Hypernuclei Production in Heavy-Ion Collisions

(at finite baryon density)

STAR

CPOD 2024

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for the STAR collaboration

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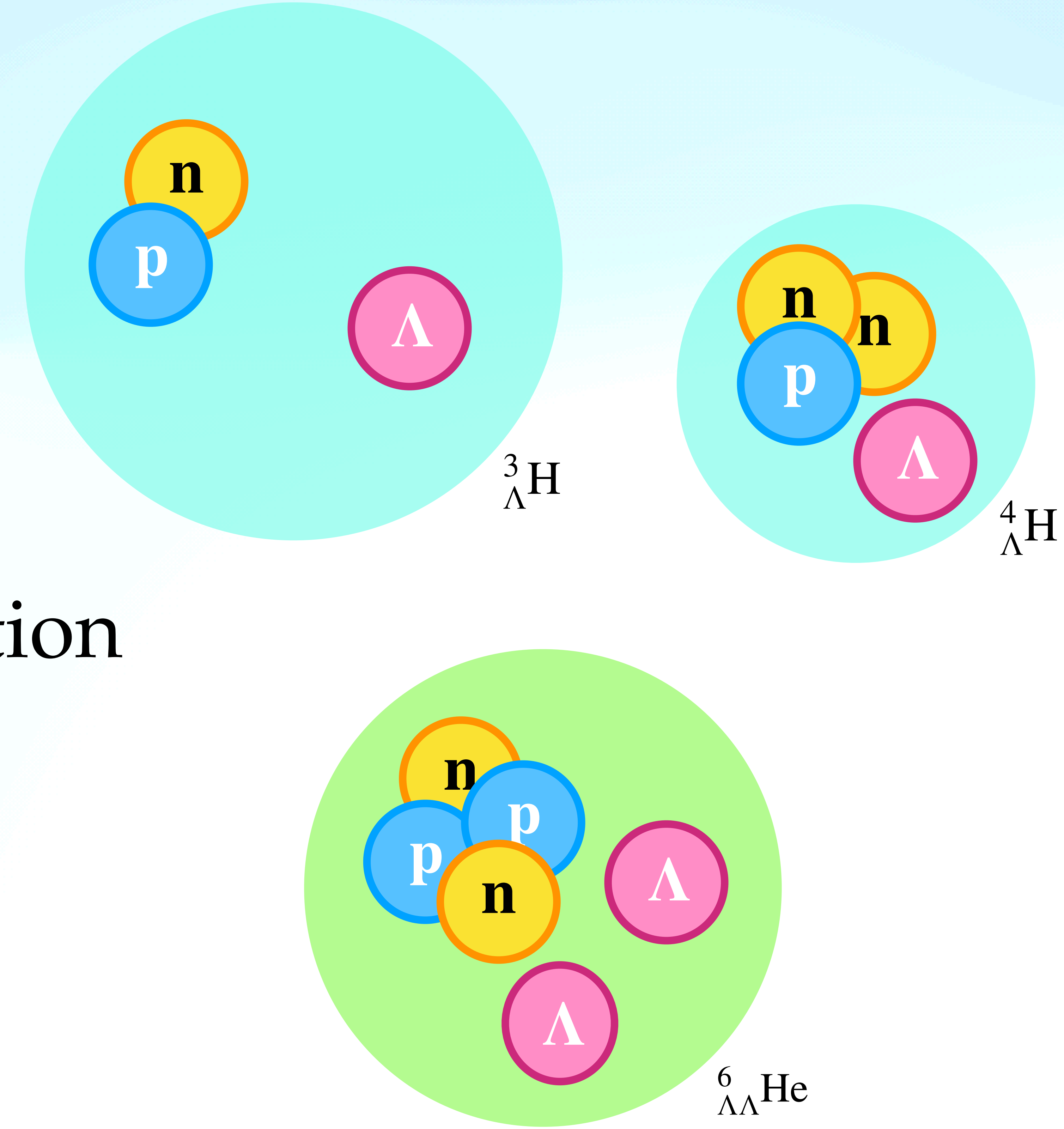
20th May, 2023



Outline

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

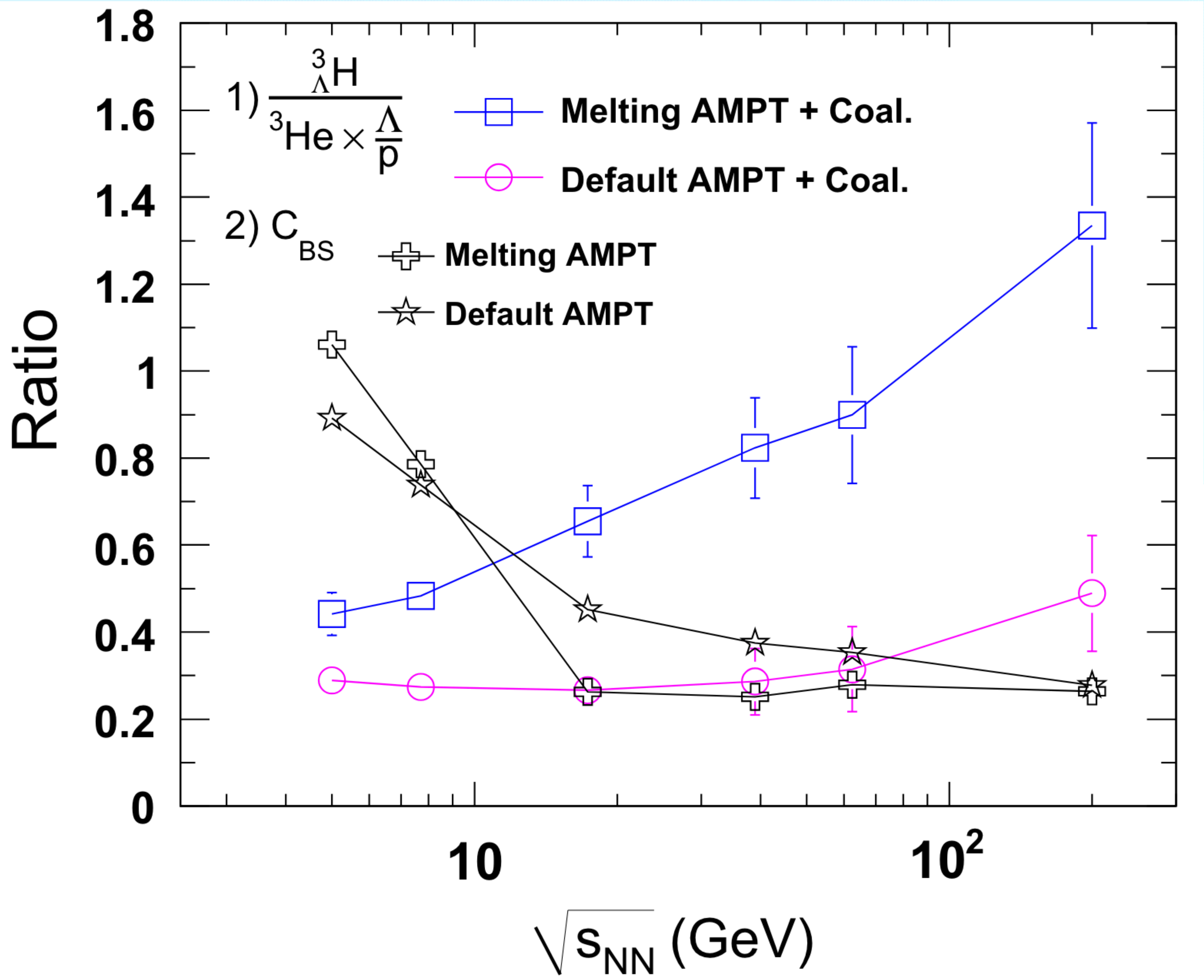
Supported in part by U.S. DEPARTMENT OF ENERGY

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**

- $S_3 = \dfrac{{}^{3}_{\Lambda}\mathrm{H}}{{}^{3}\mathrm{He} \times \dfrac{\Lambda}{\mathrm{p}}}$ may be enhanced in systems involving partonic interactions

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

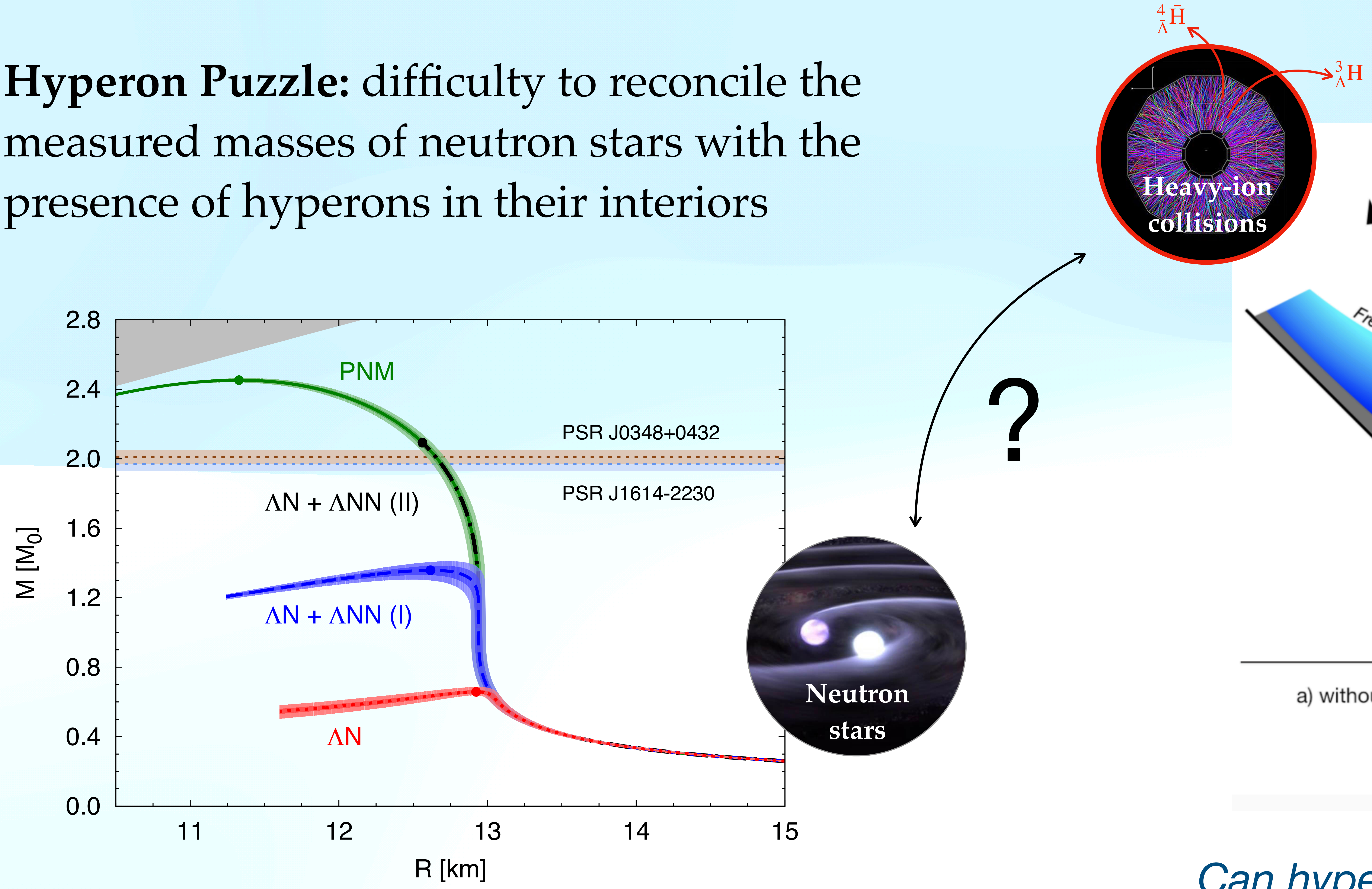


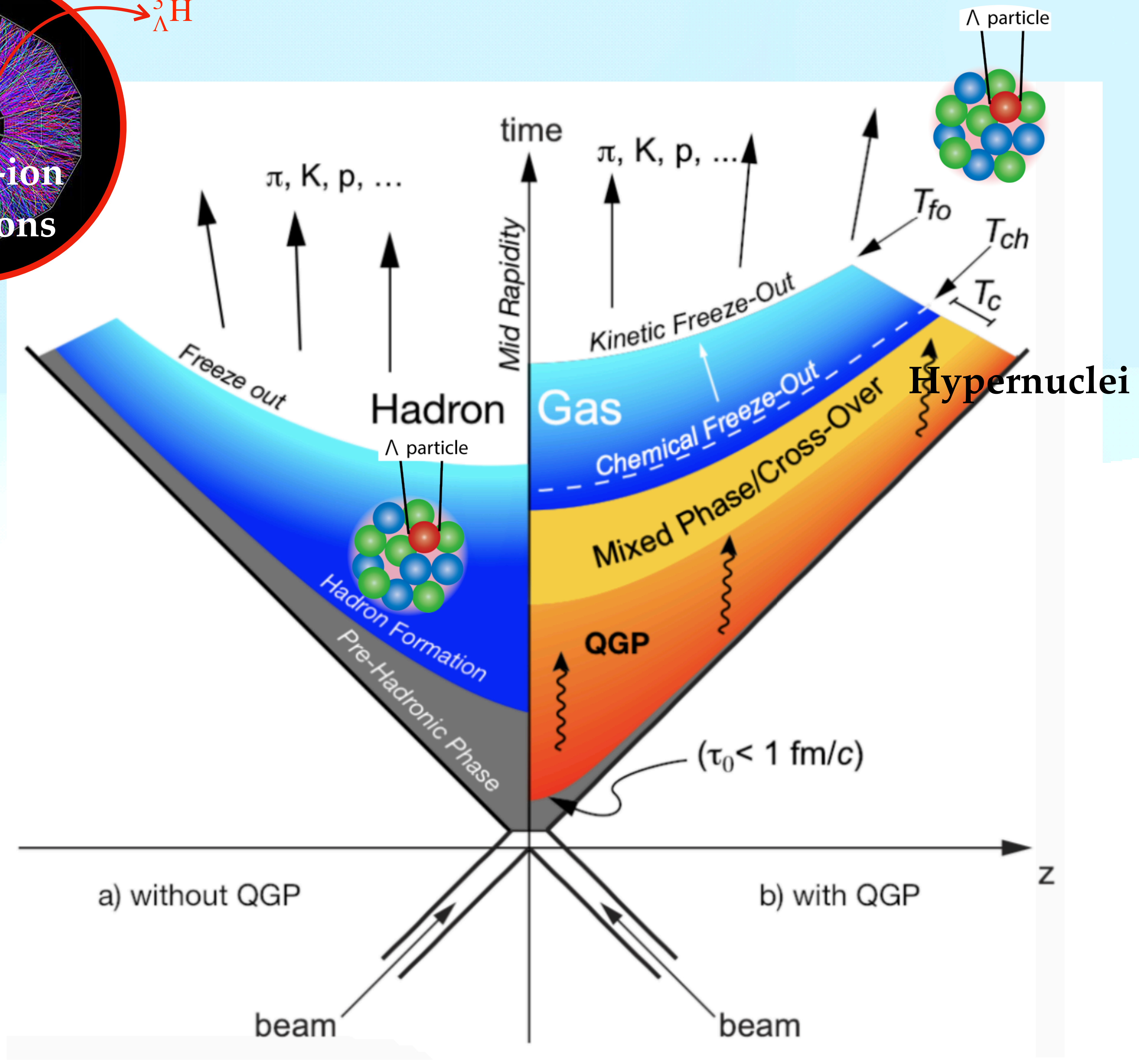
- Baryon clustering near critical point may lead to enhancement of light nuclei ($A \geq 3$) yields

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





- 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

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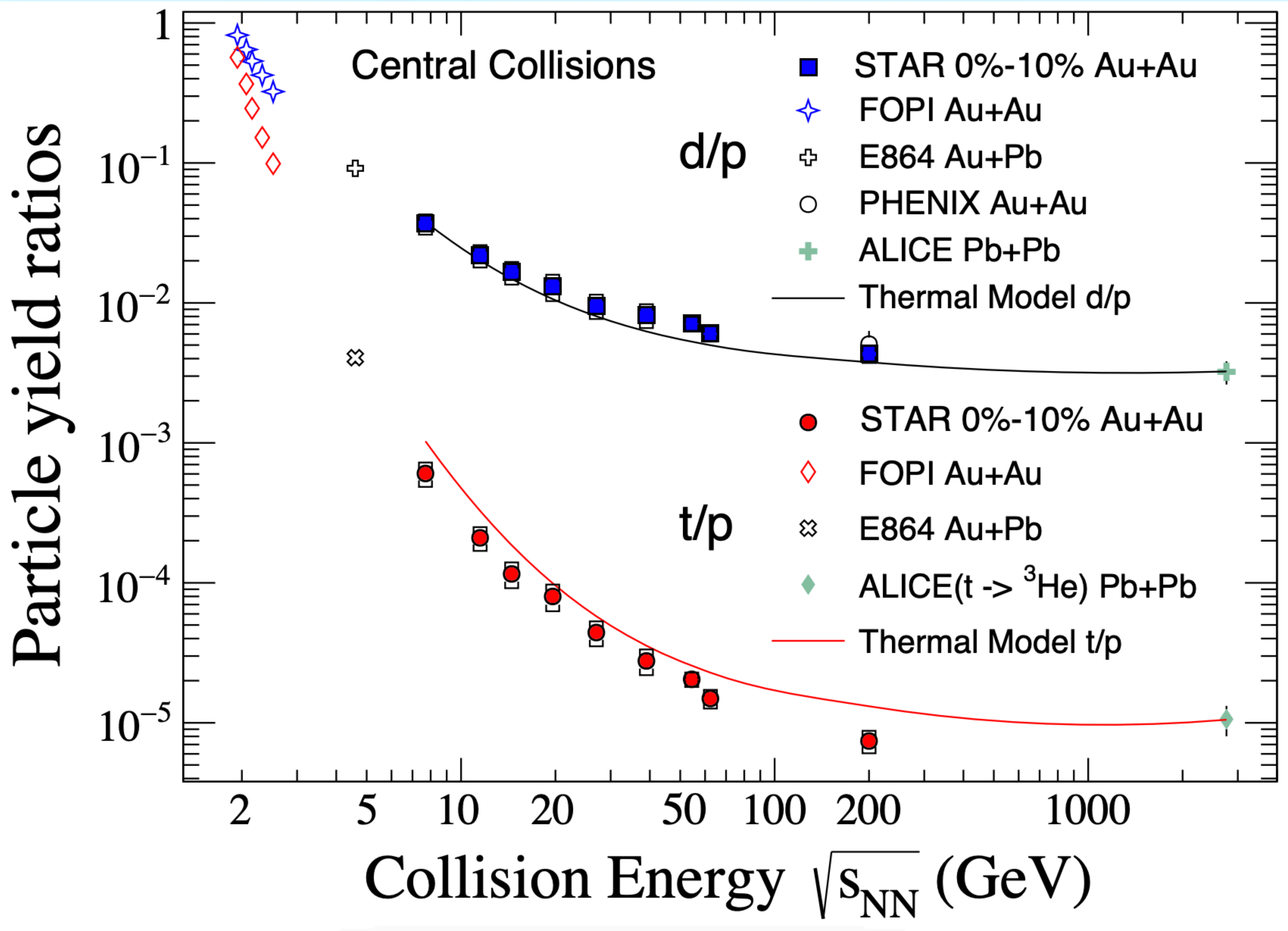
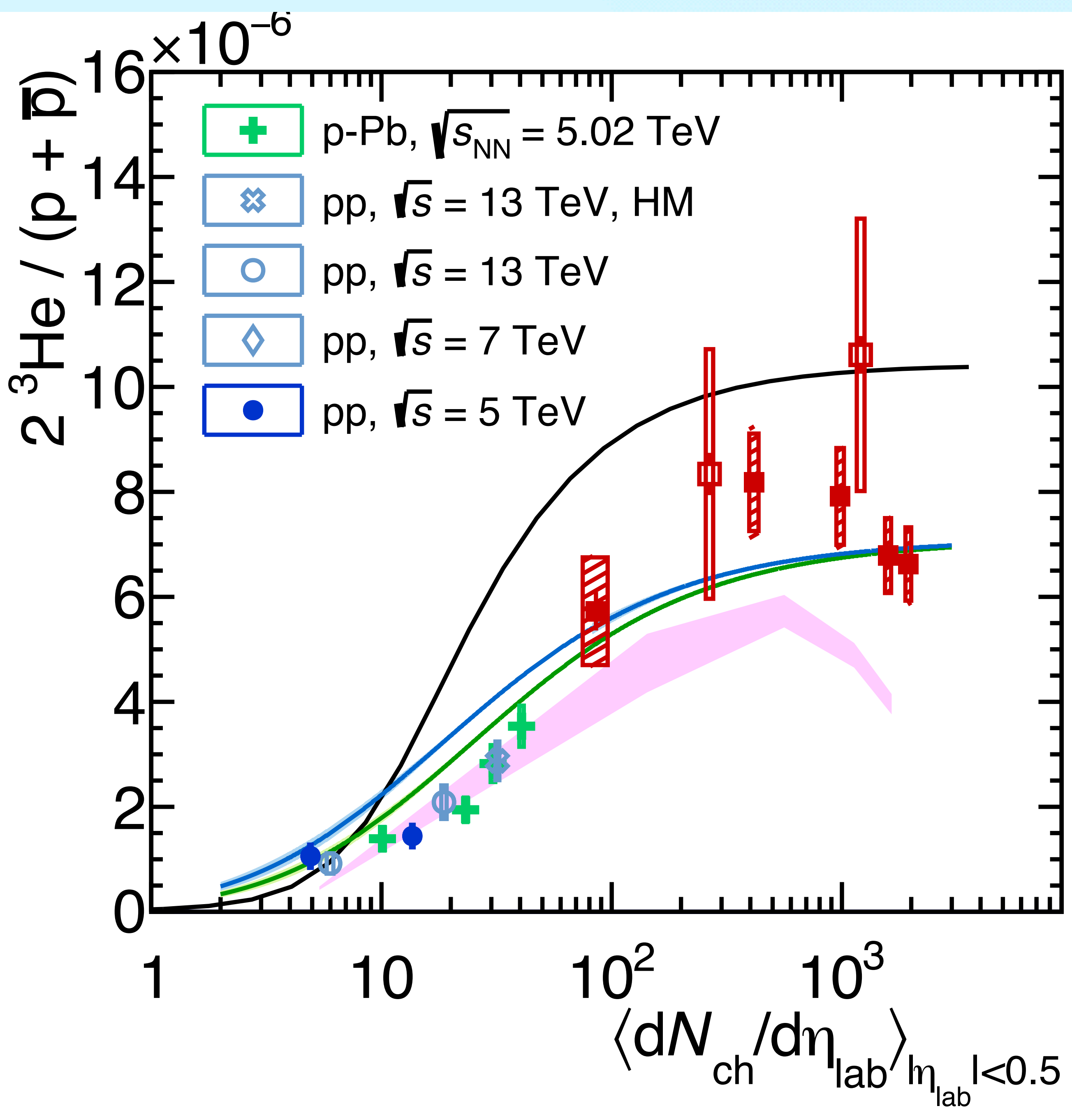
How and when are light nuclei formed in heavy ion collisions?

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

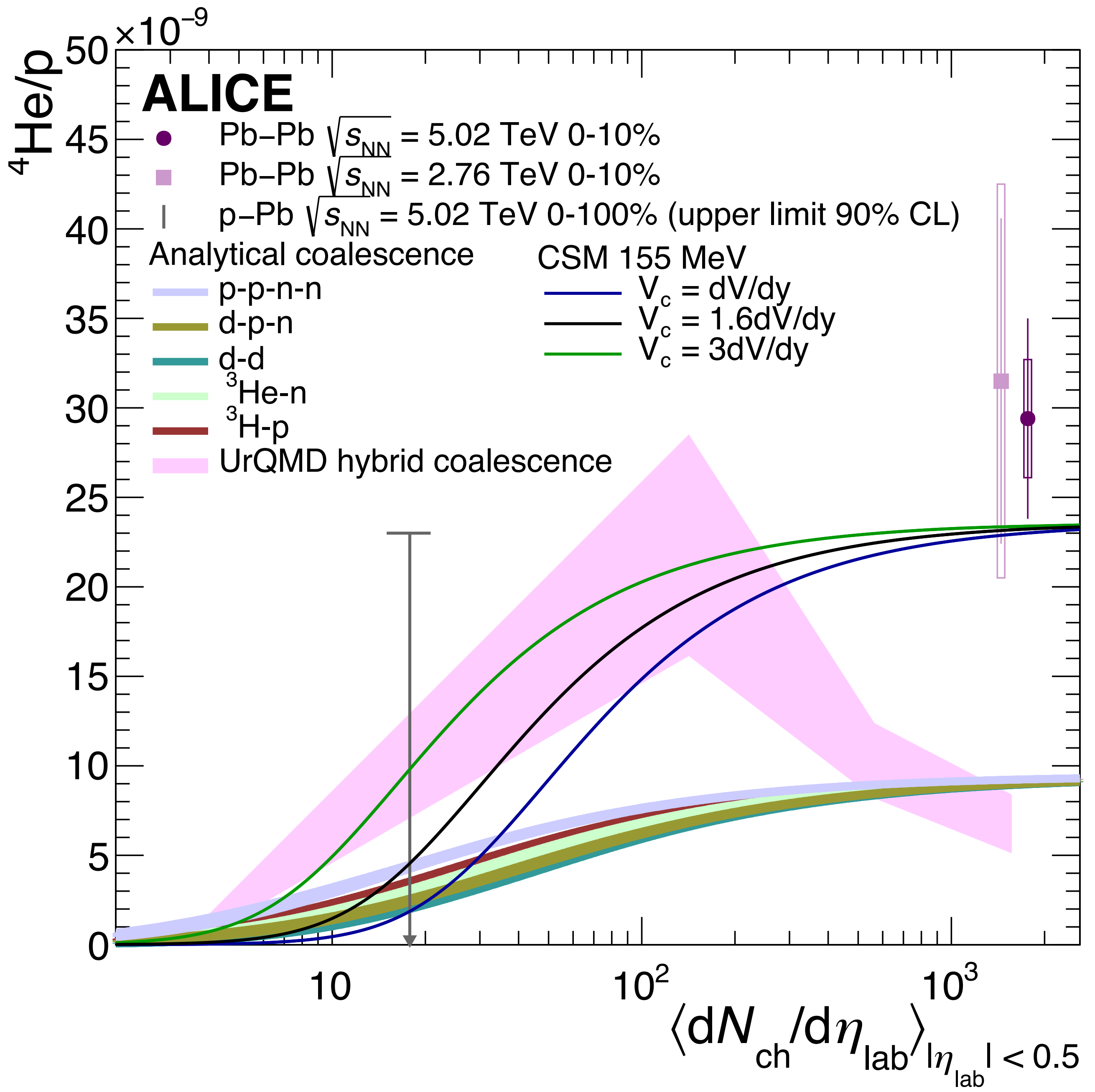
What Have We Learnt From Light Nuclei Production?



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



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

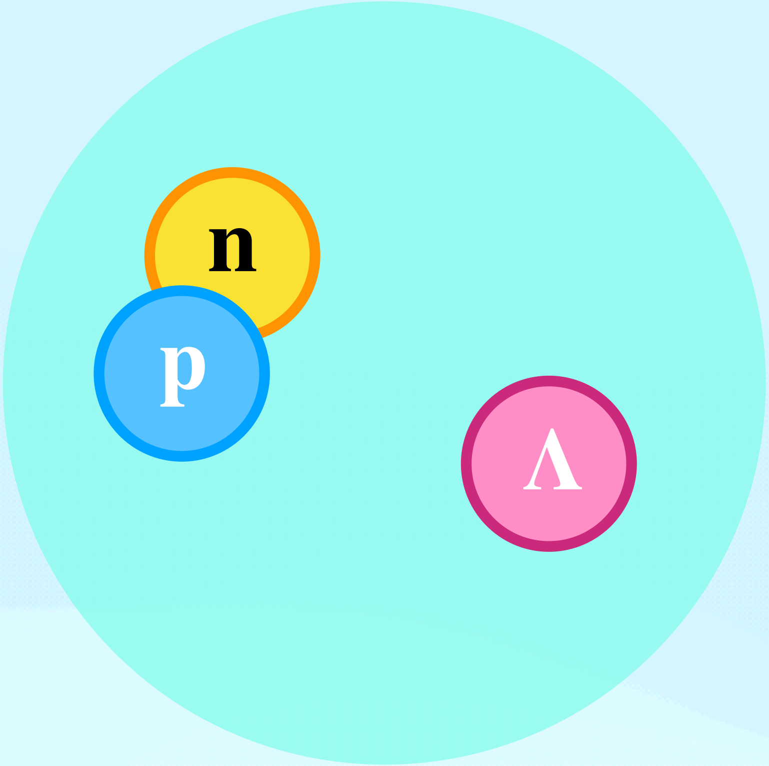
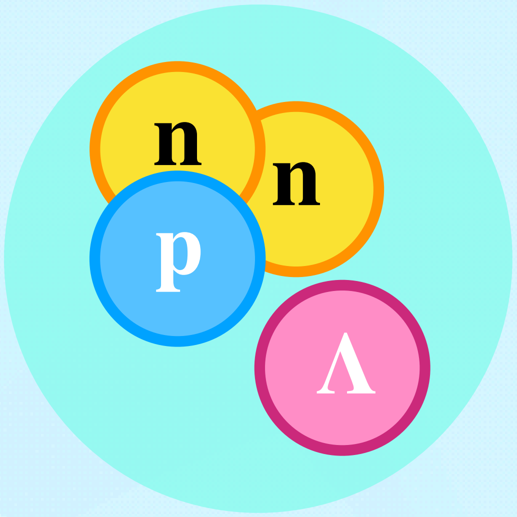


ALICE, arXiv:2311.11758v1

- d/p is fairly well described by thermal model, but t/p is overestimated
- ^{4}He/p is well described by thermal model at LHC energies, but underestimated by various implementations of coalescence formation

Recent data poses challenges for nuclei production models

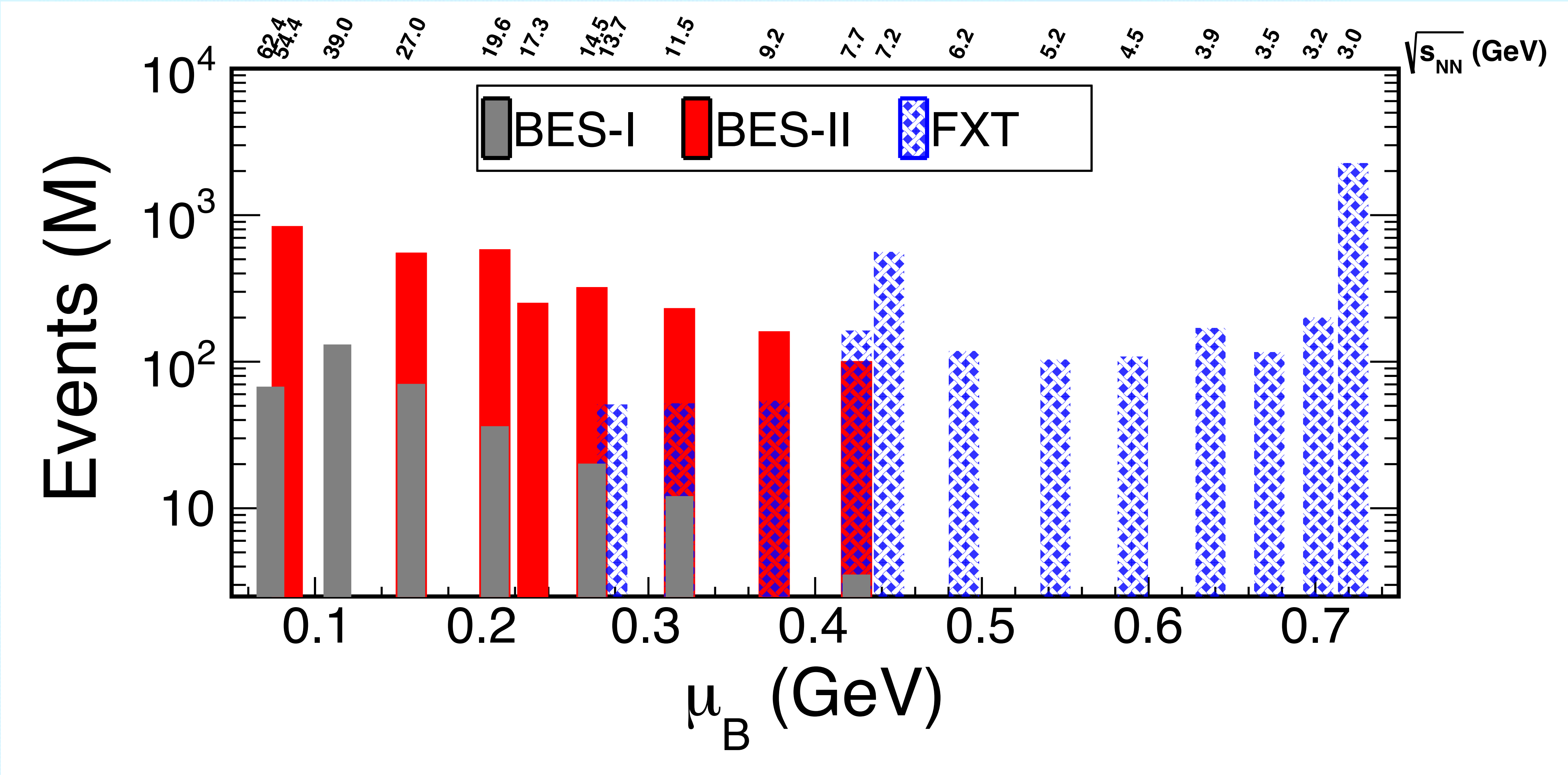
Hypertriton ($^{3}_{\Lambda}\mathrm{H}$) and Hyperhydrogen-4 ($^{4}_{\Lambda}\mathrm{H}$)

	$^{3}_{\Lambda}\mathrm{H}$ 	$^{4}_{\Lambda}\mathrm{H}$ 
RMS radius	5-10 fm	2-3 fm
Excited states	Not observed	$^{4}_{\Lambda}\mathrm{H}^{*}(1^{+}) \rightarrow {}^{4}_{\Lambda}\mathrm{H}(0^{+}) + \gamma$

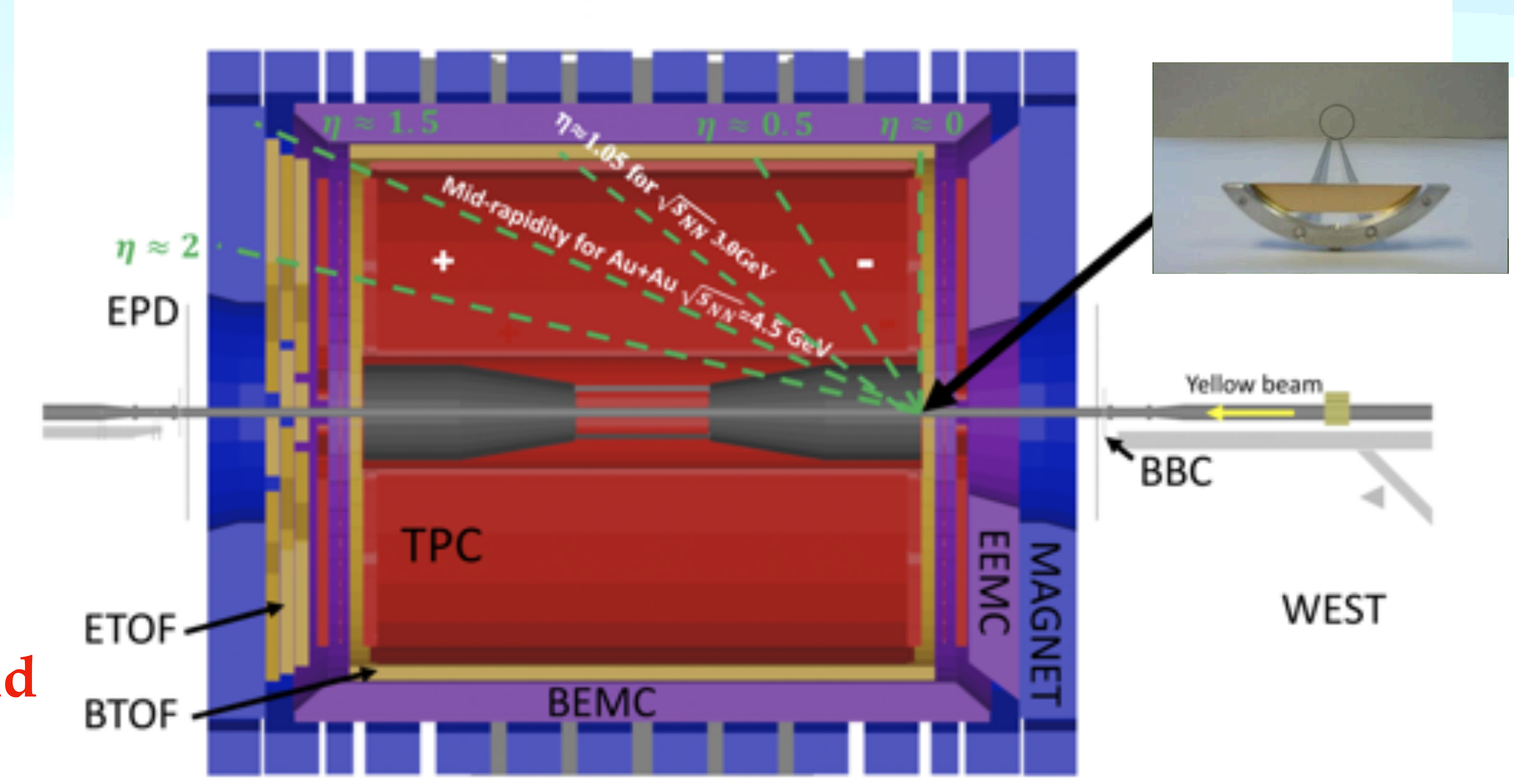
- Due to its very small binding energy and large radius, $^{3}_{\Lambda}\mathrm{H}$ production provides unique input for nuclei production models

STAR Beam Energy Scan II

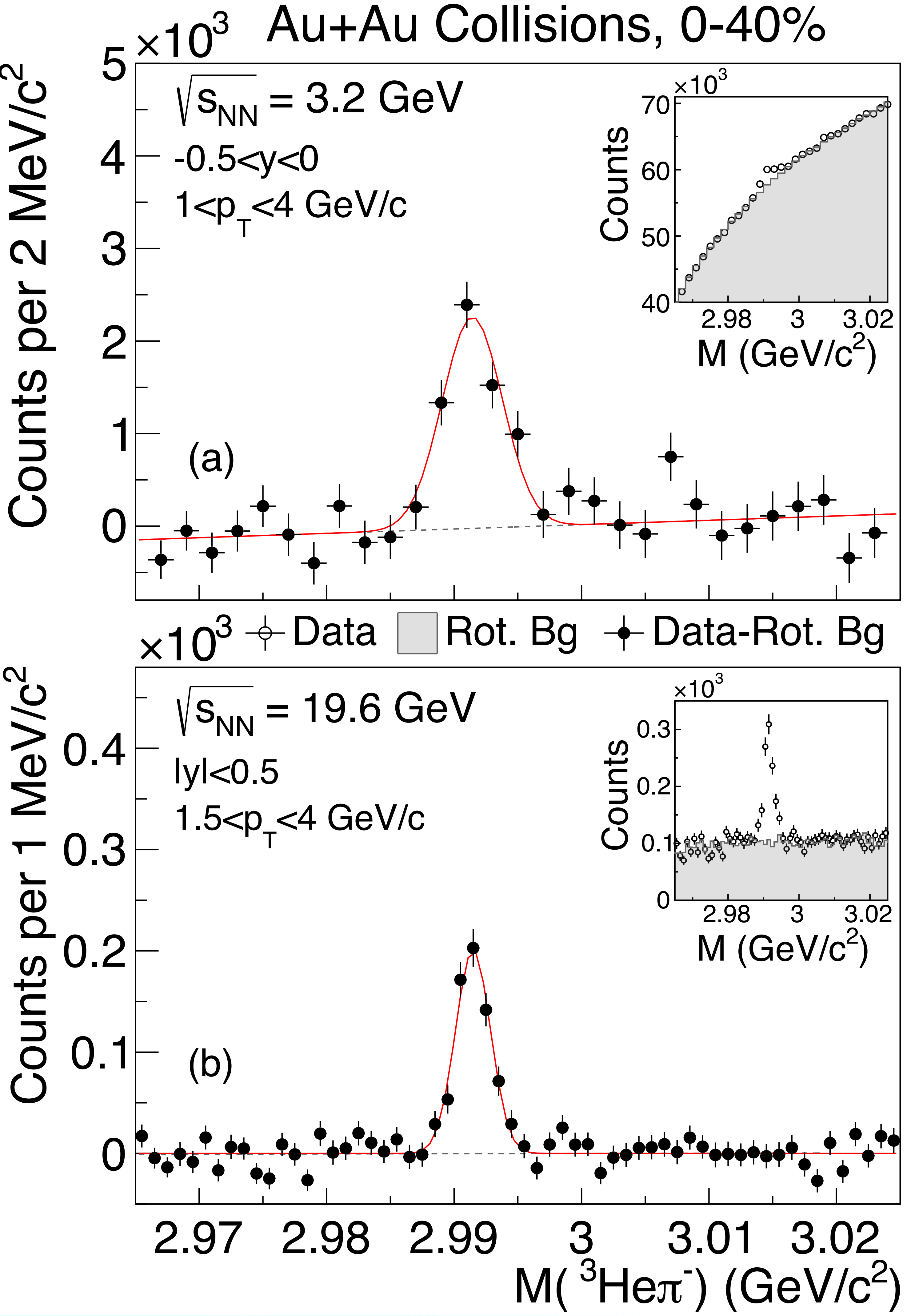
- BES-I (2009-2011)
  - Au+Au collisions $\sqrt{s_{NN}}$ = 7.7-62 GeV
  - Main objectives:
    - **Search for onset of deconfinement**
    - **Search for critical end point**

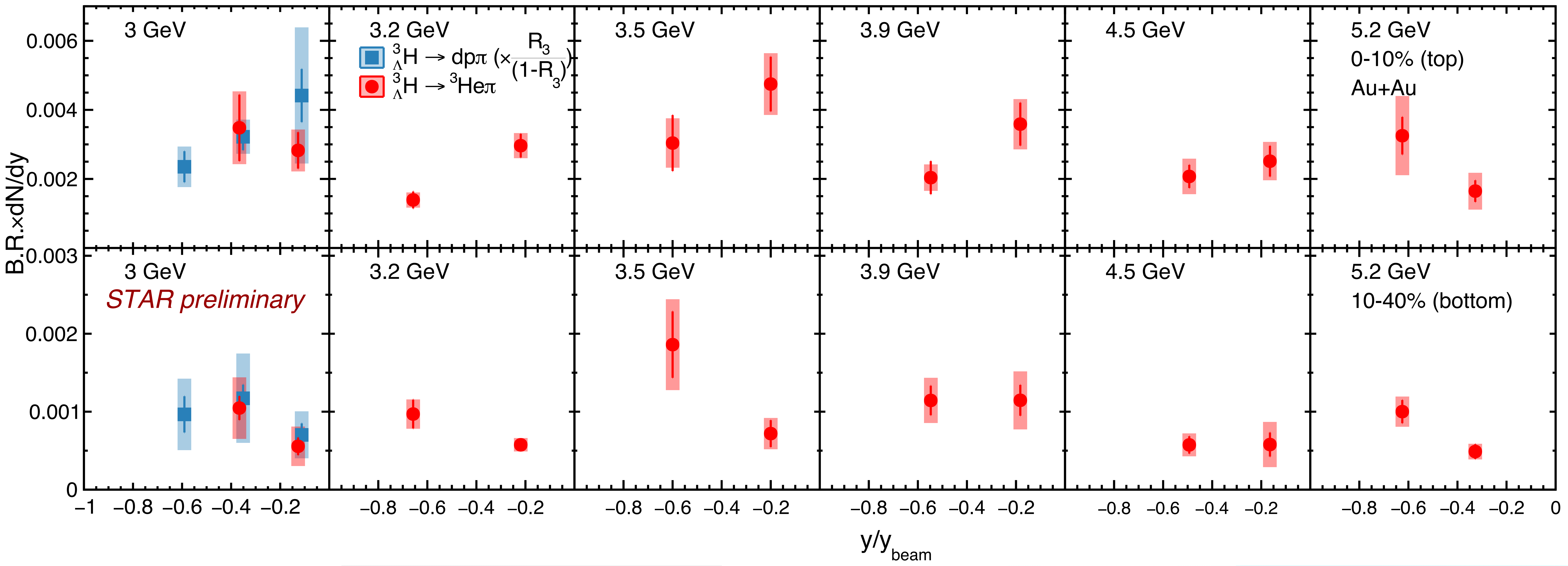


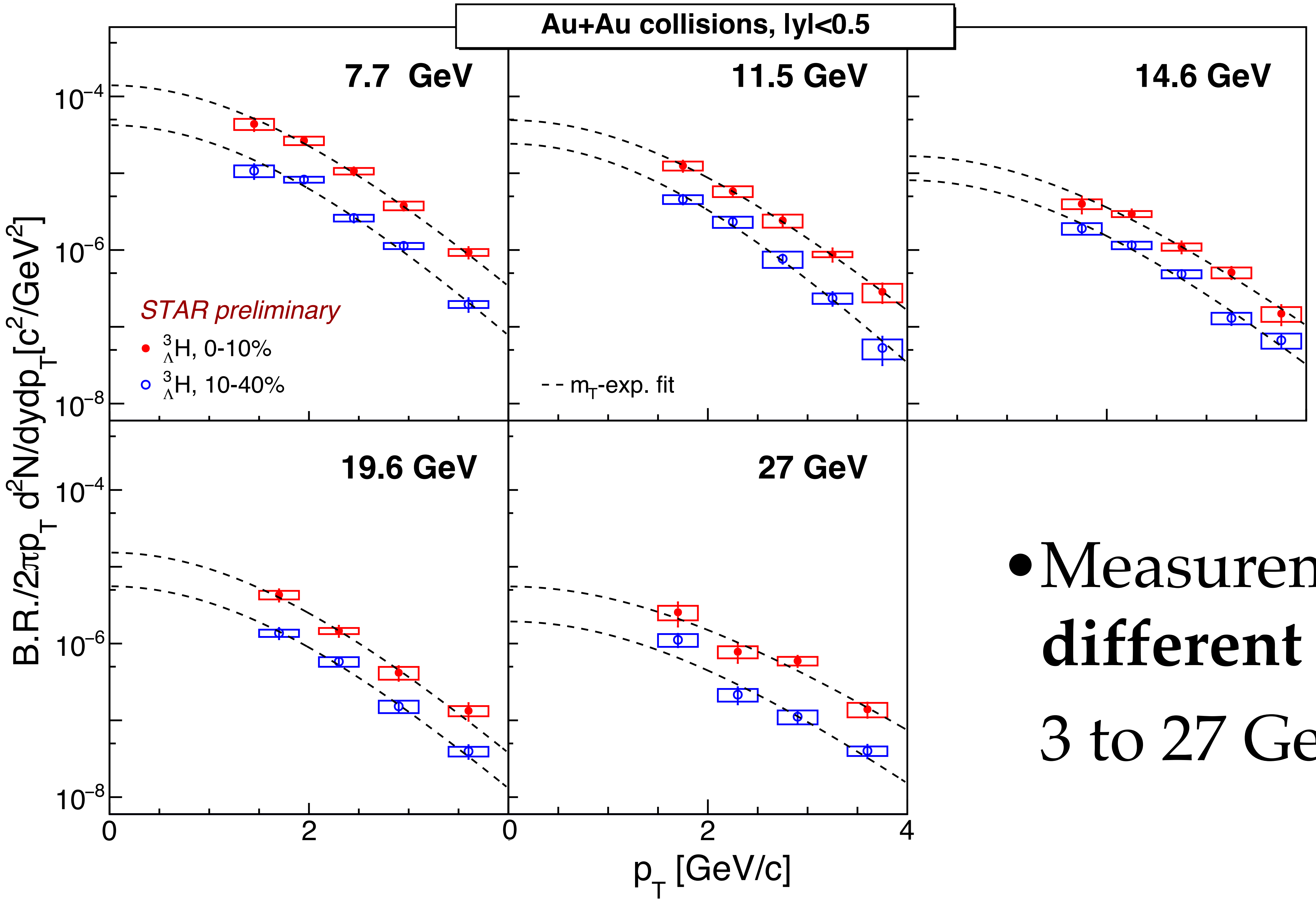
- BES-II (2017-2021)
  - High statistics Au+Au collisions $\sqrt{s_{NN}}$ = 3-54.4 GeV
  - Fixed target (FXT) collisions extend energy reach down to $\sqrt{s_{NN}}$ = 3 GeV
    - **Search for possible formation and investigate properties of dense baryonic matter**



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

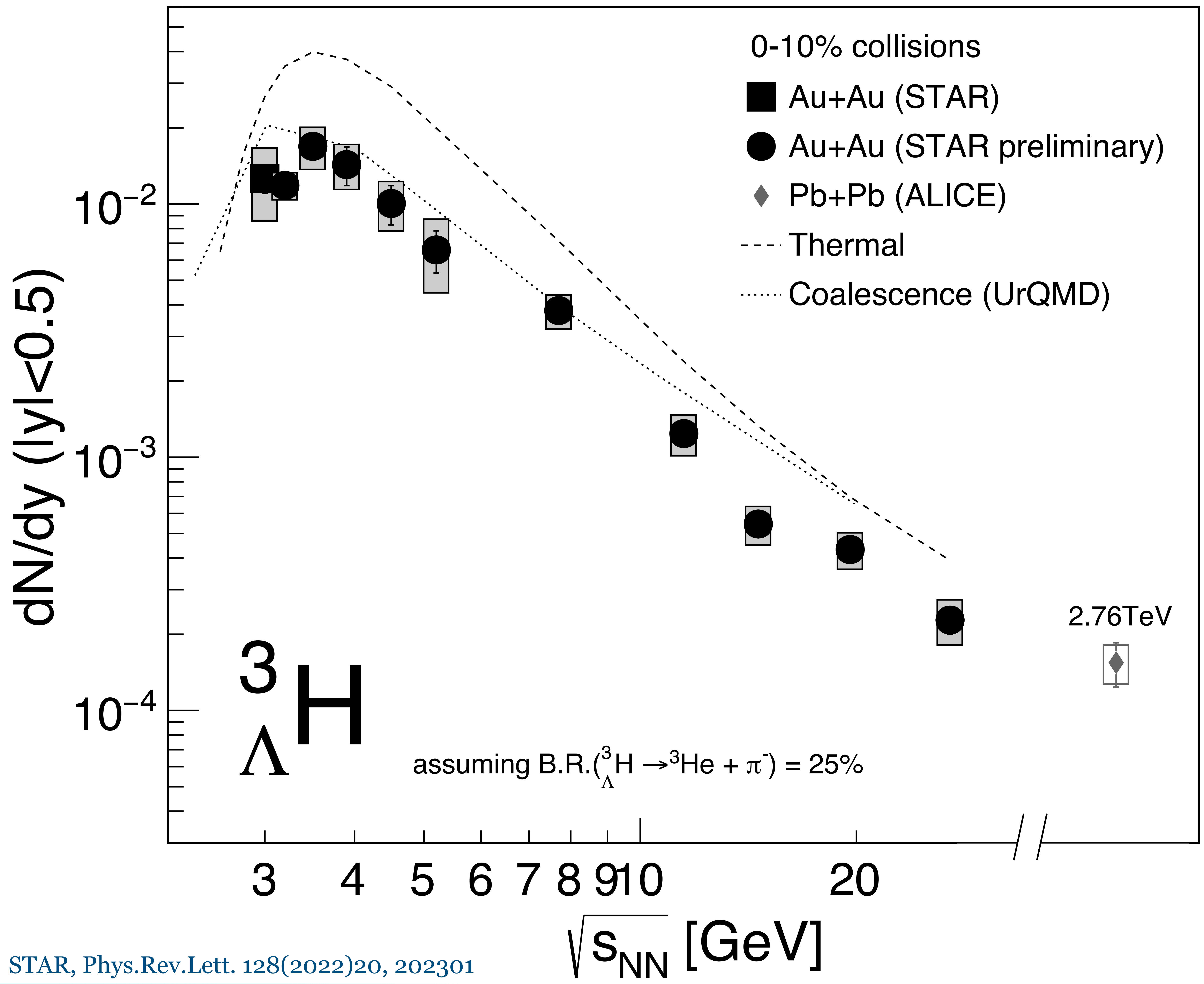






- Measurements cover **11 different energies** from $\sqrt{s_{NN}}$ = 3 to 27 GeV

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

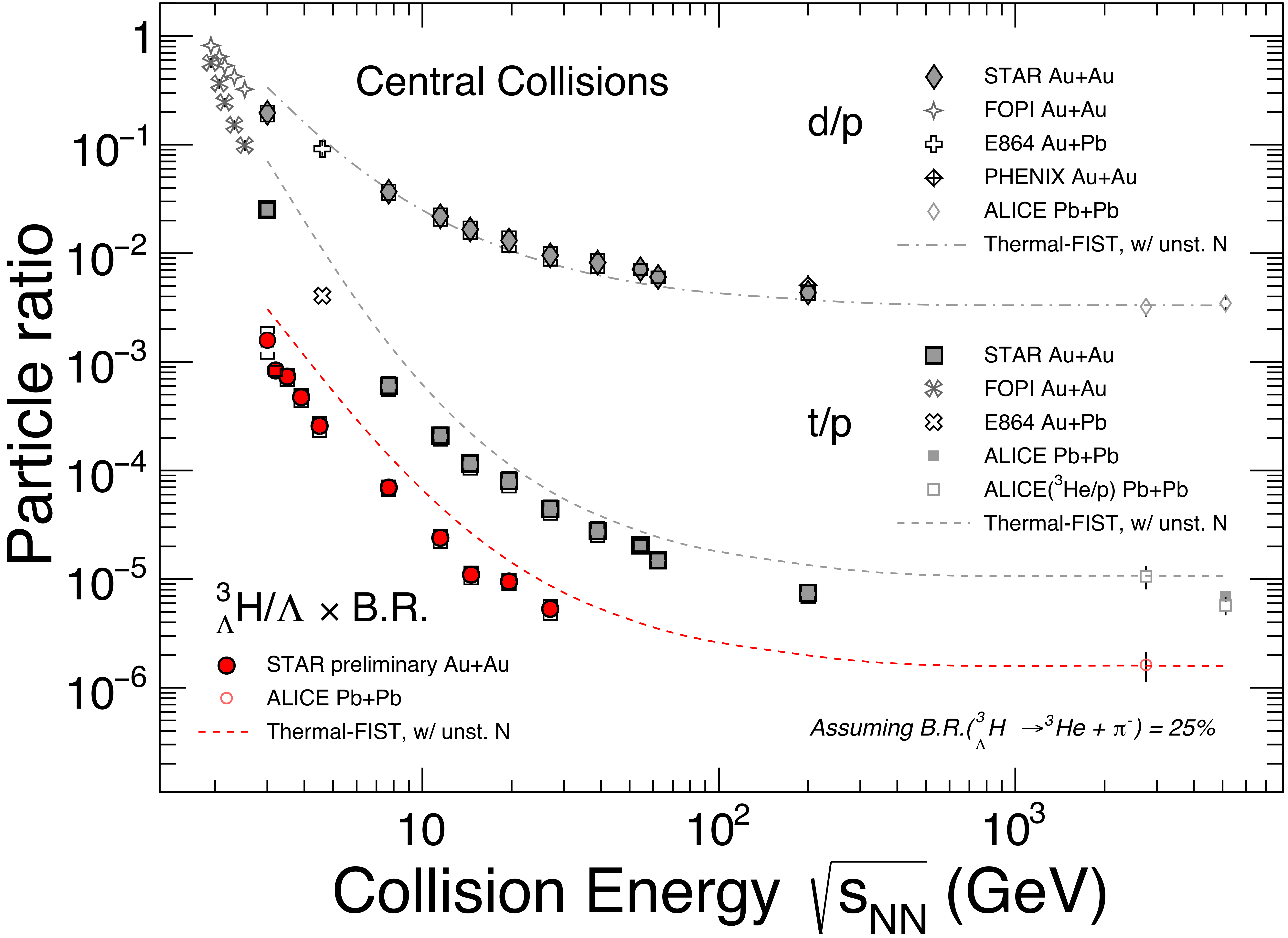


- Steep increase from $\sqrt{s_{NN}}$ = 27 to 4 GeV
- Plateaus at $\sqrt{s_{NN}}$ = 3-4 GeV
- Interplay between increasing baryon production and stronger strangeness canonical suppression towards low energies

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

STAR, Phys.Rev.Lett. 128(2022)20, 202301
ALICE, Phys. Lett. B 754(2016)360
T. Reichert et al, Phys.Rev.C 107(2023)014912

Nuclei-to-Hadron Ratios

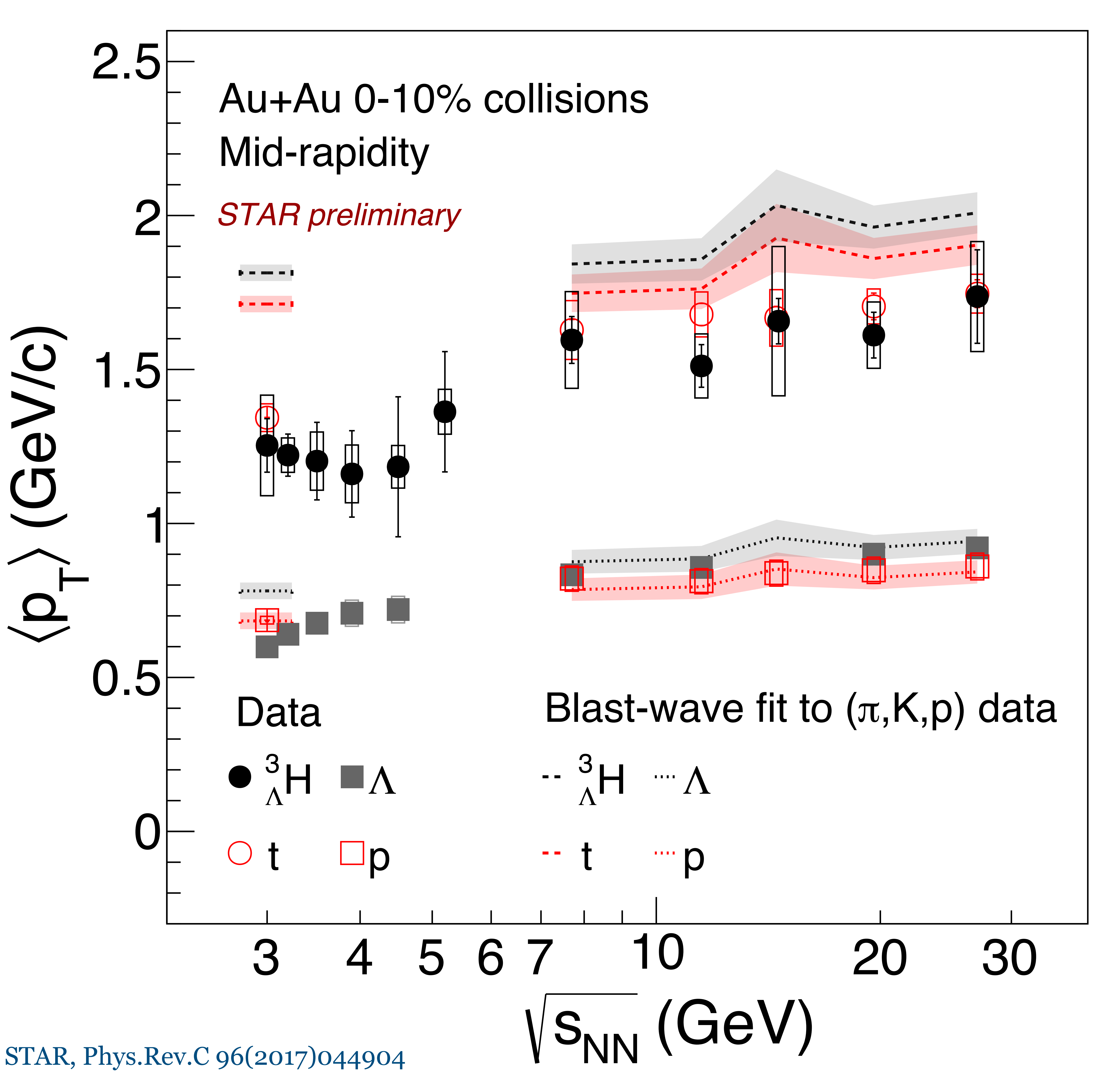


- $^{3}_{\Lambda}$H/Λ ratio in a thermal model calculation is independent of volume and strangeness correlation length
- $^{3}_{\Lambda}$H/Λ, similar to *t*/*p*, are overestimated by thermal model by a factor of 2

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

STAR, Phys. Rev. Lett. 130 (2023) 202301
STAR, arXiv: 2311.11020

Mean Transverse Momentum



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

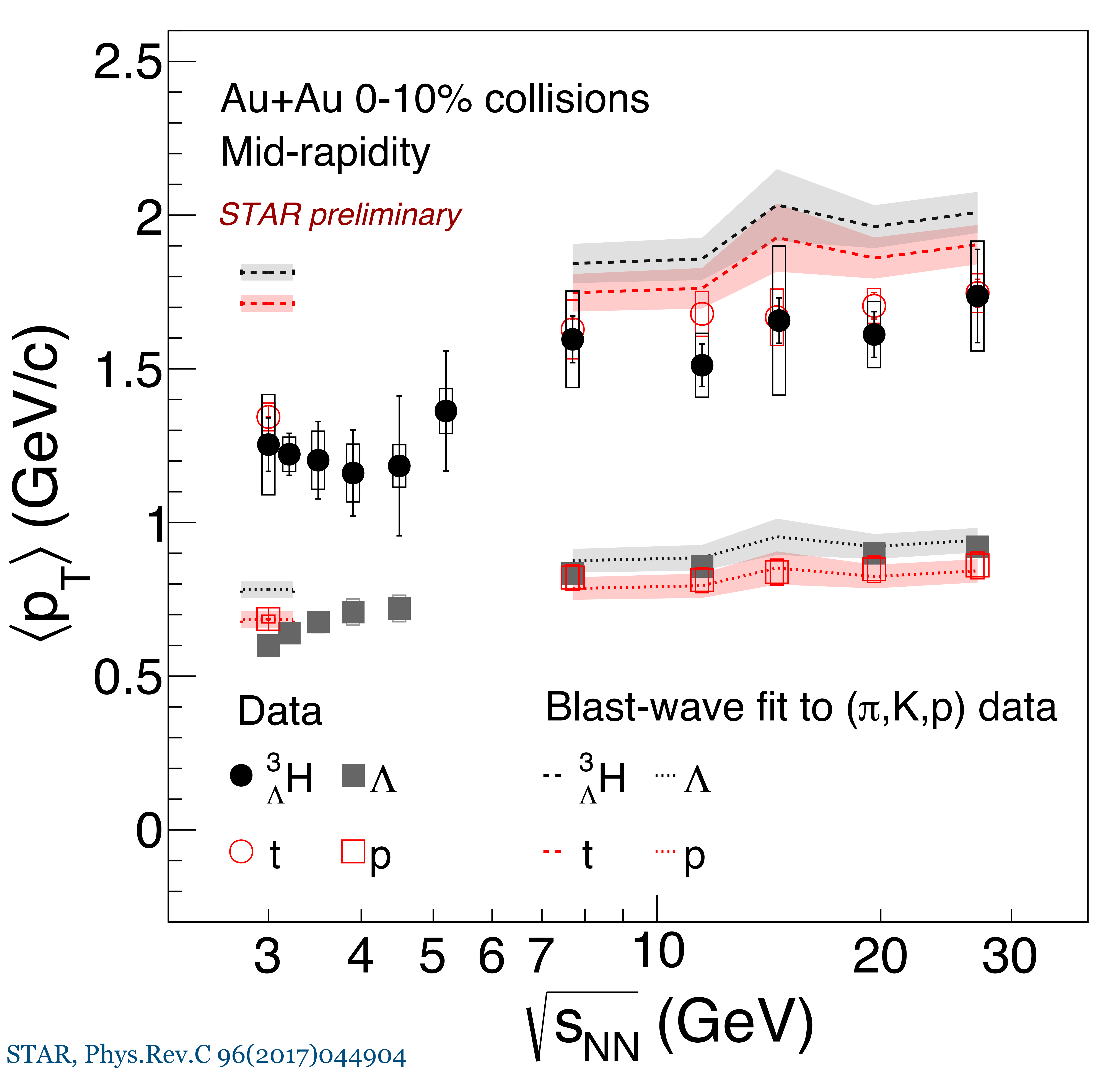
$^{3}_{\Lambda}$H (and *t*) do not follow same collective expansion as light hadrons

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

D. Liu et al, arXiv:2404.02701

STAR, Phys.Rev.C 96(2017)044904
STAR, arXiv: 2311.11020

Mean Transverse Momentum



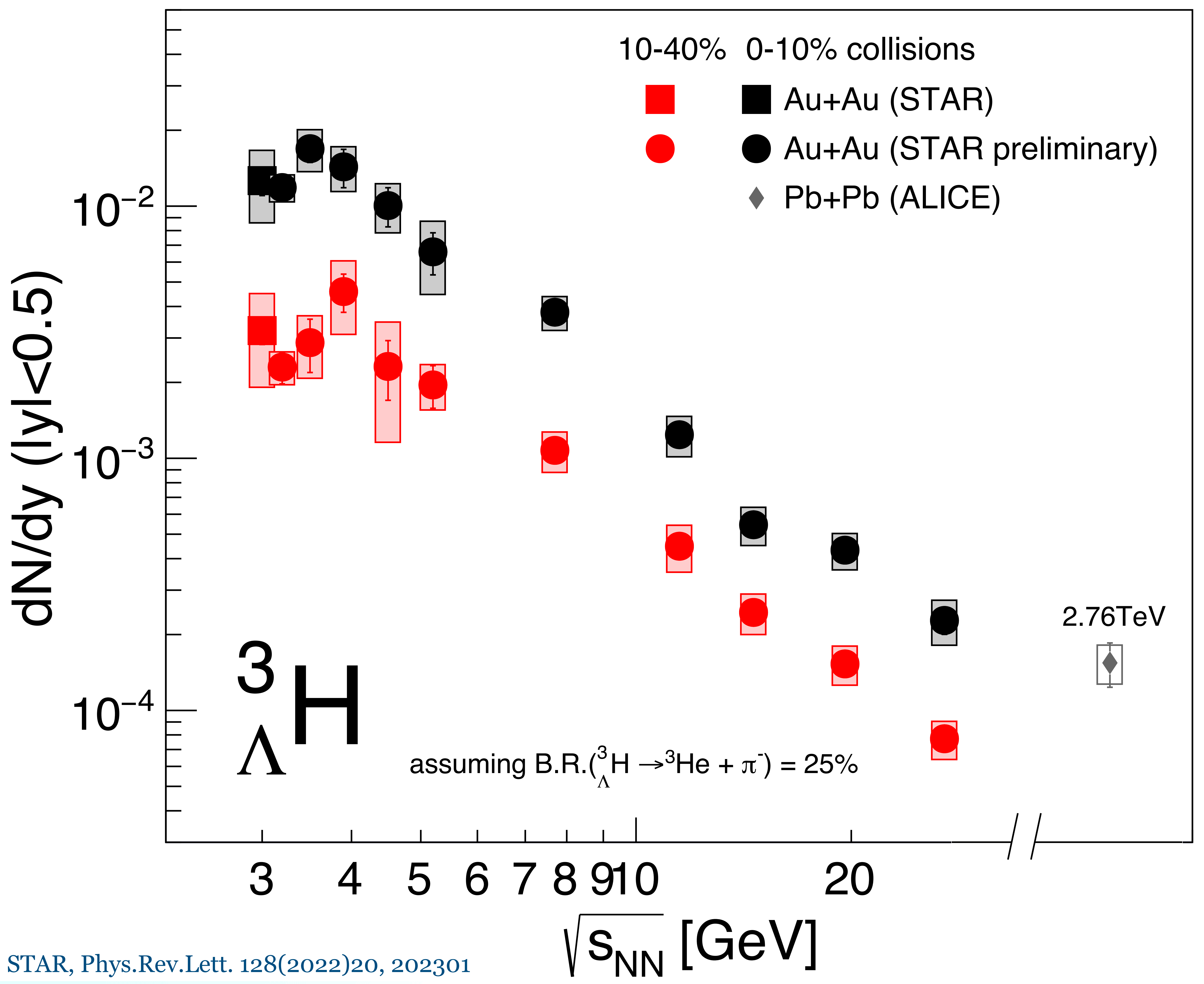
- The mean p_T for $\sqrt{s_{NN}}$ = 3-4.5 GeV and $\sqrt{s_{NN}}$ = 7.7-27 GeV seem to exhibit two different trends

Change in medium properties or expansion dynamics?

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

STAR, Phys.Rev.C 96(2017)044904
STAR, arXiv: 2311.11020

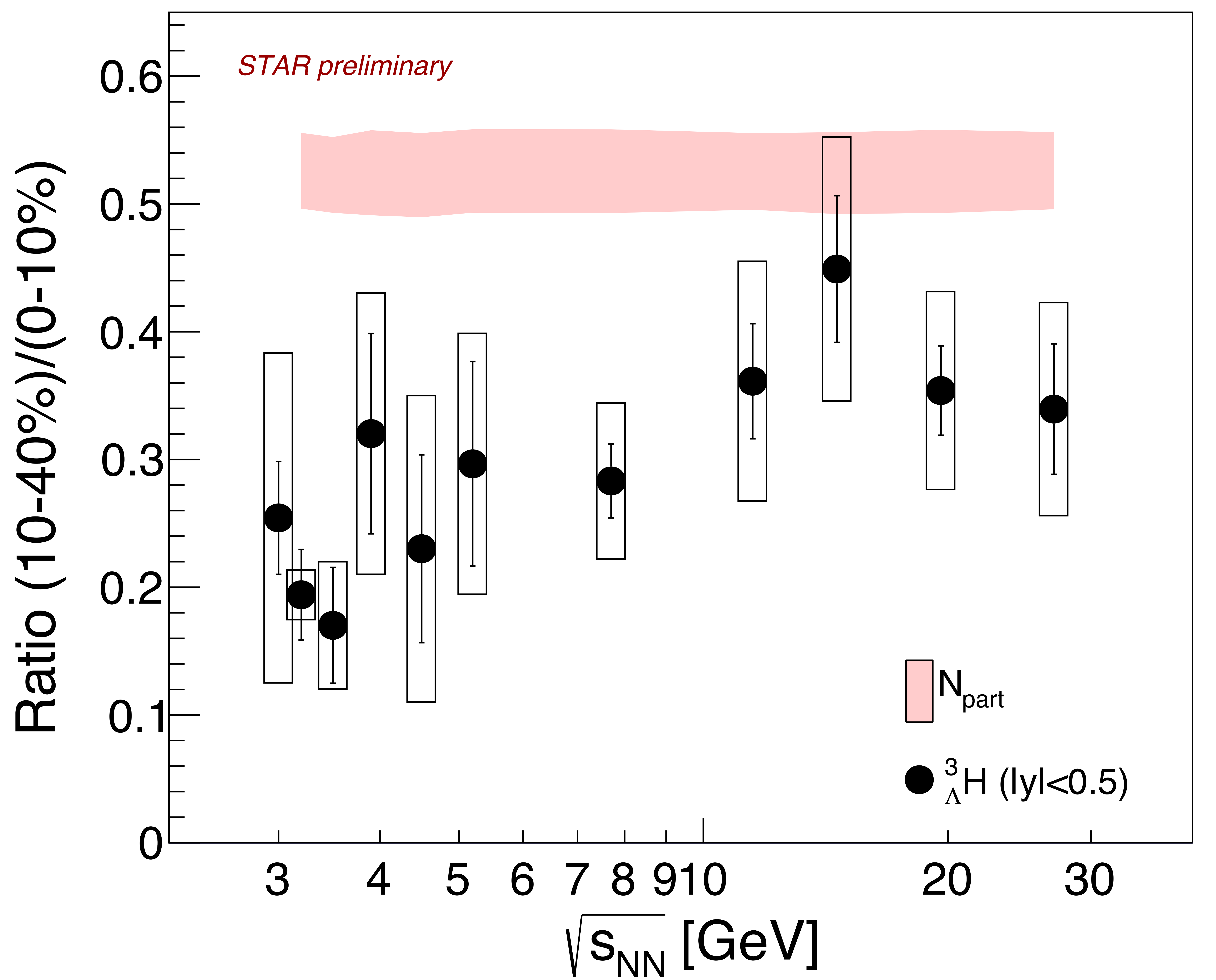
Centrality Dependence of ${}^{3}_{\Lambda}\mathrm{H}$ Production



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

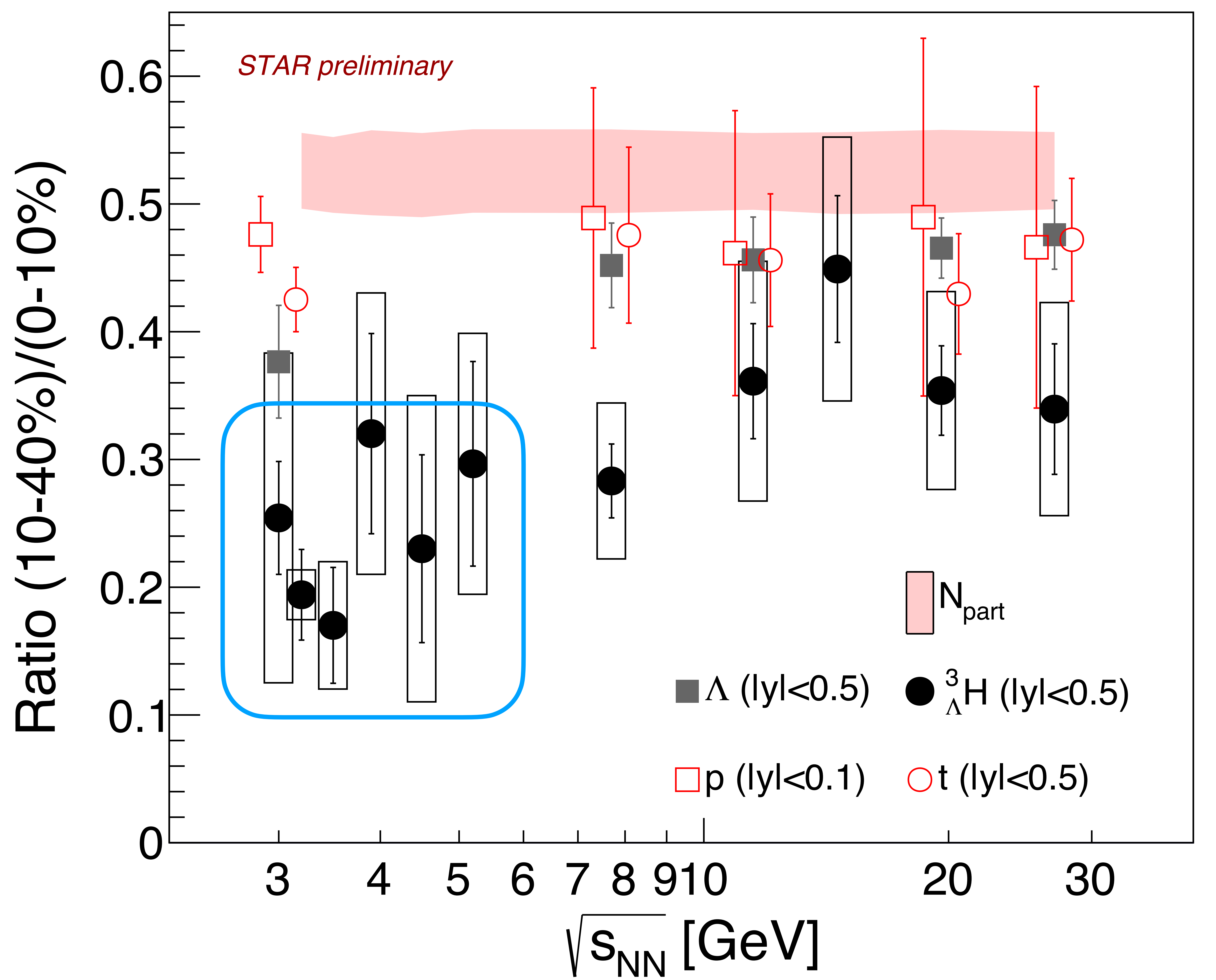
STAR, Phys.Rev.Lett. 128(2022)20, 202301
ALICE, Phys. Lett. B 754(2016)360

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



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

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



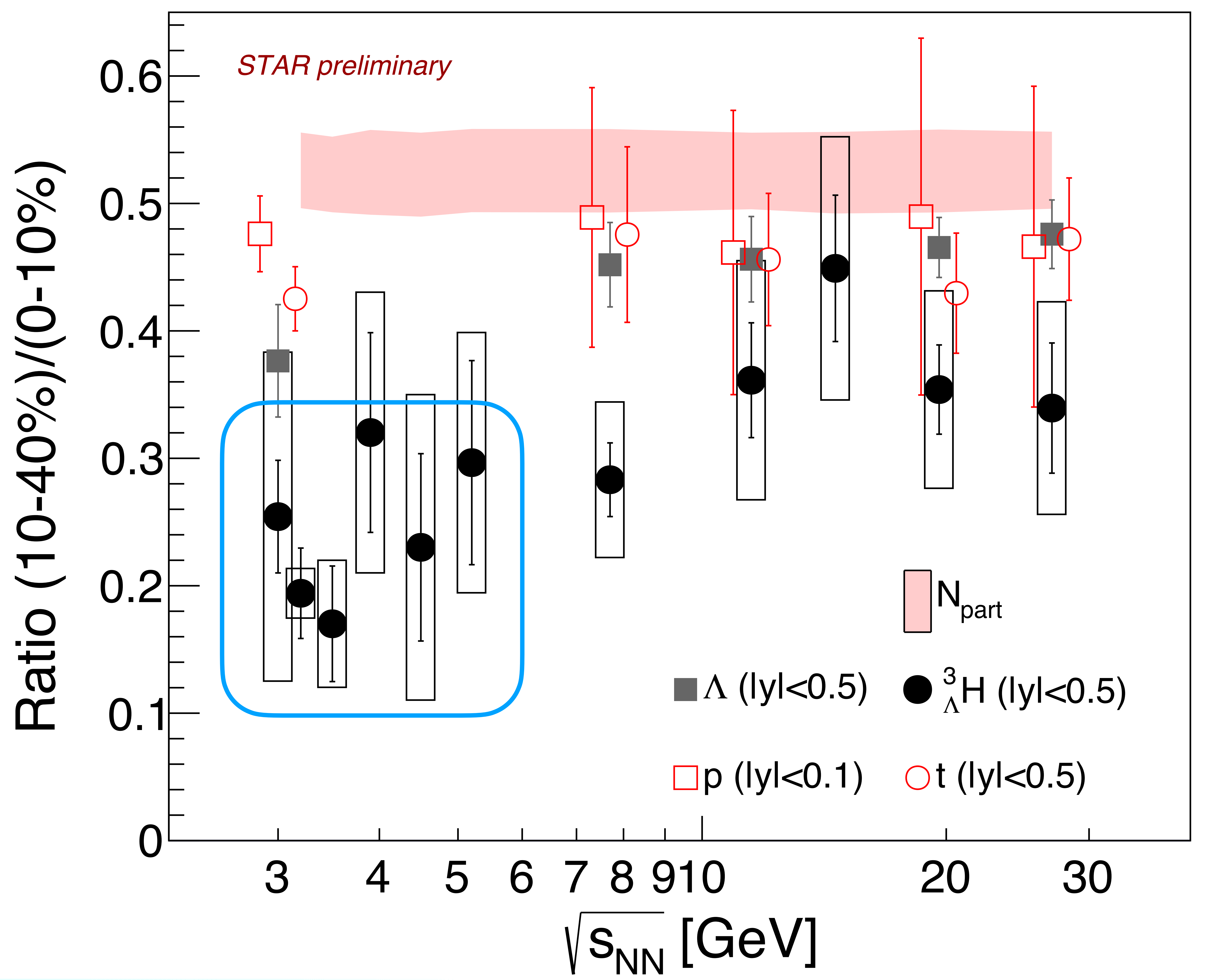
- Proton yield scales with N_{part}
- Λ yield increases more steeply than N_{part}, particularly at low collision energies

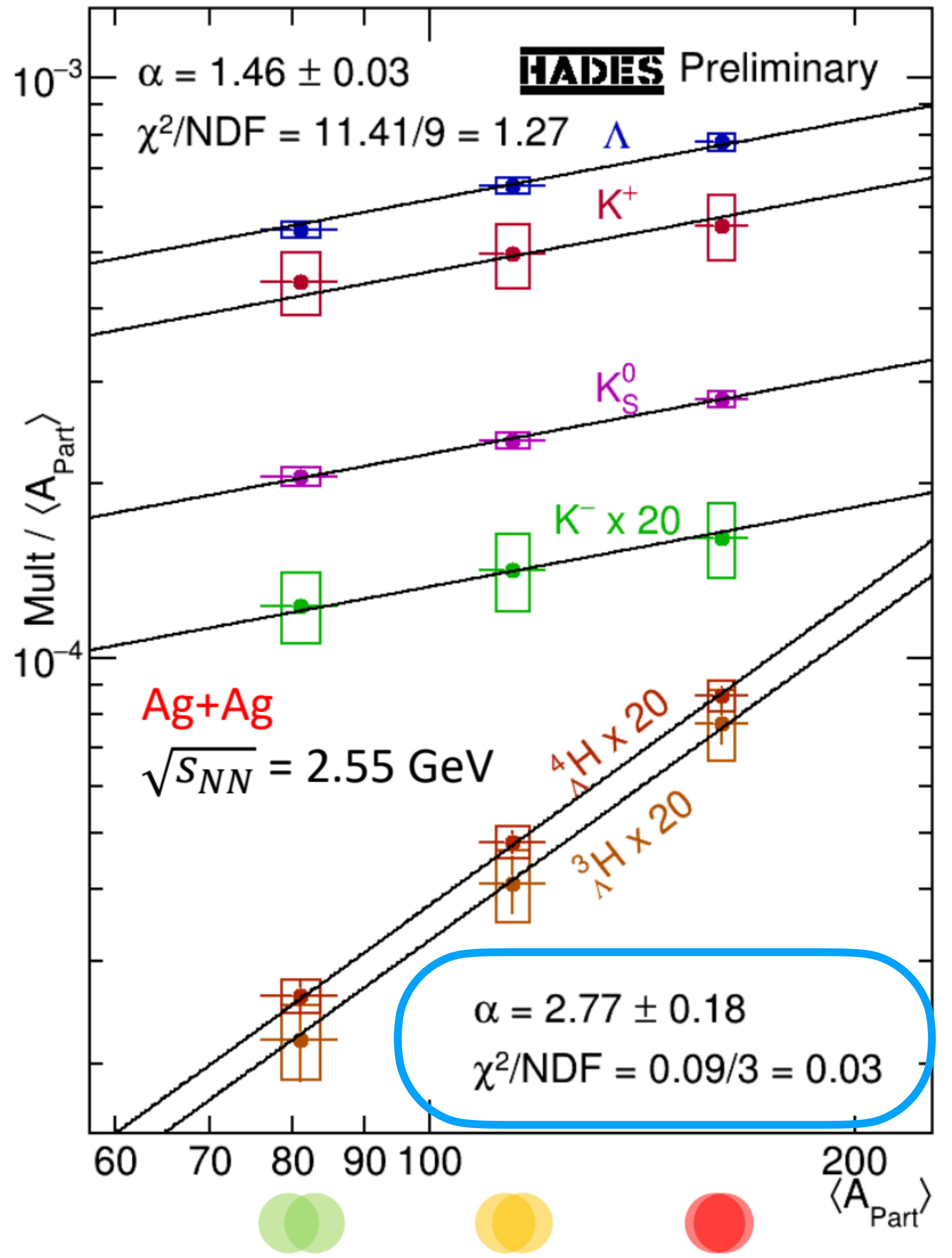
see Y. Zhou, 17:00 20/05 (Mon.)

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

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

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



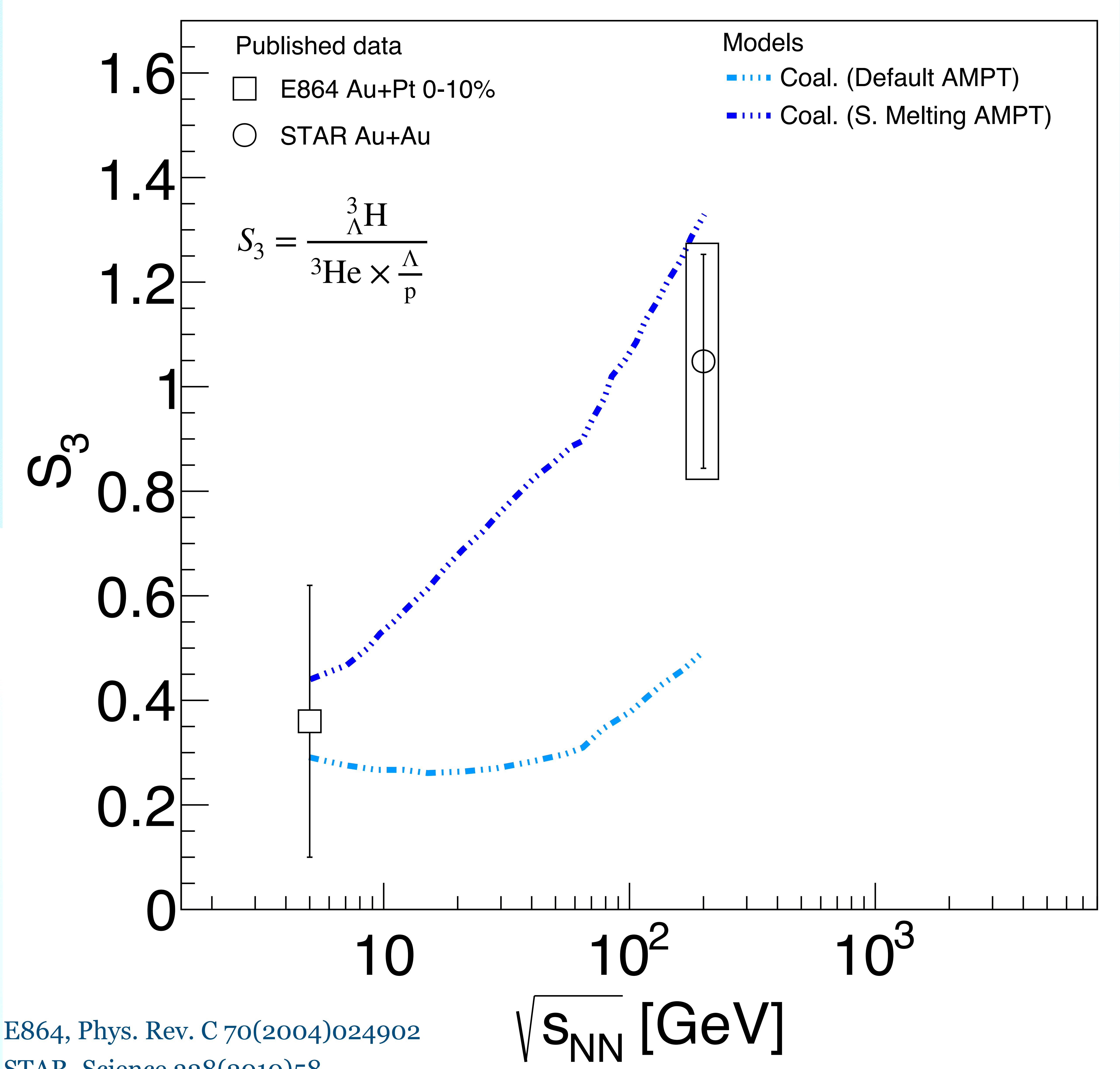


S Spies, (HADES), HYP2022

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

Suppression related to the nature of the created medium?

Strangeness Population Factor S_3

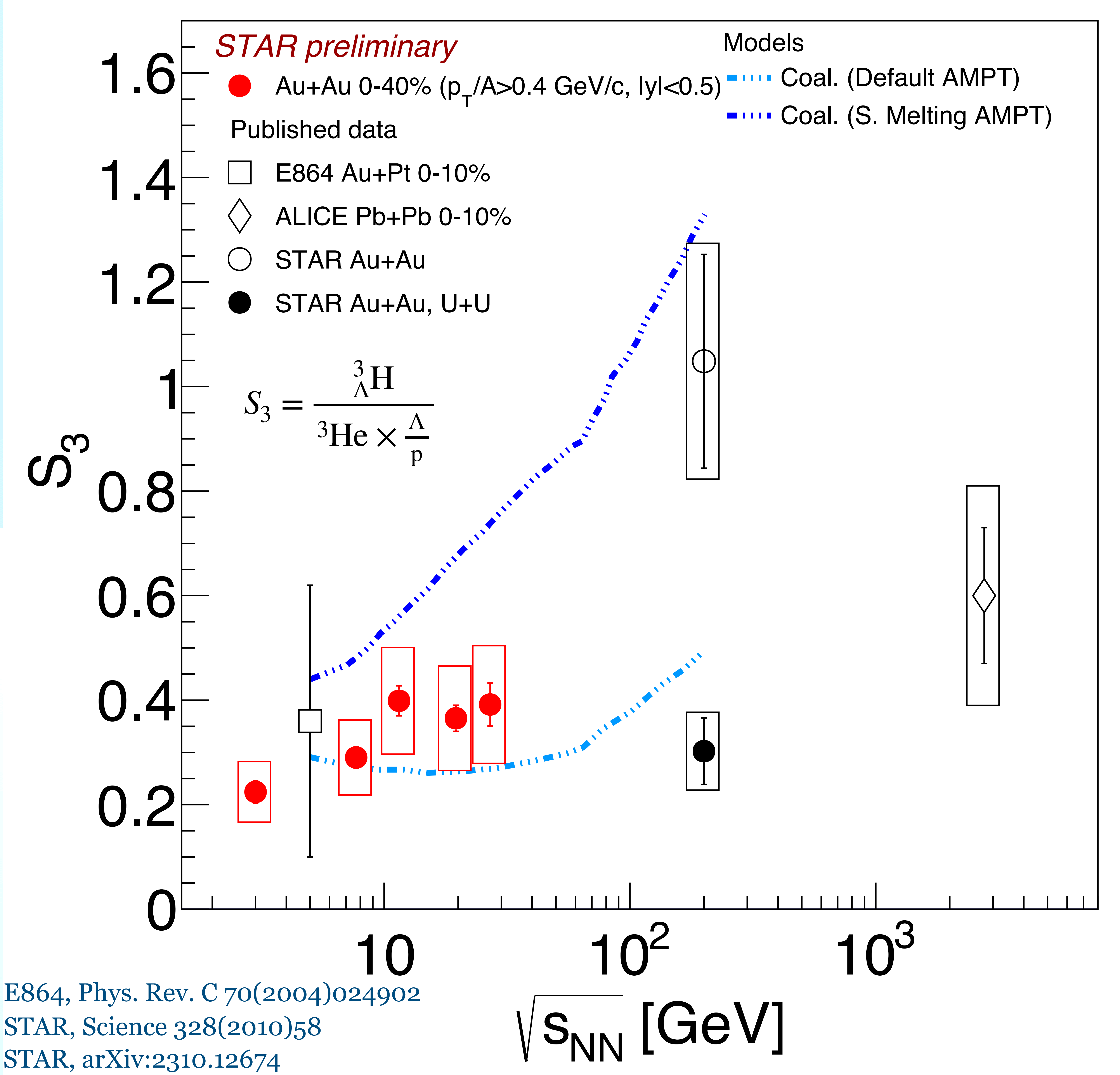


E864, Phys. Rev. C 70(2004)024902
STAR, Science 328(2010)58

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

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

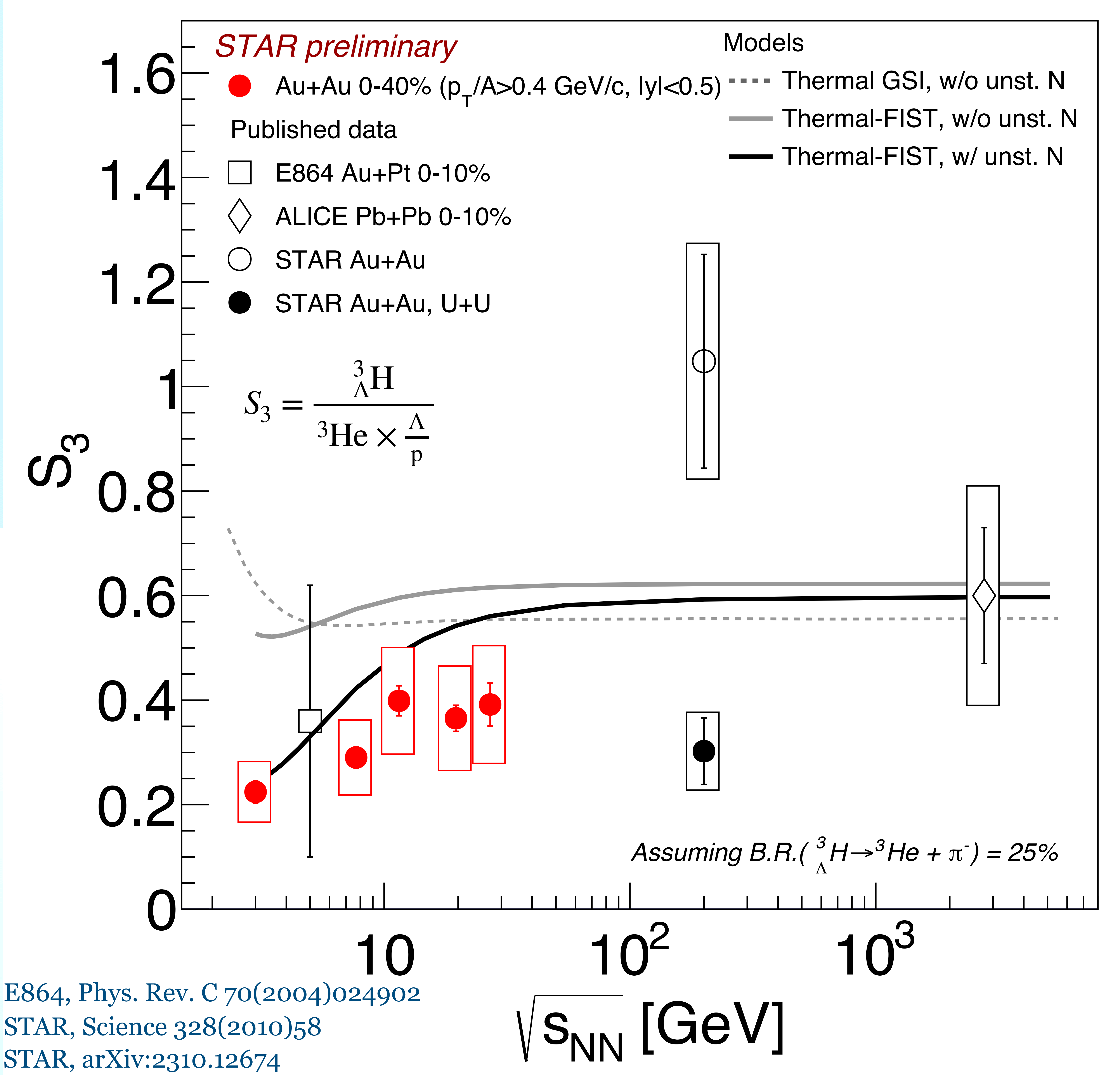
Strangeness Population Factor S_3



E864, Phys. Rev. C 70(2004)024902
STAR, Science 328(2010)58
STAR, arXiv:2310.12674
ALICE, Phys. Lett. B 754(2016)360

- 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

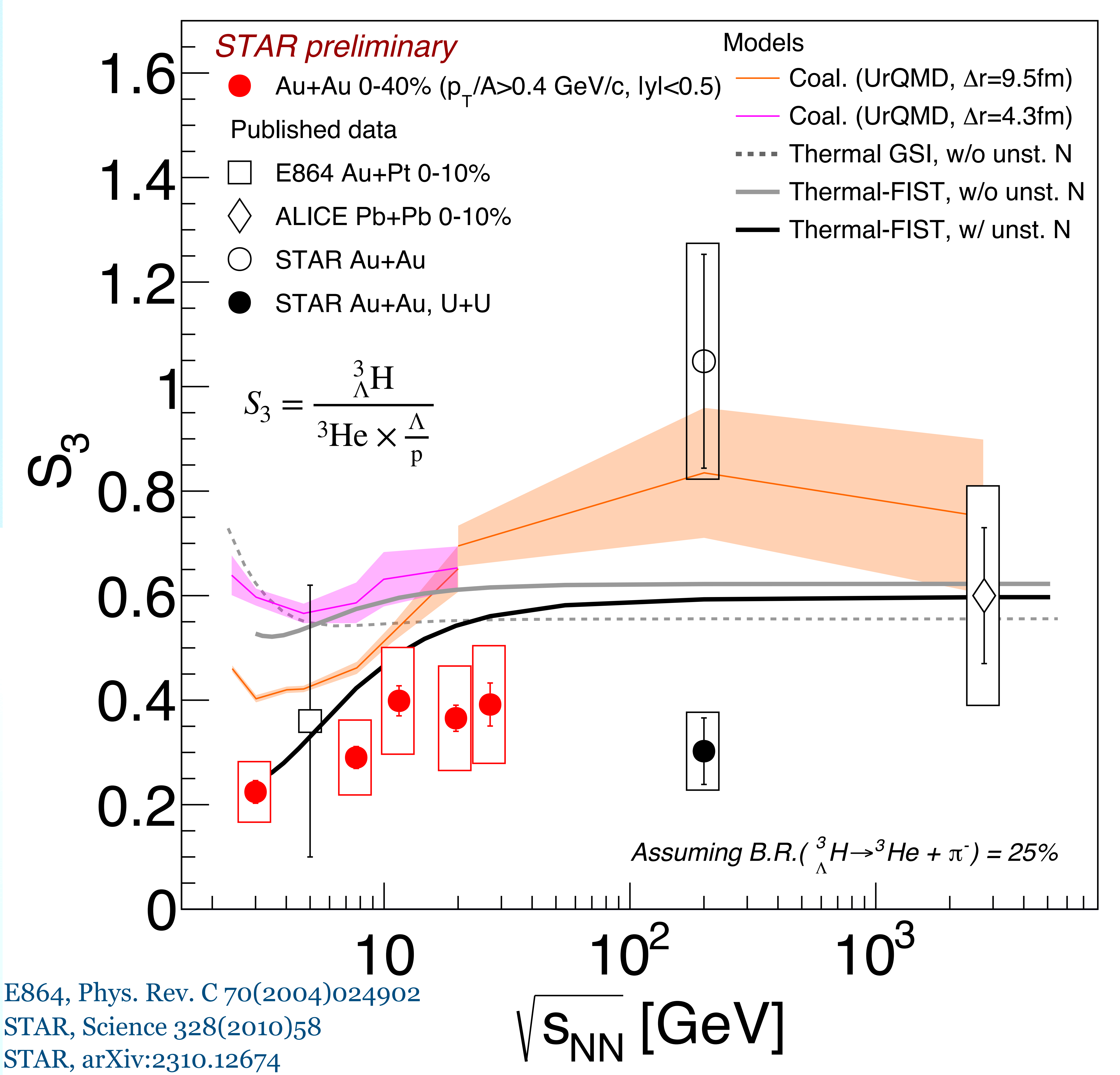


- The measured S_3 is close to thermal model predictions
- The increasing trend is driven by the decreasing feed-down to ^{3}He towards higher energies

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

E864, Phys. Rev. C 70(2004)024902
STAR, Science 328(2010)58
STAR, arXiv:2310.12674
ALICE, Phys. Lett. B 754(2016)360

Strangeness Population Factor S_3



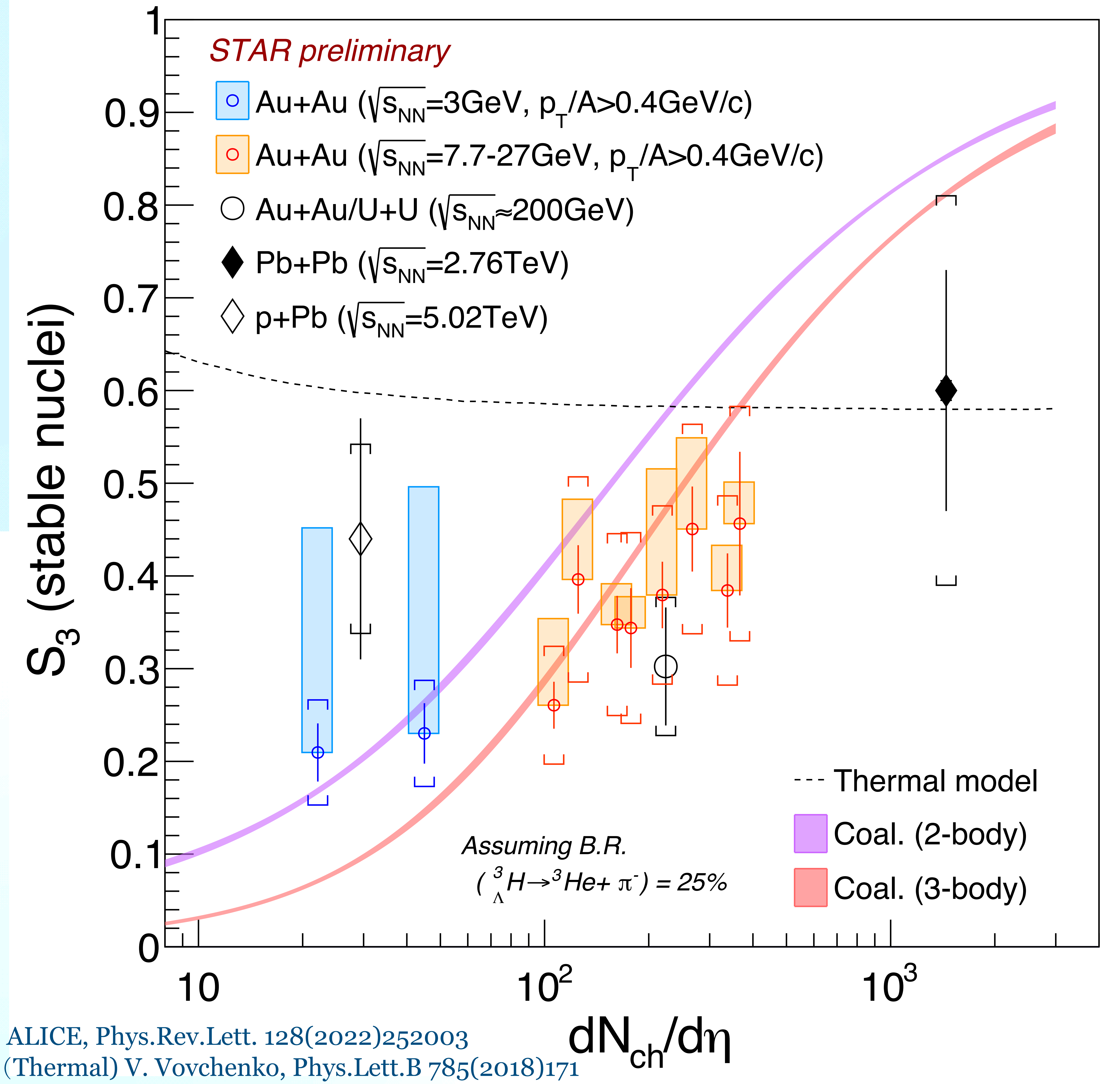
E864, Phys. Rev. C 70(2004)024902
STAR, Science 328(2010)58
STAR, arXiv:2310.12674
ALICE, Phys. Lett. B 754(2016)360

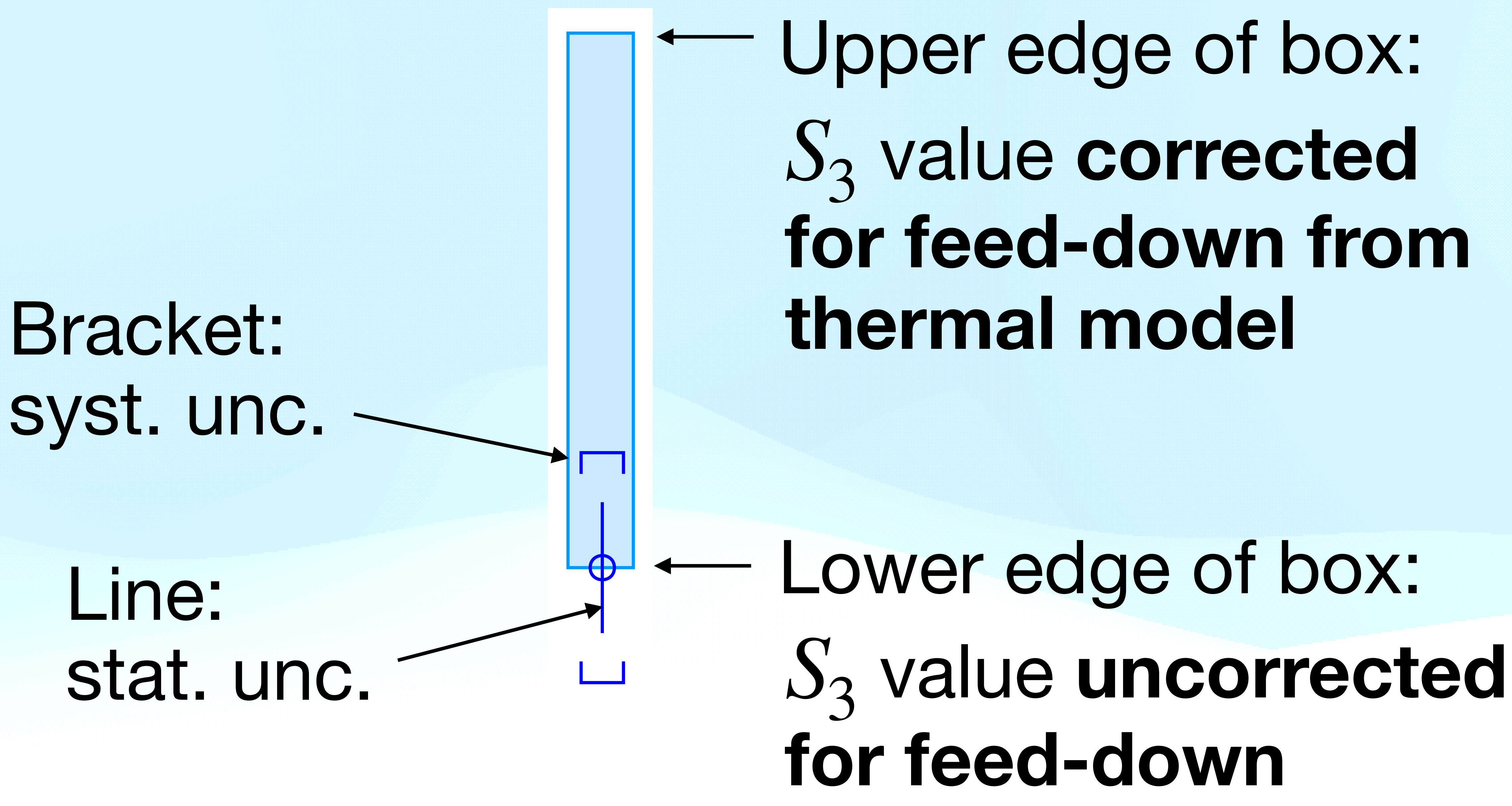
- UrQMD + Coalescence seem to overshoot the data
- A key prediction from coalescence models is the suppression of $^3_\Lambda H$ production in small systems due to its large radius

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)

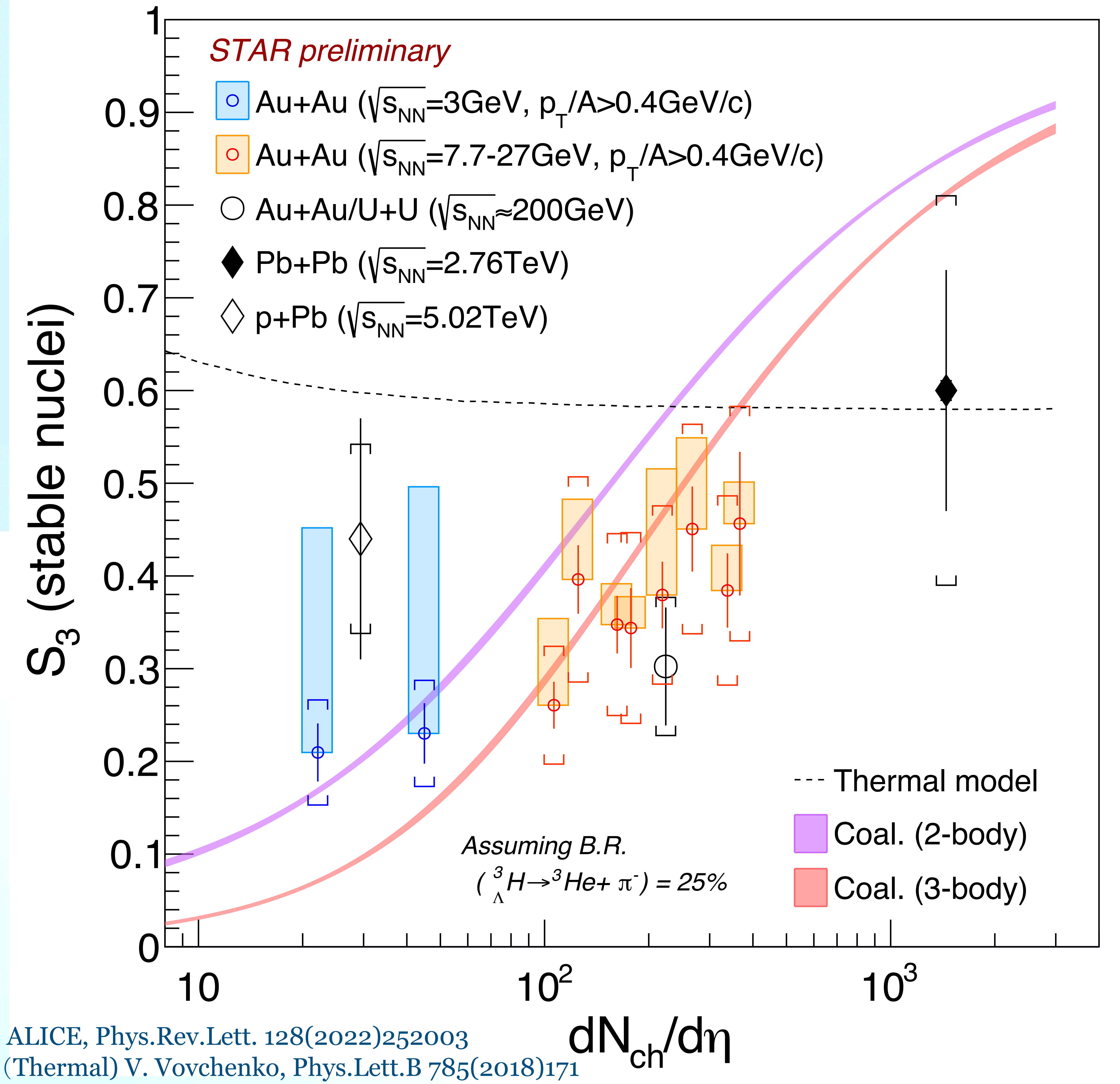




- Unstable nuclei production are suppressed relative to stable nuclei (see backup)
- The true value of S_3 (stable nuclei) very likely lies between the upper and lower limits

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

Multiplicity Dependence of S_3(stable nuclei)



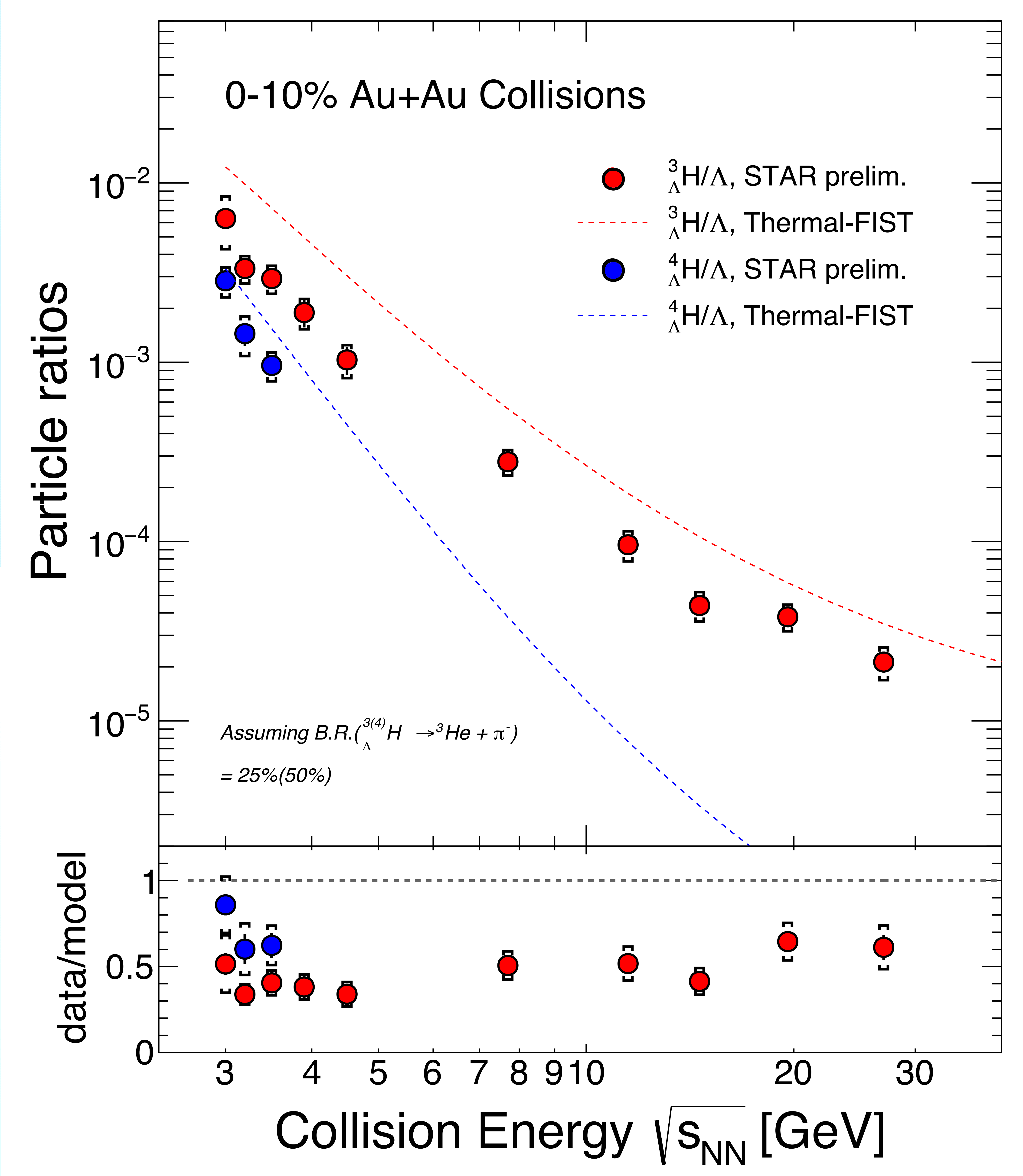
ALICE, Phys.Rev.Lett. 128(2022)252003
(Thermal) V. Vovchenko, Phys.Lett.B 785(2018)171
(Coalescence) K. Sun et al, Phys.Lett.B 792(2019)132

S_3 (stable nuclei) ≈ 0.35

- Existing data for S_3 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

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

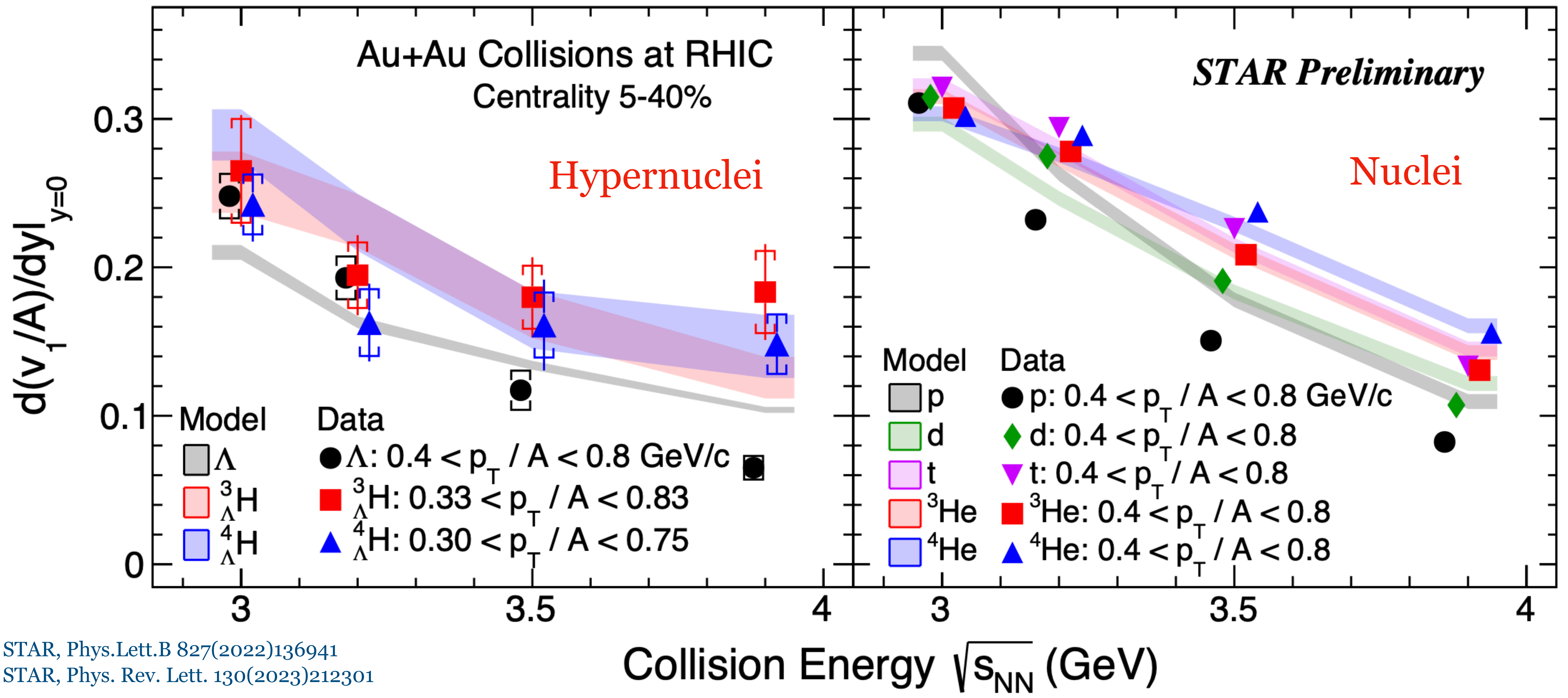


- ${}^{4}_{\Lambda}H$ yields tend to be closer to thermal model predictions compared to ${}^{3}_{\Lambda}H$

Size of hypernuclei plays a role in their production?

	RMS radius (fm)
${}^{3}_{\Lambda}H$	5-10
${}^{4}_{\Lambda}H(0^{+})$	2-3
${}^{4}_{\Lambda}H^{*}(1^{+})$	3-4

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

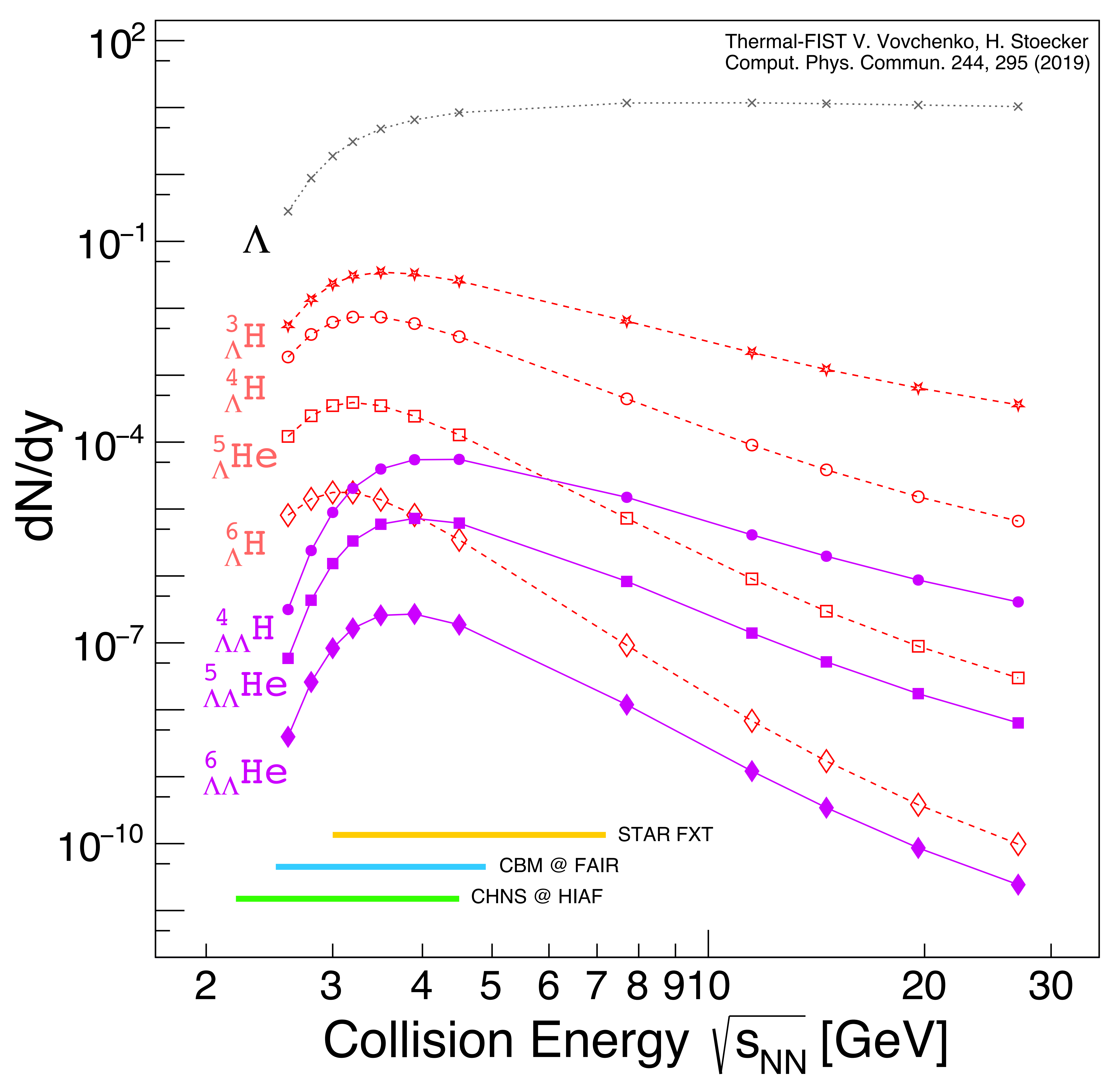
Qualitatively consistent with coalescence formation of hypernuclei

Summary

- ${}^{3}_{\Lambda}\mathrm{H}$ yields in central collisions overestimated by thermal model by a factor of 2
- ${}^{3}_{\Lambda}\mathrm{H}$ mean p_T tends to be lower than blast-wave parametrization from light hadrons
    - ${}^{3}_{\Lambda}\mathrm{H}$ 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 $dN_{ch}/d\eta$
    - Milder multiplicity dependence compared to coalescence models
- Suppression of ${}^{3}_{\Lambda}\mathrm{H}$ in 10-40% collisions at low collision energies observed
- ${}^{4}_{\Lambda}\mathrm{H}$ yields tend to be closer to thermal model predictions than ${}^{3}_{\Lambda}\mathrm{H}$
    - Data provide new input to investigate system size and nuclei size dependence of nuclei production

- ${}^{3}_{\Lambda}\mathrm{H}$ mean p_T seem to exhibit two separate trends for $\sqrt{s_{NN}} = 3 - 4.5\mathrm{GeV}$ and $7.7 - 27\mathrm{GeV}$
    - Change in medium properties or expansion dynamics?

Outlook



<u>RHIC-STAR</u>

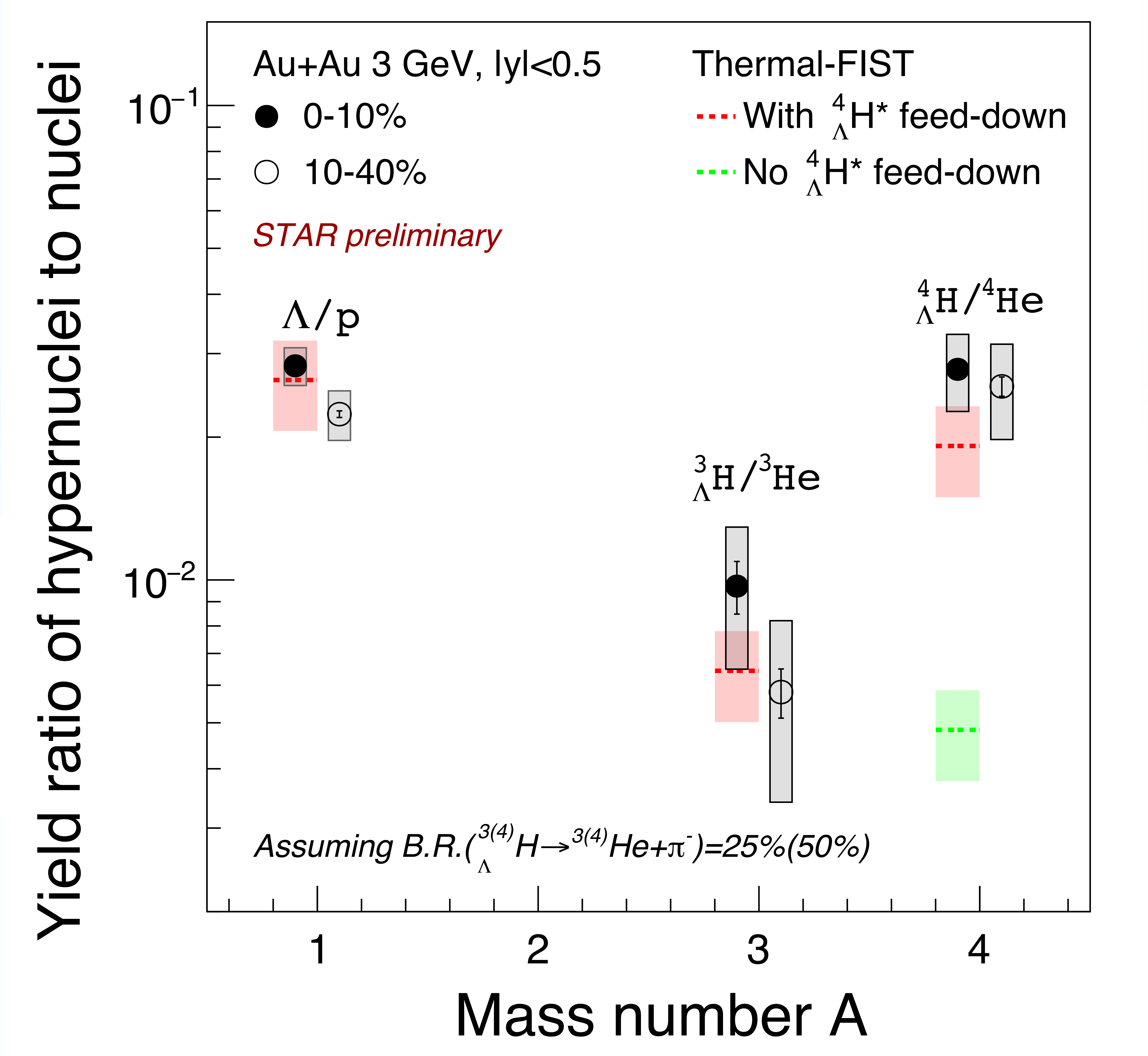
- Heavier hypernuclei, including ${}^4_\Lambda H$, ${}^4_\Lambda He$, ${}^5_\Lambda He$, ${}^6_\Lambda H$ at FXT energies
- High statistics data at RHIC top energy give opportunities for multiplicity dependence study

<u>FAIR-CBM and HIAF</u>

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


Thank you for listening!

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

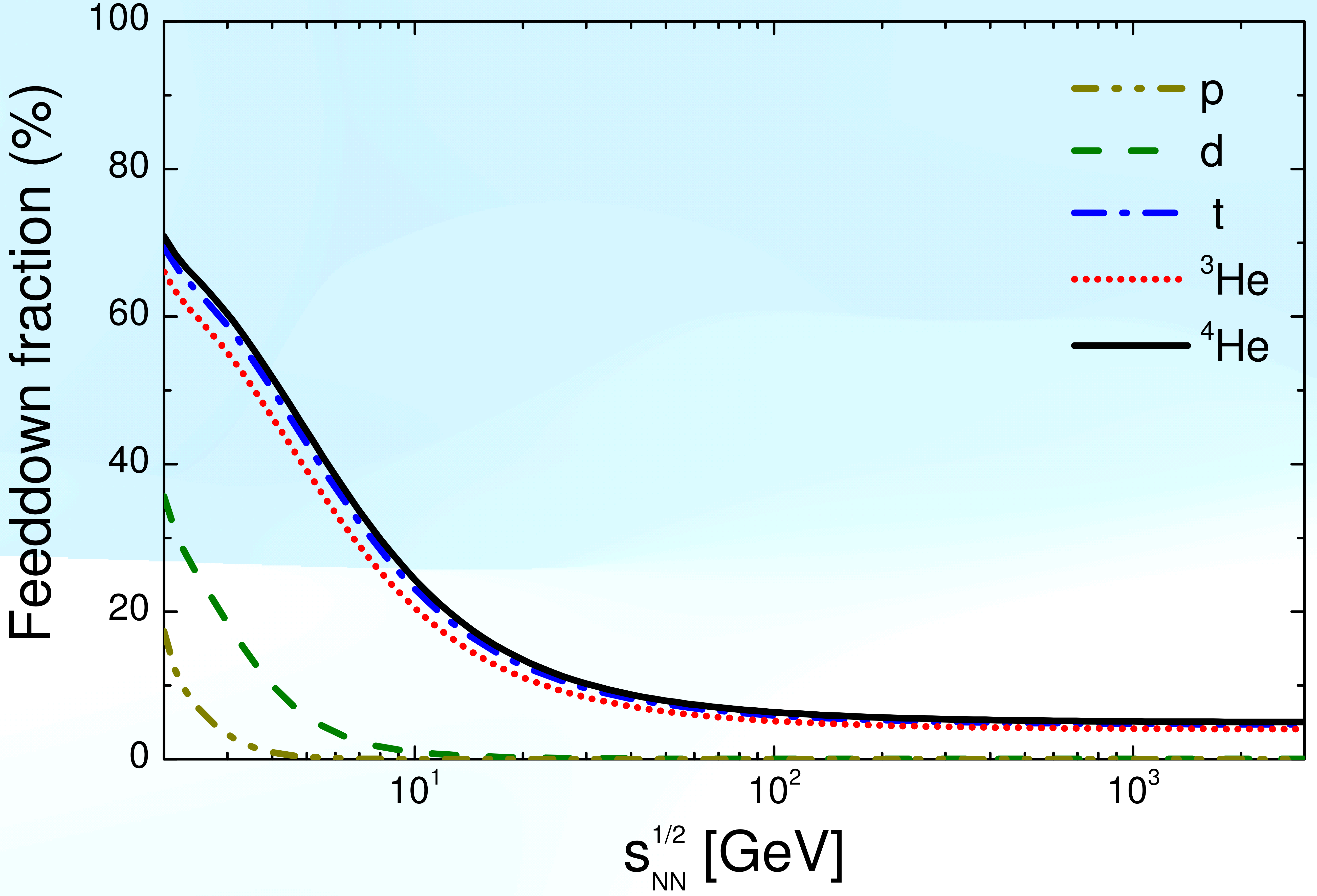


- Non-monotonic behavior of hypernuclei to nuclei yields vs mass number

Suggestive of creation of unstable hypernuclei

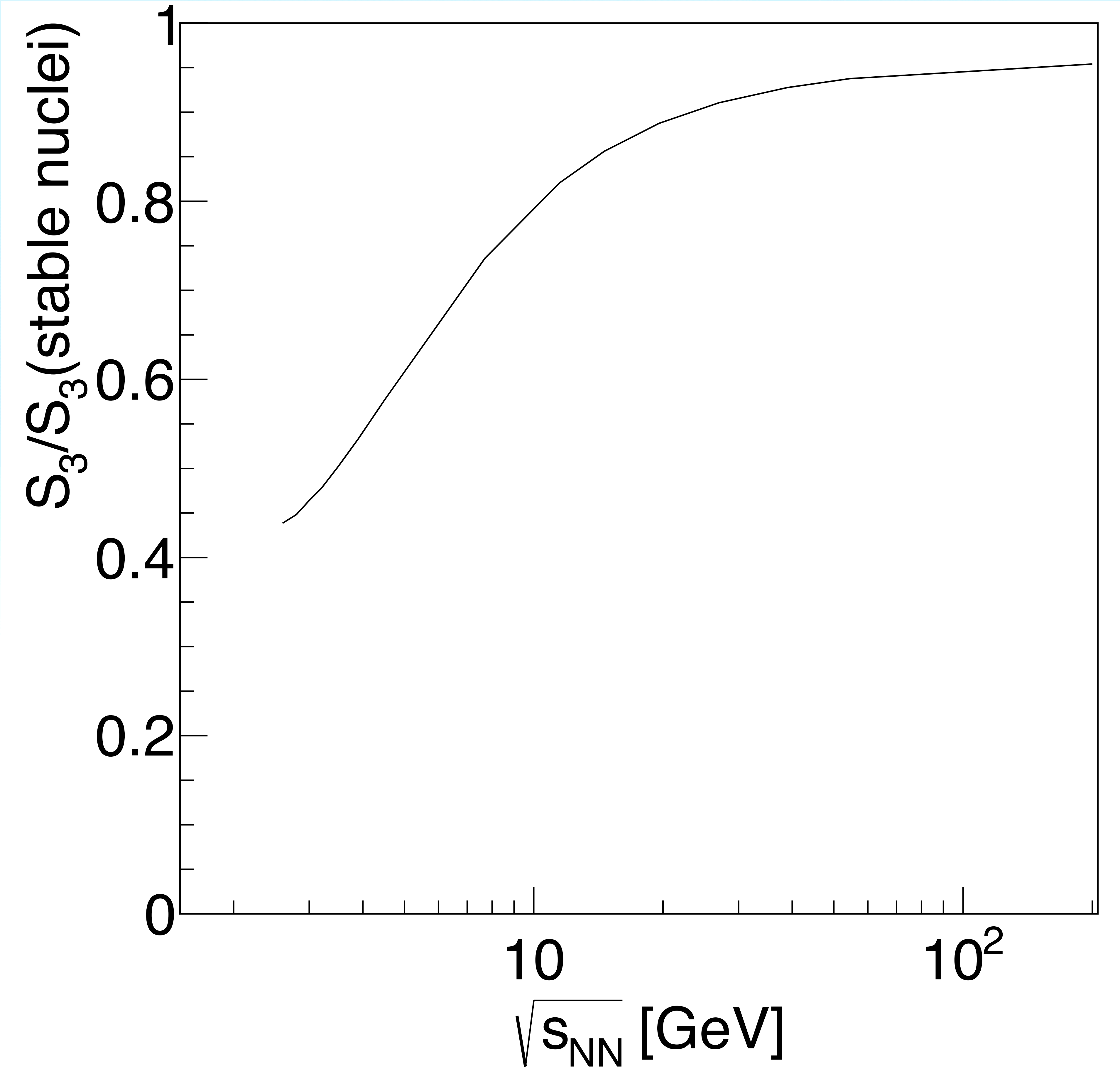
$${}^{4}_{\Lambda}H^*(1^+) \rightarrow {}^{4}_{\Lambda}H(0^+) + \gamma$$

Feed-down from Unstable Nuclei



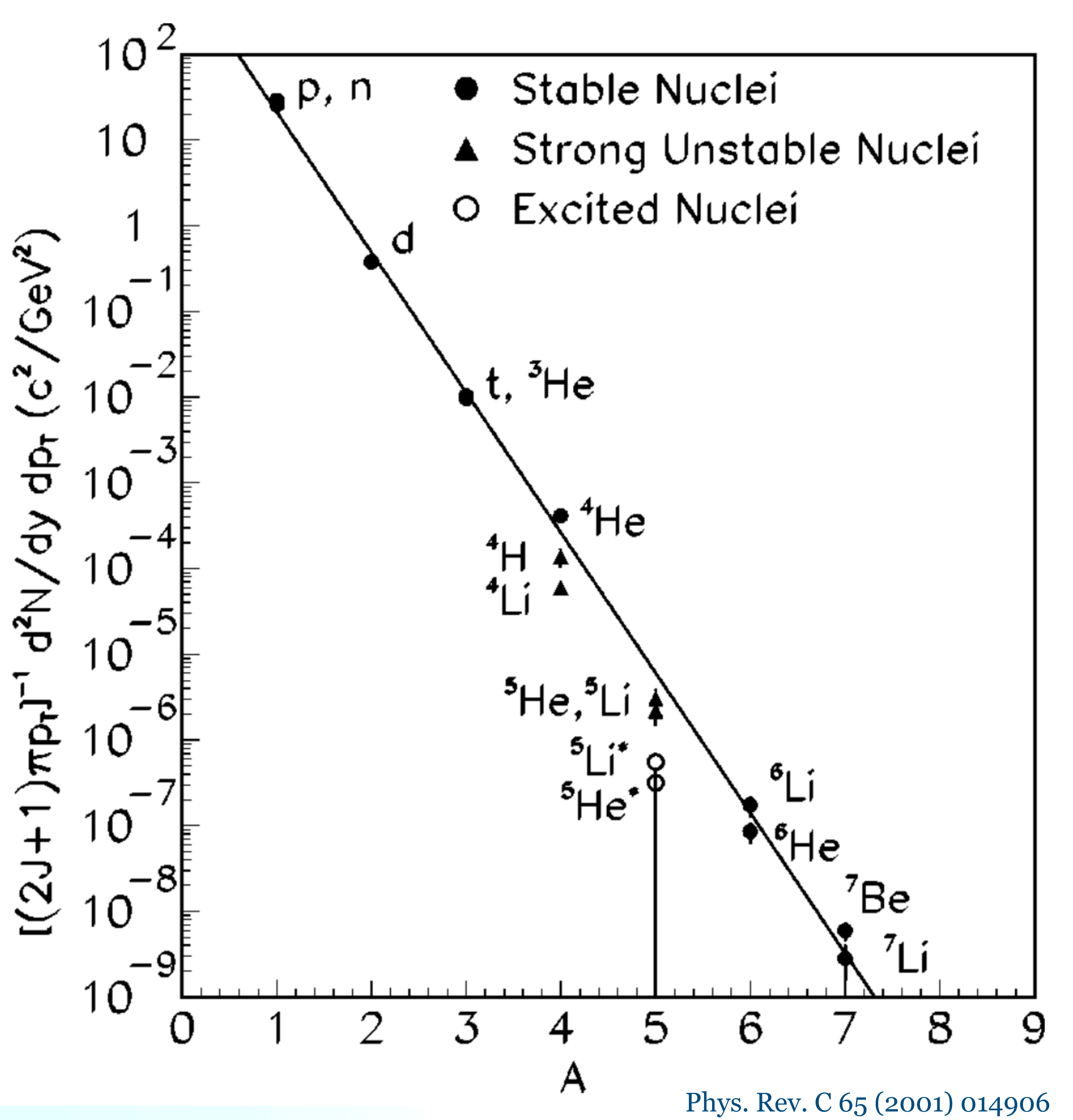
- Feed-down fractions estimated using Thermal-FIST

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



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

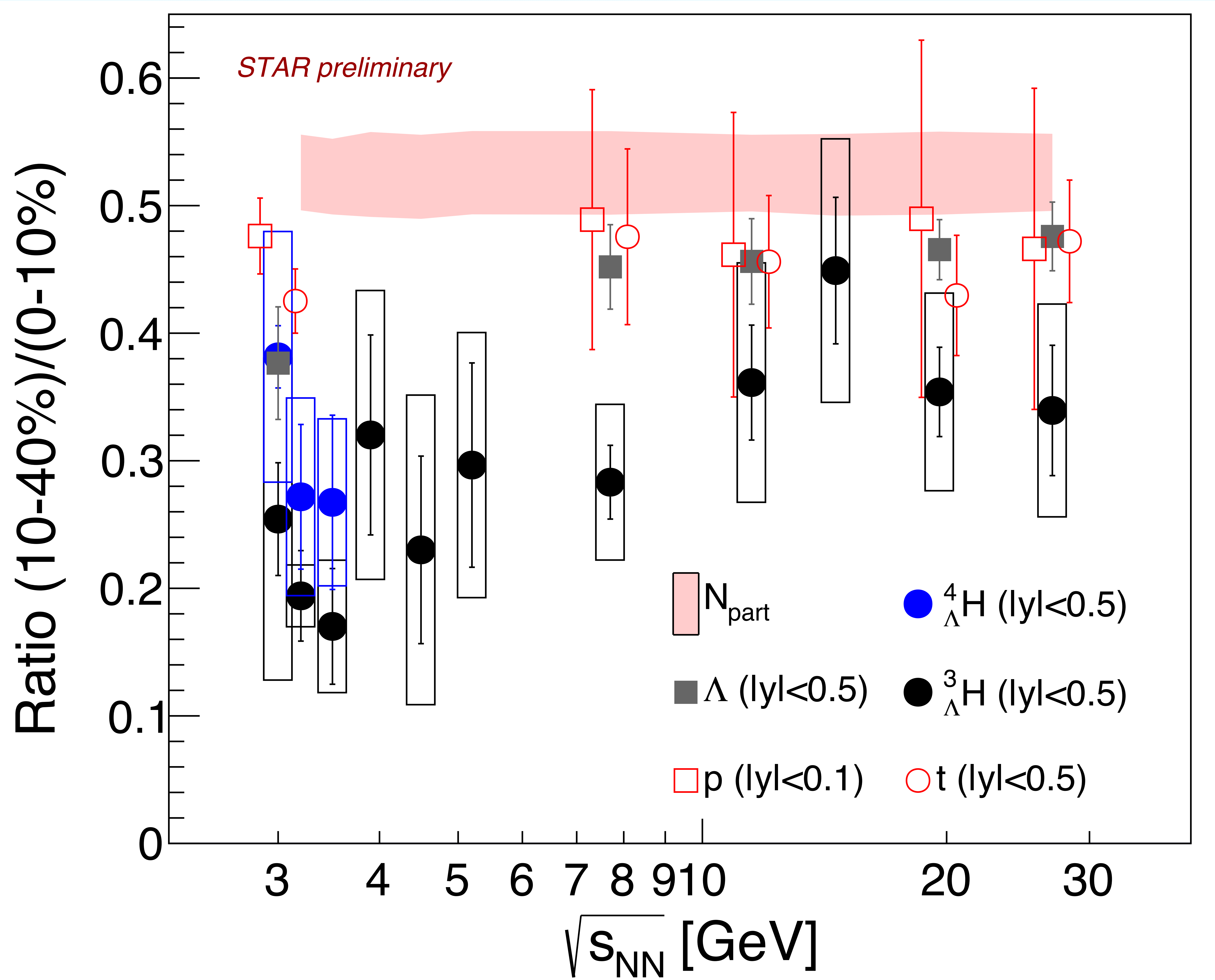
Feed-down from Unstable Nuclei



Phys. Rev. C 65 (2001) 014906

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

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