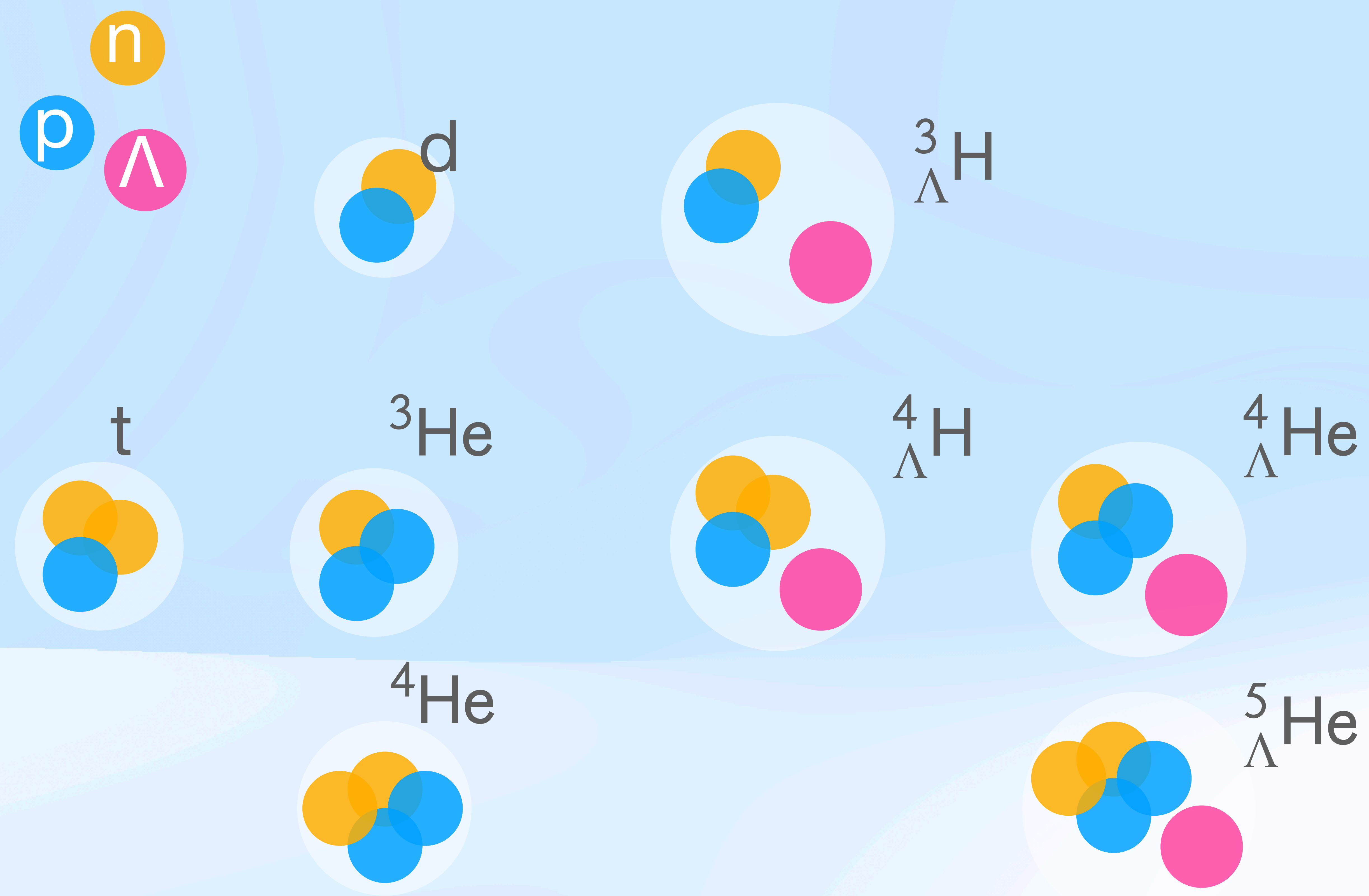
New Hypernuclei Measurements from STAR



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

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CCNU, GSI

Quark Matter 2025, Frankfurt, Germany

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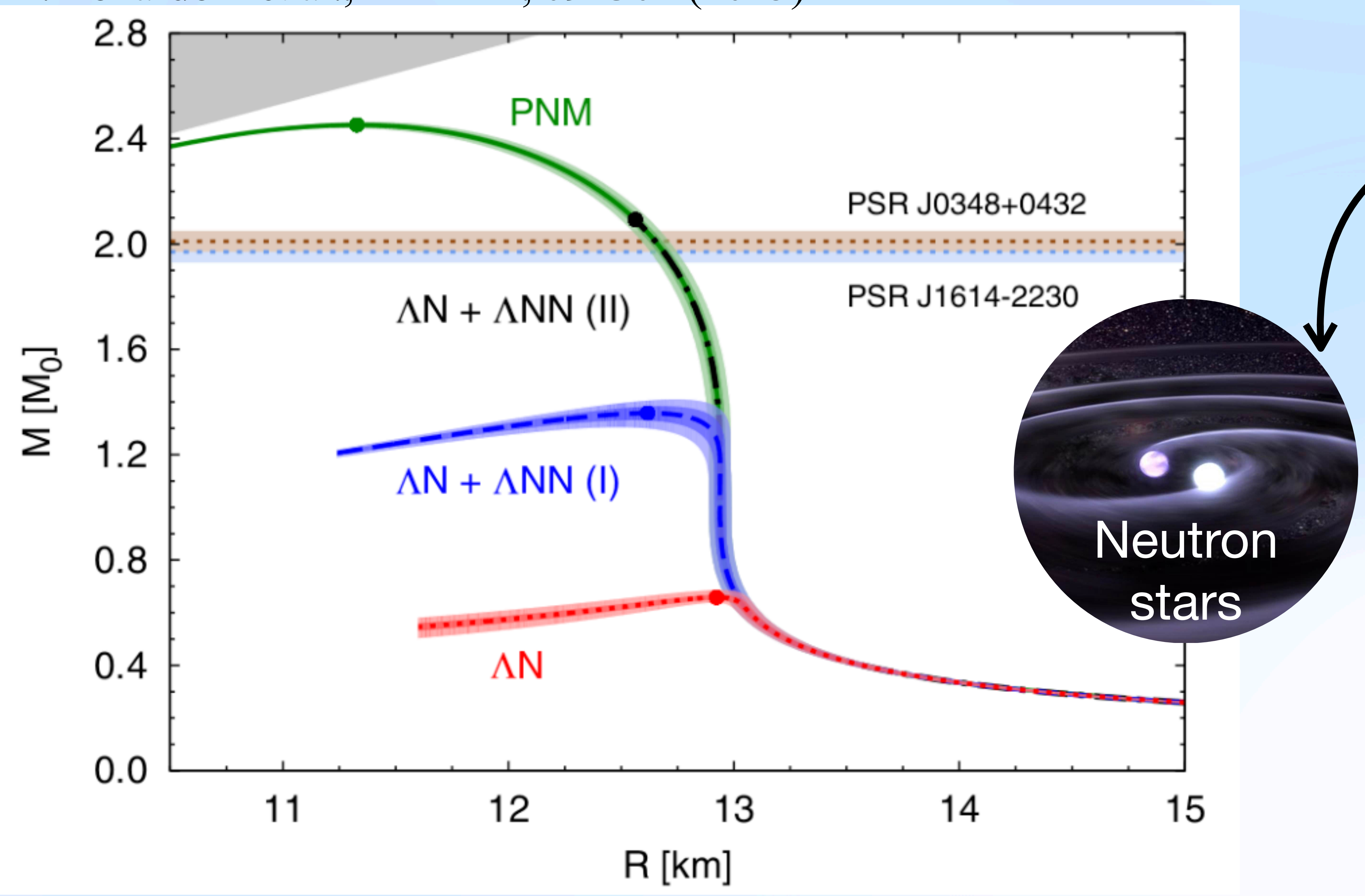
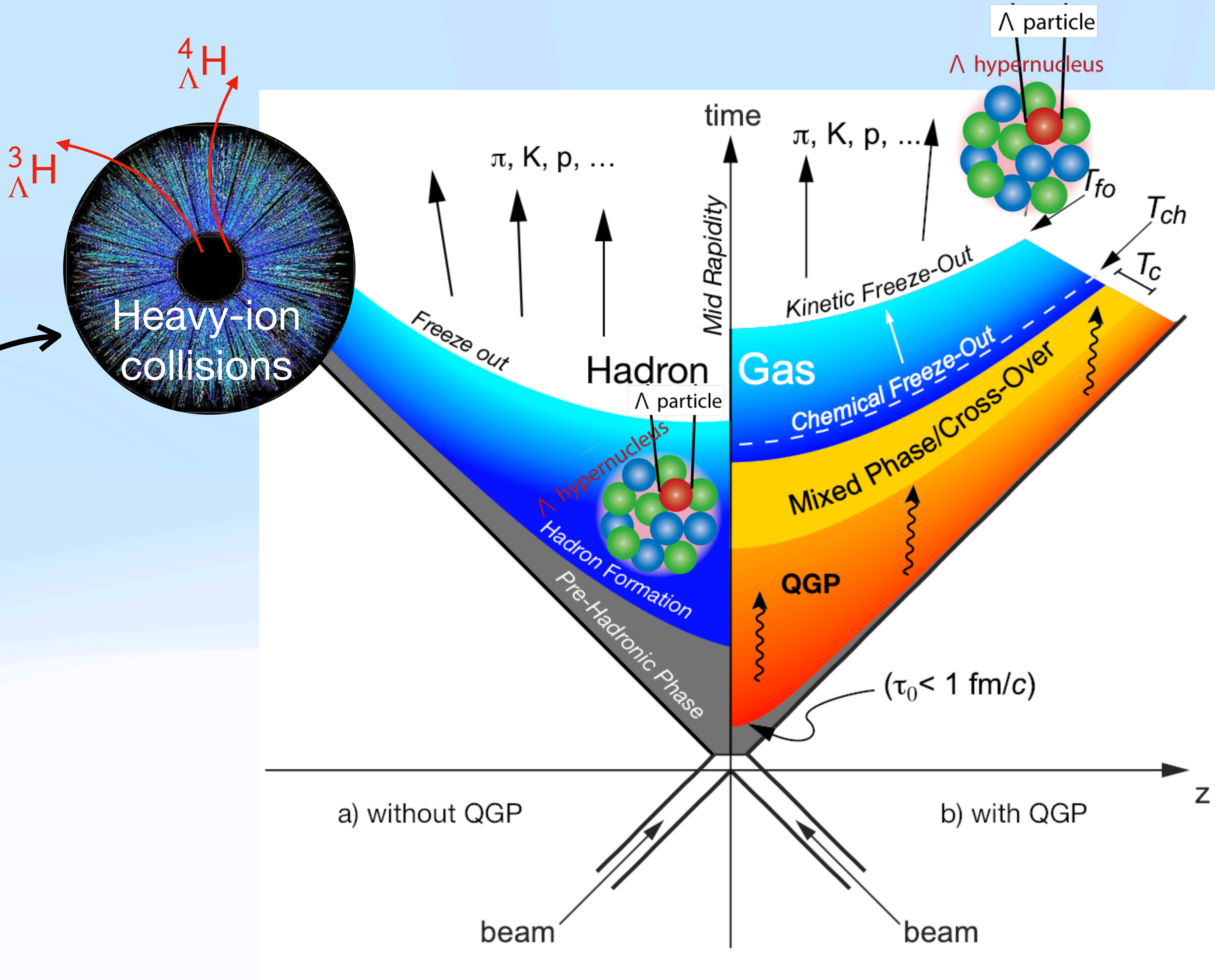
STAR 25 YEARS

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*

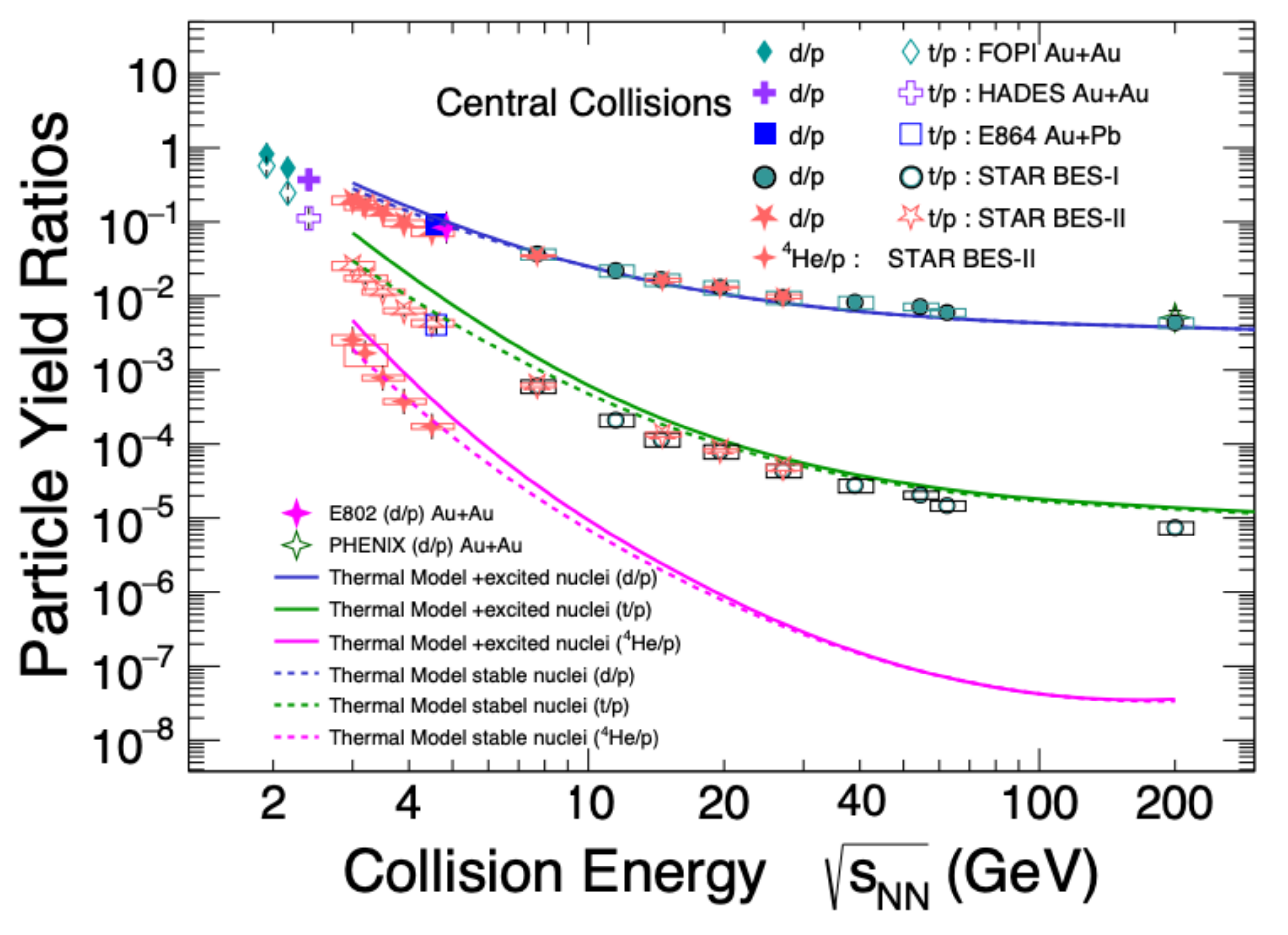
Hypernuclei Production Mechanisms

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
    - The emission source size and the nuclear radius affect the yields

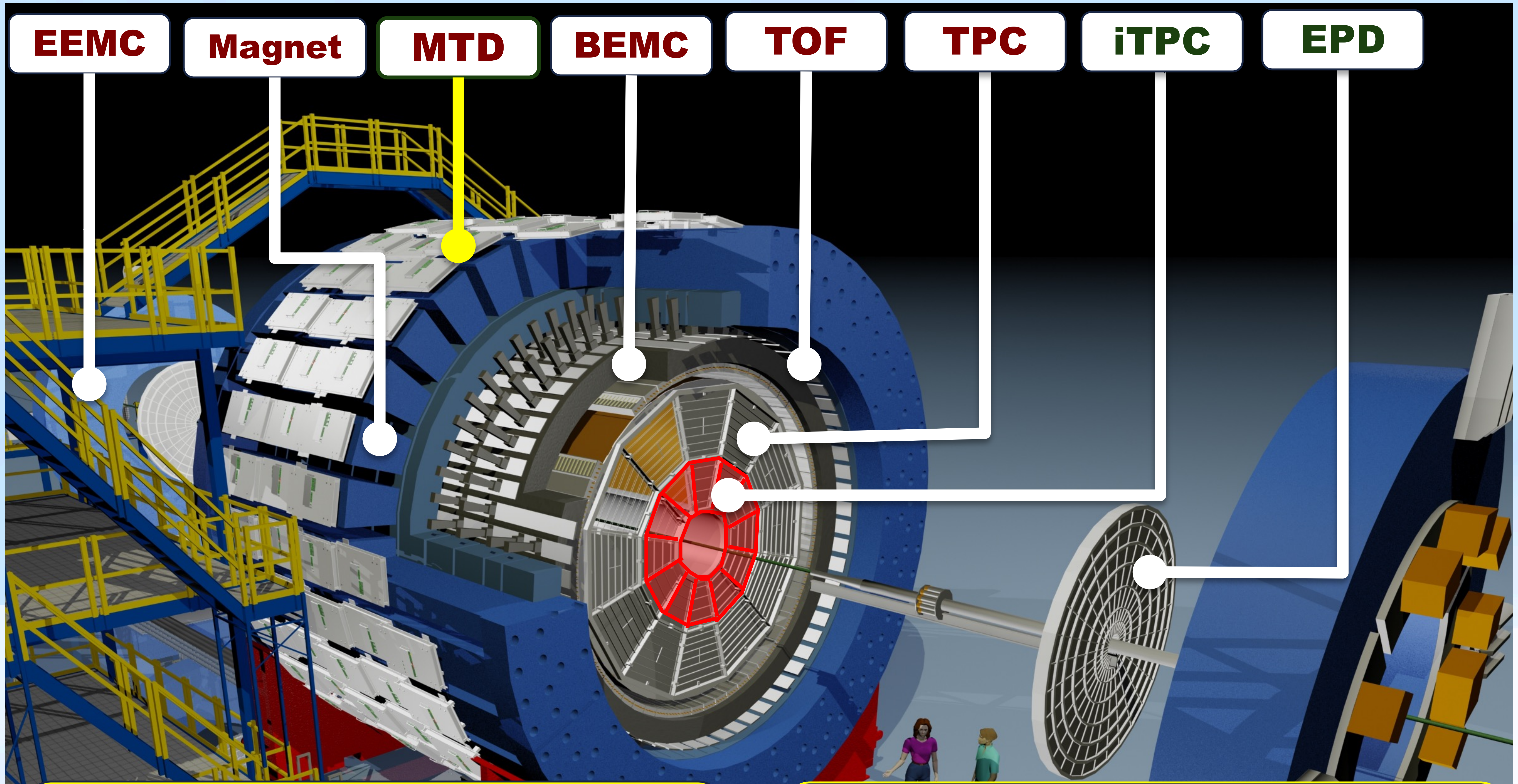
What have we learnt from light nuclei production?



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

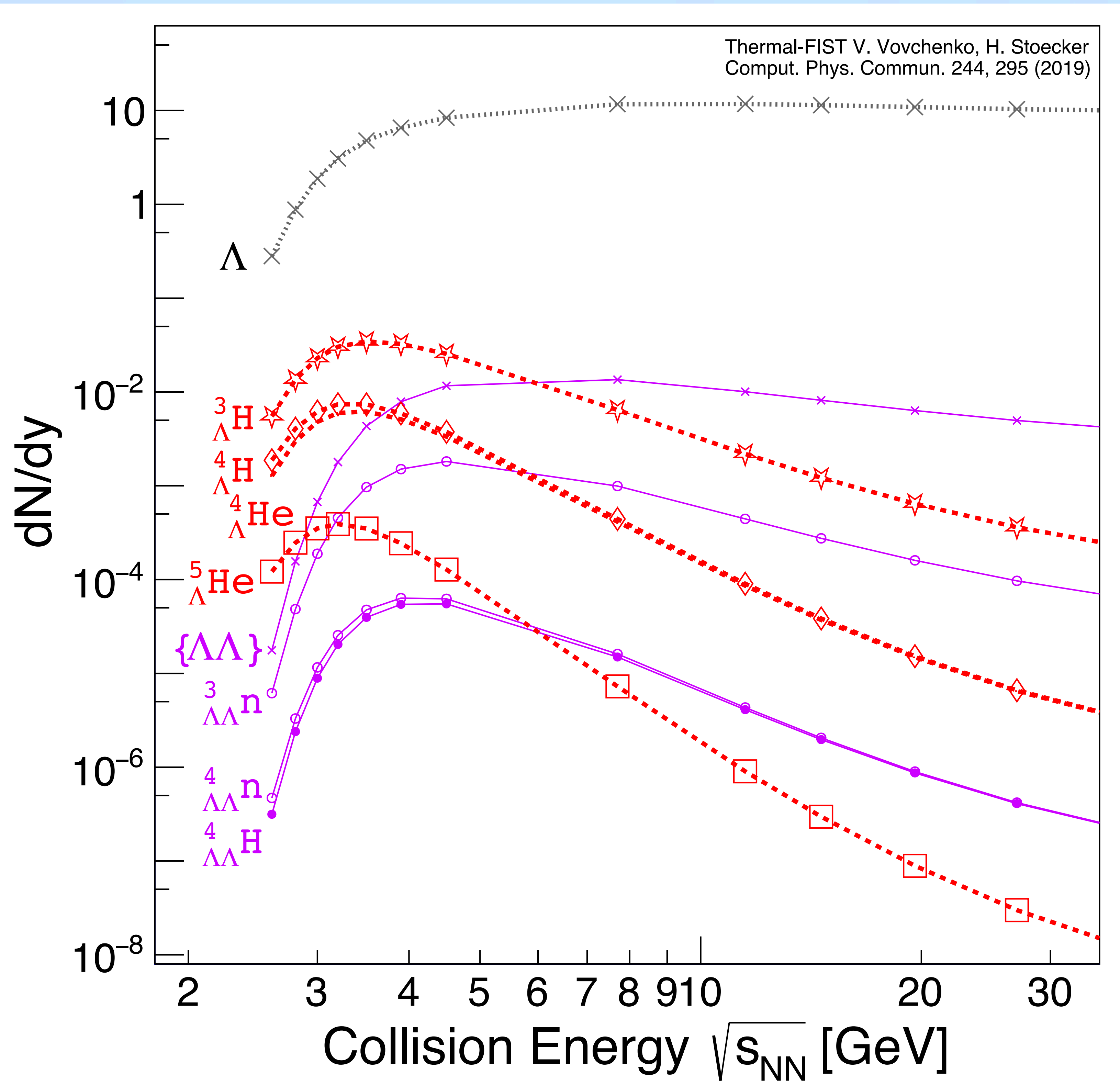
Recent nuclei measurements poses challenges for thermal model

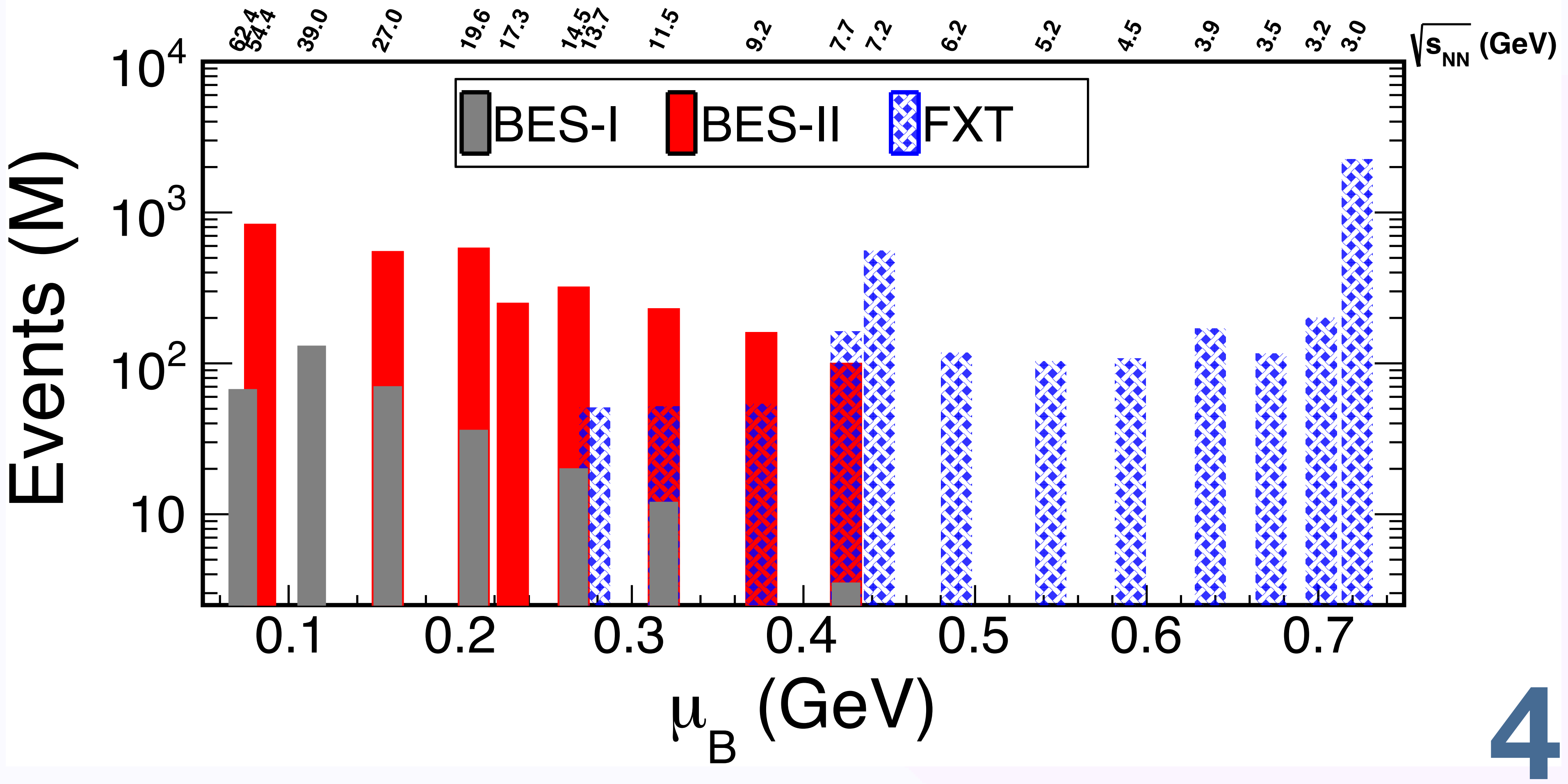
STAR and Beam Energy Scan



- **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

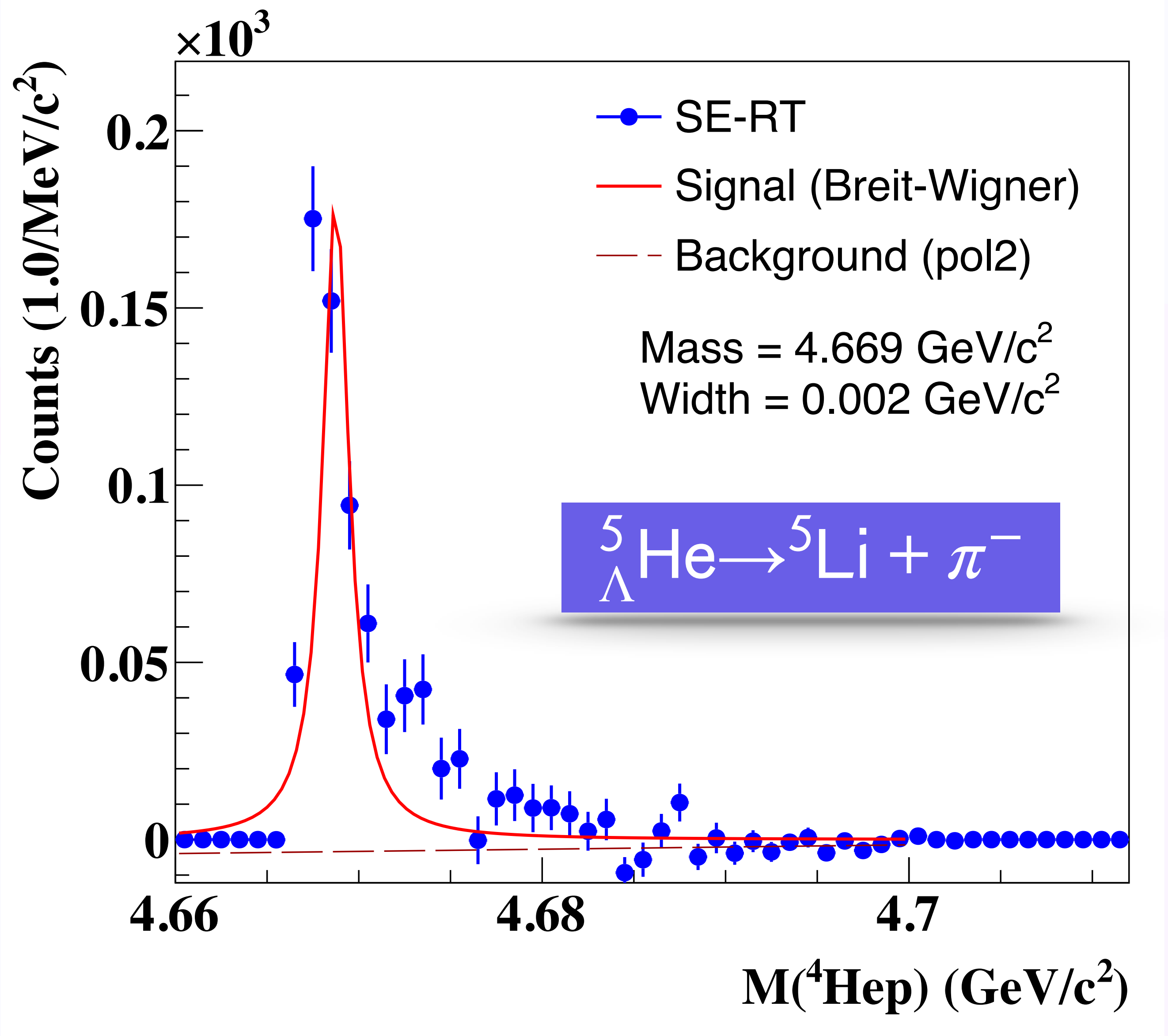
Hypernuclei Reconstruction

- Hypernuclei are reconstructed using the following decay channels:

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

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

- 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 ${}^{4}_{\Lambda}\mathrm{He}$, ${}^{5}_{\Lambda}\mathrm{He}$, the three-body decay phase space is weighted according to a Dalitz plot

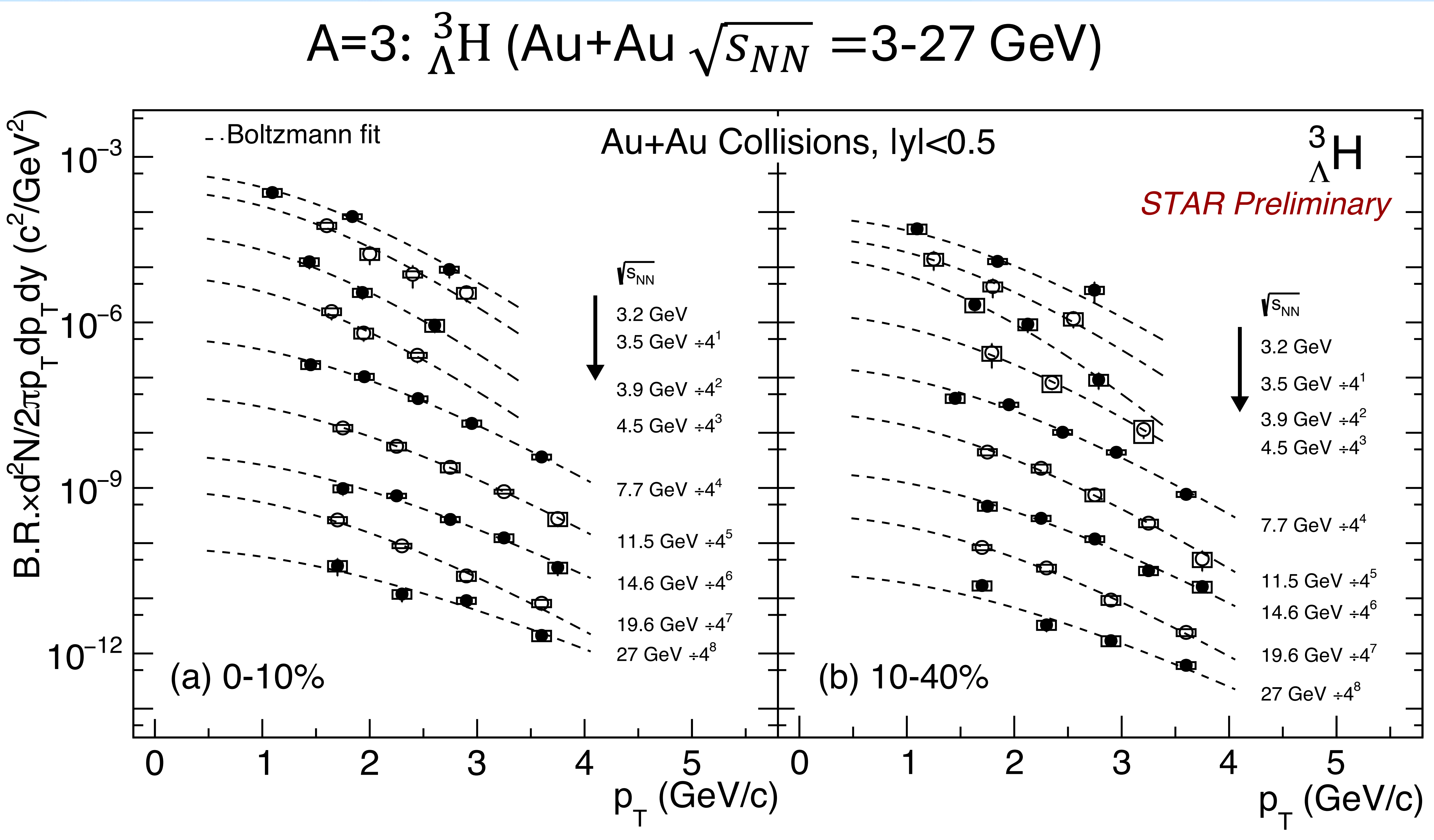


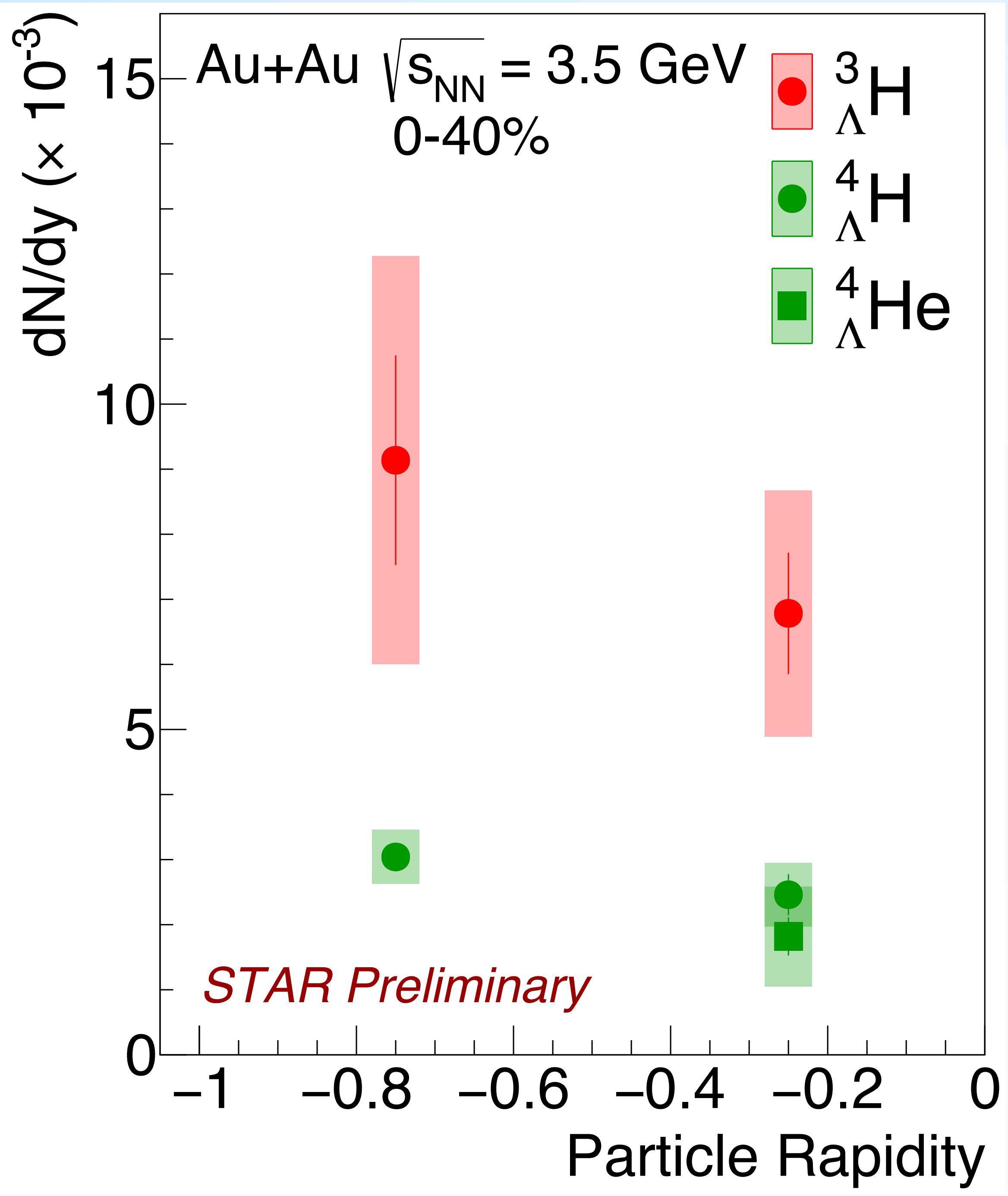
Hypernuclei p_T Spectra and Rapidity

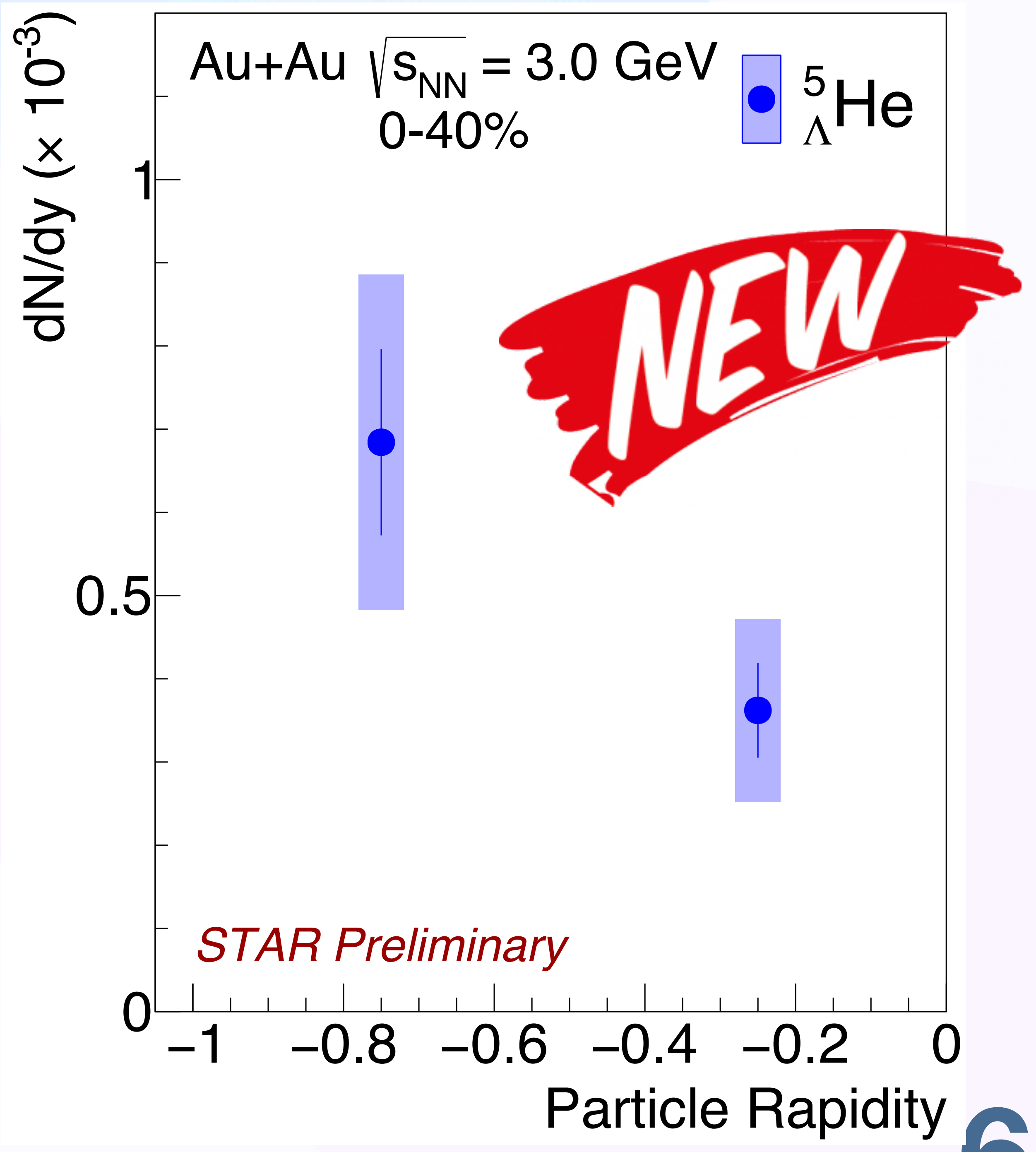
- Measurements cover different energies, different system size!
  - ${}^{3}_{\Lambda}H$ in Au+Au collisions at **3-27** GeV, Au+Au, Zr+Zr, Ru+Ru collisions at **200 GeV**
  - ${}^{4}_{\Lambda}H$, ${}^{4}_{\Lambda}He$ in Au+Au collisions at **3-3.5 GeV**
  - ${}^{5}_{\Lambda}He$ in Au+Au collisions at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

- Production enhanced at target rapidity, more pronounced for heavier nuclei

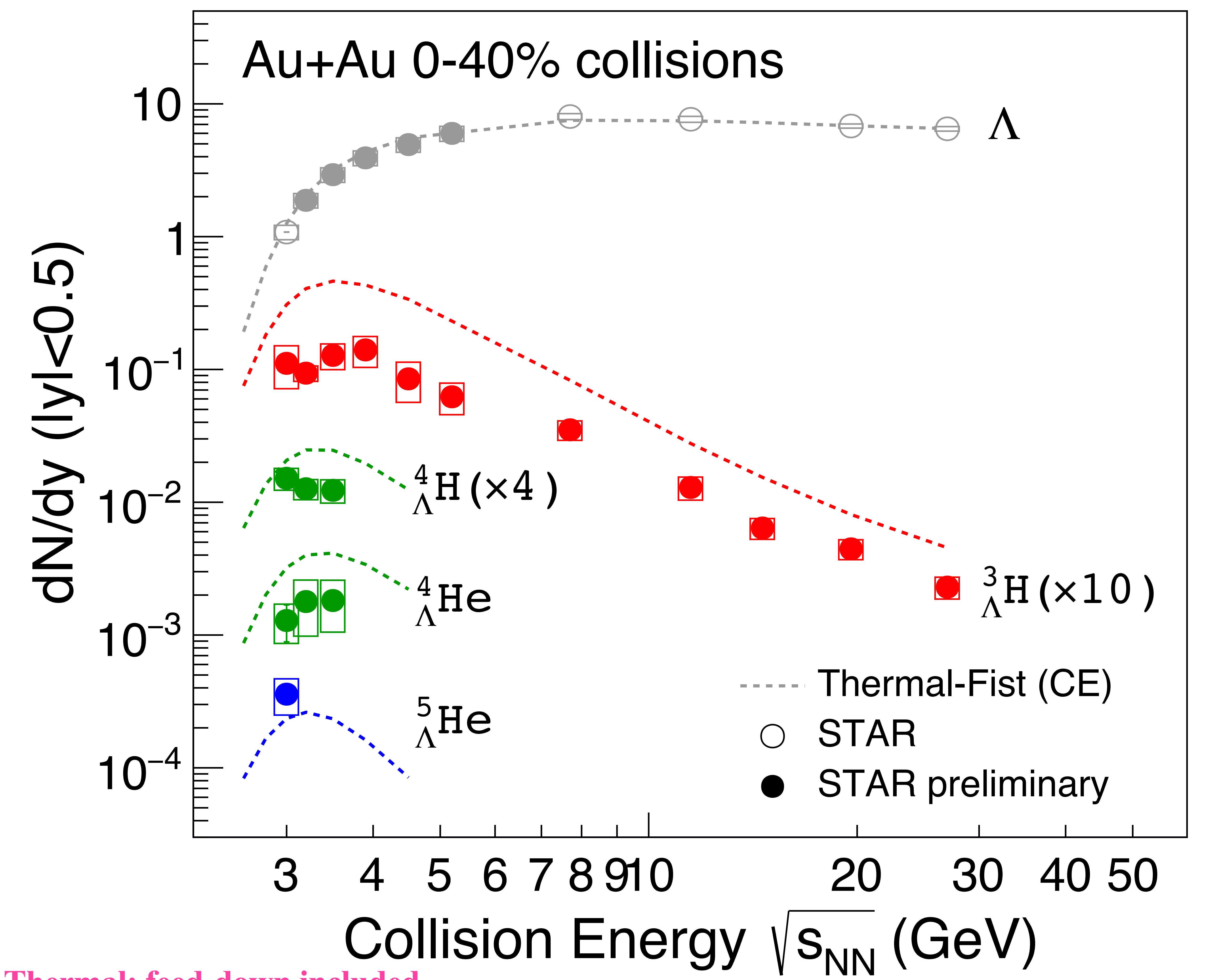
Spectator matters matter at target rapidity







Excitation Function



Thermal: feed-down included

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

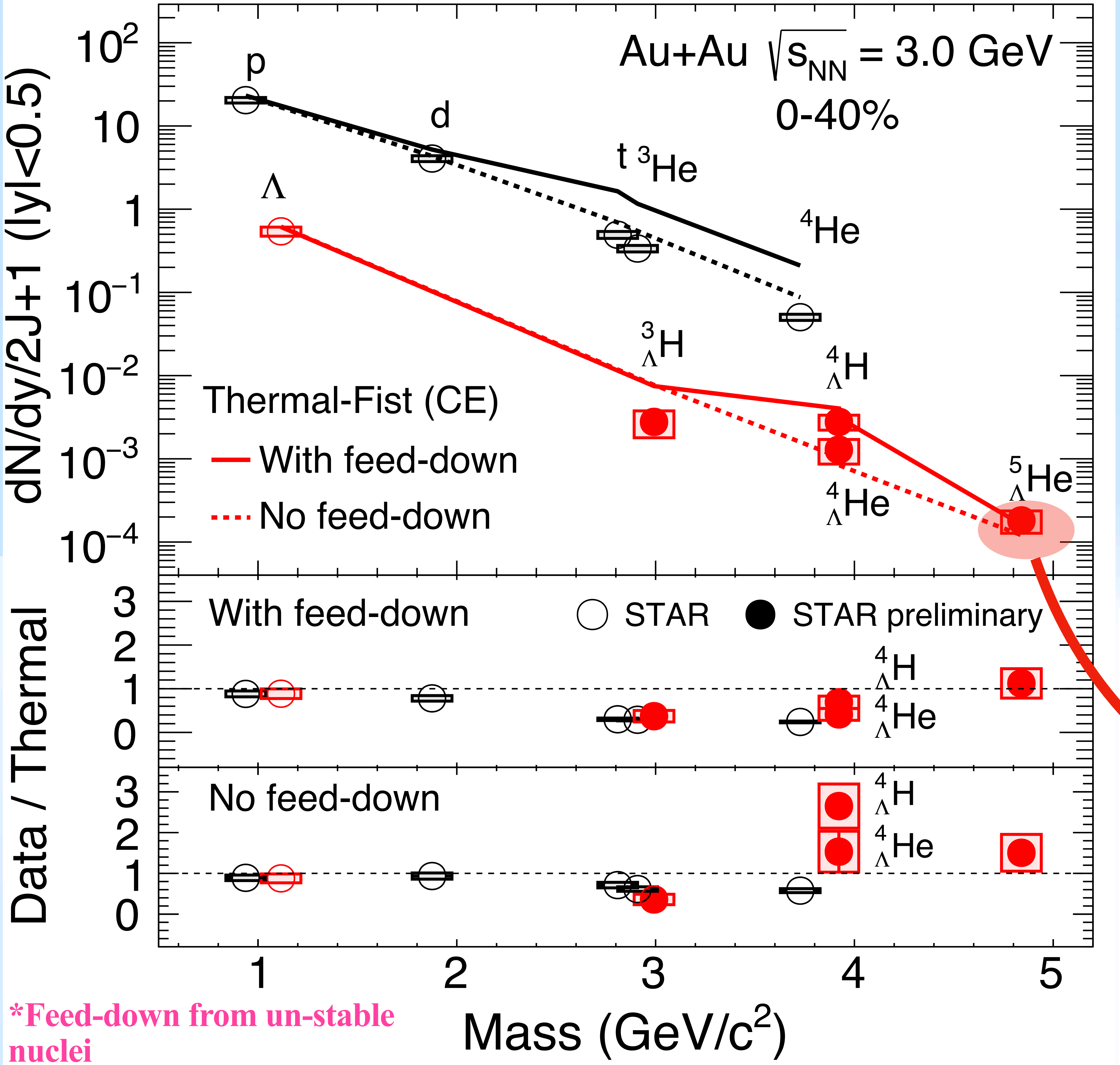
Interplay between increasing baryon production and stronger strangeness canonical suppression towards low energies

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)

Data to Thermal Model Ratio at 3 GeV

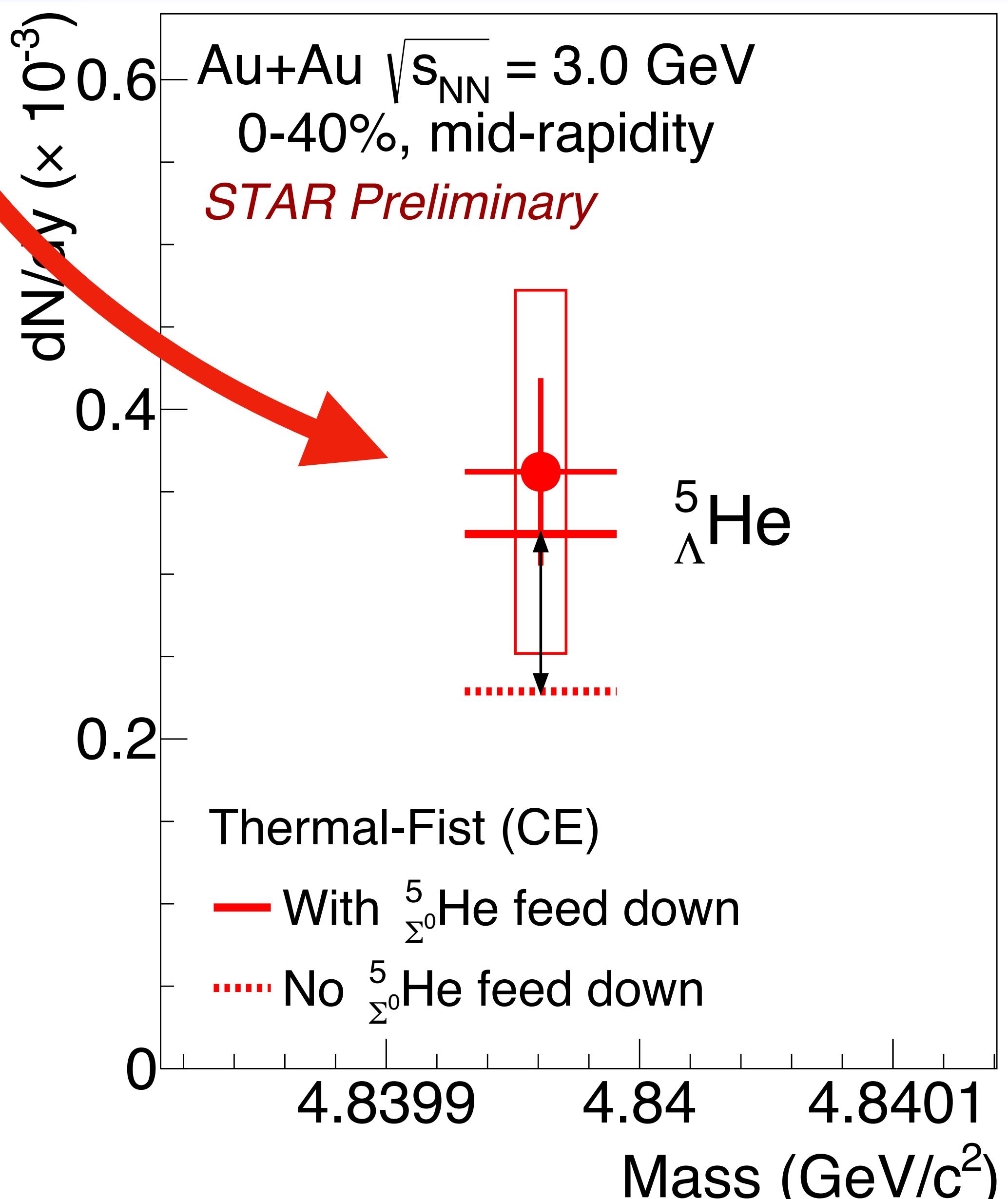


*Feed-down from un-stable nuclei

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

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

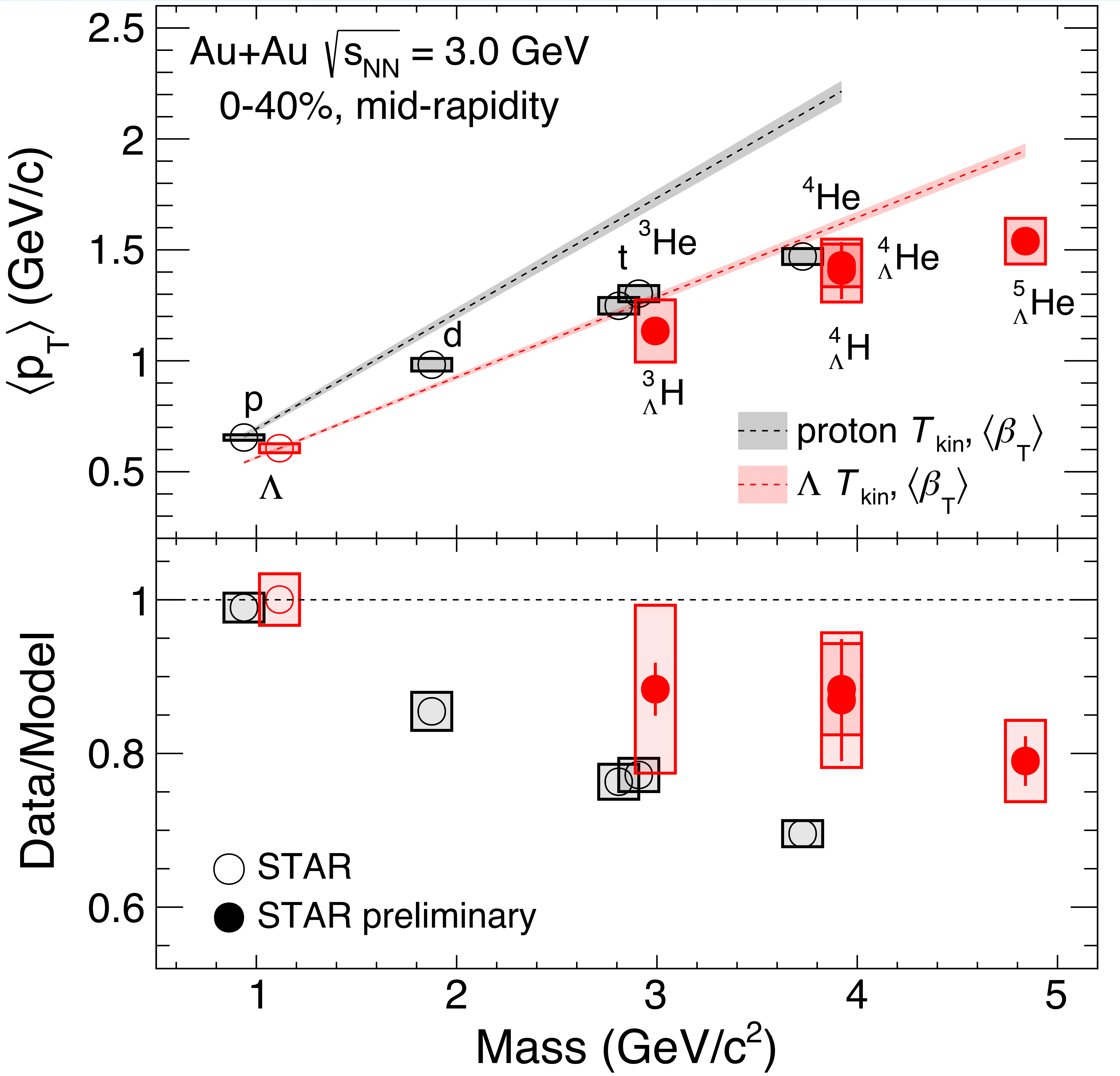
Thermal overestimate feed down fraction?



- 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

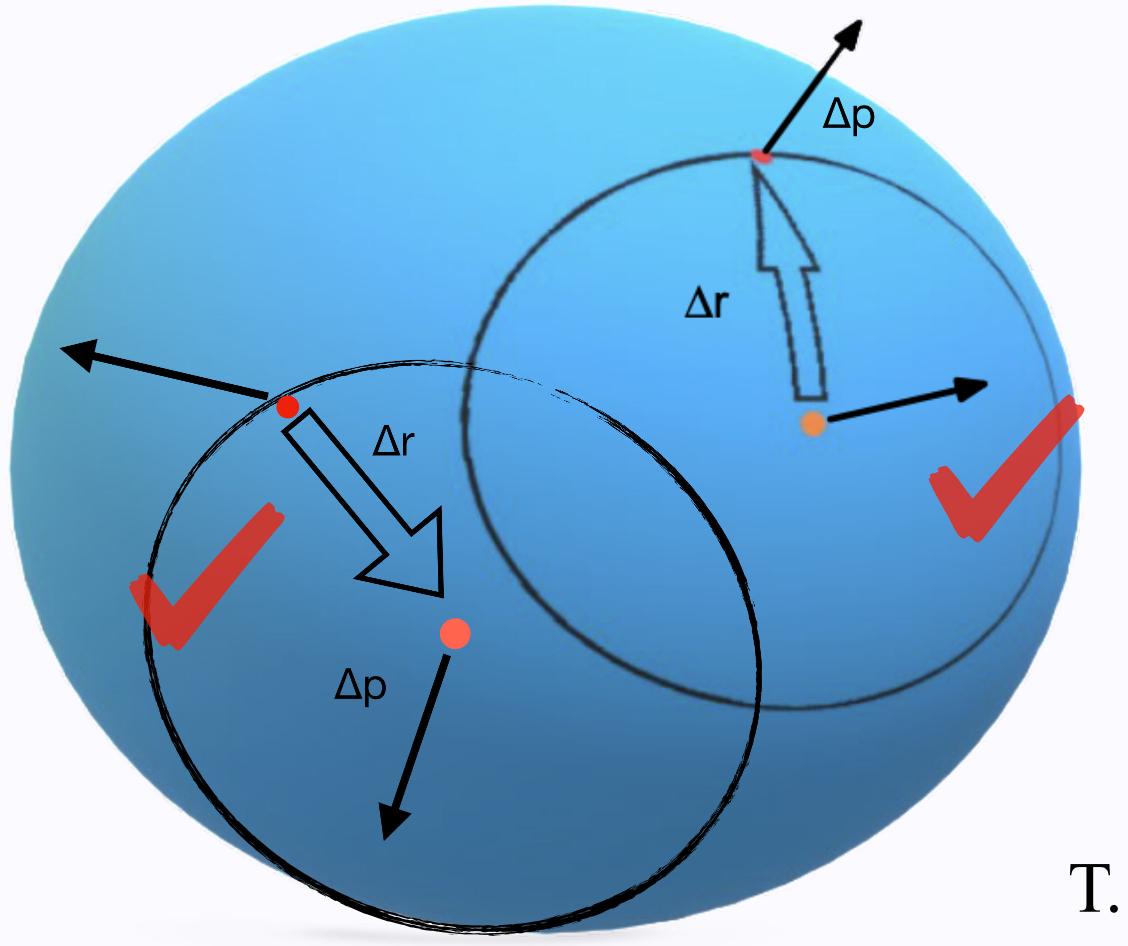
Hydrodynamic-inspired Blast-Wave model: assumes particles are emitted thermally from an expanding source with a common flow velocity $\langle \beta_T \rangle$ and kinetic freeze-out temperature T_{kin}

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

PLB 794, 50–63 (2019)

- 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 perfectly aligned
  2. The heavier nuclei, the larger deviation

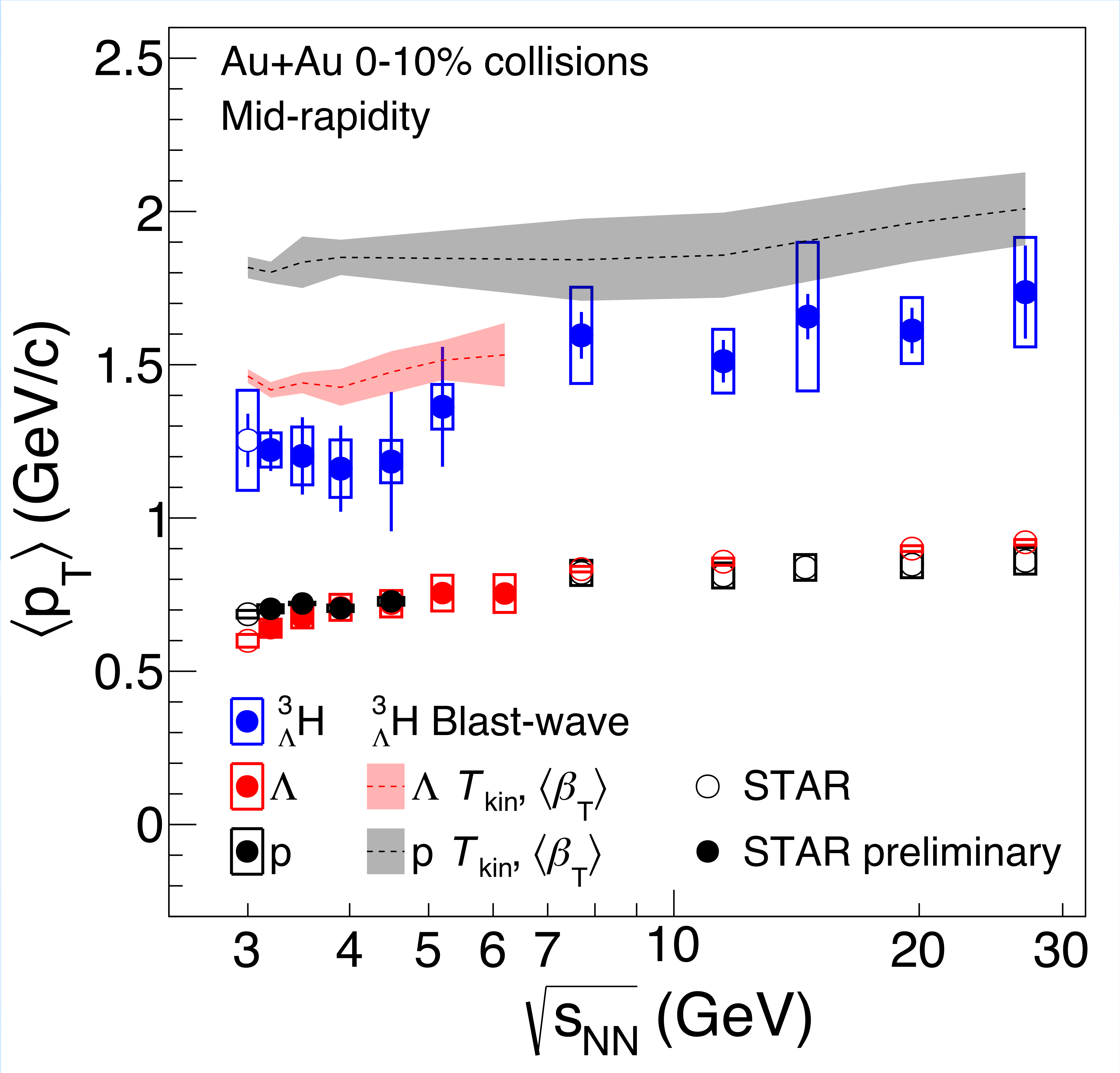
A. I. Sheikh et al., PRC 106, 054907 (2022)



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

T. Reichert, SQM 2022, slides (2022)

Mean Transverse Momentum v.s. Collision Energy



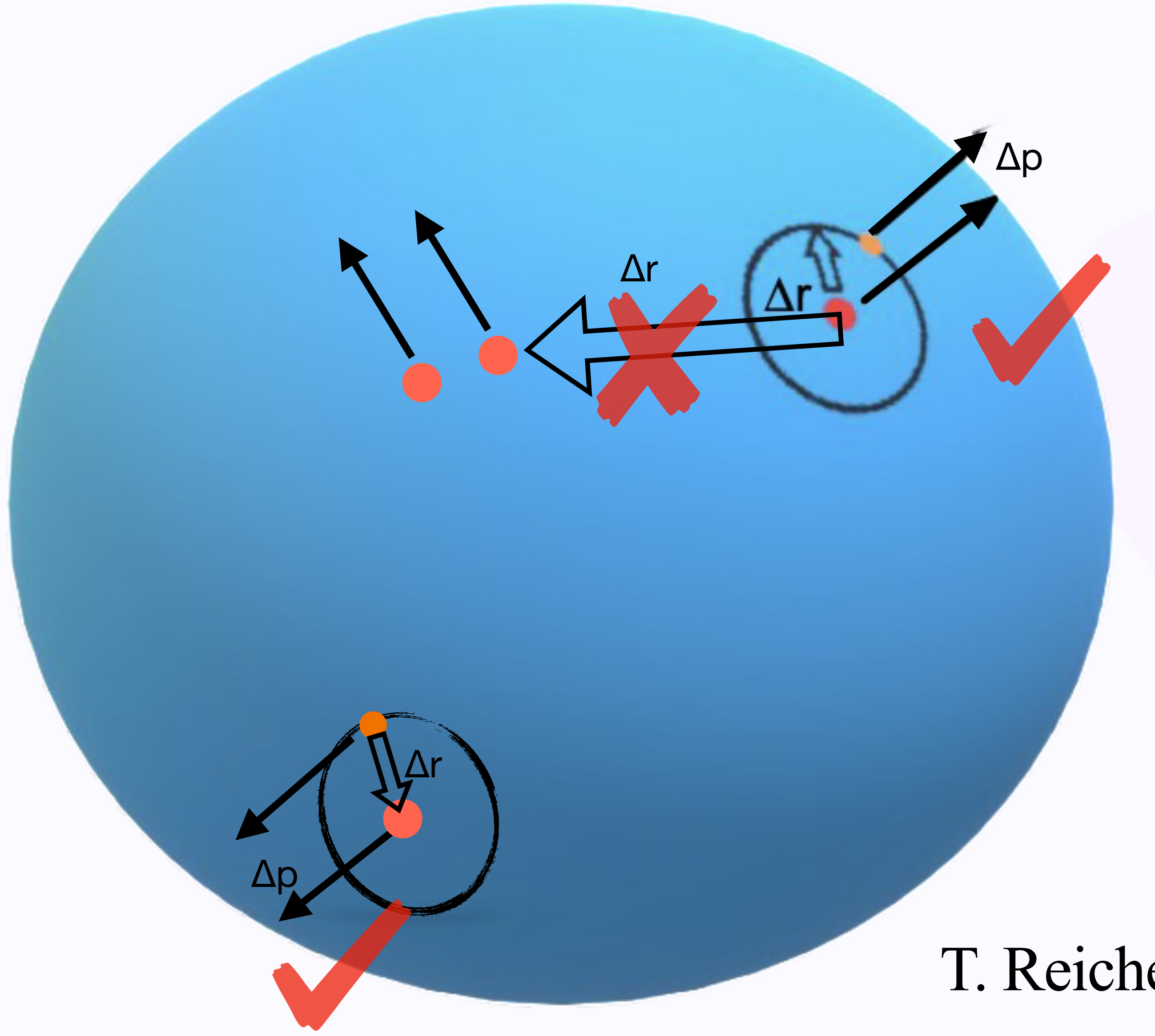
STAR, PRC 110, 054911 (2024)
STAR, PRL 128, 202301 (2022)
STAR, JHEP **2024** (2024) 139

- At $\sqrt{s_{NN}} \geq 7.7$ GeV, $^{3}_{\Lambda}H$ $\langle p_T \rangle$ tends to approaching that of protons

See poster by Yixuan Jin (xx/xx)

  - Likely due to increasing effective volume ↔ decreasing coalescence parameter B_A, where nucleons that eventually coalesce are more likely to be aligned in space and momentum

Suggests a change in the effective volume across energies

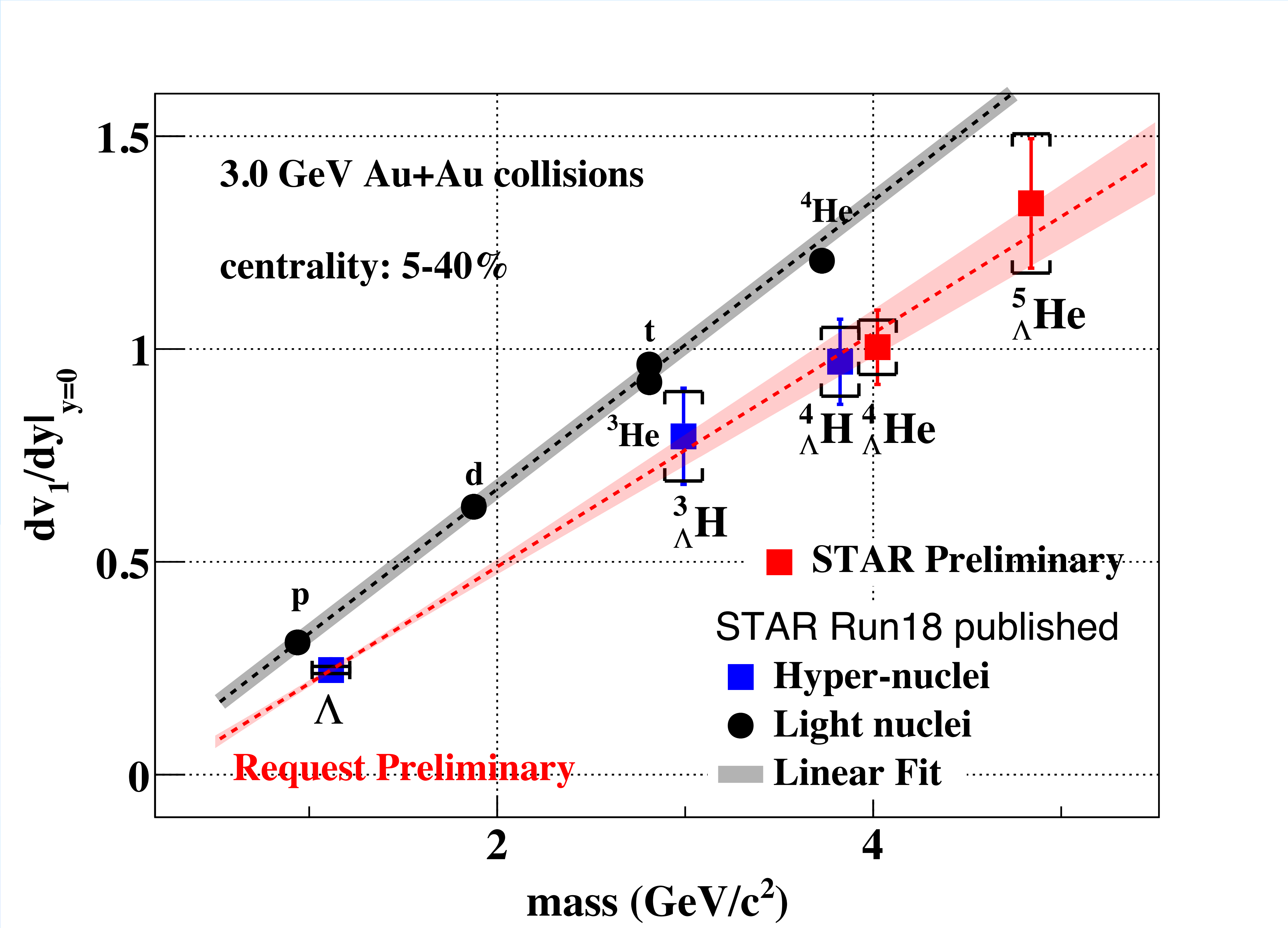


Large effective volume nucleon's *r* and *p* are correlated

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
  1. **First measurement of A = 5 hypernuclei yield and direct flow in Au+Au collisions at $\sqrt{s_{NN}}$ = 3 GeV**
  2. Mid-rapidity yields overestimated by thermal model
  3. Mean transverse momentum tends to lower than p (Λ) 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 energy
  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