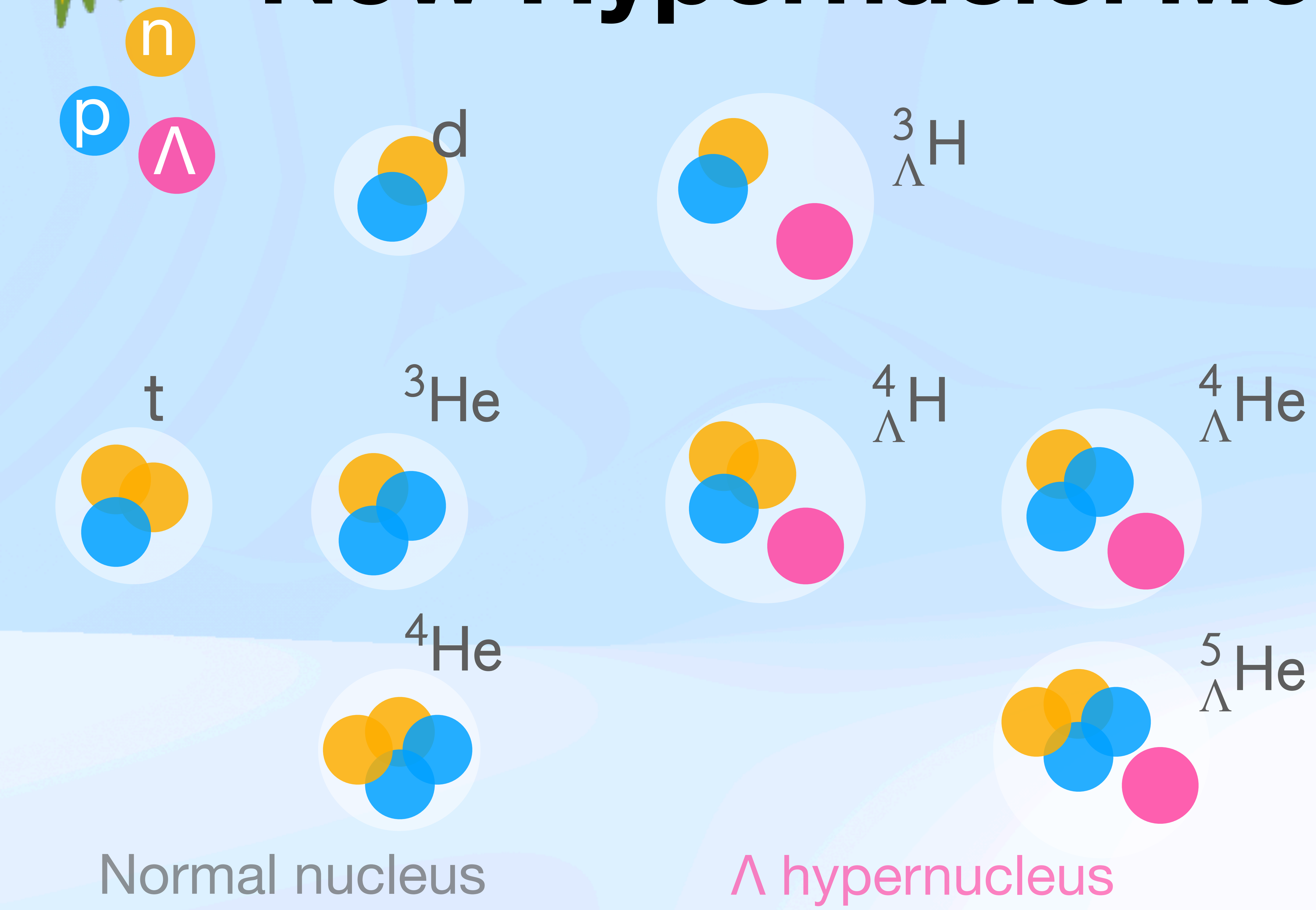
New Hypernuclei Measurements from STAR



Outline

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

Yingjie Zhou for the STAR Collaboration
CCNU, GSI

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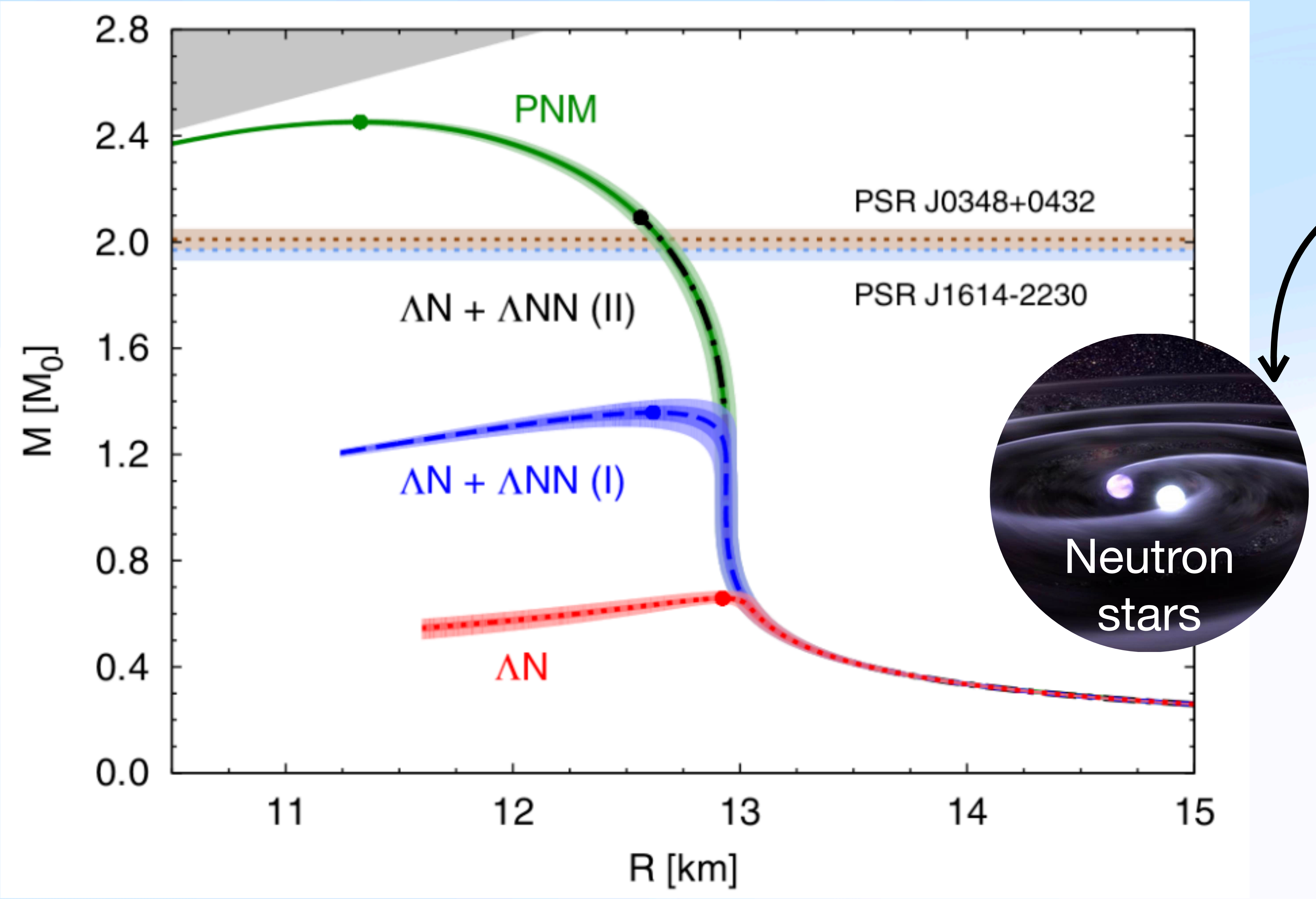
STAR 25 YEARS

Hypernuclei and Hyperon-Nucleon (Y-N) Interaction

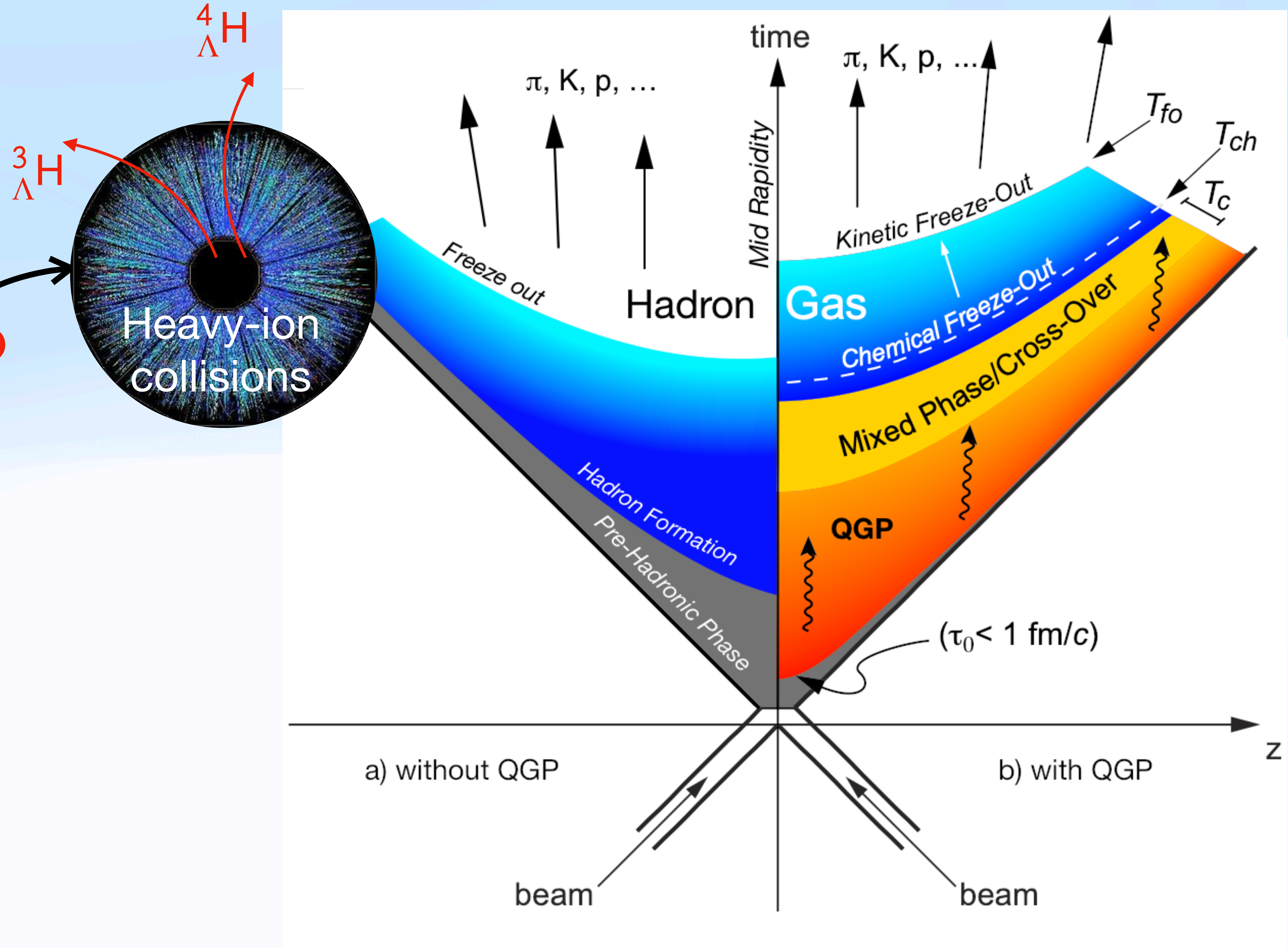
- **Hyperon Puzzle**: difficult to reconcile the measured masses of neutron stars with the presence of hyperons in their interiors

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



- 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?

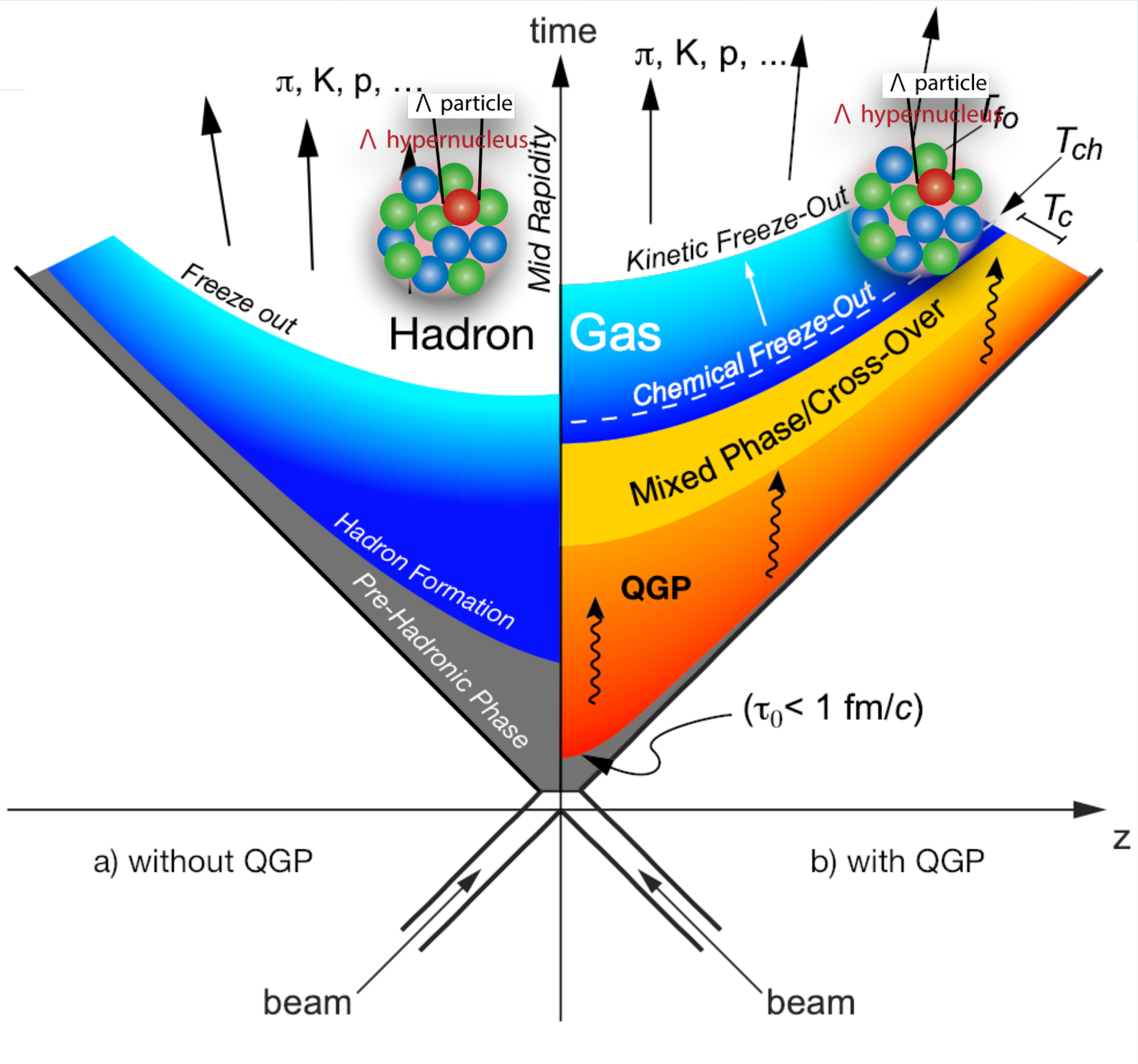
1. Thermal models
   - Hadrons and (hyper-)nuclei are treated equally
   - Yields are predicted with thermal equilibrium assumptions

✗ Do not provide Y–N interaction information

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

✓Sensitive to the freeze-out phase space, which can be affected by in-medium Y–N interactions

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



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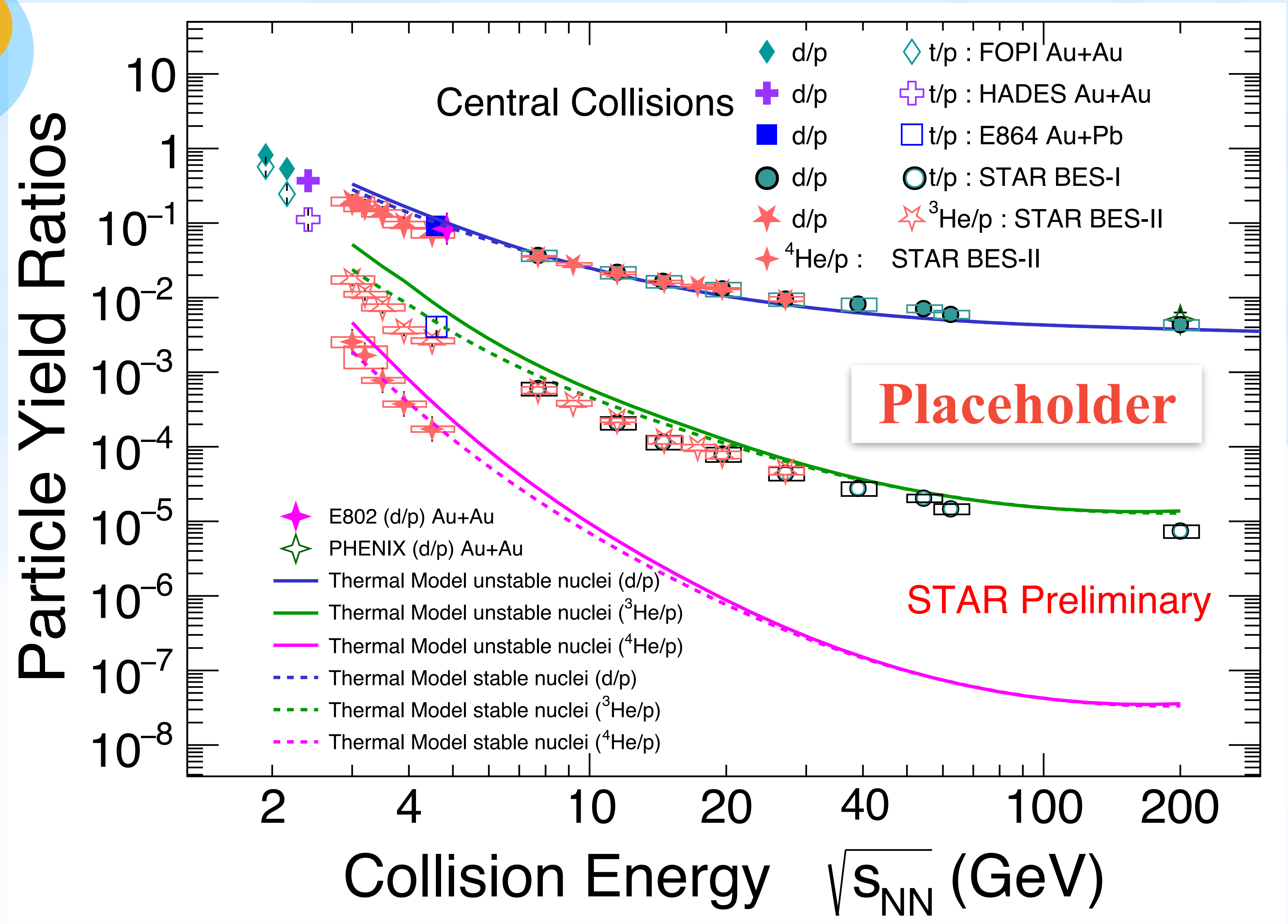
What have we learnt from light nuclei production?

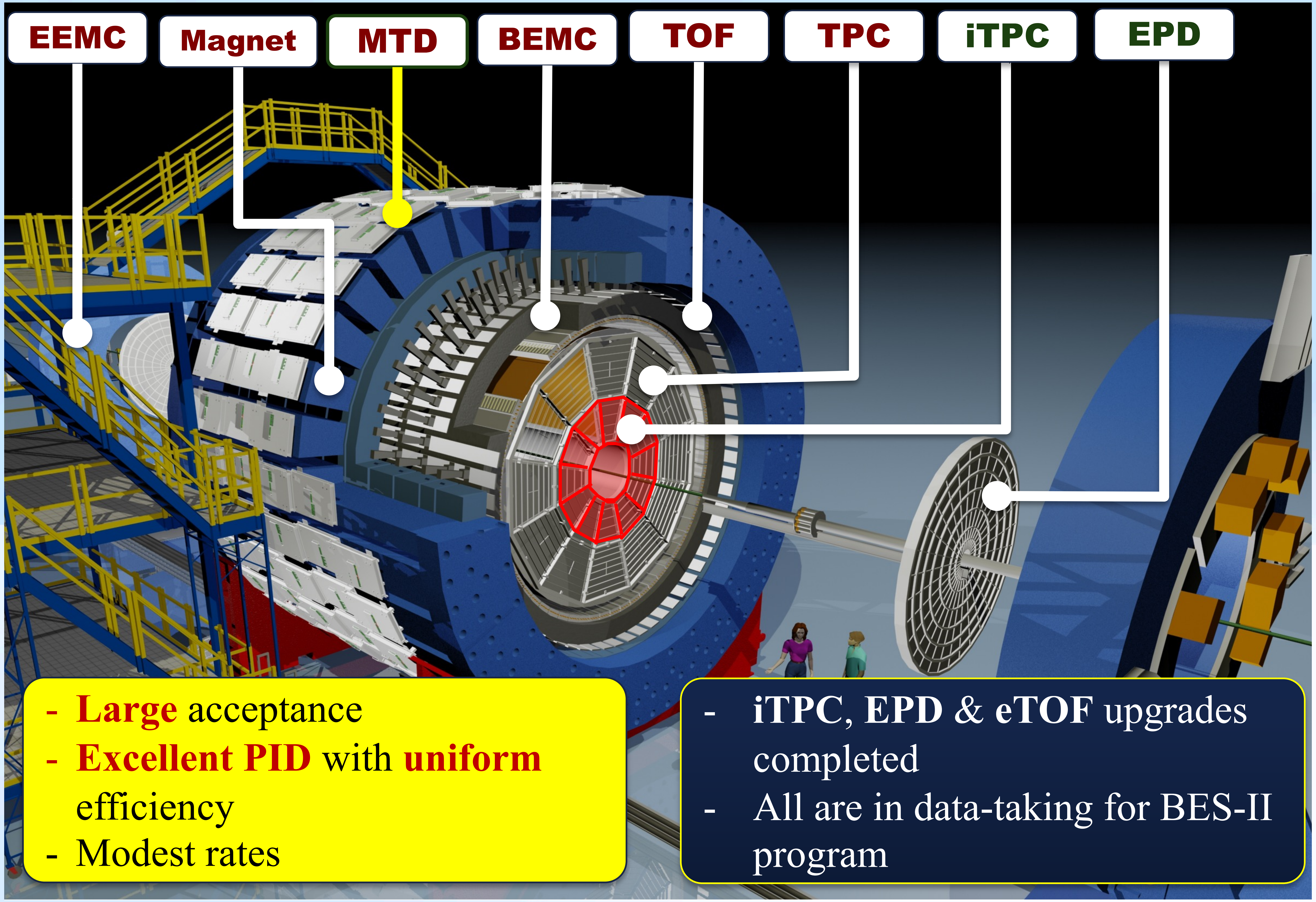
See poster by Liubing Chen (xx/xx)



- *d/p* is fairly well described by thermal model, but *^{3}He/p*, *^{4}He/p* is overestimated

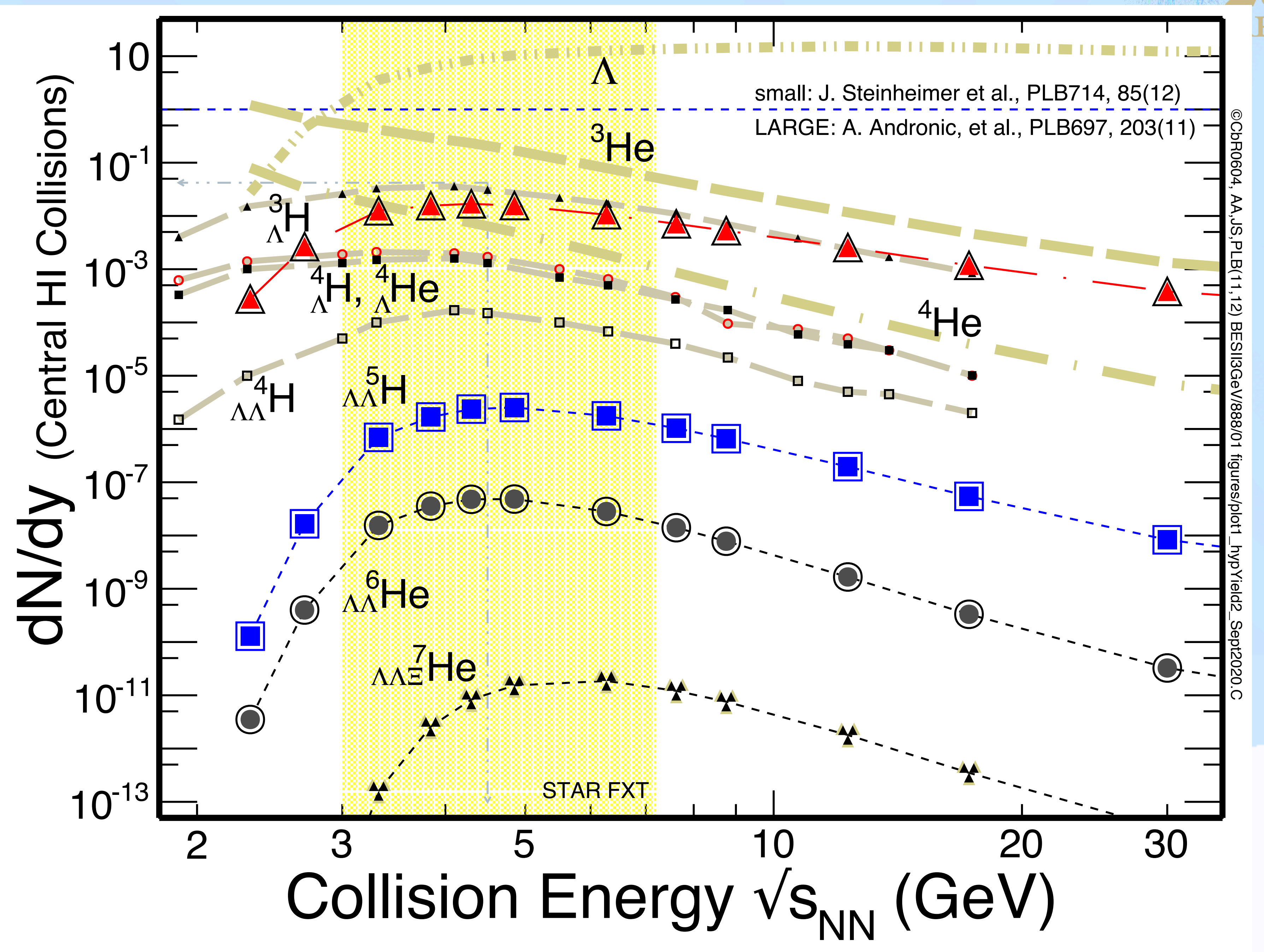
Recent nuclei measurements pose challenges for thermal model

STAR and Beam Energy Scan

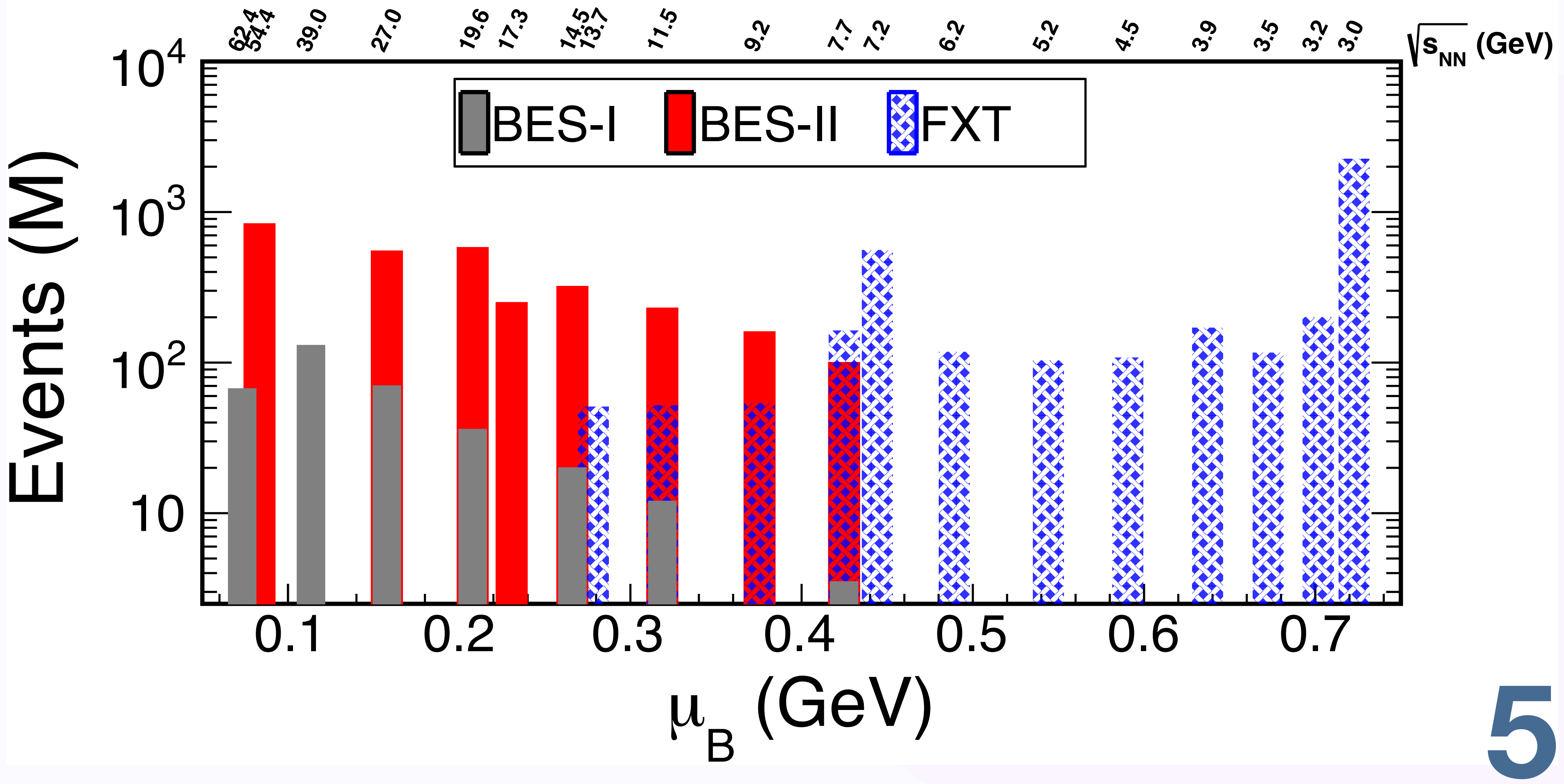


- **Large** acceptance
- **Excellent PID** with **uniform** efficiency
- Modest rates

- **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

Yingjie Zhou

Hypernuclei Reconstruction

NEW

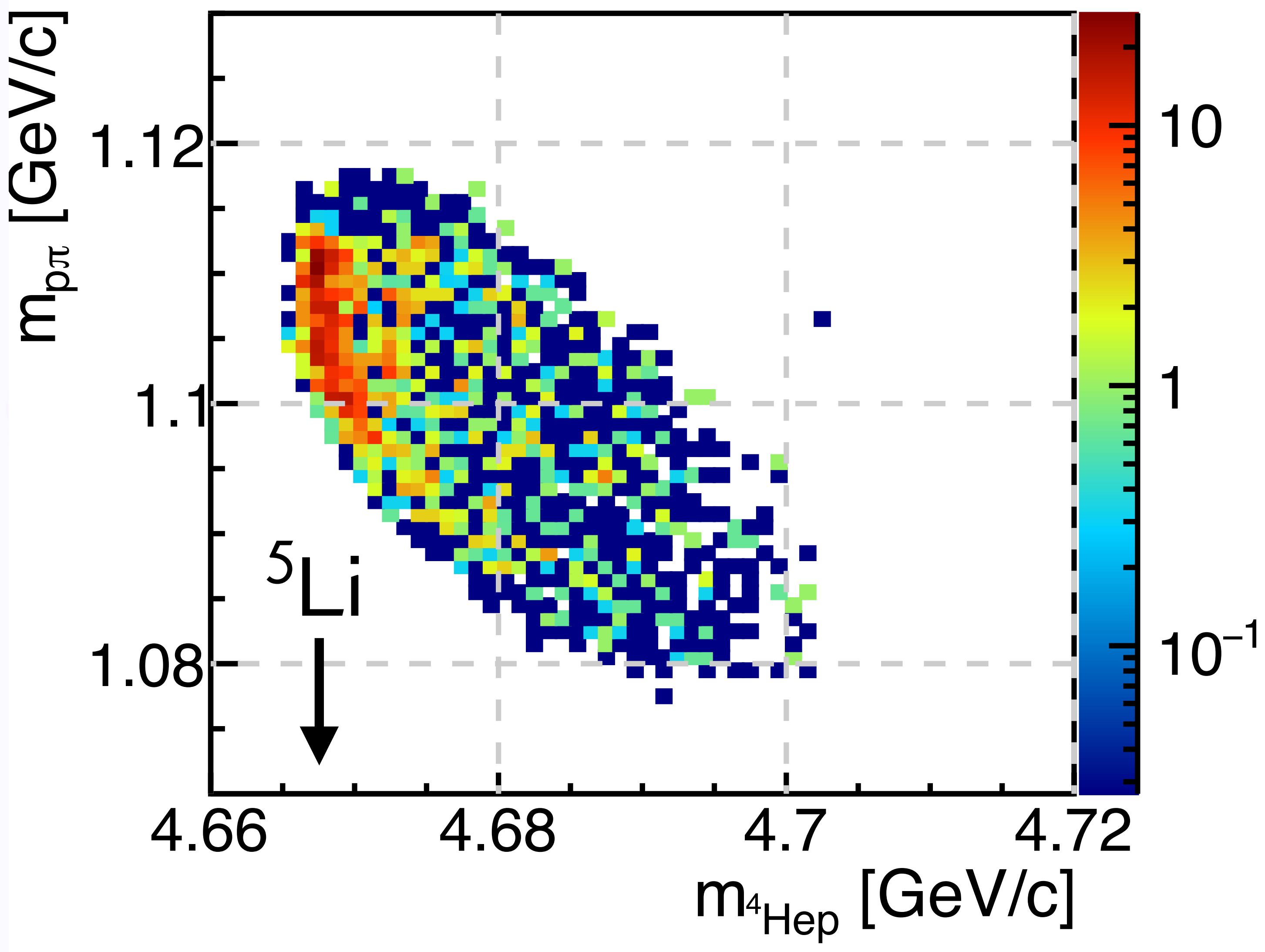
- Hypernuclei are reconstructed using the following decay channels:

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

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

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 fragment tracks
- 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

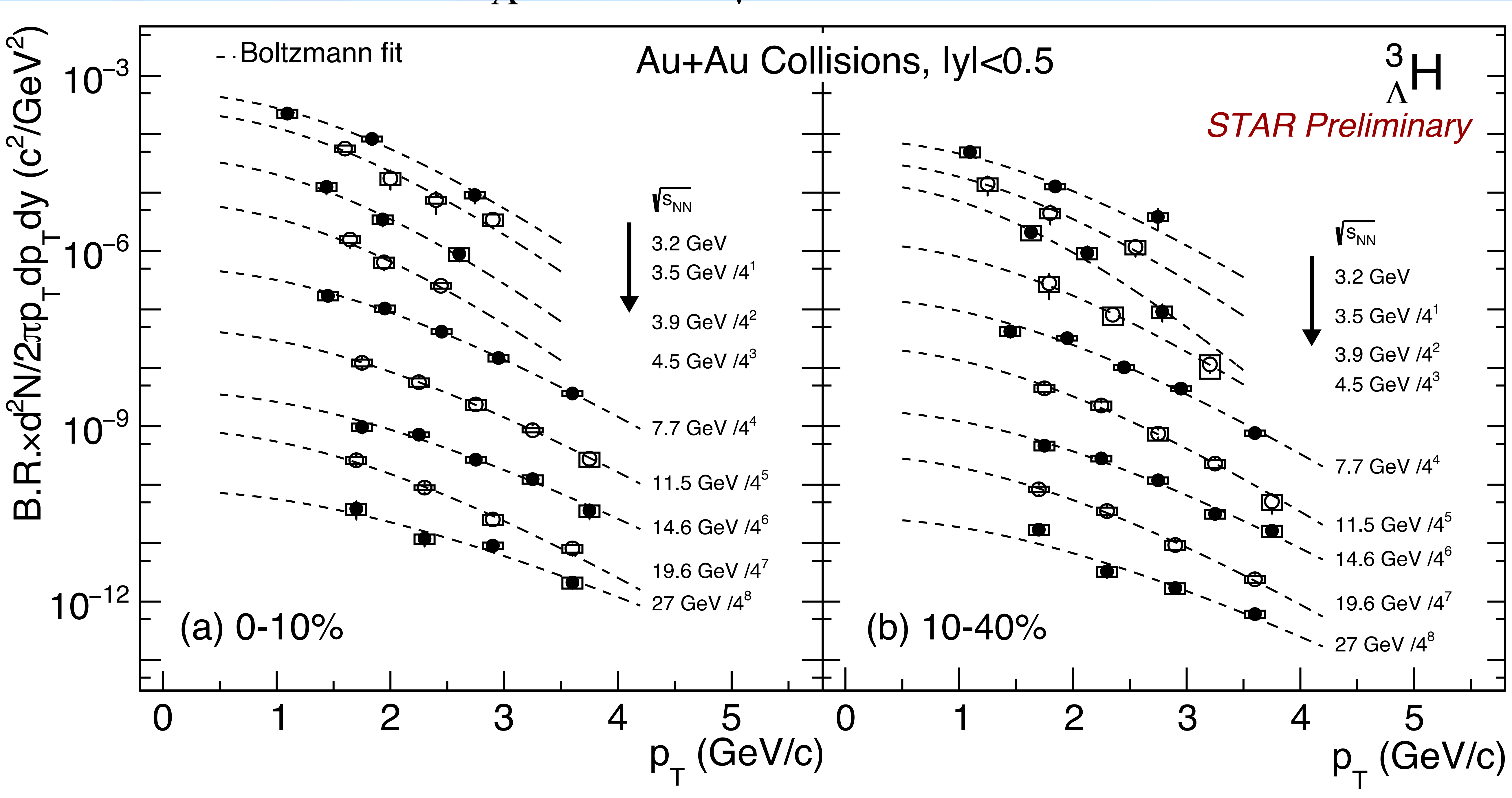
- Measurements cover different energies
  - ${}^{3}_{\Lambda}H$ in Au+Au collisions at **3-27** GeV, Au+Au collisions at **200 GeV**
  - ${}^{4}_{\Lambda}H$, ${}^{4}_{\Lambda}He$ in Au+Au collisions at **3-3.5 GeV**
  - ${}^{5}_{\Lambda}He$ in Au+Au collisions at **3 GeV**

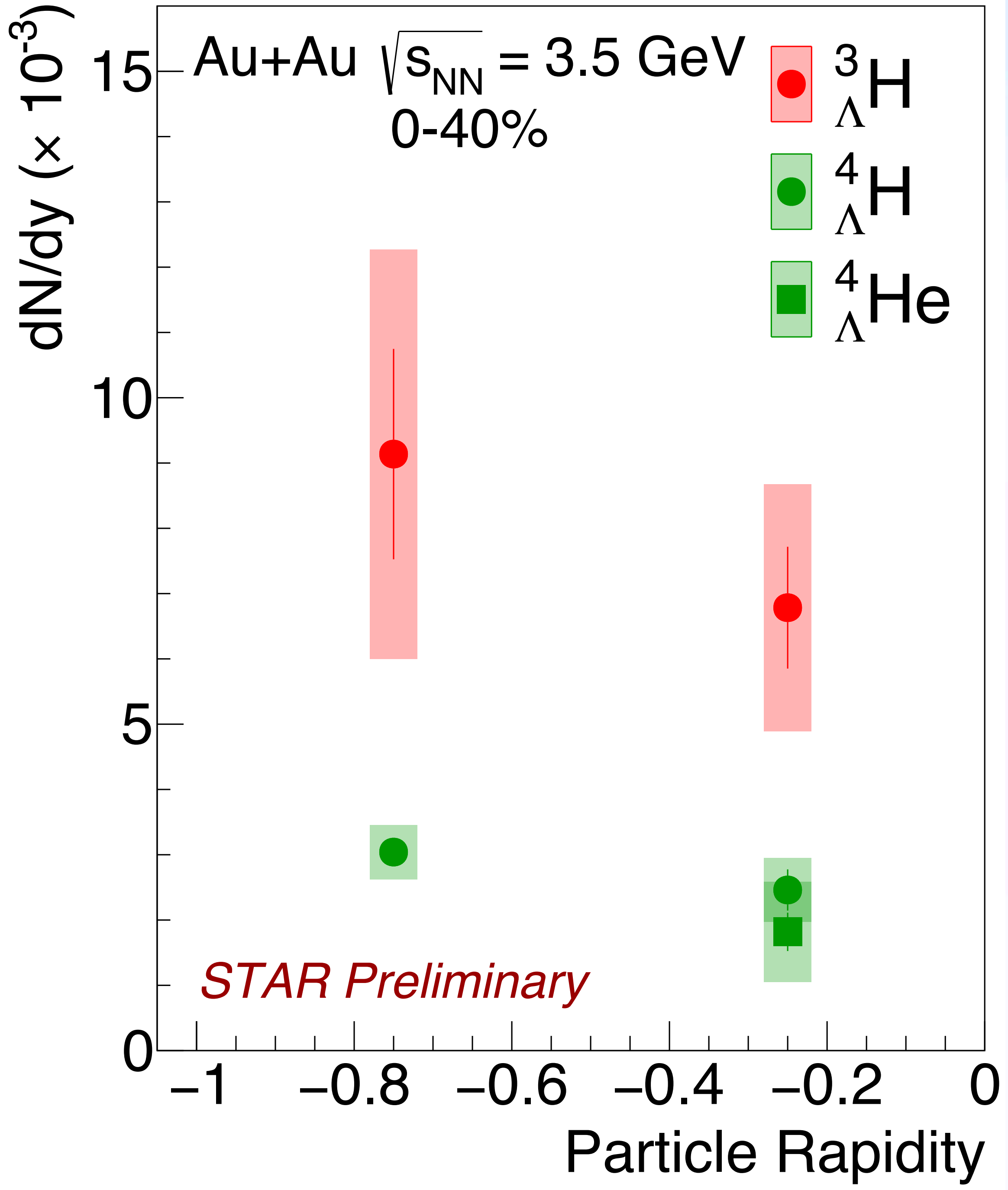
- Significant hypernuclei production at target rapidity, more pronounced for heavier hypernuclei

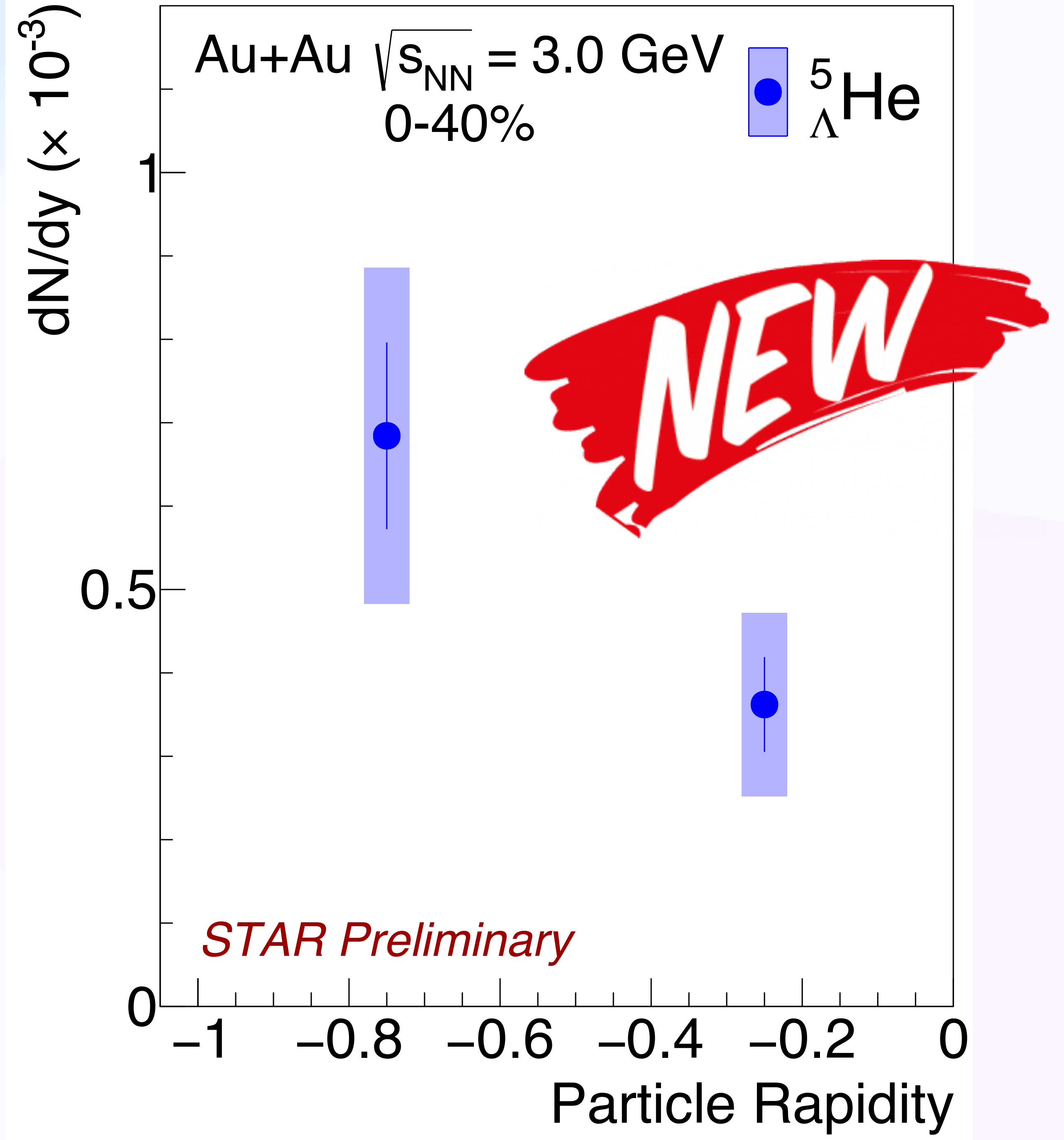
Spectator matter matters at target rapidity

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

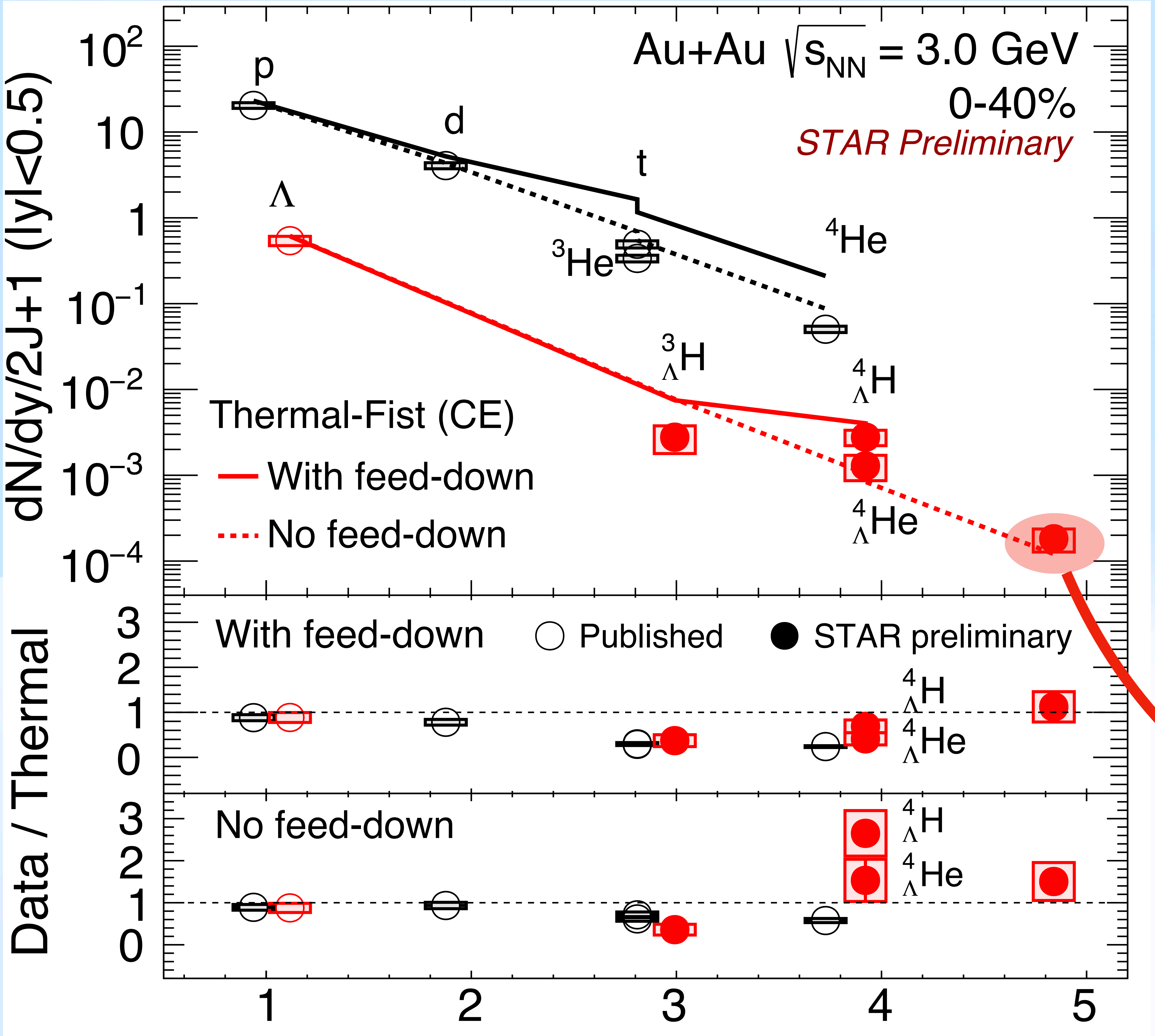
${}^{3}_{\Lambda}H$ Au+Au $\sqrt{s_{NN}}$ = 3.2-27 GeV







Particle Yields Compared to Thermal model



*Feed-down from unstable nucleus

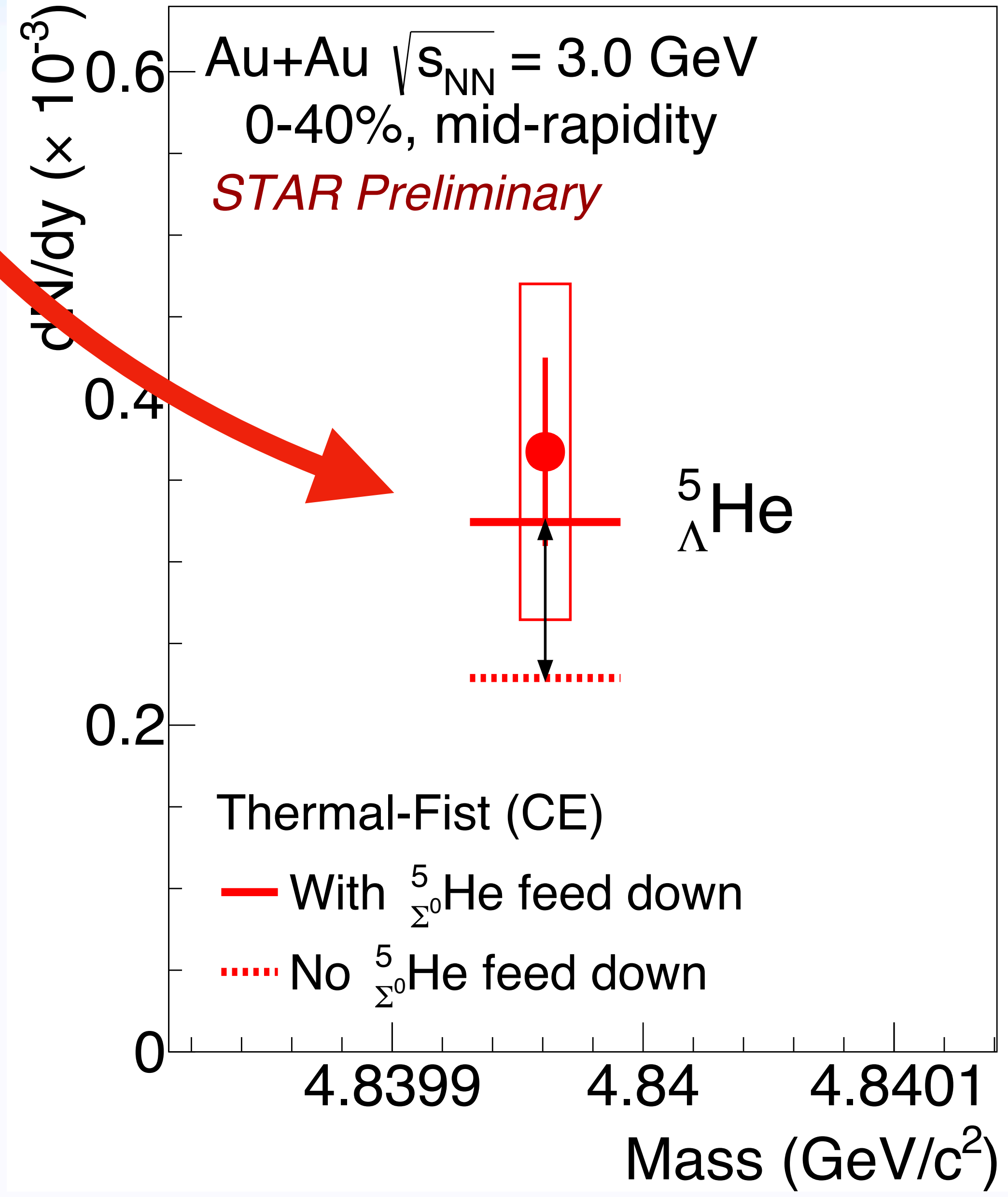
STAR, PRC 110, 054911 (2024)
STAR, PRL 128, 202301 (2022)
STAR, JHEP **2024** (2024) 139

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

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

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

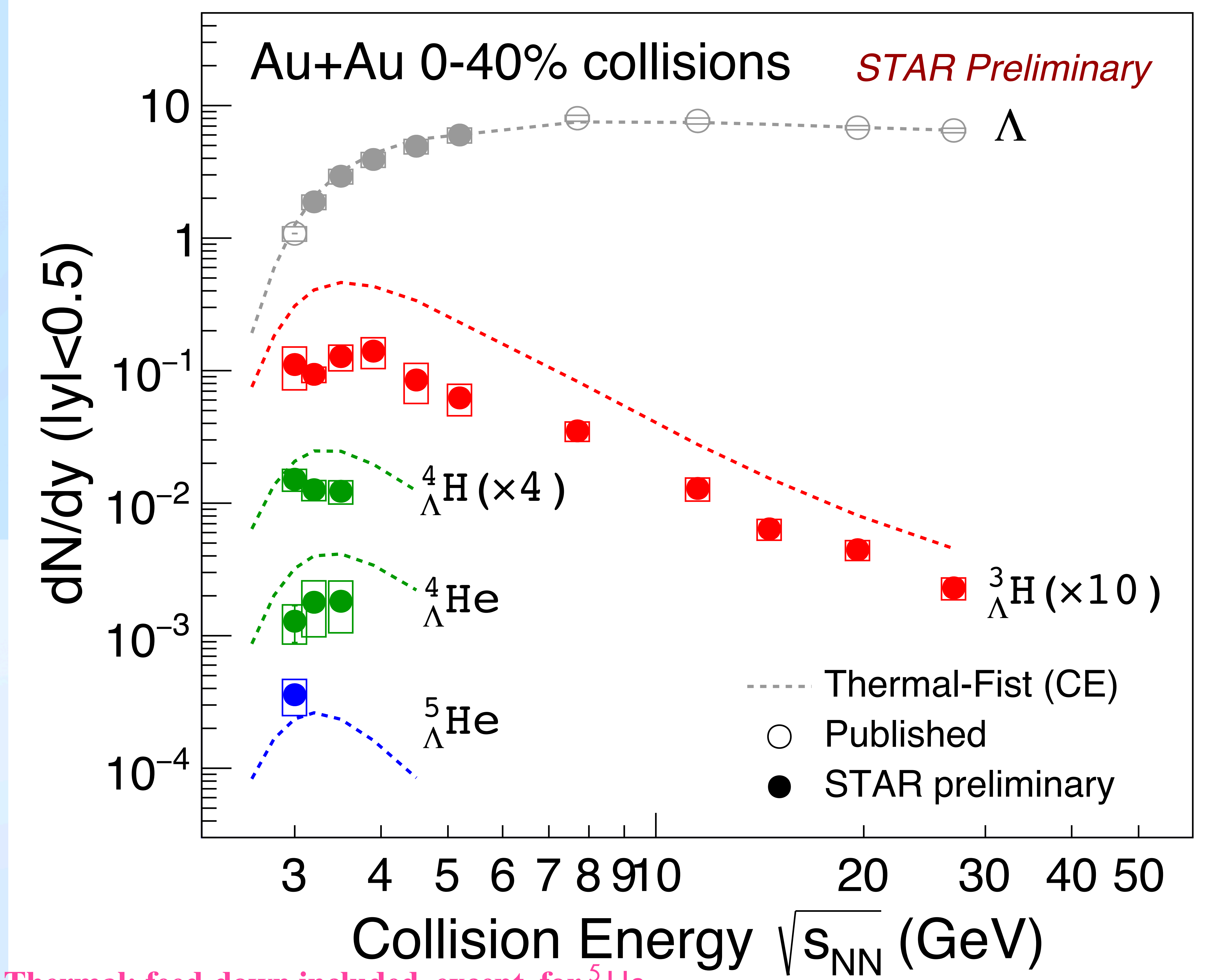
STAR, PLB 834, 137449 (2022)



- First potential evidence for the possible feed down from $^{5}_{\Sigma^0}He \rightarrow ^{5}_{\Lambda}He + \gamma$

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

Excitation Function



Thermal: feed-down included, except for $^{5}_{\Lambda}$He

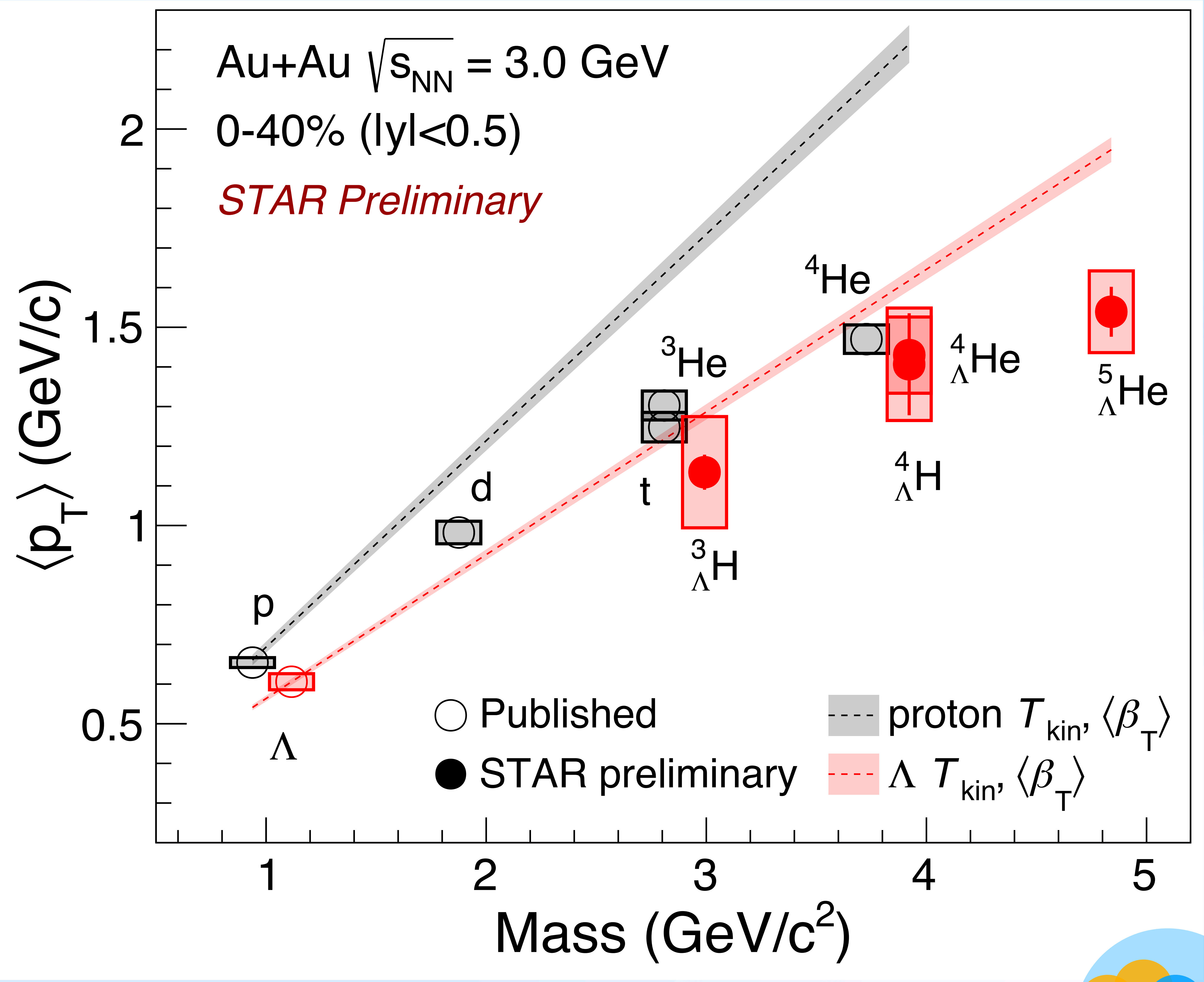
- $^{3}_{\Lambda}$H plateaus at $\sqrt{s_{NN}}$ = 3-4 GeV
  - Similar trend for $^{4}_{\Lambda}$H and $^{4}_{\Lambda}$He

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

- Across all energy, thermal model describes Λ, **overestimates** $^{3}_{\Lambda}$**H,** $^{4}_{\Lambda}$**H, and** $^{4}_{\Lambda}$He, slightly **underestimates** $^{5}_{\Lambda}$He across energy

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

Mean Transverse Momentum at 3 GeV



<u>Hydrodynamic-inspired Blast-Wave model</u>: 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

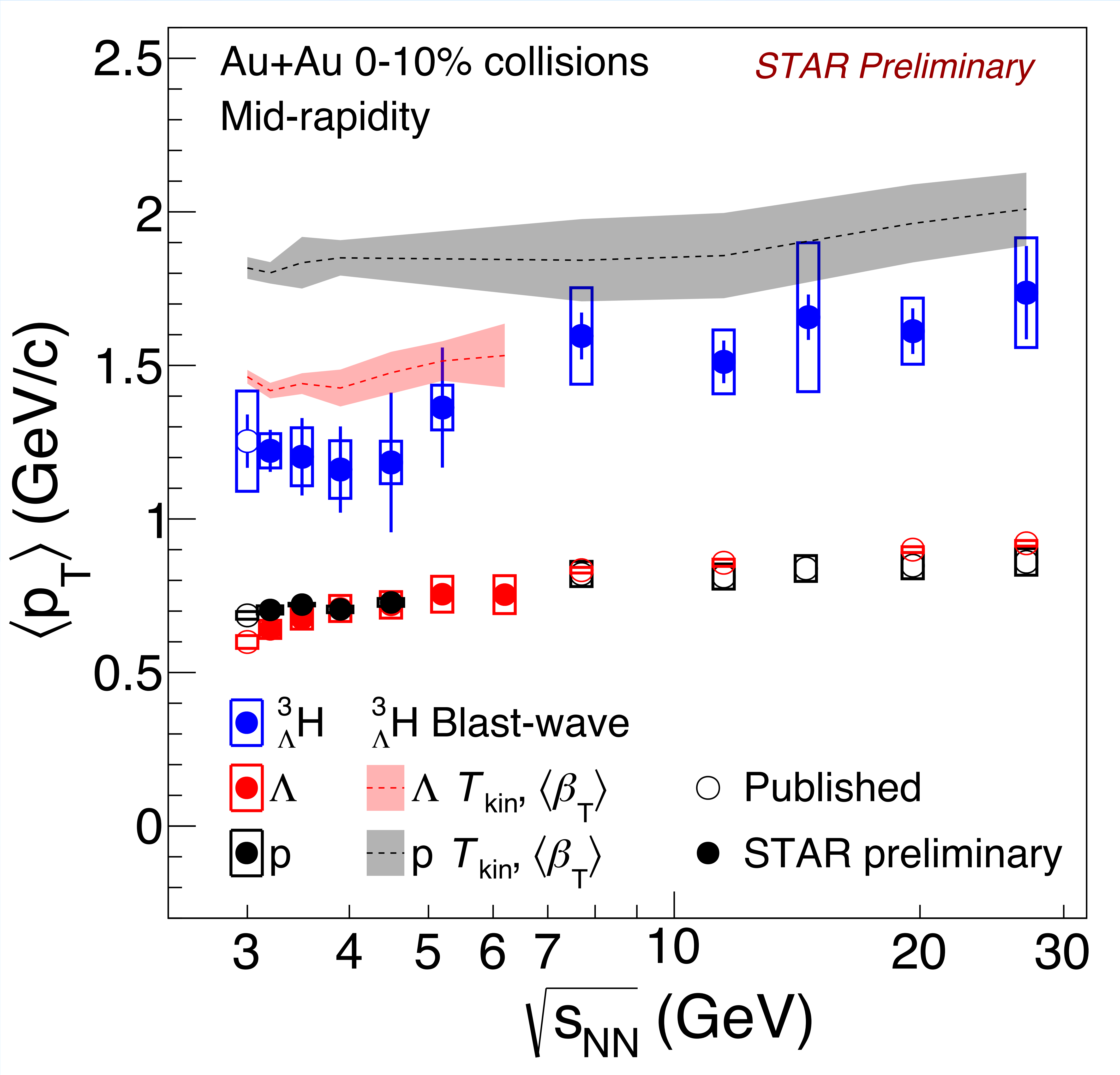
	p	Λ
$\langle \beta_T \rangle$ (c)	0.43	0.33
T_{kin} (GeV)	0.065	0.076

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

- Light (hyper-)nuclei deviate from the full hydrodynamic picture
- Hypernuclei close to Λ blast wave ansatz

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

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
  - May be due to increasing effective volume for coalescence with increasing energy

D.-N. Liu et al., PLB 855, 138855 (2024)

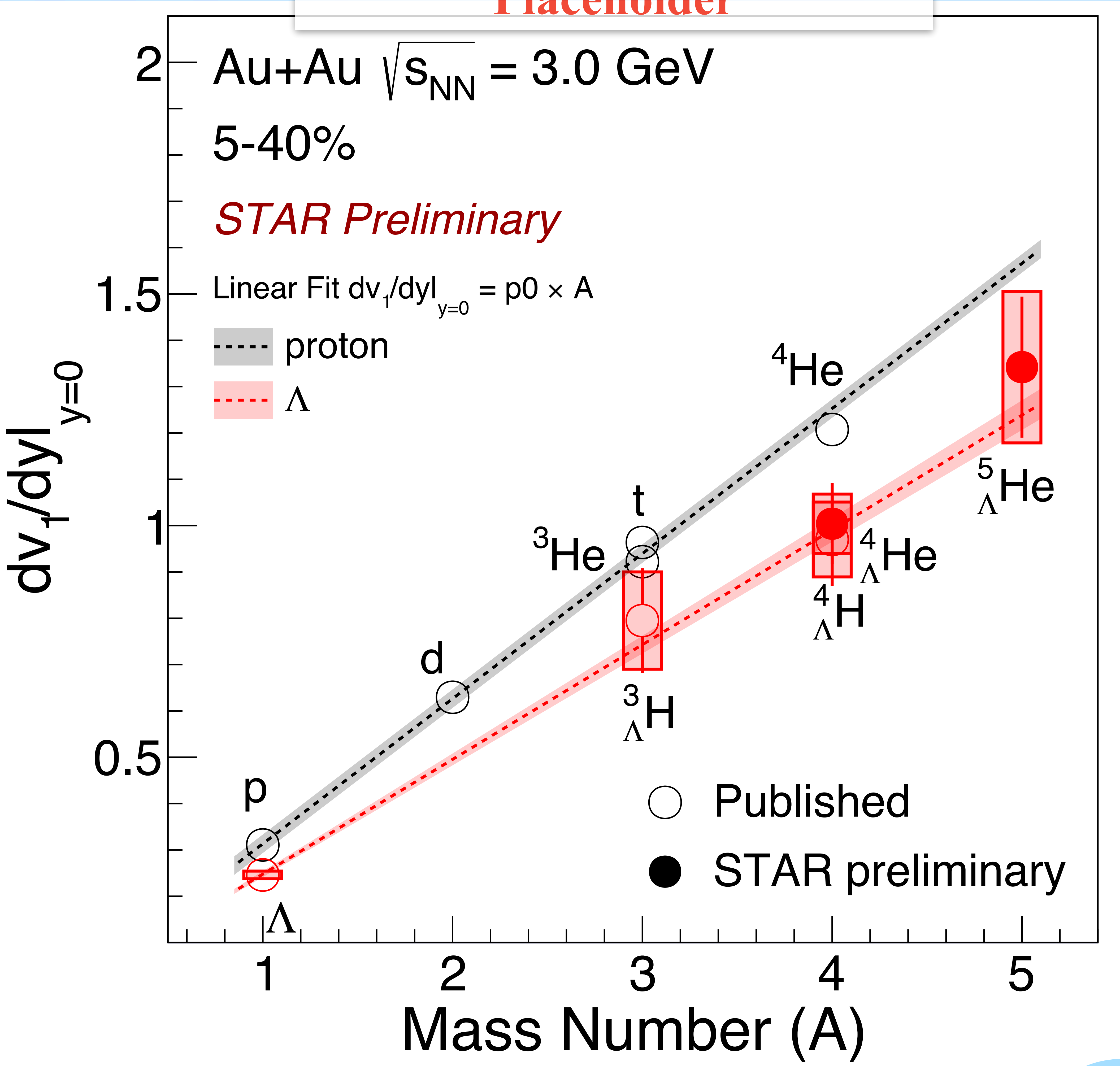
- Noticeable change between 4.5 and 7.7 GeV

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

Directed Flow at 3 GeV

See poster by Junyi Han (xx/xx)

Placeholder



- Light nuclei mid-rapidity v_1 slope increase linearly with atomic mass number *A*
- Hypernuclei v_1 slope systematically lower than light nuclei of similar *A*, and compatible with Λ atomic mass number scaling

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

Summary and Outlook

- Hypernuclei measurements 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
    4. Directed flow follow atomic mass number *A* scaling

All measurements consistently point to the coalescence production mechanism

Outlook:

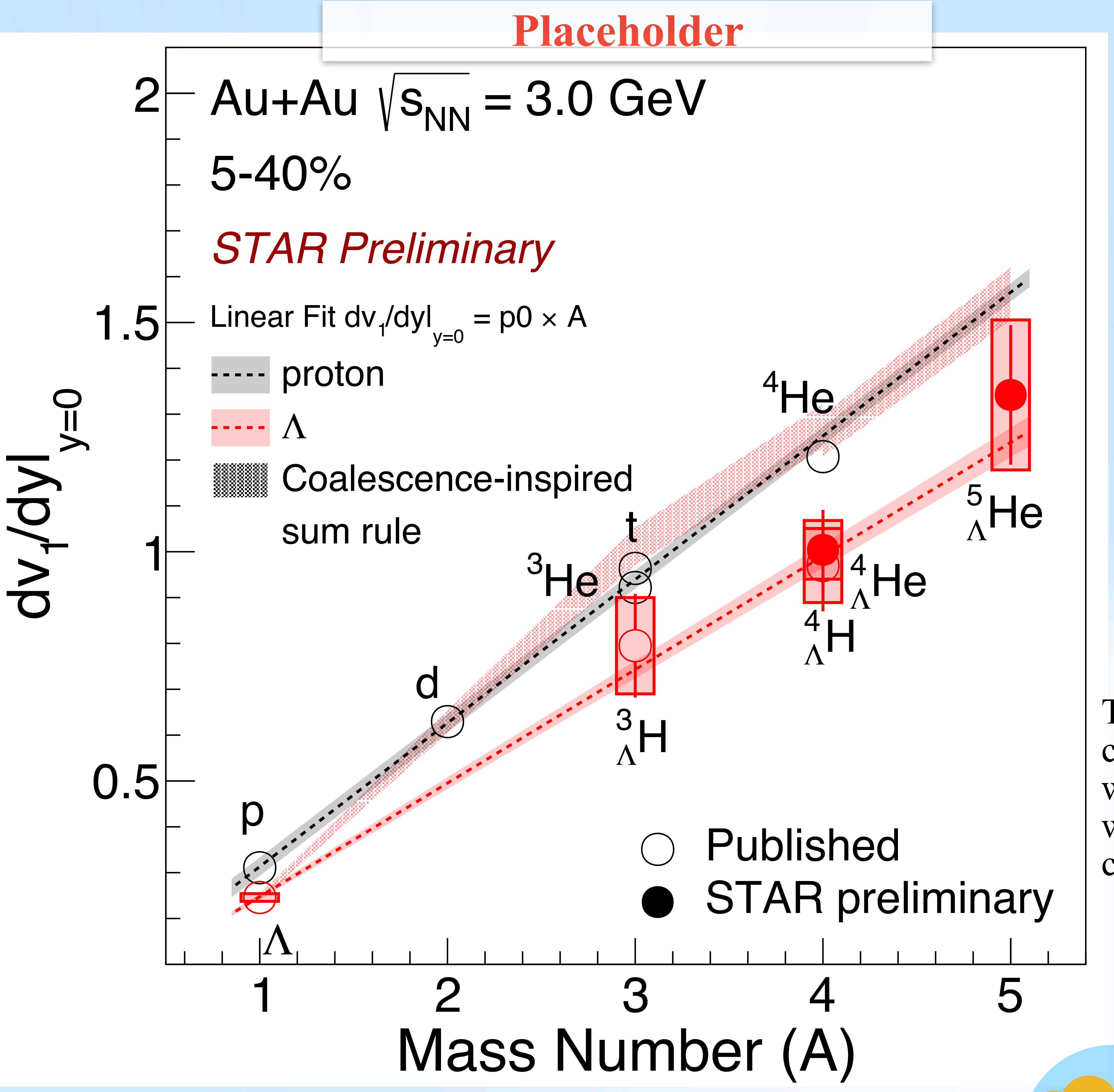
- BES-II 3 GeV 2B data: more precise measurement of A < 5 hypernuclei, ${}^{5}_{\Lambda}$He intrinsic properties (B_Λ, dalitz plot, lifetime), search for heavier hypernuclei (A > 5), double-Λ hypernuclei

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

Backup Slides Follow

Directed Flow at 3 GeV — need to be discussed

See poster by Junyi Han (xx/xx)

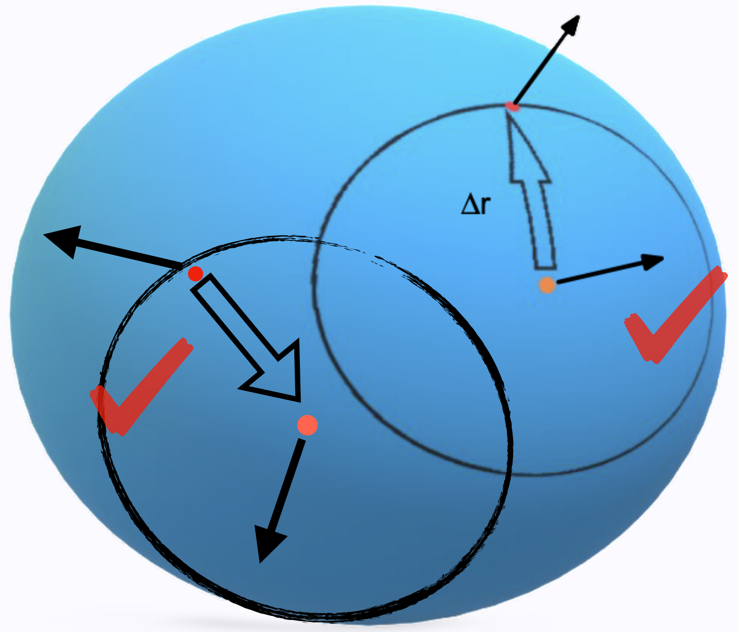


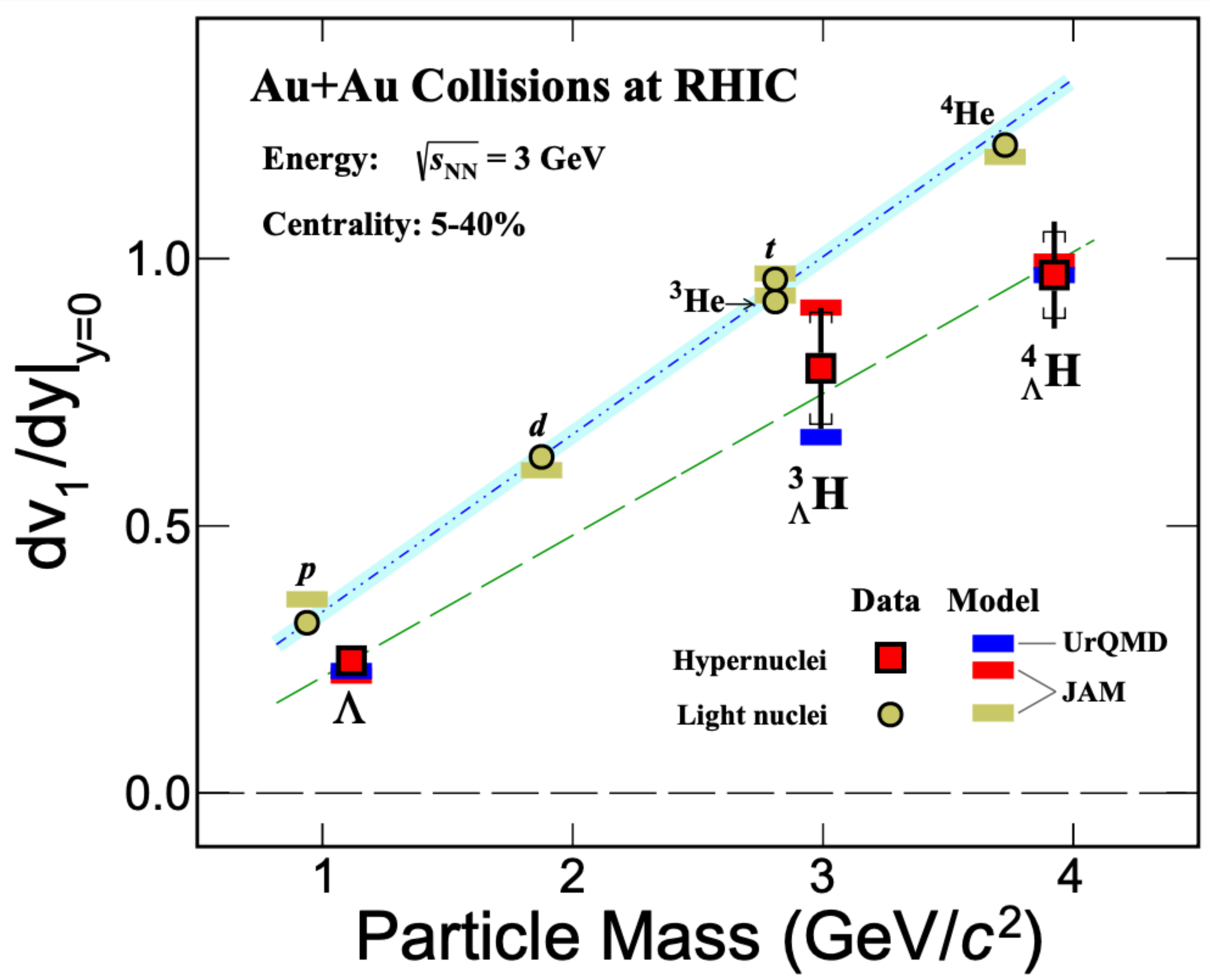
Coalescence-inspired sum rule: flow of hypernuclei = $N_{nucleon}$*nucleon v_1 + N_Λ * Λ v_1

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

- Hypernuclei v_1 slope deviate from simple coalescence-inspired sum rule, but close to Λ atomic mass number scaling
  - Could be explained by coalescence model like JAM+coalescence, or coalescence speculation, not this simple coalescence

To avoid giving the impression that the coalescence model doesn't work, and since we have already removed this blue bubble , we should not include this simple coalescence sum rule band in the figure?





Yingjie Zhou

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