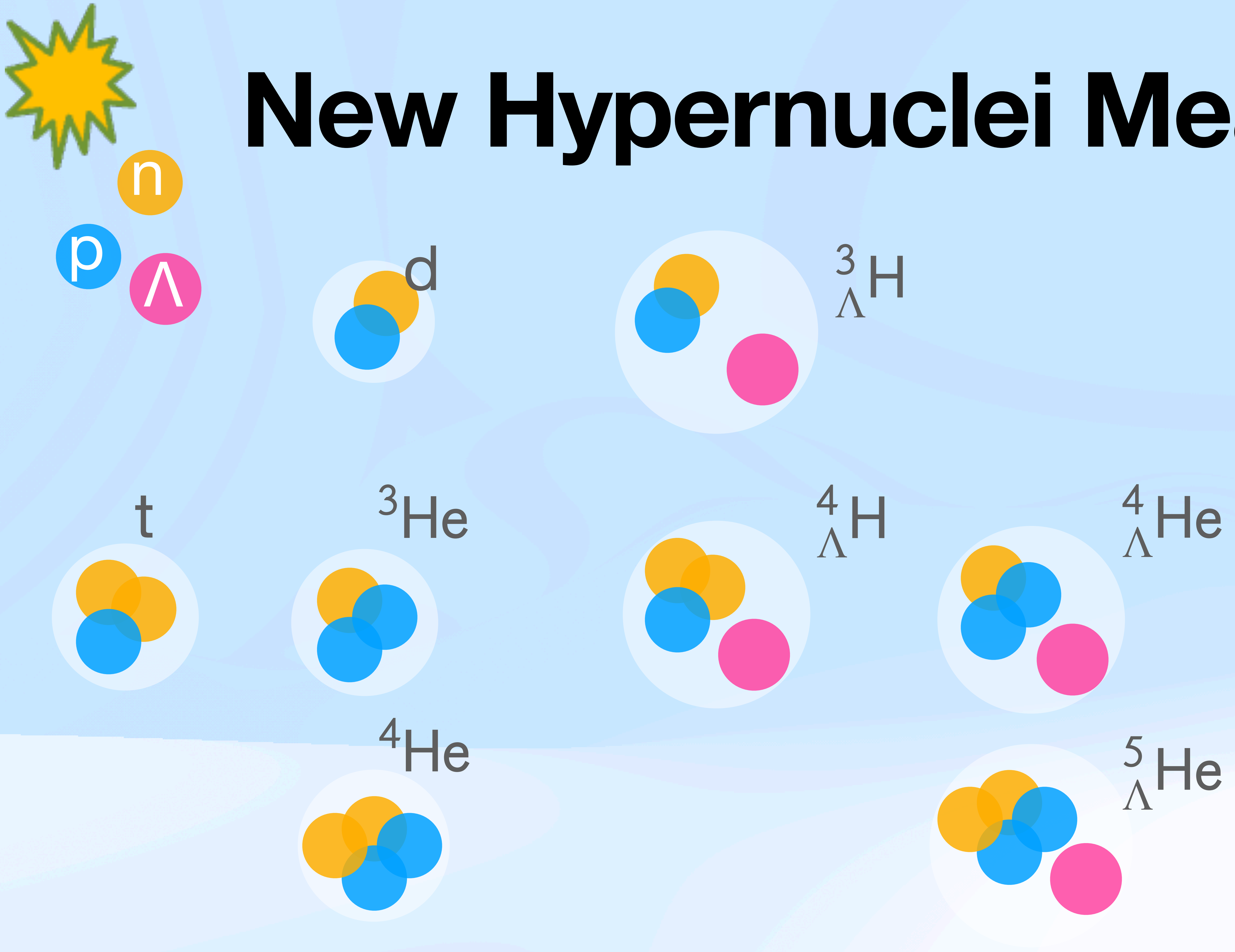
New Hypernuclei Measurements from STAR



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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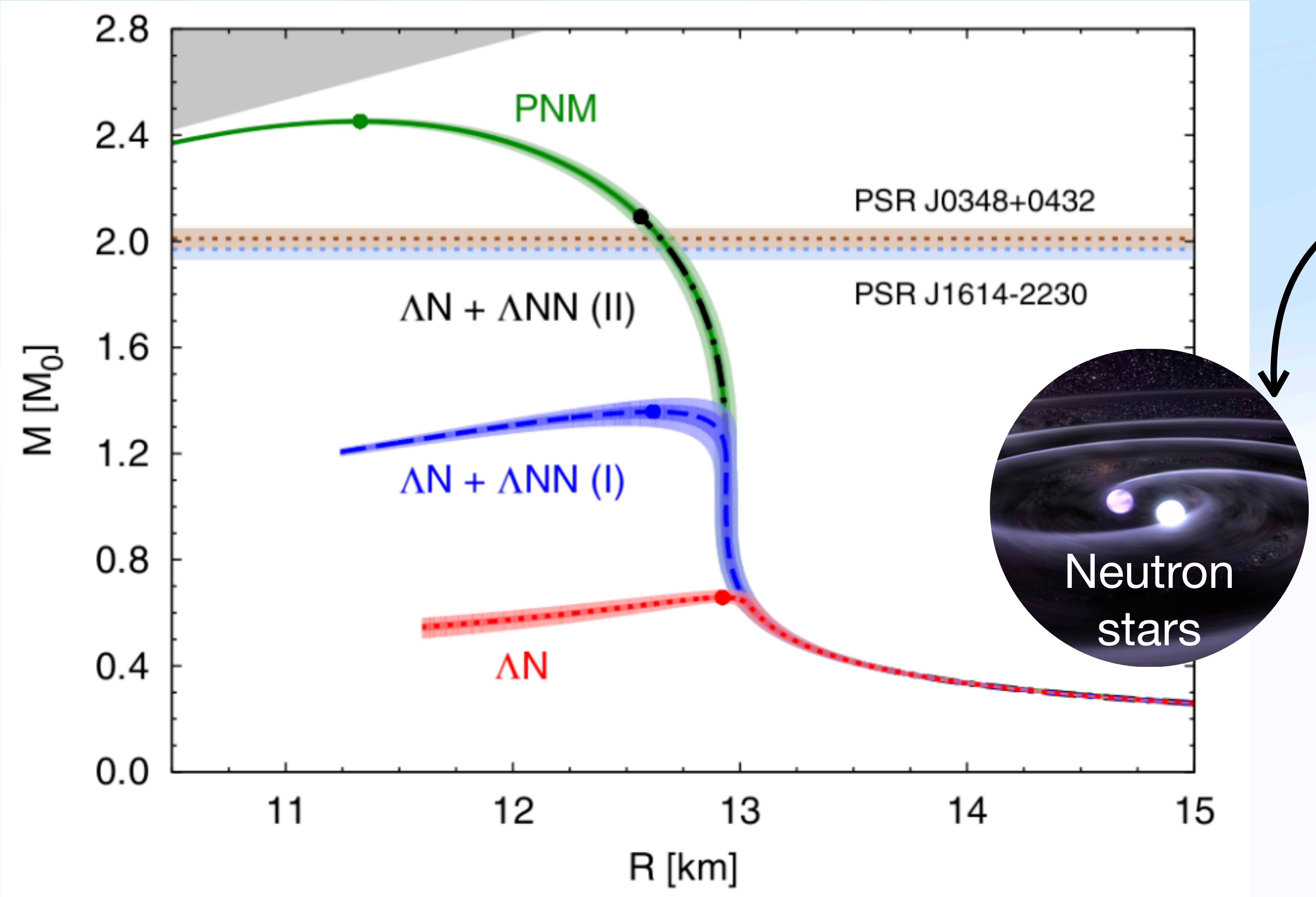
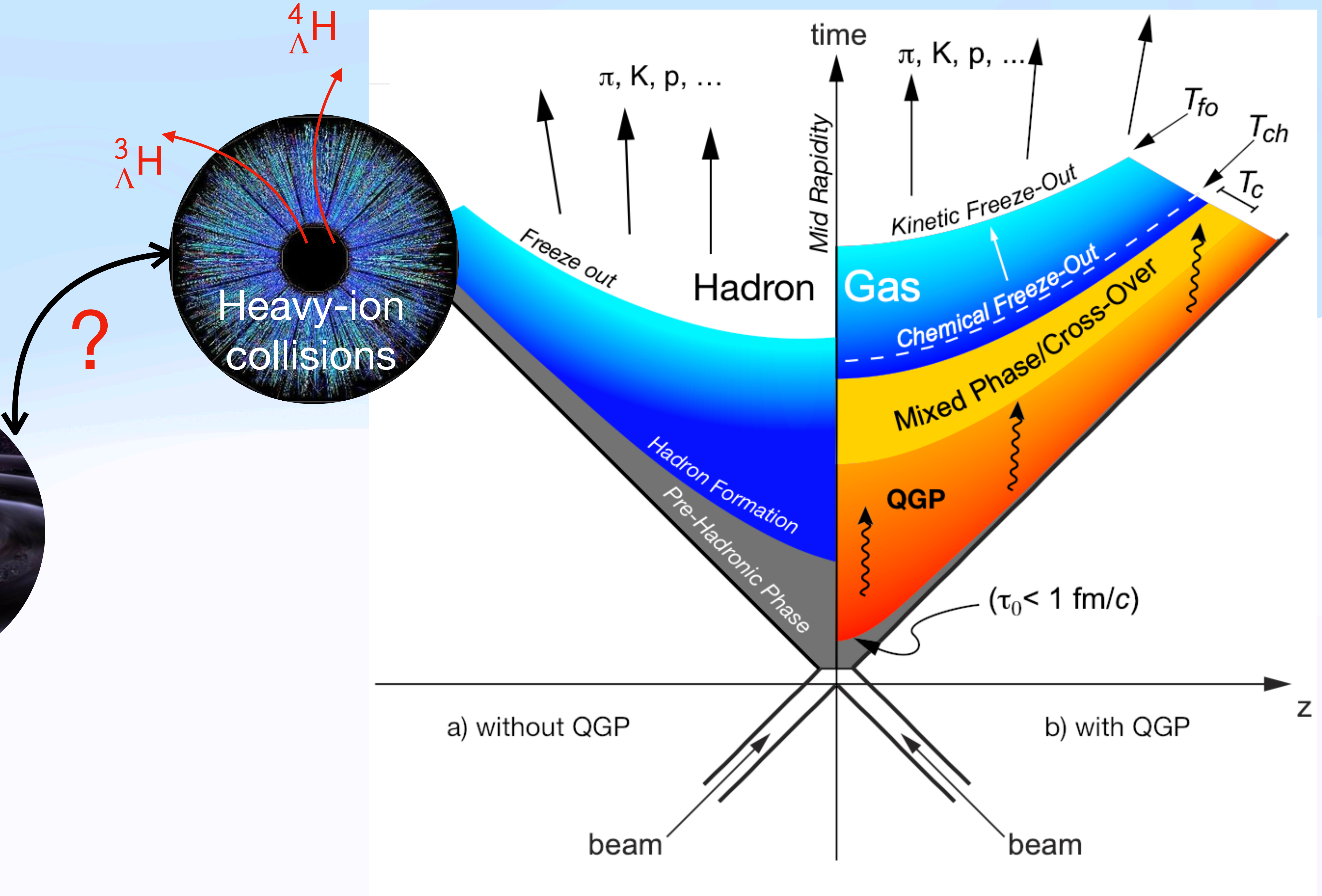
Hypernuclei and Hyperon-Nucleon (Y-N) Interaction

- **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)



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



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

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

Hypernuclei Production Mechanisms

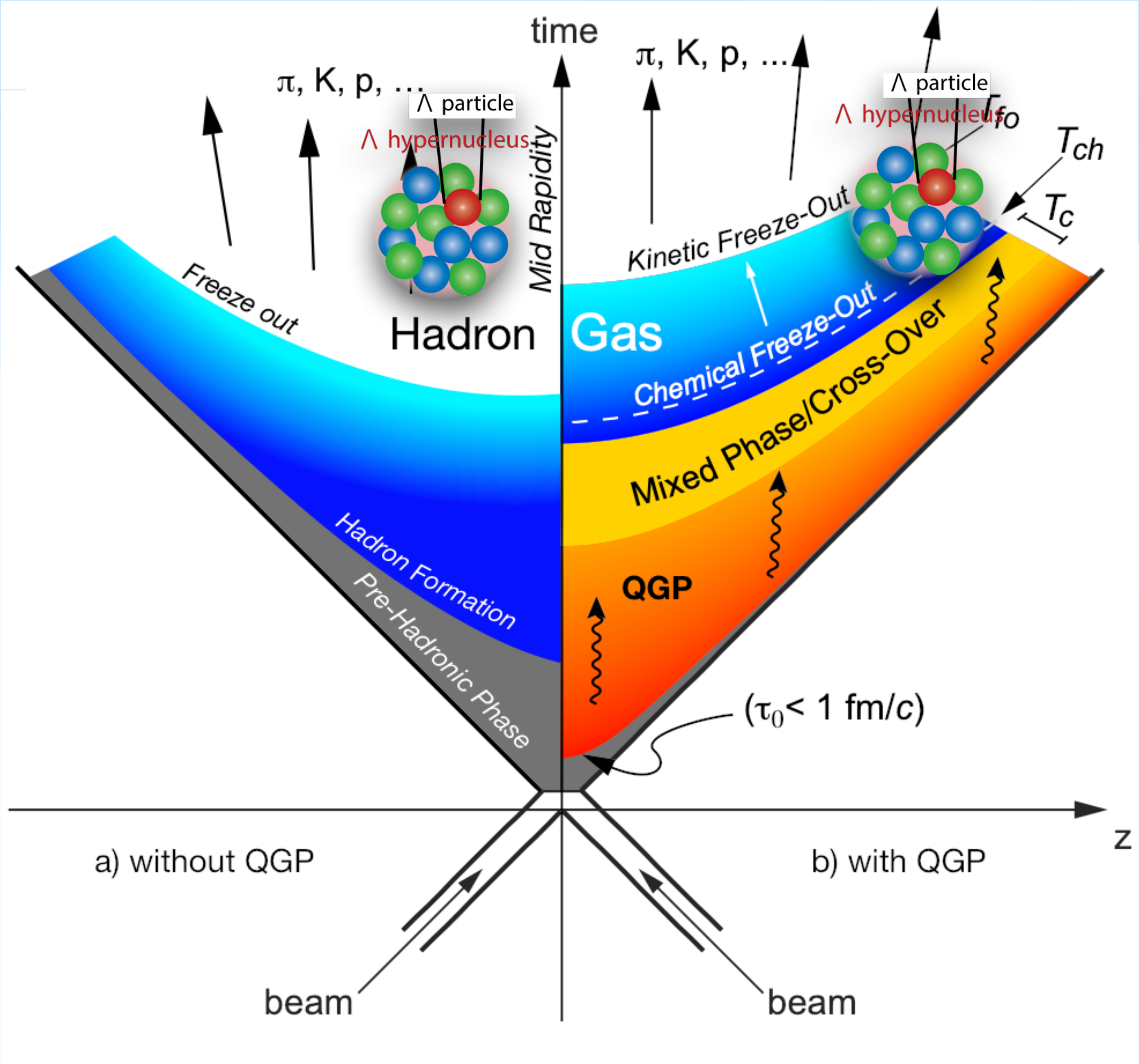
When are nuclei produced in a heavy-ion collision?

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

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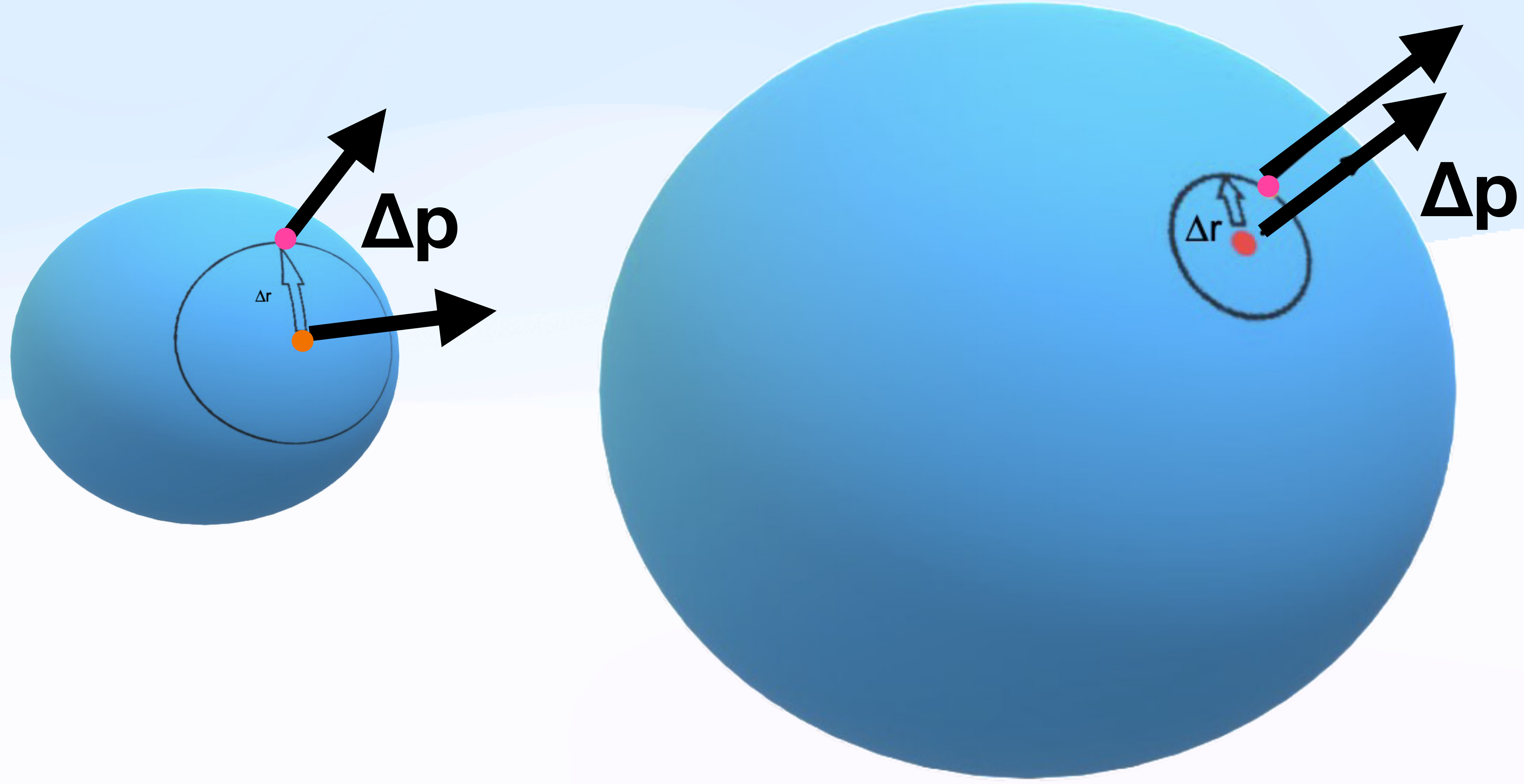
✓Sensitive to the freeze-out phase space, which can be affected by in-medium Y–N interactions

Coalescence models predict a reduction in yield and $\langle p_T \rangle$ of loosely bound (hyper)nuclei as the emission source size decreases

T. Reichert et al., PRC 107, 014912 (2023)



nucleon's *r* and *p* are less correlated

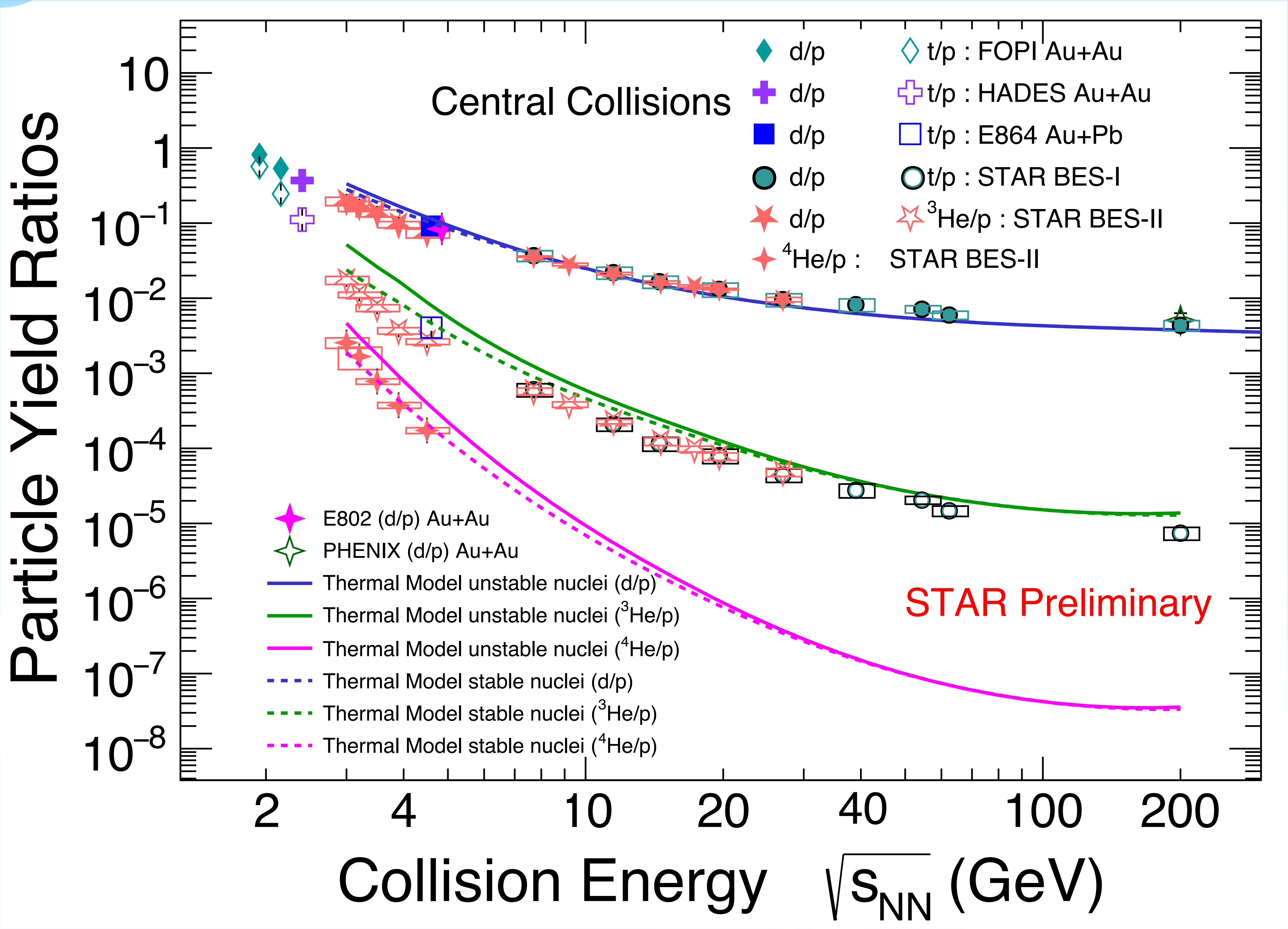
nucleon's *r* and *p* are more correlated

Increasing effective volume

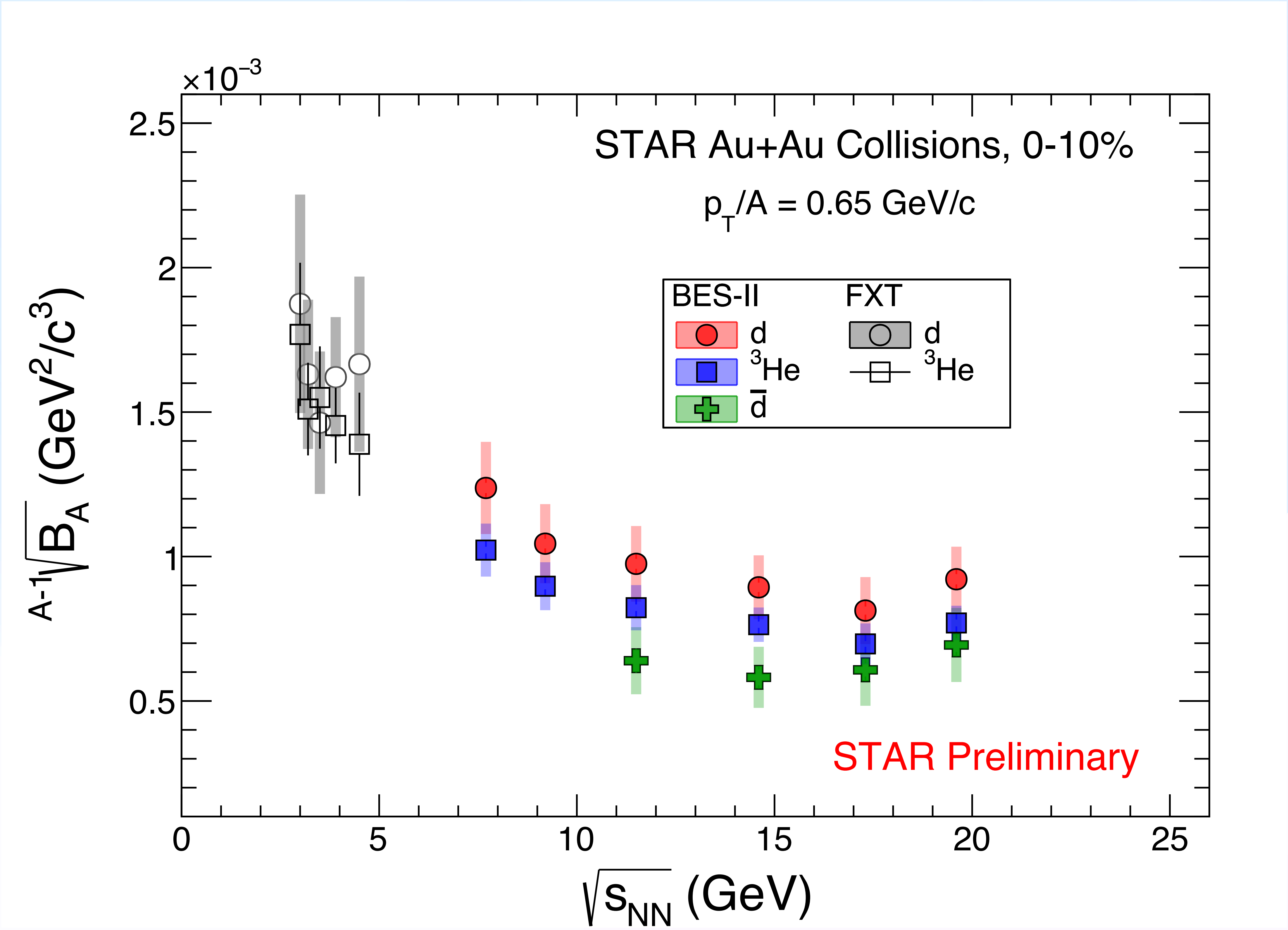
T. Reichert, SQM 2022

What have we learnt from light nuclei production?

See poster by Liubing Chen (ID: 711)



See poster by YiXuan Jin (ID: 816)



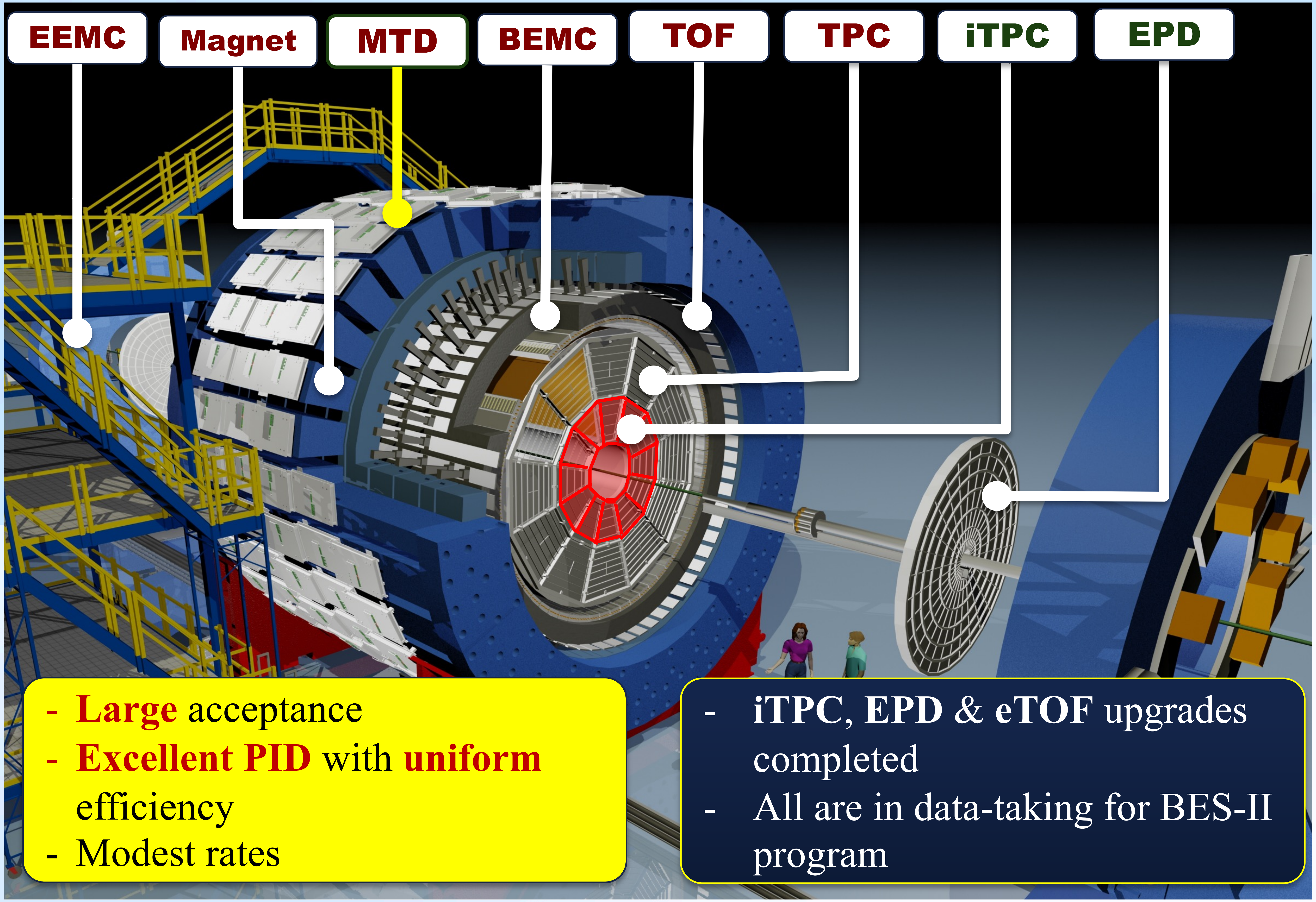
- *d/p* is fairly well described by thermal model, but *$^{3}He/p$, $^{4}He/p$* is overestimated

Recent nuclei measurements pose challenges for thermal model

- The coalescence parameters B_2, B_3 decrease with increasing energy, which indicates smaller nucleon emission source size at low energies

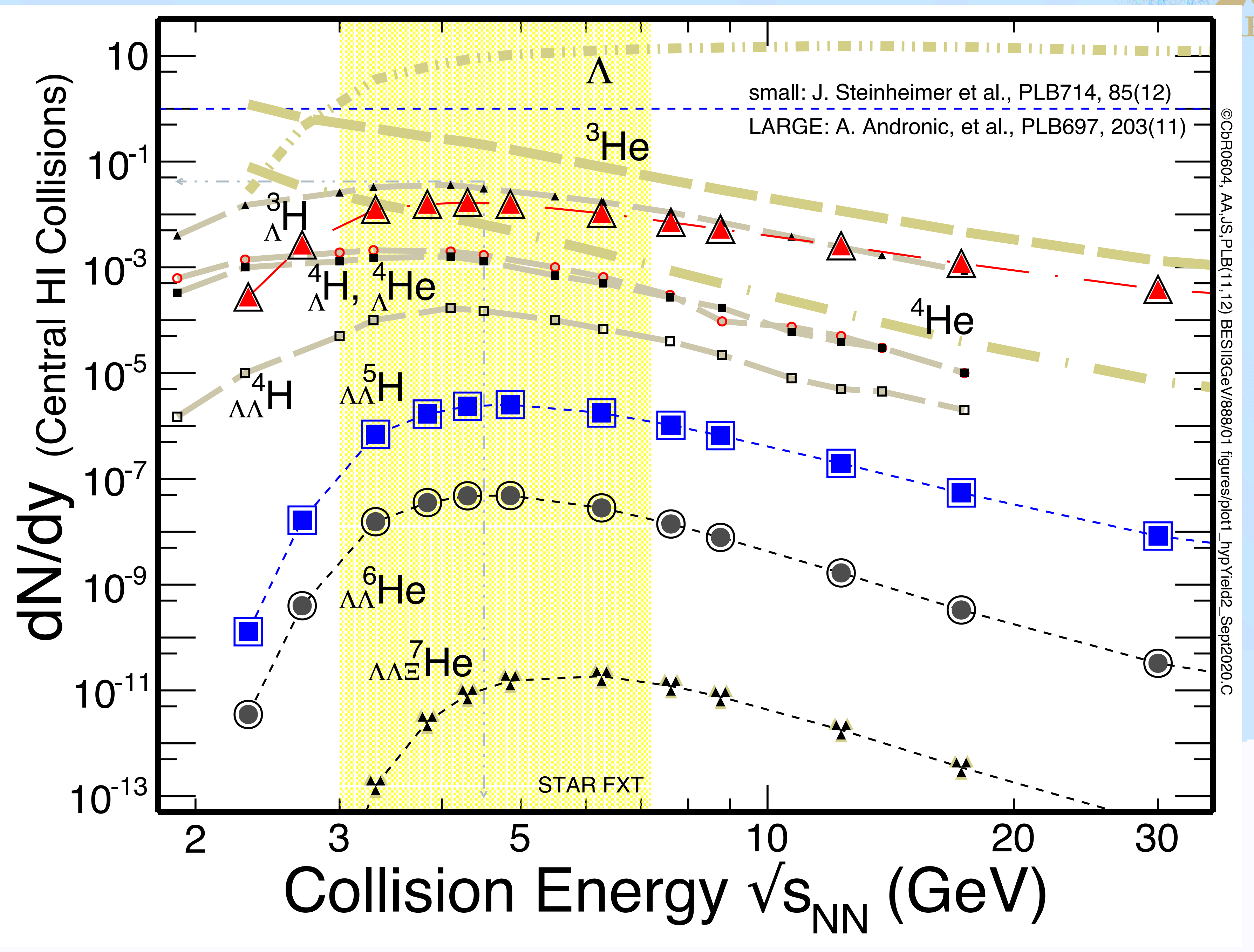
$$E_A \frac{d^3N_A}{d^3p_A} = B_A \left(E_p \frac{d^3N_p}{d^3p_p}\right)^Z \left(E_n \frac{d^3N_n}{d^3p_n}\right)^{A-Z}$$

STAR and Beam Energy Scan

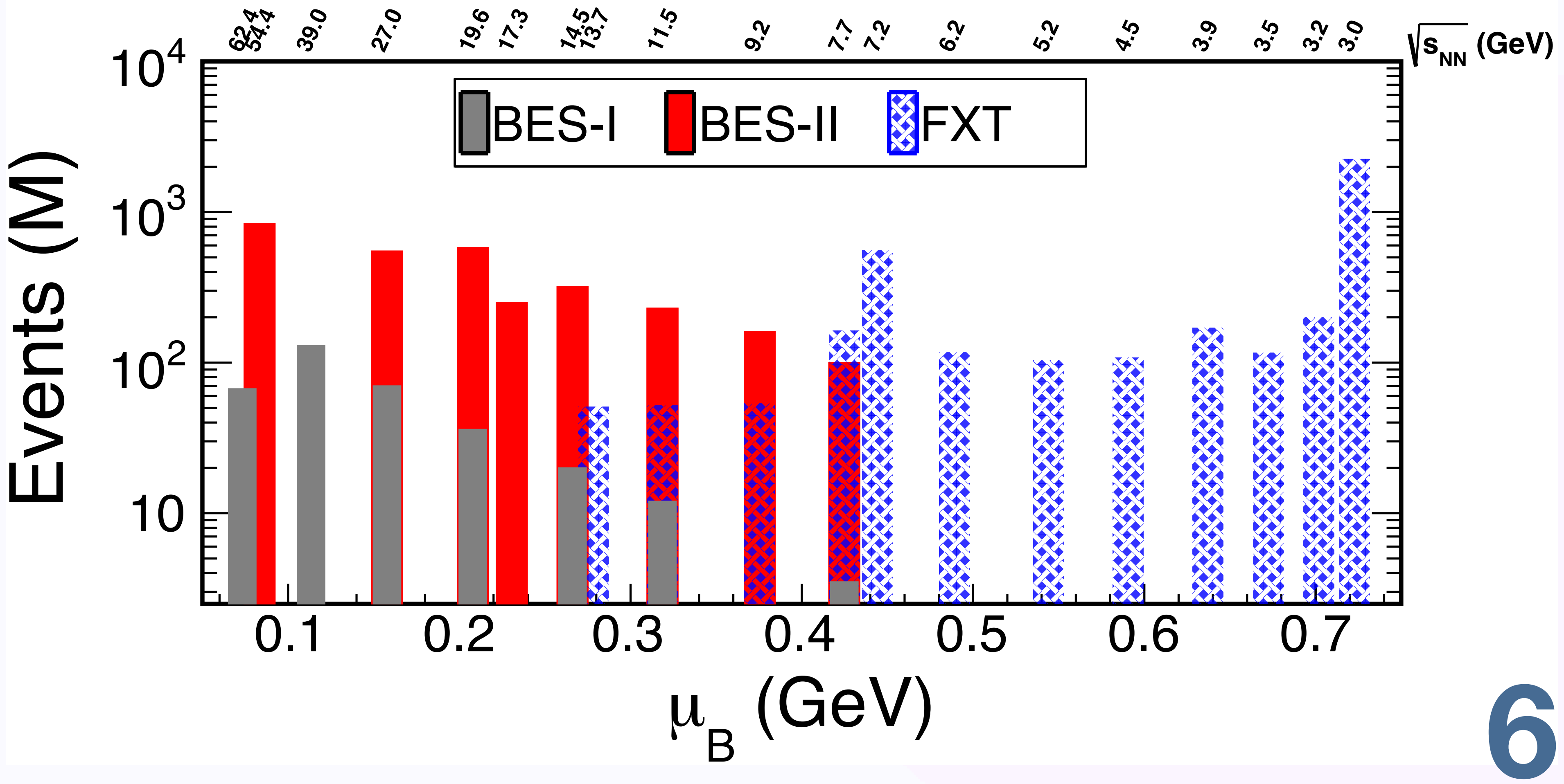


- **Large** acceptance
- **Excellent PID** with **uniform** efficiency
- Modest rates

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

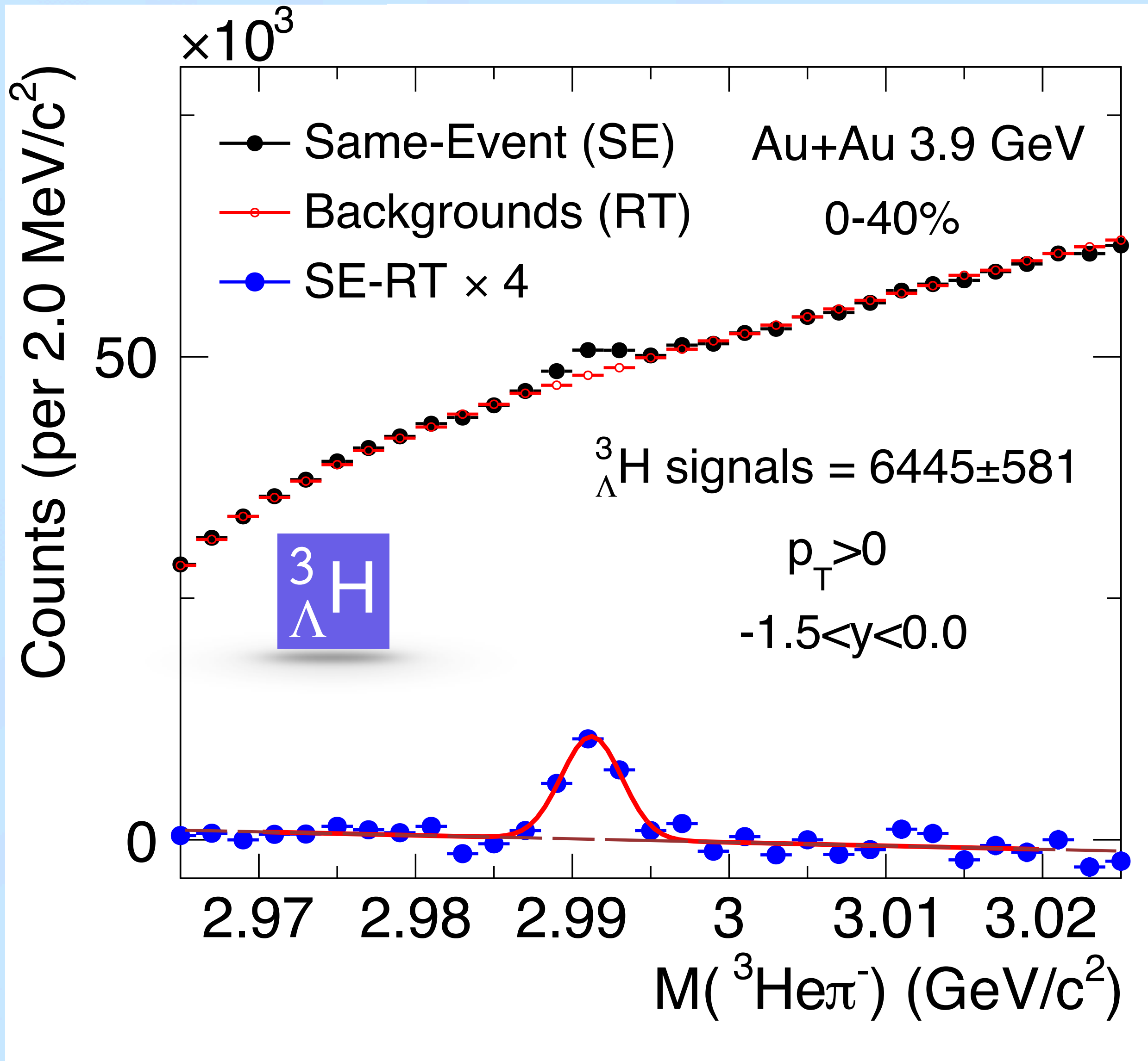


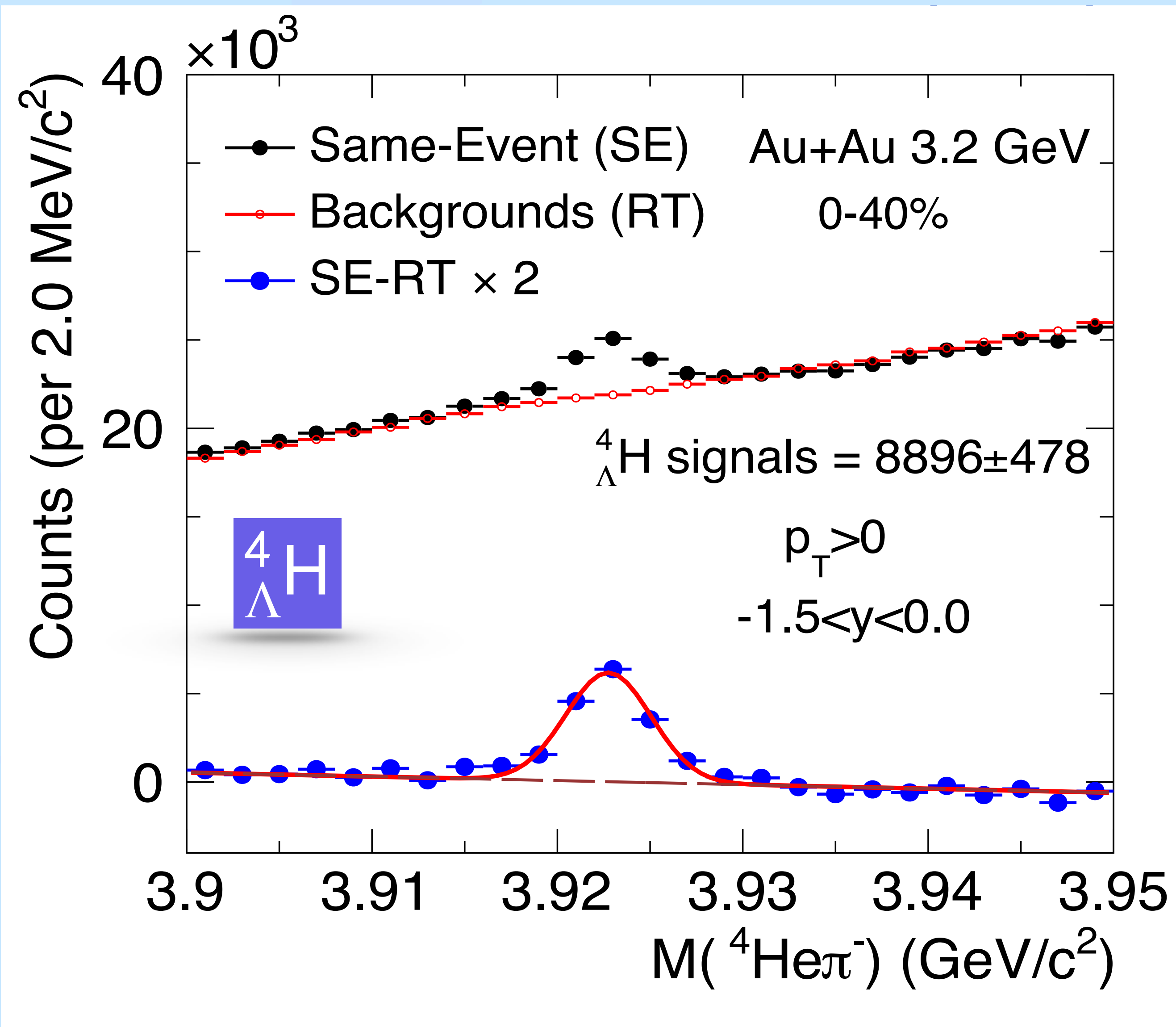
A. Andronic *et al.* Phys.Lett.B 697, 203 (2011)
J. Steinheimer *et al.* Phys.Lett.B 714, 85 (2012)

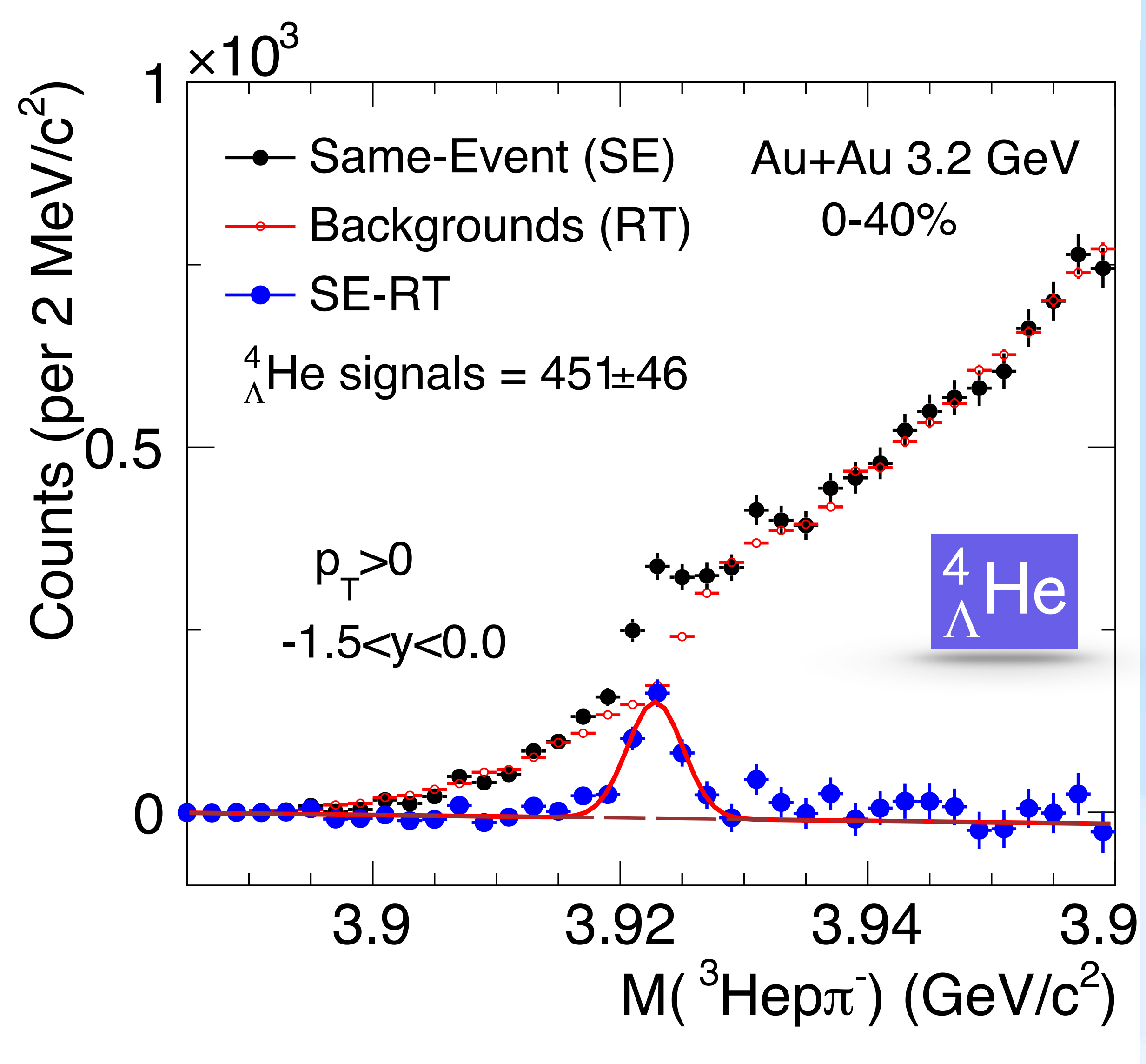


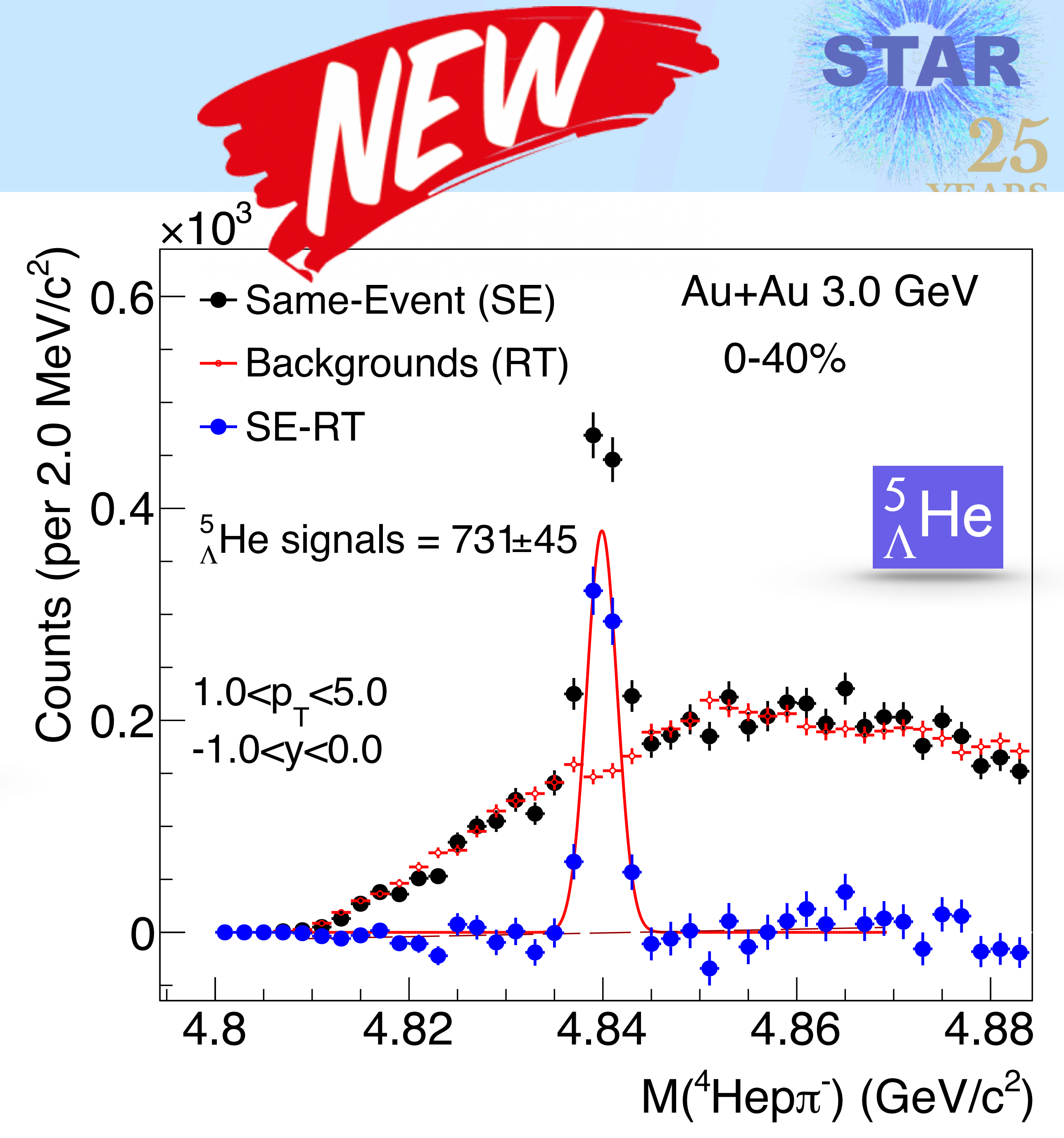
- RHIC BES-II offers great opportunity for hypernuclei measurements

Hypernuclei Reconstruction









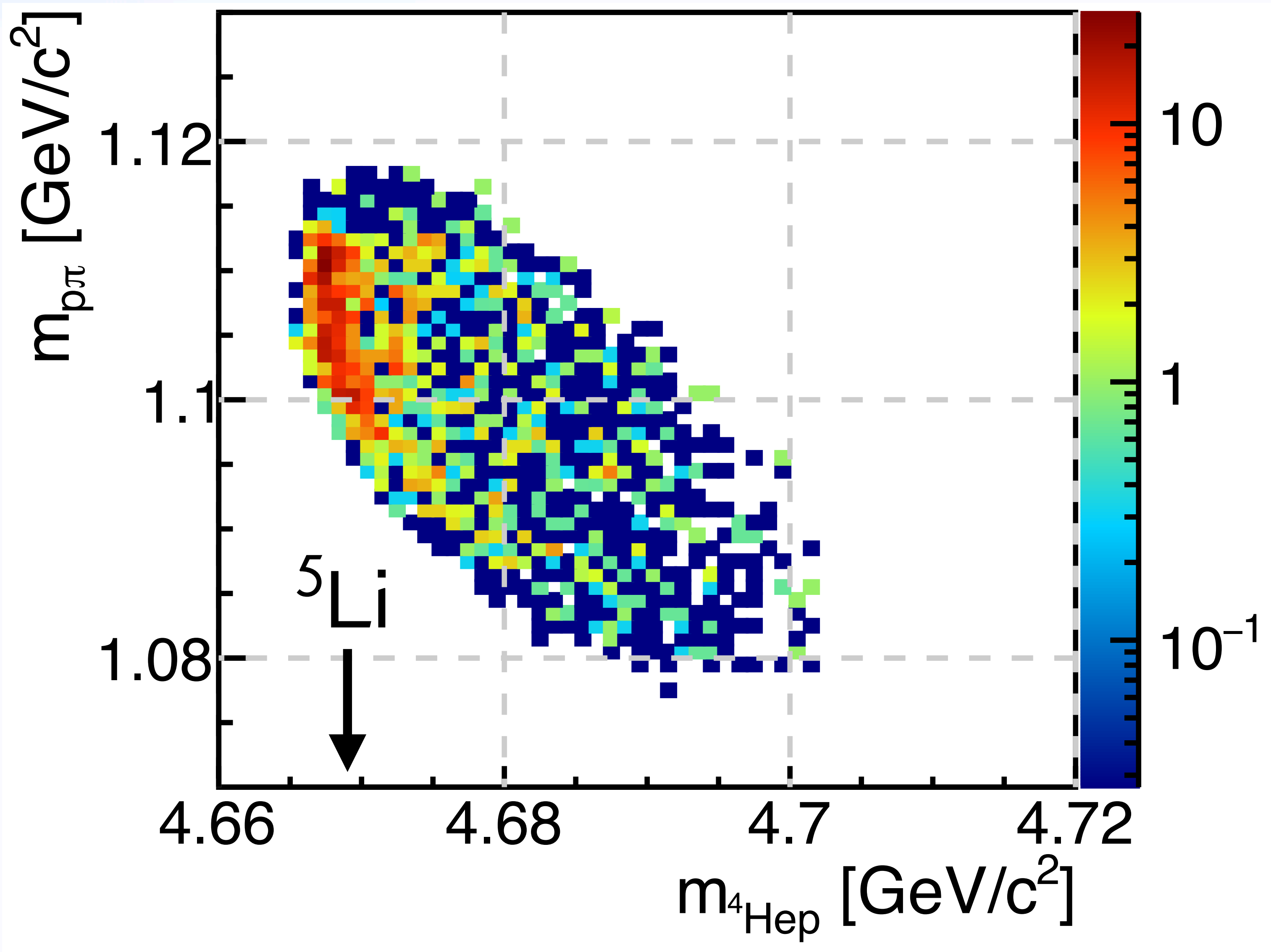
- Hypernuclei are reconstructed using the following decay channels:

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

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

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

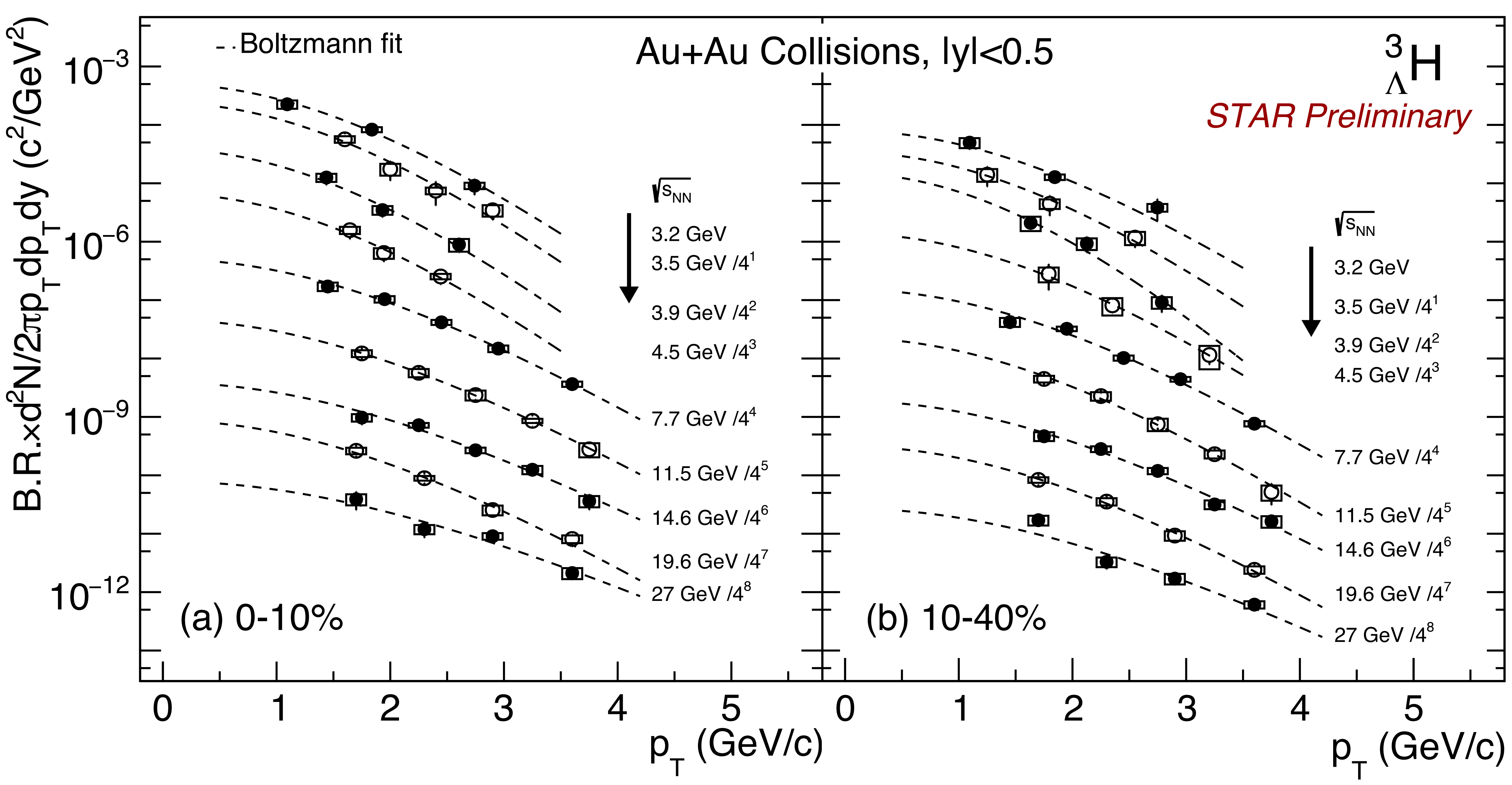
- Measurements cover different energies
  - ${}^{3}_{\Lambda}H$ in Au+Au collisions at **3-27** GeV, Au+Au collisions at **200 GeV**
  - ${}^{4}_{\Lambda}H$, ${}^{4}_{\Lambda}He$ in Au+Au collisions at **3-3.5 GeV**
  - ${}^{5}_{\Lambda}He$ in Au+Au collisions at **3 GeV**

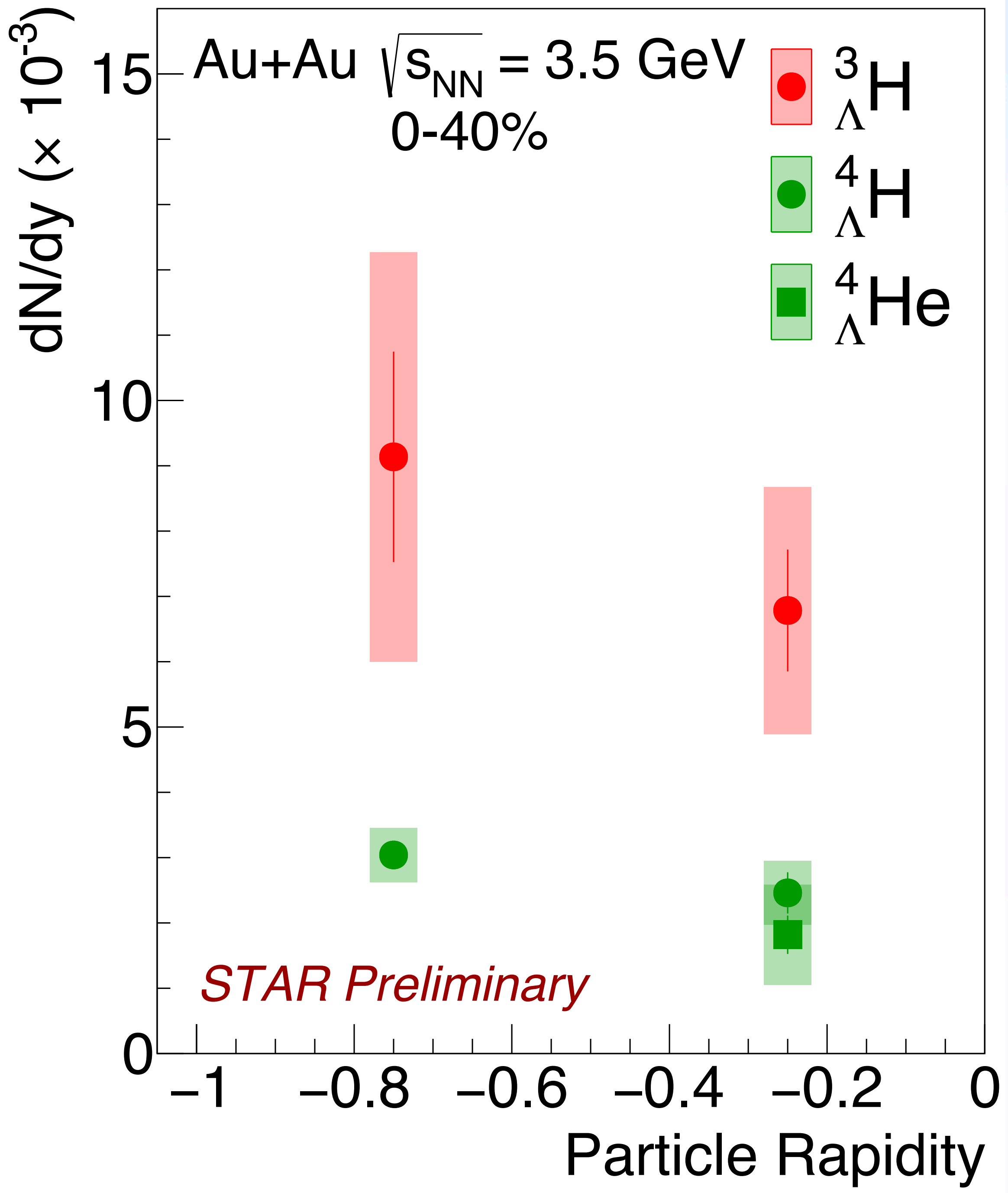
- Significant hypernuclei production at target rapidity, more pronounced for heavier hypernuclei

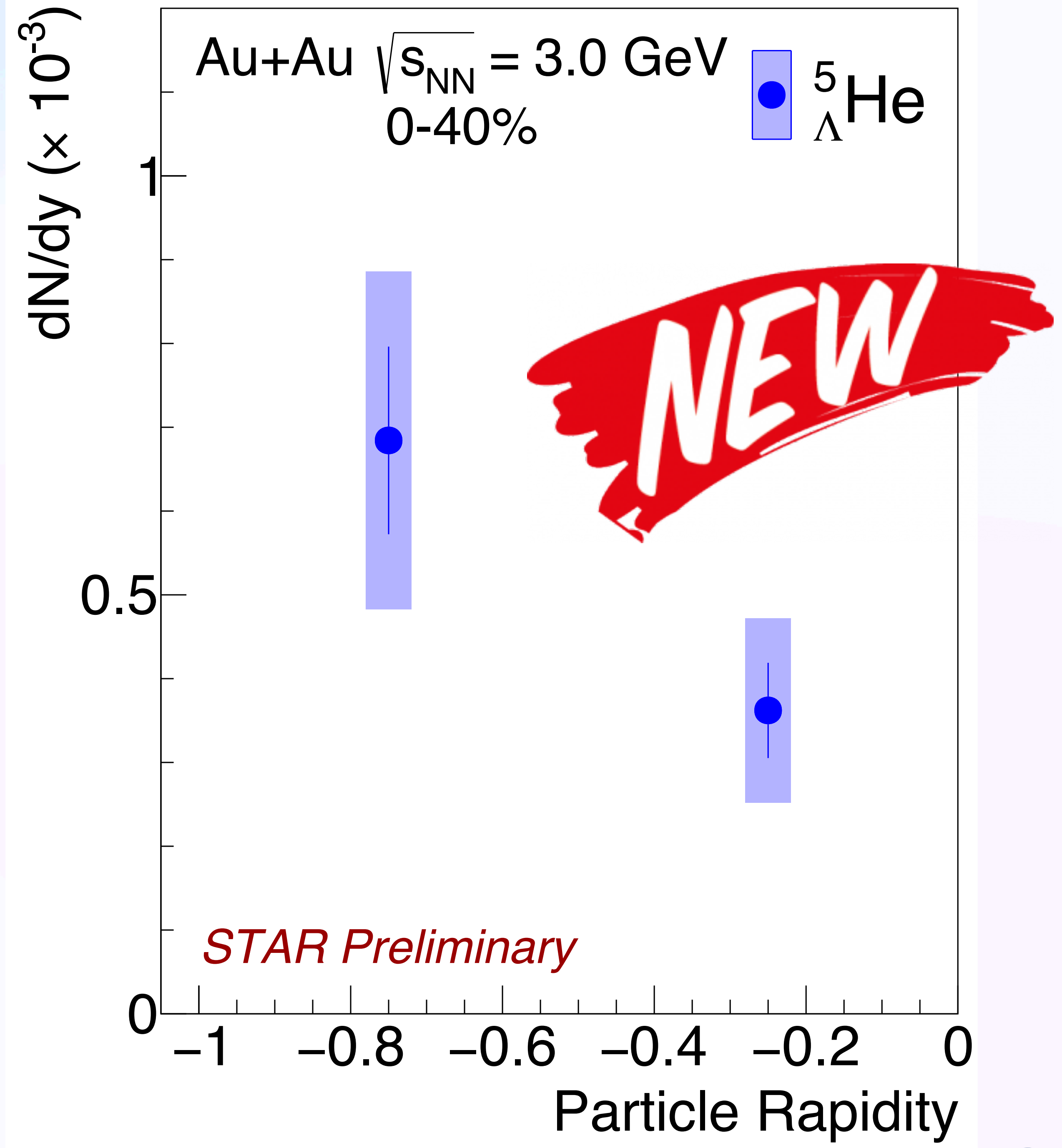
Spectator matter matters at target rapidity

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

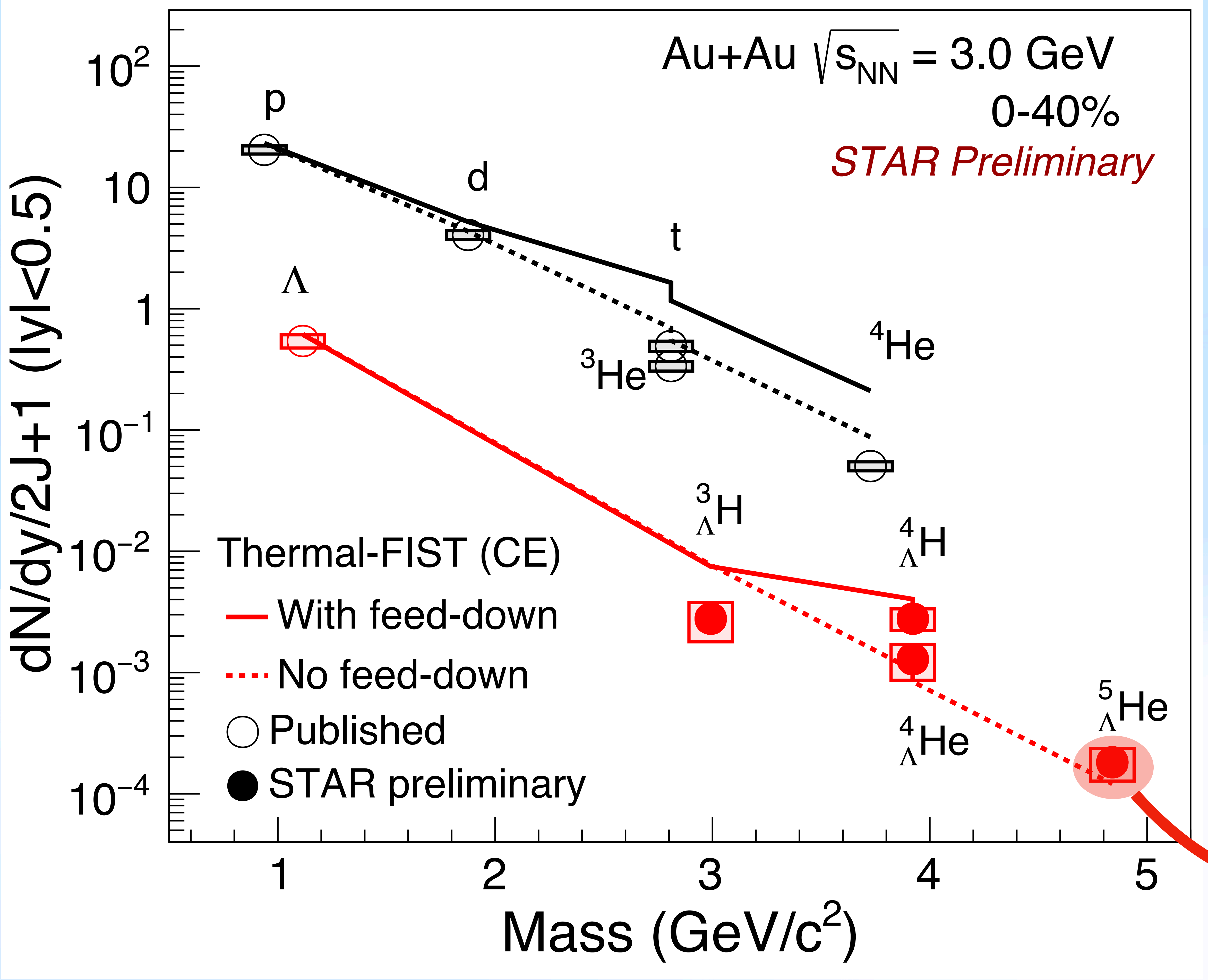
${}^{3}_{\Lambda}H$ Au+Au $\sqrt{s_{NN}}$ = 3.2-27 GeV

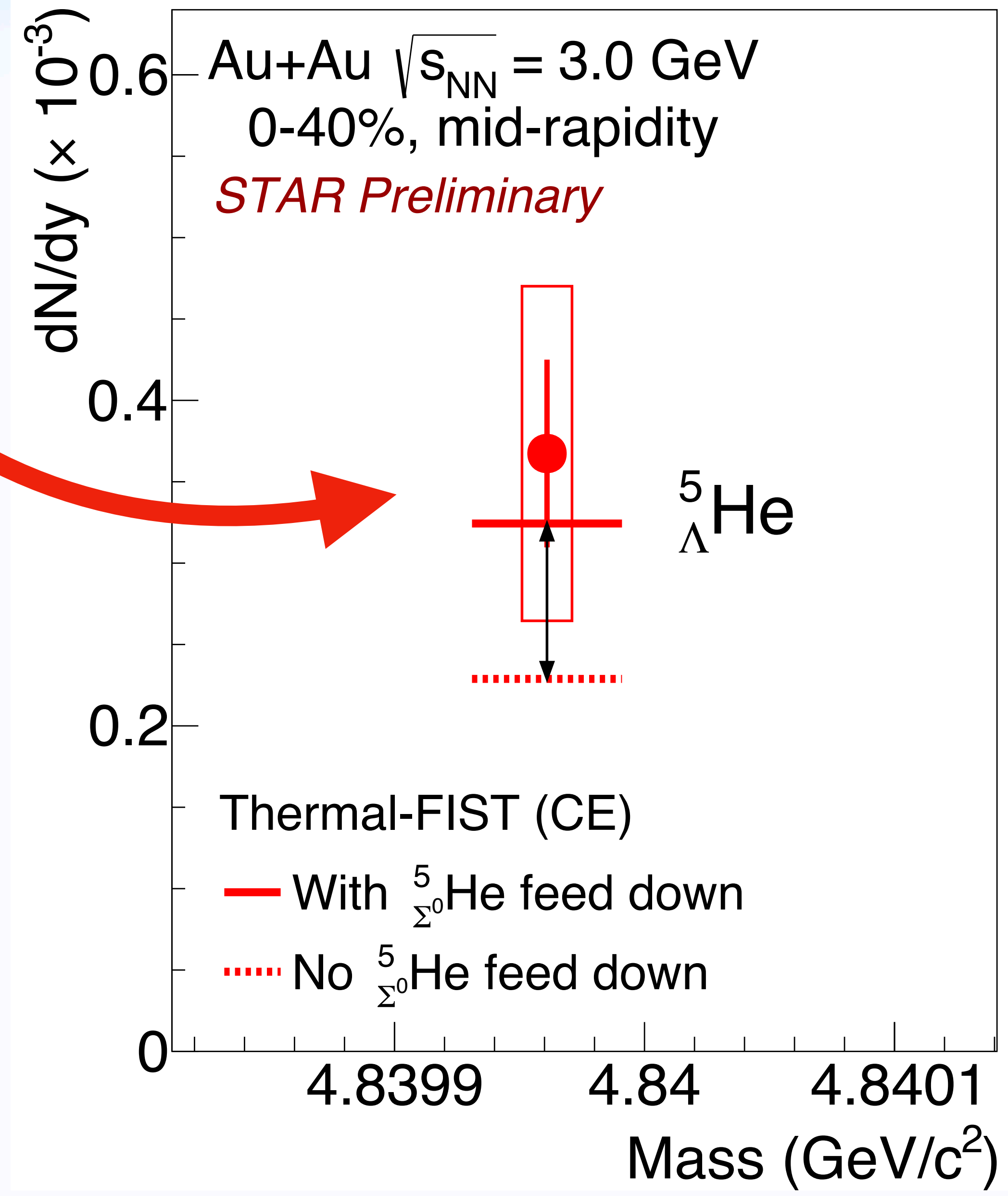






Particle Yields Comparison with Thermal Model at 3 GeV





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

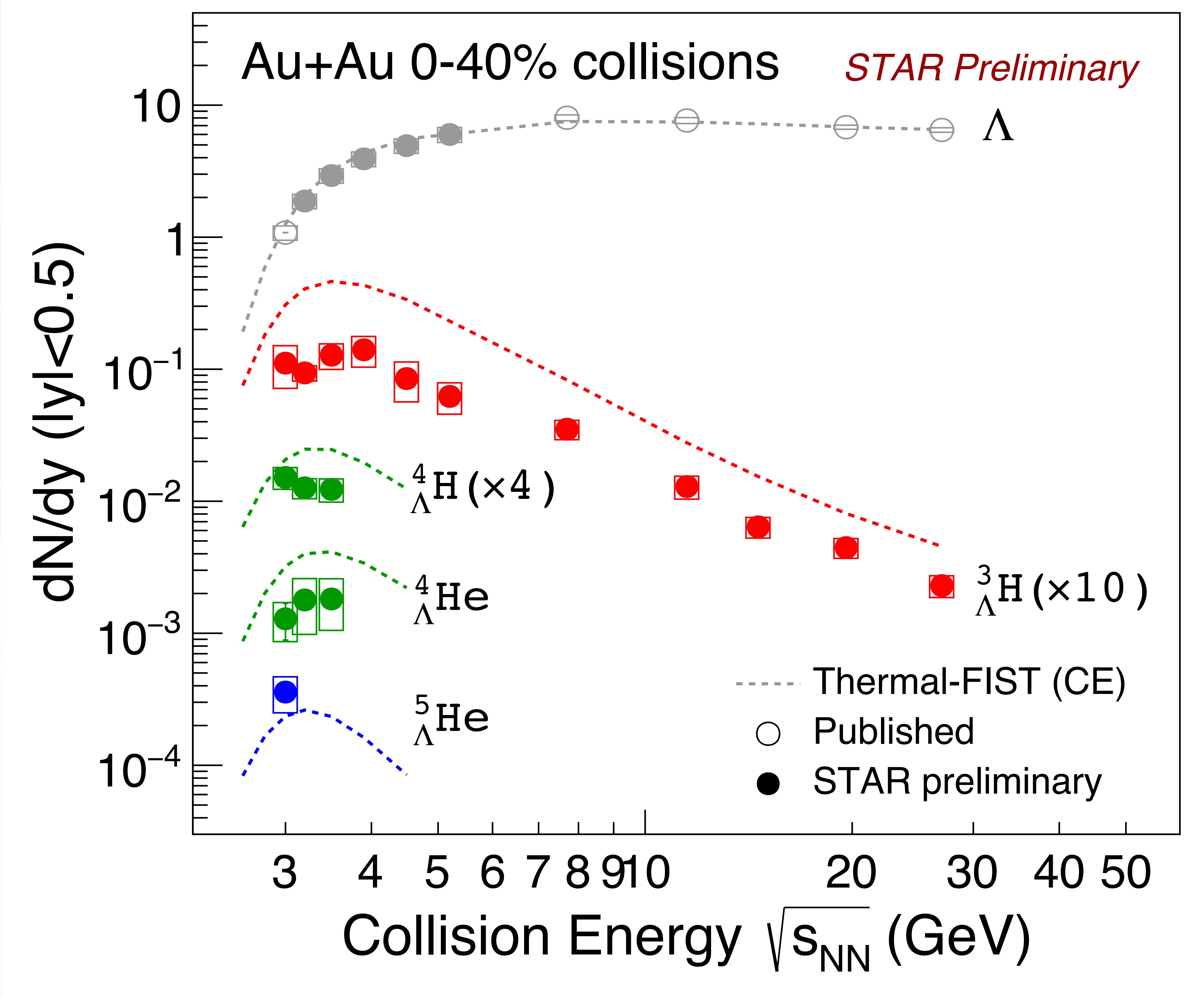
- First hint for the possible feed down from $^{5}_{\Sigma^0}\mathrm{He} \rightarrow {}^{5}_{\Lambda}\mathrm{He} + \gamma$

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

*Feed-down from unstable nuclei

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

Excitation Function



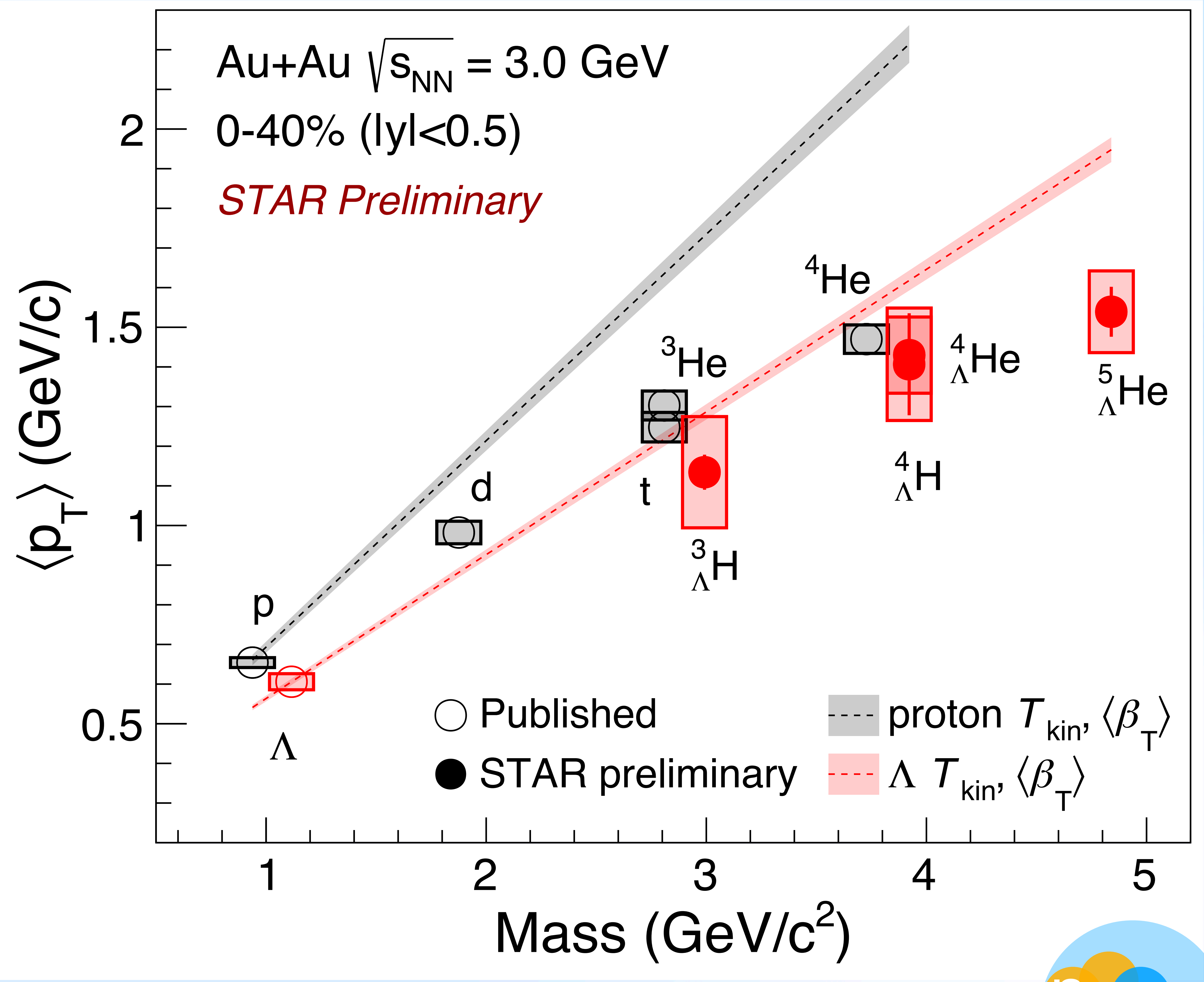
- ${}^{3}_{\Lambda}$H plateaus at $\sqrt{s_{NN}}$ = 3-4 GeV

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

- Across all energies, thermal model describes Λ, overestimates ${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H, and ${}^{4}_{\Lambda}$He, slightly underestimates ${}^{5}_{\Lambda}$He
  - Thermal model includes all unstable nuclei feed down, except ${}^{5}_{\Sigma^0}$He

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

Mean Transverse Momentum at 3 GeV



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

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 predictions using p(Λ) freeze-out parameters

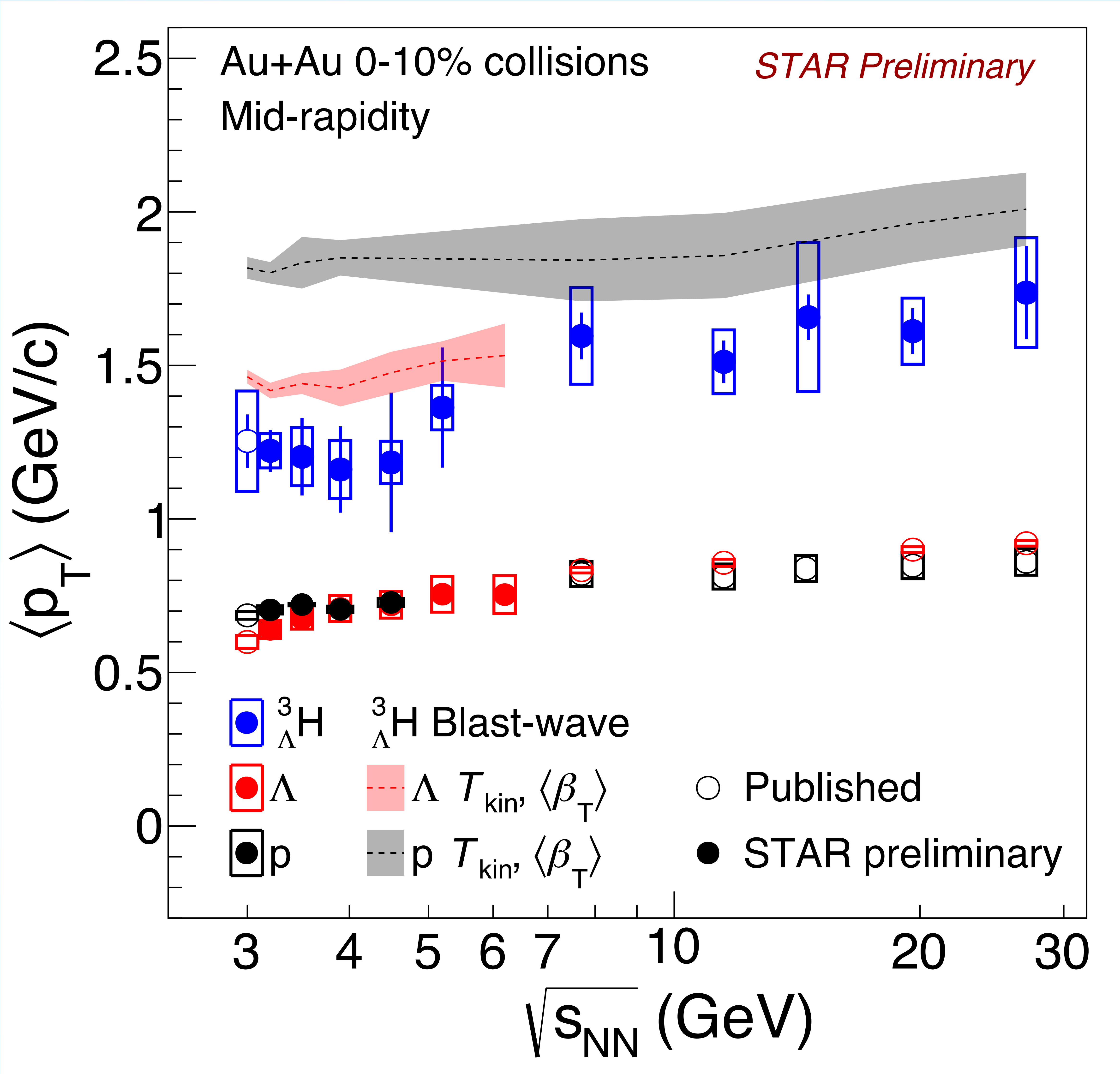
E. Schnedermann et al., PRC 48, 2462 (1993)
ALICE, PLB 794, 50–63 (2019)

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

See talk by Hongcan Li (8 Apr 2025, 16:10)

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

Mean Transverse Momentum v.s. Collision Energy



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

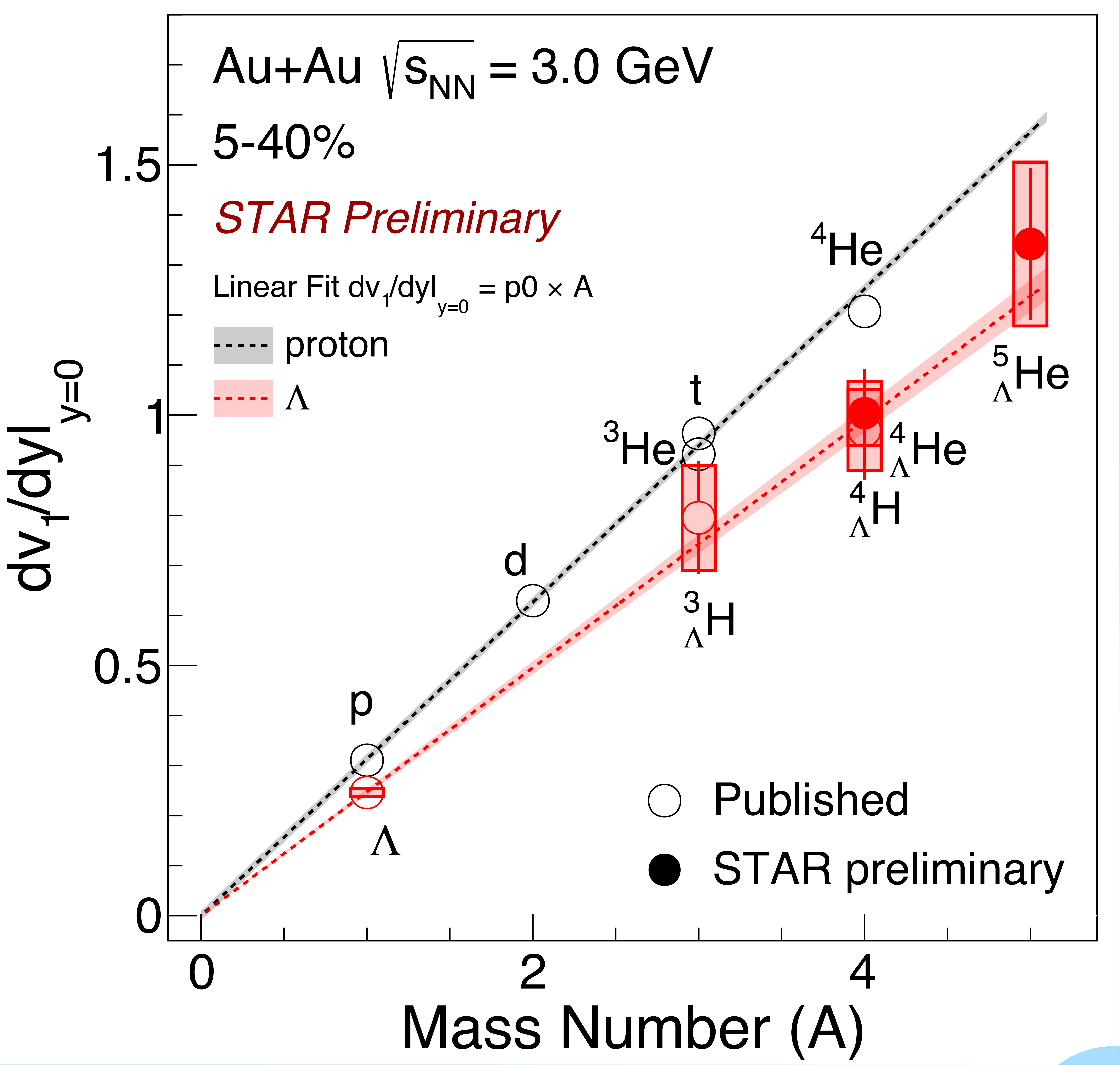
- At $\sqrt{s_{NN}} \geq 7.7$ GeV, $^{3}_{\Lambda}$H $\langle p_T \rangle$ tends to approach the blast-wave prediction with proton freeze-out parameters
  - May be due to increasing effective volume for coalescence with increasing energy

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

- Noticeable change between 4.5 and 7.7 GeV

Directed Flow at 3 GeV

See poster by Junyi Han (ID: 725)



- 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 ($^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H, $^{4}_{\Lambda}$He, and $^{5}_{\Lambda}$He) 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. Mean transverse momentum tends to be lower than hydrodynamic-inspired blast-wave model expectation at high baryon density
  3. Directed flow follow atomic mass number *A* scaling

All measurements consistently point to the coalescence production mechanism for light nuclei and hypernuclei

Outlook:

- BES-II 3 GeV 2B data: more precise measurements for hypernuclei

Thank you for your attention!