Production of Light Nuclei in Au+Au Collisions with the STAR BES-II Program

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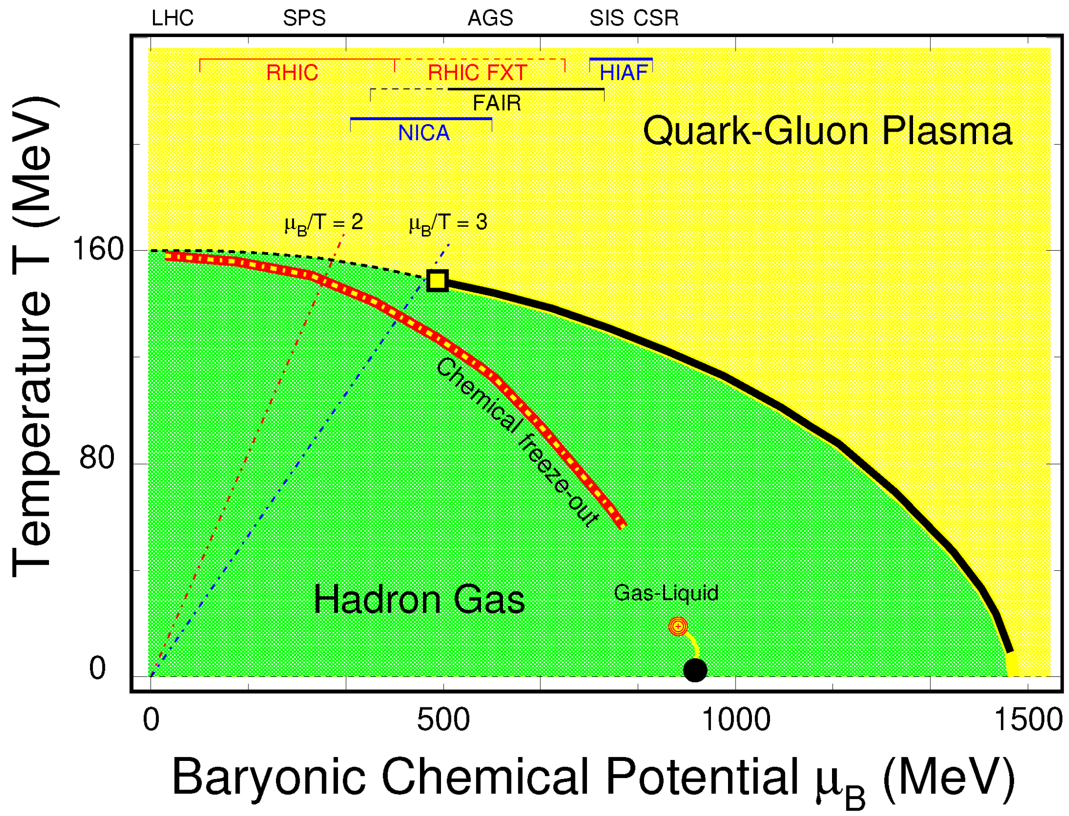
Outline

- Motivation
- The STAR Experiment
  - Dataset and Particle Identification
- Results and Discussions
  - Transverse Momentum Spectra
  - Particle Yields and Ratios
  - Coalescence Parameters
  - Nuclear Modification Factors
- Summary and Outlook

Motivation – QCD Phase Diagram and HIC

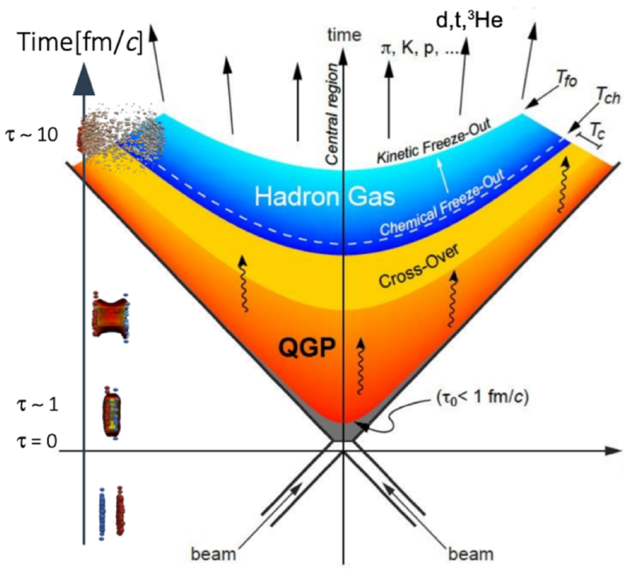


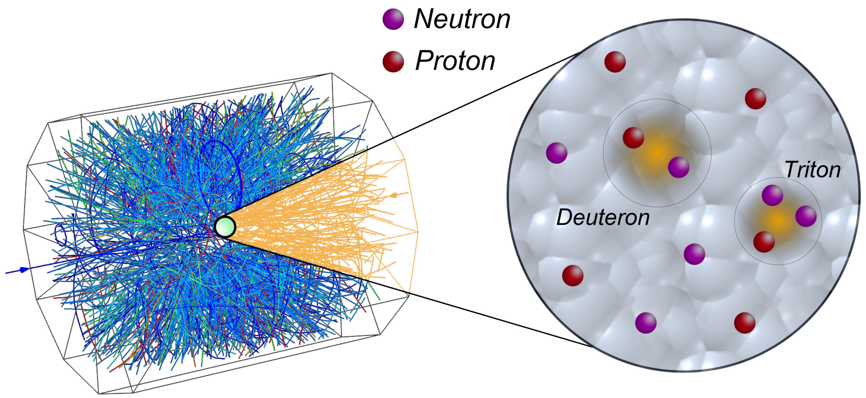
Beam Energy Scan Program at RHIC:

- Control beam energy and centrality to vary initial T and μ_{B}.
- Create QGP and explore its properties.
- Map out the crossover and/or 1st order QCD phase boundary.
- Search for the signatures of possible QCD critical point.

H.T. Ding, F. Karsch, S. Mukherjee, Int. J. Mod. Phys. E 24 (2015) 10, 1530007
X. Luo, N. Xu, Nucl. Sci. Tech. 28, 112 (2017)
X. Luo, Q. Wang, N. Xu, P. F. Zhuang. *Properties of QCD Matter at High Baryon Density.* Springer, 2022, doi:10.1007/978-981-19-4441-3
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

Motivation – Light Nuclei





1. Why Light Nuclei?

- May carry information about local baryon density fluctuations.
- Provide an effective probe to study 1st order phase boundary and the QCD critical point.

2. Observable : Yield ratio of light nuclei $(\mathrm{N_t \times N_p / N_d^2})$

- Based on coalescence model:

$$N_A = g_c \int d\Gamma \rho_s(\{x_i, p_i\}) \times W_A(\{x_i, p_i\})$$

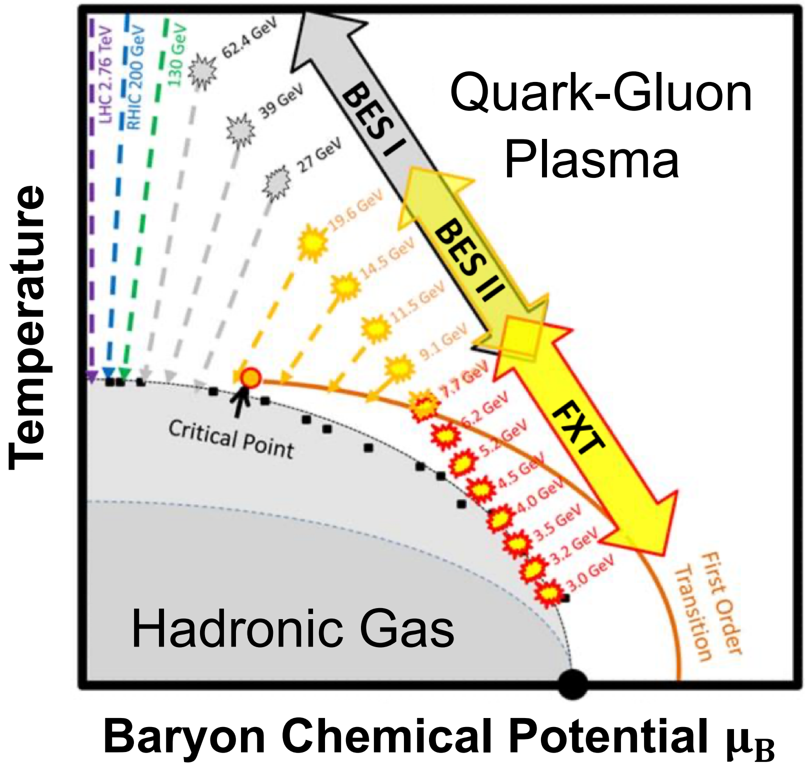
- The yield ratio is related to neutron density fluctuations:

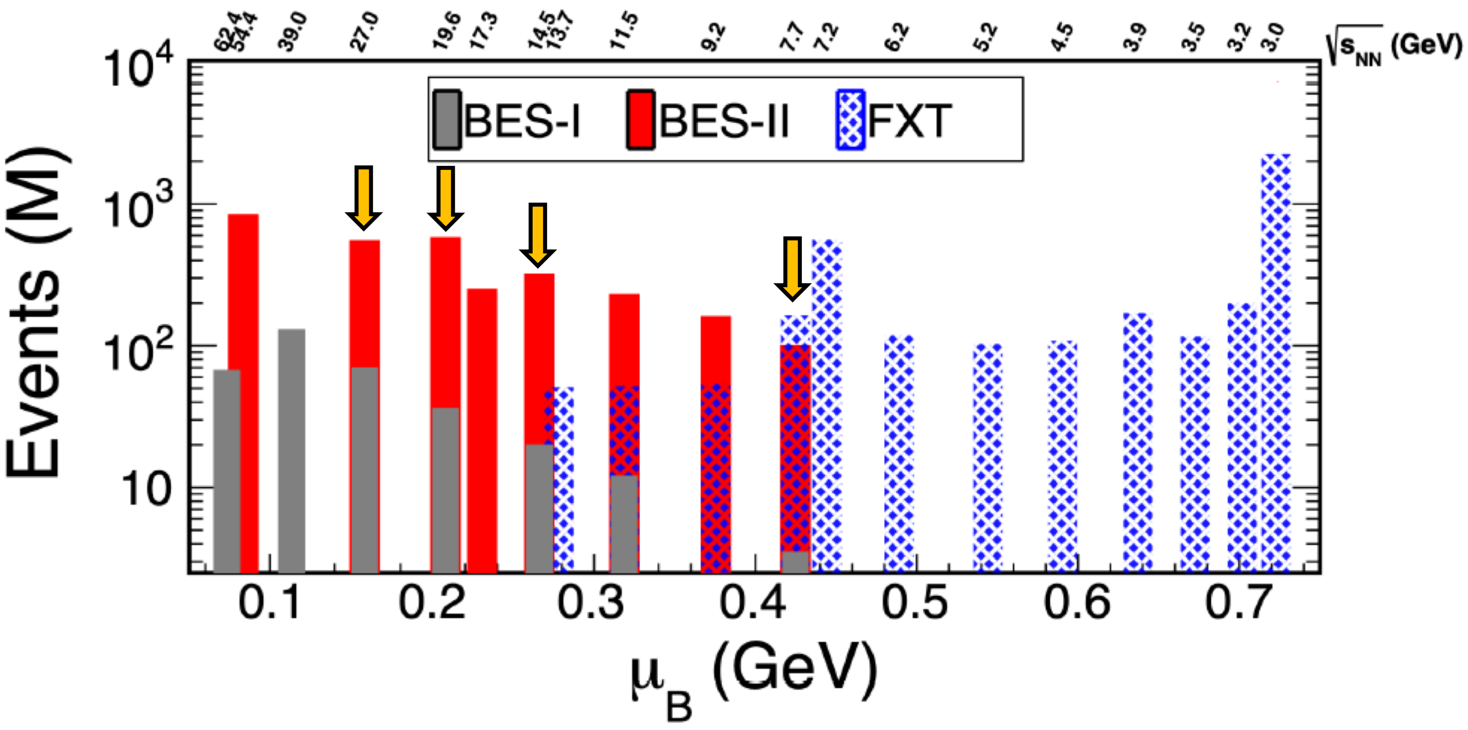
$$N_t \times N_p / N_d^2 \approx g(1 + \Delta n)$$

factor $g = \frac{1}{2\sqrt{3}}$ comes from the thermal equilibrium assumption of nucleon abundances.

K. Sun et al. Phys.Lett.B 774 (2017) 103-107
E. Shuryak et al. Phys.Rev.C 101 (2020) 3, 034914

RHIC Beam Energy Scan Program

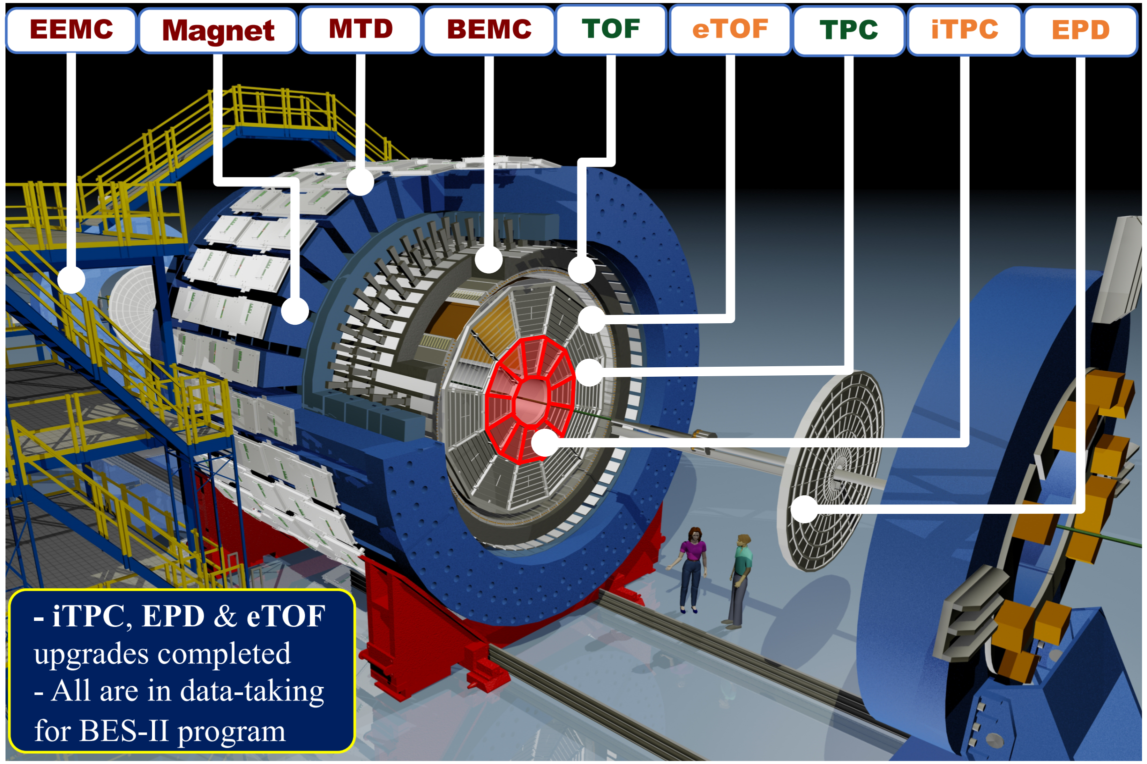




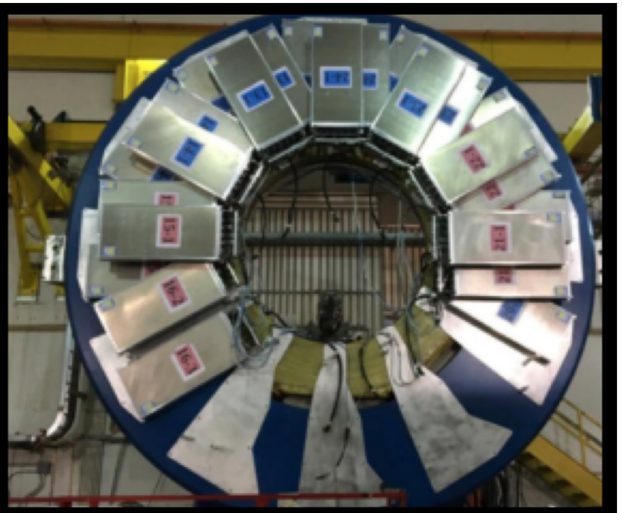
- STAR has completed BES-II data-taking with factors of 10 – 20 more statistics compared to BES-I.
- BES-II: 8 collider energies ($\sqrt{s_{\mathrm{NN}}}$ = 7.7 – 54 GeV) / 12 FXT energies ($\sqrt{s_{\mathrm{NN}}}$ = 3.0 – 13.7 GeV)
- μ_B coverage : $25 < \mu_B < 750$ MeV.

STAR Collaboration, arXiv:1007.2613
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0493
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

The Solenoidal Tracker At RHIC (STAR)



Detector upgrades for STAR BES-II



iTPC:

- Improves $\mathrm{d}E/\mathrm{d}x$
- Extends η coverage from 1.0 to 1.5
- Lower p_{T} cut-in from 125 to 60 MeV/c
- Ready in 2019

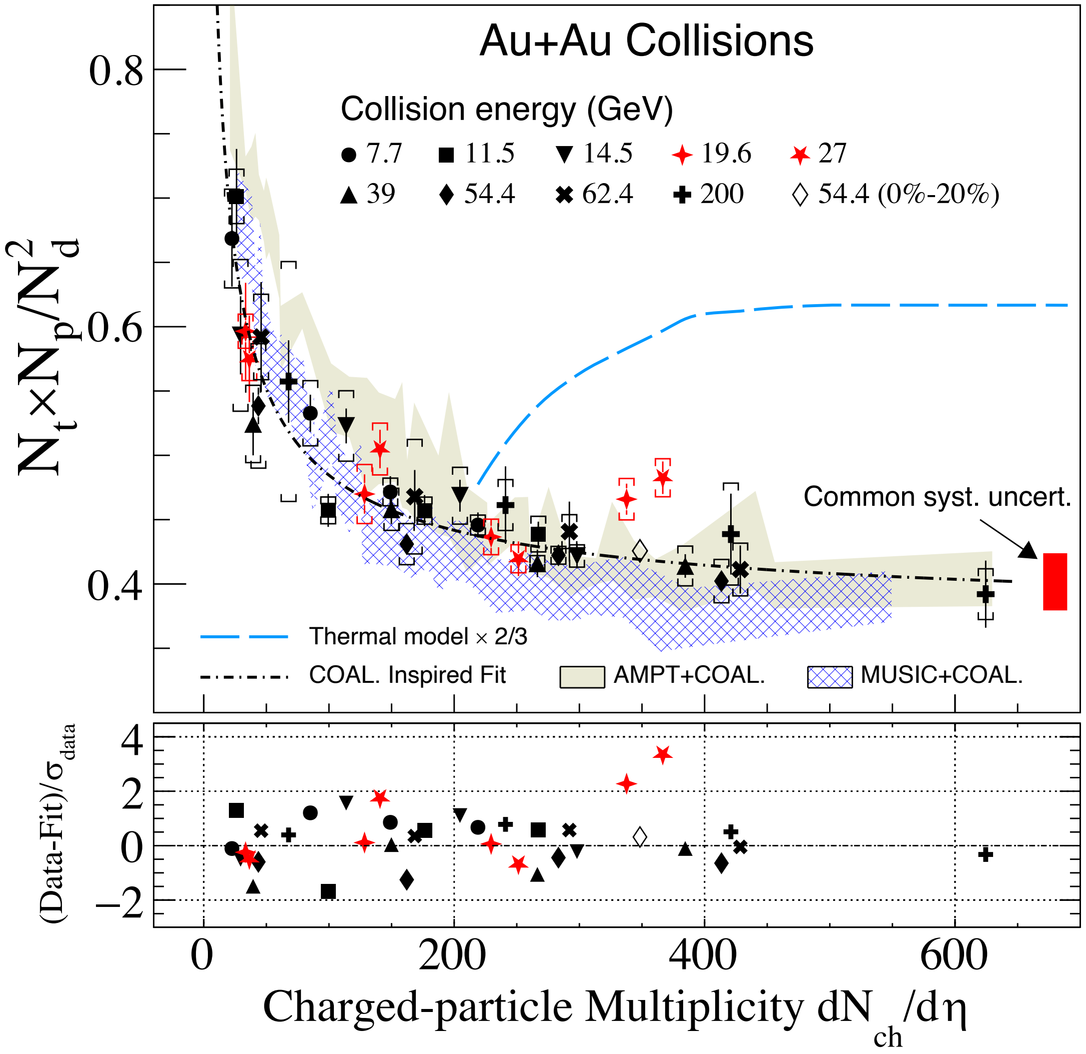
eTOF:

- Forward rapidity coverage
- η coverage from 1.0 to 1.5
- Borrowed from CBM-FAIR
- Ready in 2019

iTPC: https://drupal.star.bnl.gov/STAR/starnotes/public/sn0619
eTOF: STAR and CBM eTOF group, arXiv: 1609.05102

- **Enlarge the rapidity acceptance**
- **Improve particle identification**
- **Lower p_{T} cut-in to reduce uncertainty in spectra extrapolation**

Results from RHIC BES-I



STAR Collaboration, Phys.Rev.Lett. 130, 202301 (2023)

- The yield ratio exhibits a scaling behavior: A trend driven by the interplay between the size of light nuclei and the size of the fireball created in HIC.

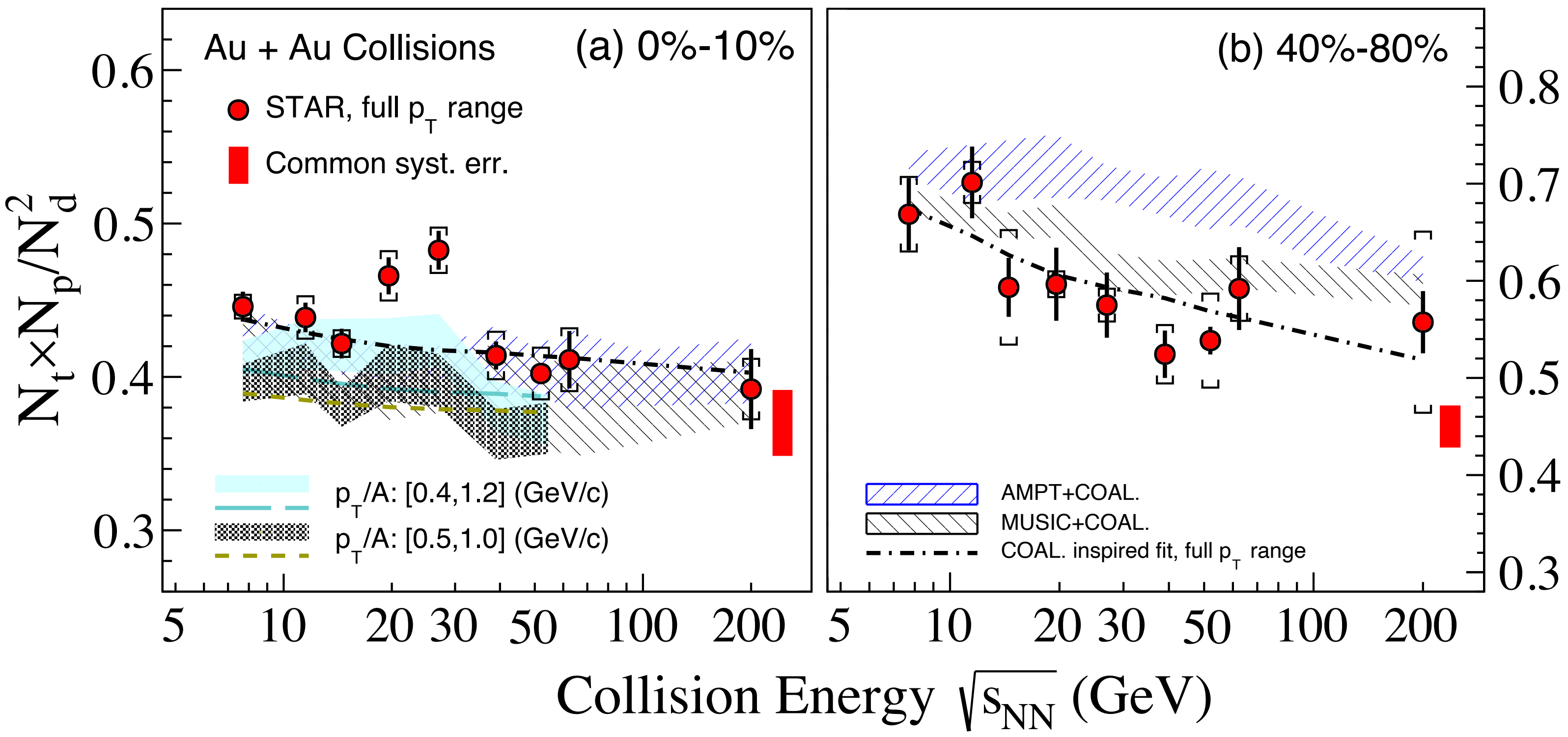
$$\frac{N_t \times N_p}{N_d^2} = p_0 \times \left(\frac{R^2 + \frac{2}{3} r_d^2}{R^2 + \frac{1}{2} r_t^2} \right)^3, \text{where } R \propto (dN_{ch}/d\eta)^{1/3}.$$

W. Zhao, K. J. Sun, C. M. Ko and X. Luo, Phys. Lett. B 820 (2021) 136571

- The ratios at $\sqrt{s_{NN}}$ = 19.6 and 27 GeV in 0-10% centrality show enhancements with respect to the coalescence baseline with a combined significance of 4.1σ.

- The thermal model overestimates the experimental data and shows a clear difference compared to the coalescence model.

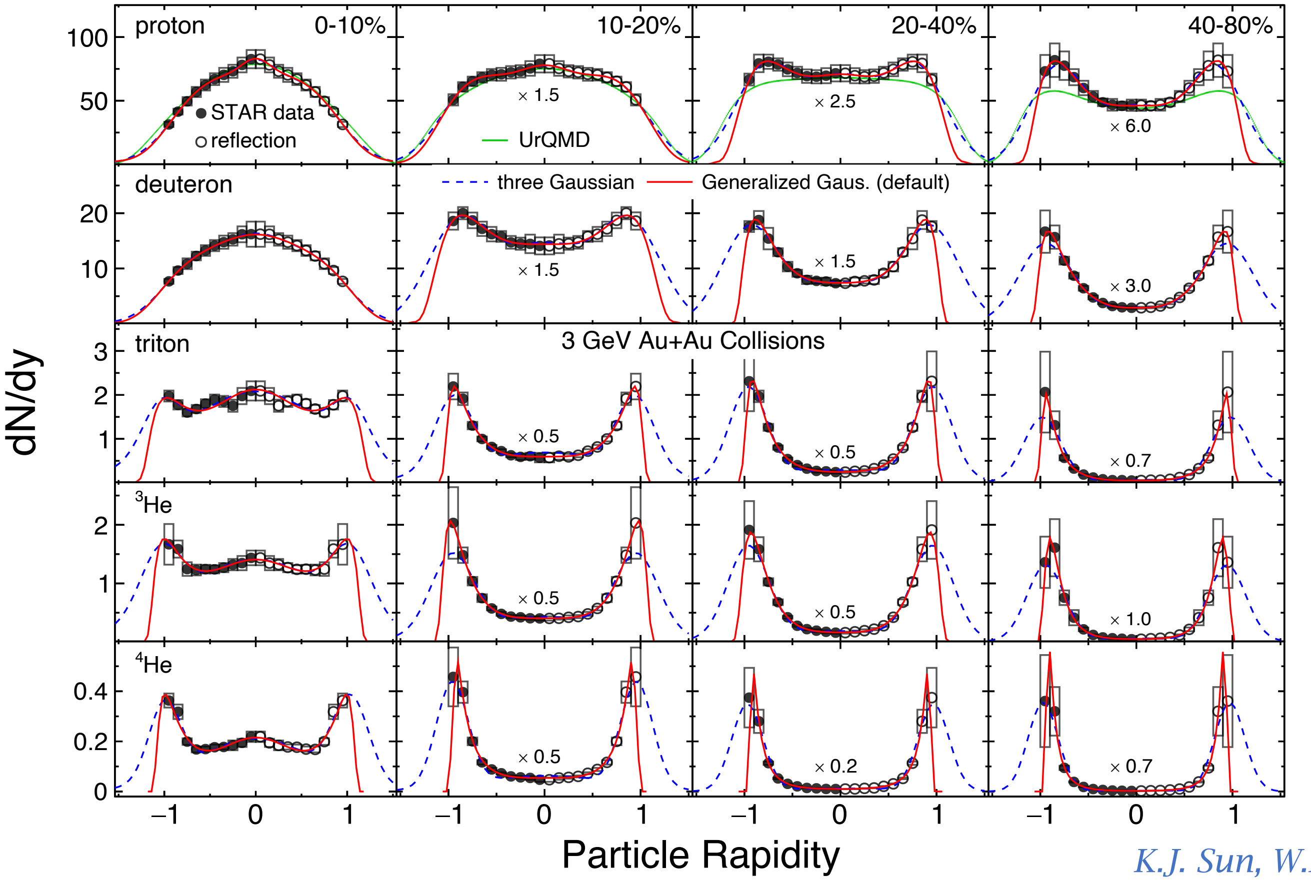
Results from RHIC BES-I

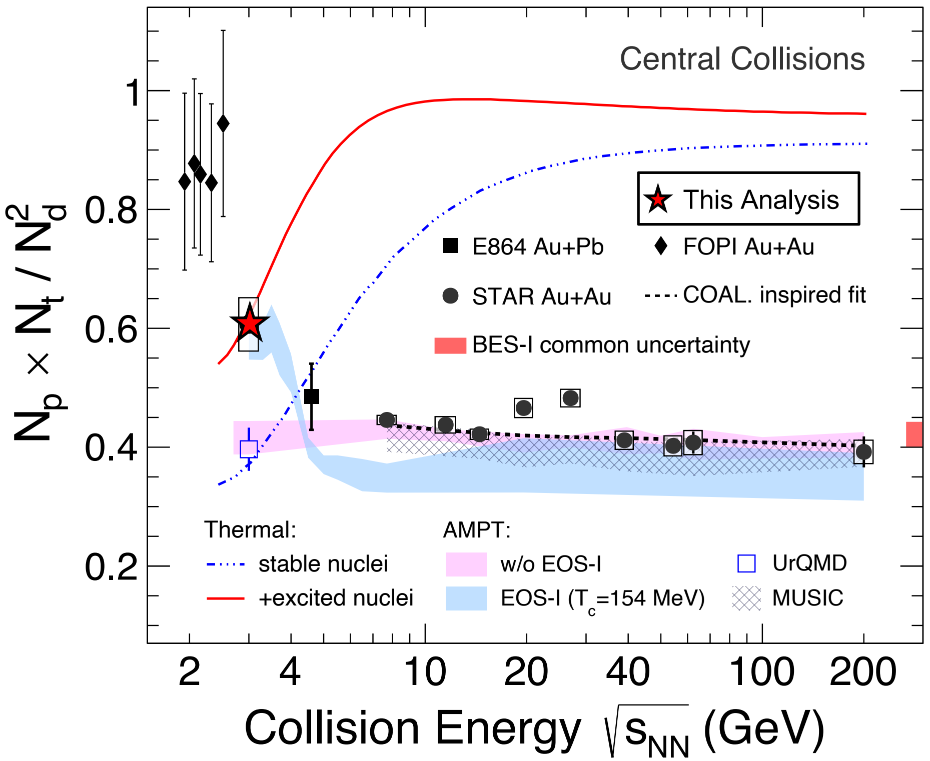


STAR Collaboration, Phys.Rev.Lett. 130 (2023) 202301

- **Non-monotonic** behavior observed in 0-10% central Au+Au collisions around $\sqrt{s_{NN}}$ = 19.6 and 27 GeV.
- **Monotonic behavior** in peripheral collisions can be well described by coalescence inspired fit.
- Flat trends are predicted by theoretical models of AMPT and MUSIC + UrQMD hybrid model.

Results from RHIC FXT at $\sqrt{s_{NN}} = 3$ GeV





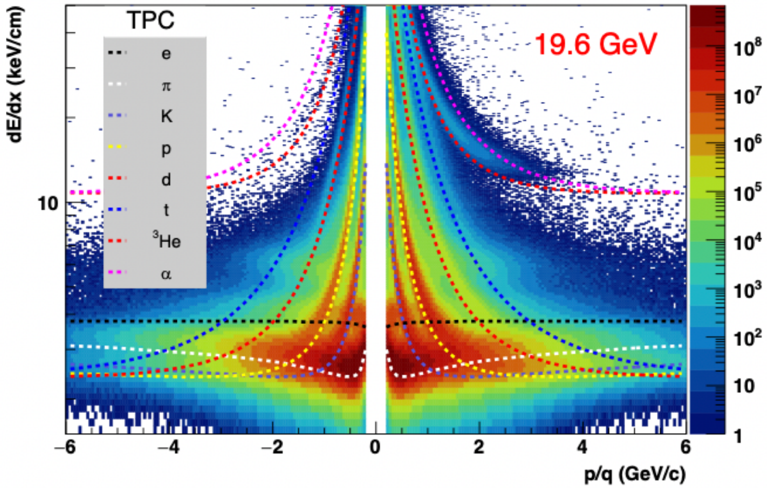
STAR Collaboration, arXiv: 2311.11020

K.J. Sun, W.H. Zhou, L.W. Chen, C.M. Ko, F. Li, R. Wang, J. Xu, arXiv: 2205.11010

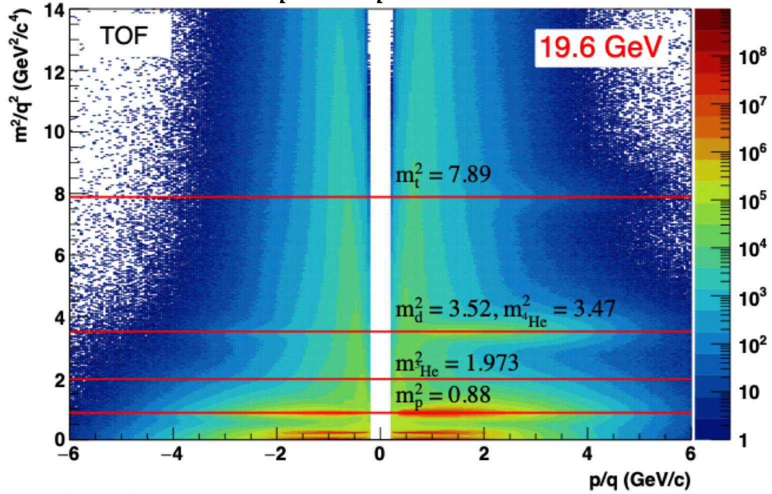
- Measured the rapidity dependence of light nuclei production.
  - The centrality dependence of rapidity density is attributed to the interplay between baryon stopping and the spectators' contribution.
- The yield ratio $N_t \times N_p / N_d^2$ of mid-rapidity measured at $\sqrt{s_{NN}} = 3$ GeV follow the trend of world data.

Particle Identification and Signal Extraction

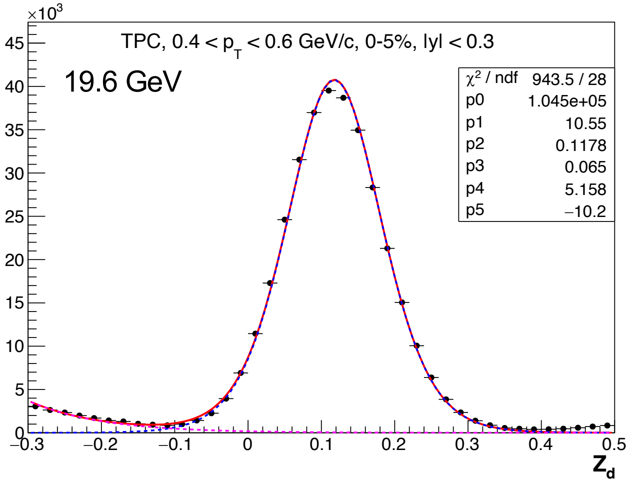
TPC: $z = \log\left(\frac{\langle dE/dx\rangle_{measure}}{\langle dE/dx\rangle_{Bichsel}}\right)$

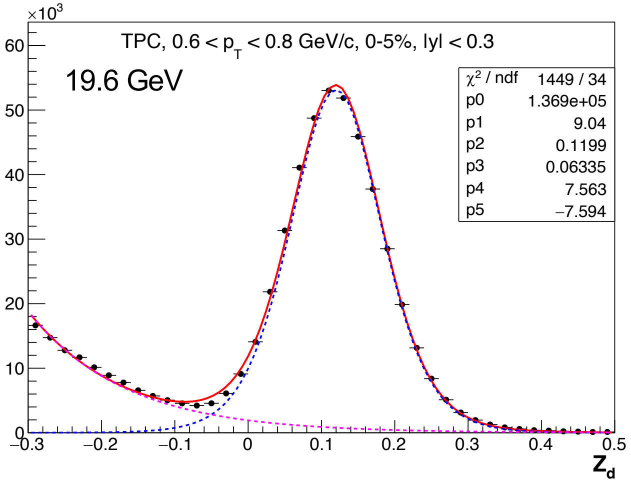


TOF: $\frac{m^2}{q^2} = \frac{p^2}{q^2}\left(\frac{c^2t^2}{L^2} - 1\right)$



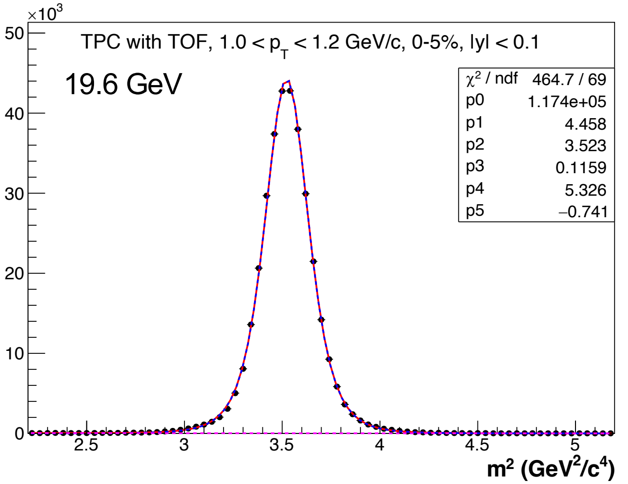
Signal Extraction Examples (19.6 GeV, deuteron, 0-5%)

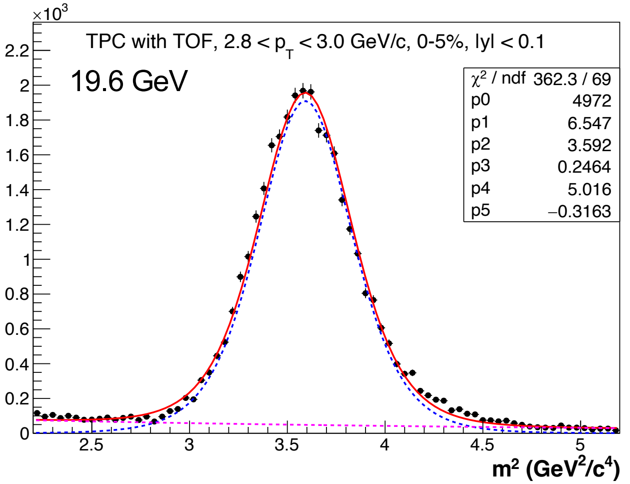




Low p_T: TPC

Signal: Gaussian (Blue)
BG: Gaussian (Magenta)
Total: (Red)

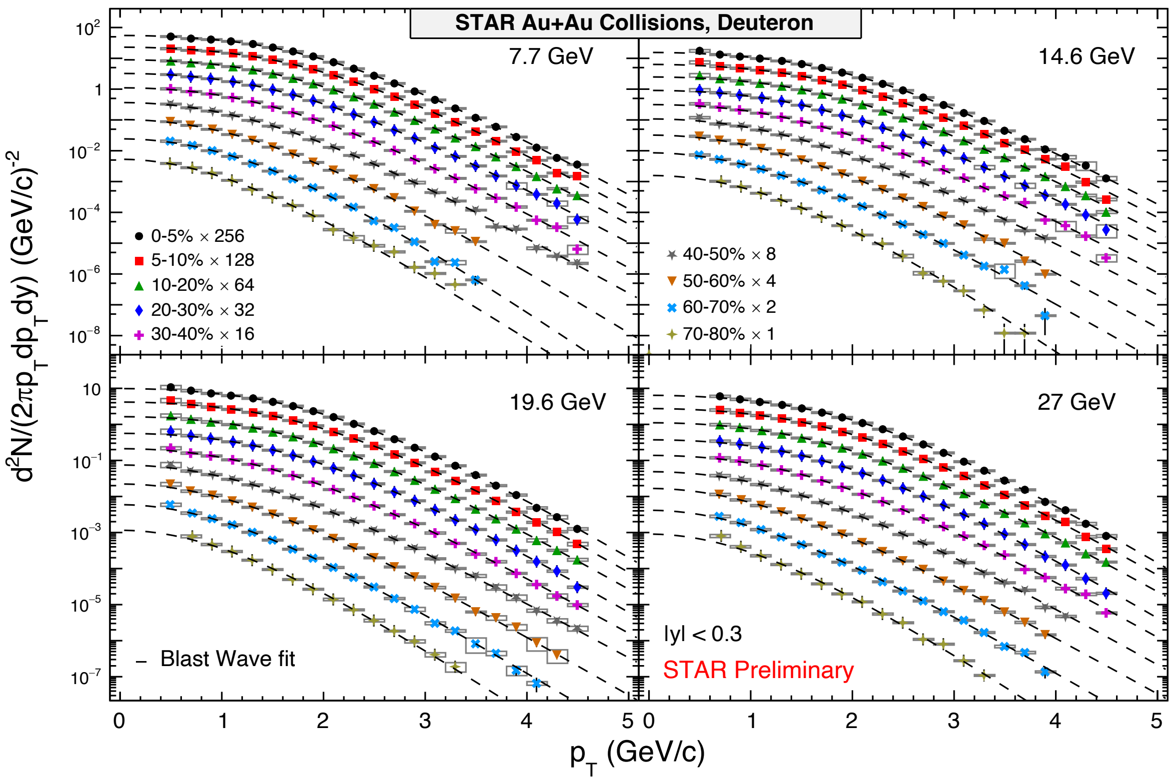


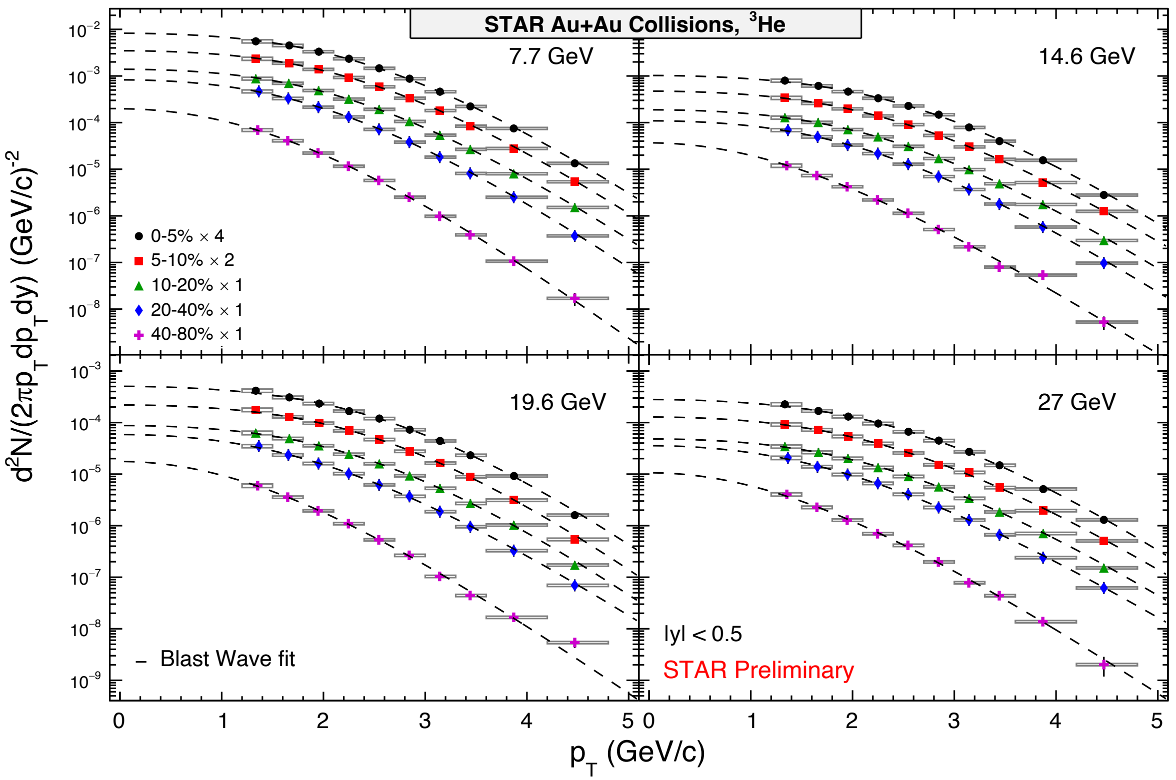


High p_T: TPC with TOF

Signal: Student-t (Blue)
BG: Gaussian (Magenta)
Total: (Red)

Transverse Momentum Spectra





❖ Blast-Wave Function

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

$\rho = \tanh^{-1}\beta_r$, $\beta_r(r) = \beta_T \left(\frac{r}{R}\right)^n$, n fix to 1 in this analysis

Freeze-out parameters:

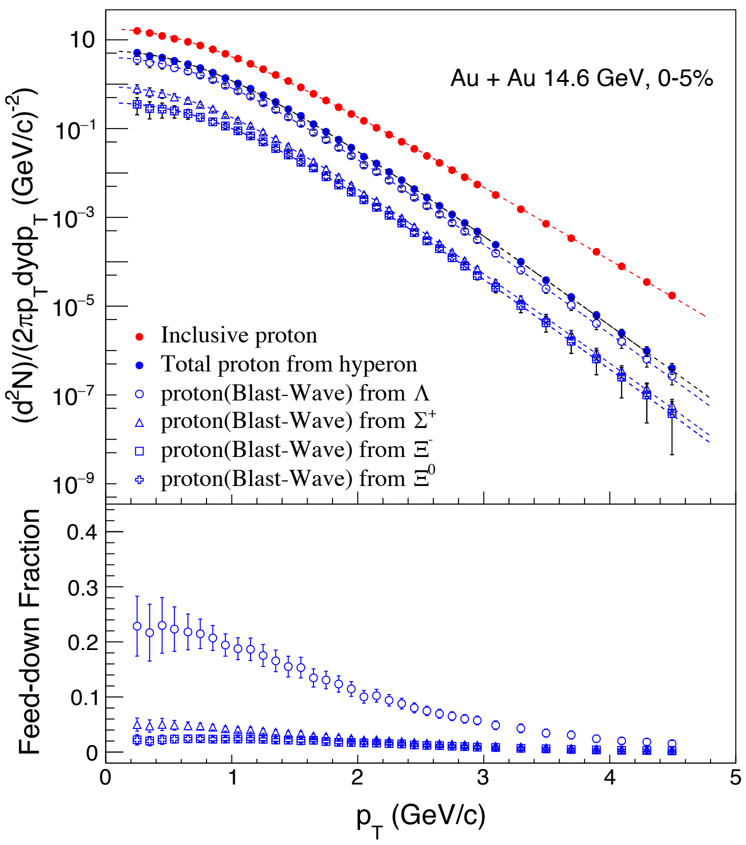
T_{kin} : kinetic freeze-out temperature

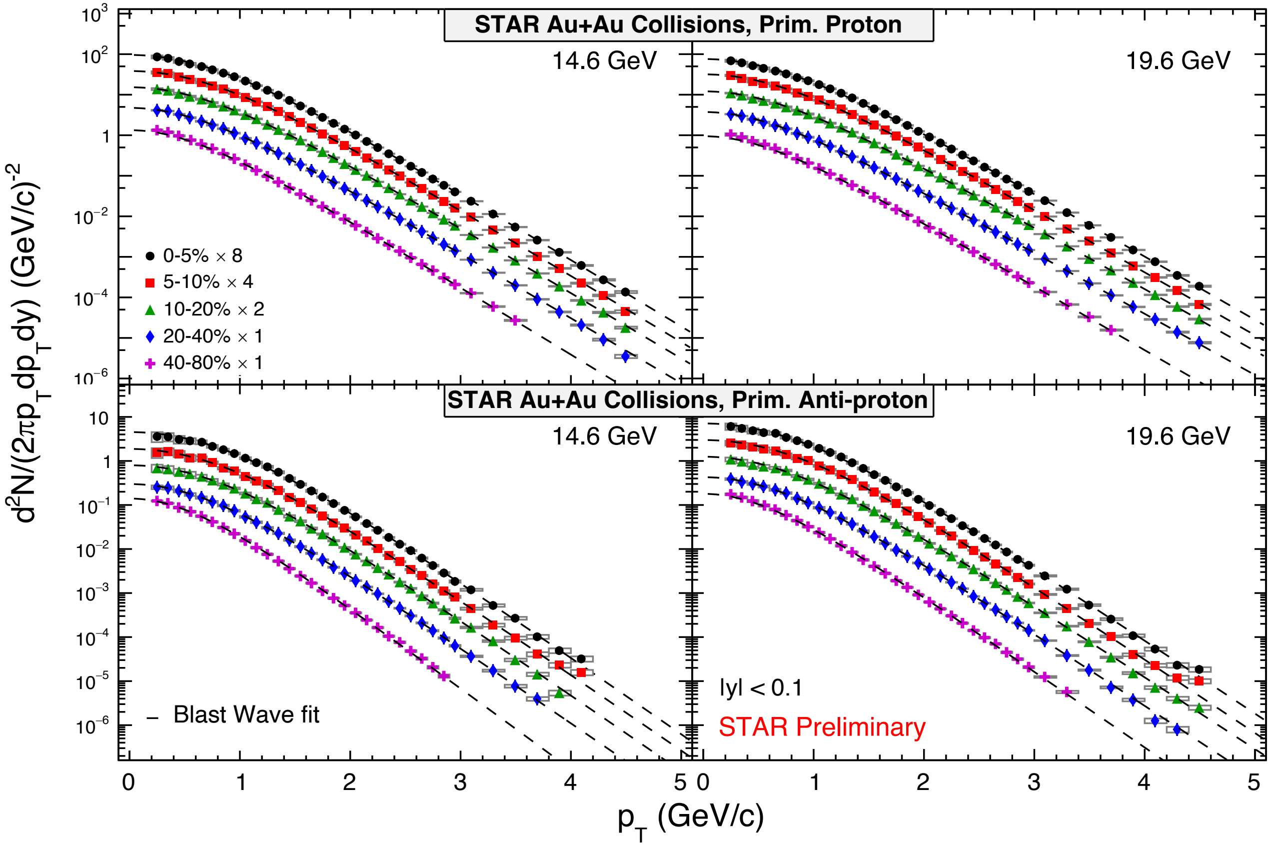
$\langle\beta_T\rangle$: average radial flow velocity

I_0 and K_1 : from Bjorken Hydrodynamic assumption

- All efficiencies and corrections are included.
- The spectra for inclusive proton, inclusive anti-proton, and anti-deuteron are shown in the backup.
- The statistical and systematic uncertainties are shown as vertical lines and boxes, respectively.
- The p_T ranges are extended in BES-II, which lead to smaller systematic uncertainties in particle yields.

(anti-)Proton Weak Decay Feed-down Correction

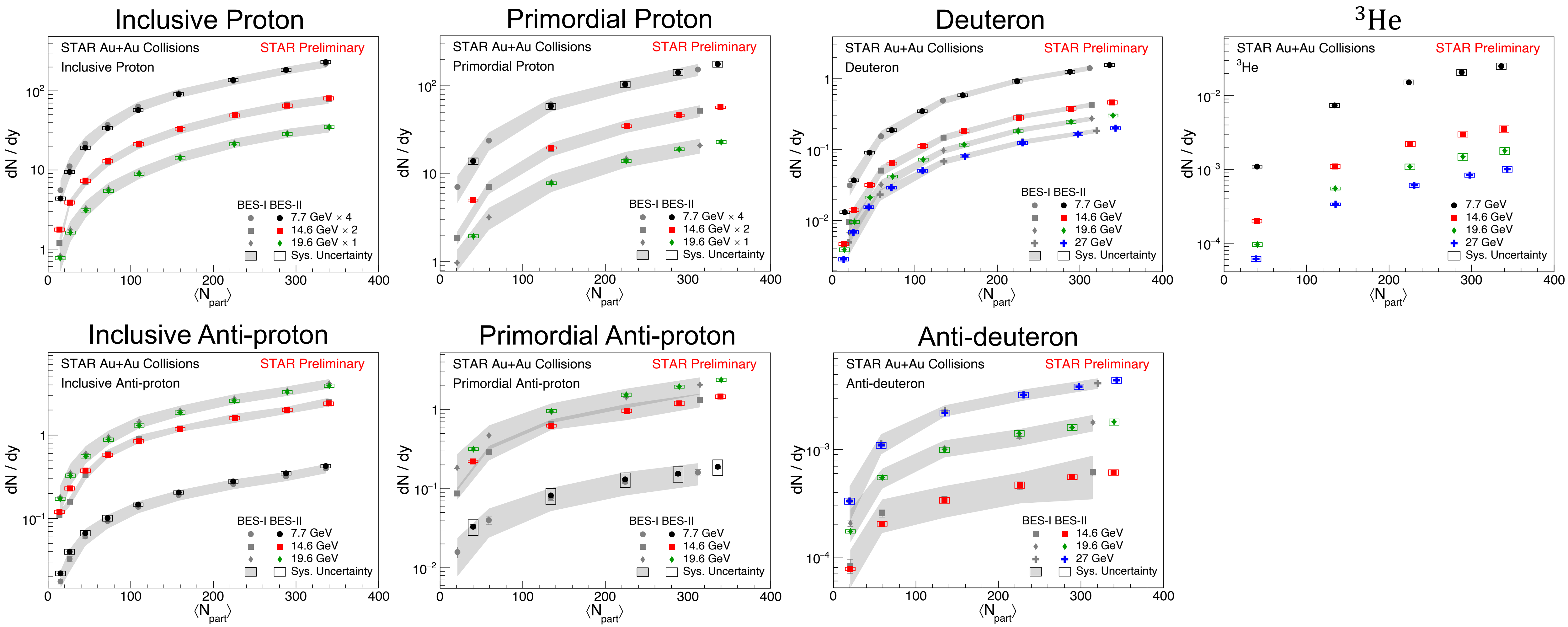




$\Lambda \rightarrow p + \pi^-$, branching ratio = 63.9 %
$\Sigma^+ \rightarrow p + \pi^0$, branching ratio = 51.57 %
$\Xi^- \rightarrow \Lambda + \pi^-$, branching ratio = 99.887 %
$\Xi^0 \rightarrow \Lambda + \pi^0$, branching ratio = 99.524 %

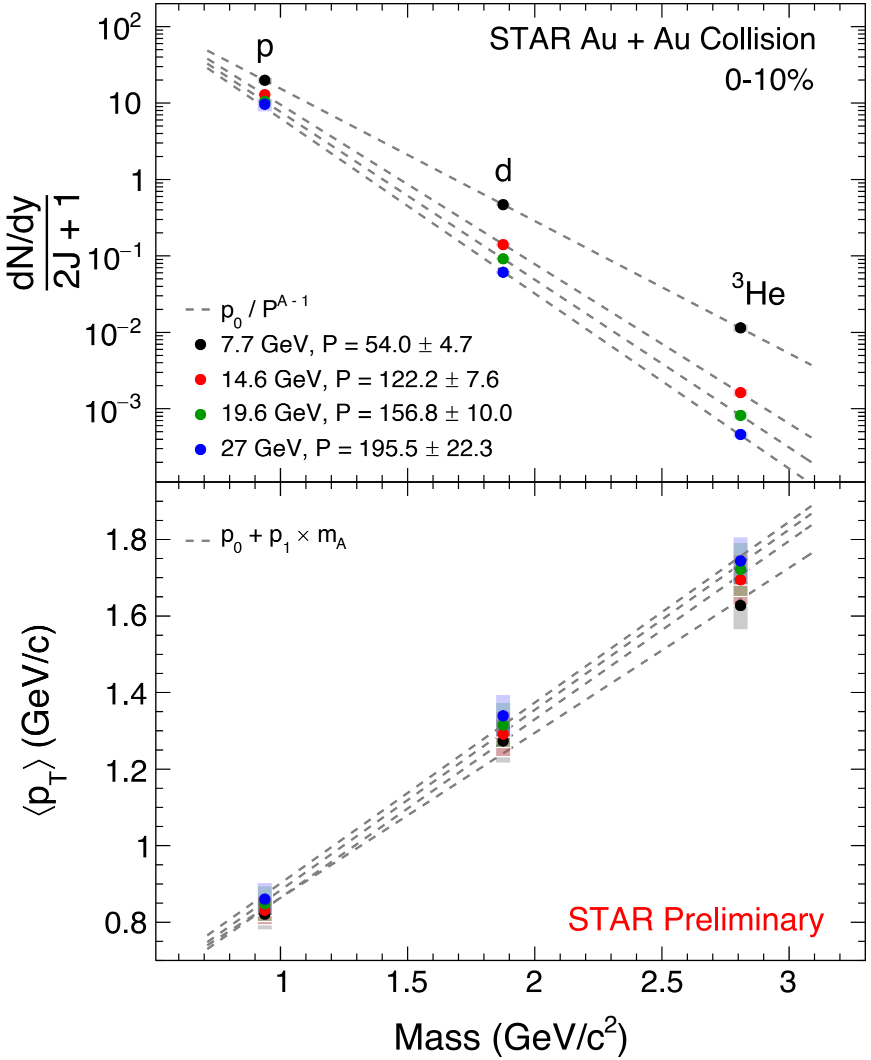
- The primordial spectra were obtained by subtracting the (anti-)proton weak decayed from strange hadrons.
- Data driven method: Use STAR published strange particle $(\Lambda, \Sigma^+, \Xi^-, \Xi^0)$ yields and embedding simulation samples.
- The spectra of Σ^+: Obtained by multiplying the Λ spectra by a factor of 0.27.
- The spectra of Ξ^0: Assumed to be the same as those of Ξ^-.

Particle Yields and Ratios



- ➢ The systematic uncertainties are reduced in BES-II because the p_{T} ranges are extended.
- ➢ Yields for light nuclei increase from peripheral to central collisions.
- ➢ dN/dy for positive particles decrease with increasing energy, while the behavior is opposite for antiparticles.

Particle Yields and Ratios



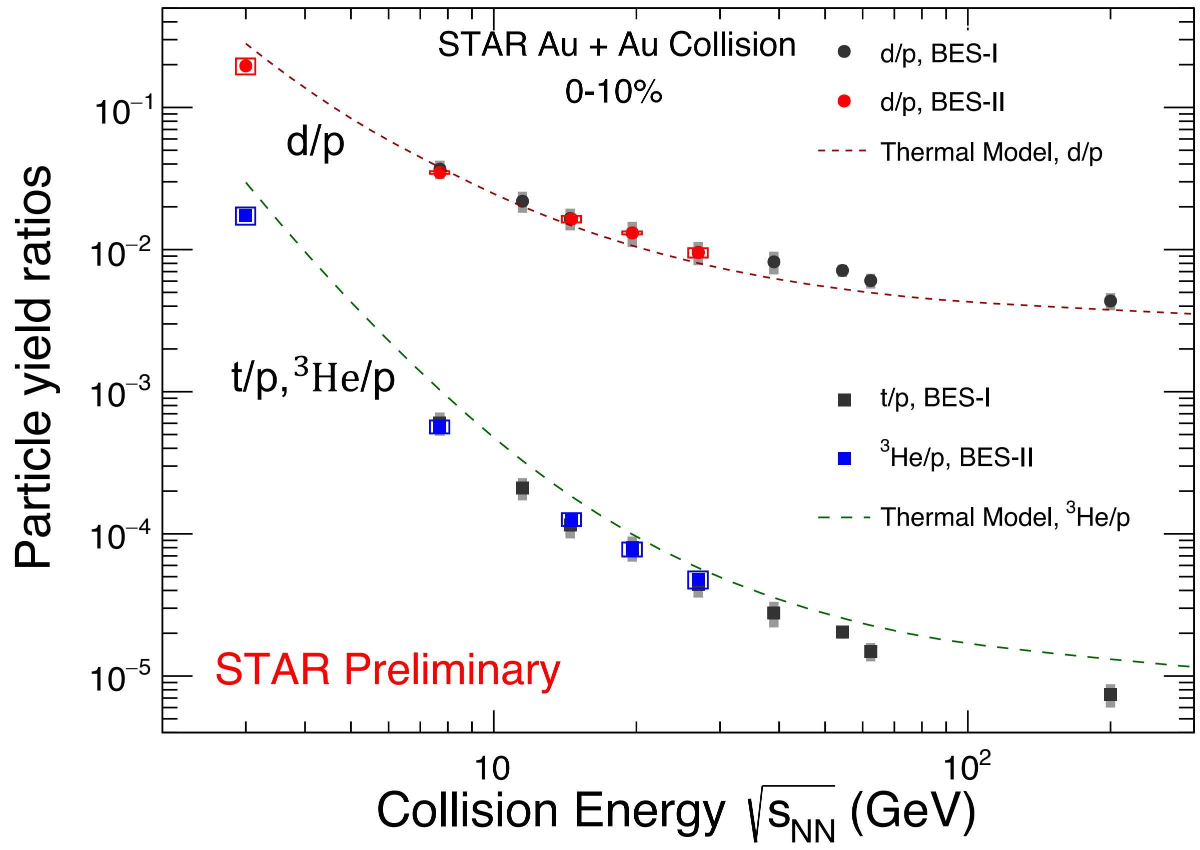
- Mass dependence of $\frac{\mathrm{dN/dy}}{2\mathrm{J}+1}$:
  - Fitted by an exponential function form p_0/P^{A-1},

    where P is the penalty factor and can be determined by the Boltzmann factor $e^{(m_N-\mu_B)/T}$ in thermal model.
  - The production of light nuclei are proportional to the spin degeneracy.
  - The penalty factor is larger at higher beam energy, which indicates that it is harder to form high-mass objects.

E864 Collaboration, Phys.Rev.Lett. 83 (1999) 5431-5434
STAR Collaboration, Phys.Rev.Lett. 130 (2023) 202301

- Mass dependence of $\langle p_\mathrm{T} \rangle$:
  - Fitted by an linear function form $p_0 + p_1 \times m_A$.
  - The $\langle p_\mathrm{T} \rangle$ increases linearly with increasing mass of the particles.

Particle Yields and Ratios



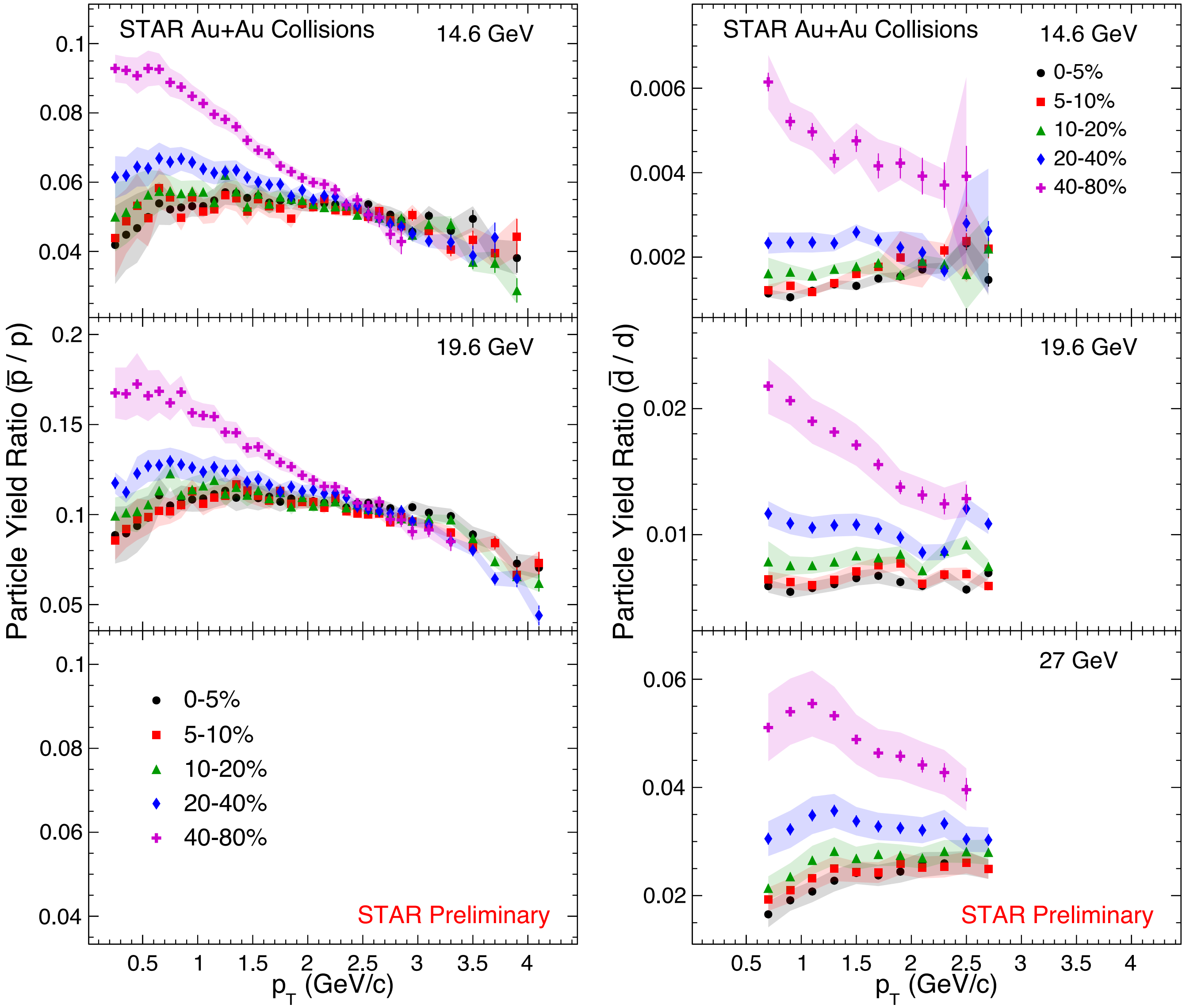
STAR, Phys. Rev. Lett. 130, 202301 (2023)

- The particle ratios are consistent with BES-I.
- The particle ratios show a monotonic decrease with collision energy.
- d/p ratio can be described well by the thermal model.
- The thermal model overestimates t/p and $^3He/p$ by a factor of approximately two.
  - The hadronic re-scatterings may play a crucial role during the hadronic expansion phase which lead to this discrepancy.

V. Vovchenko, B. Dönigus, B. Kardan, M. Lorenz, and H. Stoecker, Phys. Lett. B, (2020) 135746;

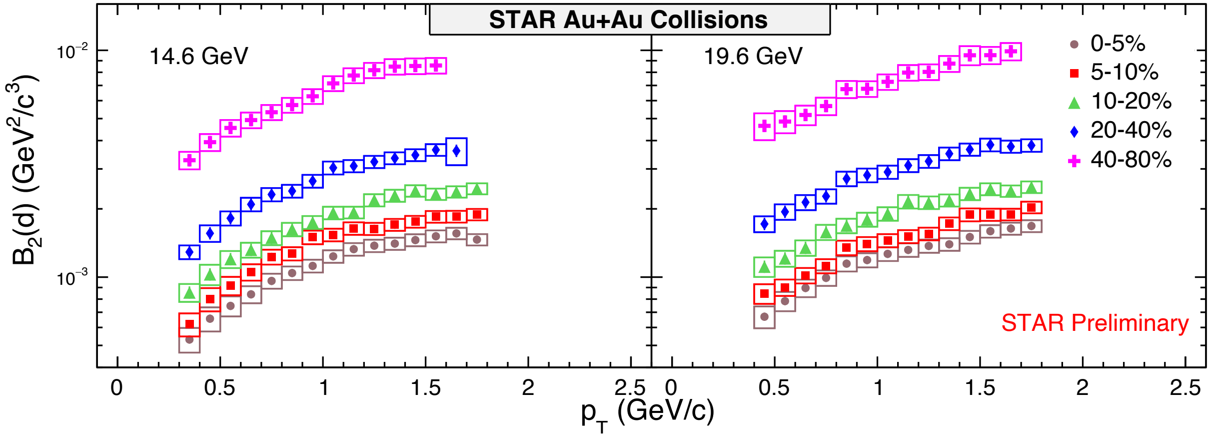
K.J. Sun, R. Wang, C. M. Ko, Y.G. Ma, and C. Shen, Nature Commun, 15 (2024) 1, 1074

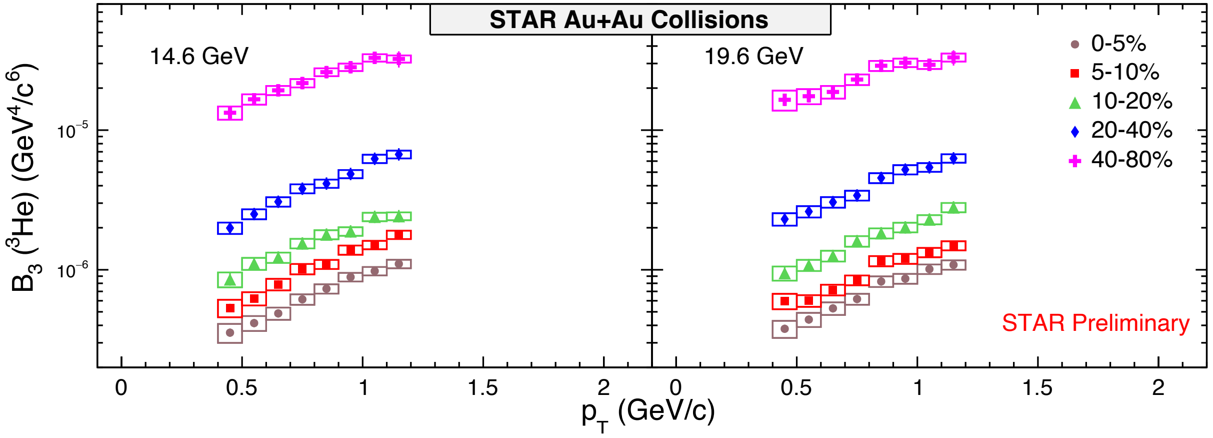
Particle Yields and Ratios



- The statistical and systematic uncertainties are shown as vertical lines and color bands, respectively.
- $\bar{p}/p$ and $\bar{d}/d$ ratios show strong centrality dependence.
  - This could be due to the annihilation between the particles and antiparticles.

Coalescence Parameter





❖ In the coalescence picture, the invariant yield of light nuclei is proportional to the invariant yield of nucleons. The coalescence parameter B_A reflects the probability of nucleon coalescence, which is related to the local nucleon density.

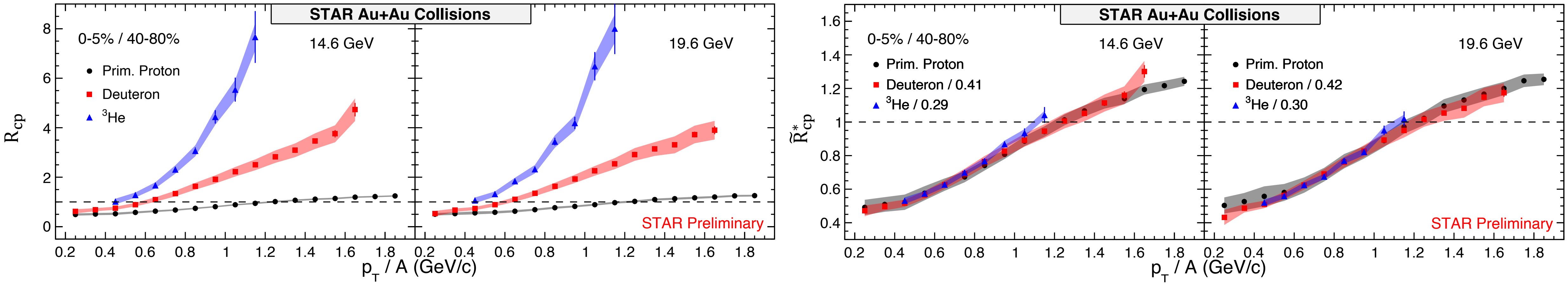
$$E_A \frac{d^3 N_A}{d^3 p_A} = B_A \left(E_p \frac{d^3 N_p}{d^3 p_p} \right)^Z \left(E_n \frac{d^3 N_n}{d^3 p_n} \right)^{A-Z} \approx B_A \left(E_p \frac{d^3 N_p}{d^3 p_p} \right)^A .$$

R. Scheibl and U. Heinz Phys.Rev.C 59 (1999) 1585-1602
STAR Collaboration, Phys.Rev.C 99 (2019) 6, 064905

➢ B_A increase with increasing p_T which might indicate an expanding collision system.

➢ B_A increase from central to peripheral collisions, which can be explained by a decreasing source volume.

Nuclear Modification Factors (R_{cp})



- ❖ $R_{cp}(p_T) = \frac{\langle N_{coll}\rangle_p}{\langle N_{coll}\rangle_c} \times \frac{d^2N^c_{AA}/dp_T dy}{d^2N^p_{AA}/dp_T dy}$, $\langle N_{coll}\rangle$ is the average number of binary nucleon−nucleon collisions per event.
- ❖ Number of constituent nucleon (NCN) scaling for $R_{cp}(p_T)$:

$$R^*_{cp}\,(p_T) = \left(\frac{B_{A,\,\mathrm{Central}}}{B_{A,\,\mathrm{Peripheral}}}\right)^{-1/A} \left(R_{cp}(Ap_T)\right)^{1/A} \left(\frac{\langle N_{coll}\rangle_c}{\langle N_{coll}\rangle_p}\right)^{1/A-1} \equiv \left(\frac{B_{A,\,\mathrm{Central}}}{B_{A,\,\mathrm{Peripheral}}}\right)^{-1/A} \tilde{R}^*_{cp}\,(p_T)$$

C. S. Zhou, Y. G. Ma, and S. Zhang. Eur.Phys.J.A 52 (2016) 12, 354

- ➢ R_{cp} for different particles exhibit distinct trends at all energies.
- ➢ In coalescence picture, the $\tilde{R}^*_{cp}$ of light nuclei will follow a common trend when scaled by a constant factor, which is determined by $\tilde{R}^{*\,\mathrm{Nuclei}}_{cp} / \tilde{R}^{*\,\mathrm{Proton}}_{cp}$ at p_T/A = 0.65 GeV/c.

Summary and Outlook

Summary:

- We report the light nuclei productions (p, d, $^3\mathrm{He}$, $\bar{\mathrm{p}}$ and $\bar{\mathrm{d}}$) in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}} = 7.7 - 27$ GeV from RHIC STAR BES-II.
- The particle ratios $N_\mathrm{d}/N_\mathrm{p}$ and $N_{^3\mathrm{He}}/N_\mathrm{p}$ have been measured.
  - The particle ratios show a monotonic decrease with collision energy.
  - The thermal model over-predicts t/p and $^3\mathrm{He}$/p by a factor of about 2.
- The coalescence parameter B_A have been measured.
  - Collective expansion leads to an increase in B_A from low to high p_T
  - Decreasing source volume results in a rise of B_A from central to peripheral collisions.
- The nuclear modification factor R_{cp} of light nuclei shows a scaling behavior, which is consistent with a nucleon coalescence mechanism of light nuclei production.

Outlook:

- Working on the compound ratios $(\mathrm{N_p} \times \mathrm{N_t}/\mathrm{N_d^2}$ and $\mathrm{N_p} \times \mathrm{N}_{^3\mathrm{He}}/\mathrm{N_d^2})$ in BES-II.
- Continue the analysis of other BES-II (collider + FXT) energies.
- Working on the production of $^4\mathrm{He}$ in BES-II.

Thank you for your attention!

Backup

Au+Au collisions at RHIC (Collider mode)				Au+Au collisions at RHIC (Fixed-Target)				
$\sqrt{s_{NN}}$ (GeV)	nEvents (M)	μ_B (MeV)	Time	$\sqrt{s_{NN}}$ (GeV)	E_{beam} (GeV)	nEvents (M)	μ_B (MeV)	Time
200	380	25	Run-10, 19	**13.7**	100	50	280	Run-21
62.4	46	75	Run-10	**11.5**	70	50	320	Run-21
54.4	1200	85	Run-17	**9.2**	44.5	50	370	Run-21
39	86	112	Run-10	**7.7**	31.2	260	420	Run-18, 19, 20
27	585	156	Run-11, 18	**7.2**	26.5	470	440	Run-18, 20
19.6	595	206	Run-11, 19	**6.2**	19.5	120	490	Run-20
17.3	256	230	Run-21	**5.2**	13.5	100	540	Run-20
14.6	340	262	Run-14, 19	**4.5**	9.8	110	590	Run-20
11.5	235	316	Run-10, 20	**3.9**	7.3	120	633	Run-20
9.2	160	372	Run-20	**3.5**	5.75	120	670	Run-20
7.7	104	420	Run-10, 21	**3.2**	4.59	200	699	Run-19
				3.0	3.85	2300	750	Run-18, 21

- STAR has completed BES-II data-taking with factors of 10-20 more statistics compared to BES-I.
- BES-II: 8 collider energies (7.7 – 54 GeV) / 12 FXT energies (3.0 - 13.7 GeV)
- μ_B coverage : $25 < \mu_B < 750$ MeV.

STAR, arXiv:1007.2613
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0493
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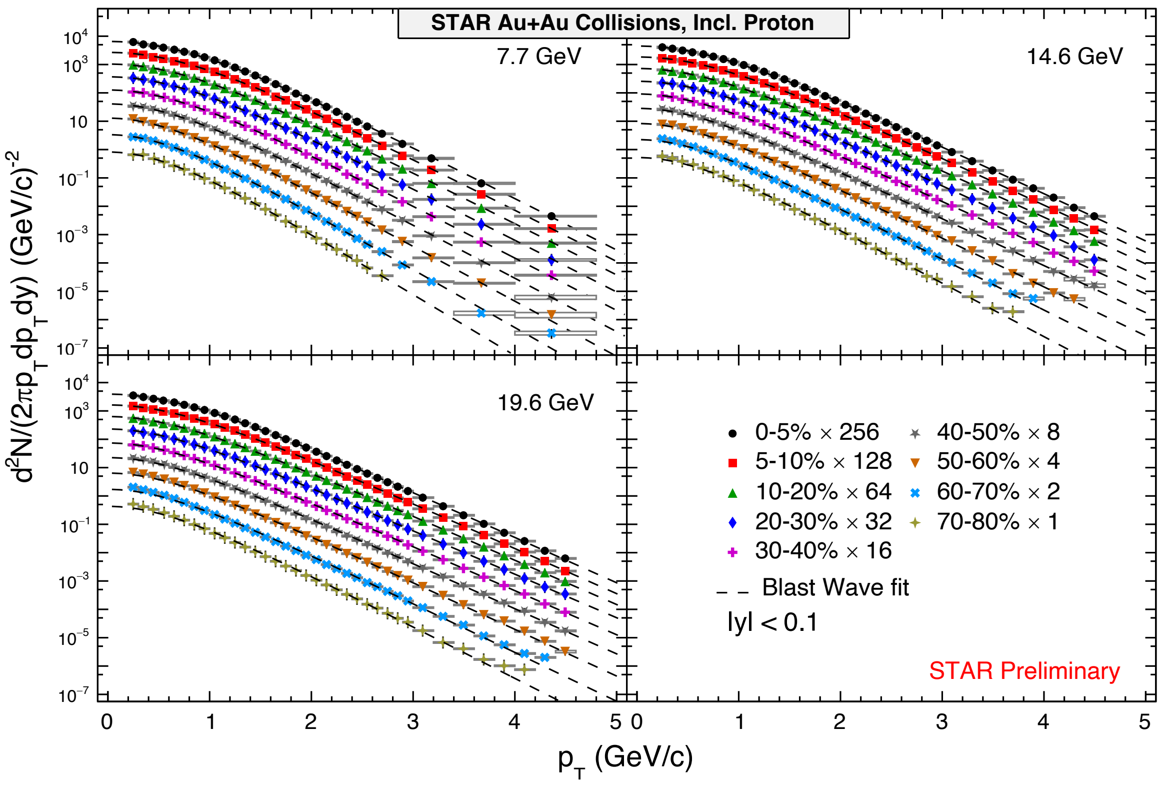
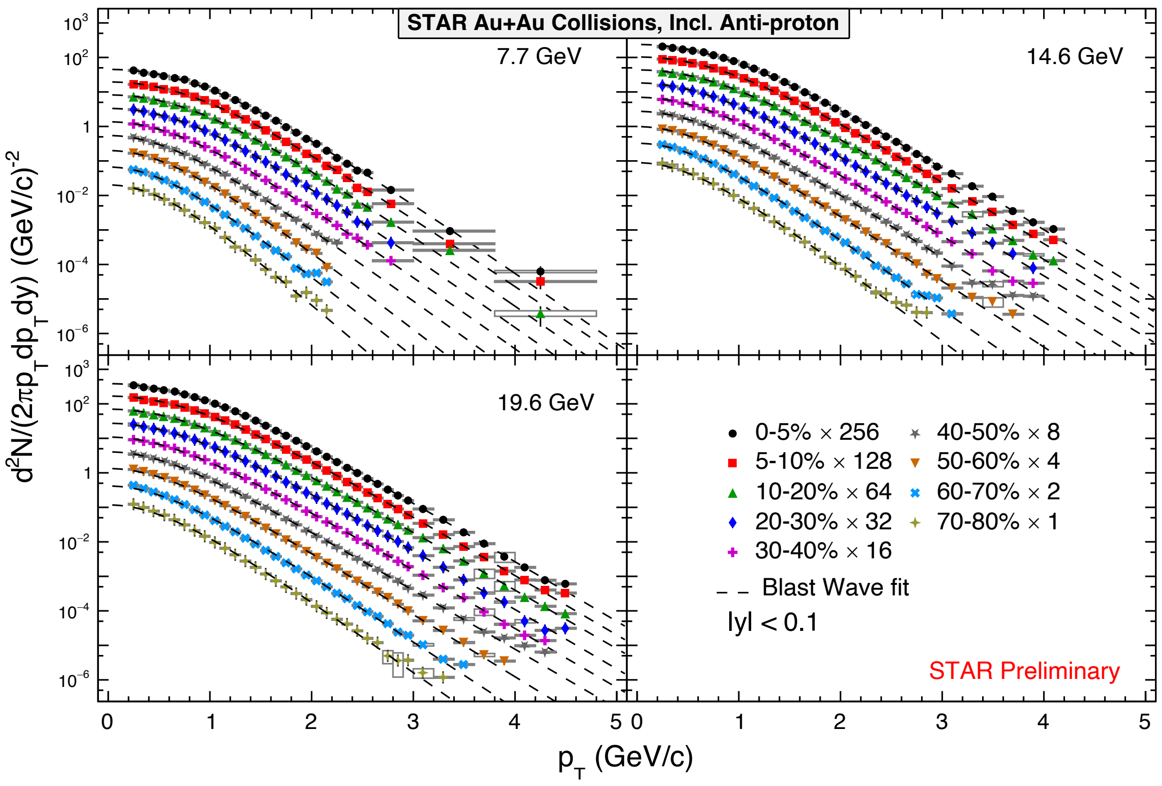
Backup – Transverse Momentum Spectra





❖ Blast-Wave Function

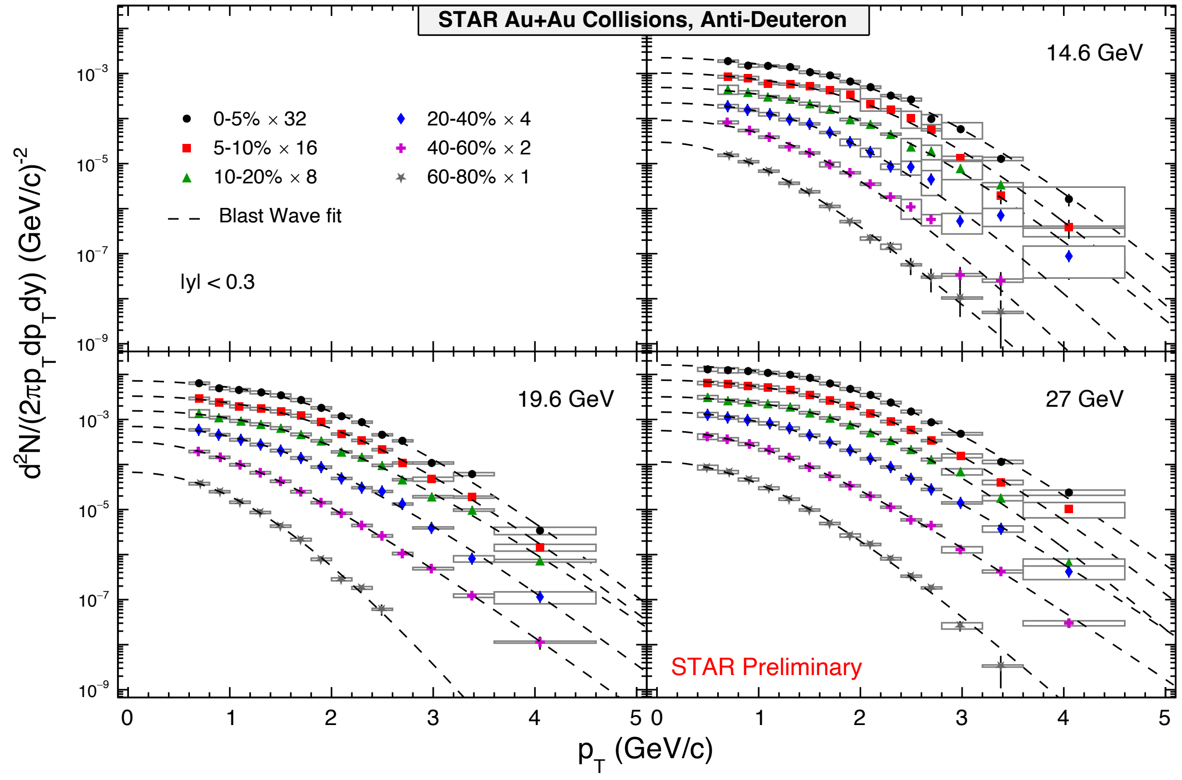
$$\frac{1}{2\pi p_T}\frac{d^2N}{dp_T dy} \propto \int_0^R r dr m_T I_0\left(\frac{p_T \sinh\rho}{T_{kin}}\right) K_1\left(\frac{m_T \cosh\rho}{T_{kin}}\right)$$

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

❖ All efficiencies and corrections are included

- ✓ Energy Loss Correction
- ✓ TPC Tracking Efficiency
- ✓ TOF Matching Efficiency
- ✓ Knock-out Protons (p)

Backup – Transverse Momentum Spectra



❖ Blast-Wave Function

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

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

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 : from Bjorken Hydrodynamic assumption

❖ All efficiencies and corrections are included

- ✓ Energy Loss Correction
- ✓ TPC Tracking Efficiency
- ✓ TOF Matching Efficiency
- ✓ Absorption Correction