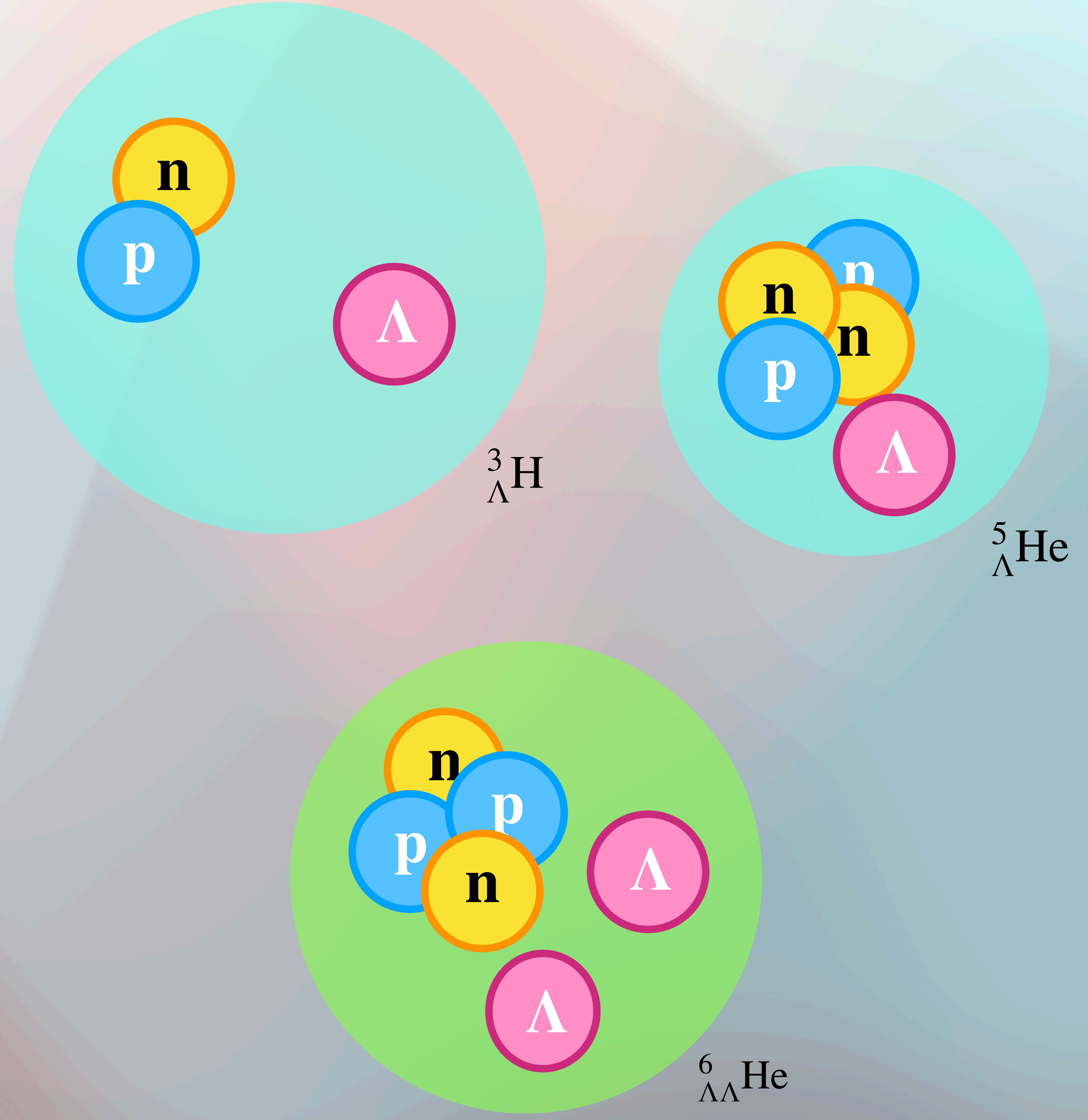
Hypernuclei Production and Collectivity (at high net baryon densities)

Some slides are taken from Y. Zhou (STAR), QM2025



Physics of High net-baryon Densities (PHD2025)

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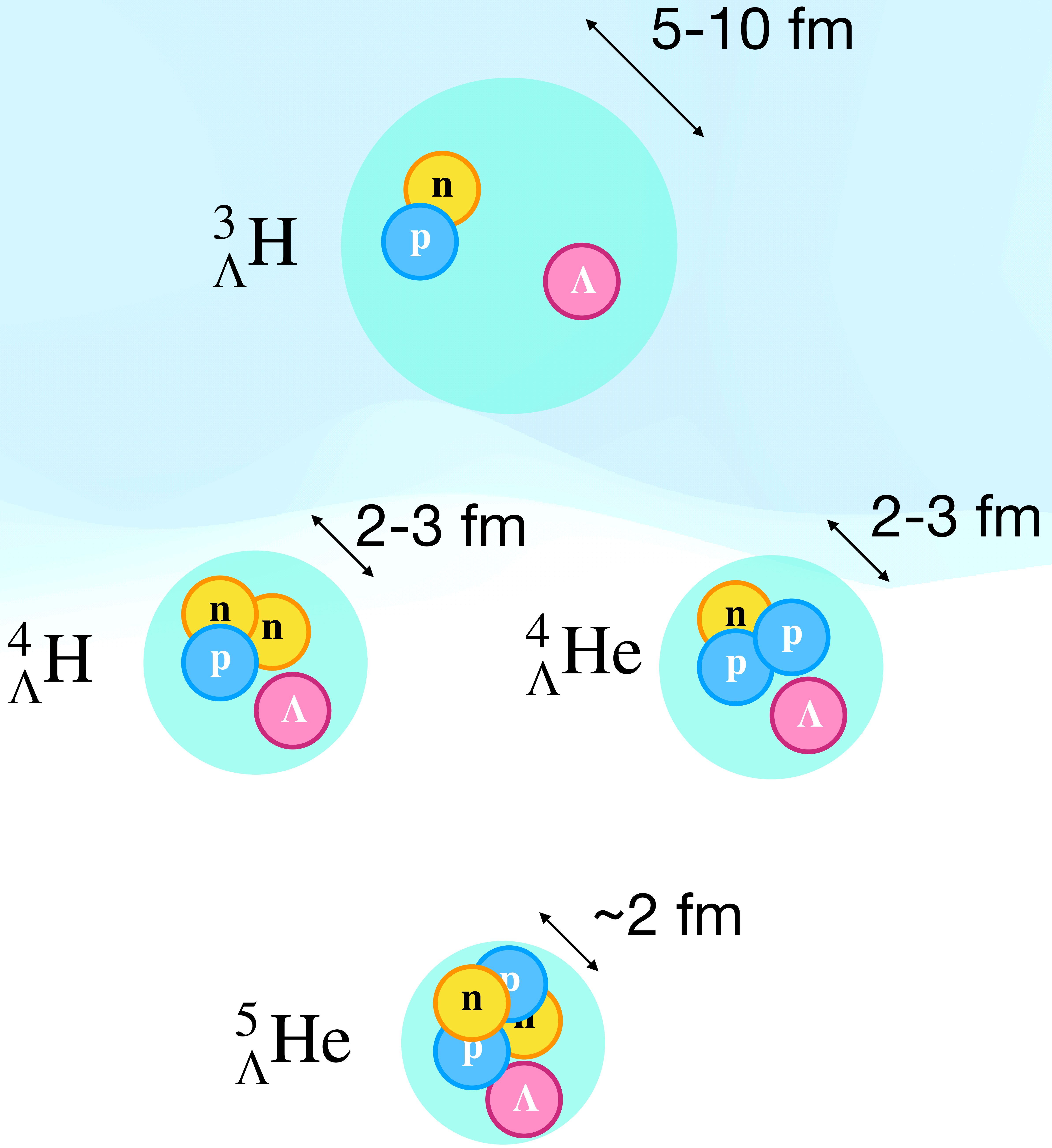
20th May, 2023

Outline

- Introduction
- Thermal model and Coalescence model
- Production at Lower Collision Energies
    - Production Yields
    - Transverse Momentum Distributions
    - Directed Flow
- Production at Higher Collision Energies
- Summary
- Motivation and Outlook

Introduction

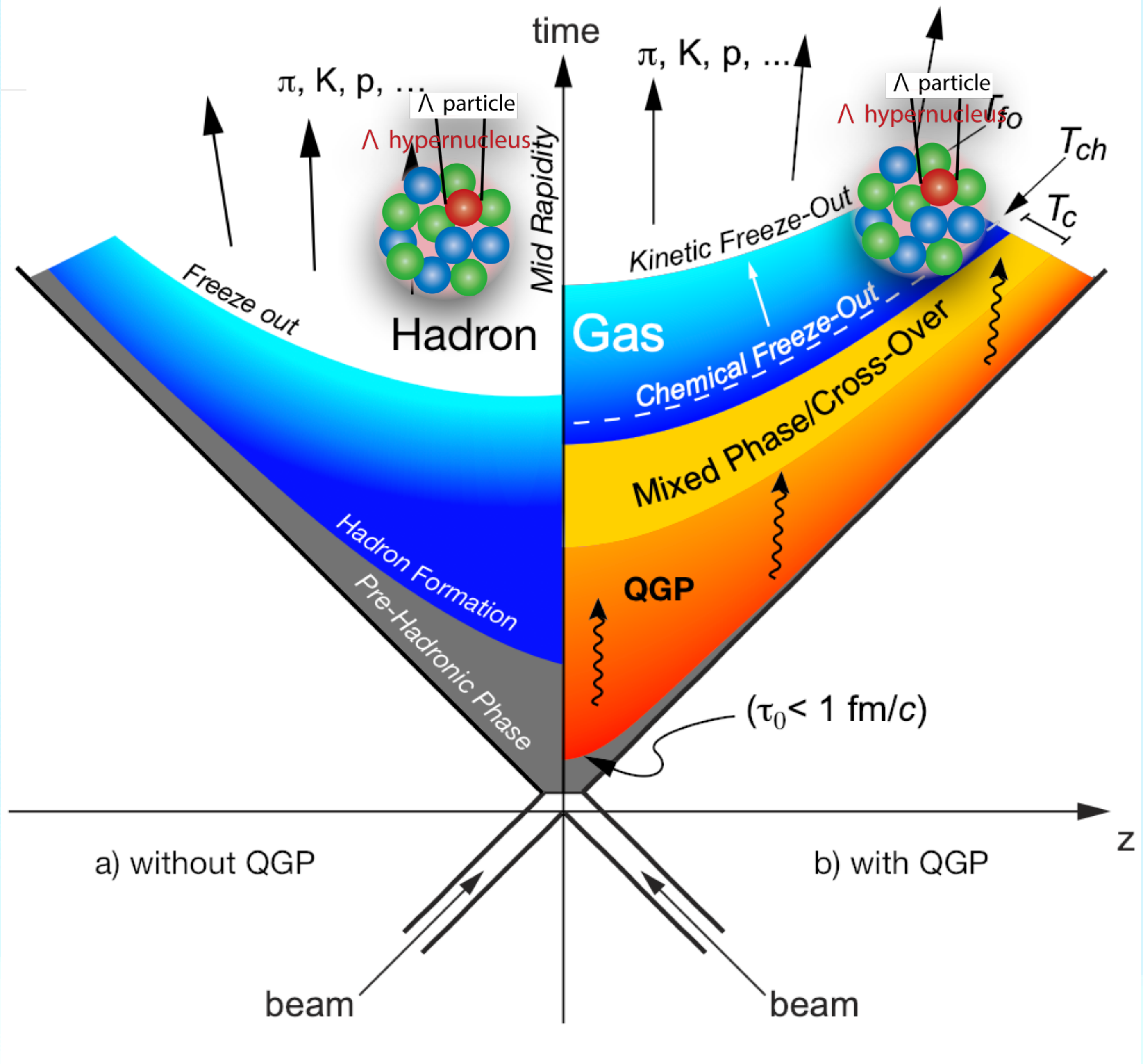
- Hypernuclei: Bound states containing one or more hyperons
- Loosely bound objects, radii comparable to size of fireball
- Production mechanisms under debate

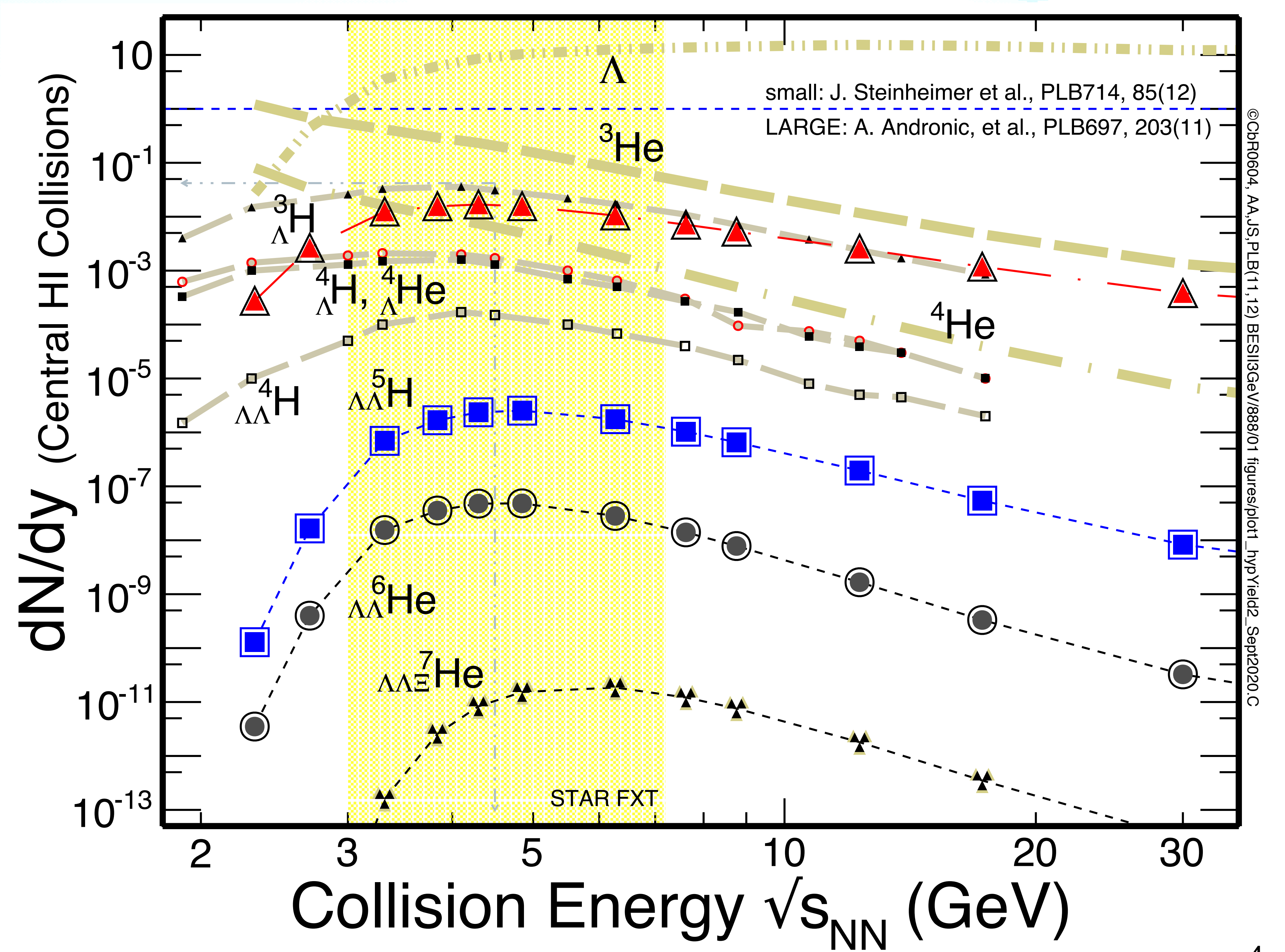


Thermal Model

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

- <u>Grand Canonical Ensemble</u>
  - Only three parameters used to describe particle yields
    - chemical freeze-out temperature T_{ch}
    - baryo-chemical potential μ_B
    - volume V
- **<u>Strangeness Canonical Ensemble</u>**
  - strangeness correlation length r_C



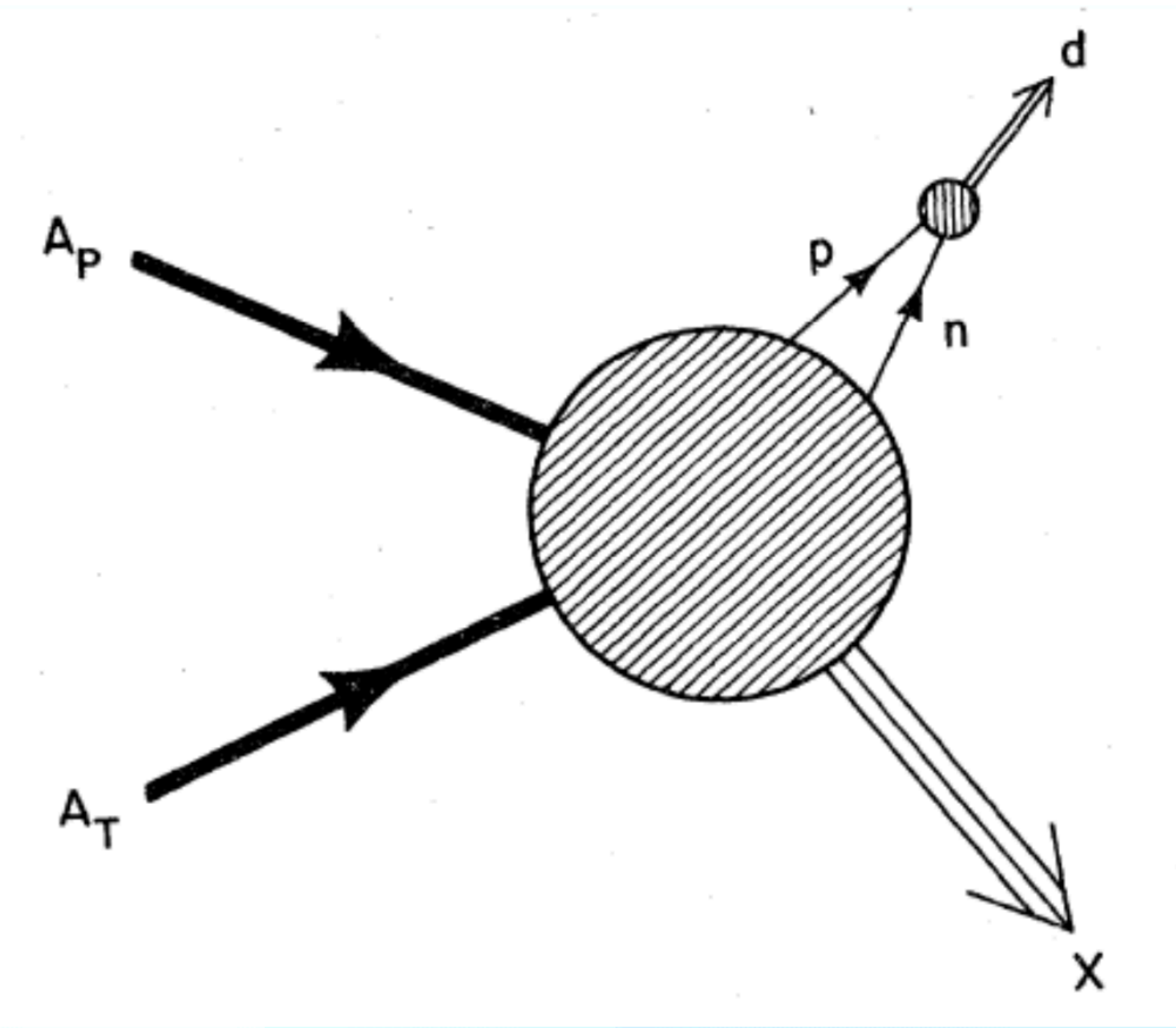


Coalescence Model

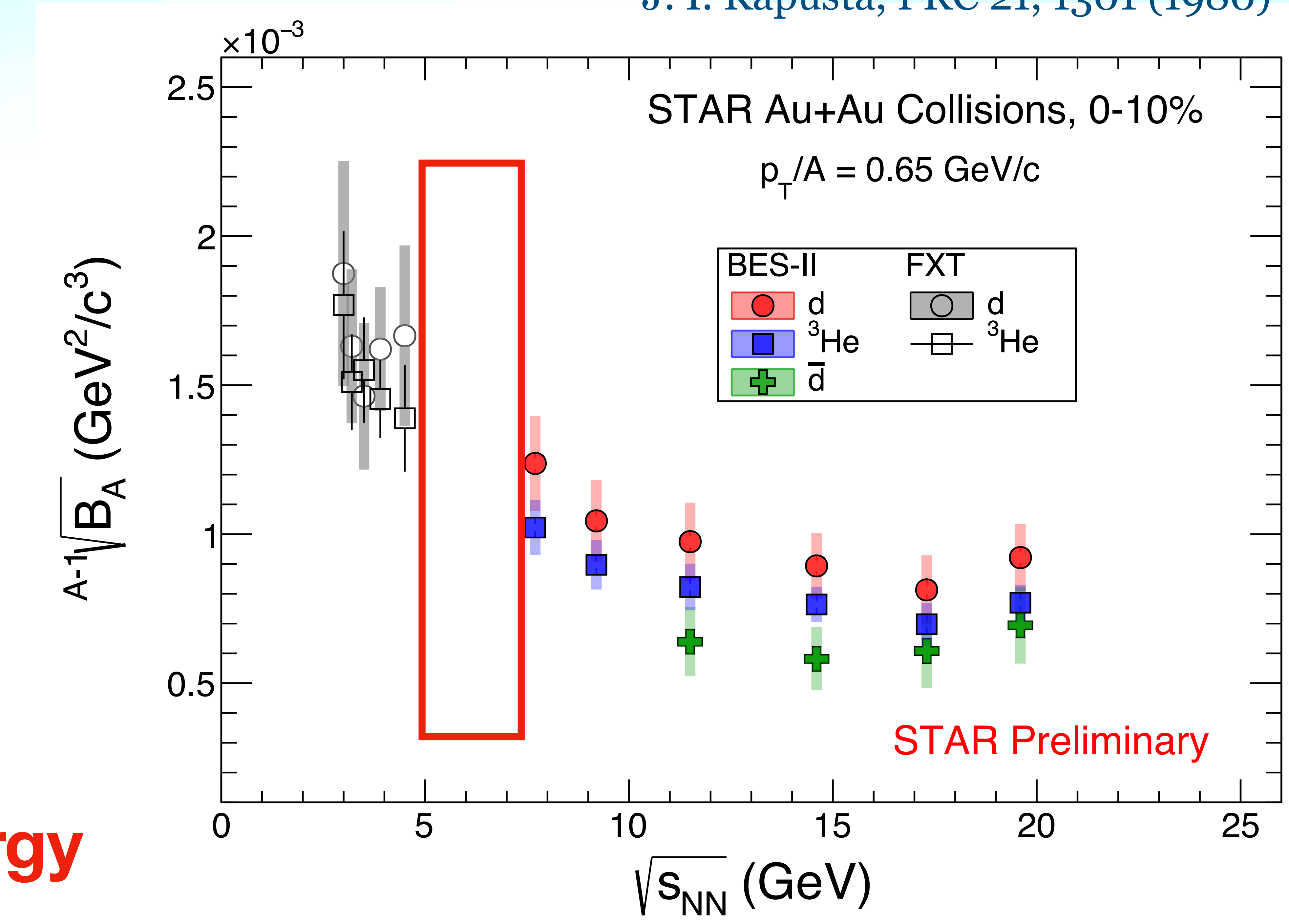
- (Hyper)nuclei are formed by nucleons (and hyperons) which are nearby in phase space after kinetic freeze-out
  - Coalescence with Wigner function formalism
    - Emission source size (phase space region where nucleons can coalesce)
    - Nuclear radius/wavefunction
- Differences b/w thermal and coalescence models for yields and transverse momentum spectra are largest **when emission source size is smaller than the radius of the nuclei**

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

- $B_A \propto (\frac{1}{V_{eff}})^{(A-1)}$, V_{eff} is the emission source volume
  - **Nucleon emission volume increases with collision energy**
  - Decrease of B_A is most noticeable between $\sqrt{s_{NN}}$ = 4.5 and 7.7 GeV



J. I. Kapusta, PRC 21, 1301 (1980)



Y. Jin, QM2025

PHQMD Model

J. Aichelin et al., PRC 101 (2020) 044905

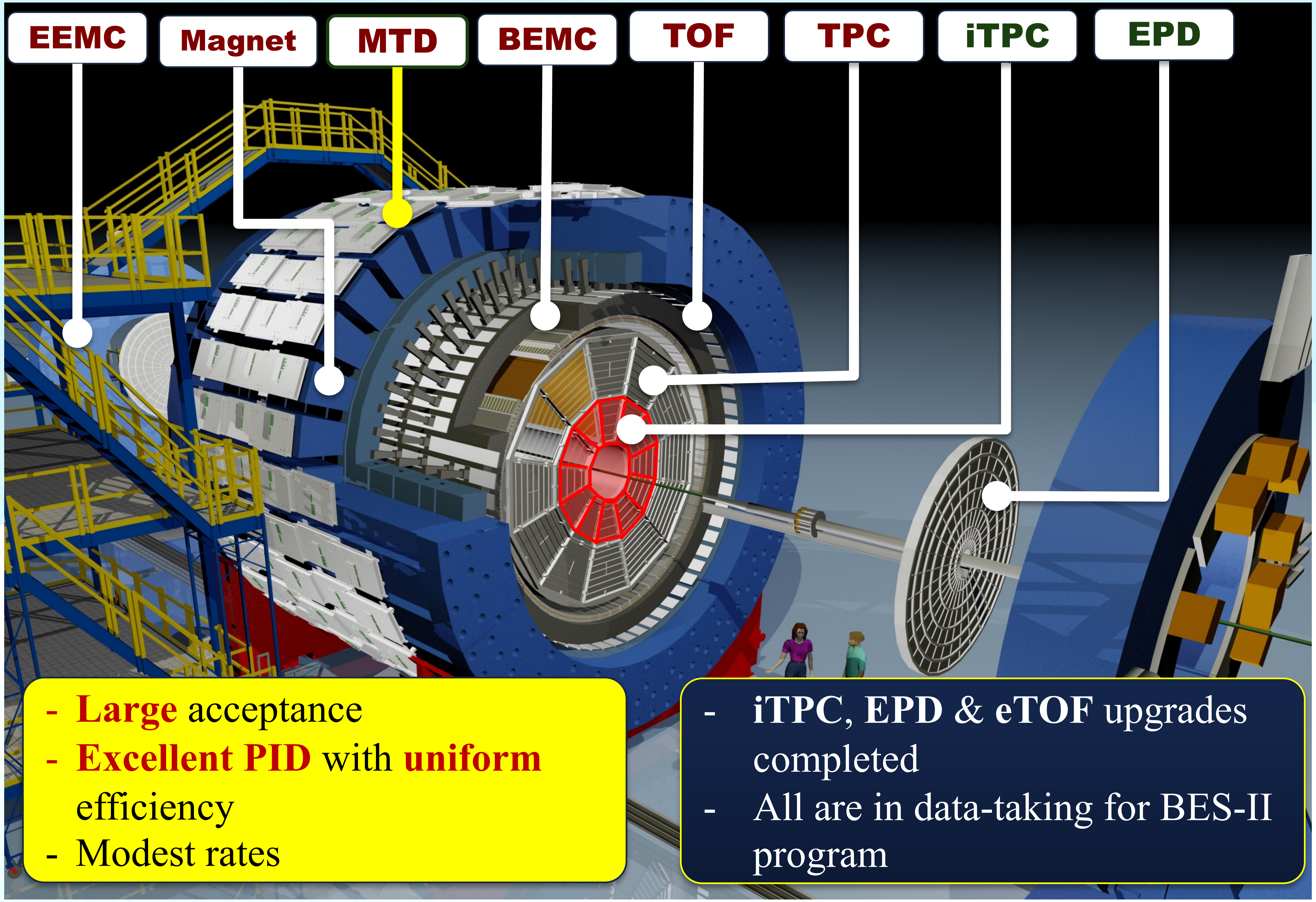
- Parton-Hadron-Quantum-Molecular Dynamics (PHQMD) model: a unified n-body microscopic transport approach for the description of heavy-ion collisions and dynamical cluster formation

- Dynamical modelling of cluster formation based on interactions

  - MST (Minimum Spanning Tree) algorithm

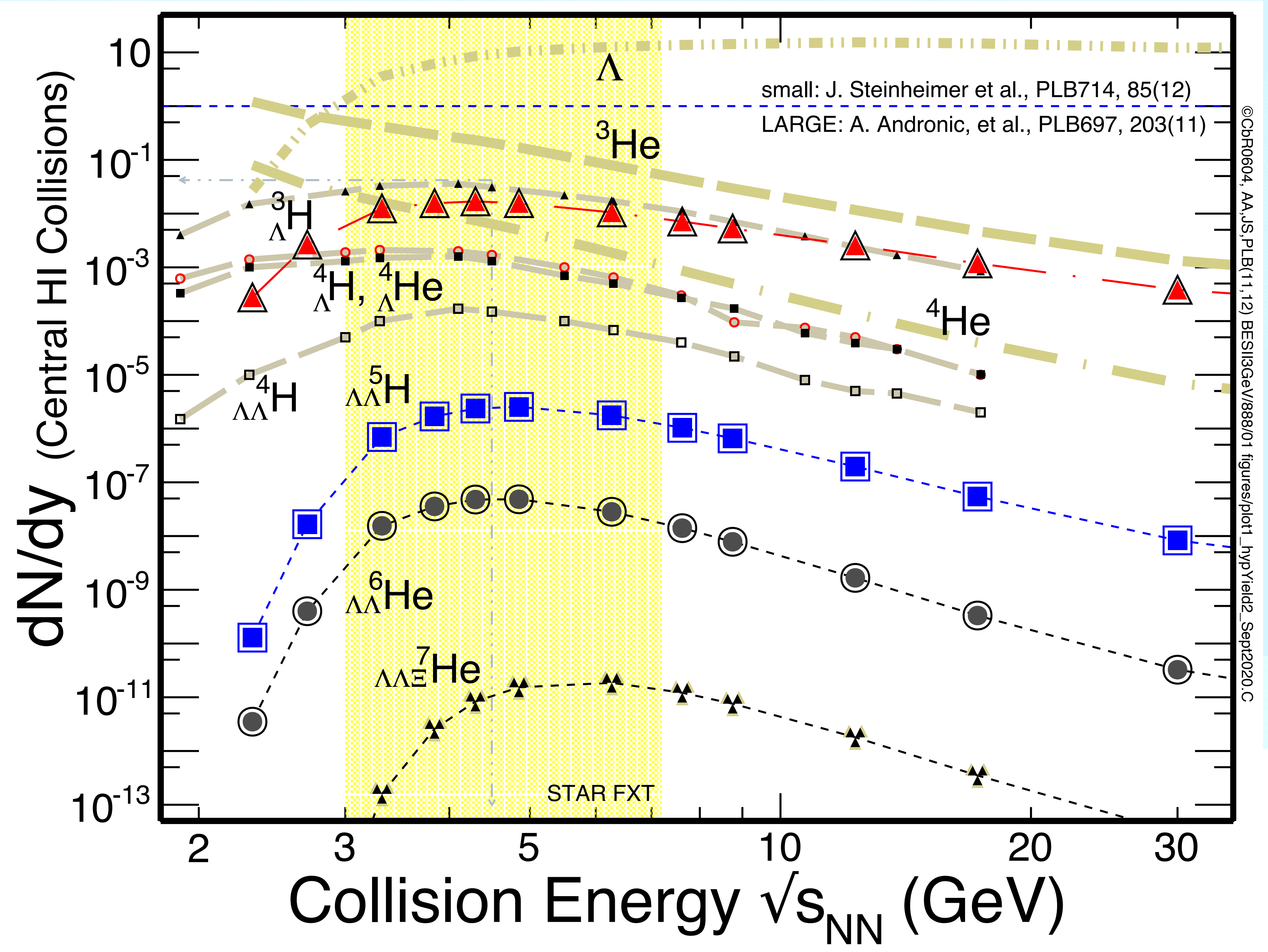
    - Two particles are “bound” if their distance in the rest frame is less than some fixed distance
    - Particle is bound to a cluster if it bounds with at least one particle of the cluster

STAR Beam Energy Scan II

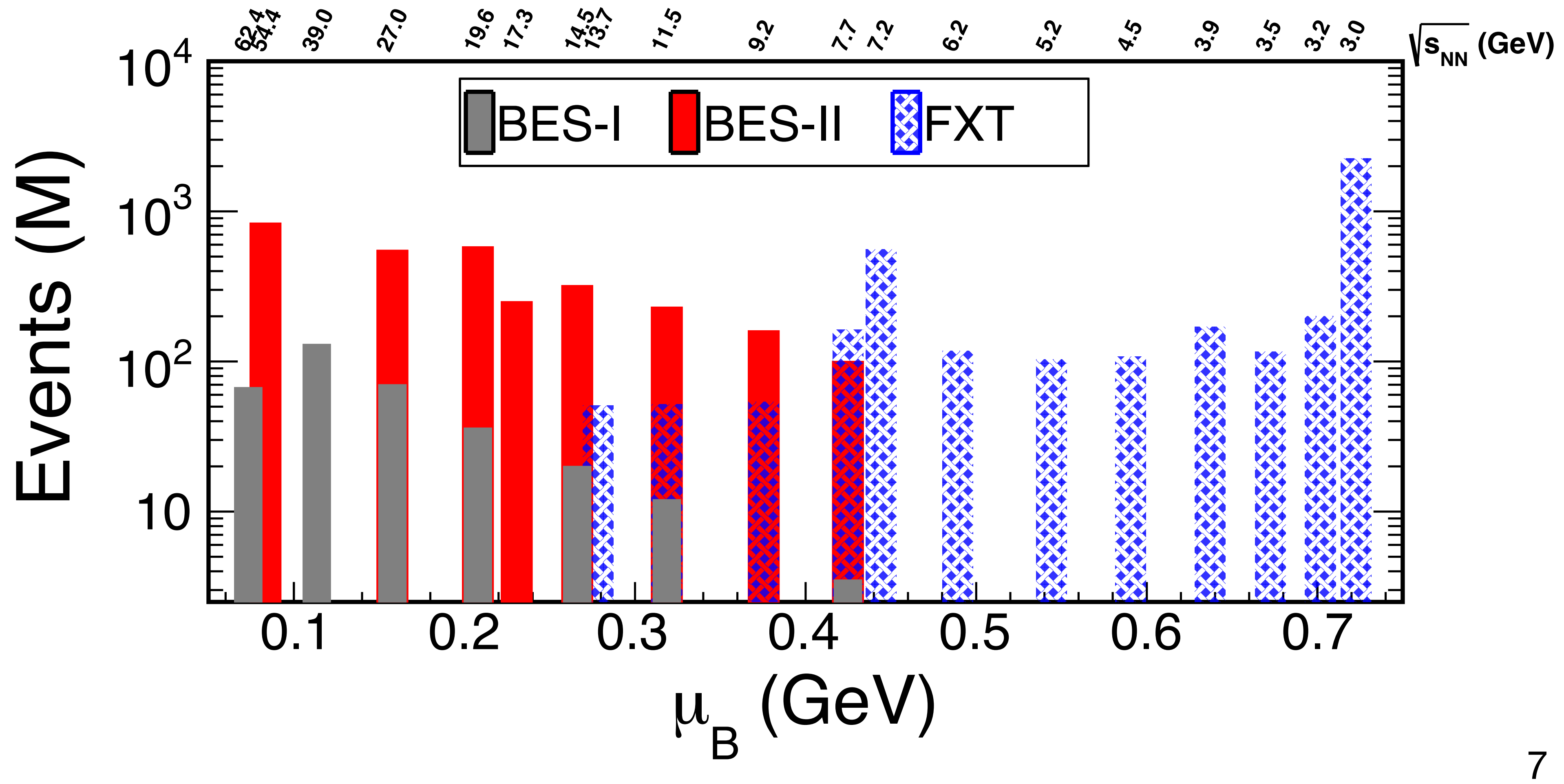


- **Large** acceptance
- **Excellent PID** with **uniform** efficiency
- Modest rates

- **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 studies

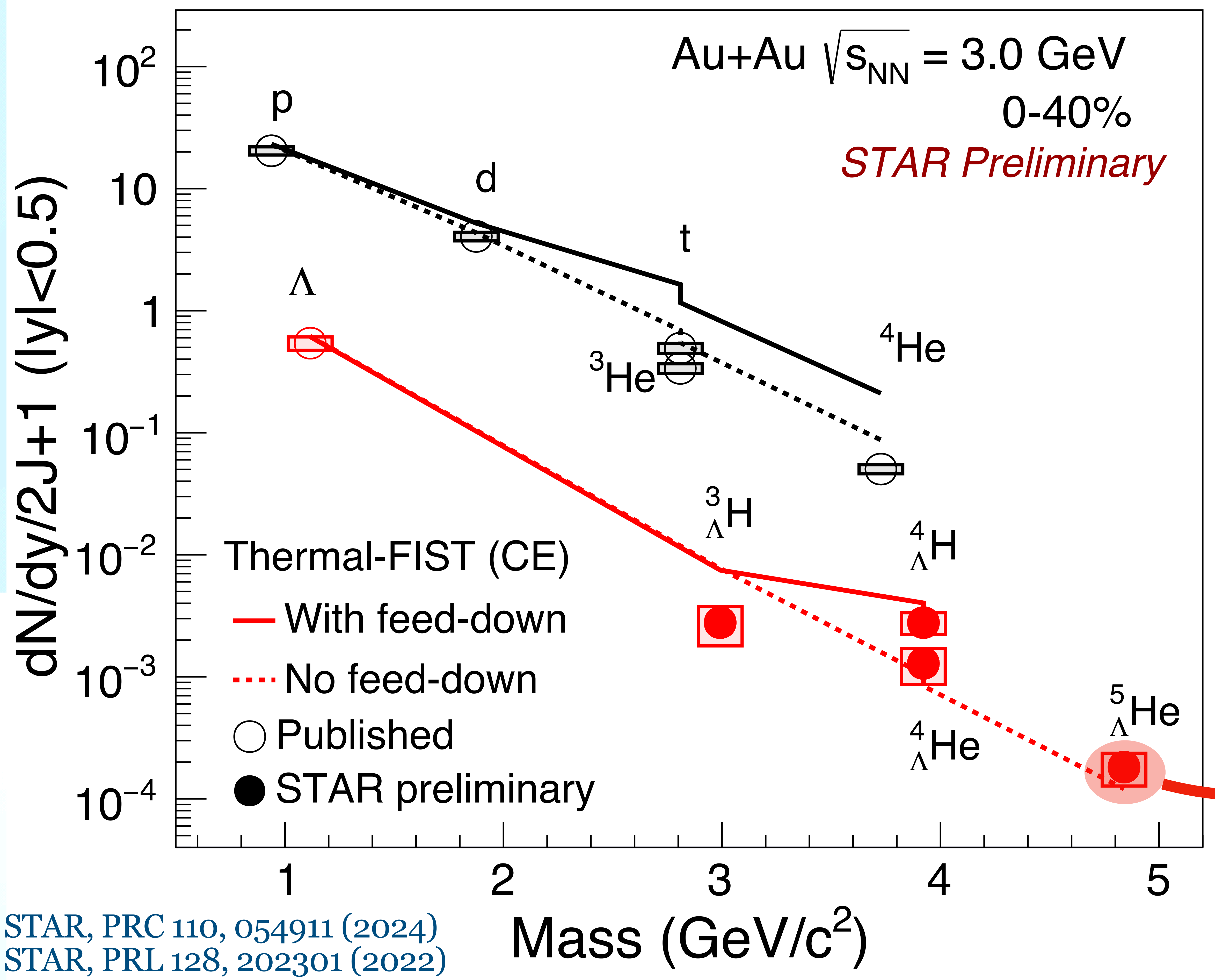
Hypernuclei Reconstruction

- Hypernuclei are reconstructed using the mesonic decay channels:

$$^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$$
$$^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi^{-}$$
$$^{4}_{\Lambda}He \rightarrow {}^{3}He + p + \pi^{-}$$
$$^{5}_{\Lambda}He \rightarrow {}^{4}He + p + \pi^{-}$$

- Combinatorial background estimated via track rotation or event mixing

(Hyper)nuclei Mid-Rapidity Yields at $\sqrt{s_{NN}}$ = 3 GeV

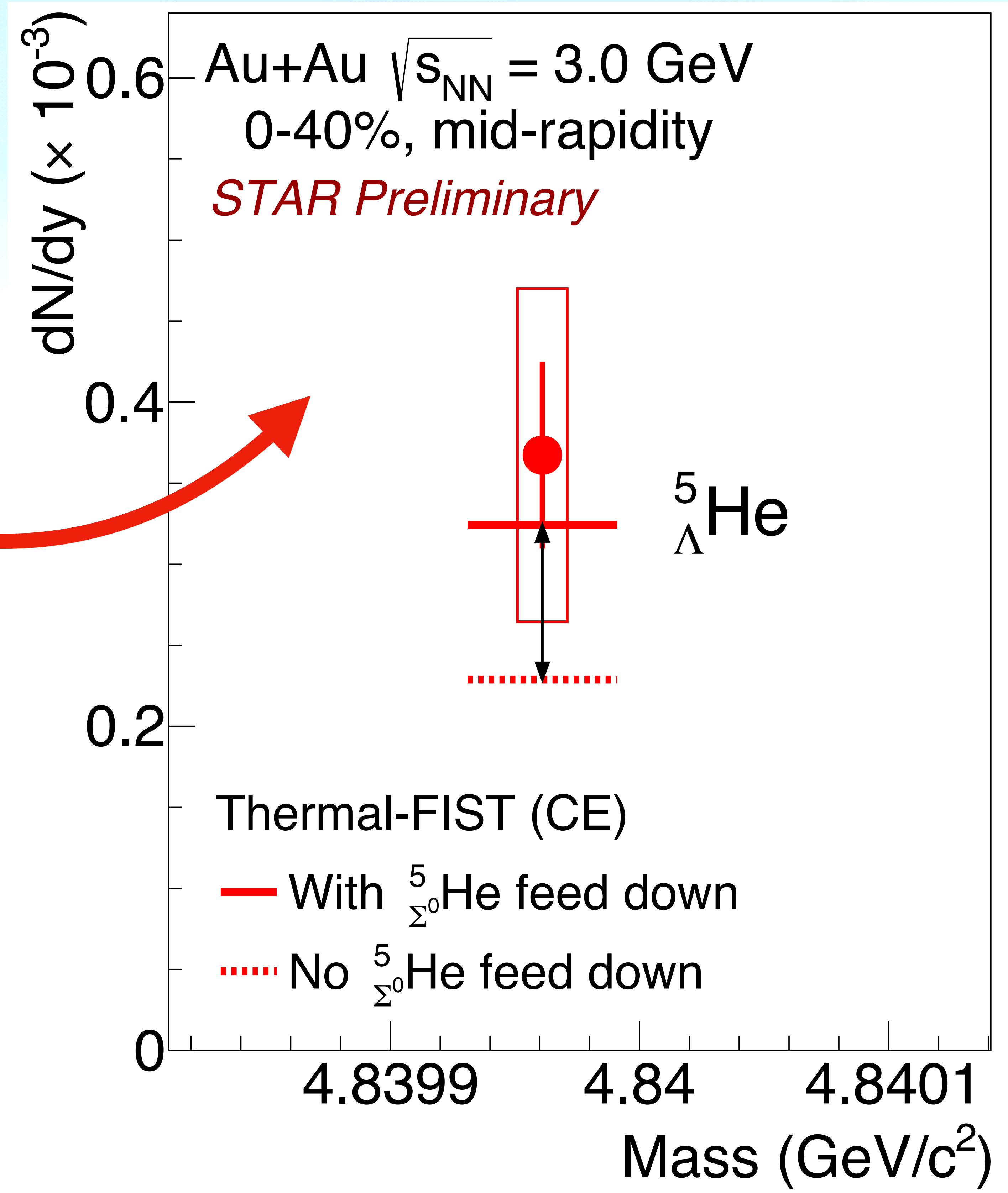


STAR, PRC 110, 054911 (2024)
STAR, PRL 128, 202301 (2022)
STAR, JHEP 10 (2024) 139

- 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

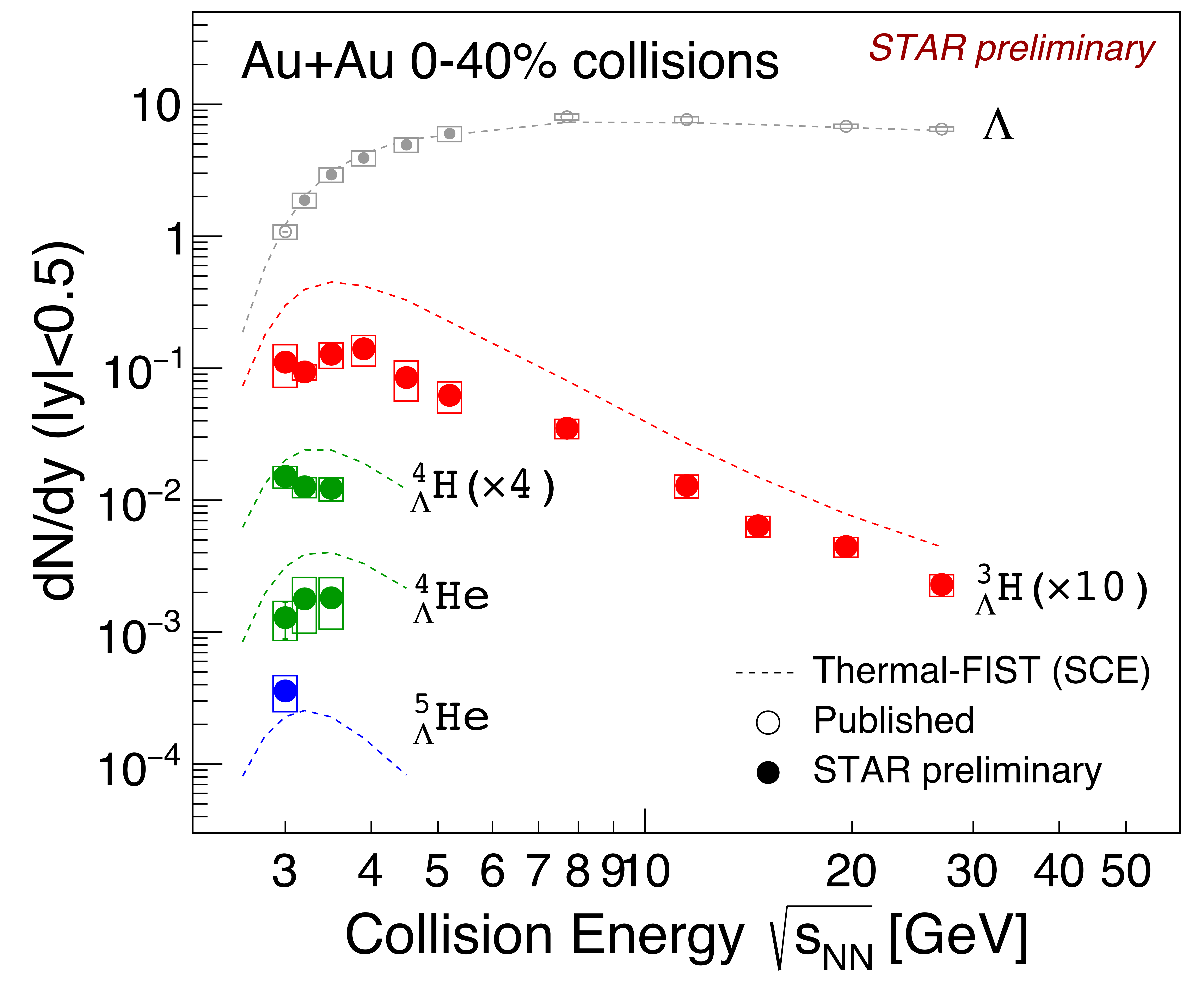
$^{4}_{\Lambda}H^{*}(1^{+}) \rightarrow {}^{4}_{\Lambda}H(0^{+}) + \gamma$
$^{4}_{\Lambda}He^{*}(1^{+}) \rightarrow {}^{4}_{\Lambda}He(0^{+}) + \gamma$



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

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

Excitation Functions

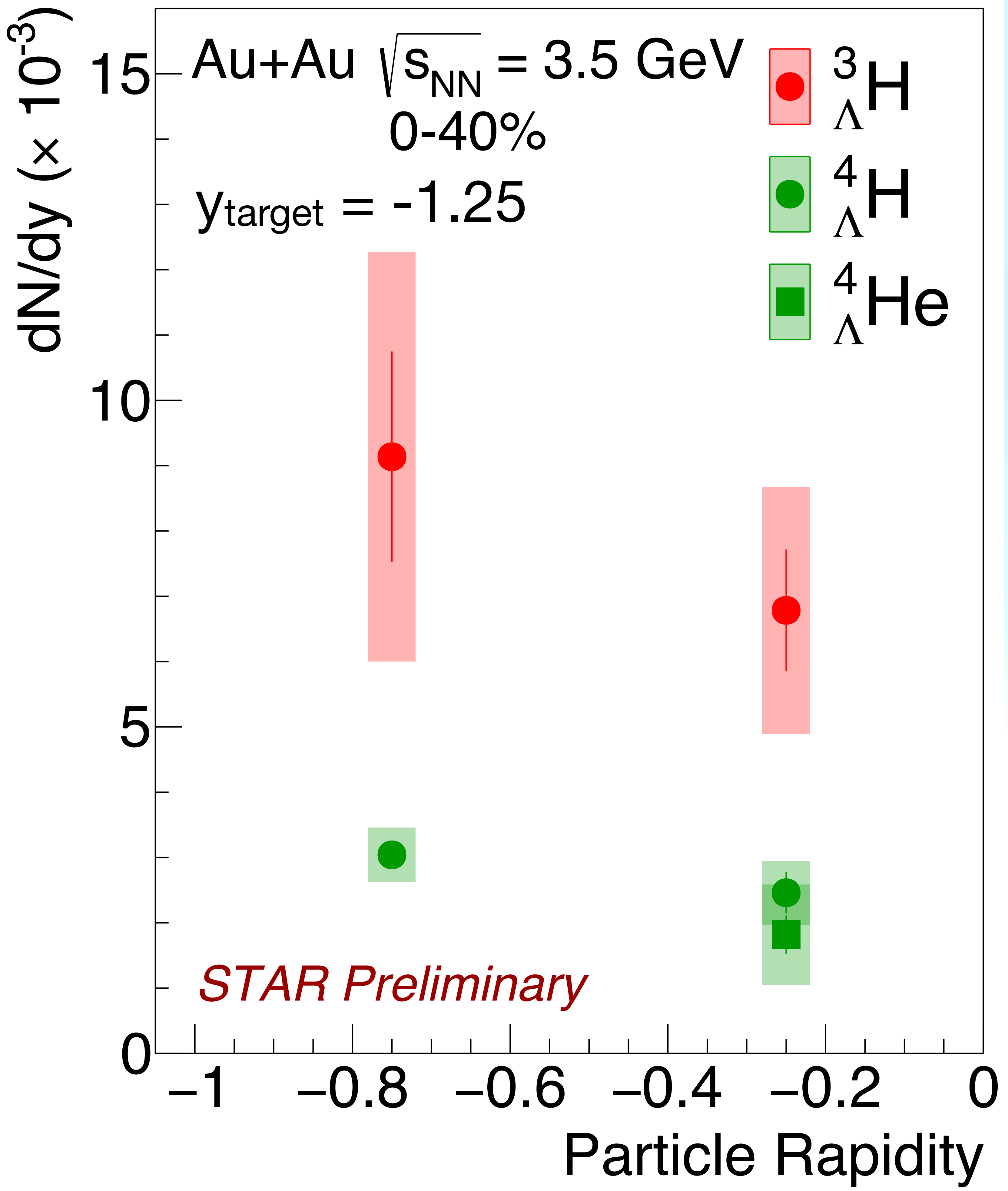


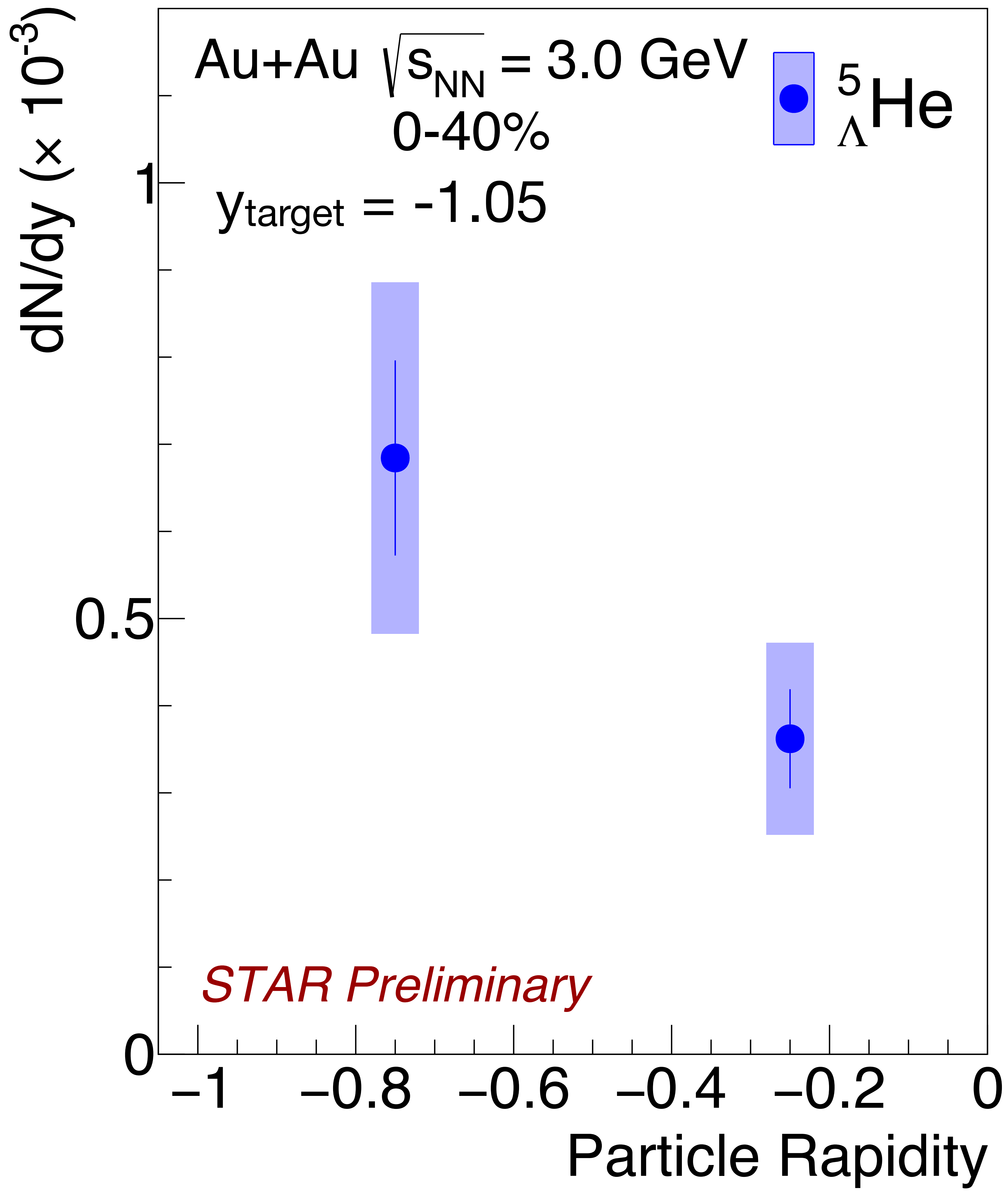
- $^{3}_{\Lambda}$H plateaus at $\sqrt{s_{NN}}$ = 3-4 GeV

  Establishes low collision energy experiments as promising tool to study exotic strange matter

- Thermal model (SCE) describes Λ, **overestimates $^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H, and $^{4}_{\Lambda}$He, slightly underestimates $^{5}_{\Lambda}$He**

Rapidity Dependence

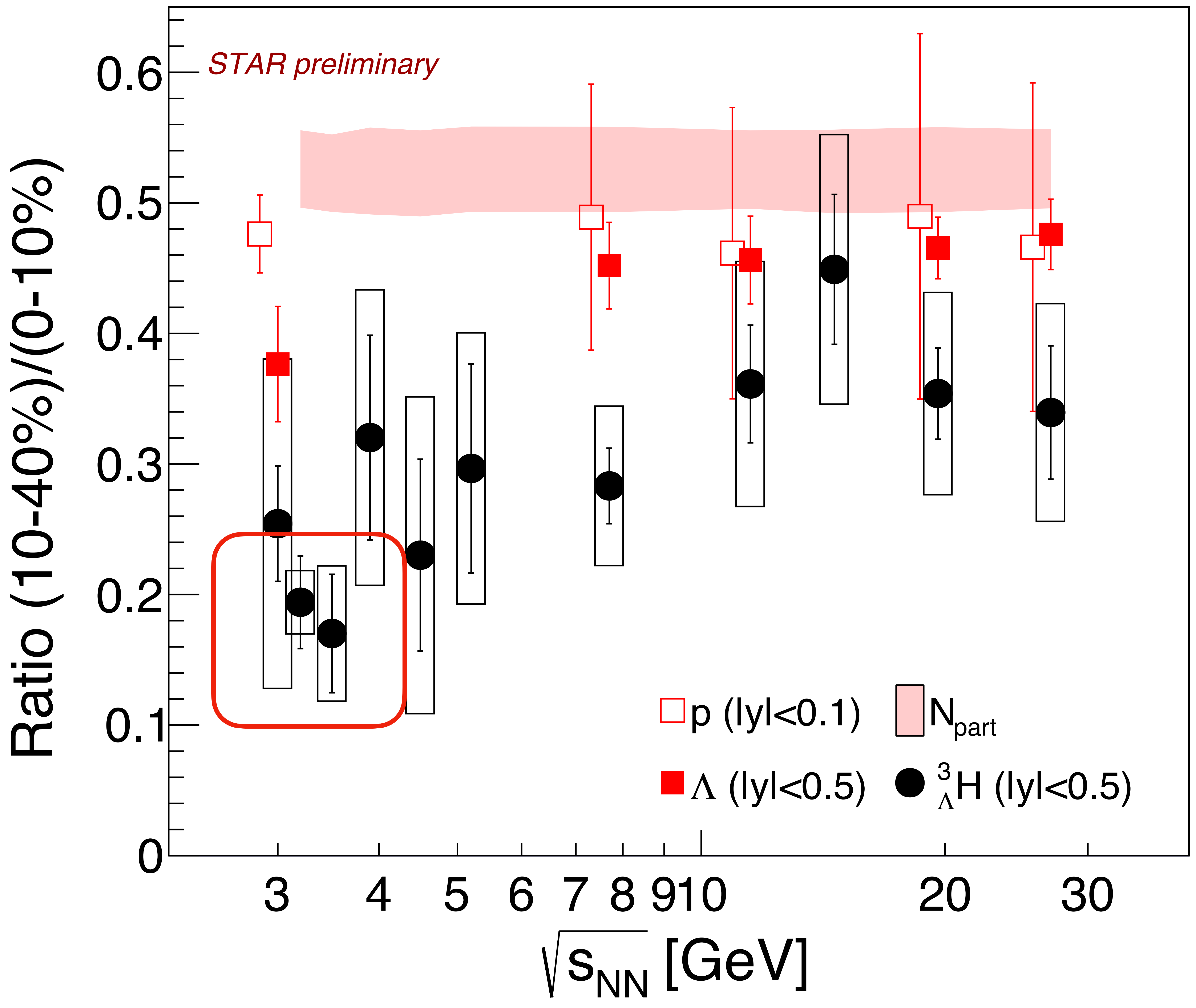




- Significant hypernuclei production near target rapidity

Spectators play an important role in hypernuclei production

Centrality Dependence



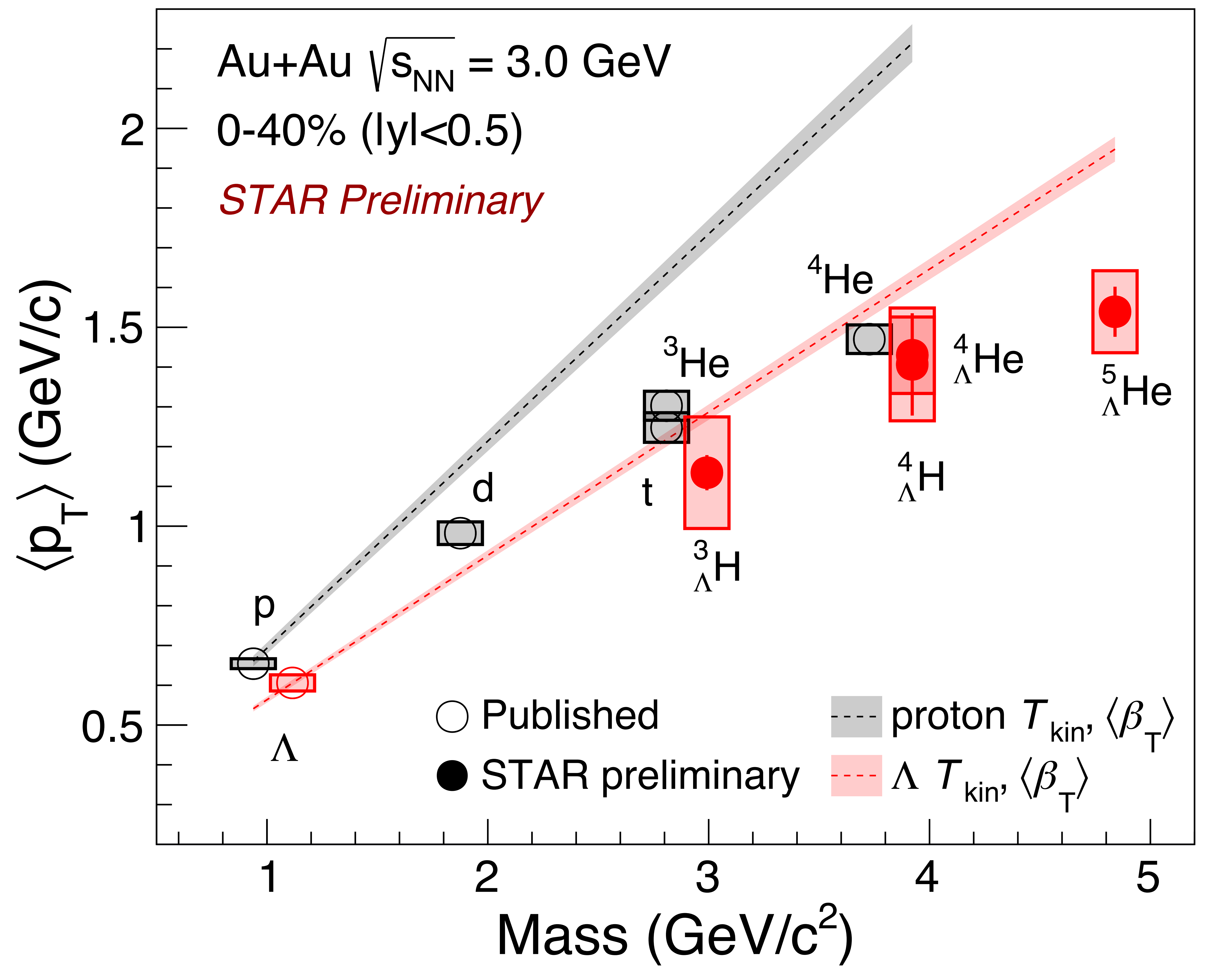
- Below $\sqrt{s_{NN}} \sim 4$ GeV, yield ratio (10-40%)/(0-10%) for $^{3}_{\Lambda}H$ is smaller compared to proton, Λ, and N_{part}

Suppression of $^{3}_{\Lambda}H$ production in more peripheral collisions compared to proton and Λ below $\sqrt{s_{NN}} \sim 4$ GeV

- Steep decline may be related to coalescence production and smaller source size in more peripheral collisions

T. Reichert et al, Phys.Rev.C 107 (2023) 1, 014912
D. Liu et al, Phys.Lett.B 855 (2024) 138855

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 mass to construct blast-wave predictions using p(Λ) freeze-out parameters

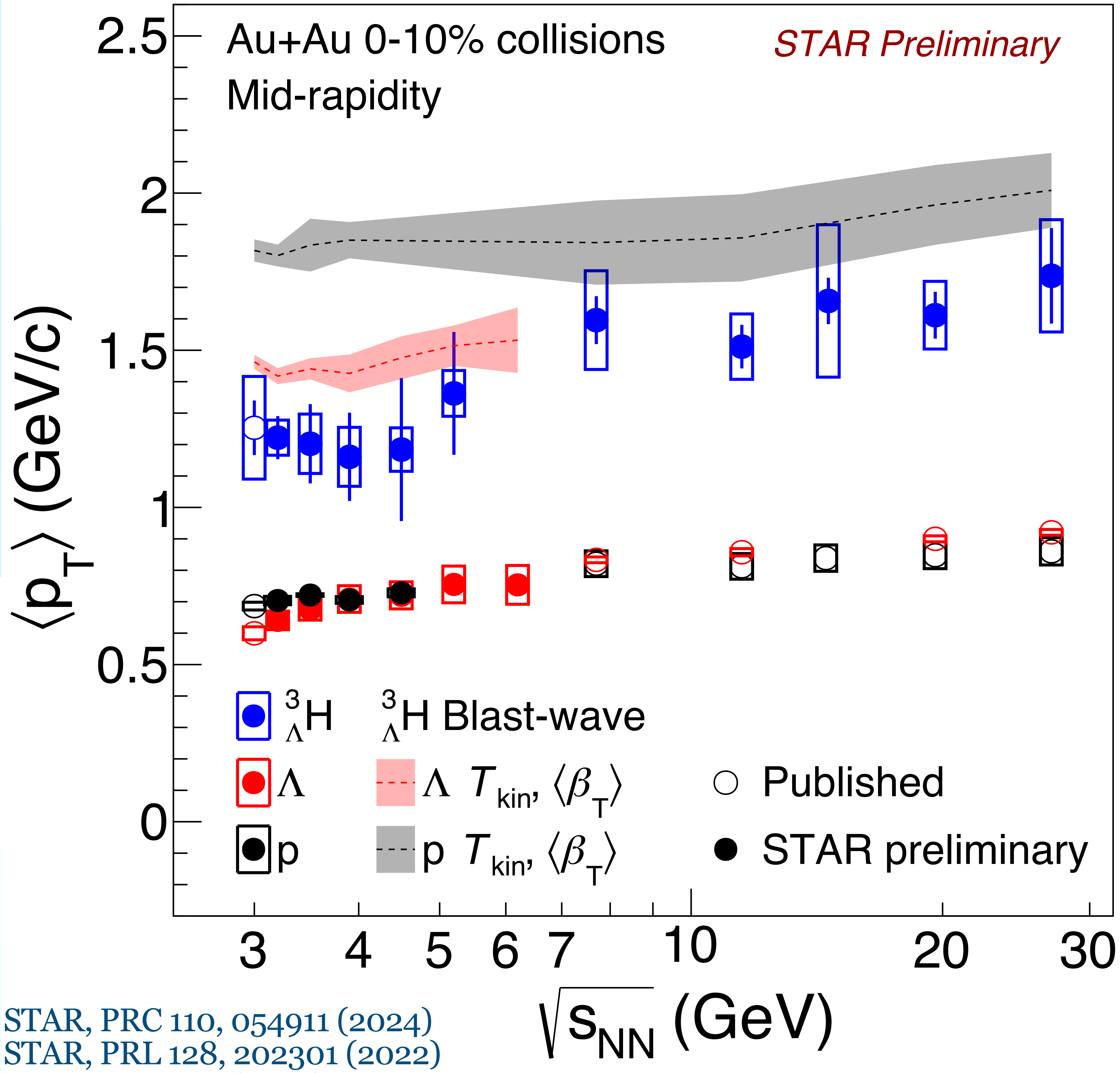
	p	Λ
$\langle \beta_T \rangle$ (c)	0.43	0.33
T_{kin} (GeV)	0.065	0.076

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

(Hyper)nuclei deviate from the hydrodynamic blast-wave picture

- Hypernuclei closer to Λ blast-wave ansatz

Insight from Blast-Wave Comparison



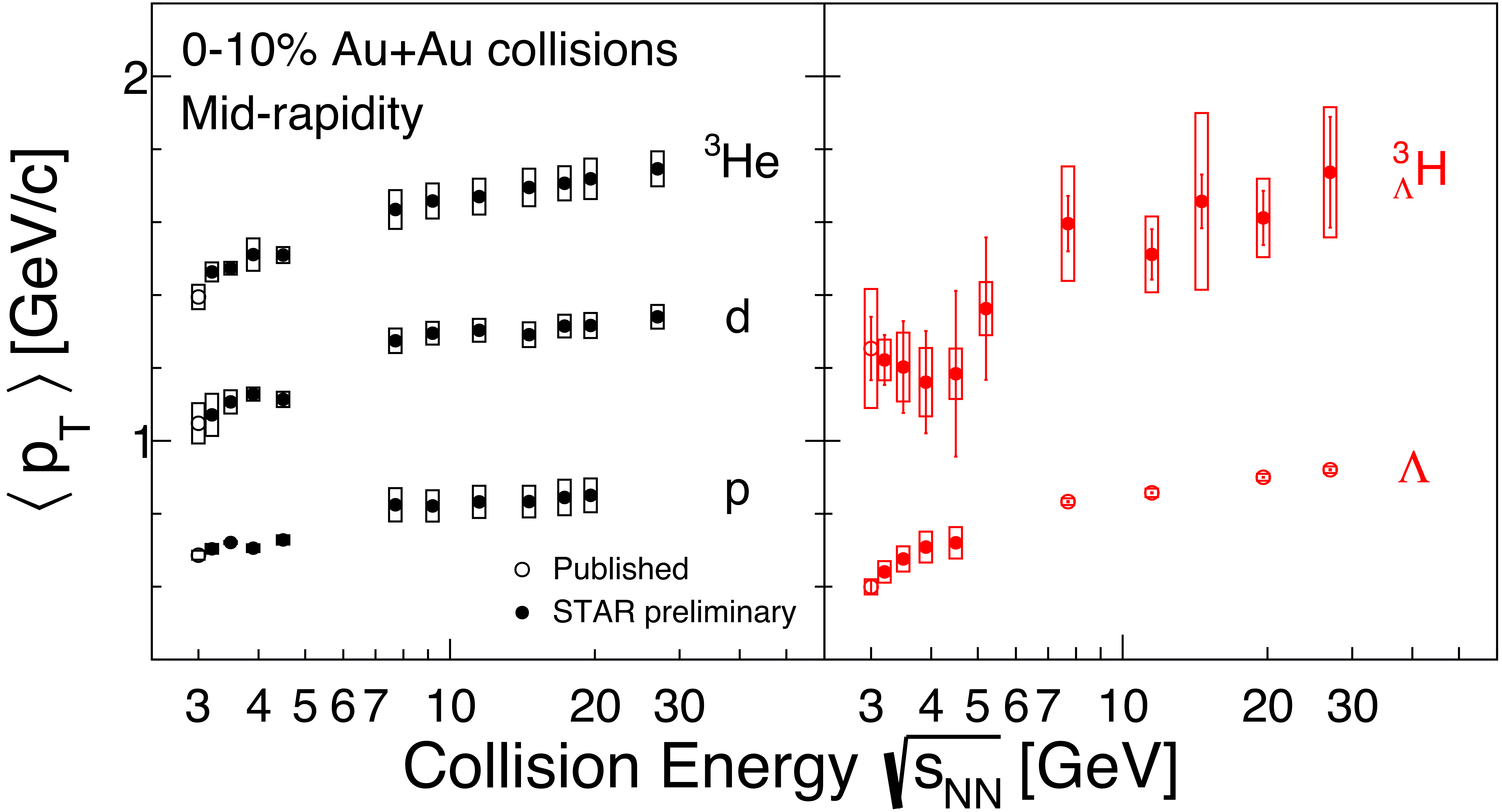
STAR, PRC 110, 054911 (2024)
STAR, PRL 128, 202301 (2022)
STAR, JHEP 10 (2024) 139

- 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)

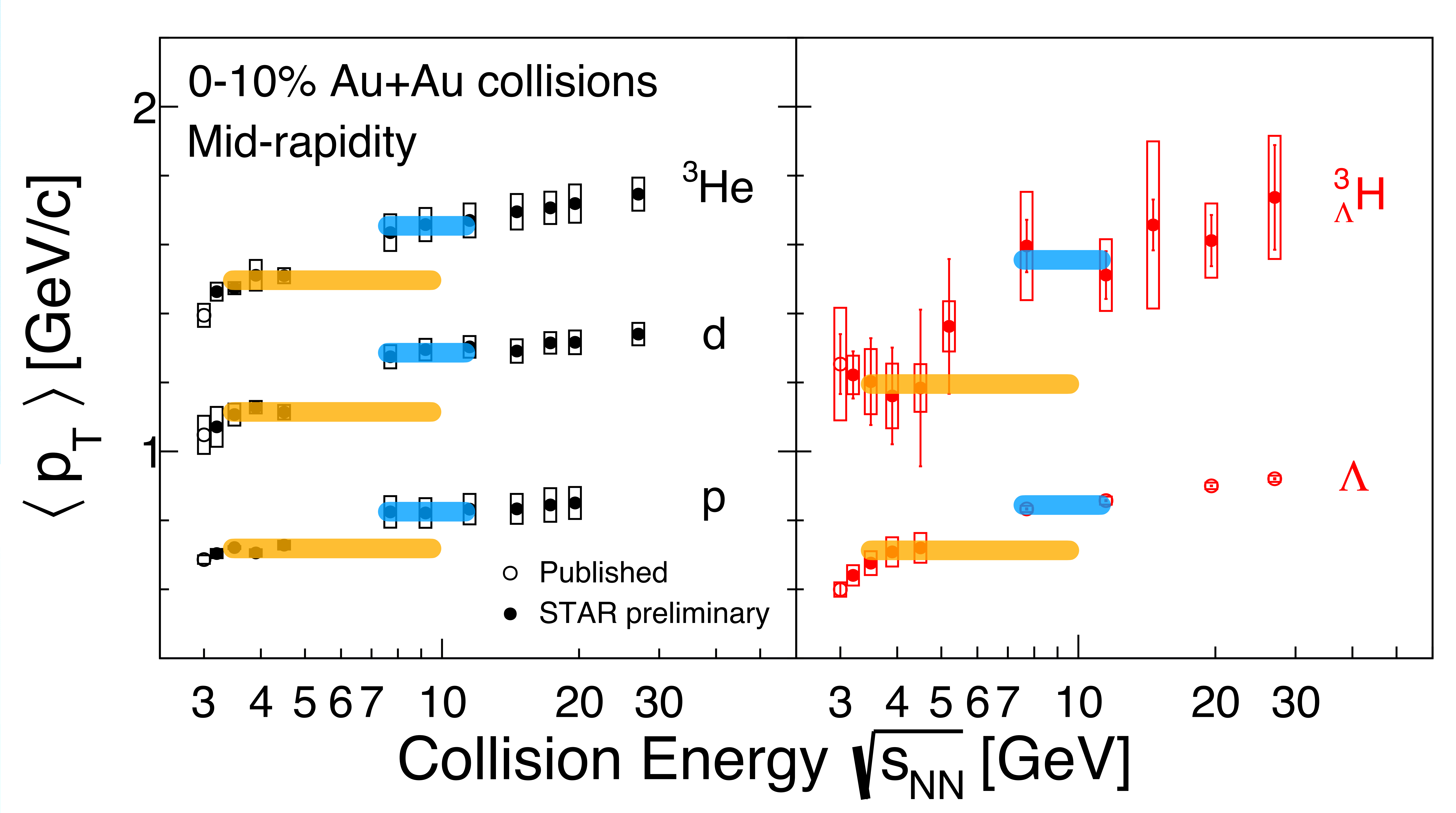
- Noticeable change between 4.5 and 7.7 GeV

Collision Energy Dependence of Mean Transverse Momentum



- Noticeable change between 4.5 and 7.7 GeV

Collision Energy Dependence of Mean Transverse Momentum

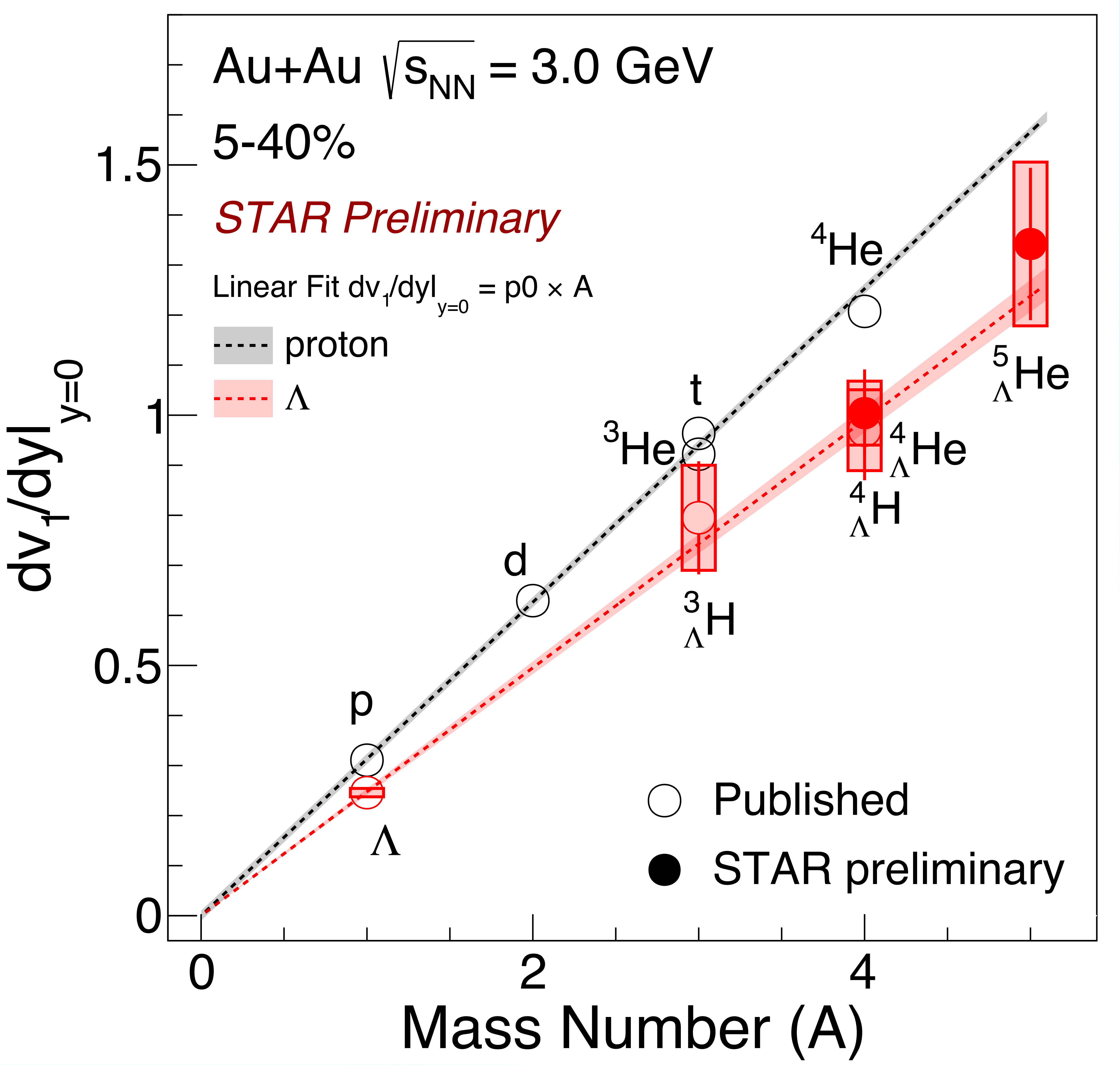


- Noticeable change between 4.5 and 7.7 GeV

Similar trends for nucleons, hyperons, nuclei, and hypernuclei

Mass Number Scaling of Directed Flow at $\sqrt{s_{NN}}$=3GeV

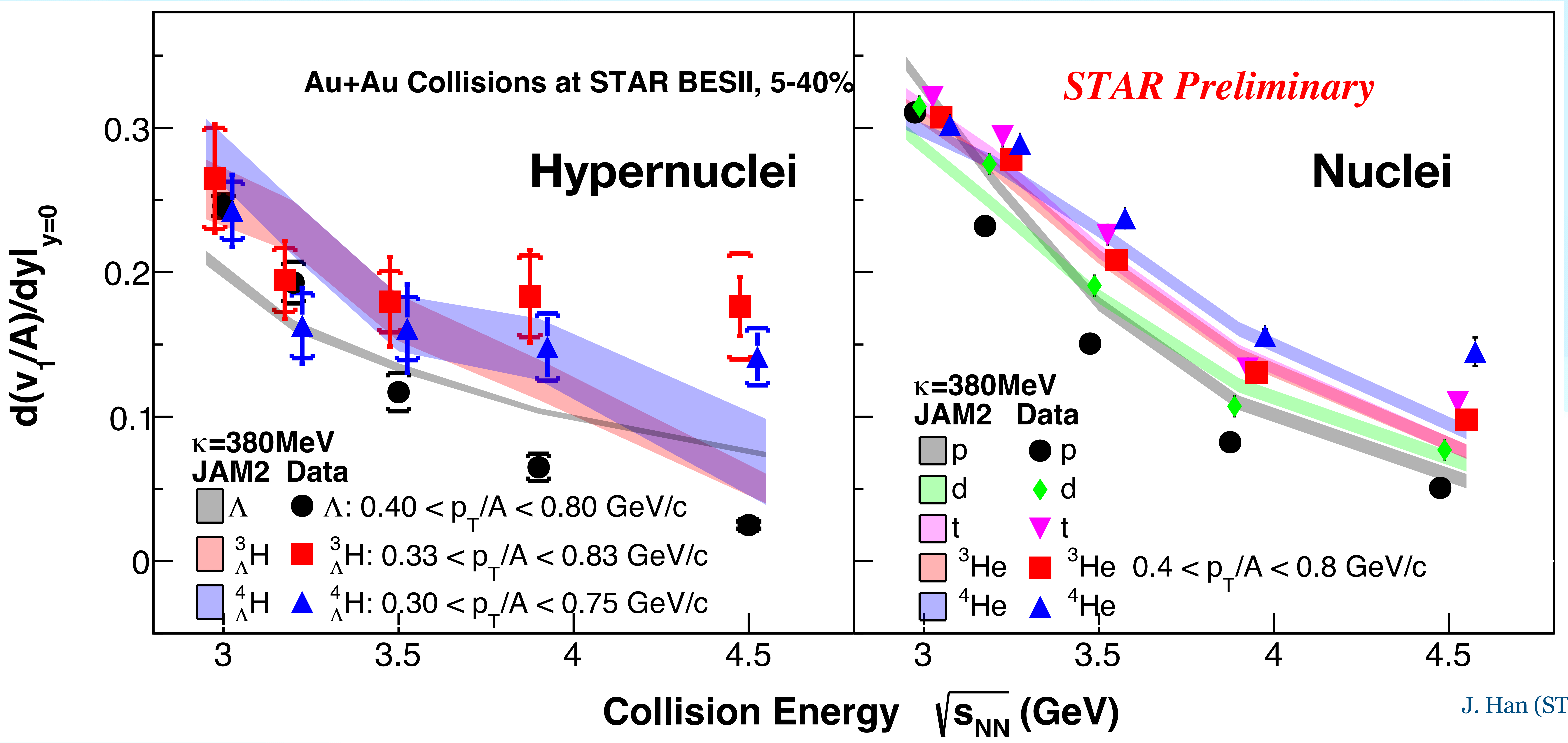
J. Han (STAR), QM2025



- 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

Qualitatively consistent with coalescence

Collision Energy Dependence of Hypernuclei Directed Flow

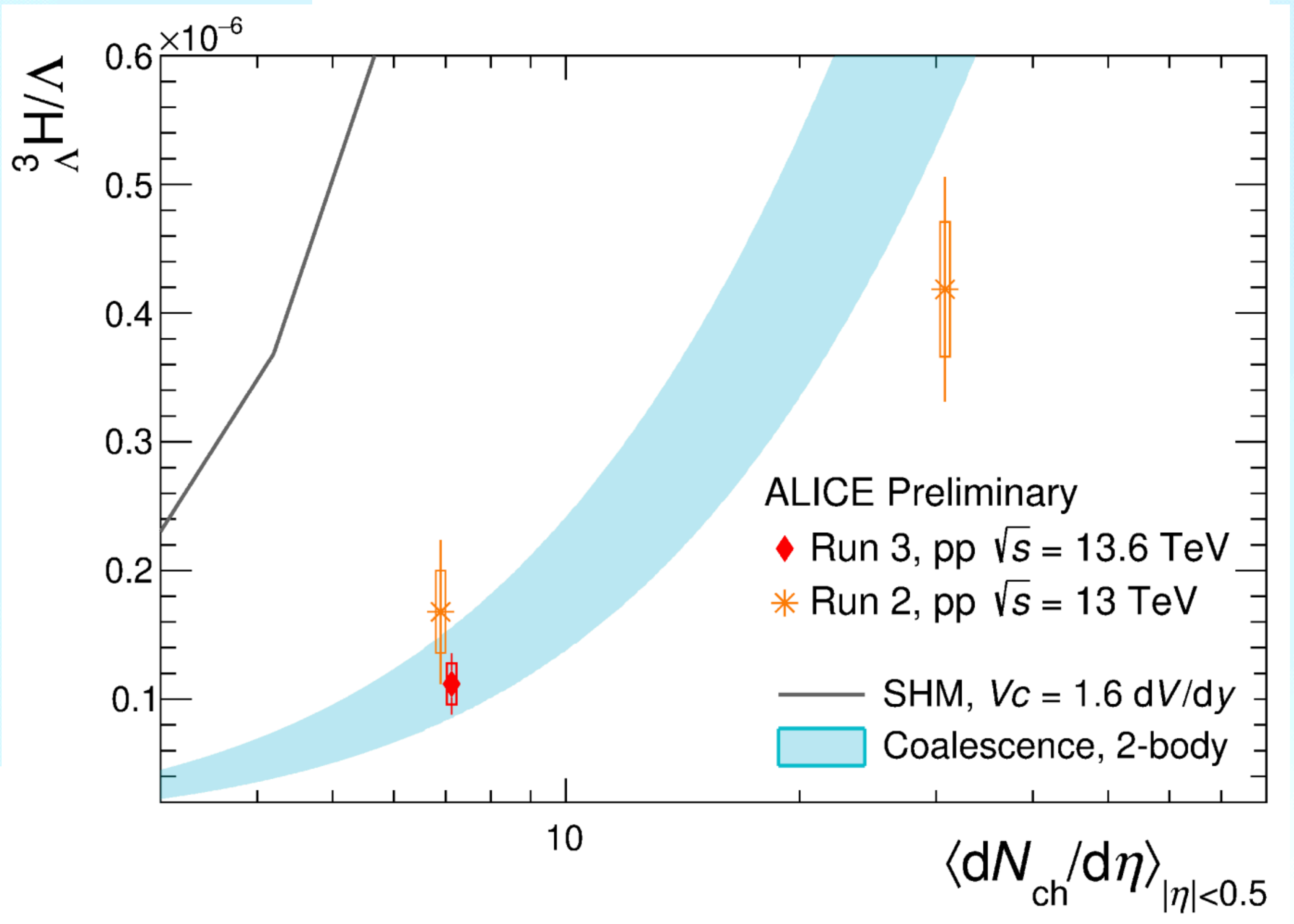


J. Han (STAR), SQM2024

- Hadronic transport model (JAM2 + coalescence) calculations qualitatively reproduce the energy dependence
    - Slight tension b/w model and data for hypernuclei at $\sqrt{s_{NN}} = 4.5$ GeV

System Size Dependence at High Collision Energies

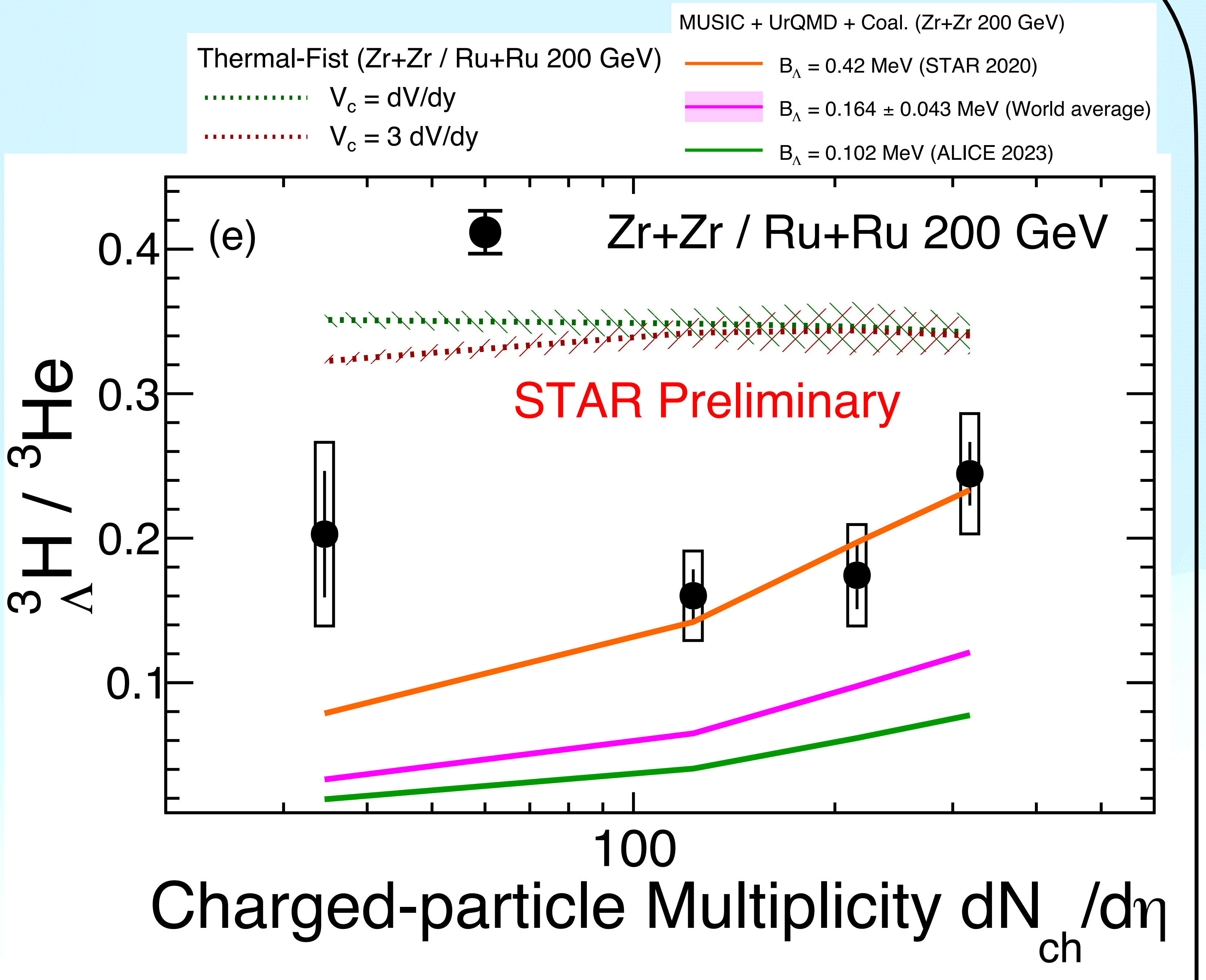
J. Ditzel (ALICE), QM2025



p+p @ $\sqrt{s}$ = 13, 13.6 GeV

$dN_{ch}/d\eta \sim O(10)$

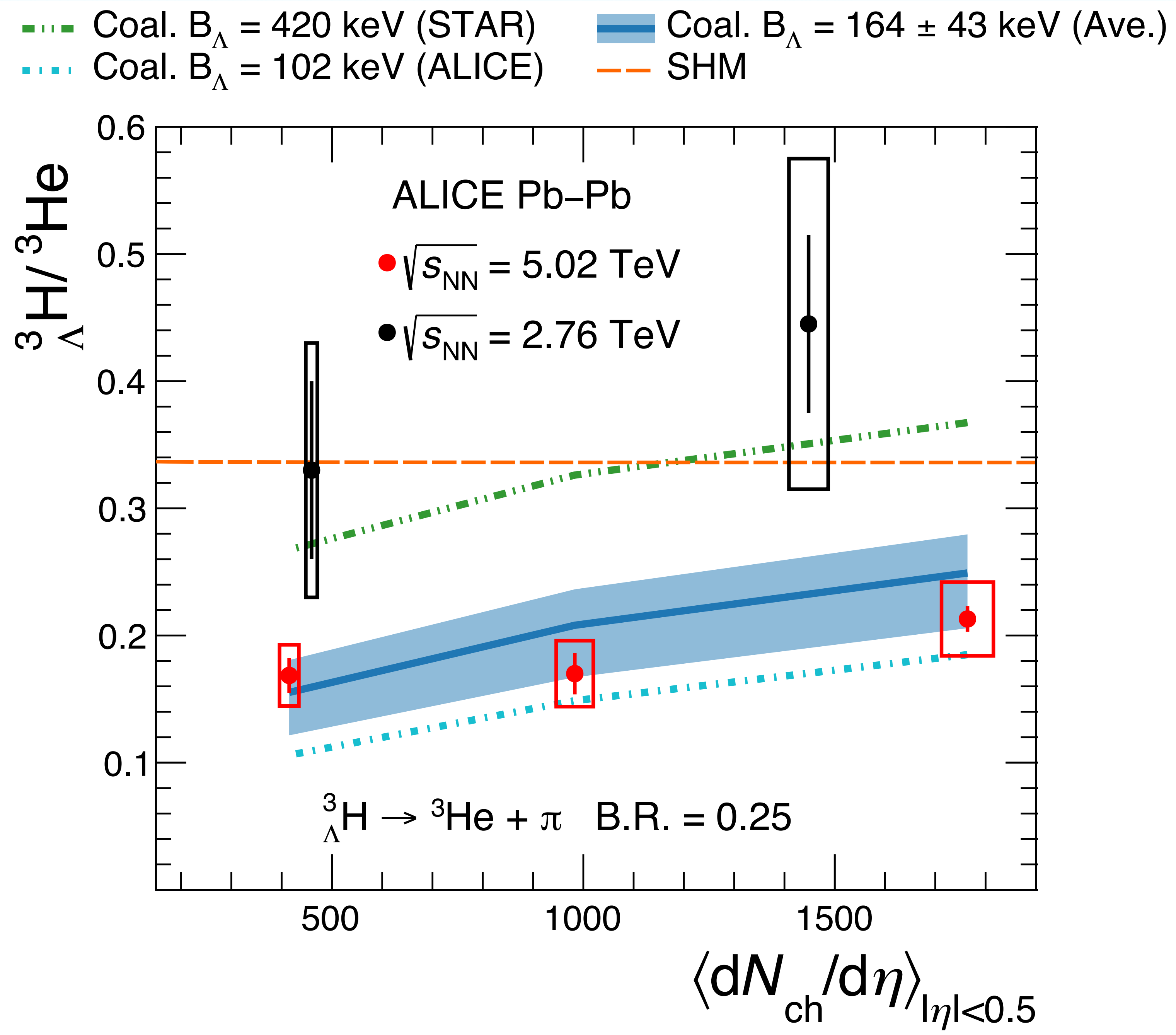
D. Li (STAR), SQM2024



Ru/Zr+Ru/Zr @ $\sqrt{s_{NN}}$ = 200 GeV

$dN_{ch}/d\eta \sim O(100)$

ALICE, Phys.Lett.B 860 (2025) 139066



Pb+Pb @ $\sqrt{s_{NN}}$ = 2.76, 5.02 TeV

$dN_{ch}/d\eta \sim O(1000)$

Small systems → Large systems

Across all systems, thermal model overestimates ${}^{3}_{\Lambda}\mathrm{H}$ production

Summary

- Hypernuclei measurements (${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H, ${}^{4}_{\Lambda}$He, and ${}^{5}_{\Lambda}$He) from STAR BES-II at $\sqrt{s_{\mathrm{NN}}}$ = 3-27 GeV
- Thermal model
  - Overpredicts ${}^{3}_{\Lambda}$H
  - Slightly overpredicts ${}^{4}_{\Lambda}$H, ${}^{4}_{\Lambda}$He if excited states are considered, significantly underpredicts if not

Feed-down contributions likely important at low collision energies

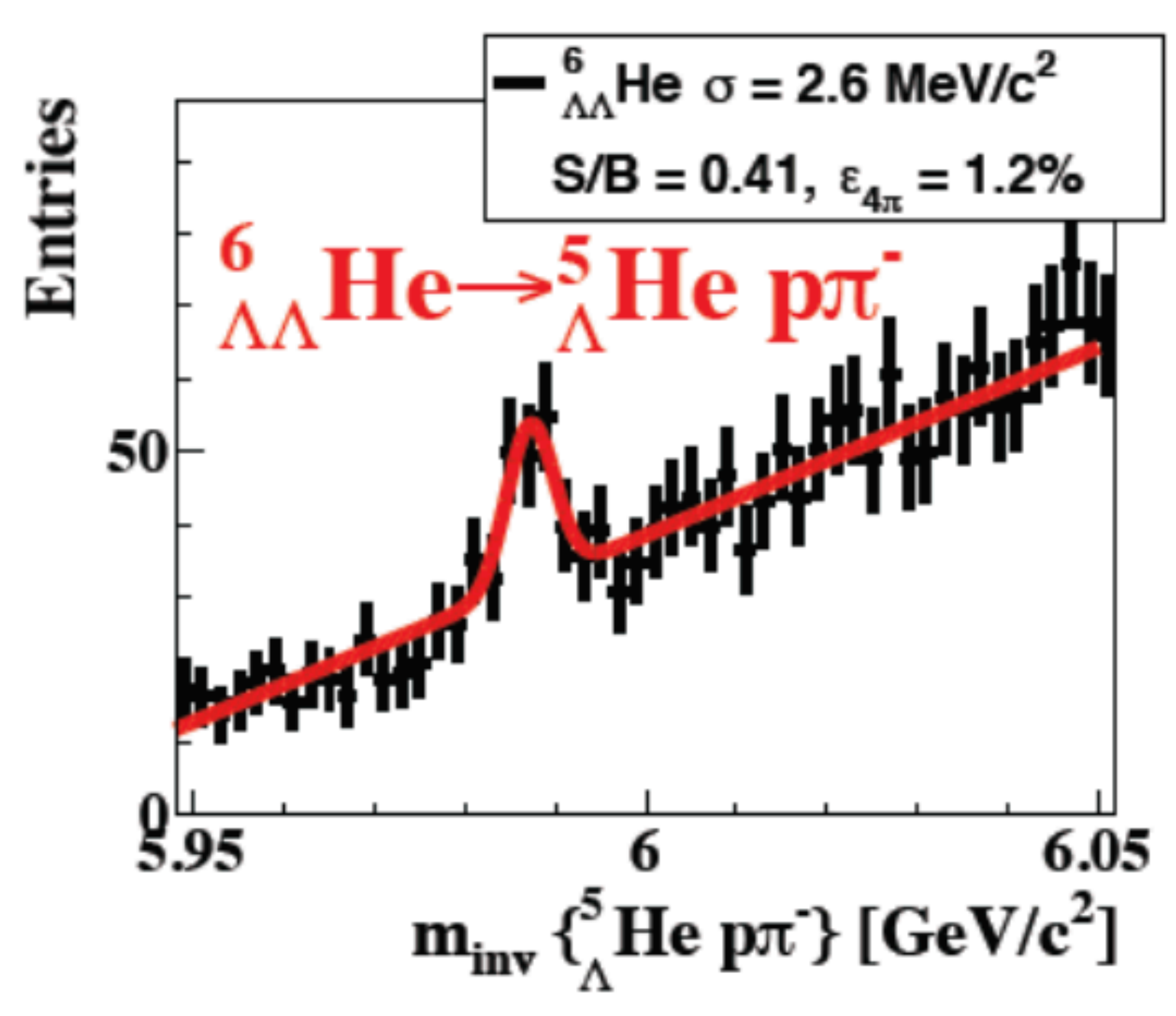
- Mean transverse momentum tends to be lower than blast-wave model expectation below $\sqrt{s_{\mathrm{NN}}} \sim$ 5 GeV
- Directed flow follow atomic mass number *A* scaling

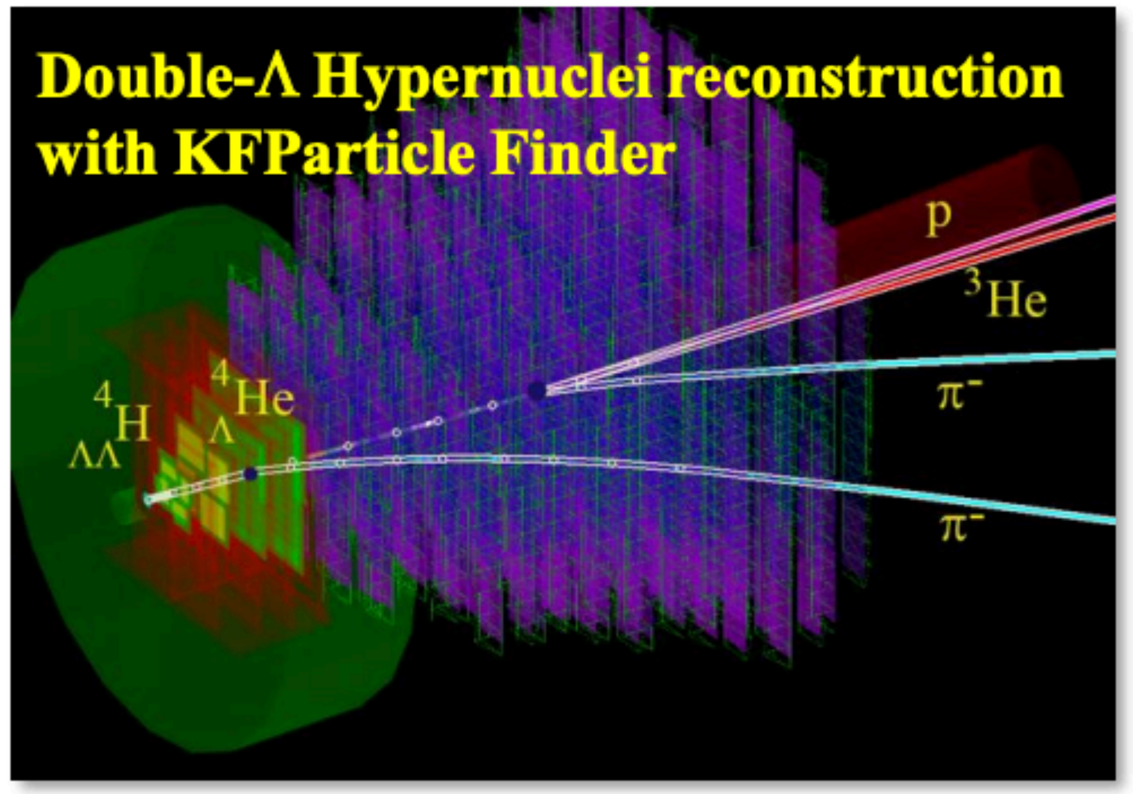
Overall, coalescence model favored for hypernuclei data

Is there any ***motivation to further improve our understanding of (hyper)nuclei production mechanism*** *and model description of yields* ***at low collision energies****?*

Outlook: (In)direct searches for Exotic Nuclei

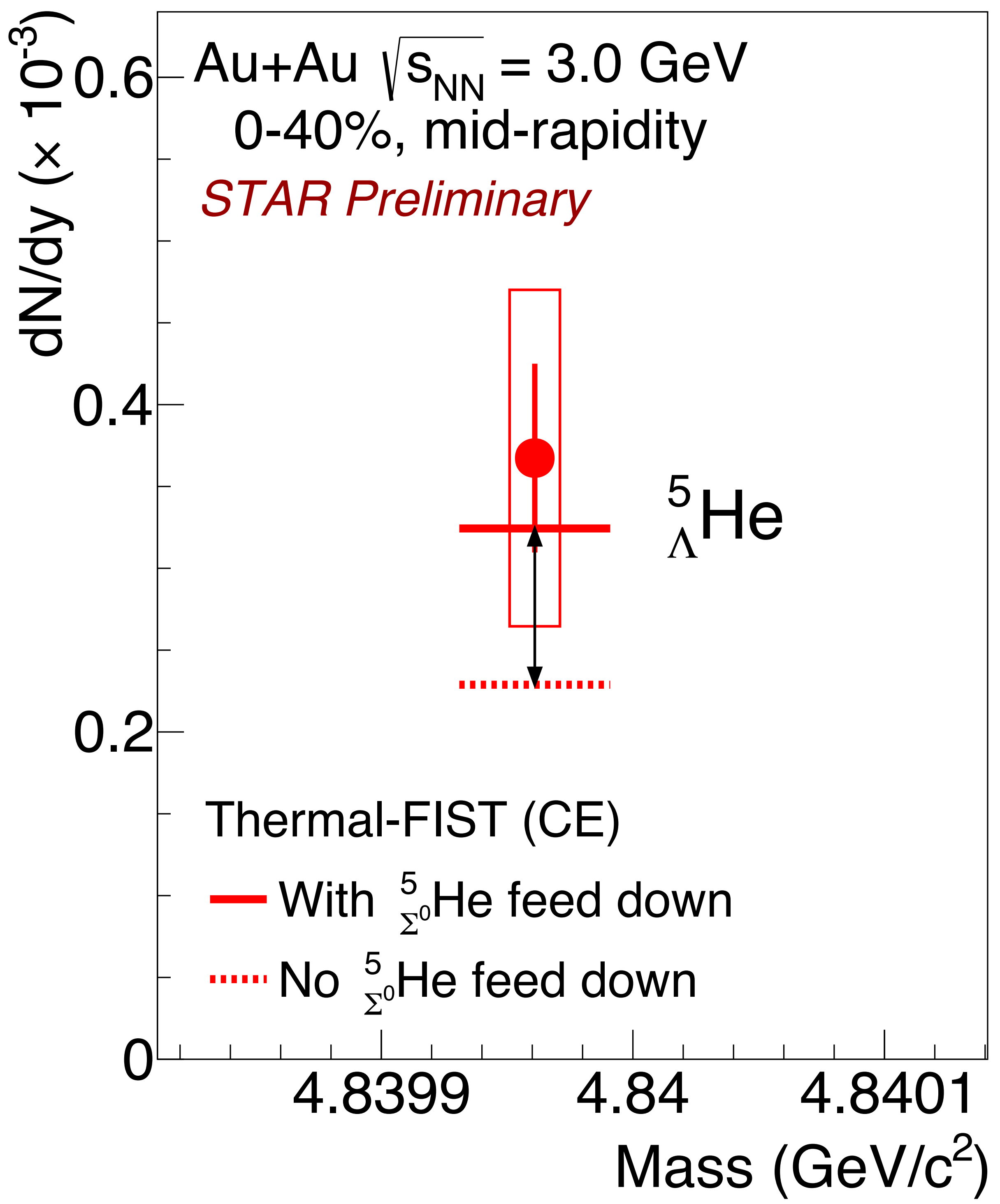
- $\Lambda\Lambda$-hypernuclei, Σ-hypernuclei, Ξ-hypernuclei, etc.
  - YY/YN interactions to resolve *hyperon puzzle*
- High statistics needed!
  - CBM@FAIR, HIAF, etc.





I. Vassiliev Y. Zhou, QM2025 poster

- Certain hypernuclei resonances are difficult to reconstruct directly e.g. $^{5}_{\Sigma^0}\mathrm{He} \rightarrow ^{5}_{\Lambda}\mathrm{He} + \gamma$



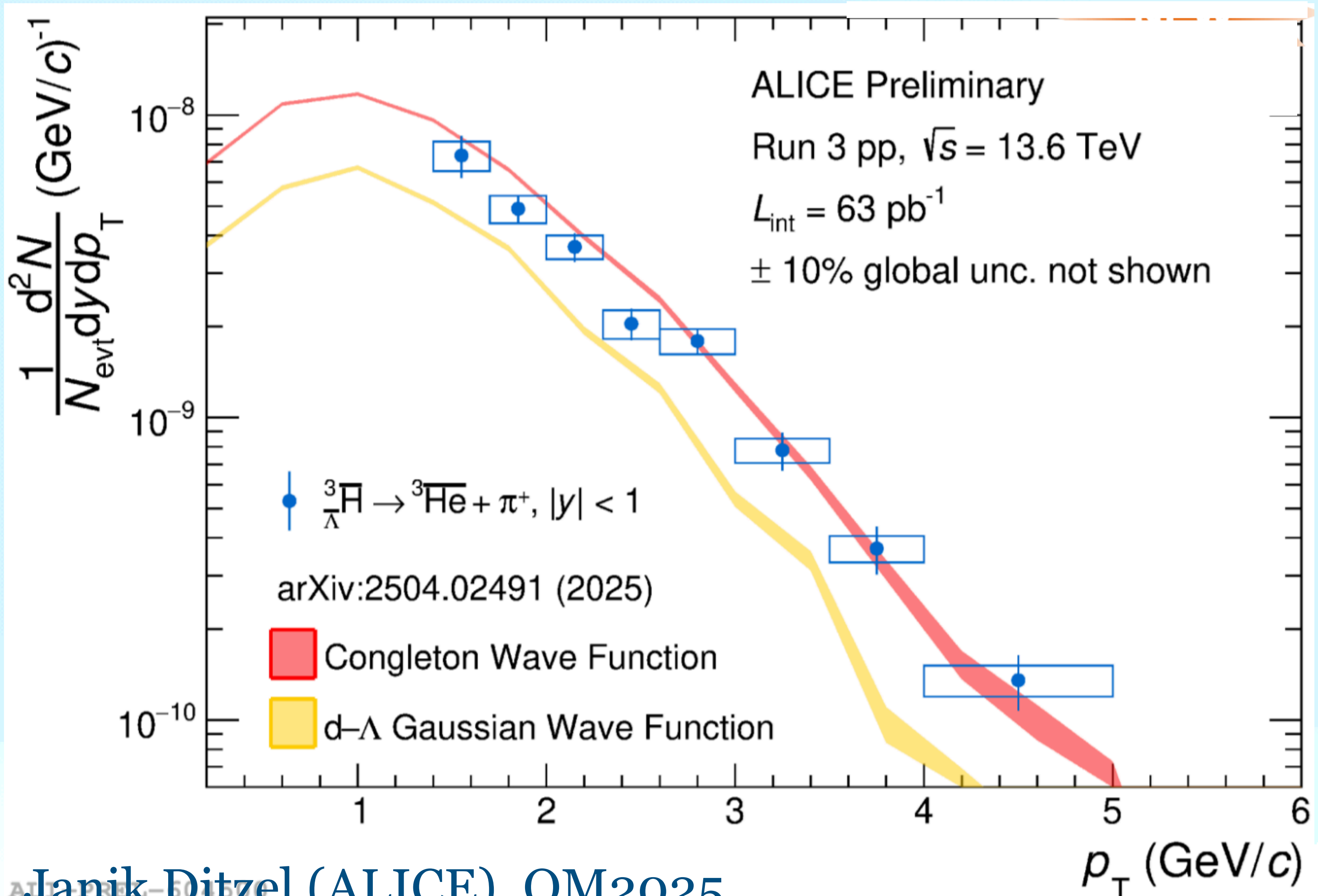
Inclusive yields may hold information on (undiscovered) hypernuclei resonances

- Consideration of (hyper)nuclei resonances in coalescence models

Outlook: Probing the Hypernuclei Wavefunction

- When hypernuclei radius > source radius, yields become sensitive to the wavefunction

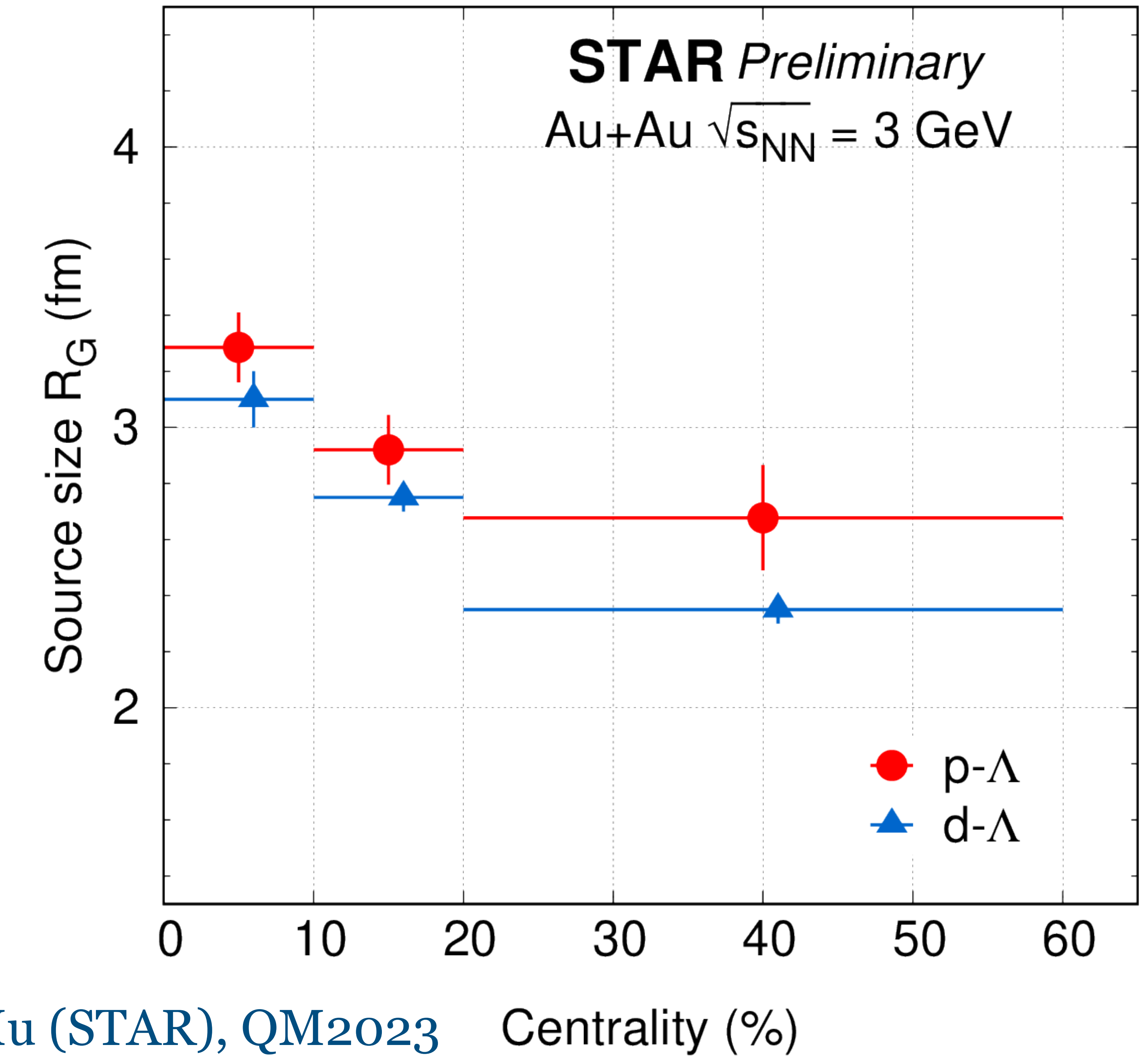
M. Mahlein et al, arXiv:2504.02491
F. Bellini et al, Phys.Rev.C 103 (2021) 1, 014907
D. Liu et al Phys.Lett.B 855 (2024) 138855
T. Reihert et al, Phys.Rev.C 107 (2023) 1, 014912



Janik Ditzel (ALICE), QM2025

- p+p data at 13.6 TeV favors Congleton wavefunction

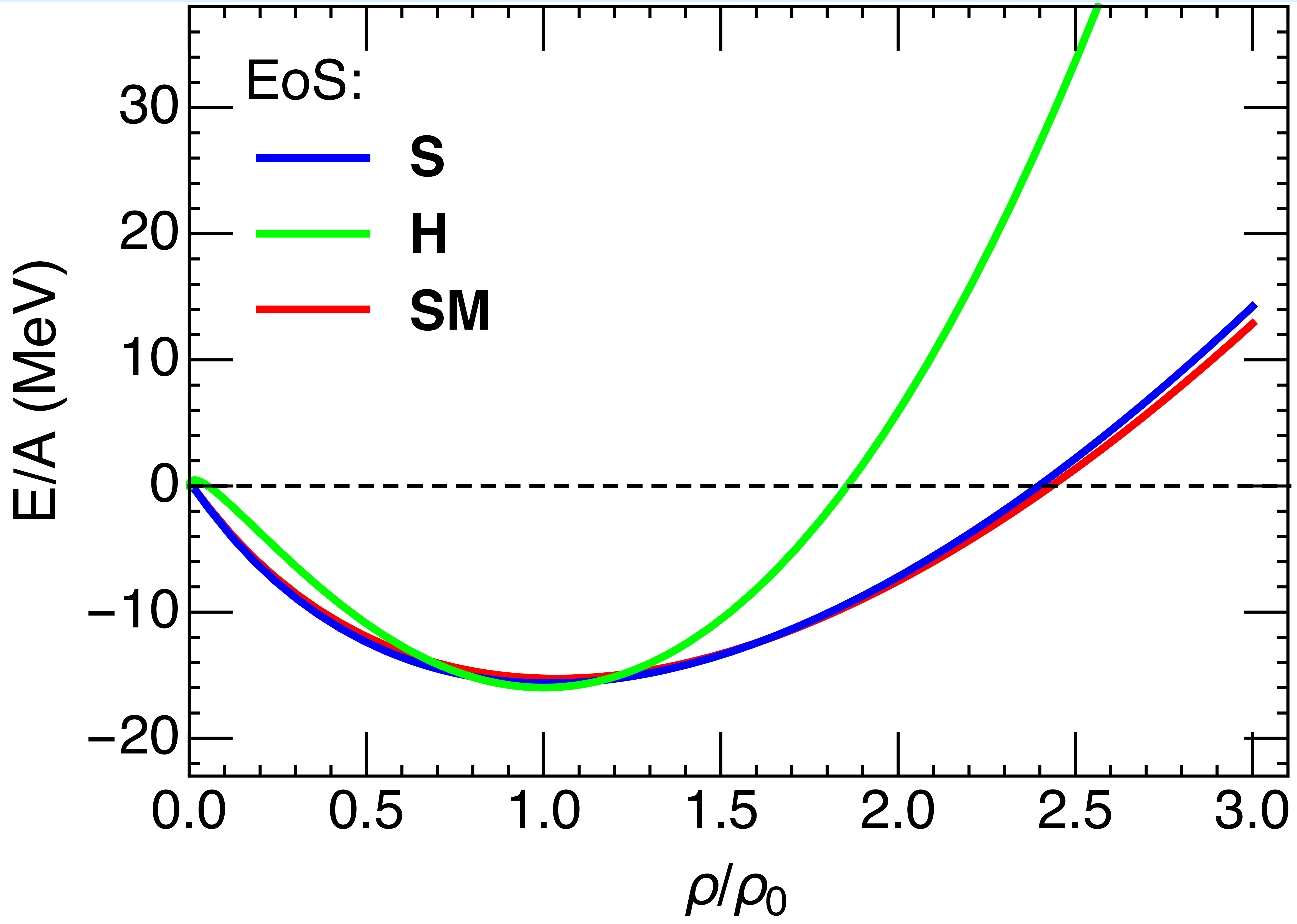
Hypernuclei yields in small systems may hold information on hypernuclei wavefunction



Y. Hu (STAR), QM2023

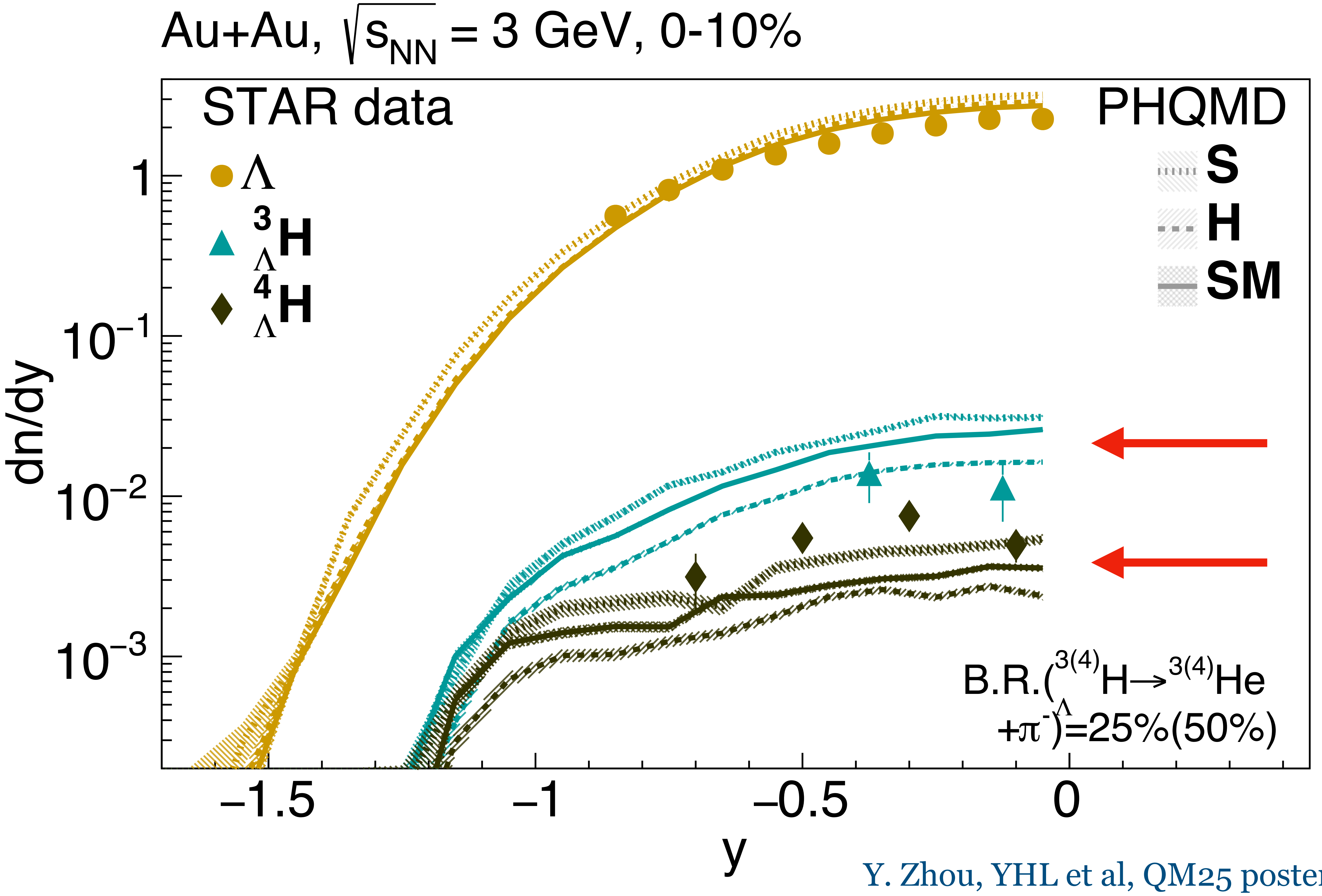
- Similar studies can be carried out at peripheral/ low collision heavy-ion collisions

Outlook: Probing the Equation of State at High Baryon Density



EoS	α [GeV]	β [GeV]	γ	K [MeV]
S	-0.3835	0.3295	1.15	200
H	-0.1253	0.071	2.0	380
SM	-0.478	0.4137	1.1	200

V. Kireyeu et al, arXiv:2411.04969



Y. Zhou, YHL et al, QM25 poster

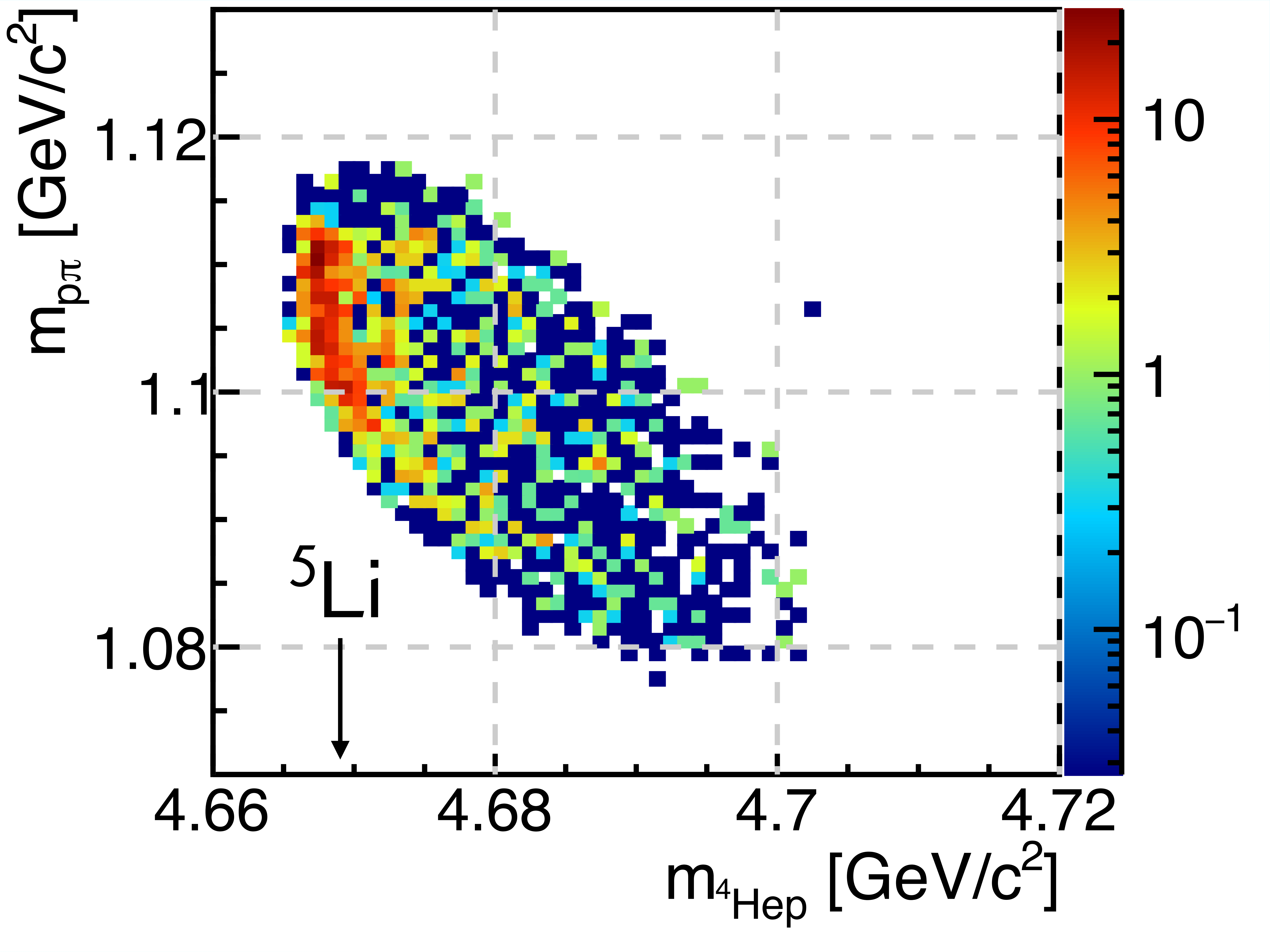
- Vary Skryme potential and compressibility modulus to construct three EoS within PHQMD appraoch

Hypernuclei yields may be sensitive to EoS

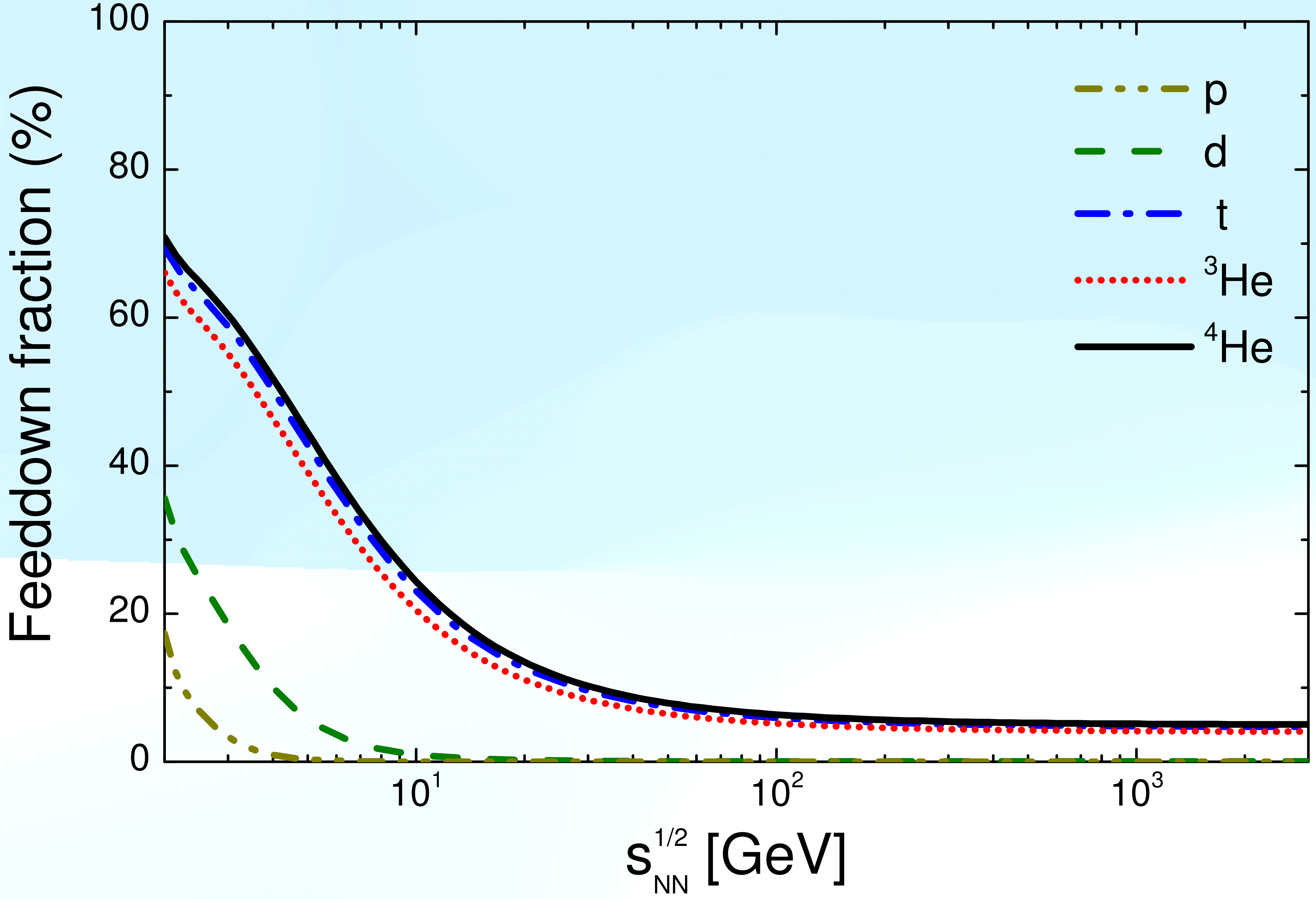
Thank you for listening!!

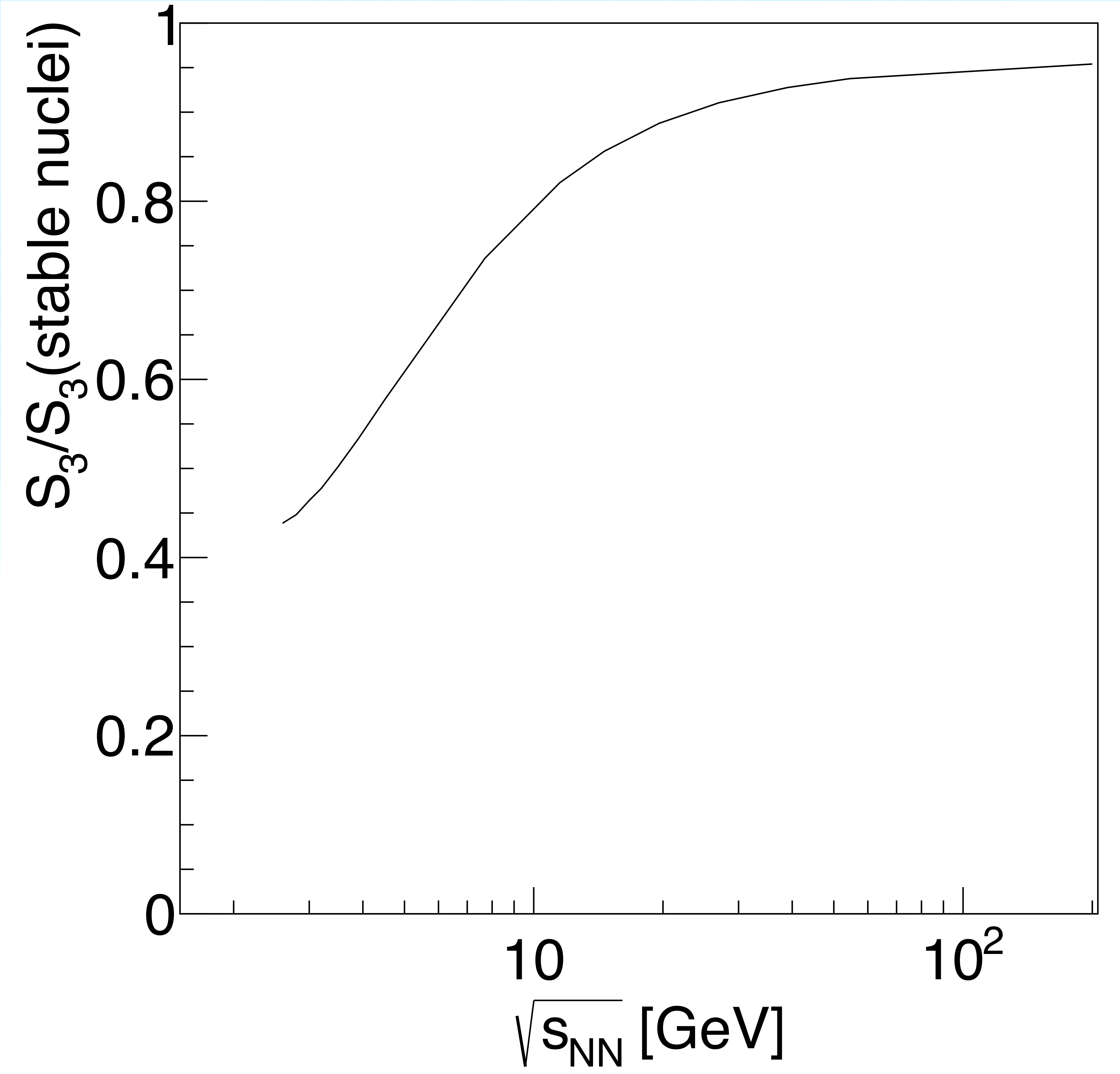
Backup slides follow

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



Feed-down from Unstable Nuclei



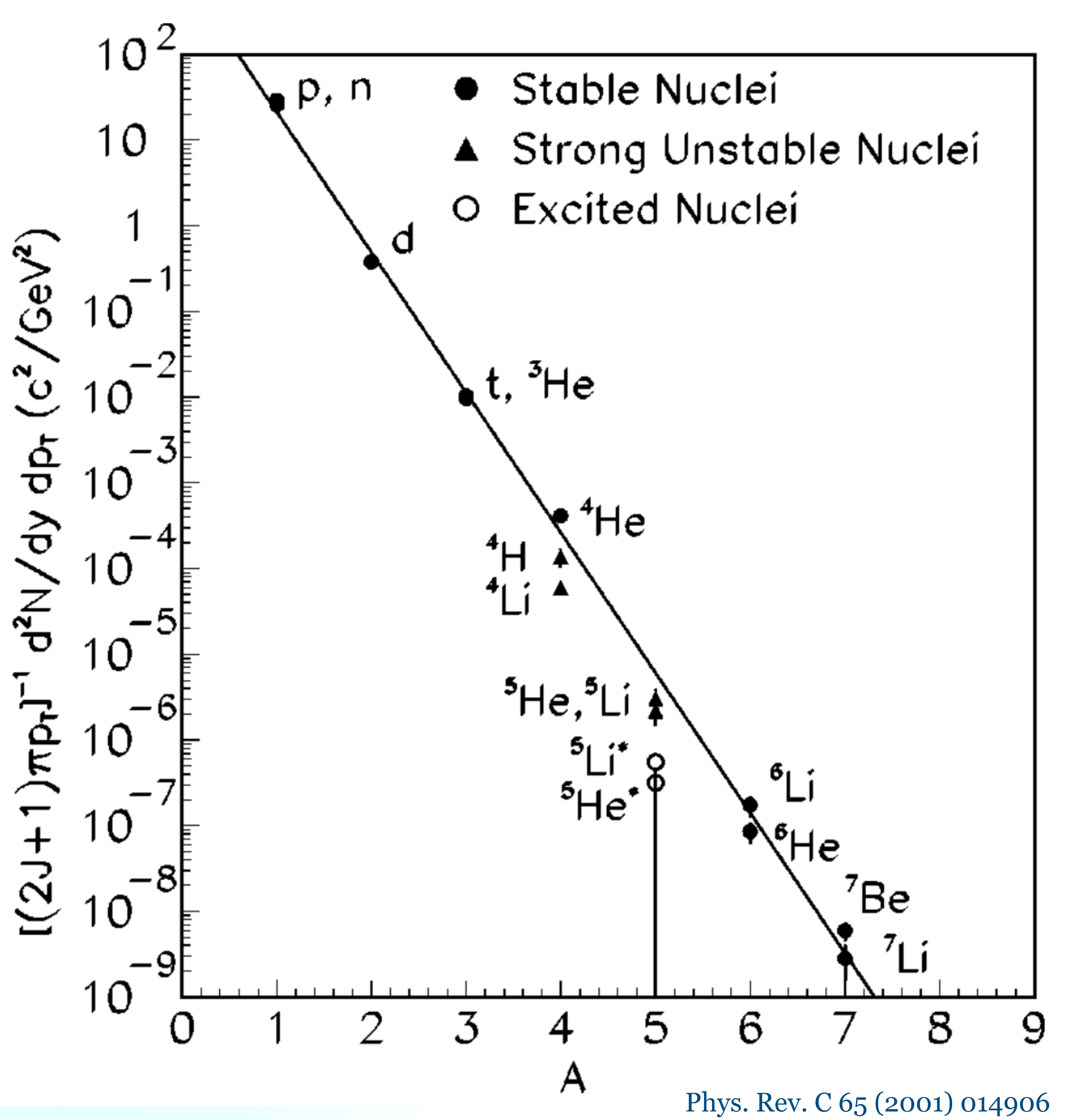


- Feed-down fractions estimated using Thermal-FIST

V. Vovchenko et al, Phys. Lett. B 809 (2020) 135746

- Feed-down correction of S_3 from unstable nuclei estimated using Thermal-FIST

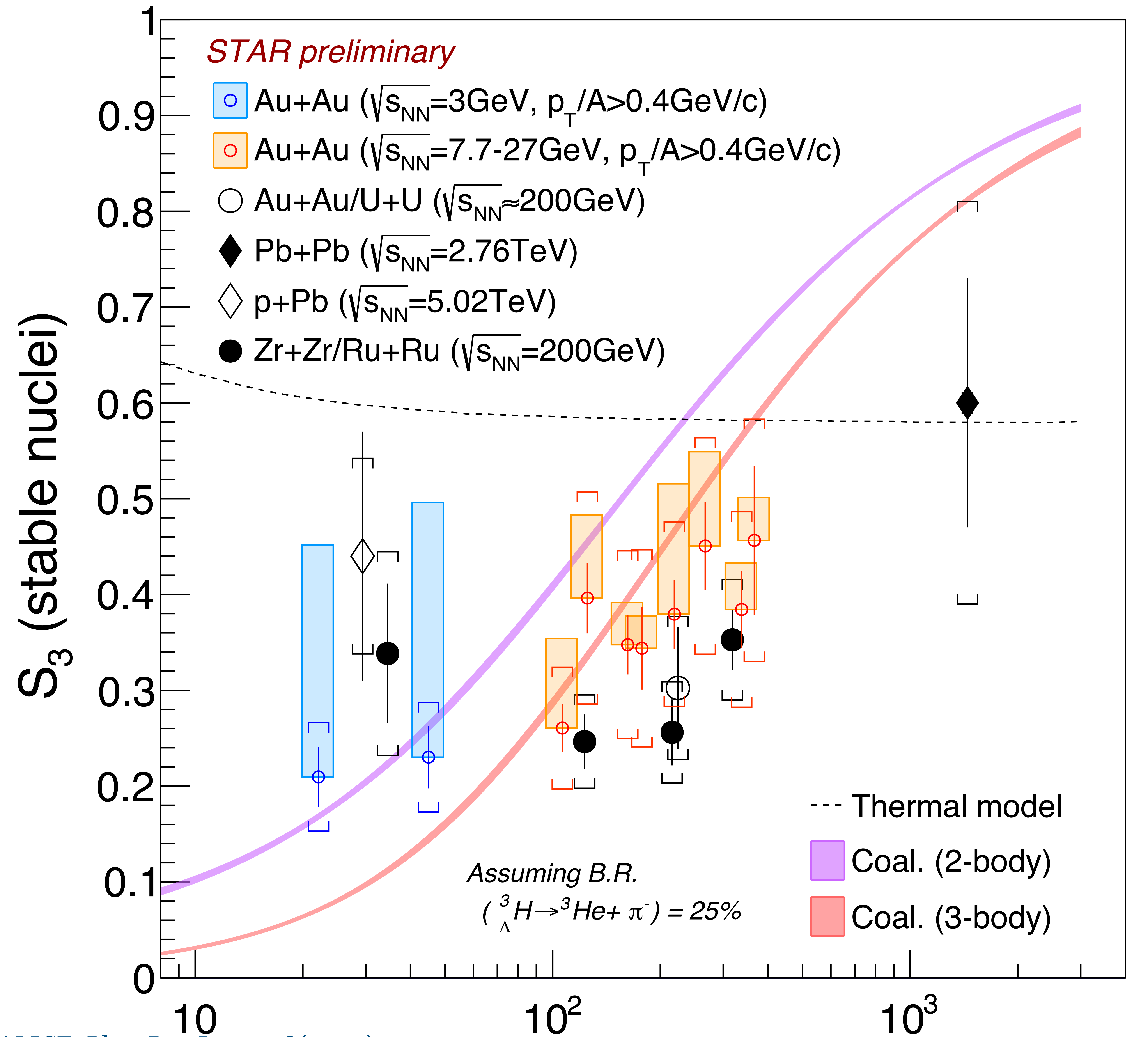
Feed-down from Unstable Nuclei



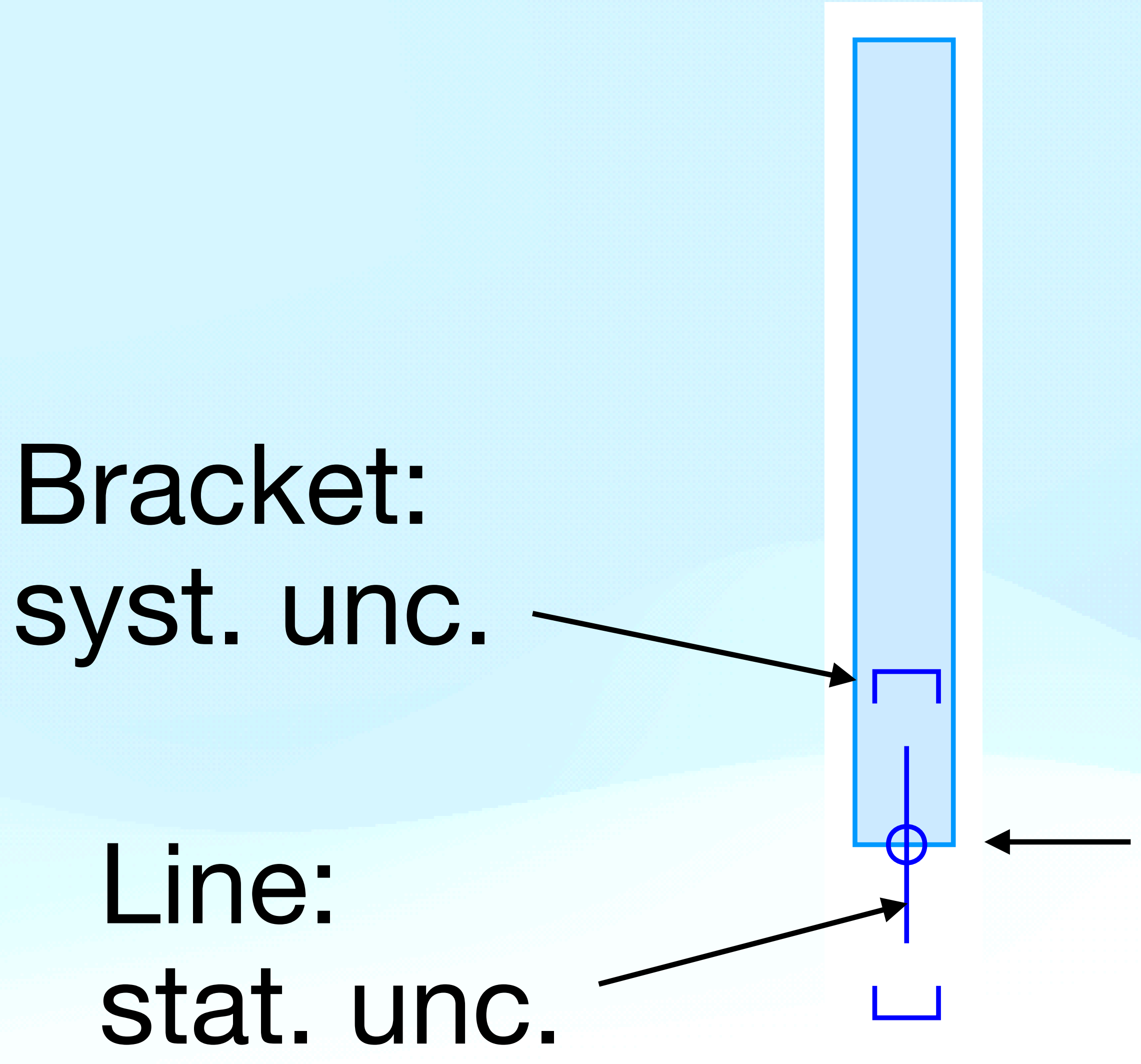
Phys. Rev. C 65 (2001) 014906

- Suppression of A=4 unstable states compared to ^{4}He ground state observed at E864

Strangeness Population Factor



ALICE, Phys.Rev.Lett. 128(2022)252003
(Thermal) V. Vovchenko, Phys.Lett.B 785(2018)171
(Coalescence) K. Sun et al, Phys.Lett.B 792(2019)132

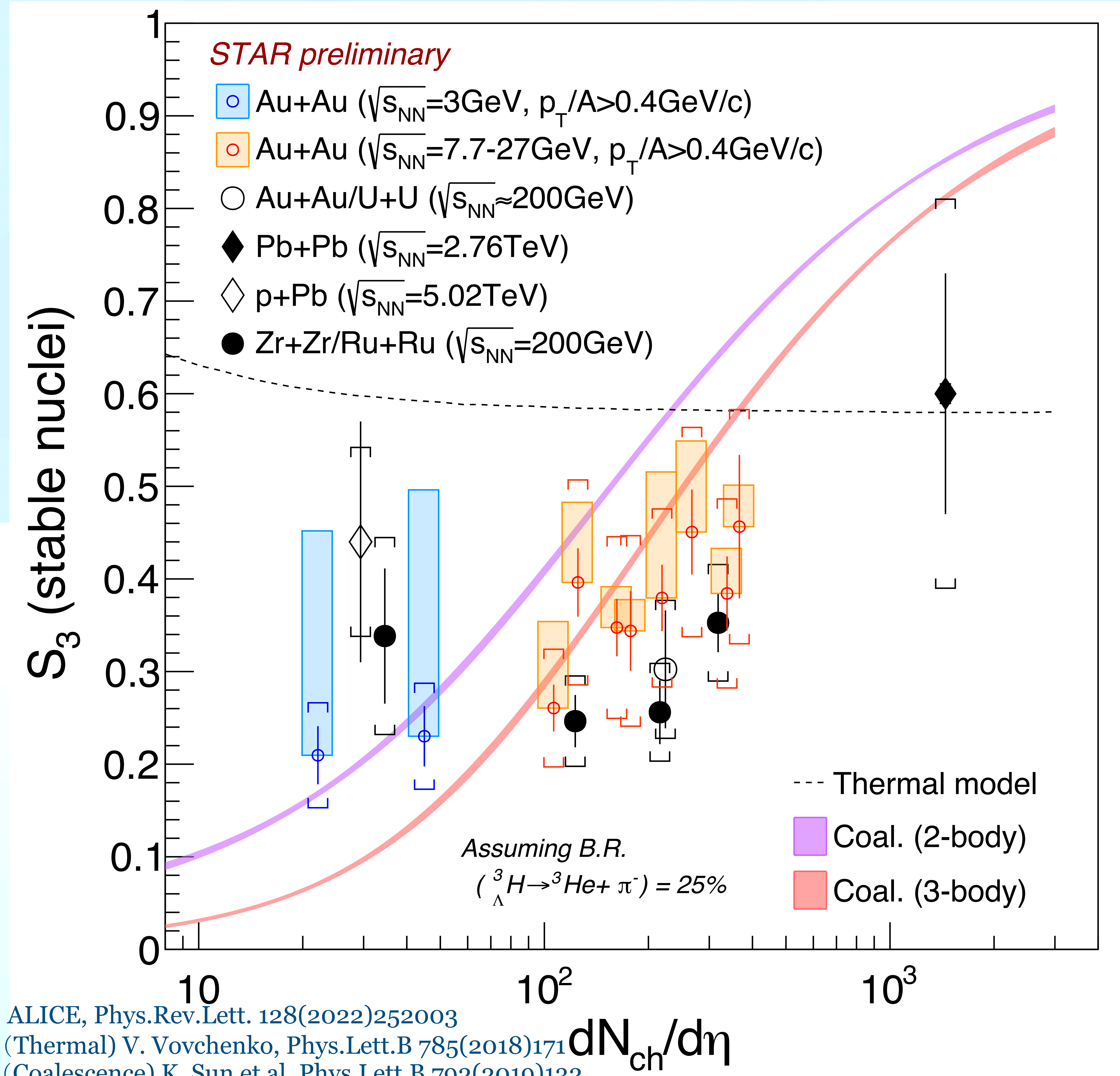


Upper edge of box: S_3 value **corrected for feed-down from thermal model**

Lower edge of box: S_3 value **uncorrected for feed-down**

- Unstable nuclei production are suppressed relative to stable nuclei (see backup)
- The true value of S_3 (stable nuclei) very likely lies between the upper and lower limits

Strangeness Population Factor

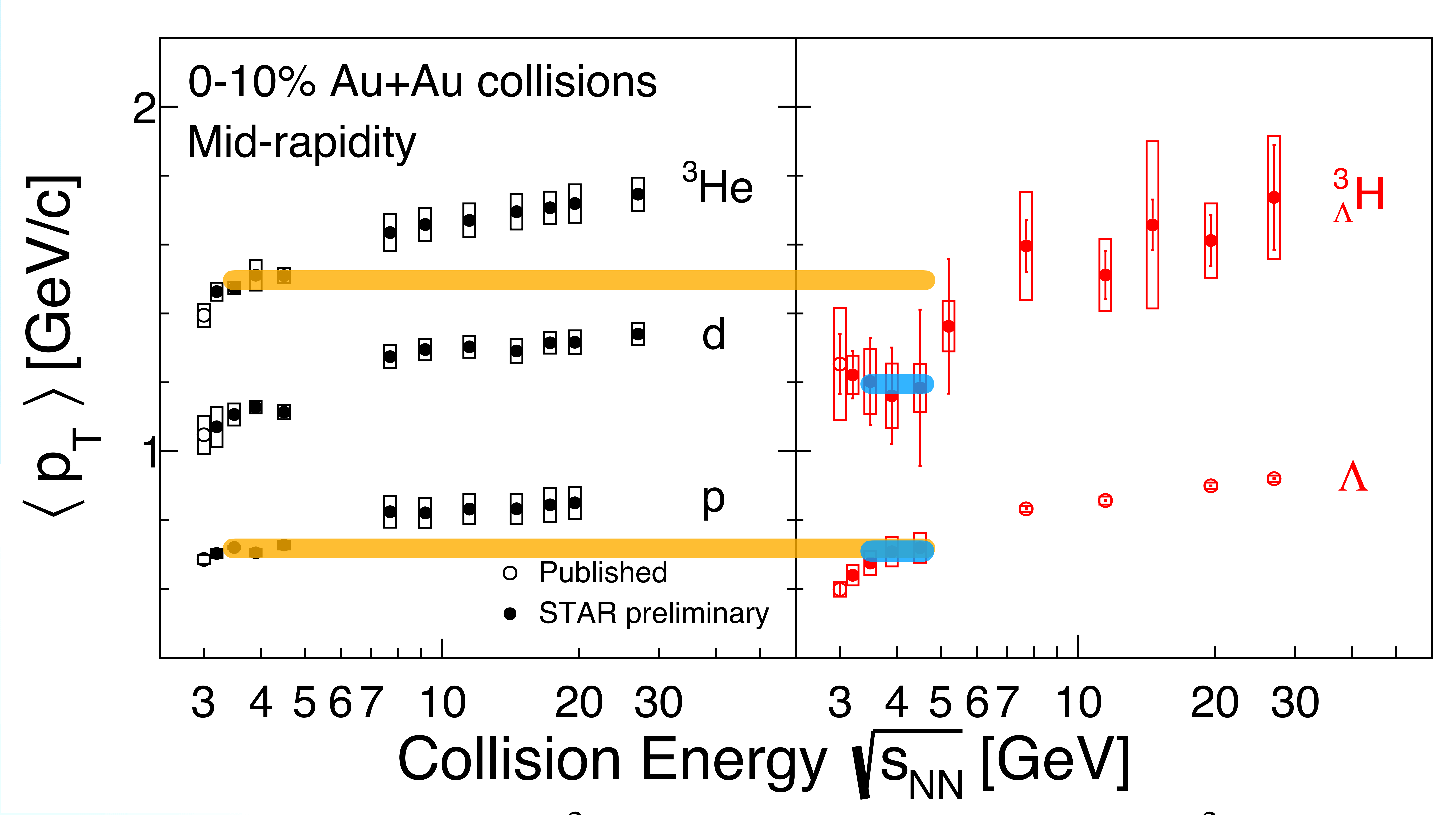


ALICE, Phys.Rev.Lett. 128(2022)252003
(Thermal) V. Vovchenko, Phys.Lett.B 785(2018)171
(Coalescence) K. Sun et al, Phys.Lett.B 792(2019)132

S_3 (stable nuclei) ≈ 0.35

- Existing data for S_3 <u>considering stable nuclei only</u> do not exhibit significant dependence on collision energy, system size

Collision Energy Dependence of Mean Transverse Momentum



- Between $\sqrt{s_{NN}}$ =3.5-4.5 GeV, $^3_\Lambda\mathrm{H}$ $\langle p_T \rangle$ tend to be lower than $^3\mathrm{He}$, even though Λ and proton $\langle p_T \rangle$ are similar