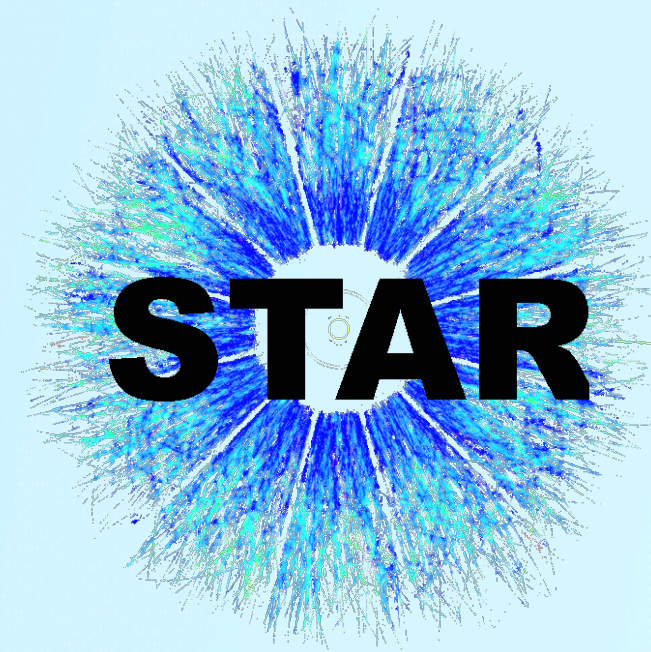


Hypernuclei Production in Heavy-Ion Collisions

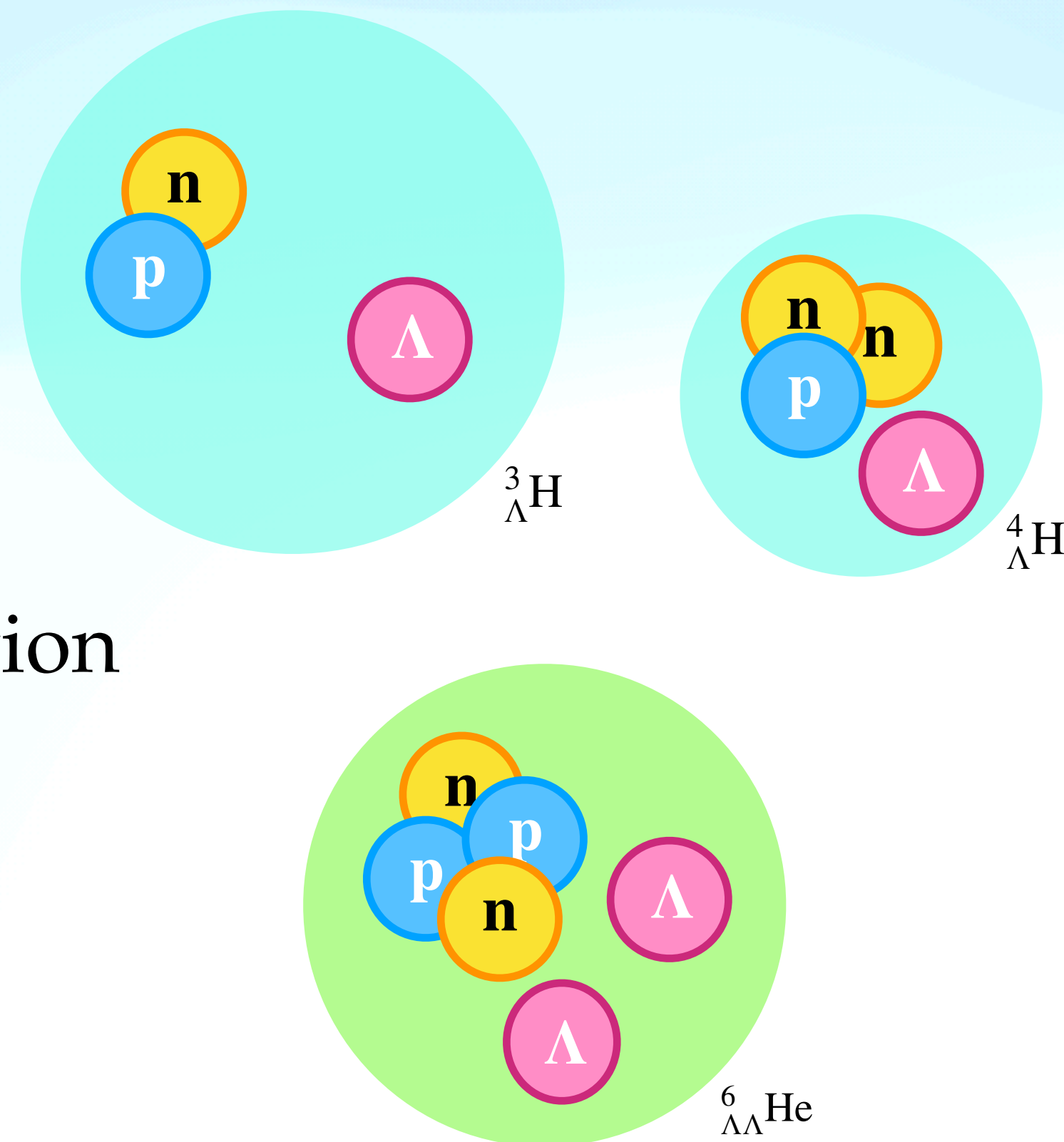
(at finite baryon density)



CPOD 2024

Yue Hang Leung
for the STAR collaboration

University of Heidelberg
20th May, 2023



Outline

- Introduction
- ${}^3_{\Lambda}\text{H}$ Yields and Particle Ratios
- Other Observables
 - ${}^4_{\Lambda}\text{H}$ Yields
 - Collective Flow
- Summary
- Outlook



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**

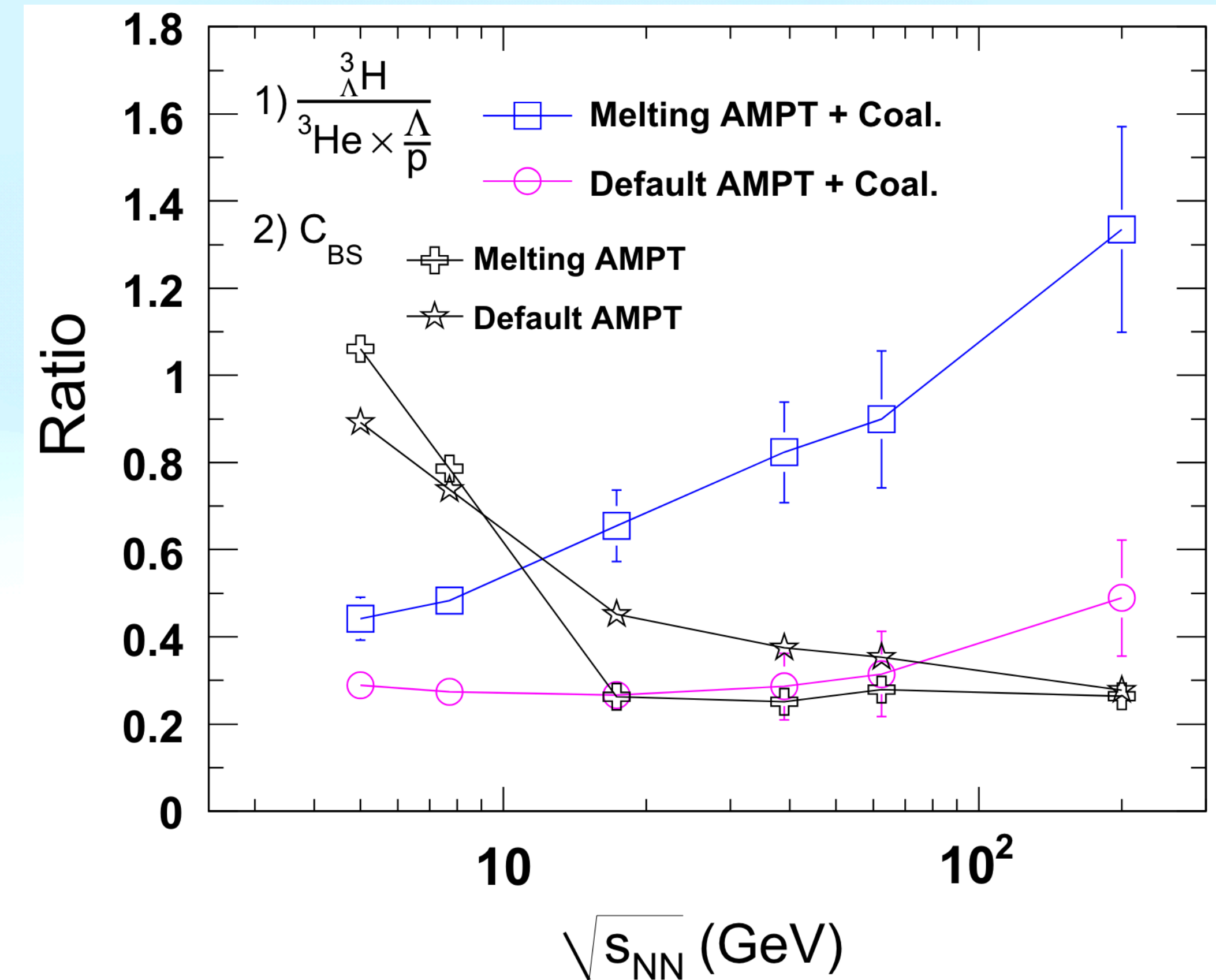
- $S_3 = \frac{{}^3_{\Lambda}\text{H}}{{}^3\text{He} \times \frac{\Lambda}{p}}$ may be enhanced in

systems involving partonic interactions

S. Zhang et al, Phys. Lett. B 684 (2010) 224

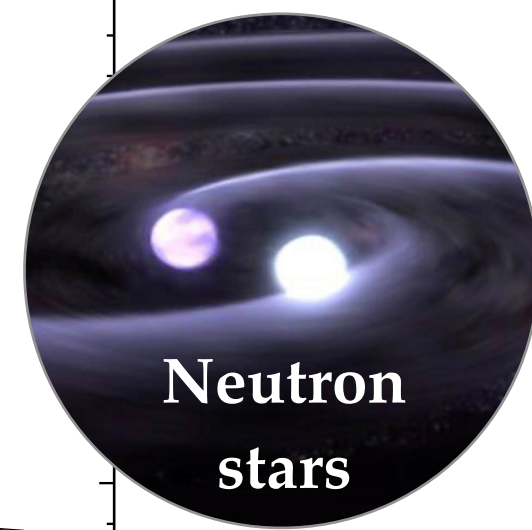
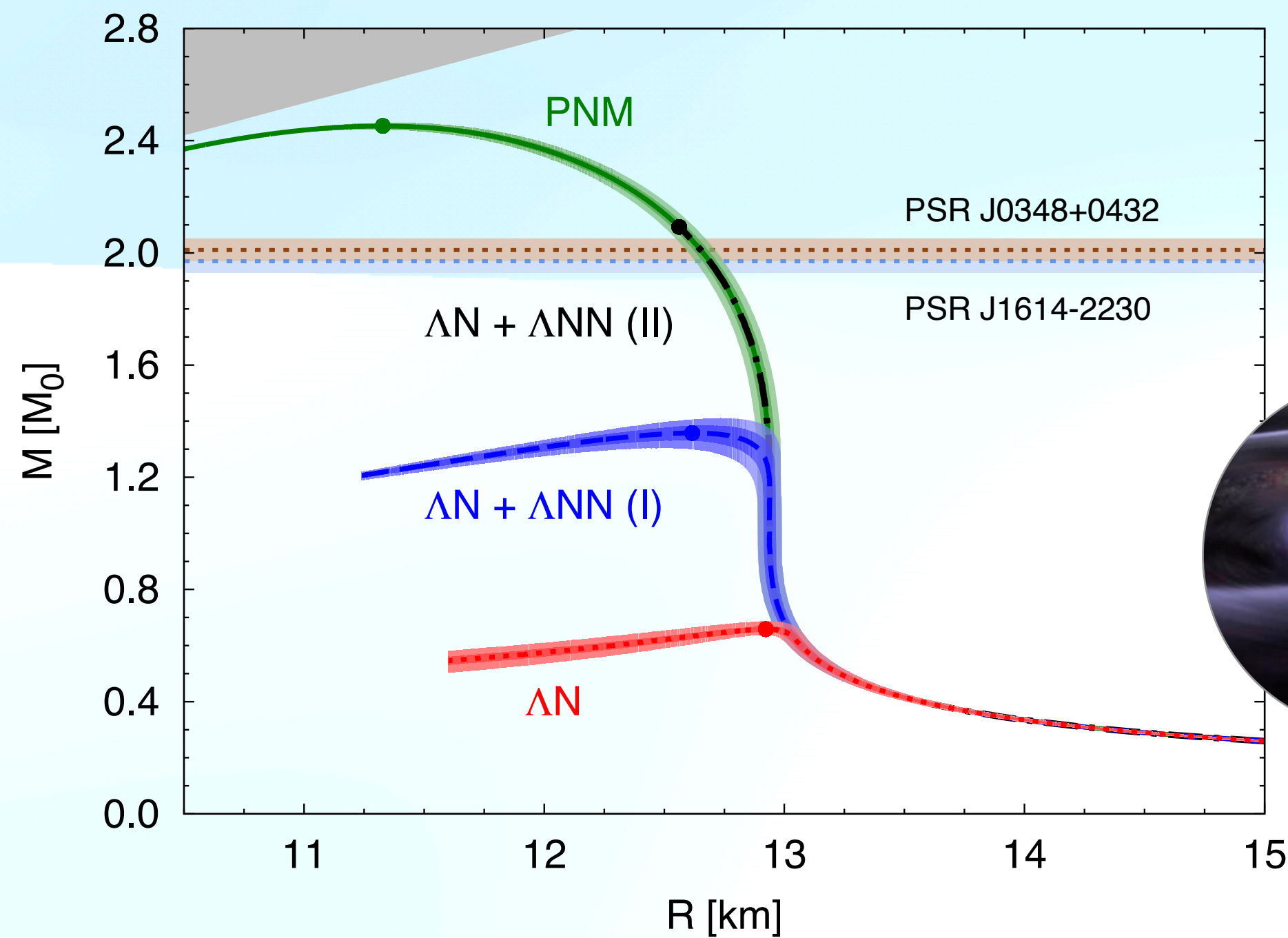
- Baryon clustering near critical point may lead to enhancement of light nuclei ($A \geq 3$) yields

E. Shuryak et al, Phys. Rev. C 101 (2020) 034914

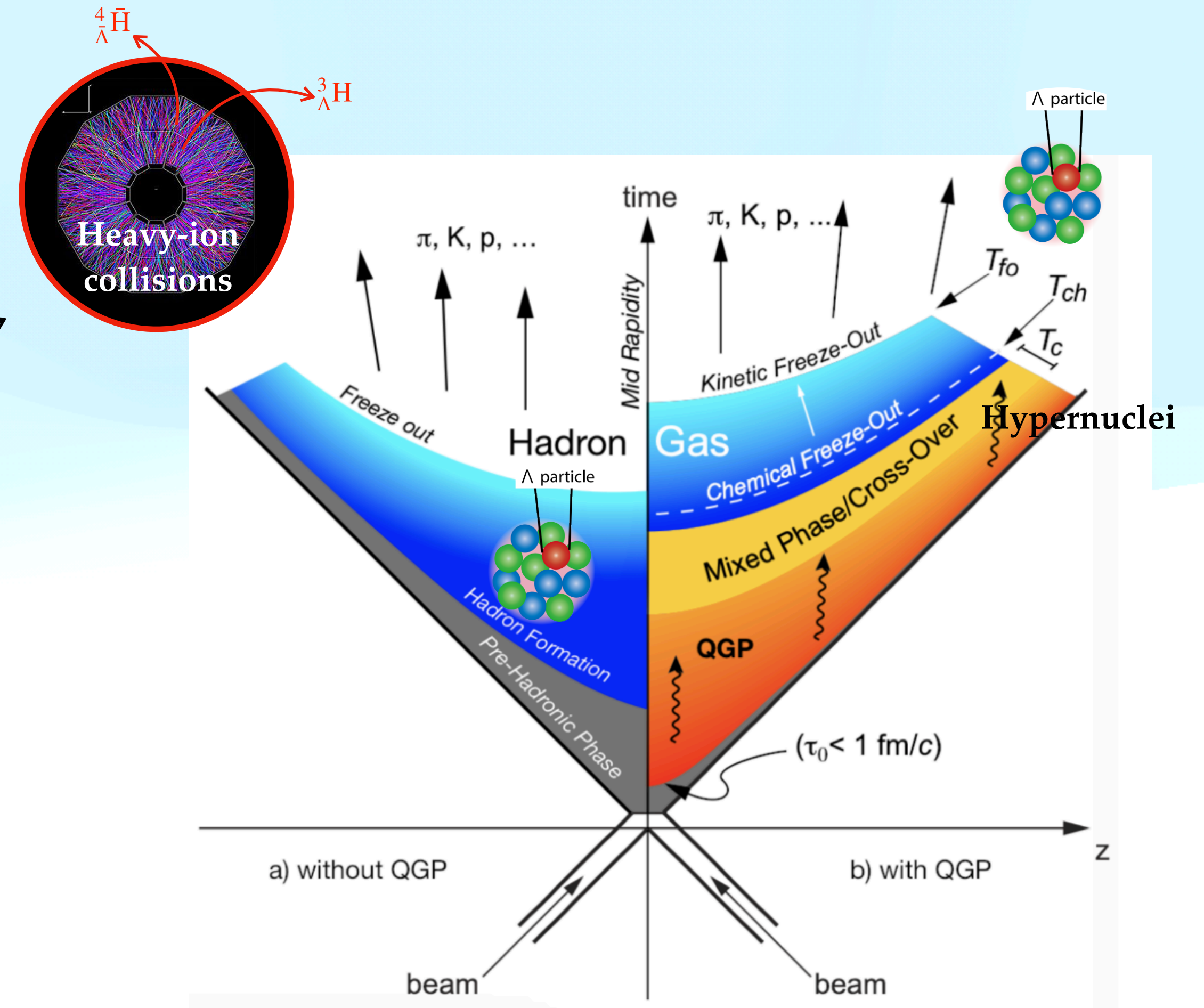


What is the role of hyperon-nucleon (YN) interaction in the equation-of-state of high baryon density matter?

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



?



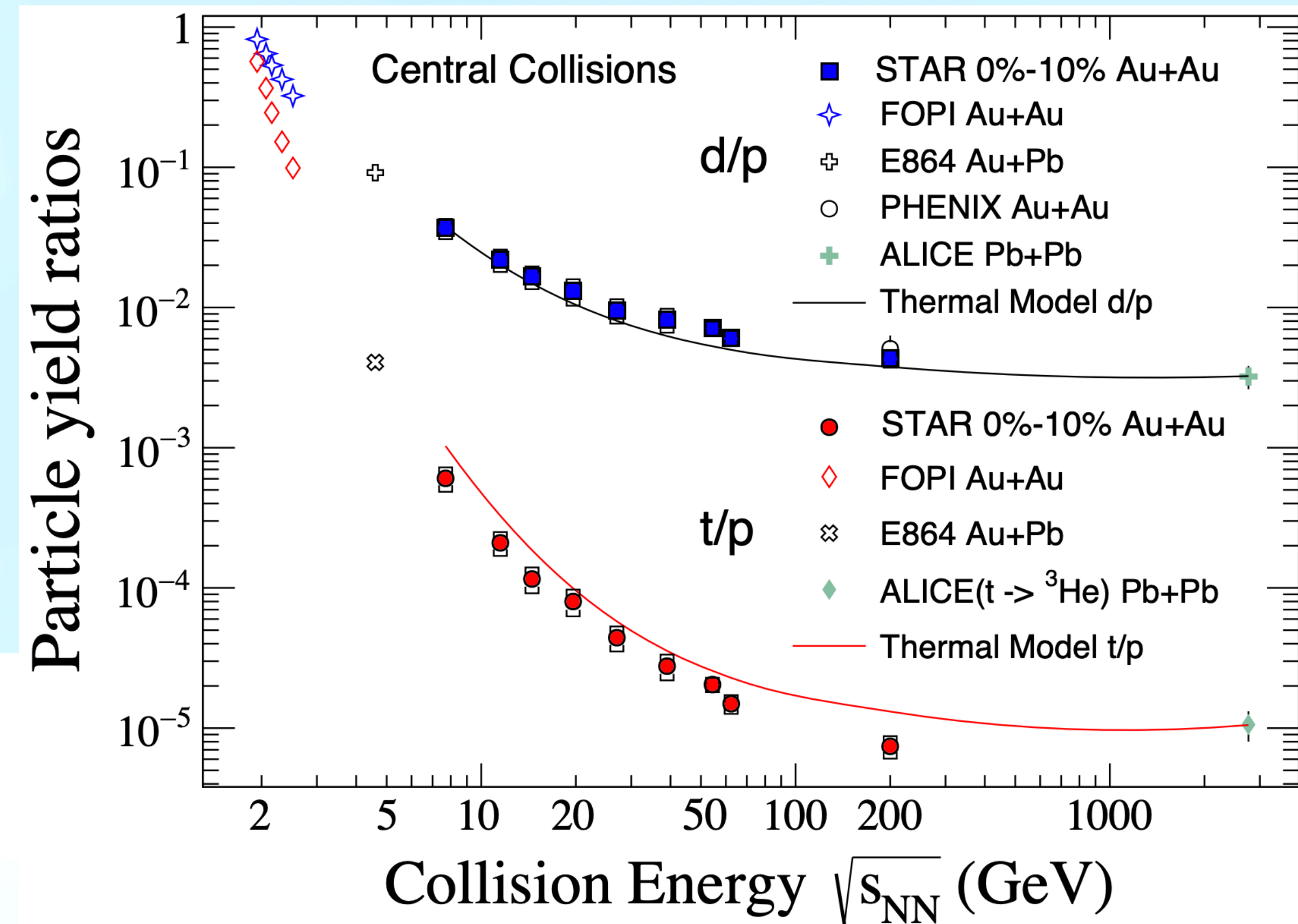
Can hypernuclei production be used to constrain the in-medium Y-N interaction?

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

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

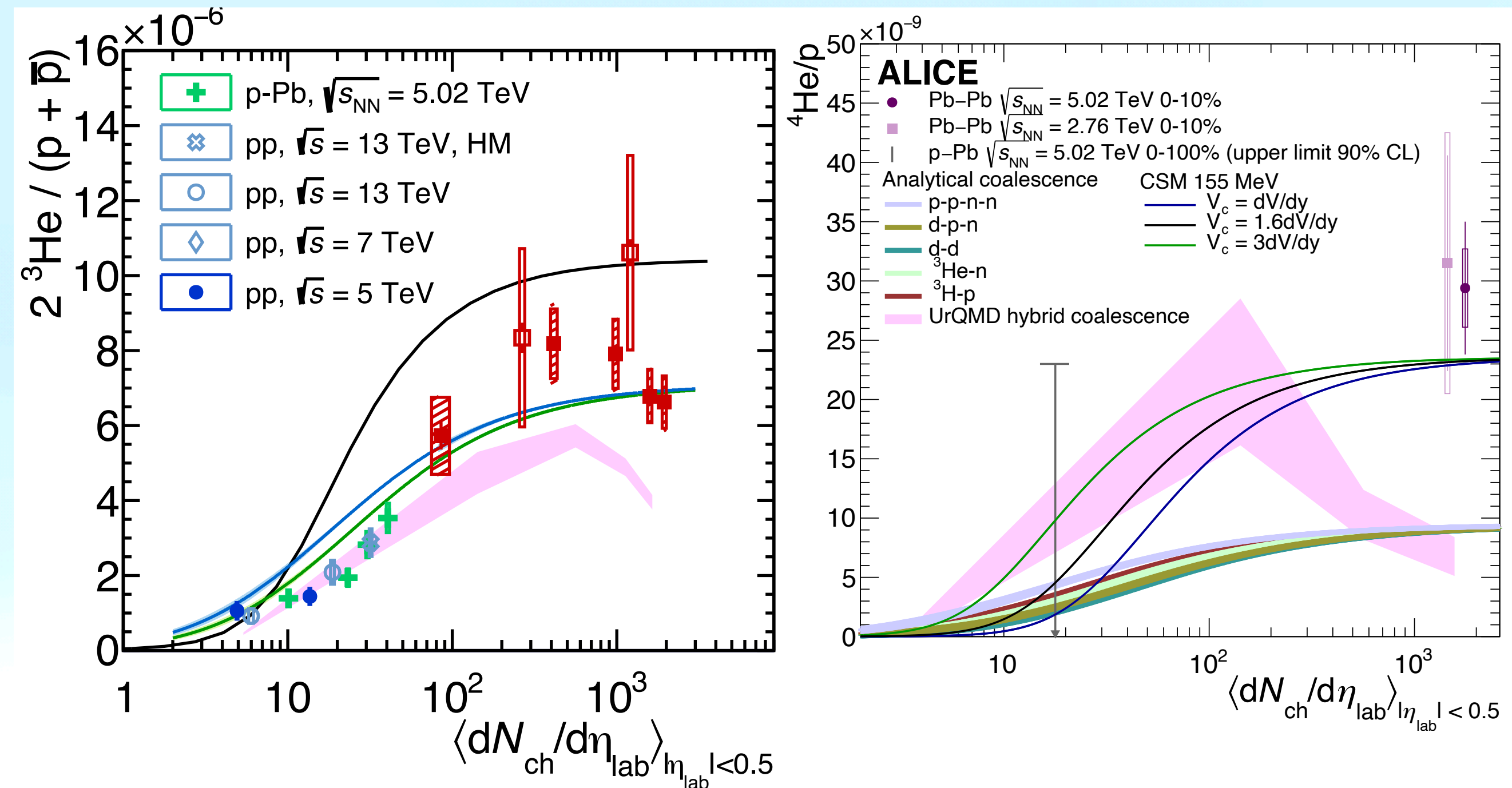
Need a solid understanding in
hypernuclei production mechanisms
before we can use them as **probes for**
medium properties

What Have We Learnt From Light Nuclei Production?



STAR, Phys. Rev. Lett. 130 (2023) 202301

- d/p is fairly well described by thermal model, but t/p is overestimated



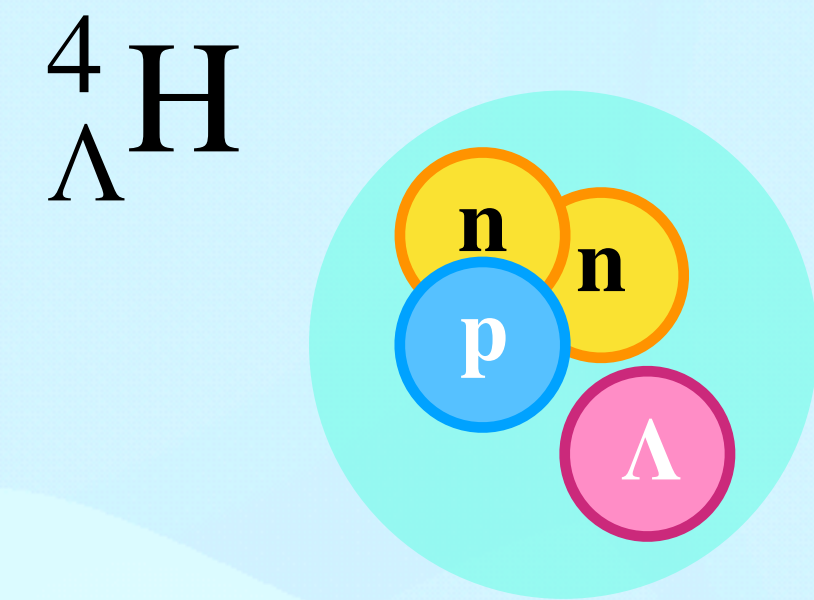
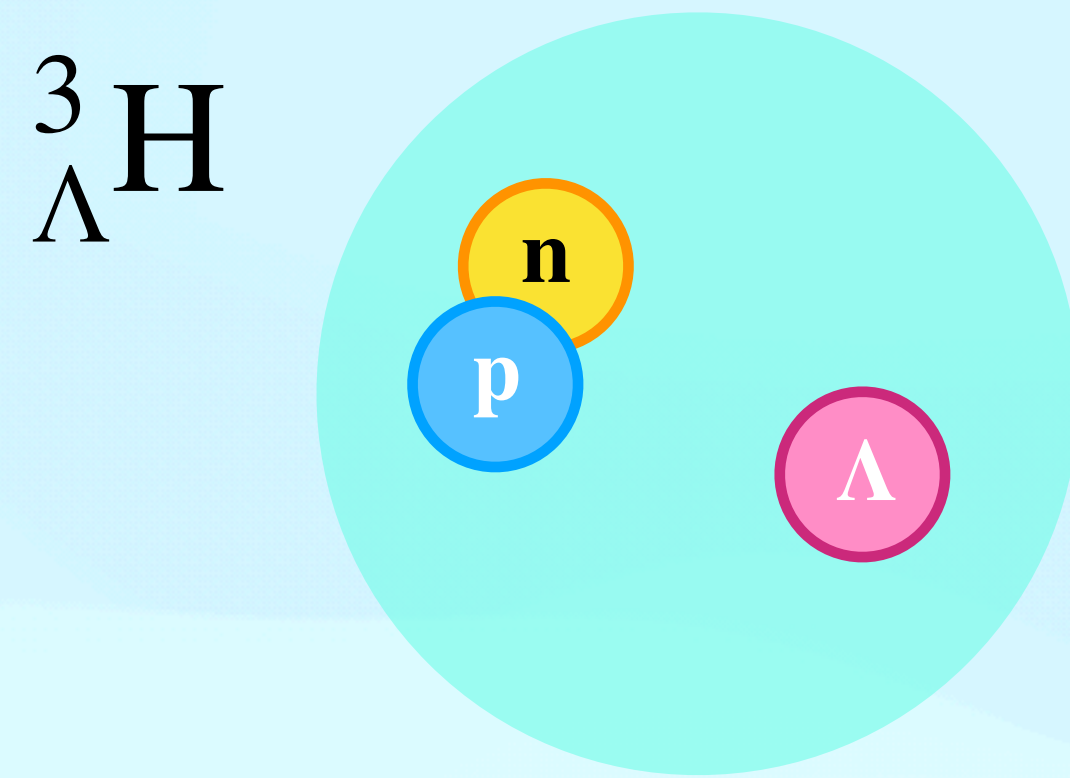
ALICE, Phys. Rev. C 107 (2023) 064904

ALICE, arXiv:2311.11758v1

- ${}^4\text{He}/p$ is well described by thermal model at LHC energies, but underestimated by various implementations of coalescence formation

Recent data poses challenges for nuclei production models

Hypertriton (${}^3_{\Lambda}\text{H}$) and Hyperhydrogen-4 (${}^4_{\Lambda}\text{H}$)



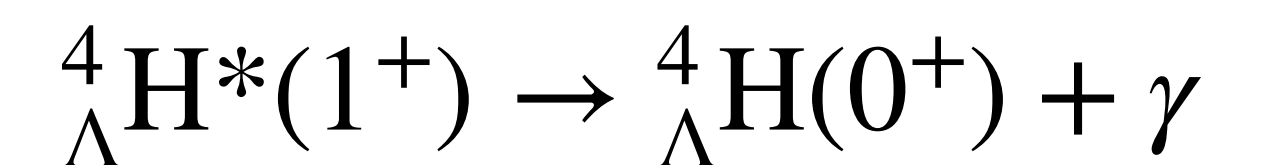
Λ binding energy

~0.1 MeV

~2.2 MeV

Excited states

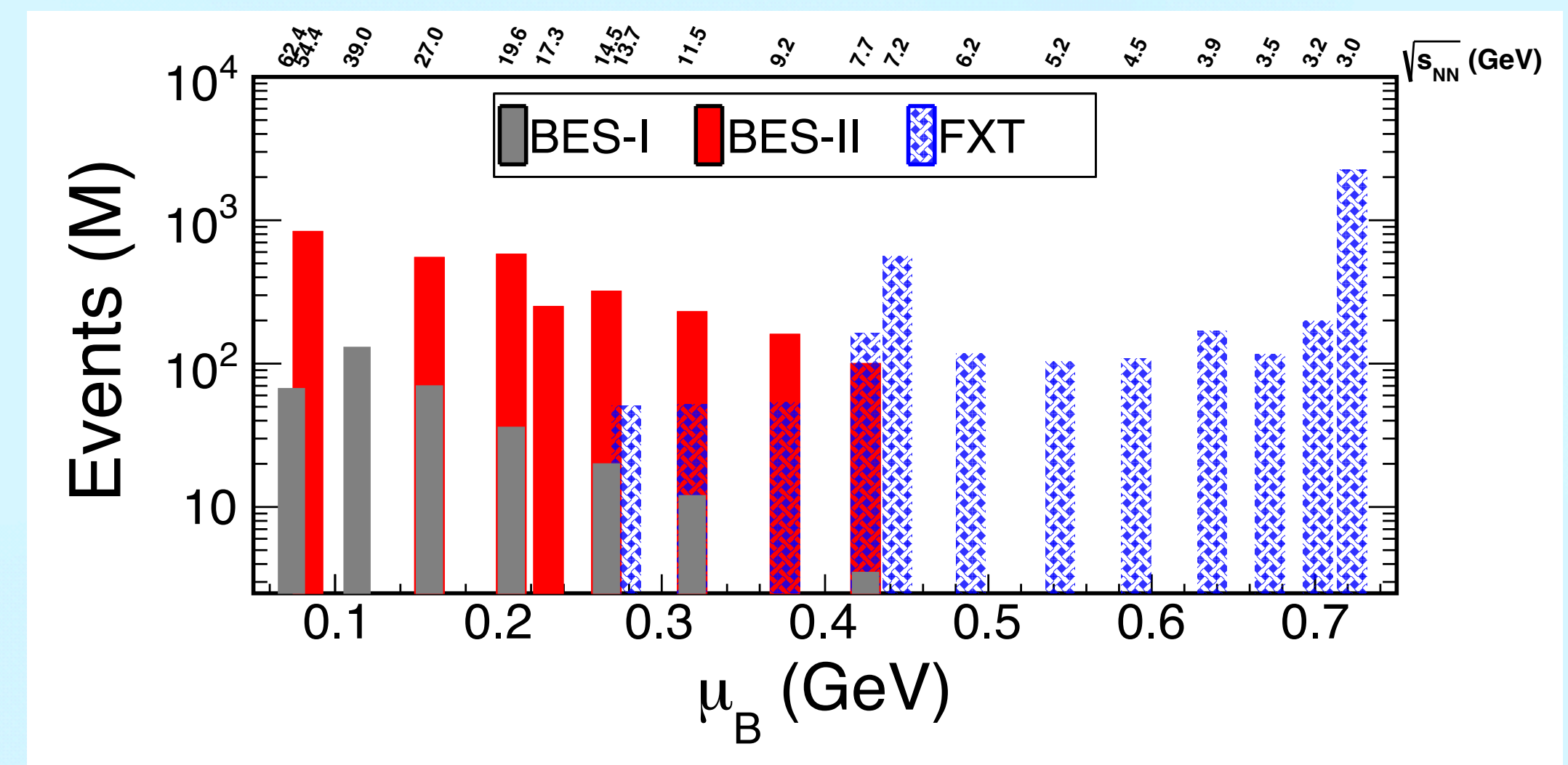
Not observed



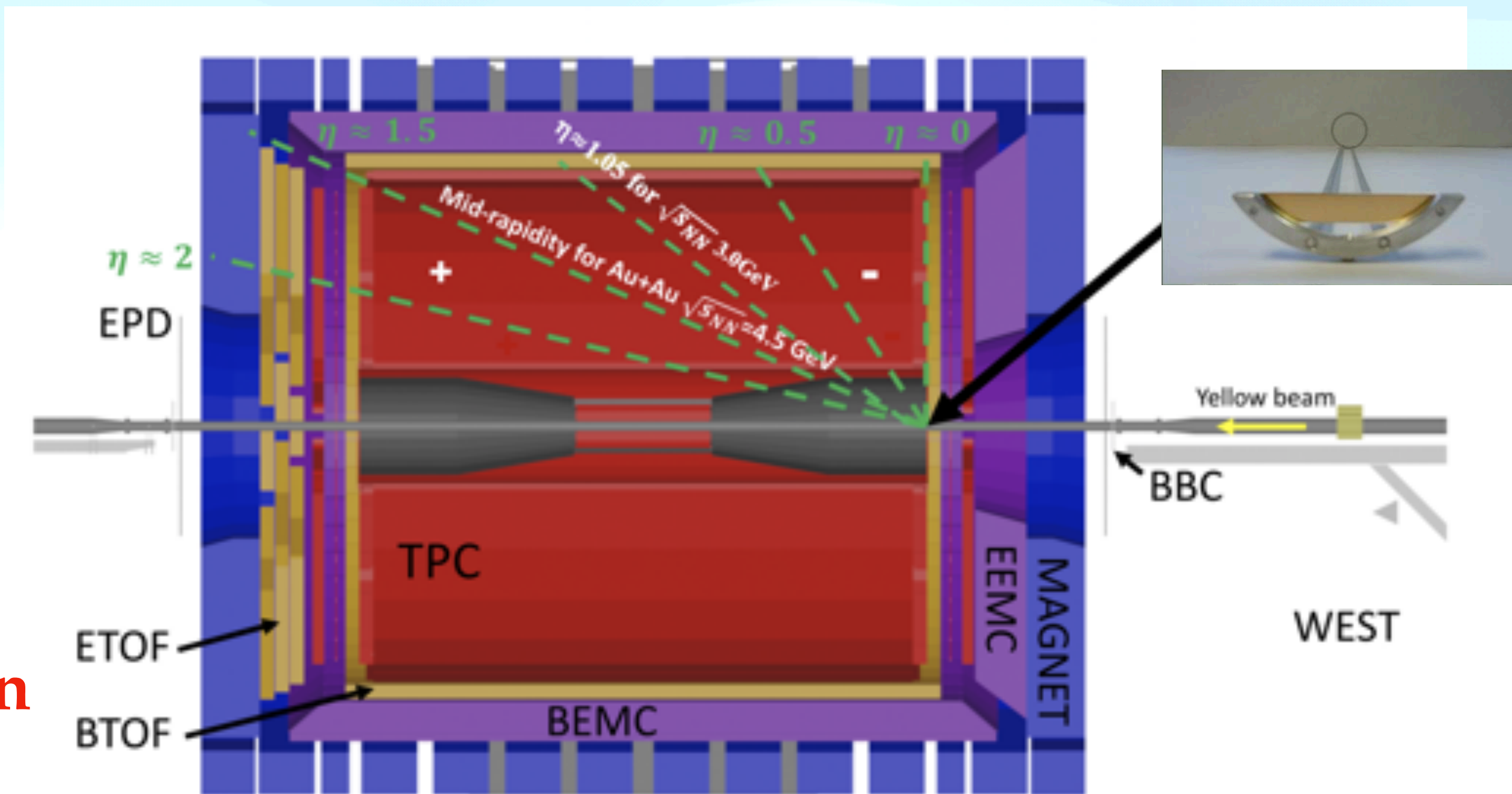
- Due to its very small binding energy, ${}^3_{\Lambda}\text{H}$ production provides unique input for nuclei production models

STAR Beam Energy Scan II

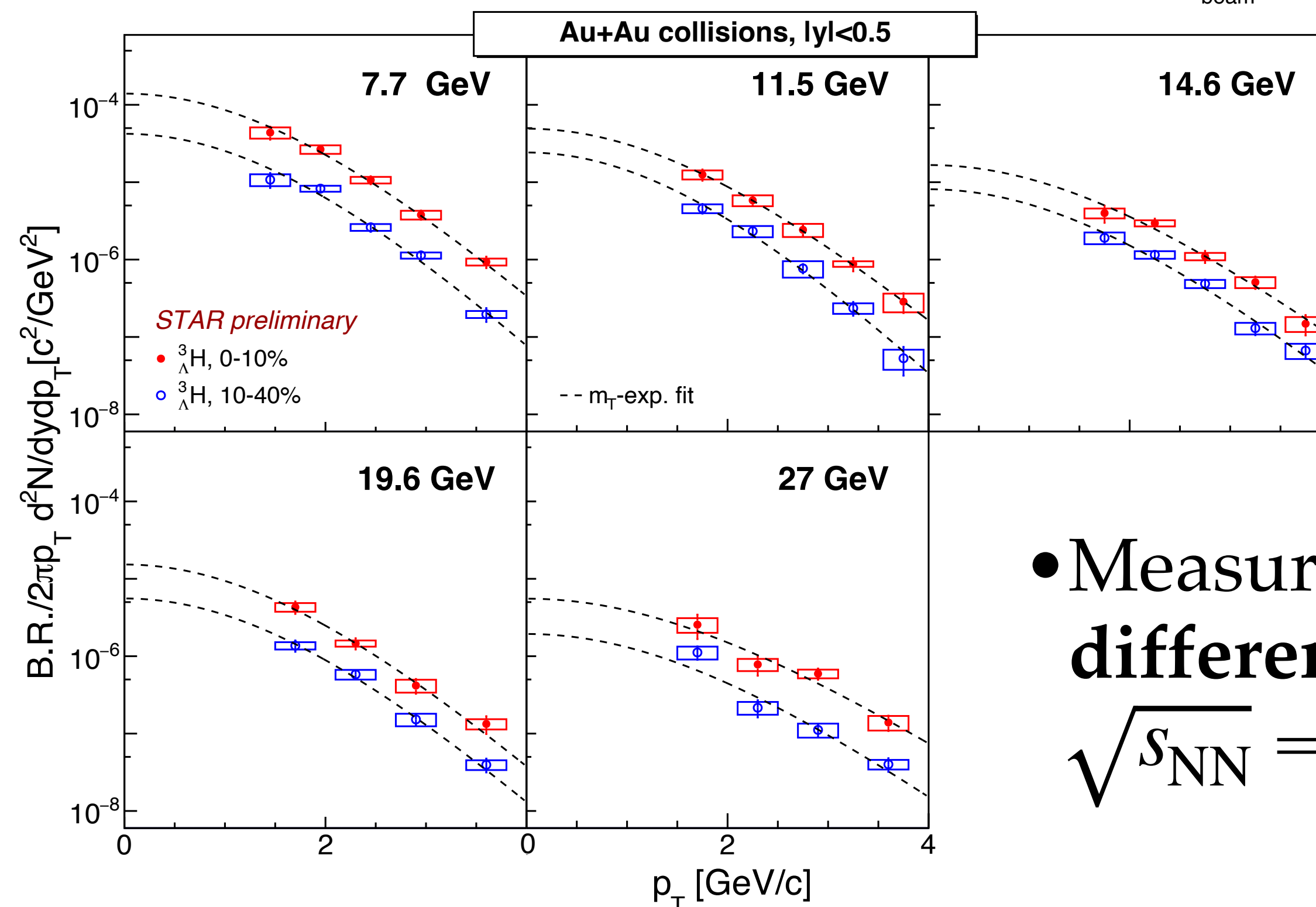
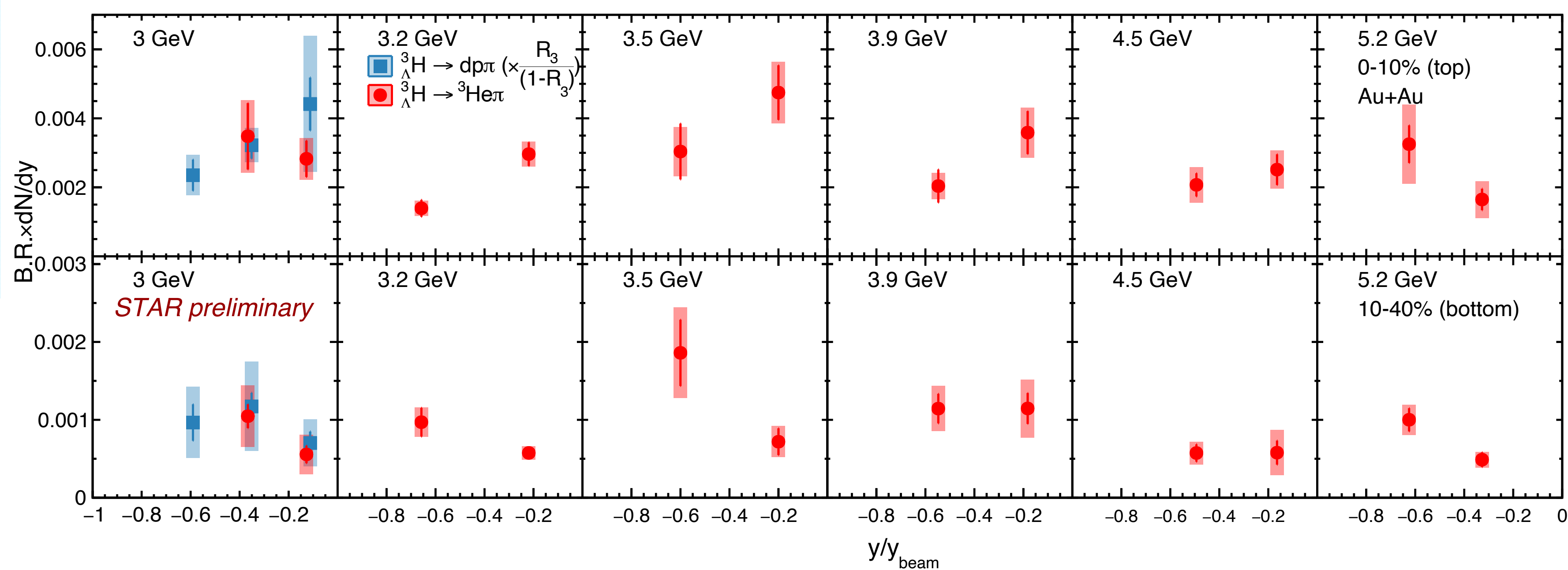
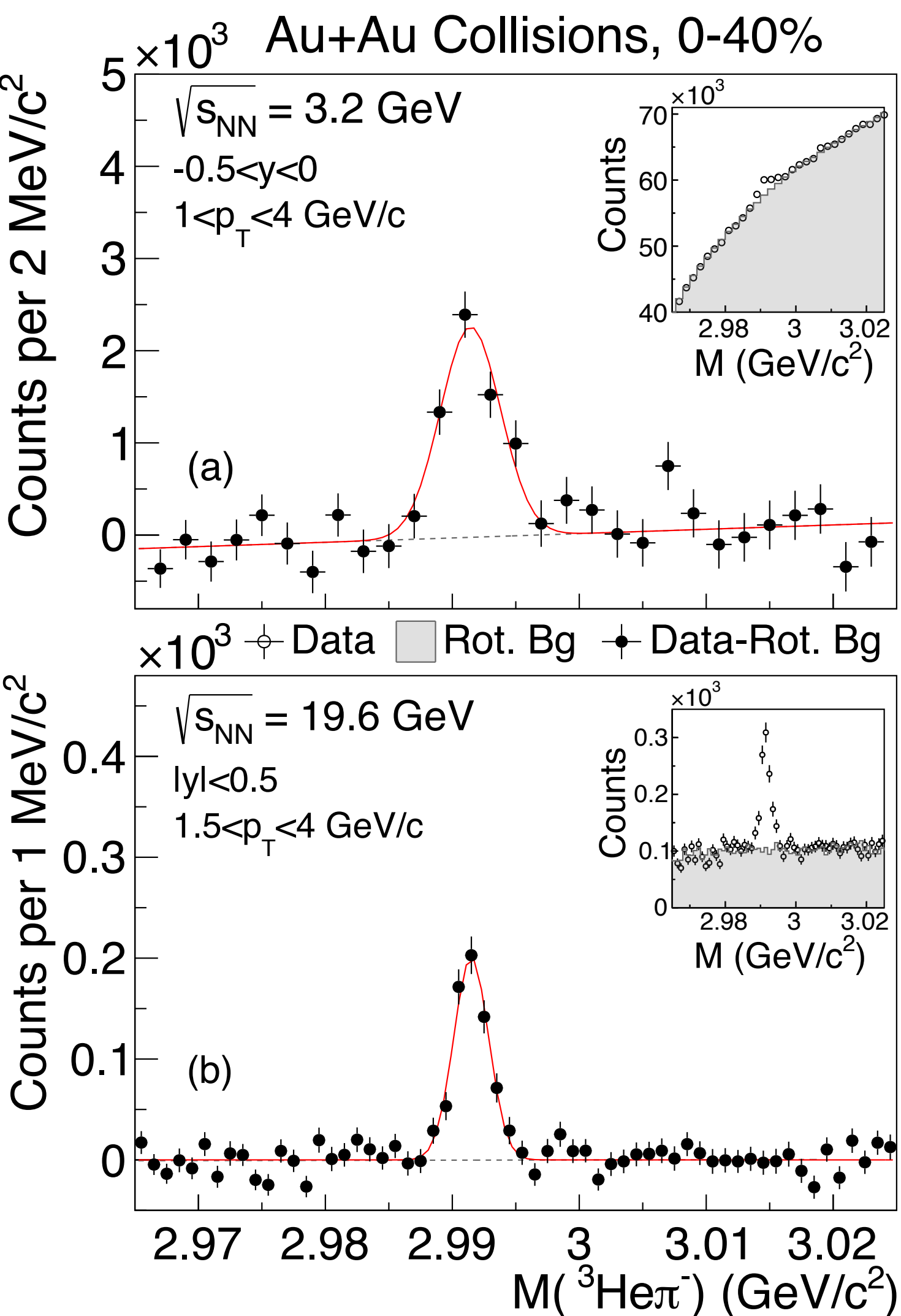
- BES-I (2009-2011)
 - Au+Au collisions $\sqrt{s_{NN}} = 7.7-62$ GeV
 - Main objectives:
 - **Search for onset of deconfinement**
 - **Search for critical end point**



- BES-II (2017-2021)
 - High statistics Au+Au collisions $\sqrt{s_{NN}} = 3-54.4$ GeV
 - Fixed target (FXT) collisions extend energy reach down to $\sqrt{s_{NN}} = 3$ GeV
 - **Search for possible formation and investigate properties of dense baryonic matter**

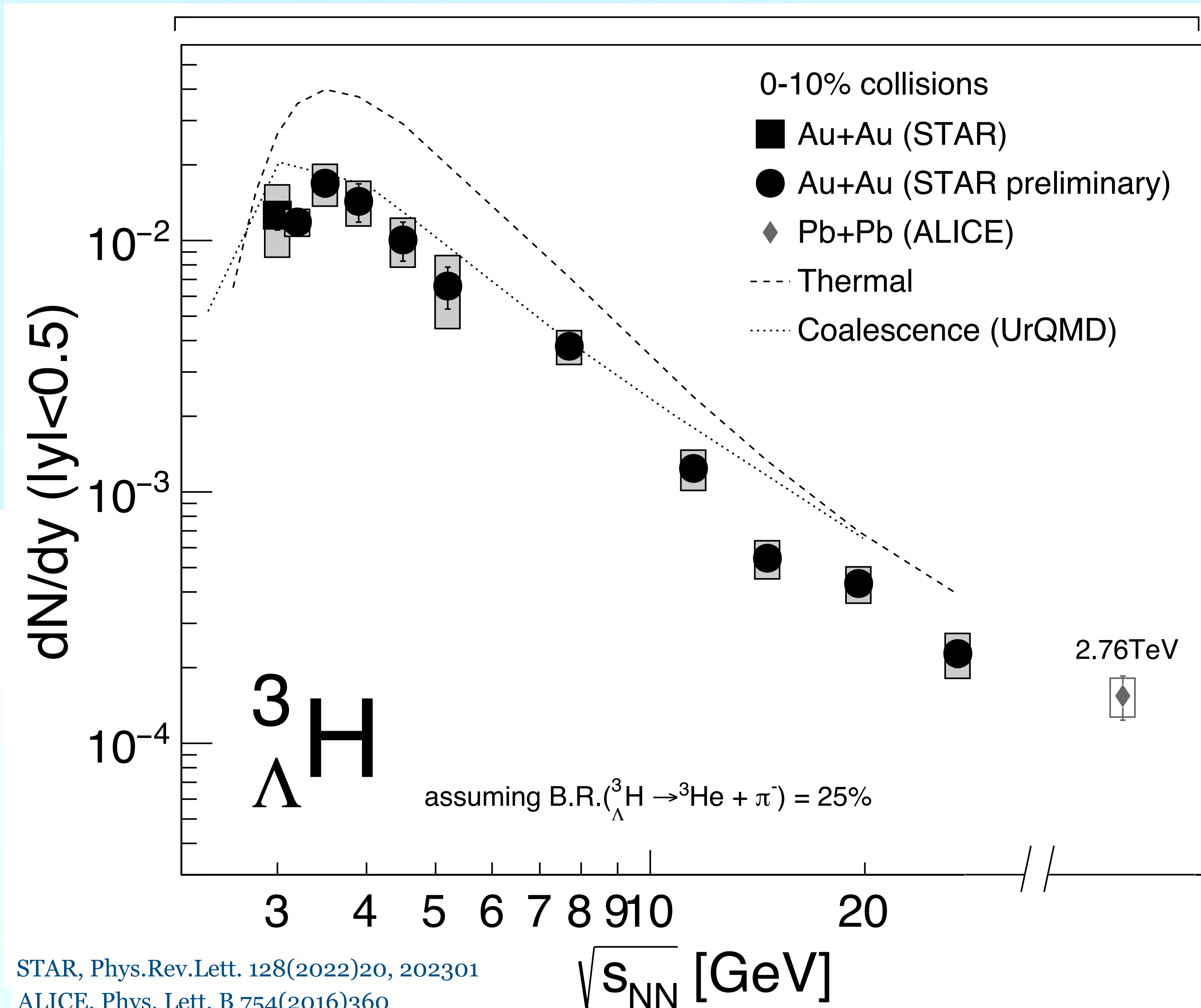


${}^3_{\Lambda}\text{H}$ Rapidity and p_T Spectra



- Measurements cover **11 different energies** from $\sqrt{s_{NN}} = 3$ to 27 GeV

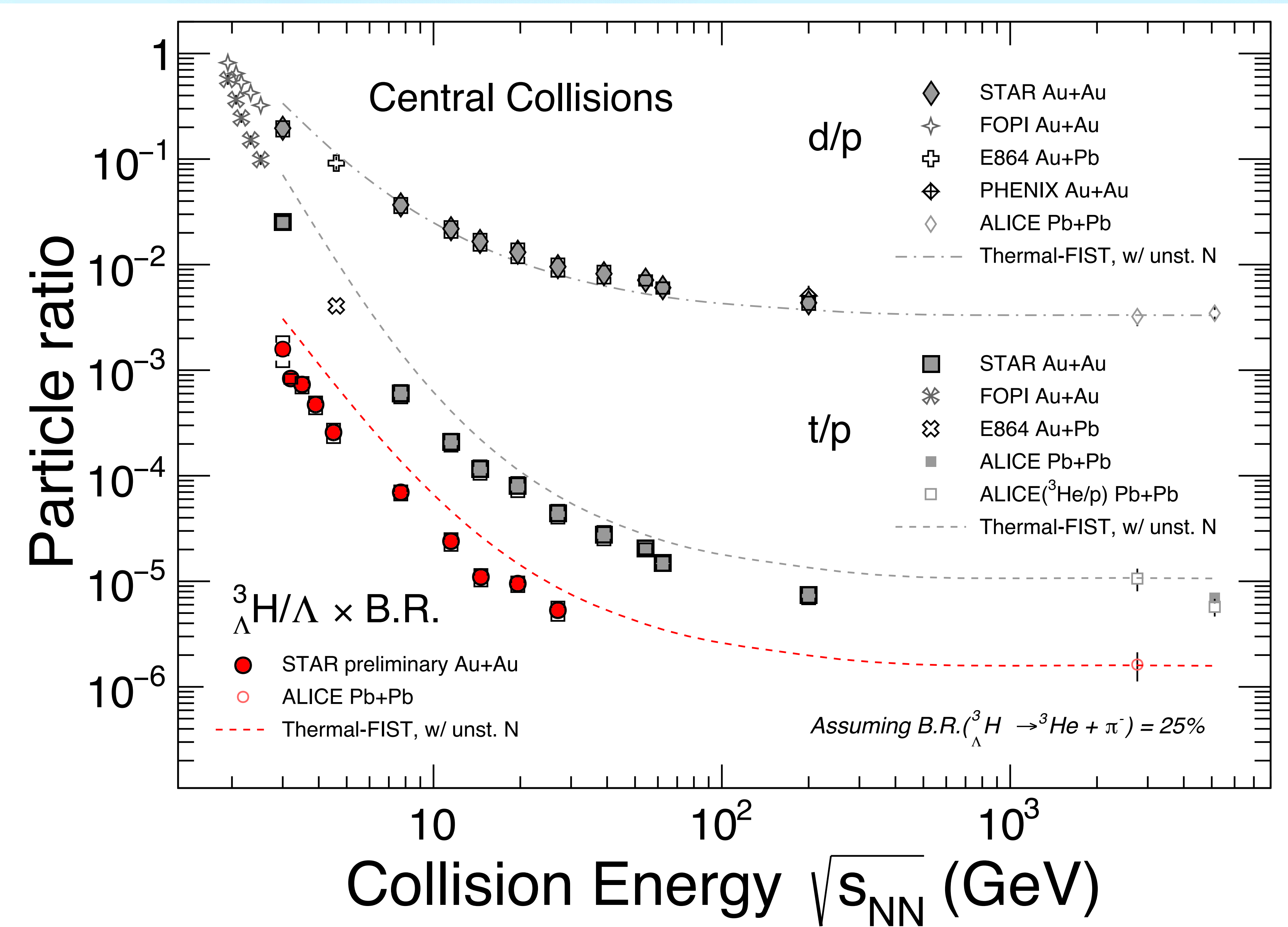
${}^3_{\Lambda}\text{H}$ Excitation Function



- Steep increase from $\sqrt{s_{\text{NN}}} = 27$ to 4 GeV
- Plateaus at $\sqrt{s_{\text{NN}}} = 3-4$ 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

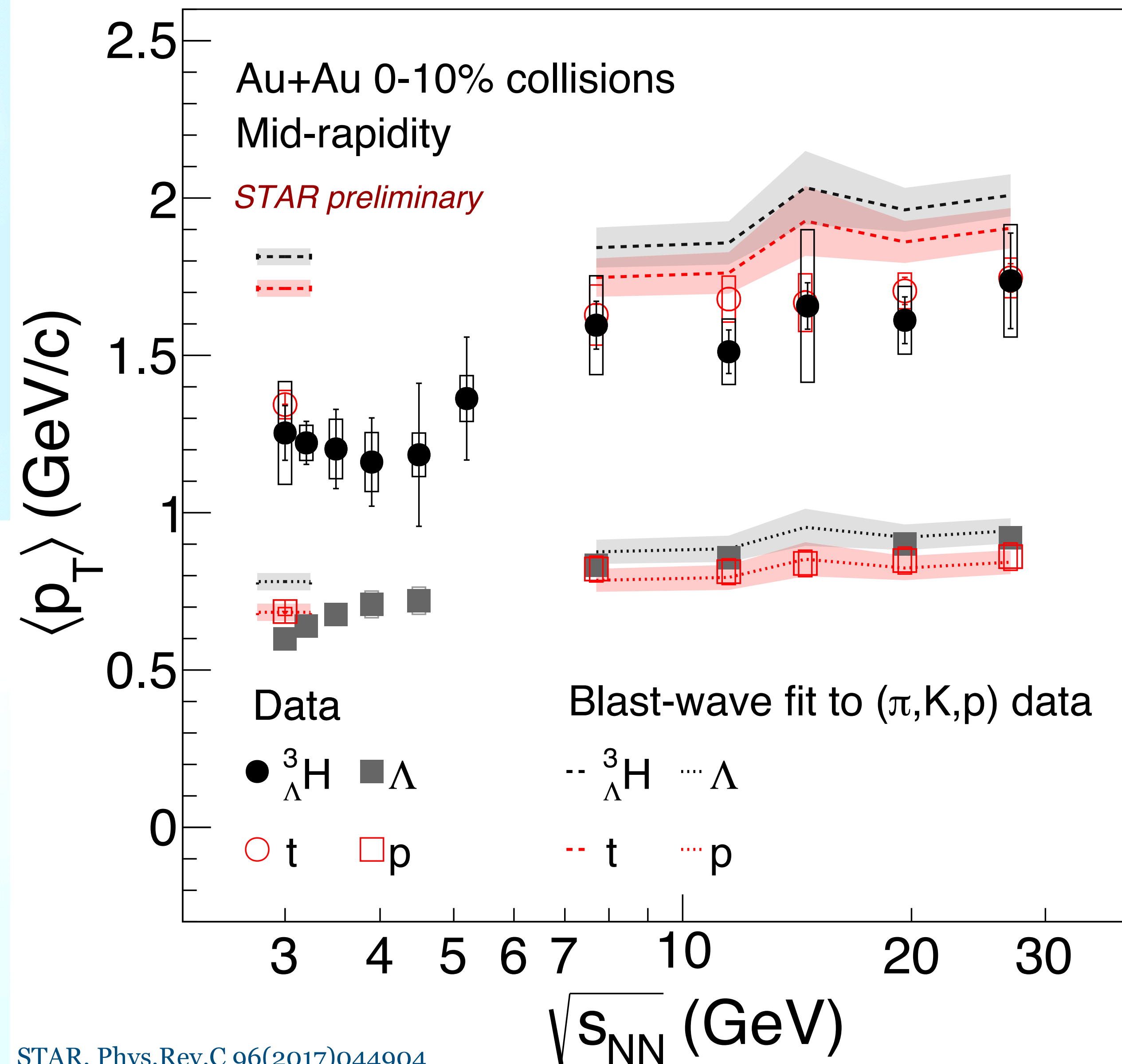
Nuclei-to-Hadron Ratios



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



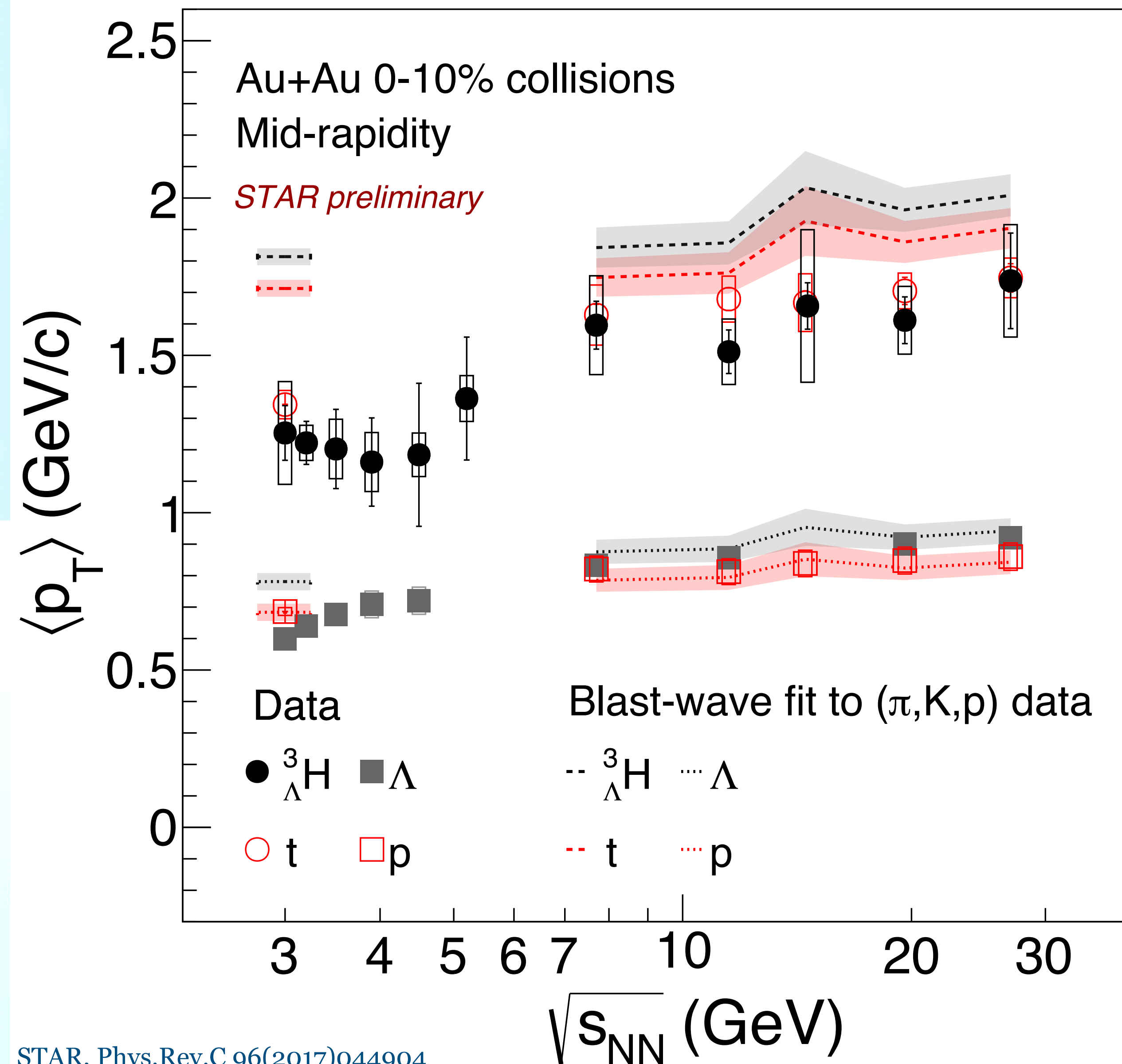
- ${}^3_{\Lambda}\text{H}$ and t have similar mean p_T
- Both ${}^3_{\Lambda}\text{H}$ and t tend to have lower mean p_T than the blast-wave parametrization using measured kinetic freeze-out parameters from light hadrons (π, K, p)

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

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

D. Liu et al, arXiv:2404.02701

Mean Transverse Momentum

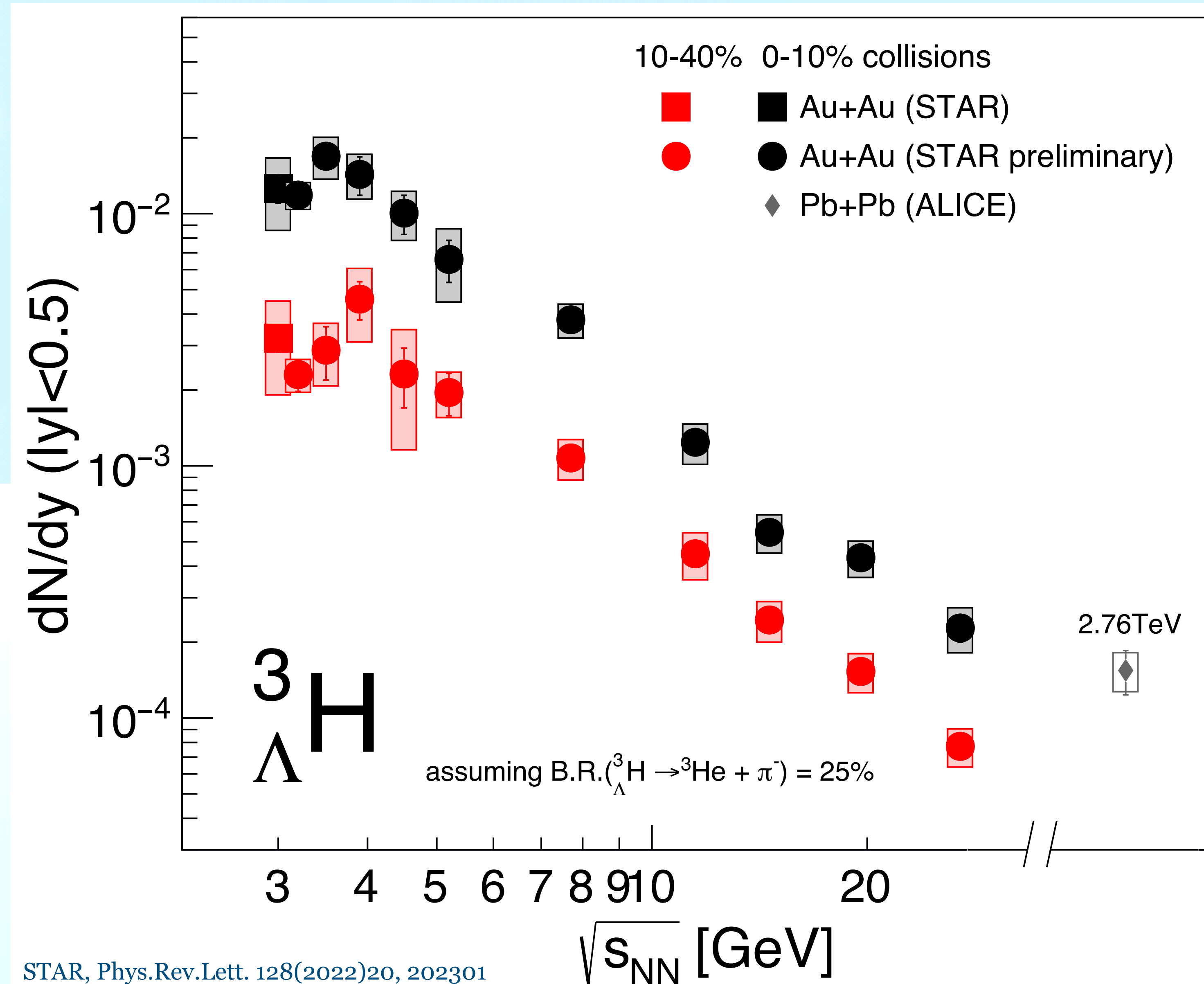


- The mean p_T for $\sqrt{s_{NN}} = 3-4.5$ GeV and $\sqrt{s_{NN}} = 7.7-27$ GeV seem to exhibit two different trends

Change in medium properties or expansion dynamics?

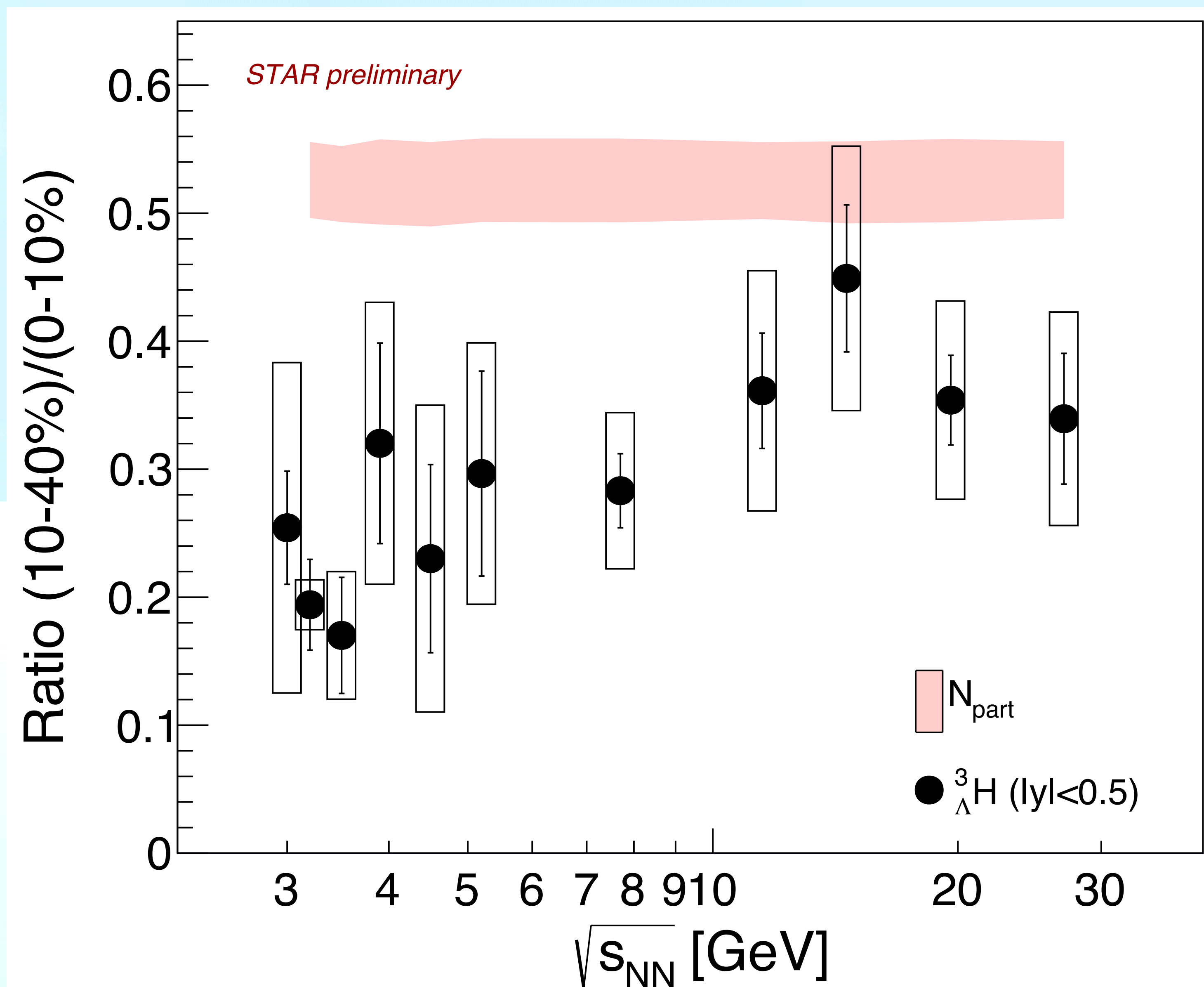
see Y. Zhou, 17:00 20/05 (Mon.)

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



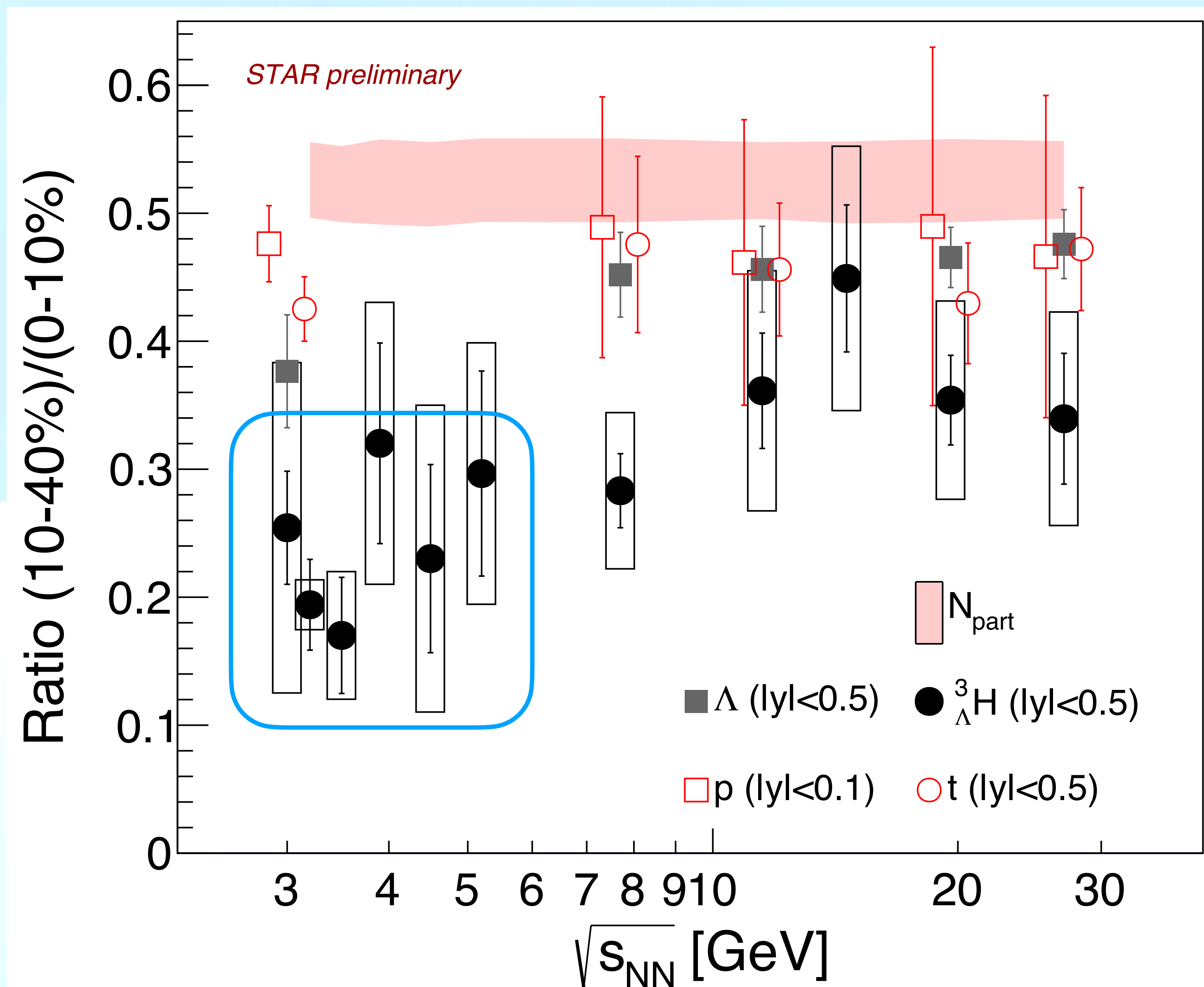
- The yield in mid-central (10-40%) collisions follows the same trend as central (0-10%) collisions

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



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

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



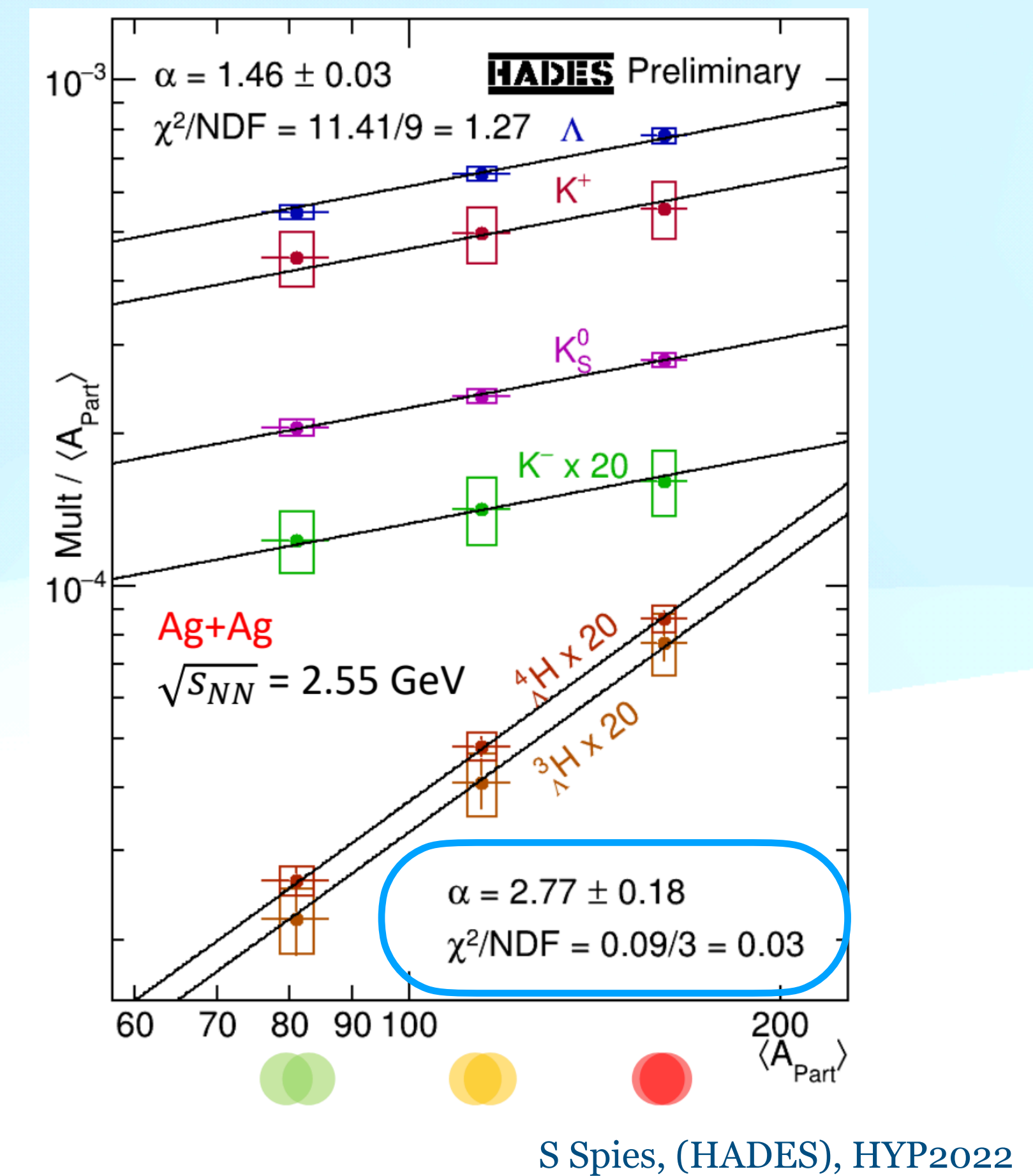
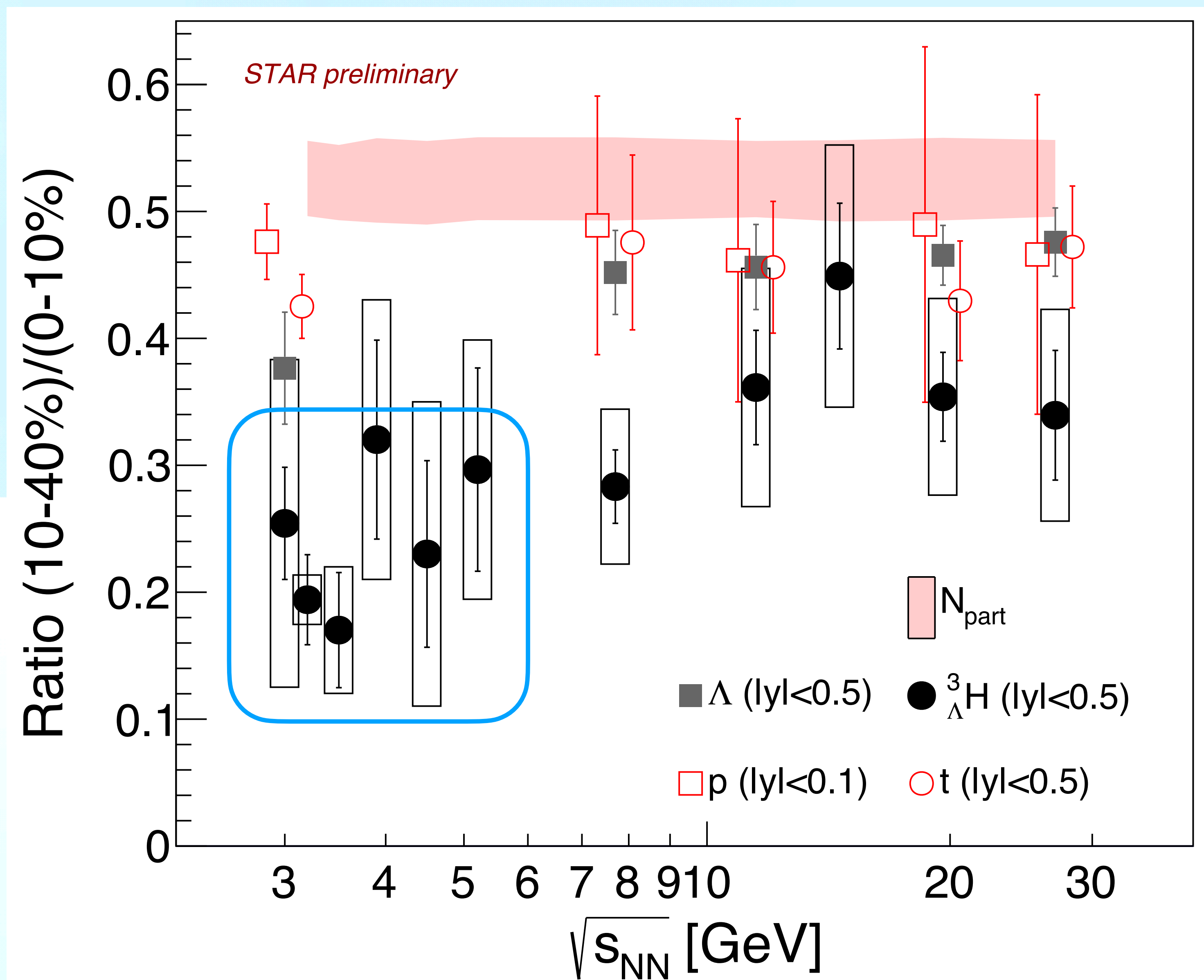
- Proton yield scales with N_{part}
- Λ yield increases more steeply than N_{part} , particularly at low collision energies

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

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

Suppression of ${}^3_{\Lambda}\text{H}$ production in more peripheral collisions at low energies

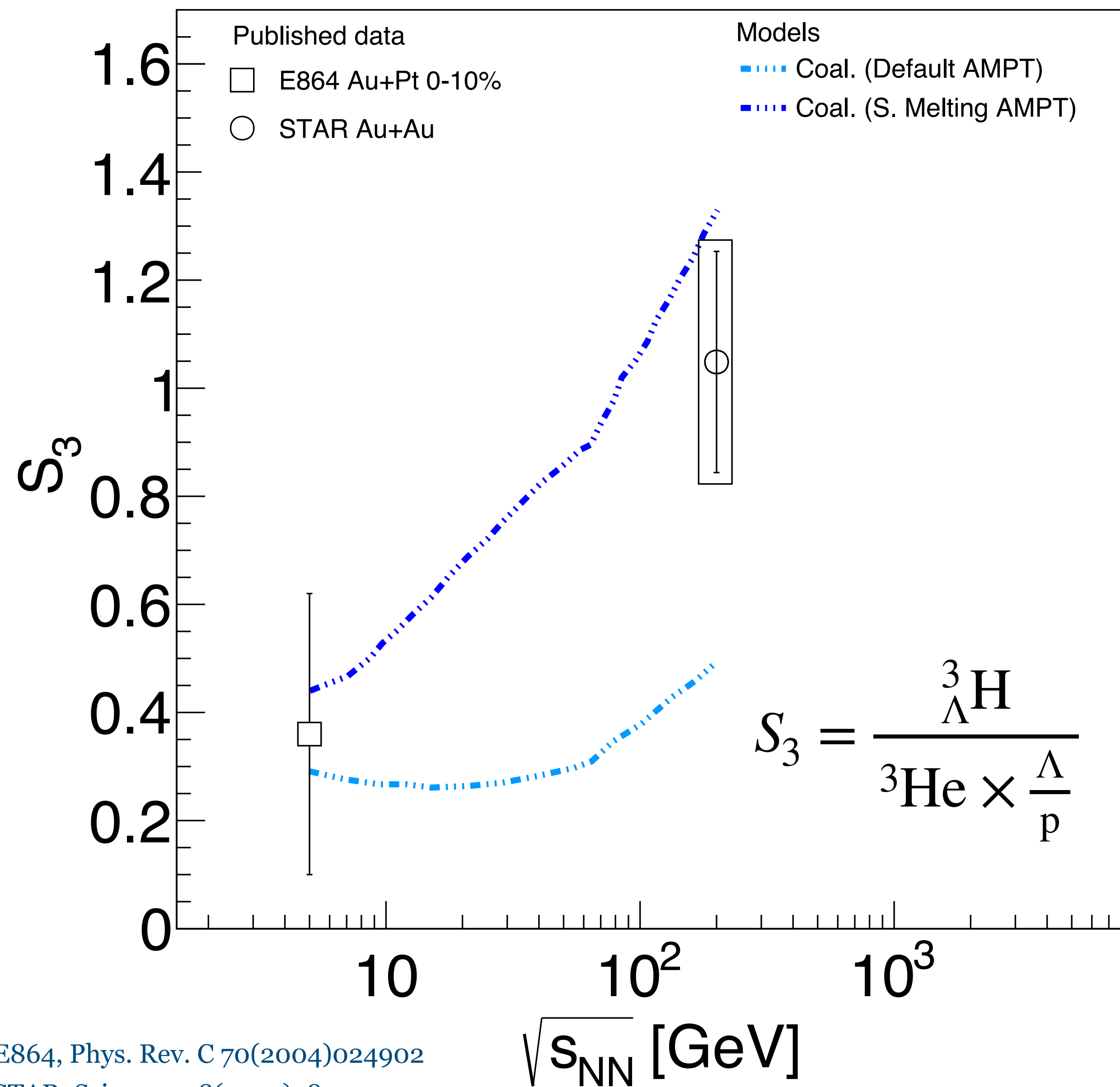
Centrality Dependence of ${}^3_{\Lambda}\text{H}$ Production



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

Suppression related to the nature of the created medium?

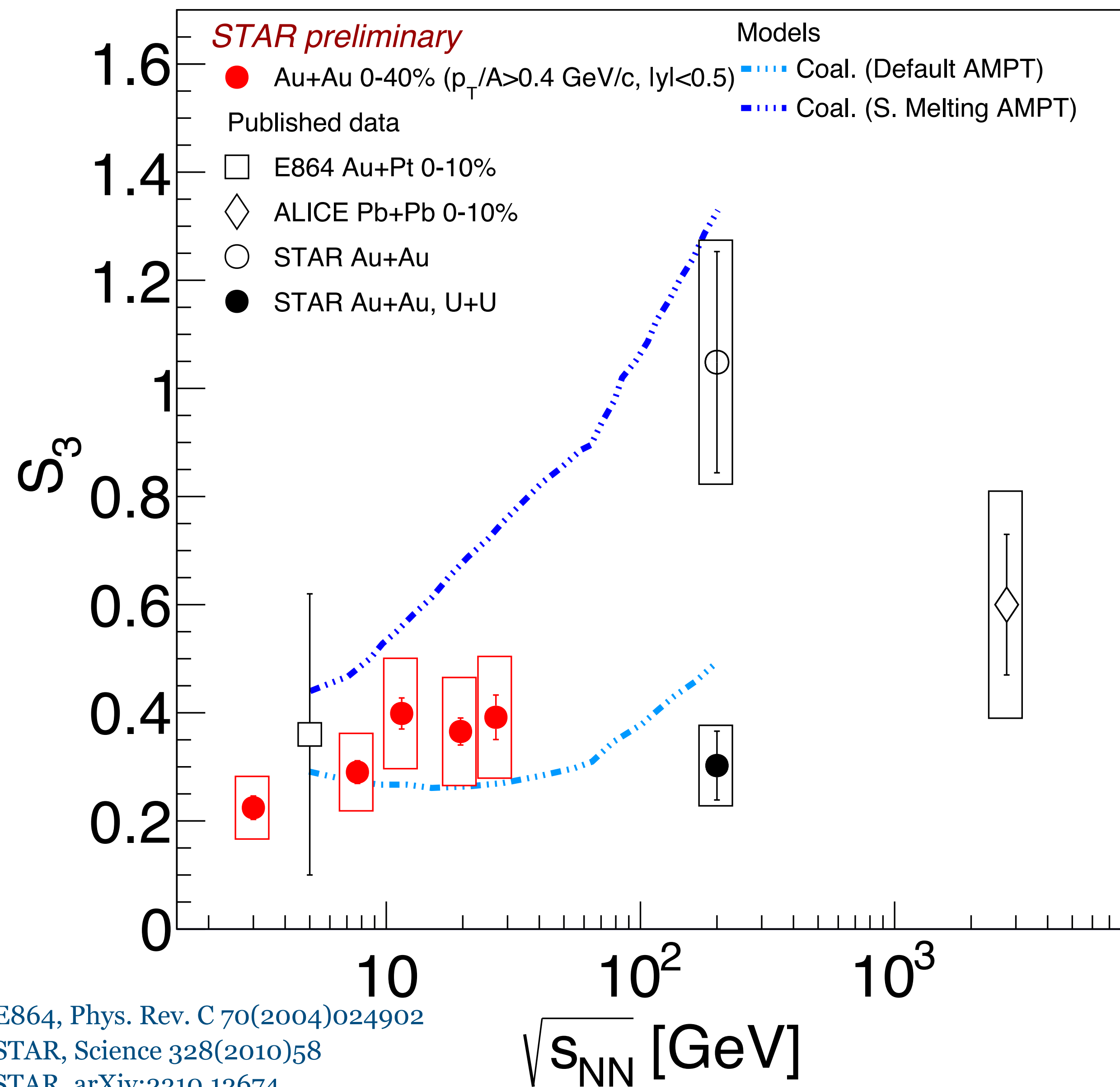
Strangeness Population Factor S_3



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

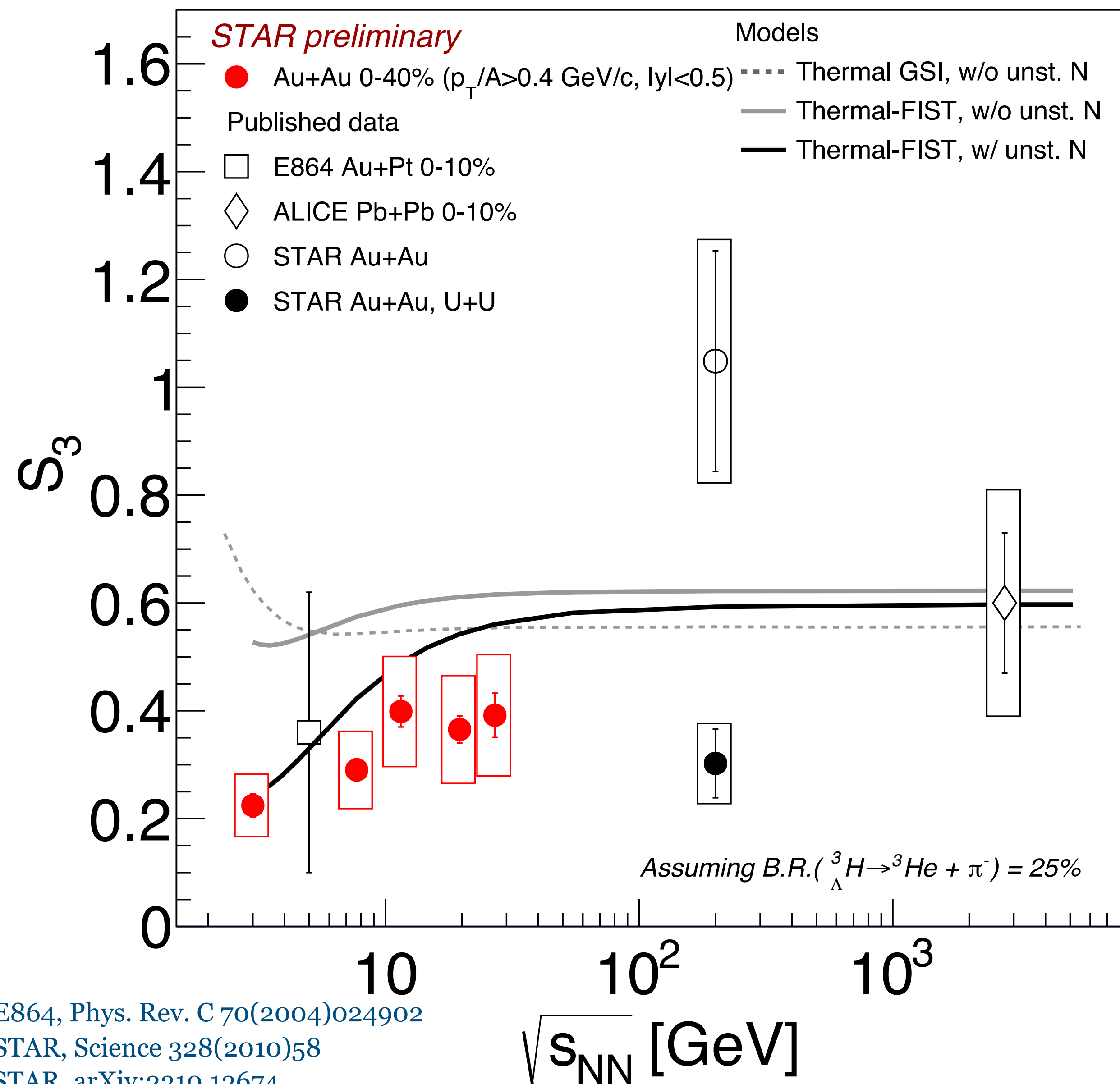
S. Zhang et al, Phys. Lett. B 684 (2010) 224

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

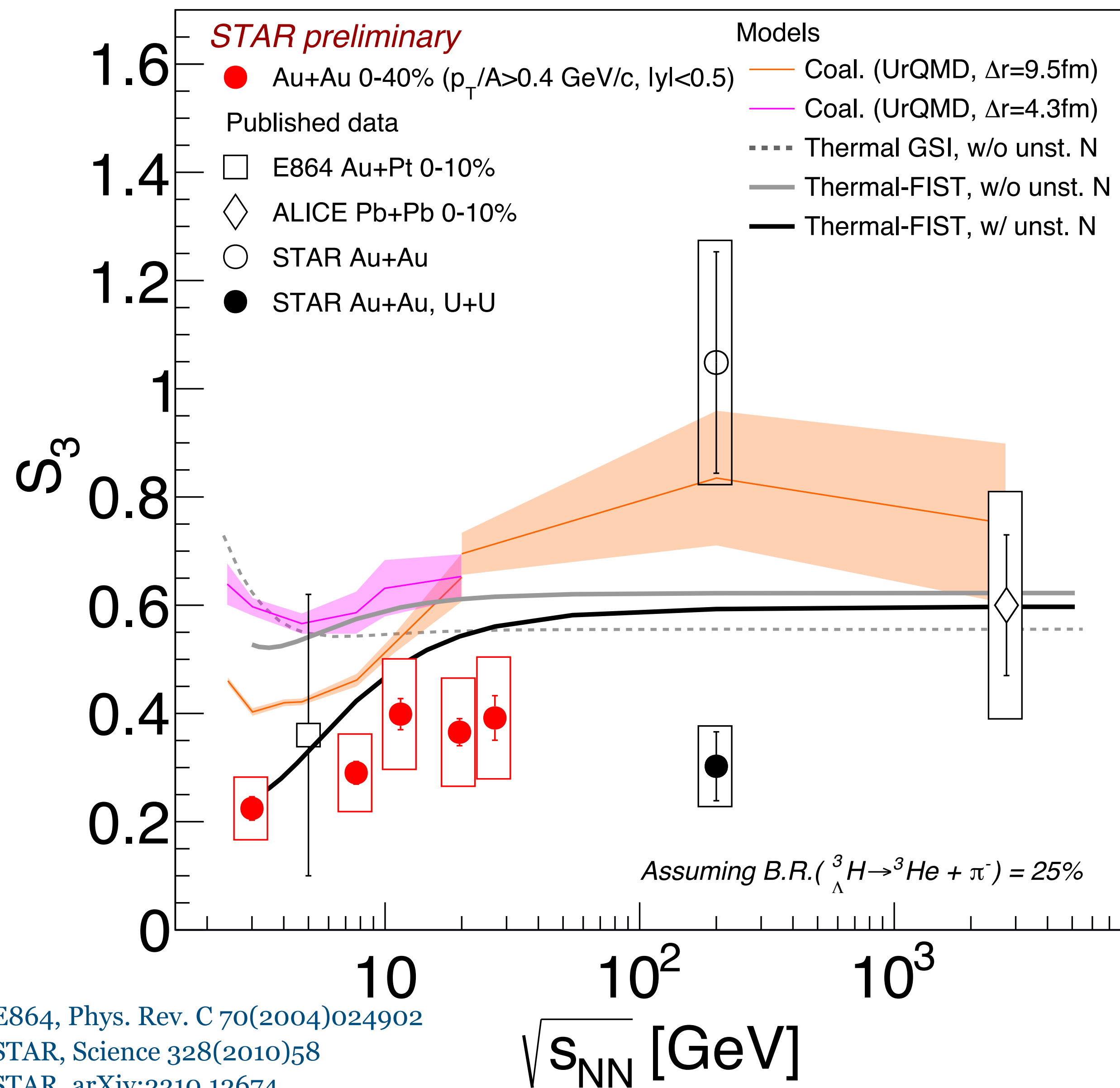
Strangeness Population Factor S_3



- The measured S_3 is close to thermal model predictions
- The increasing trend is driven by the decreasing feed-down from ${}^3\text{He}$ towards higher energies

T. Reichert et al, Phys.Rev.C 107(2023)014912

Strangeness Population Factor S_3

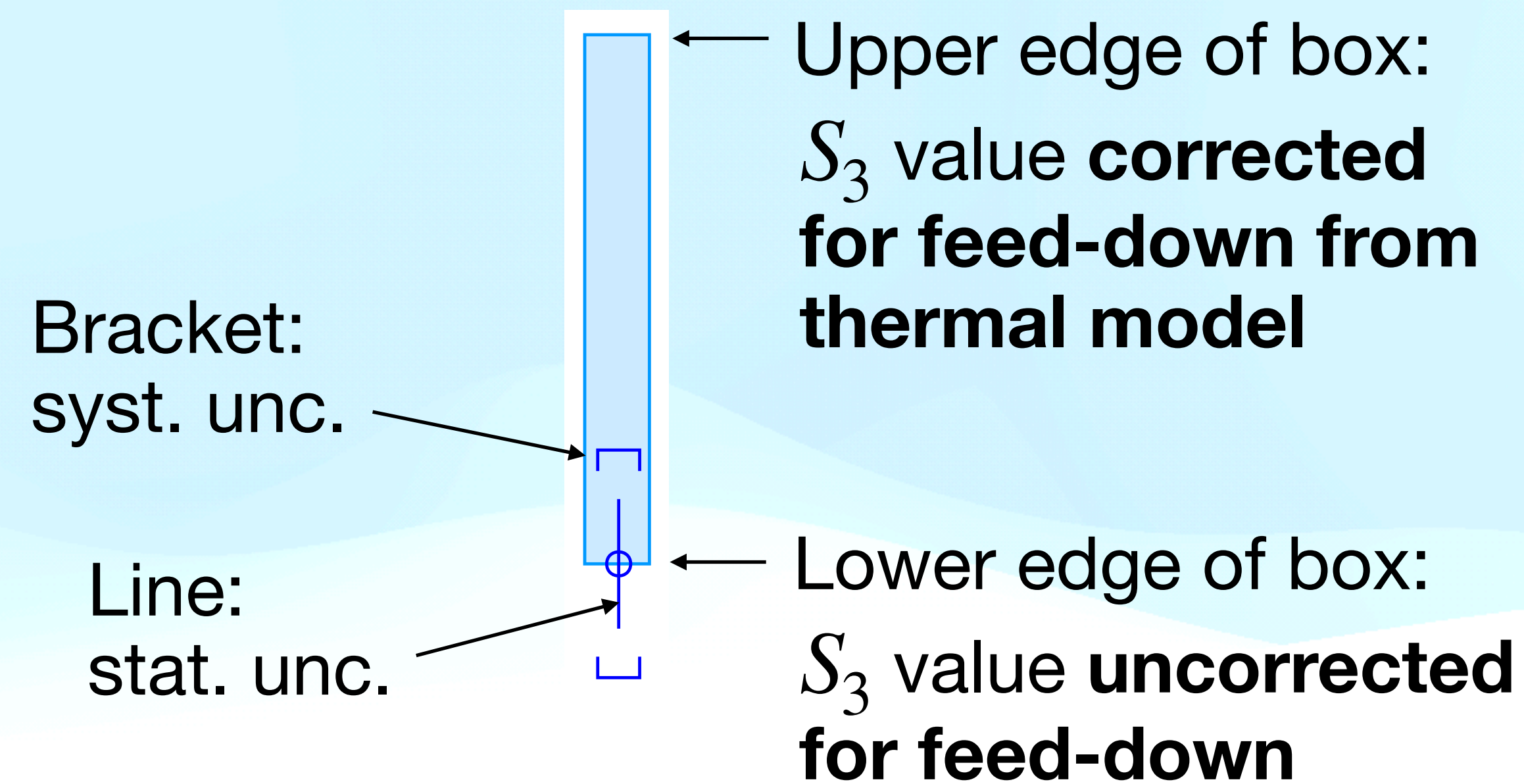
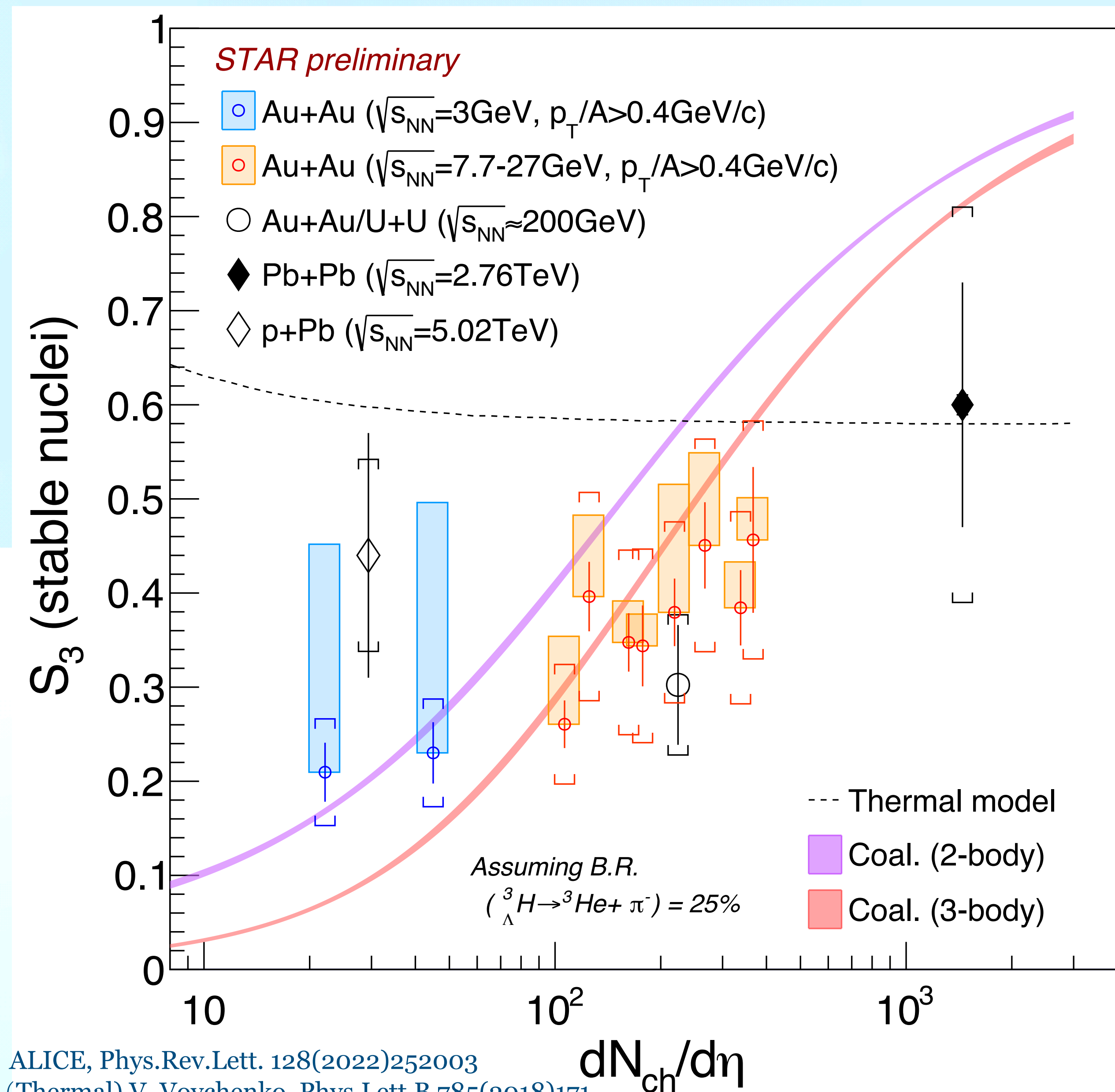


- UrQMD + Coalescence seem to overshoot the data
- A key prediction from coalescence models is the suppression of ${}^3_{\Lambda}H$ production in small systems due to its large radius

T. Reichert et al, Phys.Rev.C 107(2023)014912

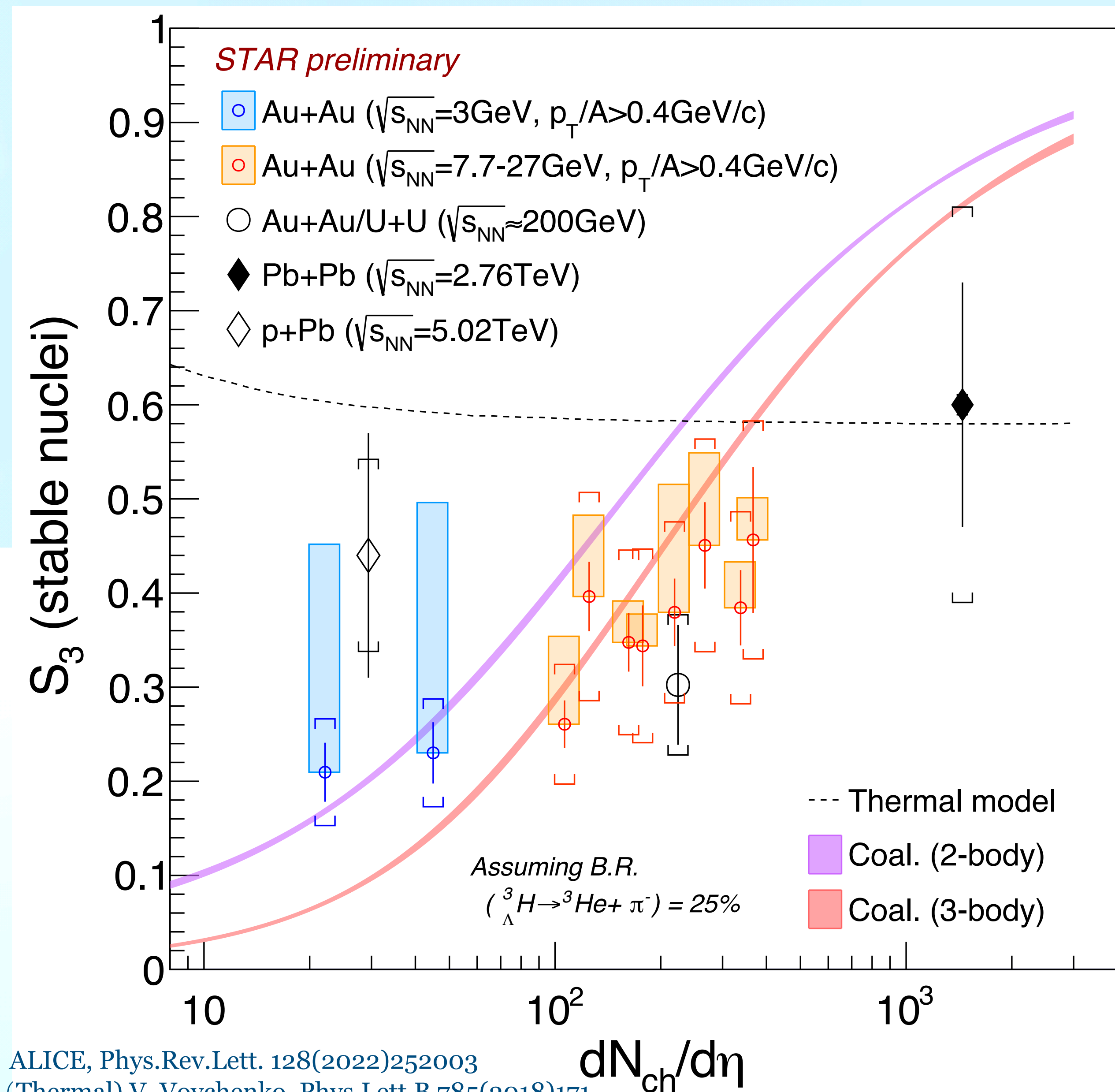
- Best represented by investigating the multiplicity dependence, since $dN_{ch}/d\eta$ is a good proxy for volume
- Possible feed-down should be accounted for when interpreting results

Multiplicity Dependence of S_3 (stable nuclei)



- 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)

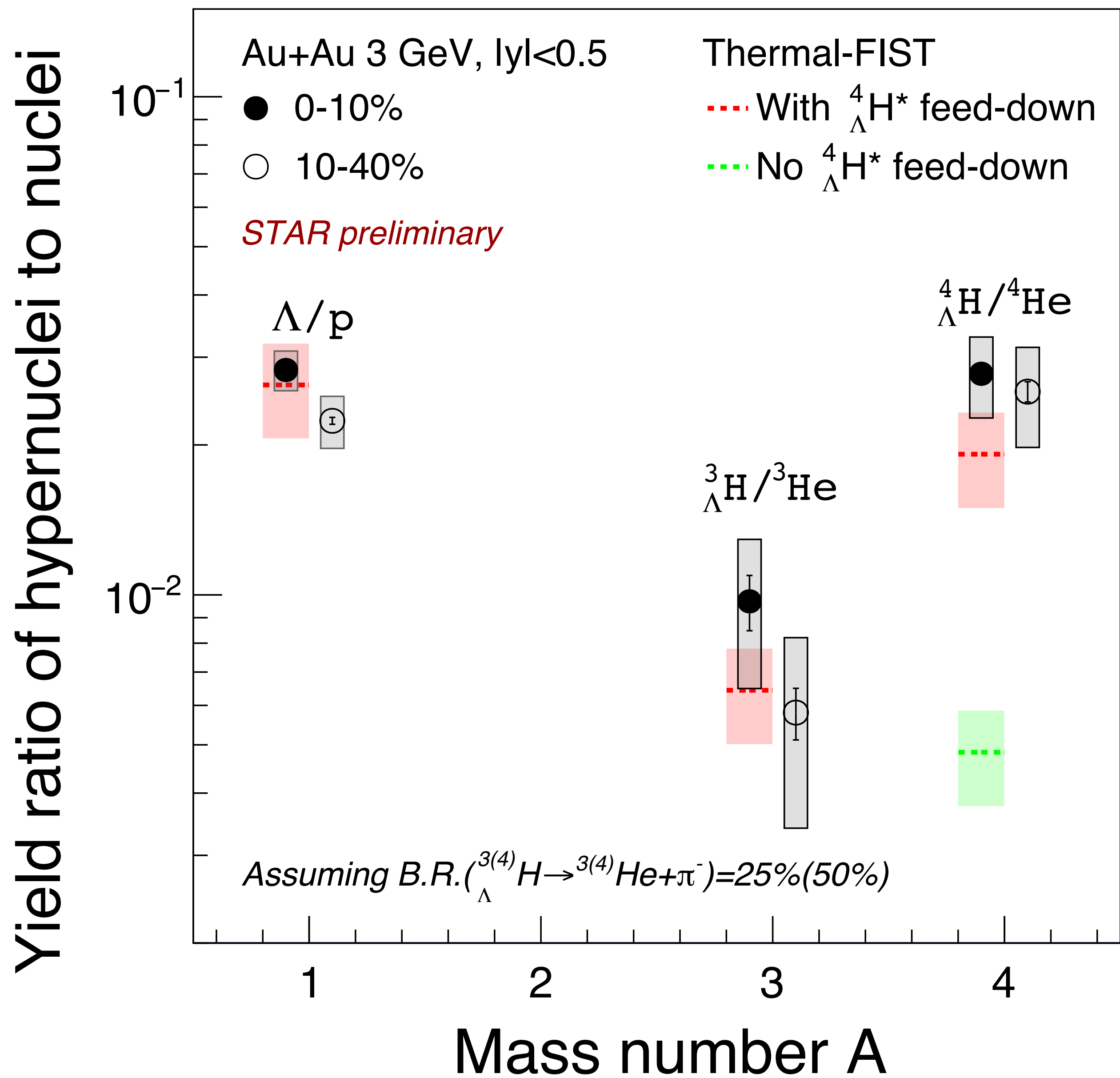


$$S_3 \text{ (stable nuclei)} \approx 0.35$$

- Existing data for S_3 considering stable nuclei only 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

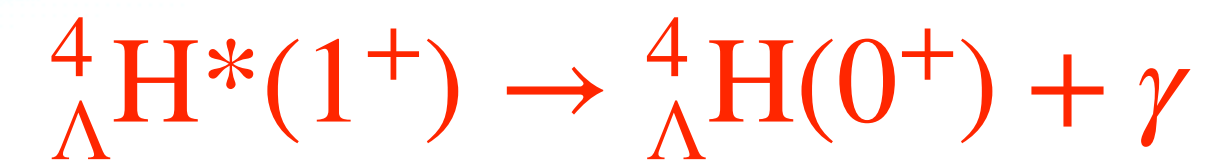
More data at very low and very high $dN_{ch}/d\eta$ is needed

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

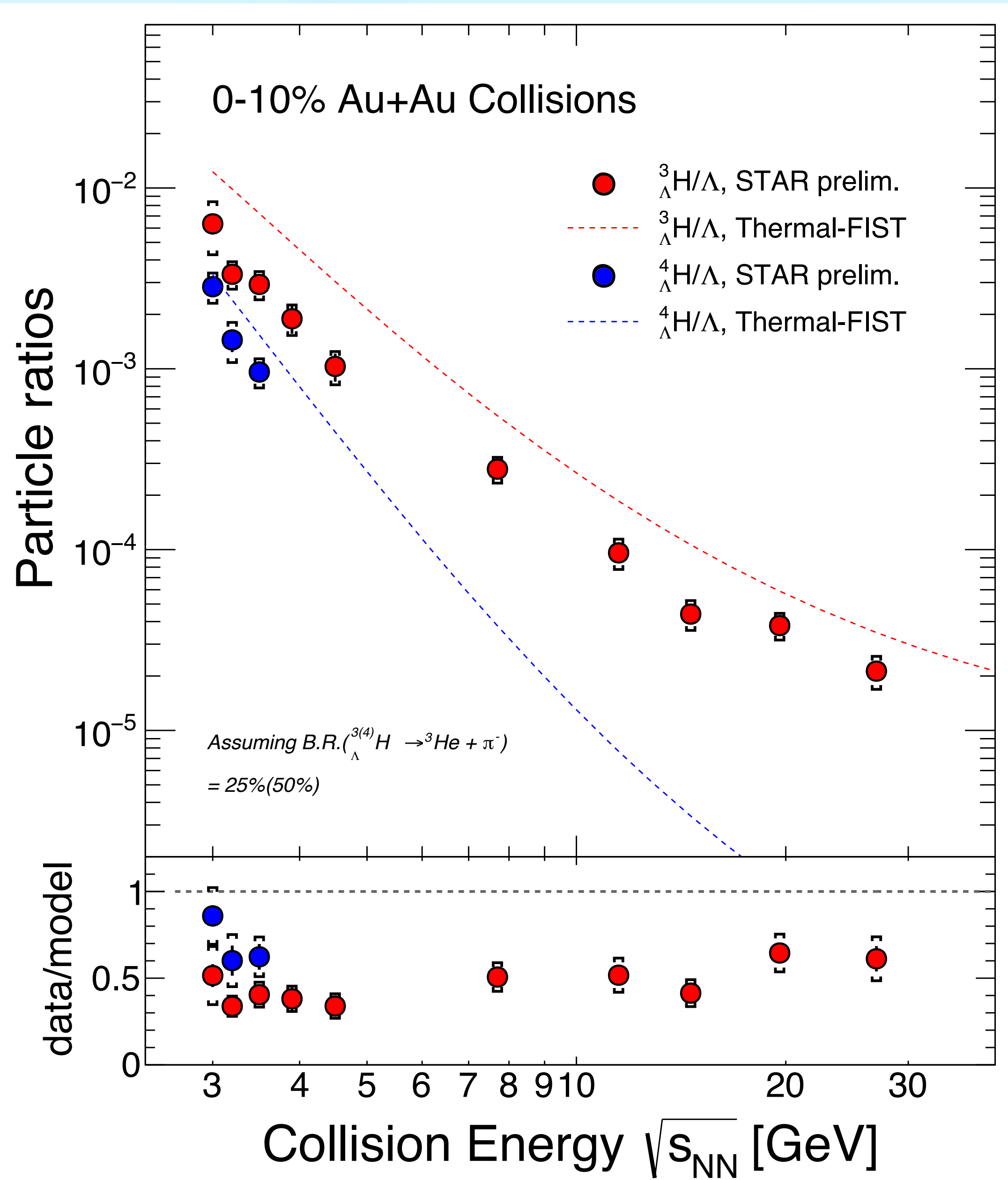


- Non-monotonic behavior of hypernuclei to nuclei yields vs mass number

Suggestive of creation of unstable hypernuclei



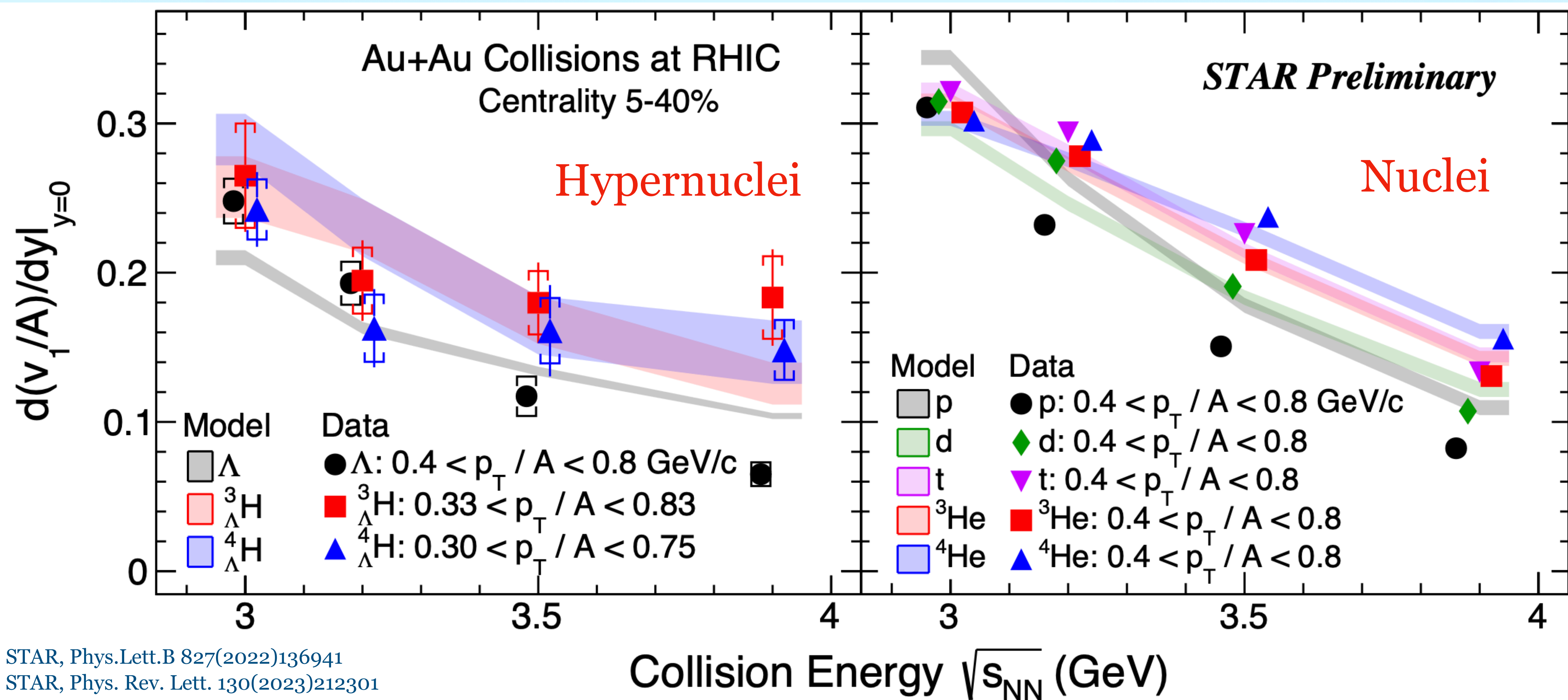
${}^4_{\Lambda}\text{H}$ Production



- ${}^4_{\Lambda}\text{H}$ yields tend to be closer to thermal model predictions compared to ${}^3_{\Lambda}\text{H}$

Size of hypernuclei plays a role in their production?

Hypernuclei Collective Flow



STAR, Phys.Lett.B 827(2022)136941
STAR, Phys. Rev. Lett. 130(2023)212301

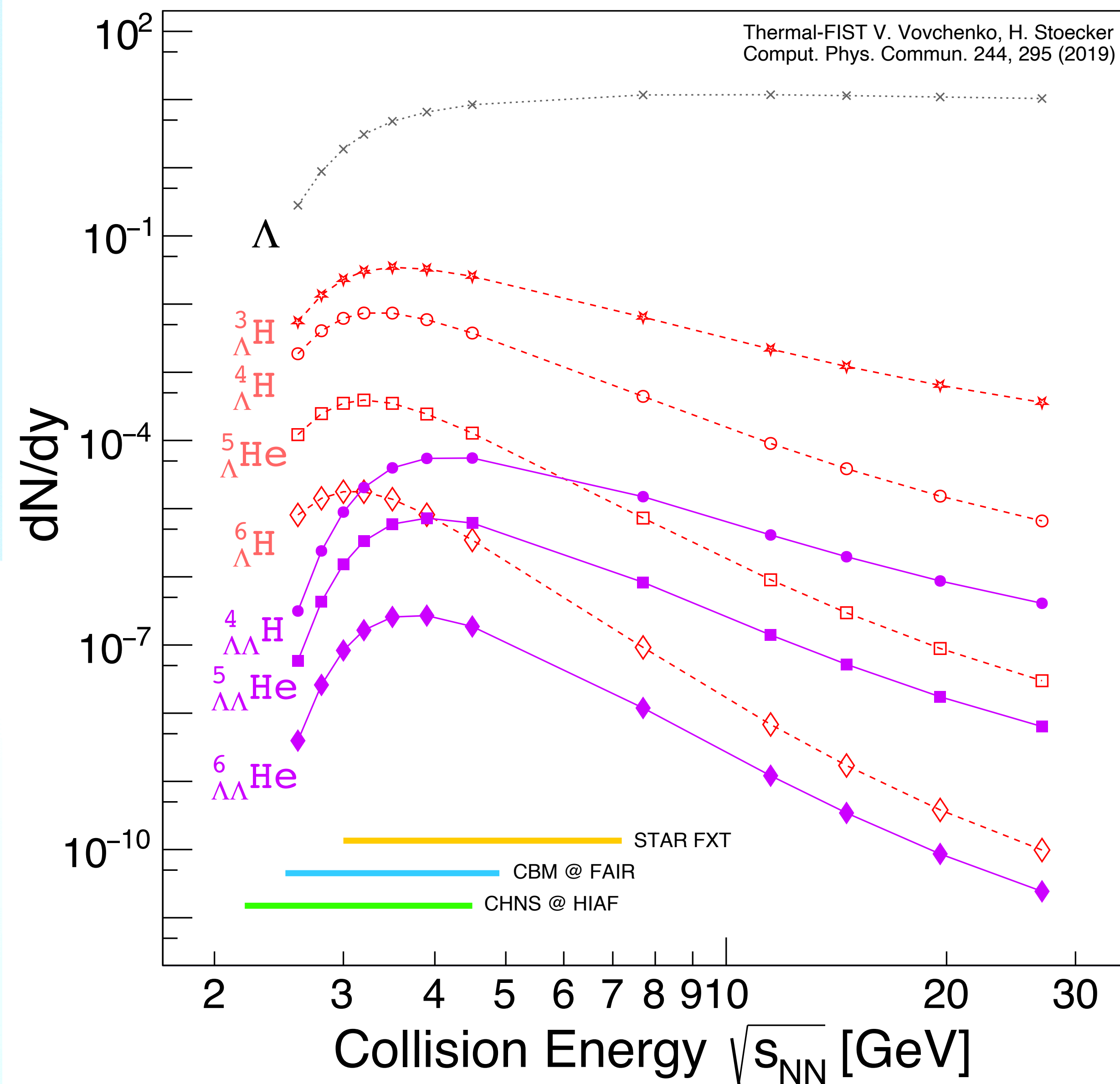
- Directed flow of hypernuclei follows mass scaling
- JAM + coalescence approx. describes the data

Qualitatively consistent with coalescence formation of hypernuclei

Summary

- ${}^3_{\Lambda}\text{H}$ yields in central collisions overestimated by thermal model by a factor of 2
- ${}^3_{\Lambda}\text{H}$ mean p_T tends to be lower than blast-wave parametrization from light hadrons
 - ${}^3_{\Lambda}\text{H}$ is not in thermal equilibrium / does not decouple at same time as light hadrons
- Data for S_3 (stable nuclei) are consistent with flat or slightly increasing trend with $dN_{\text{ch}}/d\eta$
 - Milder multiplicity dependence compared to coalescence models
- Suppression of ${}^3_{\Lambda}\text{H}$ in 10-40% collisions at low collision energies observed
- ${}^4_{\Lambda}\text{H}$ yields tend to be closer to thermal model predictions than ${}^3_{\Lambda}\text{H}$
 - Data provide new input to investigate system size and nuclei size dependence of nuclei production
- ${}^3_{\Lambda}\text{H}$ 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



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

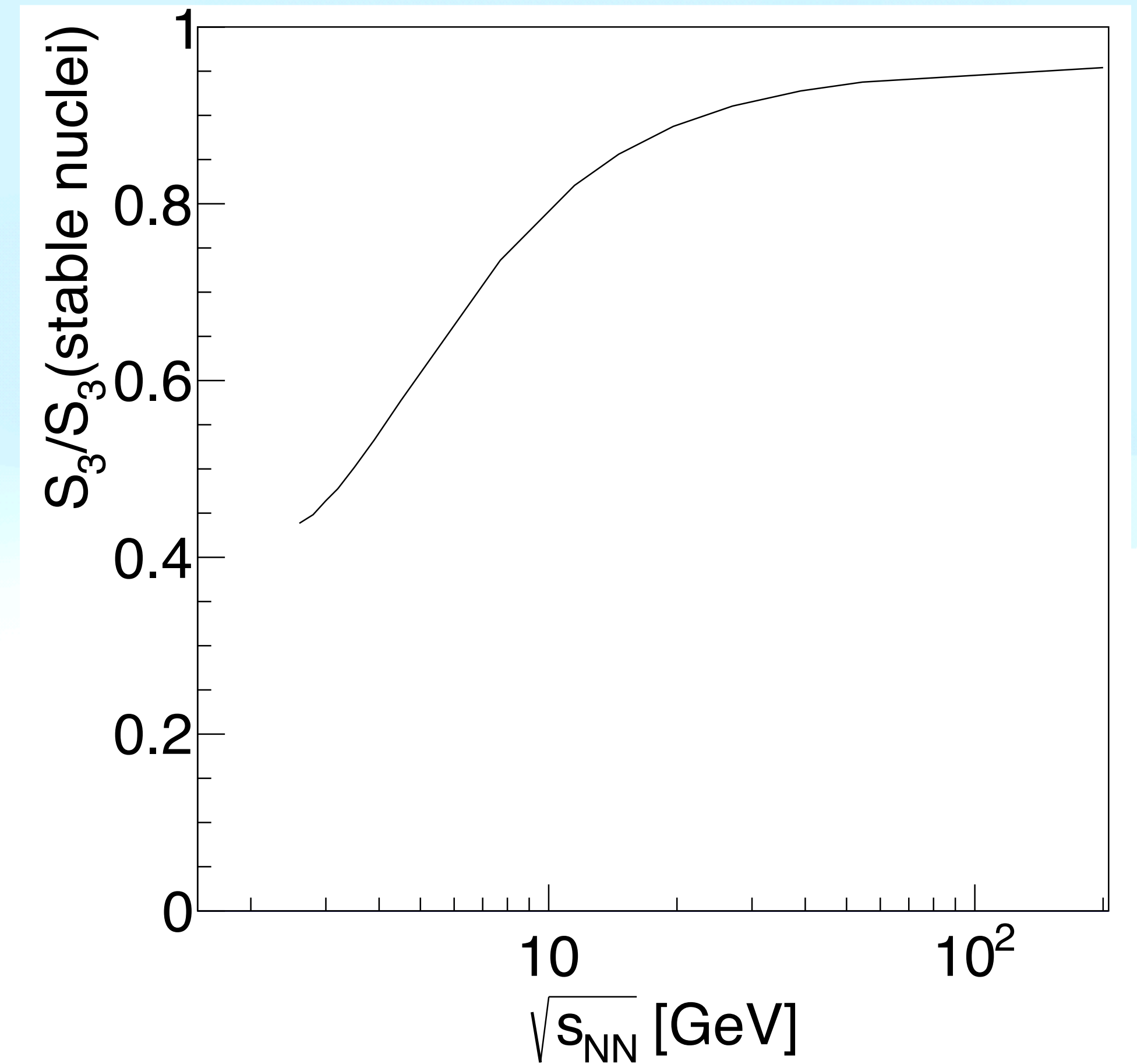
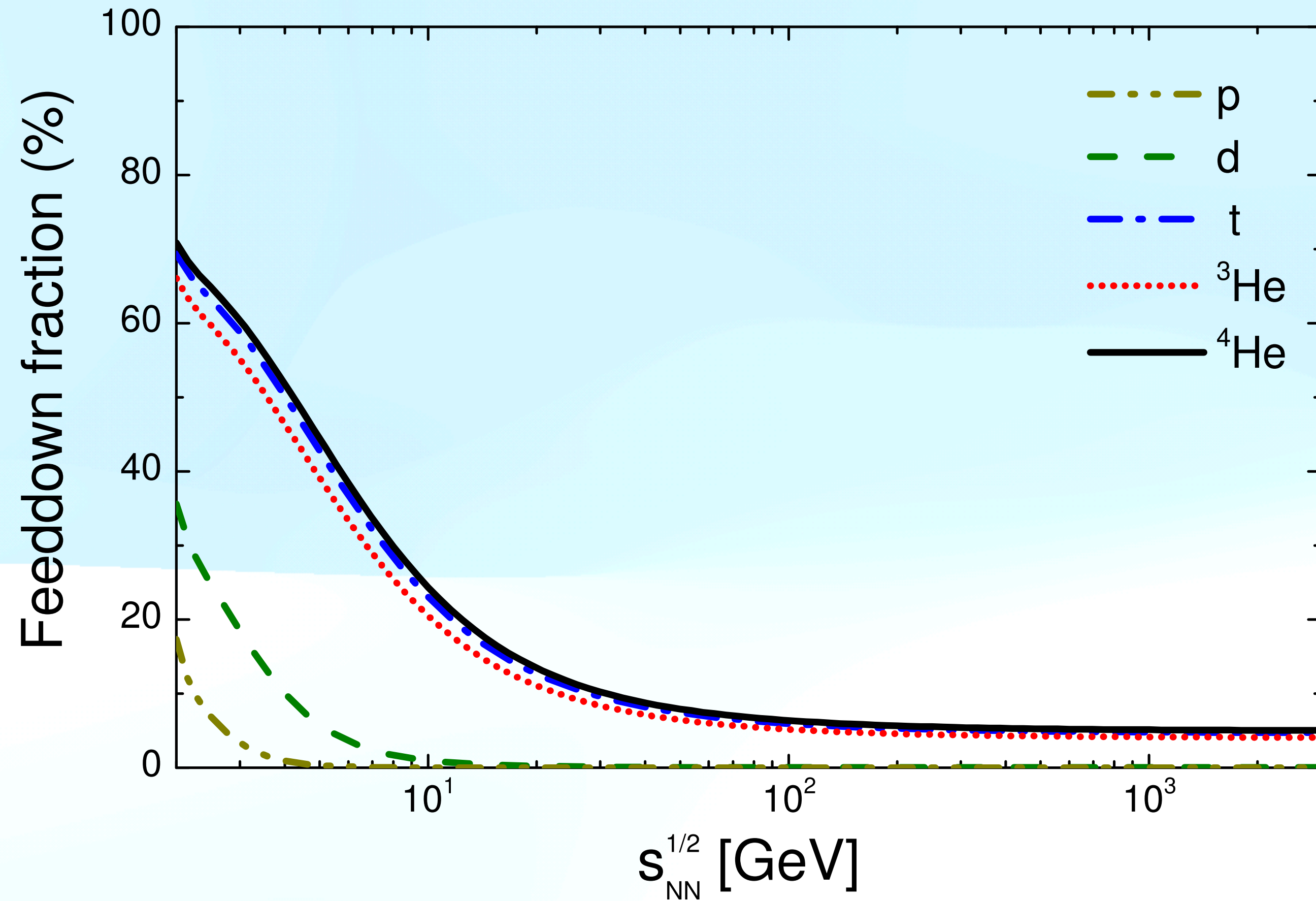
FAIR-CBM and HIAF

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

Thank you for listening!



Feed-down from Unstable Nuclei

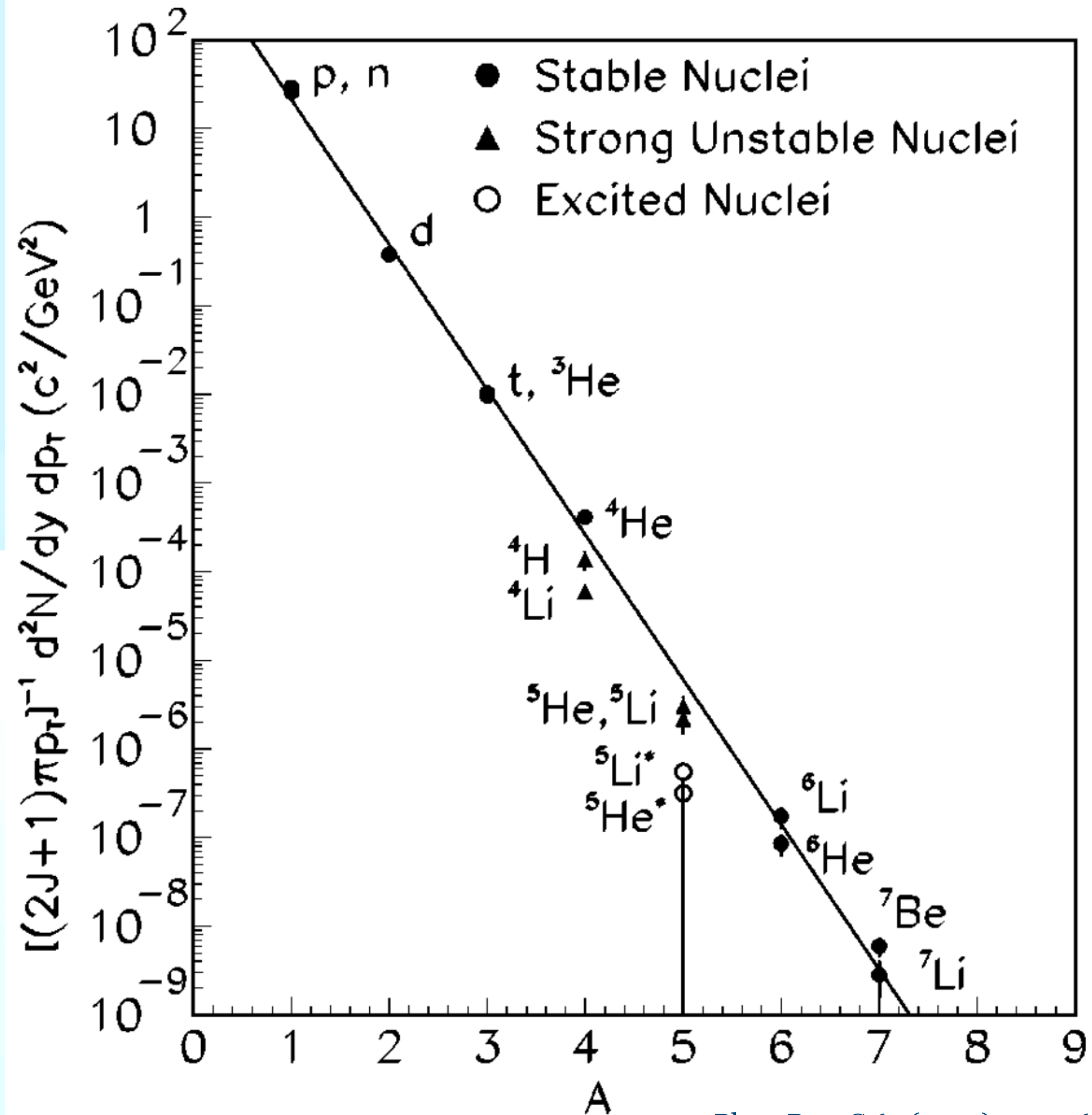


- Feed-down fractions estimated using Thermal-FIST

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

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

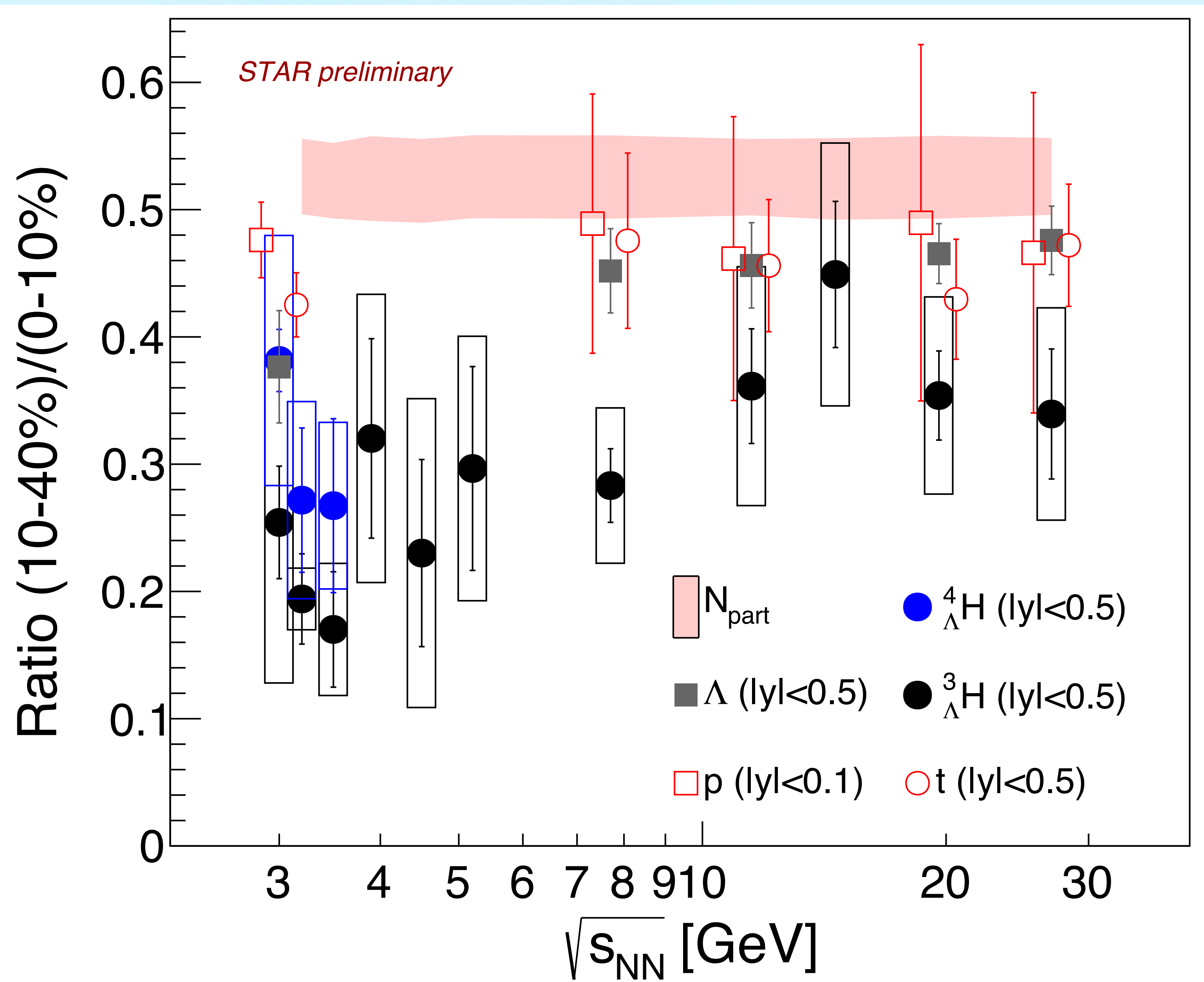
Feed-down from Unstable Nuclei



Phys. Rev. C 65 (2001) 014906

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

Centrality Dependence of ${}^4_{\Lambda}$ H Production



- Within uncertainties, the centrality dependence of ${}^4_{\Lambda}$ H production is consistent to that of ${}^3_{\Lambda}$ H at mid-rapidity