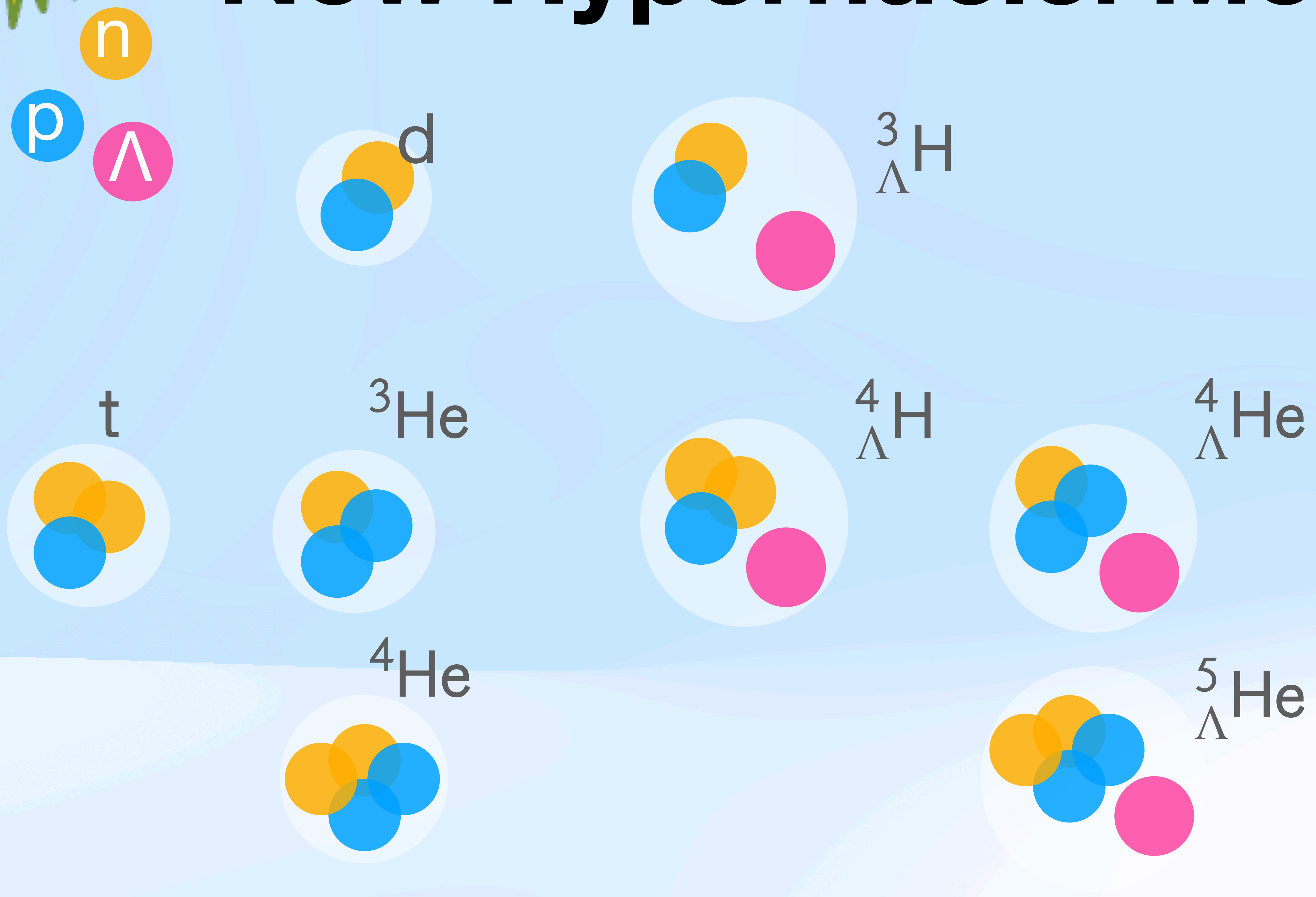
New Hypernuclei Measurements from STAR



Outline
1. Introduction
2. Particle Yields
3. Transverse Momentum Distribution
4. Collective Flow
5. Summary and Outlook

Yingjie Zhou for the STAR Collaboration
CCNU, GSI

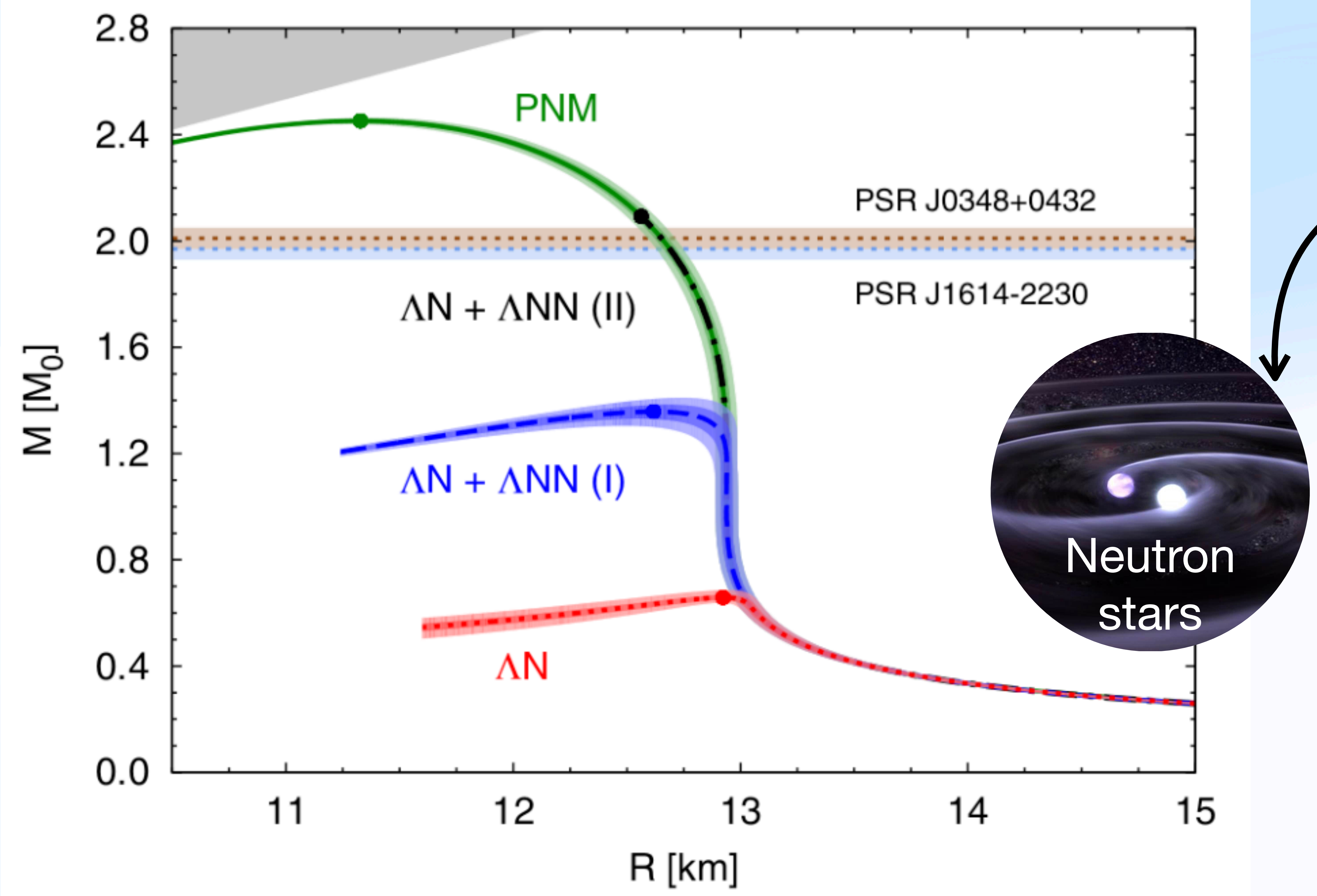
Quark Matter 2025, Frankfurt, Germany

Supported in part by U.S. DEPARTMENT OF ENERGY Office of Science

Hypernuclei and Hyperon-Nucleon (Y-N) Interaction

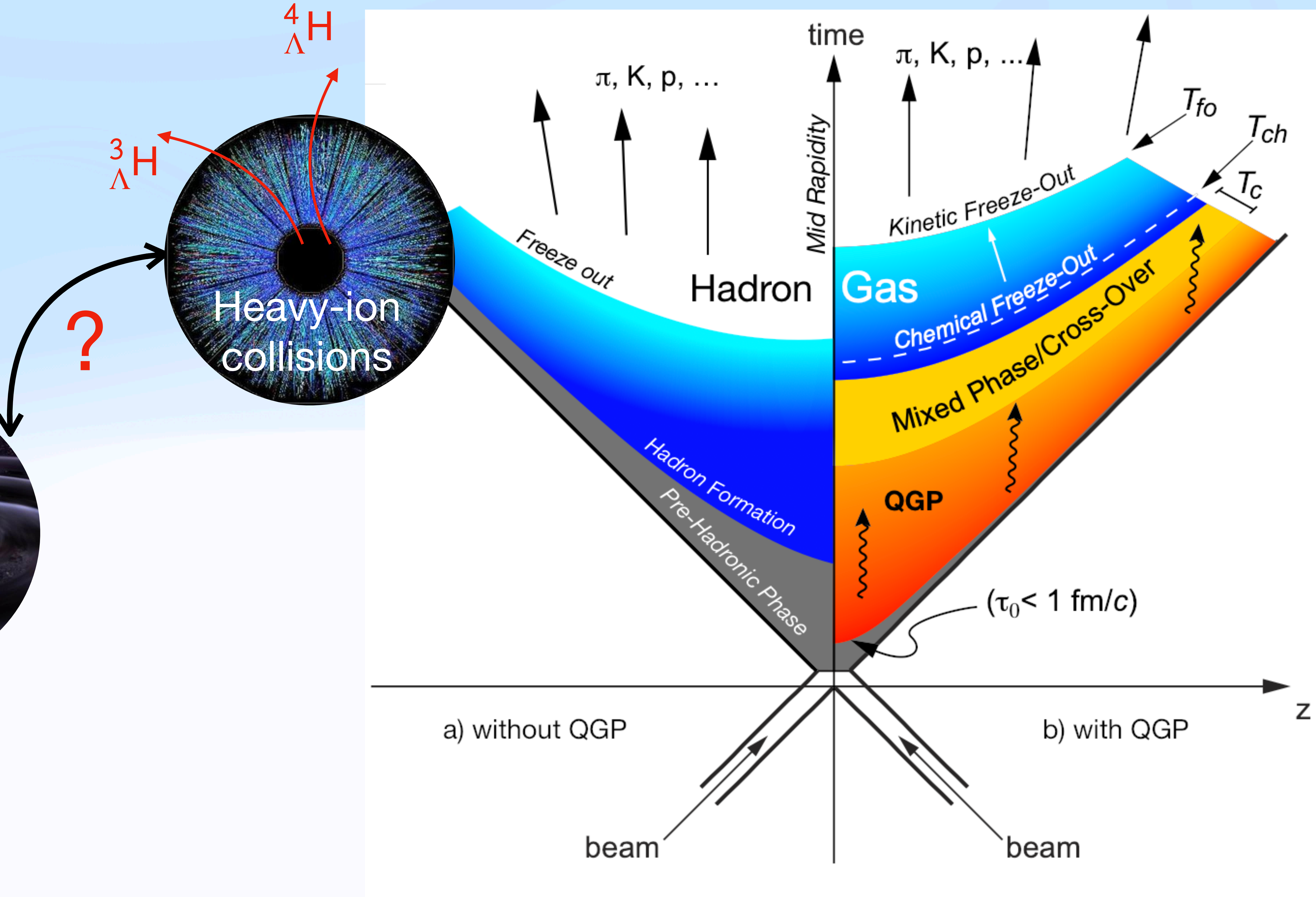
- **Hyperon Puzzle**: difficulty to reconcile the measured masses of neutron stars with the presence of hyperons in their interiors

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



- Density dependent YN, YNN interactions are essential for solving the hyperon puzzle

- Hypernuclei have been measured in heavy-ion collisions over a broad range of baryon densities



- Can hypernuclei production be used to constrain the in-medium Y-N interaction?

Hypernuclei Production Mechanisms

When are nuclei produced in a heavy-ion collision?

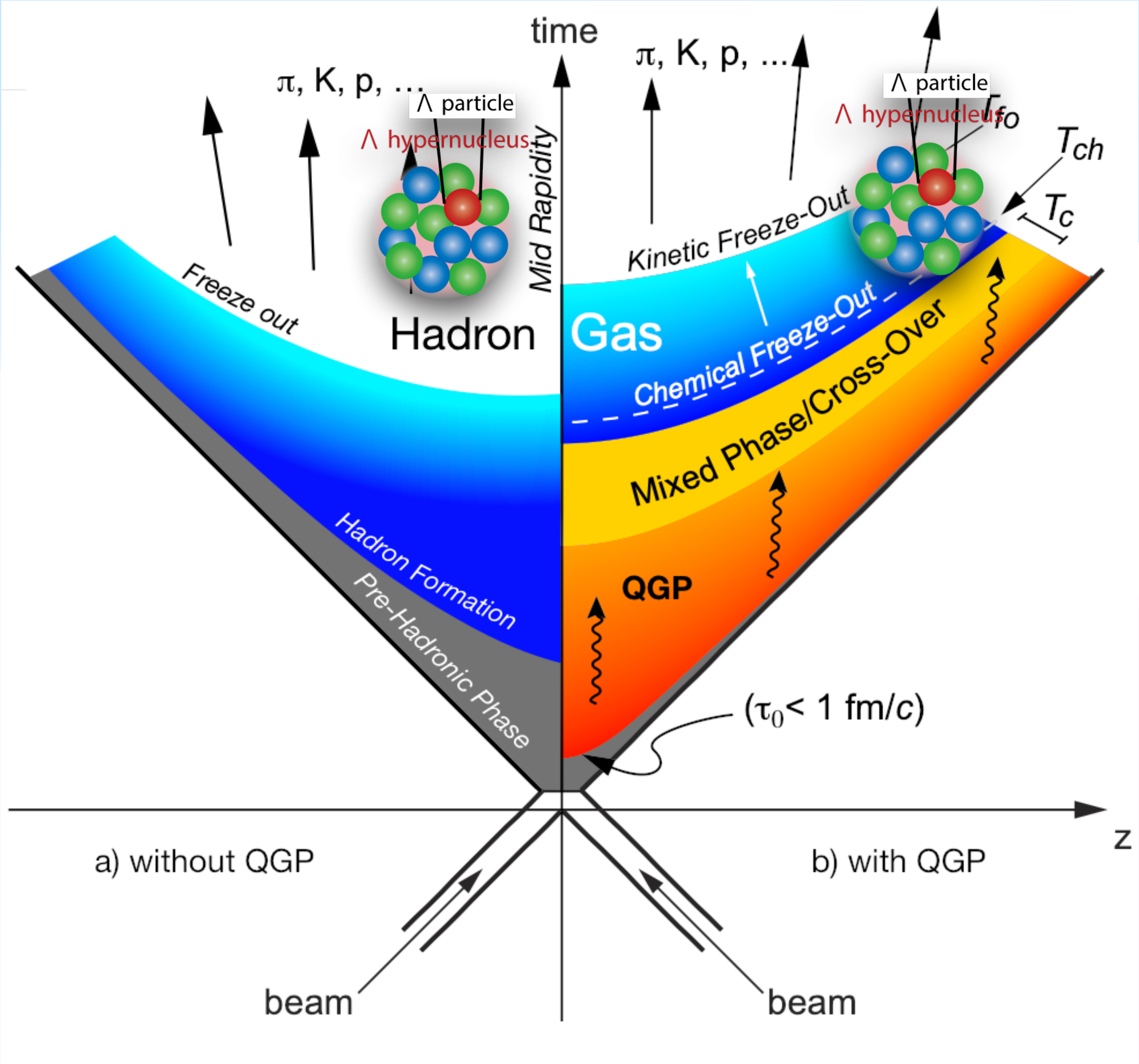
1. Thermal models
   - Hadrons and (hyper-)nuclei are treated equally
   - Yields are predicted with thermal equilibrium assumptions

✗ Y–N dynamics have minimal impact on final yield

2. Coalescence model
   - (Hyper-)nuclei formation after kinetic freeze-out
   - Nucleon coalescence
     - Wigner function
     - Emission source size and nuclear radius

✓ In-medium Y–N interactions modify freeze-out phase space, affecting coalescence and hypernuclei yields

*Need a solid understanding in **hypernuclei production mechanisms** before we can use them to probe the in-medium Y–N interaction*



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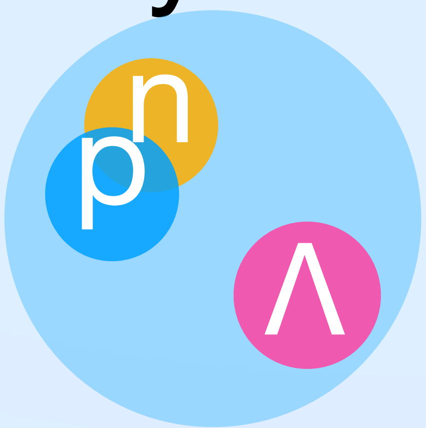

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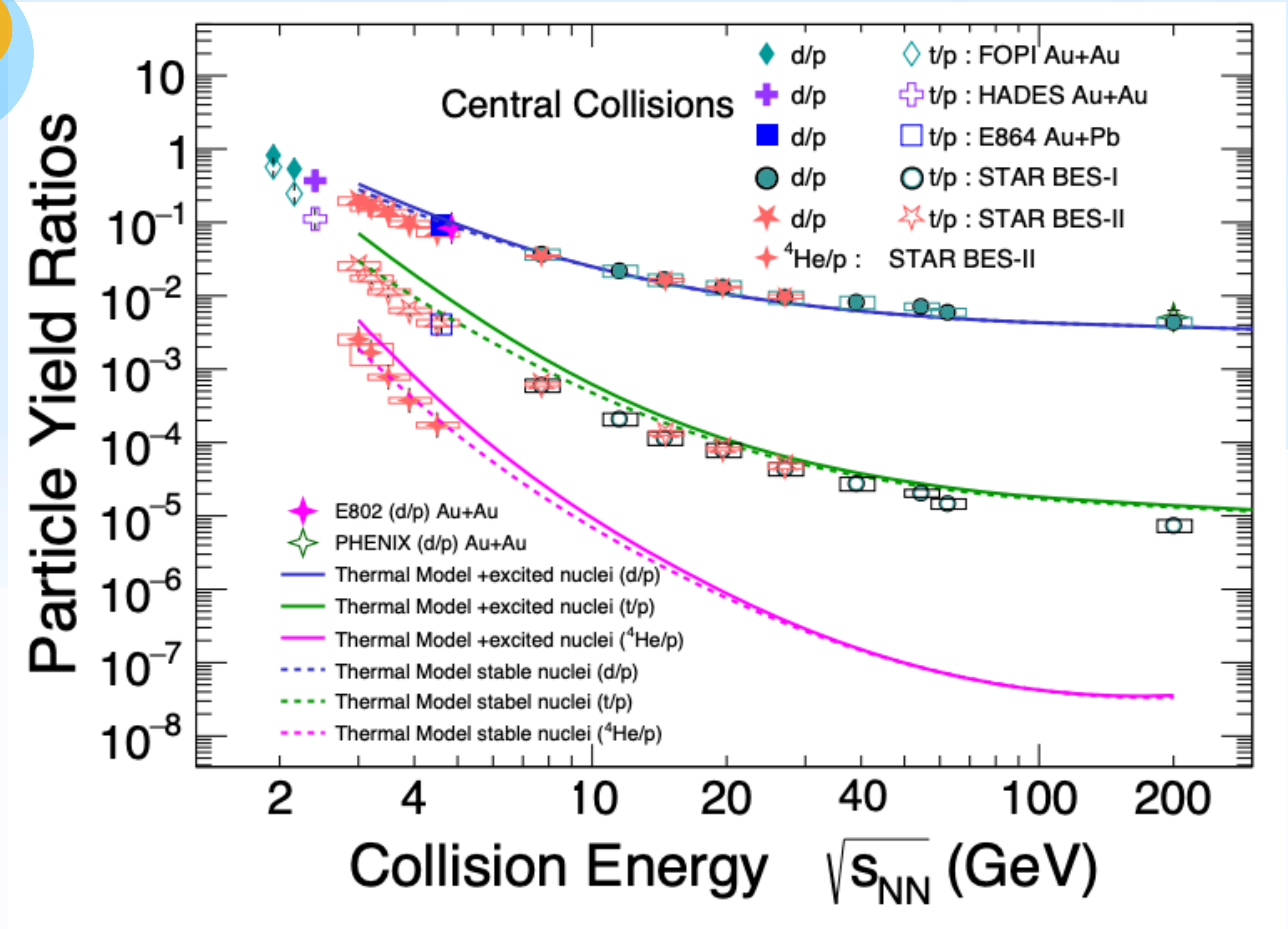
What have we learnt from light nuclei production?

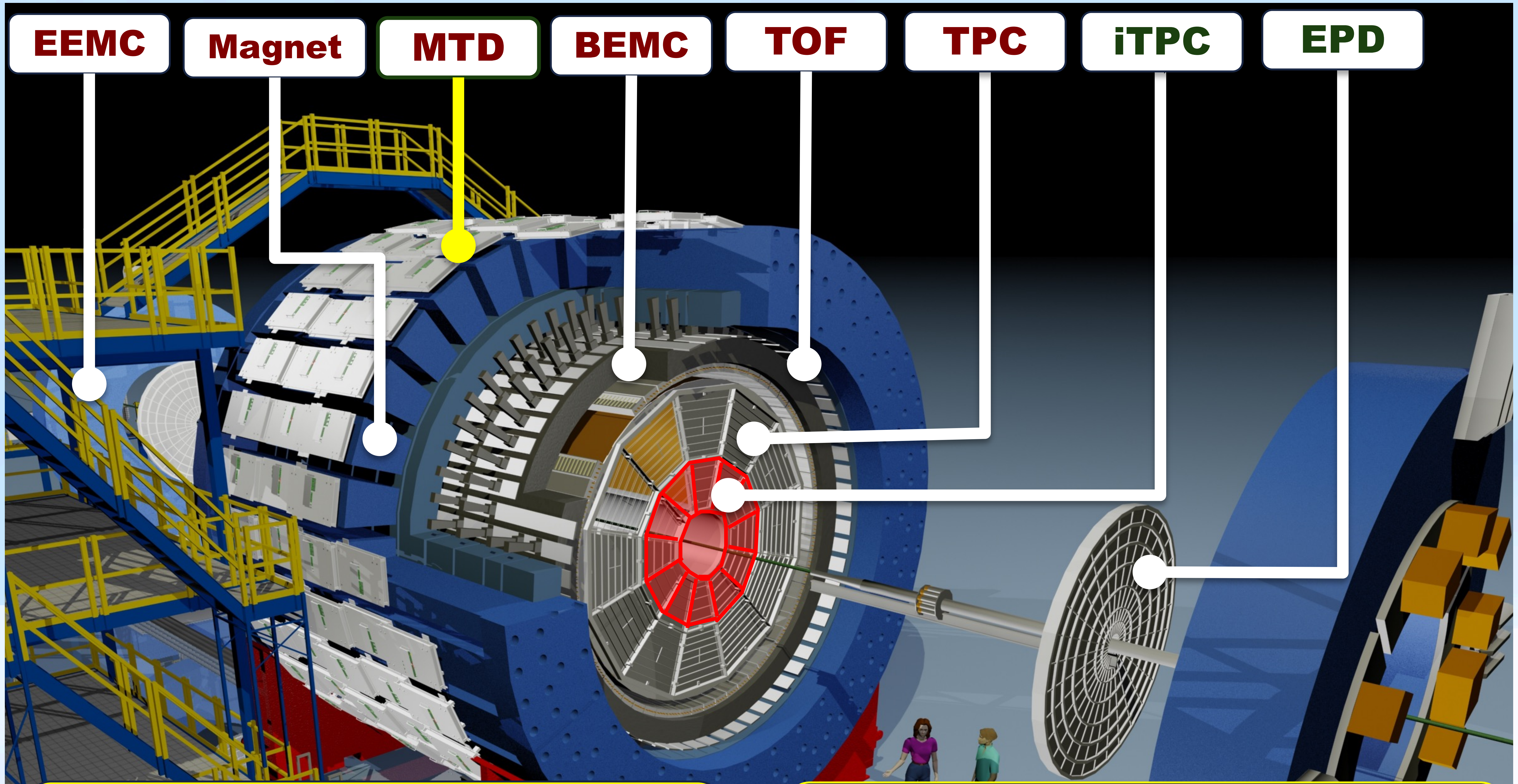
See poster by Liubing Chen (xx/xx)



- *d/p* is fairly well described by thermal model, but *t/p*, *⁴He/p* is overestimated

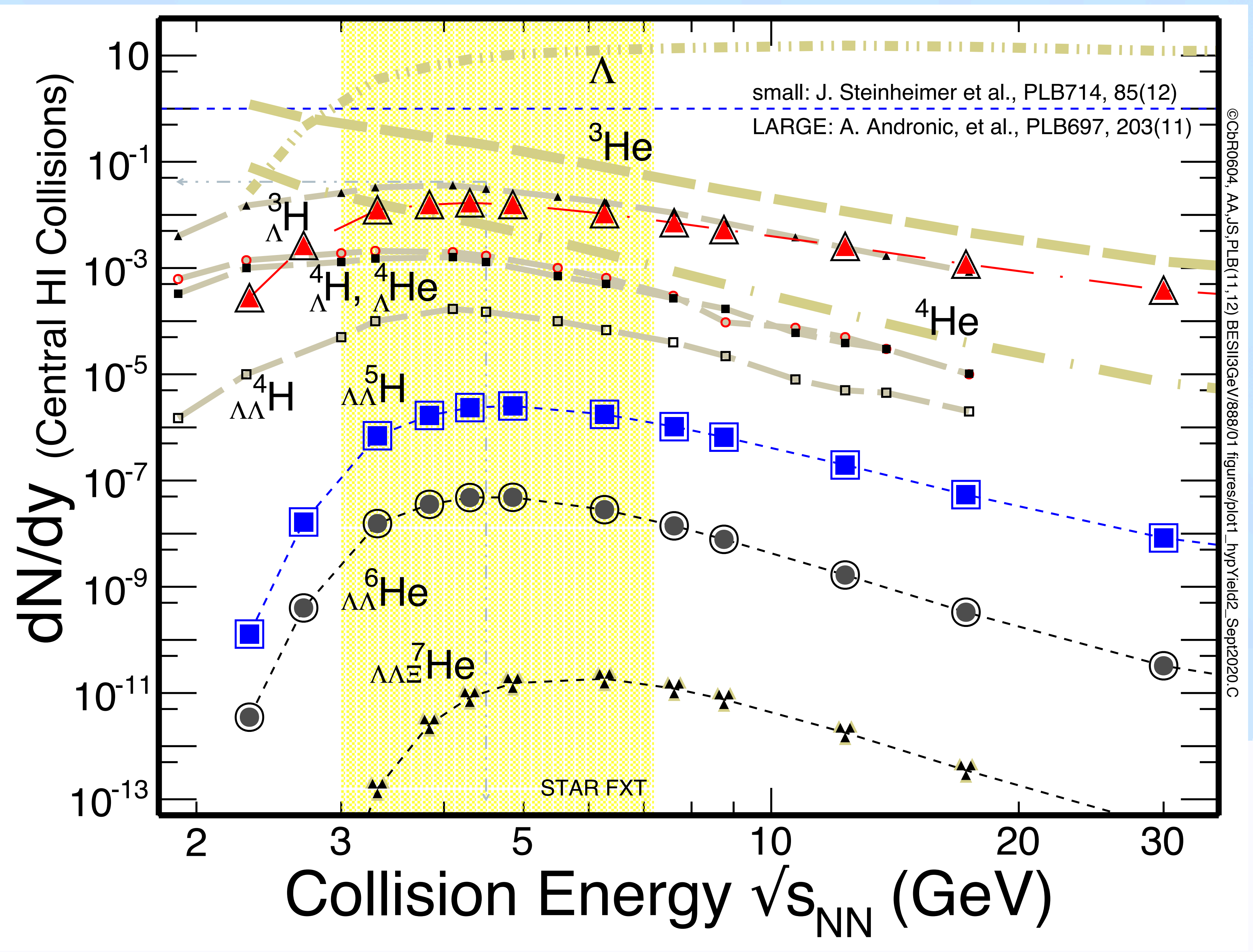
Recent nuclei measurements poses challenges for thermal model

STAR and Beam Energy Scan

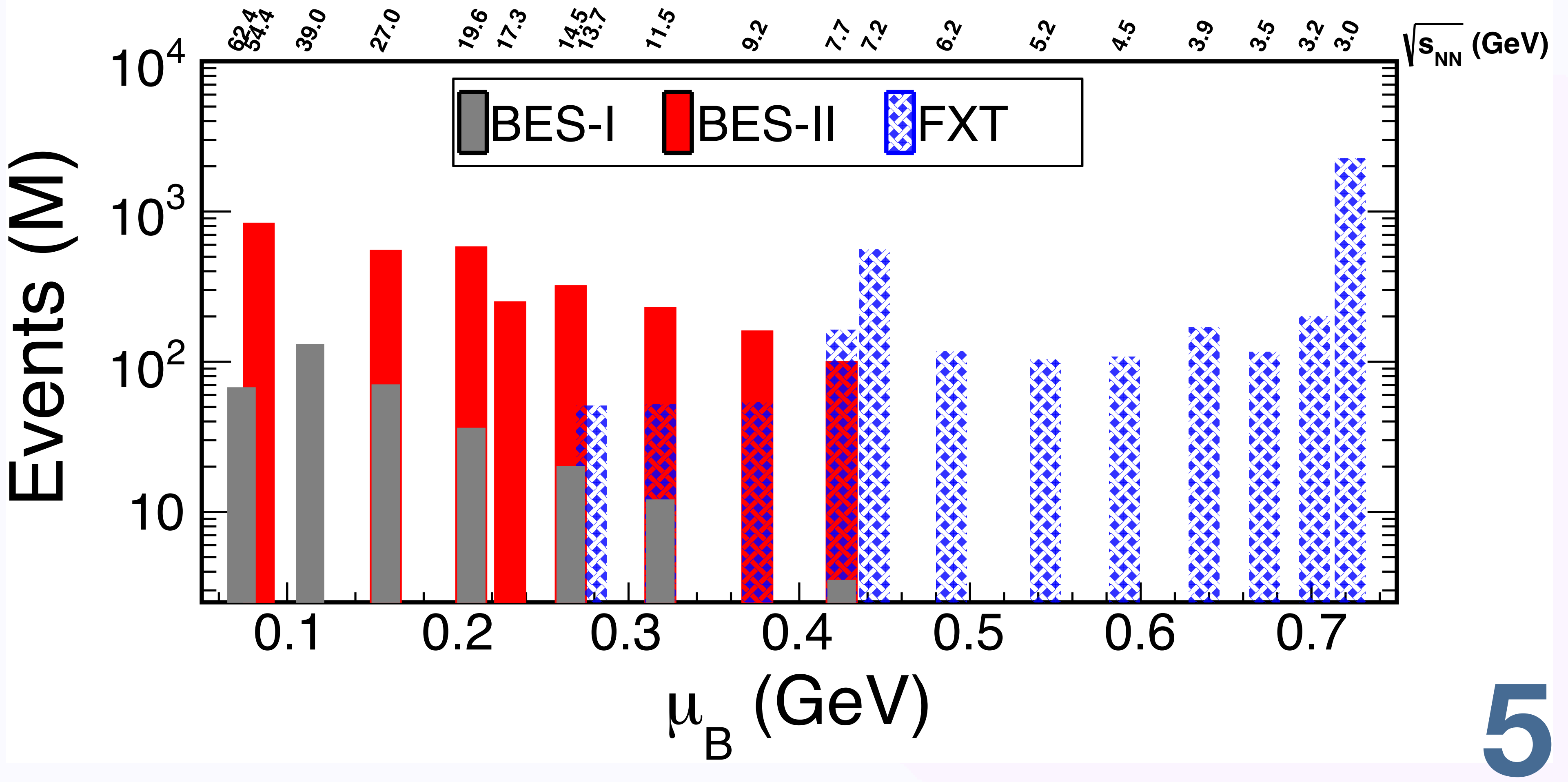


- **Large** acceptance
- **Excellent PID** with **uniform** efficiency
- Modest rates

- **iTPC, EPD & eTOF** upgrades completed
- All are in data-taking for BES-II program



A. Andronic *et al.* Phys.Lett.B 697, 203 (2011)
J. Steinheimer *et al.* Phys.Lett.B 714, 85 (2012)



- RHIC BES-II offers great opportunity for hypernuclei measurements

Hypernuclei Reconstruction

- Hypernuclei are reconstructed using the following decay channels:

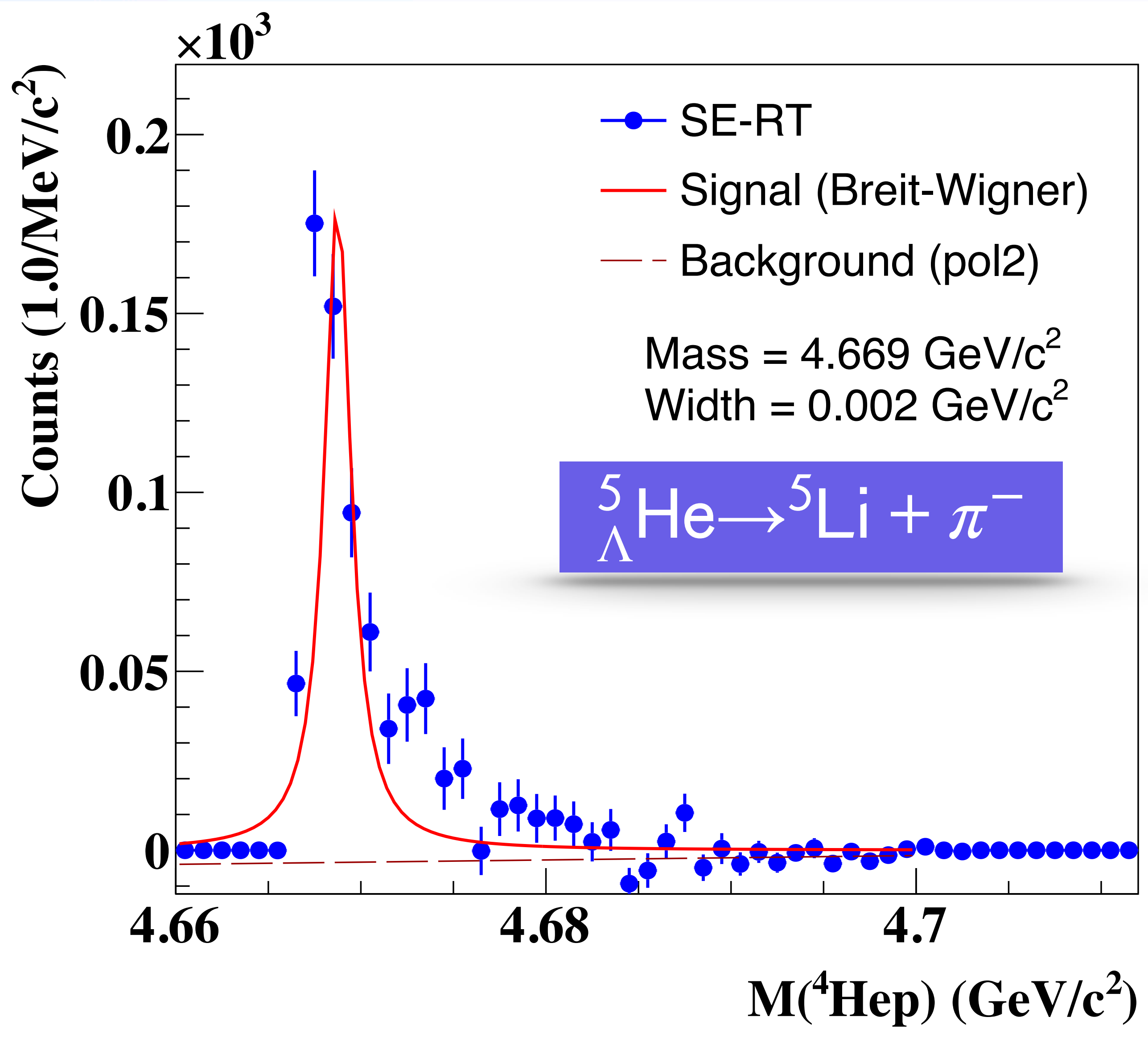
$^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^-$ $\quad$ $^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi^-$ $\quad$ $^{4}_{\Lambda}He \rightarrow {}^{3}He + p + \pi^-$

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

Helps to constrain Λ–N and *ΛNN*

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

- Combinatorial background estimated via rotating fragments tracks or event mixing
- Efficiency correction using a **data-driven** GEANT simulation
  - To account for the decay kinematics of $^{4}_{\Lambda}$He, $^{5}_{\Lambda}$He, the three-body decay phase space is weighted according to the Dalitz plot from data



Hypernuclei p_T Spectra and Rapidity

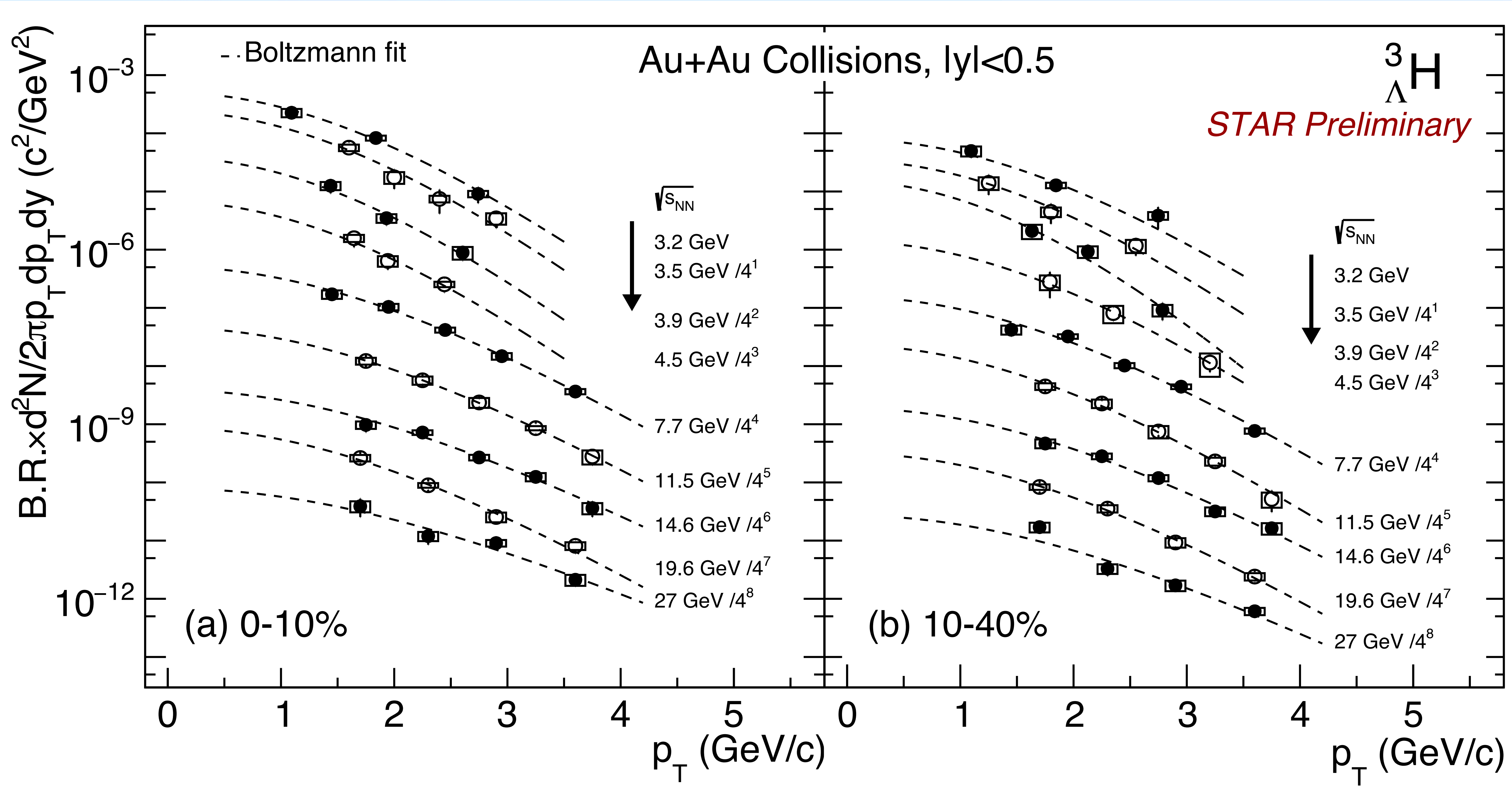
- Measurements cover different energies
  - ${}^{3}_{\Lambda}H$ in Au+Au collisions at **3-27** GeV, Au+Au collisions at **200 GeV**
  - ${}^{4}_{\Lambda}H$, ${}^{4}_{\Lambda}He$ in Au+Au collisions at **3-3.5 GeV**
  - ${}^{5}_{\Lambda}He$ in Au+Au collisions at **3 GeV**

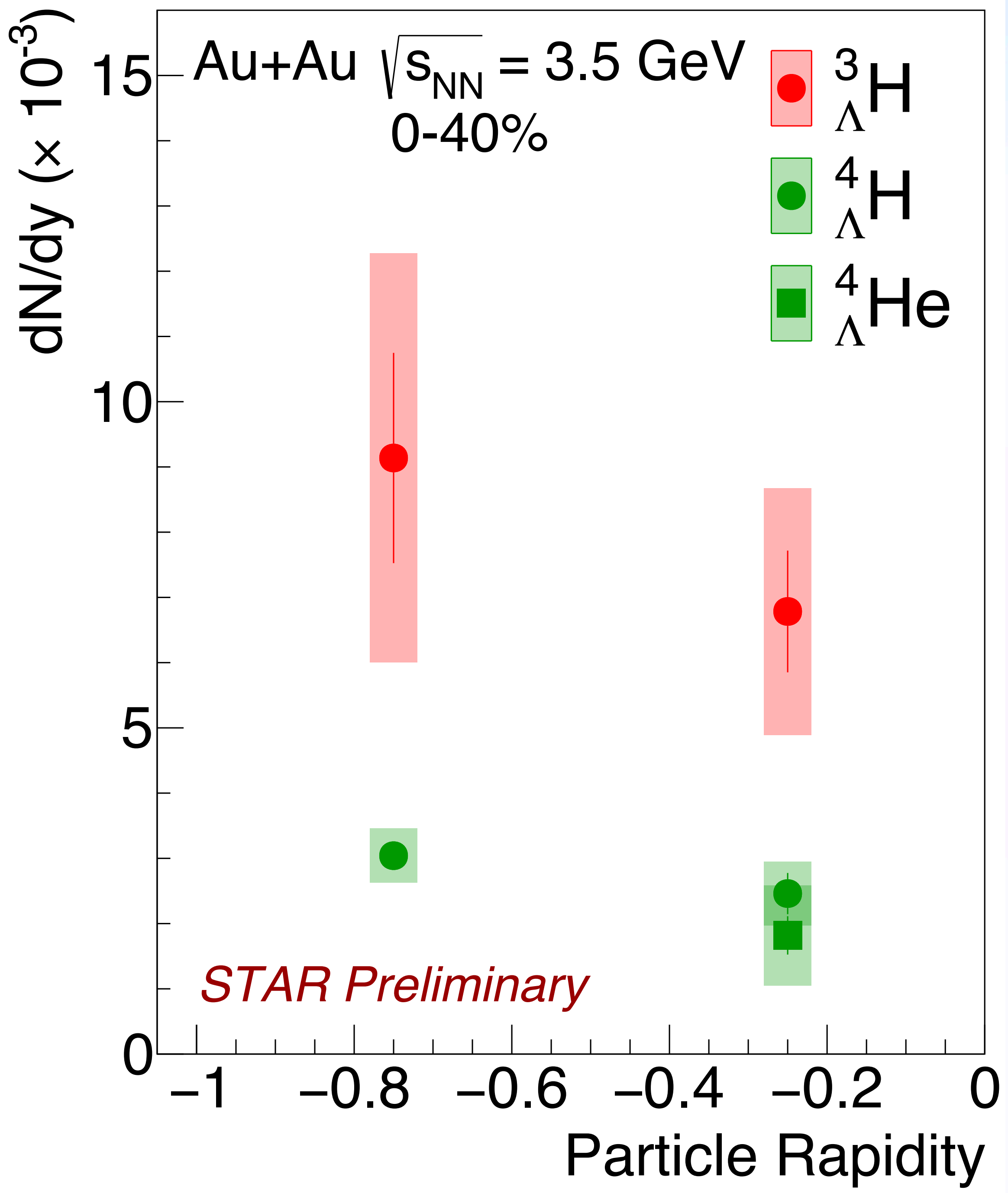
- Significant hypernuclei production at target rapidity, more pronounced for heavier hypernuclei

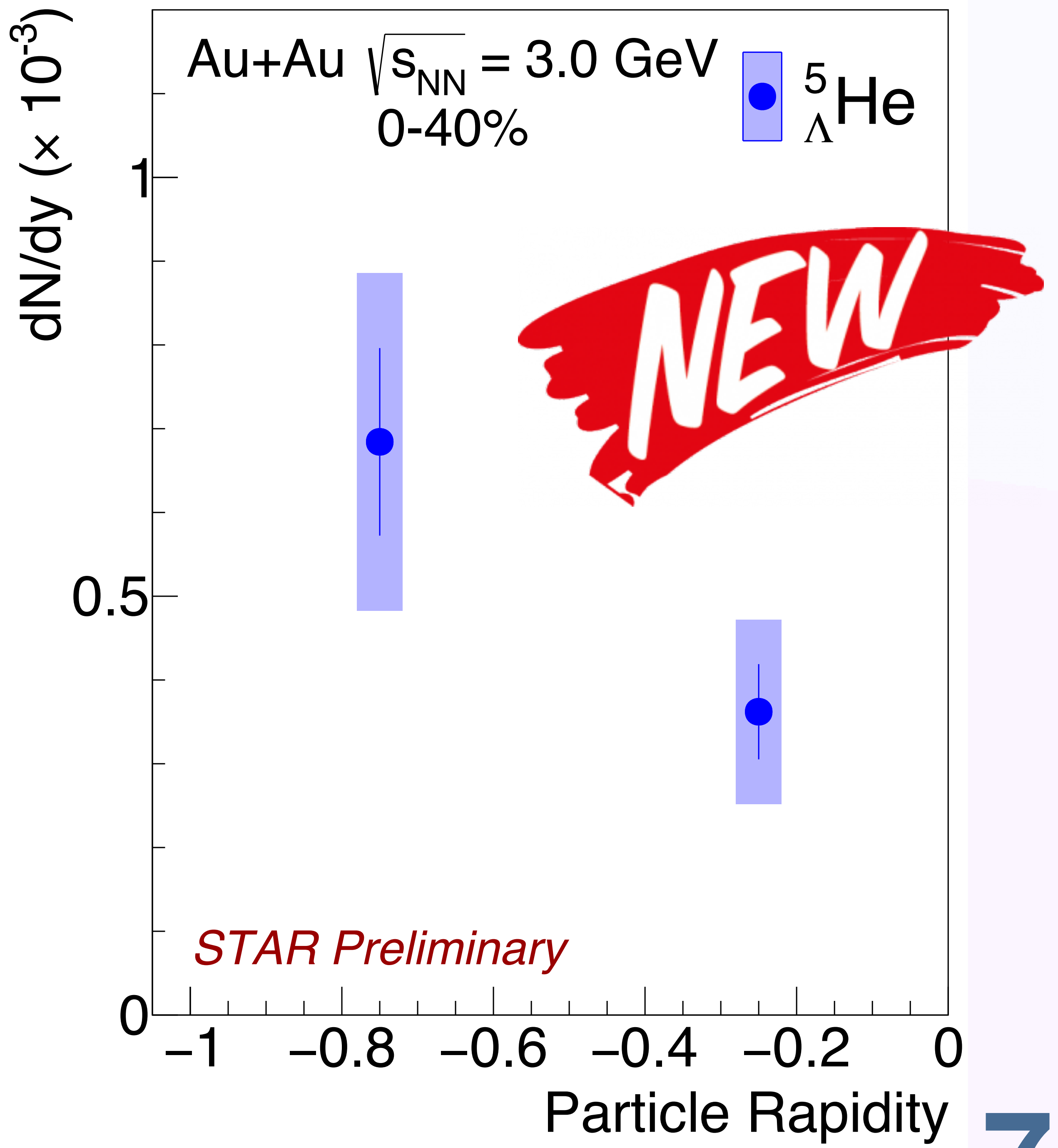
Spectator matter matters at target rapidity

A. S. Botvina et al., PRC 84, 064904 (2011)

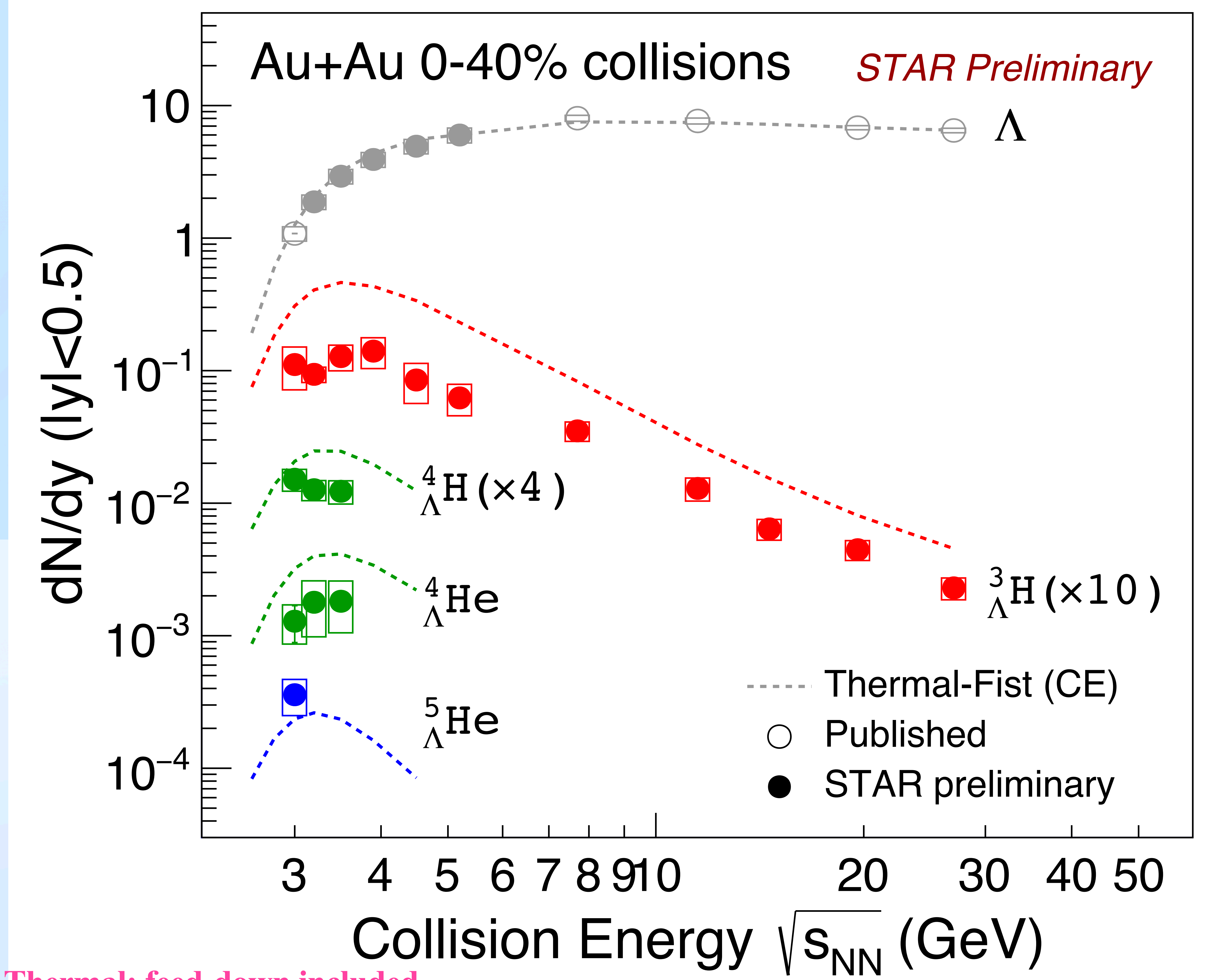
${}^{3}_{\Lambda}H$ Au+Au $\sqrt{s_{NN}}$ = 3-27 GeV







Excitation Function



Thermal: feed-down included

- $^{3}_{\Lambda}$H plateaus at $\sqrt{s_{NN}}$ = 3-4 GeV
  - Similar trend for $^{4}_{\Lambda}$H and $^{4}_{\Lambda}$He

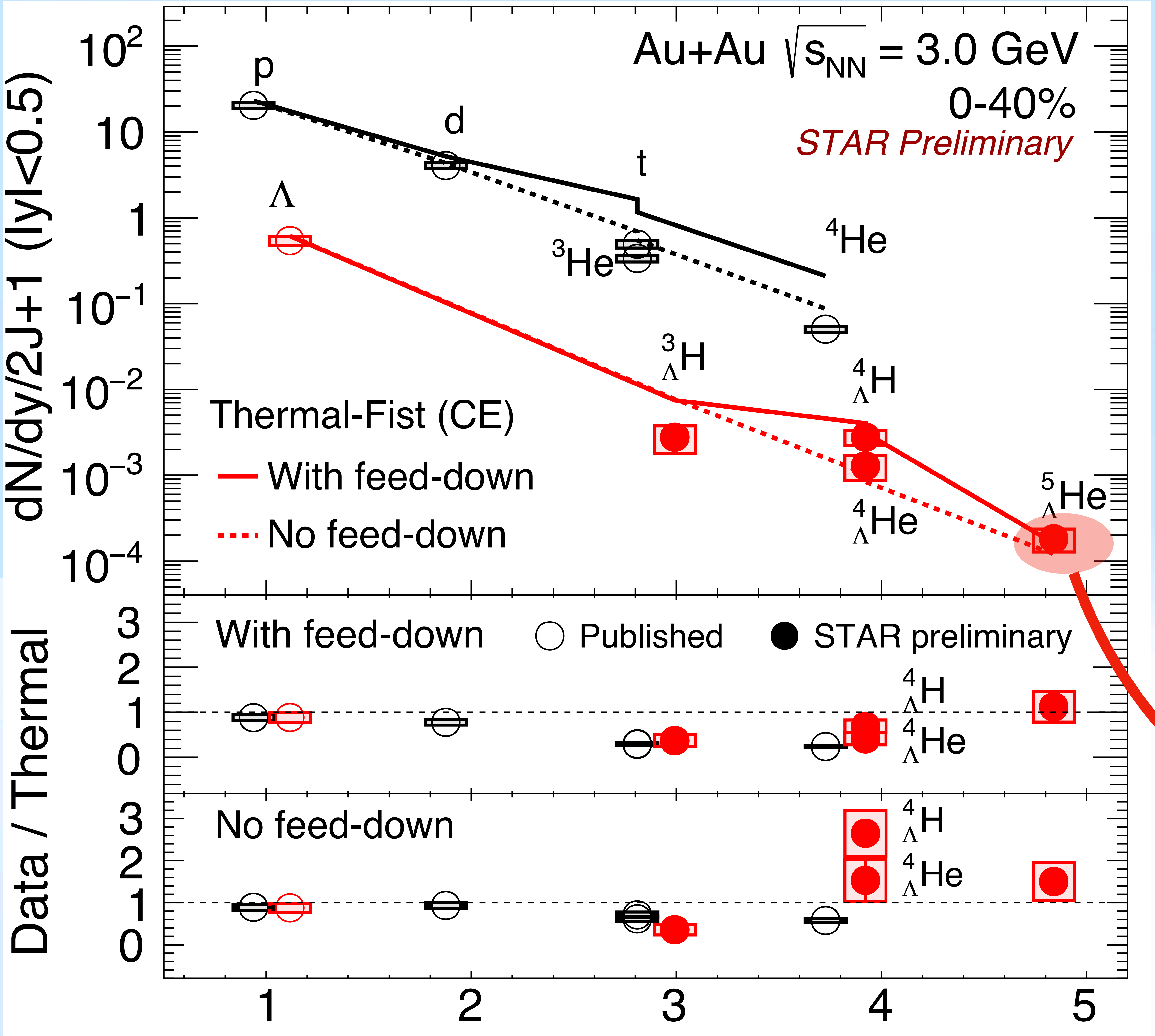
Interplay between increasing baryon production and stronger strangeness canonical suppression towards low energies

*Establishes **low energy** collision experiments as a promising tool to study **exotic strange matter***

- Thermal describes Λ, **over-estimate** $^{3}_{\Lambda}$H**,** $^{4}_{\Lambda}$H**, and** $^{4}_{\Lambda}$He, slightly **under-estimate** $^{5}_{\Lambda}$He

STAR, Phys.Rev.Lett. 128(2022)20, 202301
V. Vovchenko et al., PRC 93, 064906 (2016)

Comparison to Thermal Model at 3 GeV



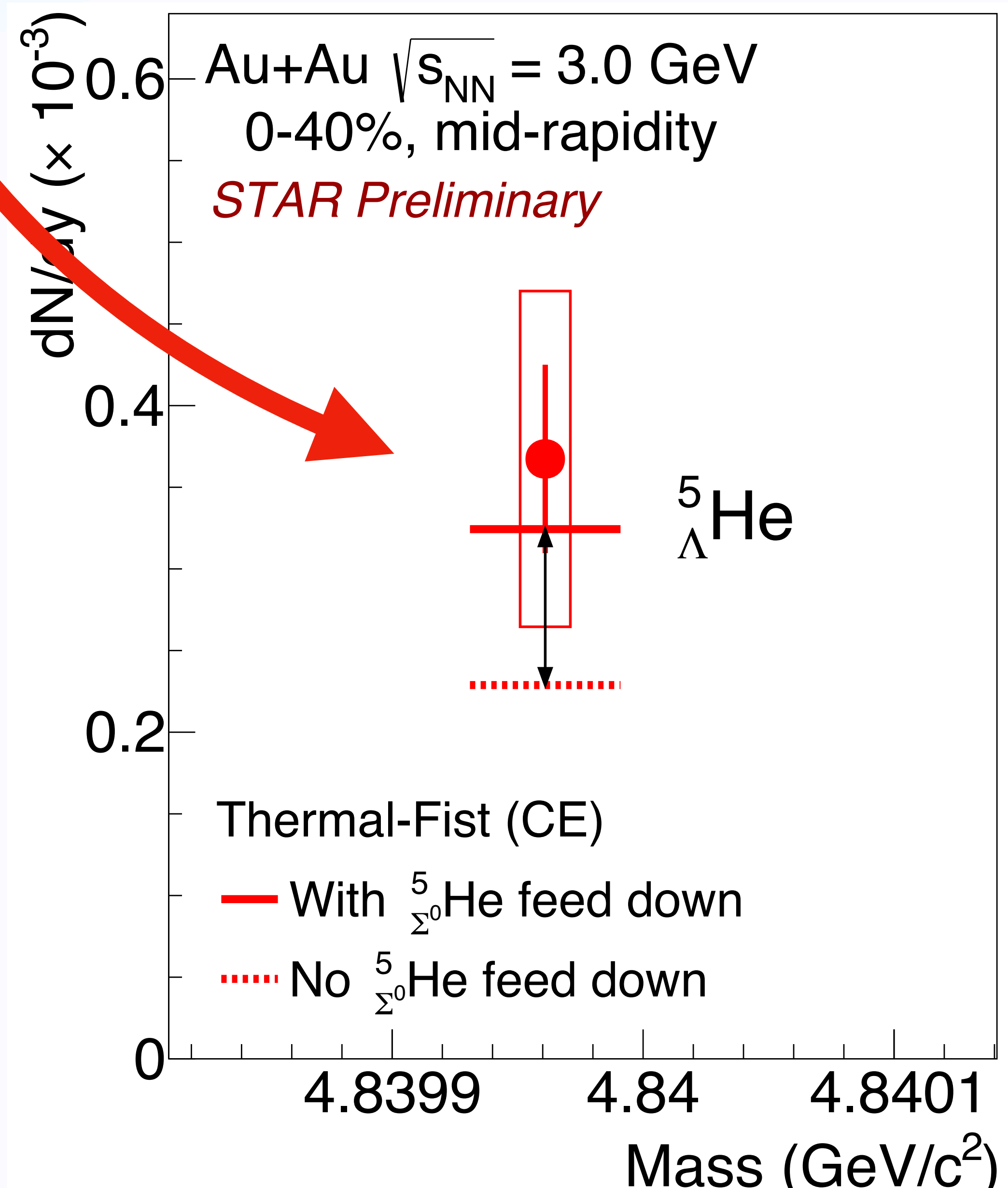
*Feed-down from unstable nuclei

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

- Thermal model predicts approx. exponential dependence of yields/(2J+1) vs A
- Light nuclei overestimated by thermal with feed-down from unstable nuclei
- Evidence of the formation of $^{4}_{\Lambda}$H and $^{4}_{\Lambda}$He excited states

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

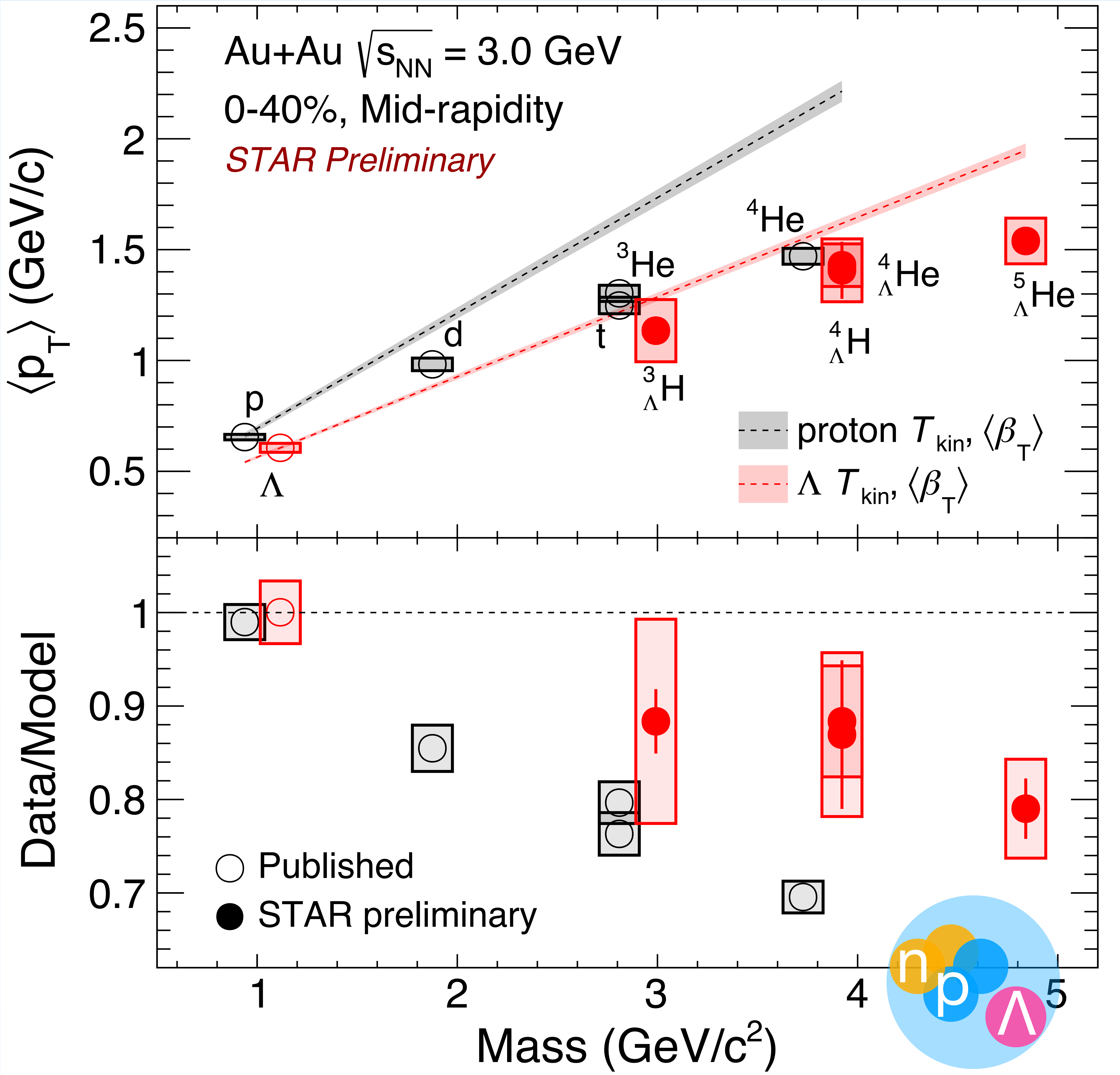
STAR, PLB 834, 137449 (2022)



- Possible feed down from $^{5}_{\Sigma^0}He \rightarrow {}^{5}_{\Lambda}He + \gamma$

J. Johnstone et al., J. Phys. G 8, L105 (1982)

Mean Transverse Momentum at 3 GeV



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

Blast wave function fit

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

T_{kin}: kinetic freeze-out temperature

$\langle \beta_T \rangle$: average transverse radial flow velocity, $\rho = \tanh^{-1} \beta_r$

n: the exponent of flow velocity profile, n=1

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

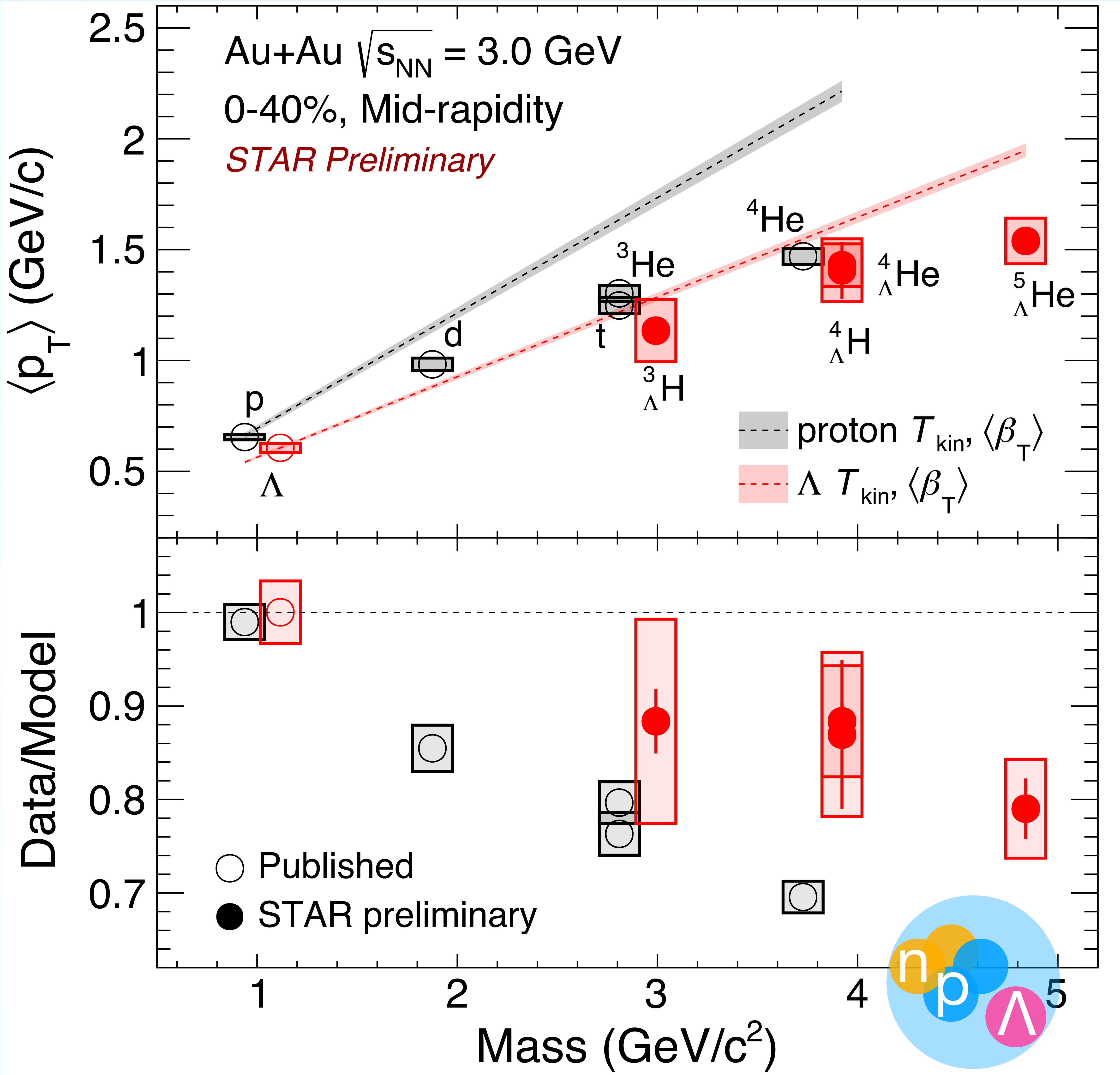
- Vary the mass to construct the blast-wave prediction using p(Λ) freeze-out parameters

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

- Light nuclei and hypernuclei deviate from the full hydrodynamic picture

Coalescence scenario?

Mean Transverse Momentum at 3 GeV

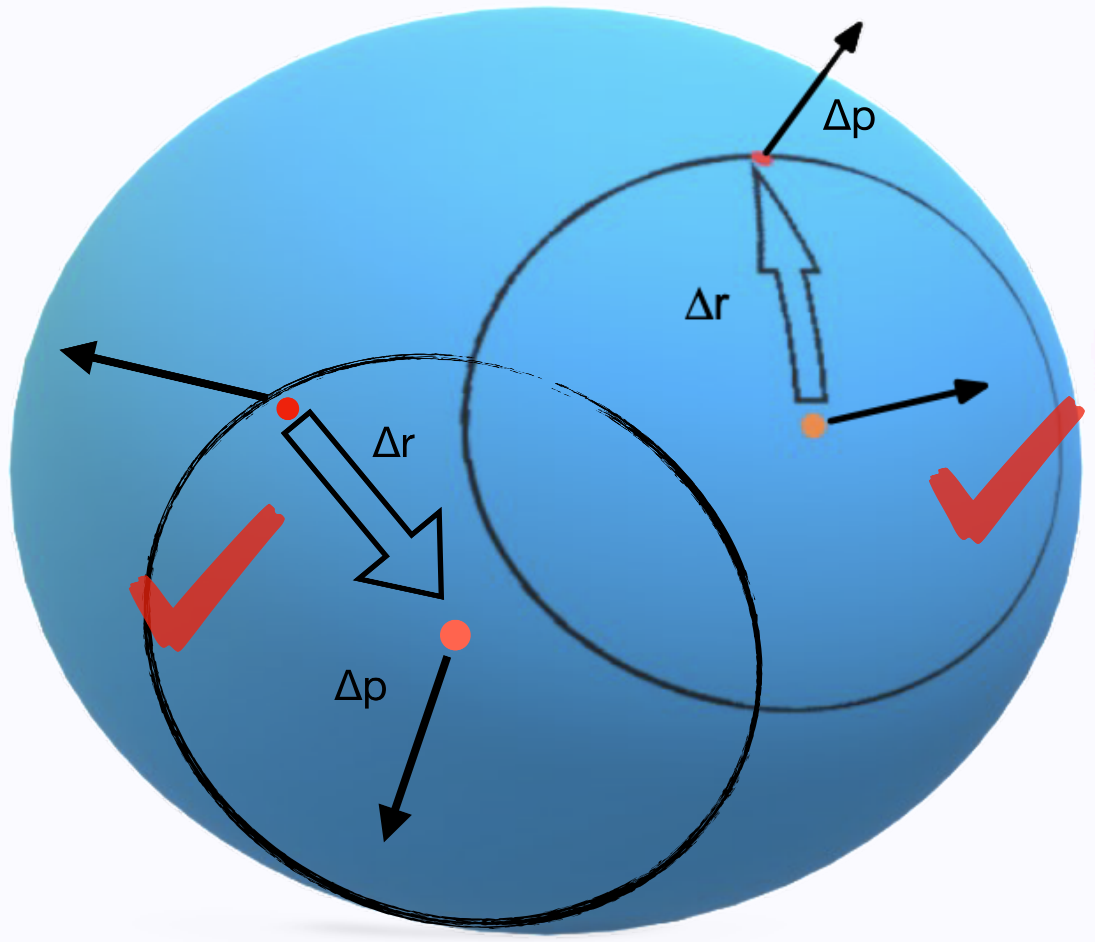


STAR, PRC 110, 054911 (2024)
STAR, PRL 128, 202301 (2022)
STAR, JHEP **2024** (2024) 139

Coalescence scenario: nuclei formed at a later stage after kinetic freeze-out

- Light nuclei and hypernuclei deviate from the full hydrodynamic picture
  1. Less correlated nucleons coalescence to nuclei, leading to smaller $\langle p_T \rangle$ than if perfectly aligned
  2. Heavier (hyper)nuclei → Large deviation from blast wave ansatz

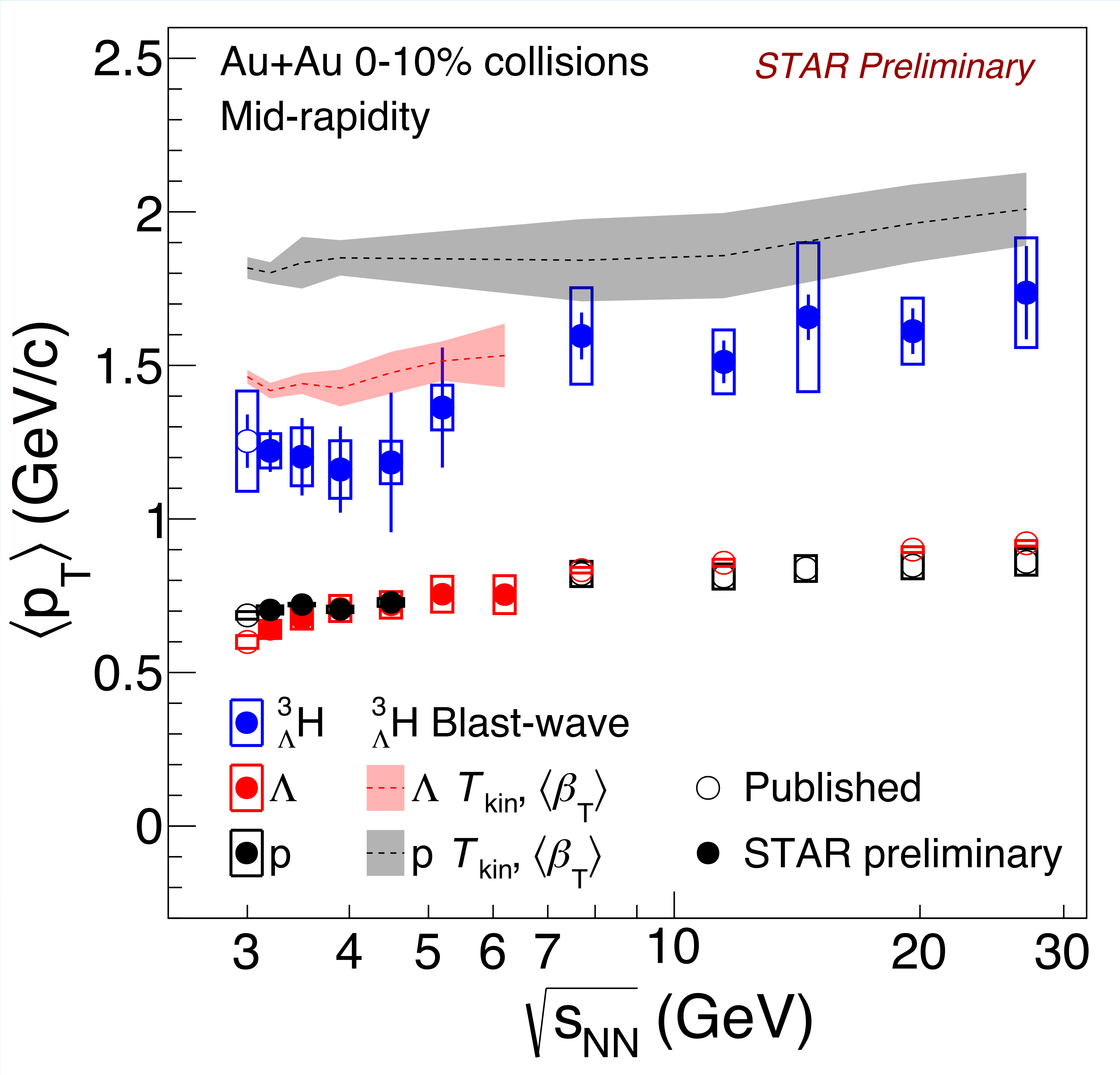
A. I. Sheikh et al., PRC 106, 054907 (2022)



Small effective volume nucleon's *r* and *p* are less correlated

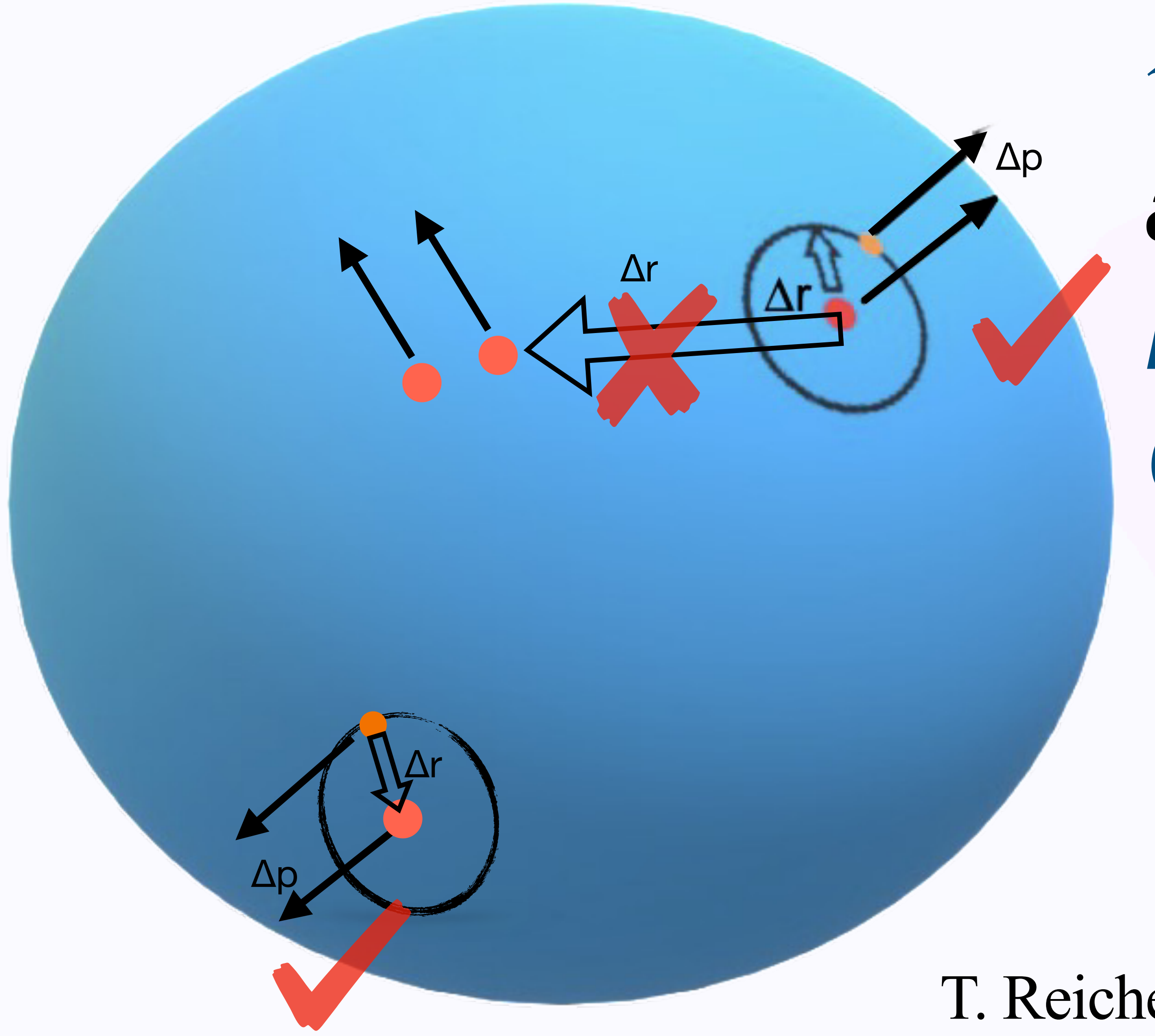
T. Reichert, SQM 2022, slides (2022)

Mean Transverse Momentum v.s. Collision Energy



- At $\sqrt{s_{NN}} \geq 7.7$ GeV, $^{3}_{\Lambda}H$ $\langle p_T \rangle$ tends to approach the blast-wave prediction with proton freeze-out parameters
- Likely due to larger effective volume, where nucleons that eventually coalesce are more likely to be aligned in space and momentum

Suggests a different effective volume at $\sqrt{s_{NN}} \geq 7.7$ GeV, with an noticeable change between 4.5 and 7.7 GeV



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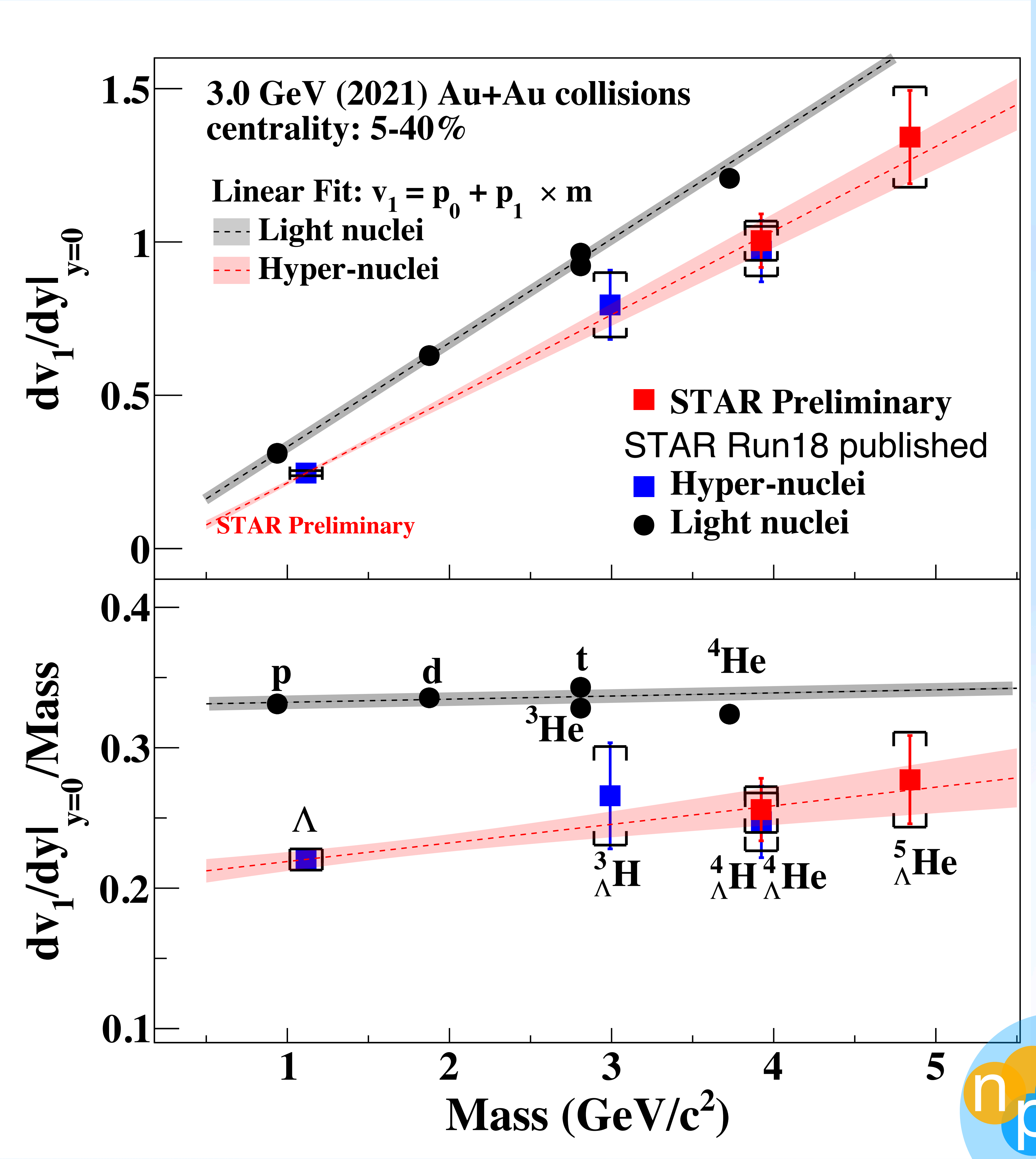
STAR, PRC 110, 054911 (2024)
STAR, PRL 128, 202301 (2022)
STAR, JHEP **2024** (2024) 139

Collective Flow at 3 GeV

See poster by Junyi Han (xx/xx)



- Directed flow of hypernuclei follows mass scaling
- Qualitatively consistent with coalescence formation of hypernuclei

STAR, PLB 827, 136941 (2022)
STAR, PRL 130, 212301 (2023)

Summary and Outlook

- Hypernuclei measurement from STAR BES-II at $\sqrt{s_{NN}}$ = 3-27 GeV
  1. **First measurement of A = 5 hypernuclei yield and directed flow in Au+Au collisions at $\sqrt{s_{NN}}$ = 3 GeV**
  2. Thermal model overestimates ${}^{3}_{\Lambda}H$, ${}^{4}_{\Lambda}H$, and ${}^{4}_{\Lambda}He$, and slightly underestimates ${}^{5}_{\Lambda}He$
  3. Mean transverse momentum tends to be lower than hydrodynamic-inspired blast-wave model at $\sqrt{s_{NN}} < 7.7$ GeV

     Consistent with coalescence picture: weaker space and momentum correlation among coalescing nucleons in a smaller effective volume at low collision energies
  4. Collective flow qualitatively consistent with coalescence model

Outlook:

- High statistics 3 GeV FXT data: more precise measurement of $A < 5$ hypernuclei, ${}^{5}_{\Lambda}He$ intrinsic properties (B_{Λ}, dalitz plot, lifetime), search for heavier hypernuclei ($A > 5$), double-Λ hypernuclei

➡ Further constrain production mechanism, structure of hypernuclei, and YN, YY, YNN interactions

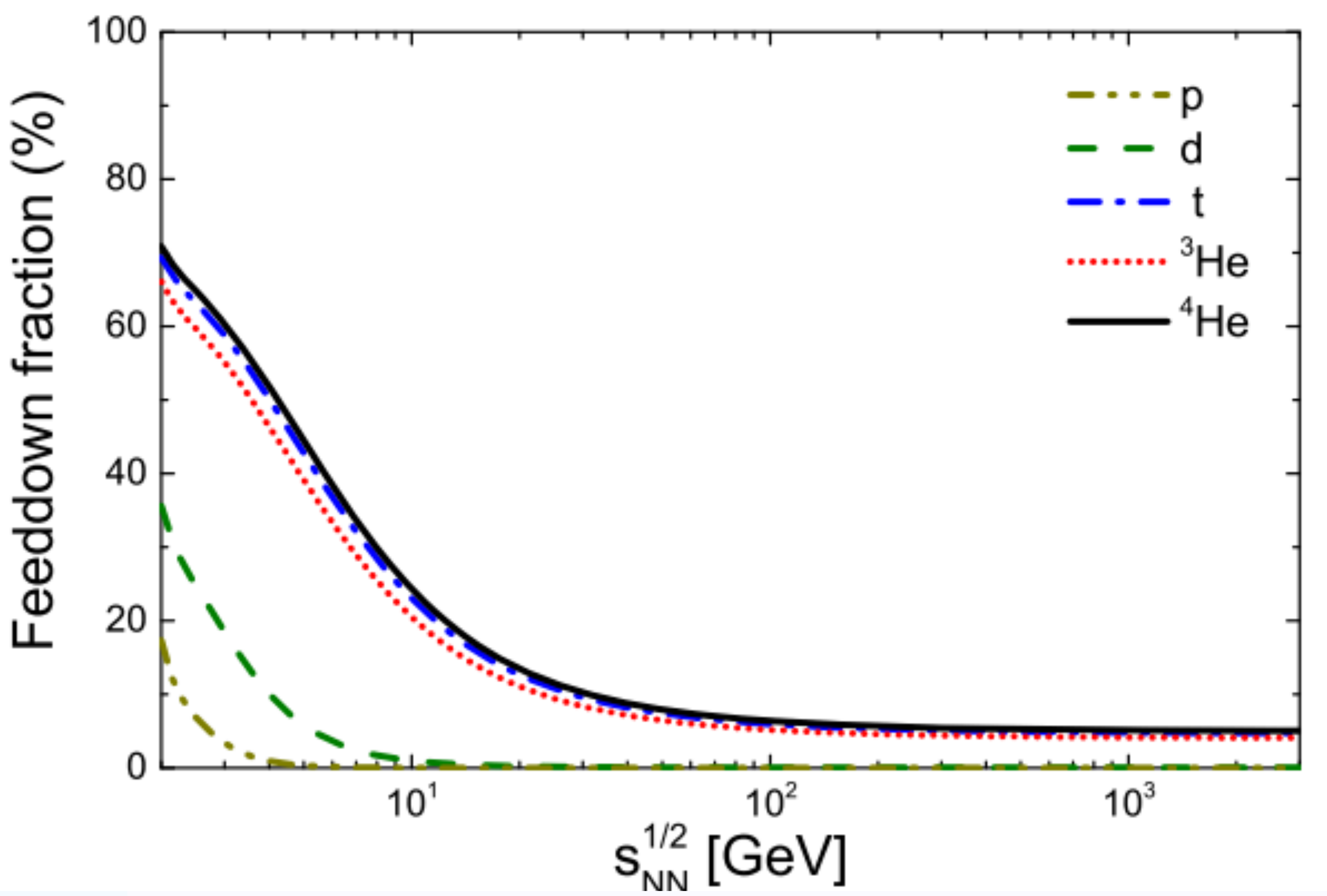
Backup Slides Follow

Feed-down from Unstable Nuclei

$A=4$	E_x (MeV)	J^π	Decay channels
^{4}H	g.s.	2^-	n(100%)
	0.31	1^-	n(100%)
	2.08	0^-	n(100%)
	2.83	1^-	n(100%)
^{4}He	g.s.	0^+	stable
	20.21	0^+	p(100%)
	21.01	0^-	n(23.8%), p(76.2%)
	21.84	2^-	n(37.3%), p(62.7%)
	23.33	2^-	n(47.3%), p(52.7%)
	23.64	1^-	n(44.5%), p(55.5%)
	24.25	1^-	n(47.0%), p(50.5%), d(2.5%)
	25.28	0^-	n(48.3%), p(51.7%)
	25.95	1^-	n(48.5%), p(51.5%)
	27.42	2^+	n(3%), p(3%), d(94%)
	28.31	1^+	n(47%), p(48%), d(5%)
	28.37	1^-	n(2%), p(2%), d(96%)
	28.39	2^-	n(0.25%), p(0.25%), d(99.5%)
	28.64	0^-	d(100%)
	28.67	2^+	d(100%)
	29.89	2^+	n(0.4%), p(0.4%), d(99.2%)
^{4}Li	g.s.	2^-	p(100%)
	0.32	1^-	p(100%)
	2.08	0^-	p(100%)
	2.85	1^-	p(100%)

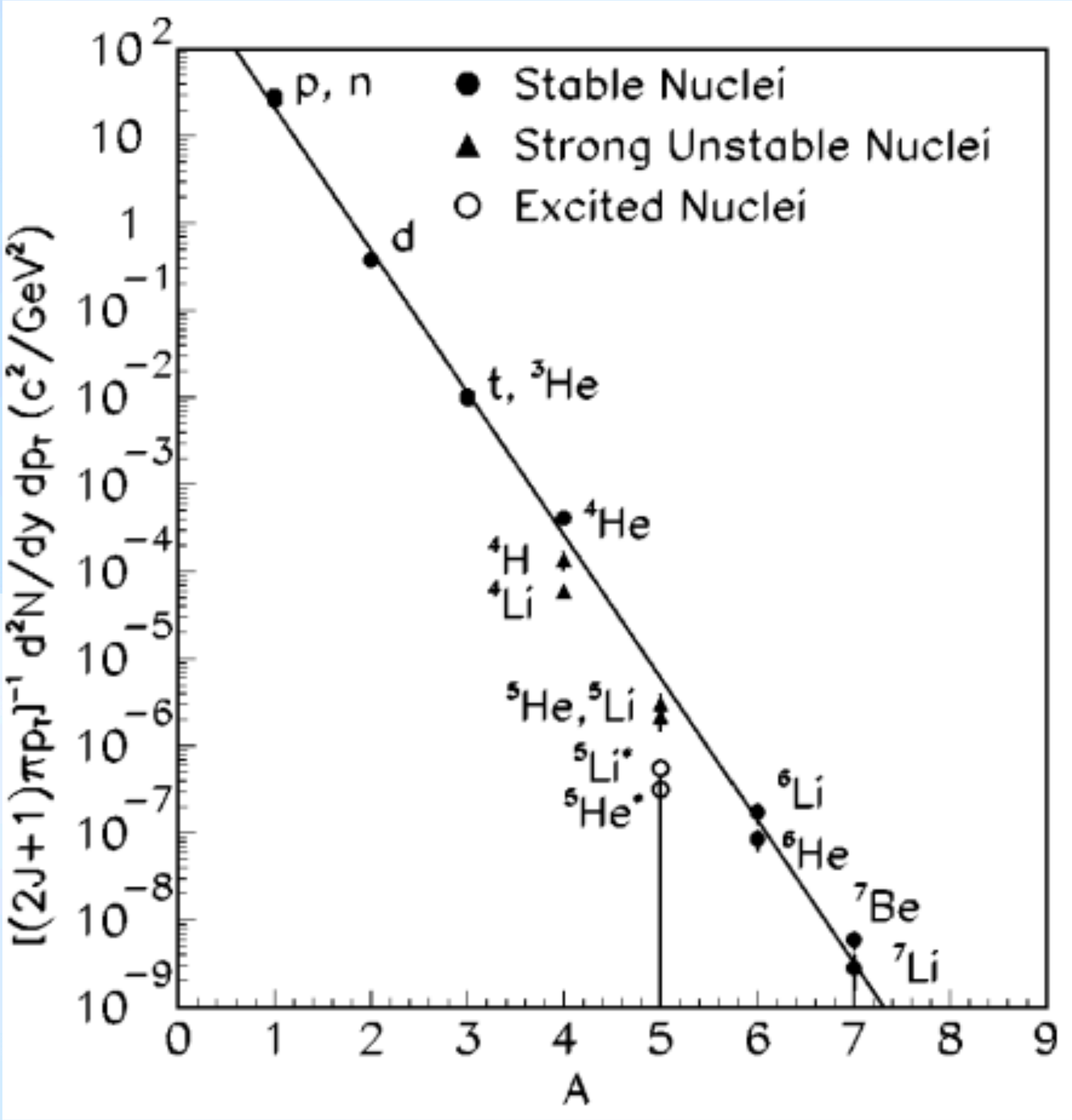
branching ratios in the right column of Table I. For the $A=5$ states the channels $^5\text{H} \to \text{t}+\text{n}+\text{n}$, $^5\text{He} \to {}^4\text{H}+\text{p}$, $^5\text{He} \to \text{t}+\text{d}$, $^5\text{Li} \to {}^4\text{He}+\text{p}$, and $^5\text{Li} \to {}^4\text{Li}+\text{n}$ are taken into account. The excited nuclei feeding will thus affect the yields of nucleons and stable light nuclei, but not other particles.

$A=5$	E_x (MeV)	J^π	Decay channels
^{5}H	g.s.	$\frac{1}{2}^+$	2n(100%)
^{5}He	g.s.	$\frac{3}{2}^-$	n(100%)
	1.27	$\frac{1}{2}^-$	n(100%)
	16.84	$\frac{3}{2}^+$	n(60%), d(40%)
^{5}Li	g.s.	$\frac{3}{2}^-$	p(100%)
	1.49	$\frac{1}{2}^-$	p(100%)
	16.87	$\frac{3}{2}^+$	p(70%), n(30%)



V. Vovchenko et al., PLB 809, 135746 (2020)

Feed-down from Unstable Nuclei

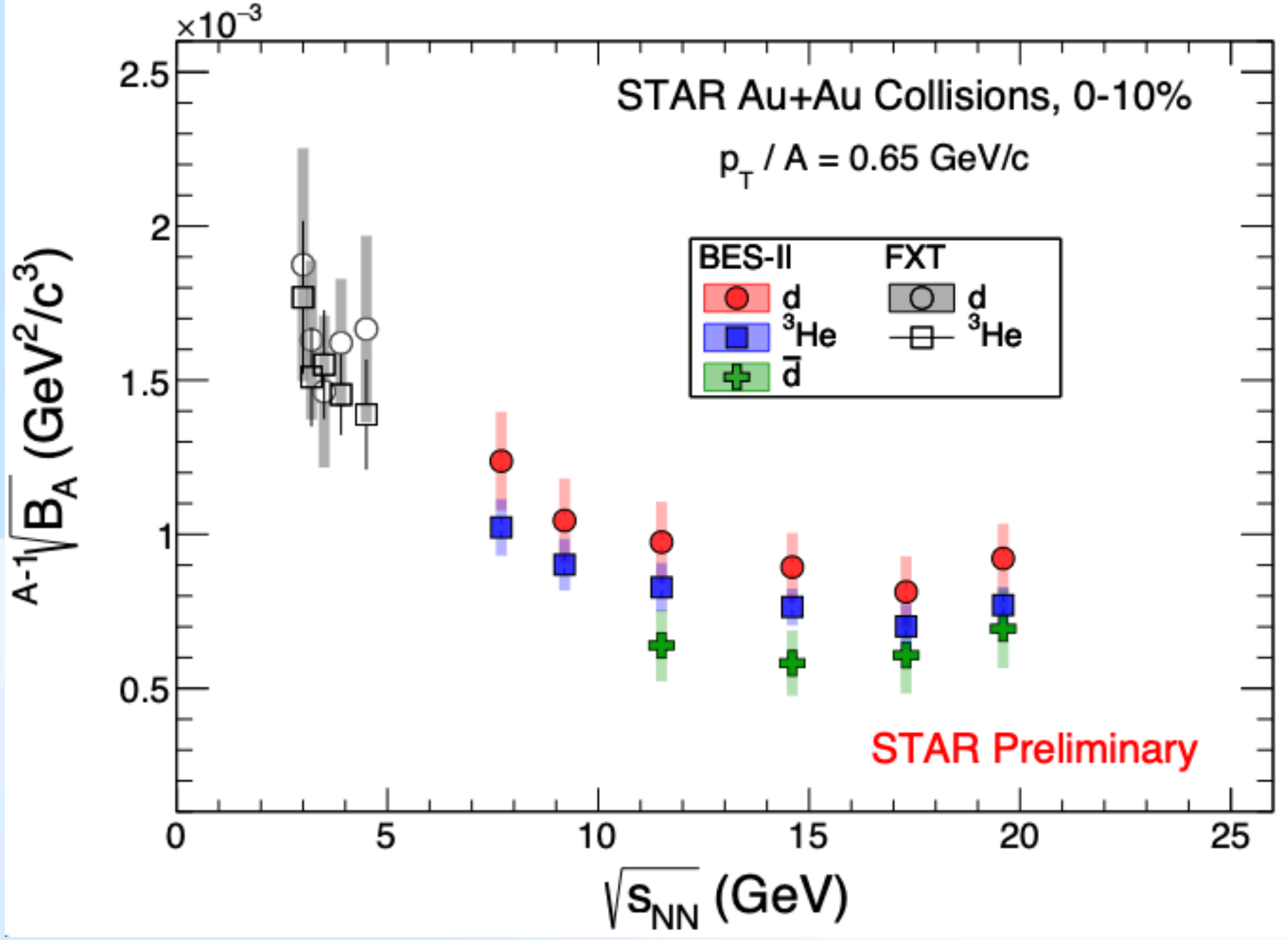


E864, PRC 65, 014906 (2001)

- Suppression of A=4 unstable states compared to ^{4}He ground state observed at E864
- Indicates unstable nuclei yield likely overestimated by thermal model

Coalescence Parameters

See poster by Yixuan Jin (xx/xx)



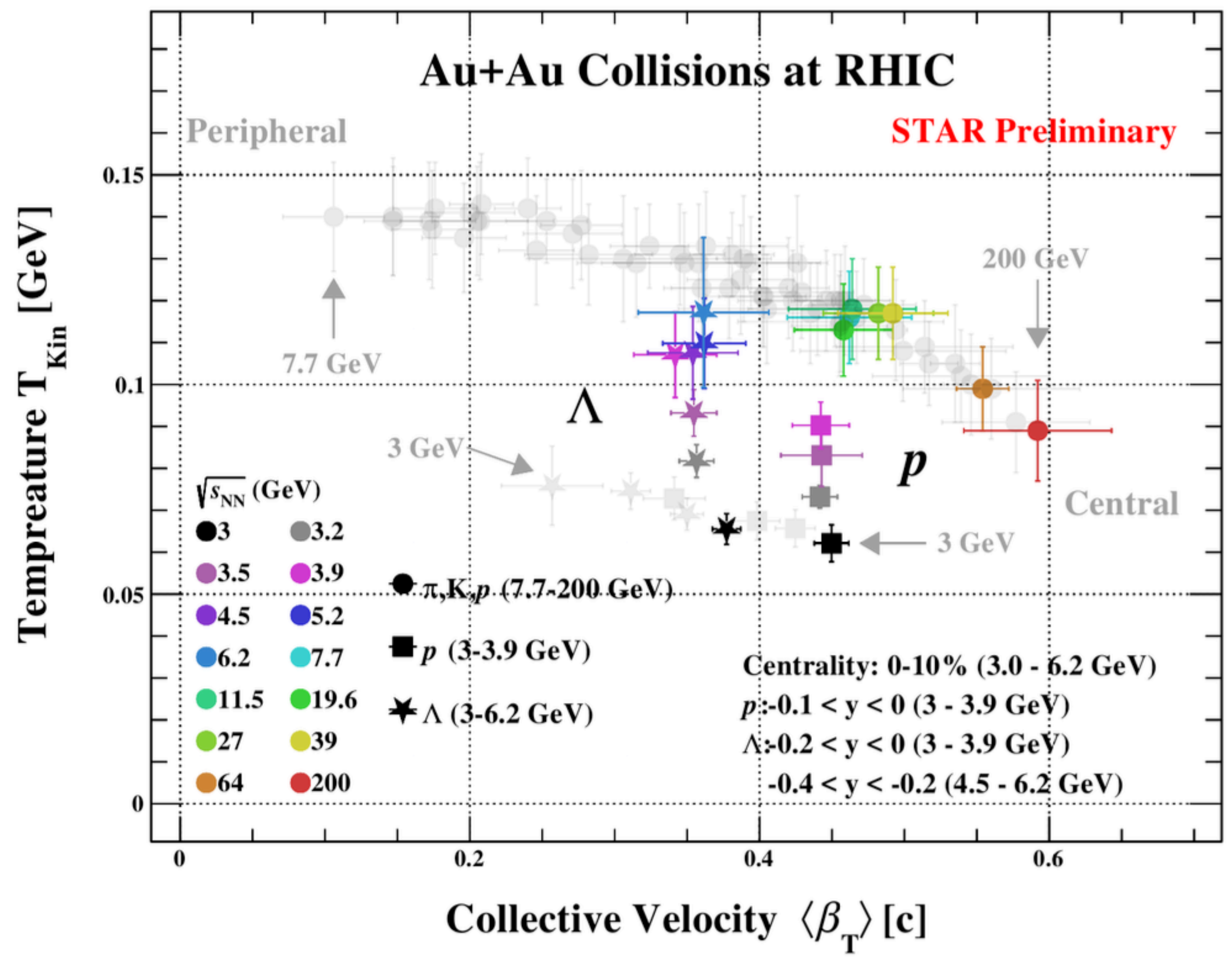
- B_A decrease with increasing energy due to the larger effective volume

STAR, PRC 99, 064905 (2019)
K. J. Sun et al., PLB 774, 103 (2017); PLB 781, 499 (2018)

https://drupal.star.bnl.gov/STAR/presentations/Quark-Matter-2025/Production-Light-Nuclei-AuAu-Collisions-STAR-BES-II-Program-1

Kinetic Freeze-out Parameters

See talk by Hongcan Li (xx/xx)



- Energy dependence at the most central collisions
- Different freeze-out parameter due to different production mechanism between proton and Λ
- Hadronic transport model UrQMD model qualitatively reproduces the trend at 3 - 6.2 GeV

https://drupal.star.bnl.gov/STAR/node/71381

Dalitz Plots

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

I. Kisel, EPJ Web Conf. 271, 08001 (2022)