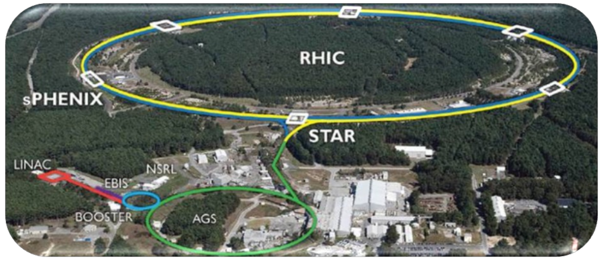
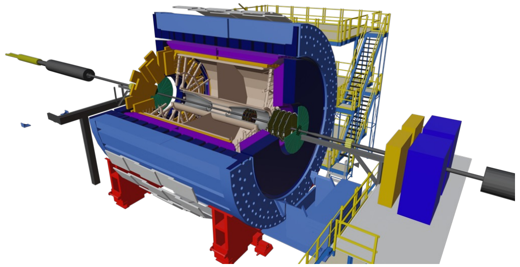
Supported by U.S. DEPARTMENT OF ENERGY | Office of Science





STAR

Measurements of Hypernuclei Properties and Production at STAR

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Lawrence Berkeley National Laboratory

BERKELEY LAB

DNP APS-JPS 2023

HAWAII 2023
Nov.26 – Dec.1
Hilton Waikoloa Village, Hawaii Big Island

Outline

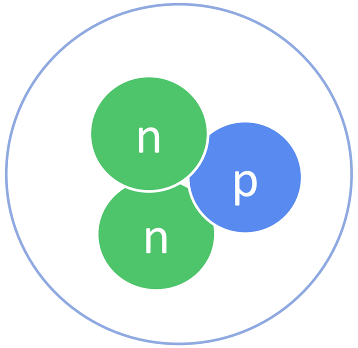
- Introduction
- The STAR experiment
- Hypernuclei measurements at STAR
  - Hypernuclei properties
  - Hypernunclei production and collectivity
- Summary and Outlook

What are Hypernuclei?

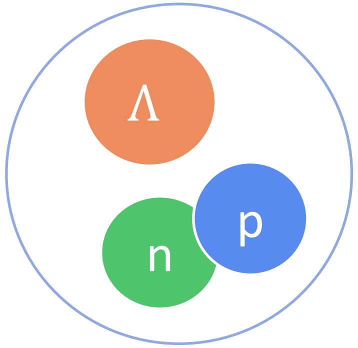
Hypernucleus: A bound system of nucleons with ≥ 1 hyperon.

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

Additional dimension in chart of nuclides



$^{3}\mathrm{H}(t)$



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

lightest hypernucleus

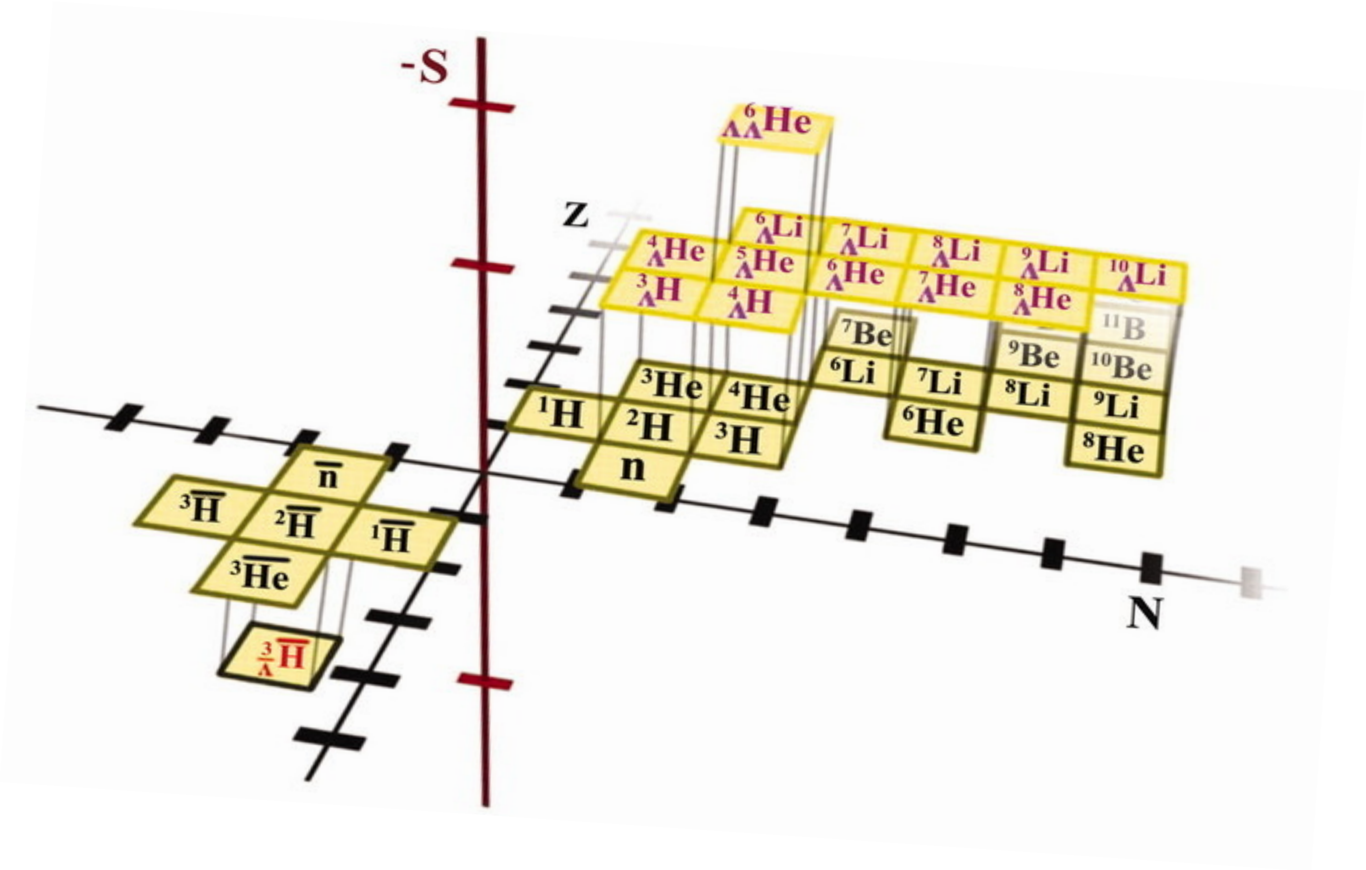
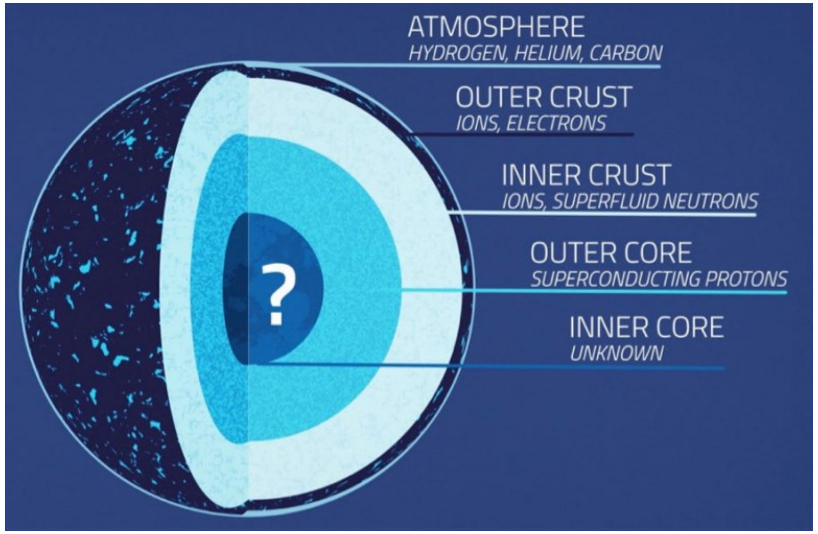


Figure from Science 328 (2010) 58-62

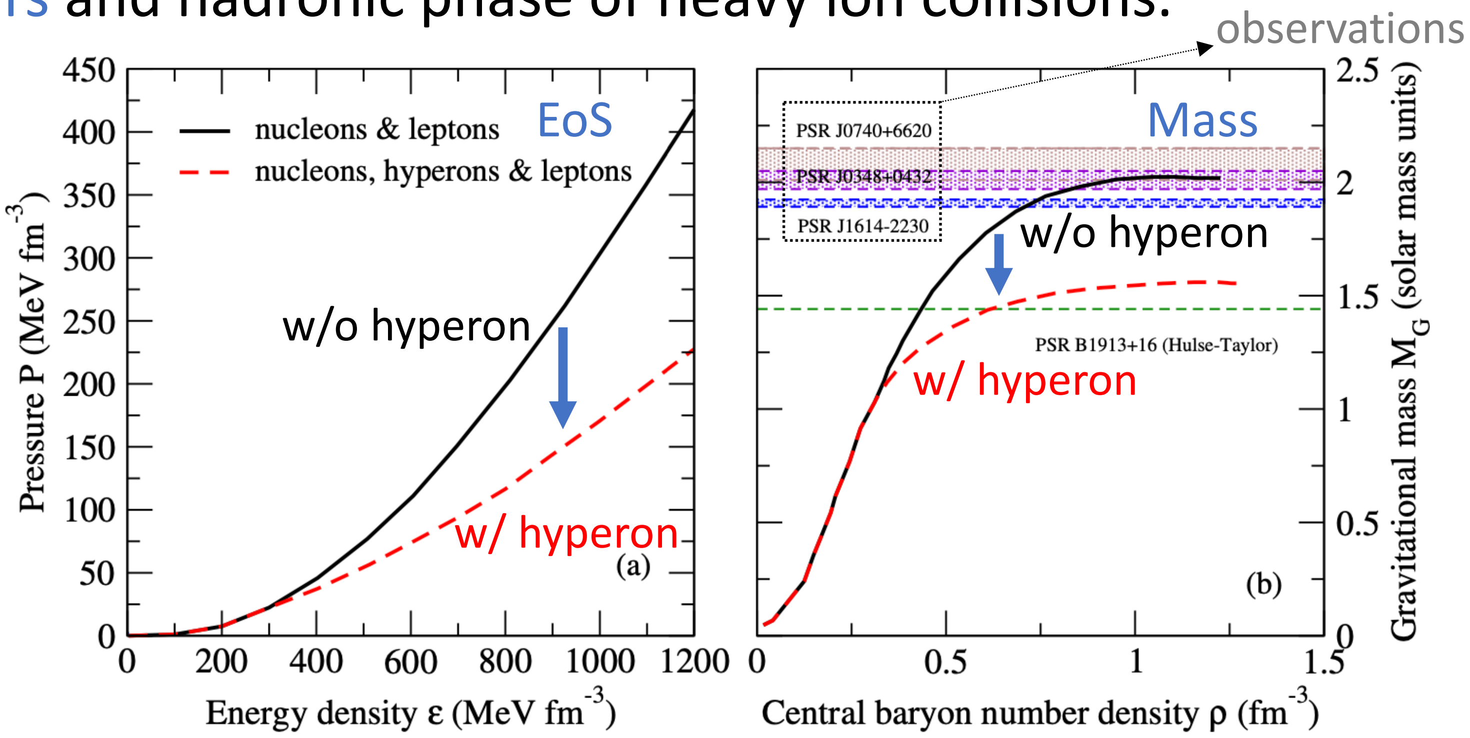
Y-N interaction and Astrophysics

Hypernucleus: Introduce additional degree of freedom in baryon interactions.

- Investigate Hyperon-Nucleon (*Y-N*) interactions in the nuclear experiments.
    - Constrain the strangeness degree of freedom of Equation of State (EoS).
        - e.g. EoS of neutron stars and hadronic phase of heavy ion collisions.



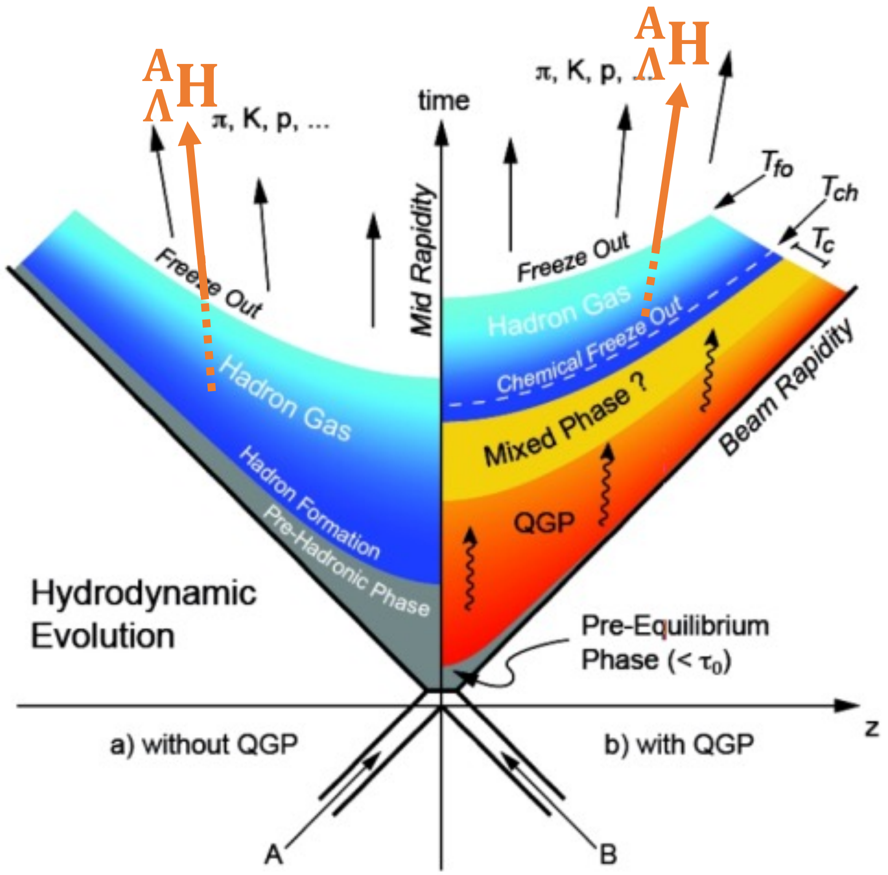
- EoS governs the structure of neutron stars.



PSR J1614-2230: Nature 467,1081 (2010)
PSR J0348+0432: Science 340, 1233232 (2013)
PSR J0740+6620: Nature Astronomy 10,1038 (2019)

EPJ Web Conf. 271 (2022) 09001
Eur. Phys. J. A (2016) 52: 29

Hypernuclei in Heavy ion Collisions



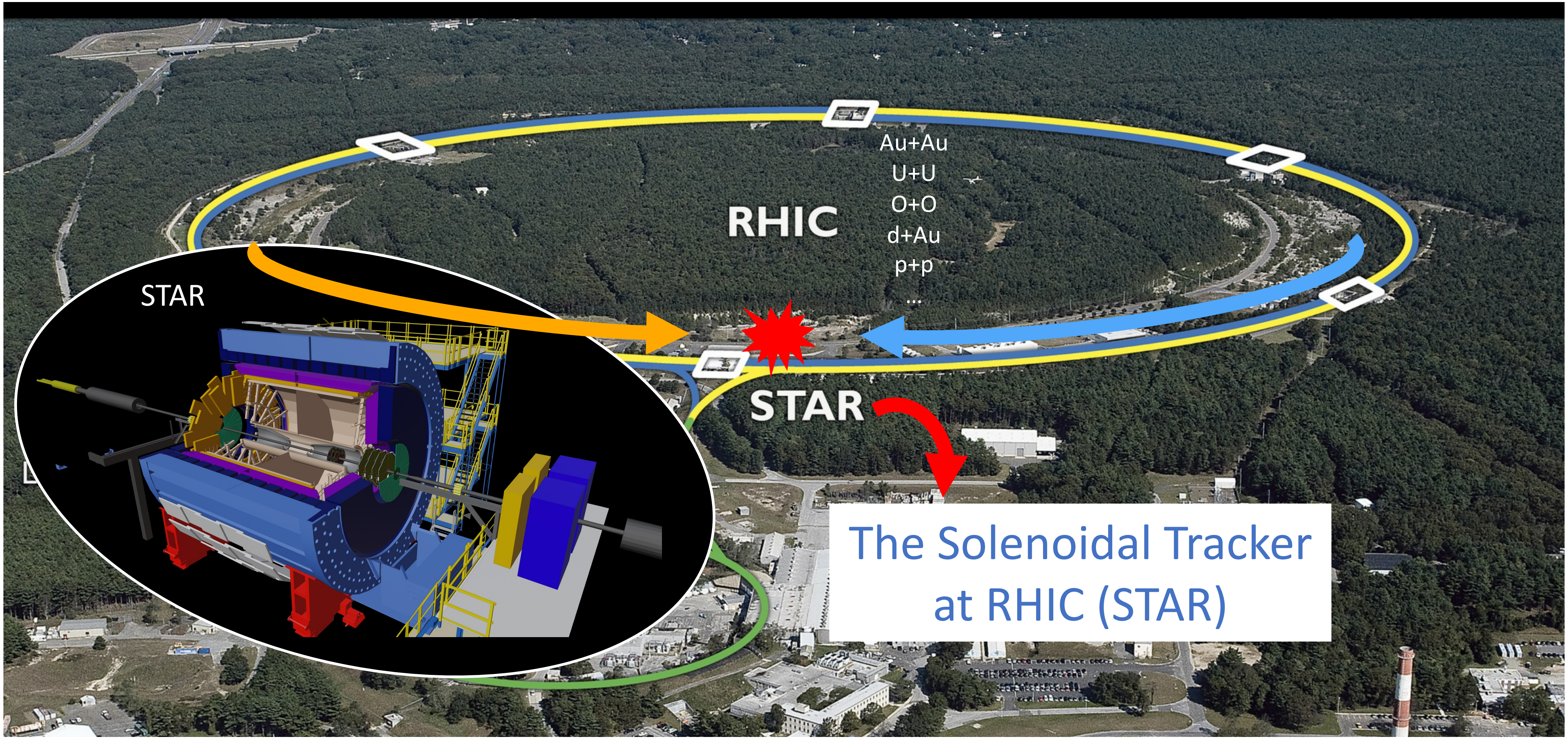
Observables:

- Intrinsic properties.
  - Lifetime, binding energy, branching ratio.
- Production yields.
- Collective flow.

Research focus:

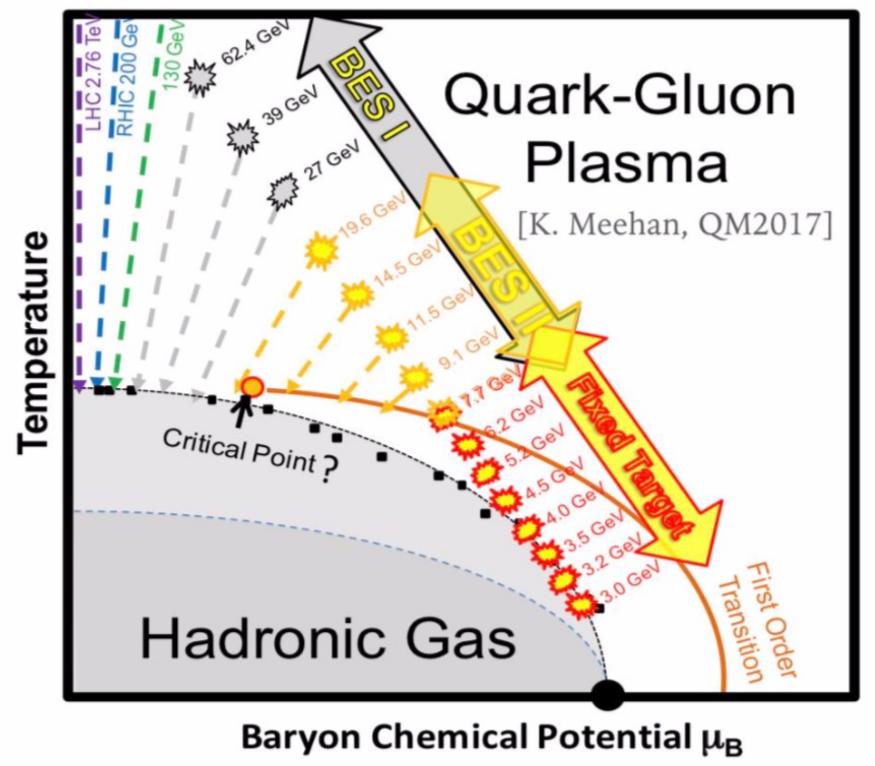
- Hyperon-Nucleon (Y-N) interactions.
- EoS of dense nuclear matter at high μ_{B}.
- Production mechanisms.

RHIC and The STAR Detector



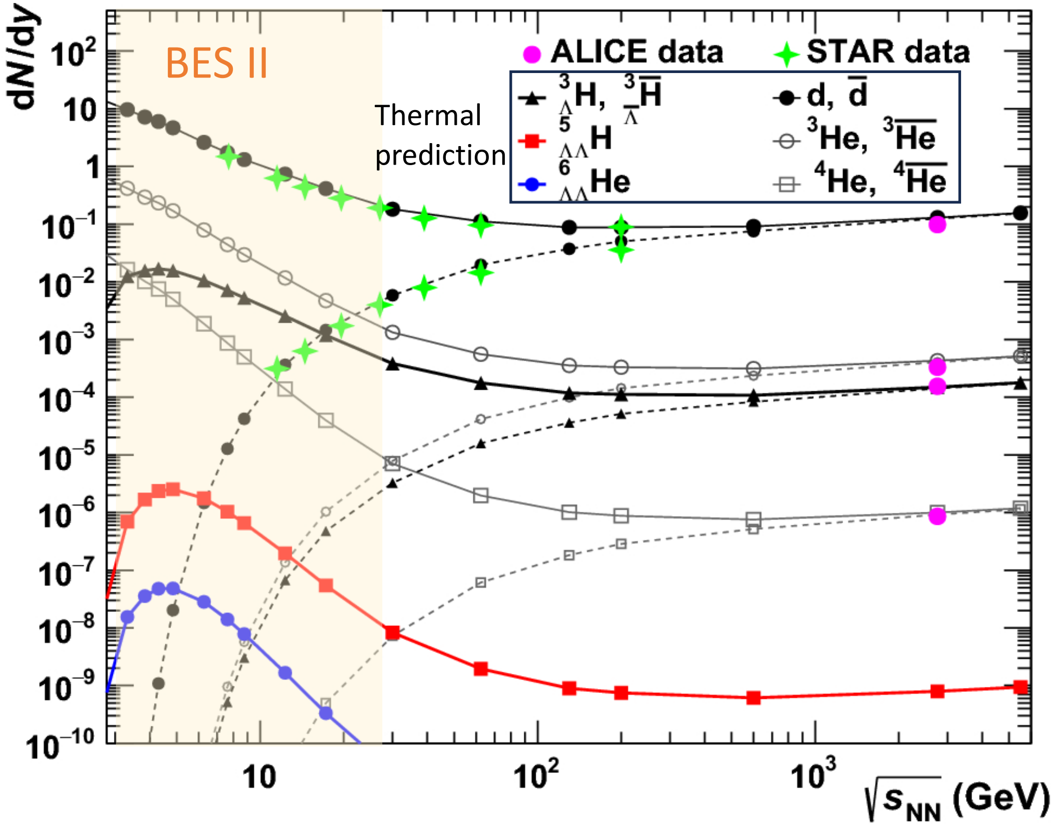
STAR Beam Energy Scan II Program (BES II)

- Mapping the QCD diagram in the region of $200 < \mu_B \leq \sim 720$ 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 - High collision rates.



Opportunities:
Abundant production of hypernuclei at BES II energies!

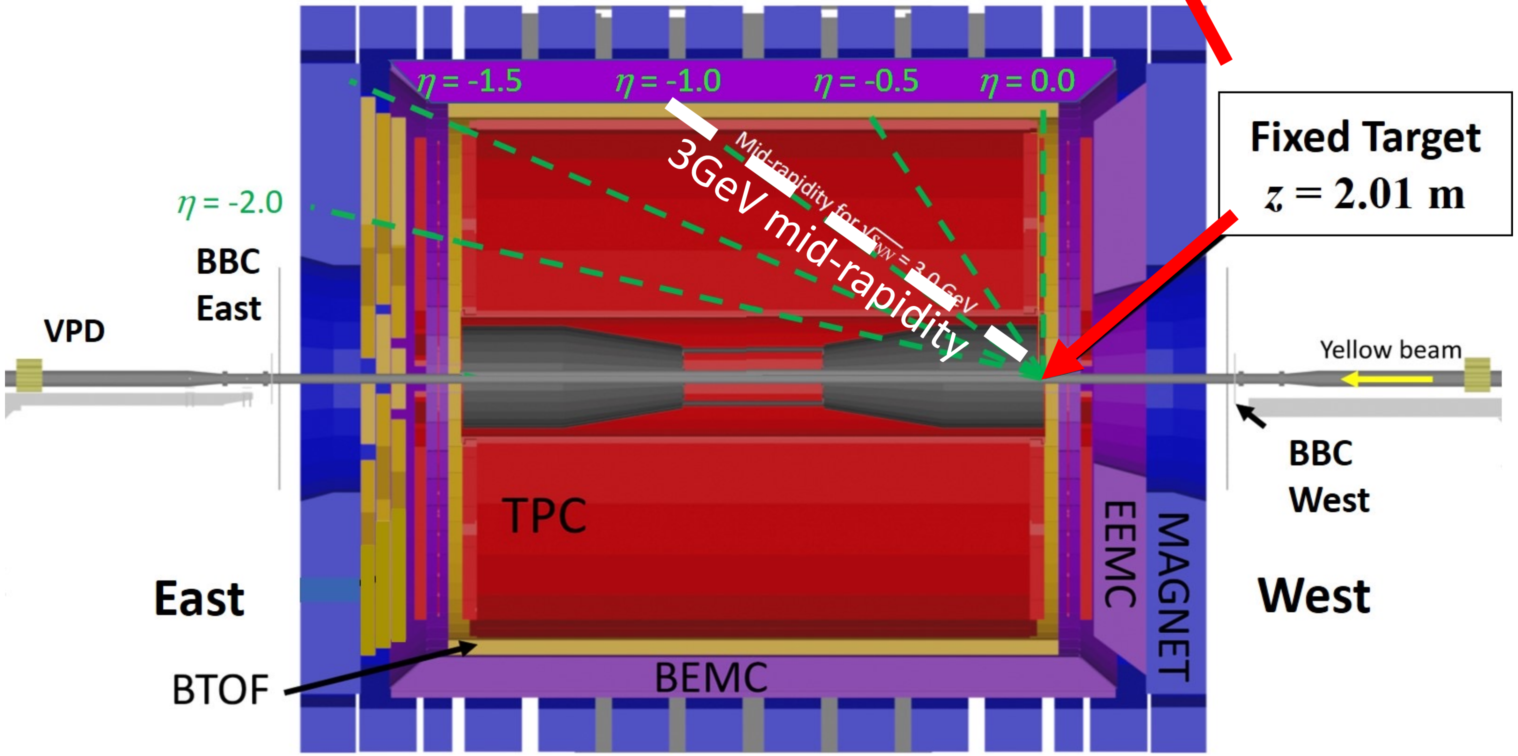
Thermal model predictions

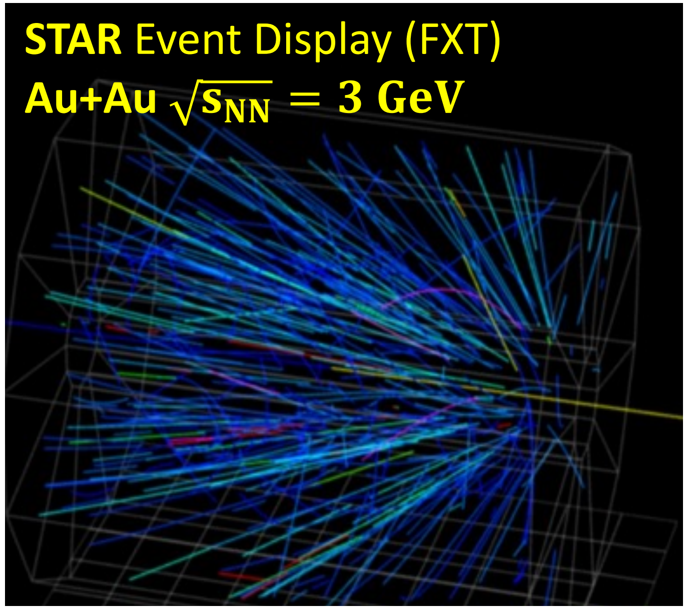


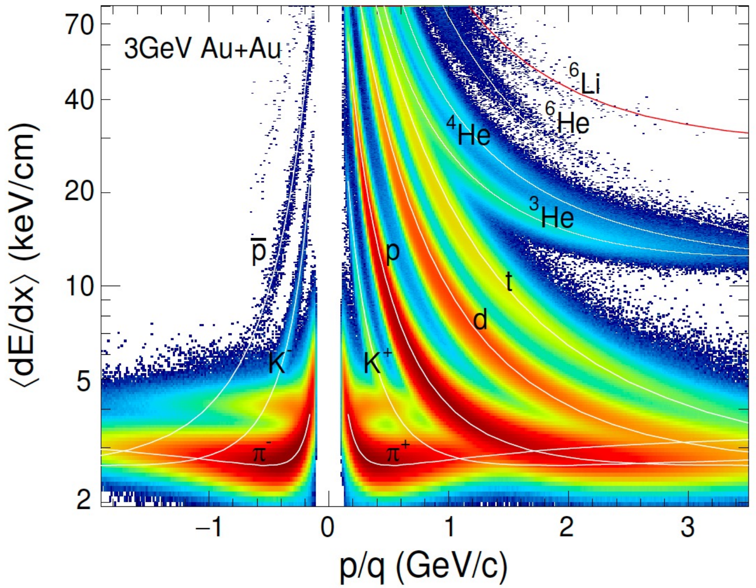
Thermal model: B. Dönigus, Eur. Phys. J. A 56:280 (2020)
A. Andronic et al, PLB 697, 203 (2011)

Fixed-Target Setup at STAR

Gold foil,
250 μm thick







Signal reconstruction

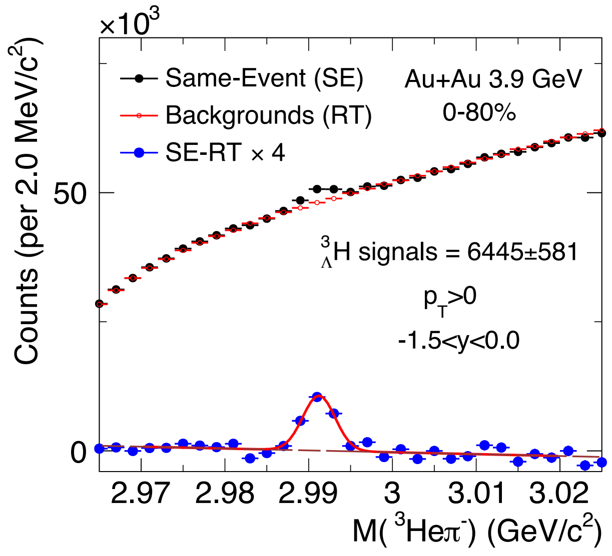
- Decay channel:

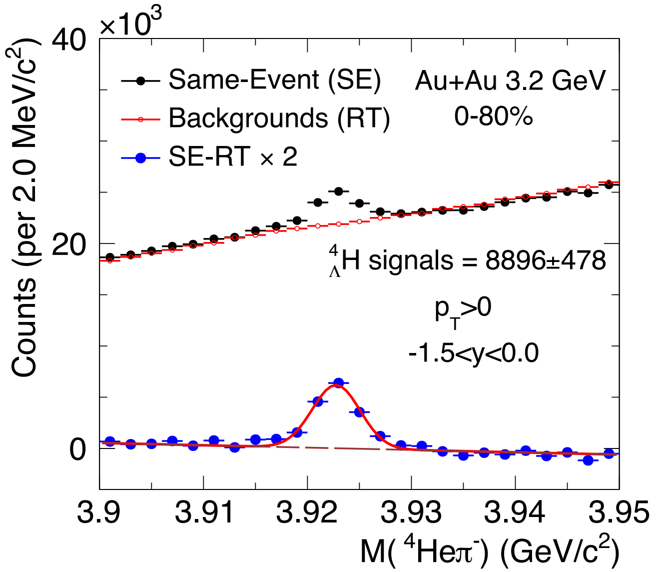
  ${}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He}\,\pi^{-}$ ~ B.R. 20-25%,

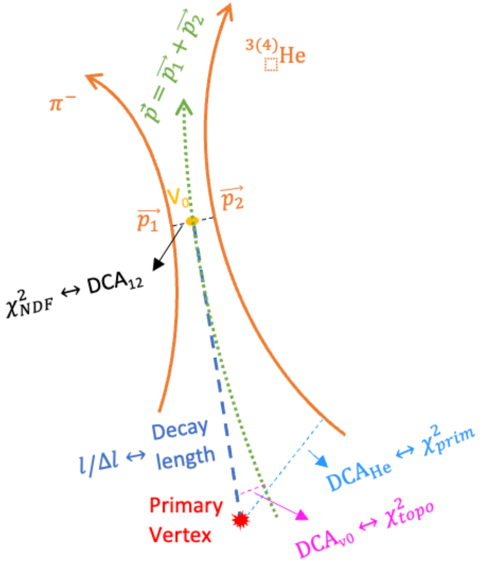
  ${}^{4}_{\Lambda}\mathrm{H} \rightarrow {}^{4}\mathrm{He}\,\pi^{-}$ ~ B.R. 50%,

  ${}^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d}\mathrm{p}\pi^{-}$ ~B.R. ~ 40-50%,

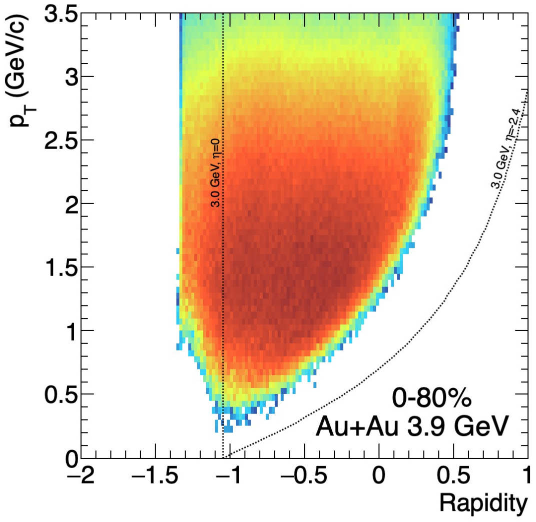
  ${}^{4}_{\Lambda}\mathrm{He} \rightarrow {}^{3}\mathrm{He}\mathrm{p}\pi^{-}$ ~B.R. ~ 23%
- Backgrounds reconstructed by rotation of ${}^{3(4)}\mathrm{He}$.



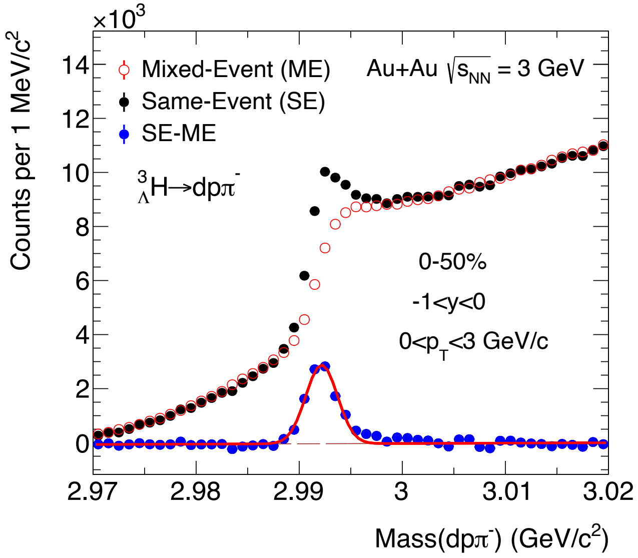


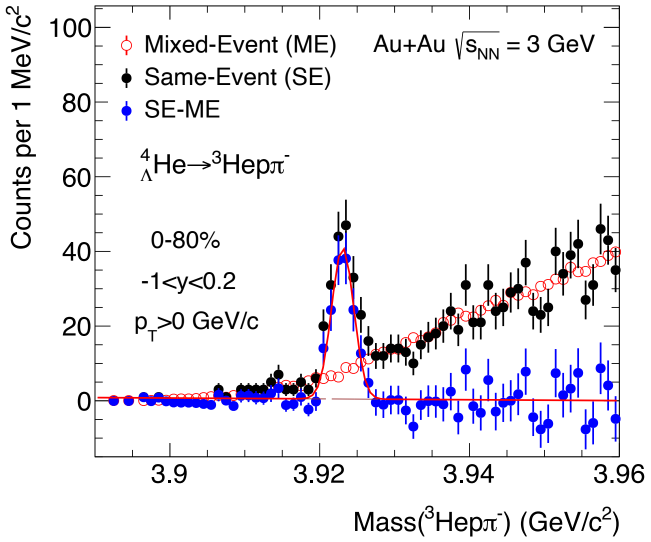


2-body decay topology

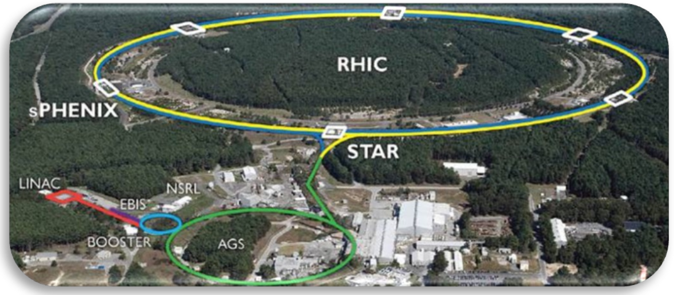


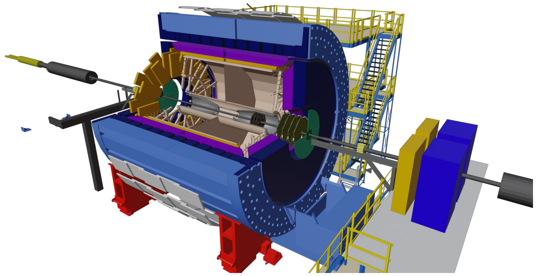
Acceptance of ${}^{3}_{\Lambda}\mathrm{H}$ (from MC)





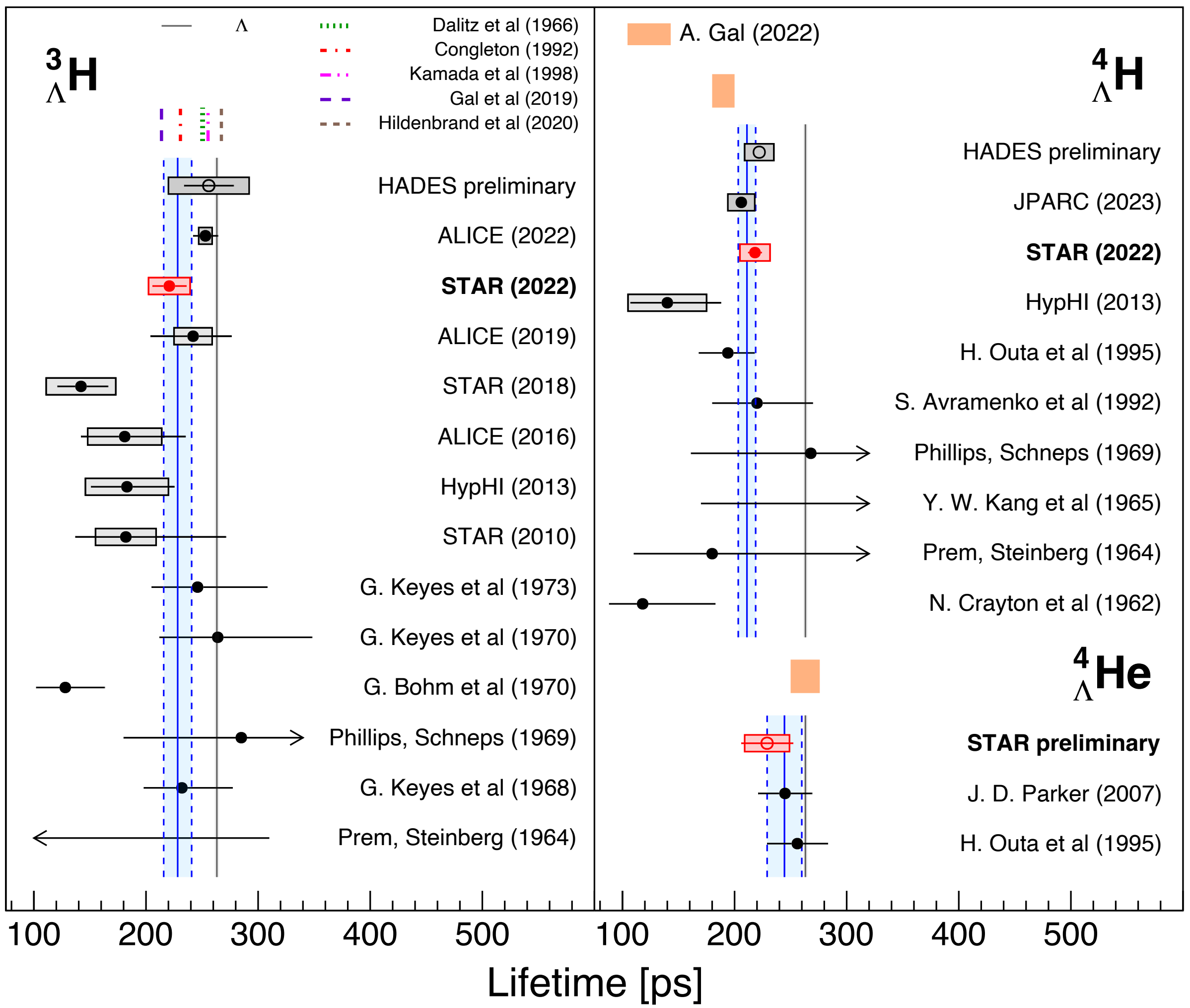
Measurements of Hypernuclei Properties at STAR

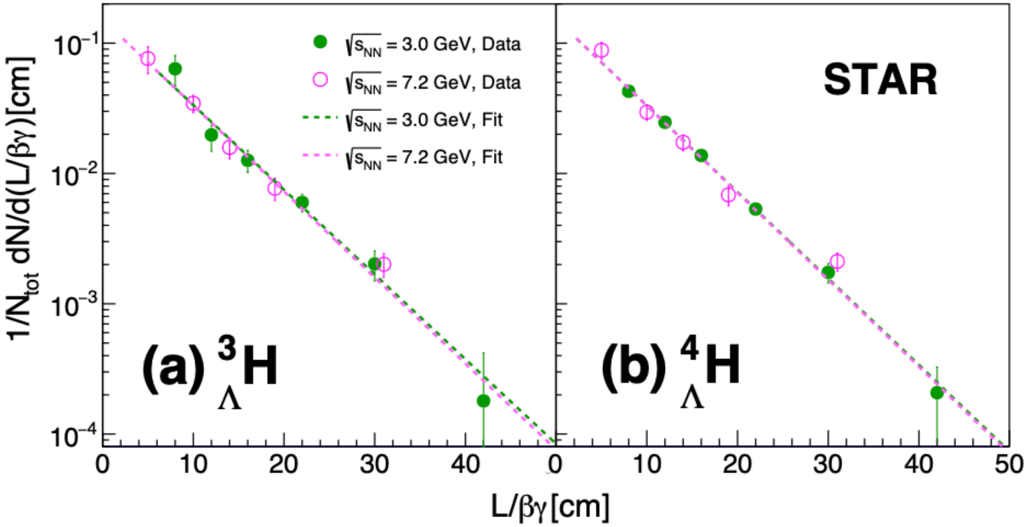




Hypernuclei Lifetimes

${}^{3}_{\Lambda}$H, ${}^{4}_{\Lambda}$H lifetime: STAR, PRL 128, 202301 (2022)





A. Gal et al, PLB791, 48 (2019)

${}^{3}_{\Lambda}$H: Global avg. = $(87\pm5)\%\tau(\Lambda)$, $2.8\sigma < \tau(\Lambda)$.

- Calculations with pion FSI consistent with data.

${}^{4}_{\Lambda}$H, ${}^{4}_{\Lambda}$He: $\tau({}^{4}_{\Lambda}\mathrm{H})/\tau({}^{4}_{\Lambda}He)$ = 0.86±0.06.

- Lifetime ratio consistent with calculation based on isospin rule.

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

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

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

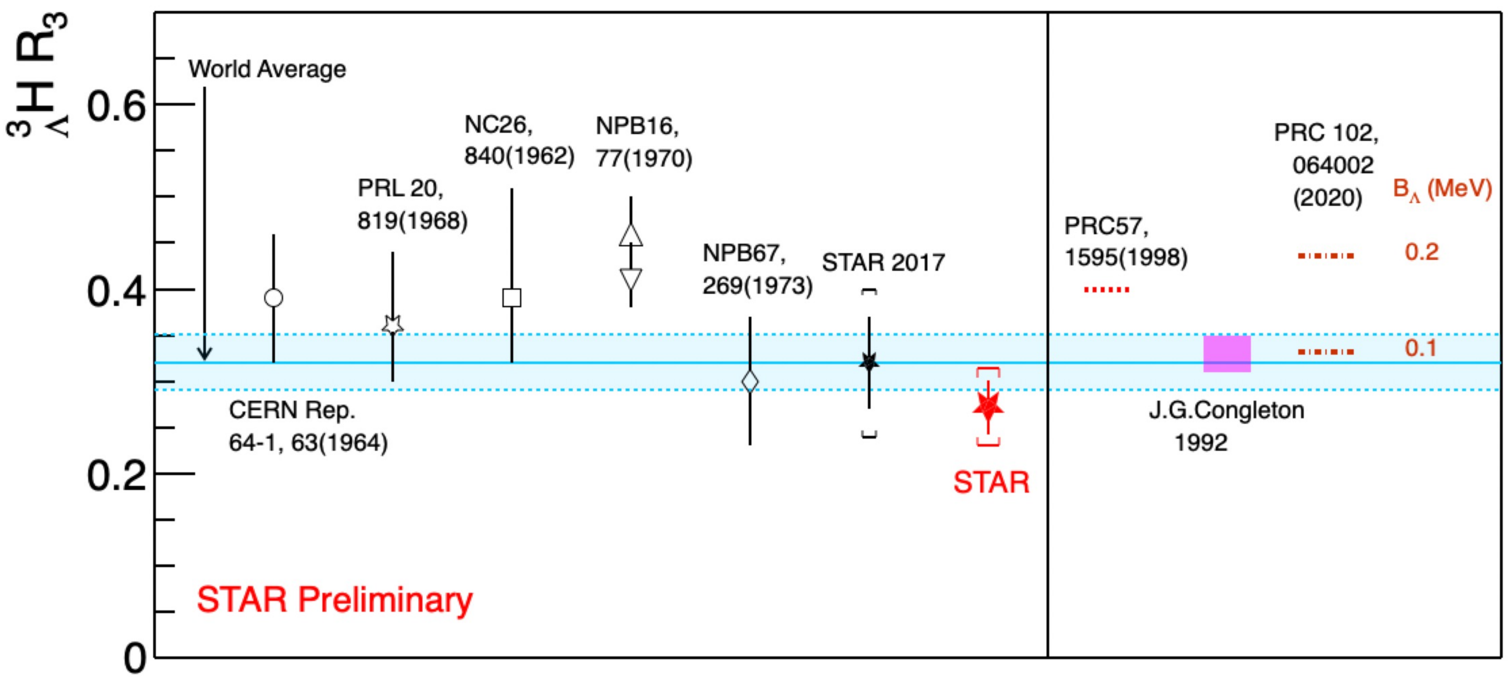
Improved precision on R_3.

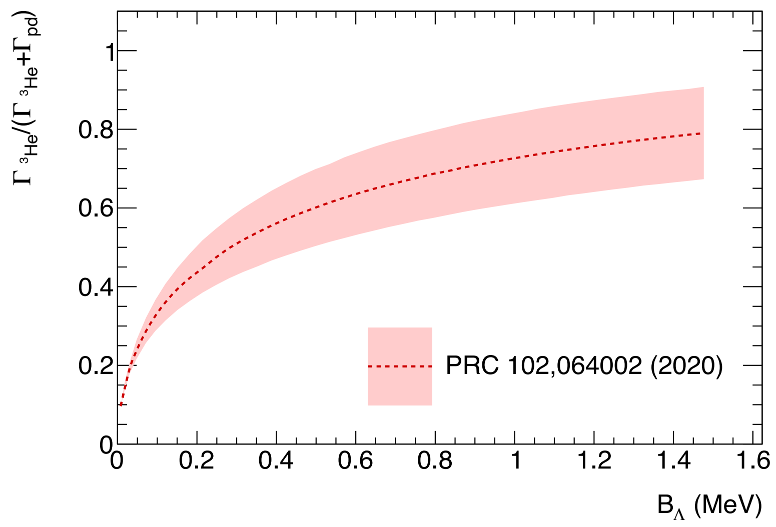
- Stronger constraints on absolute B.R. and hypertriton internal structure models.
- Model comparison show data favors small B_Λ.

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

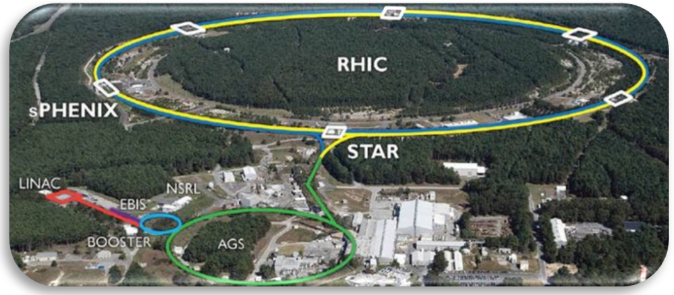
STAR: $R_3 = 0.272 \pm 0.030 \pm 0.042$

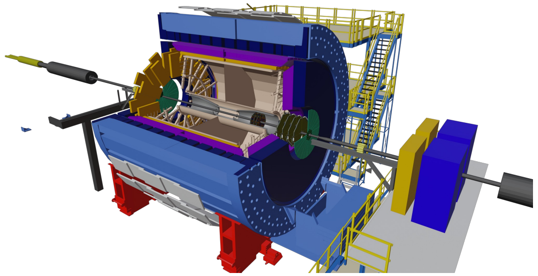
Updated world average: 0.32 ± 0.03





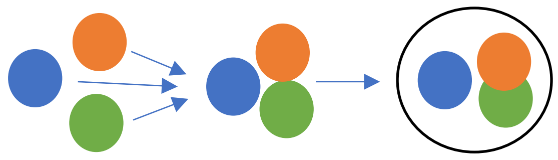
Hypernuclei Production and Collectivity in Au+Au Collisions

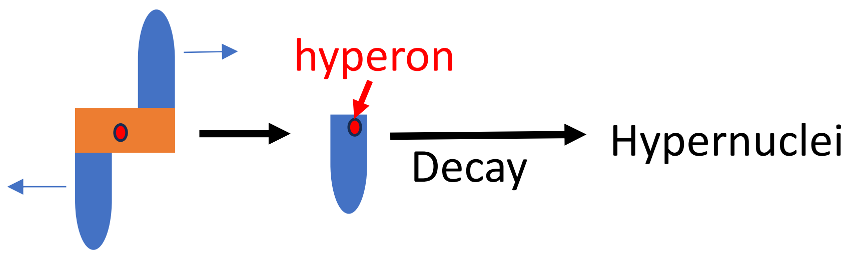




Hypernuclei production mechanism in HIC

- **When and how loosely bound hypernuclei are formed in HIC?** ${}^{3}_{\Lambda}\mathrm{H}\ B_{\Lambda}$~0.07-0.4 MeV, T_{ch}>>B_{Λ}
- **Formation mechanism can be classified as:**
  - Coalescence formation
    - Dominates at mid-rapidity.
      - Baryons / nuclei very close in phase space ($\vec{p}, \vec{r}$).
  - Nuclear fragmentation of hypercluster
    - Dominates at beam rapidity.
      - Dominate for heavy hypernuclei formation.





- **Production models**

Thermal model

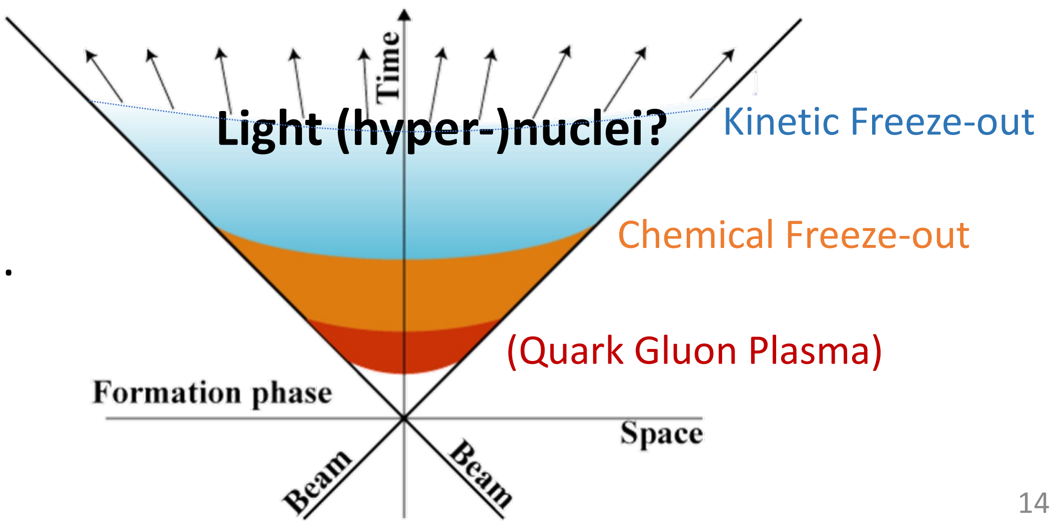
- Hadron chemical freeze out T_{ch} and μ_B.

Coalescence approach

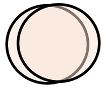
- Coalescence via final state interactions among nucleons.

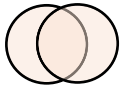
Dynamical cluster formation

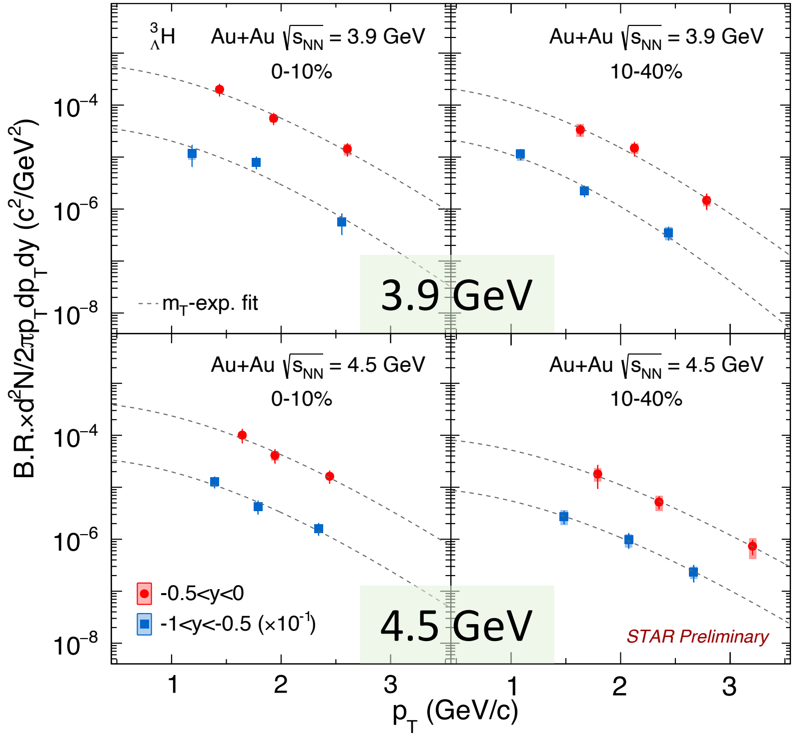
- Reaction-based; clusters can be formed before kinetic freeze-out.

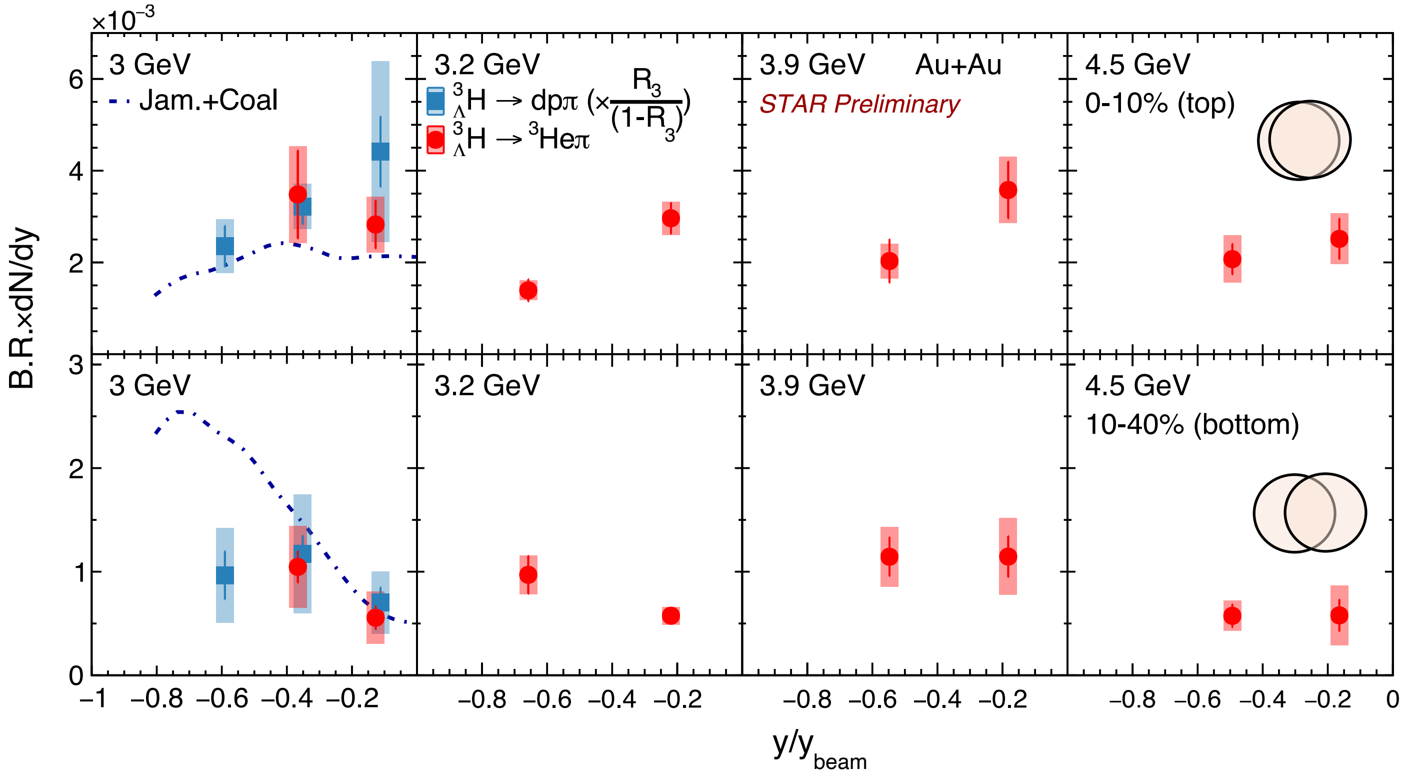


${}^{3}_{\Lambda}\mathrm{H}$ p_T Spectra, dN/dy in 3-4.5 GeV


0-10%


10-40%



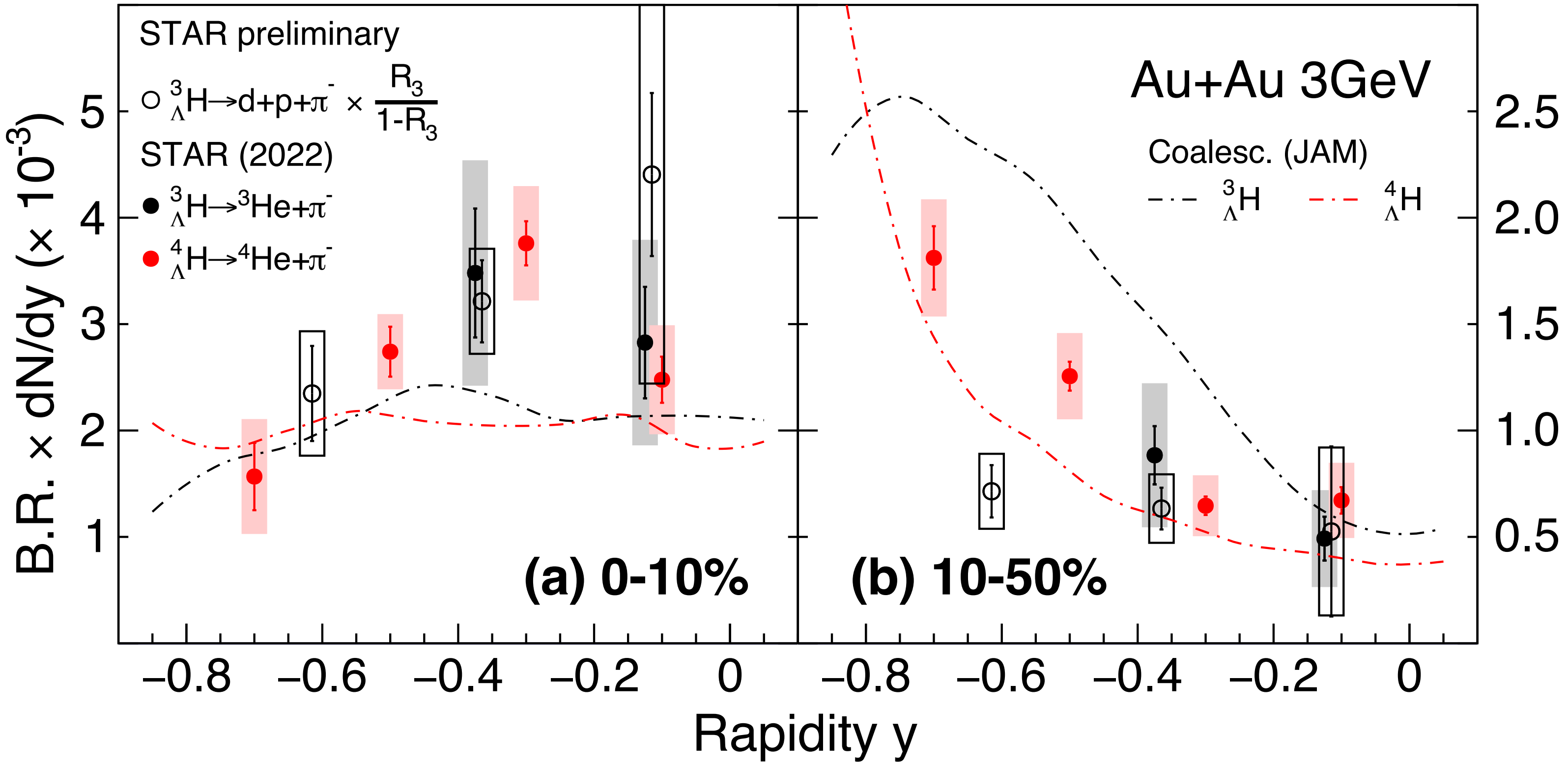


- Utilizing datasets collected by STAR Fixed-Target program, ${}^{3}_{\Lambda}\mathrm{H}$ p_T spectra, dN/dy are measured at $\sqrt{s_{NN}}$ = 3-4.5 GeV in Au+Au collisions.

3 GeV ${}^{3}_{\Lambda}\mathrm{H} \to {}^{3}\mathrm{He} + \pi^-$: PRL 128, 202301 (2022)

${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ dN/dy at 3 GeV

0-10% 10-50%



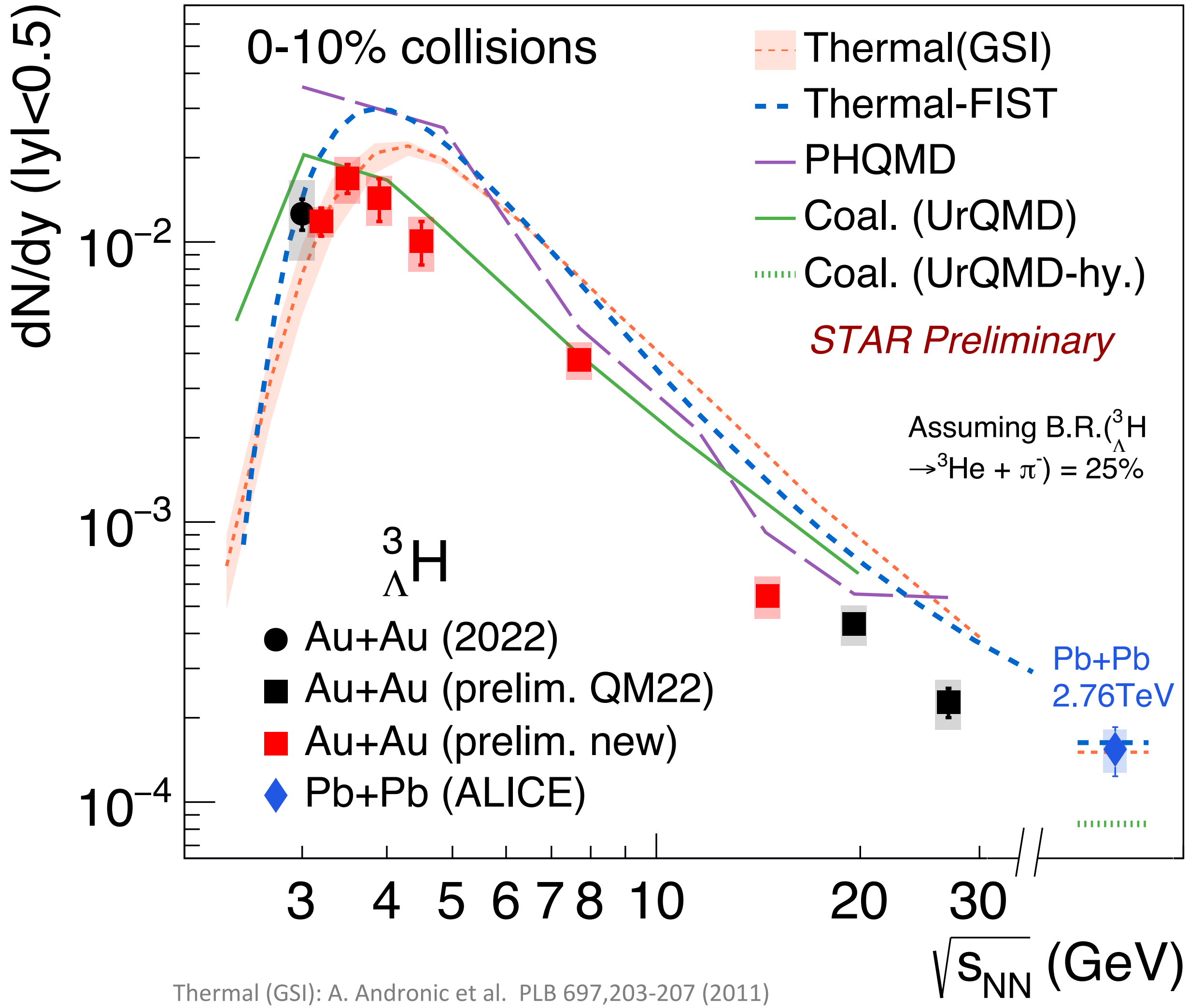
JAM+Coal.

- Tuned to match proton and Λ spectra from data;
- Instant coalescence after kinetic freeze-out
- Two body coalescence: d/t+Λ

- Coalescence models with tuned parameters:
  - Qualitatively describe the trend of ${}^{4}_{\Lambda}H$ yields versus rapidity.
  - Fail to describe the ${}^{3}_{\Lambda}H$ tendency in 10-50% centralities.

3 GeV ${}^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$: PRL 128, 202301 (2022)

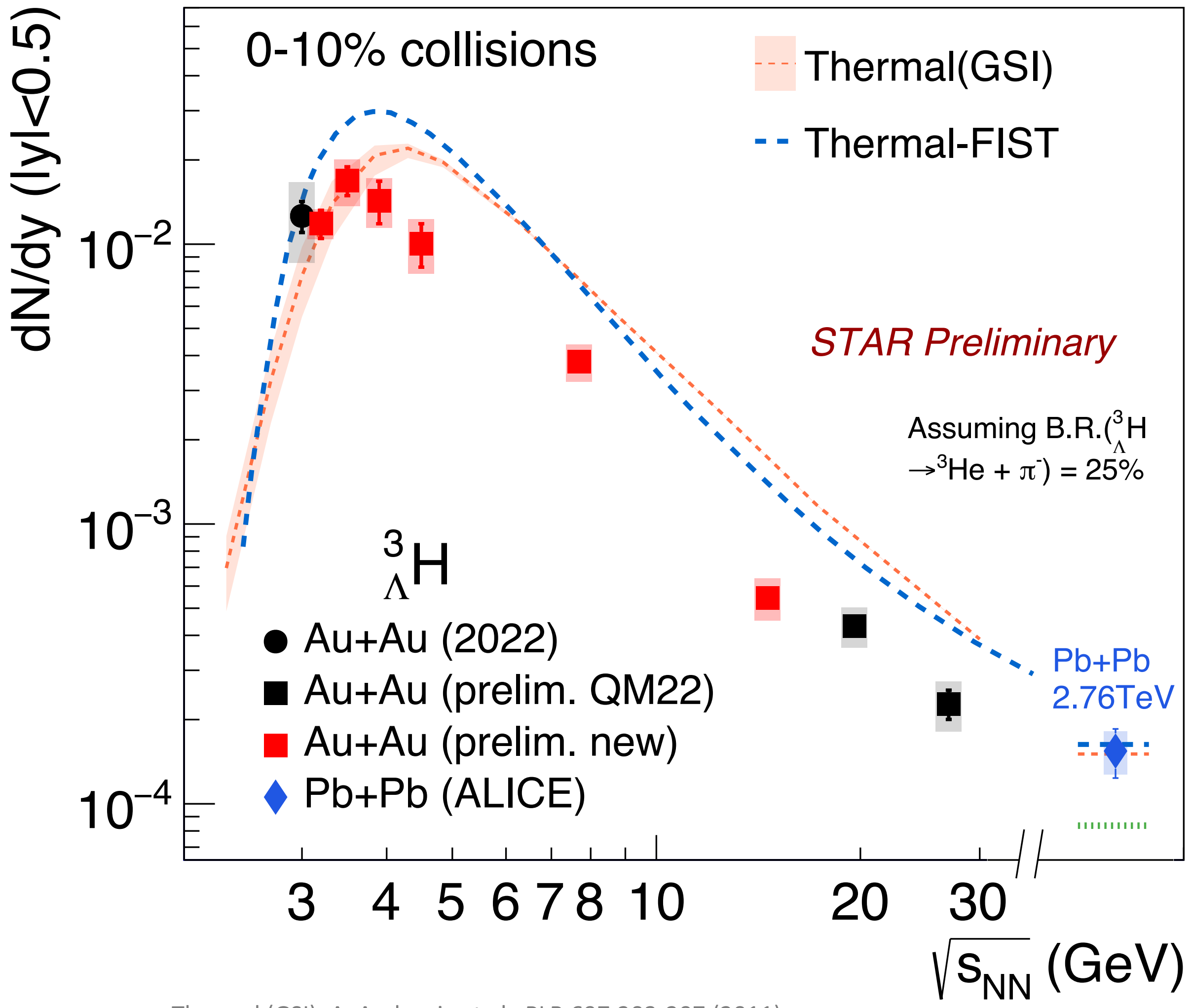
Energy Dependence of ${}^{3}_{\Lambda}H$ production



Thermal (GSI): A. Andronic et al. PLB 697,203-207 (2011)
Thermal-FIST, Coal. (UrQMD): T. Reichert et al. PRC 107 (2023) 1, 014912
PHQMD: S. Gläßel et al. PRC 105, 014908 (2022),
V. Kireyeu et al. arXiv:1911.09496
Pb+Pb: ALICE, PLB 754, 360 (2016)
STAR at 3 GeV: PRL 128, 202301 (2022)

- ${}^{3}_{\Lambda}H$ yields peak at $\sqrt{s_{NN}}$ = 3-4 GeV, then decrease toward higher energy.
  - Decreasing trend results from increasing baryon density at lower energies.

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



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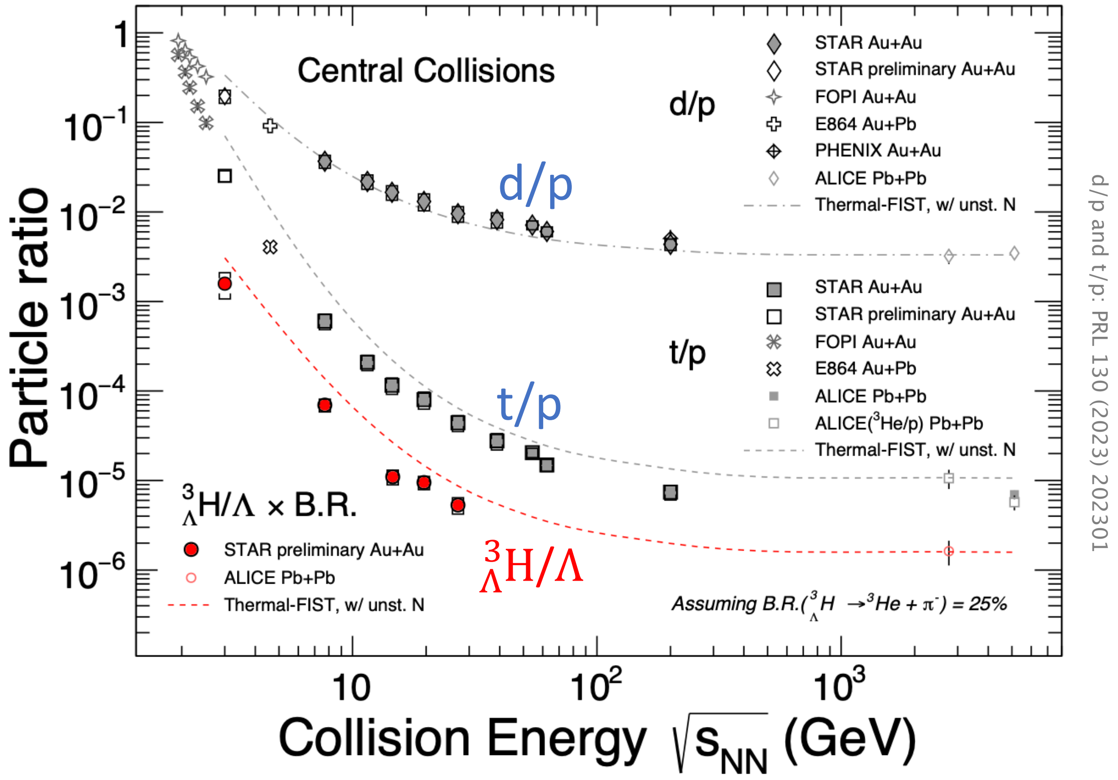
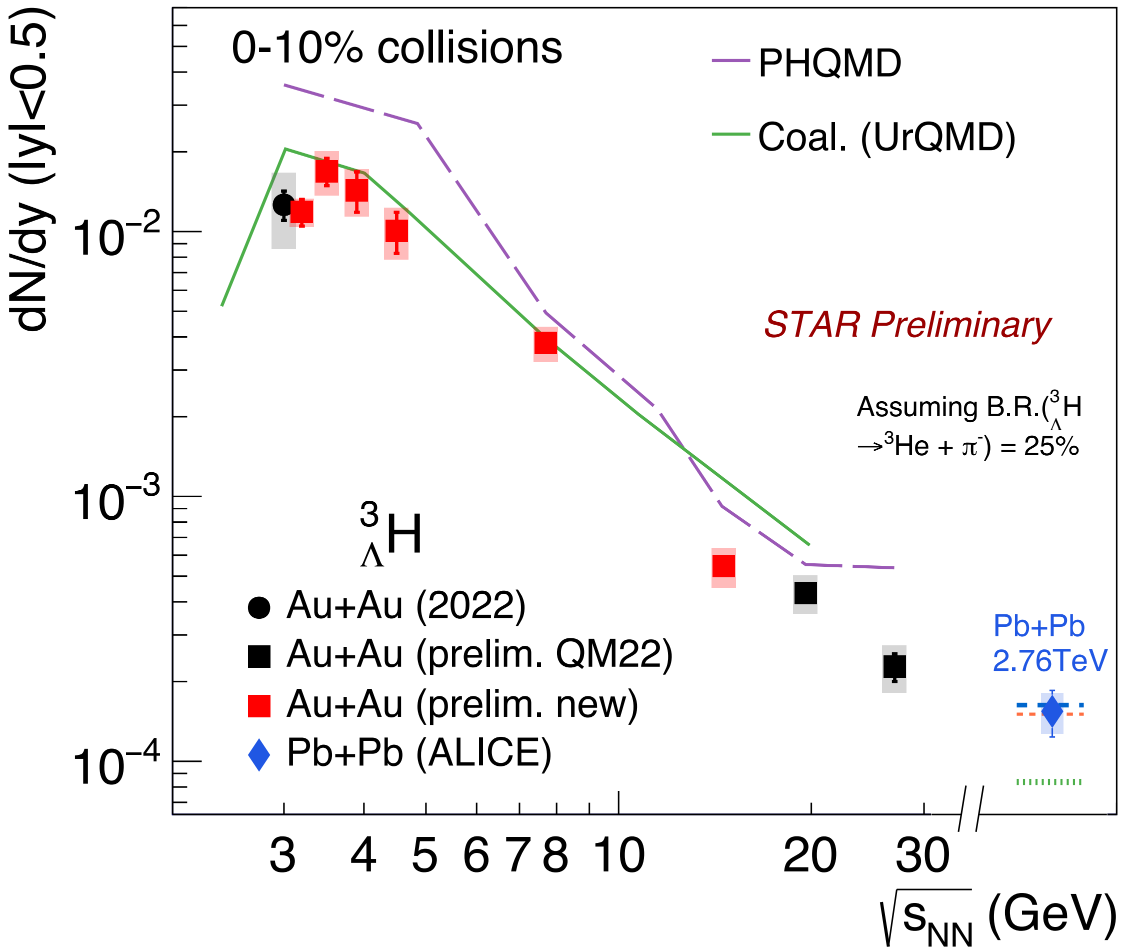
V. Kireyeu et al. arXiv:1911.09496
Pb+Pb: ALICE, PLB 754, 360 (2016)
STAR at 3 GeV: PRL 128, 202301 (2022)

- **Thermal model**
  - Hadron chemical freeze-out T and μ_B.



Hypernuclei yields are not fixed at hadron chemical freeze-out.

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



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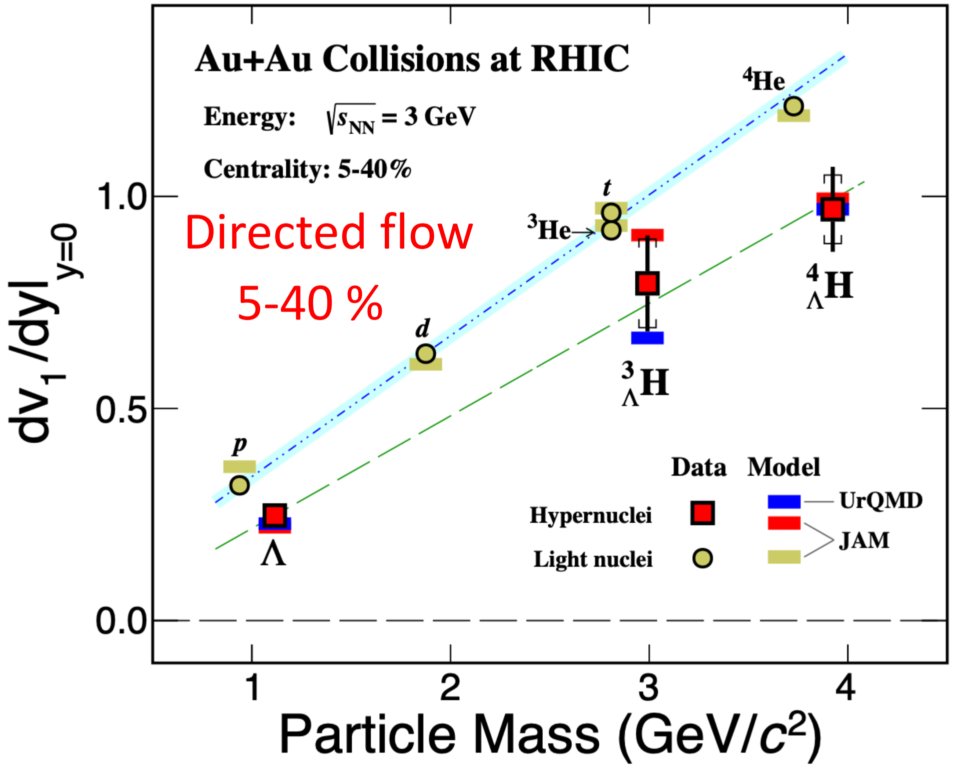
STAR at 3 GeV: PRL 128, 202301 (2022)

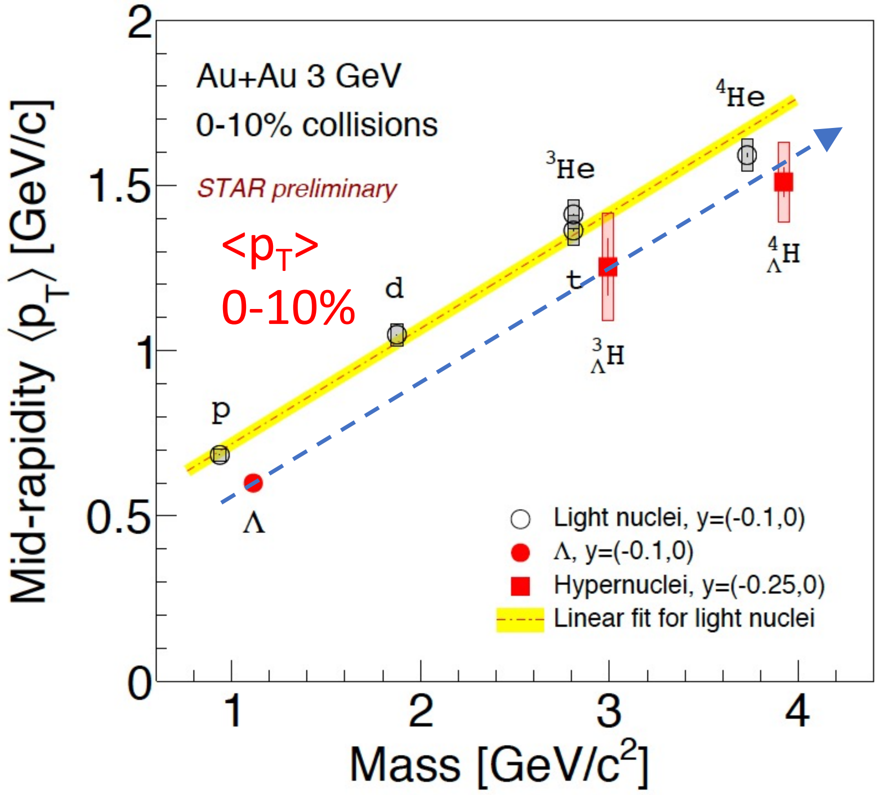
- **UrQMD + Coal.**
  - Instant coalescence after hadron kinetic freeze-out.
  - Coalescence condition:
    - $|\vec{p_1} - \vec{p_2}| < \Delta P, |\vec{r_1} - \vec{r_2}| < \Delta R.$
- **PHQMD**
  - Transport model + dynamical cluster formation.
    - Cluster can be formed before hadron kinetic freeze out.
    - Assuming Y-N potential = 2/3 N-N potential.

- Strong constraints on model calculations!

Directed Flow (v_1) and <p_T> at 3 GeV

PRL 130 (2023) 212301





- v_1 slope following mass number scaling.

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

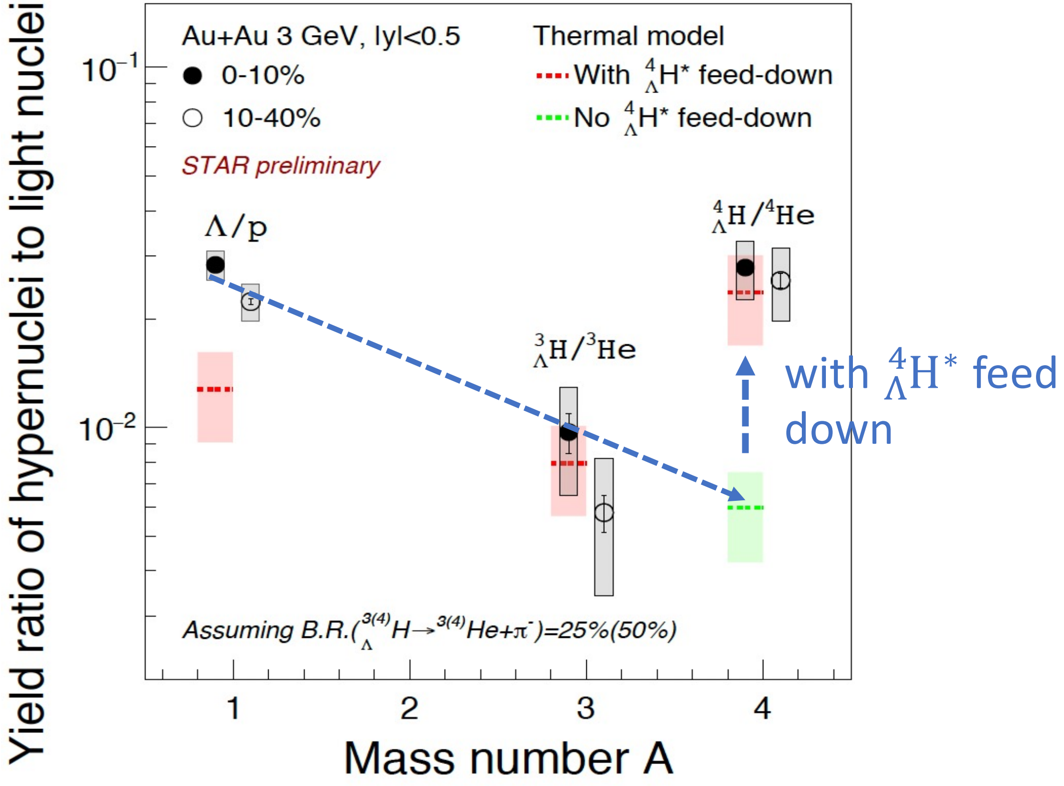
- Similar phenomena also seen in <p_T>.
  - Radial flow contribution.

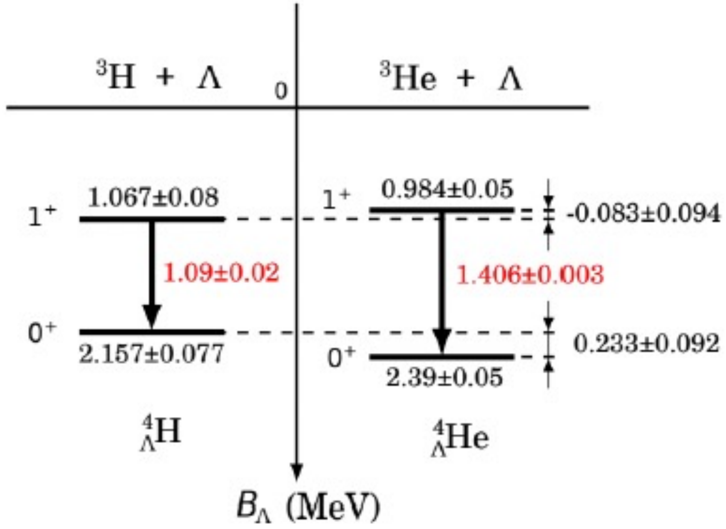
Mid-rapidity results qualitatively consistent with that the hypernuclei production is from coalescence of hyperons and nucleons.

Feeddown Contribution from Excited states

- Thermal model calculation, including excited ${}^{4}_{\Lambda}\mathrm{H}^{*}$ feed down, shows a similar trend as data.

Data support the creation of excited A=4 hypernuclei in heavy ion collisions.

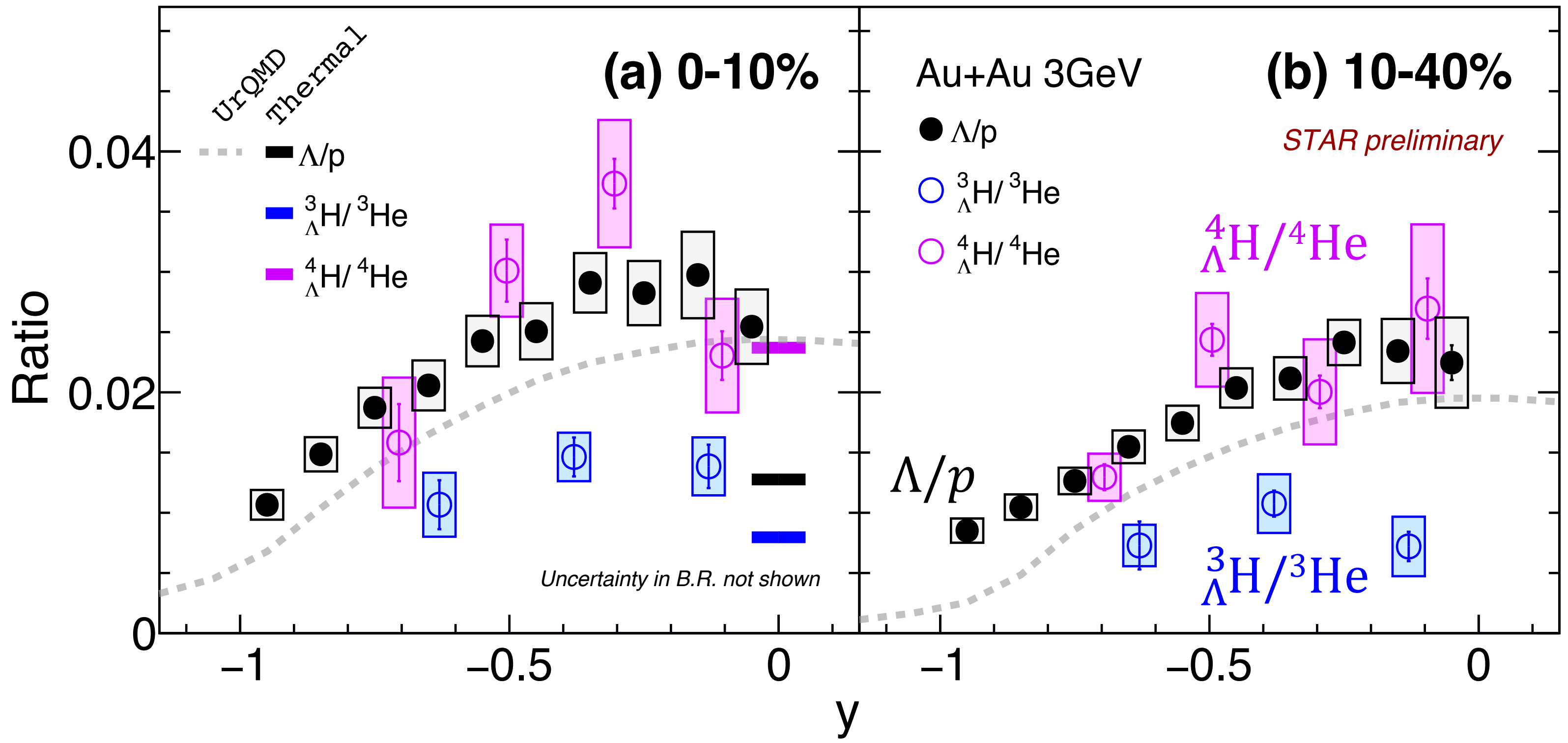




$${}^{4}_{\Lambda}\mathrm{H}^{*}(J^{+}=1) \rightarrow {}^{4}_{\Lambda}\mathrm{H}(J^{+}=0)+\gamma$$

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

Hyper-to-light Nuclei Yield Ratios at 3 GeV



Note: ${}^{3}_{\Lambda}$H R_3=27%, $B.R.\left({}^{4}_{\Lambda}H \rightarrow {}^{4}He\,\pi^{-}\right) = 50\%$, uncertainties from B.R. not shown.

- ${}^{3}_{\Lambda}H/{}^{3}He$ yield ratios is lower than that of Λ/p at both 0-10% and 10-40% centrality in Au+Au collisions at $\sqrt{s_{NN}}$ = 3 GeV.
- ${}^{4}_{\Lambda}H/{}^{4}He$ yield ratios are comparable to that of Λ/p.
  - Enhanced ${}^{4}_{\Lambda}$H production indicates a significant excited state feed-down contributions.

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

Strangeness Population Factor

- Understand difference between *N-N* and *Y-N* interaction. S. Zhang et al, PLB 684, 224 (2010)

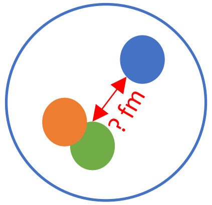
$$S_A = \frac{{}^A_\Lambda \mathrm{H}(\mathrm{A} \times \mathrm{p_T})}{{}^A\mathrm{He}(\mathrm{A} \times \mathrm{p_T}) \times \frac{\Lambda}{\mathrm{p}}(\mathrm{p_T})} = \frac{\mathrm{B_A}({}^A_\Lambda \mathrm{H})(\mathrm{p_T})}{\mathrm{B_A}({}^A\mathrm{He})(\mathrm{p_T})}$$

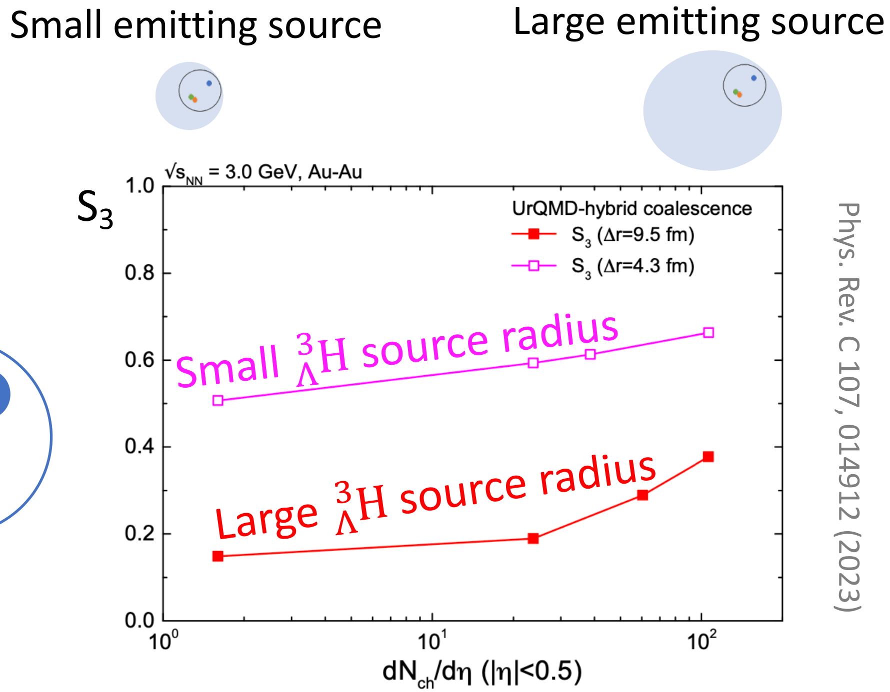
$$E_A \frac{d^3 N_A}{dp_A^3} = B_A \left(E_{\mathrm{p,n}} \frac{d^3 N_{\mathrm{p,n}}}{dp^3_{\mathrm{p,n}}} \right)^A \Bigg|_{\vec{p}_\mathrm{p} = \vec{p}_\mathrm{n} = \frac{\vec{p}_A}{A}}$$

Under some coalescence scenarios: PRC 99, 054905 (2019)

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

Source size Radius





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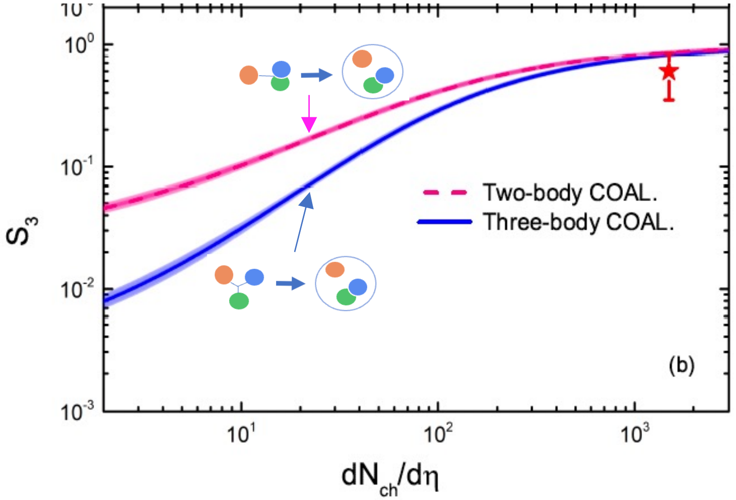

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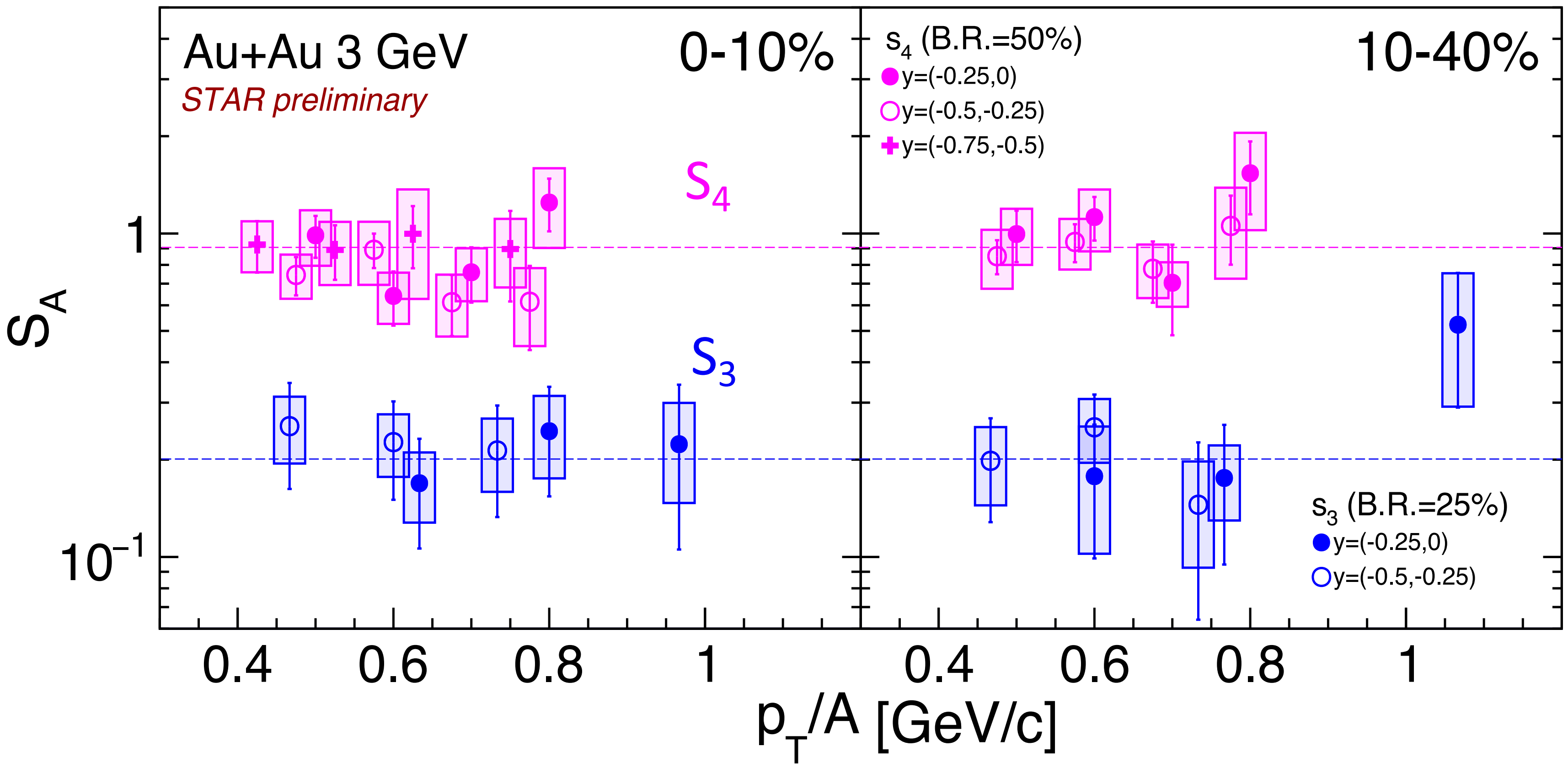
- Direct connection to coalescence parameters.
- Larger radius would have stronger source size dependence.
- Additional constrains on hypertriton structure.

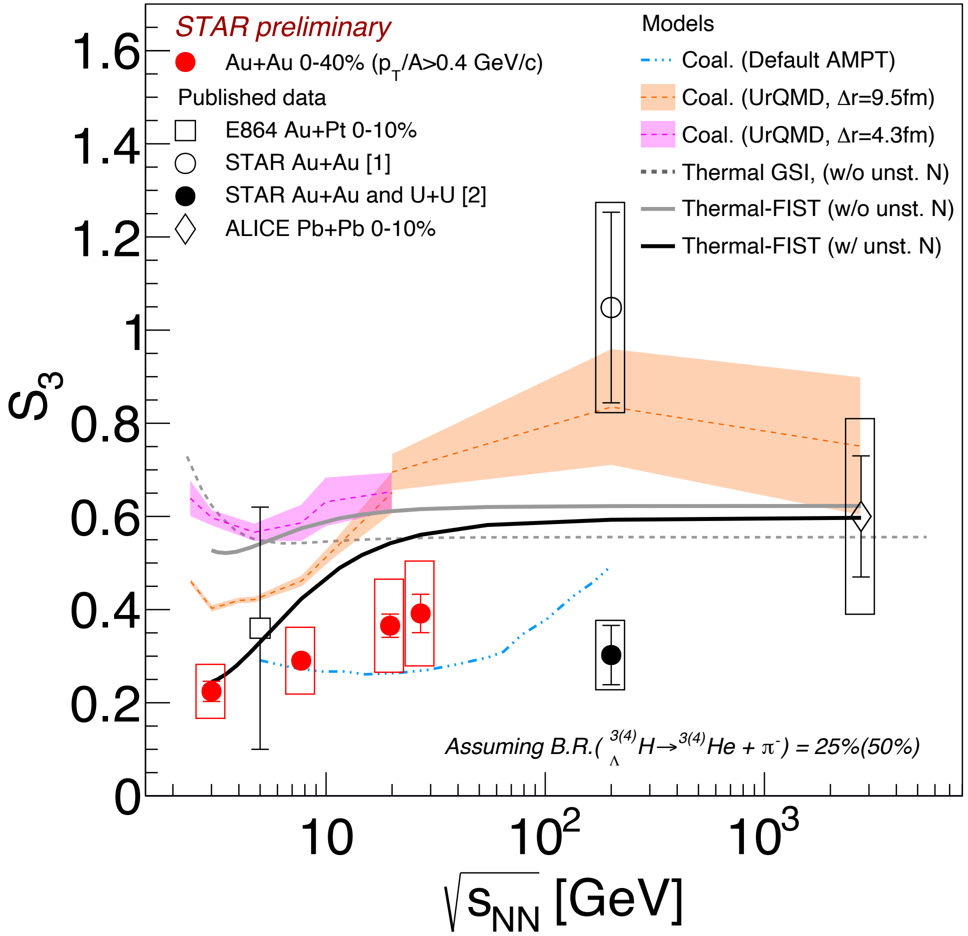
Strangeness Population Factor



No obvious p_T, rapidity and centrality dependence of S_A observed at 3 GeV.

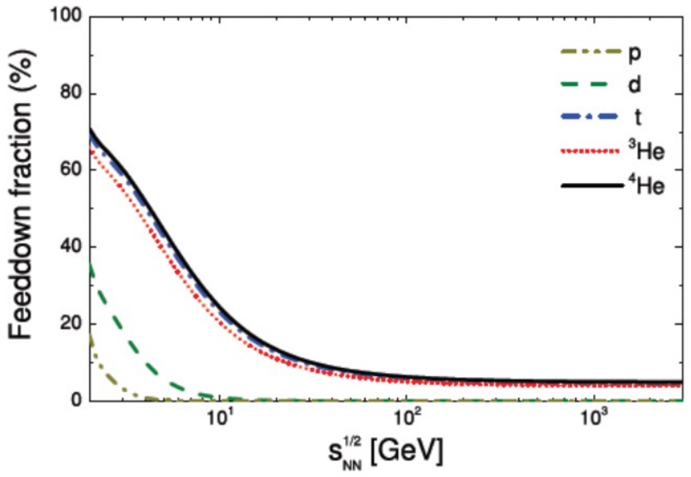
- Evidence that B_A of light and hypernuclei follow similar tendency versus p_T, rapidity and centrality.

Energy Dependence of S_3



STAR [2]: $0.7<p_T/M<1.5$ c

- Increasing trend toward higher energies.
- Thermal-FIST calculations show that feed-down from unstable nuclei to light nuclei would lower S_3 in low energies.



Thermal-FIST calculations

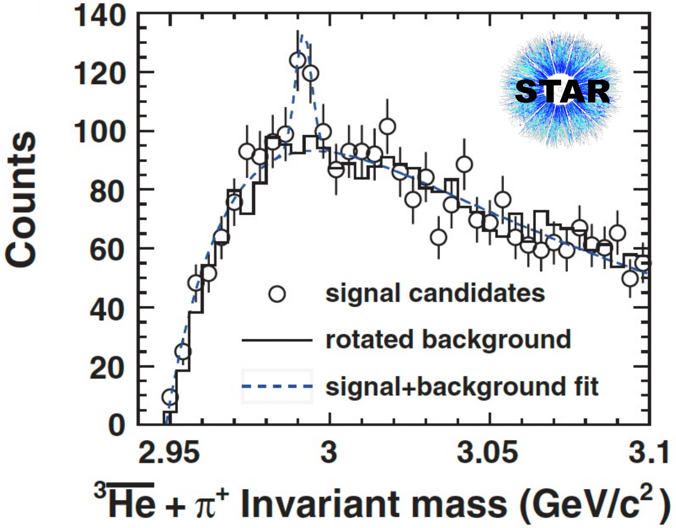
STAR [1]: Science 328, 58 (2010)
STAR [2]: arXiv:2310.12674 (2023)
Pb+Pb 2.76 TeV: ALICE, PLB 754,360 (2016)
Au+Pt 5 GeV: E864, PRC 70, 024902 (2004),
E864, J. Phys. Conf. Ser. 110, 032010 (2008)

A. Andronic et al, PLB 697 (2011)203 (Thermal GSI)
T. Reichert et al, PRC 107 (2023) 1, 014912 (UrQMD, Thermal-FIST)
S. Zhang et al, PLB 684(2010)224 (AMPT+coal.)

Anti-matter Hypernuclei

- STAR observed ${}^{4}_{\Lambda}\overline{\mathrm{H}}$ in 2023.
  - The heaviest observed antimatter nuclear and hypernuclear cluster to date.
  - Benefit from high energy heavy ion collisions where $\mu_B \to 0$.
- Lifetime of ${}^{4}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\overline{\mathrm{H}}$ are consistent within uncertainties.

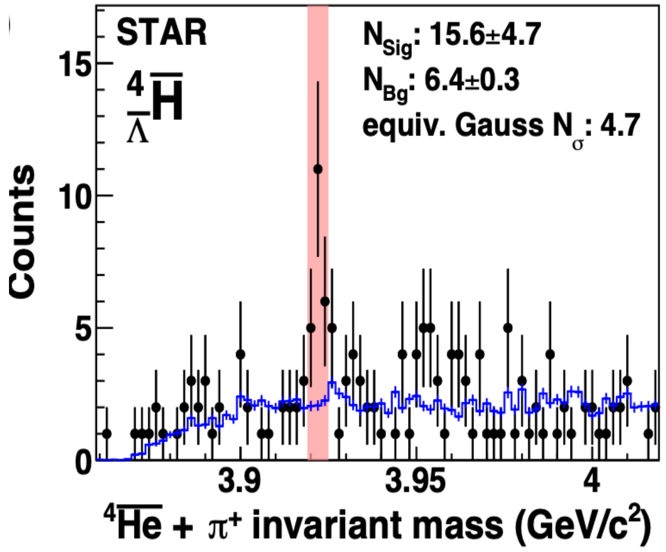
${}^{3}_{\Lambda}\overline{\mathrm{H}}$ was observed in 2010



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

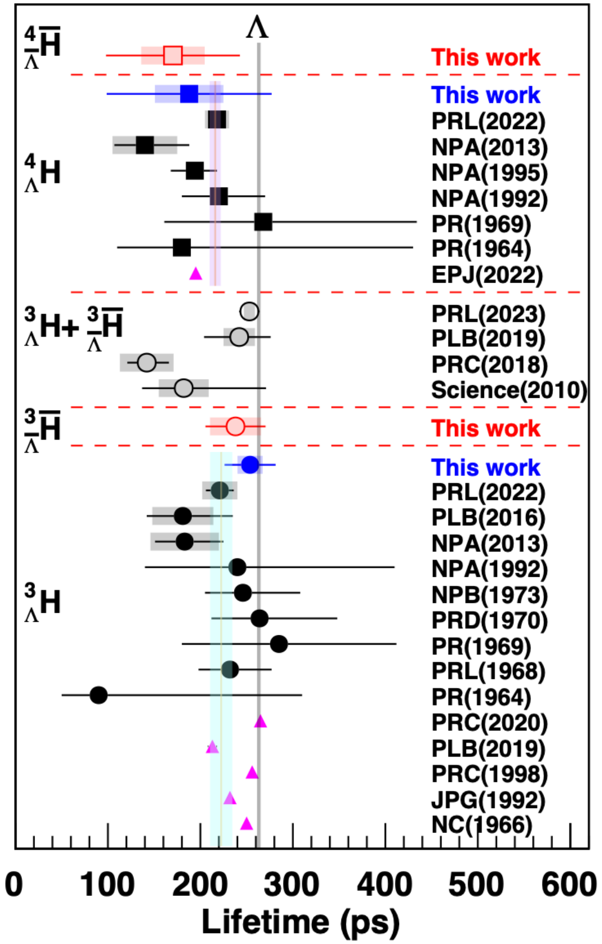
Science 328 (2010) 58-62

Discovery of A=4 anti-hypernuclei



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

arXiv:2310.12674, submitted to Nature



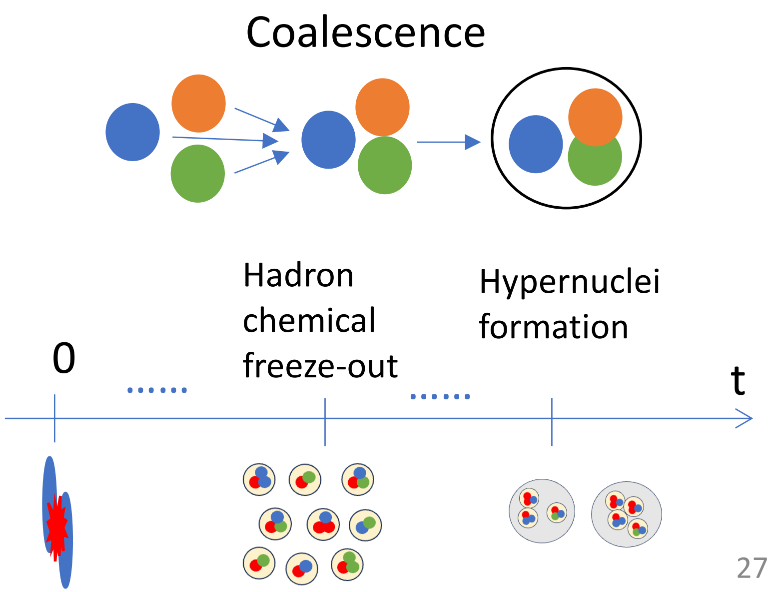
Summary

What we have measured:

- Properties: Lifetime of ${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{He}$; ${}^{3}_{\Lambda}\mathrm{H}$ R_3.
- Collectivity and production yields:
  - The directed flow (v_1), mean p_T, dN/dy of ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$ at $\sqrt{s_{NN}}$ = 3 GeV.
  - ${}^{3}_{\Lambda}\mathrm{H}$ excitation function from $\sqrt{s_{NN}}$ = 3-27 GeV at mid-rapidity.
- STAR discovered A=4 anti-matter hypernuclei.

Take home message:

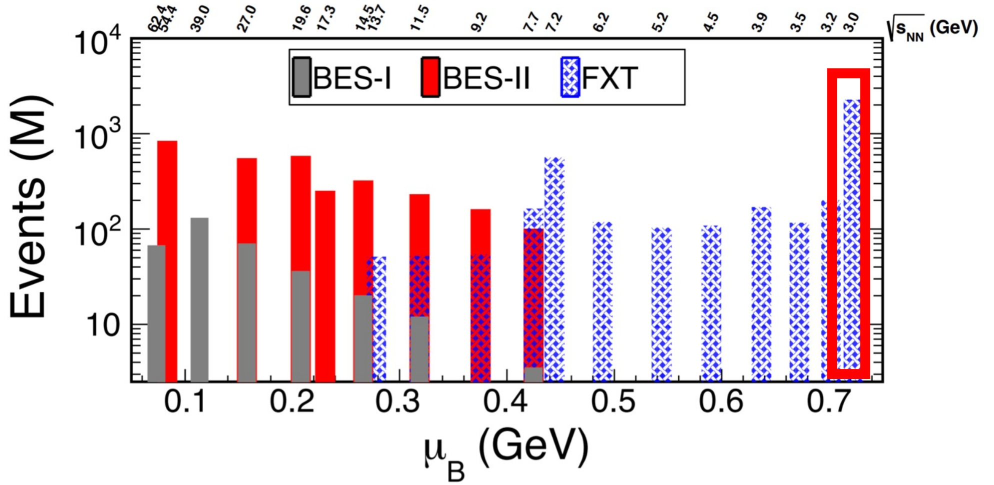
- Hypernuclei are **abundantly produced** in heavy ion collisions!
- STAR data at 3 GeV support **coalescence mechanism** of hypernuclei formation at mid-rapidity.
- Hypernuclei **are not in equilibrium** at hadron chemical freeze-out at RHIC energies.



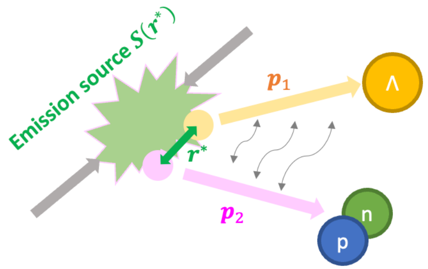
Future Perspective of Hypernuclei at STAR

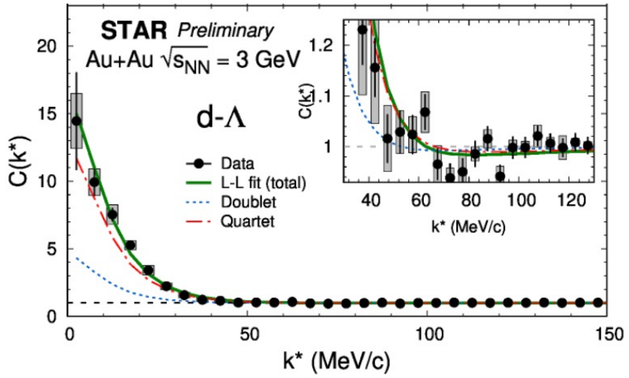
Huge datasets from BES-II and 200 GeV collisions.

3 GeV 2B events!

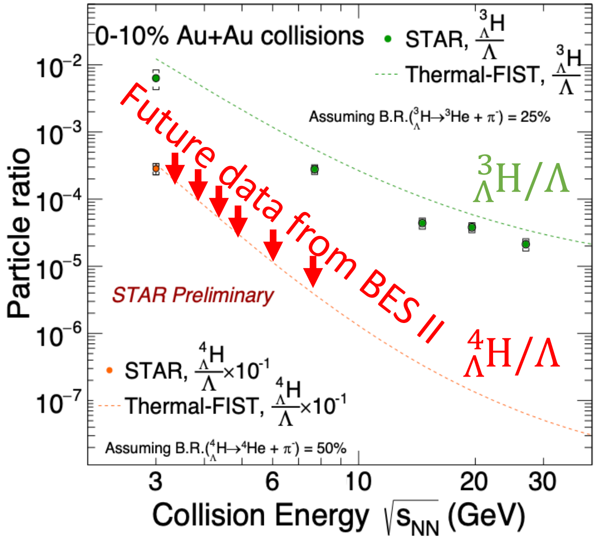


- Precise measurements on hypernuclei intrinsic properties.
- Further investigation on production mechanism.
  - A>3 hypernuclei.
  - Source size dependence.
- Search of double Λ hypernuclei ($Y-Y$ interaction).
  - e.g. ${}^{4}_{\Lambda\Lambda}$He-> ${}^{4}_{\Lambda}$Heπ, ${}^{5}_{\Lambda\Lambda}$He -> ${}^{5}_{\Lambda}$Heπ
- Precise measurements on particle correlations.
  - $p-\Lambda, d-\Lambda, \Lambda-\Lambda$ correlations.

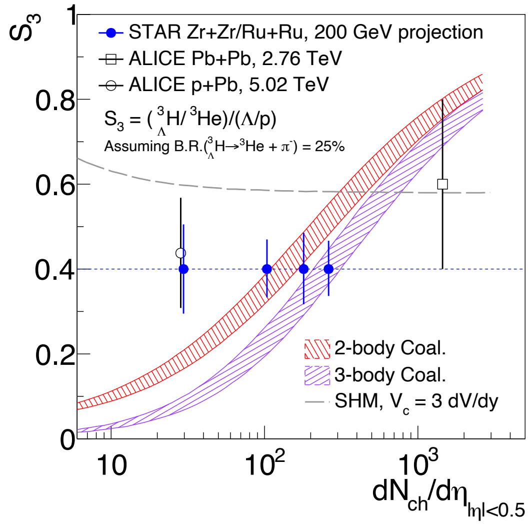




${}^{A}_{\Lambda}\mathrm{H}/\Lambda$ vs energy



S_3 vs $dN/d\eta$



Thank you!