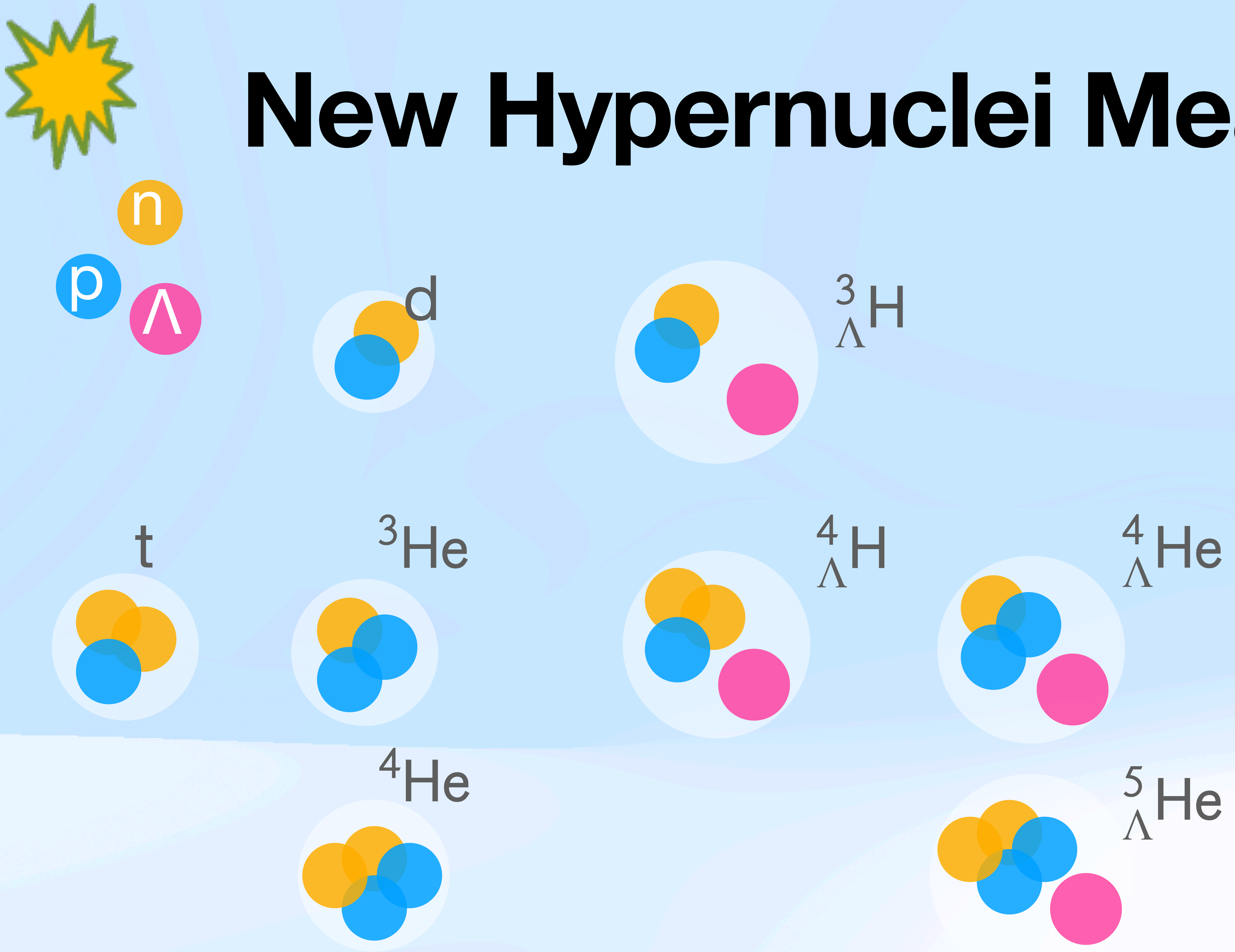
New Hypernuclei Measurements from STAR



Outline

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

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Quark Matter 2025, Frankfurt, Germany

FAIR GSI

CENTRAL CHINA NORMAL UNIVERSITY

QM 25

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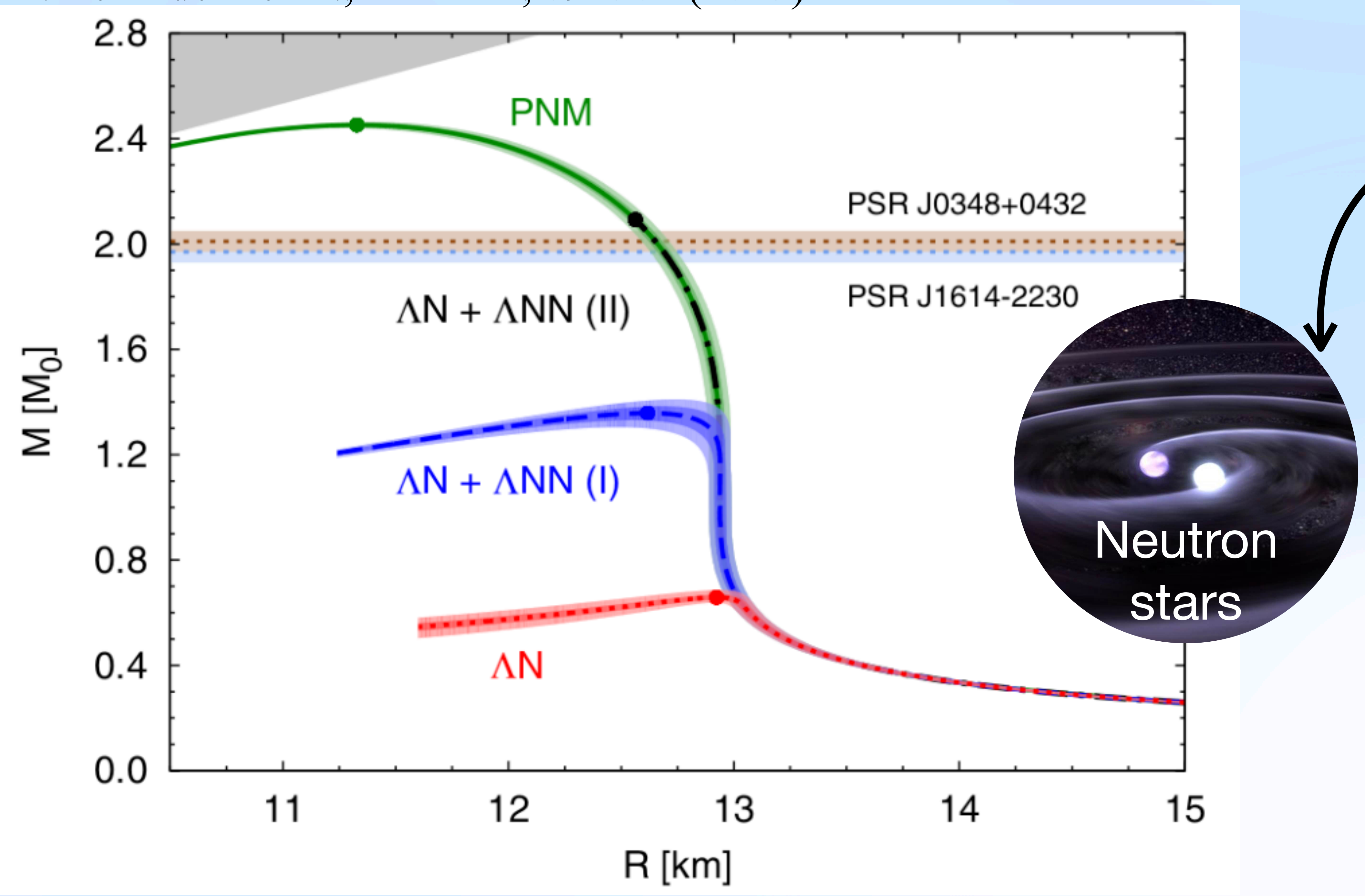
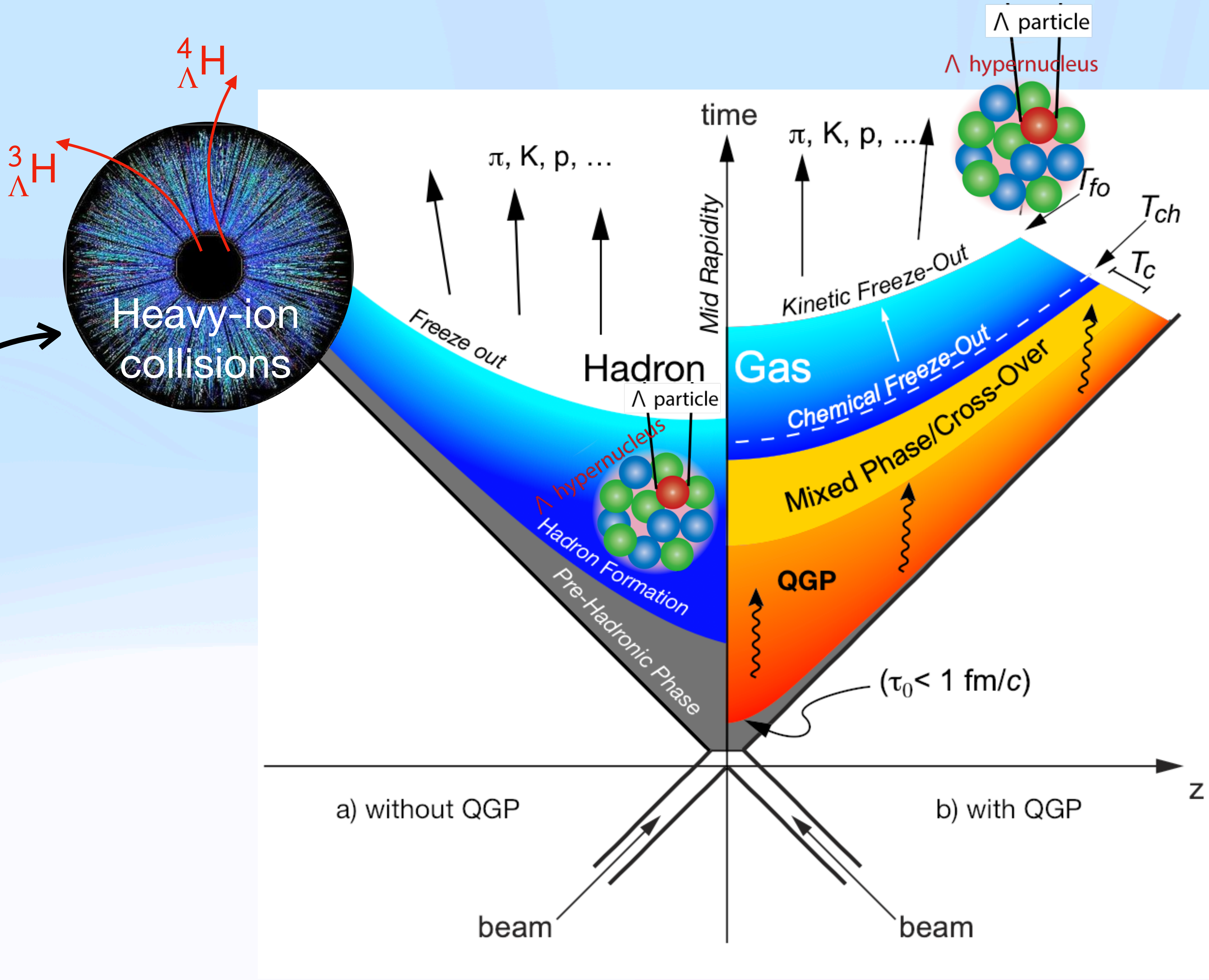
STAR 25 YEARS

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

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

Need a solid understanding in ***hypernuclei production mechanisms*** *before we can use them as probes for medium properties*

Hypernuclei Production Mechanisms

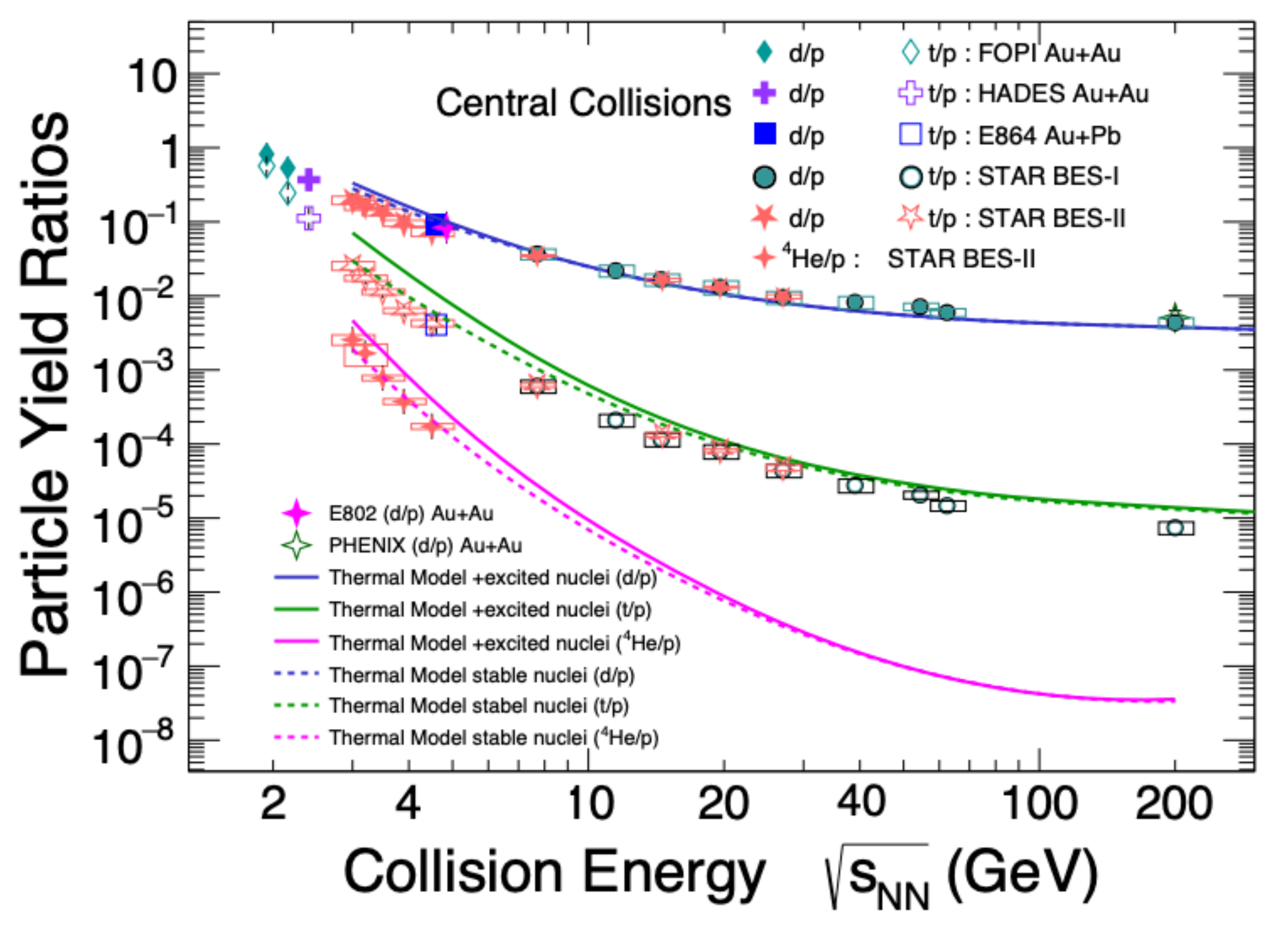
See poster by Liubing Chen (xx/xx)

When are nuclei produced in a heavy-ion collision?

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

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

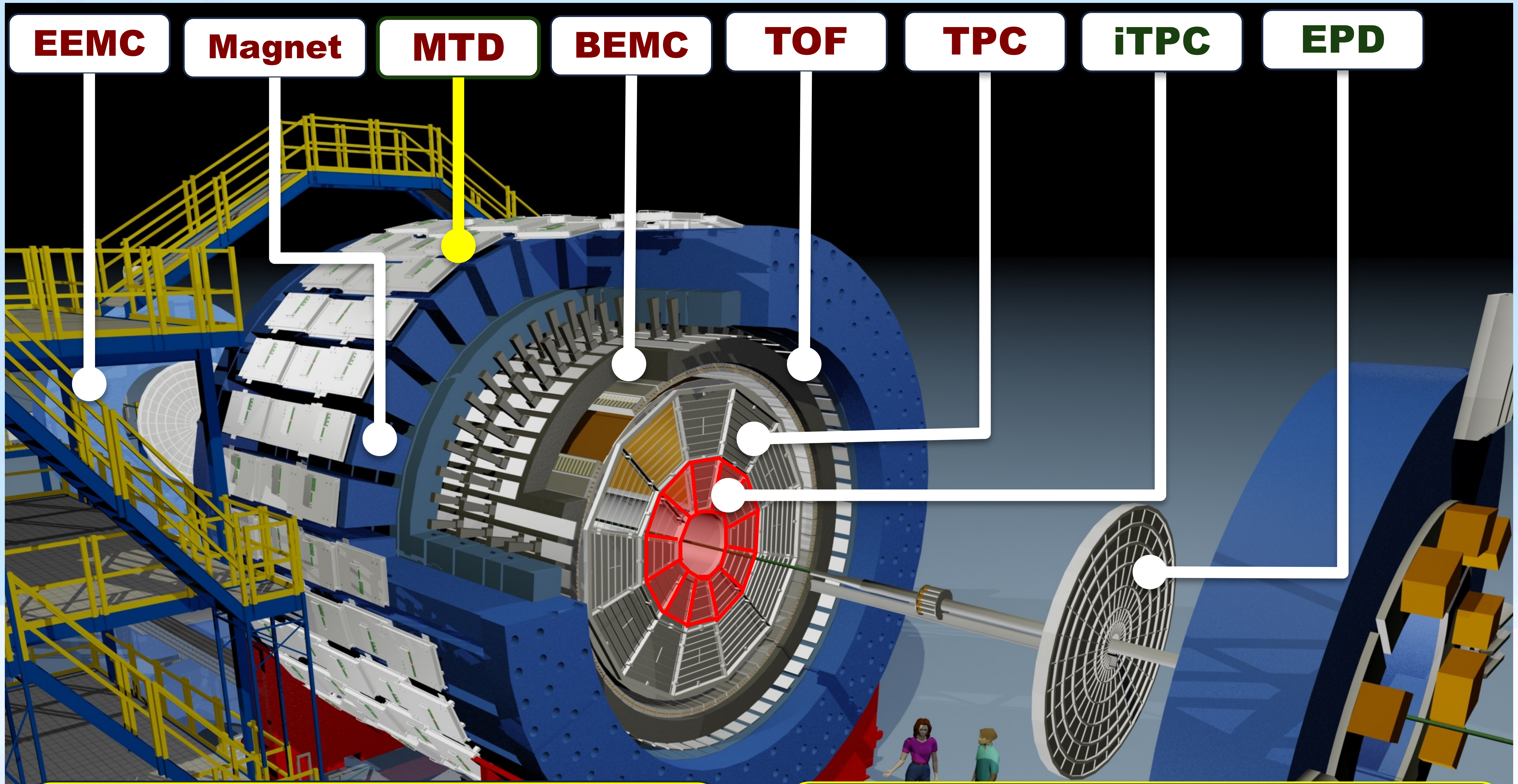
What have we learnt from light nuclei production?



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

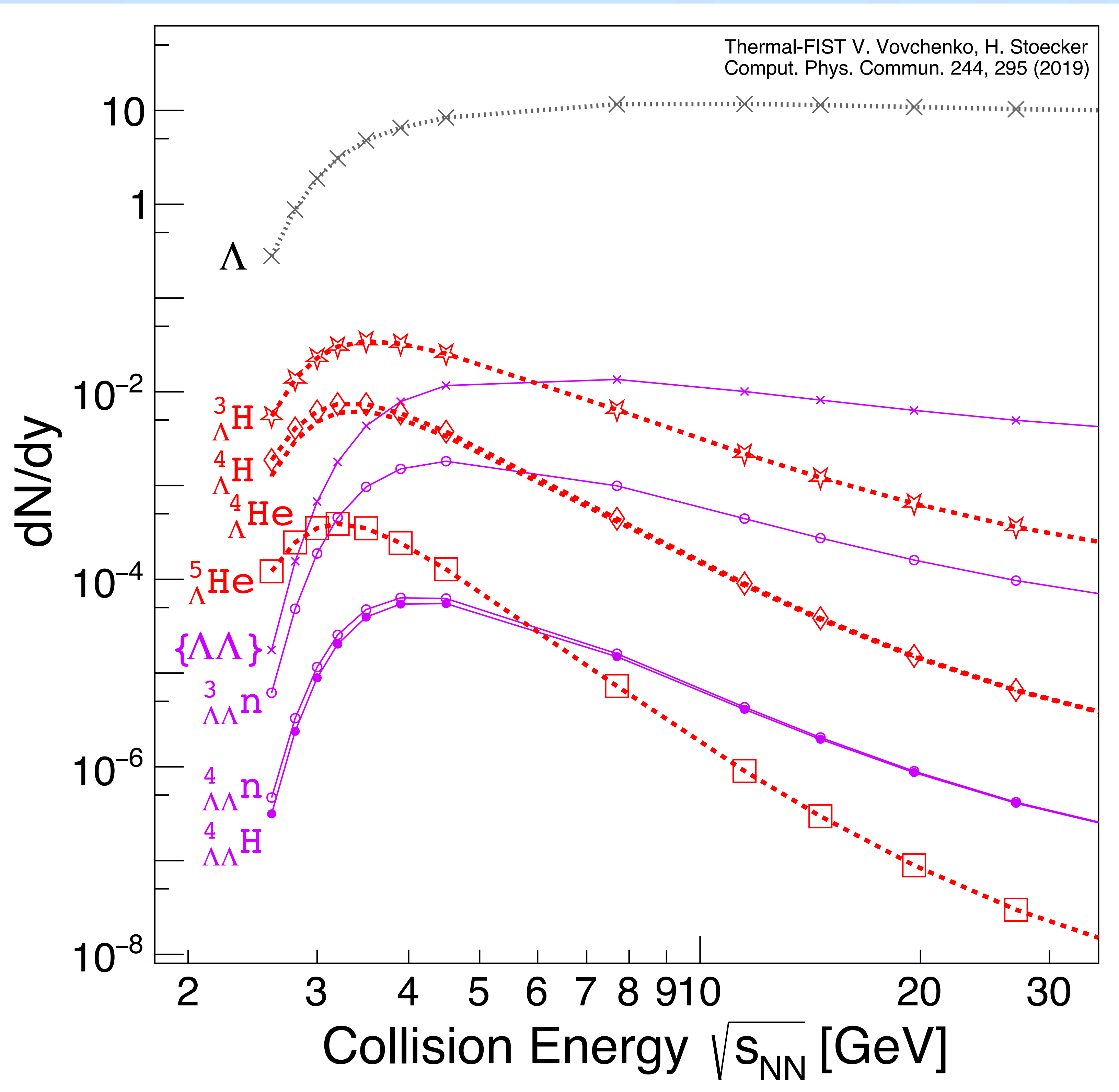
Recent nuclei measurements poses challenges for thermal model

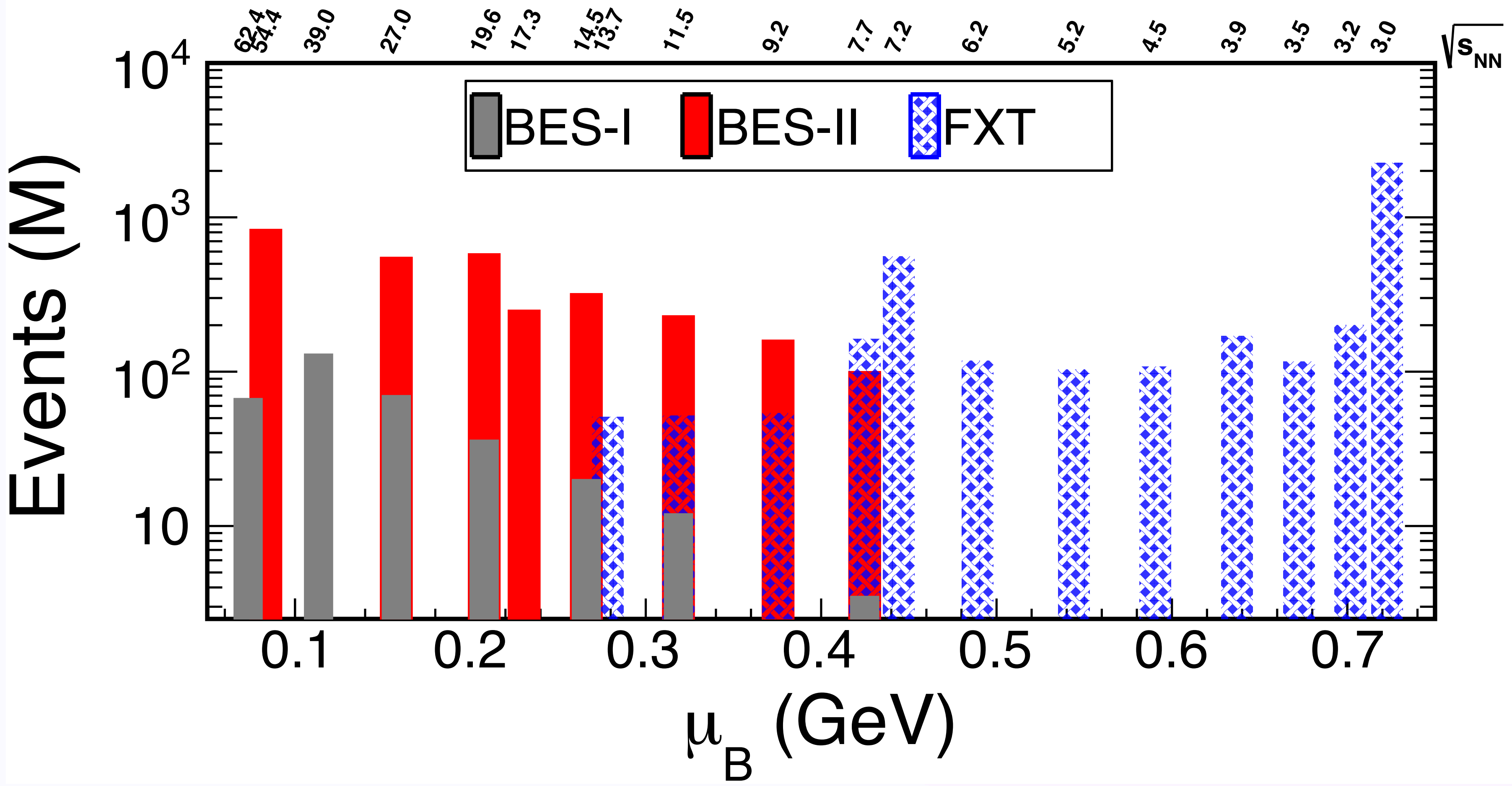
STAR and Beam Energy Scan



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

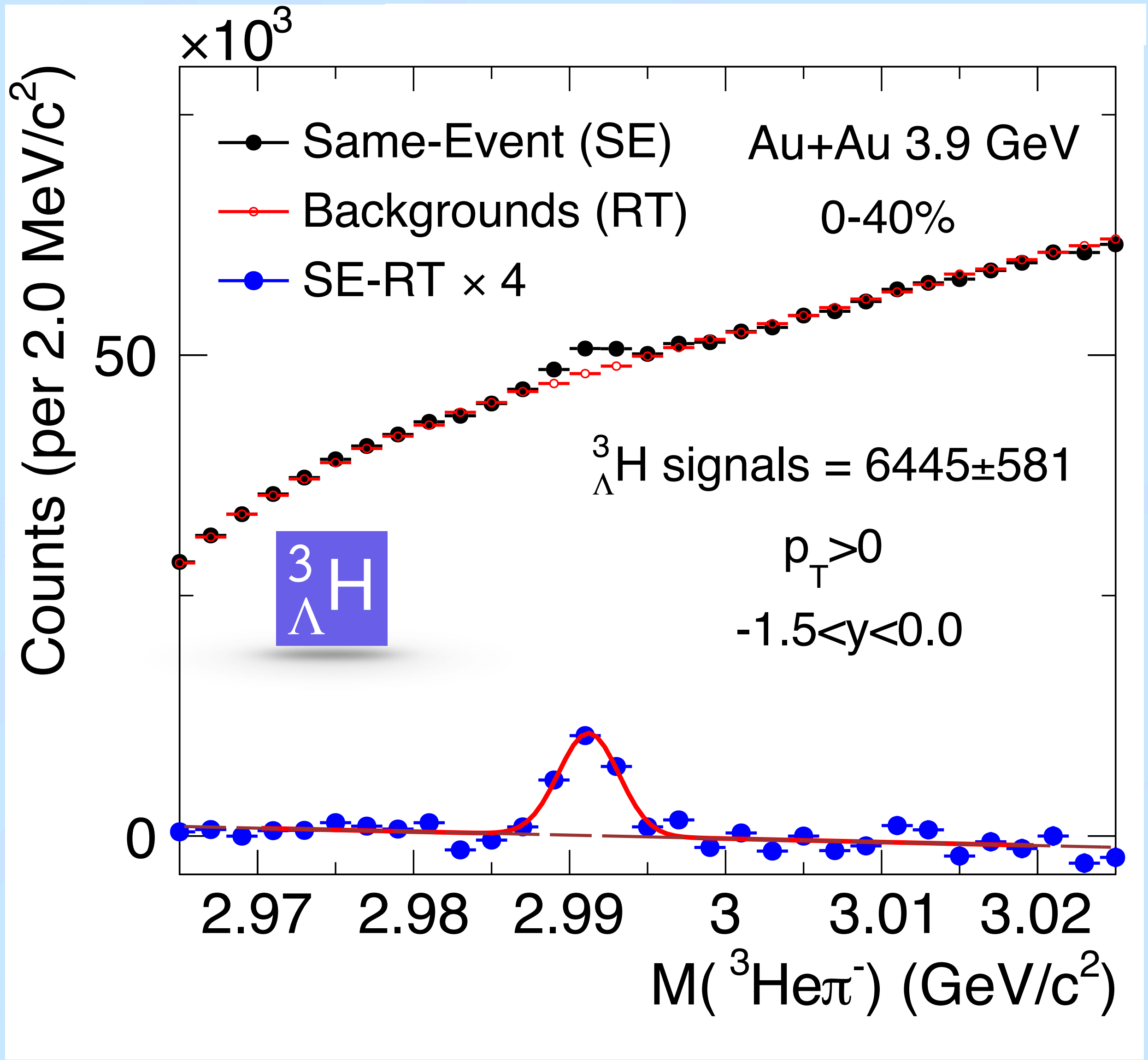
- **iTPC, EPD & eTOF** upgrades completed
- All are in data-taking for BES-II program

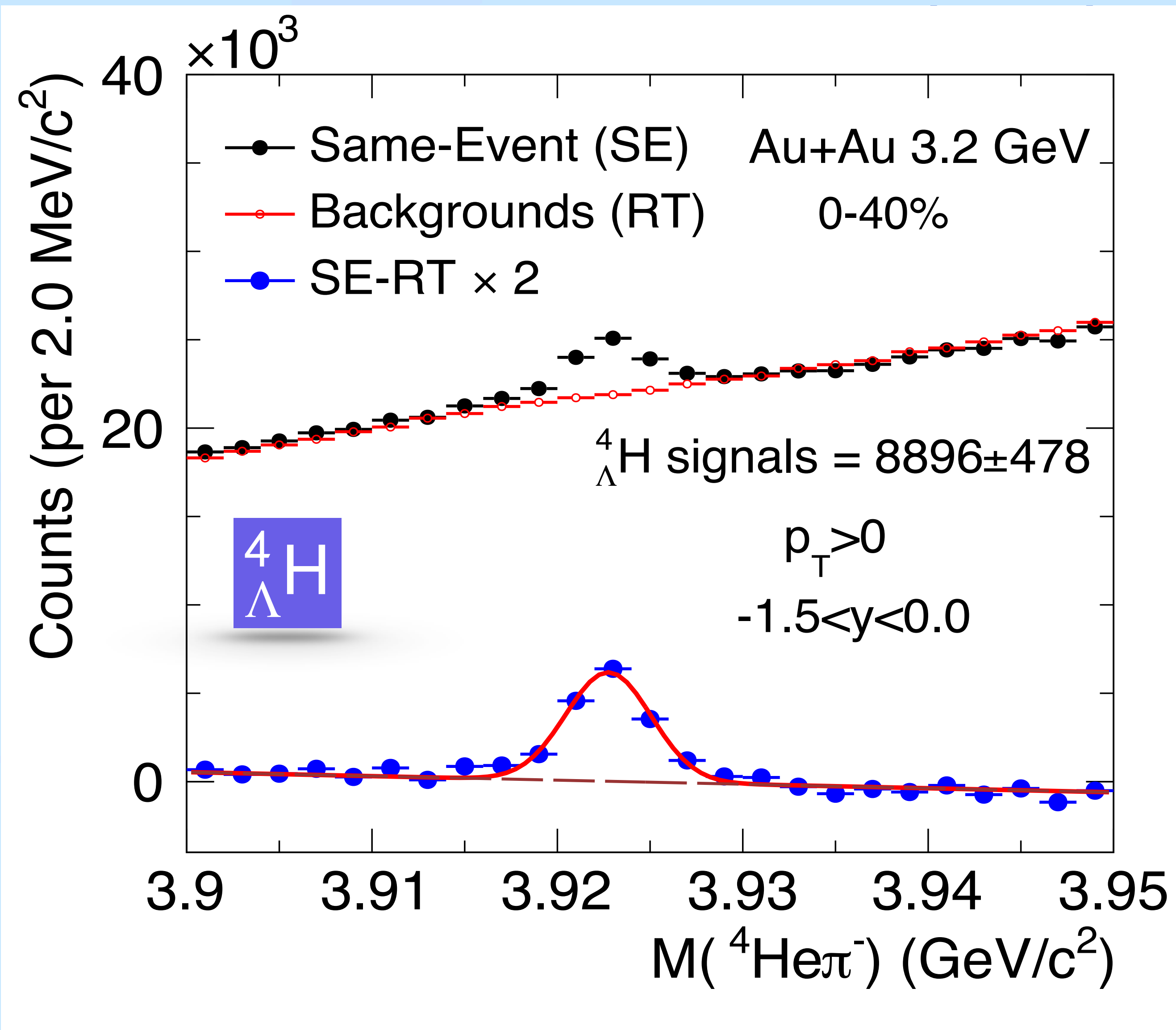


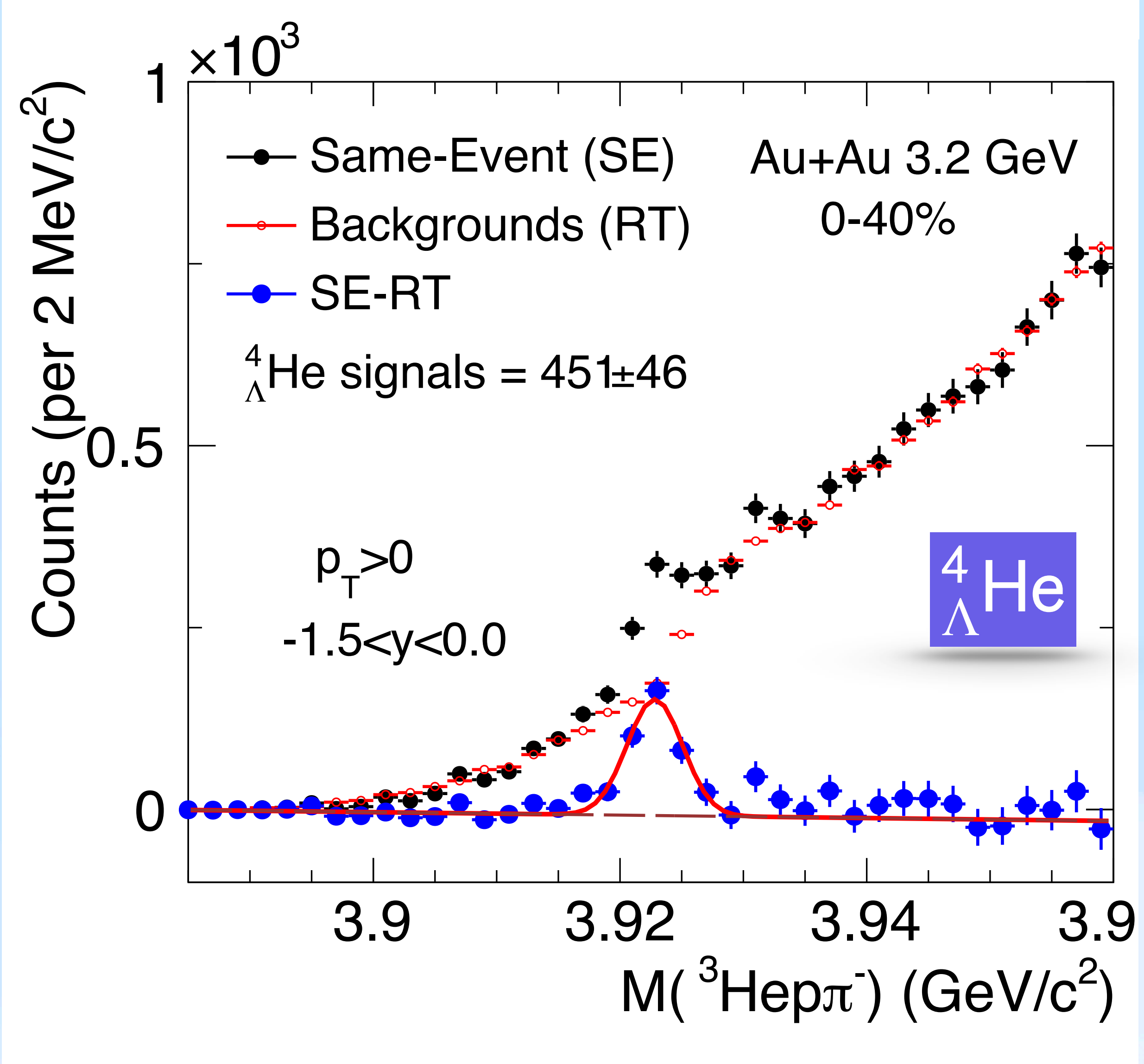


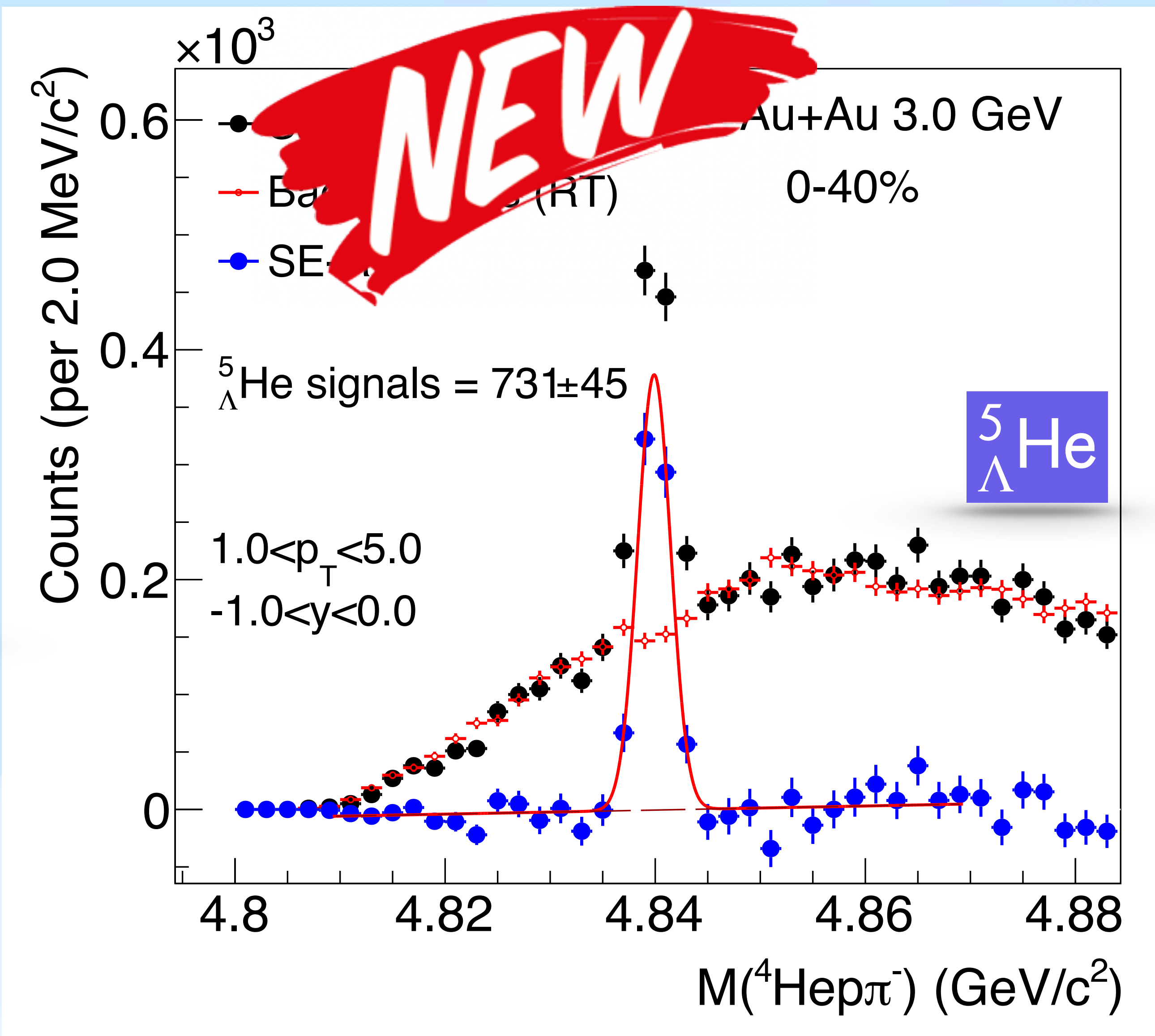
- RHIC BES-II offers great opportunity for hypernuclei measurements

Hypernuclei Reconstruction







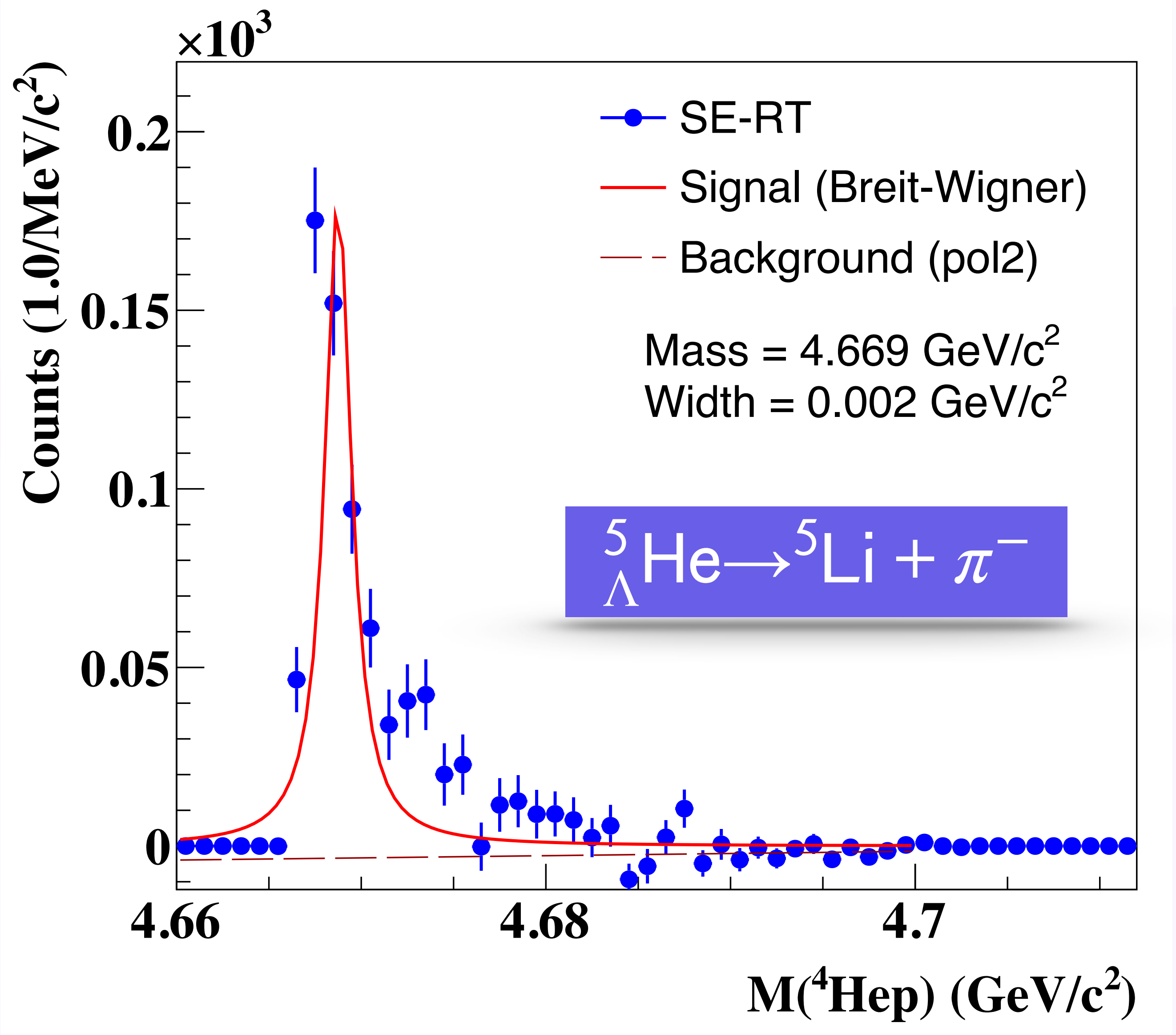


- Hypernuclei are reconstructed using the following decay channels:

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

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

- 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

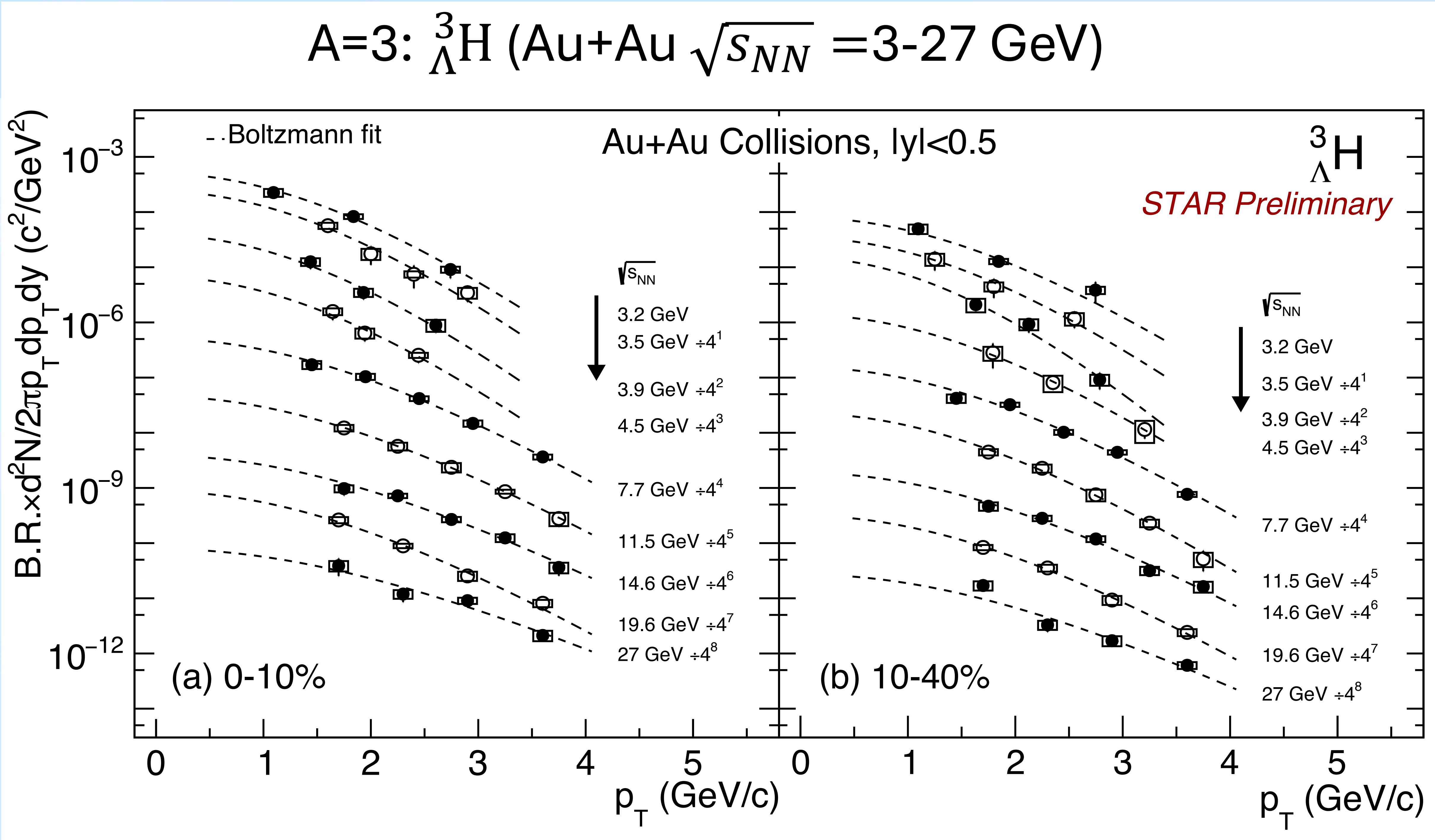


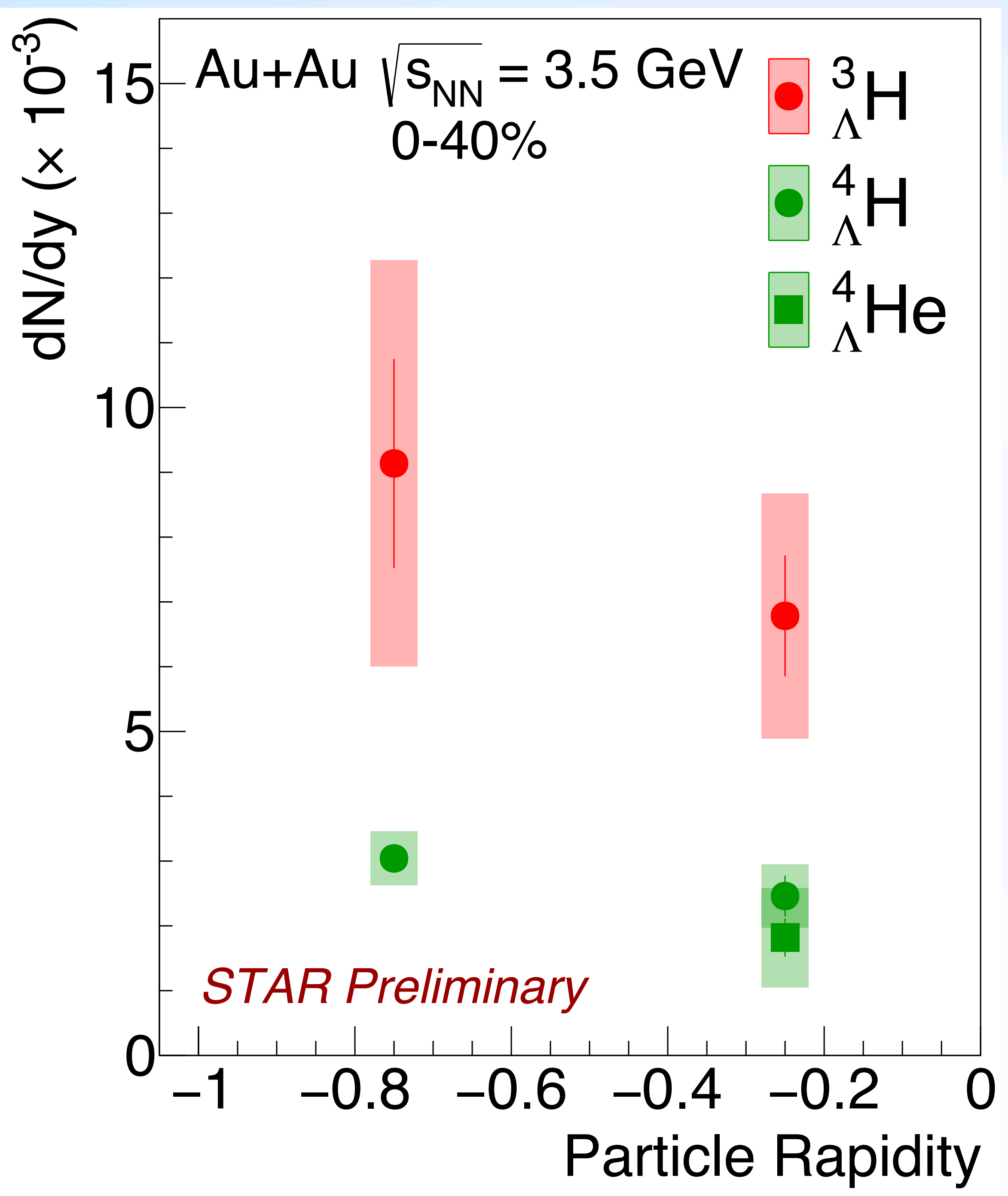
Hypernuclei p_T Spectra and Rapidity

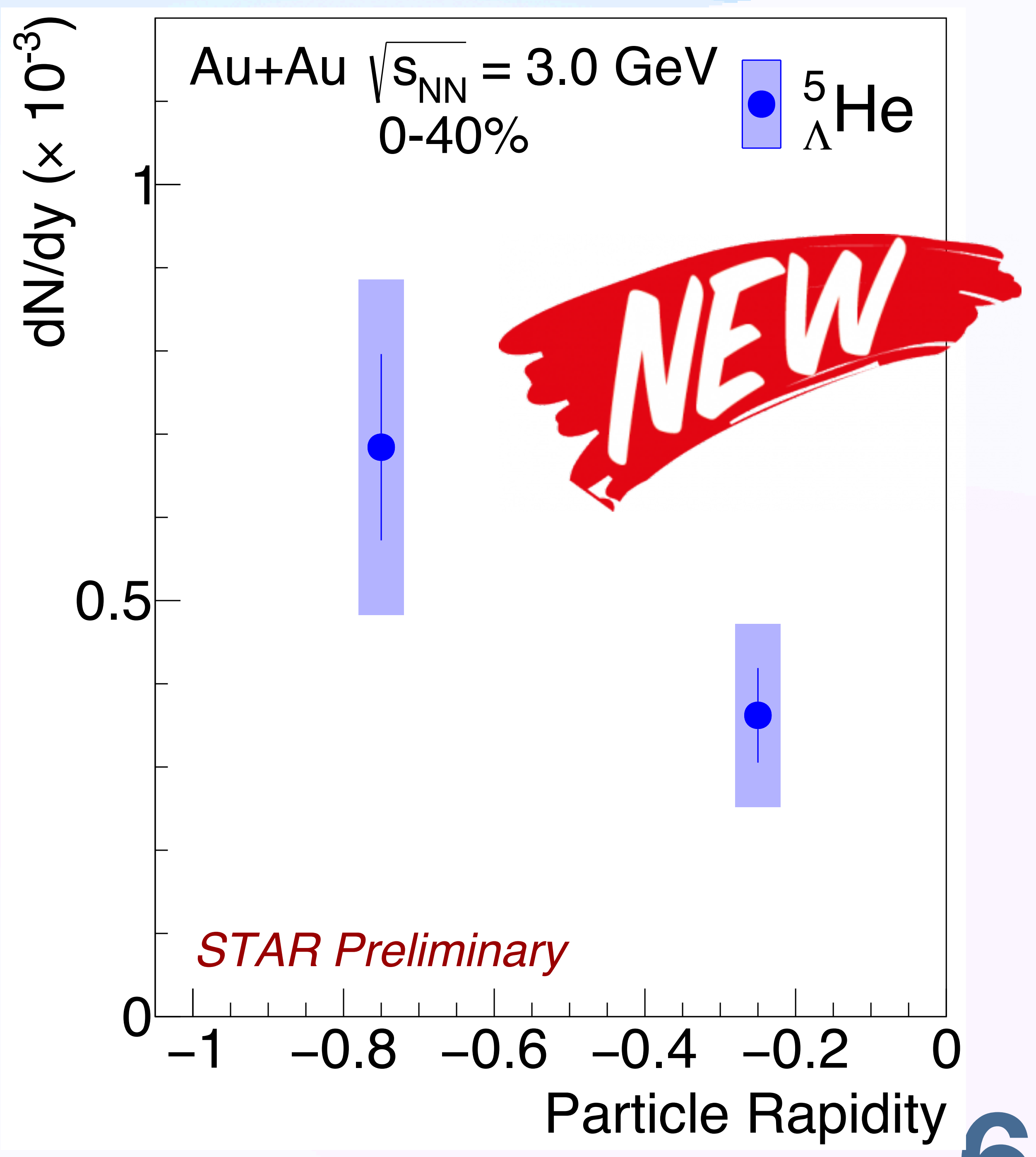
- Measurements cover different energies
  - ${}^{3}_{\Lambda}H$ in Au+Au collisions at **3-27** GeV, Au+Au collisions at **200 GeV**
  - ${}^{4}_{\Lambda}H$, ${}^{4}_{\Lambda}He$ in Au+Au collisions at **3-3.5 GeV**
  - ${}^{5}_{\Lambda}He$ in Au+Au collisions at **3 GeV**

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

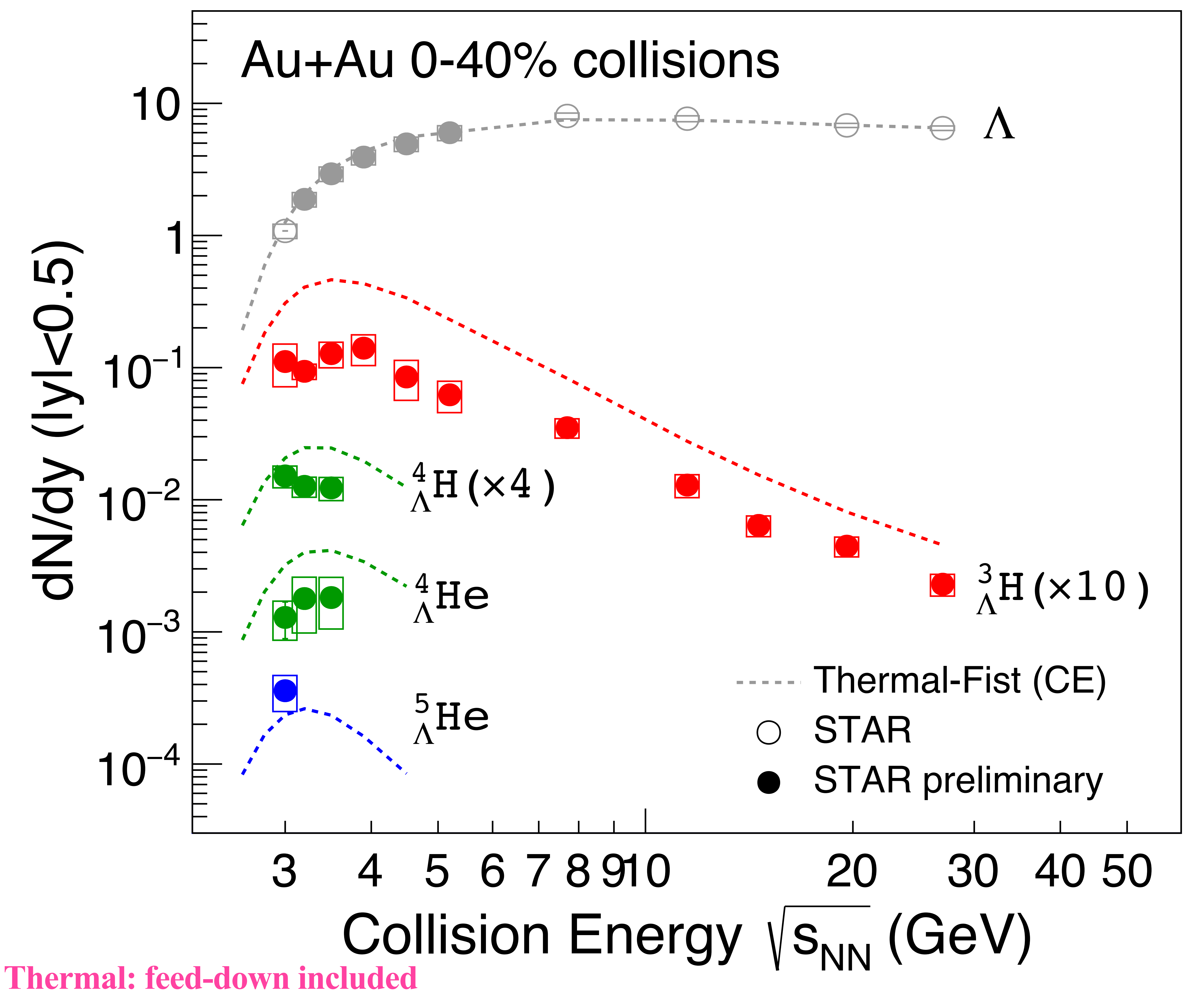
Spectator matter matters at target rapidity







Excitation Function



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

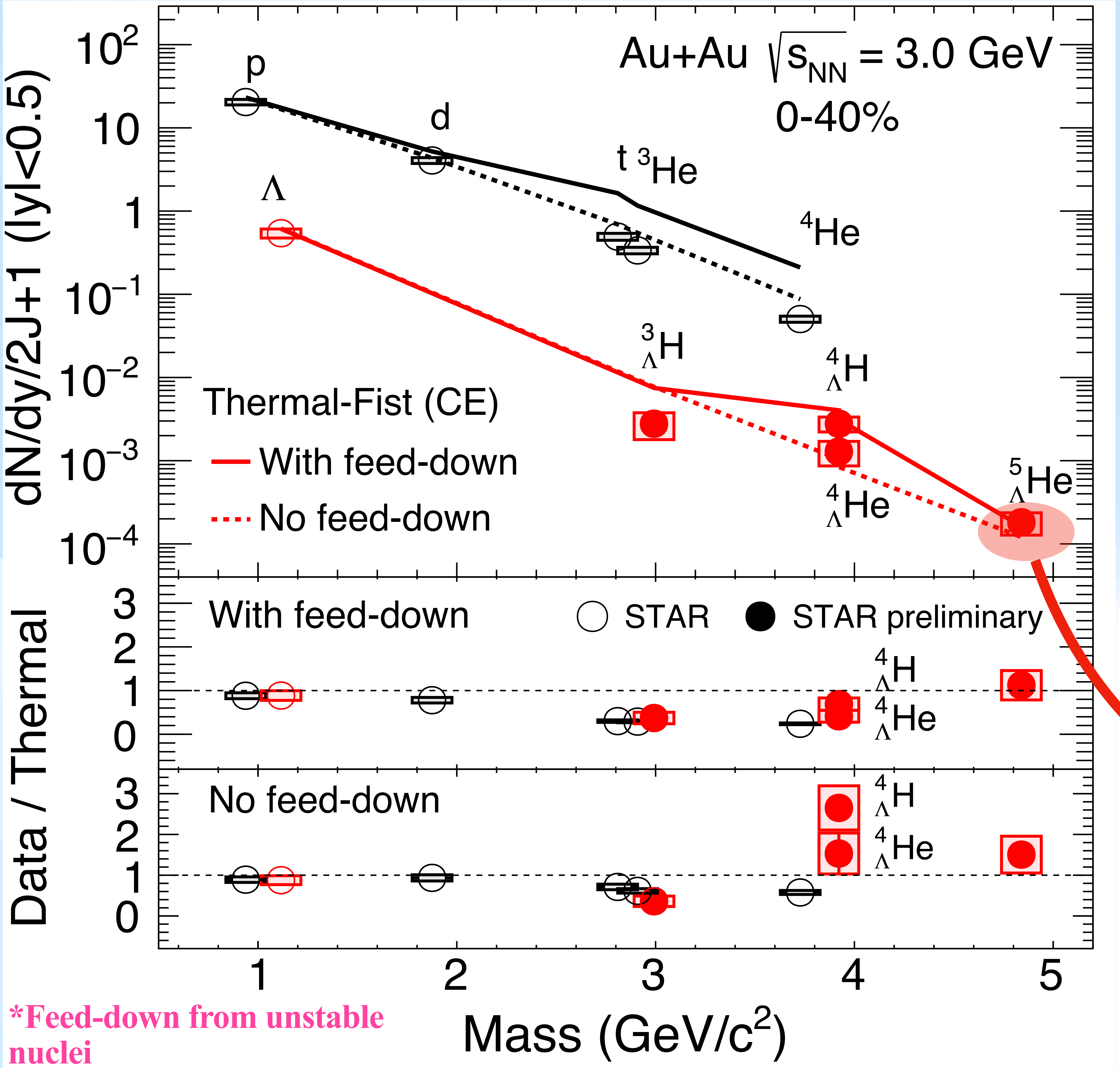
Interplay between increasing baryon production and stronger strangeness canonical suppression towards low energies

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** ${}^{5}_{\Lambda}He$

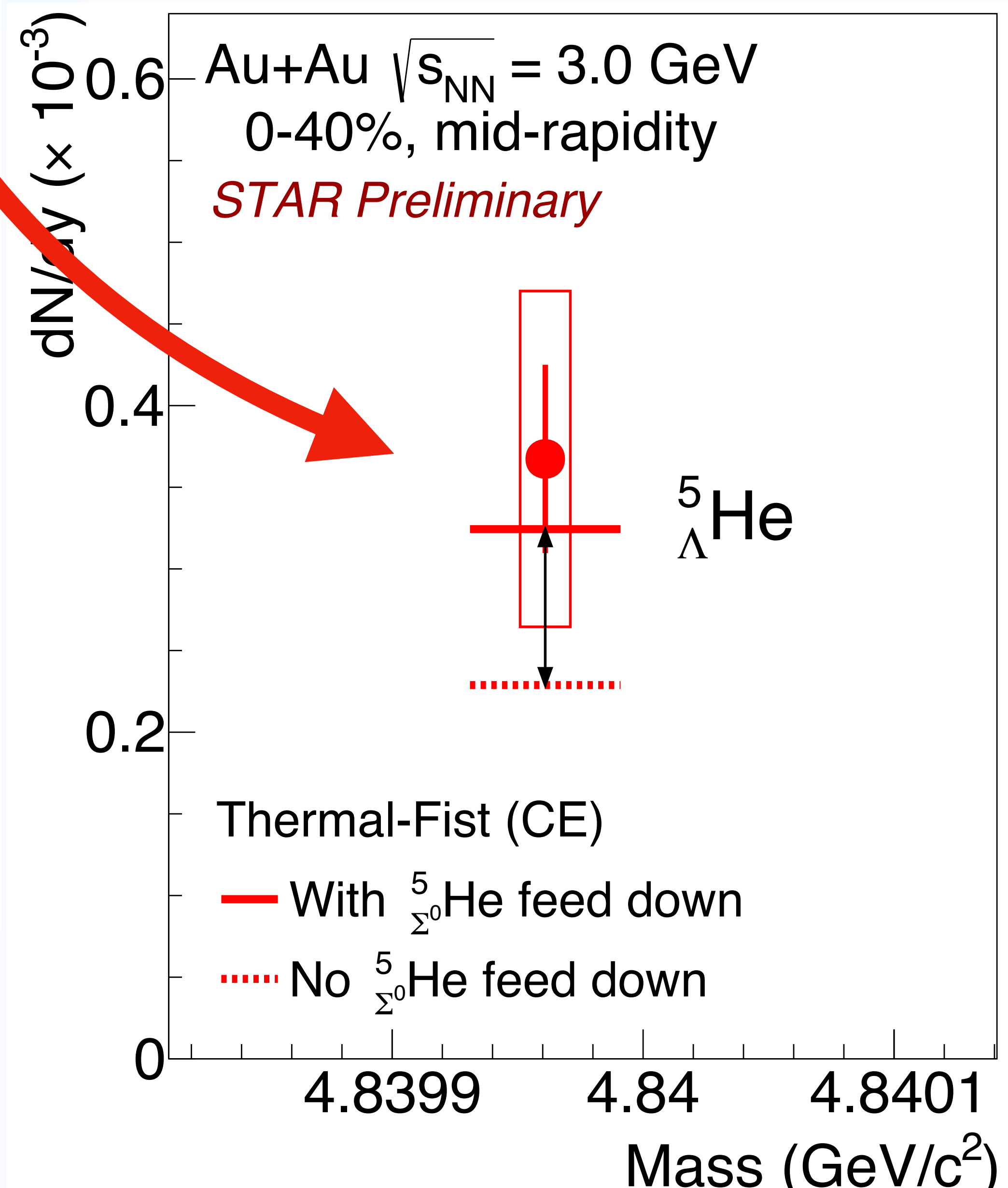
STAR, Phys.Rev.Lett. 128(2022)20, 202301
V. Vovchenko et al., PRC 93, 064906 (2016)

Comparison to Thermal Model at 3 GeV



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

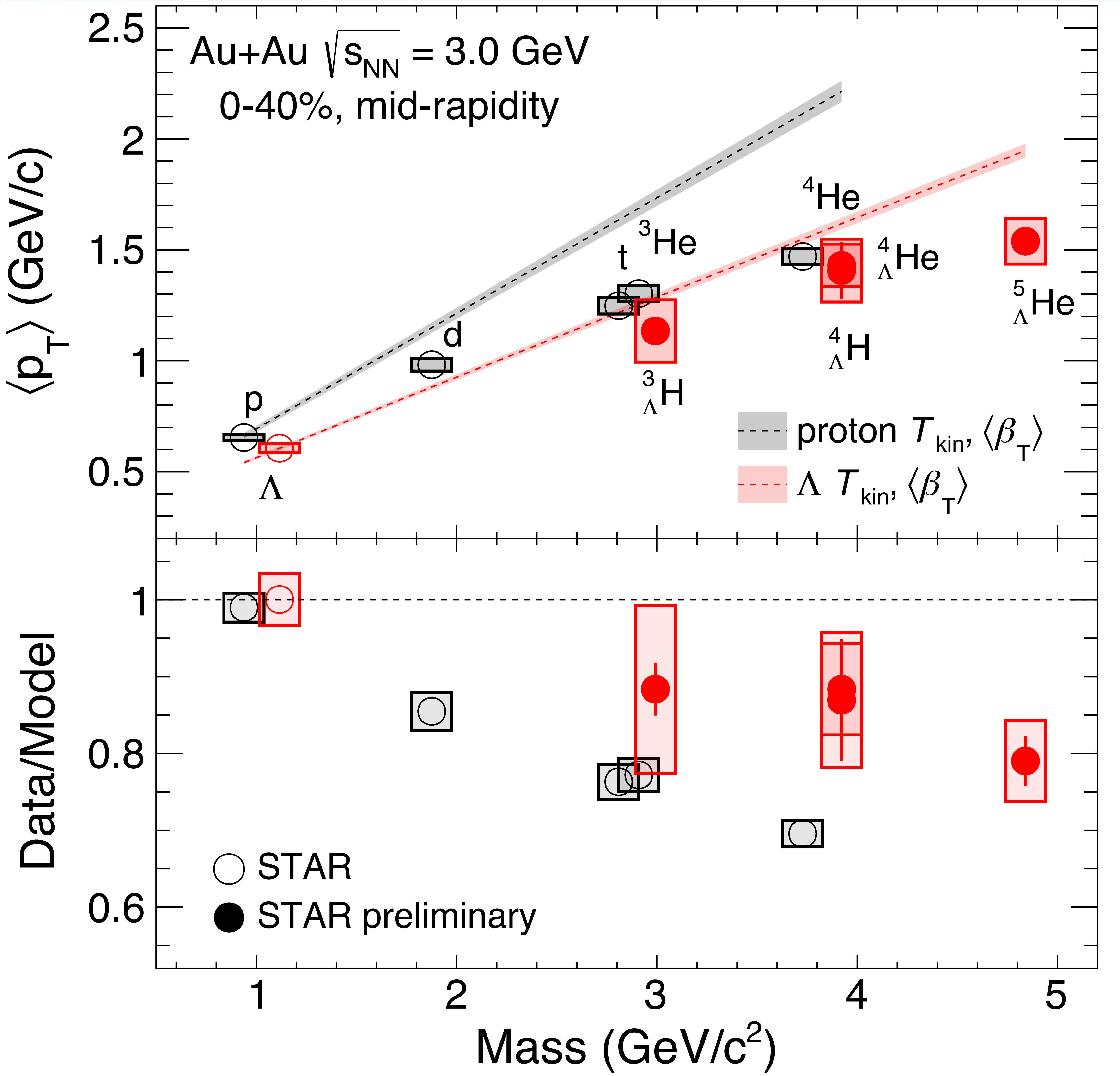
- Thermal model predict approx. exponential dependence of yields/(2J+1) vs A
- Light nuclei overestimated by thermal with feed-down from unstable nuclei
- Evidence of the formation of $^{4}_{\Lambda}H$ and $^{4}_{\Lambda}He$ excited states



- 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}: the 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}

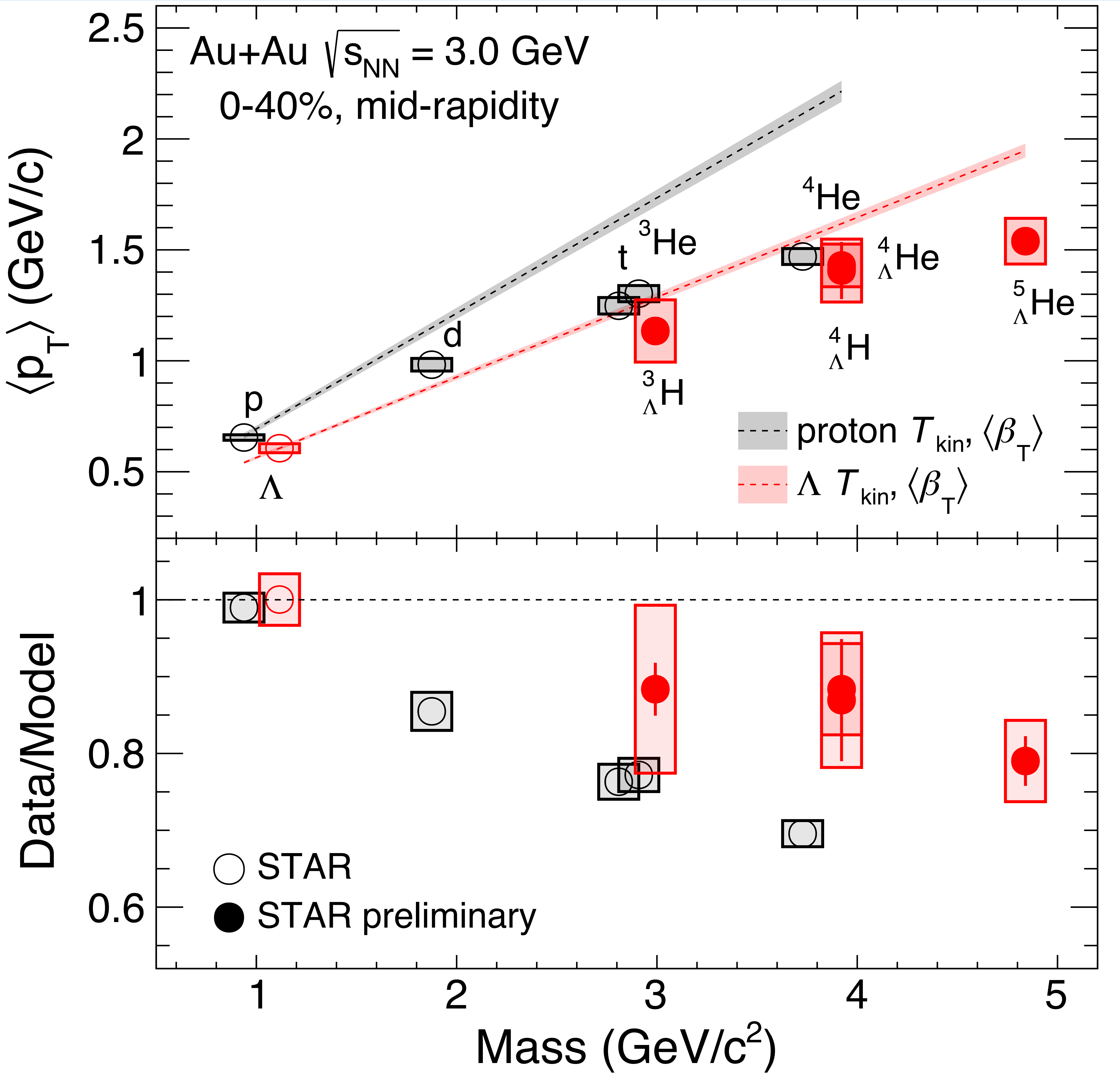
- Vary the mass to construct the p(Λ) lines

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

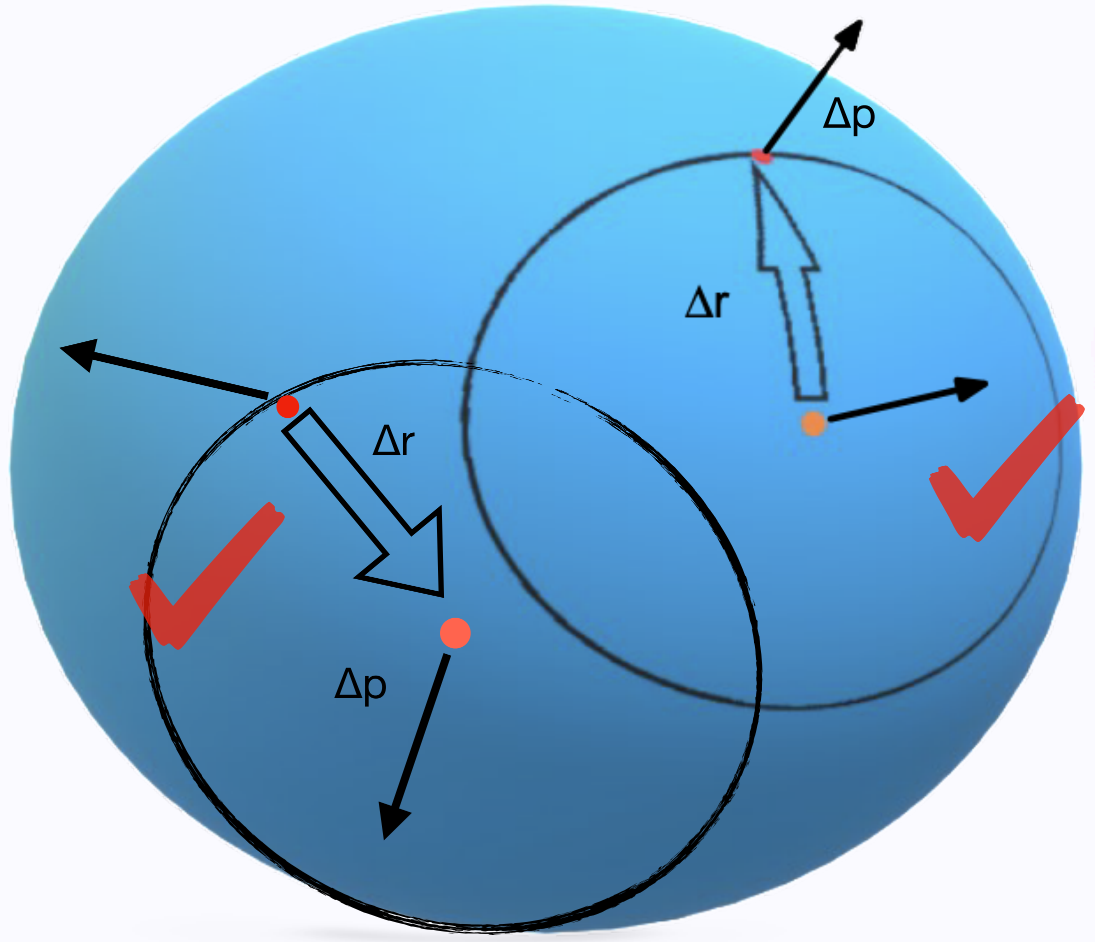


STAR, PRC 110, 054911 (2024)
STAR, PRL 128, 202301 (2022)
STAR, JHEP **2024** (2024) 139

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

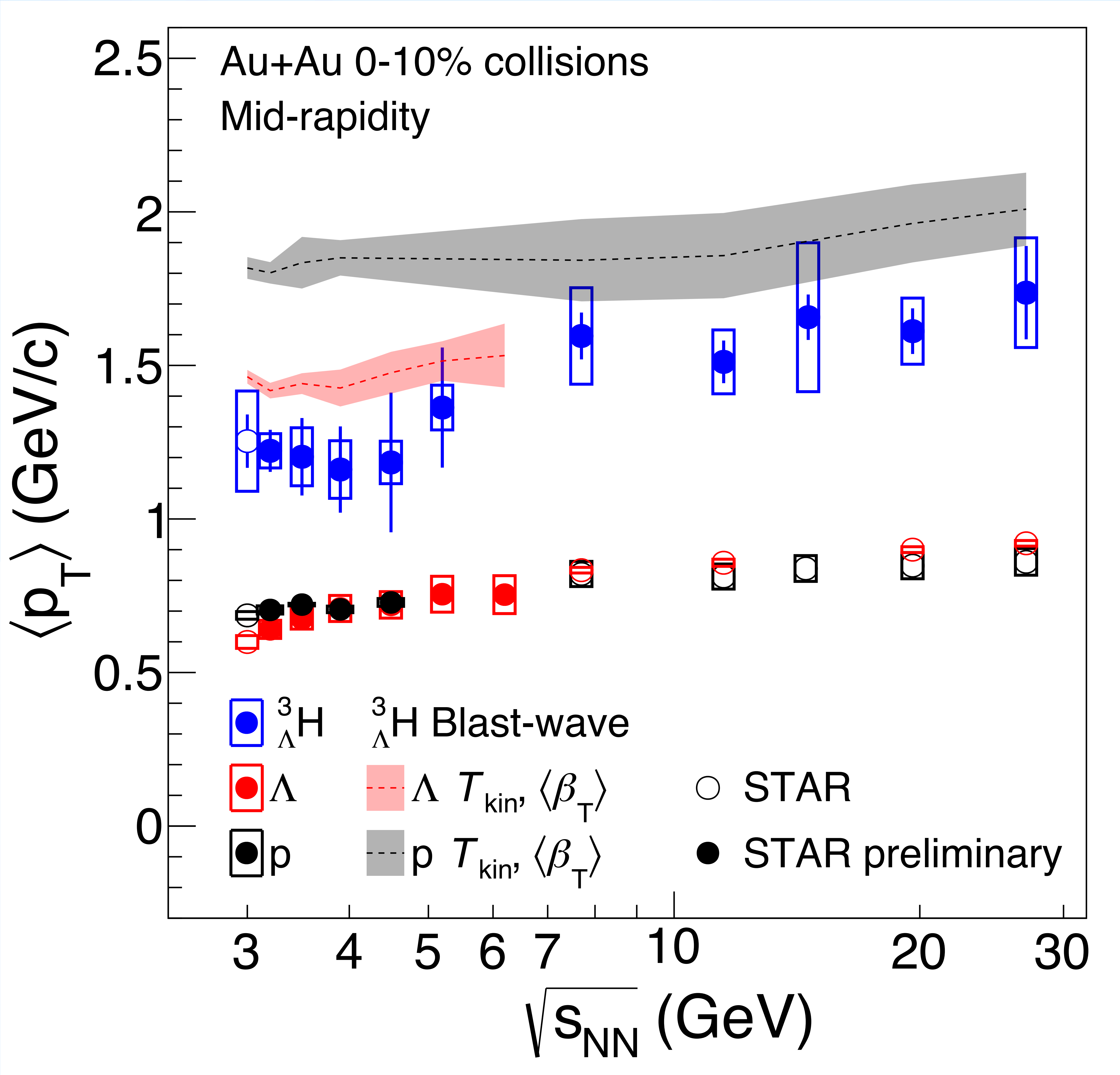
A. I. Sheikh et al., PRC 106, 054907 (2022)



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

T. Reichert, SQM 2022, slides (2022)

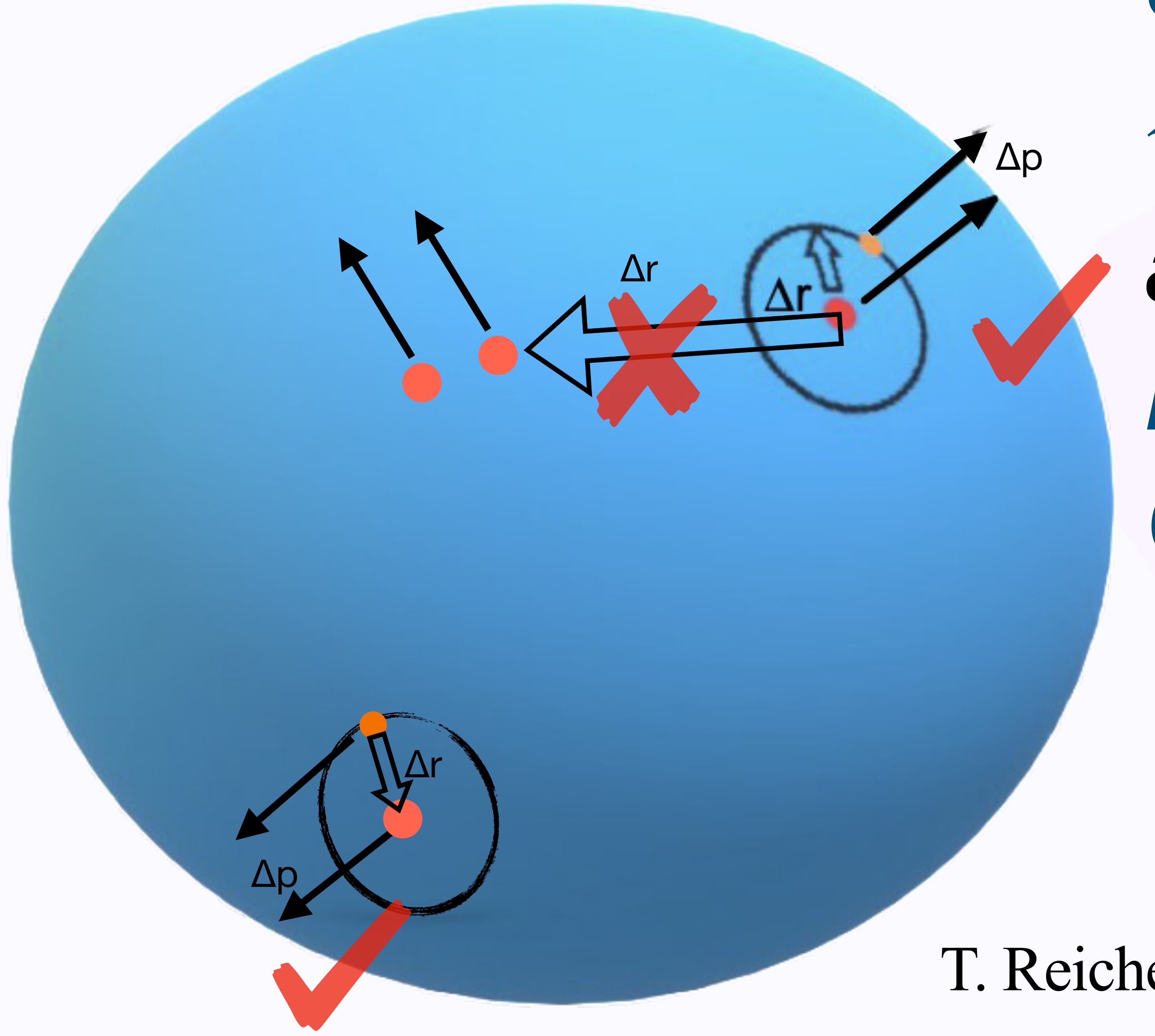
Mean Transverse Momentum v.s. Collision Energy



STAR, PRC 110, 054911 (2024)
STAR, PRL 128, 202301 (2022)
STAR, JHEP **2024** (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
- 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 abrupt change between 4.5 and 7.7 GeV

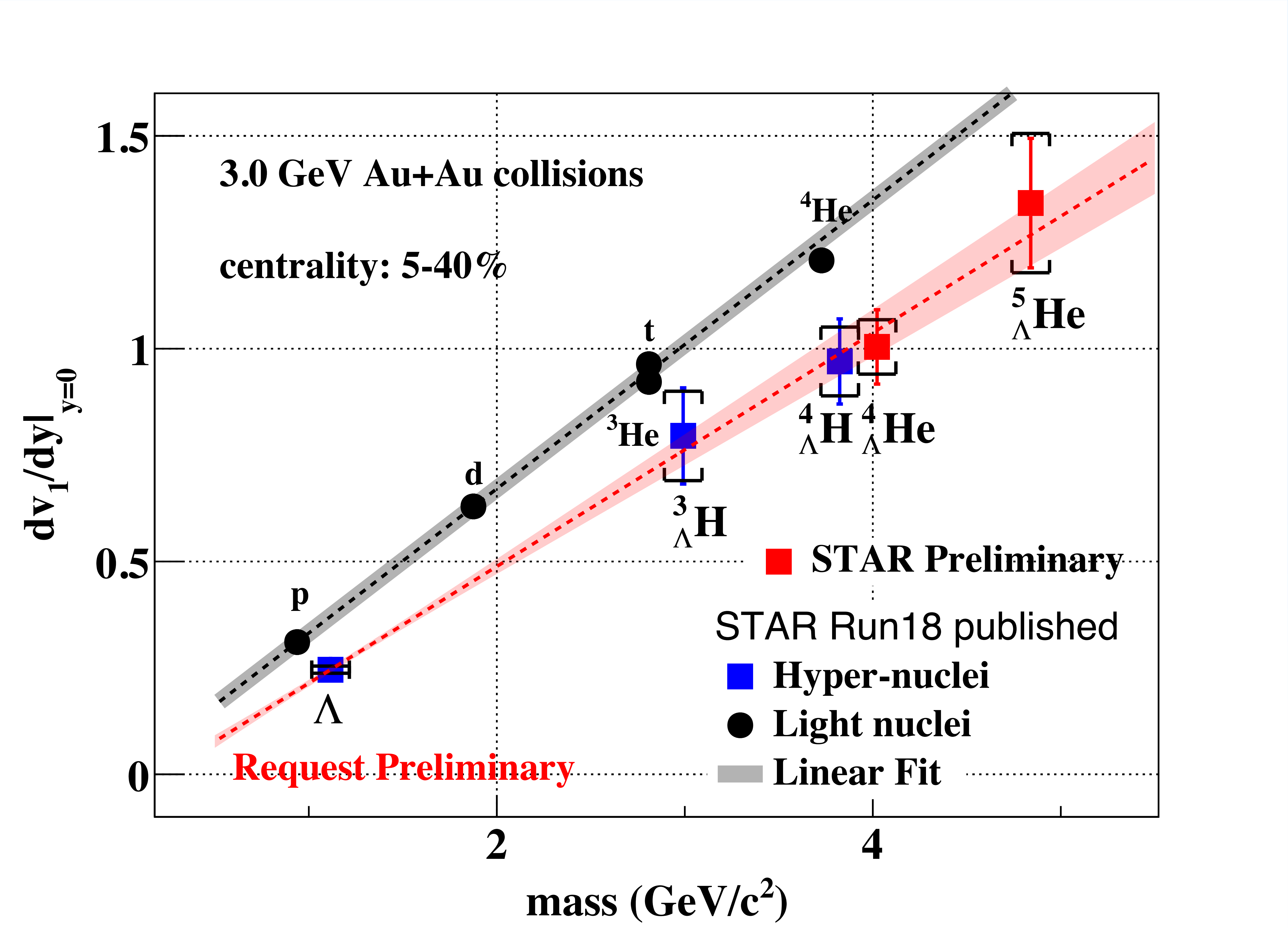


Large effective volume nucleon's *r* and *p* are correlated

T. Reichert, SQM 2022, slides (2022)

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 and RHIC top energy data: more precise measurement, and search for heavier hypernuclei (A > 5), double-Λ hypernuclei

  ➡ Further constrain production mechanism, and YN, YY, YNN interactions