Recent Results on Light (Anti-)(Hyper-) Nuclei Production at STAR

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Outline

- Introduction
- RHIC-STAR Experiment
- Results
  - Transverse Momentum Spectra
  - Averaged Transverse Momentum $\langle p_{\mathrm{T}} \rangle$
  - Particle Yields and Ratios
  - Coalescence Parameters
- Summary and Outlook

Introduction

Light Nuclei and Hypernuclei

- Loosely bound objects
- Small binding energies

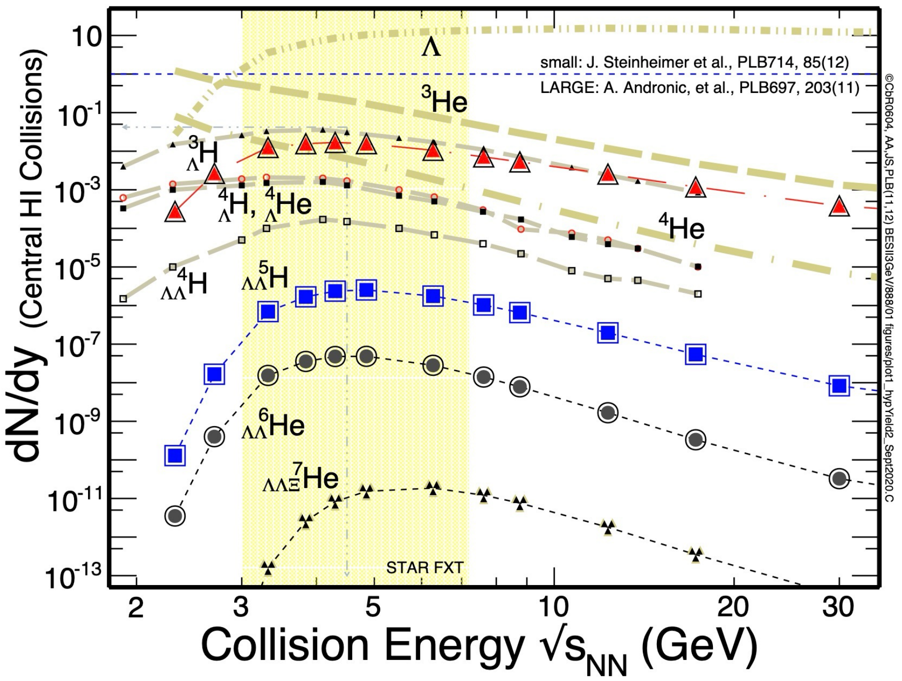
❖ Production Mechanisms

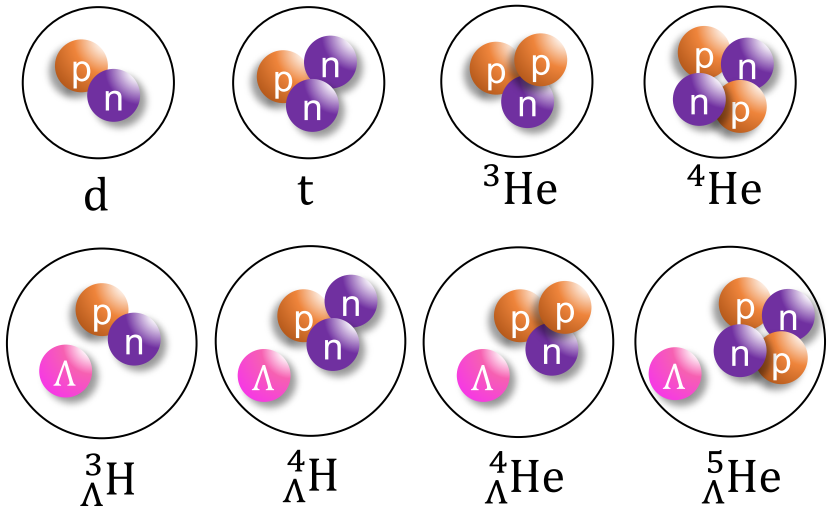
- Thermal model

  Yields determined by chemical equilibrium at common <u>chemical freeze-out temperature</u> (T_{ch}), <u>chemical potential</u> (μ_B) and <u>fireball volume</u> (V).

- Coalescence model

  Nucleons coalesce to form a composite particle after the kinetic freeze-out.





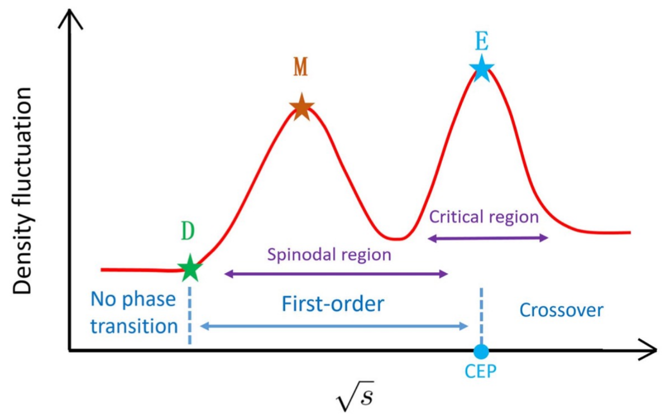
A. Andronic et al, Phys.Lett.B 697 (2011) 203-207;
J. Cleymans et al, Phys.Rev.C 84 (2011) 054916;
A. Andronic et al, Nature 561 (2018) 7723, 321-330
K.J. Sun et al, Phys.Lett.B 792 (2019) 132-137;
W.B. Zhao et al, Phys.Rev.C 102 (2020) 4, 044912;
H. Liu et al, Phys.Lett.B 805 (2020) 135452;

Introduction

❖ Probing Critical Point

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

- λ: varies smoothly with T and μ_B of emission source
- $\sigma \approx r_d \approx r_t$ is the root-mean-radius of light nuclei

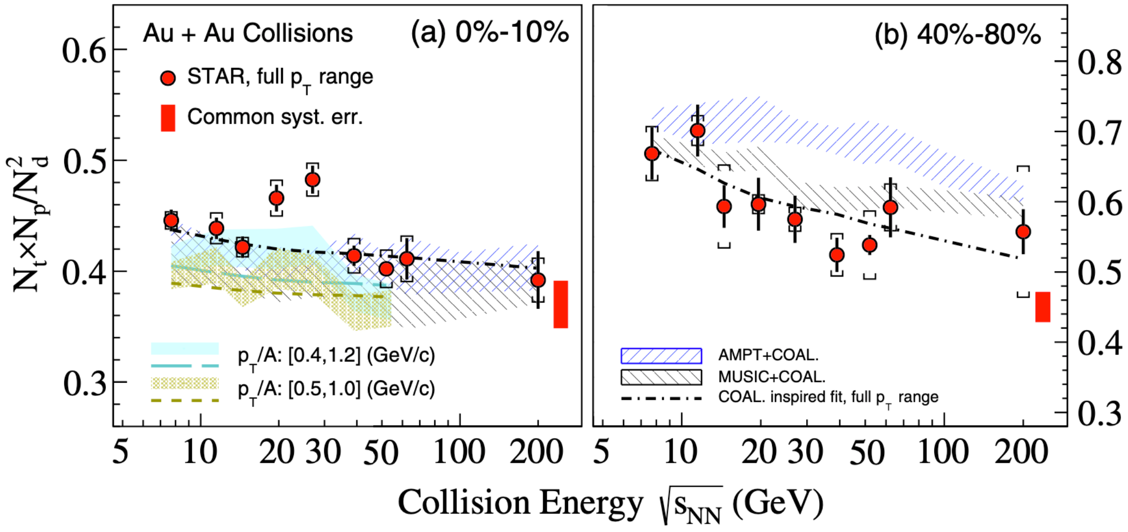


○ Neutron Density Fluctuation (Δn)

Coexistence of two phases can lead to large density inhomogeneity and fluctuations.

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

Near the critical point, the correlation length (ξ) increases, leading to long-range correlations.



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

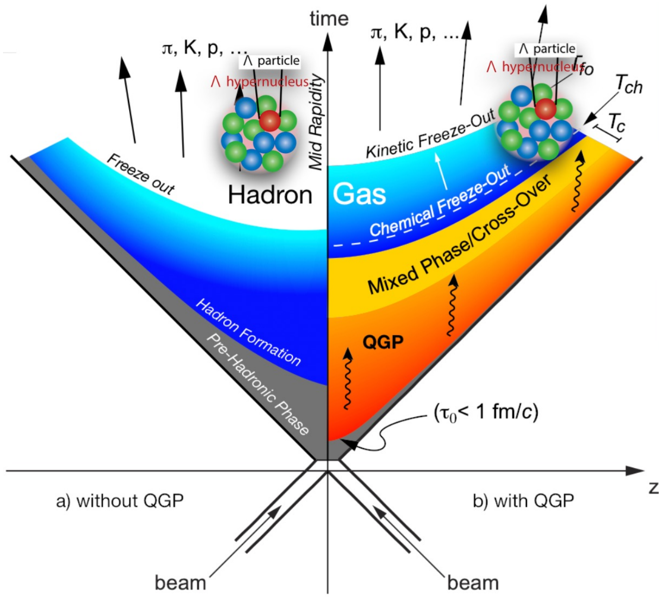
[STAR Collaboration] Phys.Rev.Lett. 130 (2023) 202301

Introduction

❖ Probe to Y-N (Y-N-N) Interaction

Inner structure governed by interactions between nucleons and hyperons.

H. Le et al., PRL 134, 072502 (2025)
A. Jinno et al., PRC 110, 014001 (2024)



- Equation of State (EoS)

  The strangeness degree of freedom in EoS at high baryon density region.

- Wave Function

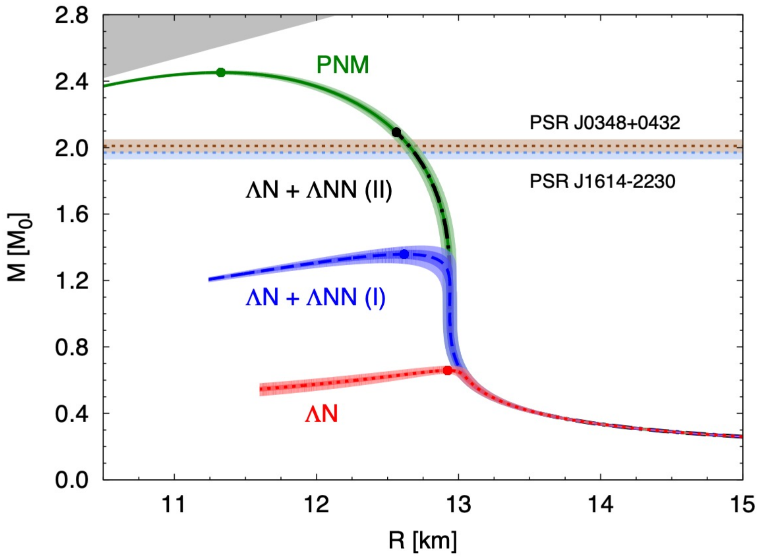
  Probe short-distance structure of hypernuclear wave functions.

  Phys.Rev.C 103, 014907 (2021)

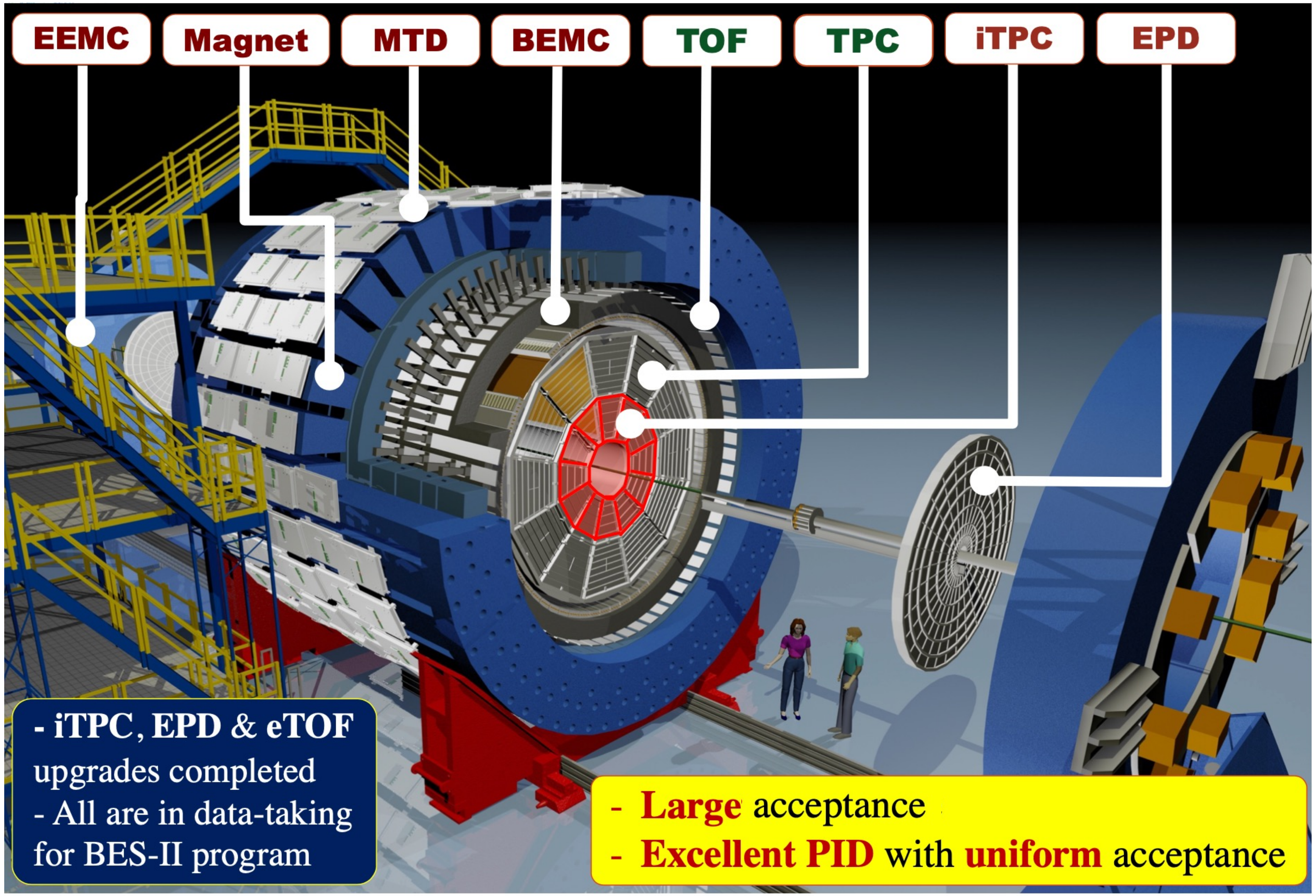
- Hyperon Puzzle

  Difficult to reconcile the measured masses of neutron stars with the presence of hyperons in their interiors.

  D. Lonardoni et al., PRL 114, 092301 (2015)



The Solenoidal Tracker At RHIC (STAR)



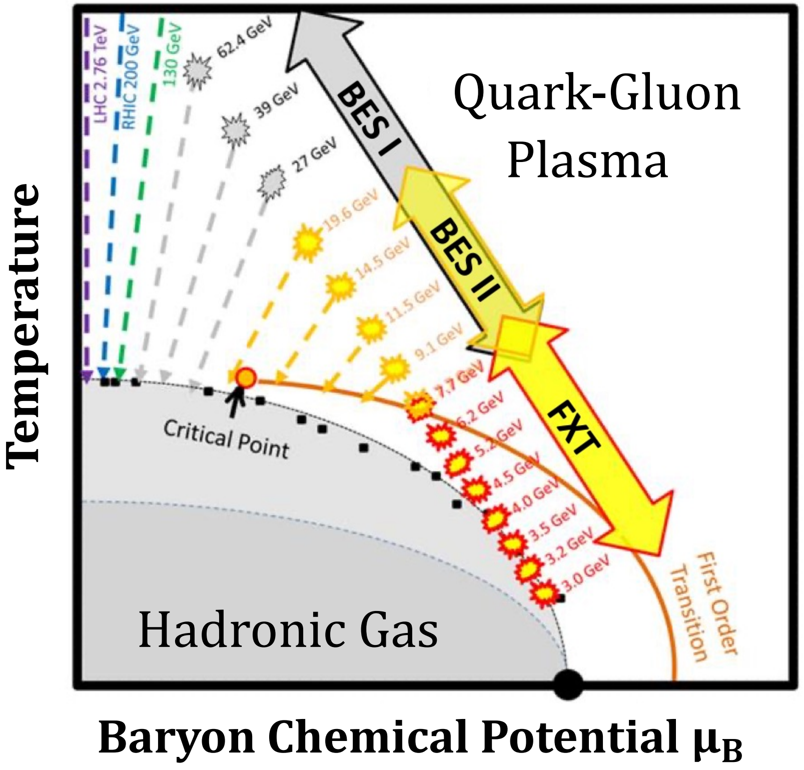
Main sub-detectors for PID

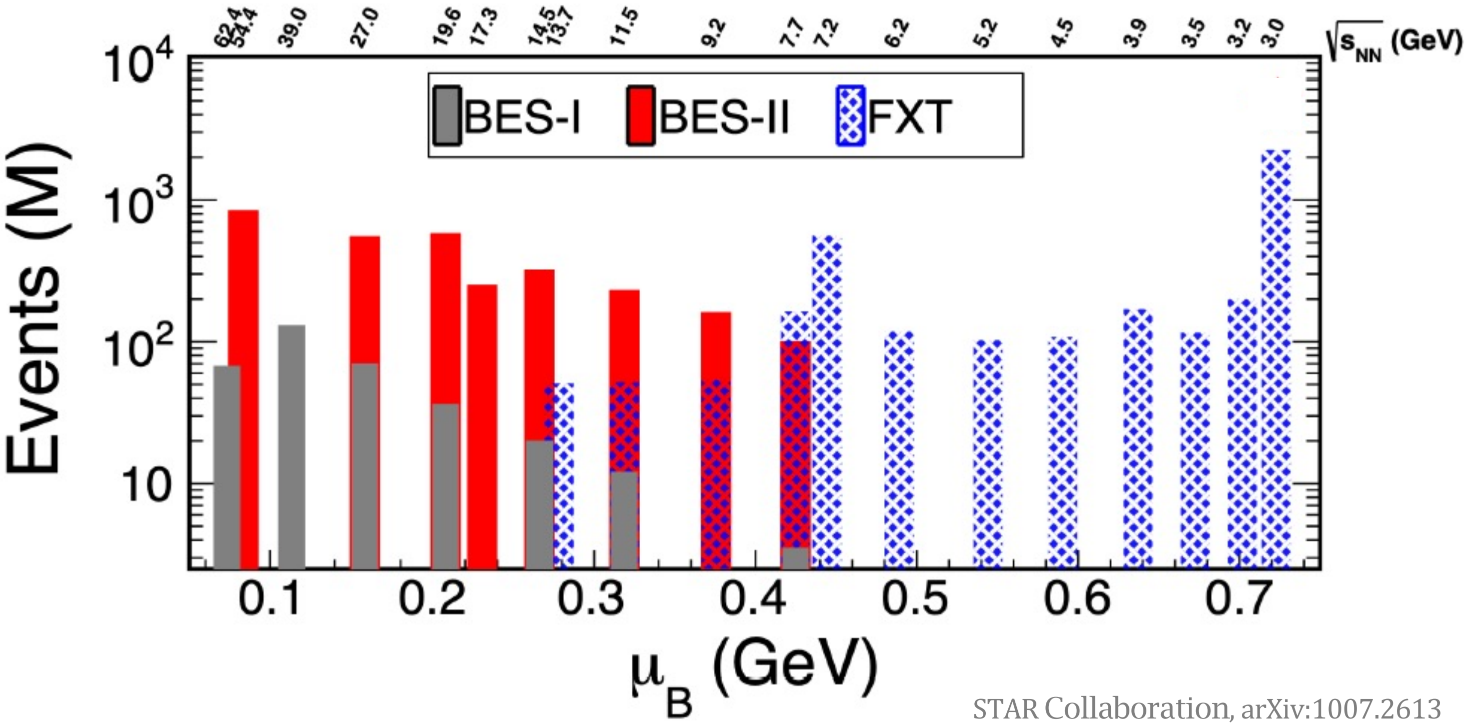
- Time Projection Chamber (TPC)
  Ionization energy loss (dE/dx)
- Time of Flight (TOF)
  $m^2 = p^2(c^2t^2/L^2 - 1)$

BES-II Upgrades

- iTPC (2019+)
  Extends η acceptance, improves tracking and dE/dx resolution
- eTOF (2019+)
  Extends rapidity and η coverage
- EPD (2018+)
  Improved event plane resolution

RHIC Beam Energy Scan Program

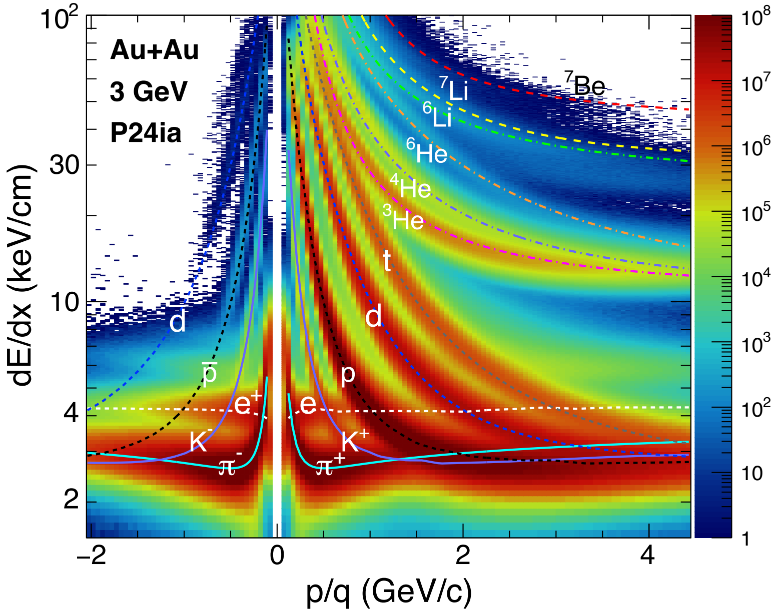


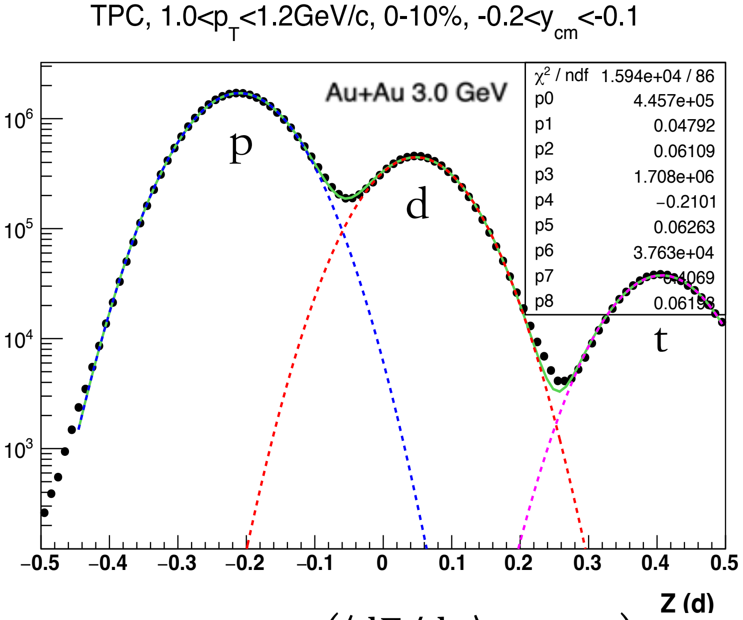


STAR Collaboration, arXiv:1007.2613
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0493
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

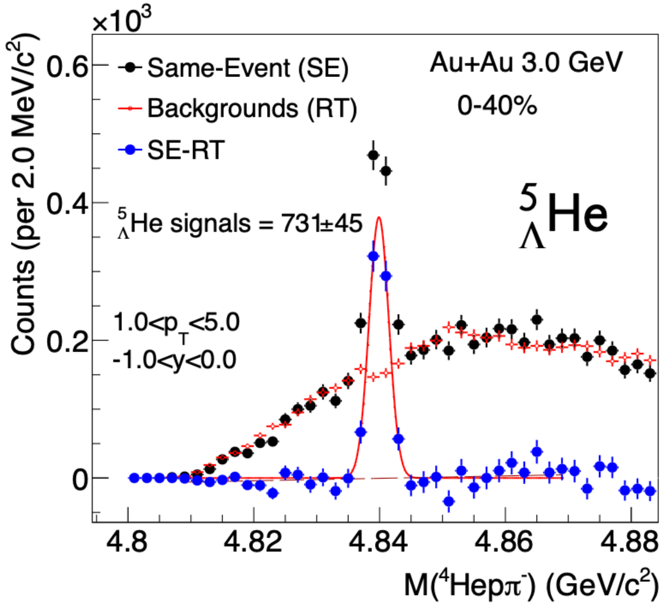
- STAR has completed BES-II data-taking with factors of 10 – 20 more statistics compared to BES-I.
- BES-II: 8 collider energies ($\sqrt{s_{NN}}$ = 7.7 – 54 GeV) / 12 FXT energies ($\sqrt{s_{NN}}$ = 3.0 – 13.7 GeV)
- μ_B coverage : 25 < μ_B < 750 MeV.
- BES-II 3 GeV (2 B events): access to heavier nuclei, improved precision for light and hypernuclei.

Particle Identification and Hypernuclei Reconstruction

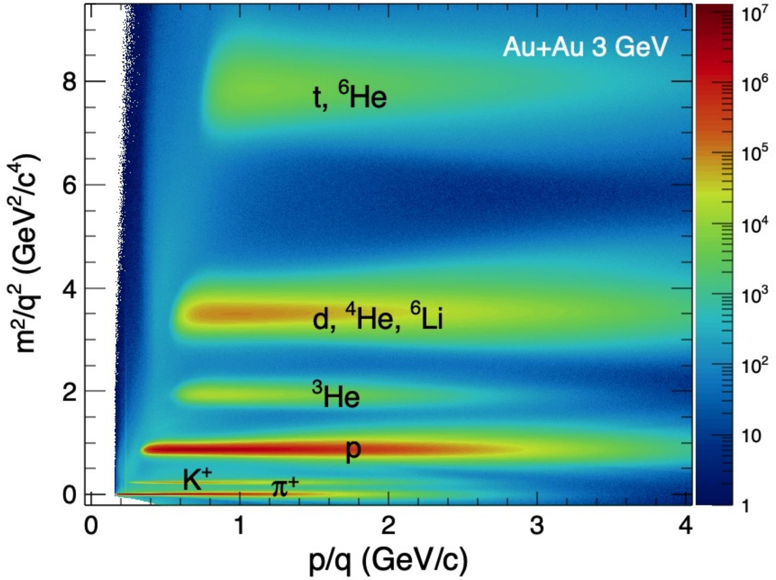




$$\text{TPC: } Z = \ln\left(\frac{\langle dE/dx\rangle_{\text{measure}}}{\langle dE/dx\rangle_{\text{Bichsel}}}\right)$$



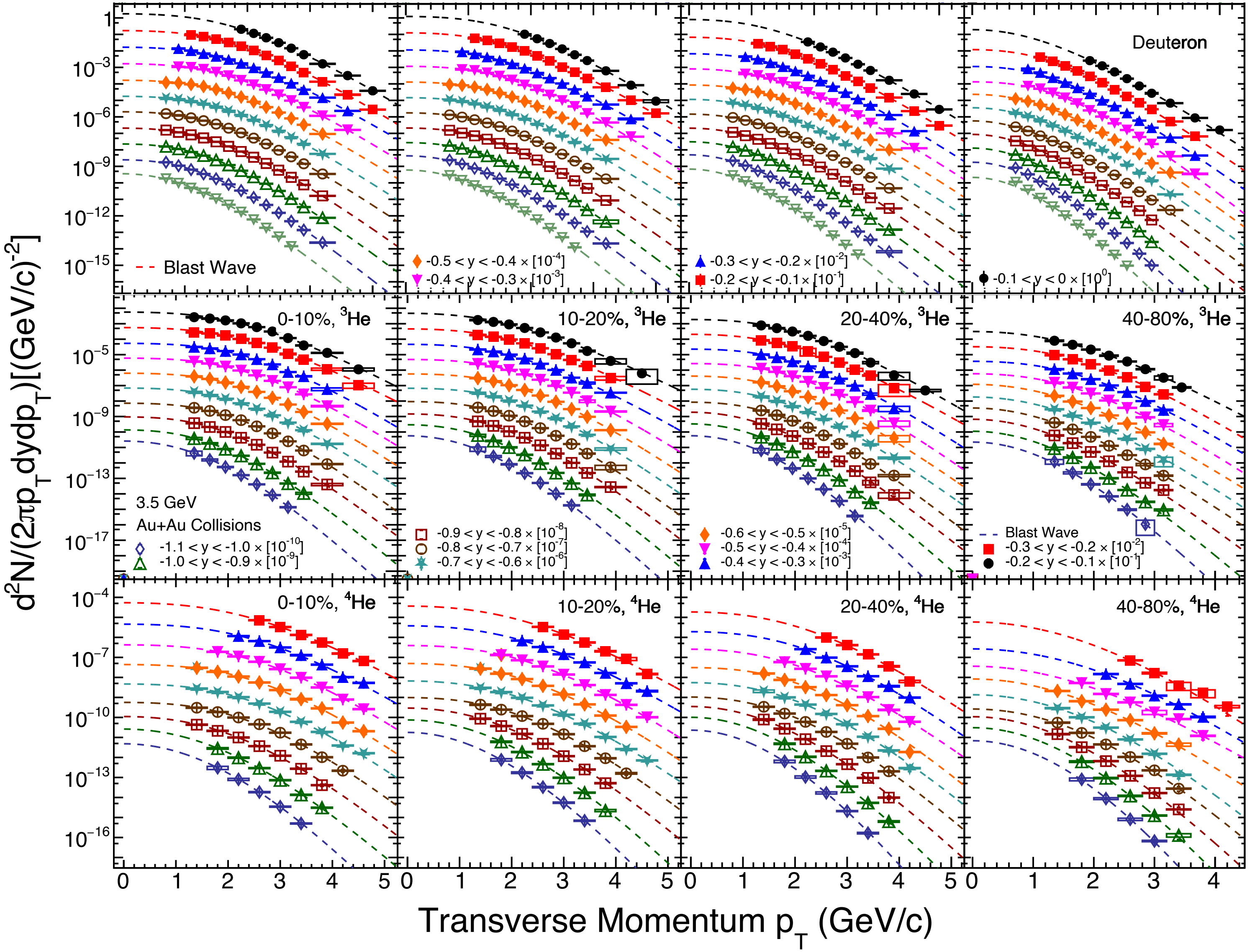
$$^{5}_{\Lambda}\text{He} \rightarrow {}^{4}\text{He} + p + \pi^{-}$$



- Measured yield coverage in Au+Au collisions from BES-II:

Particle	p, d, ^{3}He	^{4}He	$\bar{p}$, $\bar{d}$	$^{3}_{\Lambda}$H	$^{4}_{\Lambda}$H, $^{4}_{\Lambda}$He	$^{5}_{\Lambda}$He
$\sqrt{s_{NN}}$ (GeV)	3.0 – 27	3.0 – 4.5	7.7 – 27	3.0 – 27	3.0 – 3.5	3.0

Light Nuclei p_T Spectra



➢ Blast-Wave Function

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

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

Kinetic Freeze-out Parameters:

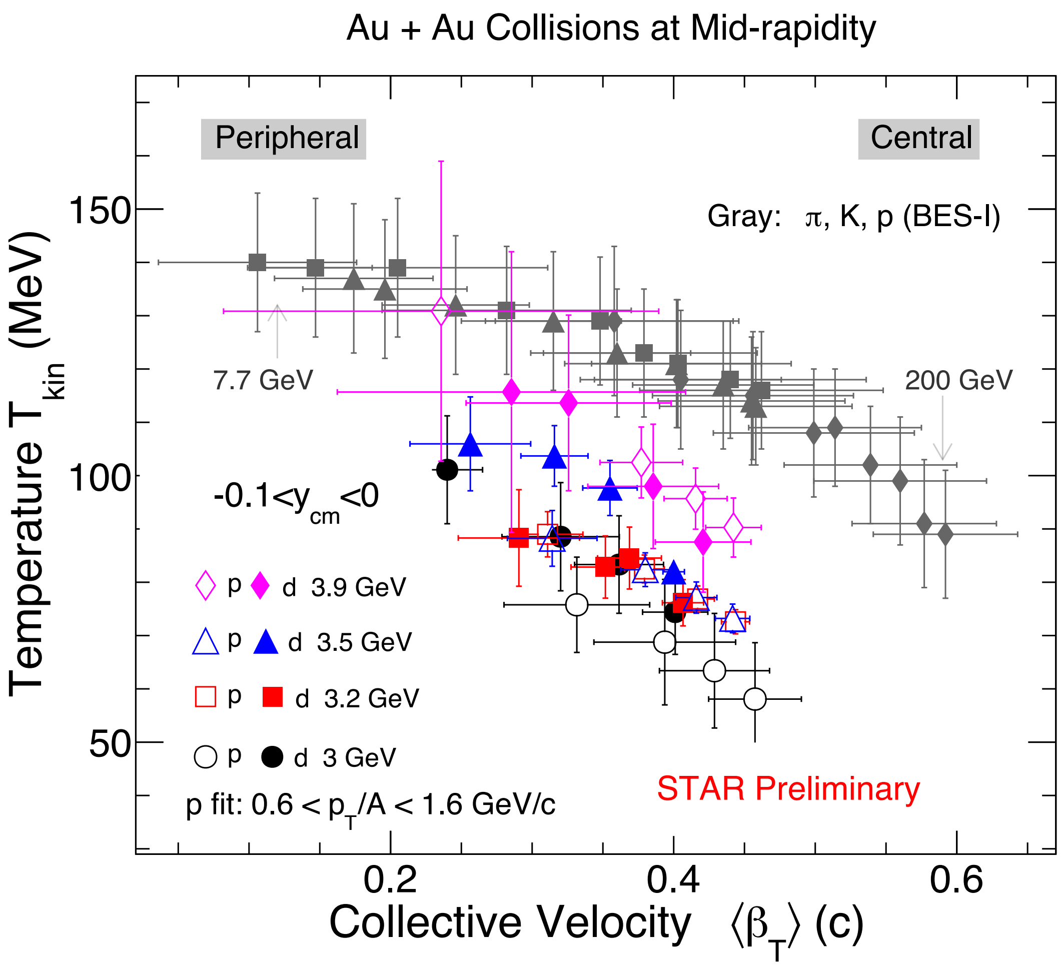
T_{kin} : kinetic freeze-out temperature

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

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

J.D. Bjorken, Phys.Rev.D 27 (1983) 140-151;
E. Schnedermann et al. Phys.Rev.C 48 (1993) 2462-2475

Kinetic Freeze-out Parameters



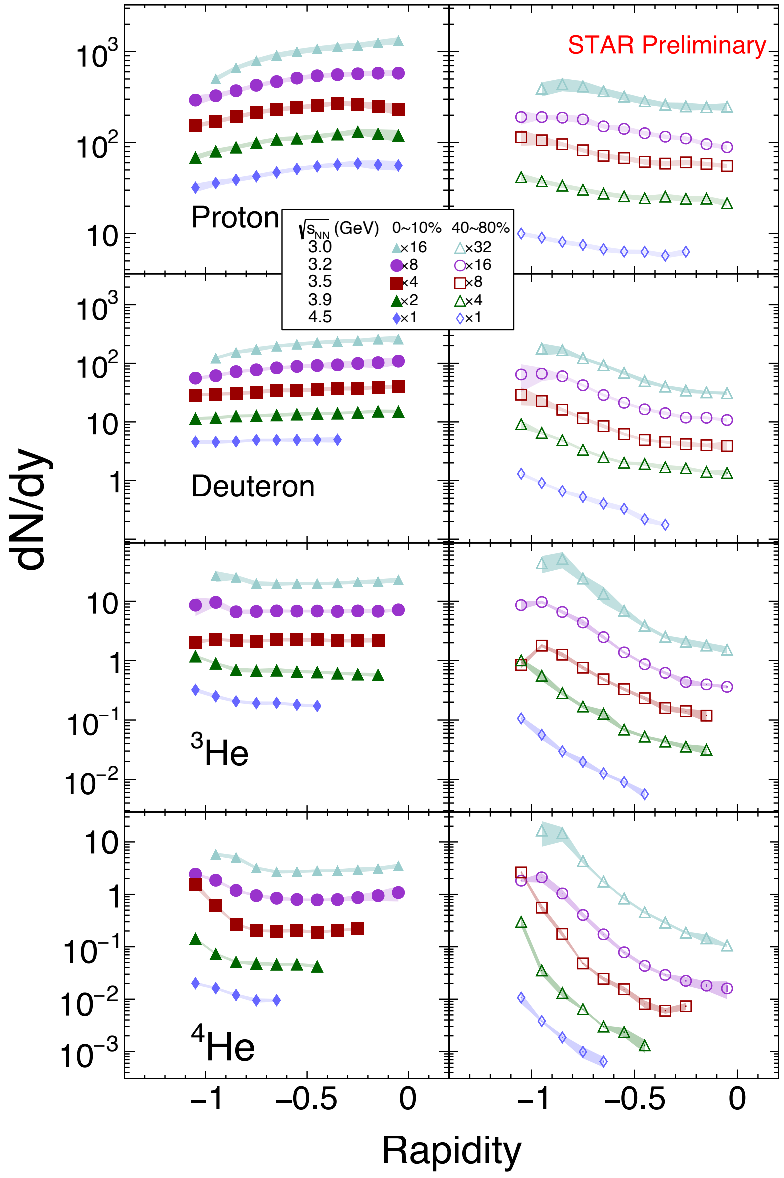
STAR, Phys.Rev.C 110, 054911 (2024)
STAR, Phys.Rev.C 96, 44904 (2017)

Hydrodynamic-inspired Blast-Wave model: Assumes particles are emitted thermally from an expanding source with a common $\langle\beta_T\rangle$ and T_{kin}.

- At $\sqrt{s_{\mathrm{NN}}} = 3.0 - 3.9$ GeV, different T_{kin} and $\langle\beta_{\mathrm{T}}\rangle$ trends suggest separate kinetic freeze-out surfaces for p and d.

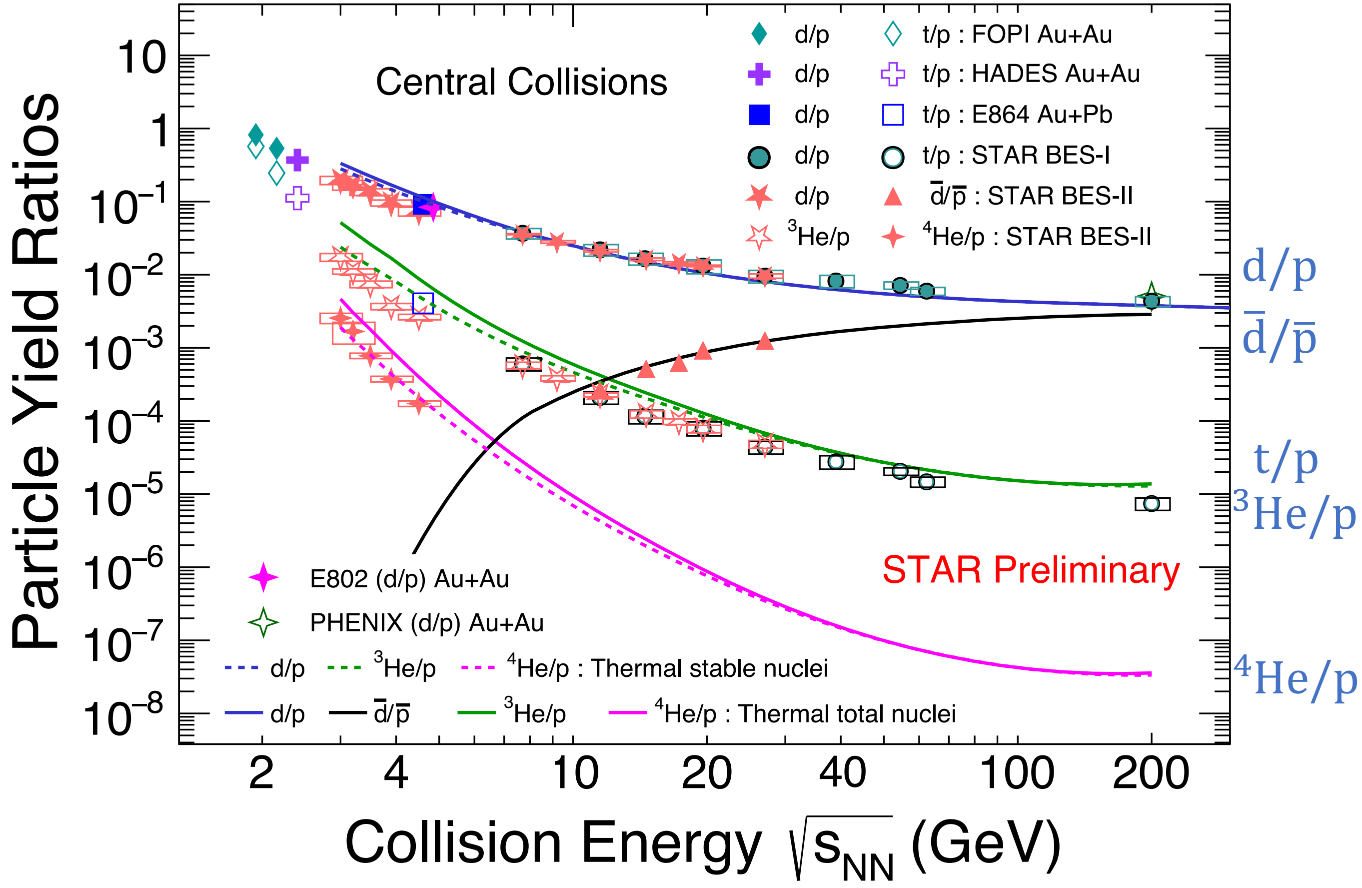
Deuterons deviate from the hydrodynamical blast-wave picture.

Particle Yields



- dN/dy of protons and light nuclei show significant centrality and rapidity dependence at 3 – 4.5 GeV.
- Heavier nuclei show stronger dN/dy variations with rapidity and centrality, suggesting a contribution from **spectator fragmentation**.

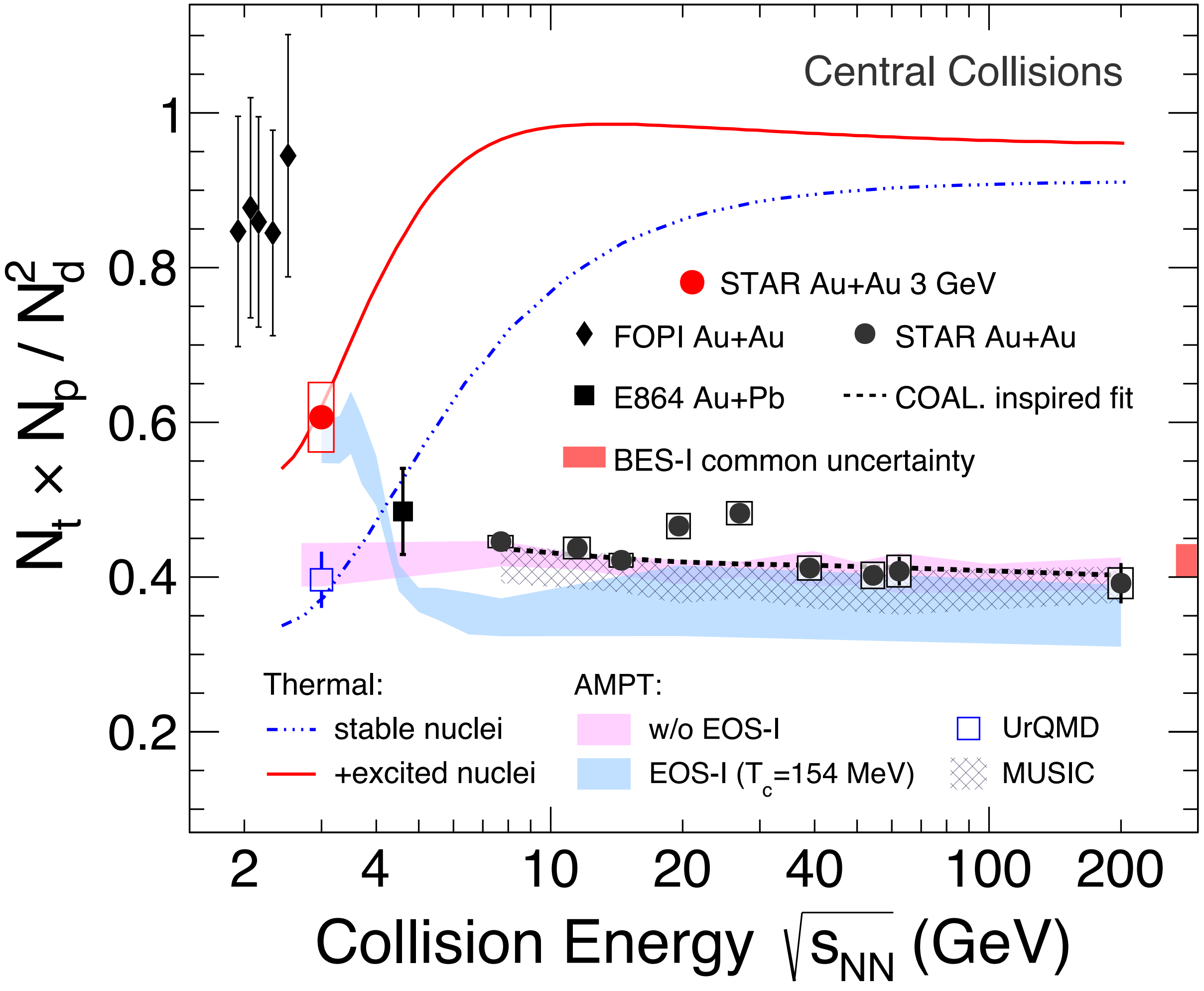
Nuclei-to-Nucleon Yield Ratios



- The trends of ratios can be qualitatively described by the **Thermal-FIST.**
- $\mathbf{d/p}, \mathbf{\bar{d}/\bar{p}}$ are well reproduced by the thermal model for $\sqrt{s_{NN}} \geq 7.7$ GeV, but d/p is overestimated at $\sqrt{s_{NN}} < 7.7$ GeV.
- $\mathbf{t/p}, \mathbf{^{3}He/p}$ are overestimated by about a factor of 2, possibly due to the hadronic re-scattering effect.
- Considering only stable nuclei, $\mathbf{^{4}He/p}$ from thermal model is consistent with the experiment data.

K. Sun et al. Nature Commun. 15 (2024) 1, 1074;
V. Vovchenko et al., PLB 809, 135746 (2020);
[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.

Compound Yield Ratios



Compound Ratios: $\frac{N_t \times N_p}{N_d^2}$

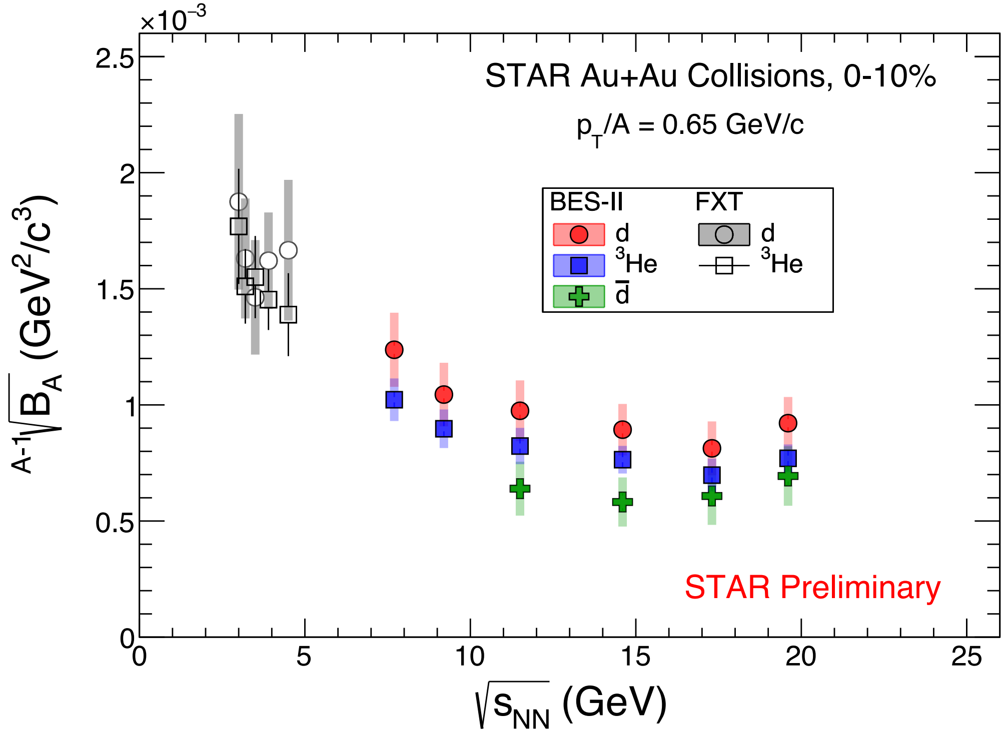
- AMPT reproduces data with a first-order phase transition with $T_c = 154$ MeV.
- The thermal model shows an opposite trend to the experimental data.
- The measurement of $N_t \times N_p / N_d^2$ in BES-II is ongoing.

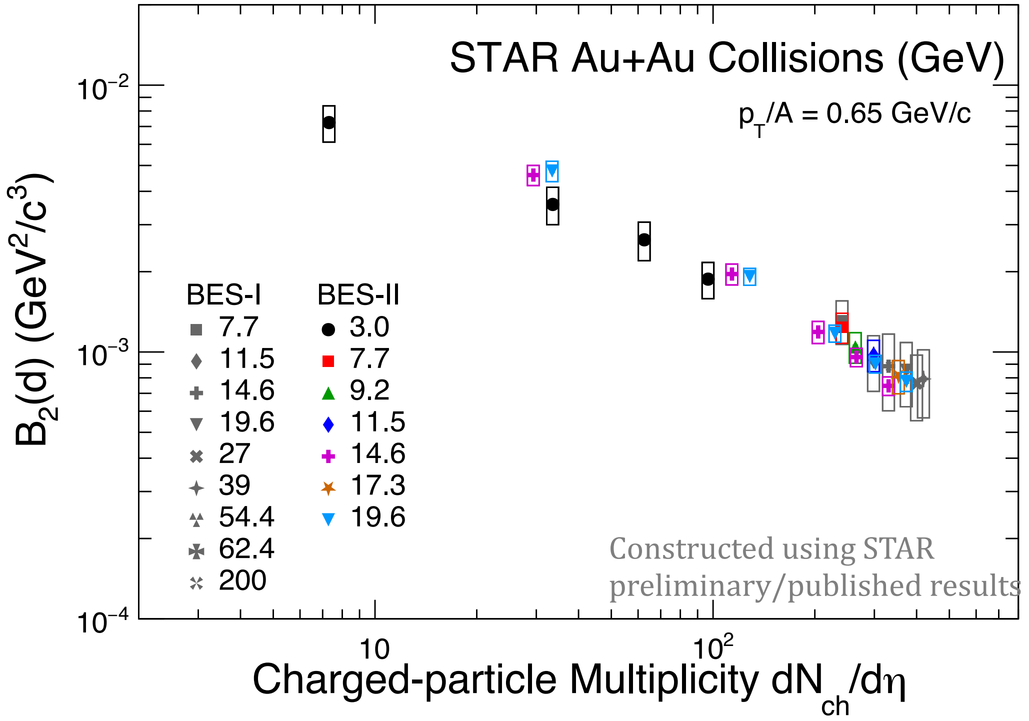
V. Vovchenko, et al. Phys. Rev. C 93(2016) 6, 064906
E. Shuryak et al. Eur.Phys.J.A 56 (2020) 9, 241
K. Sun et al. Phys.Rev.C 103 (2021) 6, 064909
K. Sun et al. arXiv: 2205.11010

Coalescence Parameters

- $E_{\mathrm{A}} \frac{d^3 N_{\mathrm{A}}}{d^3 p_{\mathrm{A}}} = B_{\mathrm{A}} \left(E_{\mathrm{p}} \frac{d^3 N_{\mathrm{p}}}{d^3 p_{\mathrm{p}}} \right)^{\mathrm{Z}} \left(E_{\mathrm{n}} \frac{d^3 N_{\mathrm{n}}}{d^3 p_{\mathrm{n}}} \right)^{\mathrm{A-Z}}$, A and Z are the mass and charge number of the nucleus.
- $B_A \propto \left(\frac{1}{V_{\mathrm{eff}}} \right)^{A-1}$, reflect the probability of nucleon coalescence.

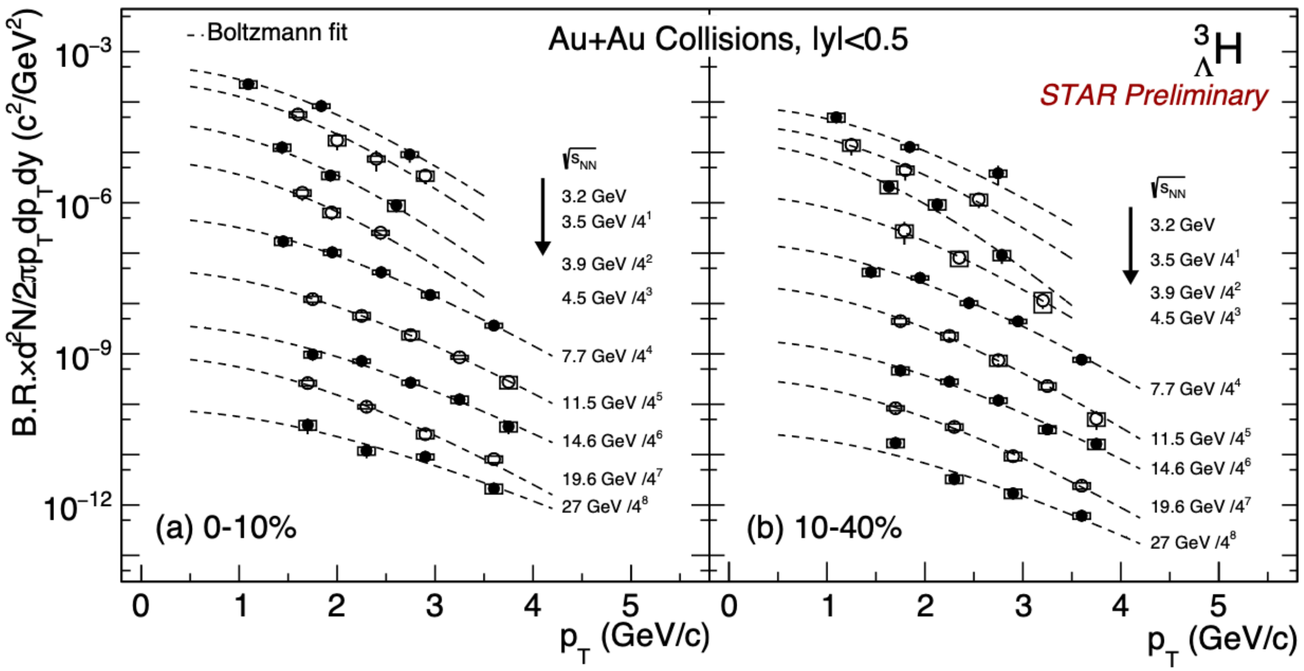
R. Scheibl and U. Heinz Phys.Rev.C 59 (1999) 1585-1602
STAR, Phys.Rev.C 99 (2019) 6, 064905
STAR, Phys.Rev.C 110, 054911 (2024)

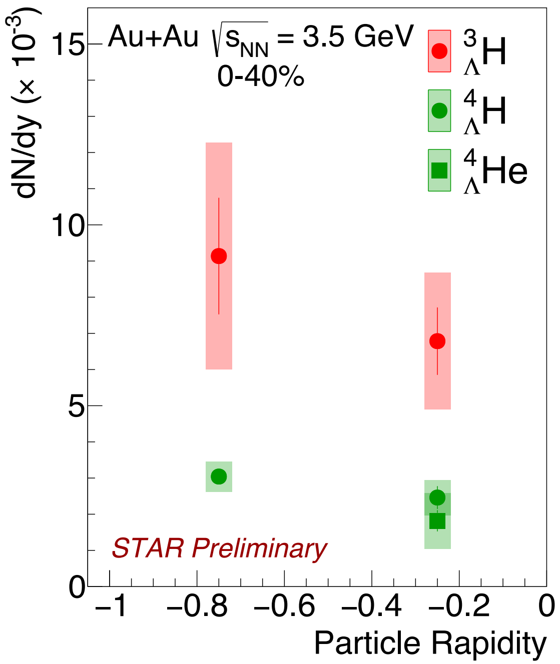


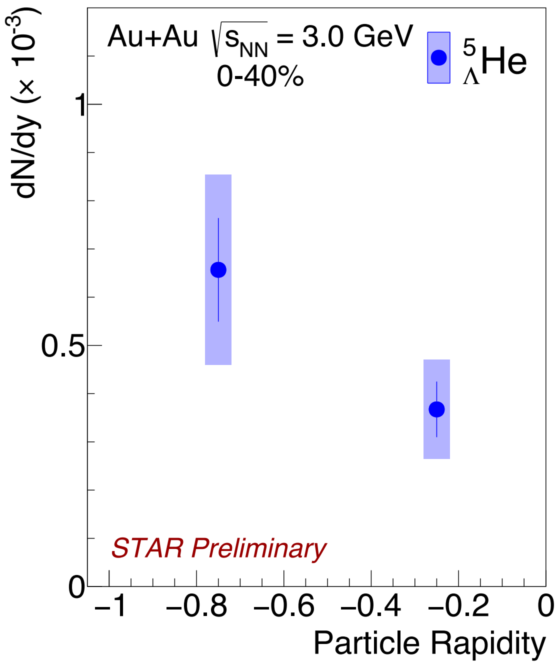


- $\sqrt[A-1]{B_A}$ decreases with increasing energy and $dN_{\mathrm{ch}}/d\eta$, implying an enlarged effective volume and reduced coalescence probability.
- No significant differences are observed among d, $\bar{\mathrm{d}}$, and ^{3}He.

Hypernuclei p_T Spectra







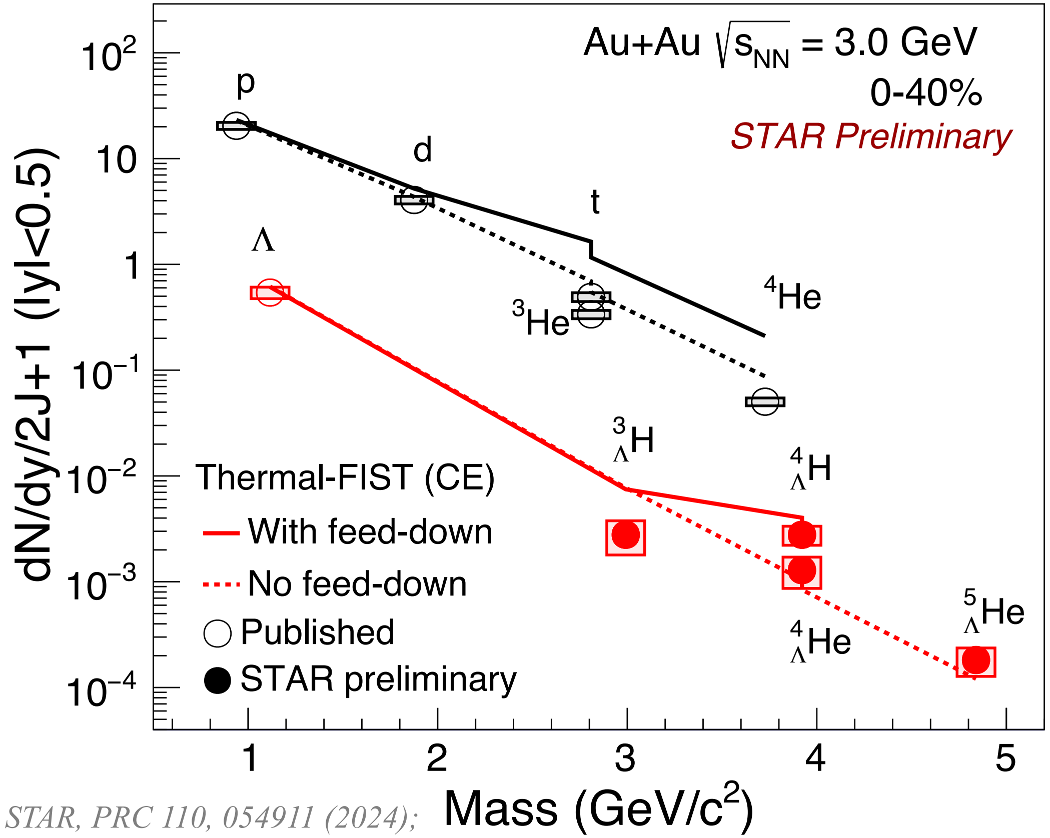
❖ Hypernuclei are reconstructed using the decay channels:

$^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^-$, $^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi^-$, $^{4}_{\Lambda}He \rightarrow {}^{3}He + p + \pi^-$, $^{5}_{\Lambda}He \rightarrow {}^{4}He + p + \pi^-$.

B.R.: https://hypernuclei.kph.uni-mainz.de/

- ➢ Significant hypernuclei production at target rapidity, more pronounced for heavier hypernuclei.
- ➢ Spectators also play an important role in hypernuclei production.
- ➢ First measurement of A = 5 hypernuclei yield in Au+Au collisions at $\sqrt{s_{NN}}$ = 3 GeV.

Particle Yields

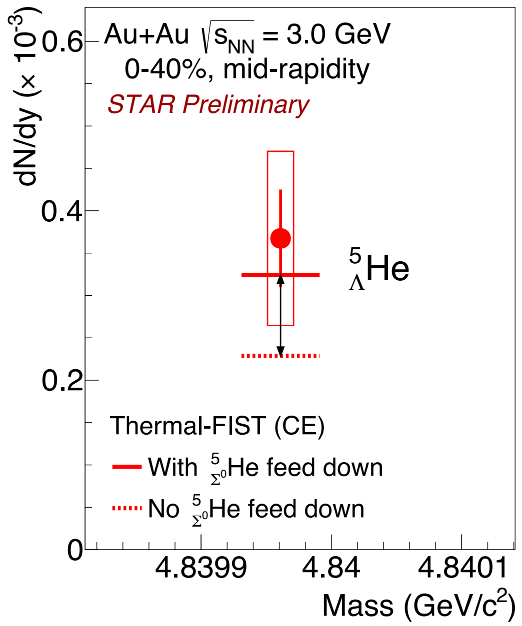


STAR, PRC 110, 054911 (2024);
STAR, PRL 128, 202301 (2022)
STAR, JHEP 10 (2024) 139

Feed-down: Contribution from decays of excited states

- $^{4}_{\Lambda}\mathrm{H}^{*}(1^{+}) \rightarrow {}^{4}_{\Lambda}\mathrm{H}(0^{+}) + \gamma$
- $^{4}_{\Lambda}\mathrm{He}^{*}(1^{+}) \rightarrow {}^{4}_{\Lambda}\mathrm{He}(0^{+}) + \gamma$

STAR, PLB 834, 137449 (2022)



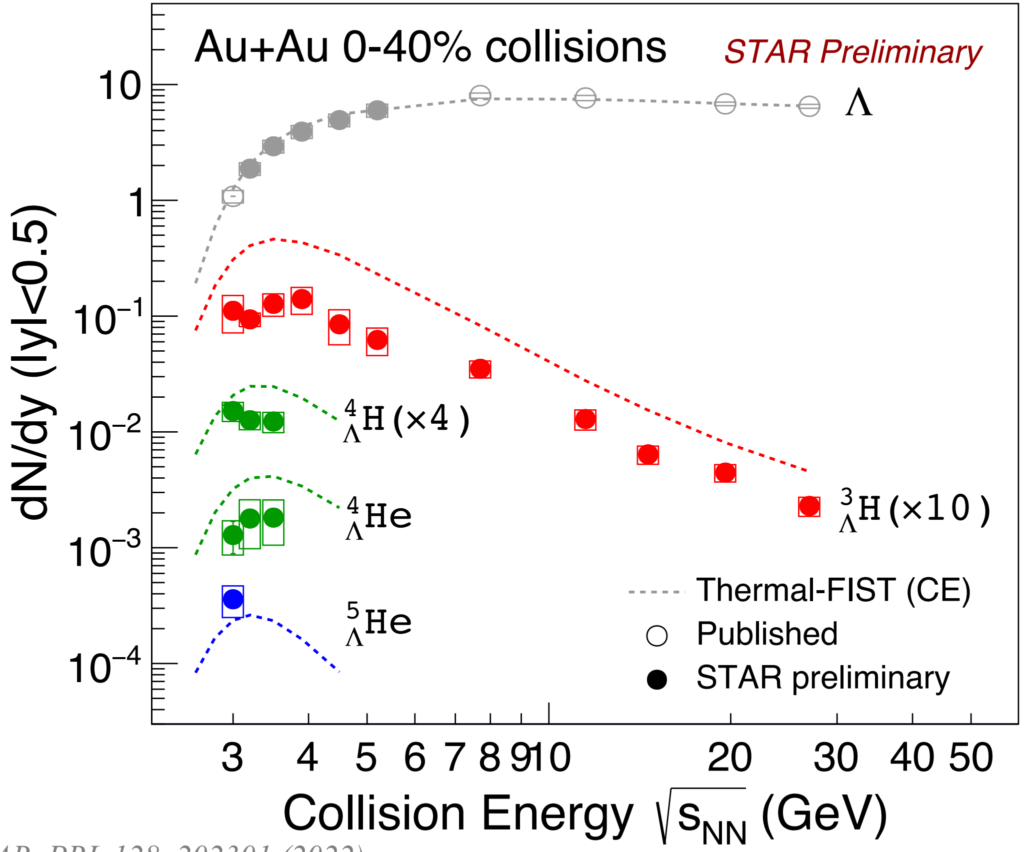
Hint of possible feed-down from $^{5}_{\Sigma^0}\mathrm{He} \rightarrow {}^{5}_{\Lambda}\mathrm{He} + \gamma$

J. Johnstone et al., JPG 8, L105 (1982)

Thermal-FIST predictions compared with data:

- Strongly overestimate $^{3}_{\Lambda}$H.
- Overestimate $^{4}_{\Lambda}$H, $^{4}_{\Lambda}$He after including feed-down from excited states.
- Slightly underestimate $^{5}_{\Lambda}$He.

Particle Yields



STAR, PRL 128, 202301 (2022)
V. Vovchenko et al., PRC 93, 064906 (2016)

Thermal-FIST(CE):
Includes unstable nuclei feed-down, except $^{5}_{\Sigma^0}$He.

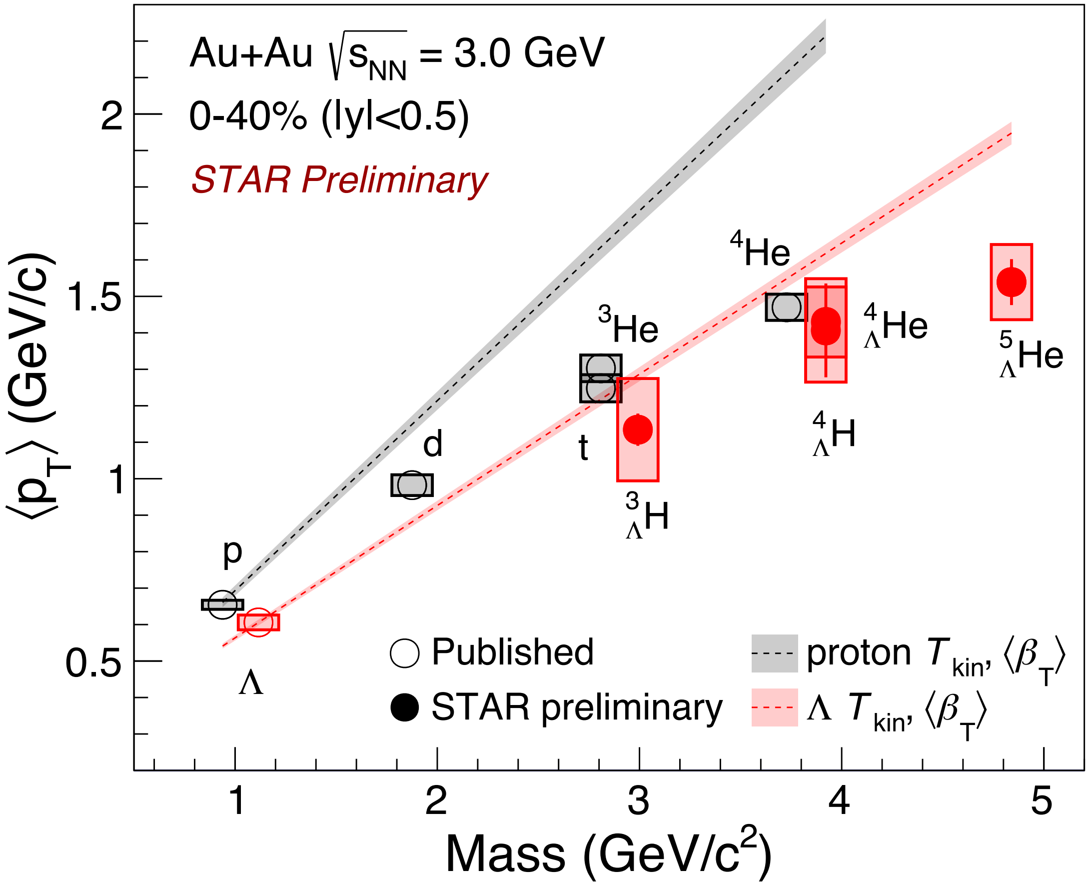
- $^{3}_{\Lambda}$H yield plateau ($\sqrt{s_{NN}}$ = 3-4 GeV)

  Interplay of high baryon density and strong strangeness suppression.

Thermal-FIST predictions compared with data:

- Strongly overestimate $^{3}_{\Lambda}$H.
- Overestimate $^{4}_{\Lambda}$H, $^{4}_{\Lambda}$He after including feed-down from excited states.
- Slightly underestimate $^{5}_{\Lambda}$He.

Averaged Transverse Momentum $\langle p_T \rangle$



STAR, PRC 110, 054911 (2024)
STAR, PRL 128, 202301 (2022)
STAR, JHEP 10 (2024) 139

Vary the mass to construct the blast-wave predictions using p(Λ) freeze-out parameters.

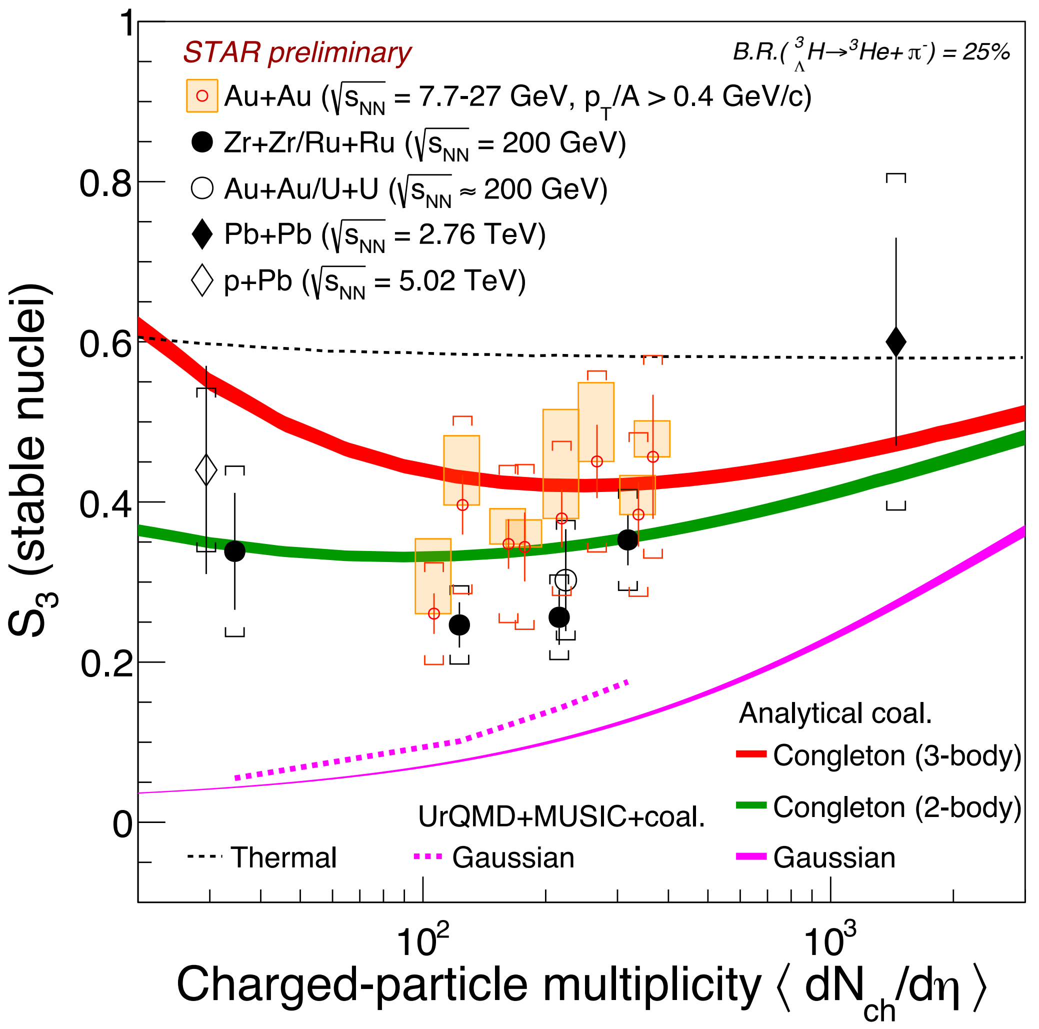
	p	Λ
$\langle \beta_T \rangle$(c)	0.43	0.33
T_{kin}(GeV)	0.065	0.076

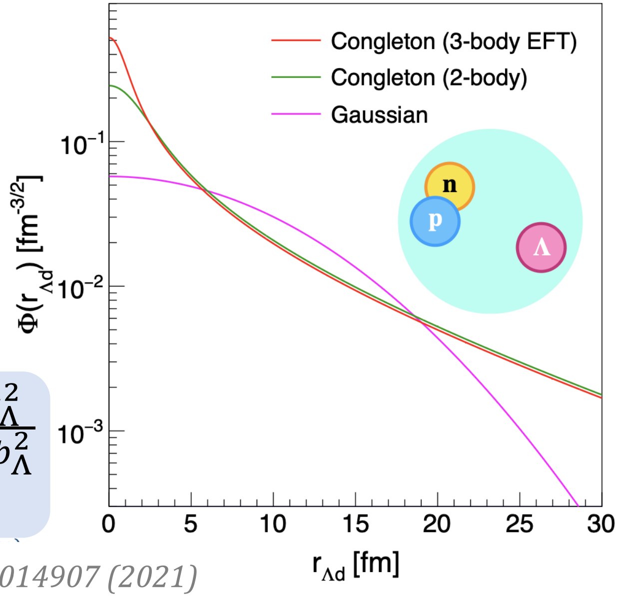
E. Schnedermann et al., PRC 48, 2462 (1993)
ALICE, PLB 794, 50–63 (2019)

- Hypernuclei closer to Λ blast-wave ansatz.
- Kinematics of light (hyper-)nuclei deviate from the collective expansion of the bulk matter.

Strangeness Population Factor

$$S_3 = \frac{^3_\Lambda\mathrm{H}}{^3\mathrm{He} \times \Lambda/p}$$





Wigner-function coalescence:

❖ **Gaussian:**

$$\Phi_{^3_\Lambda\mathrm{H}}(r_{pn}, r_\Lambda) = \left(\frac{1}{3\pi^2 b_{pn}^2 b_\Lambda^2}\right)^{\frac{3}{4}} e^{-\frac{r_{pn}^2}{4b_{pn}^2} - \frac{r_\Lambda^2}{3b_\Lambda^2}}$$

Phys.Rev.C 103, 014907 (2021)

❖ **Congleton:**

$$\hat{\Phi}_{^3_\Lambda\mathrm{H}(d\Lambda)}(q) = A\,\frac{e^{-\frac{-q^2}{Q_\Lambda^2}}}{q^2 + \alpha_\Lambda^2}$$

J.Phys.G 18, 339-357 (1992)

- ○ 2-body model of $^3_\Lambda$H: $(Q_\Lambda, \alpha_\Lambda) = (1.17, 0.068)\mathrm{fm}^{-1}$
- ○ 3-body effective field theory: $(Q_\Lambda, \alpha_\Lambda) = (2.5, 0.068)\mathrm{fm}^{-1}$

Phys.Rev.C 100, 034002 (2019)

- ➢ Thermal model overestimates S_3.
- ➢ Gaussian wave function underestimates S_3.
- ➢ Coalescence using Congleton wave function describe S_3 across wide range of energies.

STAR, Phys.Rev.Lett. 128 (2022) 20, 202301
STAR, Nature 2024, 77 (2024)
Thermal: Comput.Phys.Commun. 244, 295 (2019)
ALICE, Phys.Rev.Lett. 128, 252003 (2022)
ALICE, Phys.Lett.B 754 (2016) 360-372
Coalescence: arXiv: 2510.06758

Summary and Outlook

Summary:

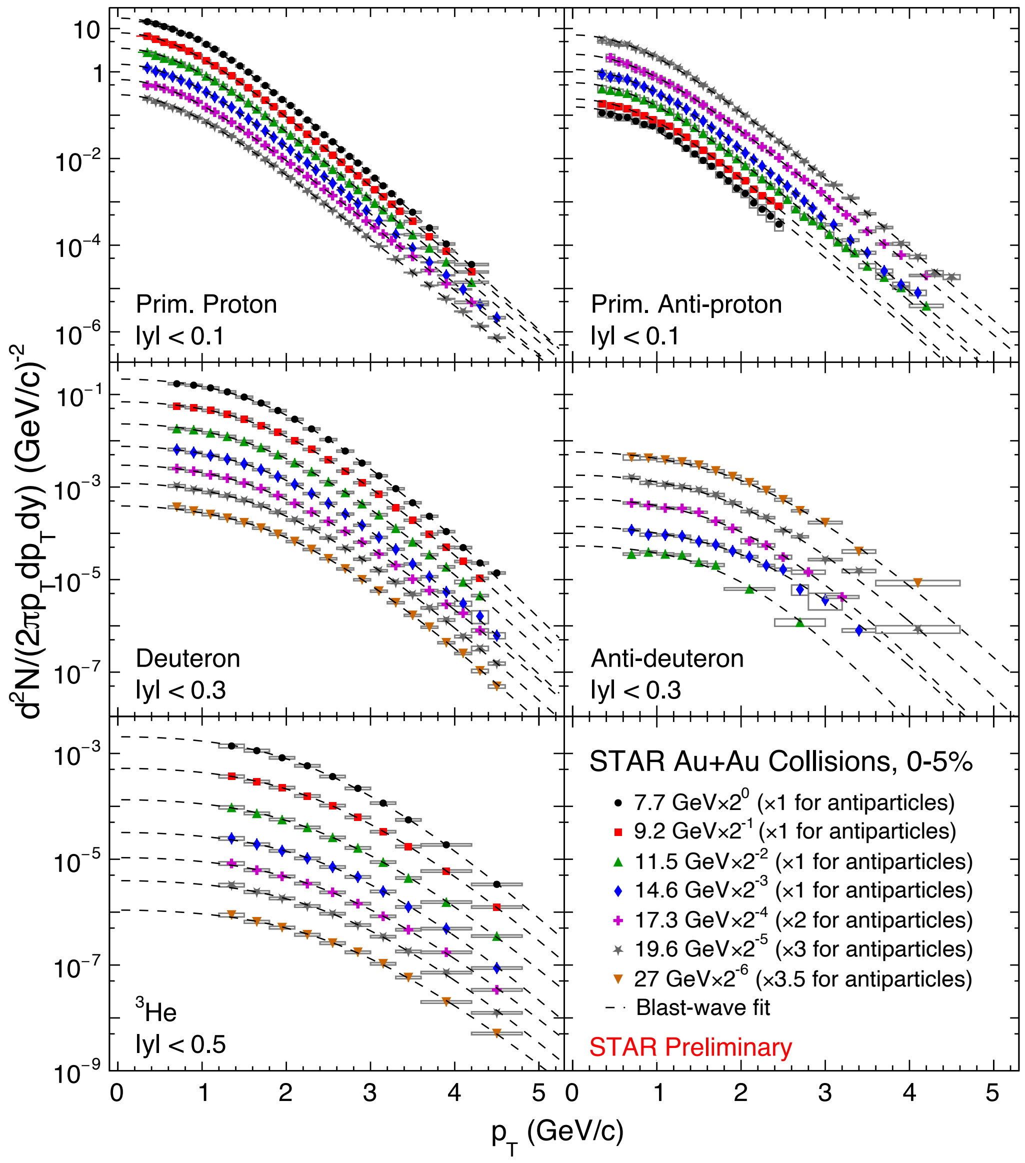
- Light nuclei (d, $\bar{d}$, ^{3}He, and ^{4}He) and hypernuclei ($^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H, $^{4}_{\Lambda}$He, and $^{5}_{\Lambda}$He) productions in Au+Au collisions from RHIC STAR BES-II at $\sqrt{s_{\mathrm{NN}}} = 3 - 27$ GeV.
- The coalescence parameters indicates the effective volume increases with energy.
- Light nuclei and hypernuclei measurements consistently point to the coalescence production mechanism.

Outlook:

- Measure the compound ratio ($N_p \times N_t / N_d^2$) using BES-II data.
- Extend measurements to heavier nuclei over a broad energy range from $\sqrt{s_{\mathrm{NN}}} = 3 - 27$ GeV.
- BES-II 3 GeV 2B data: more precise measurements for light (hyper)nuclei.

Thank you for your attention!

Backup – Transverse Momentum Spectra



- Obtained spectra for p, d, ^{3}He, $\bar{p}$ and $\bar{d}$ as a function of p_T in Au+Au collisions at 7.7 – 27 GeV.
- The low p_T reach is extended in BES-II, which leads to smaller systematic uncertainties in p_T-integrated yields.
- Blast-Wave Function

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

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

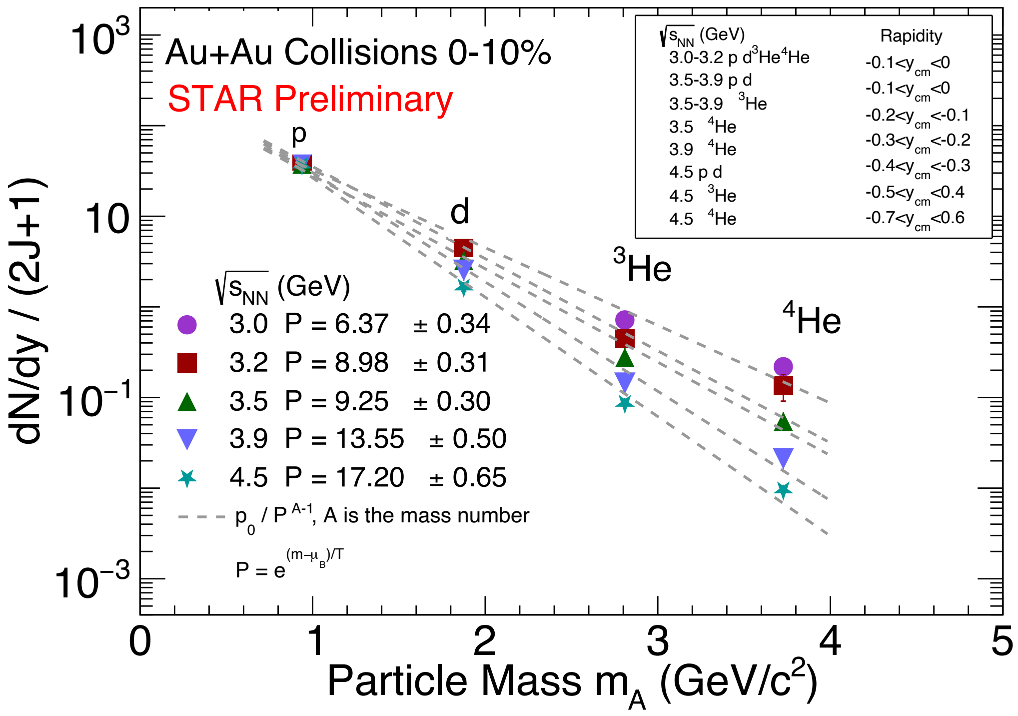
Kinetic Freeze-out Parameters:

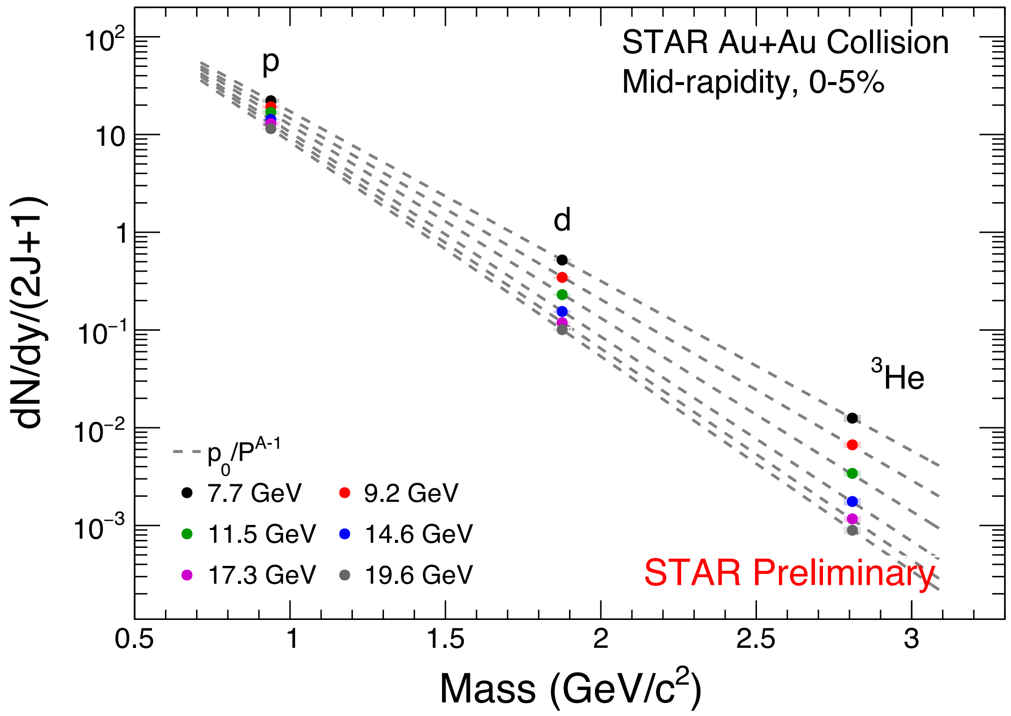
T_{kin} : kinetic freeze-out temperature
$\langle\beta_T\rangle$: average radial flow velocity

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

J.D. Bjorken, Phys.Rev.D 27 (1983) 140-151;
E. Schnedermann et al. Phys.Rev.C 48 (1993) 2462-2475

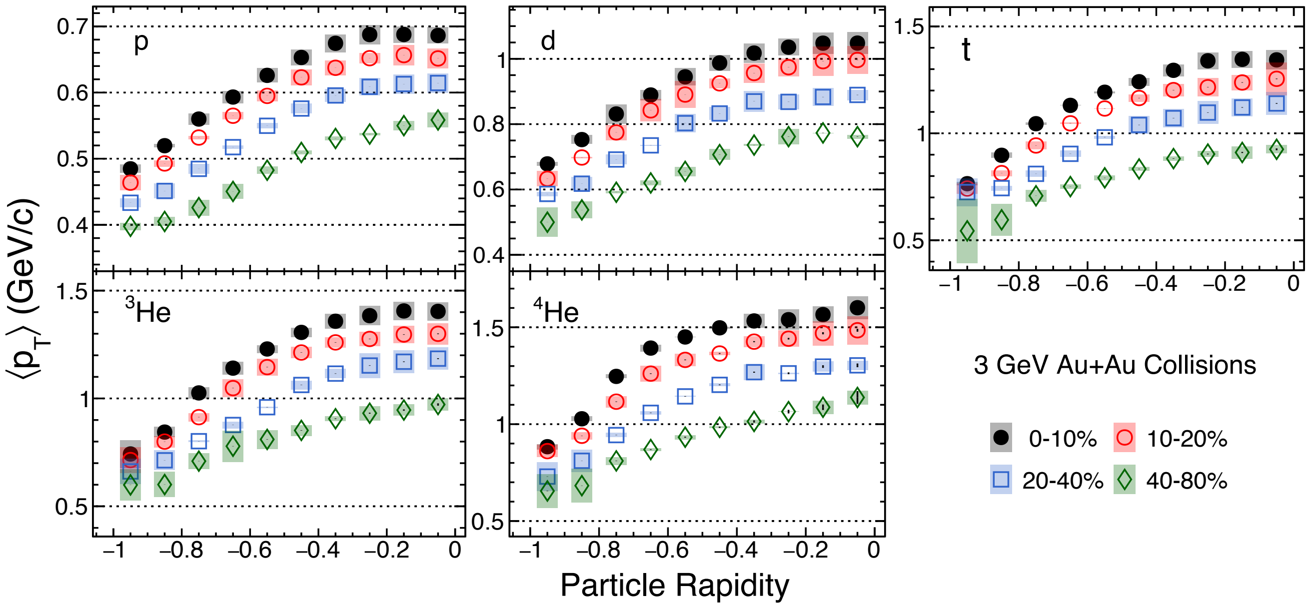
Backup – Particle Yields

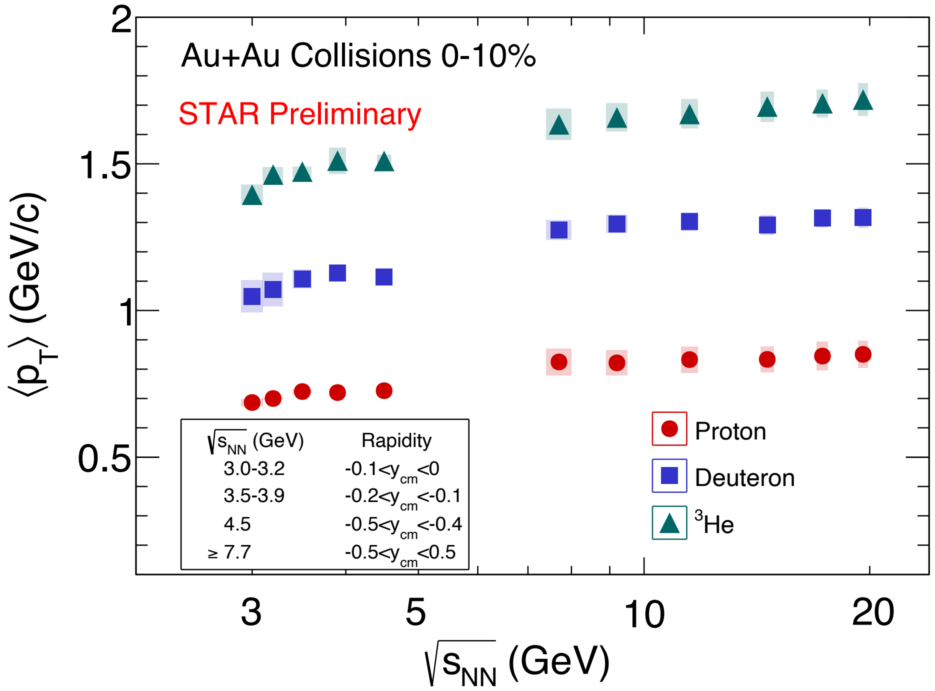




- The production of light nuclei are proportional to the spin degeneracy.
- Light nuclei yields decrease exponentially with increasing particle mass.
- Slope decrease indicates that light nuclei are more easily formed at low energies.

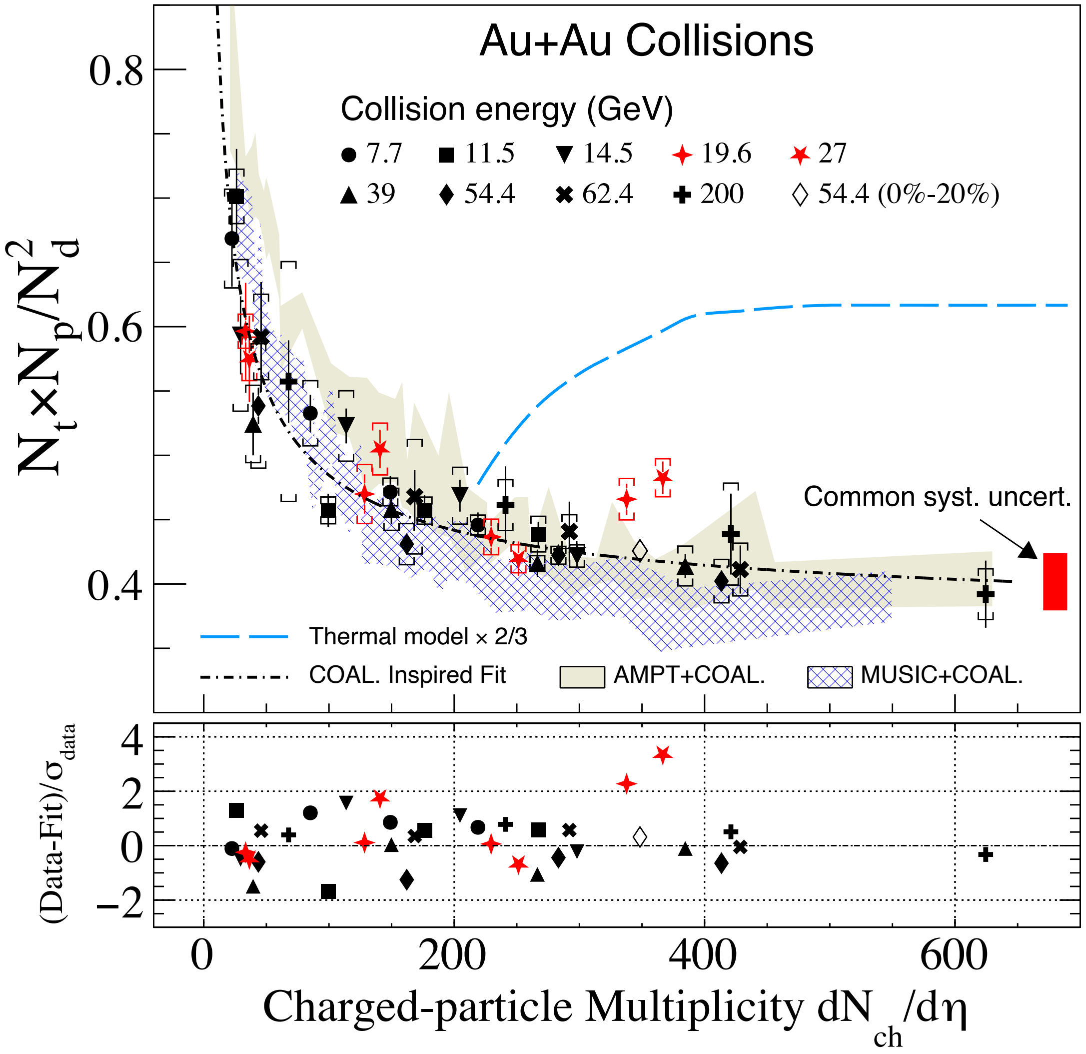
Backup – Averaged Transverse Momentum $\langle p_T \rangle$





- $\langle p_T \rangle$ of protons and light nuclei as a function of centrality, rapidity, and collision energy.
- Centrality dependence reflects that the collective expansion in the radial direction is stronger in central collisions than in peripheral collisions.
- 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.

Backup – 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, 136571 (2021)

- The ratio of 19.6 and 27 GeV from 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.