中国物理学会高能物理分会第十一届全国会员代表大会暨学术年会

Recent light hypernuclei measurements from STAR experiment

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Outline

- **Introduction**
- **Review of hypernuclei measurements from STAR**
- **Hypernuclei measurements progress in STAR BES-II**
  - Hypernuclei internal structure

    branching ratios, lifetimes, binding energies …
  - Hypernuclei production in HI

    production yields/mechanisms, collectivity …
- **Summary and outlook**

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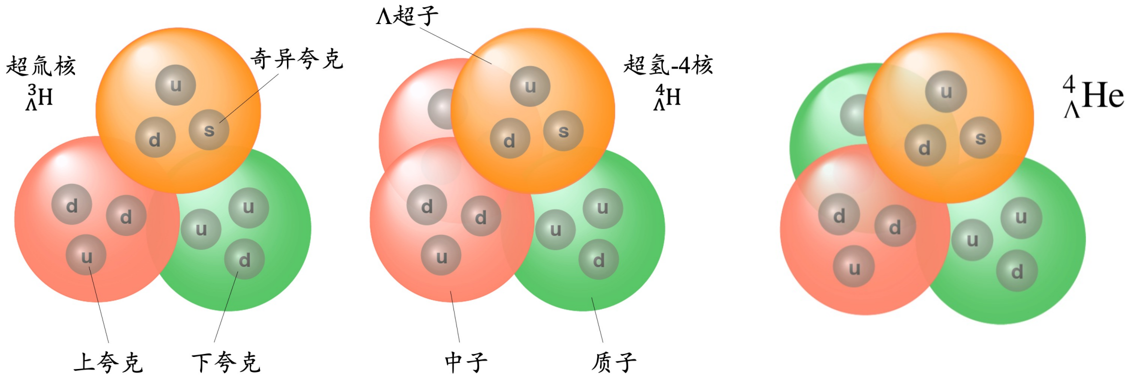
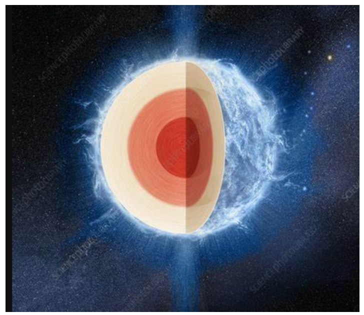
Introduction: what and why

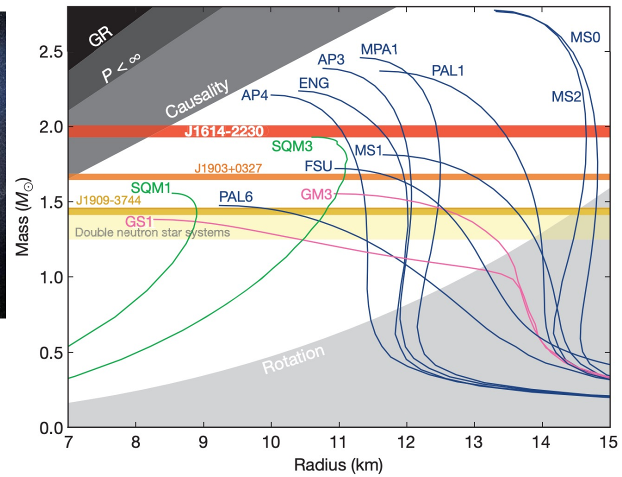
- What is hypernuclei?
  Bound nuclear systems of non-strange and strange baryons.



Marian Danysz (right) and Jerzy Pniewski (left) discovered hypernuclei in 1952

- Why is hypernuclei?
  - Probe hyperon-nucleon (Y-N) interactions
    Simple/light hypernuclei are cornerstones.
  - Strangeness in high-density nuclear matter.
    EoS of neutron stars.





Nature 467, 1081 (2010)

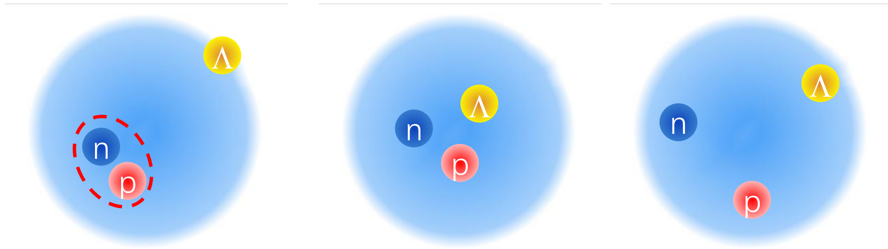
Introduction: how

Experimentally, measurement of hypernuclei allow us to understand,

- Internal structure of hypernuclei

  Week decay, lifetime is close to free Λ hyperon.

  Loosely bounded, binding energy, branching ratios ...

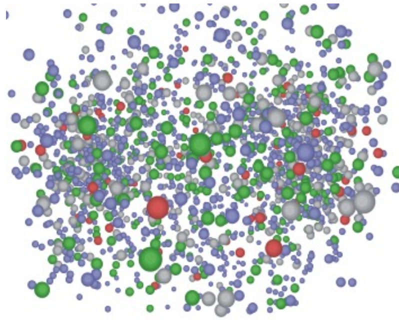


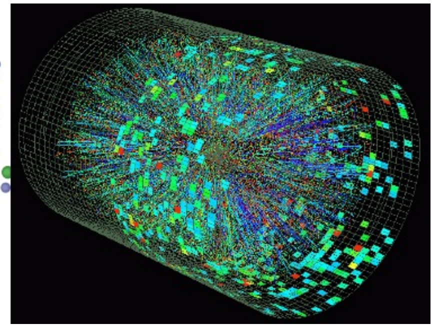
  Understanding hypernuclei structure may give more constraints on the Y-N interaction

- Production in high energy heavy-ion collisions

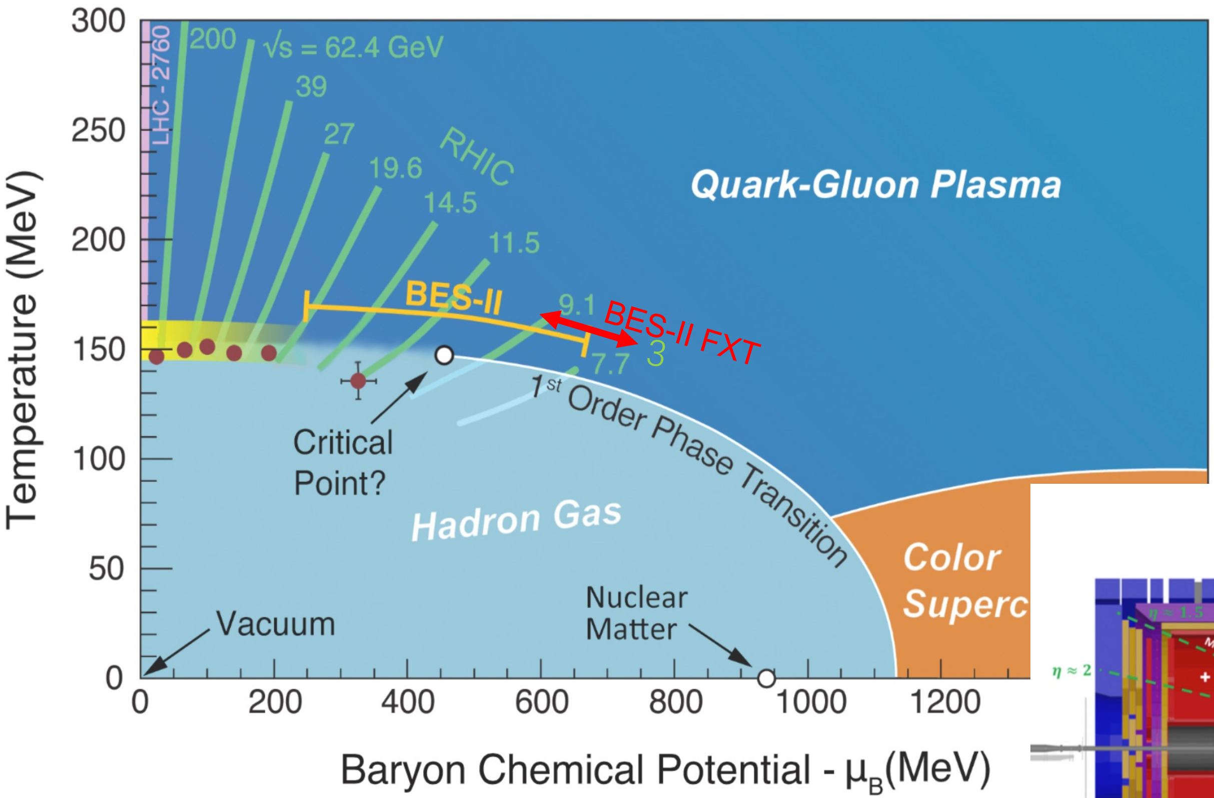
  production yields/mechanisms, collectivity …

  The formation of loosely bound states (how they survive) in violent heavy-ion collisions is not well understood





Introduction: RHIC BES-II program

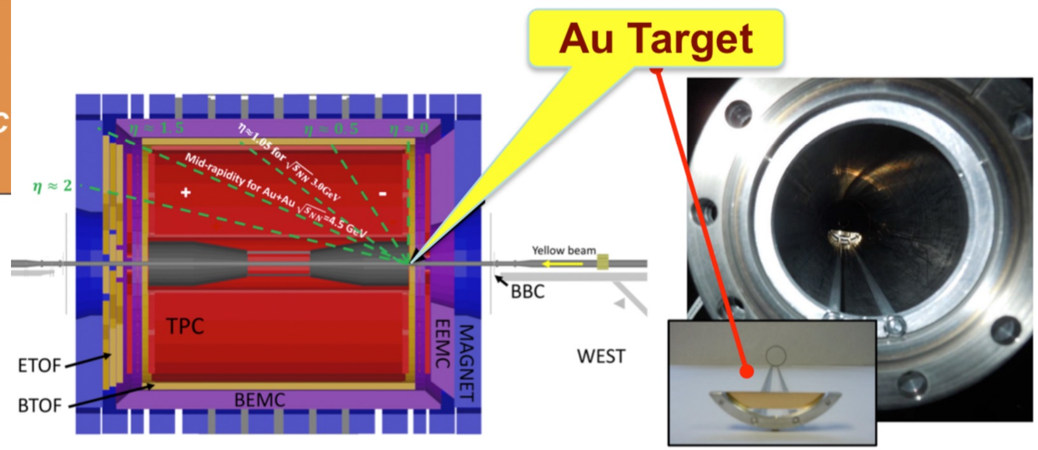


RHIC BES-II program:

Collider mode: 7.7 - 19.6 GeV

Fixed Target (FXT) mode: extends collision energy down to 3.0 GeV

μ_B coverage: 20-720 MeV



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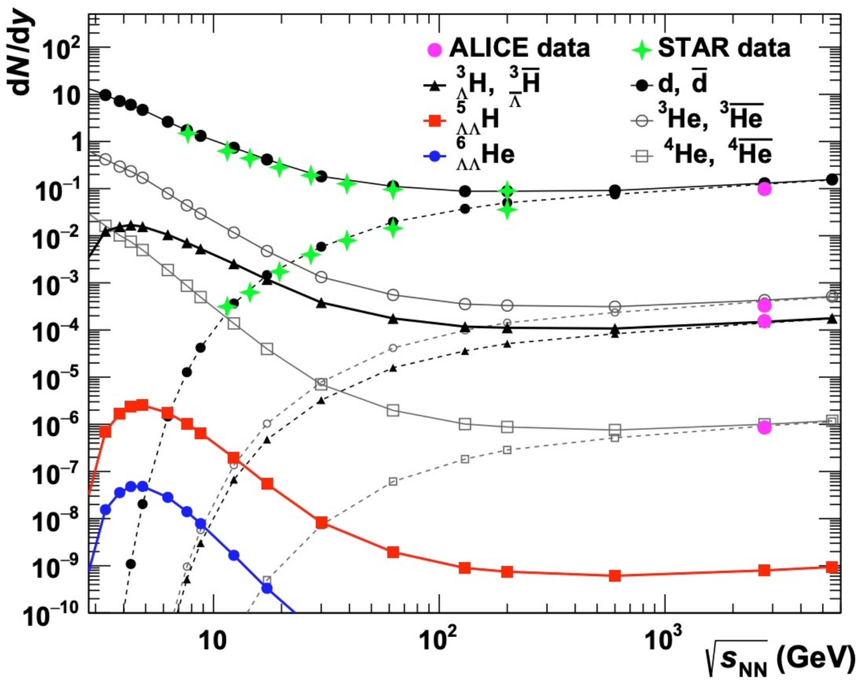

B. Dönigus, EPJA (2020) 56:280

Year	$\sqrt{s_{NN}}$ [GeV]	Events
2018	27	555 M
	3.0	258 M
	7.2	155 M
2019	19.6	478 M
	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
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	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

- Coalescence and statistical-thermal models predict: At lower beam energies, the hypernuclei production is expected to be enhanced due to high baryon density.
- Large statistics from STAR BES-II provide a great opportunity to study hypernuclei production.

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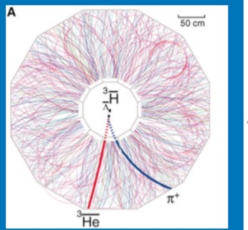
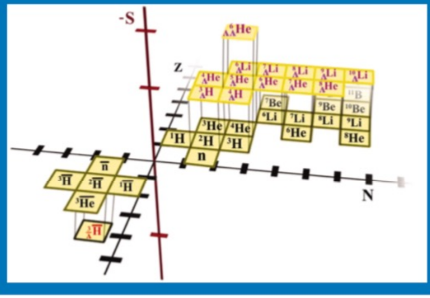
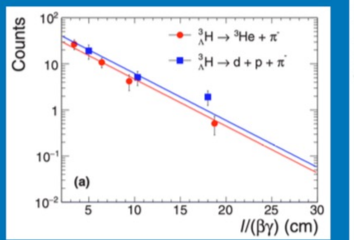
Review of hypernuclei measurements from STAR

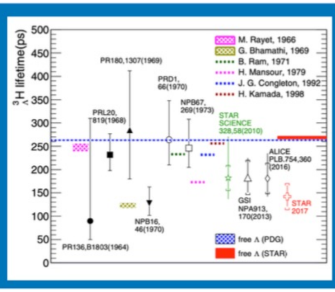




STAR collaboration **found the anti-hyper triton.**

Science 328, 58 (2010) (STAR)

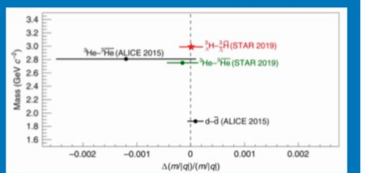


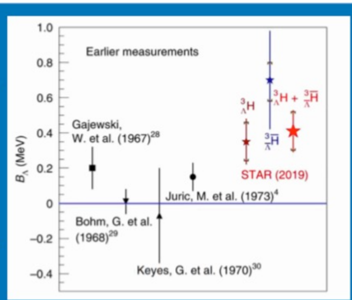


Lifetime measurement of ${}^{3}_{\Lambda}\mathrm{H}$

Science 328, 58 (2010) (STAR)

PRC 97, 054909 (2018) (STAR)





Measurement of mass difference and binding energy of ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{3}_{\Lambda}\overline{\mathrm{H}}$

Nature Phys. 16 (2020) 409 (STAR)

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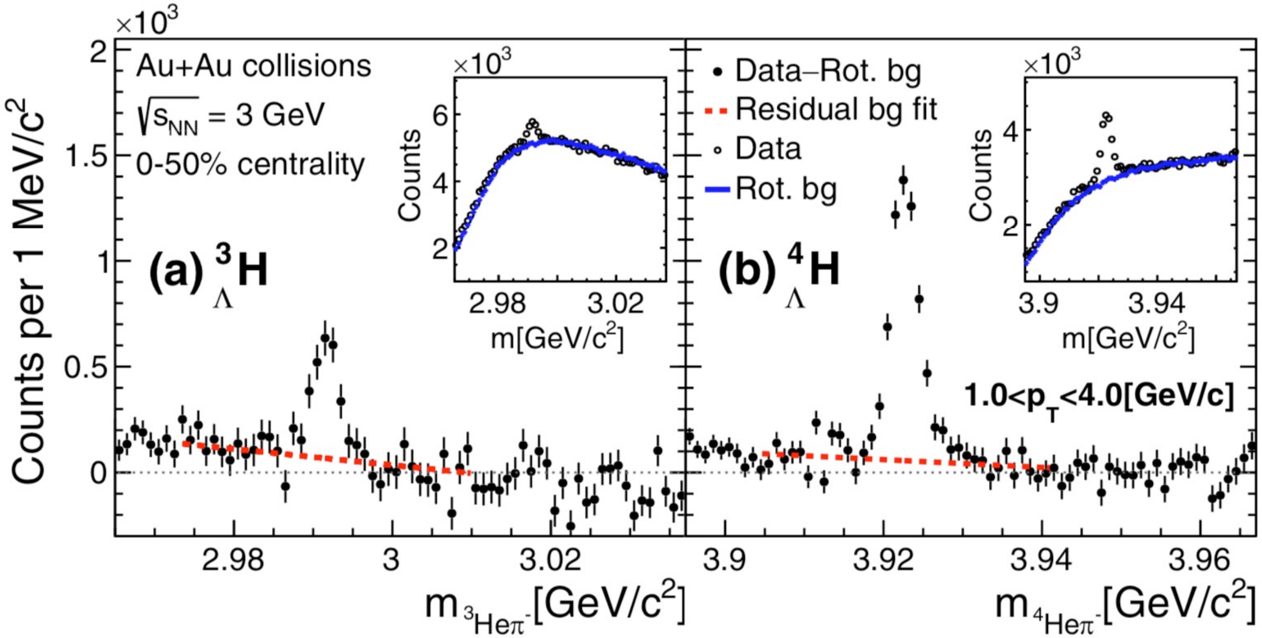
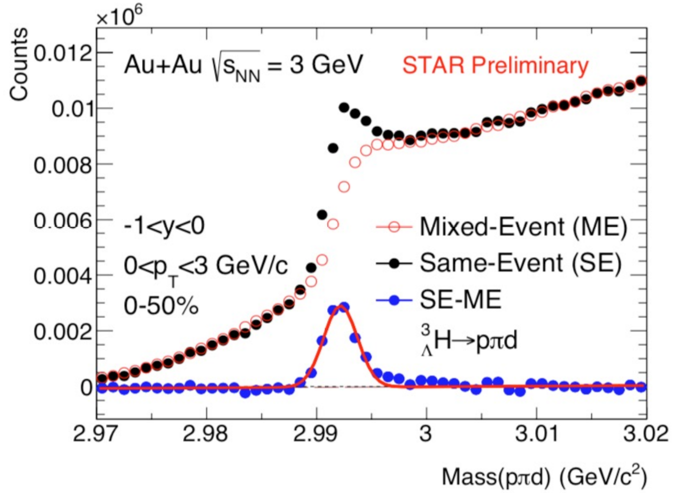
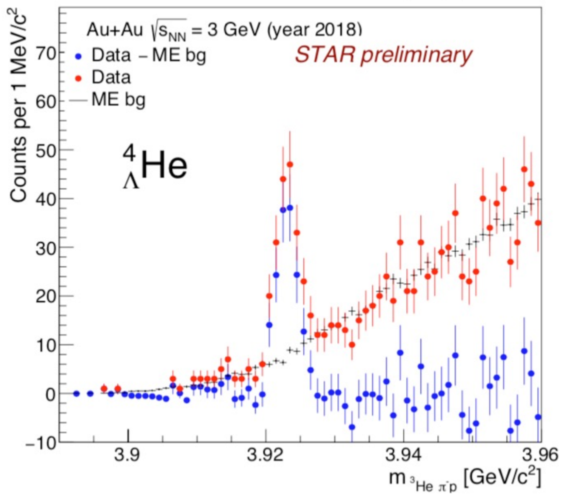
Hypernuclei reconstructions







- Decay channels:

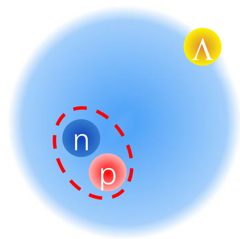
$^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}\mathrm{He} + \pi^{-}$ $\quad$ $^{3}_{\Lambda}\mathrm{H} \rightarrow \mathrm{d} + \mathrm{p} + \pi^{-}$

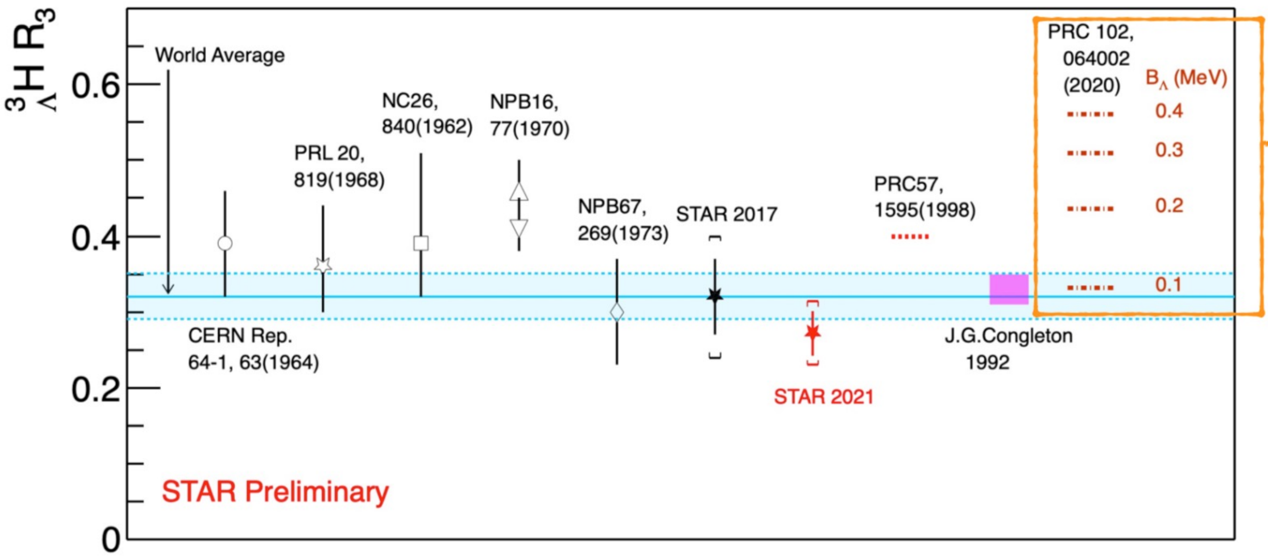
$^{4}_{\Lambda}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \pi^{-}$ $\quad$ $^{4}_{\Lambda}\mathrm{He} \rightarrow {}^{3}\mathrm{He} + \mathrm{p} + \pi^{-}$

- Combinatorial background estimated via rotating pion tracks or event mixing

Hypertriton relative branching ratio (R_3)

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





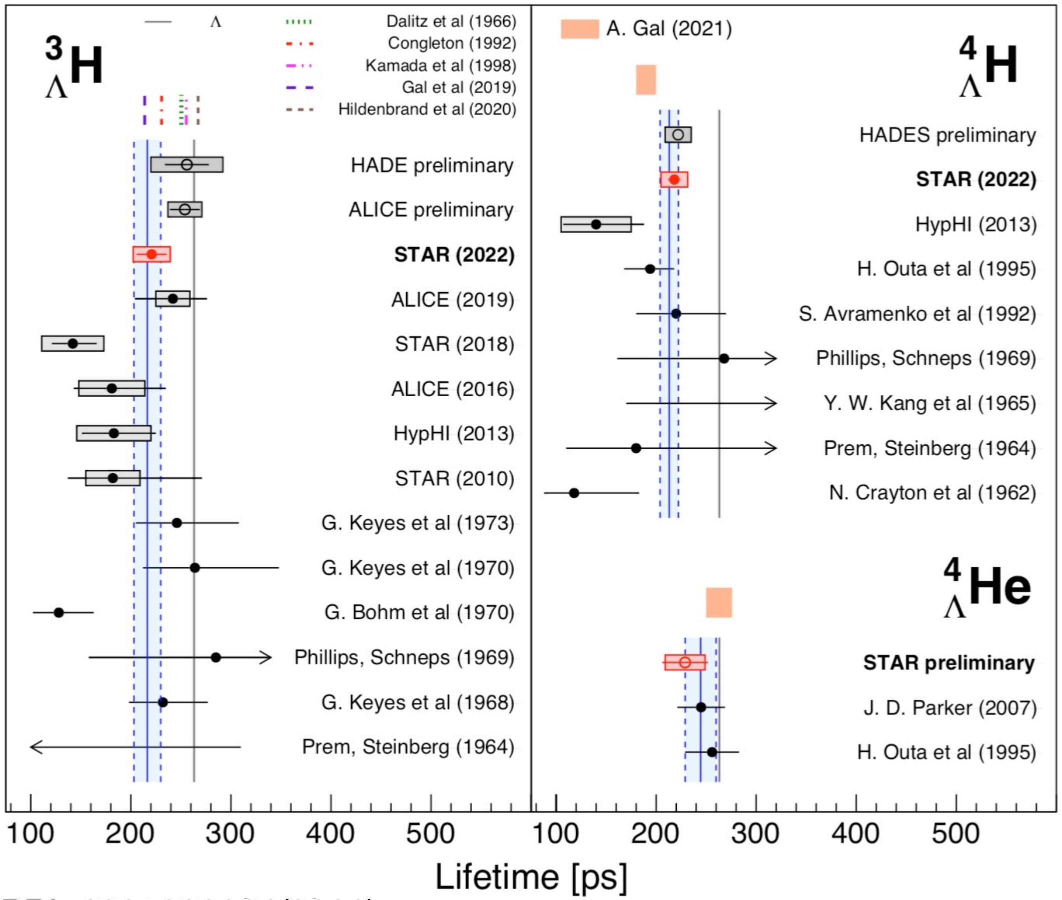
R_3 may be sensitive to the binding energy of ${}^3_\Lambda H$

- STAR 2021 (preliminary):
  $R_3 = 0.272 \pm 0.030 \pm 0.042$
  - Updated world average R_3 is consistent with theory calculation assuming B_Λ~ 0.1 MeV

Improved precision on R_3

- Stronger constraints on hypernuclear interaction models used to describe ${}^3_\Lambda H$
- Stronger constraints on absolute B.R.s

Lifetimes for light hypernuclei



PRL 128, 202301(2022)

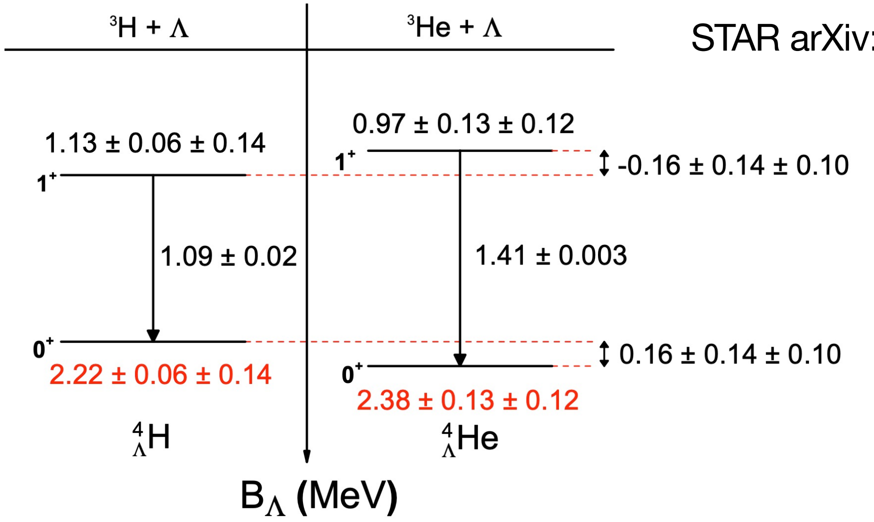
$^{3}_{\Lambda}$H: $\tau = 221 \pm 15(\text{stat.}) \pm 19(\text{syst.})[\text{ps}]$

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

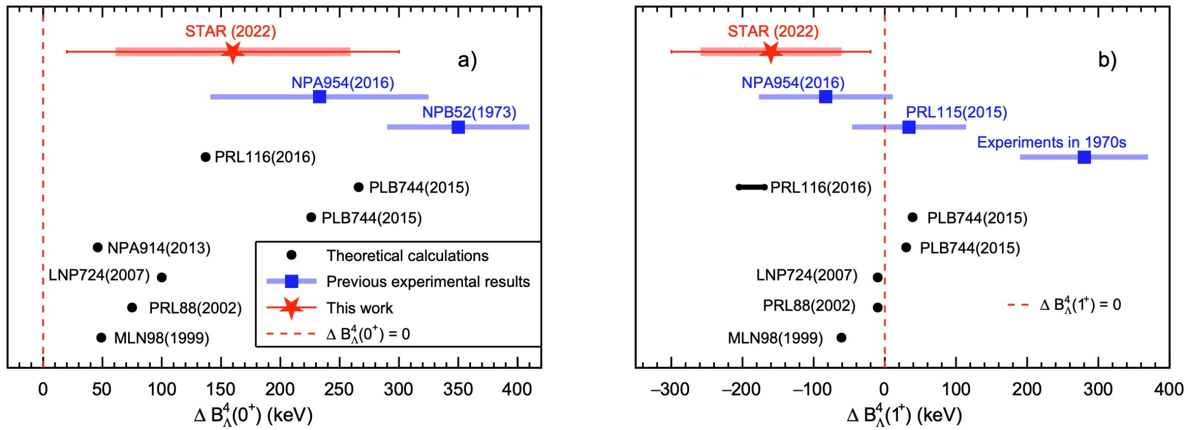
$^{4}_{\Lambda}$He: $\tau = 229 \pm 23(\text{stat.}) \pm 20(\text{syst.})[\text{ps}]$

- Lifetime of light hypernuclei $^{3}_{\Lambda}$H , $^{4}_{\Lambda}$H and $^{4}_{\Lambda}$He are shorter than that of free Λ (with 1.8σ, 3.0σ, 1.1σ)
- Consistent with former measurements (within 2.5σ for $^{3}_{\Lambda}$H , $^{4}_{\Lambda}$H)
- Results consistent with model calculations including pion FSI and calculations under Λd 2-body picture within 1σ
- $^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H results with improved precision provide tighter constraints on models

B_Λ and ΔB_Λ of ${}^4_\Lambda\mathrm{H}$ and ${}^4_\Lambda\mathrm{He}$



STAR arXiv: 2207.00778



- Λ binding energies(B_Λ) of ${}^4_\Lambda$H and ${}^4_\Lambda$He and their differences ΔB_Λ
  - For ground states, $\Delta B^4_\Lambda(0^+) = B_\Lambda({}^4_\Lambda\mathrm{He},0^+) - B_\Lambda({}^4_\Lambda\mathrm{H},0^+)$
  - For excited states, the results are obtained from the γ-ray transition energies E_γ

$$B^4_\Lambda({}^4_\Lambda\mathrm{He/H},1^+) = B_\Lambda({}^4_\Lambda\mathrm{He/H},0^+) - E_\gamma({}^4_\Lambda\mathrm{He/H})$$

$$\Delta B^4_\Lambda(1^+) = B_\Lambda({}^4_\Lambda\mathrm{He},1^+) - B_\Lambda({}^4_\Lambda\mathrm{H},1^+)$$

- Λ binding-energy difference

→ Study charge symmetry breaking (CSB) effect in A = 4 hypernuclei

- Differences are comparable large values and have opposite sign in 0^+ and 1^+ states
  - Consistent with the calculation including a CSB effect within uncertainties.

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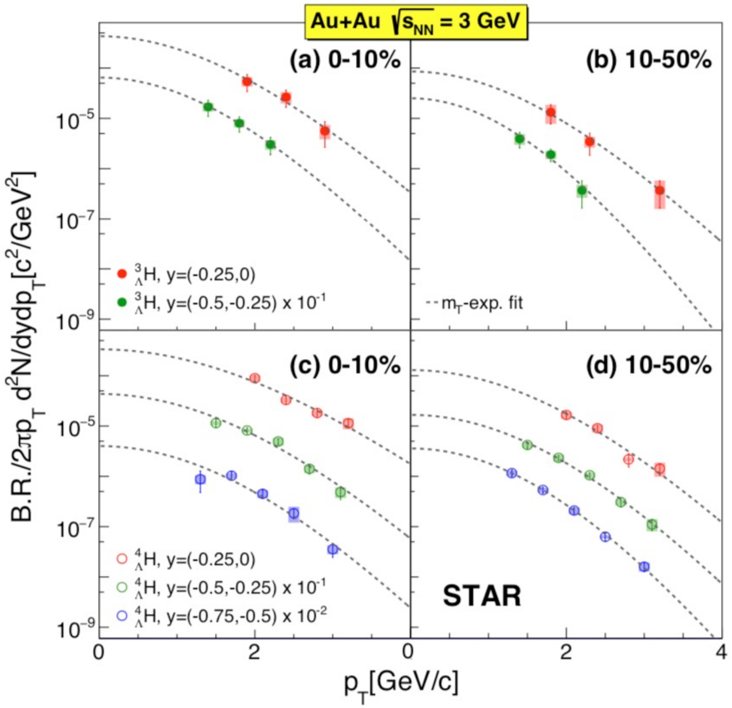
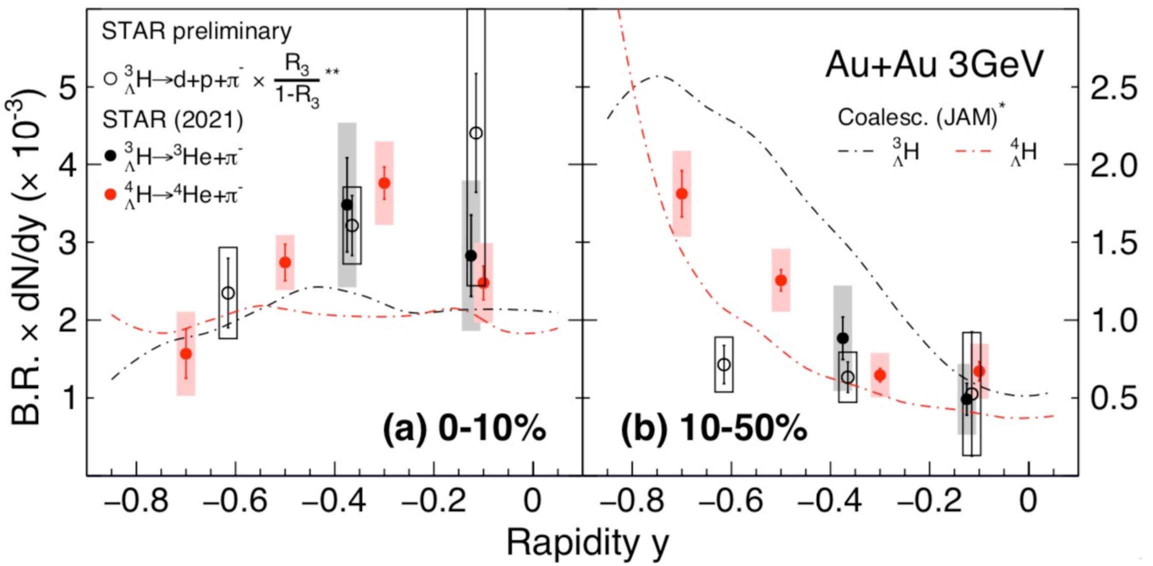
Light hypernuclei production yields at 3 GeV

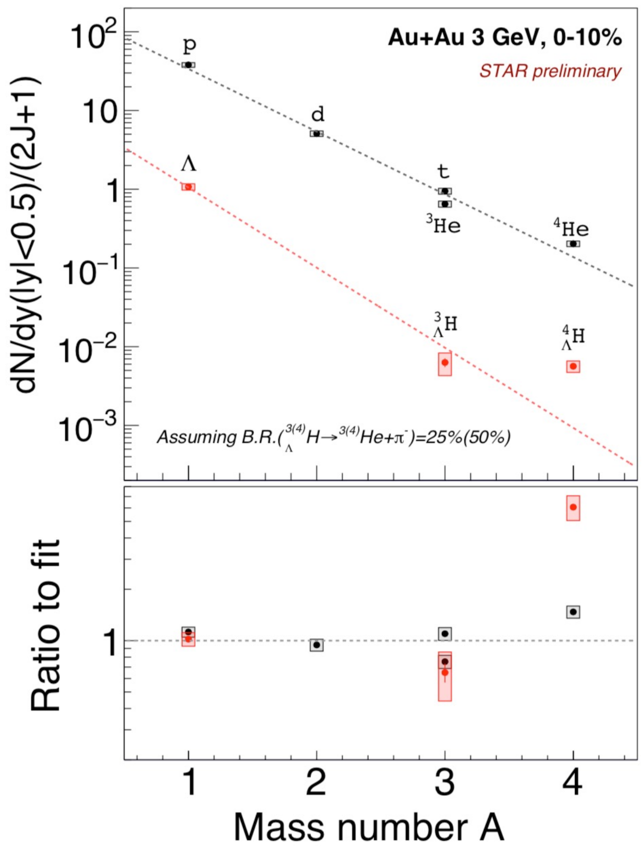


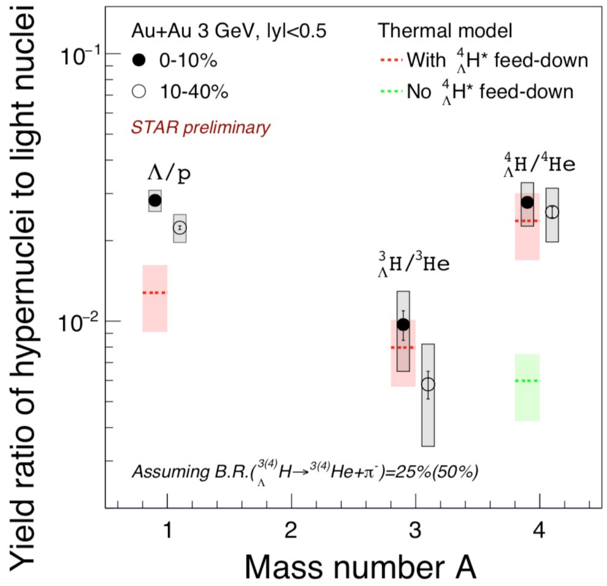
PRL 128, 202301(2022)



- First measurement of dN/dy of light hypernuclei in heavy-ion collisions.
- Different trends in the ${}^{4}_{\Lambda}\mathrm{H}$ rapidity distributions in central (0-10%) and semi-central (10-50%) collisions.
- Transport model (JAM) with coalescence reproduces trends of ${}^{4}_{\Lambda}\mathrm{H}$ but failed to describe ${}^{3}_{\Lambda}\mathrm{H}$.

Comparison to Λ and light nuclei at 3 GeV

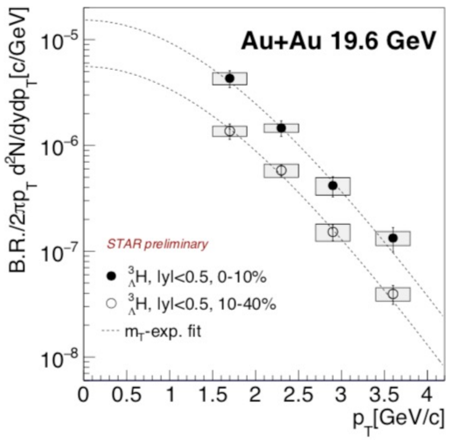


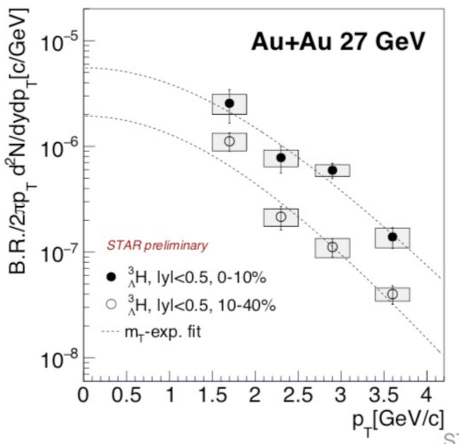


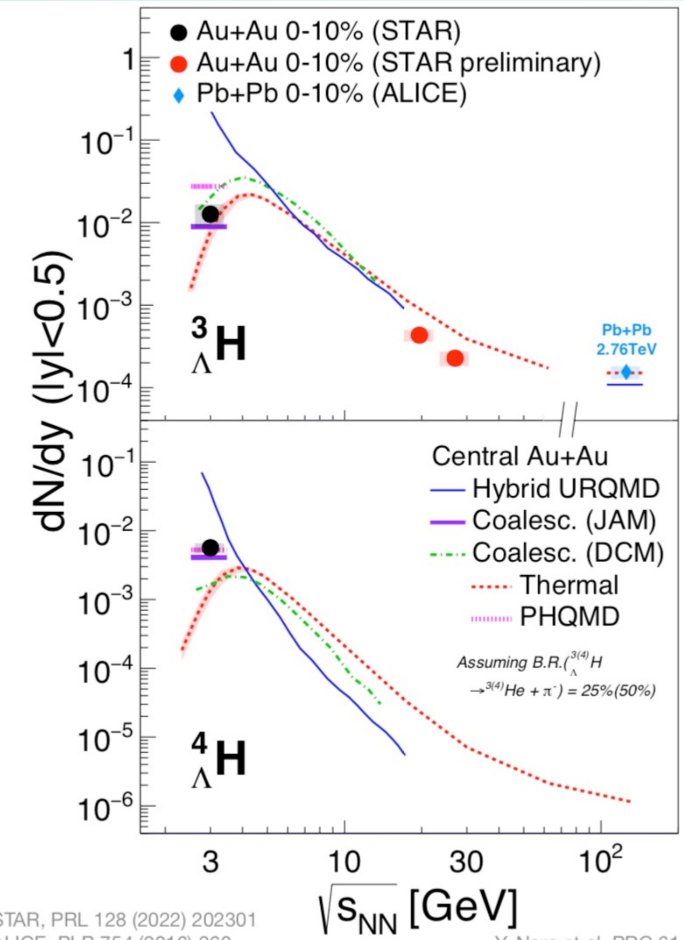
Thermal model:
A. Andronic et al,
PLB 697 (2011) 203.

- 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 (Λ, $^{3}_{\Lambda}H$, $^{4}_{\Lambda}H$).
- Non-monotonic behavior in hyper-to-light-nuclei ratio vs A observed. Thermal model calculations including from excited $^{4}_{\Lambda}H^*$ feed-down show a similar trend.

Energy dependence of hypernuclei production in HIC





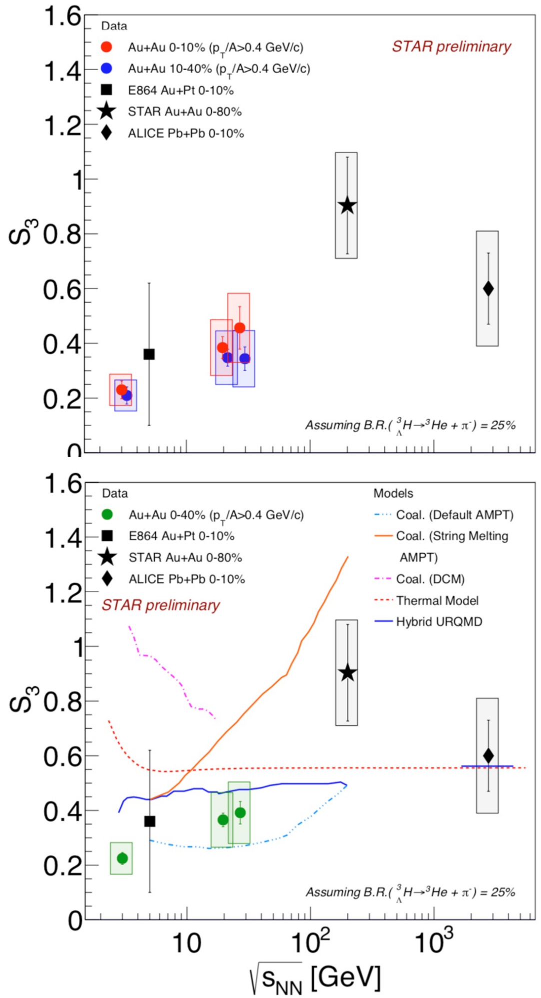


- $^{3}_{\Lambda}$H yield at mid-rapidity increases from 2.76 TeV to 3 GeV
  - Driven by increase in baryon density at low energies
- Thermal model reproduces the trend, but slightly overestimate the yields of $^{3}_{\Lambda}$H at 19.6 and 27 GeV. Meanwhile, $^{4}_{\Lambda}$H is underestimated.
- Coalescence(DCM) cannot describe $^{3}_{\Lambda}$H, $^{4}_{\Lambda}$H yields using same coalescence parameters, whereas coalescence(JAM) using different parameters approximately can
- PHQMD describes $^{4}_{\Lambda}$H at 3 GeV, but slightly overestimates $^{3}_{\Lambda}$H
- Hybrid URQMD overestimates both yields at 3 GeV by an order of magnitude

Provide first constrains for hypernuclei production models in the high-baryon-density region

STAR, PRL 128 (2022) 202301
ALICE, PLB 754 (2016) 360
A. Andronic et al, PLB 697 (2011) 203 (Thermal model)
J. Steinheimer et al, PLB 714 (2021) (H. URQMD, DCM)
Y. Nara et al, PRC 61 (1999) 024901 (JAM)
S. Gläßel et al, arXiv: 2106,14839 (PHQMD)

Ratio of hypernuclei yield to light nuclei (S_A)

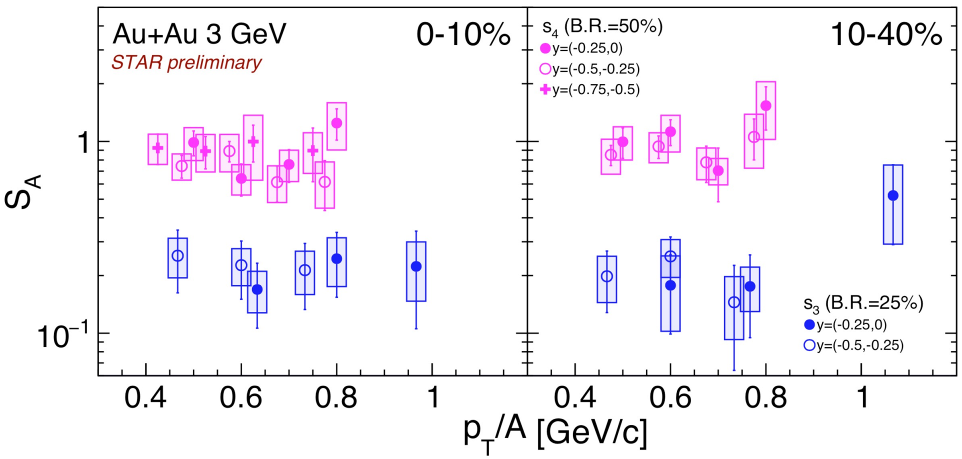


STAR, Science 328 (2010) 58
ALICE, PLB 754 (2016) 360
E864, PRC 70 (2004) 024902
NA49, J.Phys.CS110(2008)032010

A. Andronic et al, PLB 697 (2011) 203
(Thermal model)

J. Steinheimer et al, PLB 714 (2021)
(H. URQMD, Coal.(DCM))

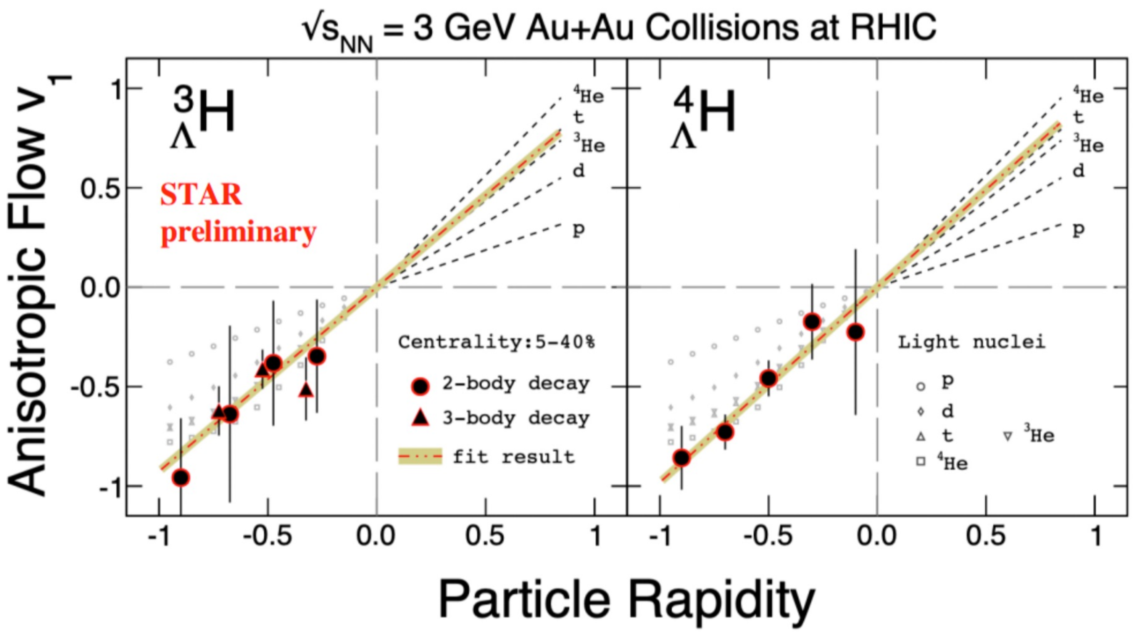
S. Zhang PLB 684(2010)224
(Coal.+AMPT)

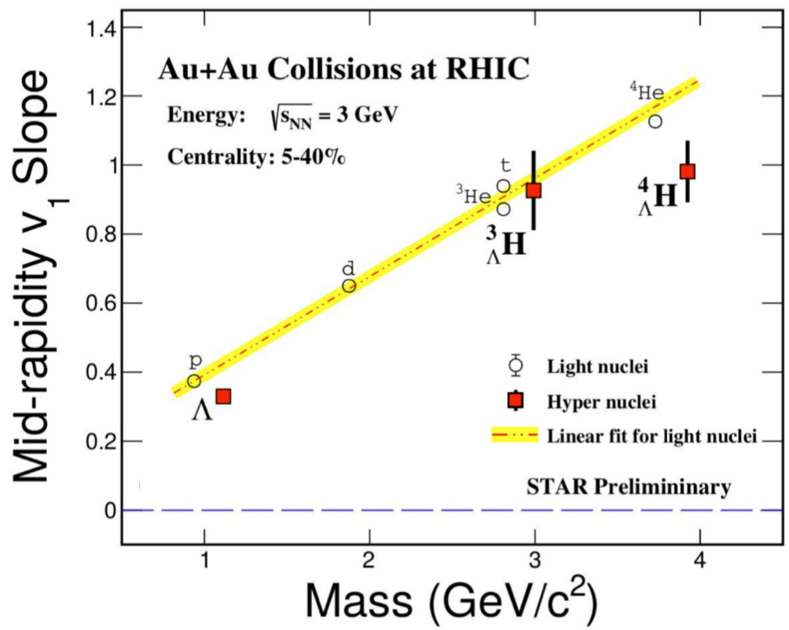


$$S_A = \frac{^A_\Lambda H}{^A He \times \frac{\Lambda}{p}}$$

- S_A: Ratio of hypernuclei yield compared to light nuclei.
- S_A vs p_T/A, expect ~ 1 if no suppression naively,
  - $S_3 < 1 \longrightarrow$ relative suppression of $^3_\Lambda H$ to ^3He.
  - $S_4 > S_3 \longrightarrow$ enhanced $^4_\Lambda H$ production due to feed-down from excited states.
- No clear centrality dependence.
- Hint of an increasing trend from 3 GeV – 2.76 TeV.
- None of the models describe the S_3 data quantitatively.

Light hypernuclei directed flow at 3 GeV





- First measurements of ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ directed flow (v_1) from 5 - 40% centrality
- v_1 slopes of ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ seem to follow a mass number scaling.

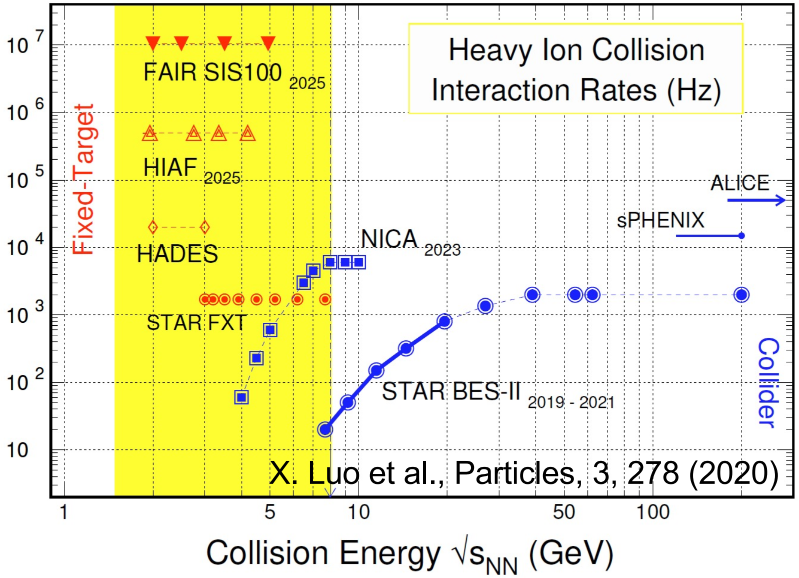
→ **Imply coalescence is a dominant process for hypernuclei formation in heavy-ion collisions**

Summary

STAR BES-II provides a unique opportunity to study hypernuclei, especially at high-baryon-density region

- $^{3}_{\Lambda}\mathrm{H}$, $^{4}_{\Lambda}\mathrm{H}$ lifetimes measured with improved precision
- Relative branching ratio R_3 of $^{3}_{\Lambda}\mathrm{H}$ with improved precision
  - Precision lifetime and R_3 provide stronger constraints on hyper nuclear interaction models
- Λ binding-energy difference between $^{4}_{\Lambda}\mathrm{H}$ and $^{4}_{\Lambda}\mathrm{He}$
  - Hint of CSB effect at A=4
- First measurement of $^{3}_{\Lambda}\mathrm{H}$ and $^{4}_{\Lambda}\mathrm{H}$ collectivity v_1
  - Mass number scaling is observed for the light hypernuclei → qualitatively consistent with coalescence
- First measurement of $^{3}_{\Lambda}\mathrm{H}$ and $^{4}_{\Lambda}\mathrm{H}$ dN/dy vs y in heavy-ion collisions.
  - Provide first constraints to hypernuclei production models @ high μ_{B}

Outlook: High baryon density frontier



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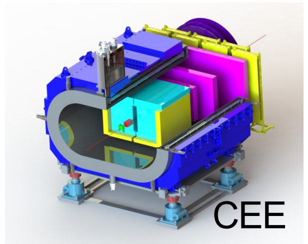
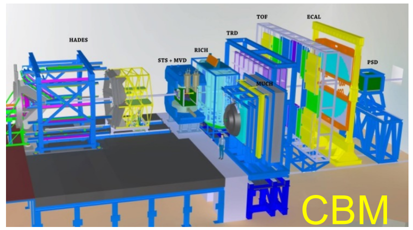
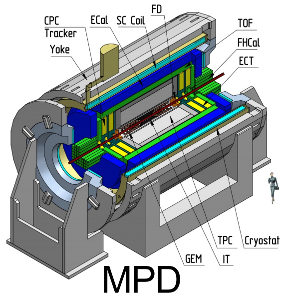






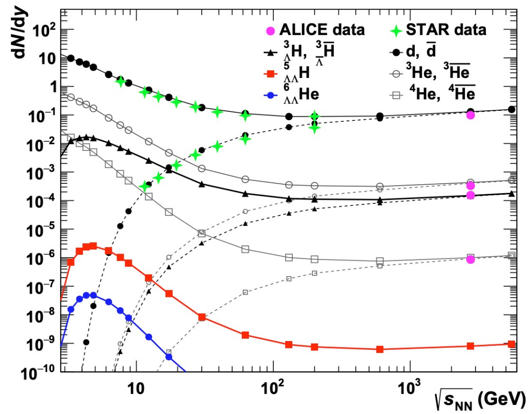
STAR iTPC/ETOF fully installed in 2019

High statistics of STAR BES-II/FXT data

NICA/MPD 4-11 GeV

FAIR/CBM 2-5 GeV

HIAF/CEE 1-4.25 GeV



Aim for precision measurements.

Searching for new hypernuclei states, A=5, Λ-Λ…

Thanks for your attention !