



New Hypernuclei Measurements from STAR

n

p

Λ



d



${}^3_{\Lambda}\text{H}$



t



${}^3_{\Lambda}\text{He}$



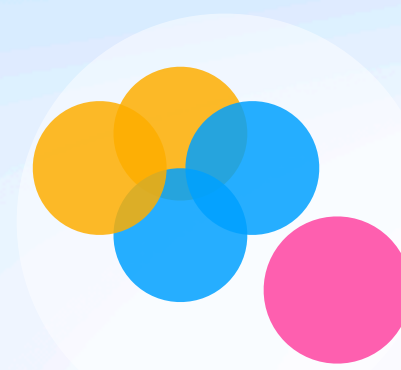
${}^4_{\Lambda}\text{H}$



${}^4_{\Lambda}\text{He}$



${}^4_{\Lambda}\text{He}$



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

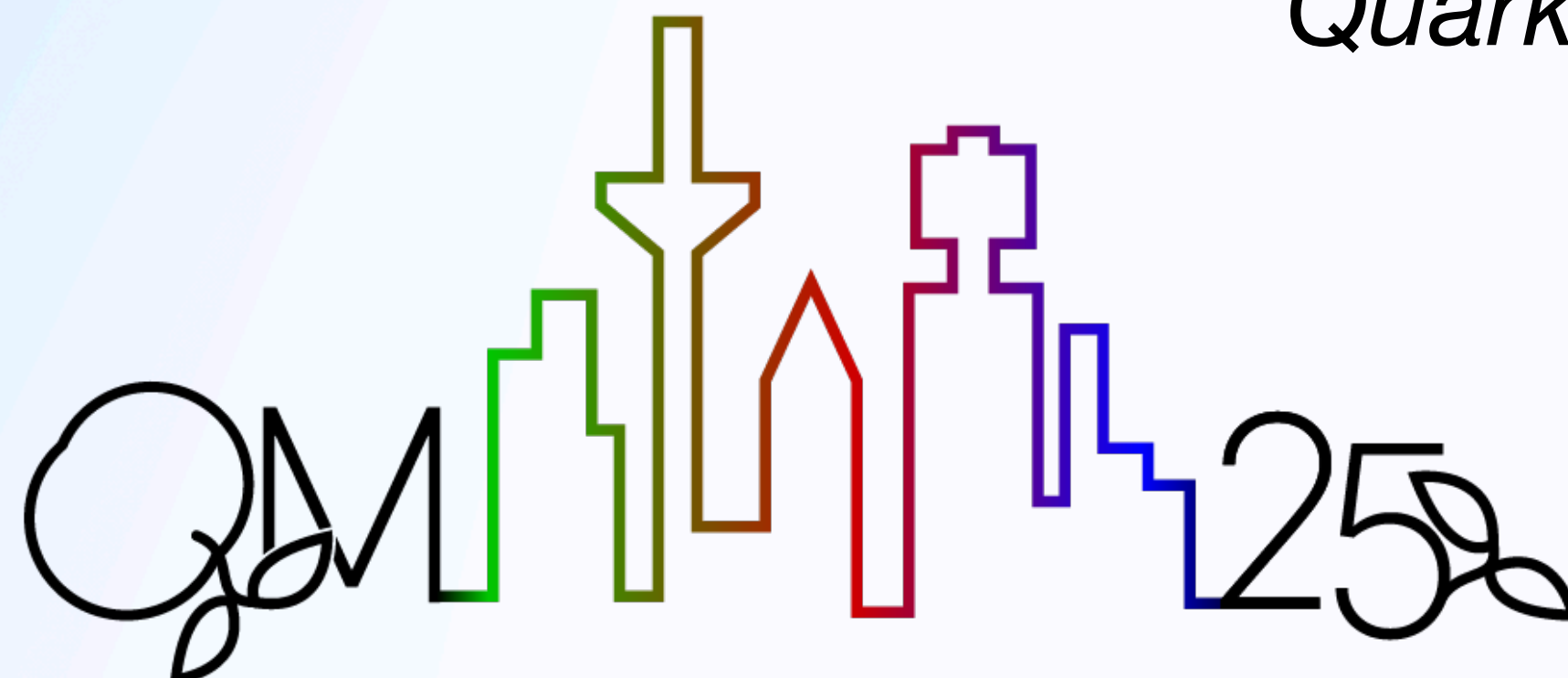
Outline

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

*Yingjie Zhou for the STAR Collaboration
CCNU, GSI*

Apr. 9, 2025

Quark Matter 2025, Frankfurt, Germany



Supported in part by



U.S. DEPARTMENT OF
ENERGY

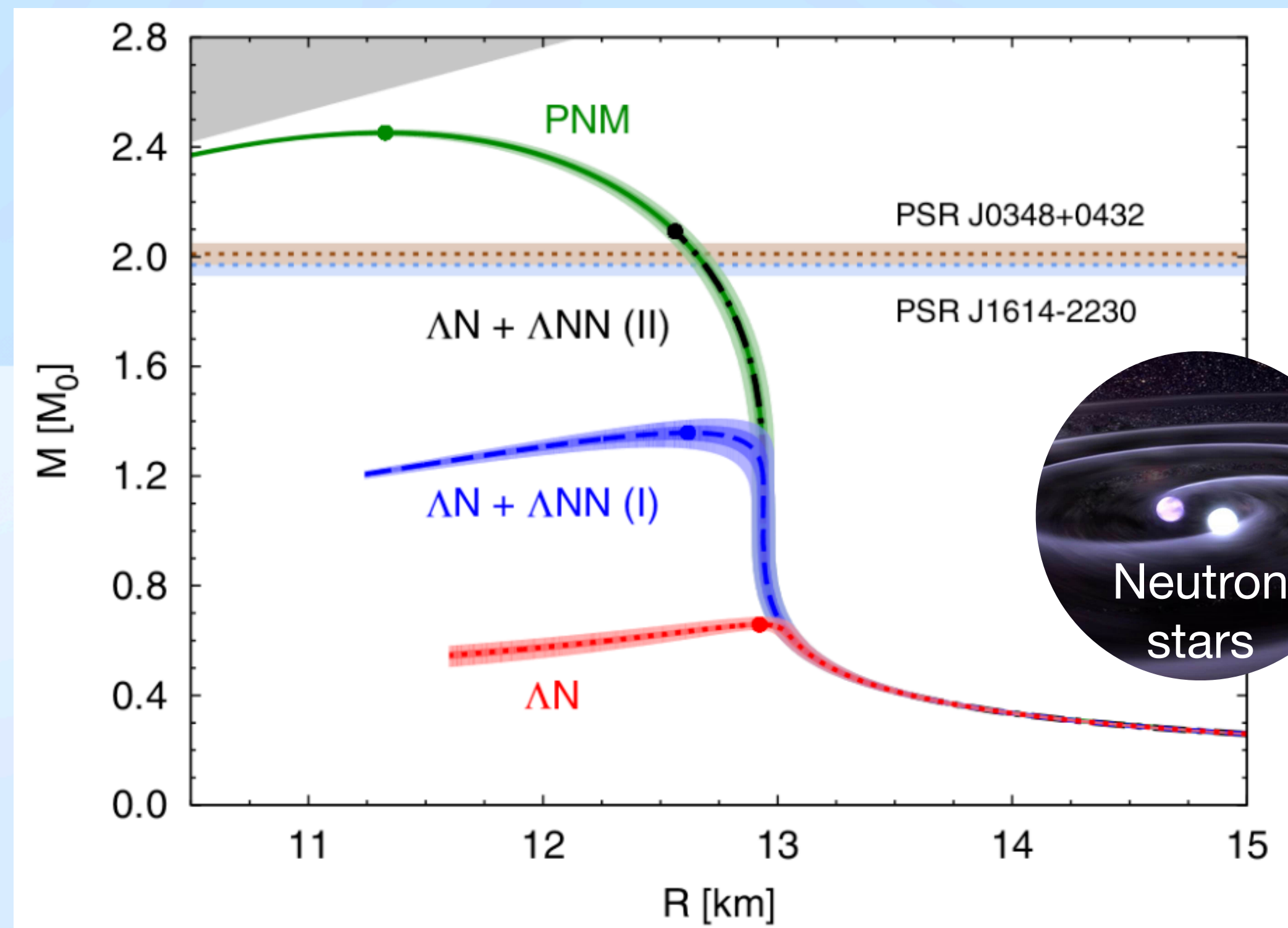
Office of
Science



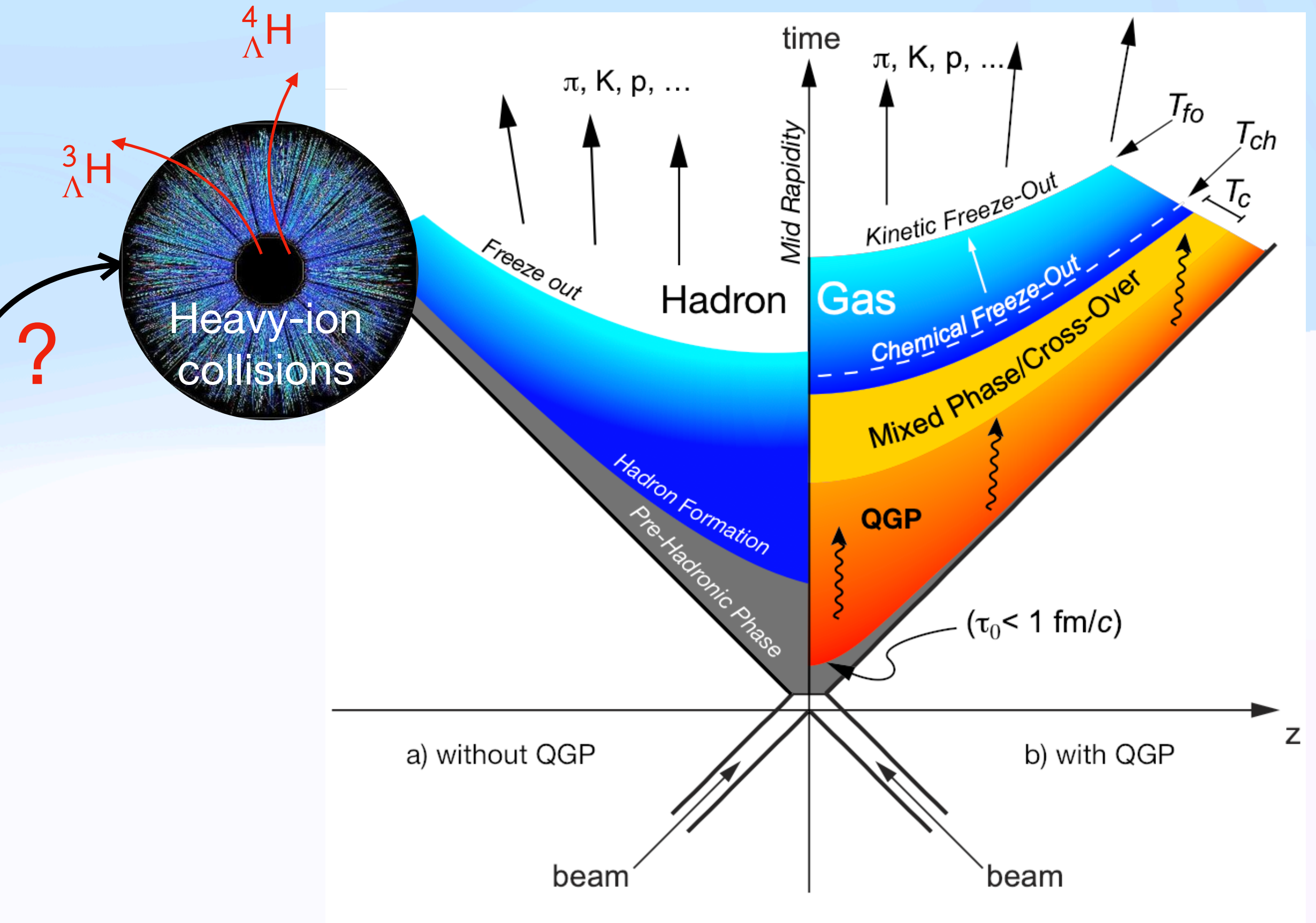
Hypernuclei and Hyperon-Nucleon (Y-N) Interaction

- **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)



- 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

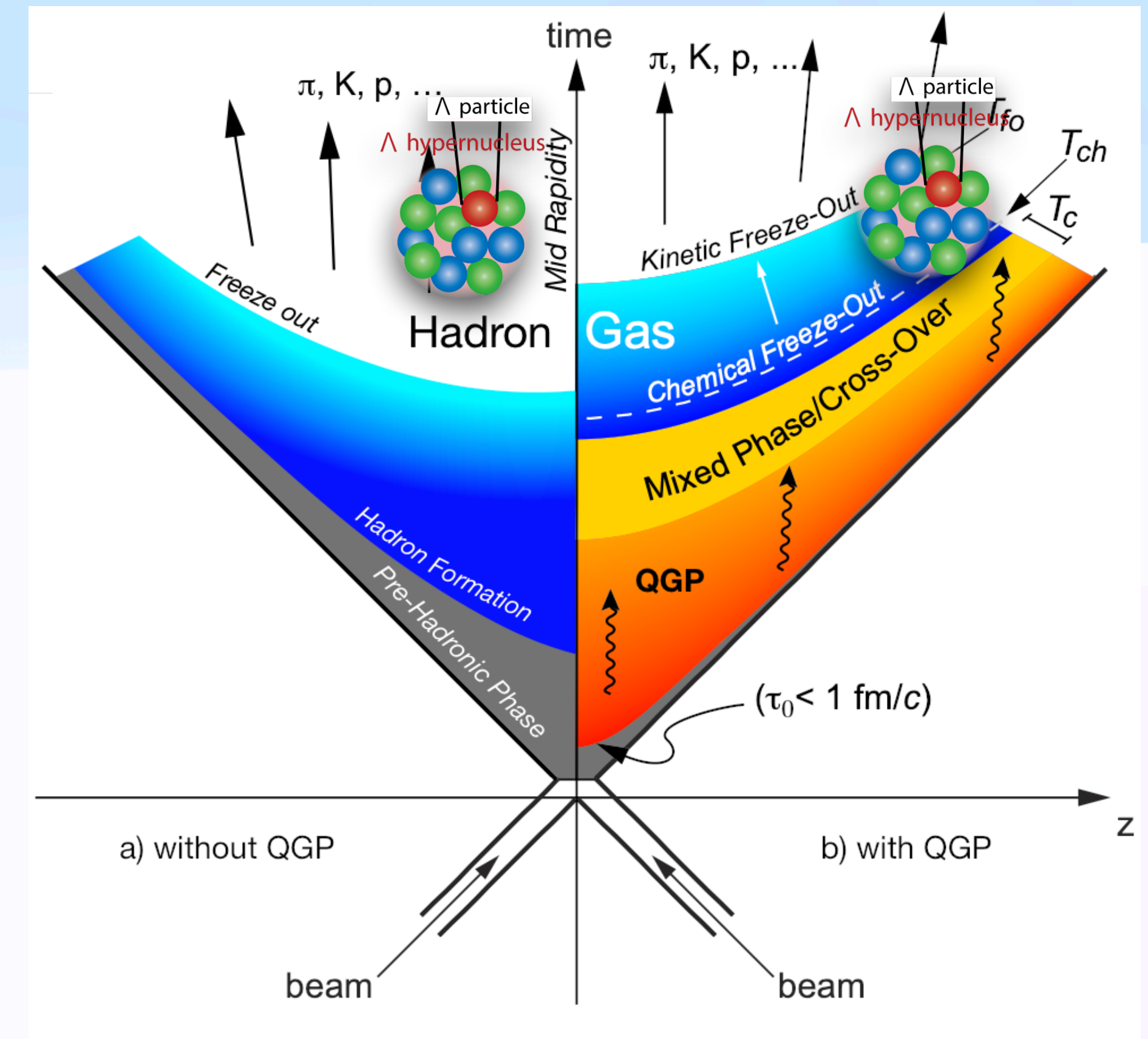
✗ Y–N dynamics have minimal impact on final yield

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*



Hypernuclei Production Mechanisms

When are nuclei produced in a heavy-ion collision?

1. Thermal models

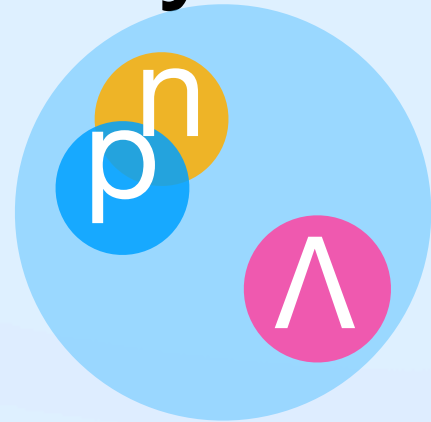
- Hadrons and (hyper-)nuclei are treated equally
- Yields are predicted with thermal equilibrium assumptions

$\times$ Y–N dynamics have minimal impact on final yield

2. Coalescence model

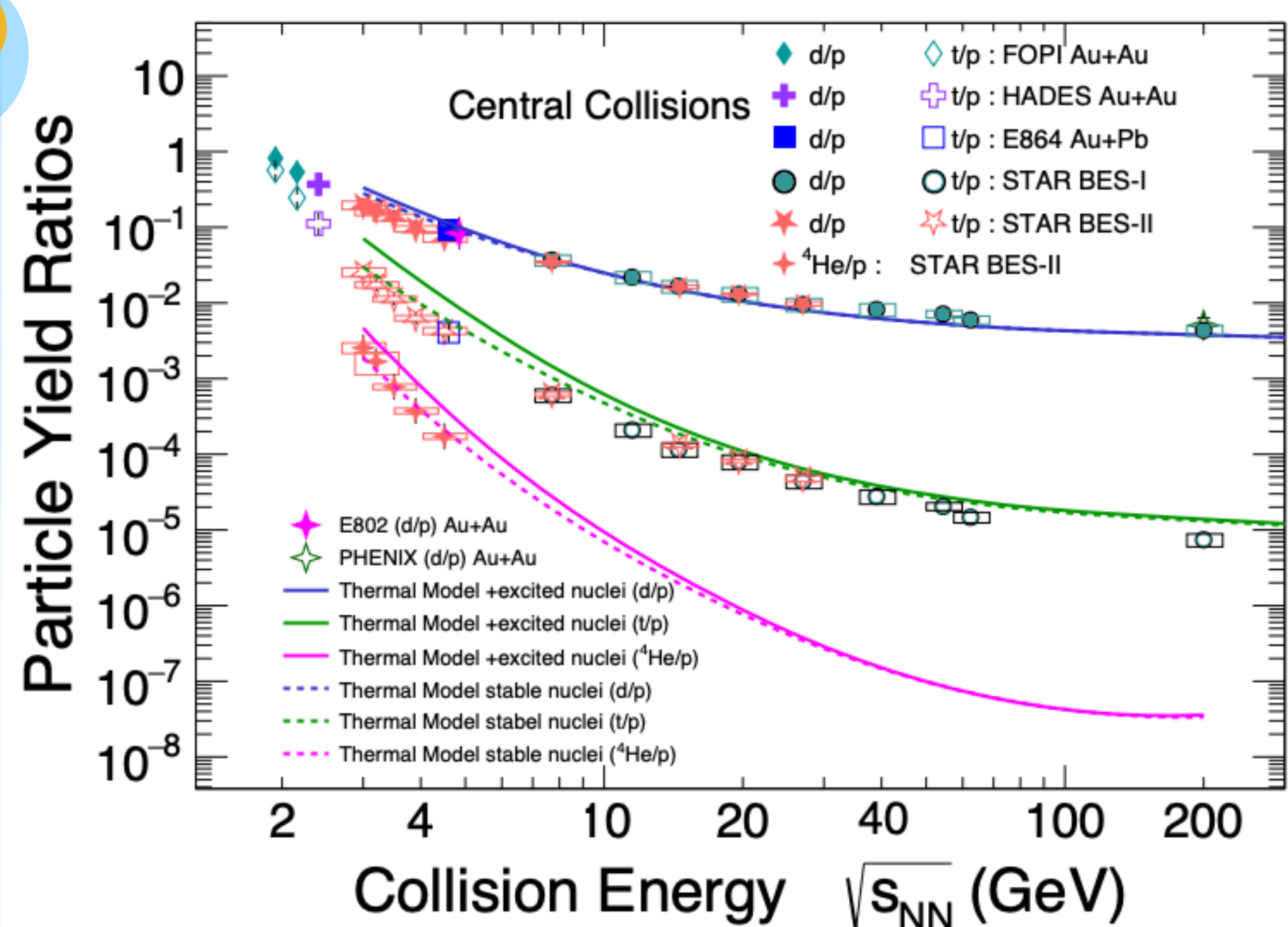
- (Hyper-)nuclei formation after kinetic freeze-out
- Nucleon coalescence
 - Wigner function
 - Emission source size and nuclear radius

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



What have we learnt from light nuclei production?

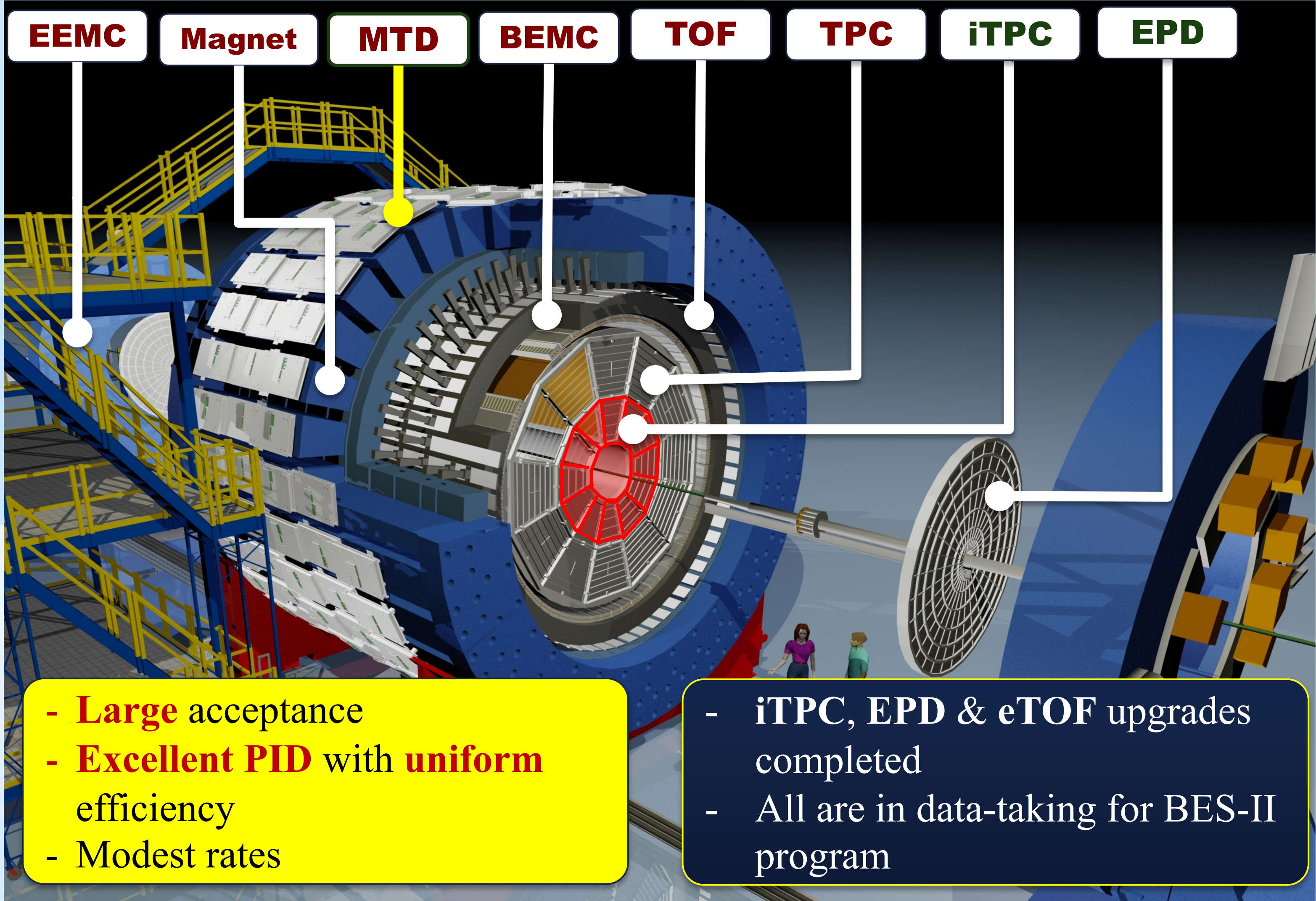
See poster by Liubing Chen (xx/xx)



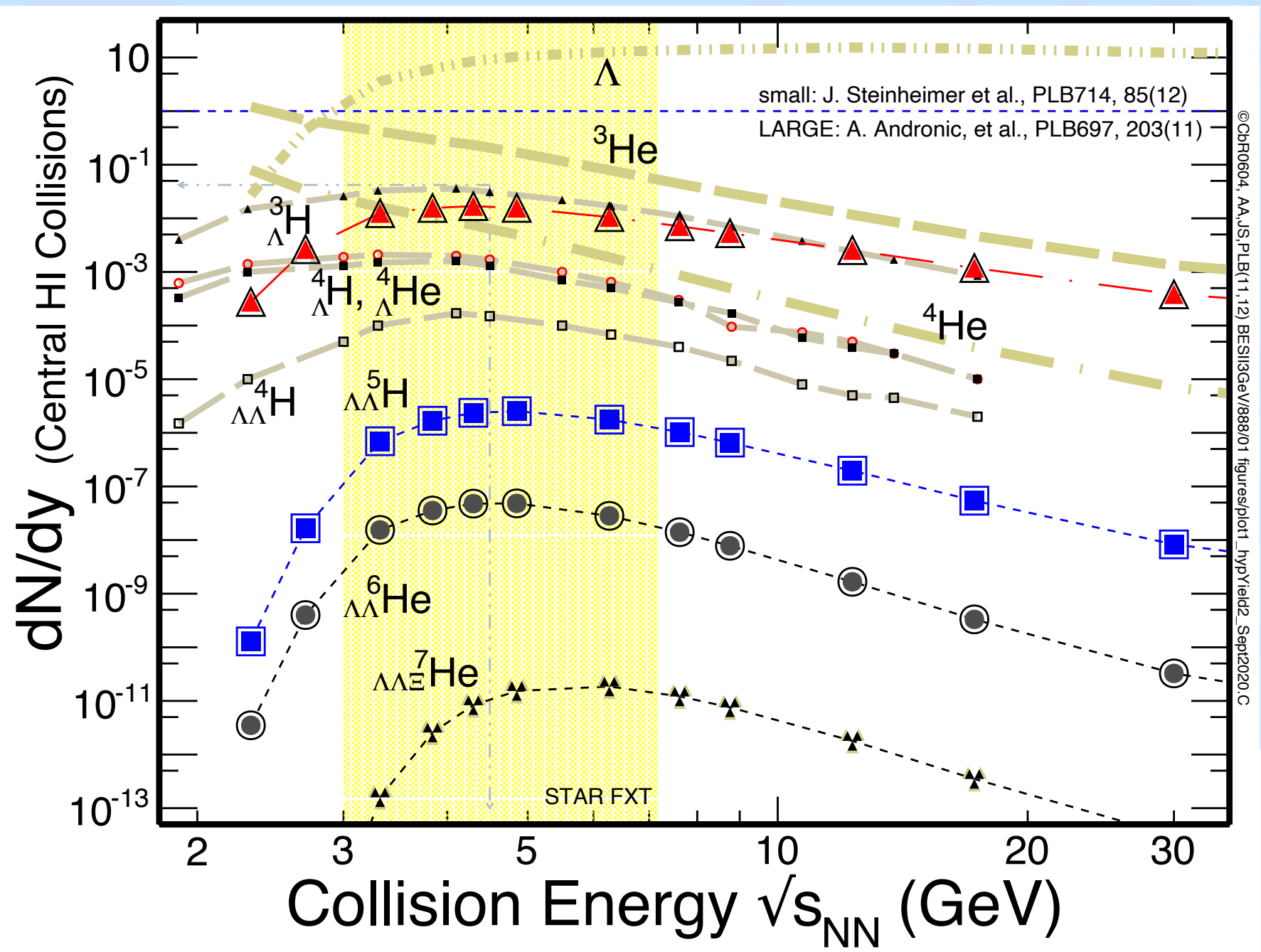
- d/p is fairly well described by thermal model, but t/p , $^4\text{He}/p$ is overestimated

Recent nuclei measurements poses challenges for thermal model

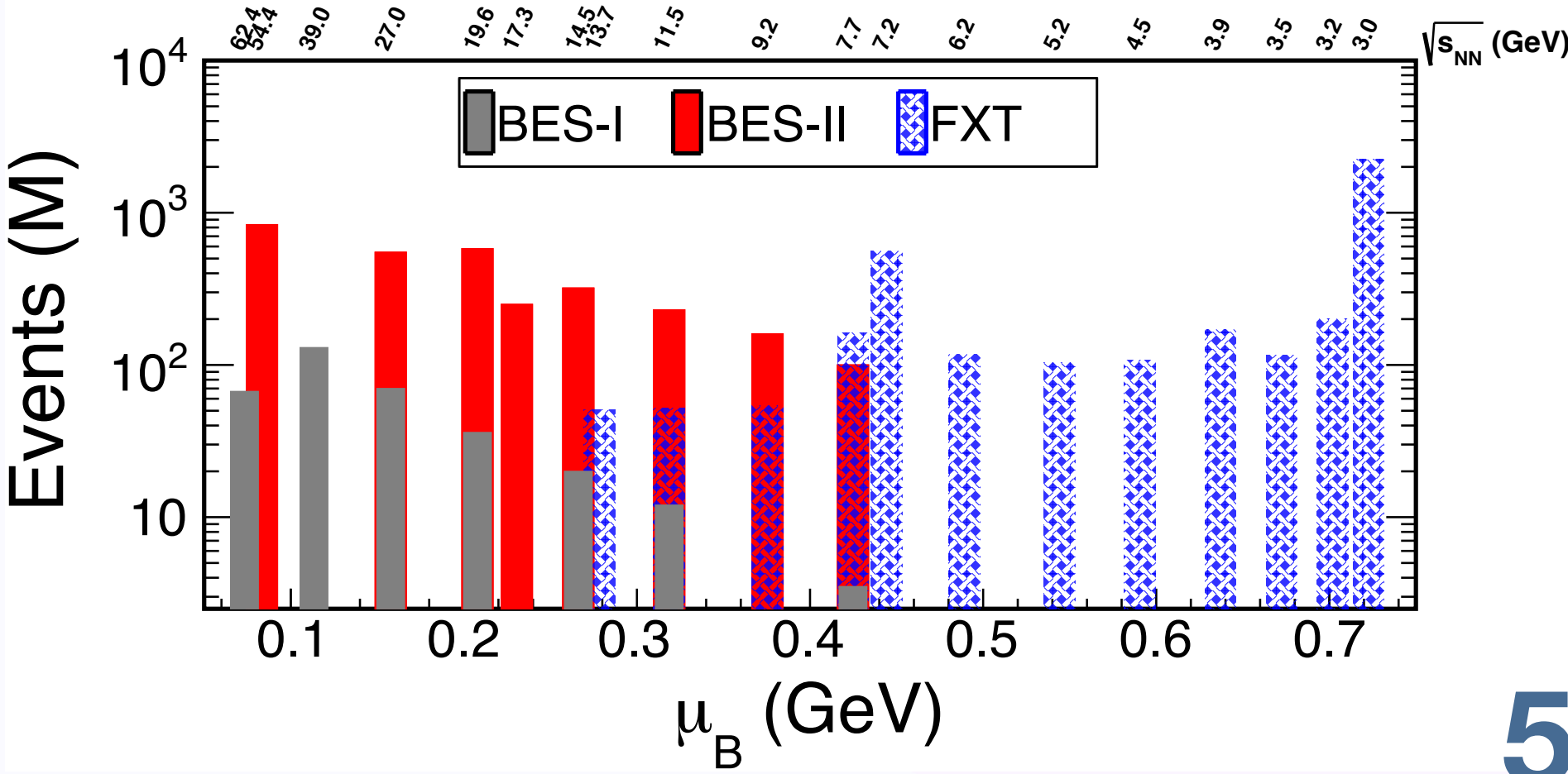
STAR and Beam Energy Scan



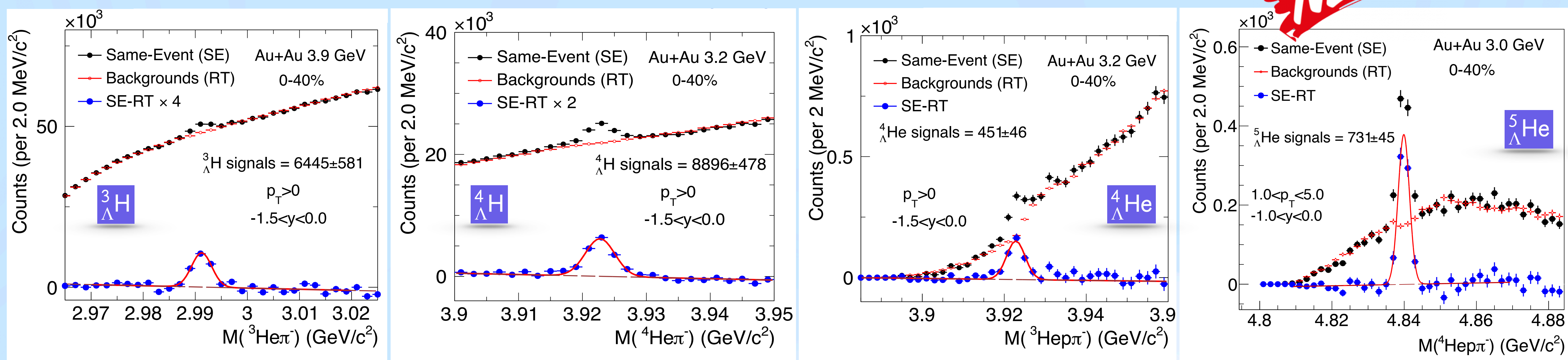
- RHIC BES-II offers great opportunity for hypernuclei measurements



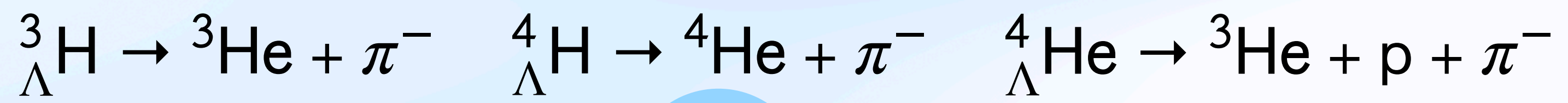
A. Andronic *et al.* Phys.Lett.B 697, 203 (2011)
J. Steinheimer *et al.* Phys.Lett.B 714, 85 (2012)



Hypernuclei Reconstruction



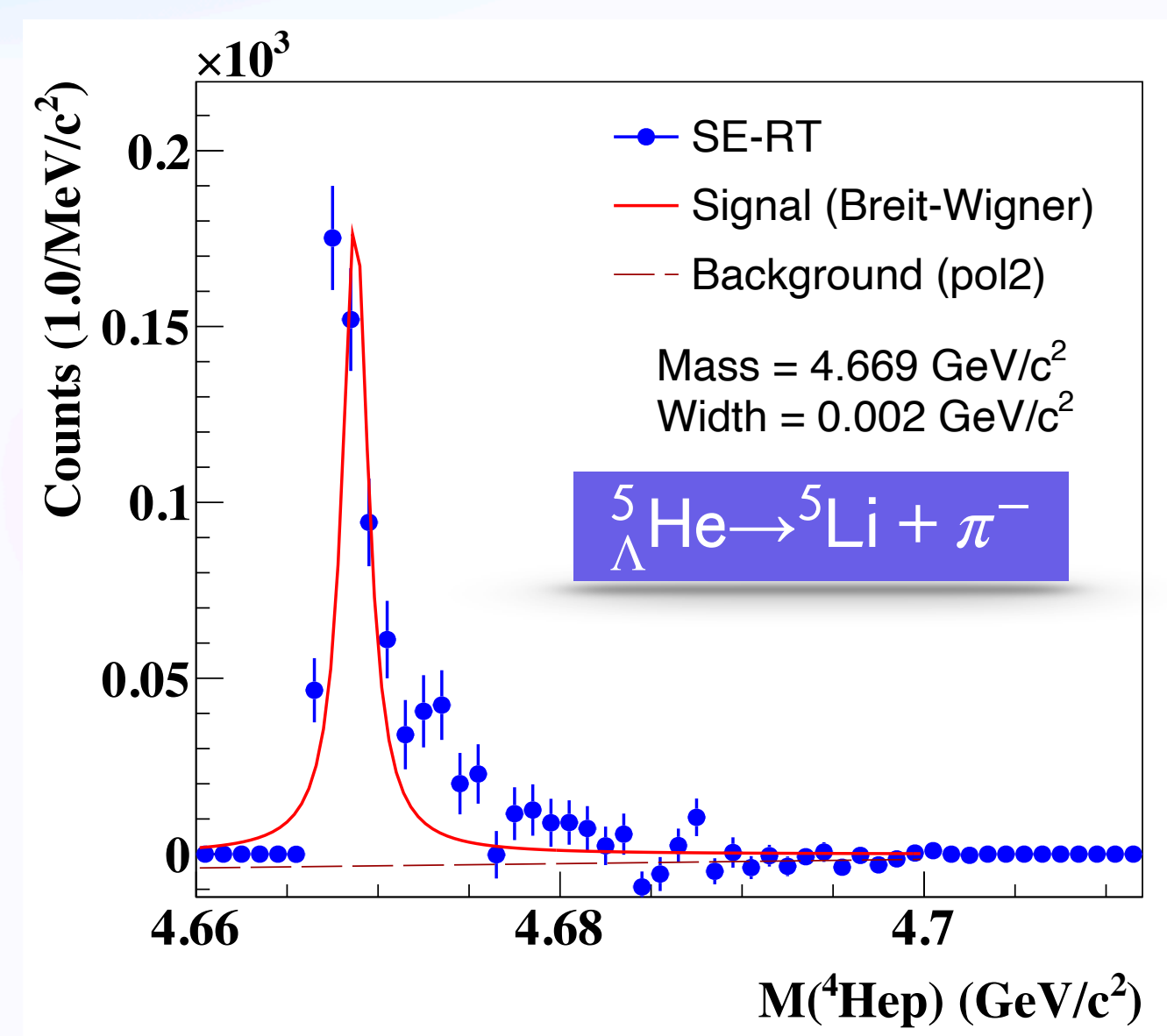
- Hypernuclei are reconstructed using the following decay channels:



Helps to constrain Λ -N and Λ NN

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

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

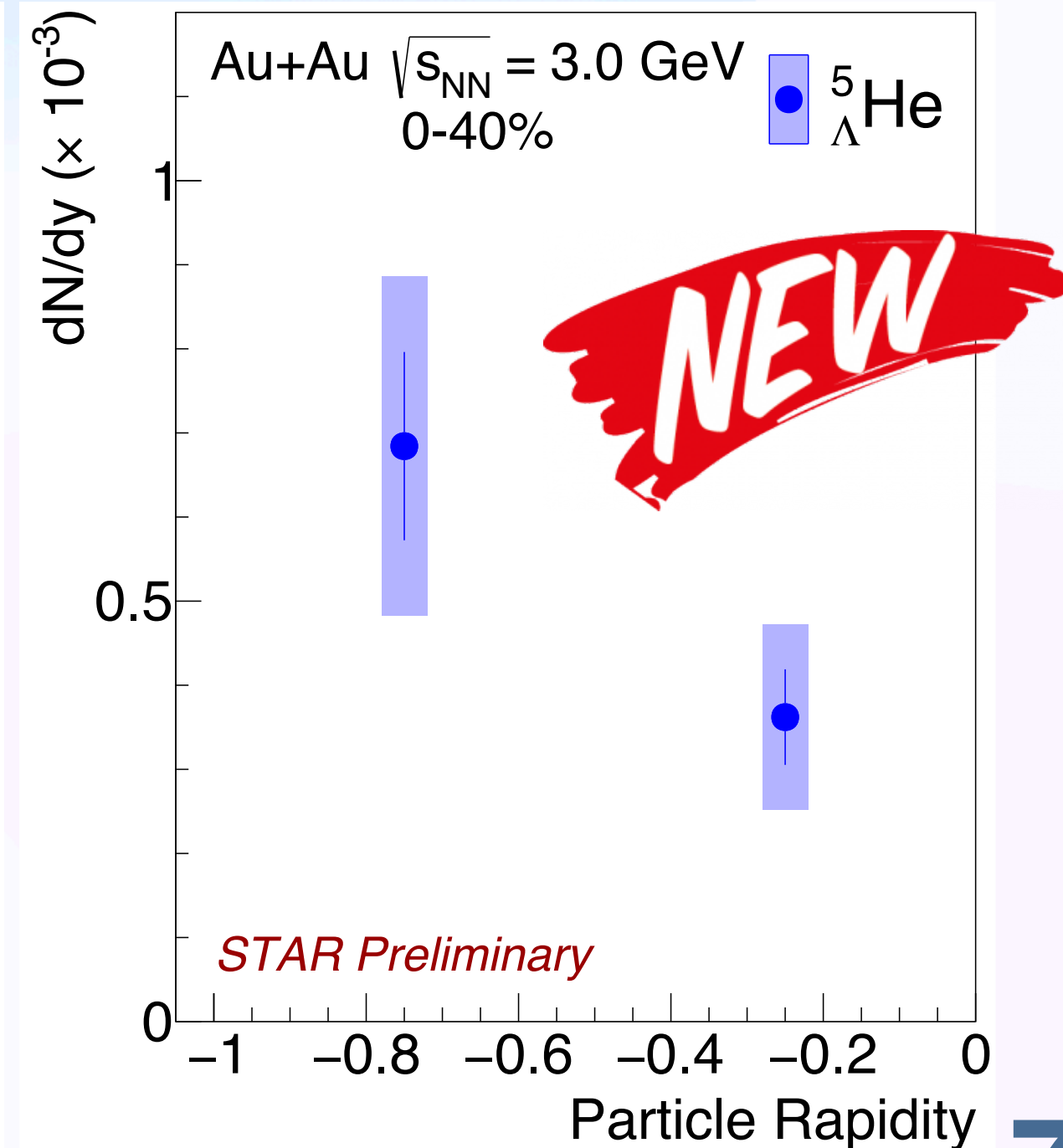
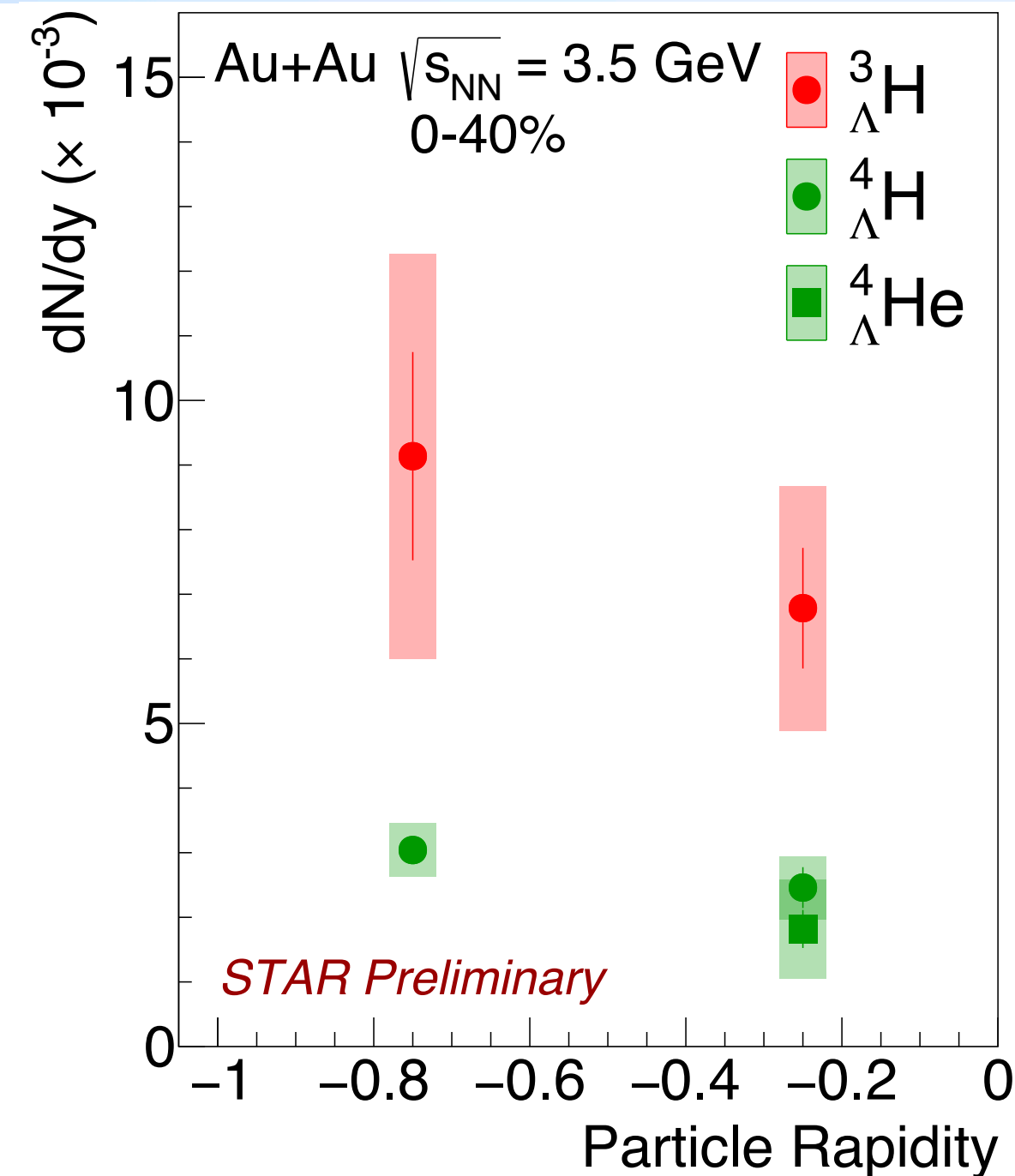
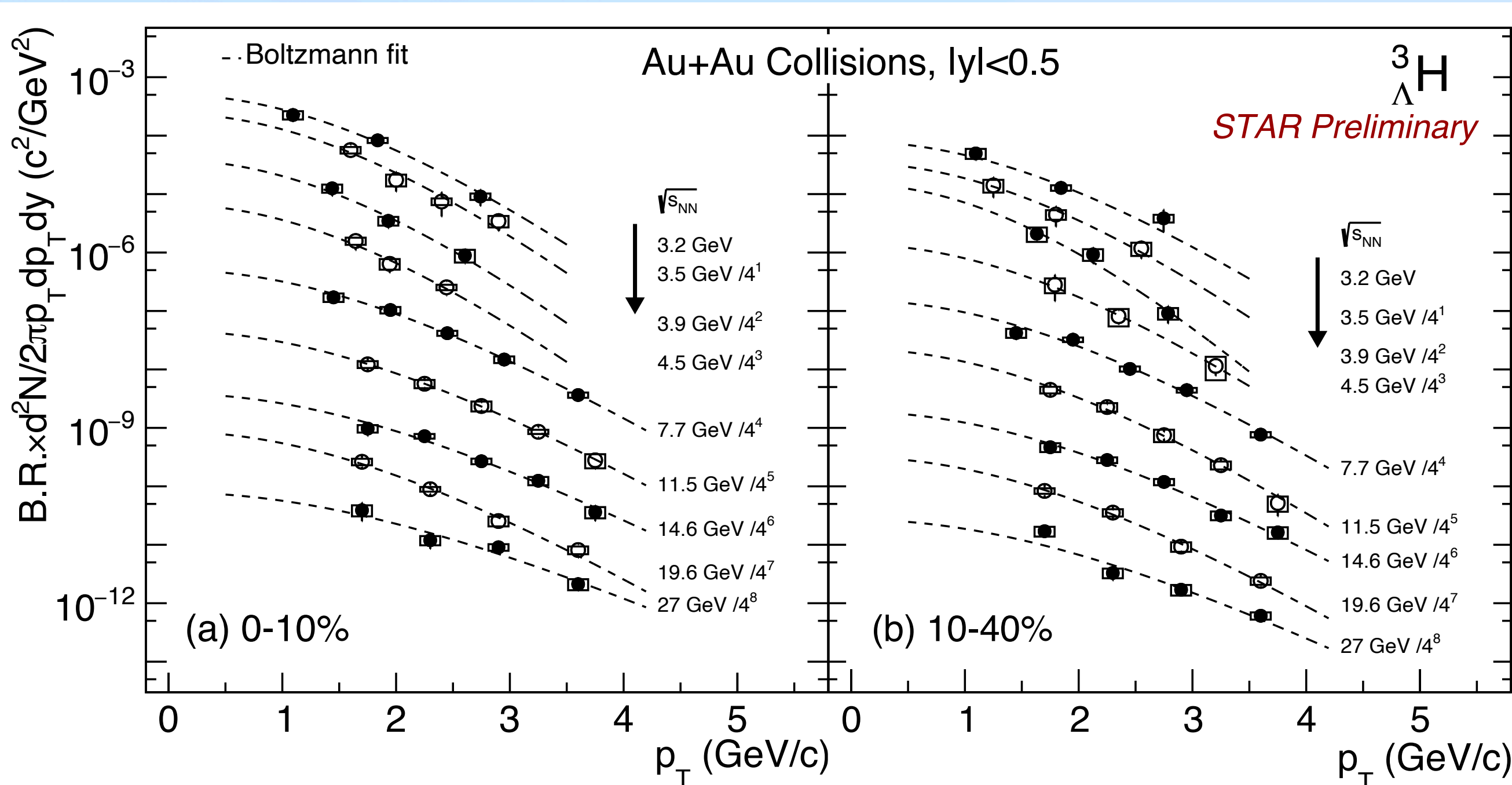


Hypernuclei p_T Spectra and Rapidity

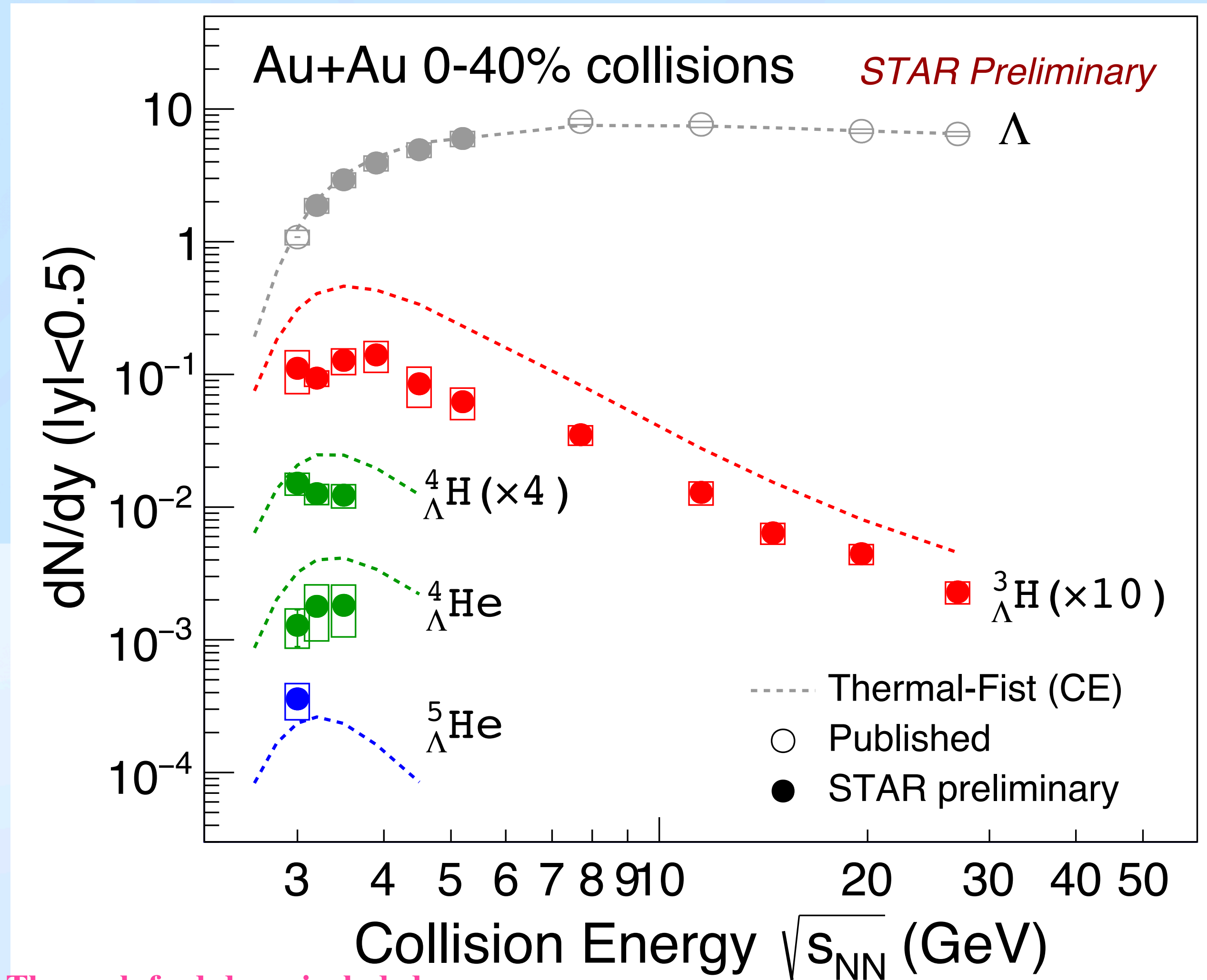
- Measurements cover different energies
 - ${}^3_{\Lambda}\text{H}$ in Au+Au collisions at **3-27 GeV**, Au+Au collisions at **200 GeV**
 - ${}^4_{\Lambda}\text{H}$, ${}^4_{\Lambda}\text{He}$ in Au+Au collisions at **3-3.5 GeV**
 - ${}^5_{\Lambda}\text{He}$ in Au+Au collisions at **3 GeV**
- Significant hypernuclei production at target rapidity, more pronounced for heavier hypernuclei
Spectator matter matters at target rapidity

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

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



Excitation Function



Thermal: feed-down included

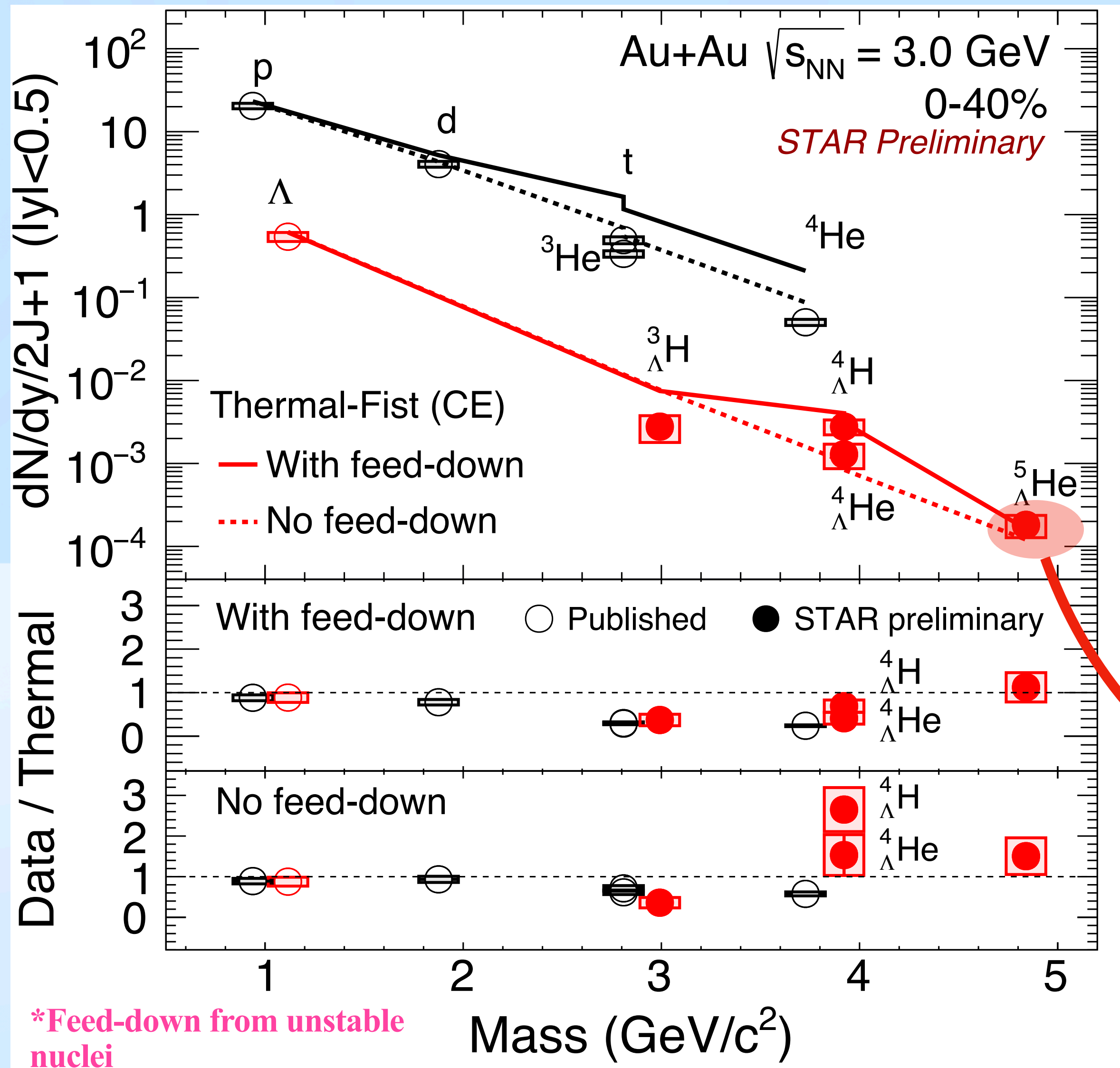
- ${}^3_{\Lambda}\text{H}$ plateaus at $\sqrt{s_{NN}} = 3\text{-}4$ GeV
- Similar trend for ${}^4_{\Lambda}\text{H}$ and ${}^4_{\Lambda}\text{He}$

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***

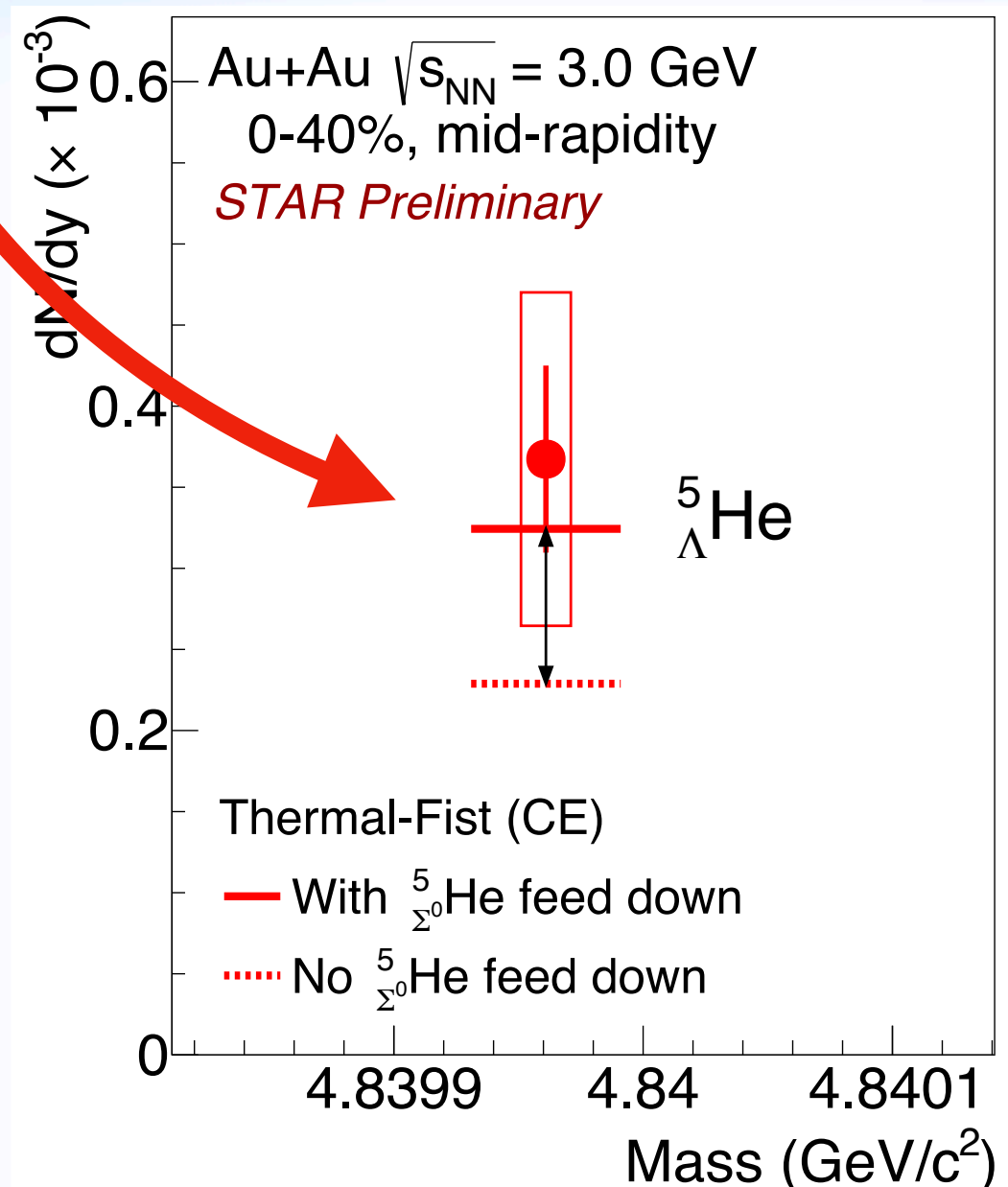
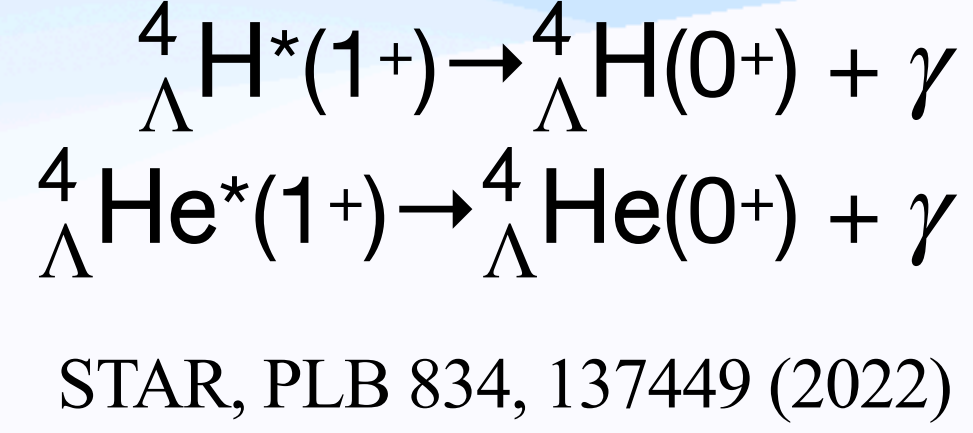
- Thermal describes Λ , **over-estimate** ${}^3_{\Lambda}\text{H}$, ${}^4_{\Lambda}\text{H}$, and ${}^4_{\Lambda}\text{He}$, slightly **under-estimate** ${}^5_{\Lambda}\text{He}$

Comparison to Thermal Model at 3 GeV



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

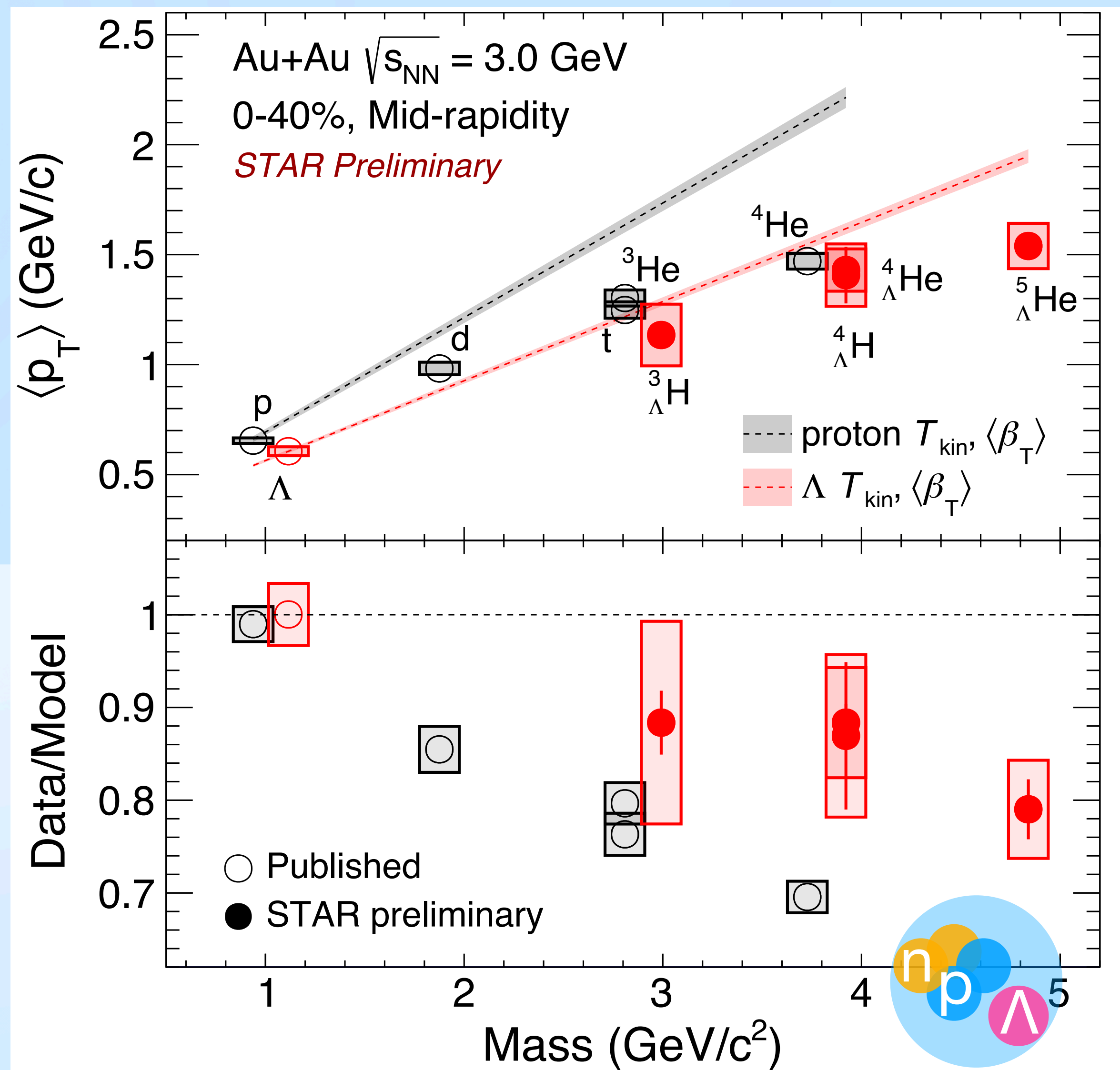
- Thermal model predicts approx. exponential dependence of yields/(2J+1) vs A
- Light nuclei overestimated by thermal with feed-down from unstable nuclei
- Evidence of the formation of $^4_{\Lambda}H$ and $^4_{\Lambda}He$ excited states



- 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



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 $p(\Lambda)$ freeze-out parameters

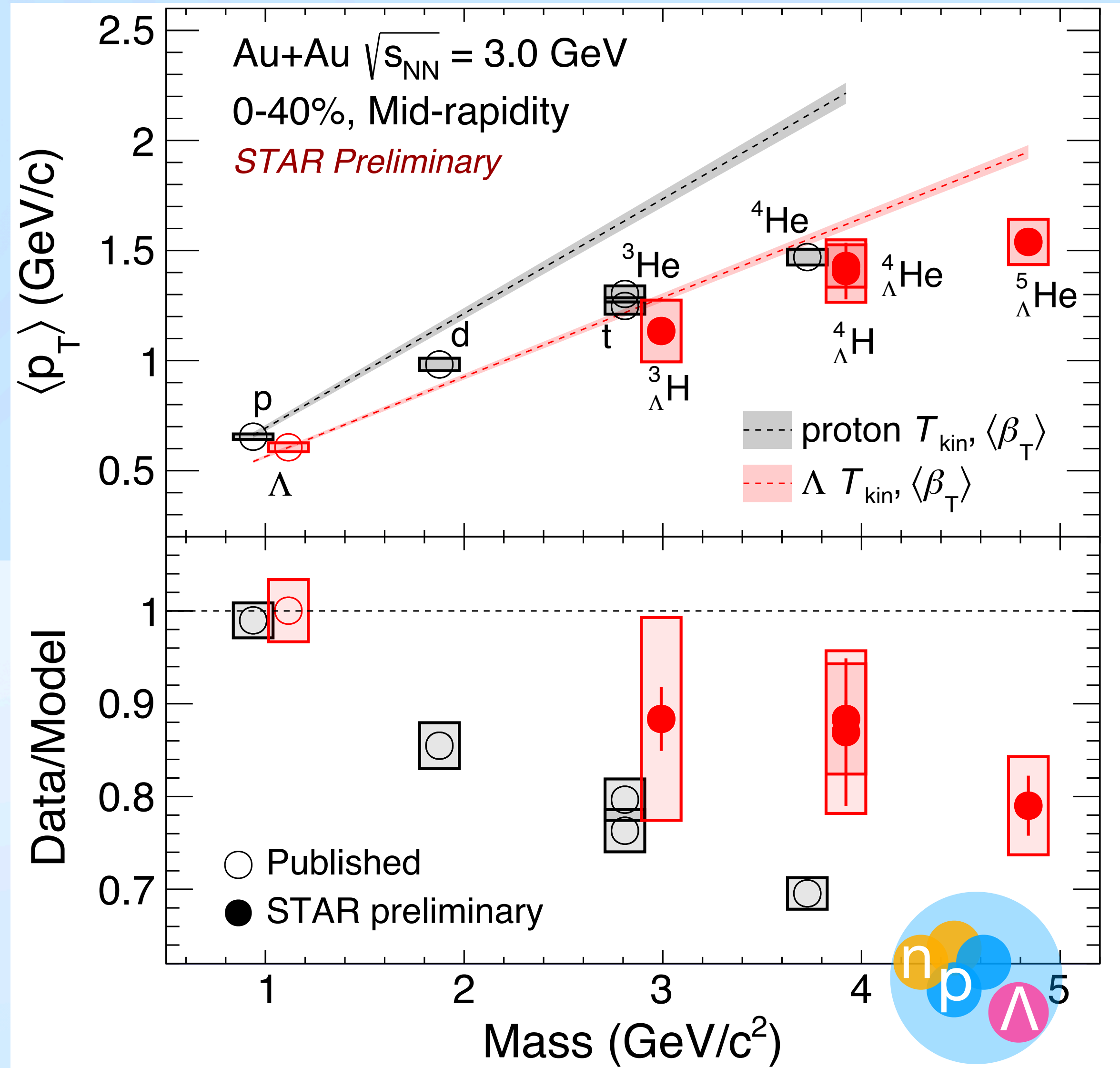
E. Schnedermann et al., PRC 48, 2462 (1993)
ALICE, PLB 794, 50–63 (2019)

- Light nuclei and hypernuclei deviate from the full hydrodynamic picture

Coalescence scenario?

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

Mean Transverse Momentum at 3 GeV

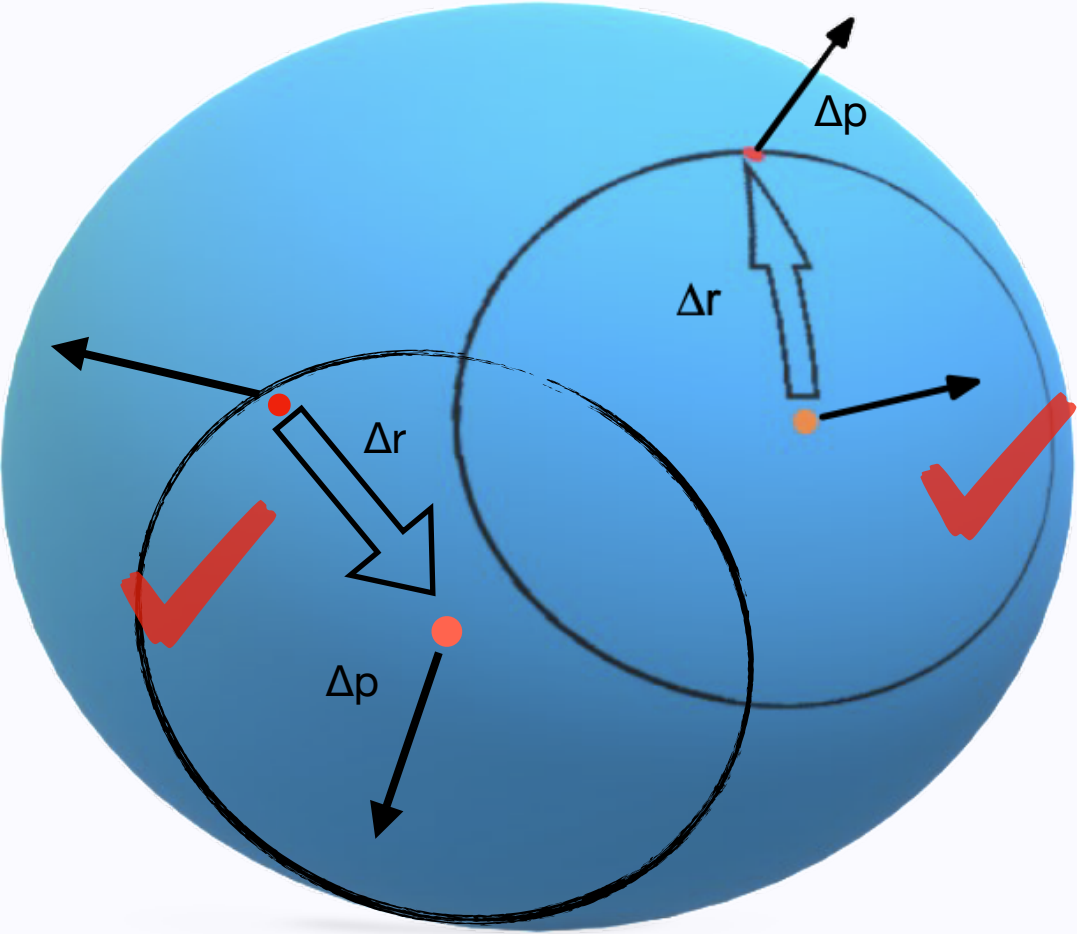


STAR, PRC 110, 054911 (2024)
 STAR, PRL 128, 202301 (2022)
 STAR, JHEP **2024** (2024)139

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** coalesce to nuclei, leading to **smaller $\langle p_T \rangle$** than if perfectly aligned
 2. Heavier (hyper)nuclei → Large deviation from blast wave ansatz

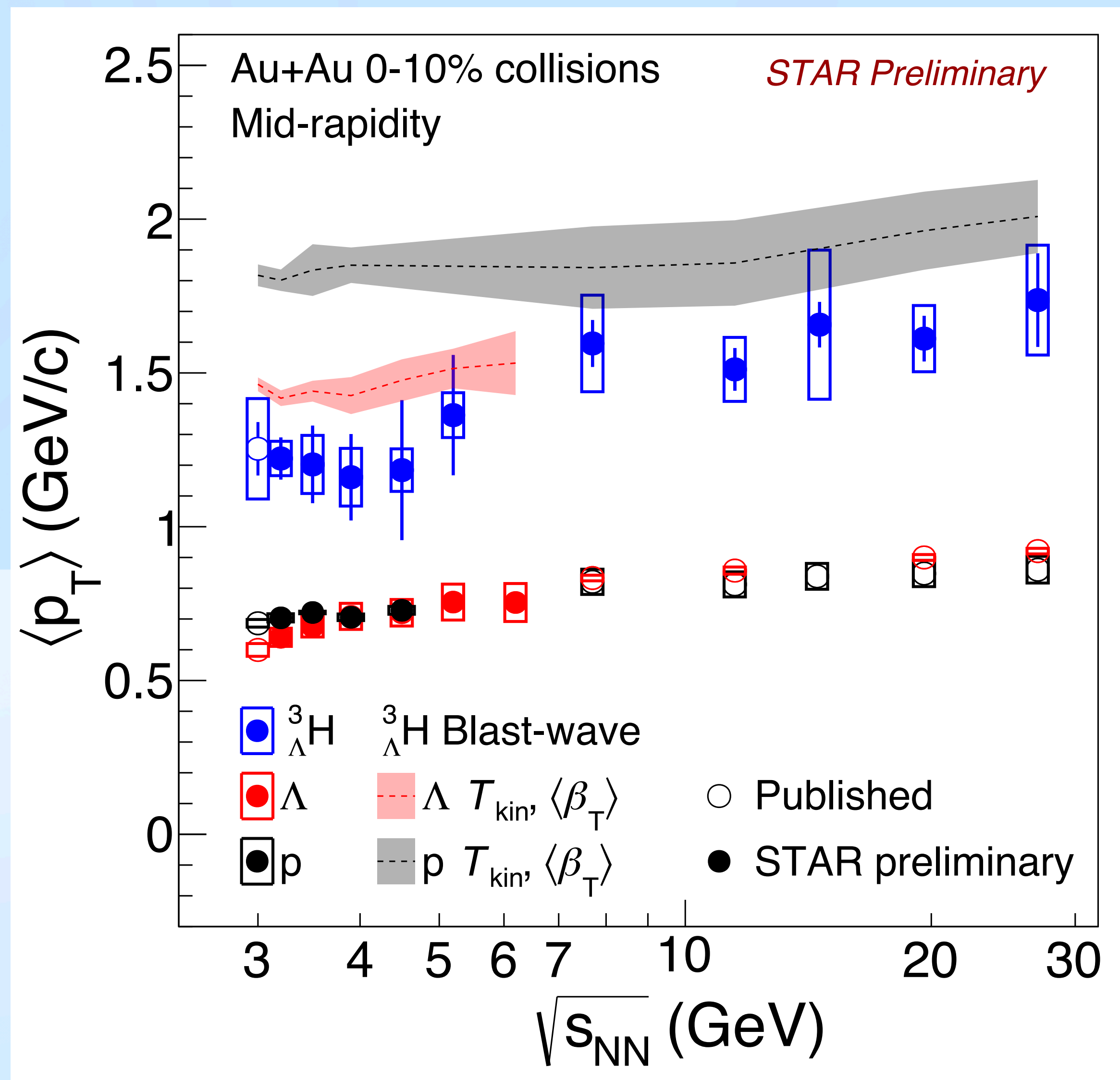
A. I. Sheikh et al., PRC 106, 054907 (2022)



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

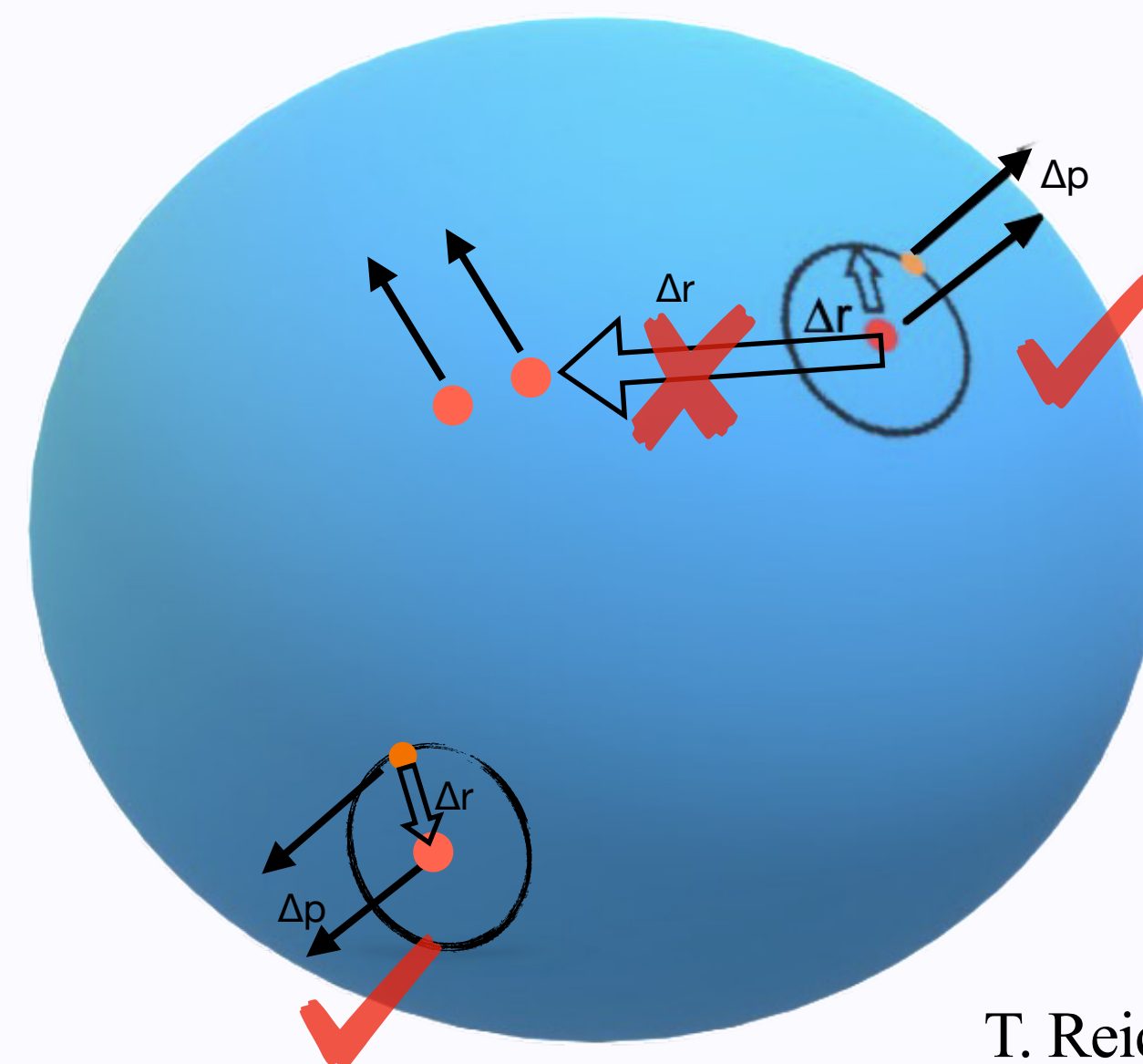
T. Reichert, SQM 2022, slides (2022)

Mean Transverse Momentum v.s. Collision Energy



- At $\sqrt{s_{NN}} \geq 7.7$ GeV, ${}^3_{\Lambda}\text{H}$ $\langle p_T \rangle$ 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

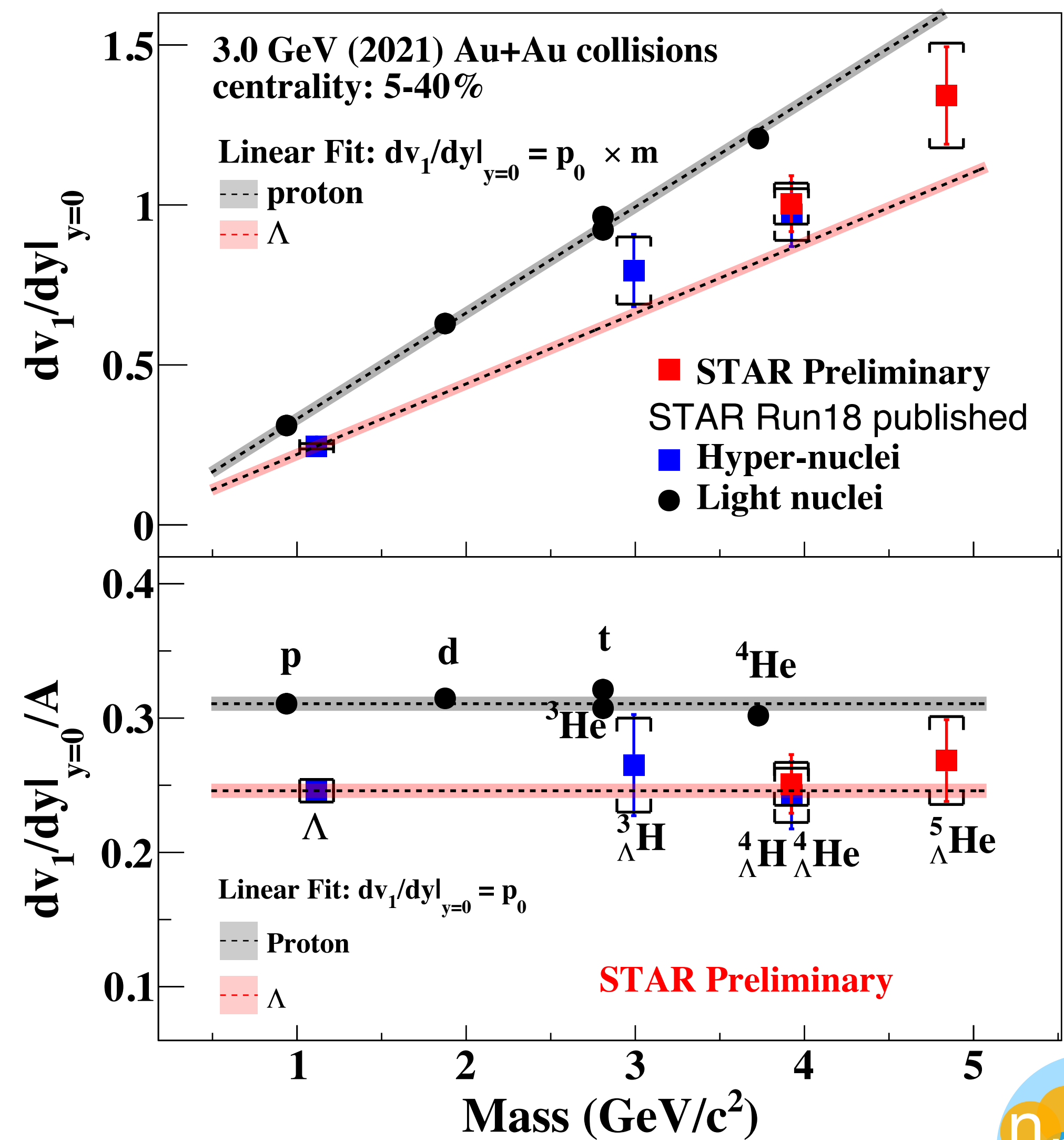


Large effective volume nucleon's r and p are correlated

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)



Coalescence-inspired sum rule: flow of hypernuclei = $N_{\text{nucleon}} \times \text{nucleon } v_1 + N_\Lambda \times \Lambda v_1$

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

- 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
 1. Reflects the weaker directed flow of the Λ
 2. Heavier hypernuclei → Closer to same- A light nuclei flow, Λ 's weaker flow less visible

Qualitatively consistent with coalescence formation of hypernuclei



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 ${}^3_{\Lambda}\text{H}$, ${}^4_{\Lambda}\text{H}$, and ${}^4_{\Lambda}\text{He}$, and slightly underestimates ${}^5_{\Lambda}\text{He}$
 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. Directed flow qualitatively consistent with coalescence model

Outlook:

- High statistics 3 GeV FXT data: more precise measurement of $A < 5$ hypernuclei, ${}^5_{\Lambda}\text{He}$ 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

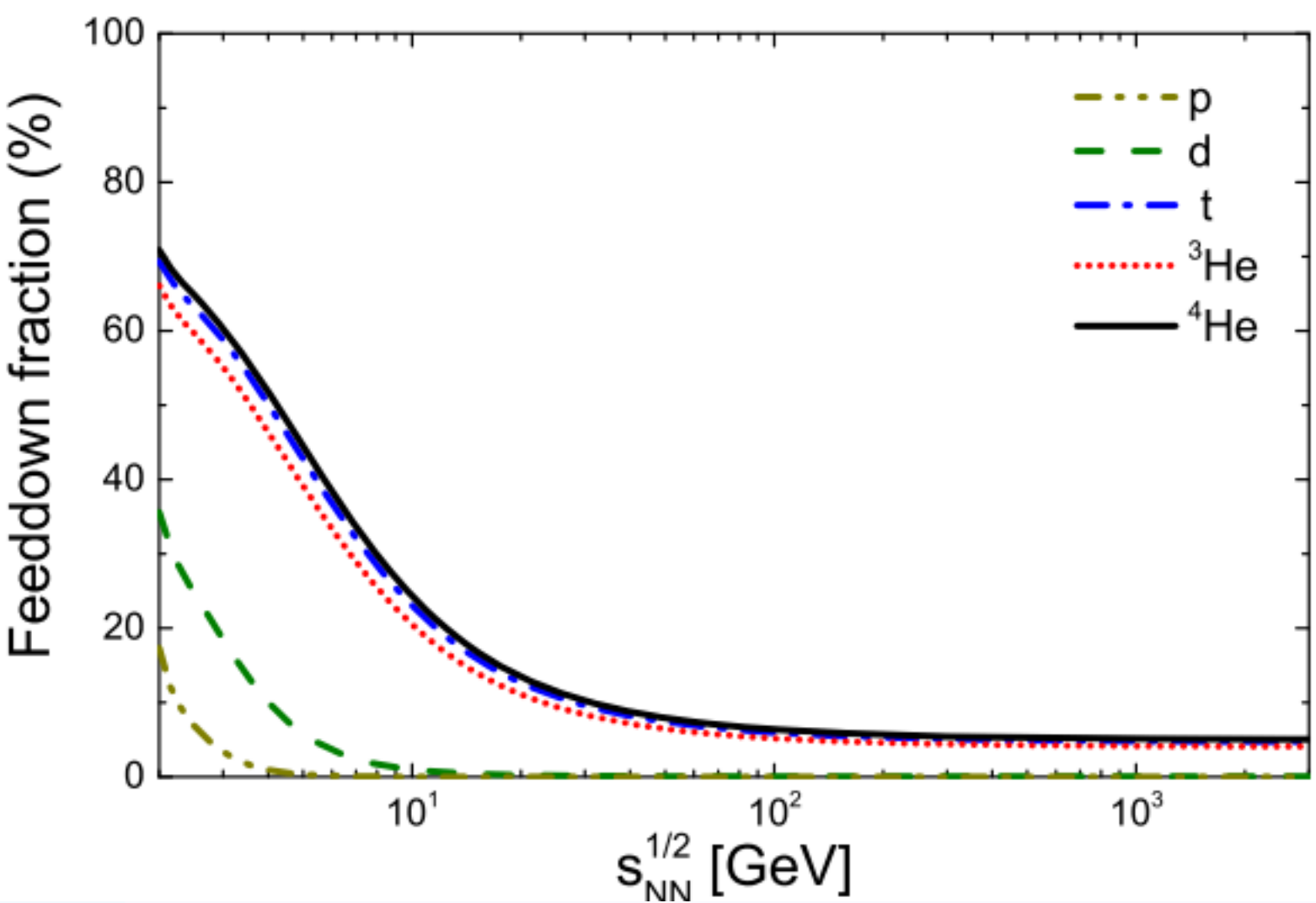
Backup Slides Follow

Feed-down from Unstable Nuclei

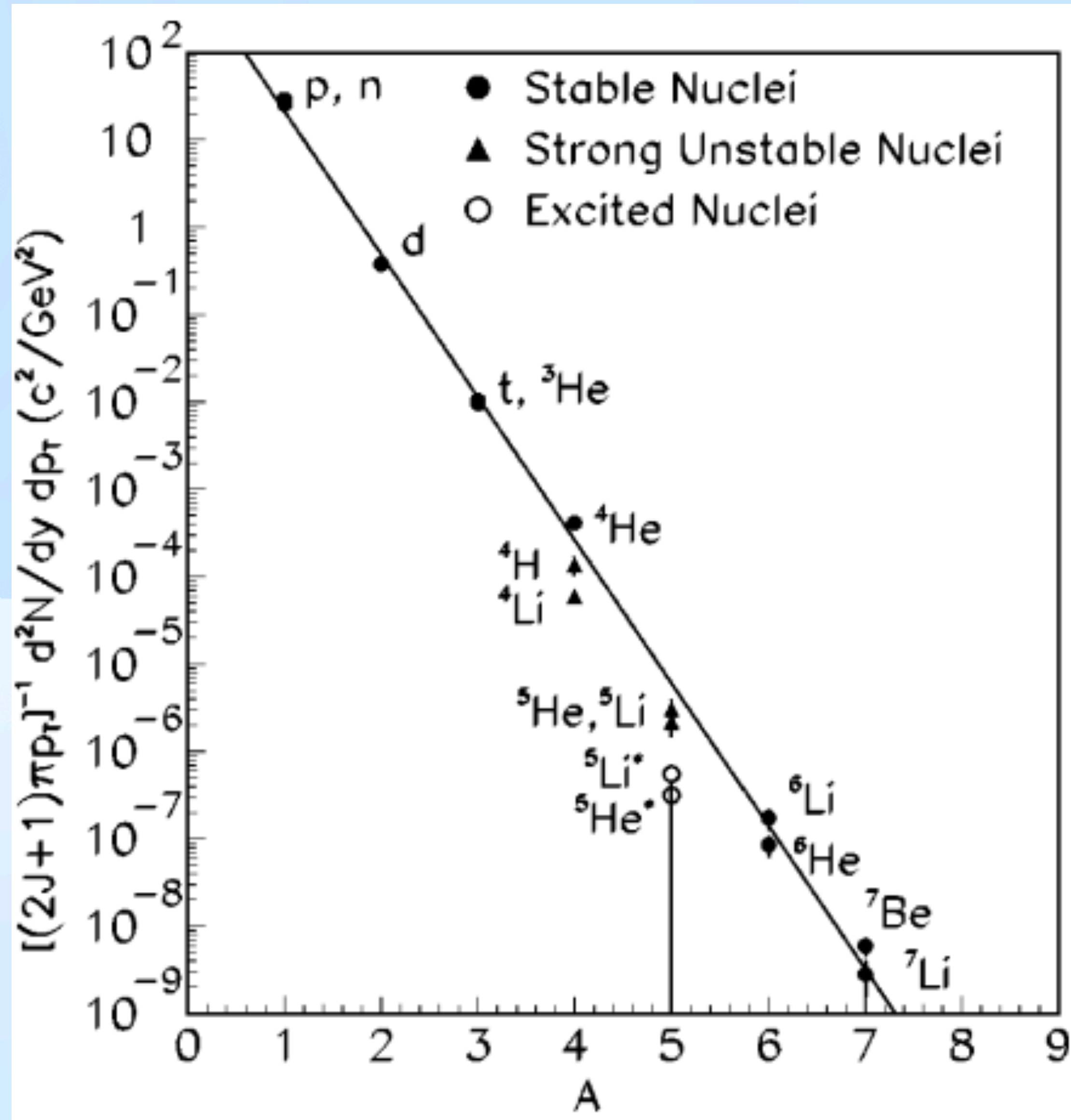
$A = 4$	E_x (MeV)	J^π	Decay channels
${}^4\text{H}$	g.s.	2^-	n(100%)
	0.31	1^-	n(100%)
	2.08	0^-	n(100%)
	2.83	1^-	n(100%)
${}^4\text{He}$	g.s.	0^+	stable
	20.21	0^+	p(100%)
	21.01	0^-	n(23.8%), p(76.2%)
	21.84	2^-	n(37.3%), p(62.7%)
	23.33	2^-	n(47.3%), p(52.7%)
	23.64	1^-	n(44.5%), p(55.5%)
	24.25	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%)
${}^4\text{Li}$	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 ${}^5\text{H} \rightarrow \text{t} + \text{n} + \text{n}$, ${}^5\text{He} \rightarrow {}^4\text{H} + \text{p}$, ${}^5\text{He} \rightarrow \text{t} + \text{d}$, ${}^5\text{Li} \rightarrow {}^4\text{He} + \text{p}$, and ${}^5\text{Li} \rightarrow {}^4\text{Li} + \text{n}$ 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
${}^5\text{H}$	g.s.	$\frac{1}{2}^+$	2n(100%)
${}^5\text{He}$	g.s.	$\frac{3}{2}^-$	n(100%)
	1.27	$\frac{1}{2}^-$	n(100%)
	16.84	$\frac{3}{2}^+$	n(60%), d(40%)
${}^5\text{Li}$	g.s.	$\frac{3}{2}^-$	p(100%)
	1.49	$\frac{1}{2}^-$	p(100%)
	16.87	$\frac{3}{2}^+$	p(70%), n(30%)



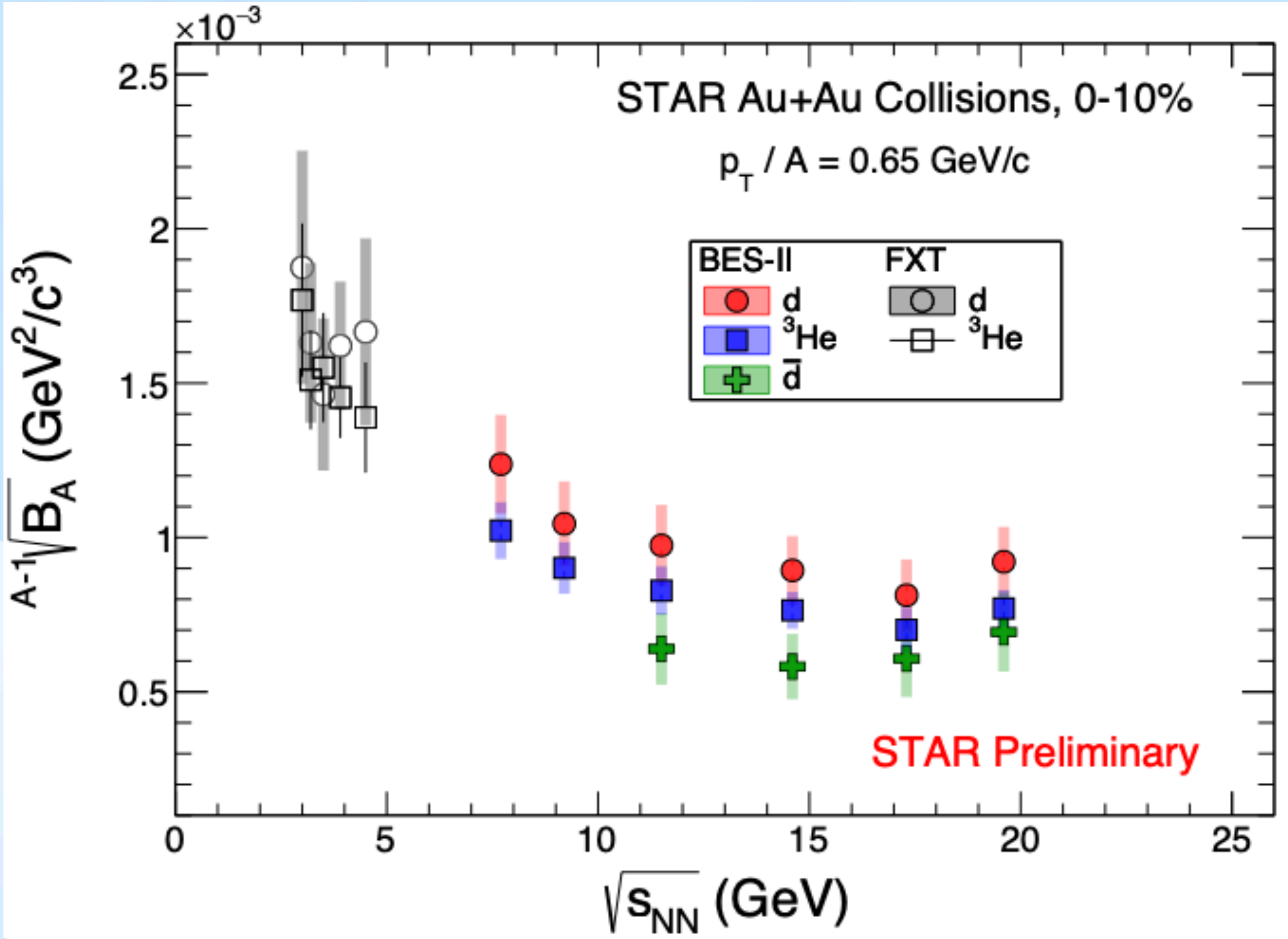
Feed-down from Unstable Nuclei



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

Coalescence Parameters

See poster by Yixuan Jin (xx/xx)

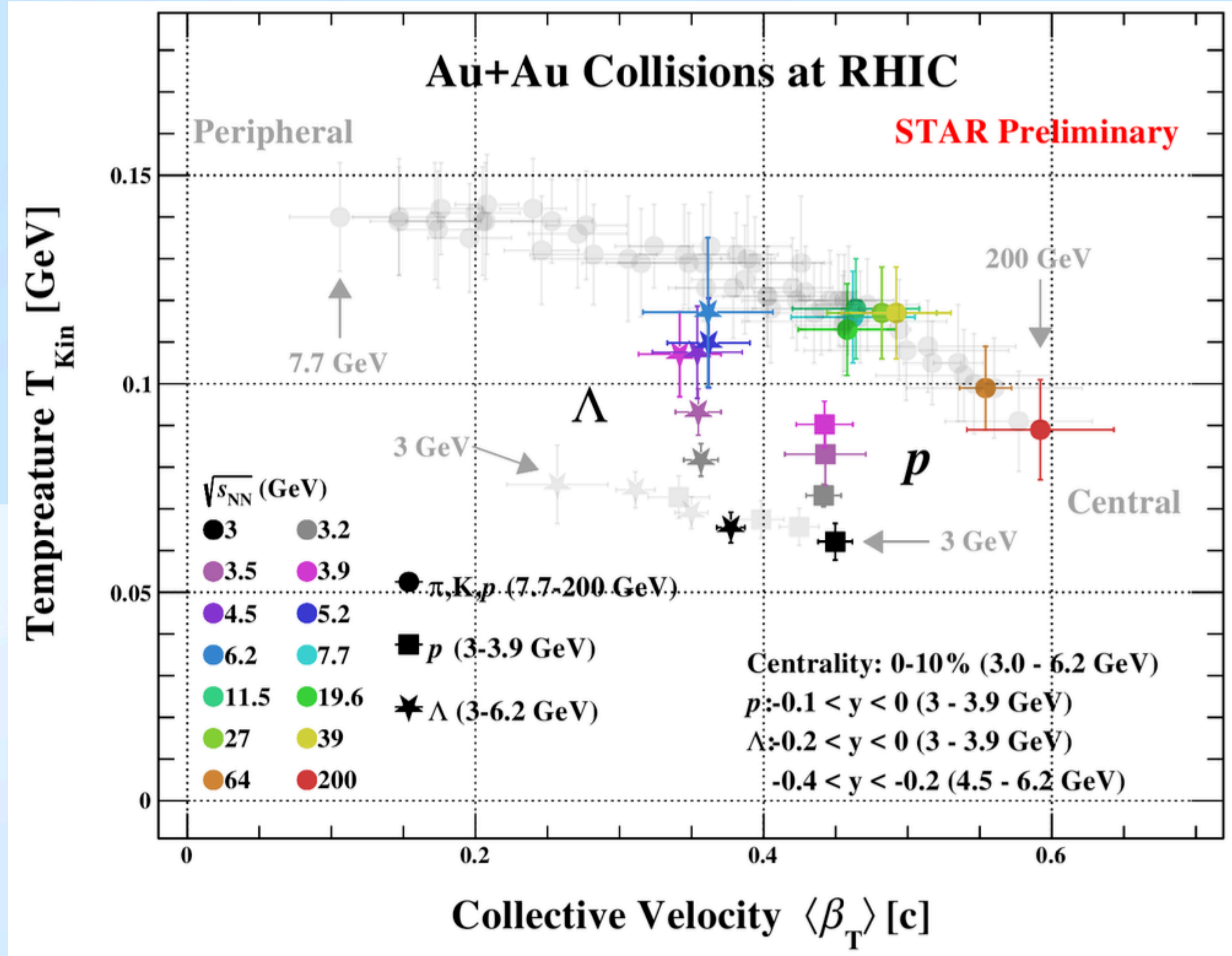


- B_A decrease with increasing energy due to the larger effective volume

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

Kinetic Freeze-out Parameters

See talk by Hongcan Li (xx/xx)



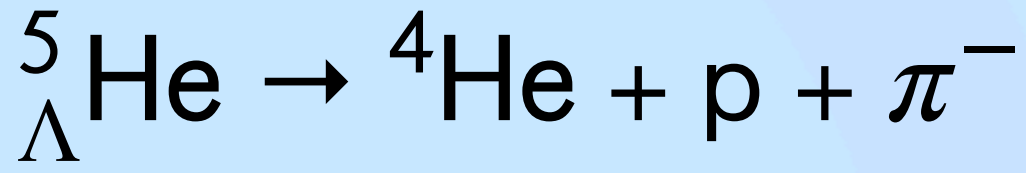
- At $\sqrt{s_{NN}} < 3.9$ GeV, data show $\langle \beta_T \rangle^\Lambda < \langle \beta_T \rangle^p$ with similar kinetic freeze out temperature
 - Possibly due to different production mechanism

Λ : produced
proton: transported + produced

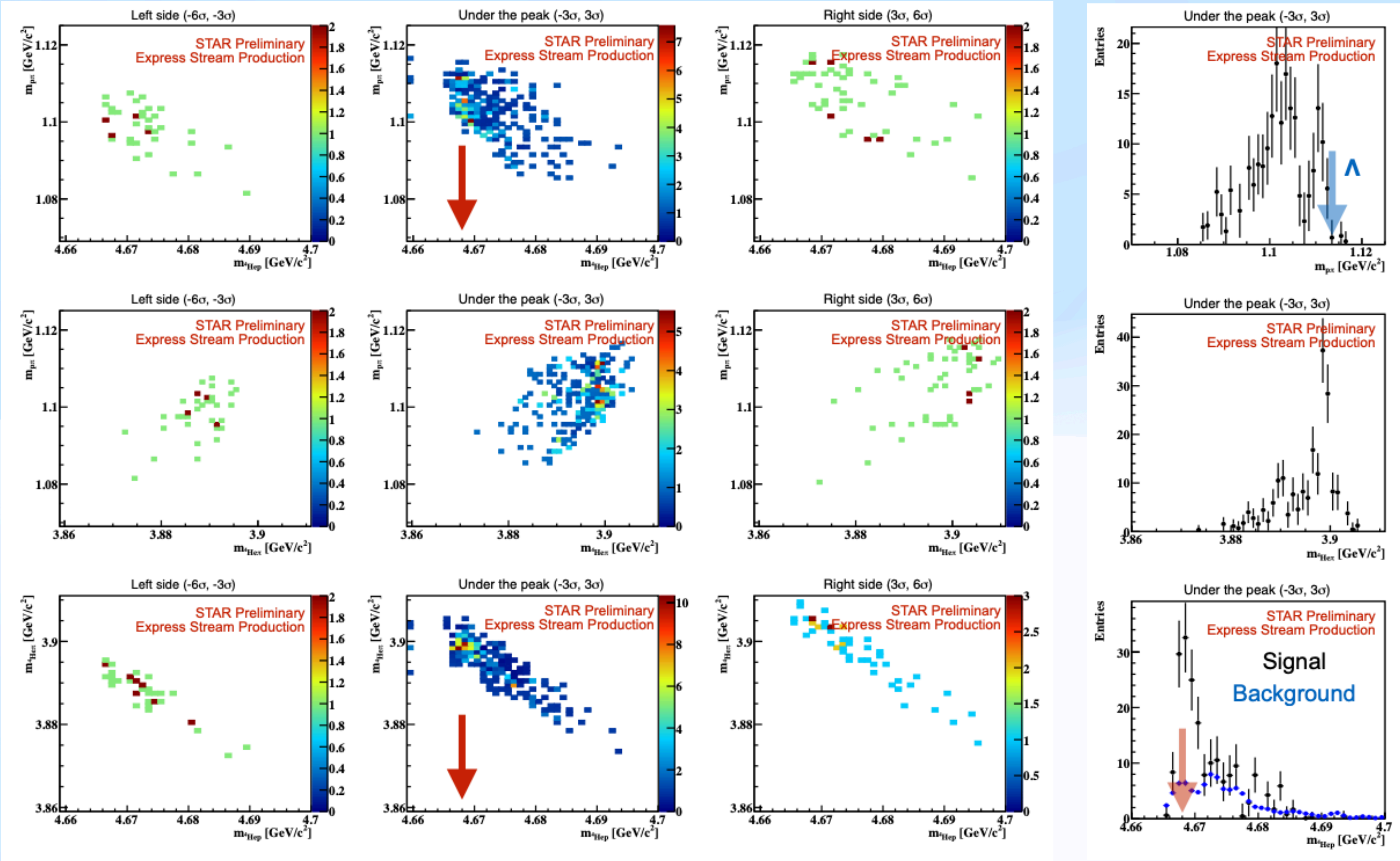
freeze out from more outward-moving regions $\rightarrow$ larger $\langle \beta_T \rangle$

- Hadronic transport model UrQMD model qualitatively reproduces the trend at 3 - 6.2 GeV

Dalitz Plots



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



- Observed 2-body ${}^5\text{Li}\pi$ decay (${}^5\text{Li}$: $M = 4.668$ GeV, $\sigma = 2.2$ MeV)

Signal Extraction

Mixing Event

Rotation background

Significance

Thermal Model

<Npart> scaling

See talk by Hongcan Li (xx/xx)

