

② **Kinetic freeze-out:** Elastic collisions cease, momentum distributions of particles get fixed

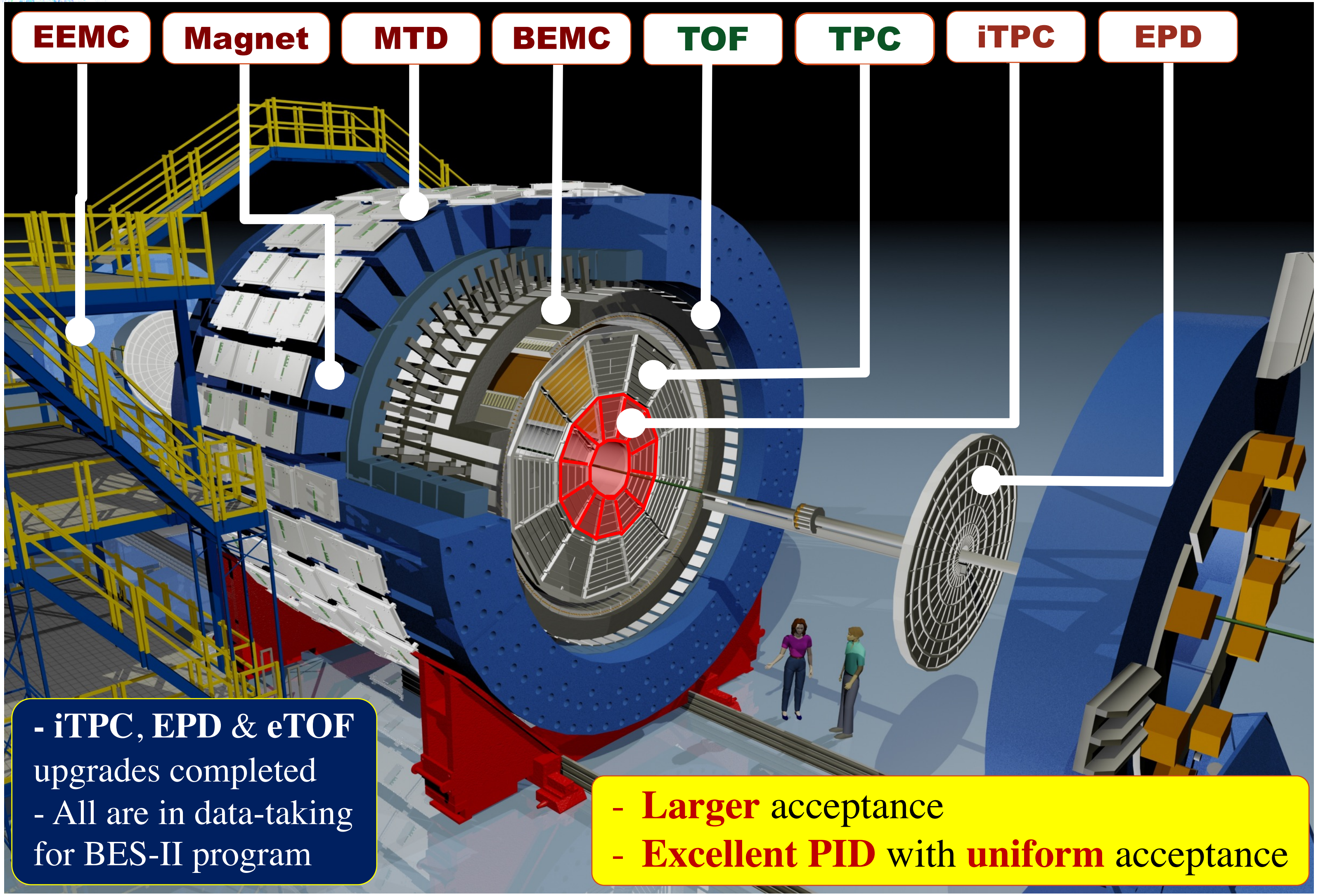
2. Why Light Nuclei ?

① **Light nuclei** carry information about local baryon density fluctuations

② Provides an effective probe to study first-order phase boundary and the QCD **C**ritical **P**oint

K. Sun et al. Phys.Lett.B 774 (2017) 103-107
E. Shuryak et al. Phys.Rev.C 101 (2020) 3, 034914
H. Agakishiev et al. [STAR Collaboration] Nature 473 (2011) 353

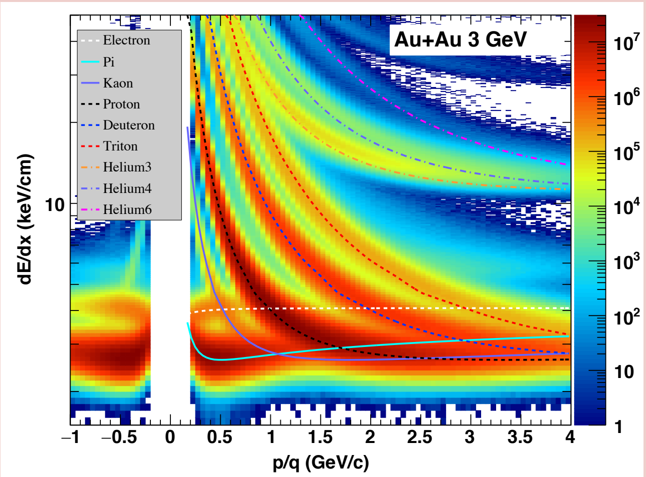
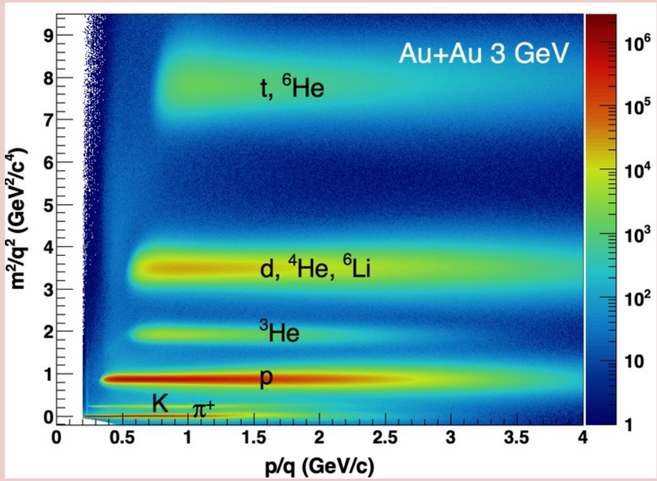
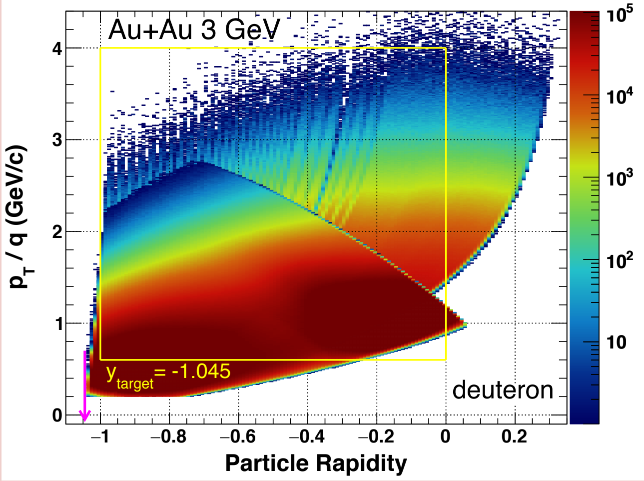
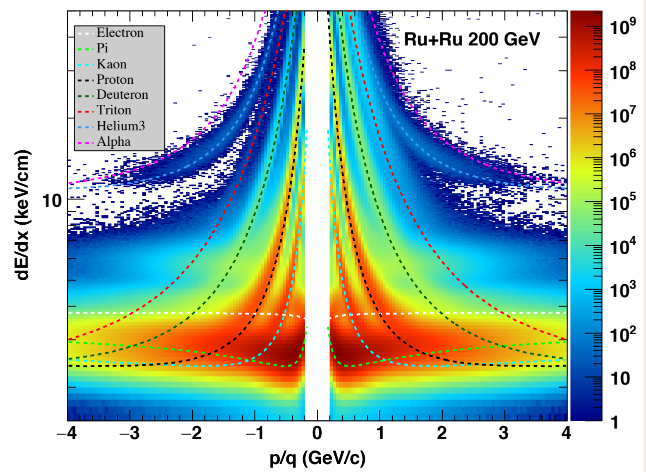
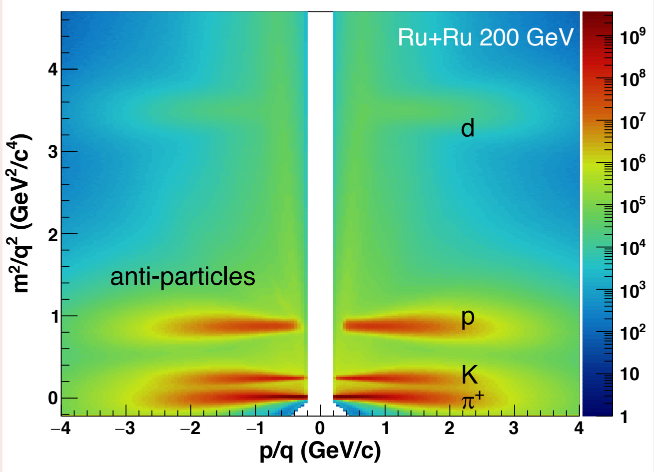
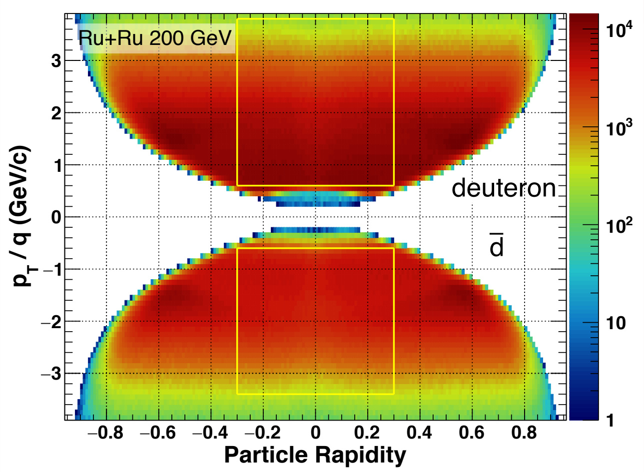
STAR Detector & Data Sets



Energy (GeV)	3	200
Year	2018	2018
Collision	Au3.85 (FXT)	Zr+Zr/ Ru+Ru
nEvents (10^6)	~258	~2020/ 1930

- Fixed target program with $\sqrt{s_{NN}}$ = 3 - 13.7 GeV, extends μ_B coverage up to 750 MeV

Analysis Method – Particle Identification

$\sqrt{s_{NN}}$ (GeV)	TPC PID	TOF PID	Phase Space (d)
3 GeV (Fixed Target Au+Au Collisions)			
200 GeV (Isobar Zr+Zr / Ru+Ru Collisions)			

Analysis Method – Corrections

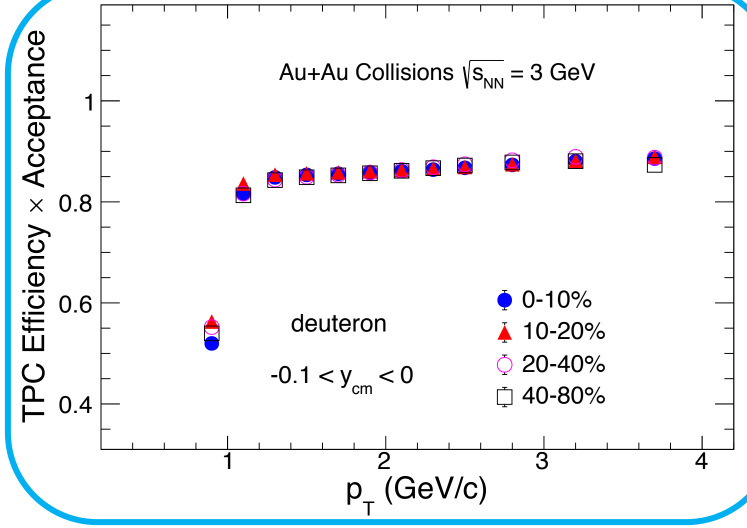
3 GeV	✓	✓	✓	N/A	N/A
200 GeV	✓	✓	✓	✓	✓
Correction	Energy loss corr.	TPC tracking eff.	TOF matching eff.	Absorption corr.	Background corr.

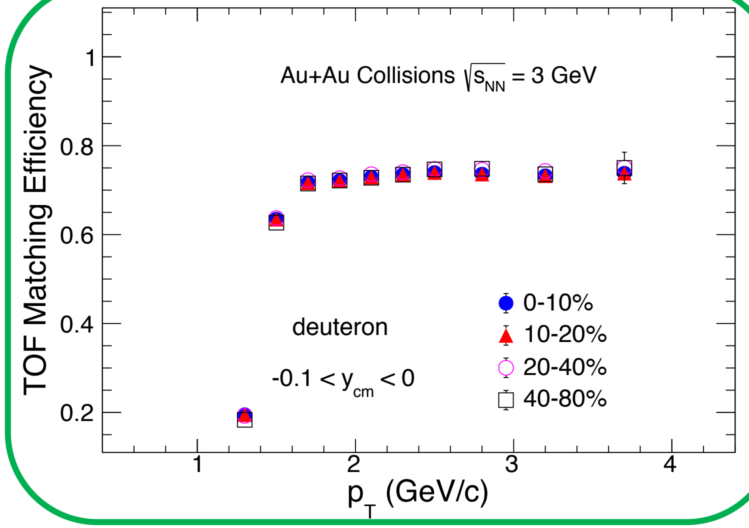
Energy loss corr.:

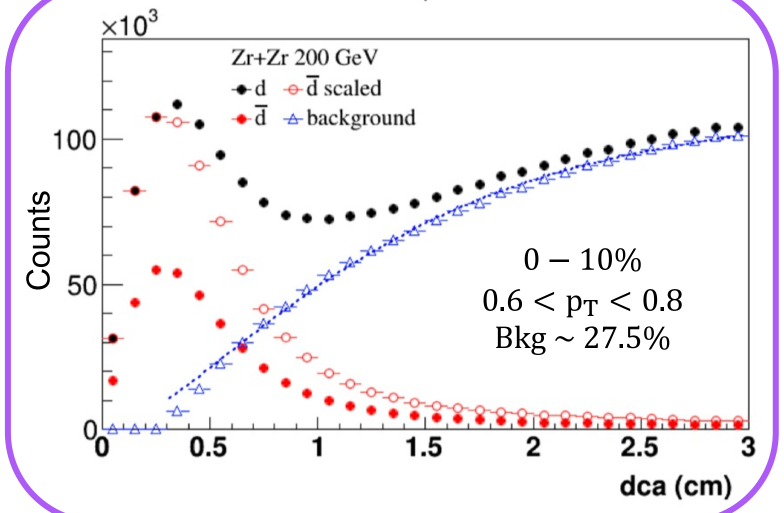
$$f(p_T) = p_0 + p_1\left(1 + \frac{p_2}{p_T^2}\right)^{p_3}$$

Absorption corr.:

$$f(p_T) = \sum_{i=0}^{8} p_i p_T^i$$



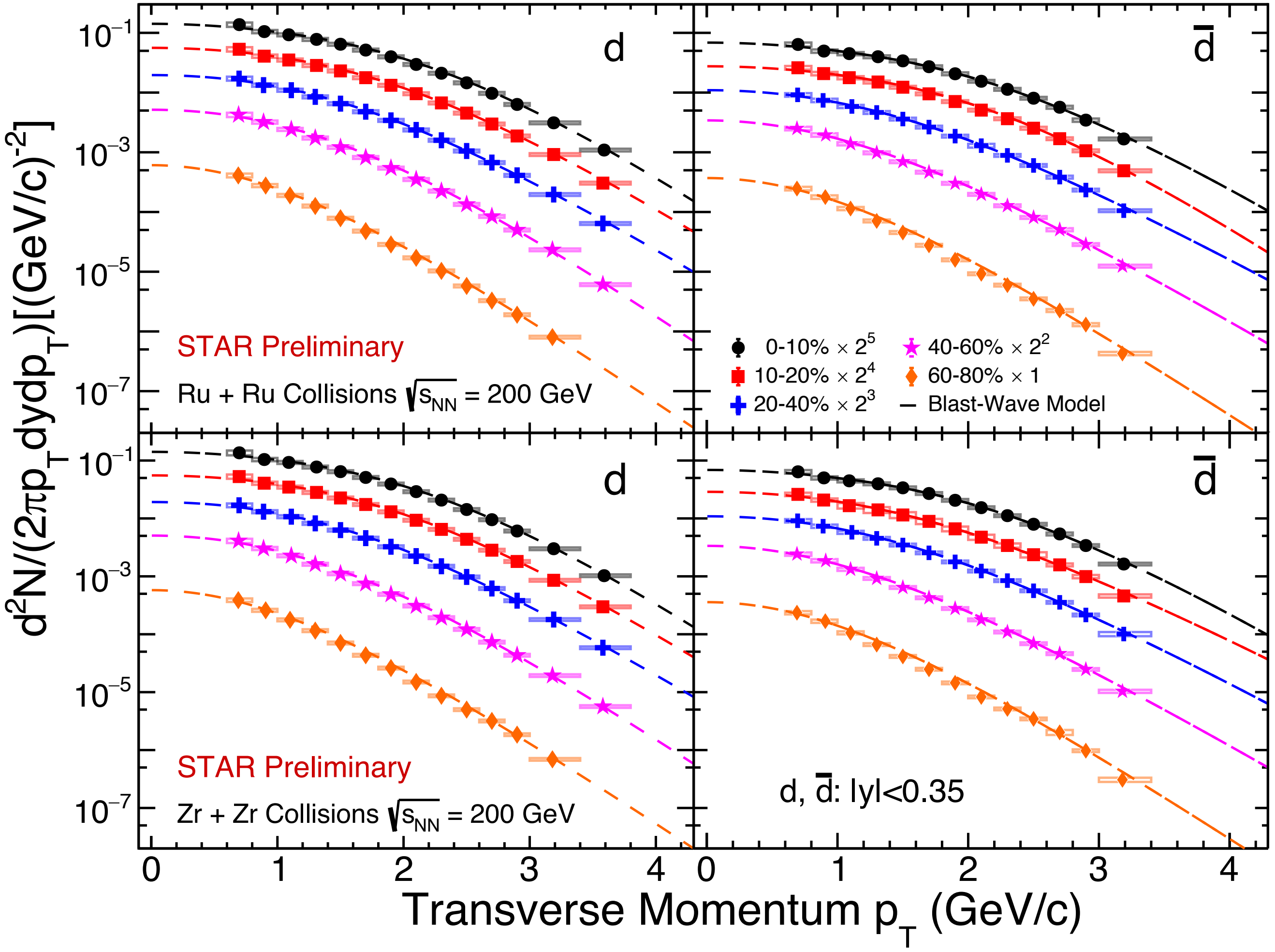




Result at $\sqrt{s_{NN}}$ = 200 GeV

Ru+Ru & Zr+Zr Collisions

Transverse Momentum Spectra

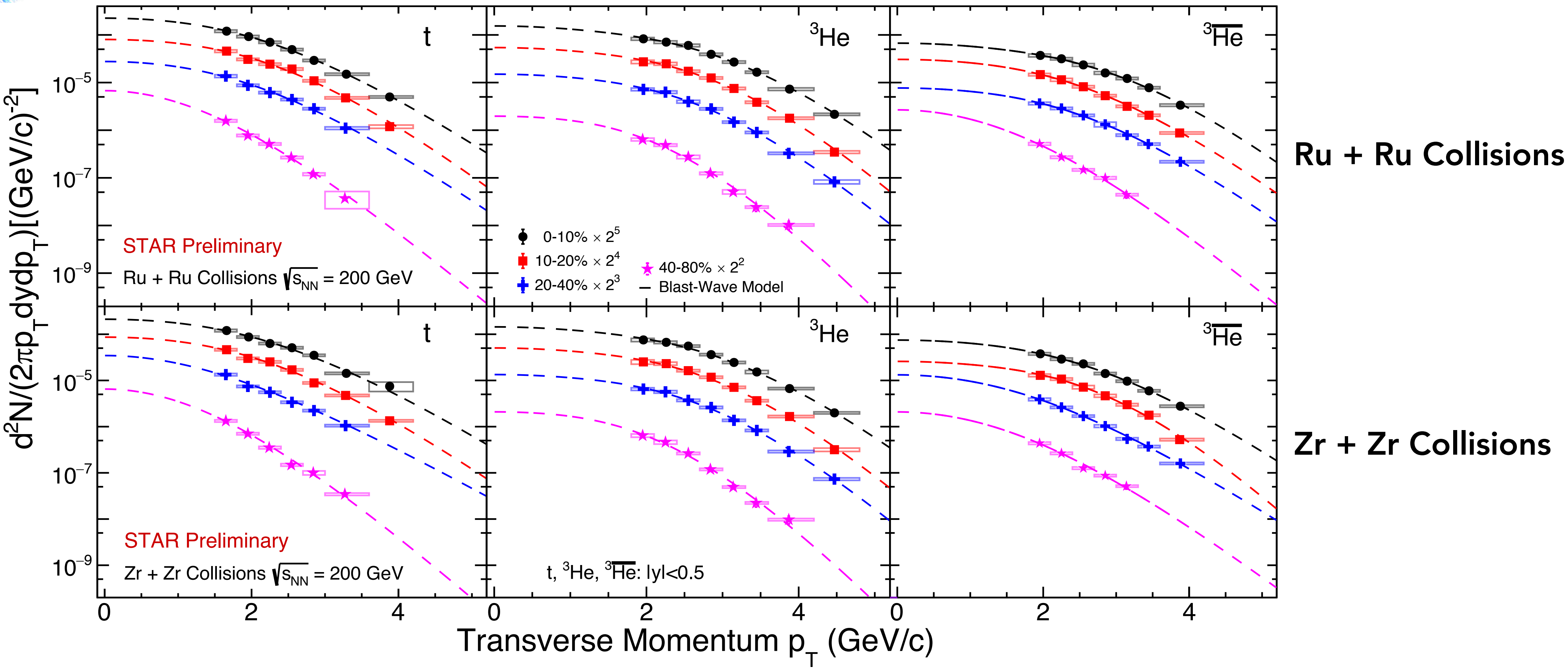


Ru + Ru Collisions

Zr + Zr Collisions

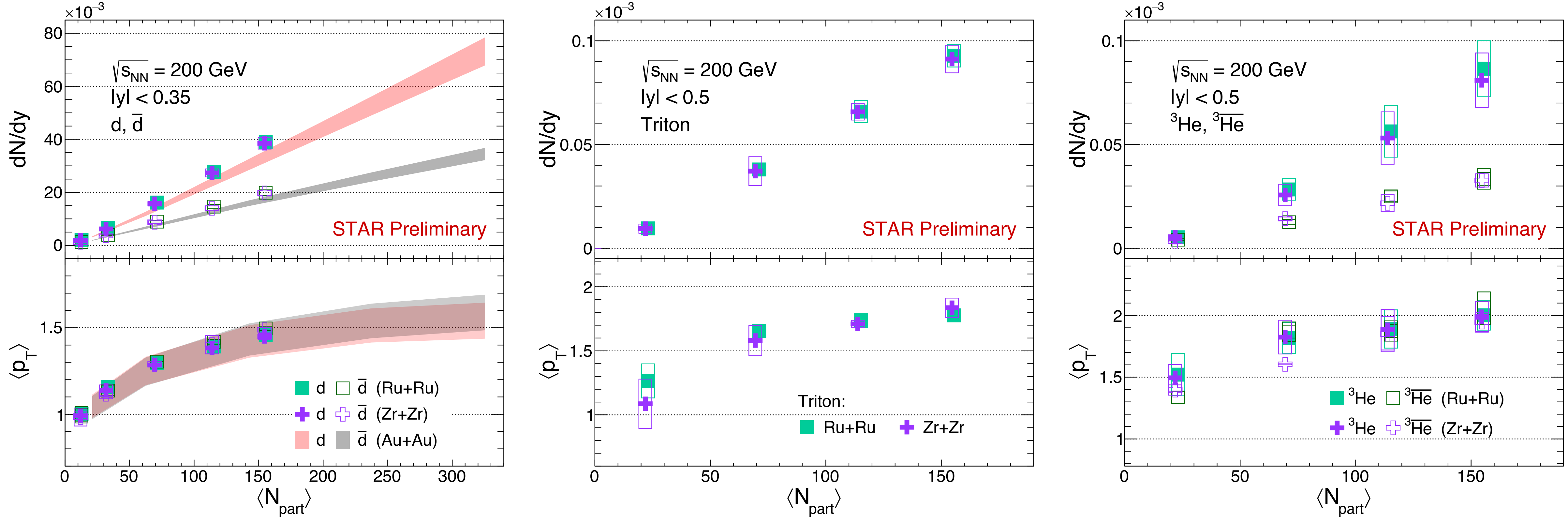
- Transverse momentum spectra of d and $\bar{d}$ at mid-rapidity in Ru+Ru and Zr+Zr collisions for various centralities at $\sqrt{s_{NN}}$ = 200 GeV

Transverse Momentum Spectra



➢ Transverse momentum spectra of t, $^3\mathrm{He}$, and $\overline{^3\mathrm{He}}$ at mid-rapidity in Ru+Ru and Zr+Zr collisions for various centralities at $\sqrt{s_{NN}}$ = 200 GeV

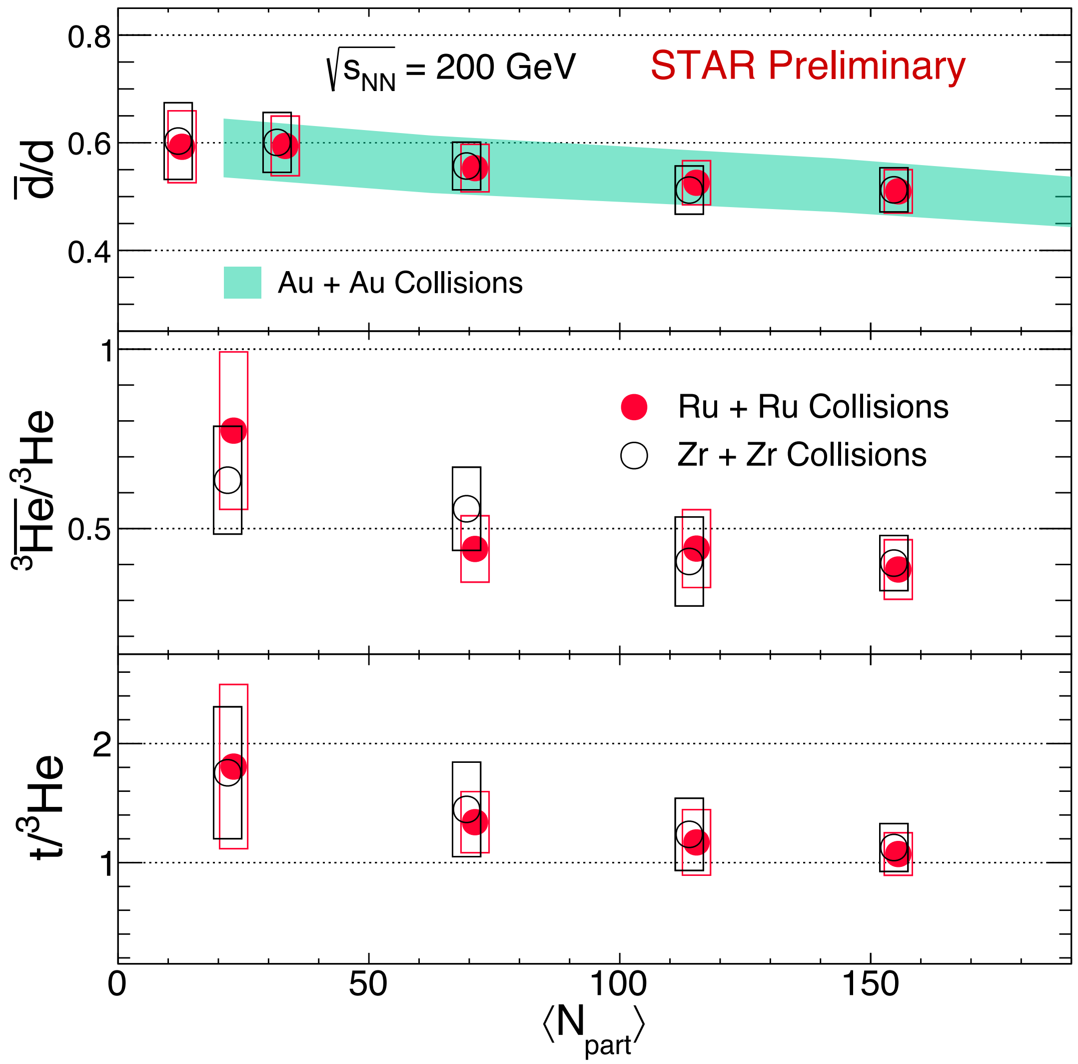
Centrality Dependence of dN/dy & $\langle p_T \rangle$



- Yields and $\langle p_T \rangle$ of light nuclei as a function of collision centrality
- dN/dy and $\langle p_T \rangle$ of d and $\bar{d}$ in Ru+Ru and Zr+Zr collisions agree well with Au+Au collisions within the uncertainty

J. Adam et al. [STAR Collaboration] Phys.Rev.C 99 (2019) 6, 064905

Centrality Dependence of Particle Ratios

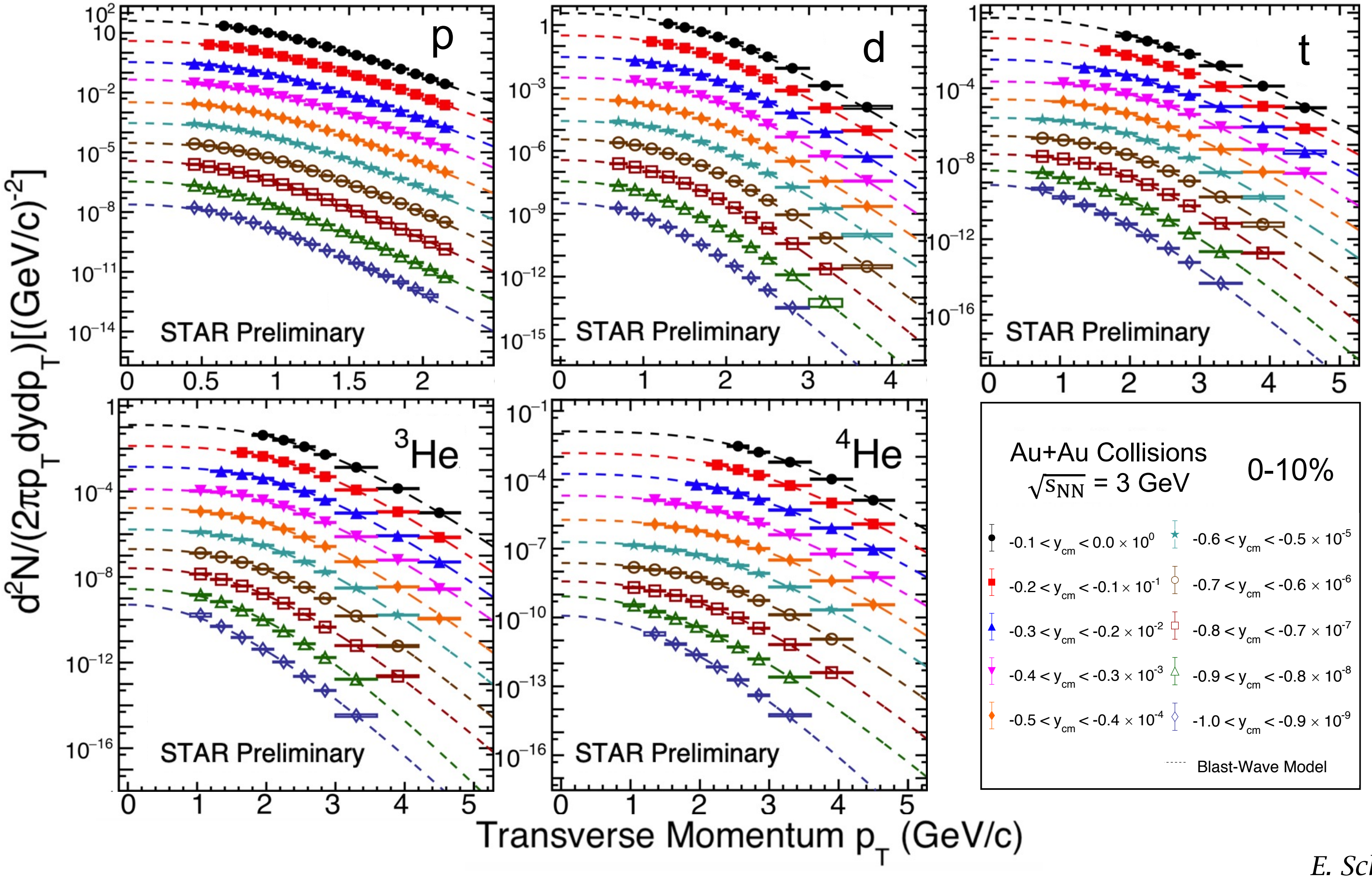


- The particle ratios ($\bar{d}/d$, $\overline{^3He}/^3He$ and $t/^3He$) increase from central to peripheral collisions
- $\bar{d}/d$ in Ru+Ru and Zr+Zr collisions are consistent with Au+Au collisions within the uncertainty

Result at $\sqrt{s_{NN}}$ = 3 GeV

Au+Au Collisions

Transverse Momentum Spectra



- Transverse momentum spectra of p, d, t, ^{3}He, and ^{4}He with rapidity slices in central (0-10%) Au+Au collisions at $\sqrt{s_{NN}}$ = 3 GeV

w/o feed-down correction for proton: ~2%

- Blast-Wave Function

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

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

Freeze-out parameters:

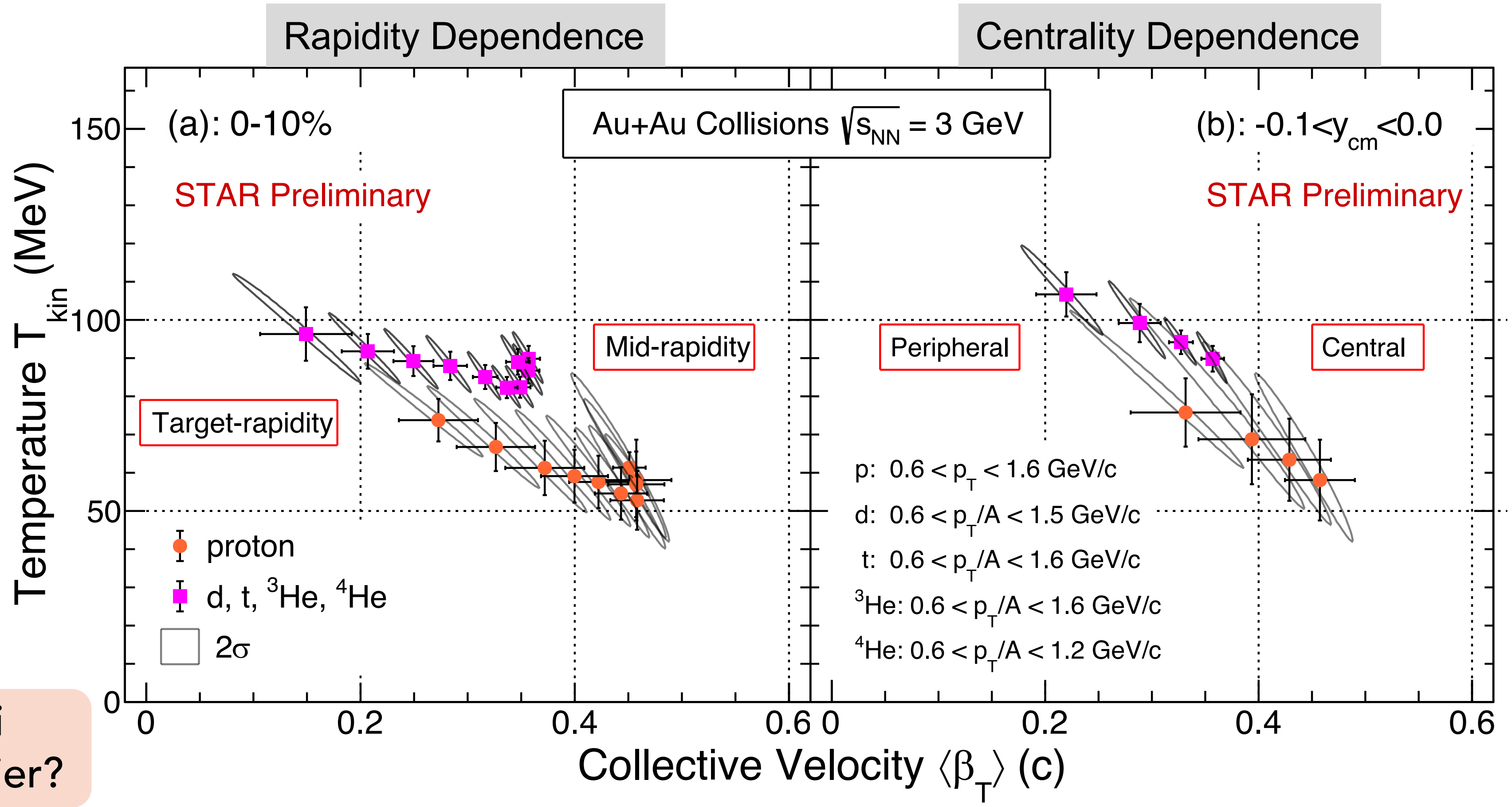
T_{kin} : kinetic freeze-out temperature

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

n : n=1 (I_0 and K_1 are from Bjorken Hydrodynamic assumption)

E. Schnedermann et al. Phys.Rev.C 48 (1993) 2462-2475

Kinetic Freeze-out Dynamics at 3 GeV

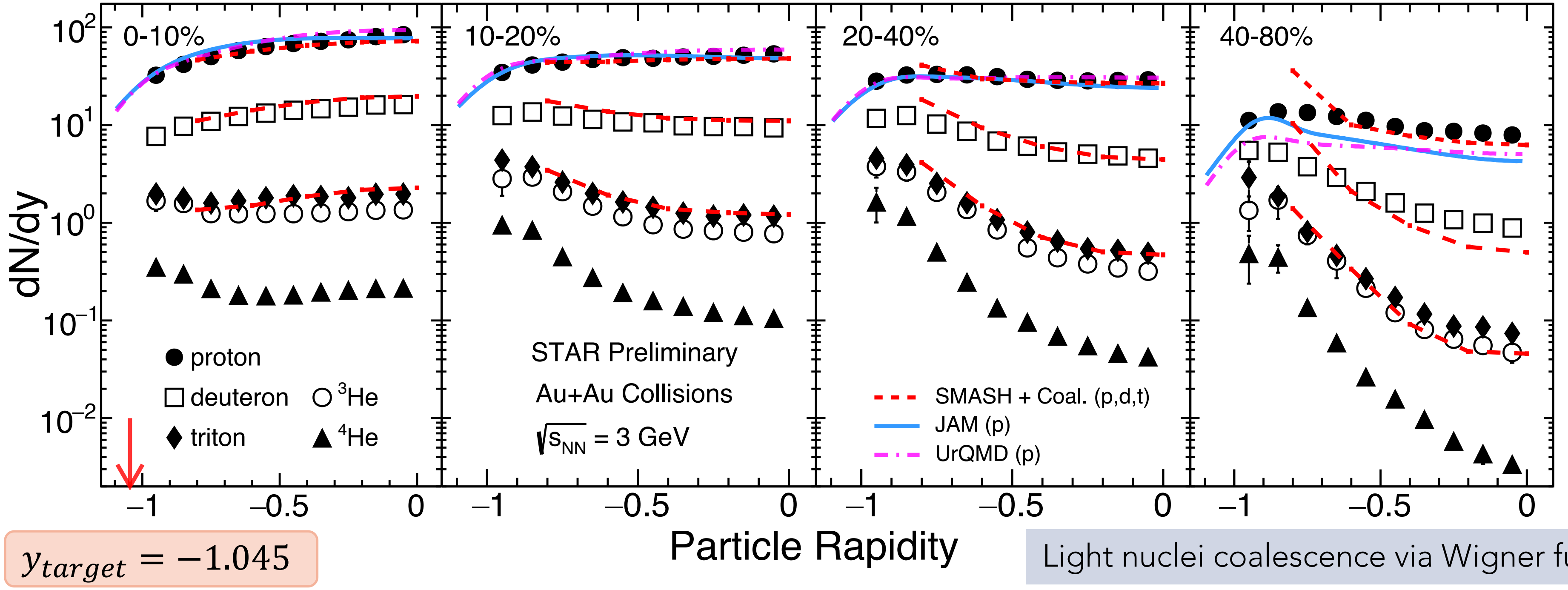


Light Nuclei freeze out earlier?

- ➢ The kinetic freeze-out parameters (T_{kin} and $\langle\beta_T\rangle$) show rapidity and centrality dependence
- ➢ The freeze-out parameter (T_{kin}) of the light nuclei is systematically higher than that of the protons

J. Adams et al. [STAR Collaboration] Nucl.Phys.A 757 (2005) 102-183

Centrality & Rapidity Dependence of Yields

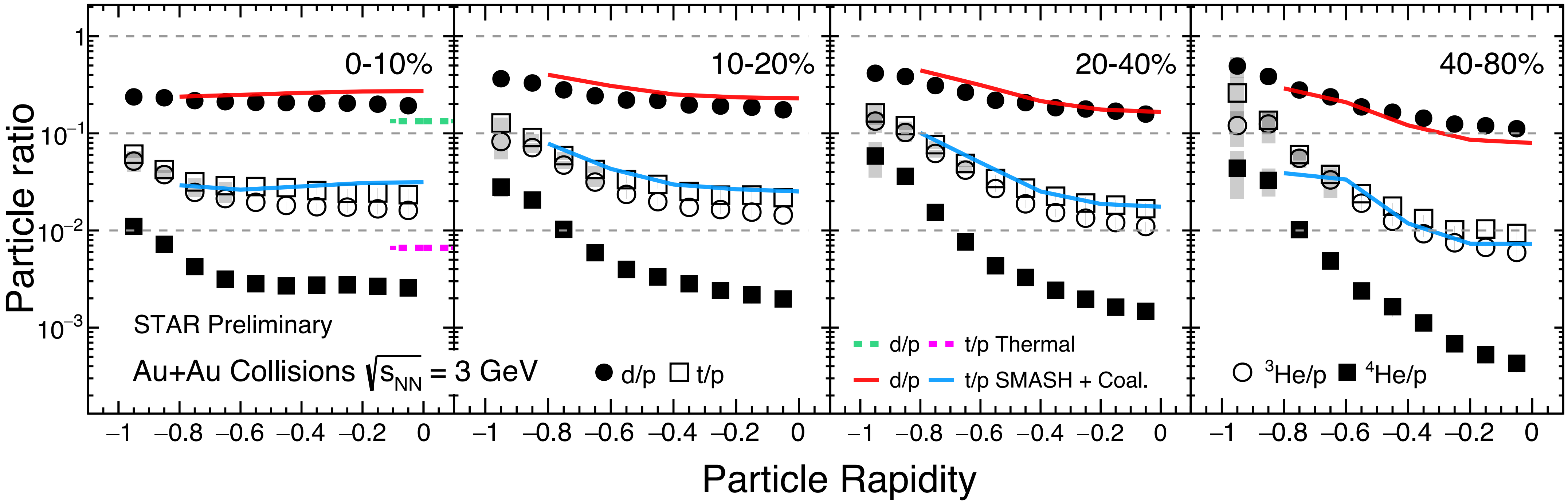


Light nuclei coalescence via Wigner function

- dN/dy of protons and light nuclei show significant centrality and rapidity dependence
- 3 GeV with good rapidity coverage provides the opportunity to calculate 4π yields accurately
- Yields of d and t are described by the SMASH + Coal. model except the 40-80% centrality bin
- dN/dy of p is reproduced by the SMASH, JAM, and UrQMD models in centrality bins: 0-10%, 10-20%, and 20-40%

J. Weil et al. Phys.Rev.C 94 (2016) 5, 054905
L. W. Chen et al. Phys.Rev.C 68 (2003) 017601
W. Zhao et al. Phys.Rev.C 98 (2018) 5, 054905

Rapidity Dependence of Particle Yield Ratios

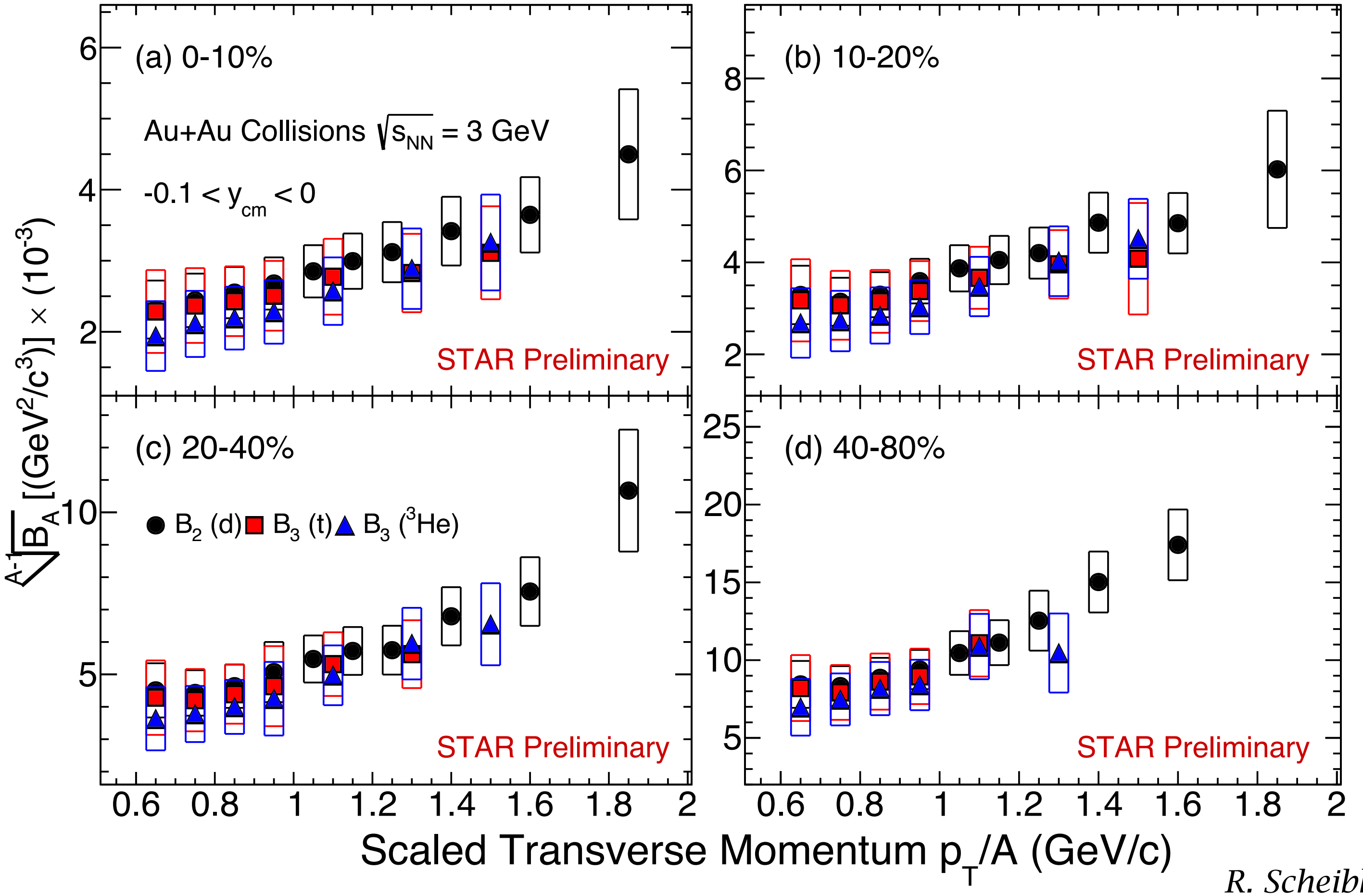


- ➢ The formation probability of light nuclei increases from middle to target rapidity
- ➢ Rapidity dependence is stronger in peripheral collisions
- ➢ The SMASH + Coalescence model reproduces the trends of d/p and t/p, but the thermal model underpredicts these ratios

A Andronic et al. Nature 561 (2018) 7723, 321-330

Coalescence Parameters

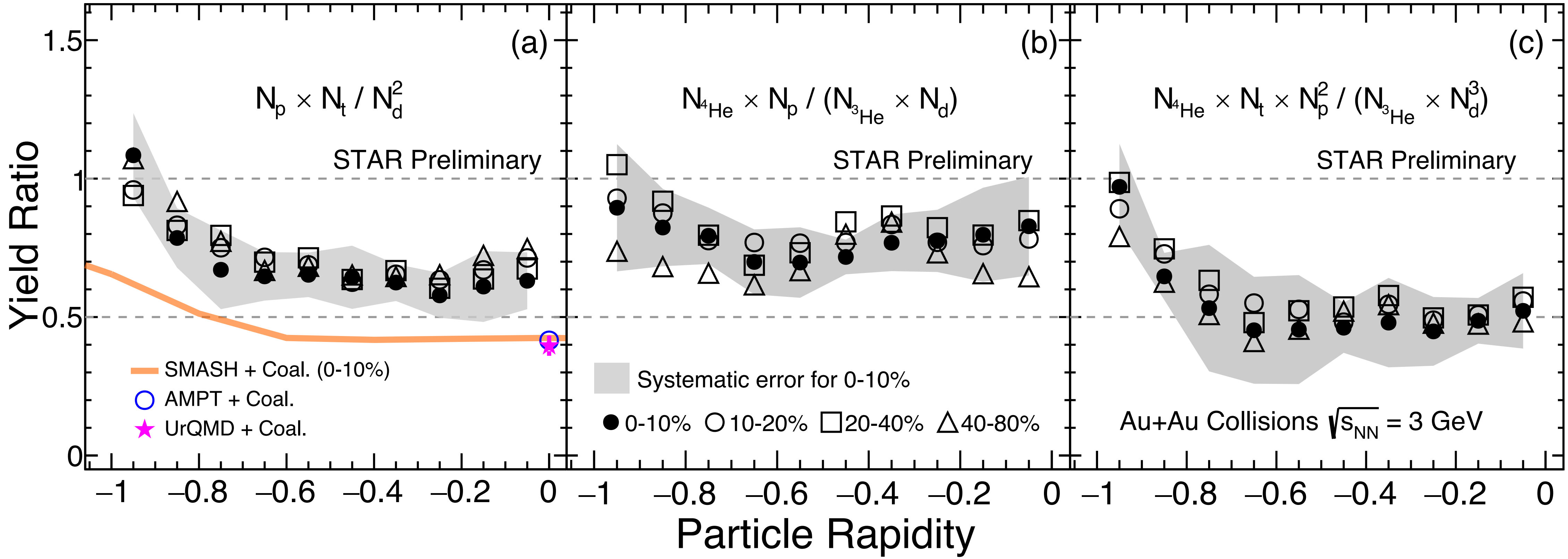
$$E_A \frac{d^3N_A}{dp_A^3} = B_A (E_p \frac{d^3N_p}{dp_p^3})^Z \, (E_n \frac{d^3N_n}{dp_n^3})^{A-Z} \approx B_A (E_p \frac{d^3N_p}{dp_p^3})^A \Big|_{p_p=p_n=\frac{p_A}{A}}$$



- $B_A \propto (1/V)^{(A-1)}$ 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
*J. Adam et al. **[STAR Collaboration]** Phys.Rev.C 99 (2019) 6, 064905*

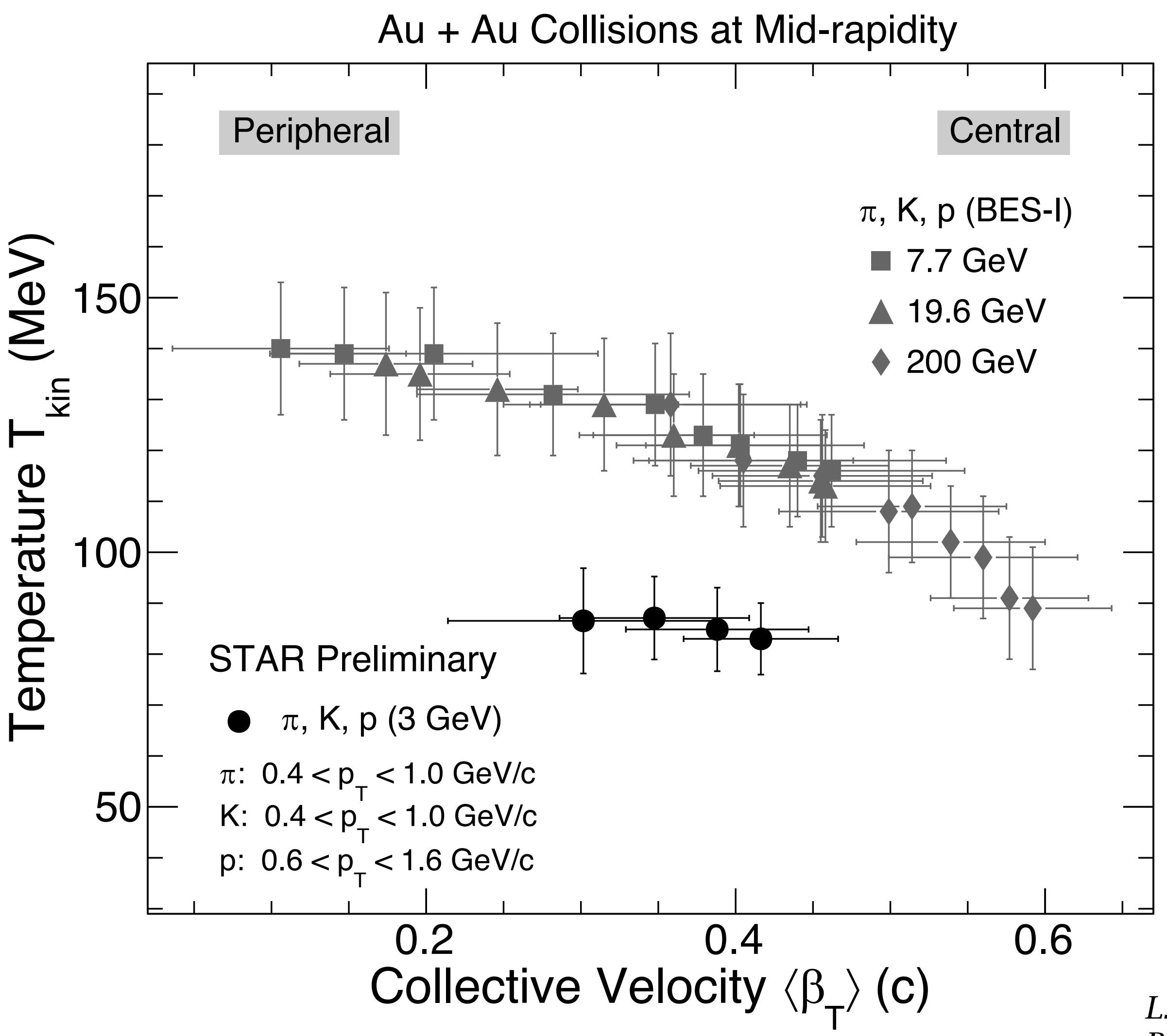
Rapidity Dependence of Yield Ratios



- Yield ratios show rapidity dependence, but no obvious centrality dependence
- $N_p \times N_t / N_d^2$: SMASH, AMPT, and UrQMD models underpredict the ratio in Au+Au collisions at 3 GeV

K. Sun et al. Phys.Rev.C 103 (2021) 6, 064909
E. Shuryak et al. Eur.Phys.J.A 56 (2020) 9, 241

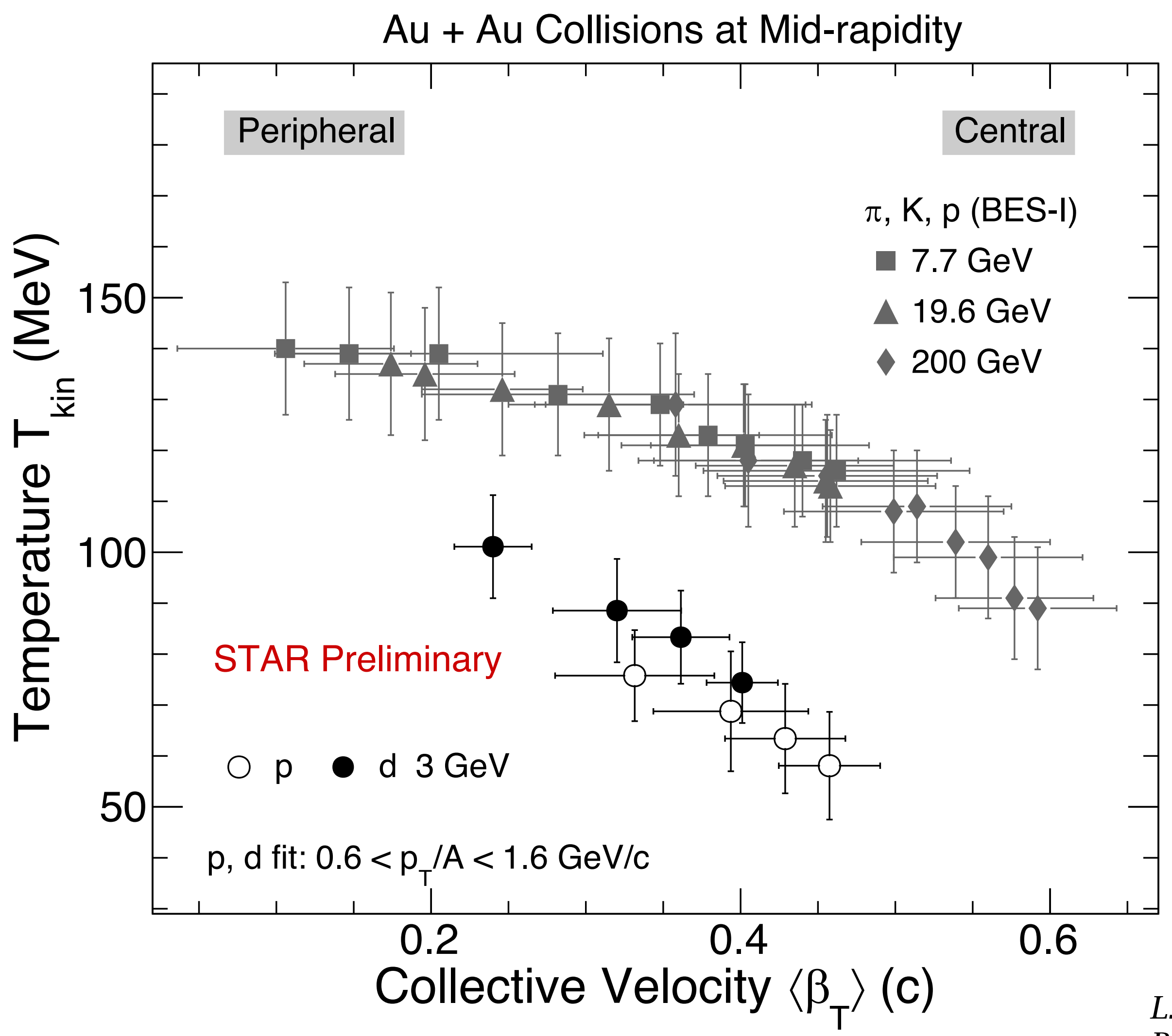
Discussions – Simultaneous Fitting of π, K, p



- At 3 GeV Au+Au collisions, the freeze-out parameters (T_{kin}, $\langle\beta_T\rangle$) show different trend compared to that of higher energy collisions

L. Adamczyk et al. [STAR Collaboration] Phys.Rev.C 96 (2017) 4, 044904
B.I. Abelev et al. [STAR Collaboration] Phys.Rev.C 79 (2009) 034909

Discussions – Separate Fitting of p, d

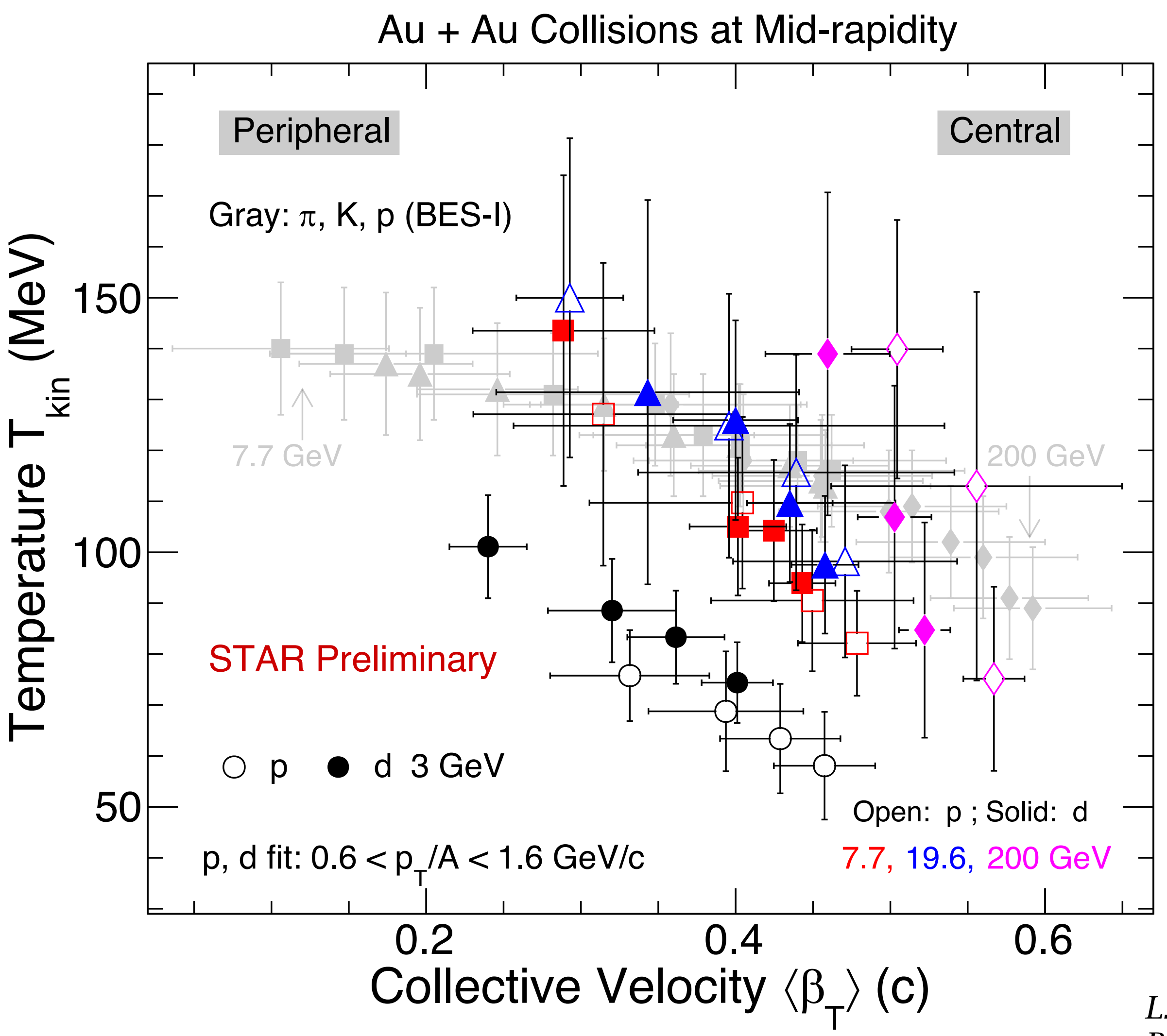


- At 3 GeV Au+Au collisions, the freeze-out parameters (T_{kin}, $\langle\beta_T\rangle$) show different trend compared to that of higher energy collisions

Indicate a different equation of state (EoS)

L. Adamczyk et al. [STAR Collaboration] Phys.Rev.C 96 (2017) 4, 044904
B.I. Abelev et al. [STAR Collaboration] Phys.Rev.C 79 (2009) 034909

Discussions – Separate Fitting of p, d



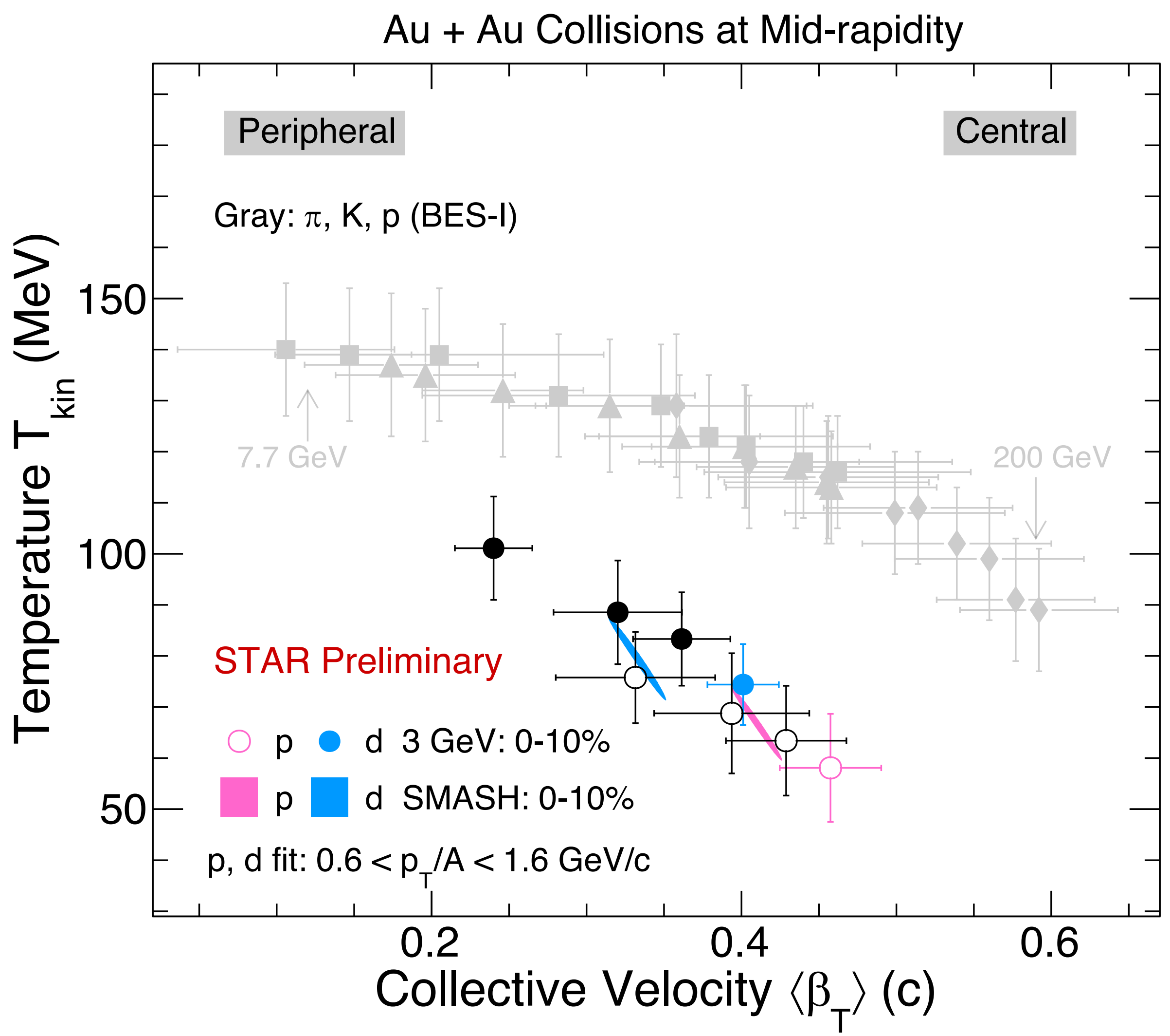
- At 3 GeV Au+Au collisions, the freeze-out parameters (T_{kin}, $\langle\beta_T\rangle$) show different trend compared to that of higher energy collisions

Indicate a different equation of state (EoS)

- The freeze-out parameter (T_{kin}) of d is systematically higher than that of p at 3 GeV, which is different from higher energies

L. Adamczyk et al. [STAR Collaboration] Phys.Rev.C 96 (2017) 4, 044904
B.I. Abelev et al. [STAR Collaboration] Phys.Rev.C 79 (2009) 034909

Discussions – Separate Fitting of p, d



- At 3 GeV Au+Au collisions, the freeze-out parameters (T_{kin}, $\langle\beta_T\rangle$) show different trend compared to that of higher energy collisions

Indicate a different equation of state (EoS)

- The freeze-out parameter (T_{kin}) of d is systematically higher than that of p at 3 GeV, which is different from higher energies

Similar trend seen in SMASH Model
$T_d > T_p$

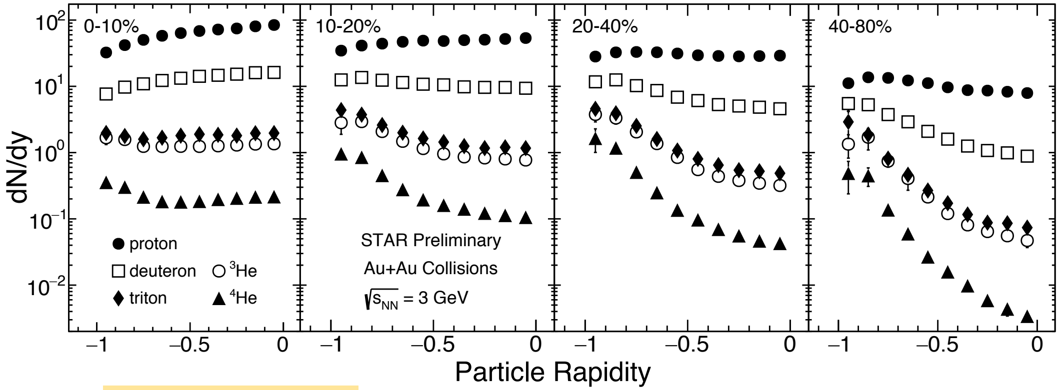
Summary

1. 200 GeV Ru+Ru and Zr+Zr collisions: First results of centrality dependent spectra of d ($\bar{d}$), t, and $^{3}\mathrm{He}$ ($\overline{^{3}\mathrm{He}}$)
   - ➜ The yields of light nuclei are consistent in Ru+Ru and Zr+Zr collisions

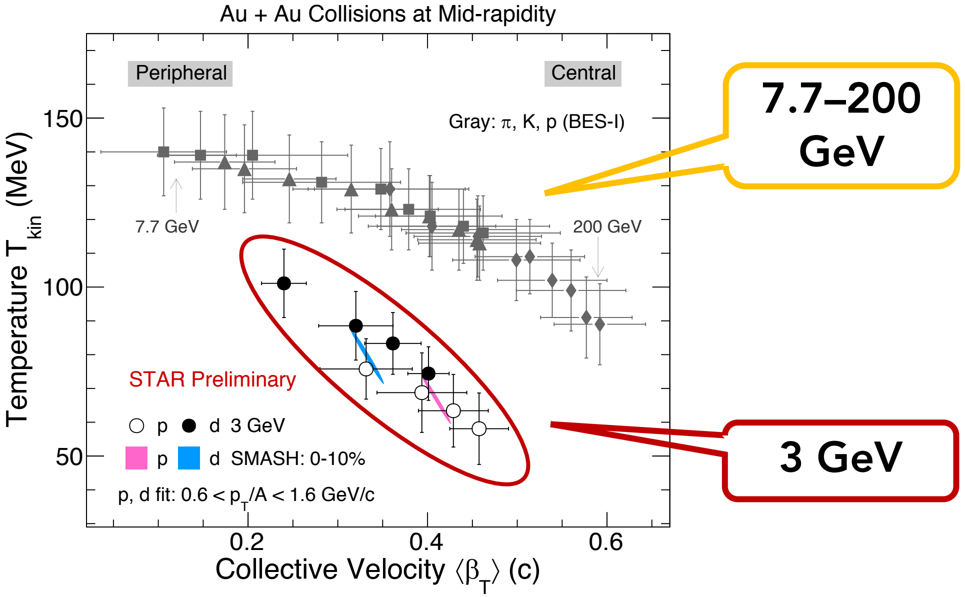
2. 3 GeV Au+Au collisions: First measurements of rapidity densities of p and light nuclei (d, t, $^{3}\mathrm{He}$, $^{4}\mathrm{He}$)
   - ➜ Strong centrality and rapidity dependences observed
   - ➜ Hadronic transport models (JAM, SMASH and UrQMD) + Coalescence reproduce the mid-rapidity yields, but thermal model underpredicts light nuclei yield ratios
   - ➜ The freeze-out parameters ($\mathrm{T_{kin}}$, $\langle\beta_{\mathrm{T}}\rangle$) show a different trend compared to that of higher energy collisions: $\mathrm{T_{kin}}(d) > \mathrm{T_{kin}}(p)$, $\langle\beta_{\mathrm{T}}\rangle(d) < \langle\beta_{\mathrm{T}}\rangle(p)$

➡ **Hot and dense medium created in the 3 GeV collisions seems different from that of high energy collisions**

Rapidity density: p, d, t, $^{3}\mathrm{He}$ & $^{4}\mathrm{He}$



Freeze-out



Outlook

Au+Au collisions at RHIC (Collider mode)		
$\sqrt{s_{NN}}$ (GeV)	nEvents (M)	μ_B (MeV)
19.6	478	206
17.3	256	230
14.6	324	262
11.5	235	320
9.2	162	370
7.7	101	420

Au+Au collisions at RHIC (Fixed-Target mode)			
$\sqrt{s_{NN}}$ (GeV)	E_{beam} (GeV)	nEvents (M)	μ_B (MeV)
13.7	100	51	280
11.5	70	52	320
9.2	44.5	54	370
7.7	31.2	113	420
7.2	26.5	89	440
6.2	19.5	118	490
5.2	13.5	103	540
4.5	9.8	108	590
3.9	7.3	117	633
3.5	5.75	116	670
3.2	4.59	201	699
3.0	3.85	2103	750

1. STAR has completed BES-II data-taking with factors of 10 – 20 more statistics compared to BES-I
2. Systematic analysis of light nuclei yields and spectra to understand their production mechanism

QM QUARK MATTER KRAKÓW 2022

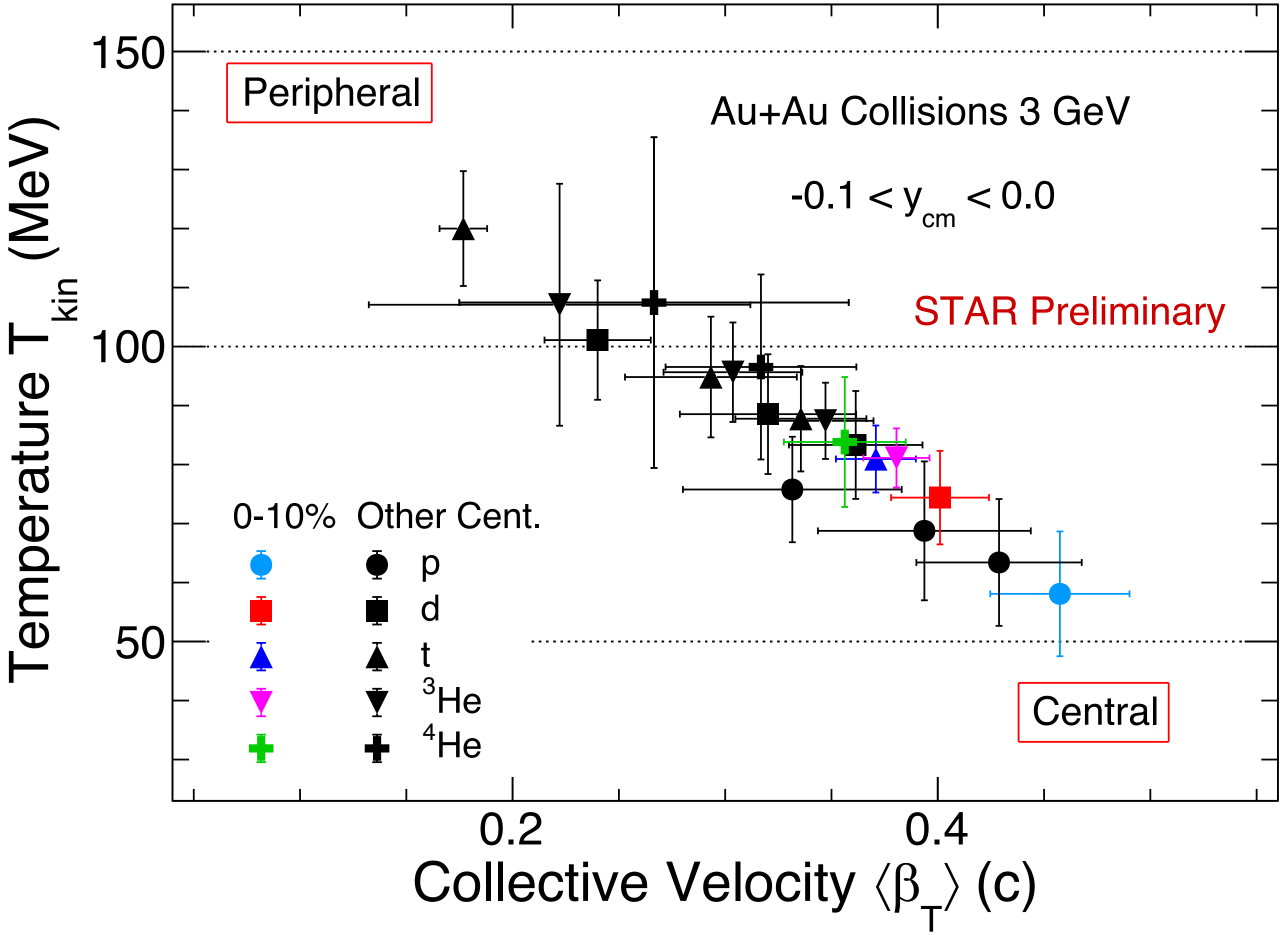
29TH INTERNATIONAL CONFERENCE ON ULTRARELATIVISTIC NUCLEUS - NUCLEUS COLLISIONS

APRIL 4-10, 2022

KRAKÓW, POLAND

Thanks for your attention!

Backup – Kinetic Freeze-out Dynamics



➢ The freeze-out parameter (T_{kin}) of the light nuclei is systematically higher than that of the protons