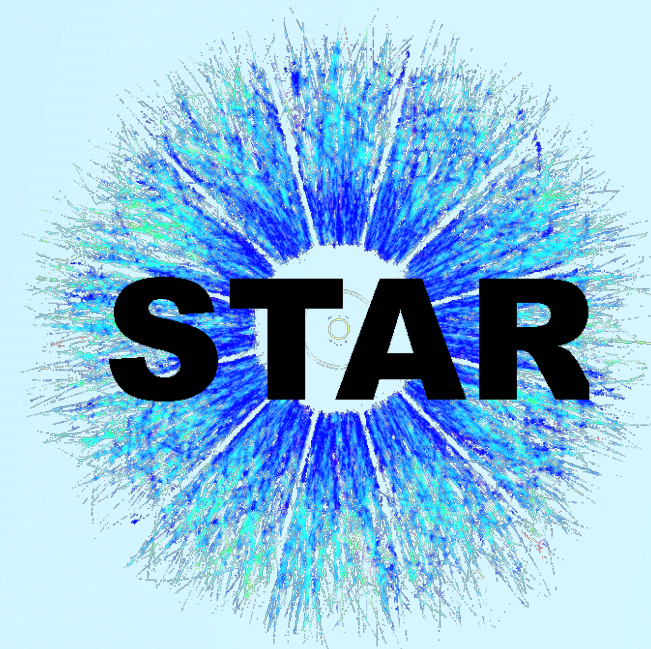# Hypernuclei Production in Heavy-Ion Collisions

(at finite baryon density)

STAR

CPOD 2024

Yue Hang Leung
for the STAR collaboration

University of Heidelberg
20th May, 2023

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

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

$^{6}_{\Lambda\Lambda}$He

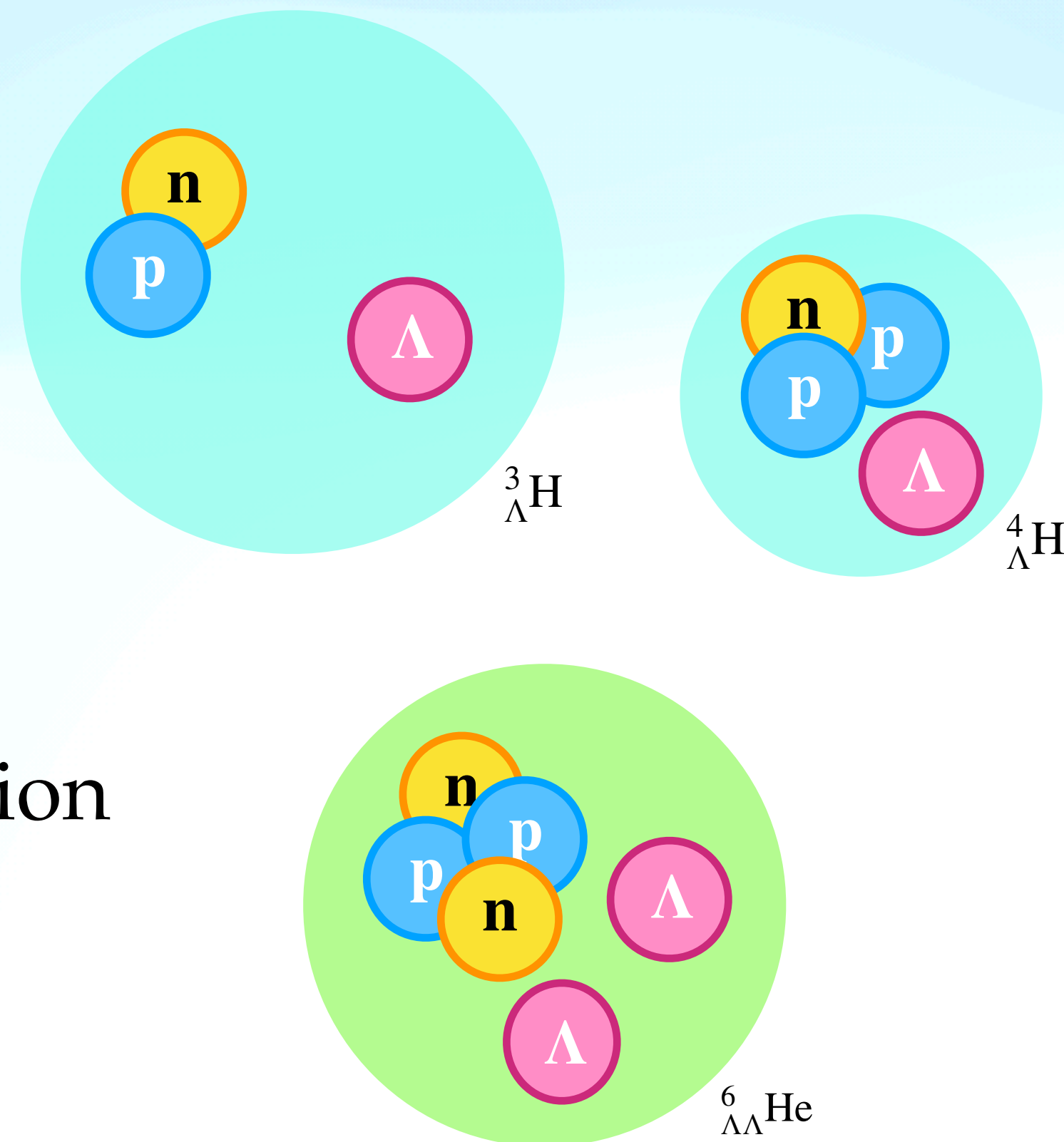# What can hypernuclei production in heavy-ion collisions tell us about the **QCD phase diagram**?

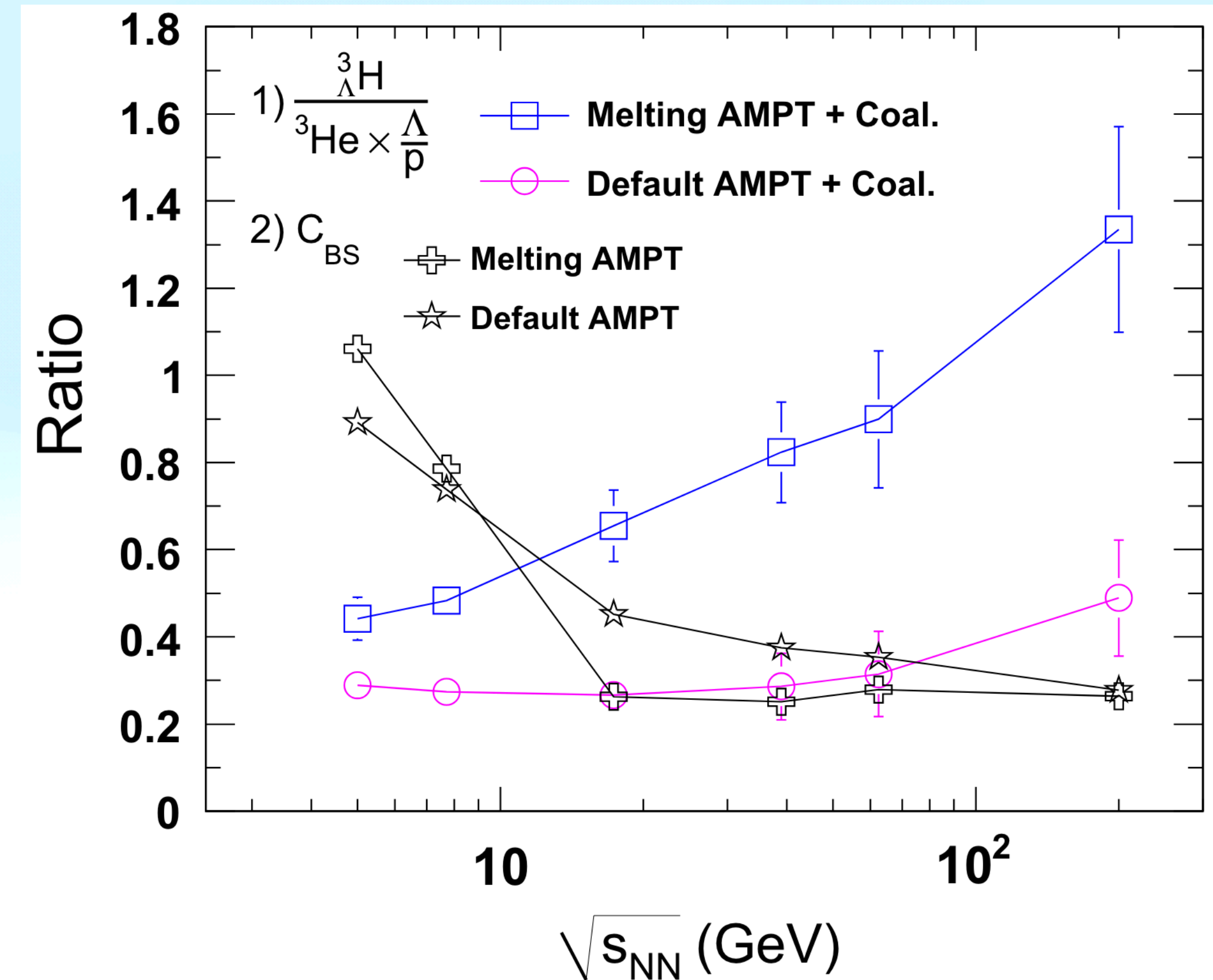- Hypernuclei yields have been suggested to be sensitive to the **onset of deconfinement**

- $$S_3 = \frac{^{3}_{\Lambda}\text{H}}{^{3}\text{He} \times \frac{\Lambda}{p}}$$ may be <u>enhanced</u> in

    systems involving partonic interactions

    Phys. Lett. B 684 (2010) 224

- Baryon clustering near critical point may lead to <u>enhancement</u> of light nuclei ($A \geq 3$) yields

    Phys. Rev. C 101 (2020) 034914

What is the role of **<u>hyperon-nucleon (YN) interaction</u>** in the equation-of-state of high baryon density matter?

- **Hyperon Puzzle:** difficulty to reconcile the measured masses of neutron stars with the presence of hyperons in their interiors

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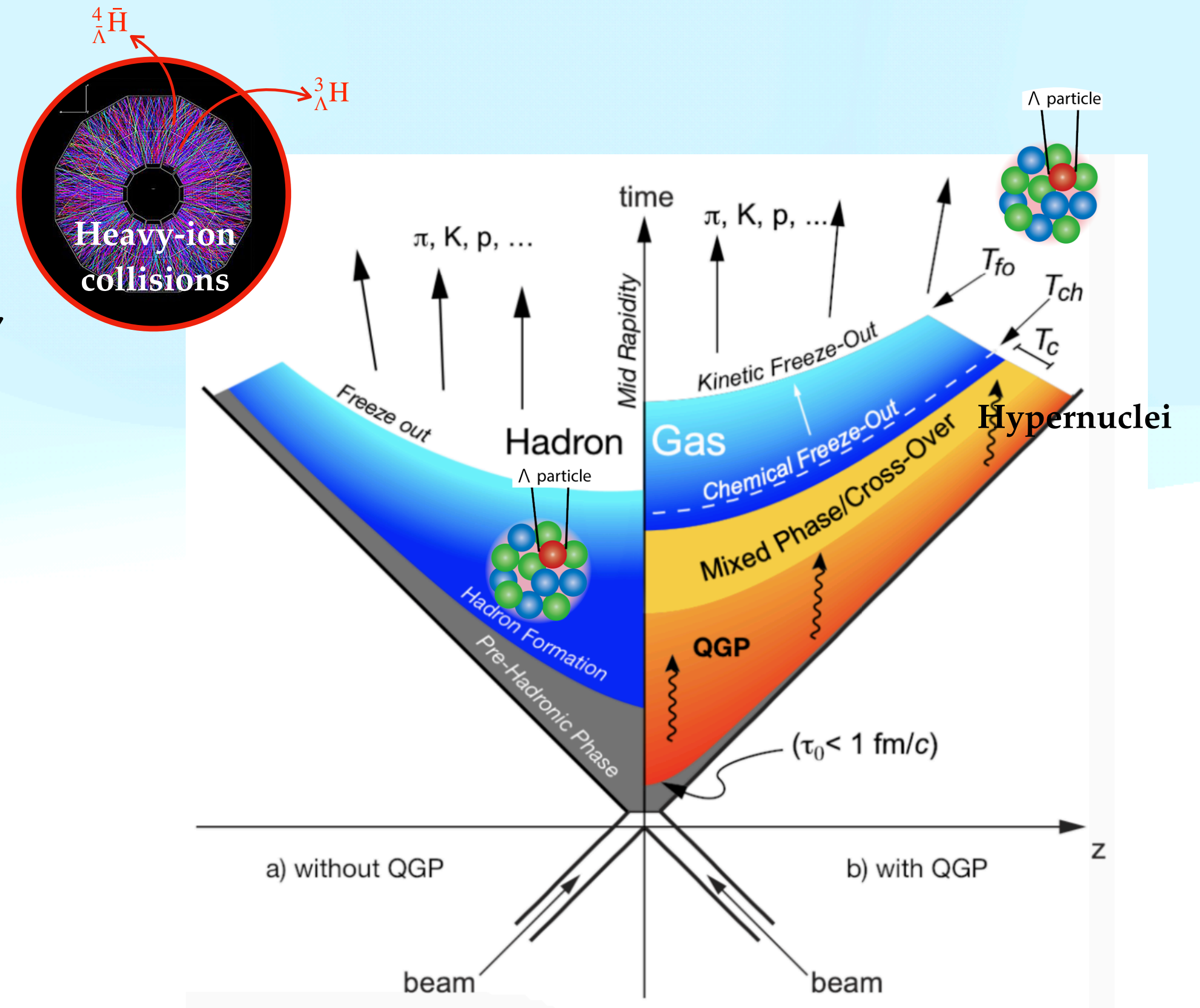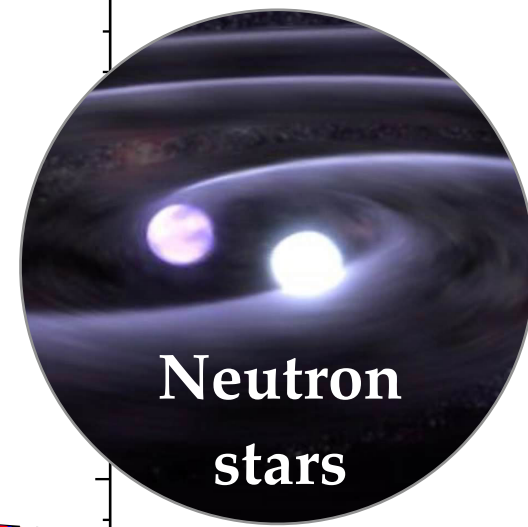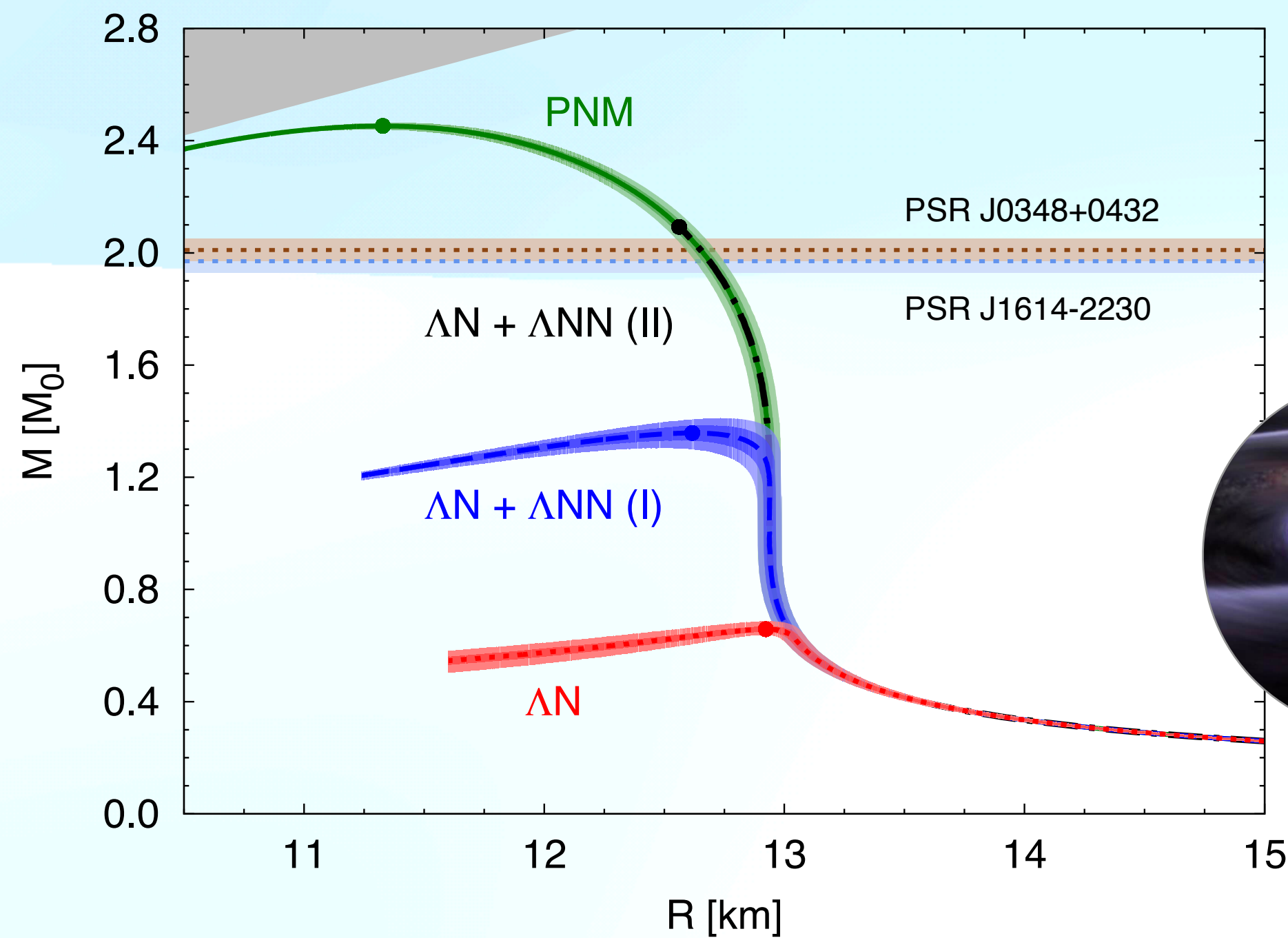
- Density dependent YN, YNN interactions are essential for solving the hyperon puzzle

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

T. Gaitanos, Nucl. Phys. A 914 (2013) 405

How and when are light nuclei formed in heavy ion collisions?

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

What Have We Learnt From Light Nuclei Production?
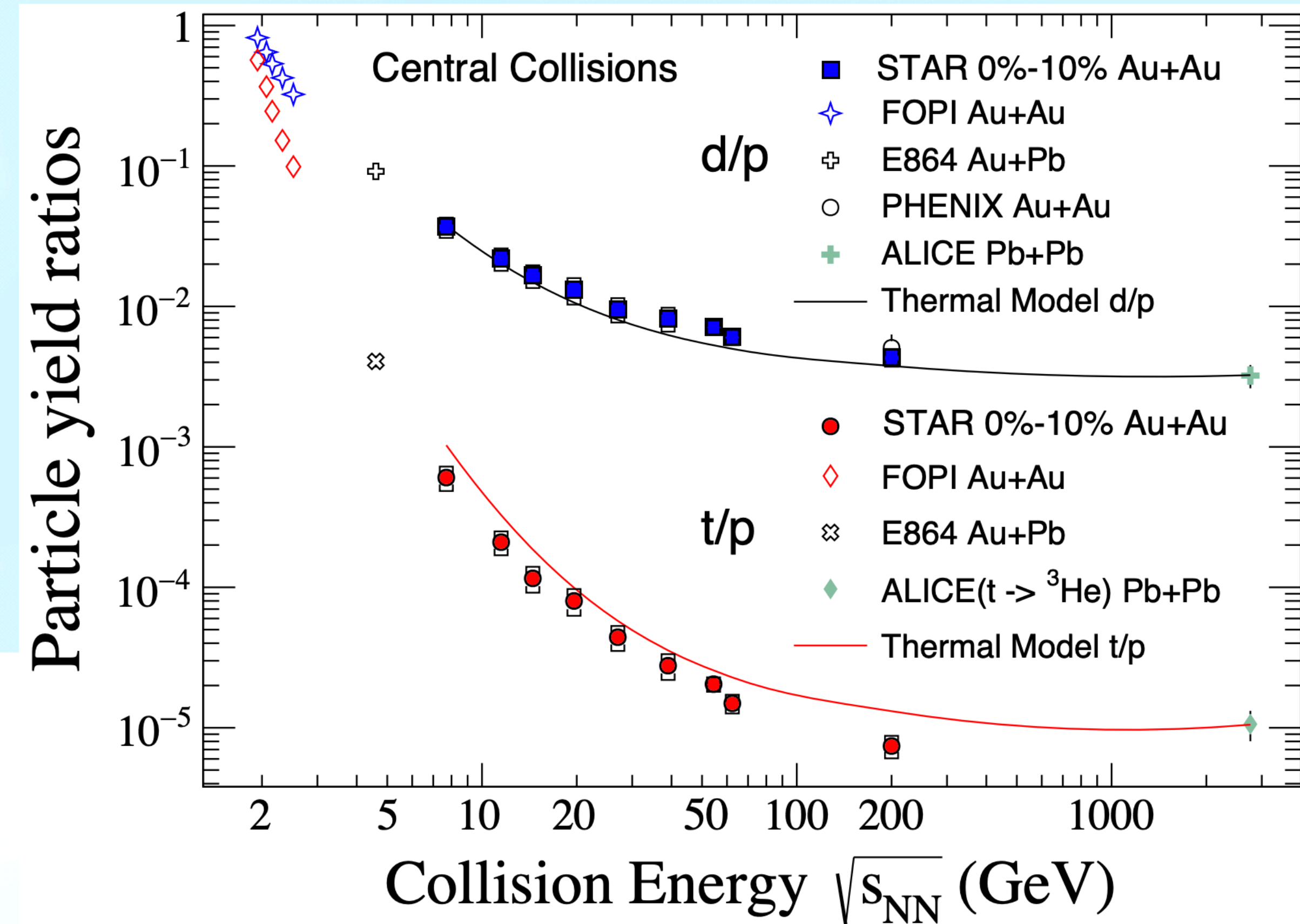
STAR, Phys. Rev. Lett. 130 (2023) 202301

ALICE, Phys. Rev. C 107 (2023) 064904

ALICE, arXiv:2311.11758v1

- d/p is fairly well described by [thermal model](#), but t/p is overestimated

- ^{4}He/p is well described by thermal model, but underestimated by various implementations of [coalescence formation](#)

Recent data poses challenges for nuclei production models

Hypertriton $(^3_\Lambda H)$ and Hyperhydrogen-4 $(^4_\Lambda H)$
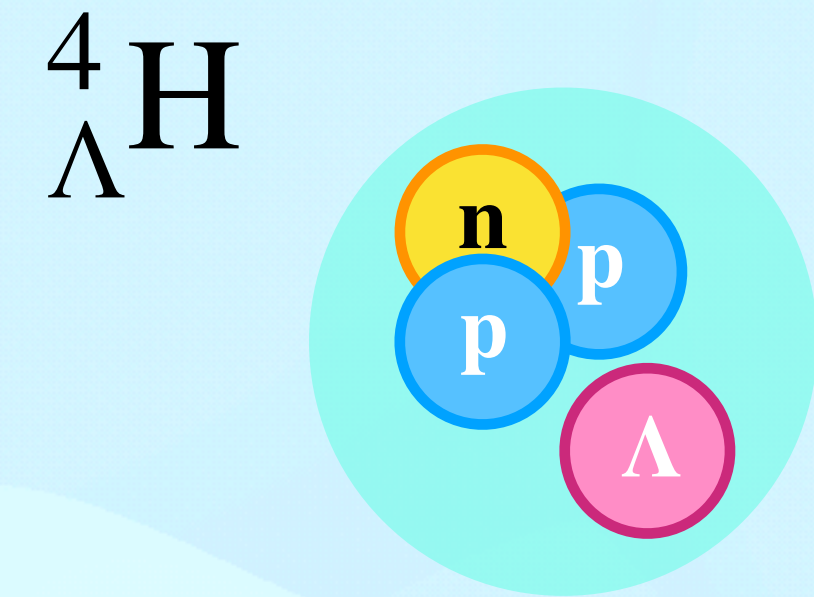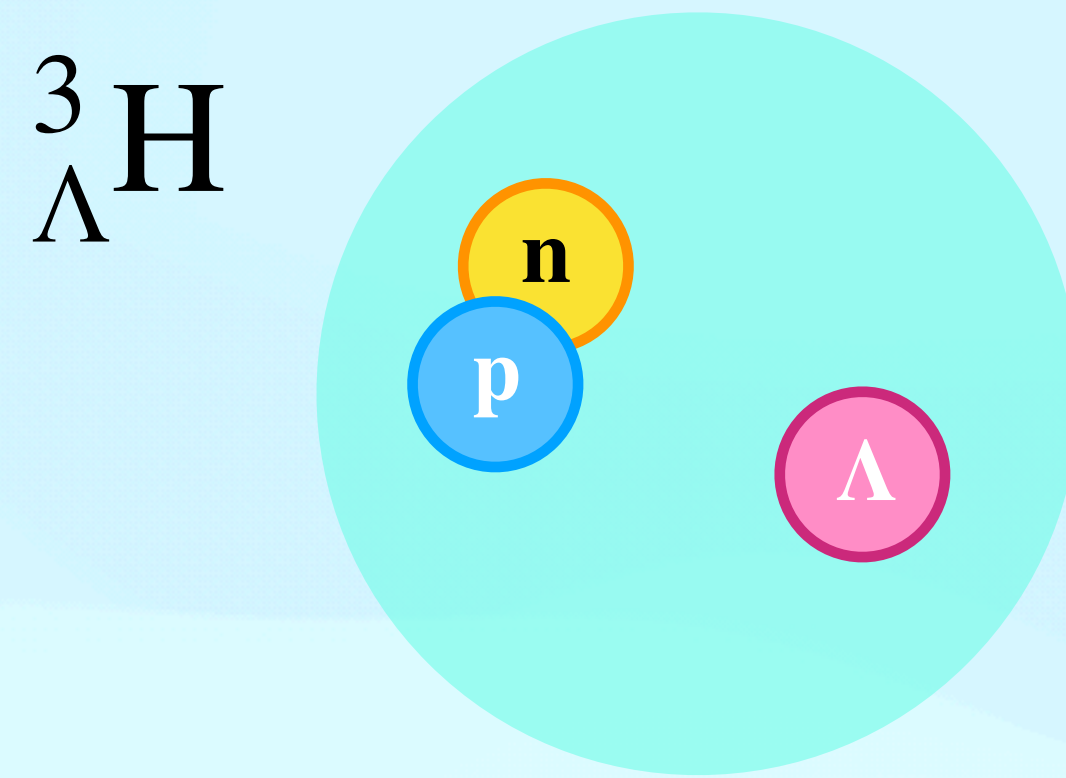
	$^3_\Lambda H$	$^4_\Lambda H$
Λ binding energy	~0.1 MeV	~2.2 MeV
Excited states	Not observed	$^4_\Lambda H*(1^+) \rightarrow {}^4_\Lambda H(0^+) + \gamma$
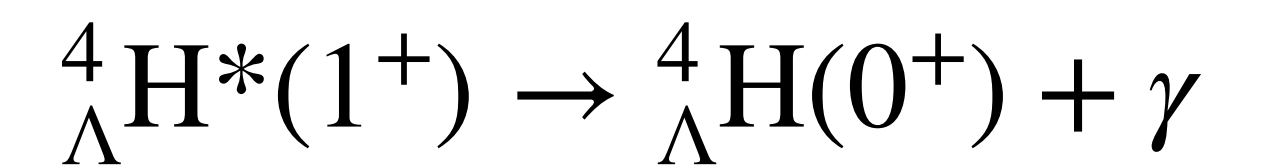
- Due to its very small binding energy, $^3_\Lambda H$ production provides unique input for nuclei production models

STAR Beam Energy Scan II

- BES-I (2009-2011)
  - Au+Au collisions $\sqrt{s_{\mathrm{NN}}} = 7.7$-62 GeV
  - Main objectives:
    - **Search for onset of deconfinement**
    - **Search for critical end point**
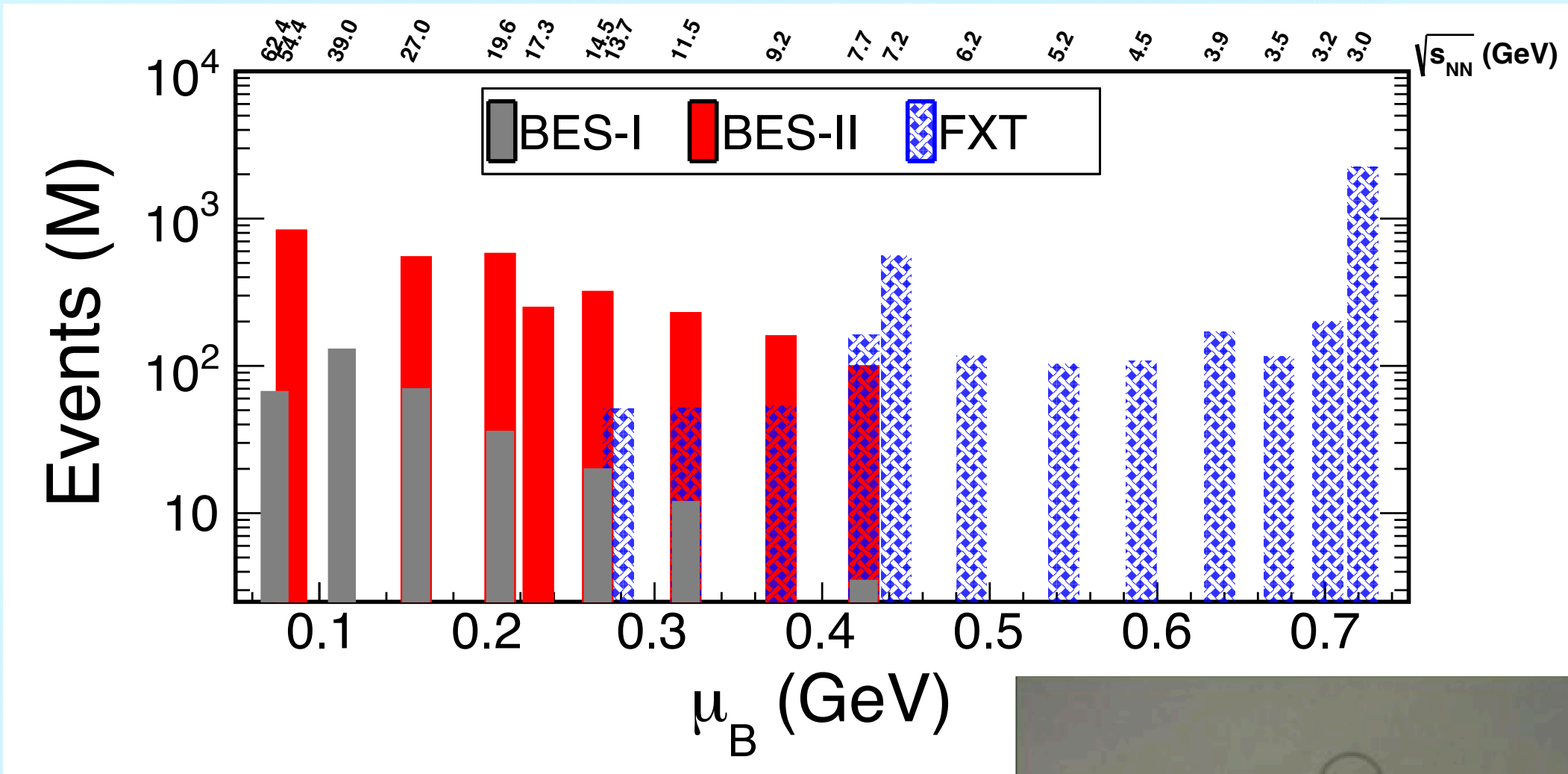
- BES-II (2018-2021)
  - High statistics Au+Au collisions $\sqrt{s_{\mathrm{NN}}} = 3$-54.4 GeV
  - Fixed target (FXT) collisions extend energy reach down to $\sqrt{s_{\mathrm{NN}}} = 3$ GeV
    - **Search for possible formation and investigate properties of dense baryonic matter**

Au+Au Collisions, 0-40%

$\sqrt{s_{NN}}$ = 3.2 GeV
-0.5<y<0
1<p_T<4 GeV/c

(a)

Data   Rot. Bg   Data-Rot. Bg

$\sqrt{s_{NN}}$ = 19.6 GeV
|y|<0.5
1.5<p_T<4 GeV/c

(b)

M(^{3}Heπ^-) (GeV/c^2)

3 GeV   3.2 GeV   3.5 GeV   3.9 GeV   4.5 GeV   5.2 GeV
0-10% (top)
Au+Au

$^3_\Lambda$H → dpπ (×$\frac{R_3}{(1-R_3)}$)
$^3_\Lambda$H → ^{3}Heπ

3 GeV   3.2 GeV   3.5 GeV   3.9 GeV   4.5 GeV   5.2 GeV
STAR preliminary   10-40% (bottom)

B.R.×dN/dy

y/y_{beam}

Au+Au collisions, |y|<0.5

7.7 GeV   11.5 GeV   14.6 GeV

STAR preliminary
$^3_\Lambda$H, 0-10%
$^3_\Lambda$H, 10-40%

m_T-exp. fit

19.6 GeV   27 GeV

B.R./2πp_T d^{2}N/dydp$_T$[c^2/GeV^2]

p_T [GeV/c]

- Comprehensive $^3_\Lambda$H measurements at 11 different energies from 3 to 27 GeV

$^{3}_{\Lambda}$H **Excitation Function**
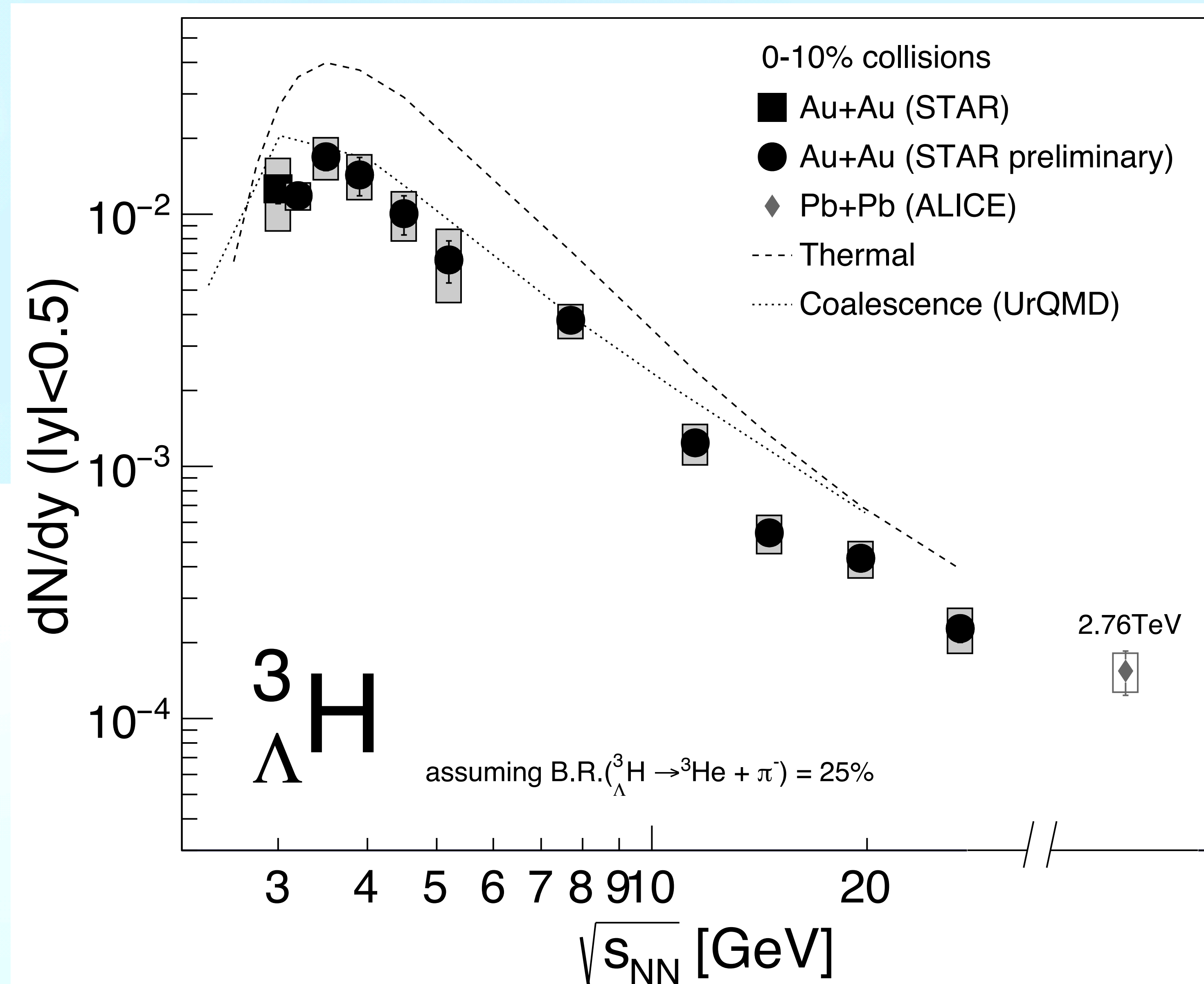
- Steep increase from 27 to 4 GeV

- Plateaus at 3-4 GeV

- 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

Nuclei-to-Hadron Ratios
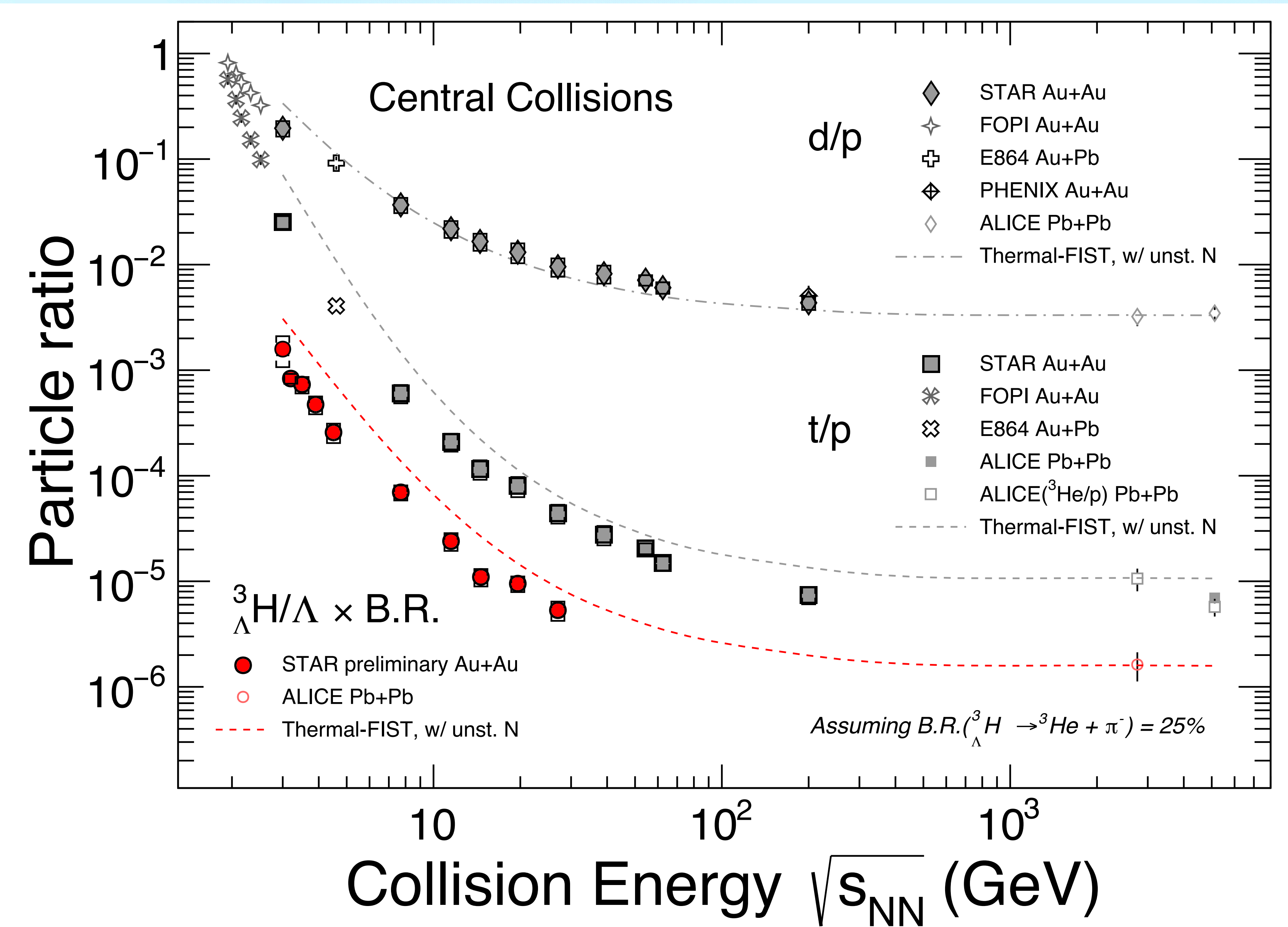
- $^3_\Lambda H/\Lambda$ ratio in a thermal model calculation is independent of volume and strangeness correlation length

- $^3_\Lambda H/\Lambda$, similar to t/p, are overestimated by thermal model by a factor of 2

$^3_\Lambda H$ (and t) yields are not in equilibrium and fixed at chemical freeze-out along with other light hadrons

Mean Transverse Momentum

- $^{3}_{\Lambda}\mathrm{H}$ and t have similar mean $\mathrm{p_T}$

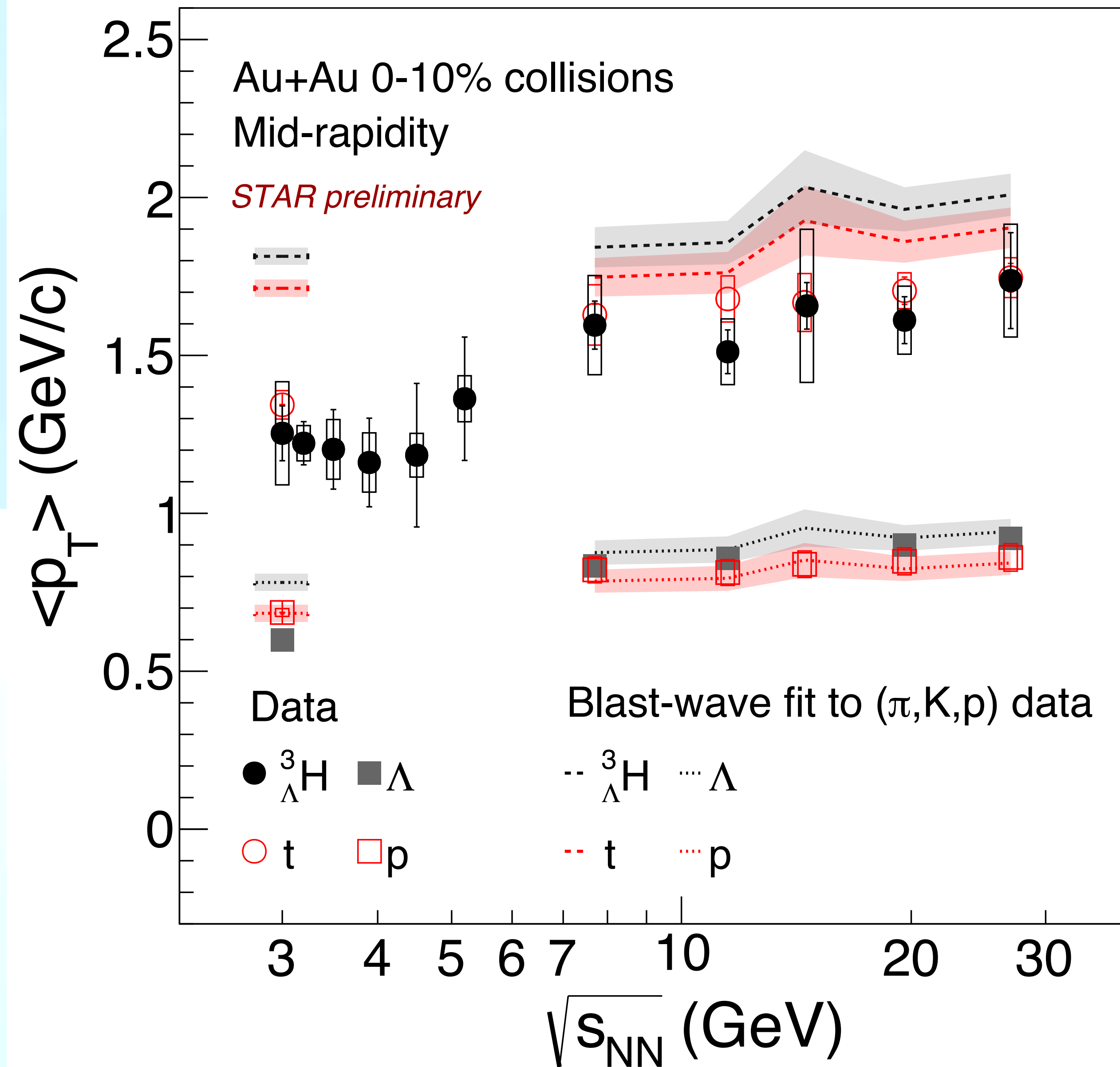- Both $^{3}_{\Lambda}\mathrm{H}$ and t tend to have lower mean $\mathrm{p_T}$ than the blast-wave parametrization using measured kinetic freeze-out parameters from light hadrons (π,K,p)

$^{3}_{\Lambda}\mathrm{H}$ (and t) do not follow same collective expansion as light hadrons

- Softening of the $^{3}_{\Lambda}\mathrm{H}$ may be explained by coalescence model with Wigner-function formalism

arXiv:2404.02701

Mean Transverse Momentum
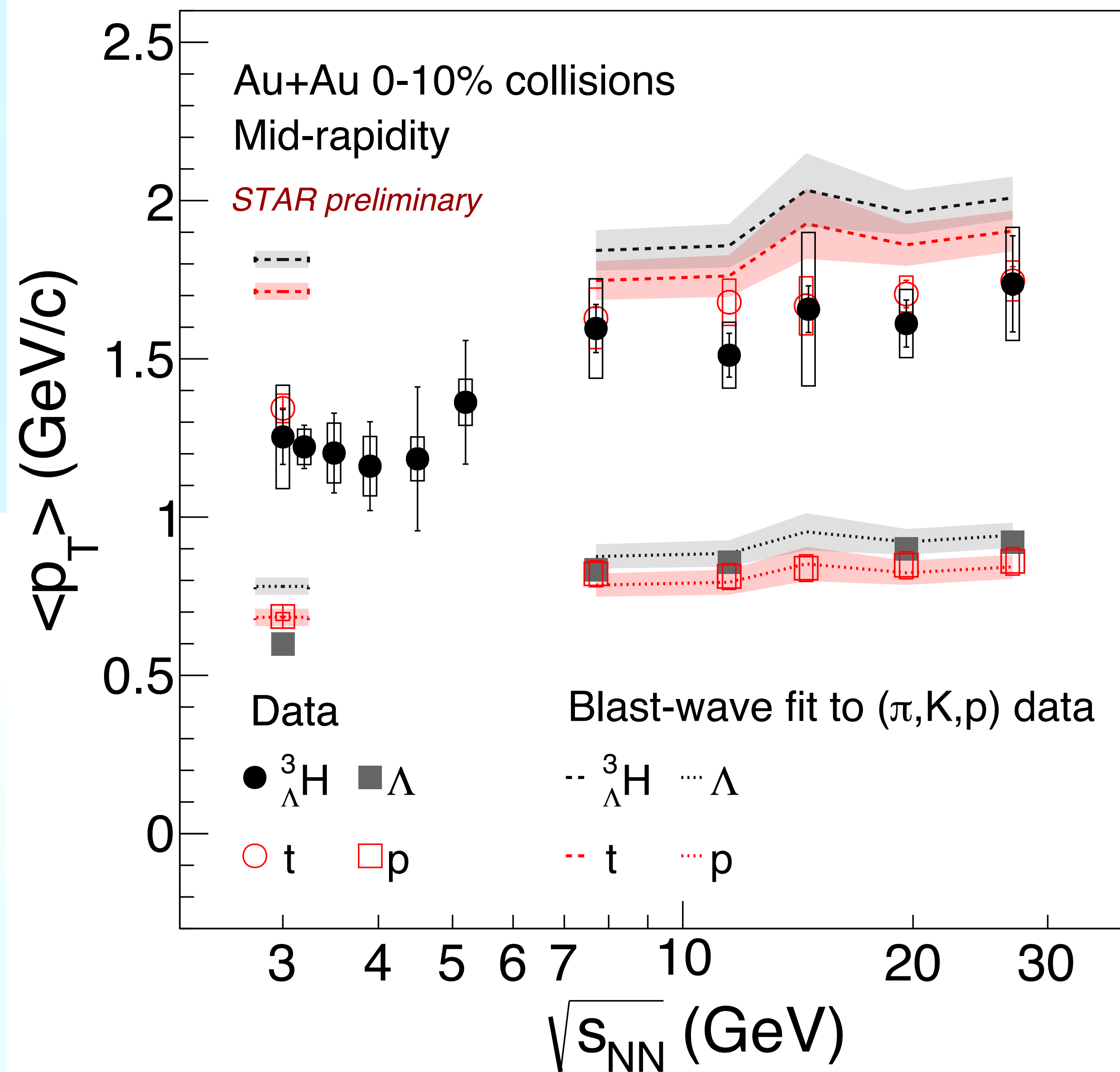
- The mean p_T for $\sqrt{s_{NN}} = 3 - 4.5\,\mathrm{GeV}$ and $\sqrt{s_{NN}} = 7.7 - 27\,\mathrm{GeV}$ seem to exhibit two different trends

Change in medium properties or expansion dynamics? see Y. Zhou, 17:00 20/05 (Mon.)

Au+Au 0-10% collisions
Mid-rapidity

STAR preliminary

Data   Blast-wave fit to (π,K,p) data

● $^3_\Lambda$H ■ Λ - - $^3_\Lambda$H ···· Λ

○ t   □ p   - - t   ···· p

Centrality Dependence of $^{3}_{\Lambda}\text{H}$ Production
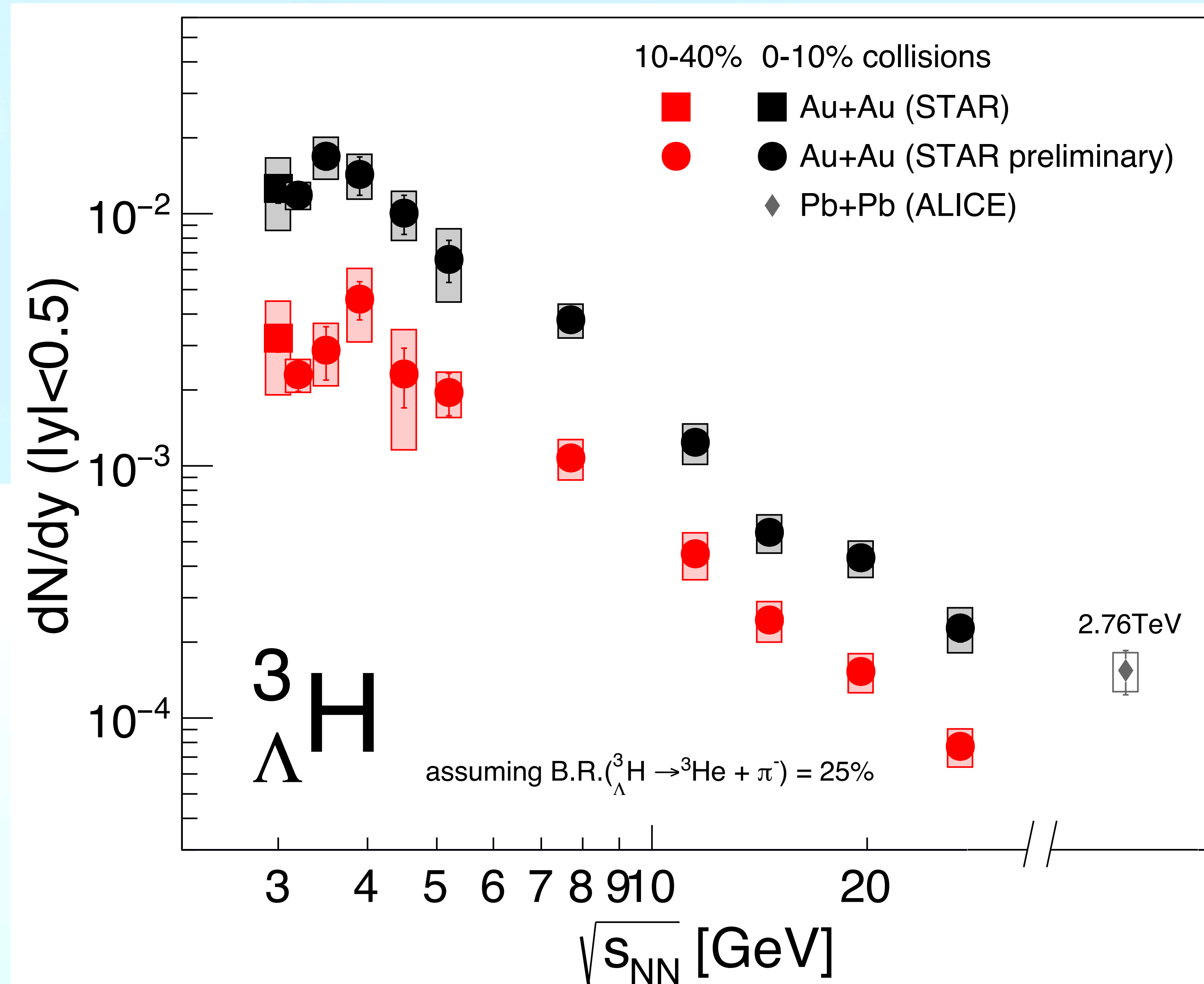
- The yield in mid-central (10-40%) collisions follow the same trend as central (0-10%) collisions

Centrality Dependence of $^{3}_{\Lambda}H$ Production

- $^{3}_{\Lambda}H$ production increases more steeply compared to N_{part}, seems to be more apparent below 7.7 GeV

Centrality Dependence of $^3_\Lambda H$ Production
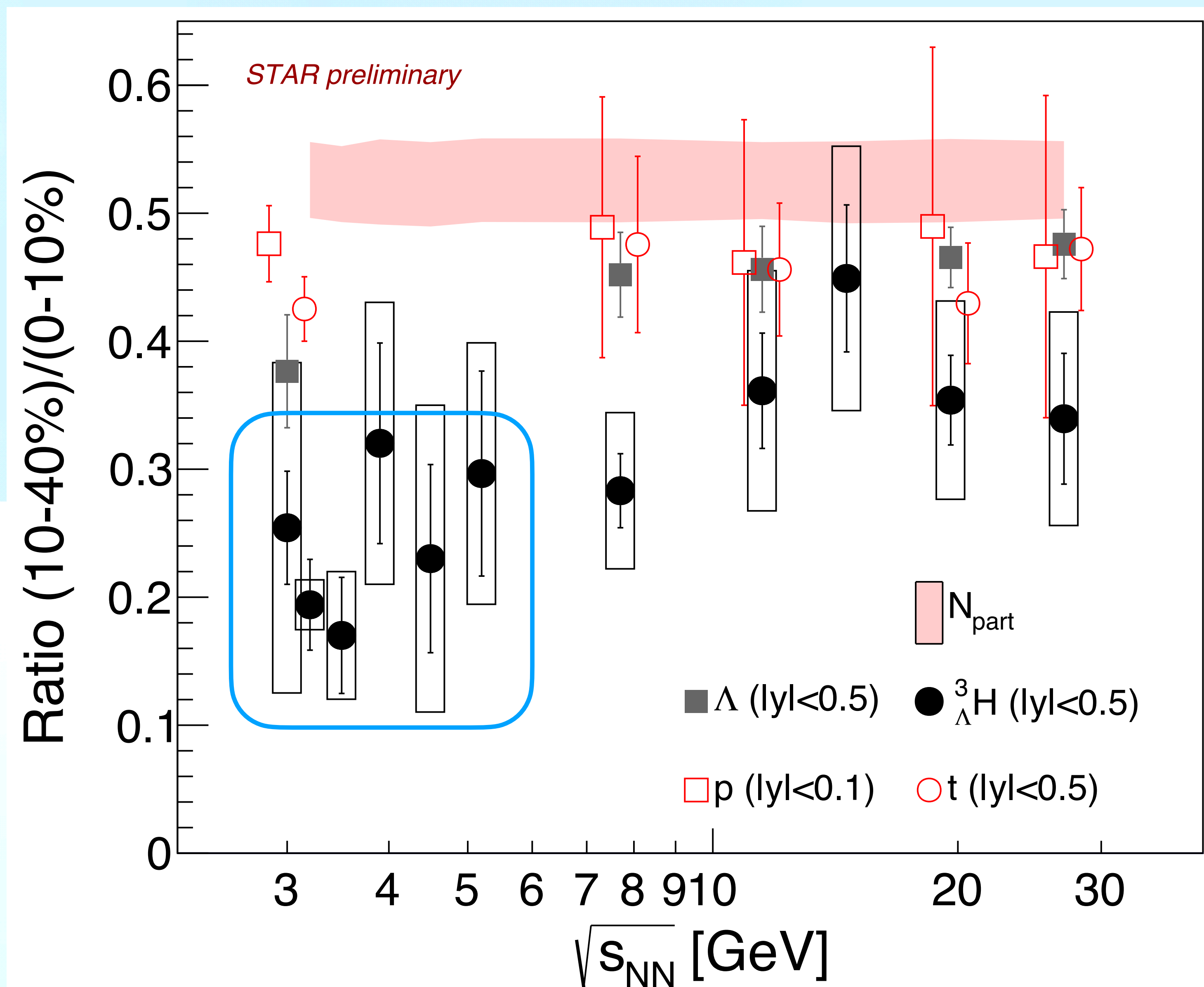
- Proton yield scales with N_{part}
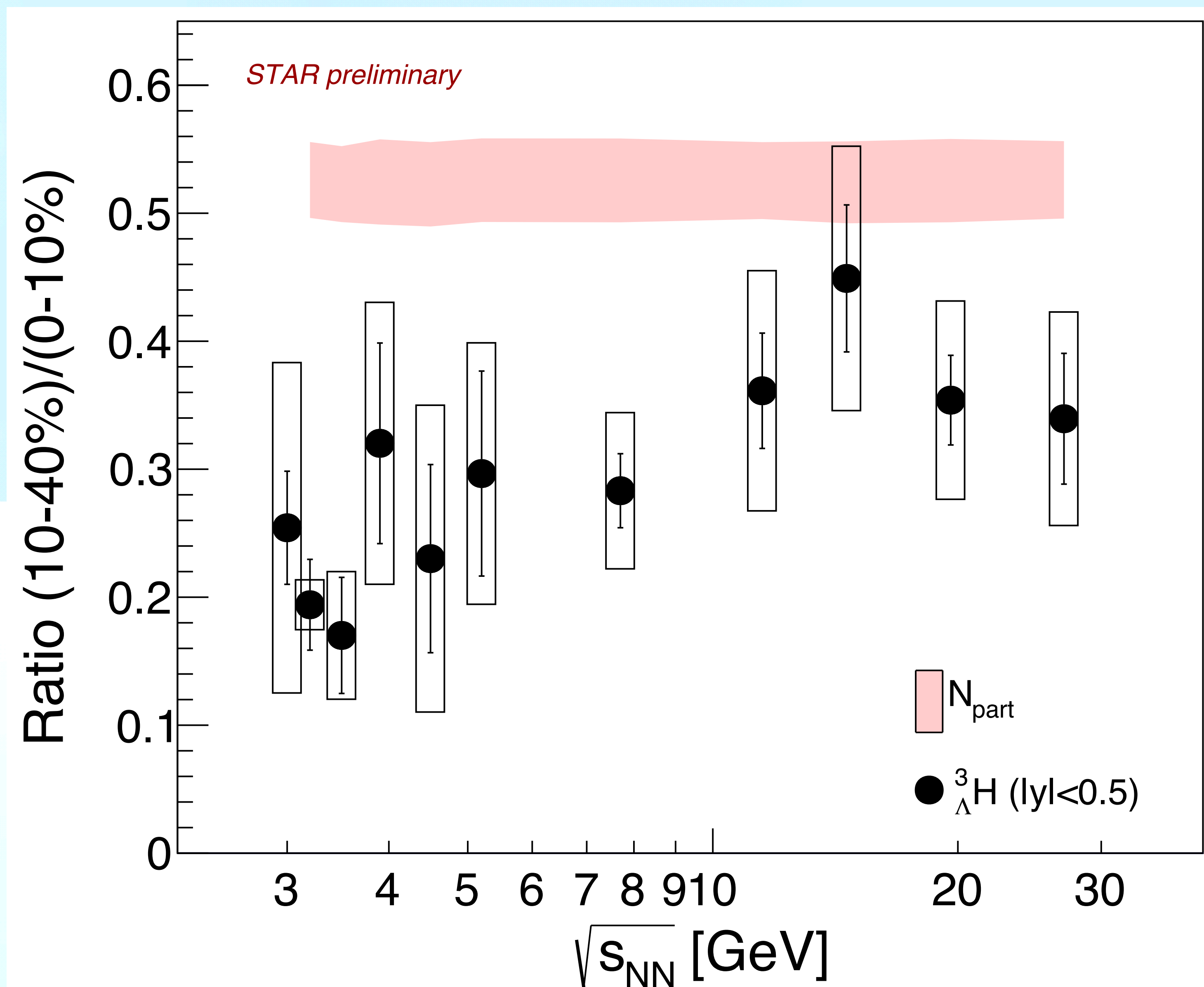
- Λ yield increases more steeply than N_{part}, particularly at low collision energies

  see Y. Zhou, 17:00 20/05 (Mon.)

- At low energies, $^3_\Lambda H$ production tends to increases more steeply than proton, Λ, ^3He

Suppression of $^3_\Lambda H$ production in <u>more peripheral collisions at low energies</u>

Centrality Dependence of $^{3}_{\Lambda}H$ Production

STAR preliminary

Ratio (10-40%)/(0-10%)

N_{part}

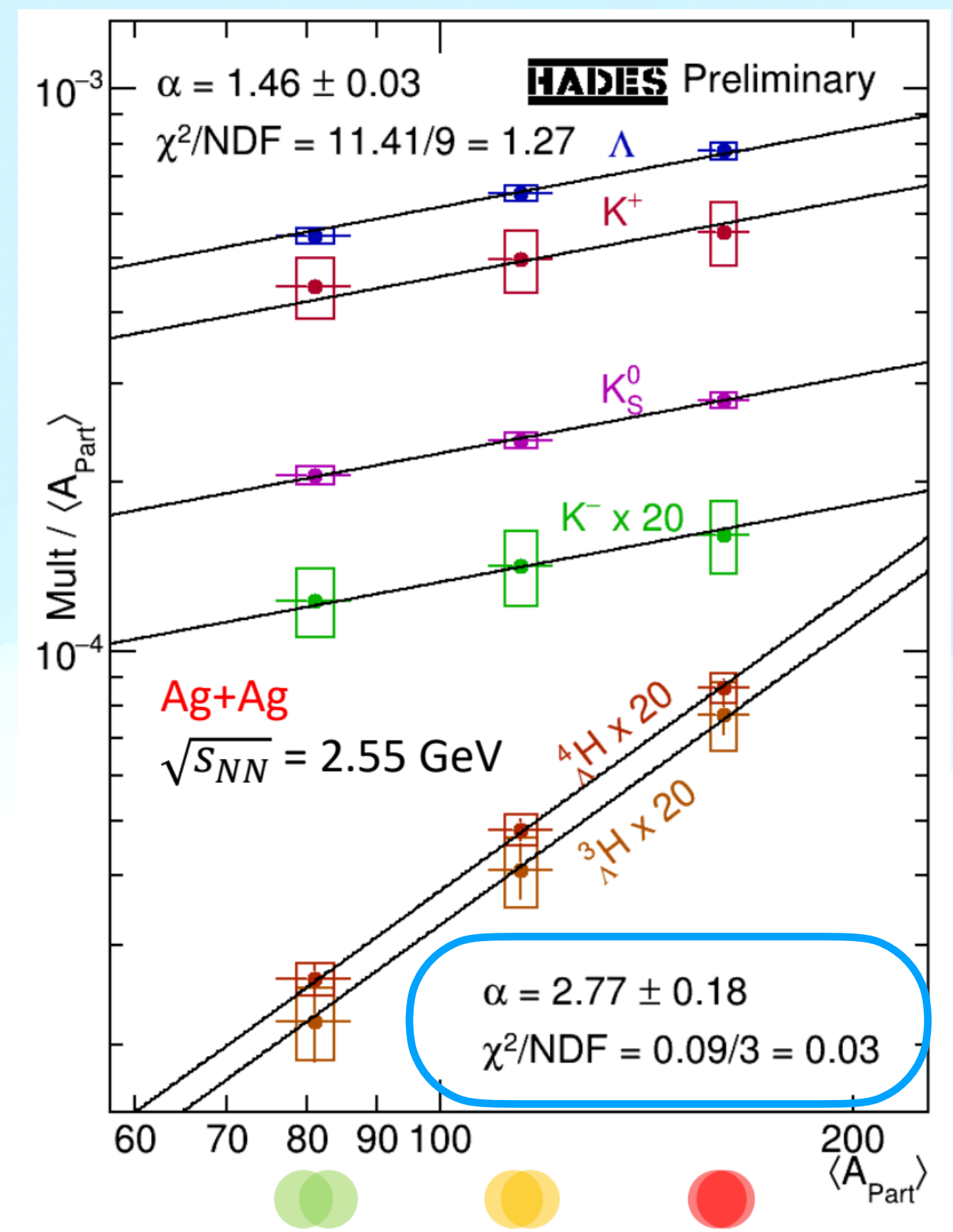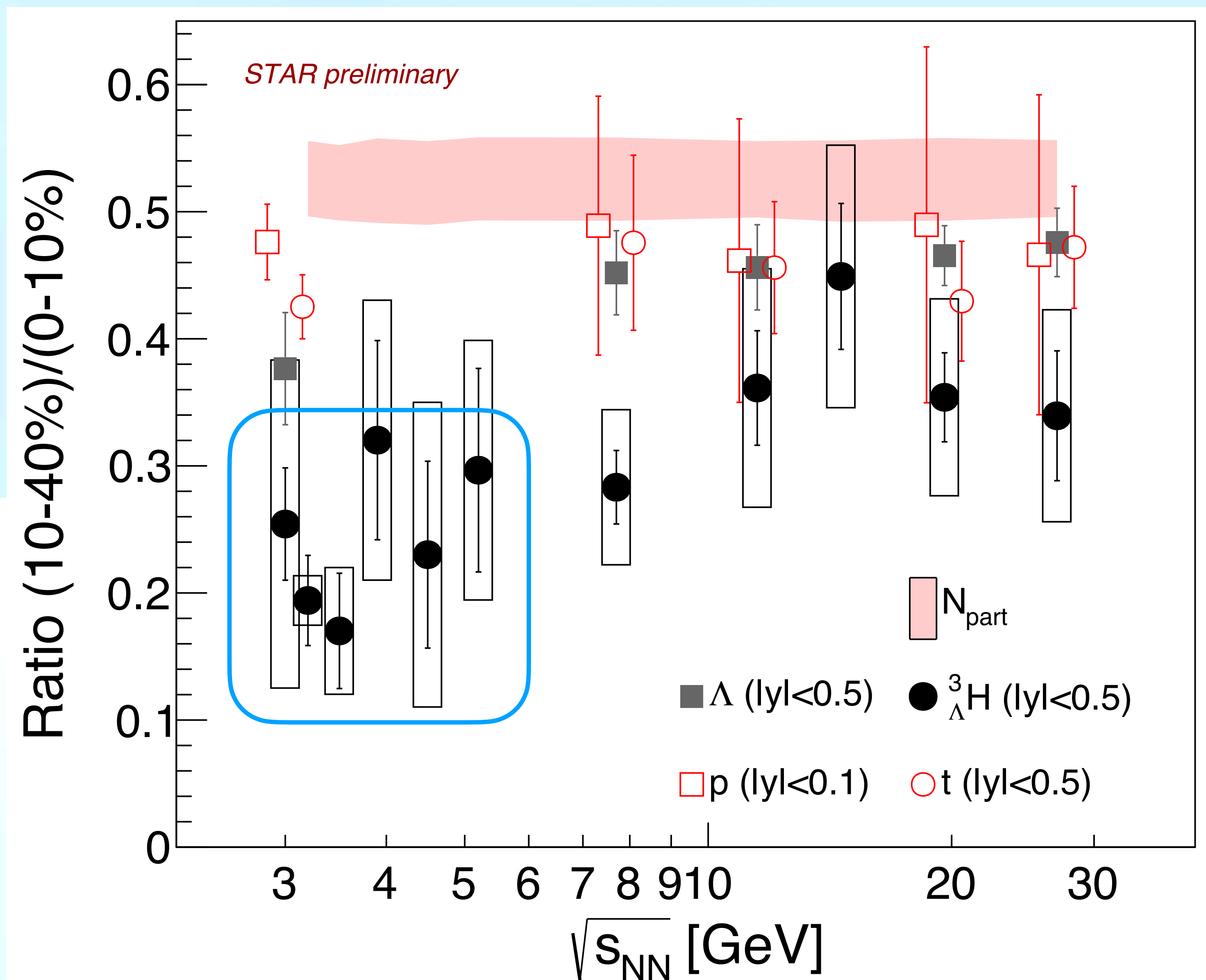Λ (|y|<0.5) $^{3}_{\Lambda}H$ (|y|<0.5)

p (|y|<0.1)   t (|y|<0.5)

$\sqrt{s_{NN}}$ [GeV]

$\alpha = 1.46 \pm 0.03$
$\chi^2/NDF = 11.41/9 = 1.27$ HADES Preliminary

Λ
K^+
K^0_S
$K^- \times 20$

Ag+Ag
$\sqrt{s_{NN}}$ = 2.55 GeV

$^4_\Lambda H \times 20$
$^3_\Lambda H \times 20$

$\alpha = 2.77 \pm 0.18$
$\chi^2/NDF = 0.09/3 = 0.03$

Mult / $\langle A_{Part} \rangle$

$\langle A_{Part} \rangle$

S Spies, (HADES), HYP2022

- Similar observation in Ag+Ag collisions at $\sqrt{s_{NN}}$=2.55 GeV

Suppression related to the nature of the created medium?

16

Strangeness Population Factor S_3
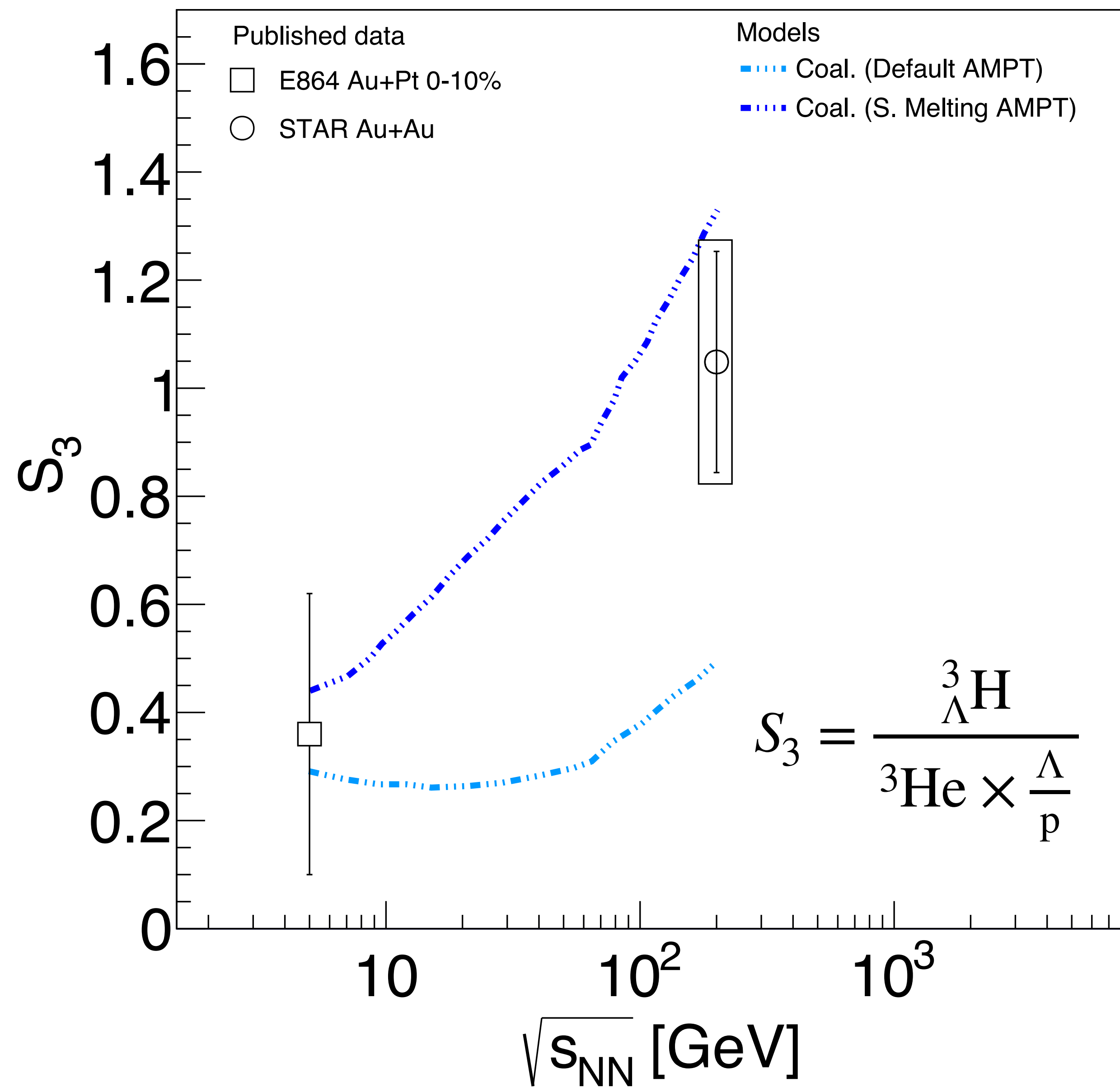
- An enhancement of S_3 was proposed as a probe for deconfinement

Phys. Lett. B 684 (2010) 224

$$S_3 = \frac{^3_\Lambda H}{^3He \times \frac{\Lambda}{p}}$$

Strangeness Population Factor S_3
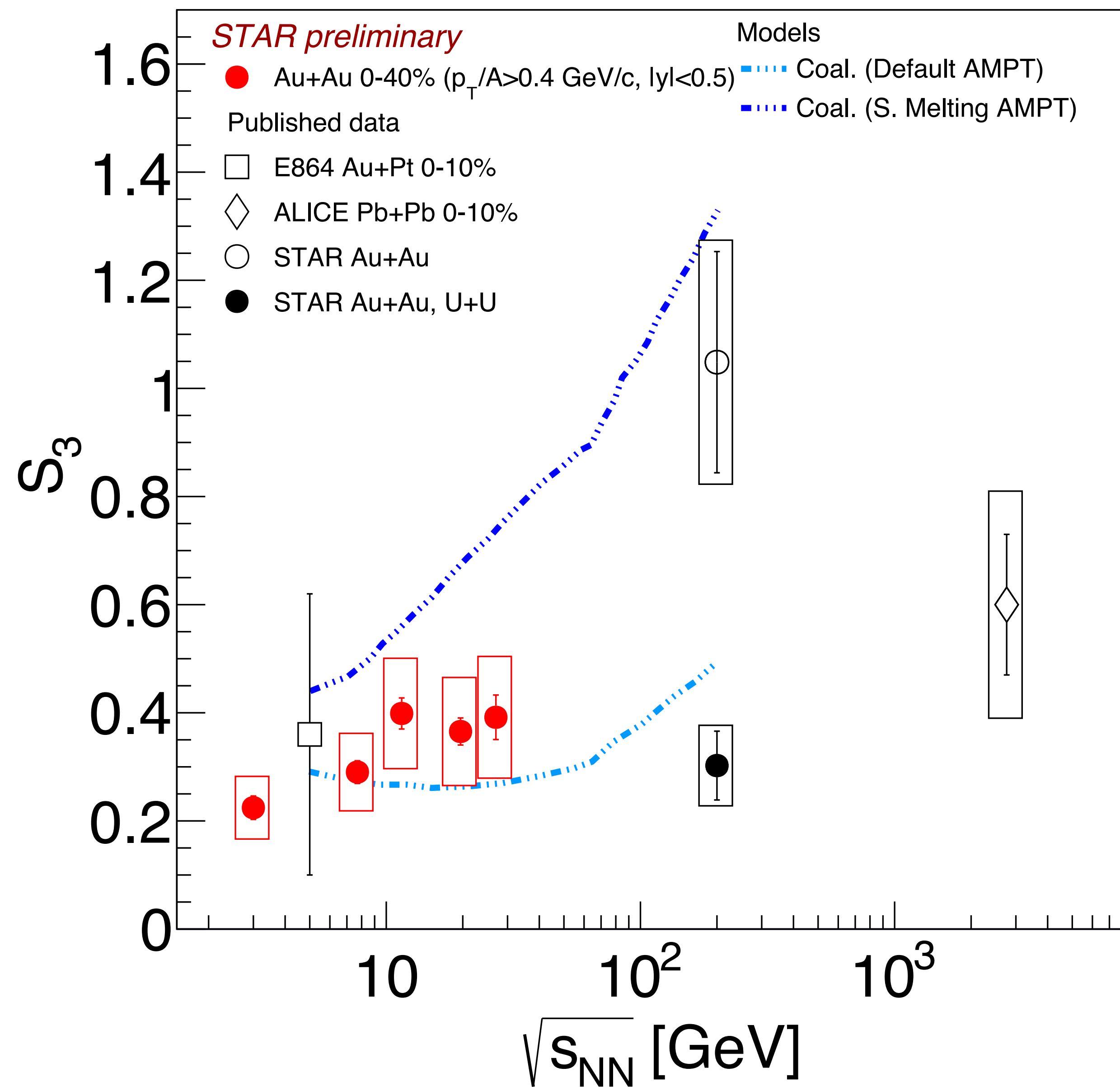
- An enhancement of S_3 was proposed as a probe for deconfinement

- Data indicates a mild increase in S_3 , **do not follow the expectations of the model**

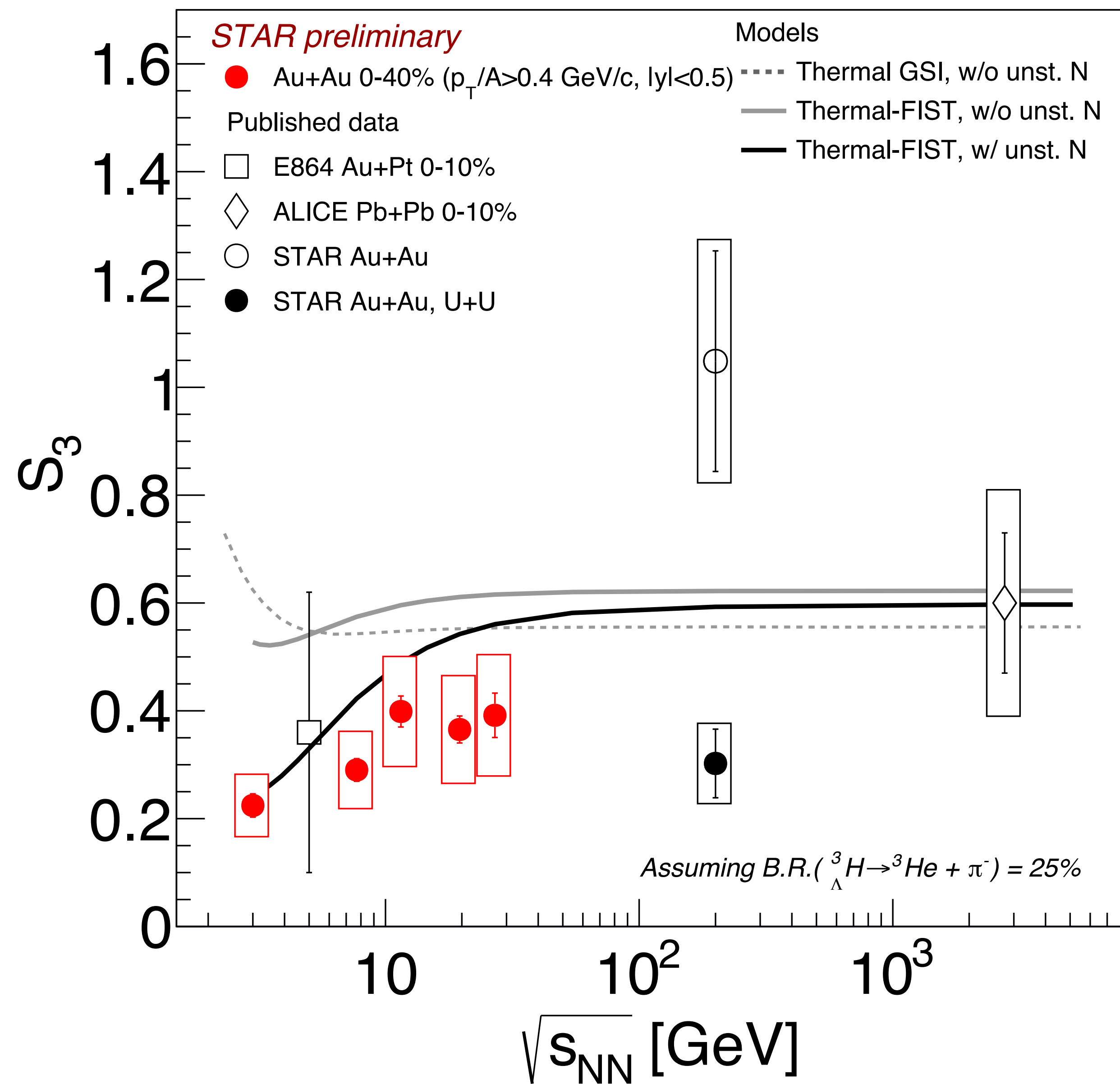# Strangeness Population Factor S_3

- The measured S_3 is close to thermal model predictions

- The increasing trend is driven by the decreasing feed-down from ^{3}He towards higher energies

Strangeness Population Factor S_3
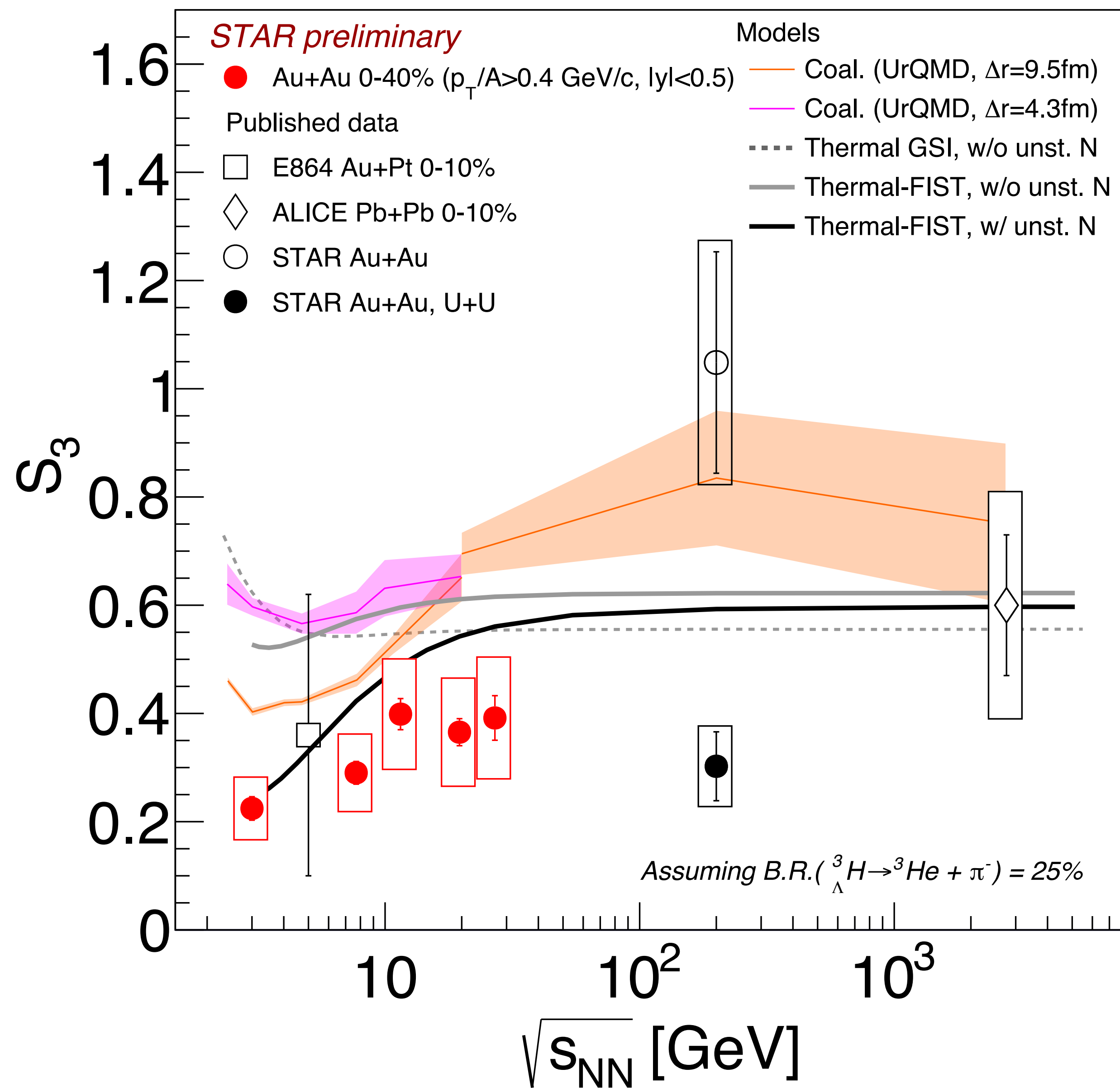
- UrQMD + Coalescence seem to overshoot the data

- A key prediction from coalescence models is the suppression of $^{3}_{\Lambda}H$ production in small systems due to its large radius

- Best represented by investigating the multiplicity dependence, since $dN_{ch}/d\eta$ is a good proxy for volume

  - Possible feed-down should be accounted for when interpreting results

Multiplicity Dependence of S_3(stable nuclei)

STAR preliminary

Legend:
- □ Au+Au ($\sqrt{s_{NN}}$=3GeV, p_T/A>0.4GeV/c)
- □ Au+Au ($\sqrt{s_{NN}}$=7.7-27GeV, p_T/A>0.4GeV/c)
- ○ Au+Au/U+U ($\sqrt{s_{NN}}$≈200GeV)
- ◆ Pb+Pb ($\sqrt{s_{NN}}$=2.76TeV)
- ◇ p+Pb ($\sqrt{s_{NN}}$=5.02TeV)

Assuming B.R.
$(^3_\Lambda H \rightarrow ^3He + \pi^-) = 25\%$

- --- Thermal model
- ▨ Coal. (2-body)
- ▨ Coal. (3-body)

Y-axis: S_3 (stable nuclei)
X-axis: $dN_{ch}/d\eta$

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

Bracket: syst. unc.

Line: stat. unc.

Lower edge of box:
S_3 value **uncorrected for feed-down**
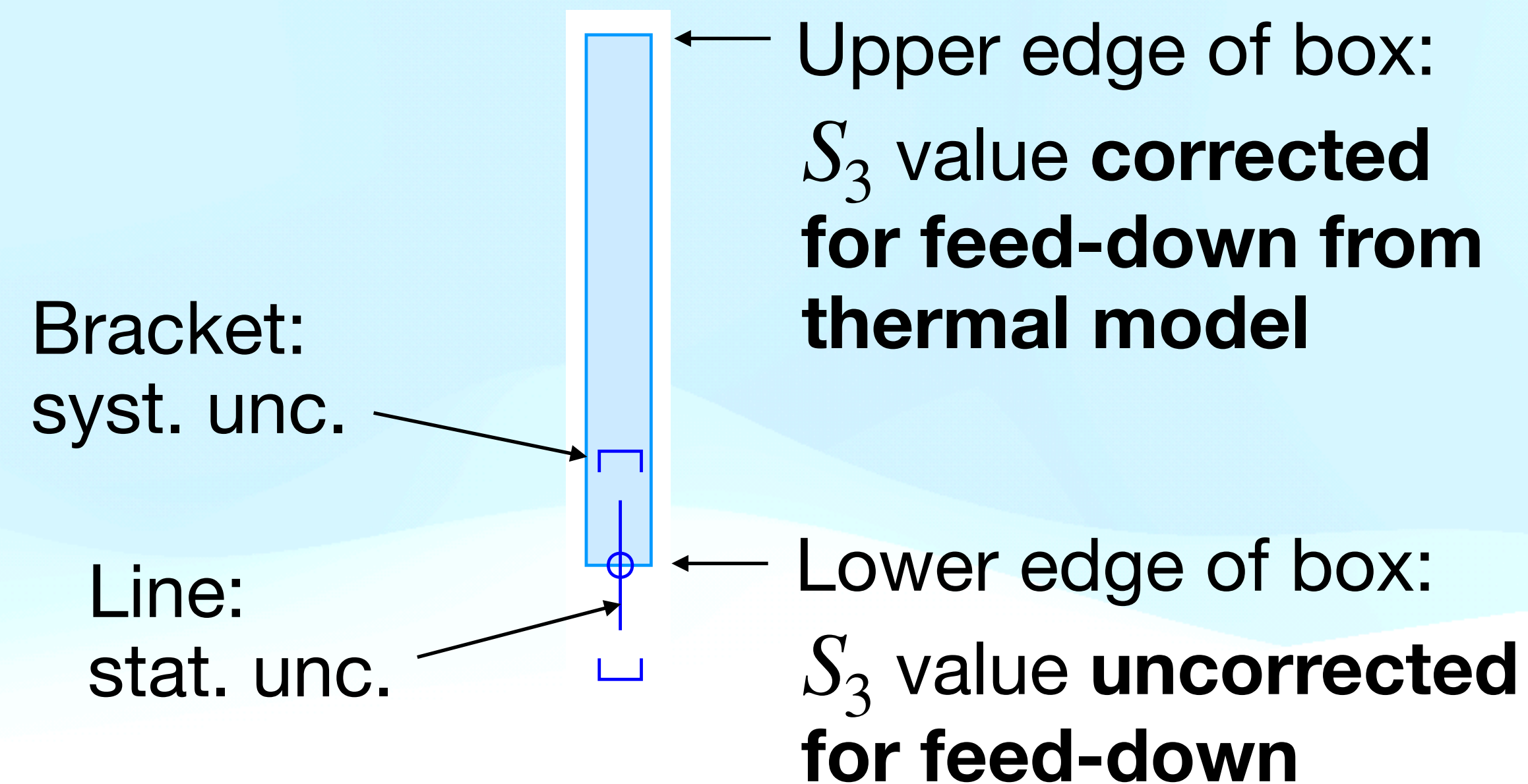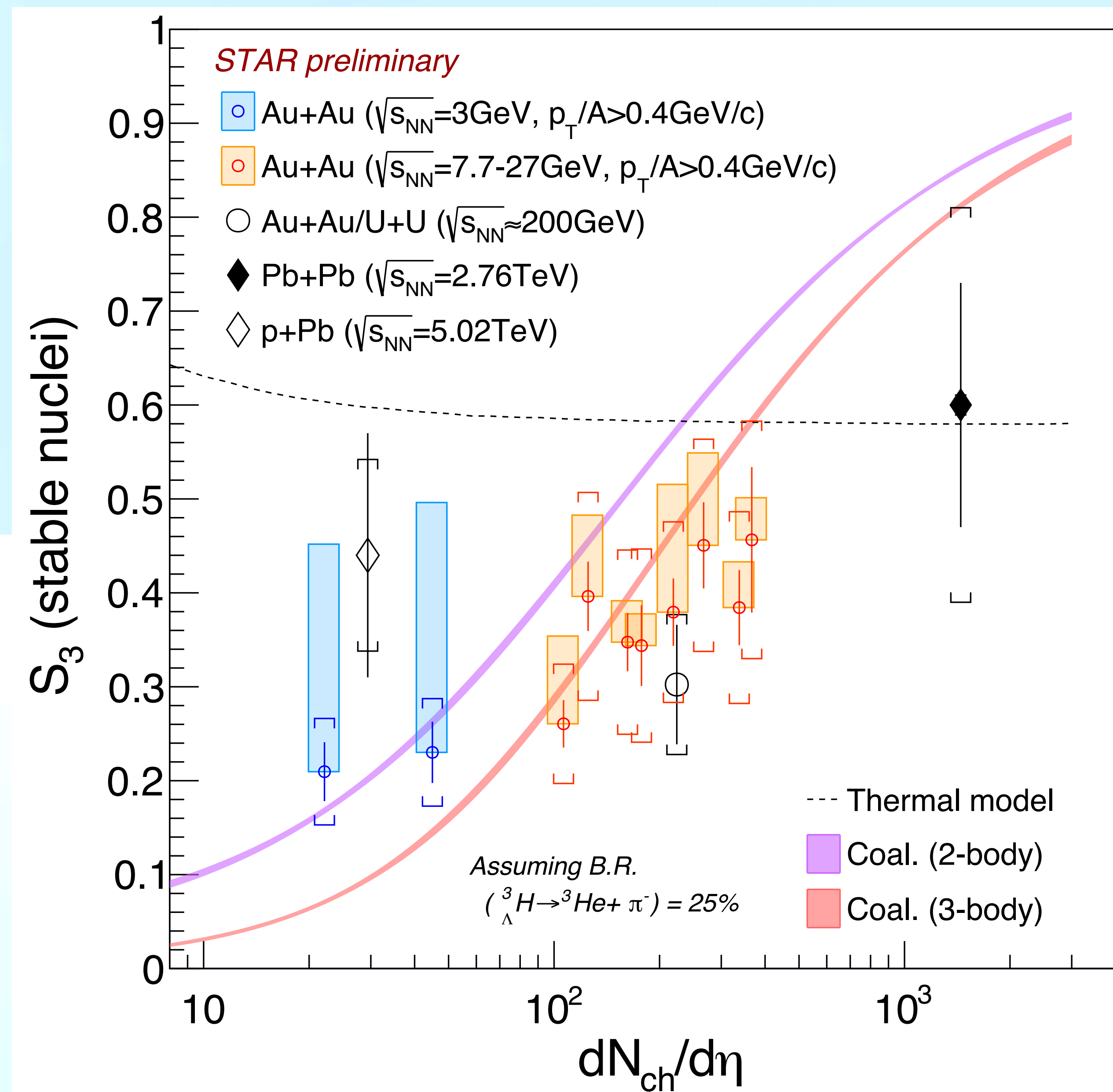
- Unstable nuclei production are suppressed relative to stable nuclei (see backup)

- The true value of S_3 (stable nuclei) very likely lies between the upper and lower limits

Multiplicity Dependence of S_3(stable nuclei)
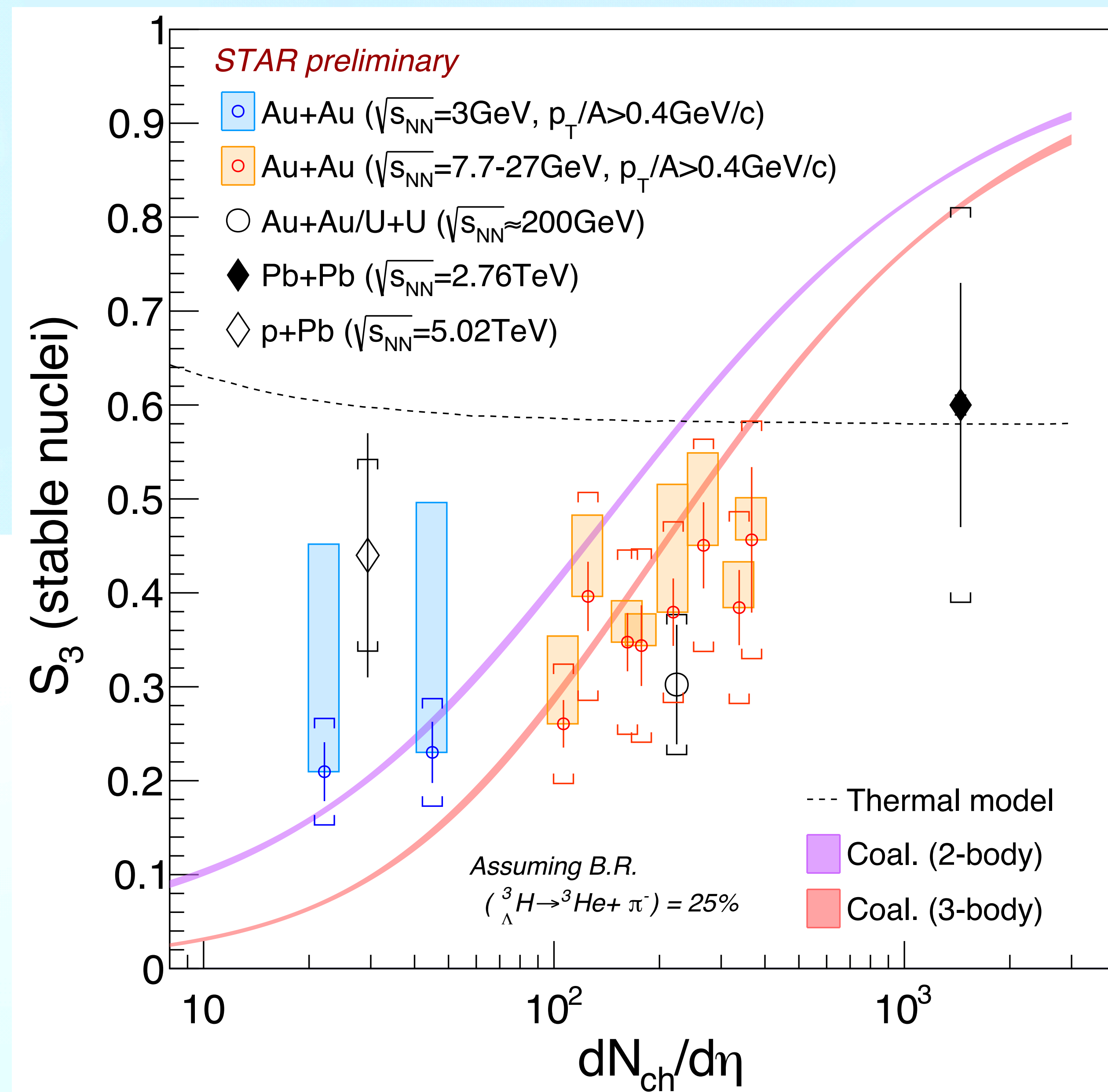
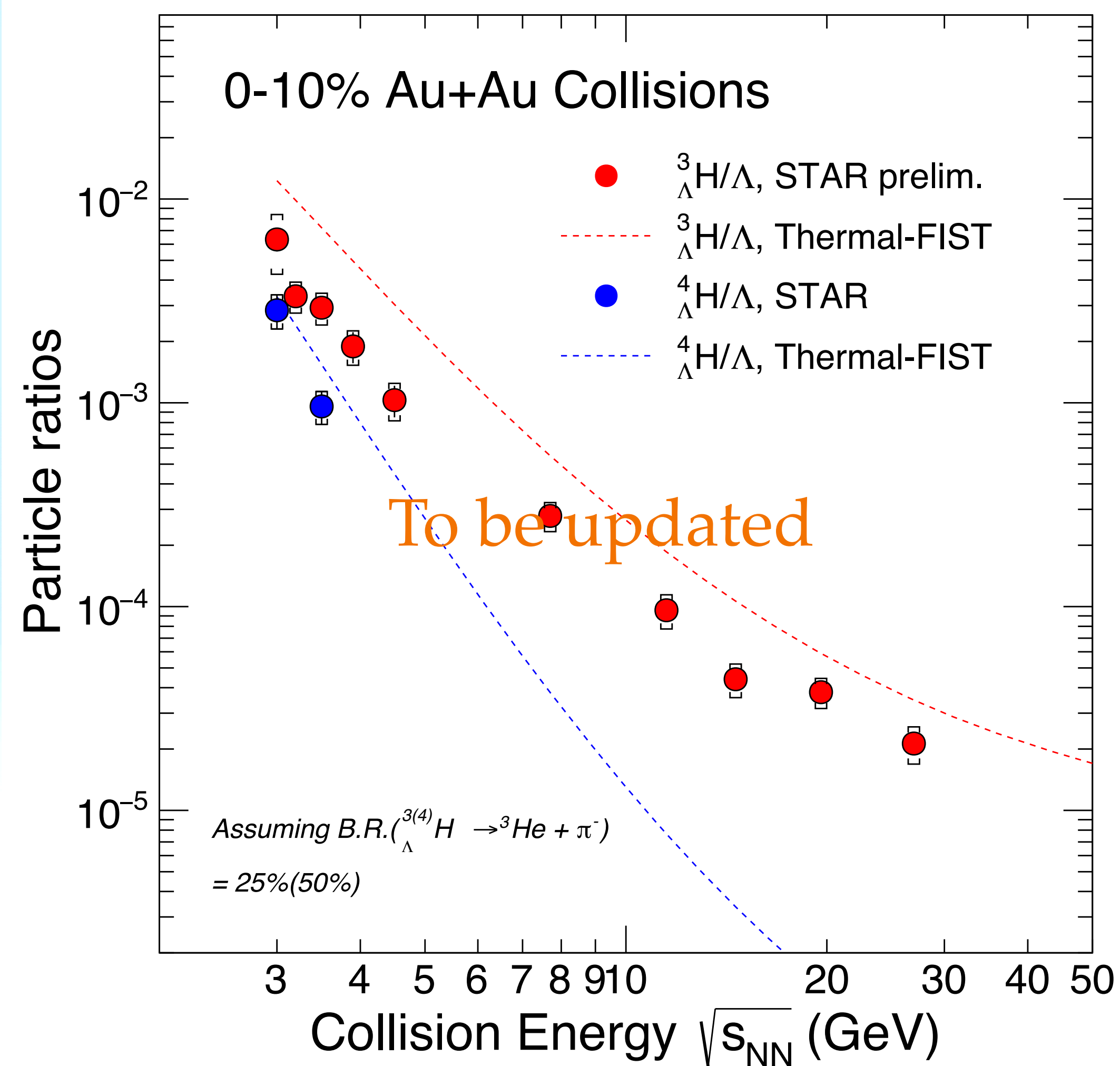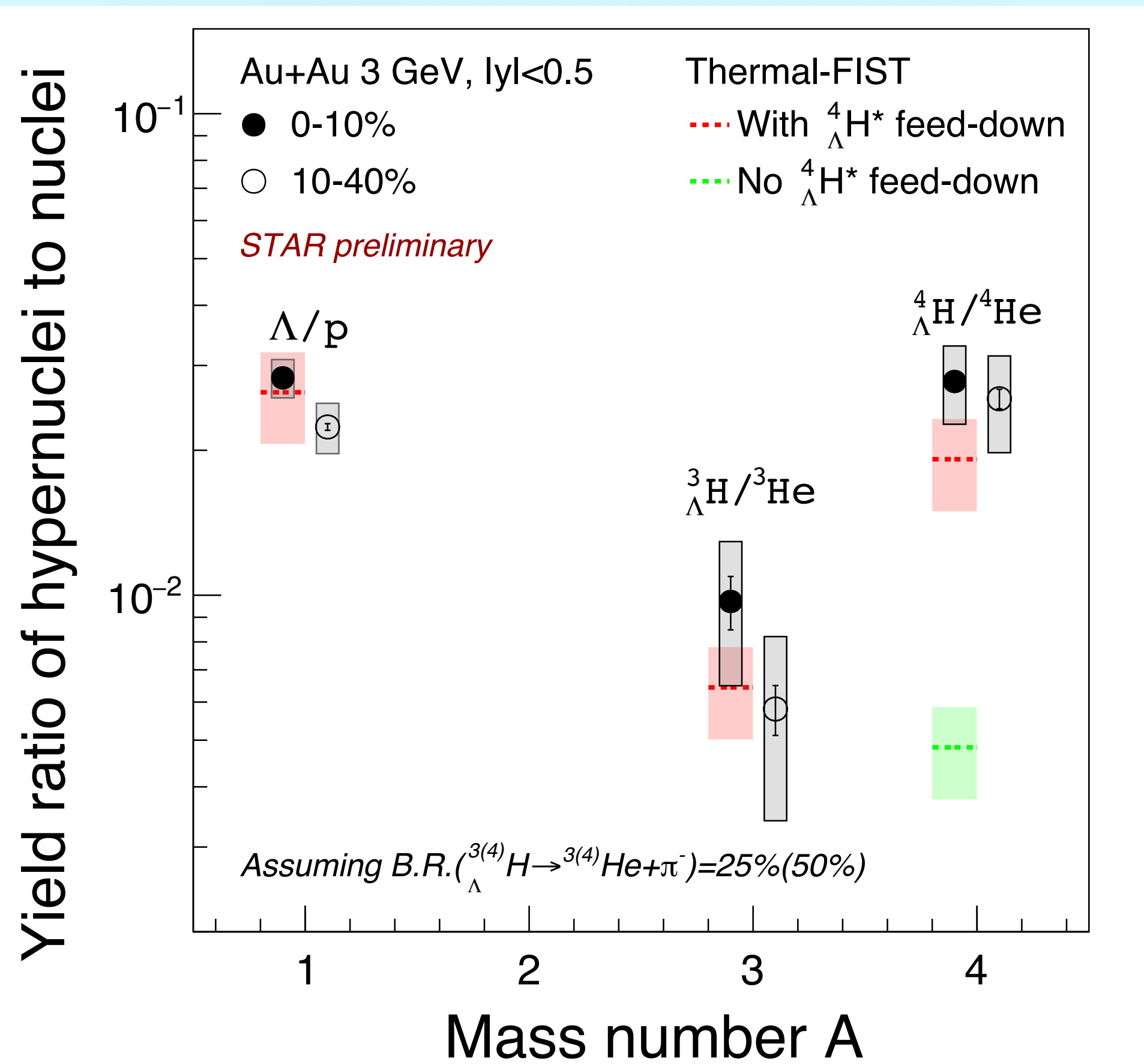S_3 (stable nuclei) ≈ 0.35

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

- Data show **milder multiplicity dependence** compared to coalescence, particularly 3-body

- Thermal model tends to overpredict S_3 at $dN_{ch}/d\eta=200$ or lower

More data at very low and very high $dN_{ch}/d\eta$ is needed

$^4_\Lambda$H Production

Au+Au 3 GeV, |y|<0.5
- 0-10%
○ 10-40%

Thermal-FIST
---- With $^4_\Lambda$H* feed-down
---- No $^4_\Lambda$H* feed-down

STAR preliminary

Λ/p

$^3_\Lambda$H/^{3}He

$^4_\Lambda$H/^{4}He

Assuming B.R.($^{3(4)}_\Lambda H \to ^{3(4)}He + \pi^-$)=25%(50%)

Yield ratio of hypernuclei to nuclei

Mass number A

0-10% Au+Au Collisions

- $^3_\Lambda$H/Λ, STAR prelim.
- ---- $^3_\Lambda$H/Λ, Thermal-FIST
- $^4_\Lambda$H/Λ, STAR
- ---- $^4_\Lambda$H/Λ, Thermal-FIST

To be updated

Assuming B.R.($^{3(4)}_\Lambda H \to ^3He + \pi^-$)
= 25%(50%)

Particle ratios

Collision Energy $\sqrt{s_{NN}}$ (GeV)

- Non-monotonic behavior of hypernuclei to nuclei yields vs mass number

Suggestive of creation of unstable hypernuclei
$^4_\Lambda$H*(1$^+$) → $^4_\Lambda$H(0$^+$) + γ
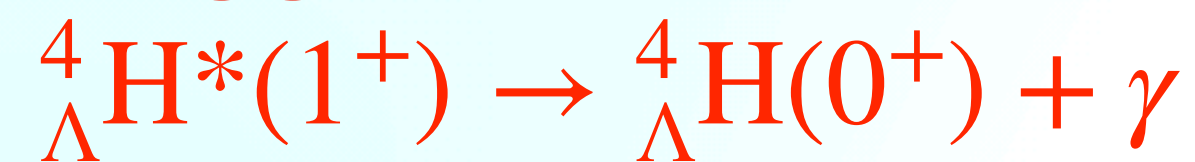
- $^4_\Lambda$H yields are closer to thermal model compared to $^3_\Lambda$H

Binding energy dependence or something else?

Hypernuclei Collective Flow
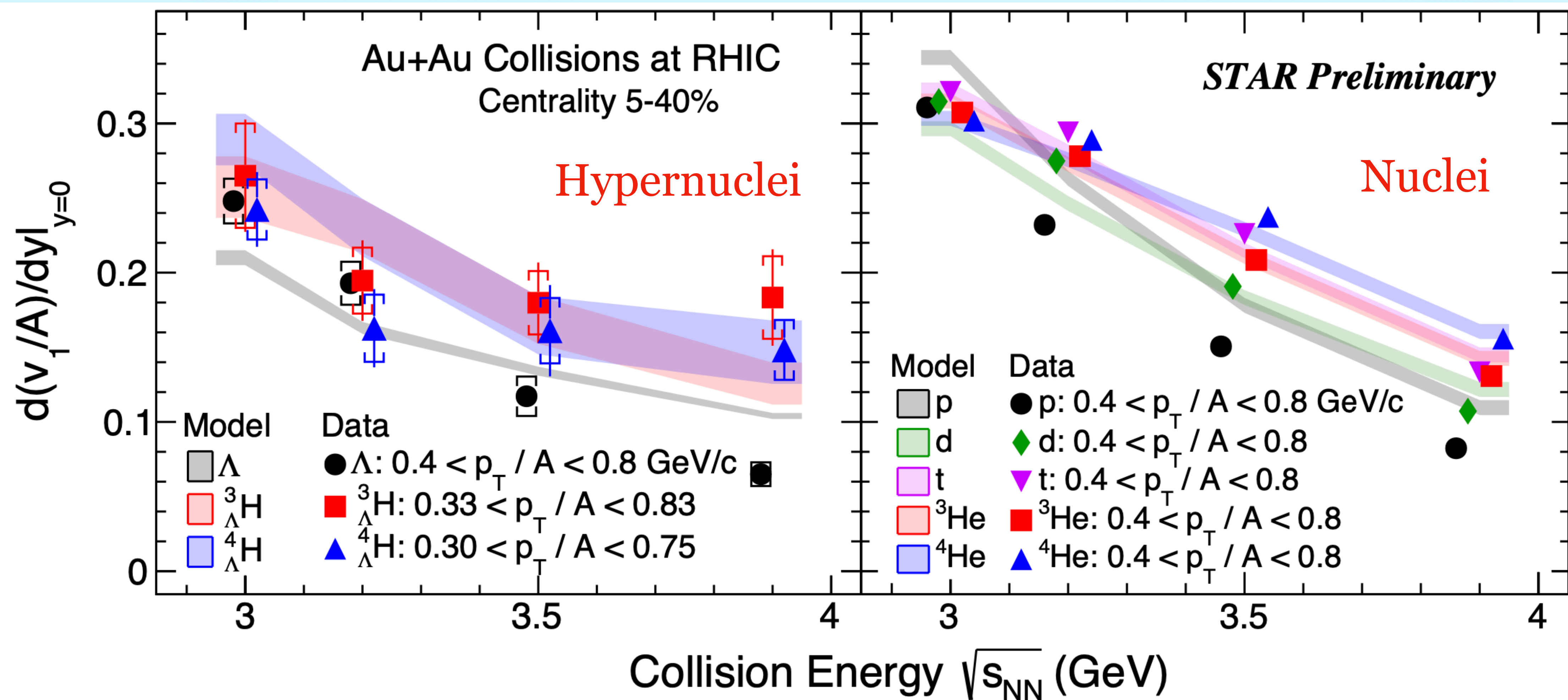
- Directed flow of hypernucei follows mass scaling
- JAM + coalescence approx. describes the data

Qualitatively consistent with coalescence formation of hypernuclei

Summary

- $^{3}_{\Lambda}$H yields in central collisions overestimated by thermal model by a factor of 2
- $^{3}_{\Lambda}$H mean p_{T} tends to be lower than blast-wave parametrization from light hadrons

  - $^{3}_{\Lambda}$H is not in thermal equilibrium with light hadrons

- Data for S_{3} (stable nuclei) are consistent with flat or slightly increasing trend with $dN_{ch}/d\eta$

  - Milder multiplicity dependence compared to coalescence models

- Suppression of $^{3}_{\Lambda}$H in 10-40% collisions at low collision energies observed
- $^{4}_{\Lambda}$H yields are much closer to thermal model predictions than $^{3}_{\Lambda}$H

  - Hypernuclei data provides new challenges for theoretical models

- $^{3}_{\Lambda}$H mean p_{T} seem to exhibit two separate trends for $\sqrt{s_{NN}} = 3 - 4.5\text{GeV}$ and $7.7 - 27\text{GeV}$

  - Change in medium properties or expansion dynamics?

Outlook

Thermal-FIST V. Vovchenko, H. Stoecker
Comput. Phys. Commun. 244, 295 (2019)
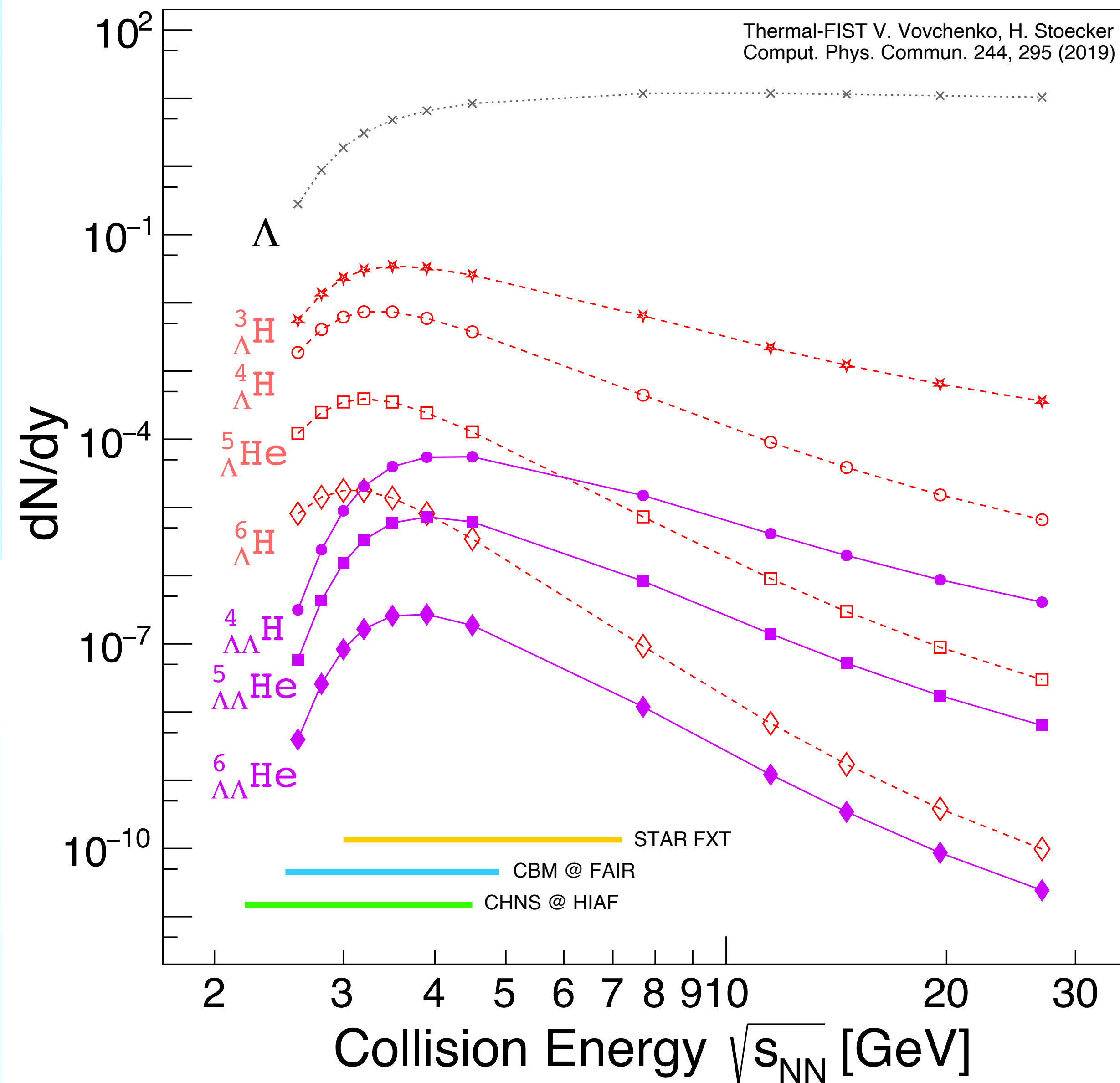
RHIC-STAR

- Heavier hypernuclei, including $^4_\Lambda H$, $^4_\Lambda He$, $^5_\Lambda He$, $^6_\Lambda H$ at FXT energies

- High statistics data at RHIC top energy give opportunities for multiplicity dependence study

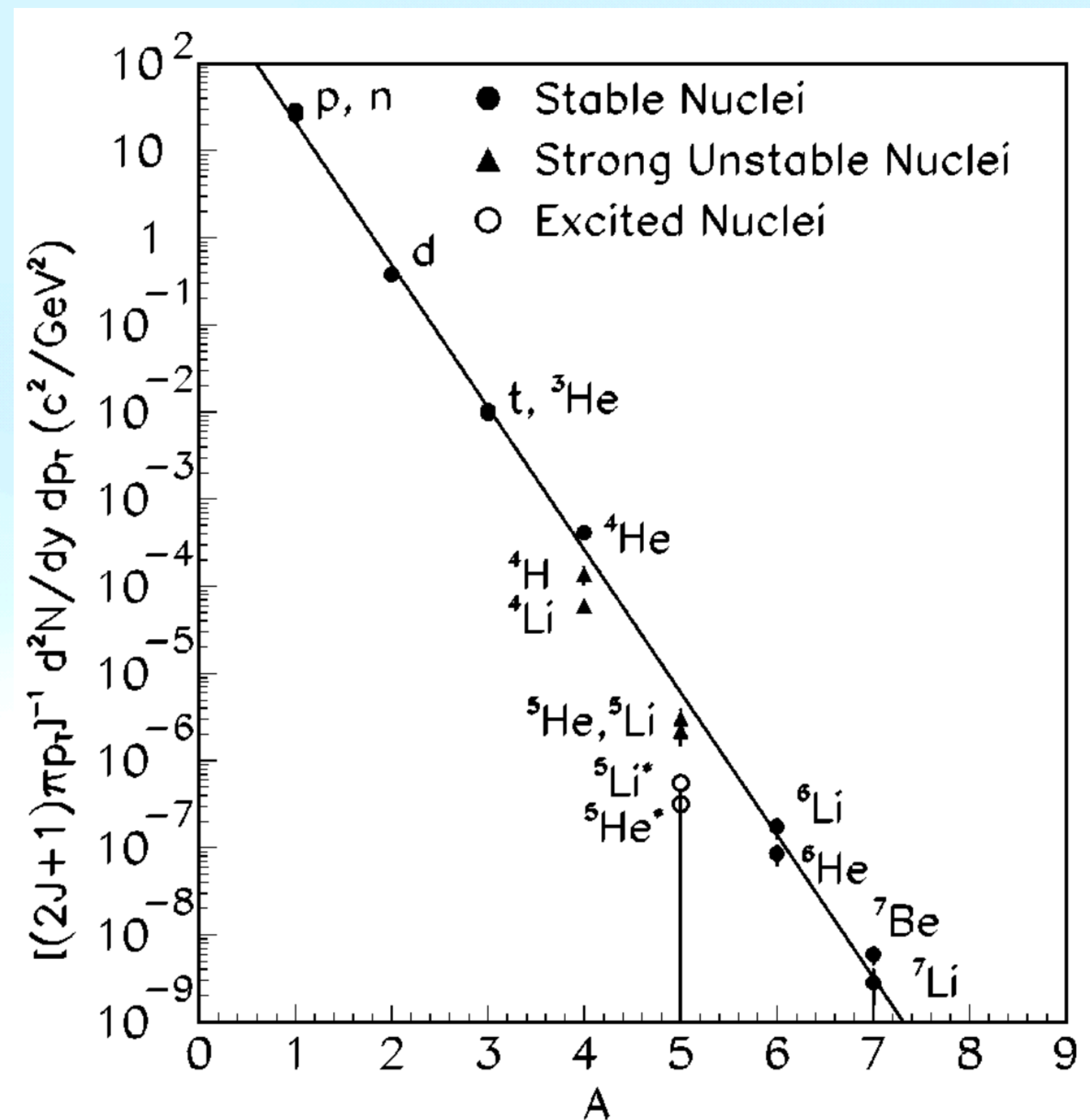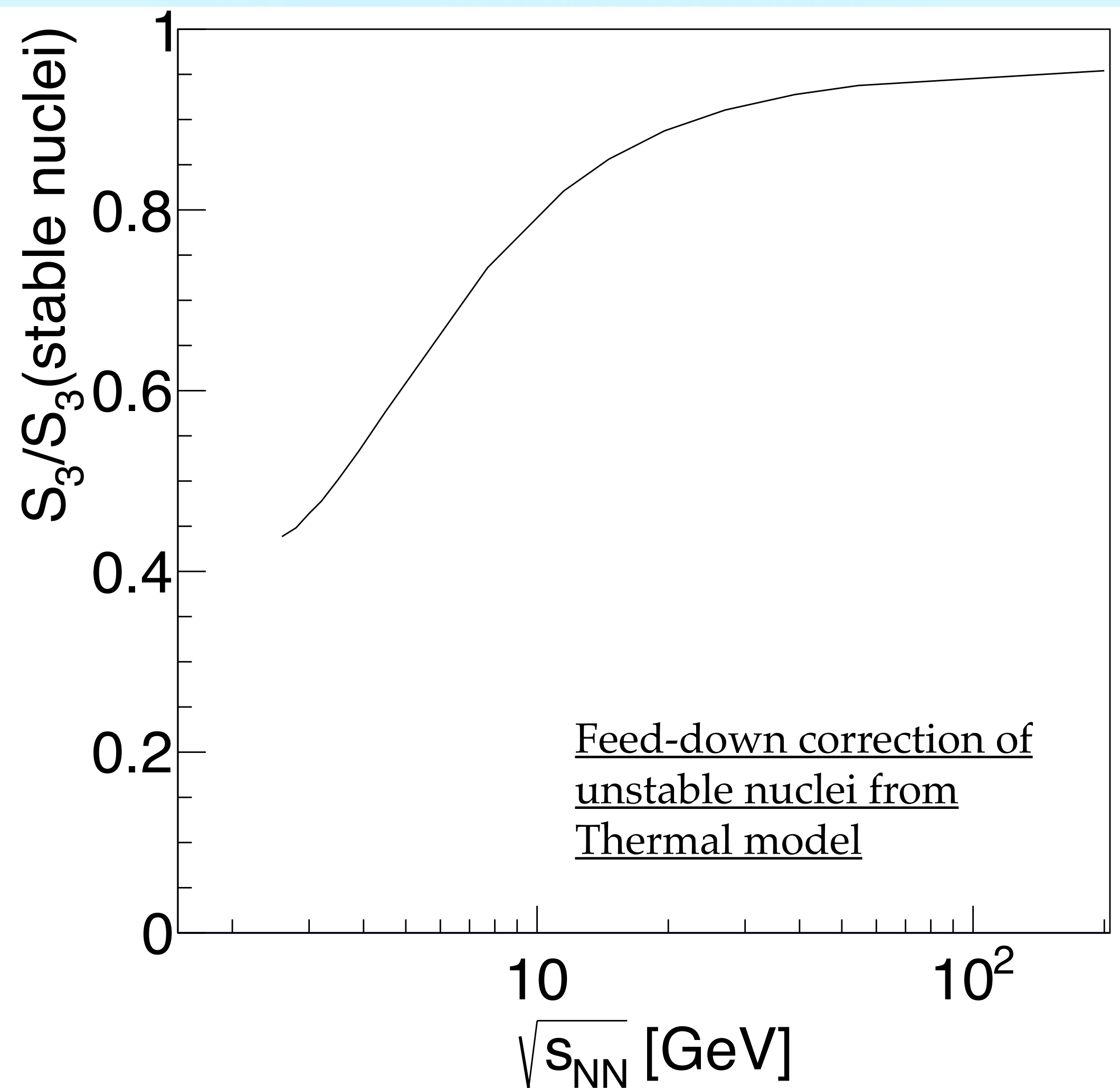## FAIR-CBM and HIAF

- Double-Λ hypernuclei to constrain Λ-Λ interaction, essential for hyperon puzzle resolution

Thank you for listening!

Feed-down from unstable nuclei

Feed-down correction of unstable nuclei from Thermal model

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

Mean Transverse Momentum as a Function of Collision Energy