Recent Hypernuclei Measurements in the High Baryon Density Region with the STAR Experiment at RHIC

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Outline

- **Introduction**
- **Hypernuclear structure**
    - Hypernuclei branching ratios
    - Hypernuclei lifetimes
- **Production in heavy-ion collisions**
    - Hypernuclei Yields
    - Particle ratios and energy dependence
    - Hypernuclei collectivity
- **Summary and outlook**

QUARK MATTER
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Hypernuclei

Hypernuclei are nuclei containing at least one hyperon

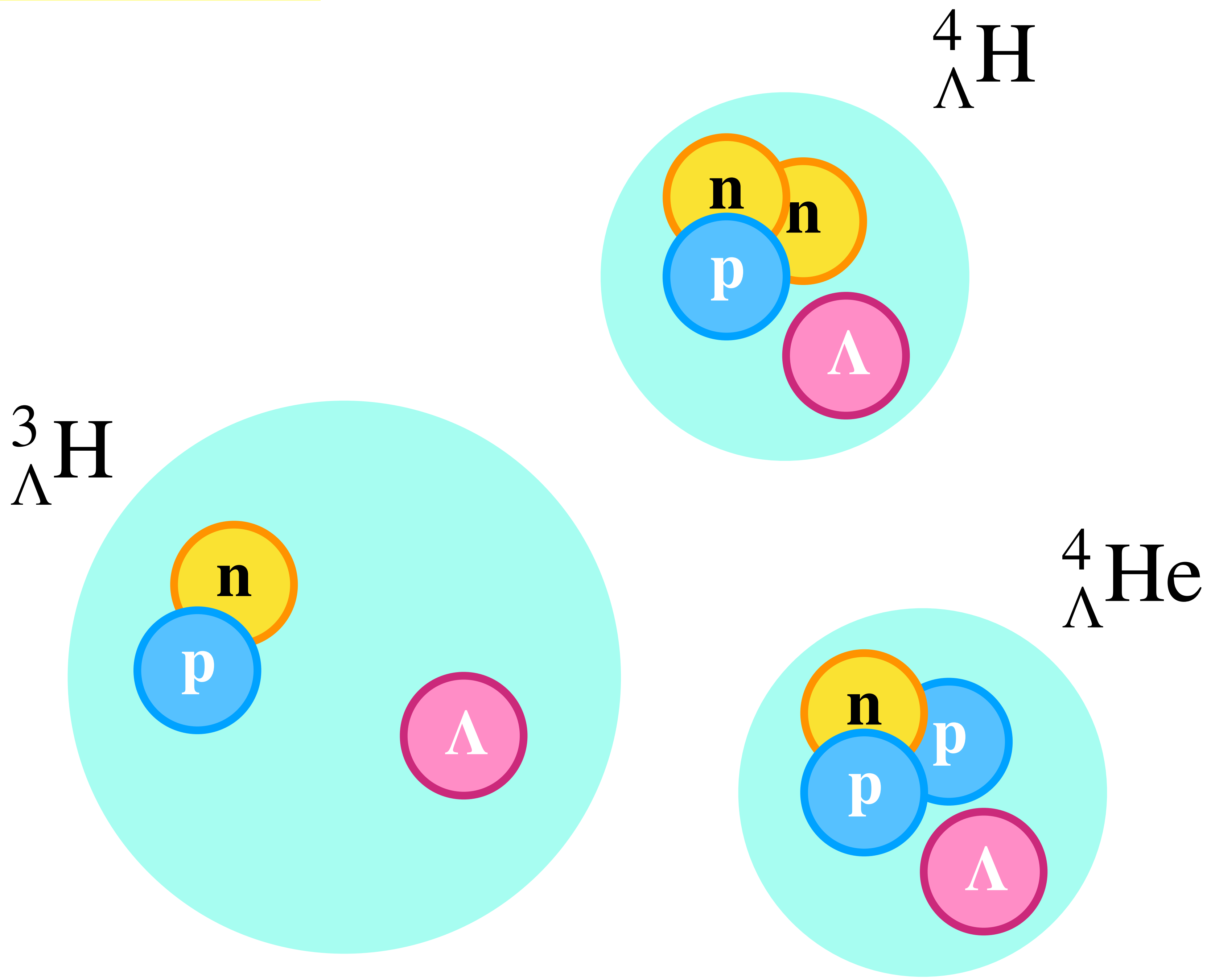
- Provide access to the hyperon–nucleon (Y-N) interaction
  - Strangeness in high density nuclear matter
    - EOS of neutron star
    - Hadronic phase of a heavy ion collision

- Experimentally, we can make measurements related to:
  - 1. Their internal structure
    - Lifetime, binding energy, branching ratios etc.

Understanding hypernuclear structure may give more constraints on the Y-N interaction

  - 2. Their production in heavy-ion collisions
    - Spectra, collectivity etc.

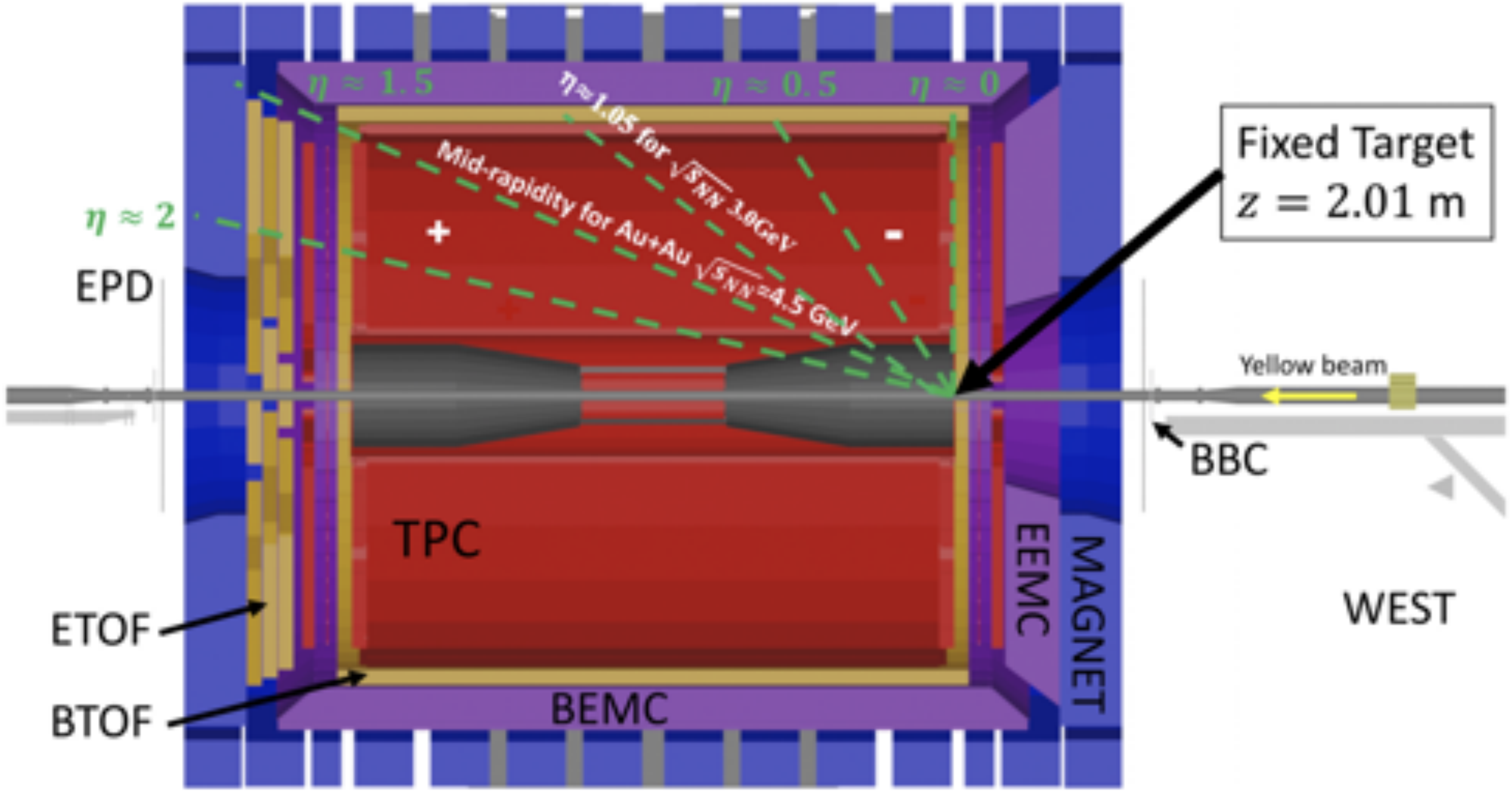
The formation of loosely bound states in violent heavy-ion collisions is not well understood



STAR and BES-II

B. Dönigus, Eur. Phys. J. A (2020) 56:280
A. Andronic et al, PLB 697 (2011)203

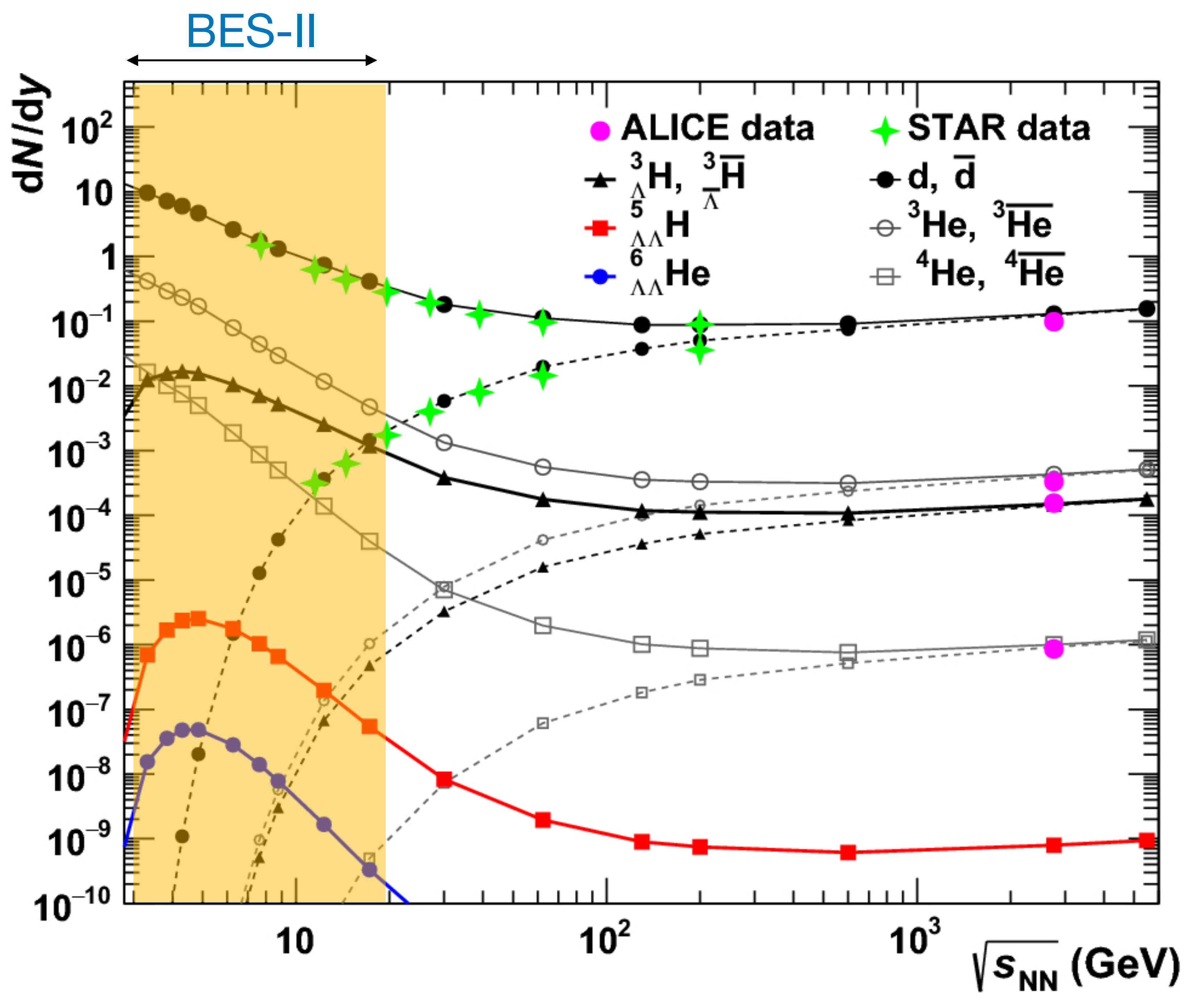
- Hypernuclei measurements are scarce in heavy-ion experiments
- At lower beam energies, hypernuclei yields are expected to be **enhanced due to high baryon density**
  - STAR BES-II -> great opportunity to study hypernuclei production



STAR Fixed-target Experiment Setup

List of BES-II datasets

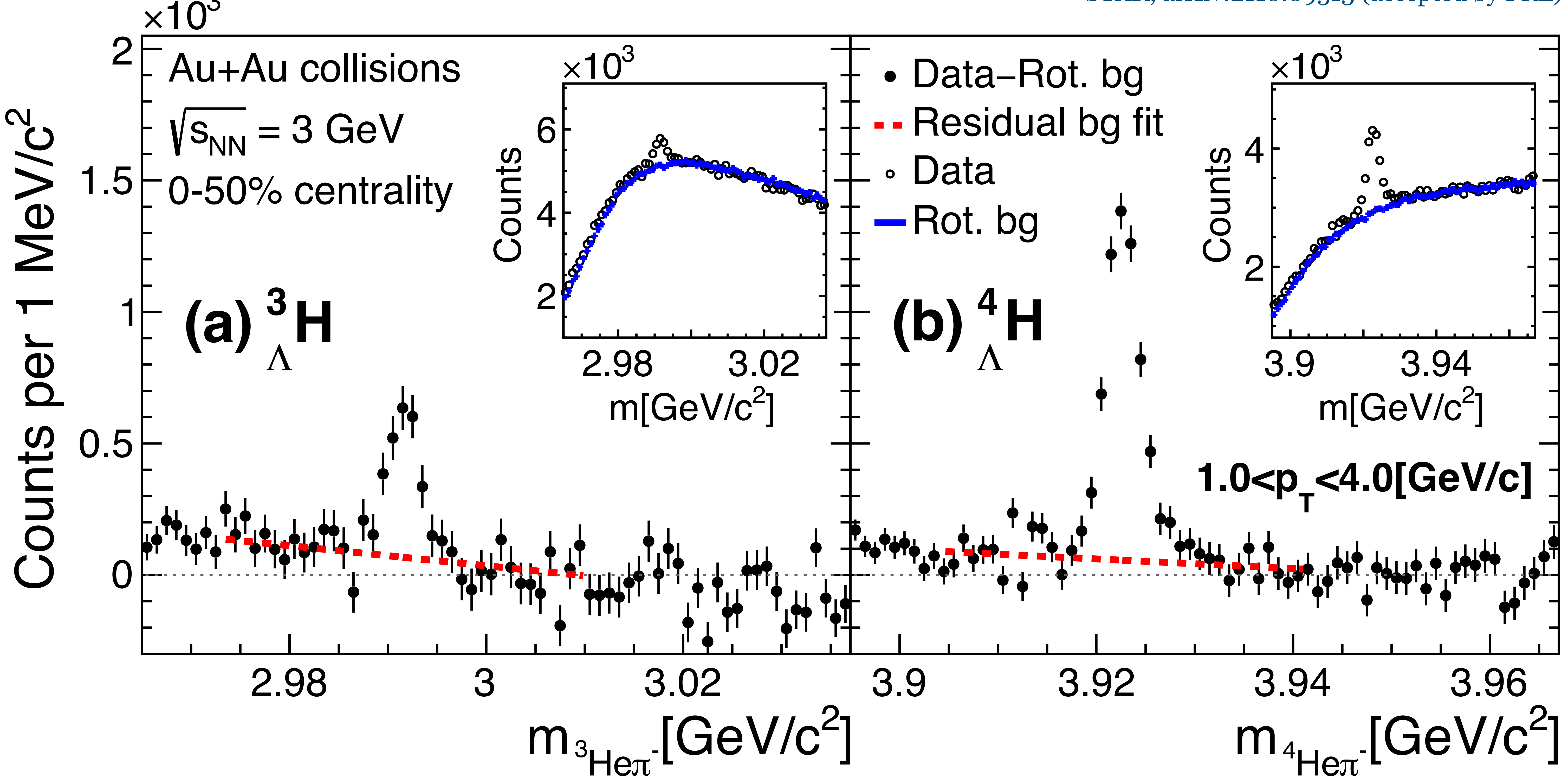
Year	$\sqrt{s_{NN}}$ [GeV]	# of Events
2018	27	555 M
	3.0	258 M
	7.2	155 M
	19.6	478 M
2019	14.6	324 M
	3.9	53 M
	3.2	201 M
	7.7	51 M
2020	11.5	235 M
	7.7	113 M
	4.5	108 M
	6.2	118 M
	5.2	103 M
	3.9	117 M
	3.5	116 M
	9.2	162 M
	7.2	317 M
2021	7.7	101 M
	3.0	2103 M
	9.2	54 M
	11.5	52 M
	13.7	51 M
	17.3	256 M
	7.2	89 M

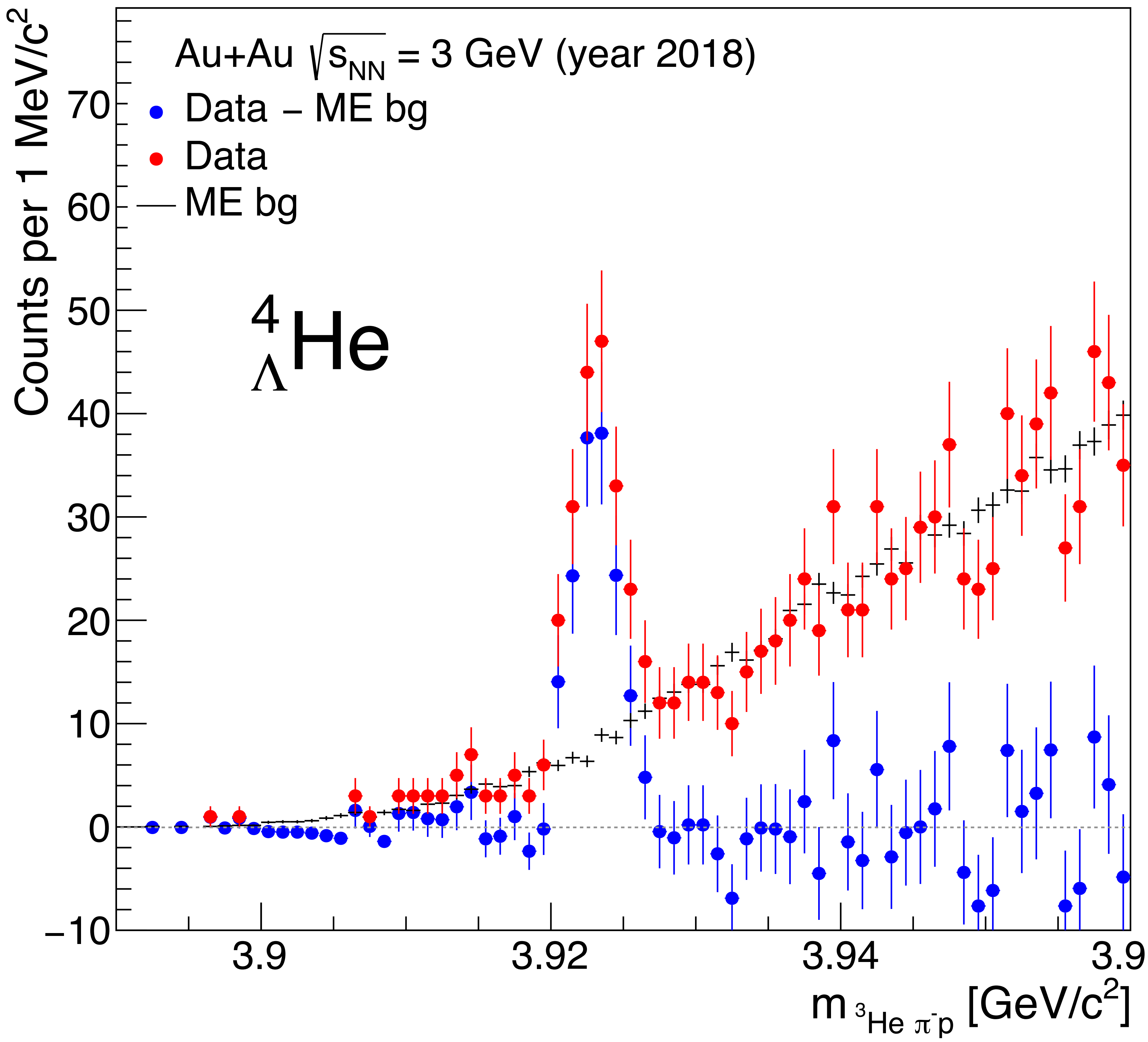


- **New results from BES-II data at:**
  - **3.0 GeV, 7.2 GeV (fixed-target mode)**
  - **19.6 GeV, 27 GeV (collider mode)**

Hypernuclei reconstruction

STAR, arXiv:2110.09513 (accepted by PRL)





- Hypernuclei are reconstructed using the following decay channels:

$${}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^- \qquad {}^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{p} + \pi^-$$

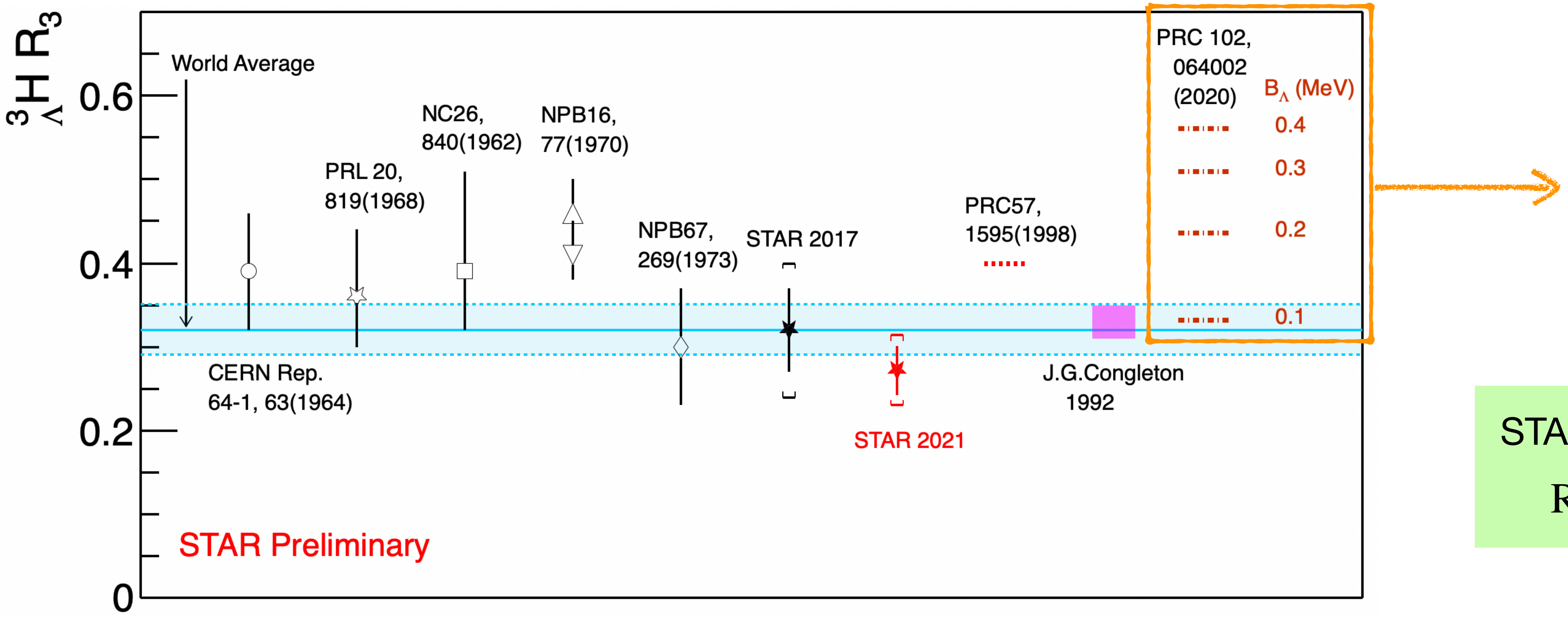
$${}^{4}_{\Lambda}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \pi^- \qquad {}^{4}_{\Lambda}\mathrm{He} \rightarrow {}^{3}\mathrm{He} + \mathrm{p} + \pi^-$$

- Good mid-rapidity coverage at 3.0 GeV (FXT)
- Combinatorial background estimated via rotating pion tracks or event mixing

Hypertriton R3

See poster by Yuanjing Ji (4/8 T16)

- Relative branching ratio: $R_3 = \dfrac{B.R.({}^3_\Lambda H \rightarrow {}^3He\pi^-)}{B.R.({}^3_\Lambda H \rightarrow {}^3He\pi^-) + B.R.({}^3_\Lambda H \rightarrow dp\pi^-)}$



R_3 may be sensitive to the binding energy of ${}^3_\Lambda H$ [1]

STAR preliminary:

$$R_3 = 0.27 \pm 0.03(\text{stat.}) \pm 0.04(\text{syst.})$$

- Improved precision on R3

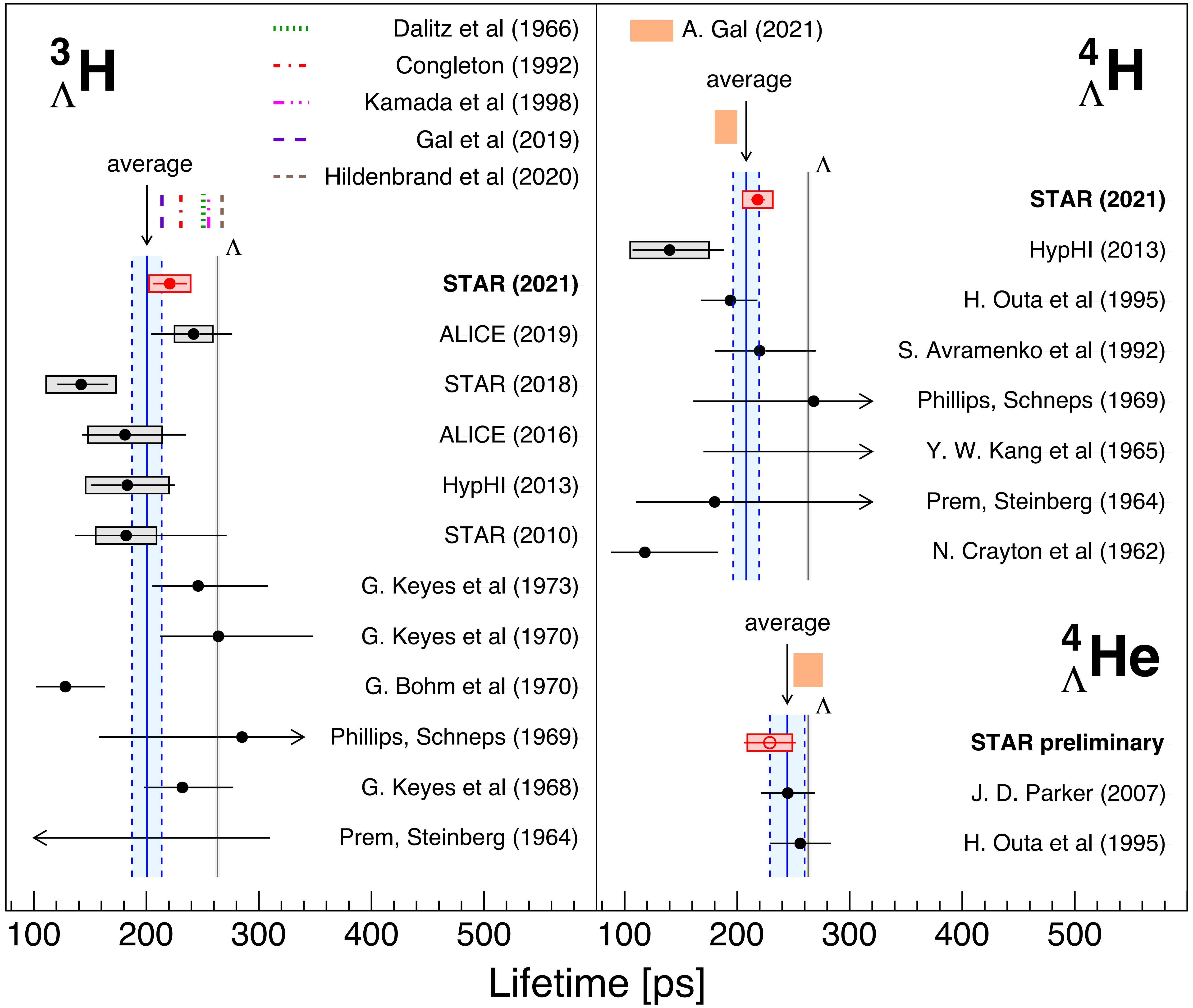
  → Stronger constraints on hypernuclear interaction models used to describe ${}^3_\Lambda H$

  → Stronger constraints on absolute B.R.s

[1] F. Hildenbrand et al, PRC 102(2020)064002

Hypernuclei lifetimes

See poster by Xiujun Li (4/8 T16)



New $^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H results with improved precision compared to previous measurements

- $^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H lifetimes shorter than τ_Λ (with 1.8σ, 3.0σ respectively)

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

- Global avg. $= (76 \pm 5)\,\%\,\tau_\Lambda$, shorter than τ_Λ (4.8σ)
- Consistent with theoretical calculations including pion FSI

A. Gal et al, PLB791(2019)48

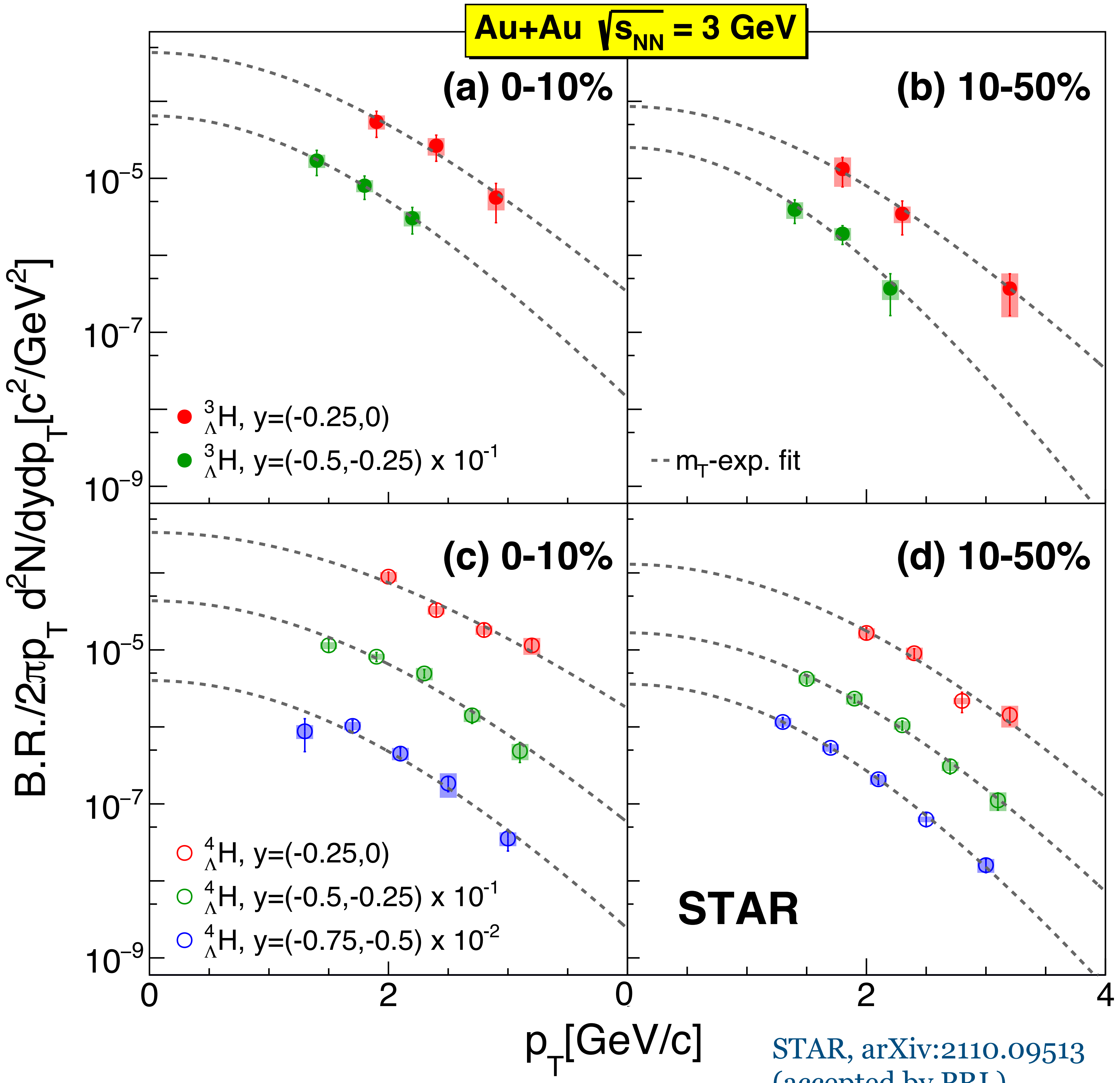
$^{4}_{\Lambda}$H, $^{4}_{\Lambda}$He

- Application of isospin rule* to A=4 hypernuclei suggests lifetime of $^{4}_{\Lambda}$H to be shorter than $^{4}_{\Lambda}$He
- $\dfrac{\tau_{avg}(^{4}_{\Lambda}\mathrm{H})}{\tau_{avg}(^{4}_{\Lambda}\mathrm{He})} = 0.85 \pm 0.07$, consistent with theoretical estimations: 0.74 ± 0.04

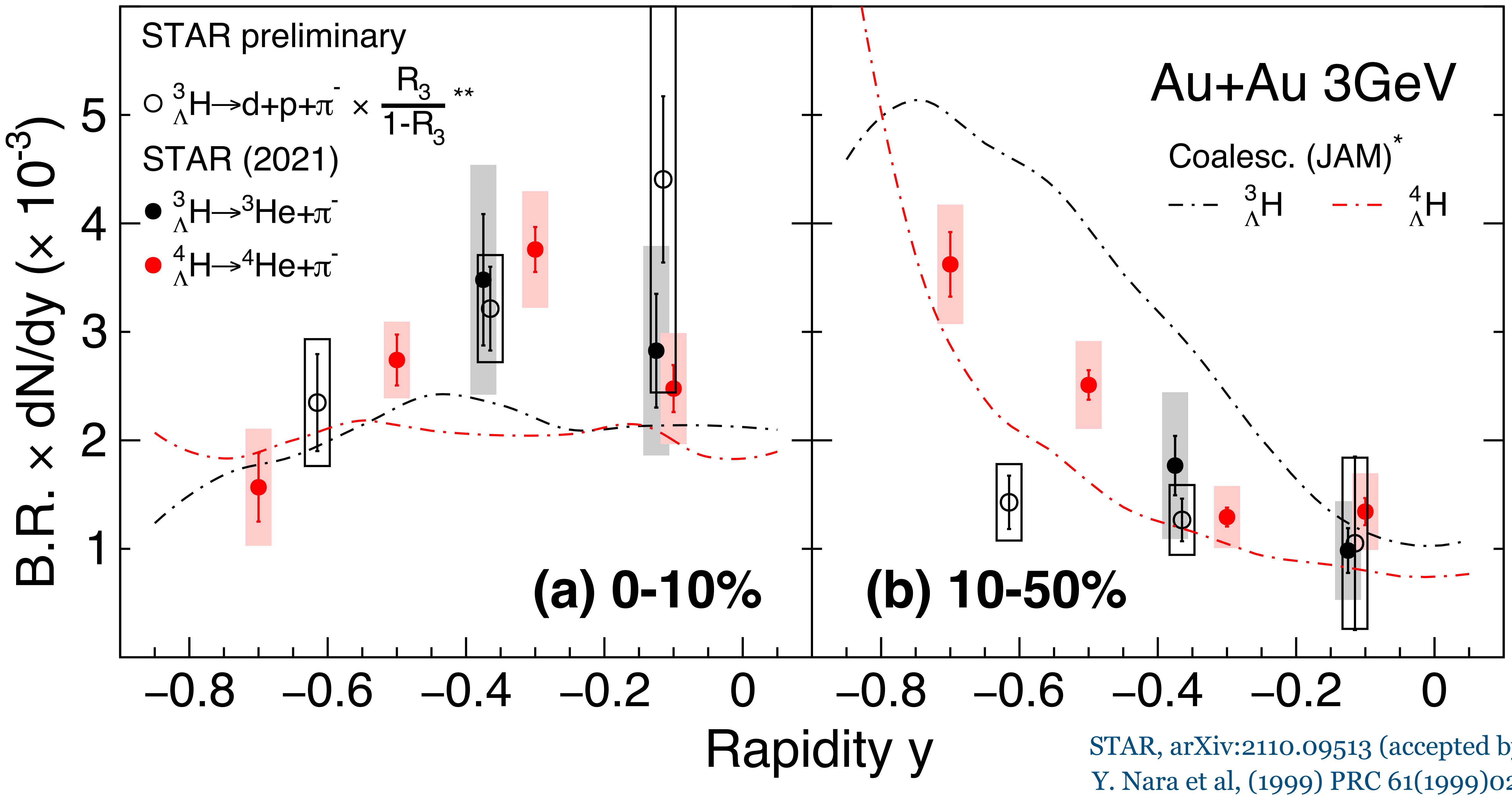
A. Gal (2021), arXiv:2108.10179

$$* \ \frac{\Gamma(^{4}_{\Lambda}\mathrm{He} \rightarrow {}^{4}\mathrm{He} + \pi^0)}{\Gamma(^{4}_{\Lambda}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \pi^-)} \approx \frac{1}{2}$$

$^{3}_{\Lambda}\mathrm{H}, ^{4}_{\Lambda}\mathrm{H}$ production at 3 GeV



STAR, arXiv:2110.09513 (accepted by PRL)



STAR, arXiv:2110.09513 (accepted by PRL)
Y. Nara et al, (1999) PRC 61(1999)024901 (JAM)

- First measurement of dN/dy of hypernuclei in HI collisions
- Different trends in the $^{4}_{\Lambda}\mathrm{H}$ rapidity distribution in central (0-10%) and mid-central (10-50%) collisions

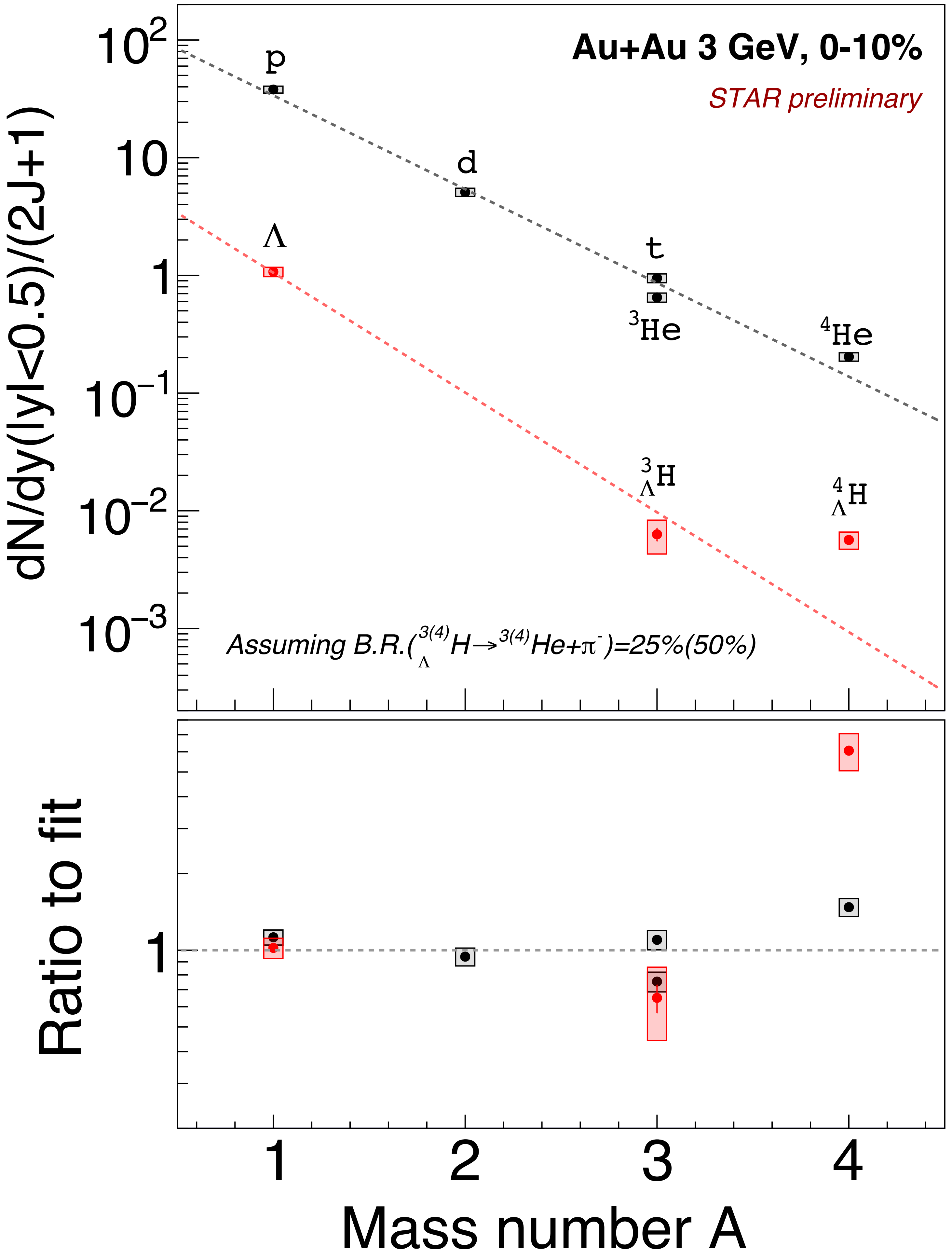
- $^{3}_{\Lambda}\mathrm{H}, ^{4}_{\Lambda}\mathrm{H}$ yields obtained as a function of p_T, rapidity and centrality

Transport model (JAM) with coalescence afterburner* qualitatively reproduces trends of $^{4}_{\Lambda}\mathrm{H}$ rapidity distributions seen in the data

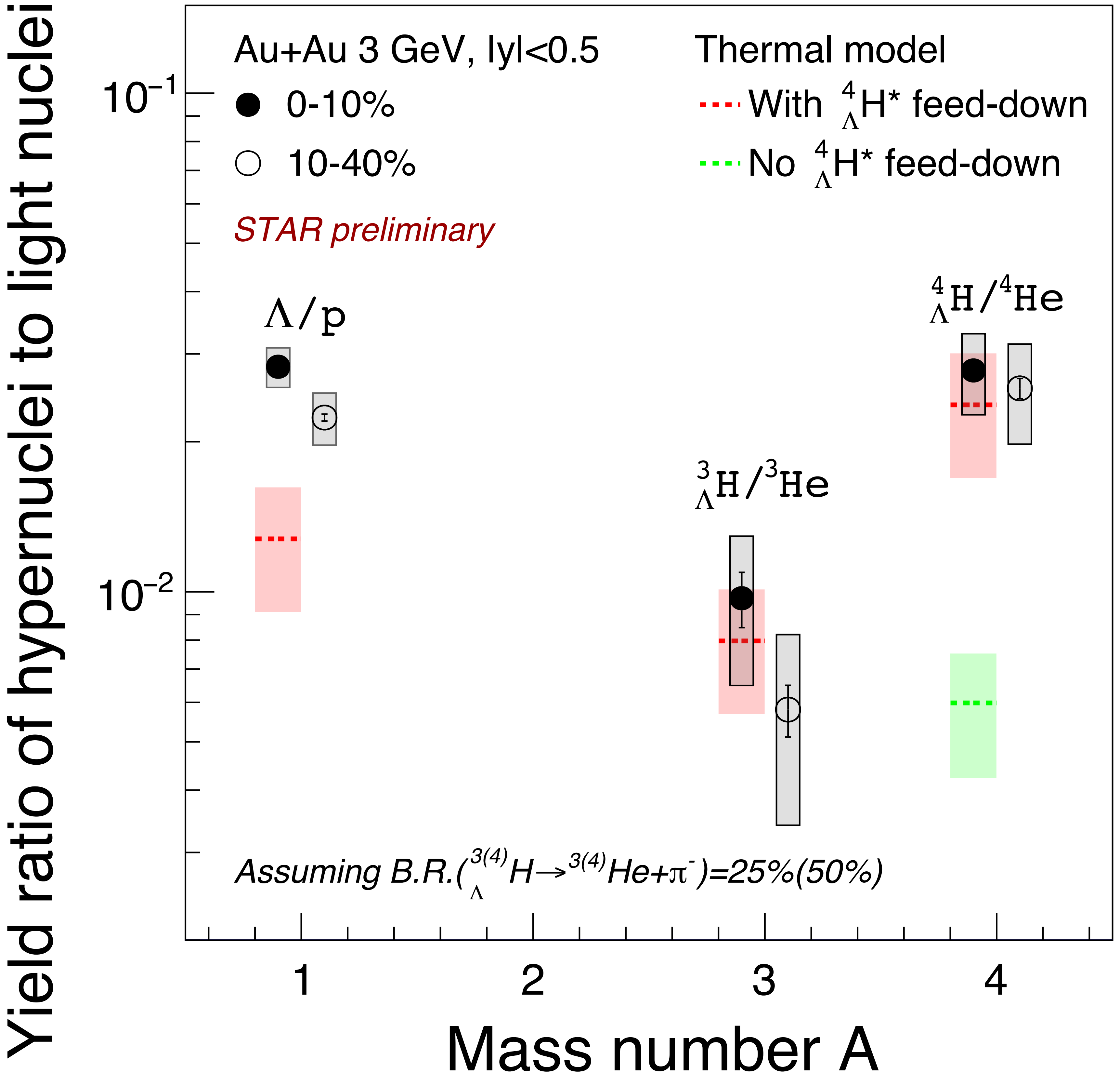
*Coalescence parameters (r_c, p_c) are tuned to fit the data, see backup
**Uncertainty in R_3 (19%) not shown

Comparison to Λ and light nuclei at 3 GeV

See talks by Hui Liu (4/7 T16), Aswini K Sahoo (4/7 T14-I)
See poster by: Yingjie Zhou (4/8 T11_2)

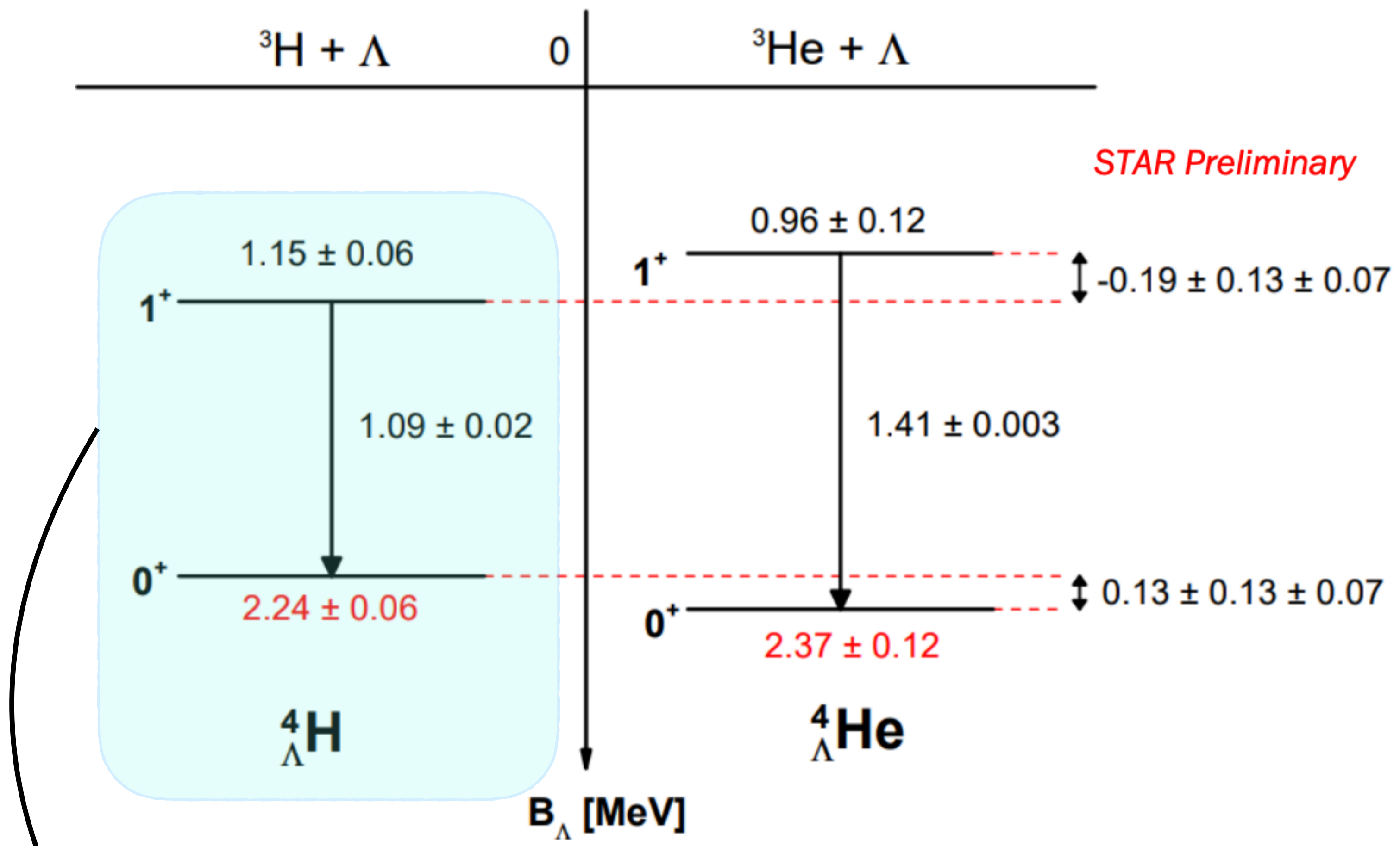


- Thermal/coalescence models predict approx. exponential dependence of yields/(2J+1) vs A
- $^4_\Lambda$H lies a factor of 6 above exponential fit to $(\Lambda, ^3_\Lambda H, ^4_\Lambda H)$



- Non-monotonic behavior in light-to hyper-nuclei ratio vs A observed
  - Thermal model calculations including excited $^4_\Lambda$H* feed-down show a similar trend

Level diagram of A=4 hypernuclei

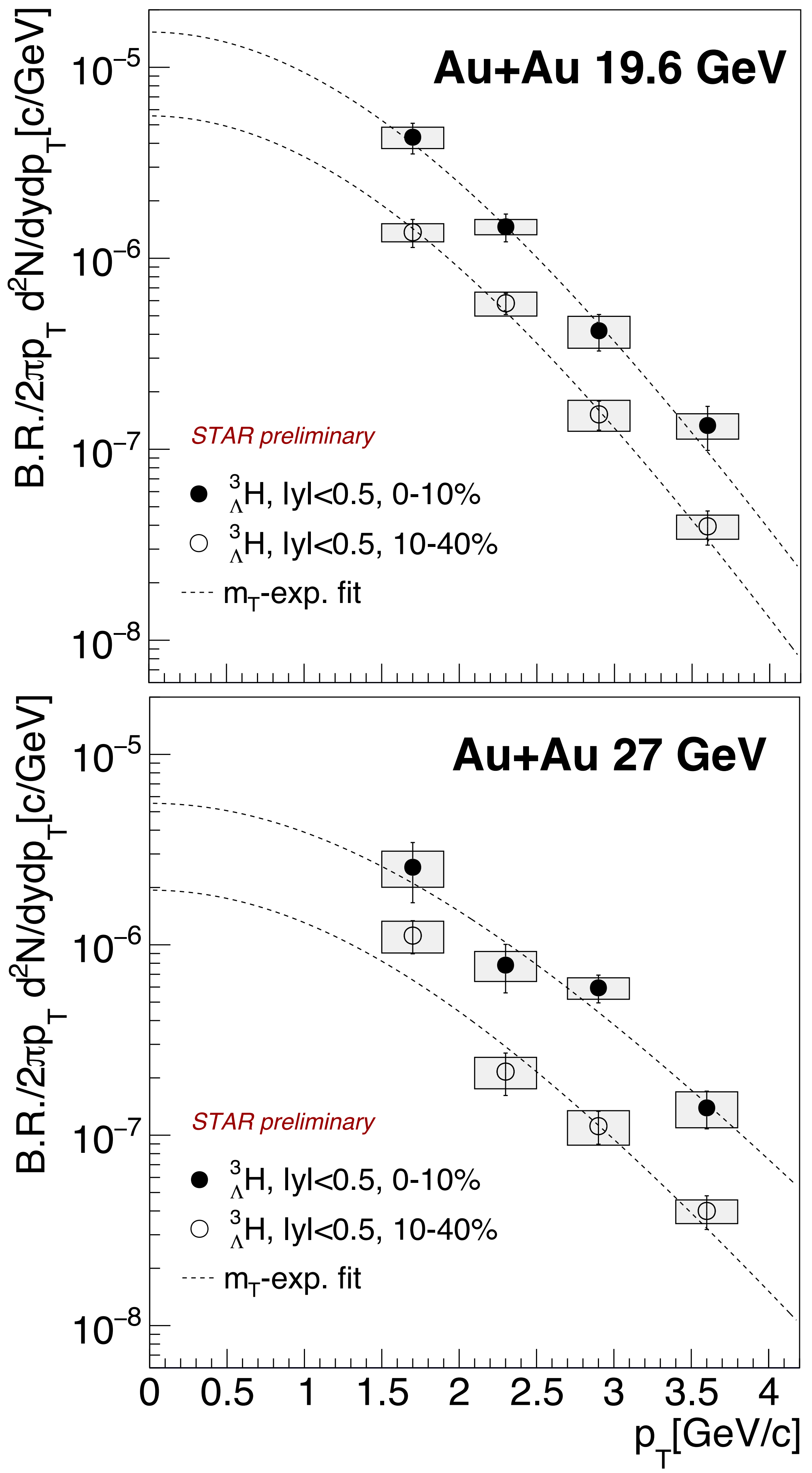


$$^4_\Lambda H^*(J^+ = 1) \to ^4_\Lambda H(J^+ = 0) + \gamma$$

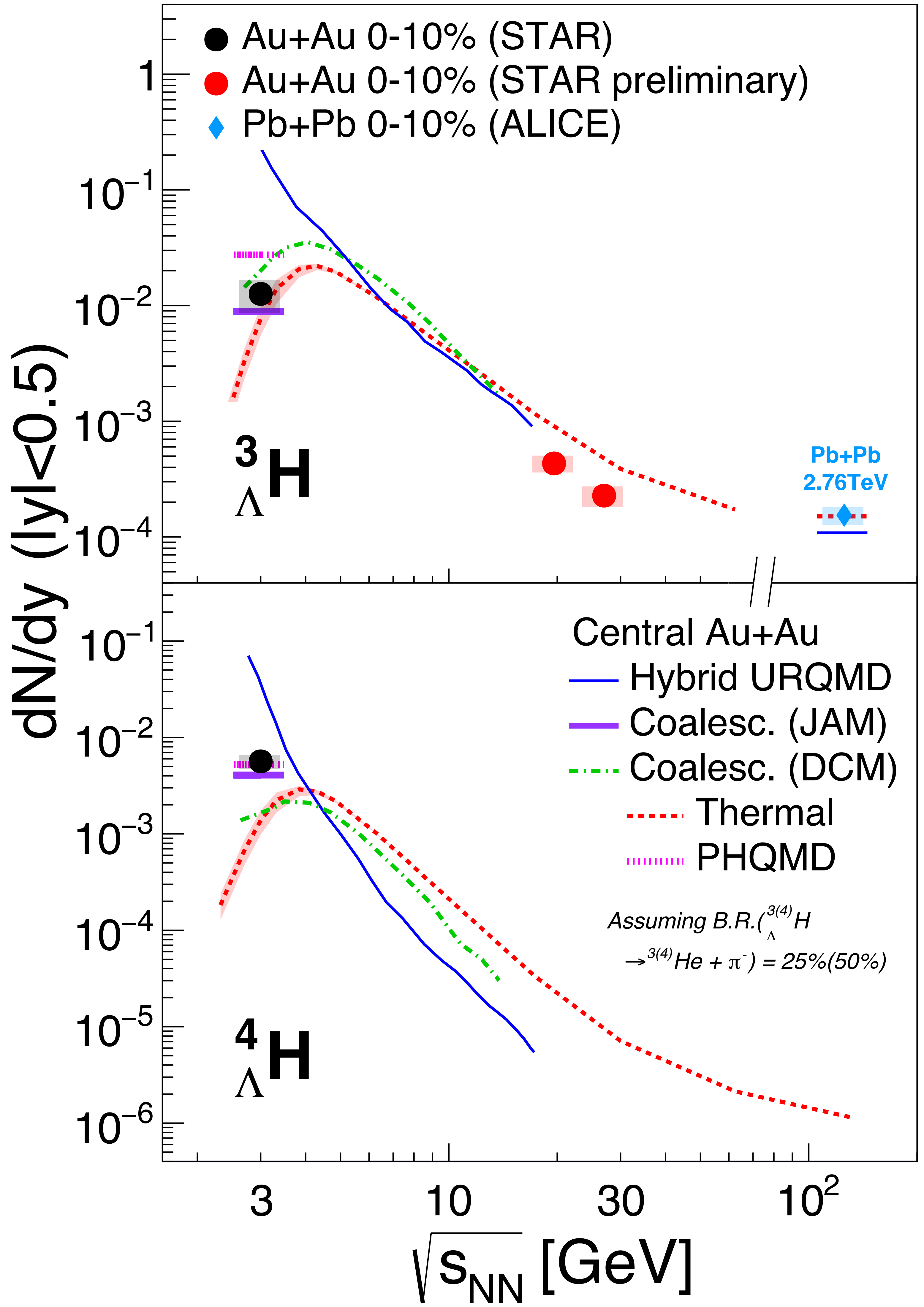
Data support creation of excited A=4 hypernuclei from heavy-ion collisions

A. Andronic et al, PLB 697 (2011)203 (updated, preliminary) (Thermal Model)

Energy dependence of hypernuclei production in heavy-ion collisions



- ${}^{3}_{\Lambda}$H mid-rapidity yields obtained as a function of p_T and centrality at 19.6 and 27 GeV



A. Andronic et al, PLB 697 (2011)203 (updated, preliminary) (Thermal Model)

ALICE, PLB 754 (2016)360

STAR, arXiv:2110.09513 (accepted by PRL)

J. Steinheimer et al, PLB 714(2012),85 (H. URQMD, Coales.(DCM))

Y. Nara et al, PRC 61(1999)024901 (JAM)

S. Gläßel et al, arXiv:2106.14839 (PHQMD)

- ${}^{3}_{\Lambda}$H yield at mid-rapidity increases from 2.76 TeV to 3 GeV
  - Driven by **increase in baryon density** at low energies
- Thermal model (GSI-Heidelberg) reproduces the trend, but does not quantitatively describe the yields
- At 3 GeV,
  - Coalescence model (DCM) cannot simultaneously describe ${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H yields using same coalescence parameters; coalescence model (JAM) using different parameters approximately can
  - PHQMD with $V_{\Lambda N} = 2/3 V_{NN}$ describes ${}^{4}_{\Lambda}$H yield, slightly overestimates ${}^{3}_{\Lambda}$H
  - Hybrid URQMD overestimates yields at 3 GeV by an order of magnitude

New data provide first constraints for hypernuclei production models in the high-baryon-density region

S_3 and S_4 at 3 GeV

See talk by Hui Liu (4/7 T16)

- Strangeness population factor:

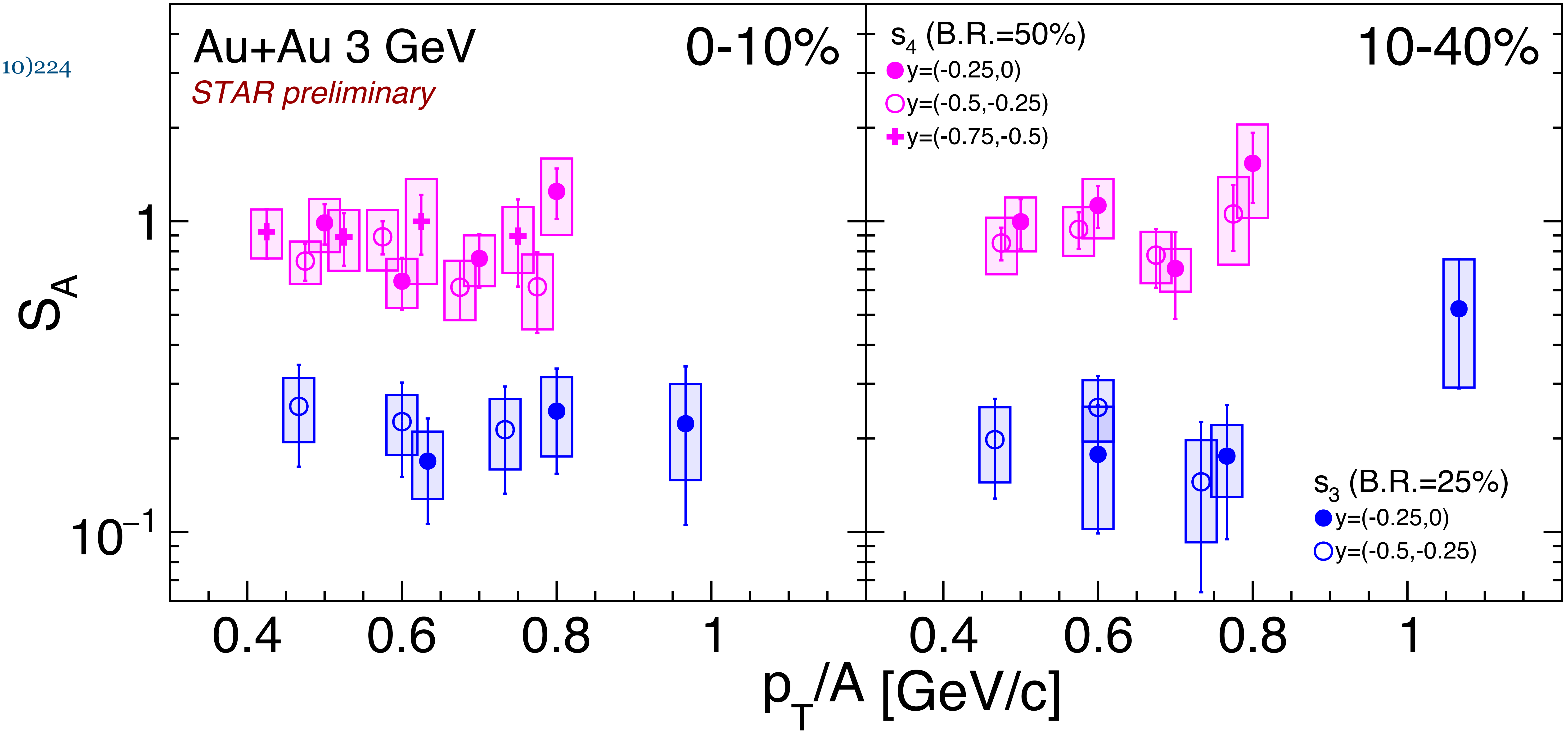
S. Zhang et al, PLB 684(2010)224

$$S_A = \frac{{}^{A}_{\Lambda}\mathrm{H}}{{}^{A}\mathrm{He} \times \frac{\Lambda}{\mathrm{p}}}$$

- The differential analogue is equal to the ratio of coalescence parameters for hypernuclei and light nuclei

$$\frac{{}^{A}_{\Lambda}\mathrm{H}(A \times p_T)}{{}^{A}\mathrm{He}(A \times p_T) \times \frac{\Lambda}{\mathrm{p}}(p_T)} = \frac{B_A({}^{A}_{\Lambda}\mathrm{H})(p_T)}{B_A({}^{A}\mathrm{He})(p_T)}$$

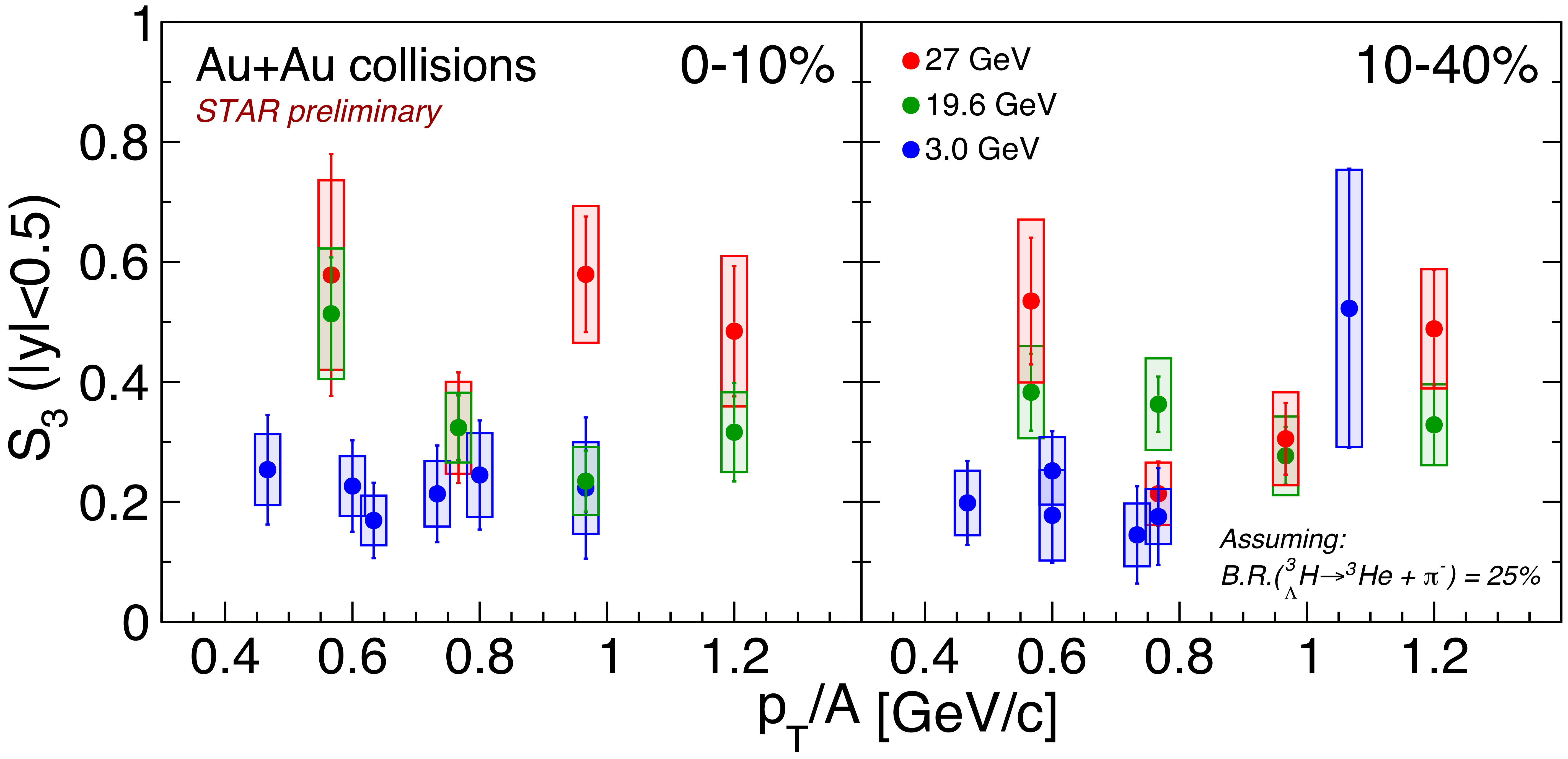
  - $S_3<1$ → relative suppression of hypertriton to ^{3}He production
  - $S_4>S_3$ → enhanced ${}^{4}_{\Lambda}\mathrm{H}$ production due to feed-down from exited state



- Although the B_A of light nuclei varies with p_T/rapidity and centrality, ratio b/w B_A of hypernuclei and light nuclei remains roughly constant

B_A of light nuclei and hypernuclei follow similar trends in p_T/rapidity/centrality

Energy dependence of S_3



- S_3 ratio* obtained for $p_T/A>0.4$ GeV for 3.0, 19.6, 27 GeV, 0-10% and 10-40% centrality

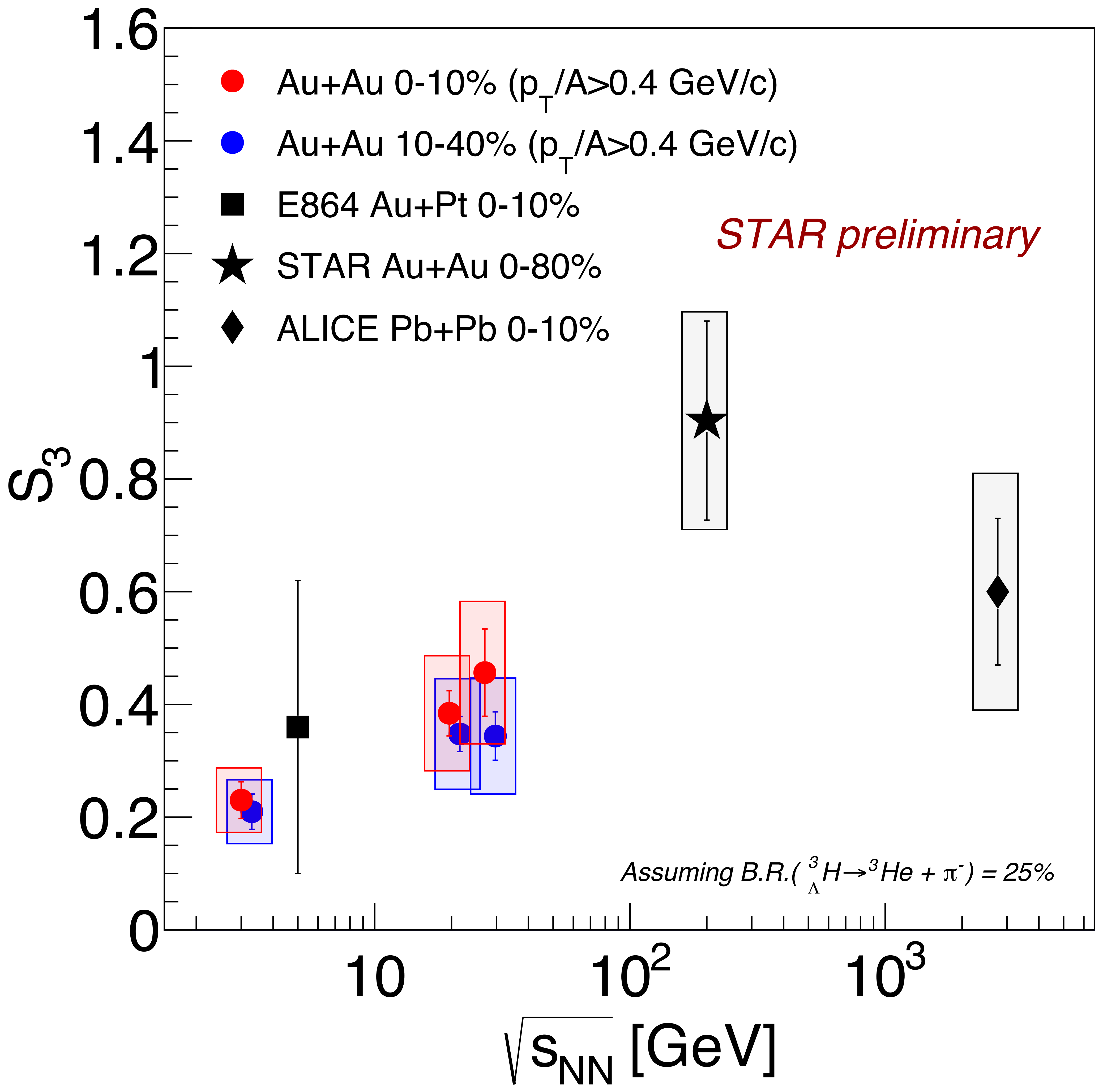
*For 19.6 and 27 GeV, take ^{3}He/t = 0.93±0.07

STAR, Science 328(2010)58

E864, PRC70(2004)024902

ALICE, PLB 754 (2016)360

NA49, J.Phys.Conf.Ser.110(2008)032010



- No clear centrality dependence
- Hint of an increasing trend from $\sqrt{s_{NN}}$ = 3 GeV to 2.76 TeV

Energy dependence of S_3

S_3:
- Does not depend on strangeness canonical volume
- Influenced by feed-down from excited baryonic states

Thermal models

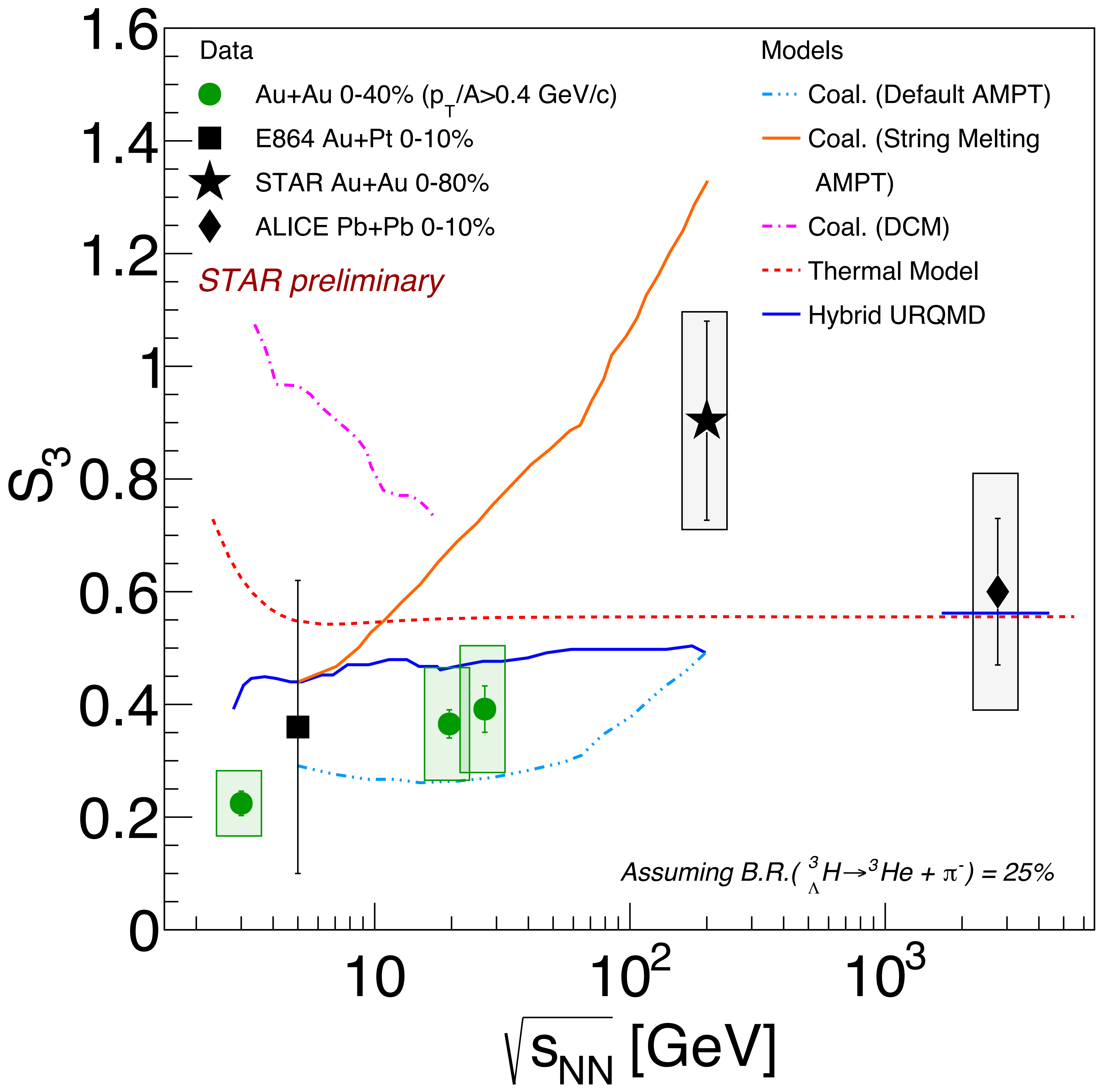
- Weak energy dependence, deviates from data at 3 GeV
- Local correlations b/w baryon number and strangeness is lost in the thermal calculation?

Coalescence models

- Different models predict different trends
- Sensitive to microscopic features:
  - Correlations in the dynamical stage
  - Size of emitting source, etc.

None of the models shown describe the S_3 data quantitatively

- Future measurements:
  - Comprehensive measurements of S_3, S_4 at low (STAR BES-II) and high (RHIC top energy+LHC) energies



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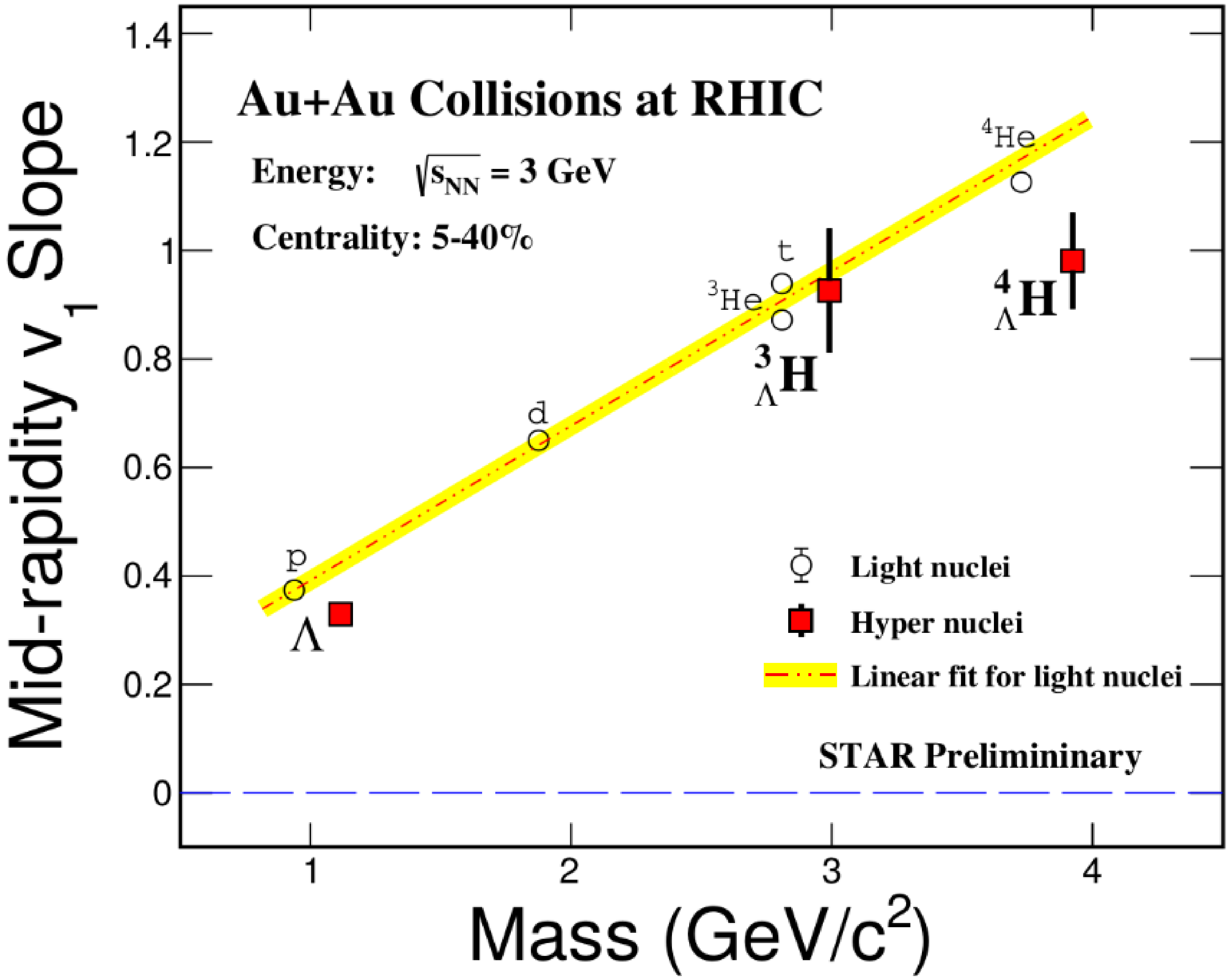
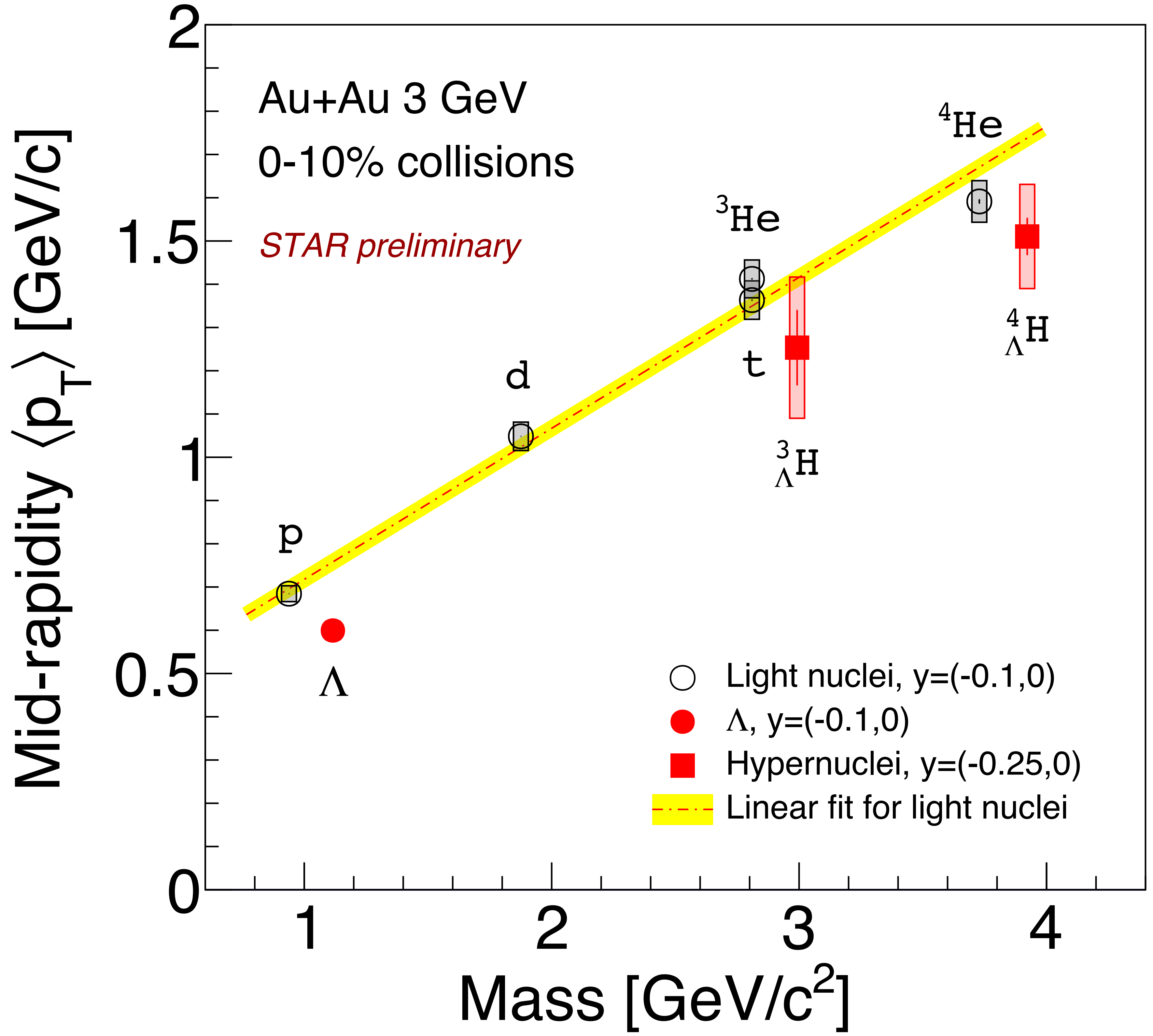
A. Andronic et al, PLB 697 (2011)203 (Thermal Model)
J. Steinheimer et al, PLB 714(2012),85 (H. URQMD, Coales.(DCM))
PLB 684(2010)224 (AMPT+coal.)

*For 19.6 and 27 GeV, take ^{3}He/t = 0.93±0.07

Hypernuclei collectivity at 3 GeV





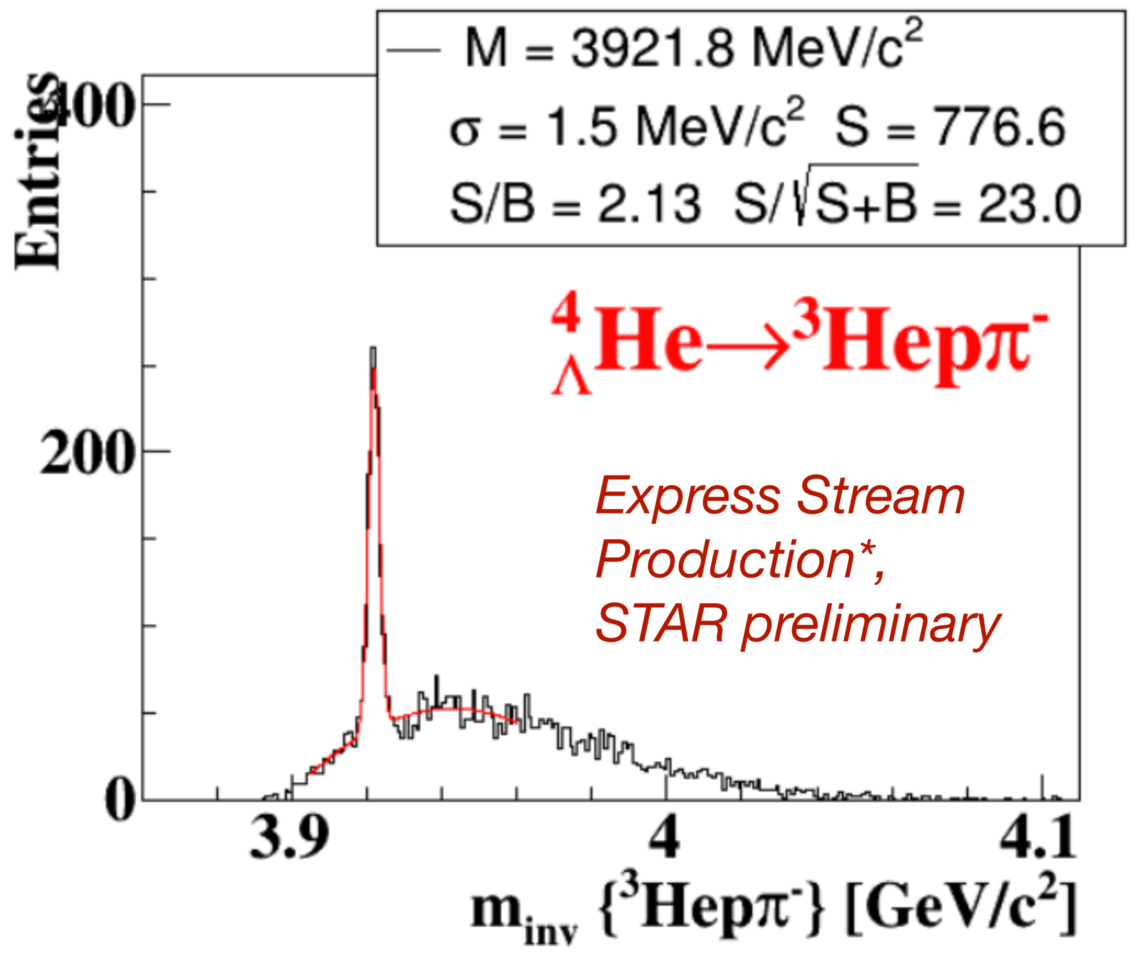
- **First observation of hypernuclei collectivity v_1** in HI collisions
- v_1 slope follows **mass number scaling** in 5-40% 3 GeV Au+Au collisions, similar to light nuclei

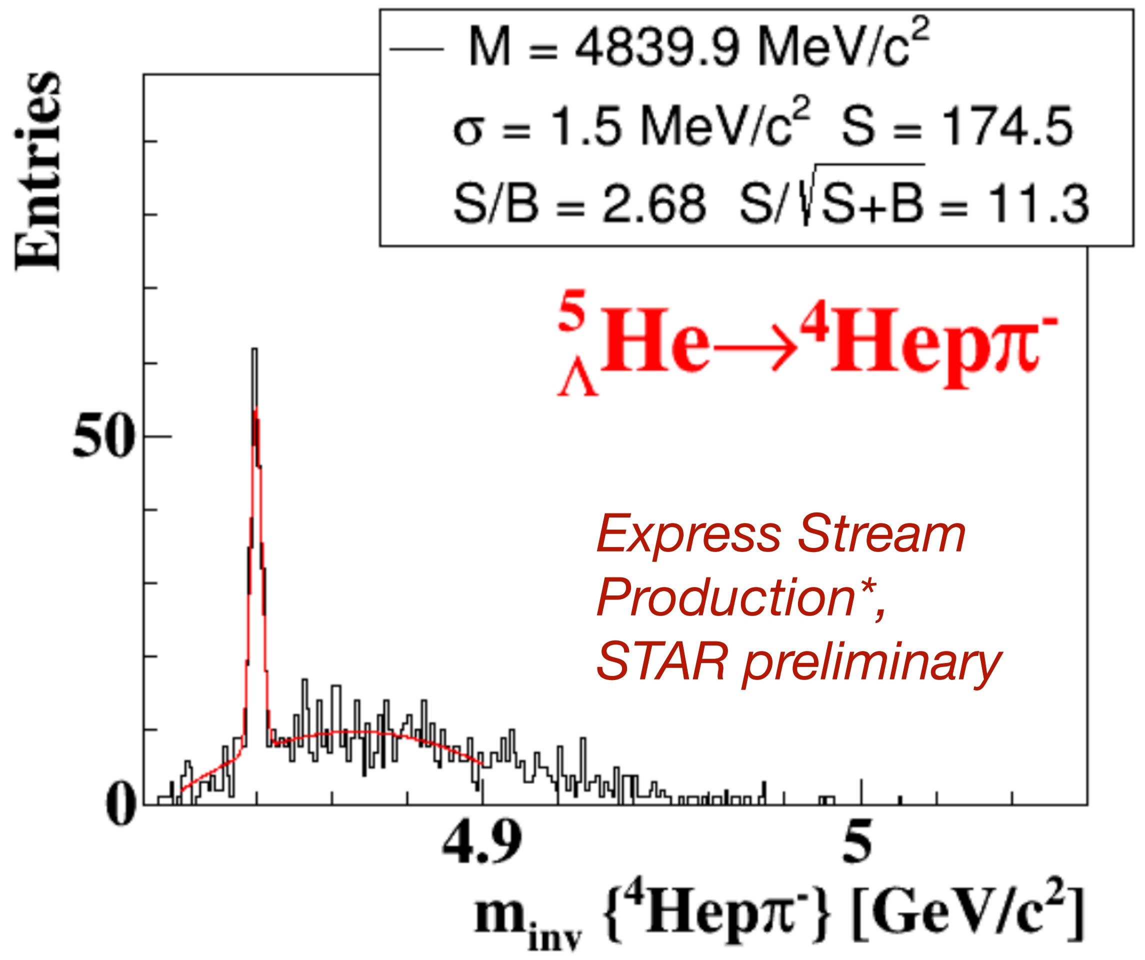
- Linear trend for light and hypernuclei $\langle p_T \rangle$ reflects dominance of collective radial motion

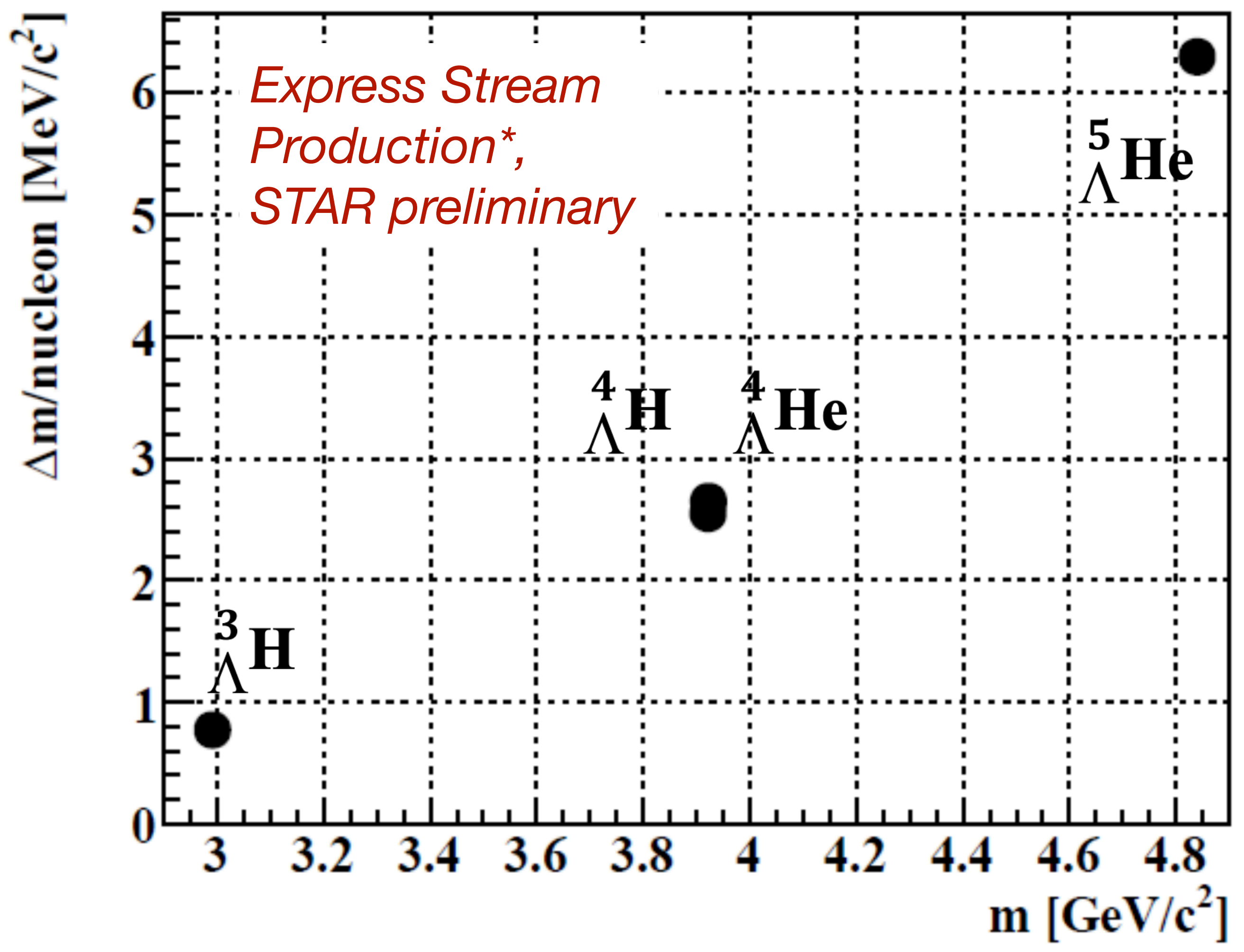
Results qualitatively consistent with hypernuclei production from coalescence of hyperons and nucleons

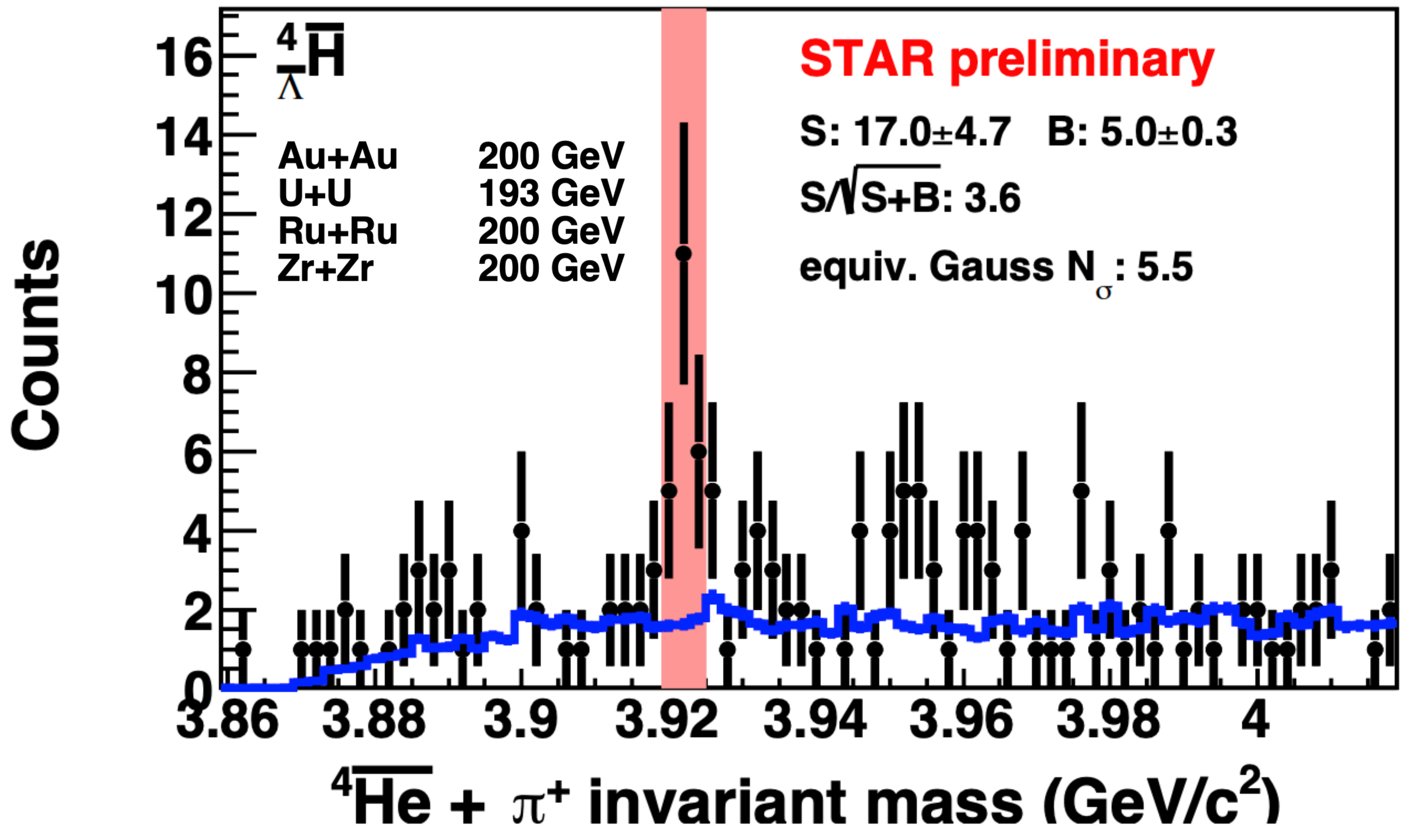
Outlook: BES-II and beyond

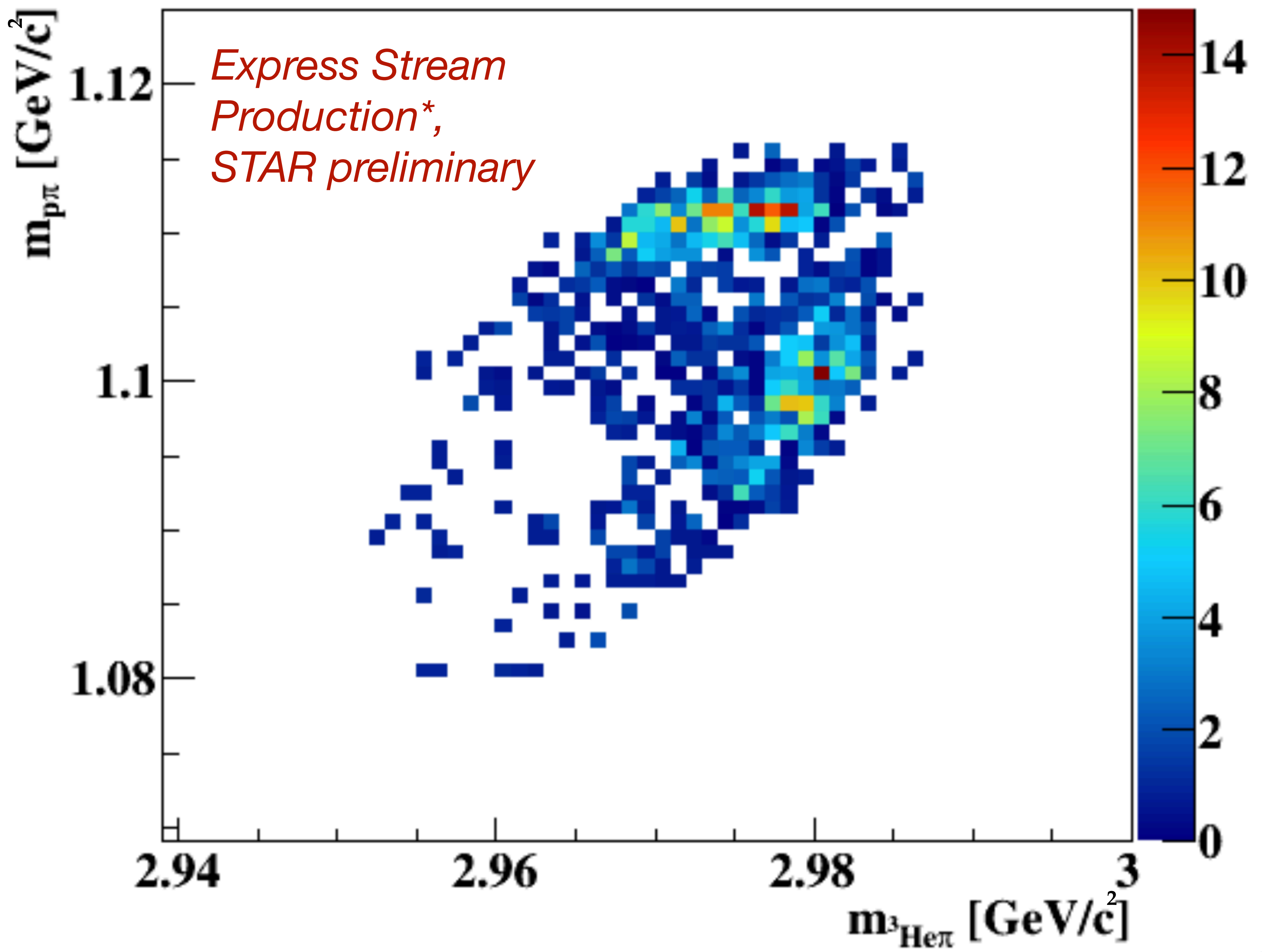
- High statistics BES-II data
  → enable detailed studies on hypernuclei structure up to A=5, e.g.:
  - $^{4}_{\Lambda}$He, $^{5}_{\Lambda}$He yields / lifetime
  - $^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H(e), $^{5}_{\Lambda}$He binding energy
  - Dalitz plot analysis of 3-body decays
- 200 GeV HI collisions (including isobar collisions)
  → opportunity to study anti-hypernuclei
  - **First observation of anti-$^{4}_{\Lambda}$H**











*Data from express stream (Au+Au $\sqrt{s_{NN}}$=3.0, 3.2, 3.5, 3.9, 4.5, 5.2, 6.2, 7.7 GeV) are not with the final calibrations

See poster by Tan Lu (4/8 T16)

Summary

- Presented first set of hypernuclei measurements in the high-baryon-density region with high statistical precision

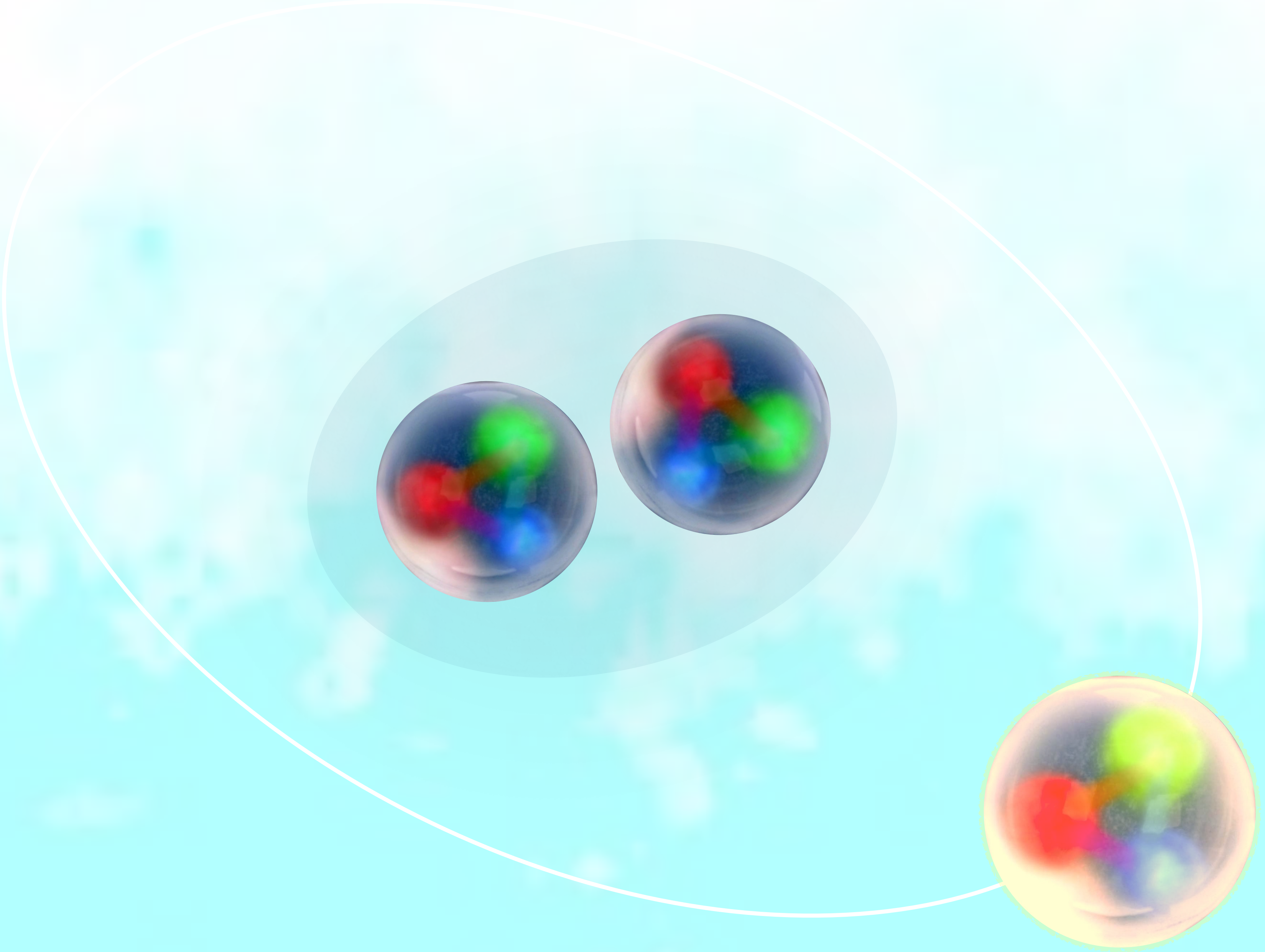
Hypernuclear structure

- ${}^{3}_{\Lambda}H$, ${}^{4}_{\Lambda}H$ **lifetimes measured with improved precision**
  - ${}^{3}_{\Lambda}H$: consistent with calculations incorporating pion FSI
  - A=4 hypernuclei: consistent with expectations from isospin rule
- New R_3 measurement
  - Improved precision gives stronger constraints on hypernuclear interaction models

Production of hypernuclei in heavy-ion collisions

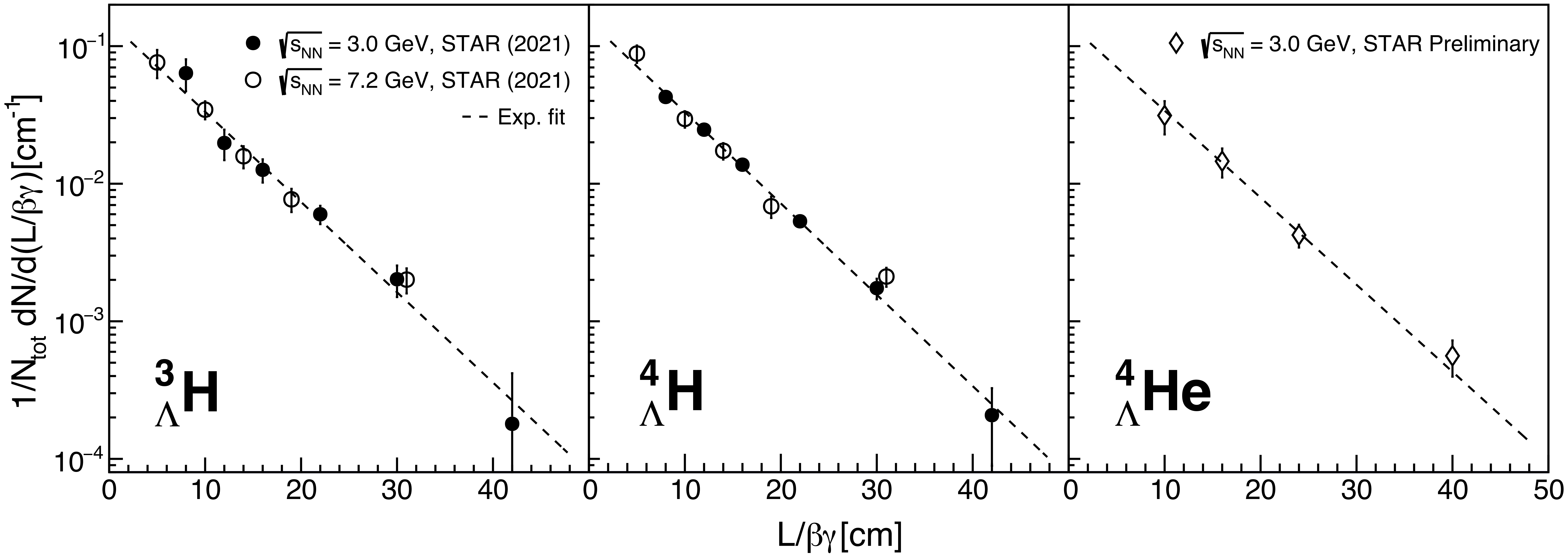
- **First observation of hypernuclei collectivity v_1**
  - Qualitatively consistent with coalescence
- **New measurements of ${}^{3}_{\Lambda}H$, ${}^{4}_{\Lambda}H$ differential yields at 3.0, 19.6 and 27 GeV**
  - Provide first constraints to hypernuclei production models @ high μ_B
  - S_3 shows weak centrality/kinematic dependence at fixed $\sqrt{s_{NN}}$; hint of increasing trend vs $\sqrt{s_{NN}}$, in tension with model calculations

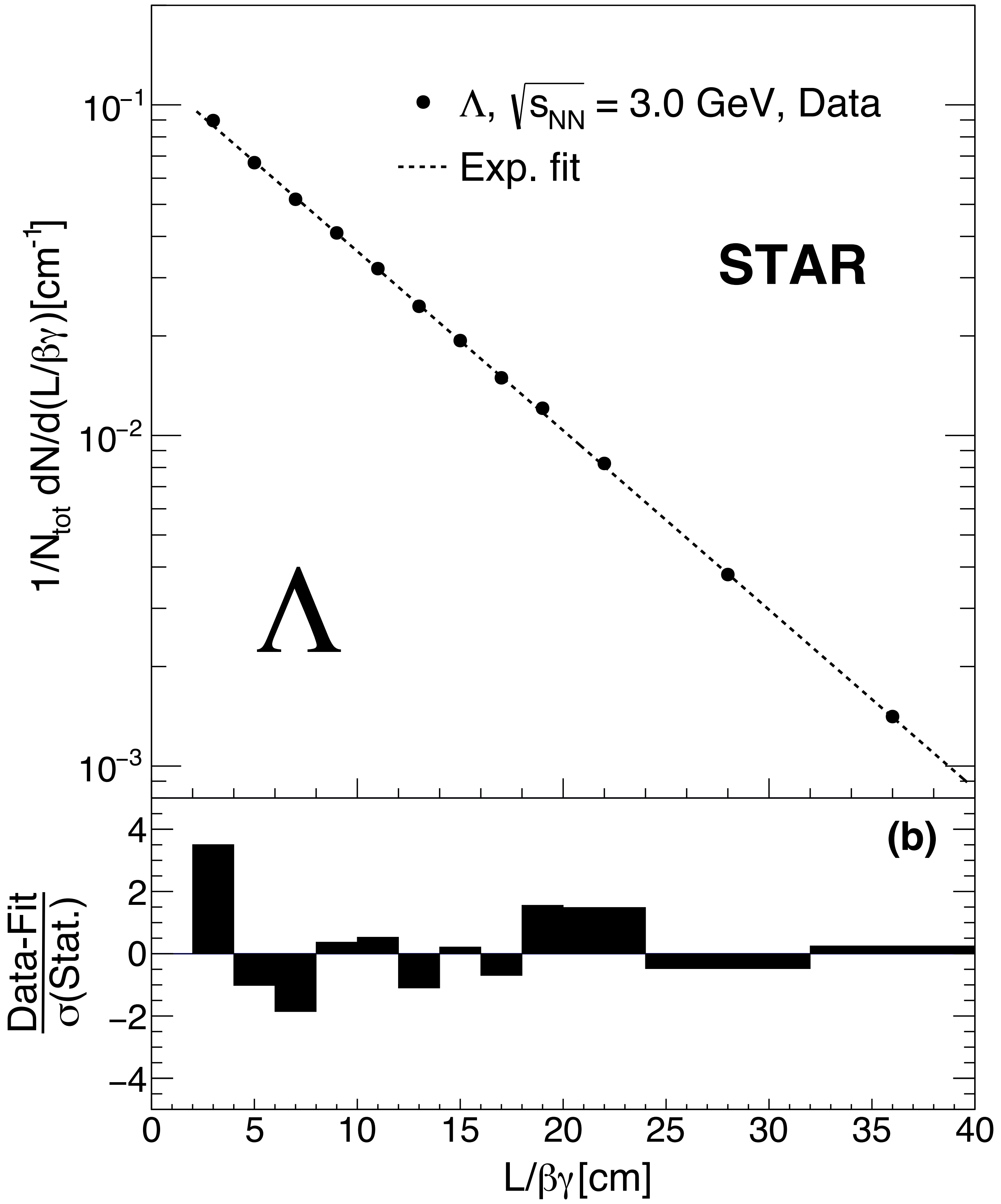
Thank you for listening !!



Backup slides follow

Analysis details: measuring lifetimes of hypernuclei





STAR, arXiv:2110.09513

- Lifetime of $^{3}_{\Lambda}H, ^{4}_{\Lambda}H, ^{4}_{\Lambda}He$ extracted via exponential fit to $\frac{dN}{d(L/\beta\gamma)}$ distributions
- Extracted Λ lifetime $267 \pm 4[ps]$ consistent with PDG $263 \pm 2[ps]$
- $^{3}_{\Lambda}H, ^{4}_{\Lambda}H$ lifetimes from 3.0 GeV consistent with 7.2 GeV analysis

$$\tau(^{3}_{\Lambda}H) = 221 \pm 15(stat) \pm 19(syst)[ps]$$

$$\tau(^{4}_{\Lambda}H) = 218 \pm 6(stat) \pm 13(syst)[ps]$$

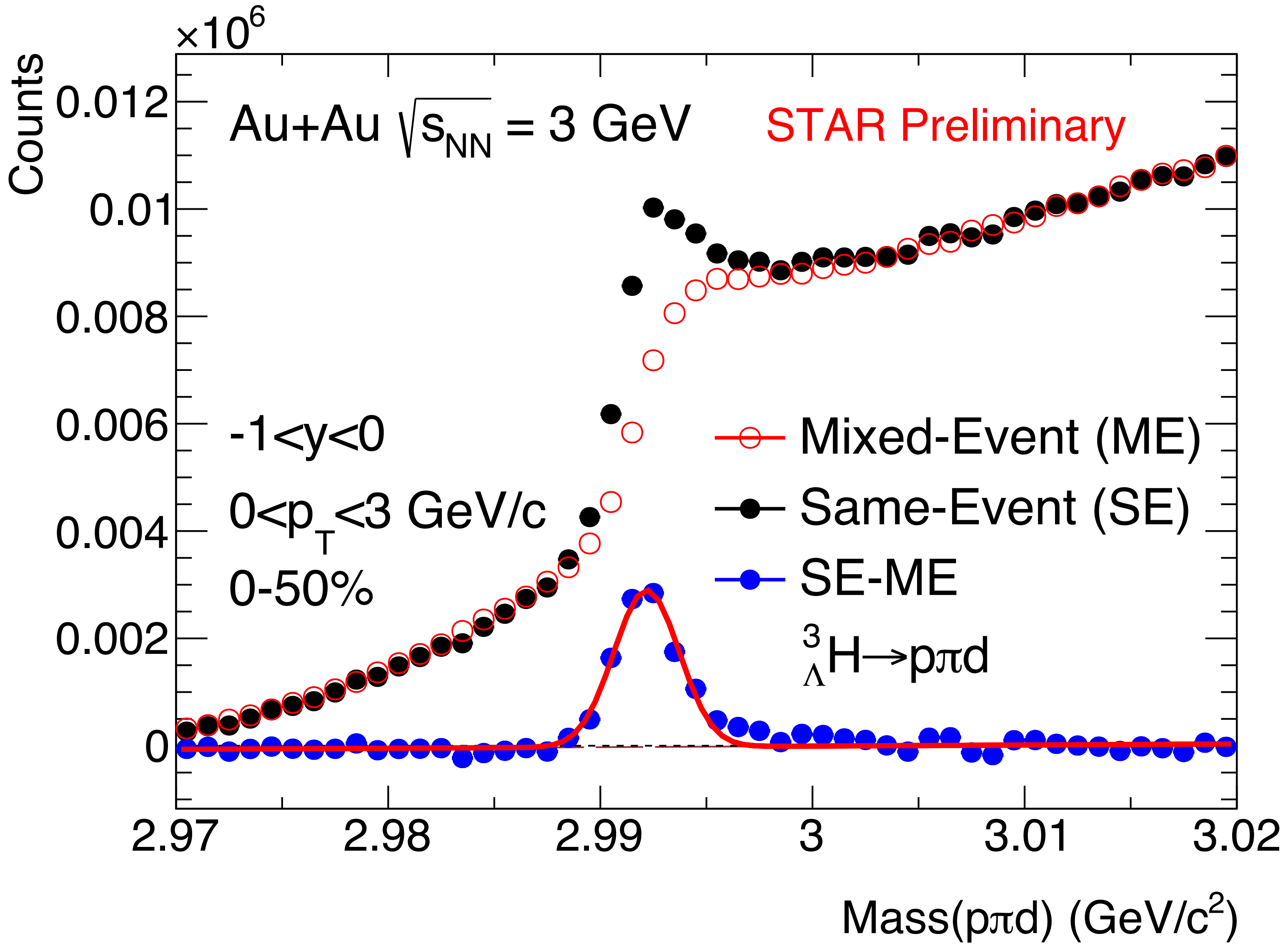
$$\tau(^{4}_{\Lambda}He) = 229 \pm 23(stat) \pm 20(syst)[ps]$$

Analysis details: $^{3}_{\Lambda}\mathrm{H}$ reconstruction via 3-body decay

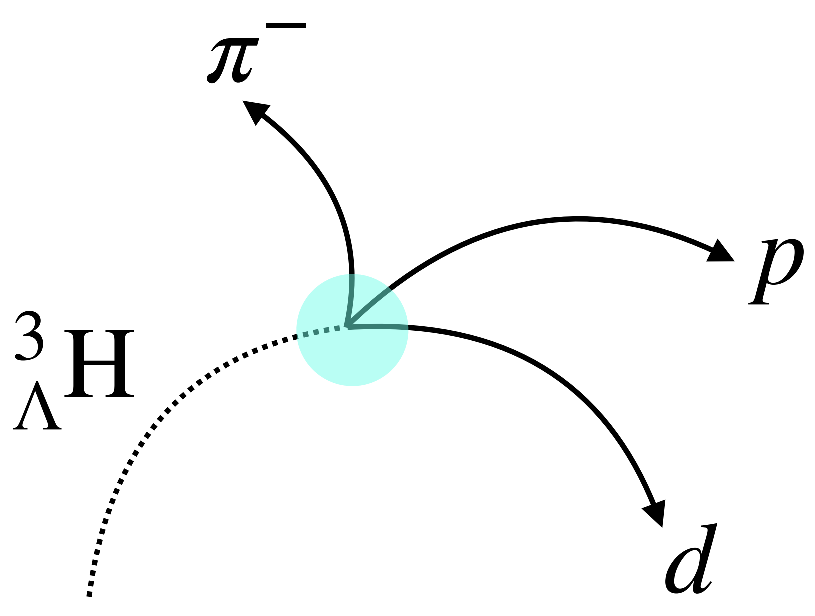
See poster by Yuanjing Ji (4/8 T16)

- To obtain corrected yields from hypertriton 3-body decay $^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{p} + \pi^{-}$:

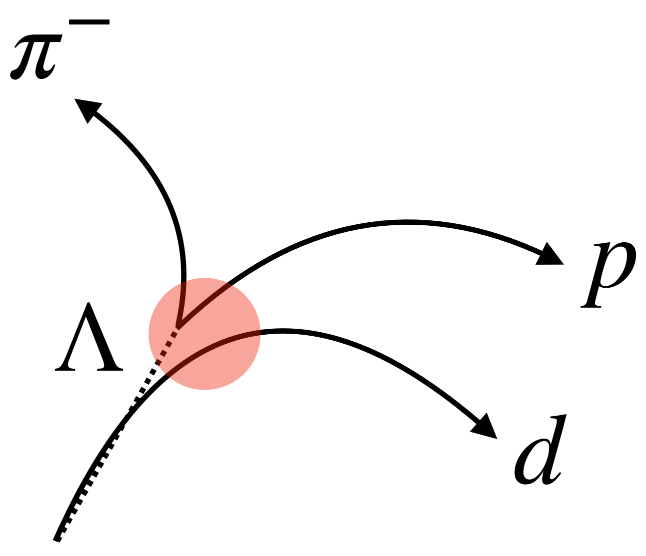
- 1. Subtract uncorrelated background, estimated via event-mixing



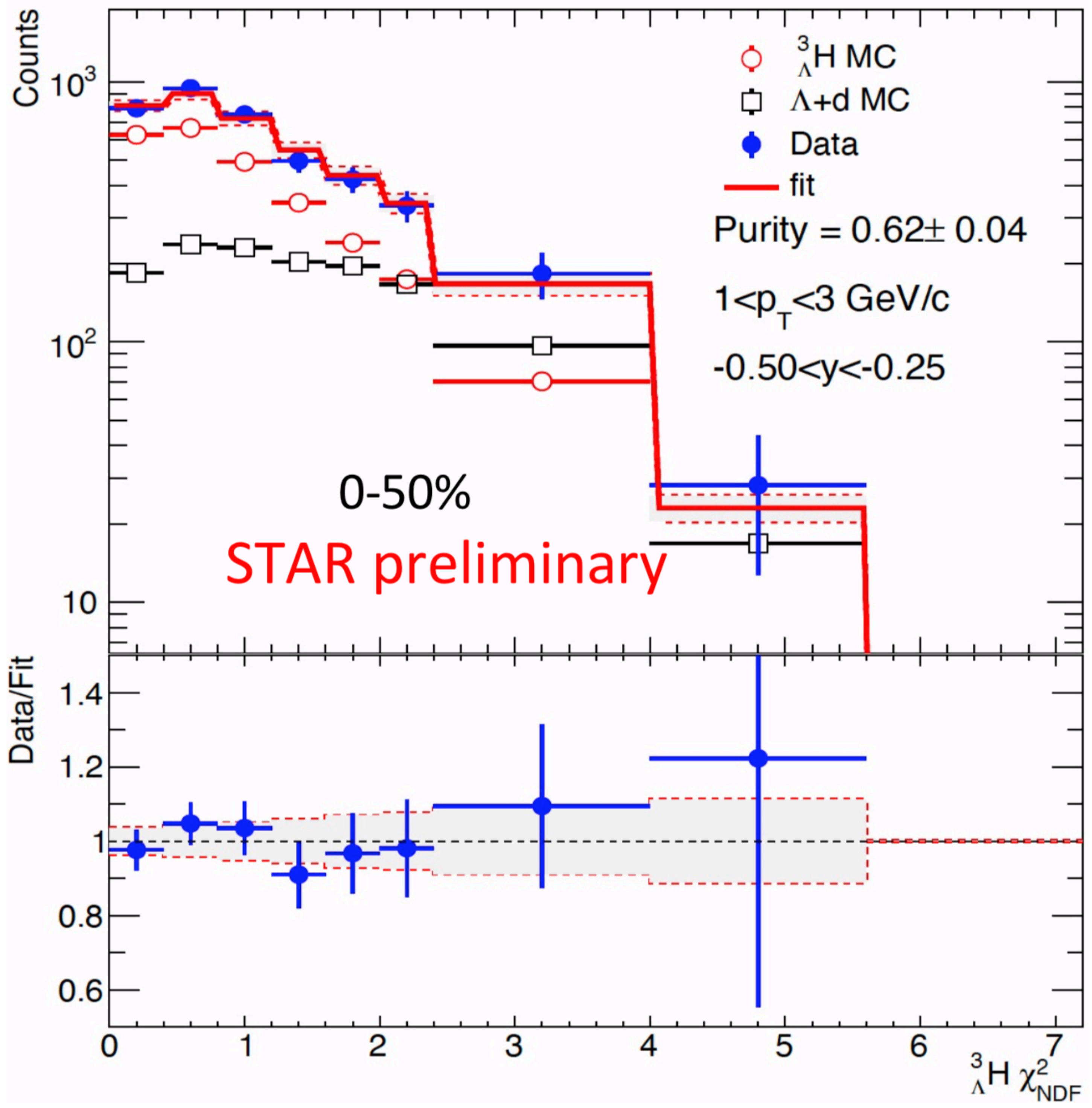
- 2. Excess around hypertriton peak contains contamination correlated backgrounds
  - Purity estimated via template fit to χ^2 of secondary vertex fit



Real signal: lower χ^2



Backgrounds: higher χ^2



- 3. Correct for efficiency of real signal

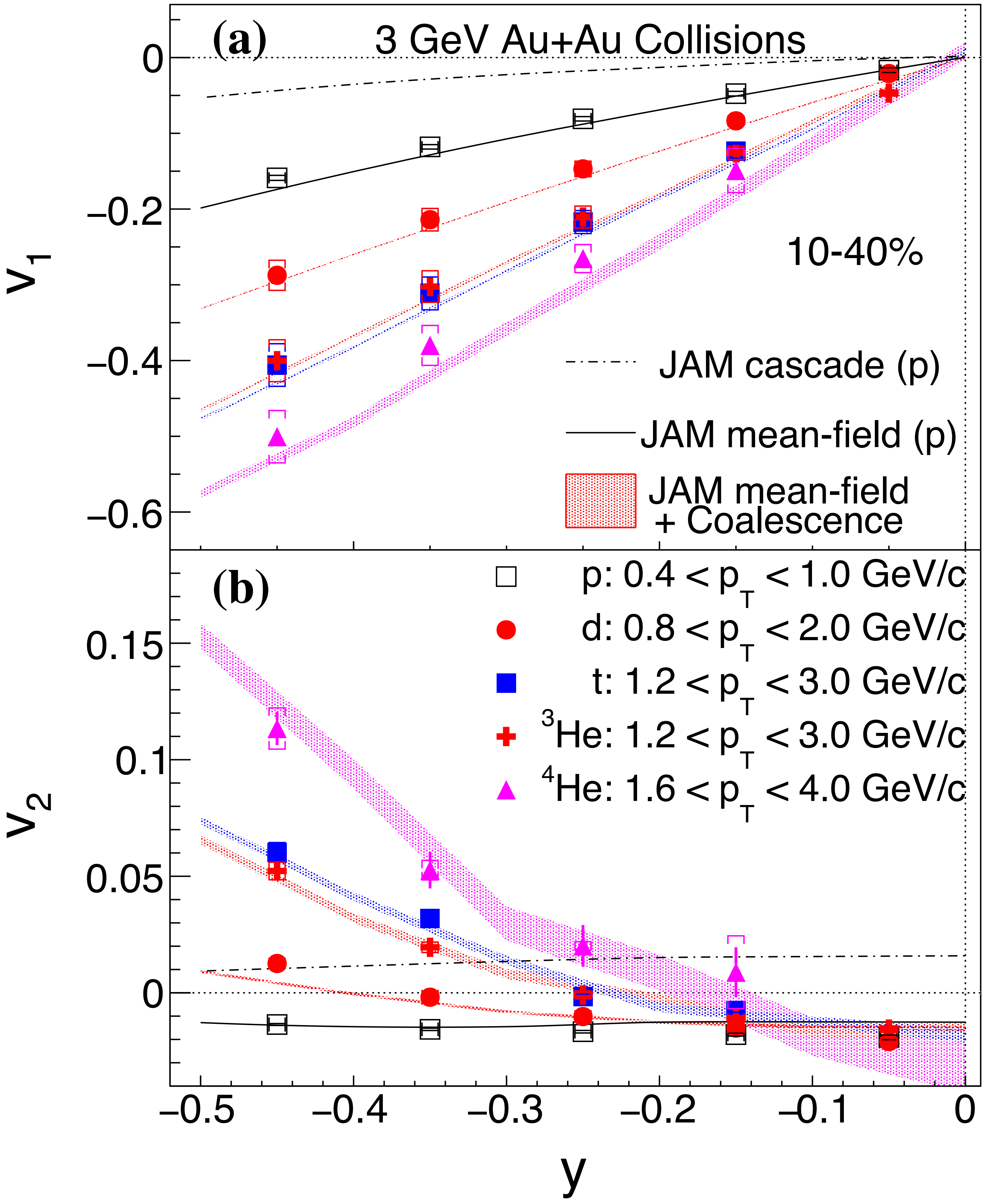
JAM + coalescence afterburner

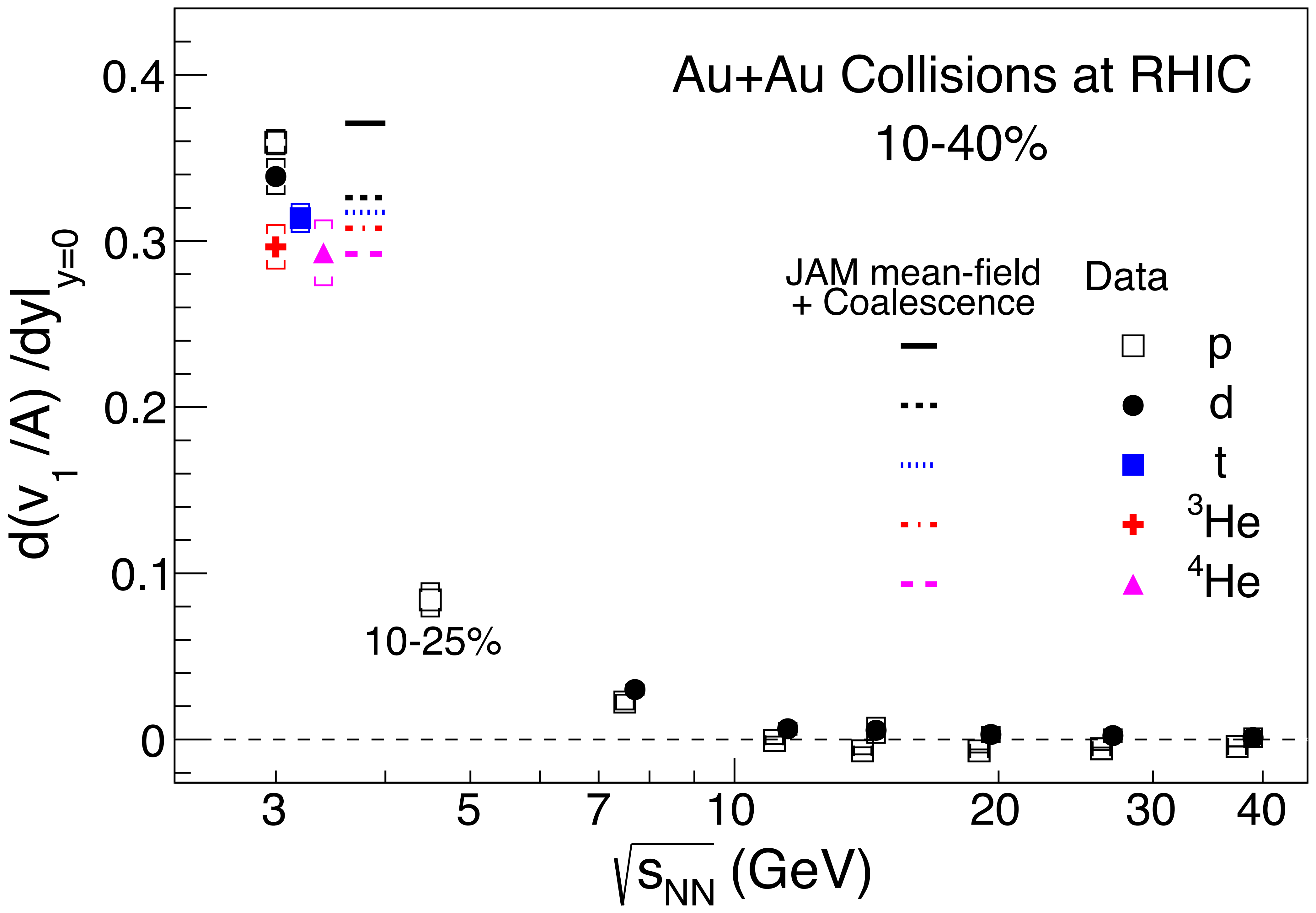
- Coalescence afterburner applier to all produced hadrons
- Deuterons and tritons formed through coalescence of nucleons
- Hypernuclei formed subsequently through coalescence of lambdas with deuterons and tritons
- Coalescence takes place if the spacial coordinates and relative momenta of constituents are within a spere of radius (r_c, p_c)

	r_c [fm]	p_c [GeV/c]
d	4.5	0.3
t	4	0.3
$^{3}_{\Lambda}\mathrm{H}$	4	0.12
$^{4}_{\Lambda}\mathrm{H}$	4	0.3

Light nuclei collectivity at 3 GeV

STAR, Phys.Lett.B 827(2022)136941





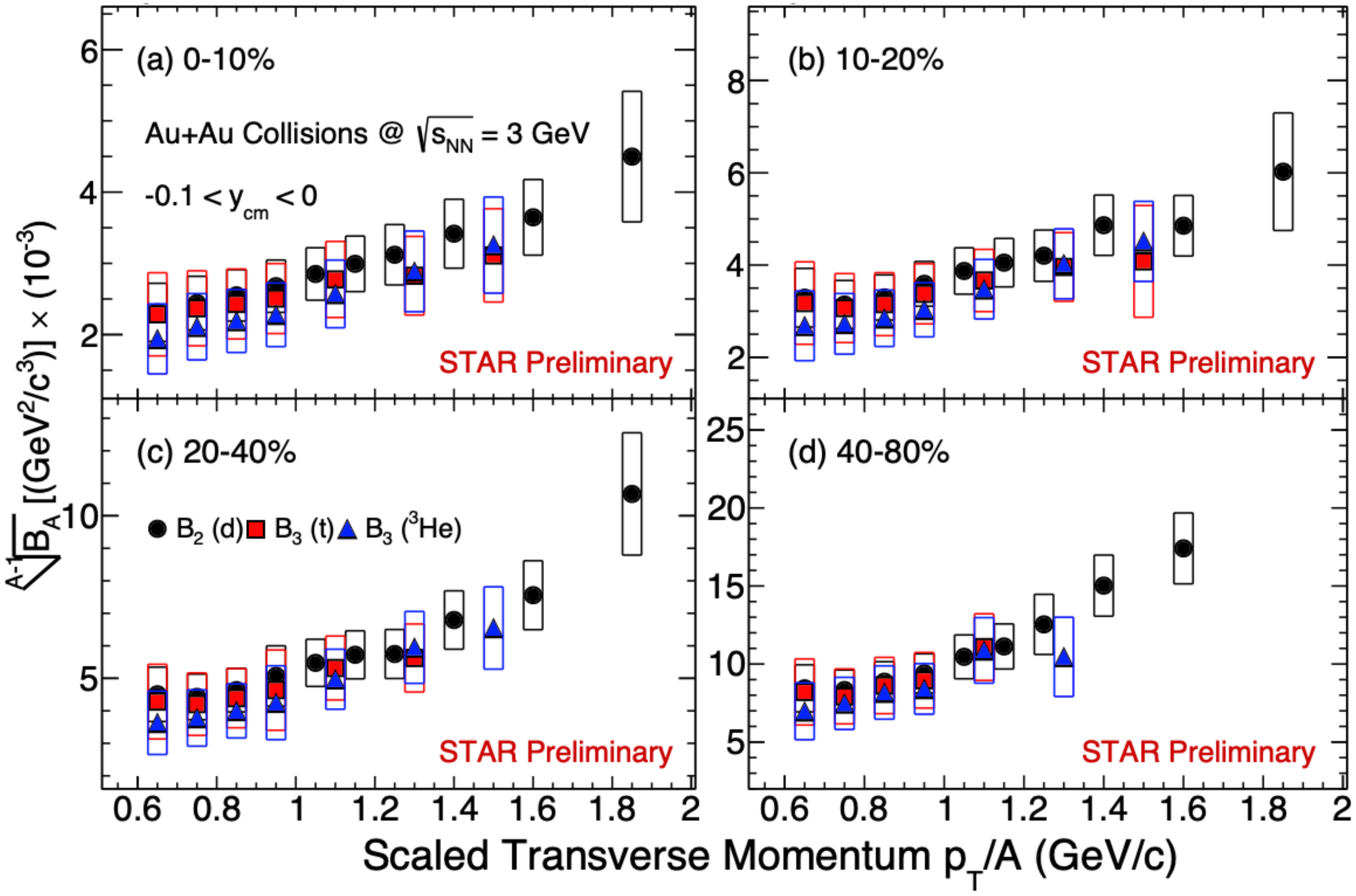
- Different scaling behavior of light nuclei dv_1/dy at low ($\sqrt{s_{NN}} \le 7.7$ GeV) and high ($\sqrt{s_{NN}} > 11.5$ GeV) energies
  → partonic vs hadronic medium?

- JAM model with baryonic mean-field and coalescence afterburner qualitatively reproduce v_1 and v_2

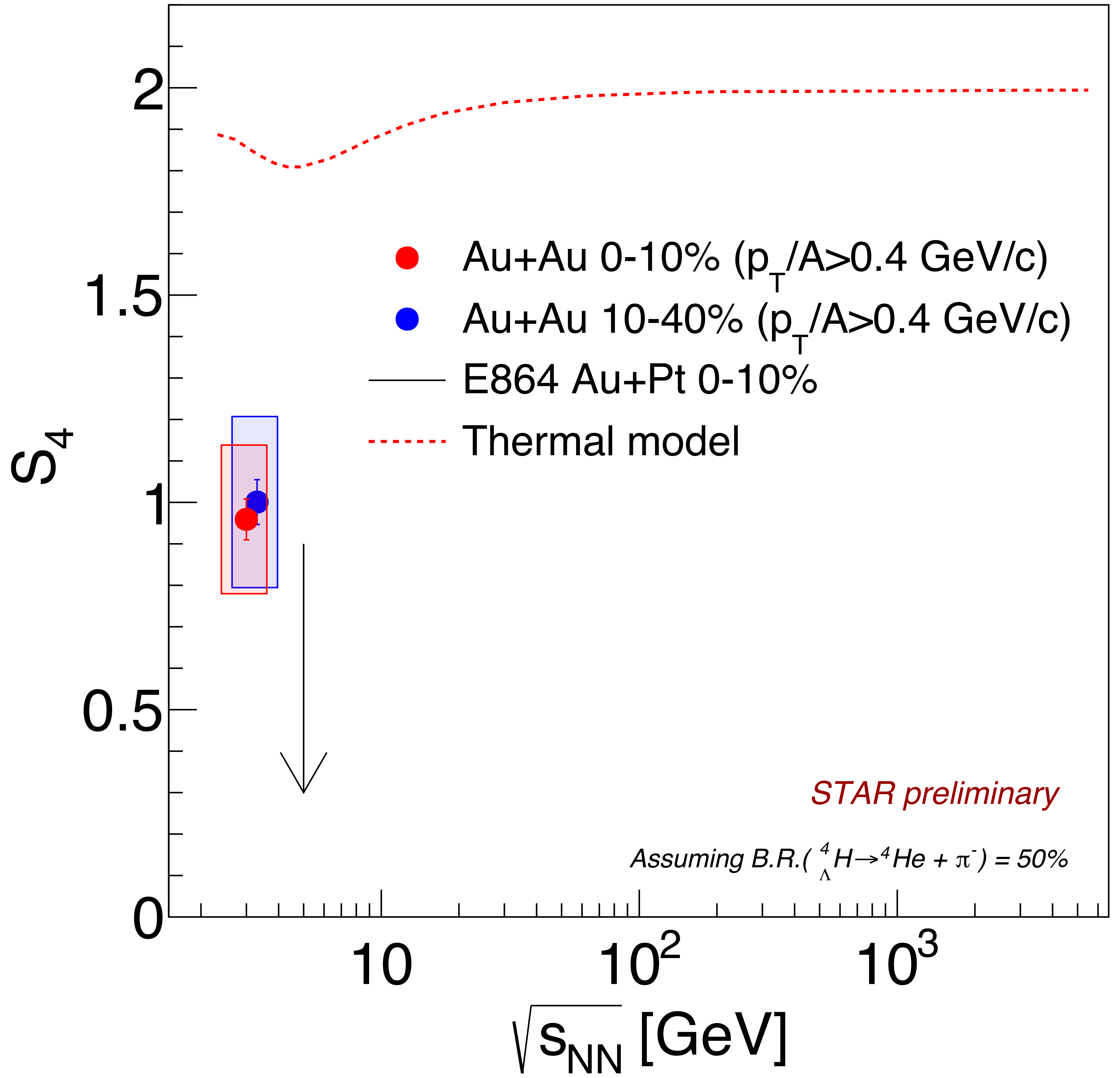
Data implies that at 3 GeV, light nuclei are likely formed via coalescence; baryonic interactions dictate their dynamics

Light nuclei coalescence parameters and S_4

$$E_A \frac{d^3N_A}{dp_A^3} = B_A \left(E_p \frac{d^3N_p}{dp_p^3}\right)^Z \left(E_n \frac{d^3N_n}{dp_n^3}\right)^{A-Z} \approx B_A \left(E_p \frac{d^3N_p}{dp_p^3}\right)^A \Big|_{p_p=p_n=\frac{p_A}{A}}$$



- $B_A \propto (1/V)^{A-1}$



- Similar to S_3, thermal model overestimates S_4 at low energies