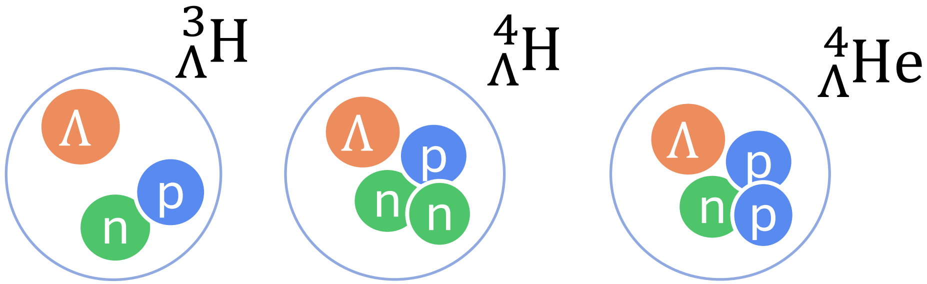
SQM 2024

The 21st International Conference on Strangeness in Quark Matter
3-7 June 2024, Strasbourg, France



Measurements of Hypernuclei Properties and Production at RHIC

Yuanjing Ji
Lawrence Berkeley National Laboratory

BERKELEY LAB

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Outline

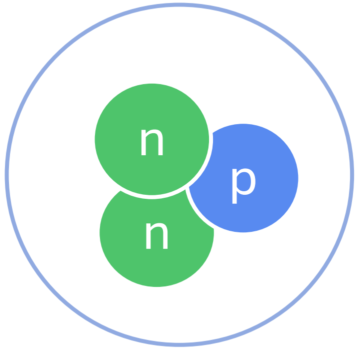
- Introduction
- RHIC Beam Energy Scan II and STAR Detector
- Hypernuclei Intrinsic Properties
  - Lifetime, ${}^{3}_{\Lambda}\mathrm{H}$ B_Λ and R_3
- Hypernuclei Production
  - Energy Dependence of dN/dy and $\langle p_T \rangle$ from 3-27 GeV Au+Au Collisions
  - Multiplicity Dependence from 200 GeV Ru+Ru/Zr+Zr Collisions
- Summary and Outlook

What are Hypernuclei?

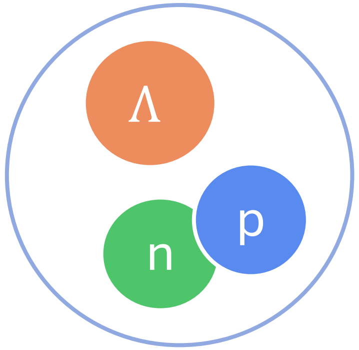
Hypernucleus: A bound system of nucleons with ≥ 1 hyperon.

Hyperon: A baryon with ≥ 1 strange quark (e.g. Λ, Ξ, Ω etc).

Additional dimension in chart of nuclides

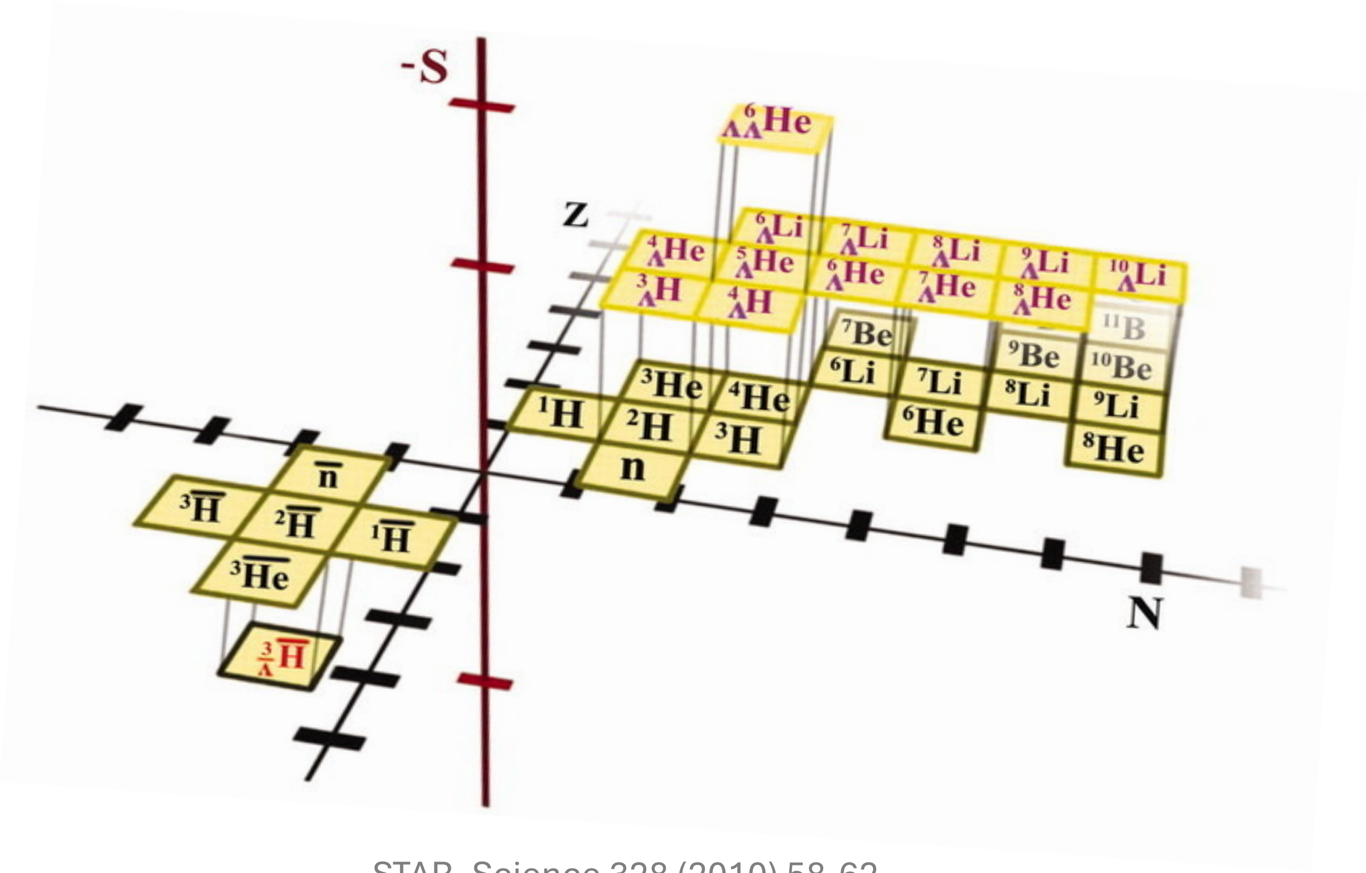


^{3}H(t)



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

lightest hypernucleus



STAR, Science 328 (2010) 58-62

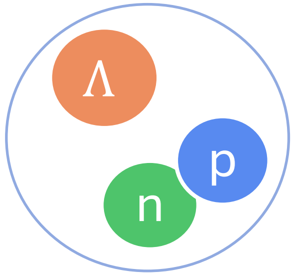
Hypernuclei and Hyperon-Nucleon (Y-N) Interaction

Hypernuclei -> probe to Y-N (Y-N-N) interaction

- Inner structure governed by interactions between nucleons (and hyperons)

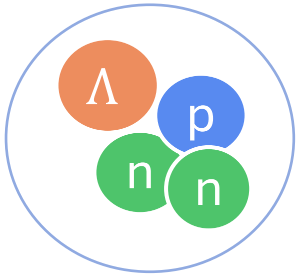
Hypertriton ($^{3}_{\Lambda}\mathrm{H}$)

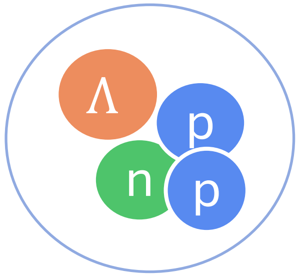
A=3:



Hyperhydrogen-4 ($^{4}_{\Lambda}\mathrm{H}$) Hyperhelium-4 ($^{4}_{\Lambda}\mathrm{He}$)

A=4:



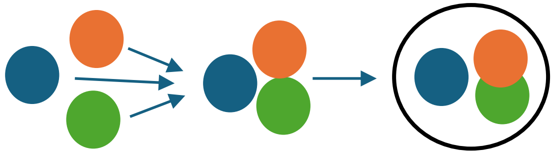


Intrinsic Properties

- How tight they bind together
- How they decay: lifetime, branching ratio

Production mechanism

- How they form in heavy ion collisions

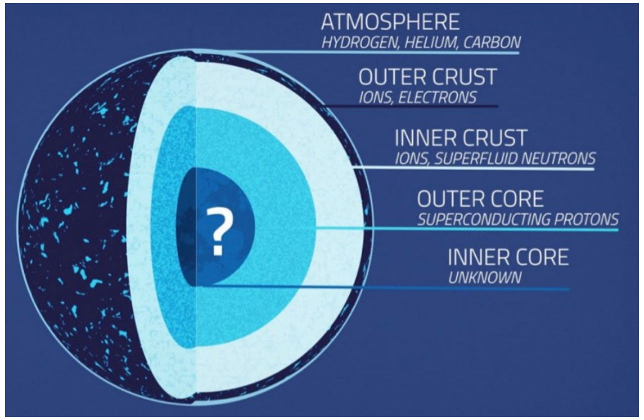


Y-N Interaction, EoS and Astrophysics

Laura Tolós, 03/06

- Equation of State (EoS) in dense nuclear matter
  - The strangeness degree of freedom in EoS at high baryon density region
- High baryon density nuclear matter
  - e.g. low energy HIC, neutron stars

Compact star

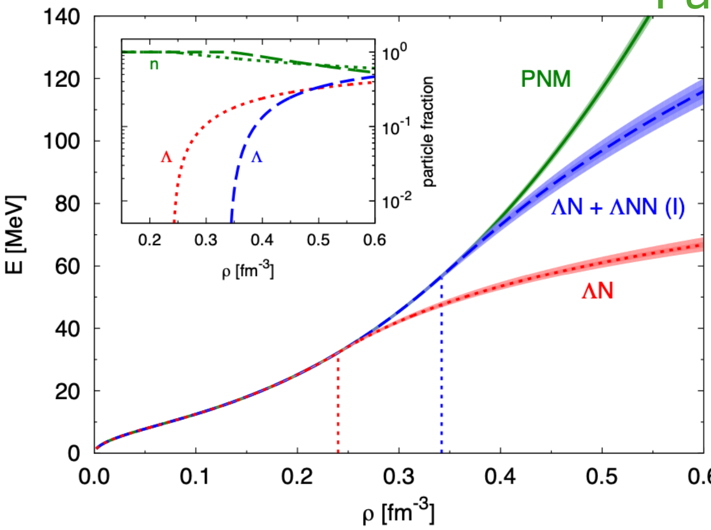


"Hyperon puzzle"

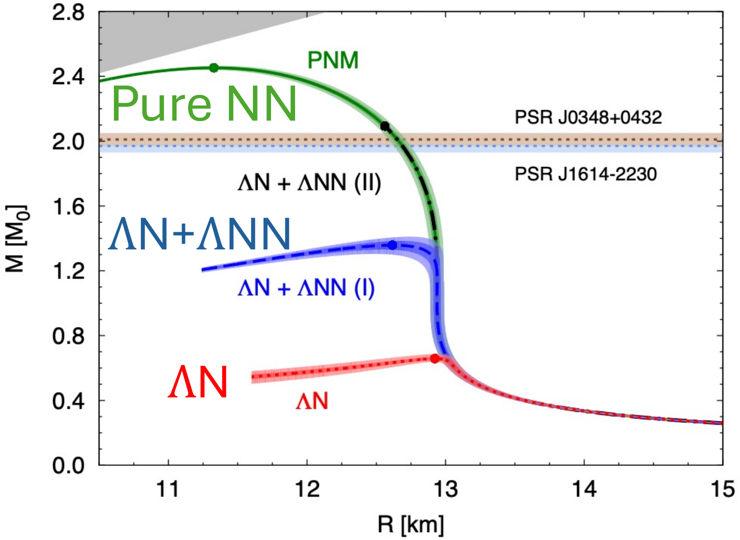
Pure NN

ΛN+ΛNN

ΛN



Presence of hyperon soften EoS



Observed heavy neutron stars

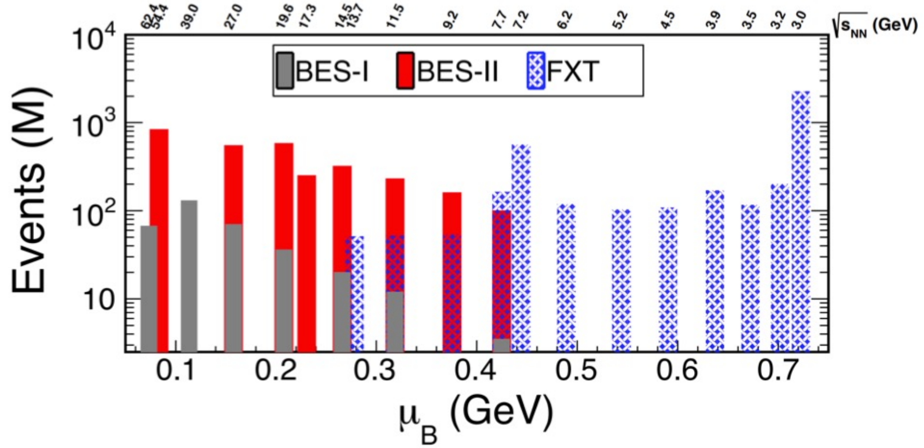
Nuclear matter EoS

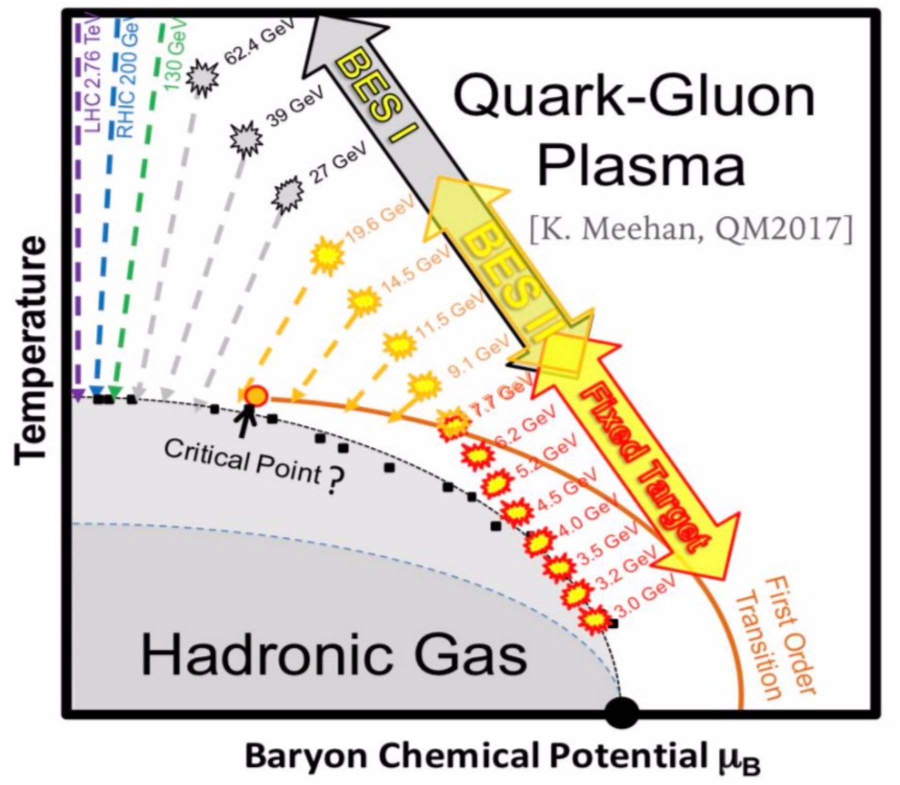
D. Lonardoni, et al. PRL 114, 092301 (2015)

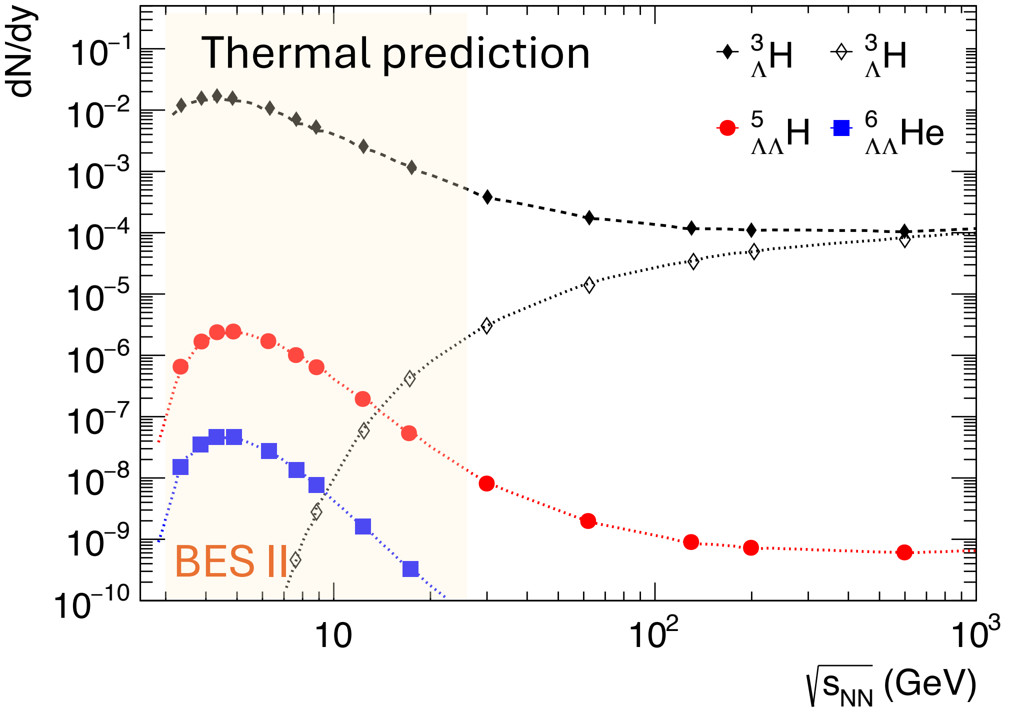
Mass vs R

STAR Beam Energy Scan II (BES II)

- Mapping the QCD diagram in the region of $200 < \mu_B \leq \sim 750$ MeV
  - Collisions species: Au+Au
  - Collider mode: $\sqrt{s_{NN}}$ = 7.7 - 27 GeV
  - Fixed-Target mode: $\sqrt{s_{NN}}$ = 3.0 – 7.7 GeV



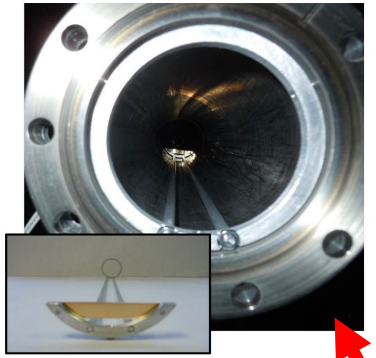


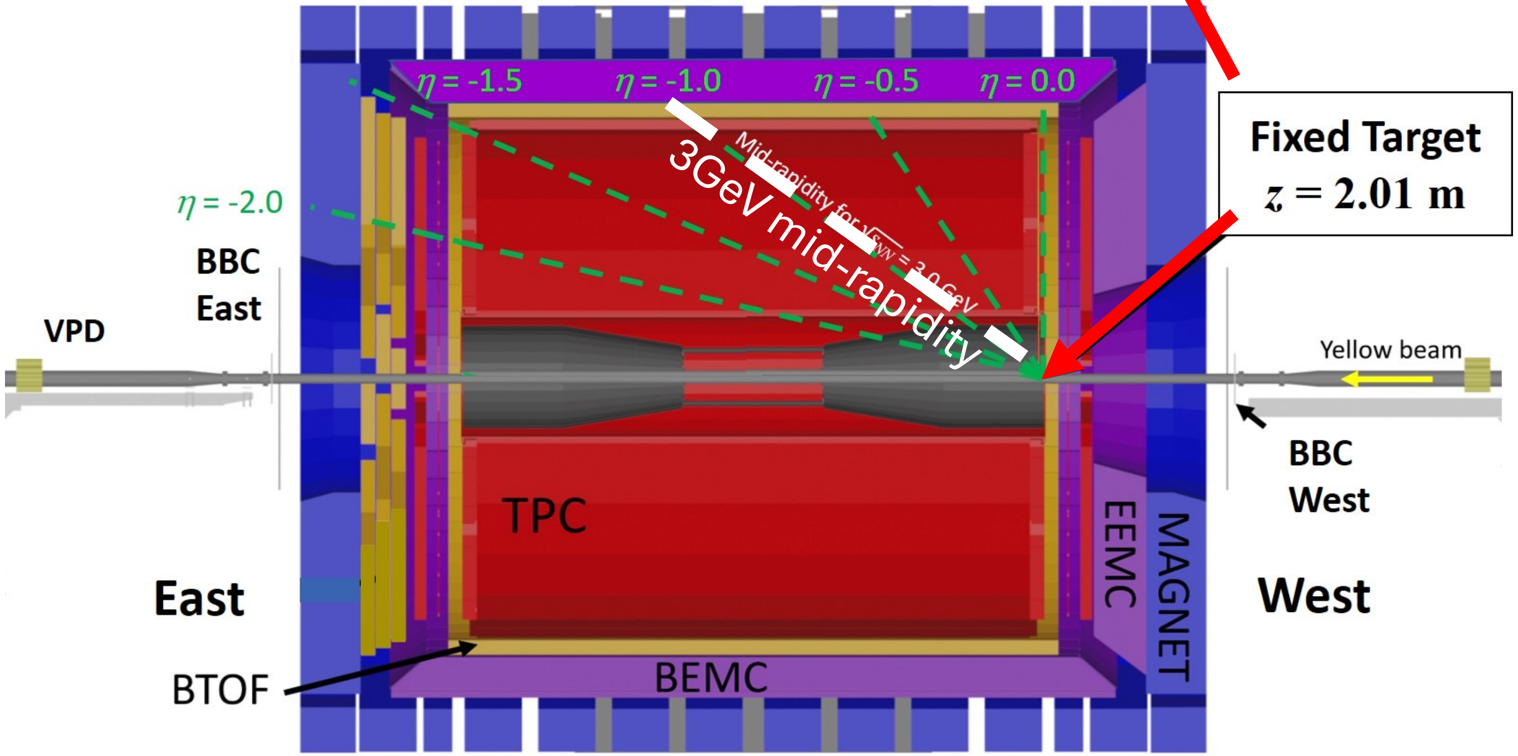


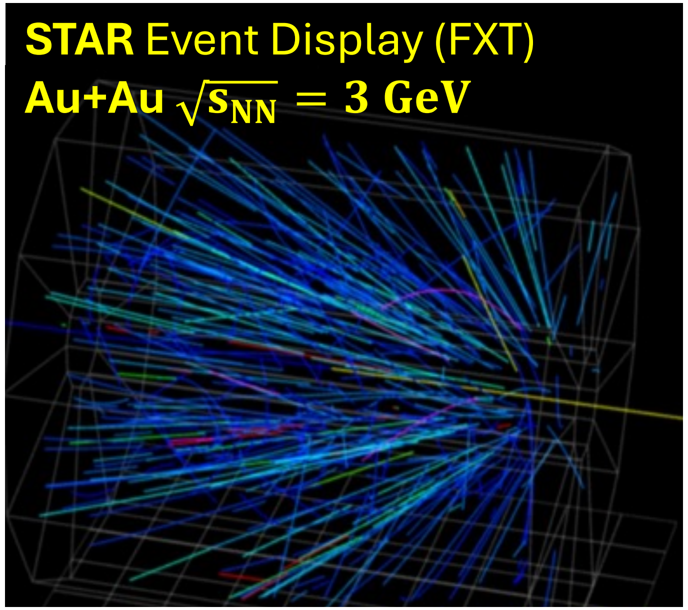
Thermal model: B. Dönigus, Eur. Phys. J. A 56:280 (2020)
A. Andronic et al, PLB 697, 203 (2011)

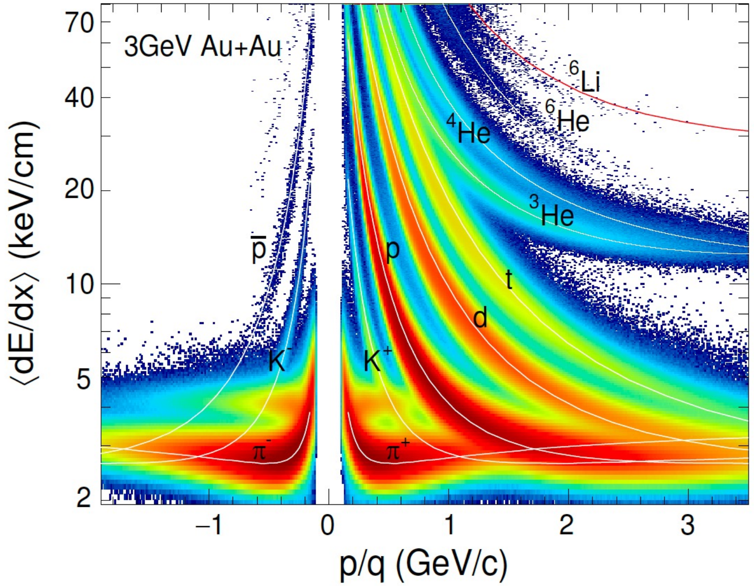
Fixed-Target Setup at STAR

Gold foil,
250 μm thick





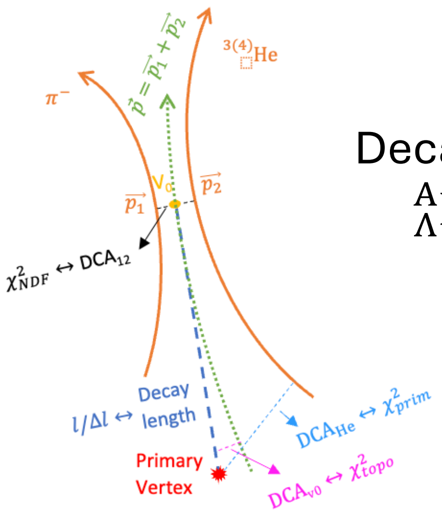




Hypernuclei reconstruction at RHIC

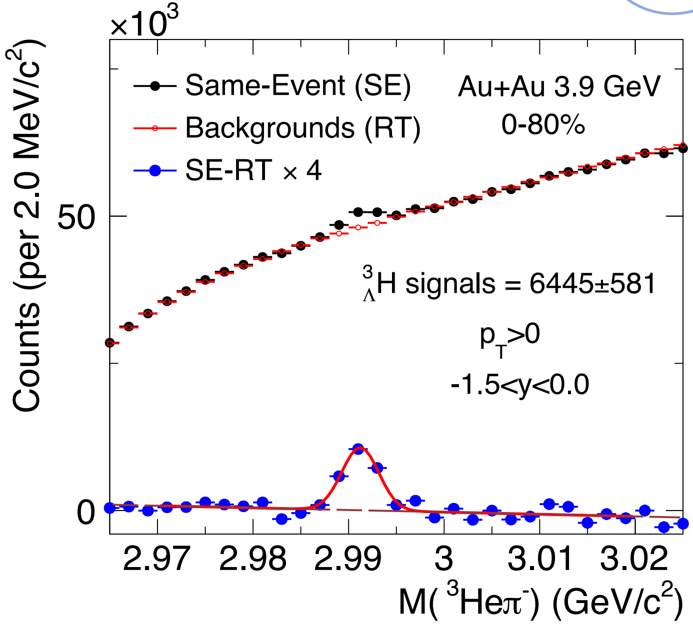
Chenlu Hu, 05/06
Xiujun Li, 04/06

- Signals are reconstructed by KFParticle package. X. Ju et al. Nucl. Sci. Tech. 34, 10, 158 (2023)
  - Combinatorial backgrounds reconstructed by rotation of $^{3(4)}He$ tracks.

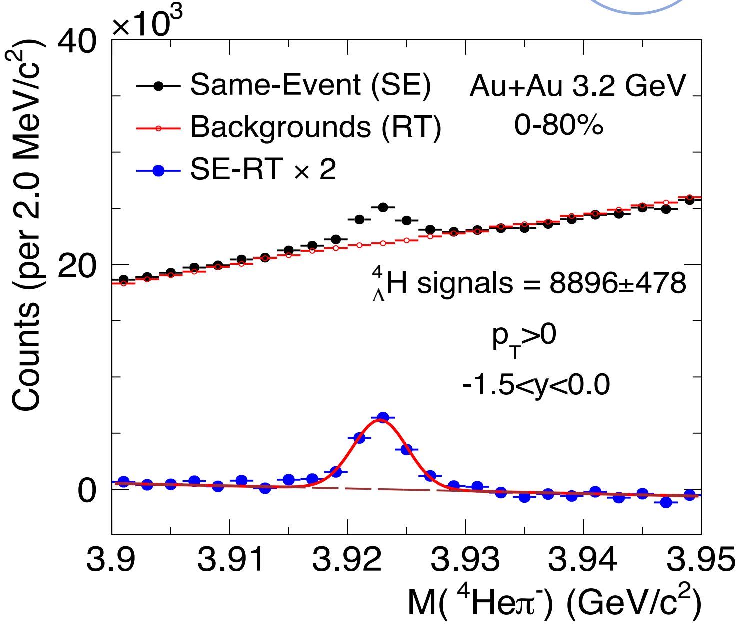


Decay topology of $^{A}_{\Lambda}H \rightarrow {}^{A}He\,\pi^-$

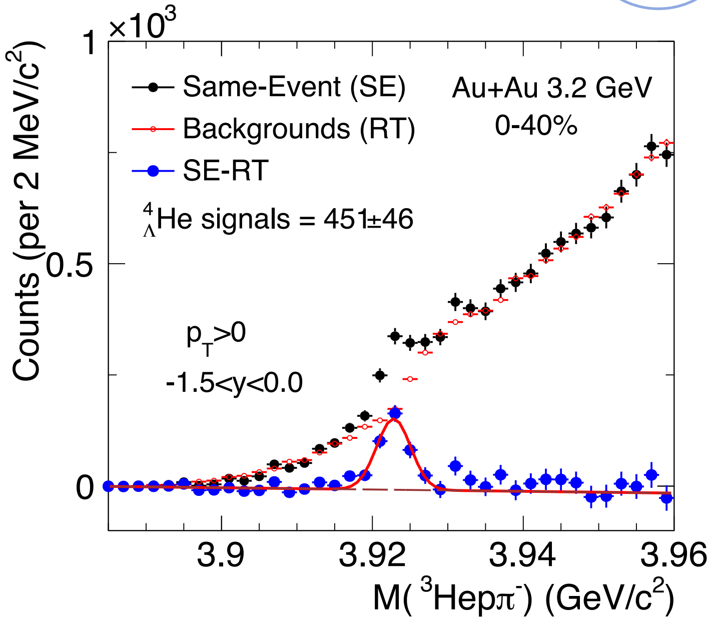
$^{3}_{\Lambda}H \rightarrow {}^{3}He\,\pi^-$



$^{4}_{\Lambda}H \rightarrow {}^{4}He\,\pi^-$

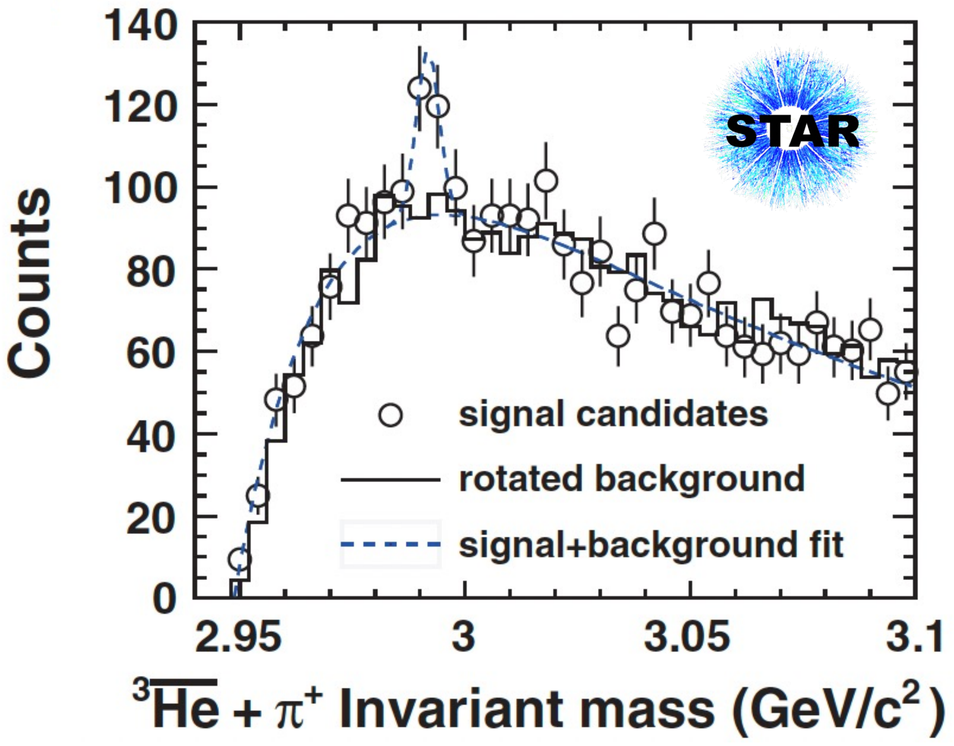


$^{4}_{\Lambda}He \rightarrow {}^{3}He\,p\pi^-$



Anti-matter Hypernuclei

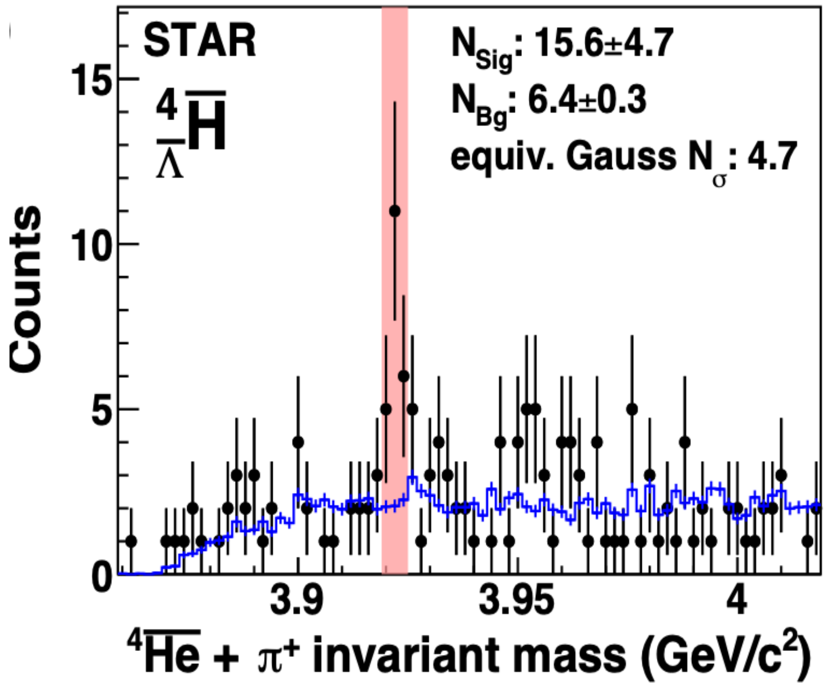
- STAR observed ${}^{4}_{\Lambda}\overline{\mathrm{H}}$ in 2023.
  - Benefit from high energy heavy ion collisions ($\mu_B \to 0$).
  - The heaviest observed antimatter nuclear and hypernuclear cluster to date.



$${}^{3}_{\Lambda}\overline{\mathrm{H}} \to {}^{3}\overline{\mathrm{He}} + \pi^{+}$$

Science 328 (2010) 58-62

Discovery of A=4 anti-hypernuclei



$${}^{4}_{\Lambda}\overline{\mathrm{H}} \to {}^{4}\overline{\mathrm{He}} + \pi^{+}$$

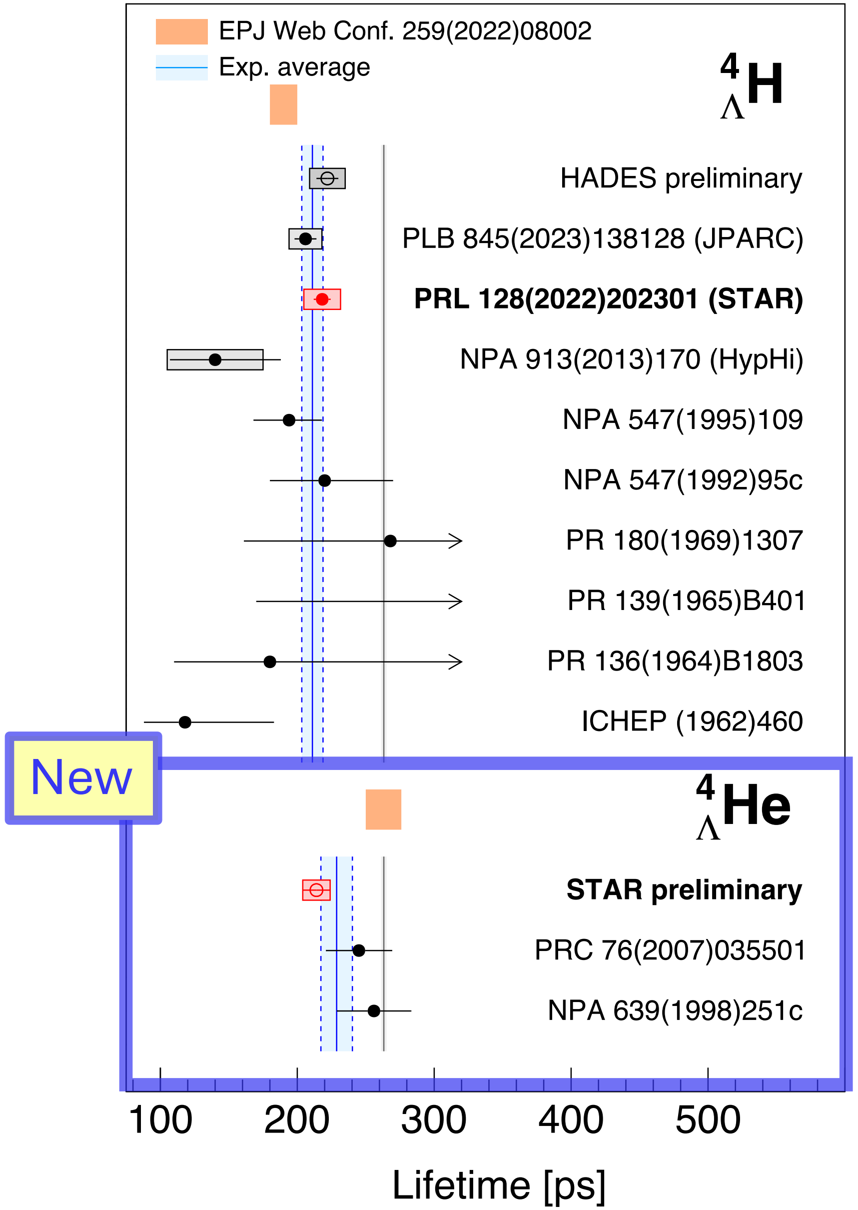
arXiv:2310.12674, submitted to Nature

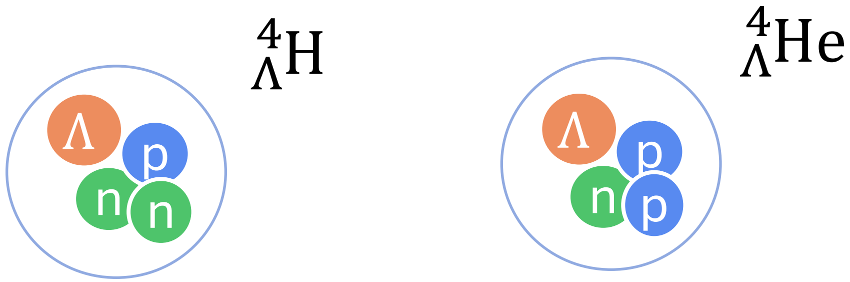
Datasets used:
- 200 GeV collisions
  - Au+Au
  - Zr+Zr/Ru+Ru
- 193 GeV collisions
  - U+U

Measurements on Hypernuclei Intrinsic Properties

${}^{4}_{\Lambda}$H and ${}^{4}_{\Lambda}$He Lifetimes

Xiujun Li, poster





A. Gal, EPJ Web Conf. 259, 08002 (2022)

- Isospin rule predicts: $* \dfrac{\Gamma({}^{4}_{\Lambda}\mathrm{He} \to {}^{4}\mathrm{He} + \pi^{0})}{\Gamma({}^{4}_{\Lambda}\mathrm{H} \to {}^{4}\mathrm{He} + \pi^{-})} \approx \dfrac{1}{2}$
  - $\tau({}^{4}_{\Lambda}\mathrm{H}) / \tau({}^{4}_{\Lambda}\mathrm{He}) = 0.74 \pm 0.04$
- New data: ${}^{4}_{\Lambda}\mathrm{He} = 214 \pm 10 \pm 10$ ps
  - Shorter than $\tau(\Lambda)$ by 3σ
  - $\tau({}^{4}_{\Lambda}\mathrm{H}) / \tau({}^{4}_{\Lambda}\mathrm{He}) = 0.92 \pm 0.06$

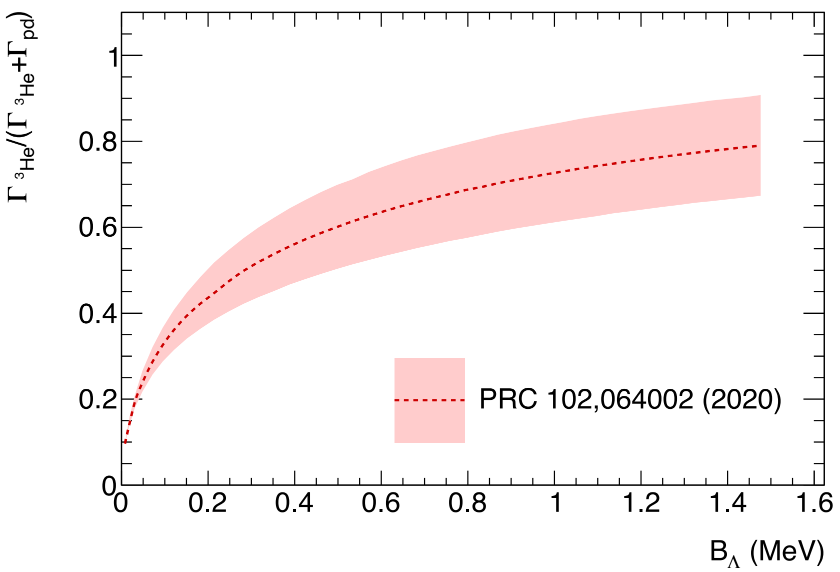
${}^{3}_{\Lambda}\mathrm{H}$ Branching Ratio R_3

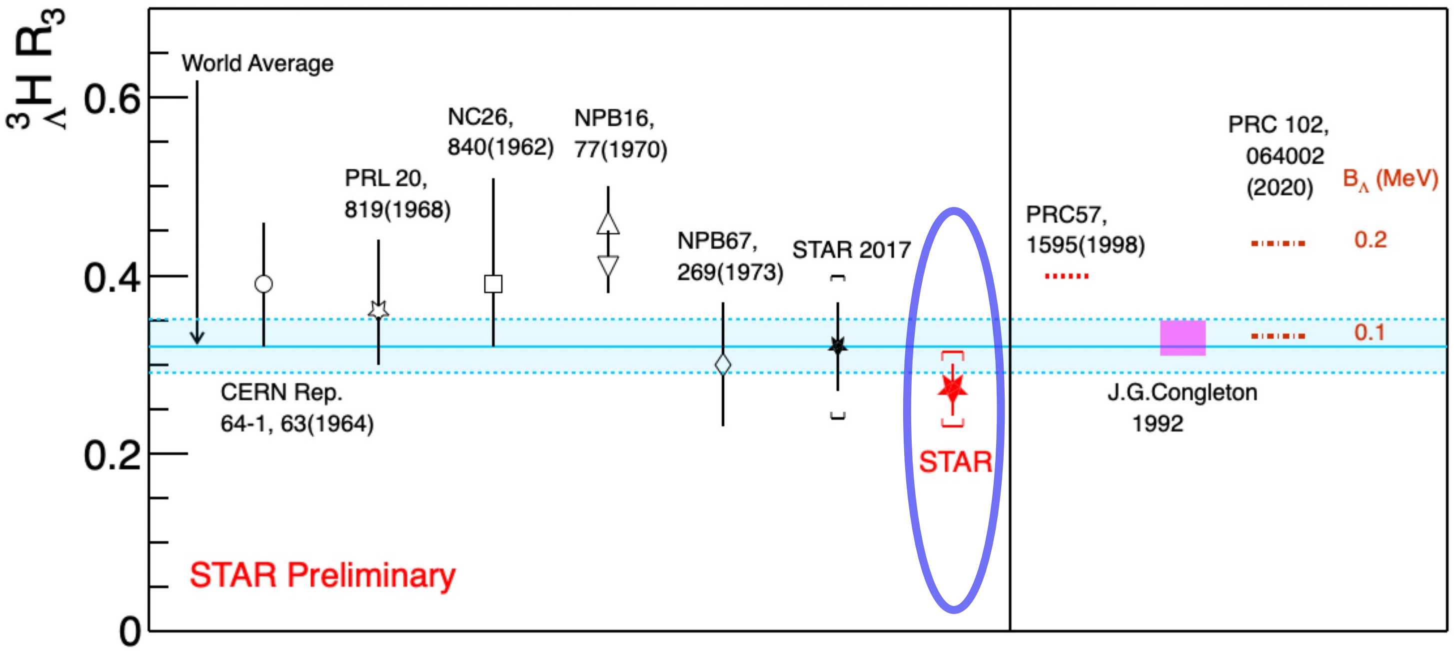
- Calculations propose that ${}^{3}_{\Lambda}\mathrm{H}$ R_3 may be sensitive to B_Λ
  - B_Λ: Λ separation energy
  - ${}^{3}_{\Lambda}\mathrm{H}\ B_\Lambda = \mathrm{M}(d) + \mathrm{M}(\Lambda) - \mathrm{M}({}^{3}_{\Lambda}\mathrm{H})$

$$R_3 = \frac{\mathrm{B.R.}({}^{3}_{\Lambda}\mathrm{H} \to {}^{3}\mathrm{He}\pi^-)}{\mathrm{B.R.}({}^{3}_{\Lambda}\mathrm{H} \to \mathrm{pd}\pi^-) + \mathrm{B.R.}({}^{3}_{\Lambda}\mathrm{H} \to {}^{3}\mathrm{He}\pi^-)}$$

STAR: $R_3 = 0.272 \pm 0.030 \pm 0.042$

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

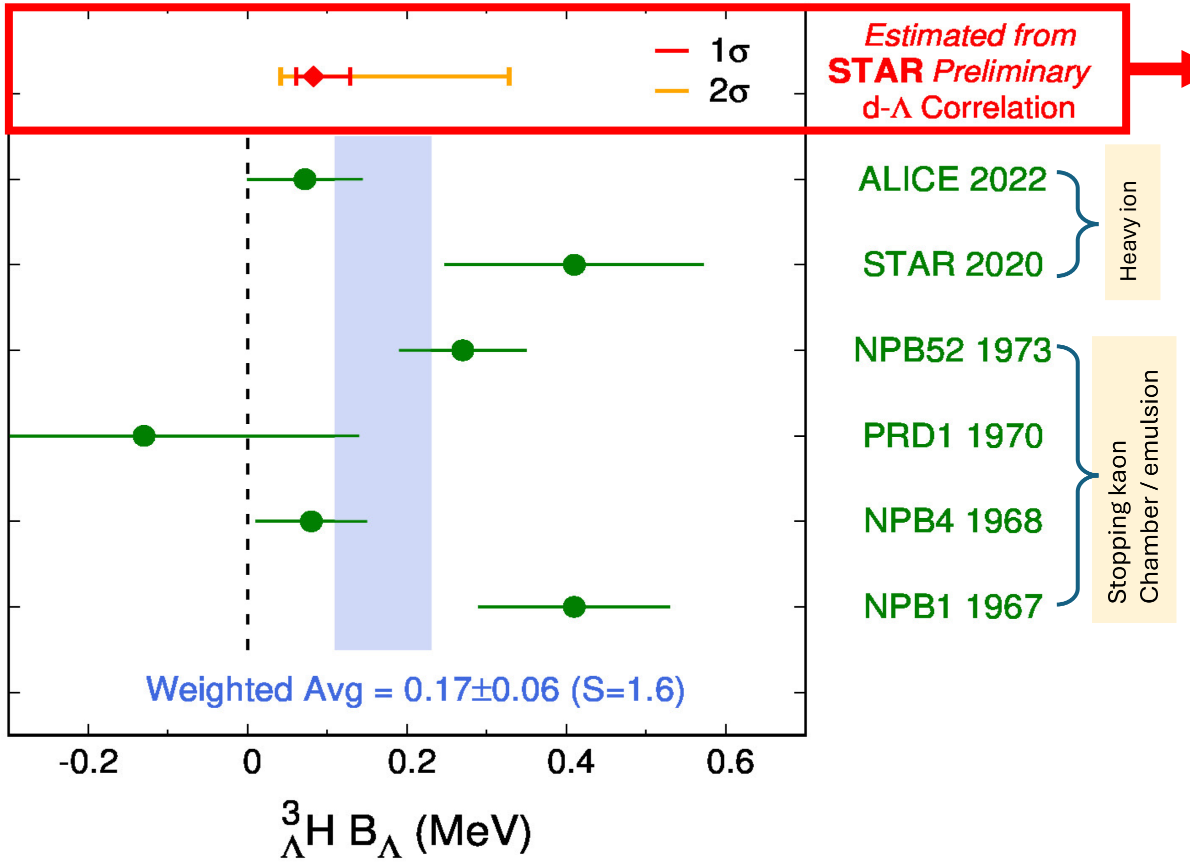




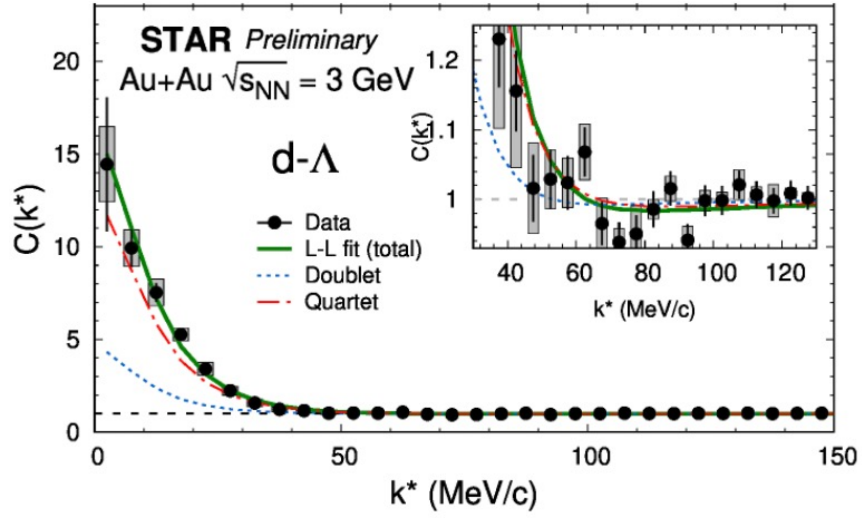
- STAR new R_3 data favors small binding energy of hypertriton.

${}^{3}_{\Lambda}$H Λ-Separation Energy (B_Λ)

- Λ separation energy (B_Λ): ${}^{3}_{\Lambda}\mathrm{H}\ B_\Lambda = \mathrm{M}(d) + \mathrm{M}(\Lambda) - \mathrm{M}({}^{3}_{\Lambda}\mathrm{H})$
  - Benchmark of *Y-N* interaction strength



- Invariant mass method
- Femtoscopy method
  - $\frac{1}{-f_0} = \gamma - \frac{1}{2} d_0 \gamma^2,\ B_\Lambda = \frac{\gamma^2}{2\mu_{d\Lambda}}$



- ${}^{3}_{\Lambda}$H is a very loosely bound state.

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Measurements on Hypernuclei Production at RHIC

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Hypernuclei Production in HIC

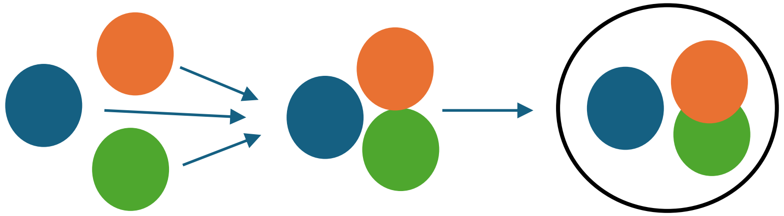
Models at mid-rapidity

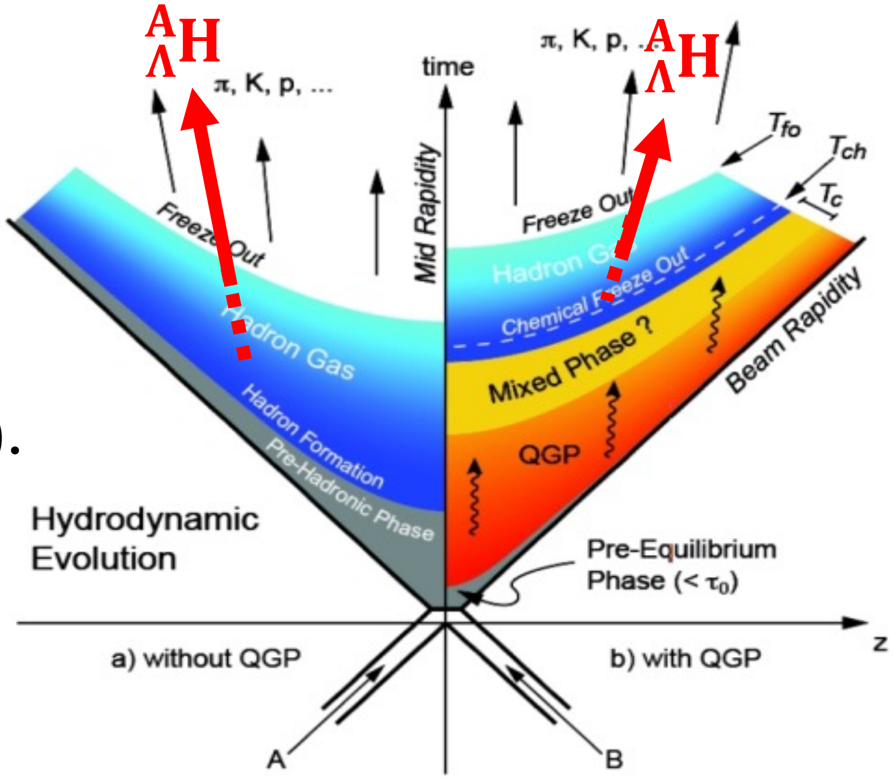
Thermal model

- Hadron chemical freeze out T_{ch} and μ_B
    - $\frac{dN}{d^3\,\mathrm{p}} \sim \exp(-\frac{E-\mu_B}{T})$
- Assuming the conserved baryon entropy after hadron chemical freeze-out

Coalescence formation

- Baryons / nuclei very close in phase space $(\vec{p}, \vec{r})$.
    - Any experimental evidence?
    - The role of *Y*-*N* interaction?



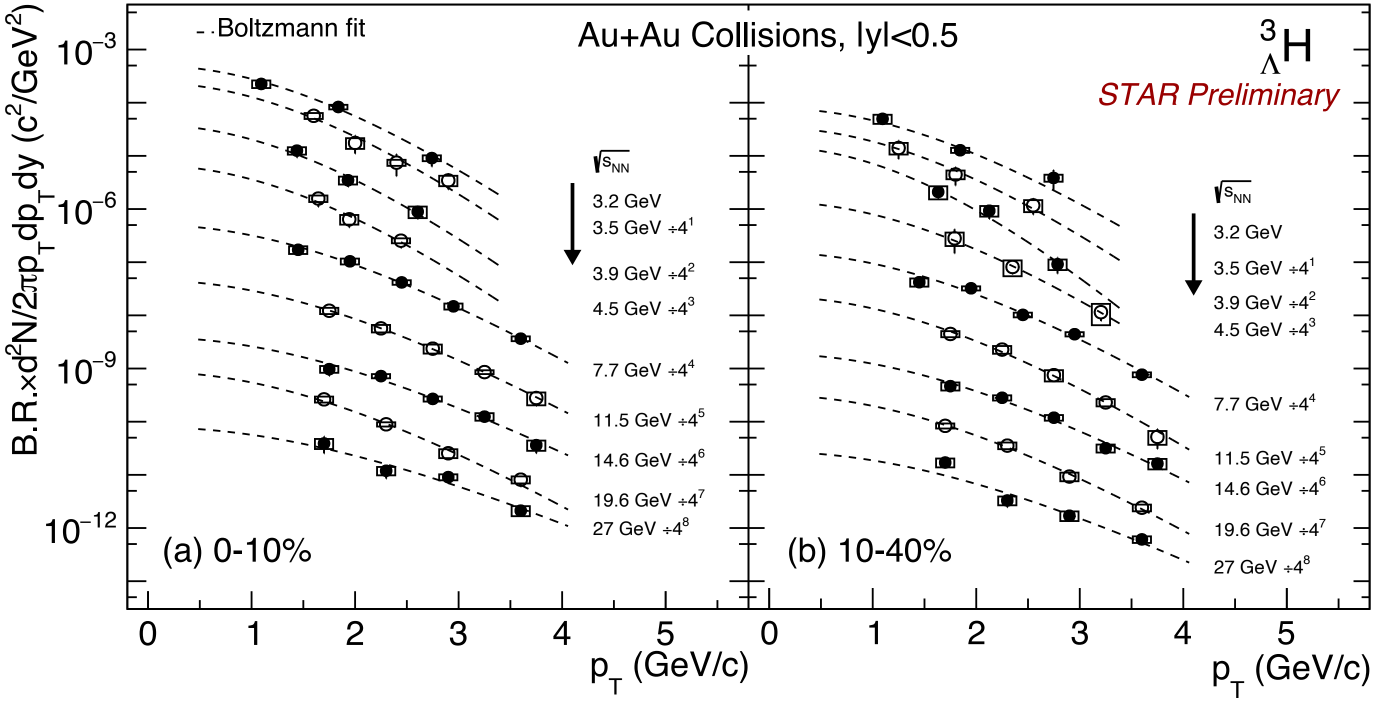


Fruitful Results from STAR BES II

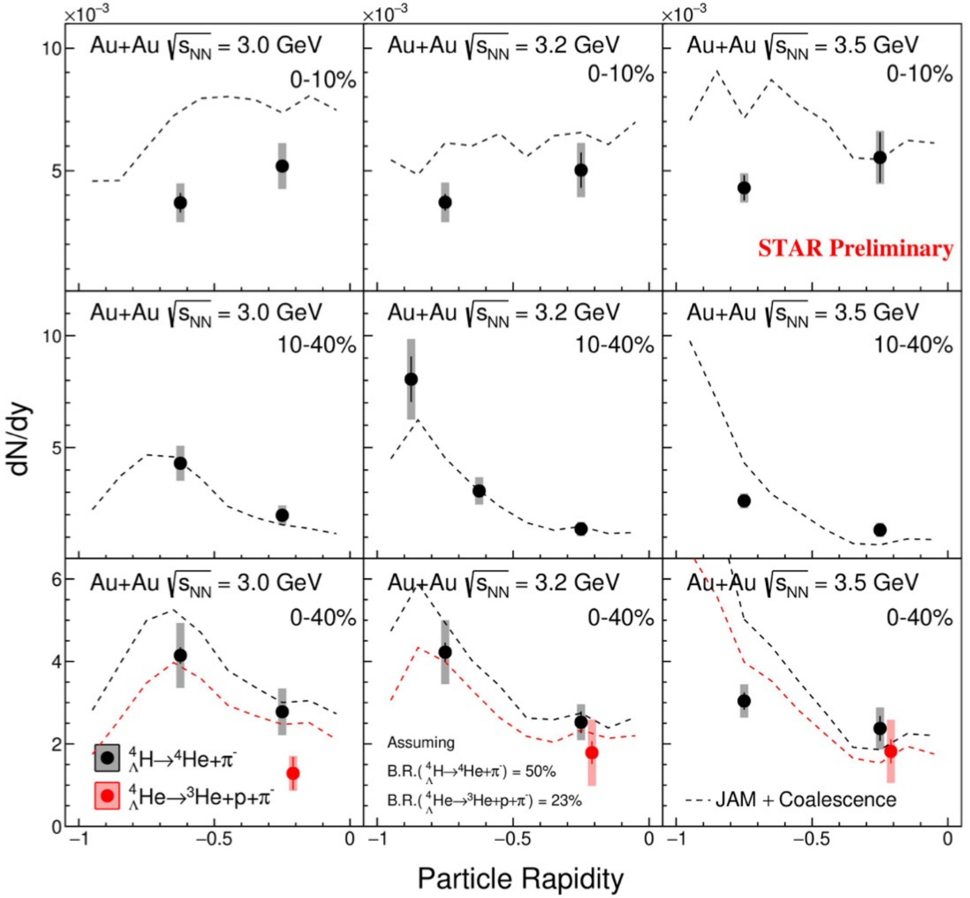
Chenlu Hu, 05/06
Xiujun Li, 04/06

- Utilizing BES II datasets, we measure:
  - ${}^{3}_{\Lambda}$H p_T spectra, dN/dy, $\langle p_T \rangle$ in Au+Au collisions at $\sqrt{s_{NN}}$ = 3-27 GeV
  - ${}^{4}_{\Lambda}$H, ${}^{4}_{\Lambda}$He p_T spectra, dN/dy, $\langle p_T \rangle$ in Au+Au collisions at $\sqrt{s_{NN}}$ =3-3.5 GeV

A=3: ${}^{3}_{\Lambda}$H (Au+Au $\sqrt{s_{NN}}$ =3-27 GeV)

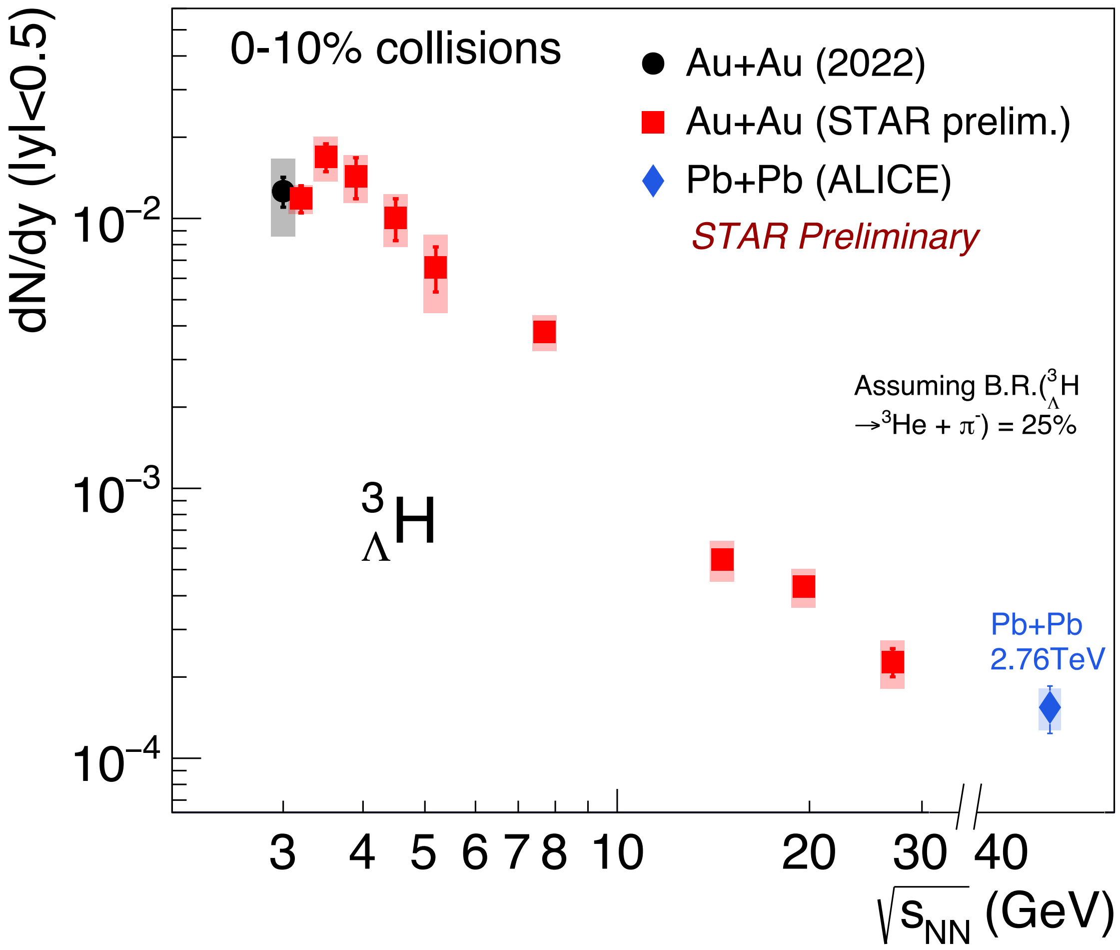


A=4: ${}^{4}_{\Lambda}$H, ${}^{4}_{\Lambda}$He (Au+Au $\sqrt{s_{NN}}$ =3-3.5 GeV)



Energy Dependence of Hypernuclei Production

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



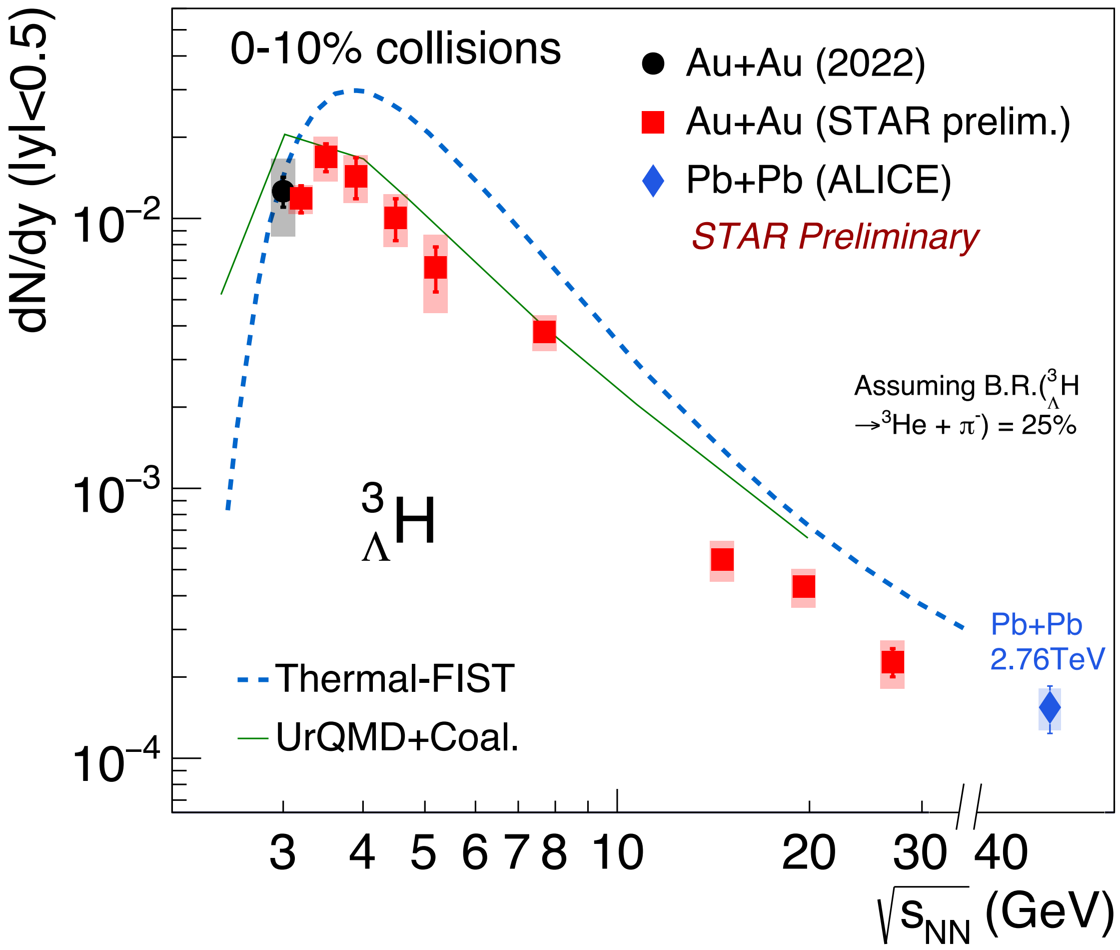
${}^{3}_{\Lambda}\mathrm{H}$ production yields reaches peak at around 3-4 GeV.

- Increase steeply from 27 to 3 GeV as $\sqrt{s_{NN}}$ goes lower
- Interplay between:
  - $\sqrt{s_{NN}}\downarrow$, baryon density$\uparrow$, yields$\uparrow$
  - $\sqrt{s_{NN}}\downarrow$, strangeness canonical suppression$\uparrow$, yields$\downarrow$

Thermal-FIST, Coal.+UrQMD: T. Reichert et al, PRC 107, 014912 (2023)
Pb+Pb: ALICE, PLB 754, 360 (2016)
Au+Au: STAR, PRL 128, 202301 (2022)

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

Xiujun Li, 04/06



UrQMD + Instant coal.

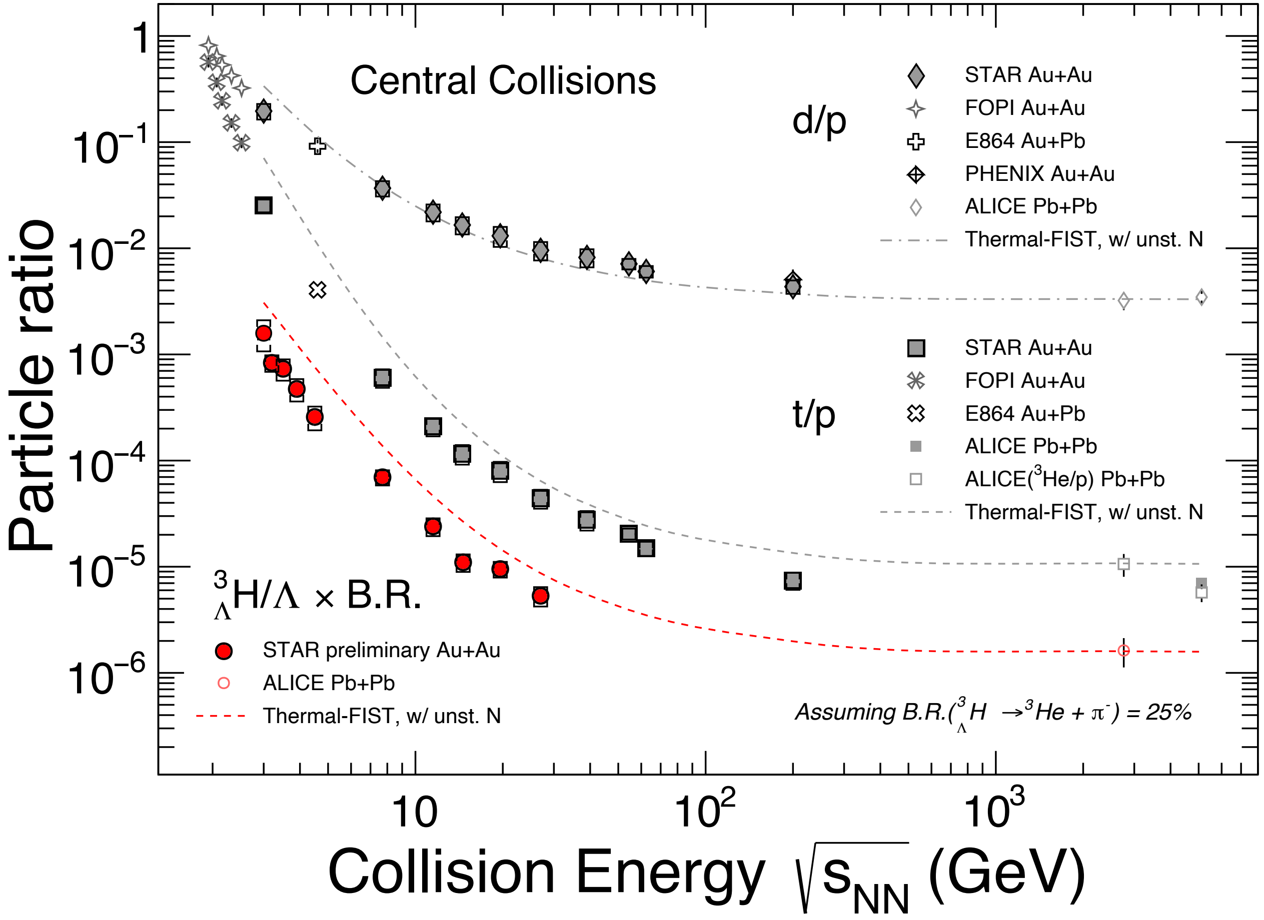
- Describe data from 3-10 GeV
- Instant coalescence after hadron kinetic freeze-out
- Coalescence condition:
  - $|\overrightarrow{p_1} - \overrightarrow{p_2}| < \Delta P, |\overrightarrow{r_1} - \overrightarrow{r_2}| < \Delta R$

Thermal-FIST model

- Hadron chemical freeze-out T and μ_B
- Strangeness canonical ensemble in low energies
- ~ 2 times larger than the data

Thermal-FIST, Coal.+UrQMD: T. Reichert et al, PRC 107, 014912 (2023)
Pb+Pb: ALICE, PLB 754, 360 (2016)
Au+Au: STAR, PRL 128, 202301 (2022)

$^{3}_{\Lambda}H/\Lambda$ Compared to Thermal Model



Thermal-FIST:
- Hadron chemical freeze-out T and μ_B.

T. Reichert et al, PRC 107 , 014912 (2023)

Thermal model at RHIC energies:
A=2 (d): Overall consistent
A=3 (t and $^{3}_{\Lambda}H$): ~2x higher than data

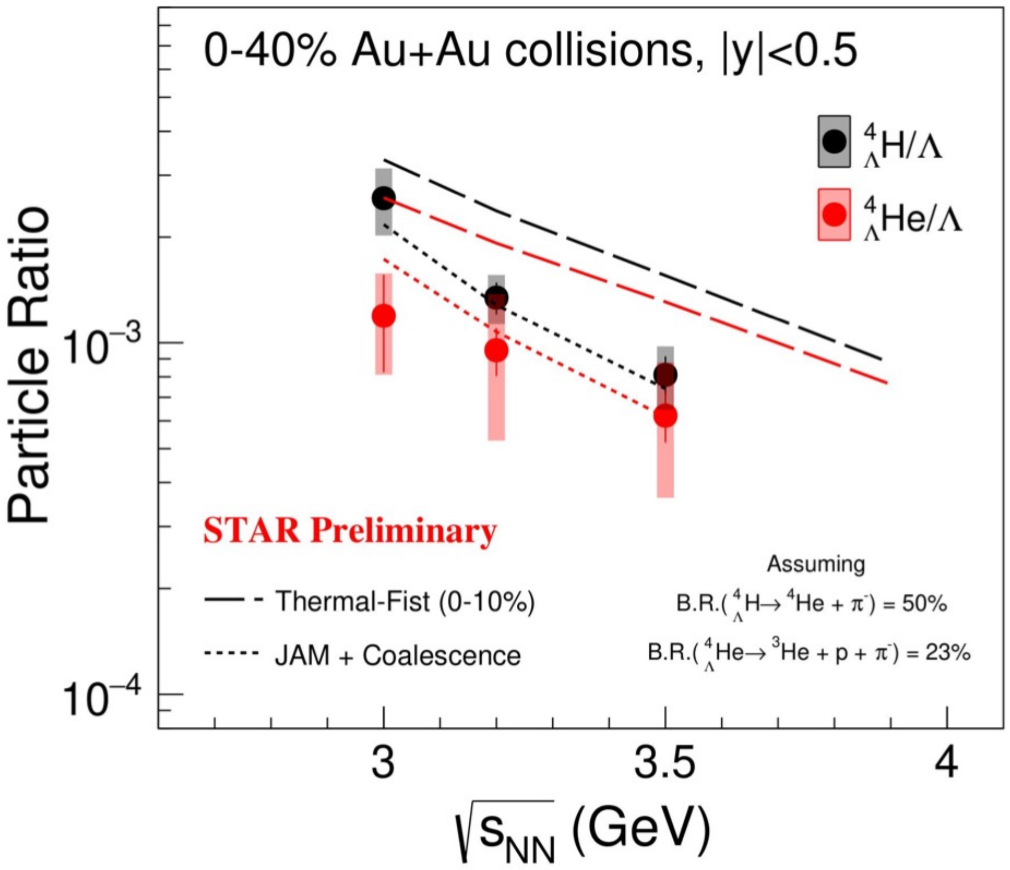
- $^{3}_{\Lambda}H$ (and t) are not in equilibrium at hadron chemical freeze out.

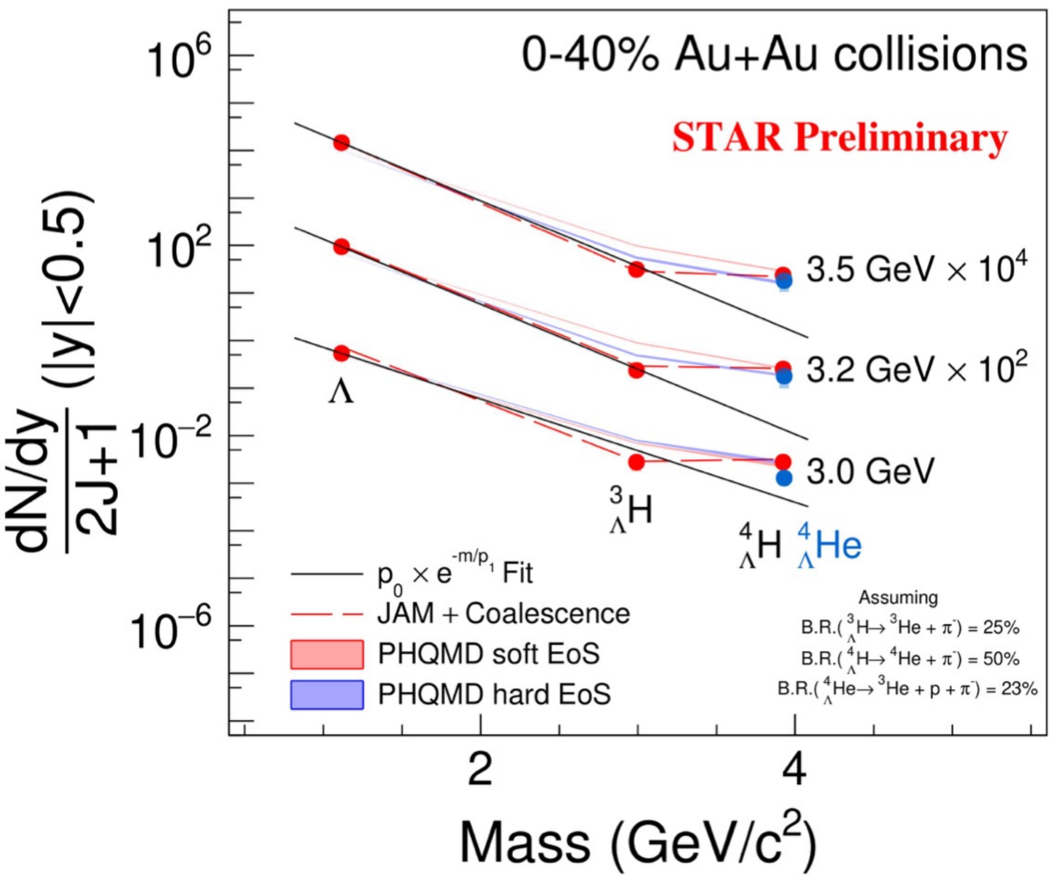
Production of ${}^4_\Lambda$H and ${}^4_\Lambda$He

Chenlu Hu, 05/06
Xiujun Li, 04/06

Thermal-FIST: T. Reichert et al, PRC 107 , 014912 (2023)

Thermal expectation: $\frac{dN}{dy} \sim \exp(-\frac{m}{T})$



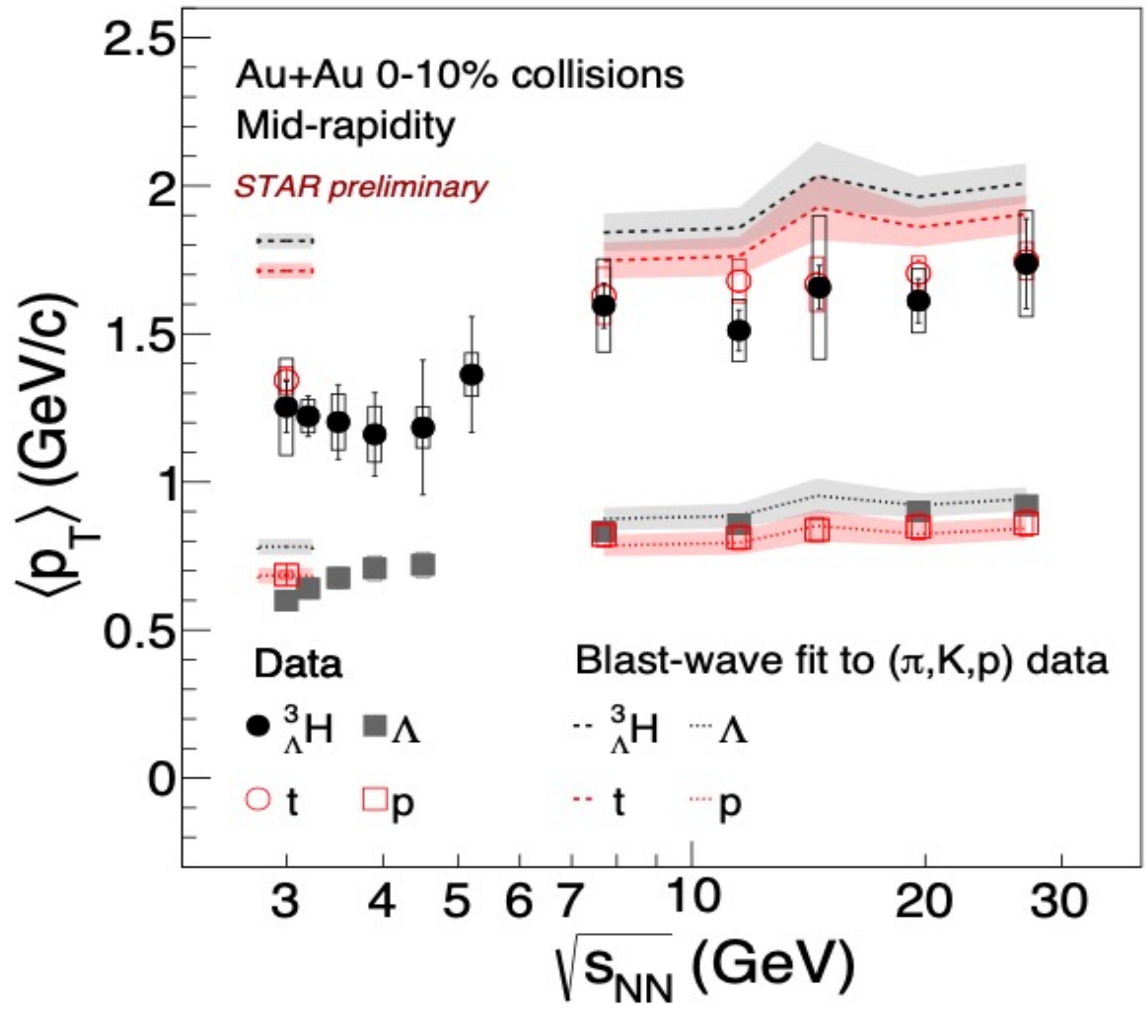


- Thermal model also over-predict ${}^4_\Lambda$H and ${}^4_\Lambda$He yields while JAM+coal. describes the data.
- Evidence of the formation of ${}^4_\Lambda$H and ${}^4_\Lambda$He excited states in 3-4 GeV collisions.

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

Energy Dependence of ${}^{3}_{\Lambda}\mathrm{H}\ \langle p_T \rangle$

Xiujun Li, 04/06



- ${}^{3}_{\Lambda}\mathrm{H}$ and $t\ \langle p_T \rangle < \langle p_T \rangle^{BW}$ at 3 GeV
- Hint of ${}^{3}_{\Lambda}\mathrm{H}$ and $t\ \langle p_T \rangle < \langle p_T \rangle^{BW} > 7.7$ GeV
  - $\langle p_T \rangle^{BW}$: Blast-wave (BW) expectation calculated using kinetic freeze-out parameters from measured light hadron (π, K, p) spectra.

Blastwave function:

$$\frac{1}{2\pi p_T}\frac{d^2N}{dp_T dy} \propto \int_0^R r dr m_T I_0\left(\frac{p_T \sinh\rho(r)}{T_{kin}}\right) \times K_1\left(\frac{m_T \cosh\rho(r)}{T_{kin}}\right)$$

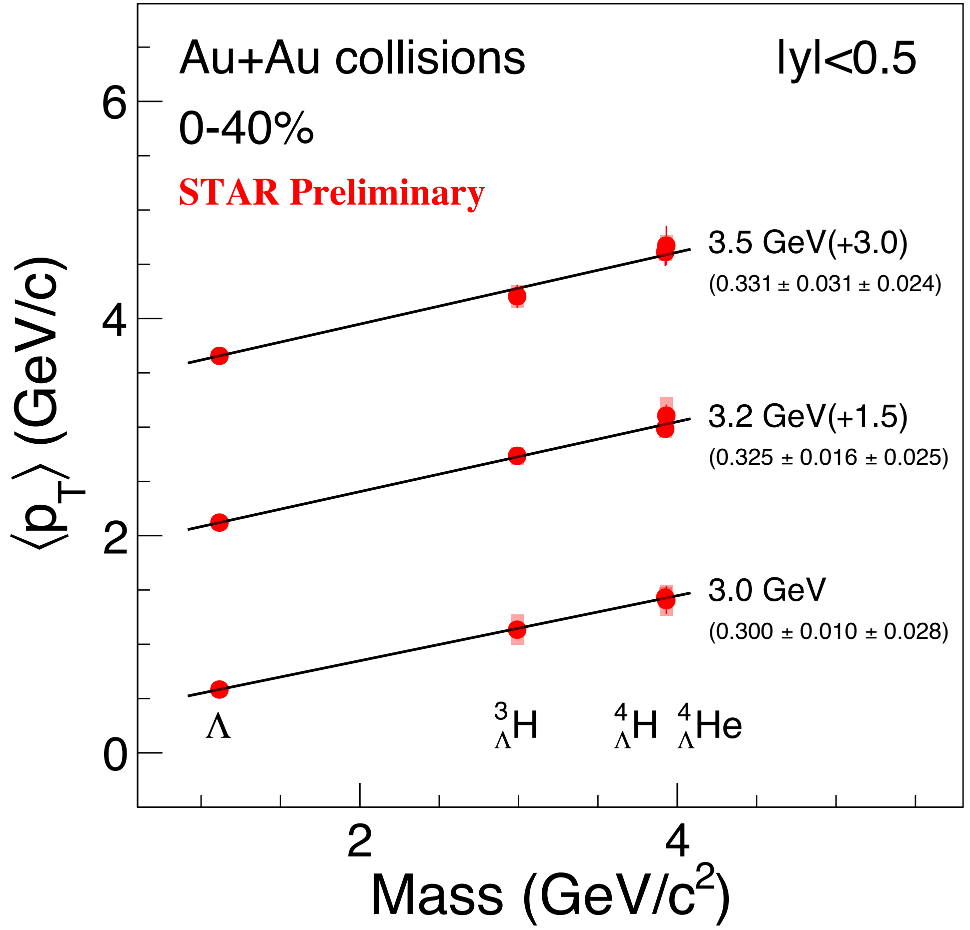
${}^{3}_{\Lambda}\mathrm{H}$ and t might do not follow the same collective expansion as light hadrons.

STAR, Phys. Rev. C 102 (2020) 34909; Phys. Rev. C 96 (2017) 44904

Hypernuclei Collectivity versus Mass

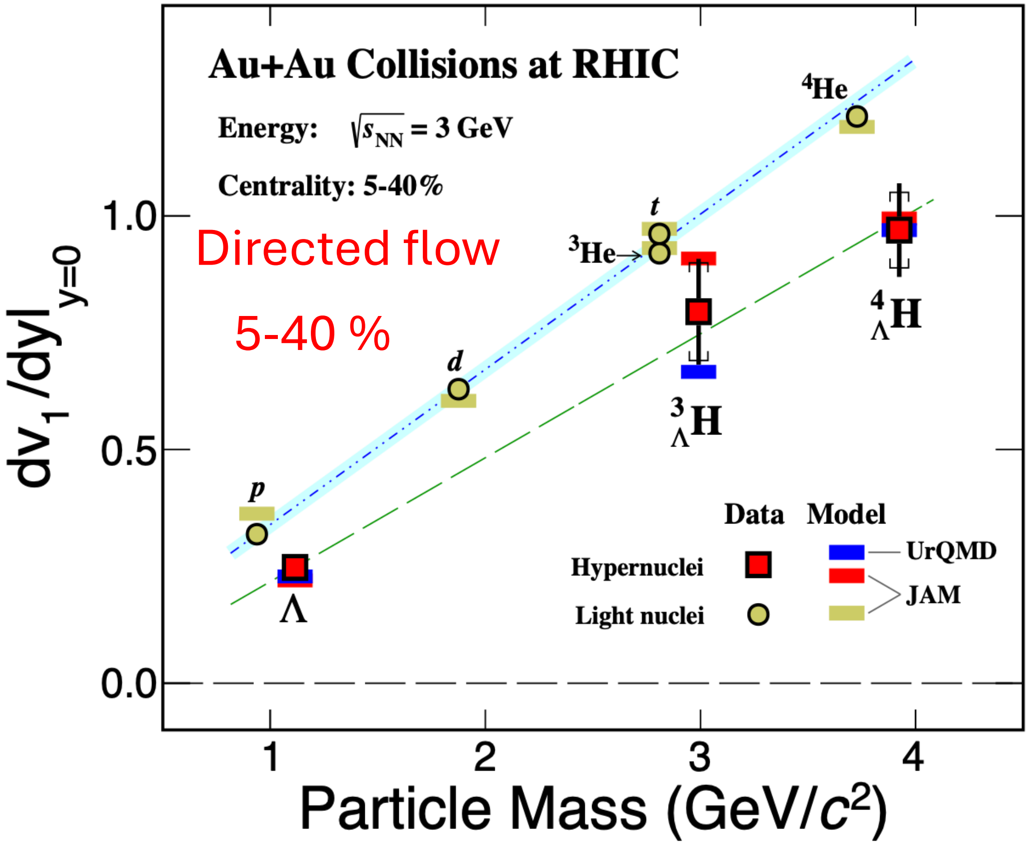
Chenlu Hu, 05/06
Junyi Han, 04/06

$\langle p_T \rangle$ -> Radial flow contributions



v_1 -> Directed flow

$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{1}^{\infty} 2v_n \cos\left[n\left(\phi - \psi_{RP}\right)\right]\right)$$



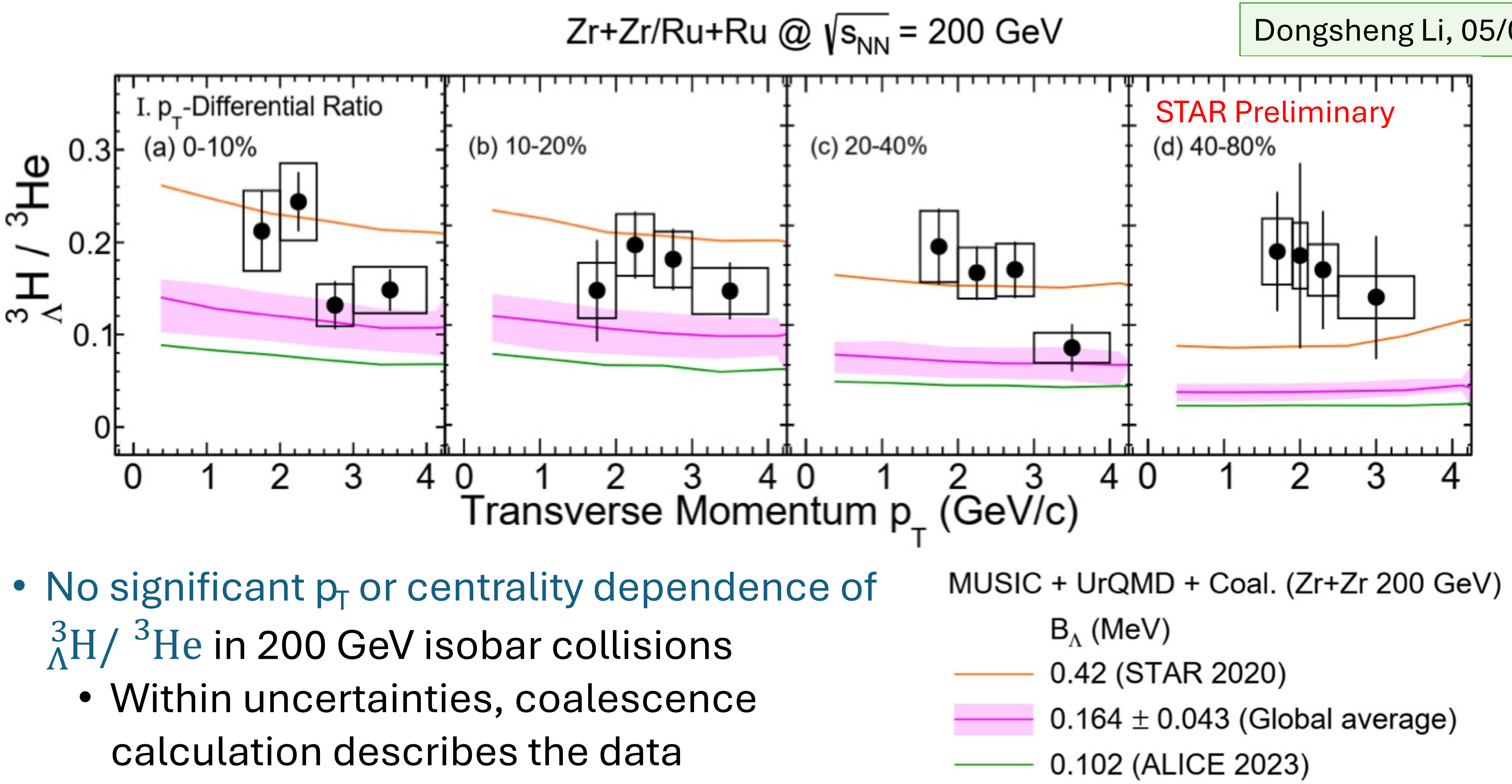
STAR, PRL 130 (2023) 212301

- Hypernuclei $\langle p_T \rangle$ (and v_1) show linear mass scaling from 3 to 3.5 GeV in mid-rapidity.
  - Consistent with coalescence formation picture.

Multiplicity Dependence of Hypernuclei Production

${}^{3}_{\Lambda}H/{}^{3}He$ Production in Zr+Zr/Ru+Ru 200 GeV

Dongsheng Li, 05/06



- No significant p_T or centrality dependence of ${}^{3}_{\Lambda}H/{}^{3}He$ in 200 GeV isobar collisions
  - Within uncertainties, coalescence calculation describes the data

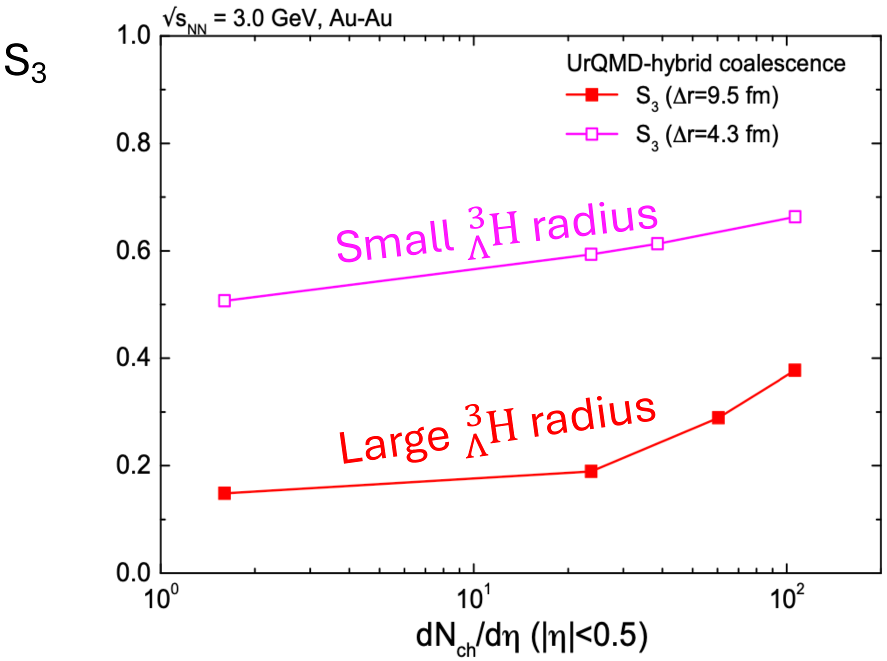
Strangeness Population Factor

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

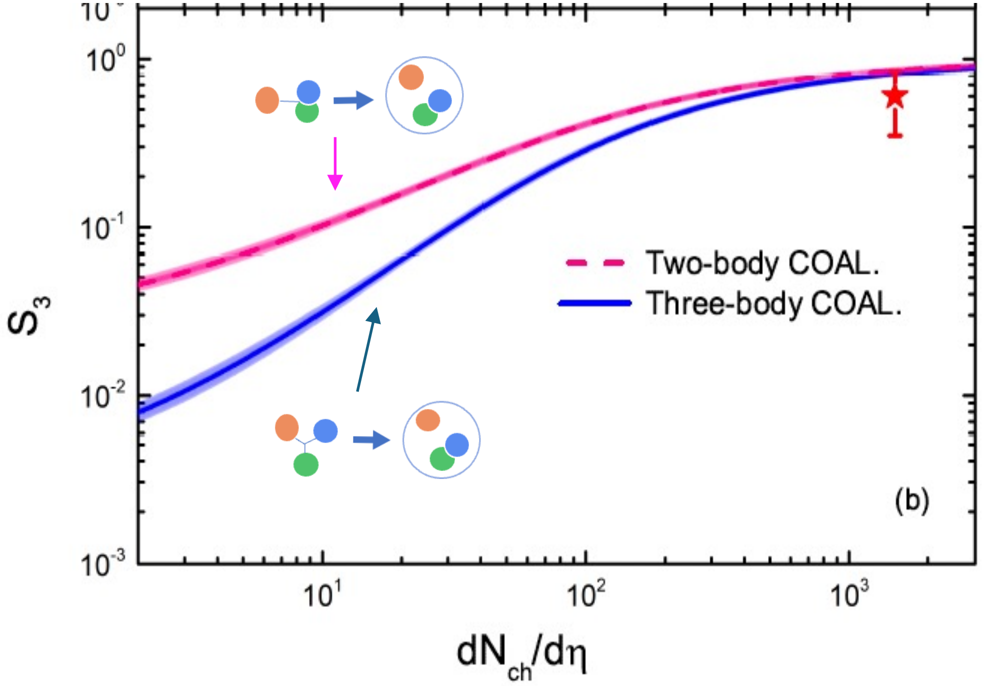
S. Zhang et al, PLB 684, 224 (2010)

$$E_A \frac{d^3 N_A}{dp_A^3} = B_A \left(E_{p,n} \frac{d^3 N_{p,n}}{dp_{p,n}^3} \right)^A \Bigg|_{\vec{p}_p = \vec{p}_n = \frac{\vec{p}_A}{A}}$$

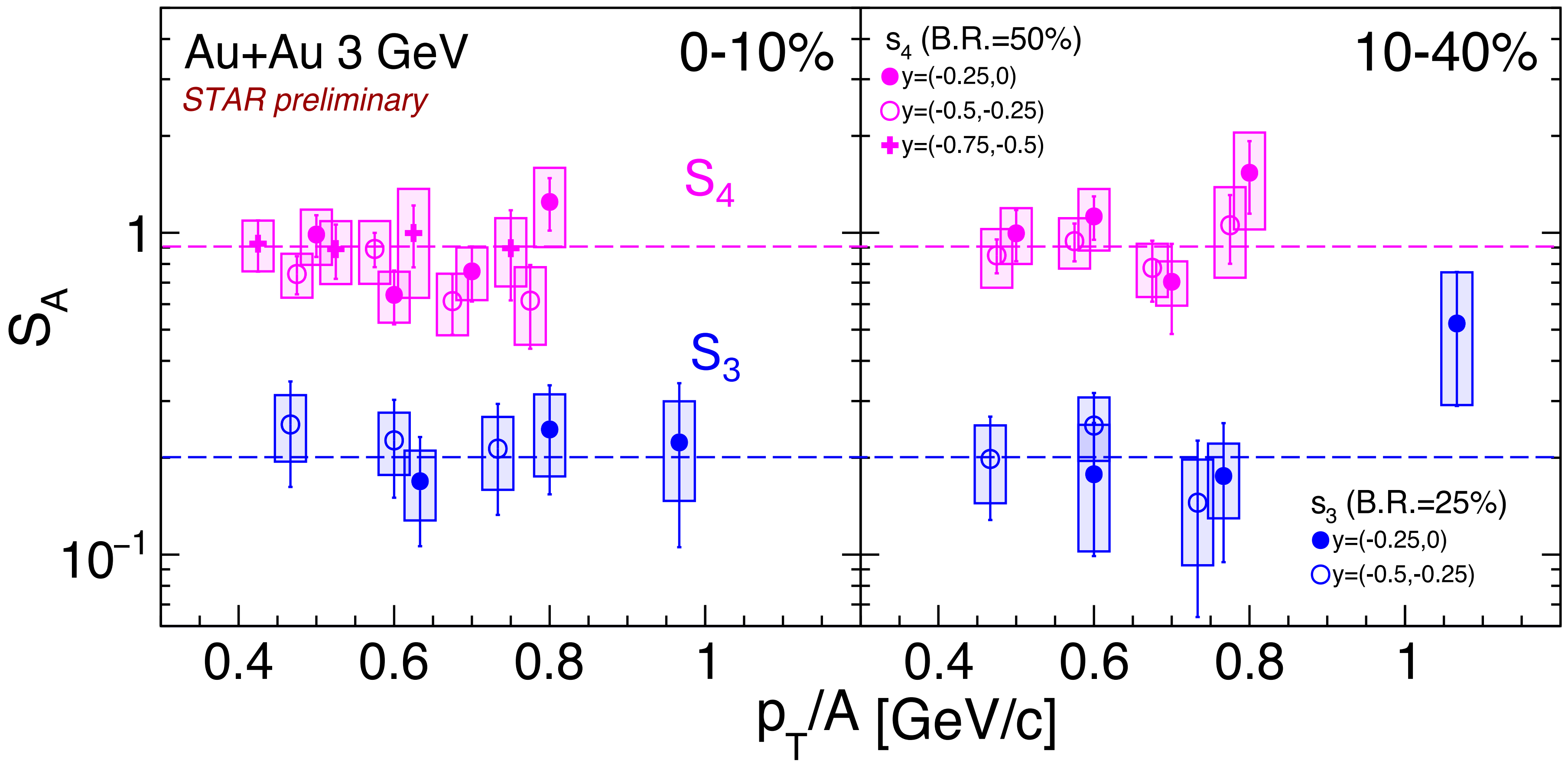
- Direct connection to coalescence parameters B_A
- S_3 vs. $dN_{ch}/d\eta$: Possible insights to nuclei radius and coalescence mechanism



K. Jia. PLB 792 (2019) 132-137



S_3 and S_4 in Au+Au 3 GeV



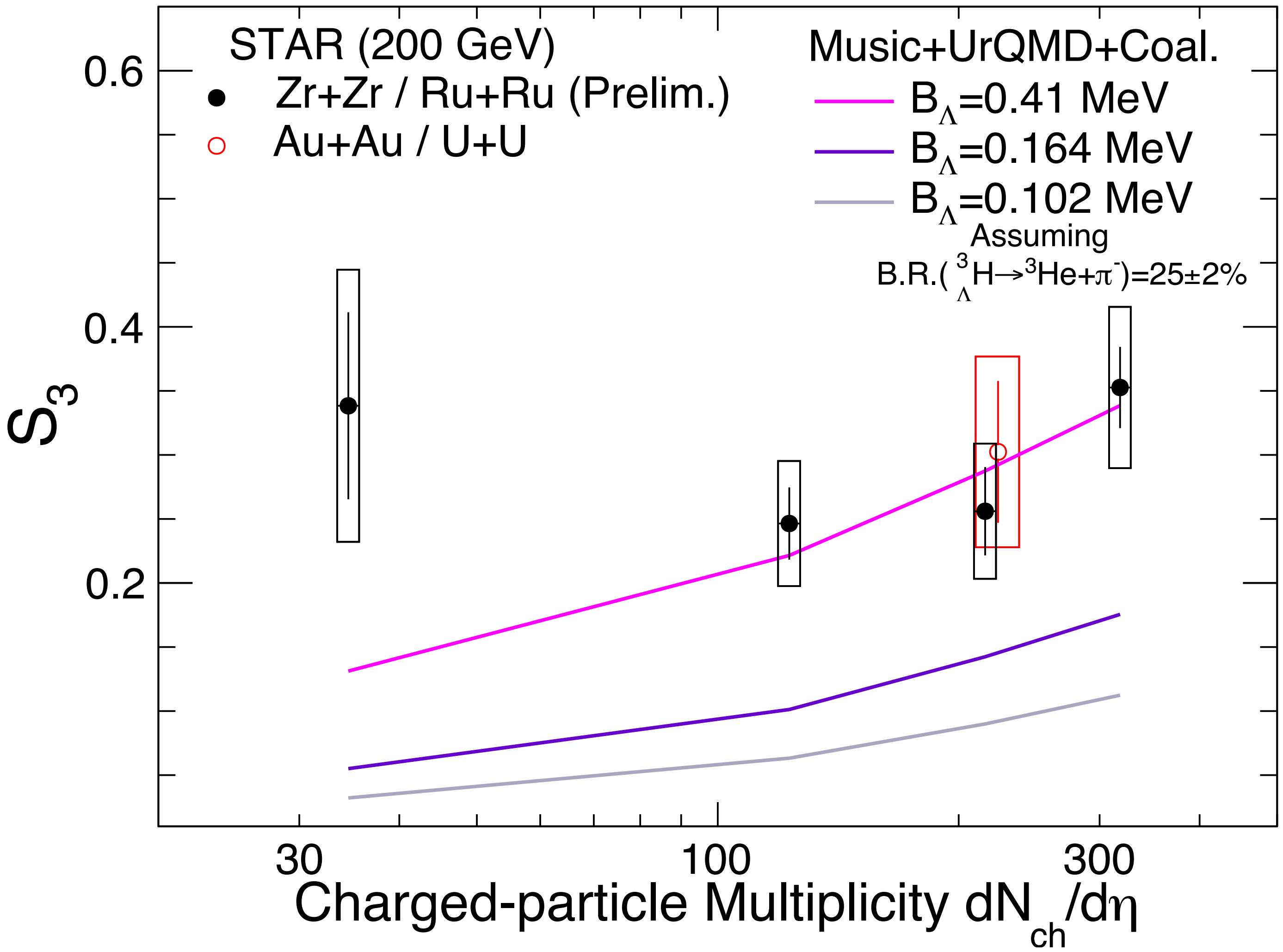
$$S_A = \frac{{}^A_\Lambda H(A \times p_T)}{{}^A_\Lambda He(A \times p_T) \times \frac{\Lambda}{p}} = \frac{B_A({}^A_\Lambda H)(p_T)}{B_A({}^A He)(p_T)}$$

- No obvious p_T, rapidity and centrality dependence of S_A observed at 3 GeV
  - Evidence that B_A of light and hyper nuclei follow similar tendency versus p_T, rapidity and centrality

Multiplicity Dependence of S_3 at $\mu_B \to 0$

Dongsheng Li, 05/06

SQM2024

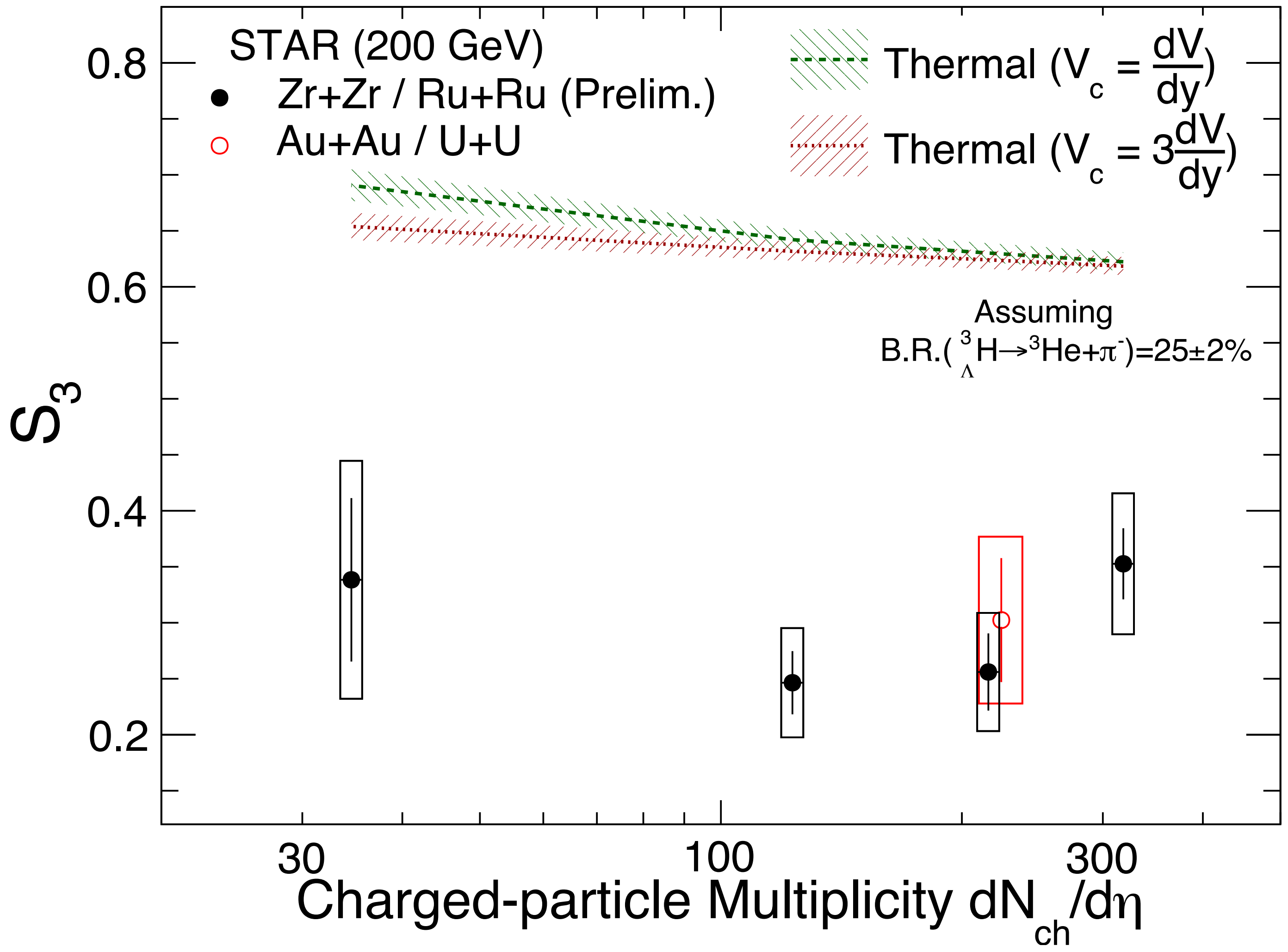


- No obvious multiplicity dependence within uncertainties
- Within uncertainties, coalescence calculations are consistent with the measured data
  - More precise data needed

STAR: arXiv:2310.12674; Science 328, 58-62 (2010)
MUSIC + UrQMD + Coal.: arXiv:2404.02701

Multiplicity Dependence of S_3 at $\mu_B \to 0$

Dongsheng Li, 05/06



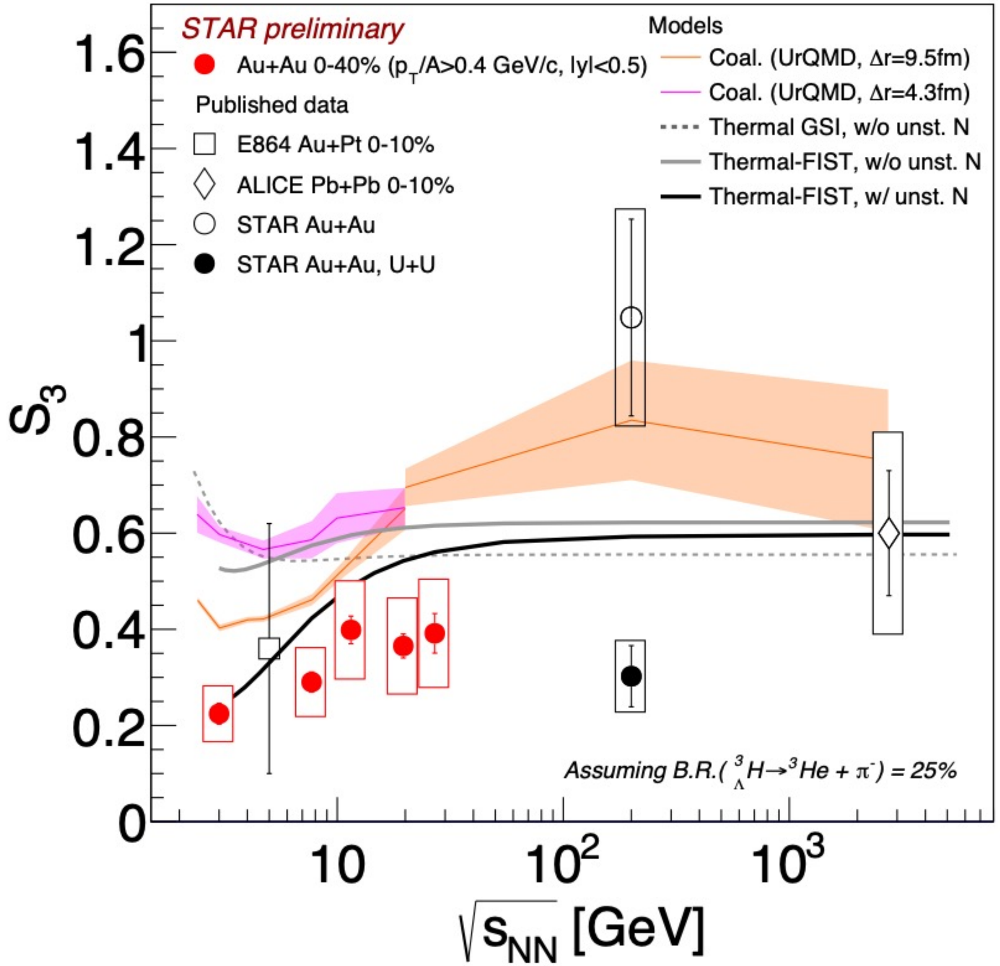
- Thermal-FIST with canonical ensemble fails to describe the data trend
  - Ratios have already canceled volume size and strangeness suppression factor

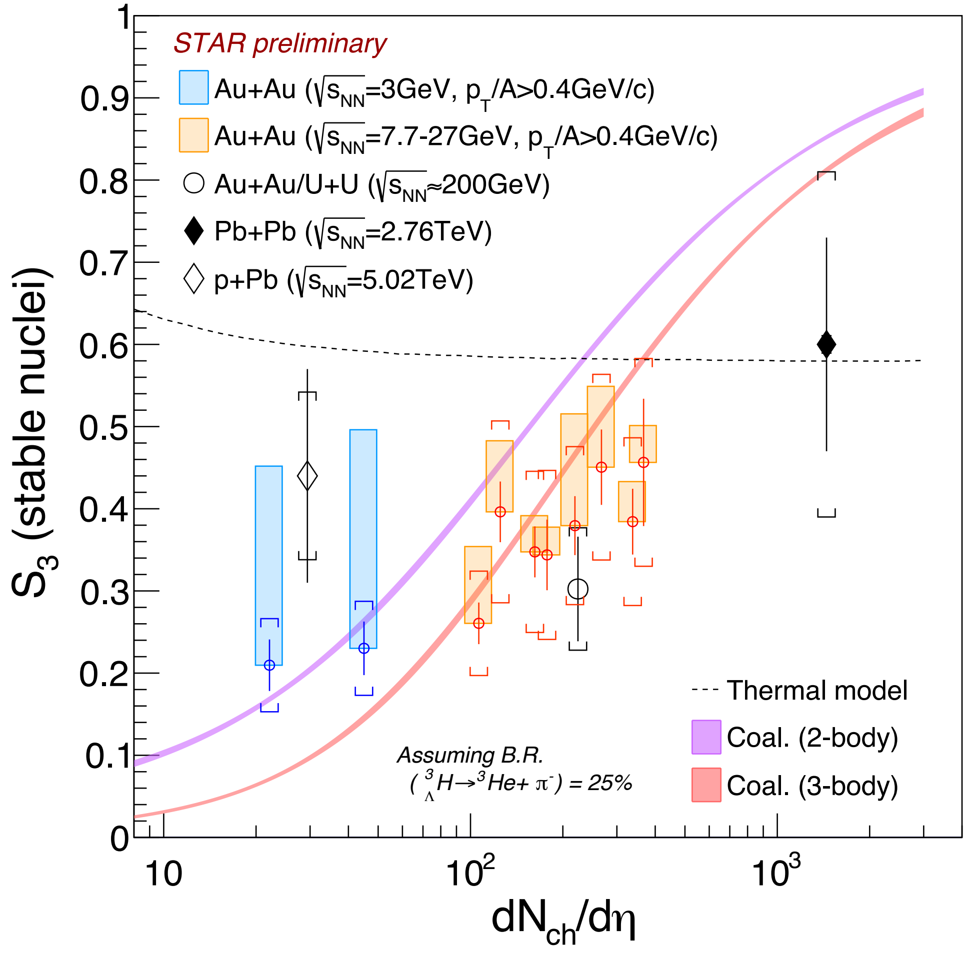
STAR: arXiv:2310.12674; Science 328, 58-62 (2010)
Thermal-FIST: Com. Phys. Comm. 244, 295 (2019)
PLB 785, 171 (2018)

T and μ_B from π/K/p spectra

System Size Dependence of S_3

Xiujun Li, 04/06
Dongsheng Li , 05/06





- Increasing trend observed in S_3 vs collisions energy.
  - Possibly due to stronger feed down contribution in lower energies.
- S_3 vs. $dN_{ch}/d\eta$: coalescence model describes the data within uncertainties.

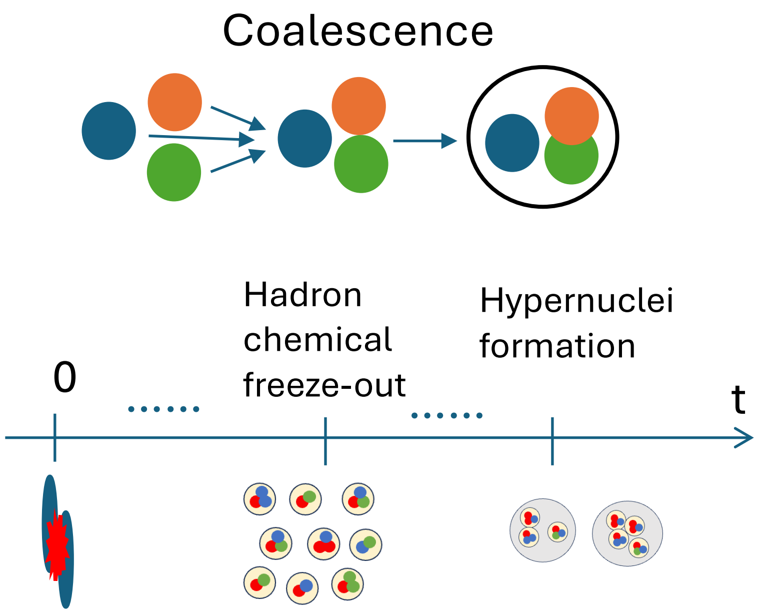
V. Vovchenko, PLB (2020) 135746

Summary

New experimental data on:

- ${}^{3}_{\Lambda}\mathrm{H}$ in 3.0 – 27 GeV Au+Au collisions
- ${}^{4}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{He}$ in 3.0 – 3.5 GeV Au+Au collisions
- ${}^{3}_{\Lambda}\mathrm{H}$ in 200 GeV Zr+Zr/Ru+Ru collisions

- Experimental data support **coalescence is a dominate mechanism** of hypernuclei formation at mid-rapidity in heavy-ion collisions at RHIC.
- Hypernuclei **are not in equilibrium** at hadron chemical freeze-out at RHIC energies.

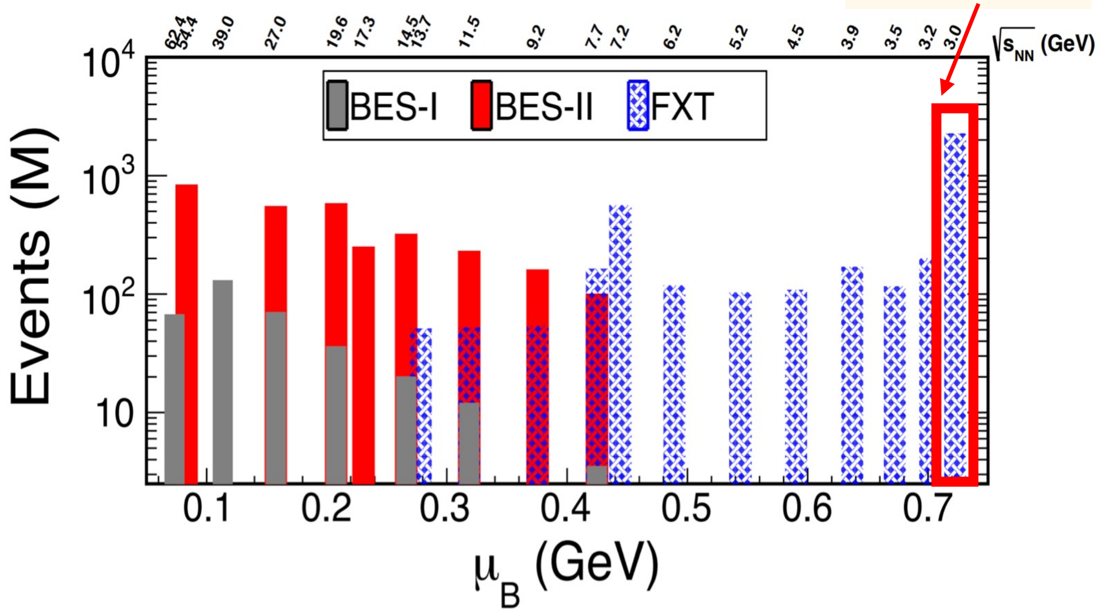


What's Next at RHIC?

Huge datasets from BES-II and 200 GeV Au+Au collisions at RHIC.
- Enable measurements on both high μ_B and $\mu_B \rightarrow 0$ region.

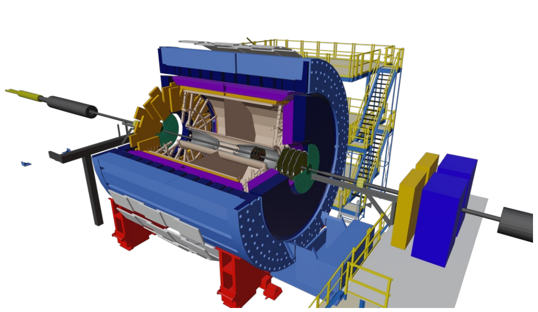
BES II datasets

3 GeV 2B events!

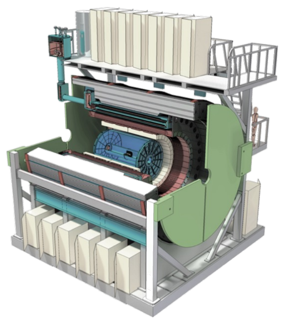


High energy runs in 2023-2025

System	Run year	No. events/Luminosity
p+p 200 GeV	2024	235 pb^{-1}
Au+Au 200 GeV	2023+2025	20B / 40 nb^{-1}



STAR



sPHENIX

Expected total significance from BES-II:

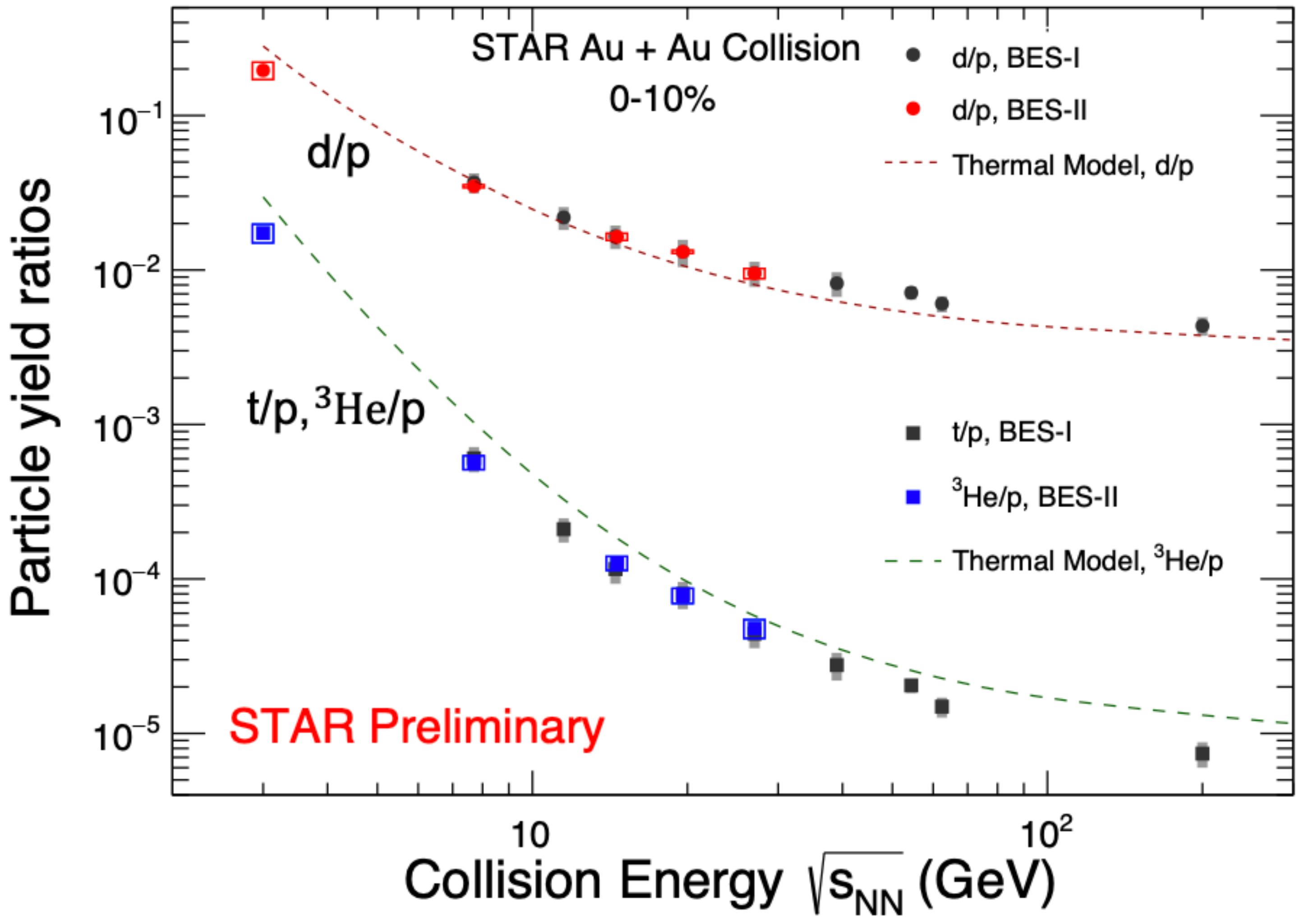
${}^{4}_{\Lambda}\mathrm{H}$: 60σ; ${}^{4}_{\Lambda}\mathrm{He}$: 40σ; ${}^{5}_{\Lambda}\mathrm{He}$: 10σ; ${}^{A}_{\Lambda\Lambda}\mathrm{H}$: ???

Thank you!

Back ups

^{3}He/p and d/p from BES II

Yixuan Jin, 05/06



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

Strangeness Population Factor

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

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

- S_A: Direct connection to coalescence parameters.
- Possible insights to nuclei radius and microscope picture of coalescence.

$$E_A \frac{d^3 N_A}{dp_A^3} = B_A \left(E_{p,n} \frac{d^3 N_{p,n}}{dp_{p,n}^3} \right)^A \Bigg|_{\vec{p}_p = \vec{p}_n = \frac{\vec{p}_A}{A}}$$

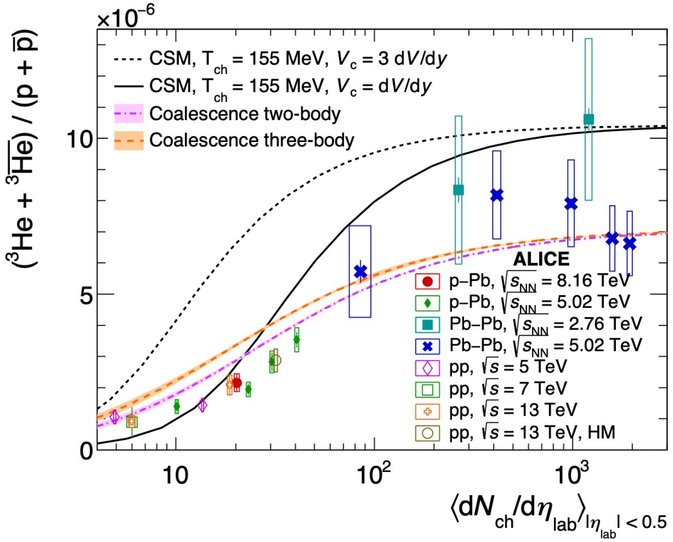
F. Bellini, PRC 99, 054905 (2019)

Under some coalescence scenarios:

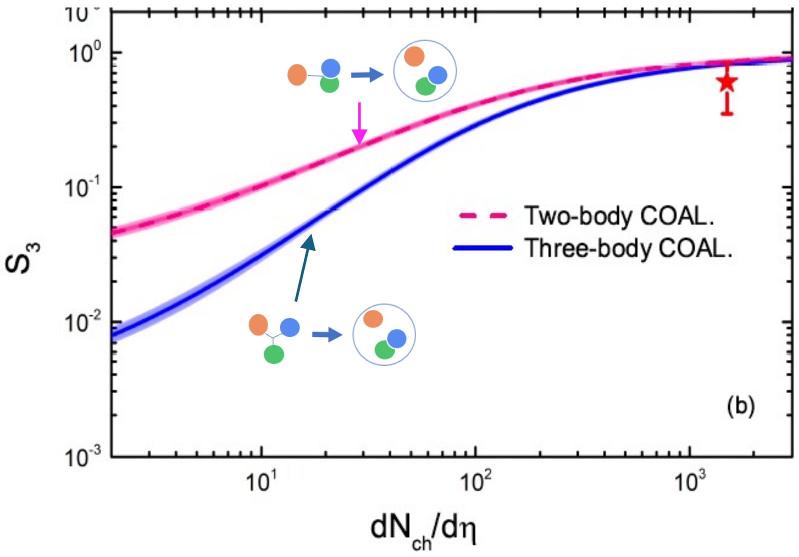
$$B_A = \frac{2J_A + 1}{2^A} \frac{1}{\sqrt{A}} \frac{1}{m_T^{A-1}} \left(\frac{2\pi}{R^2 + (\frac{r_A}{2})^2} \right)^{\frac{3}{2}(A-1)}$$

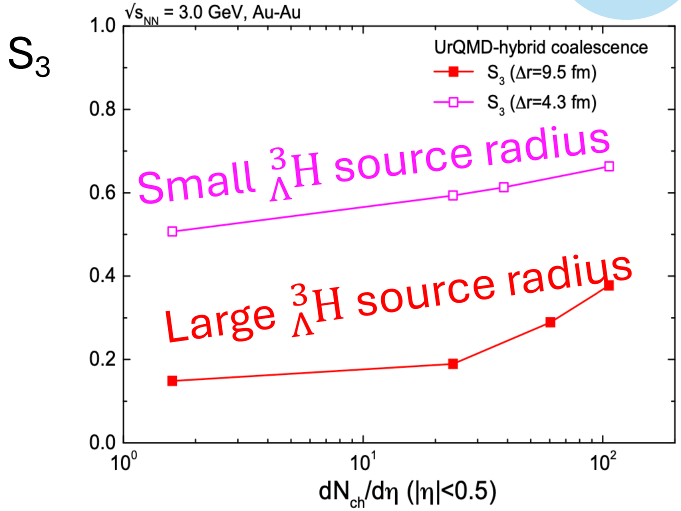
Source size Radius

Emitting source: Small Large



K. Jia. PLB 792 (2019) 132-137

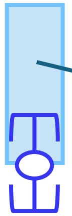


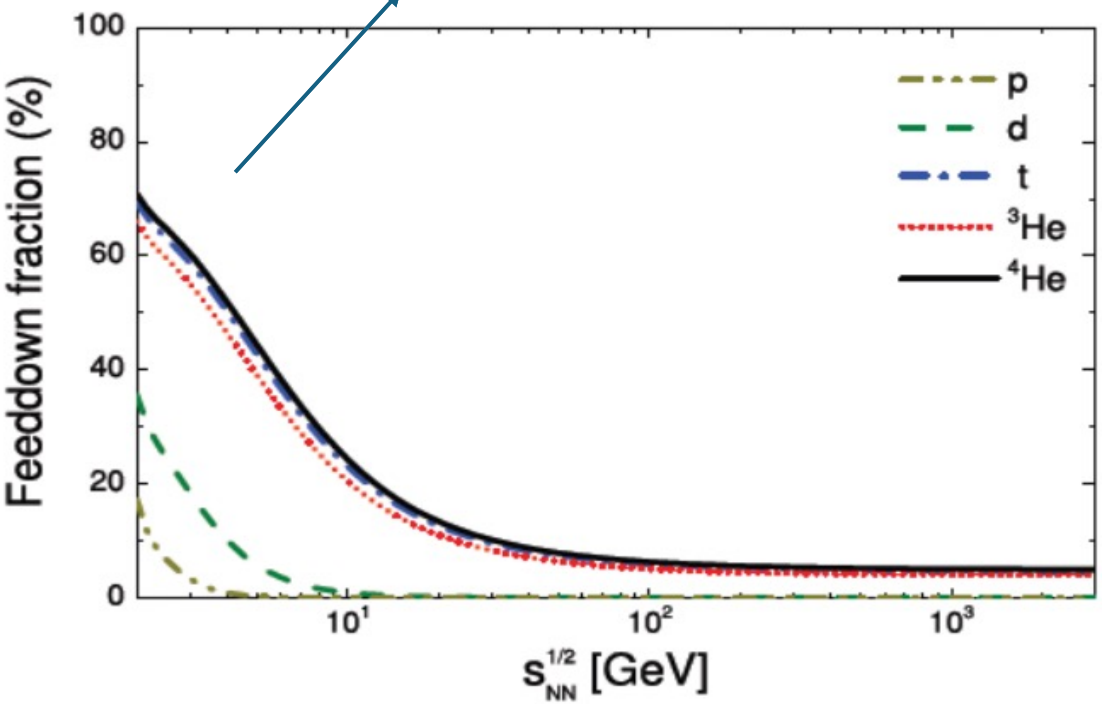


Phys. Rev. C 107, 014912 (2023)

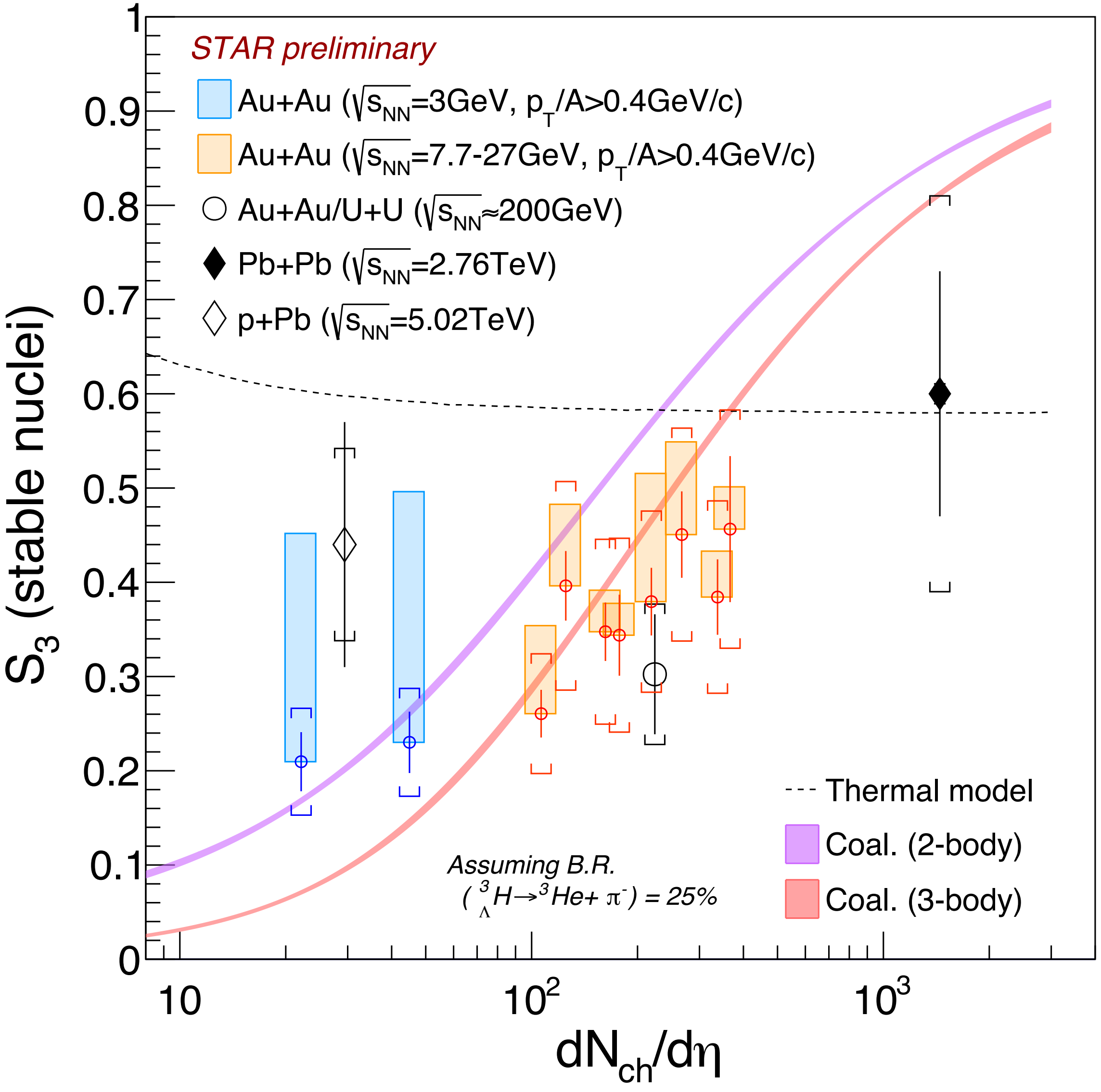
Shadow box:

Feed down from excited nuclei.





V. Vovchenko, PLB (2020) 135746



Questions and Perspectives

Near term question:

- Will we observe the unique behavior from hypernuclei that differ from light nuclei with more data?

Long term goals:

- Understanding the Y-N and three body interaction e.g. Y-N-N;
- Constrain on strangeness degree of freedom in EoS.

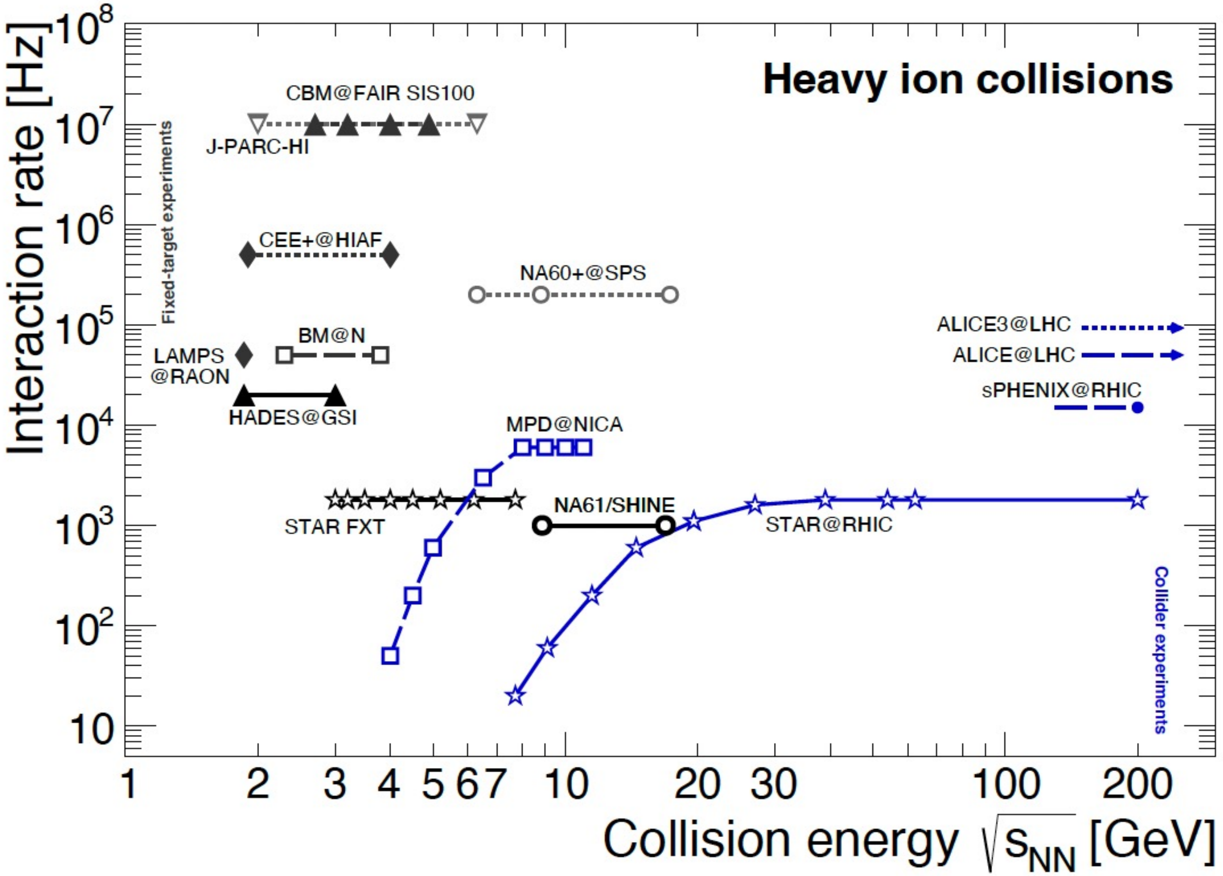
Experimental venue

- Further investigation on light hypernuclei
  - Production, e.g. kinetic freeze-out
  - Collectivity, e.g. v_2
  - Intrinsic properties
    - e.g. B_Λ, spin, B.R., lifetime etc.
- Search of double Λ hypernuclei and exotic hyperon states.
  - $Y - Y$ interaction
- Precise measurements on particle correlations.
  - $p - \Lambda, d - \Lambda, \Lambda - \Lambda$ correlations, etc.

Future Perspective

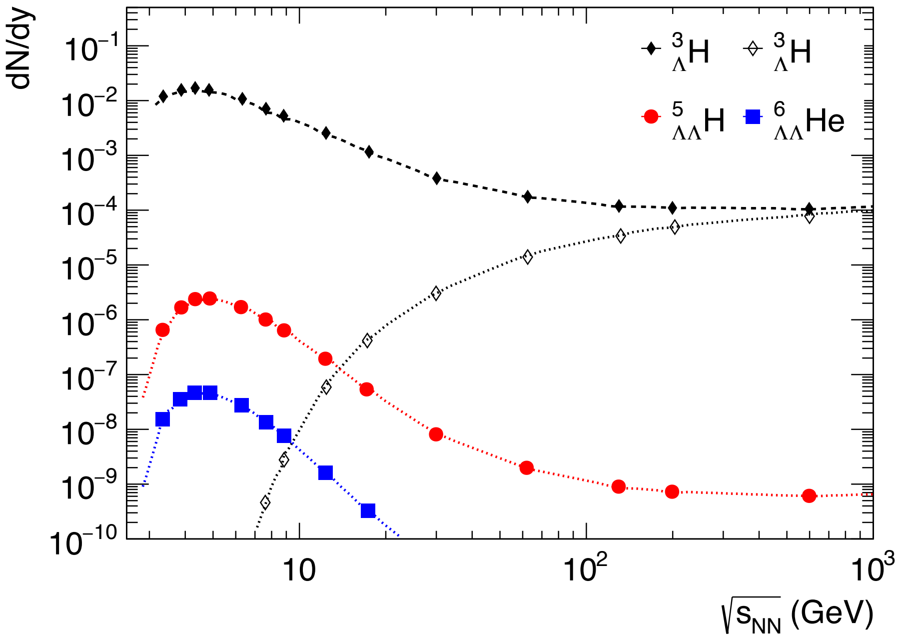
Great potential for discovering unobserved hypernuclei in heavy ion collisions.

- A>=5 and Ξ hypernuclei
- Anti-hypernuclei
- Exotic strangeness states and double Λ hypernuclei
- etc



T. Galatyuk, NPA 982 (2019)

Thermal prediction



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