第一届安徽省核物理研讨会

Hypernuclei production in heavy-ion collisions at high baryon density

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Jan 22-23, 2024

Outline

- **Introduction**
- **Recent hypernuclei measurements in STAR BES-II**
  - Hypernuclei production mechanism

    production yields, particle ratios, collectivity …
  - Hypernuclei internal structure

    branching ratios, lifetimes, binding energies …
- **Summary and outlook**

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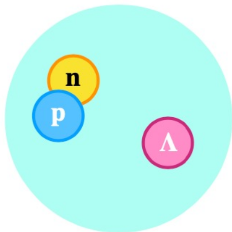
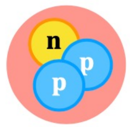
Introduction: what and why

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

^{3}He	$^{3}_{\Lambda}H$	$^{4}_{\Lambda}H$	^{4}He	$^{4}_{\Lambda}He$
p, p, n	p, n, Λ	p, n, n, Λ	p, p, n, n	p, p, n, Λ

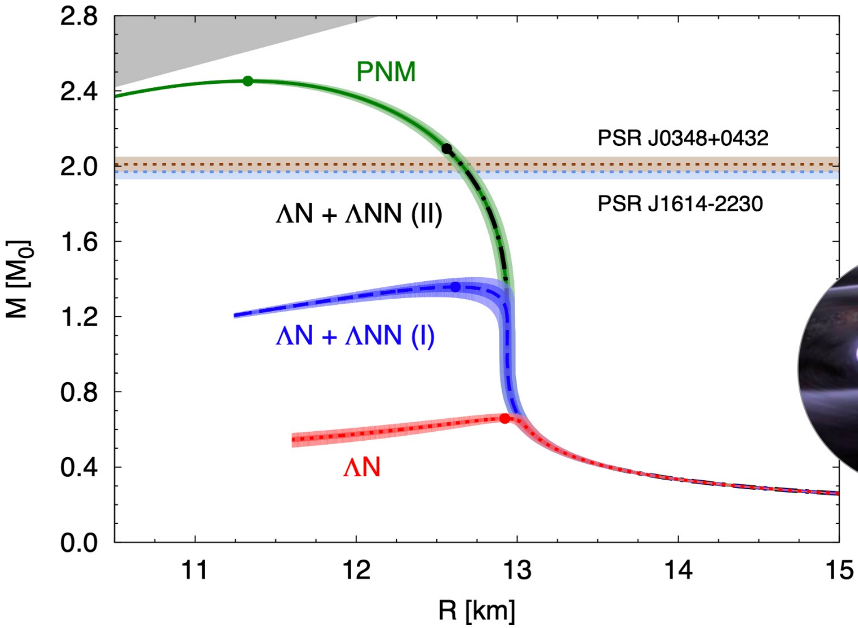
	$^{3}_{\Lambda}H$	^{3}He
		
Strangeness	+1	0
RMS Radius	~4.9 fm	1.15 fm

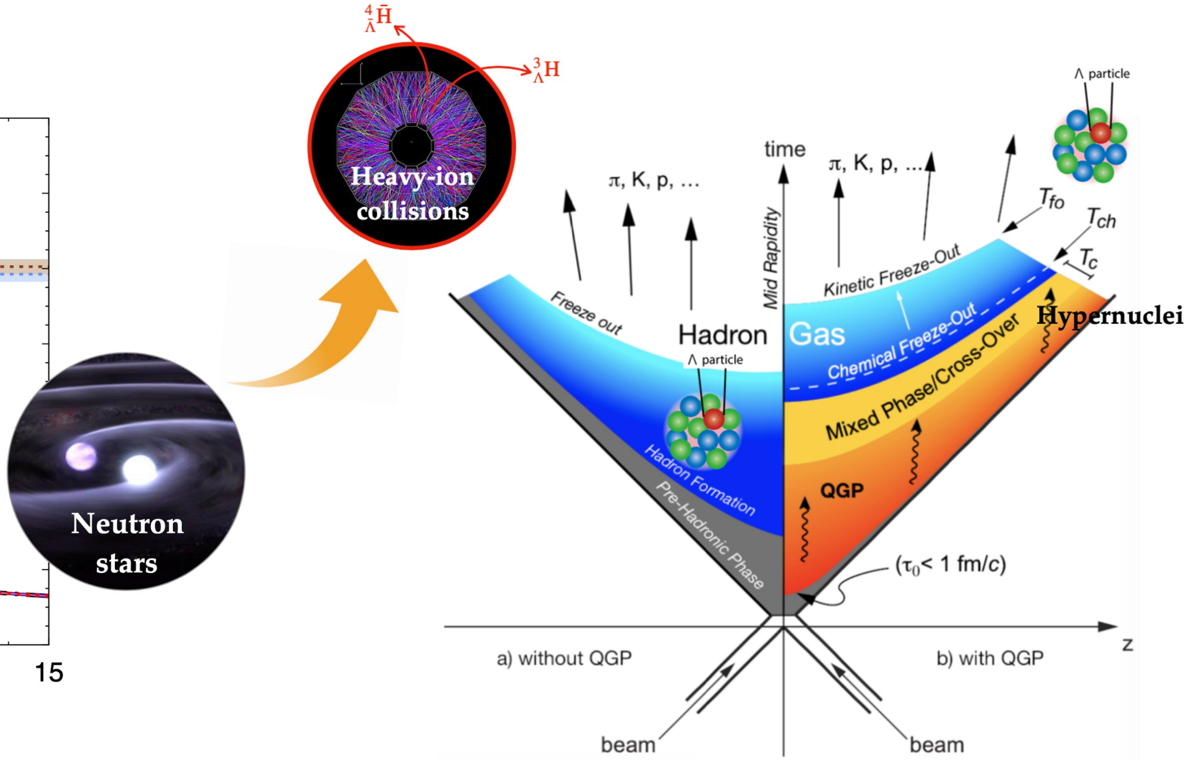
M. Danysz (right) and J. Pniewski (left) discovered hypernuclei in 1952

H. Nemura et al, Prog. Theor. Phys. 103, 929 (2000)

Introduction: what and why

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





Introduction: how

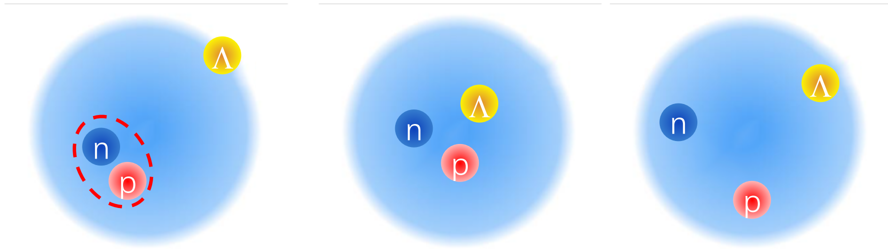
Experimentally, measurement of hypernuclei allow us to understand,

- Internal structure of hypernuclei

  Week decay, lifetime is close to free Λ hyperon.

  Loosely bounded, binding energy, branching ratios ...

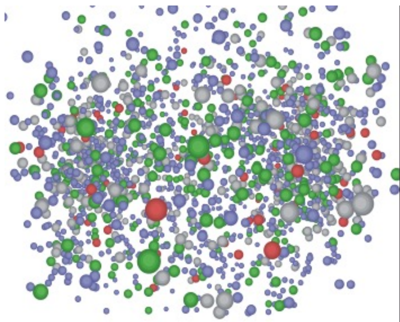
  Understanding hypernuclei structure may give more constraints on the Y-N interaction

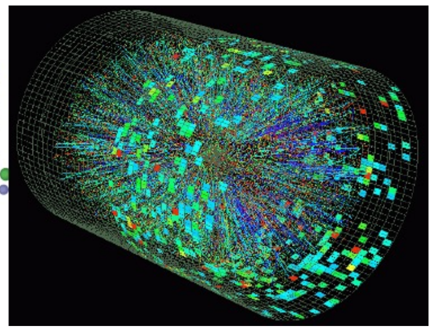


- Production in high energy heavy-ion collisions

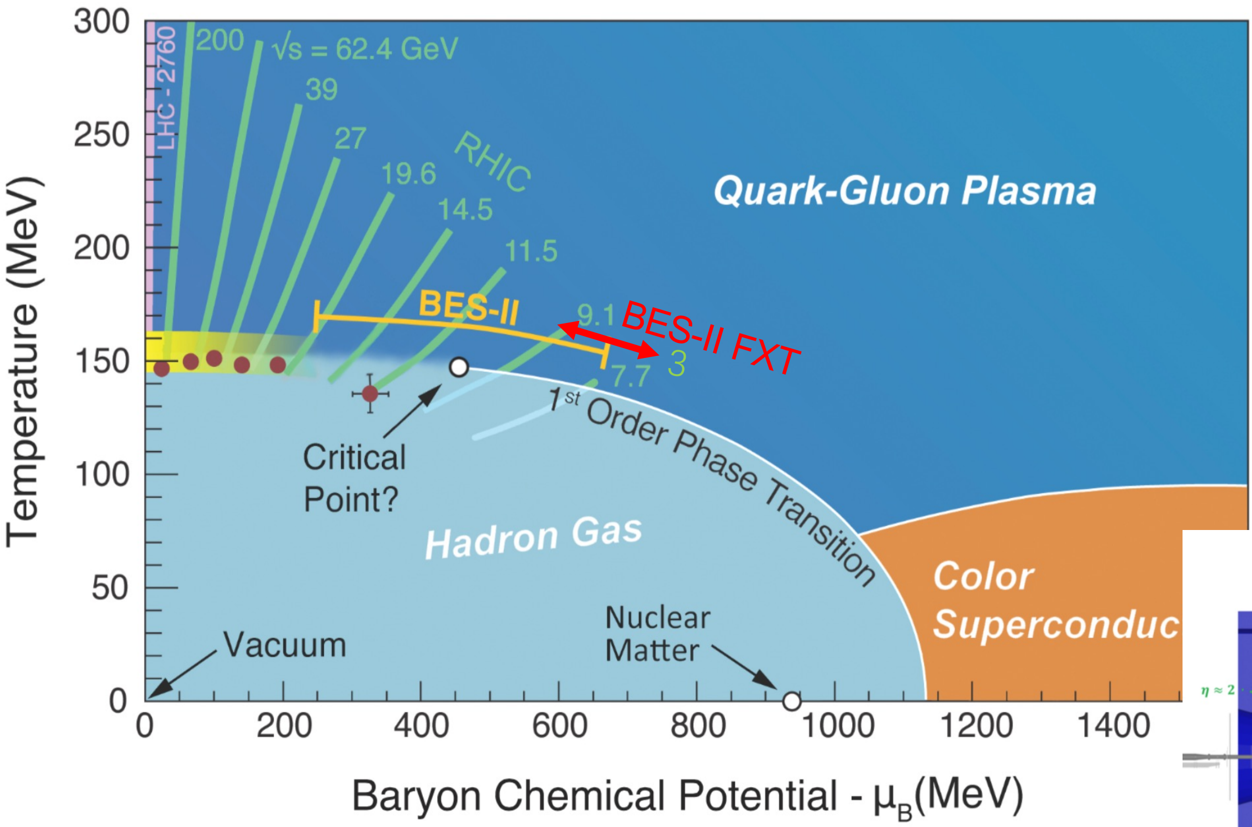
  production yields/mechanisms, collectivity …

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





Introduction: RHIC BES-II program



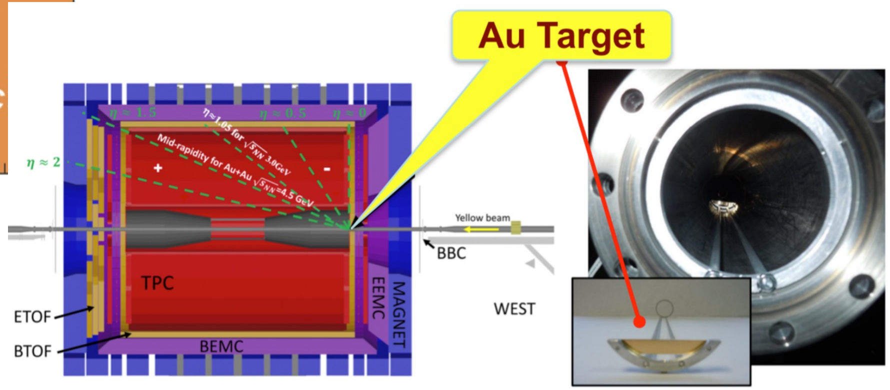
RHIC BES-II program:

Collider mode: 7.7 – 19.6 GeV

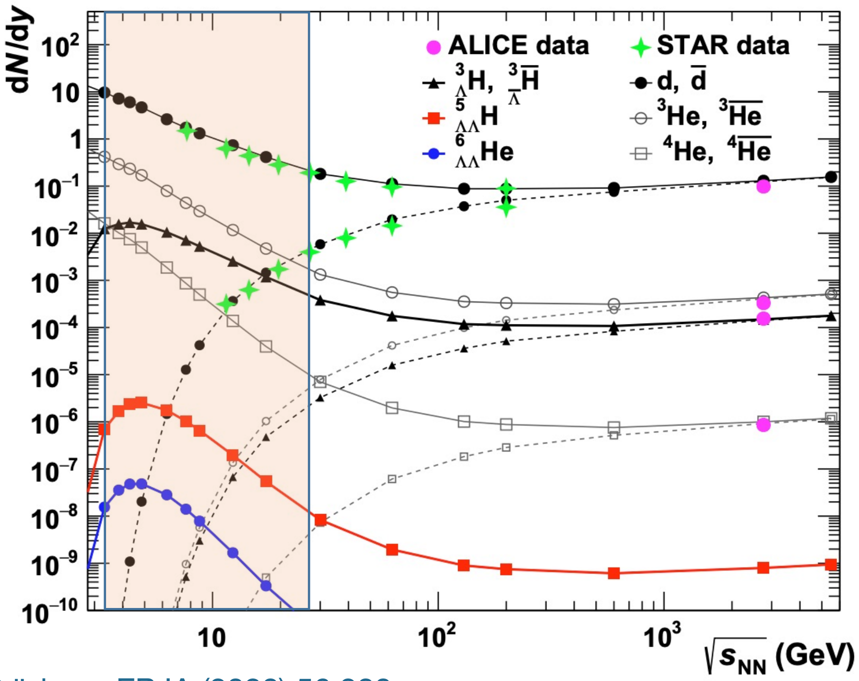
Fixed Target (FXT) mode:

extends down to 3.0 GeV

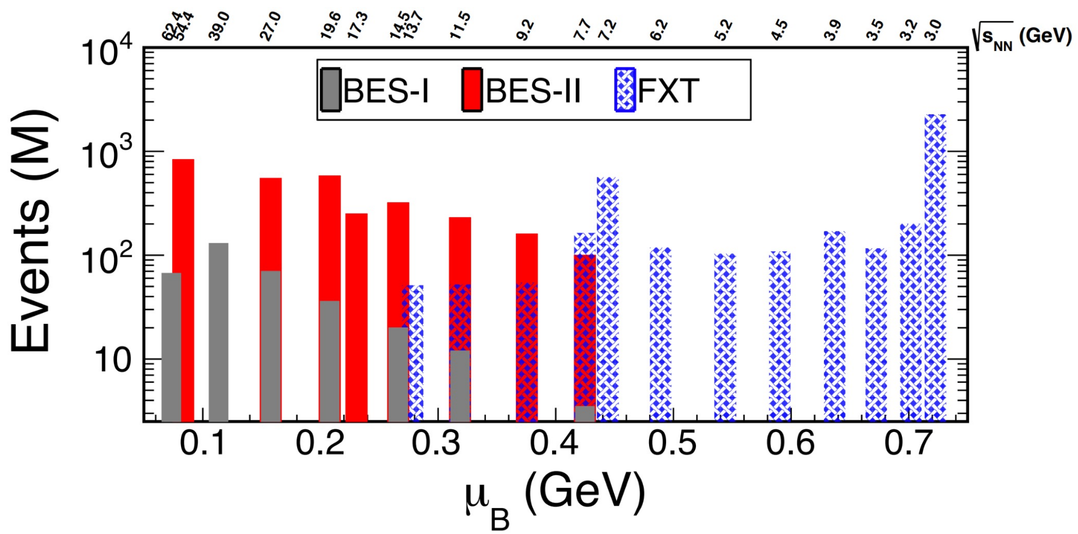
μ_B coverage: 20 – 720 MeV



Introduction: RHIC BES-II program



B. Dönigus, EPJA (2020) 56:280



- 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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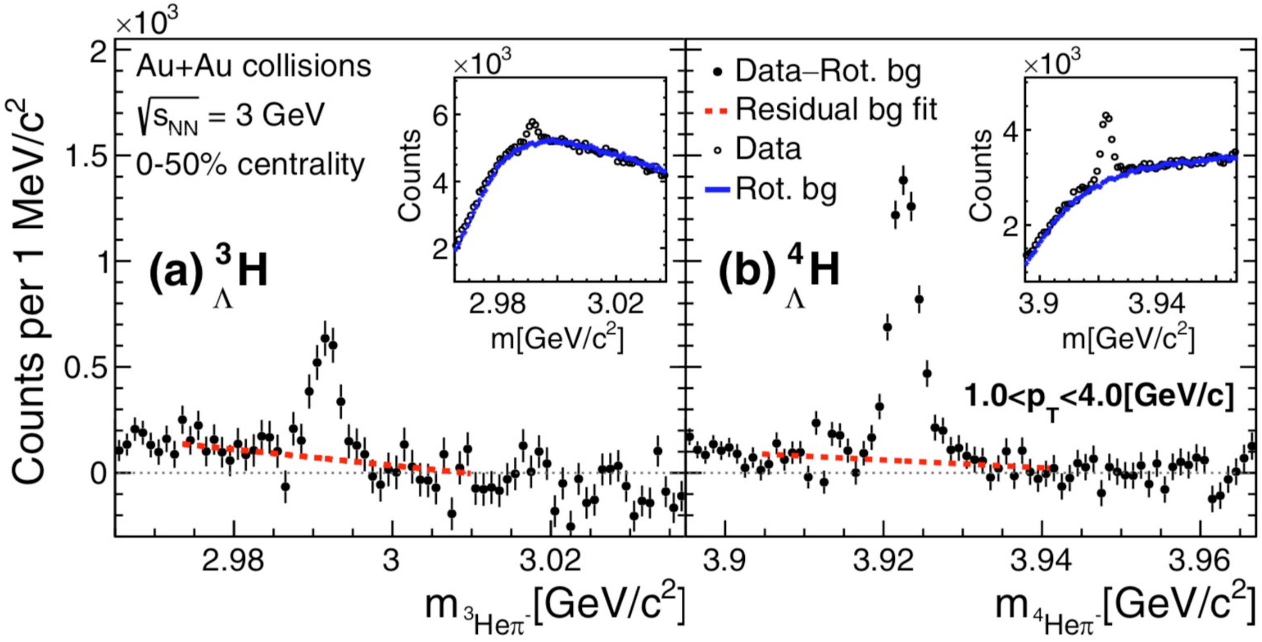
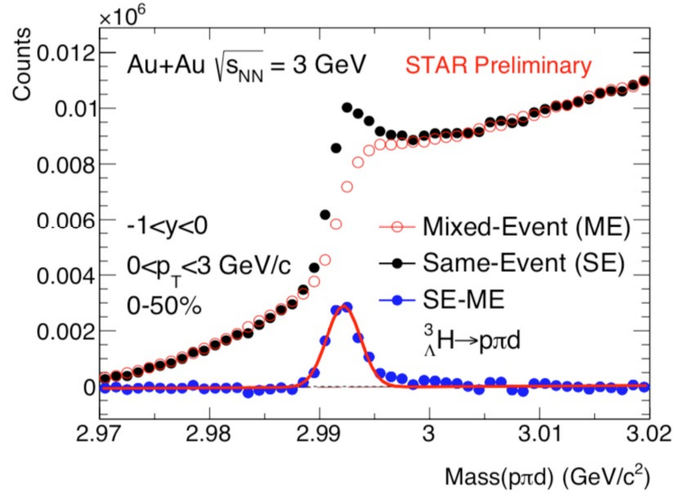
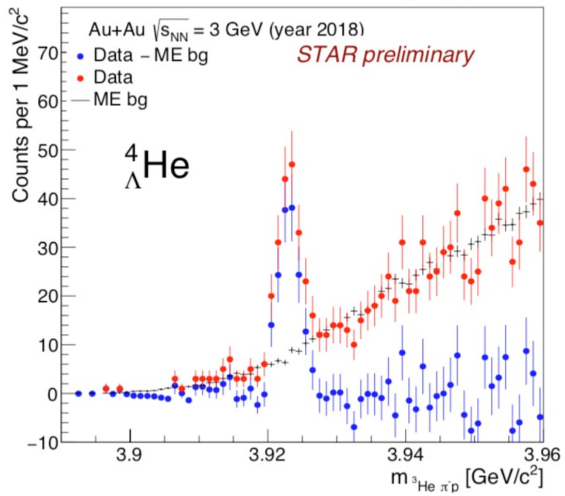
Hypernuclei reconstructions







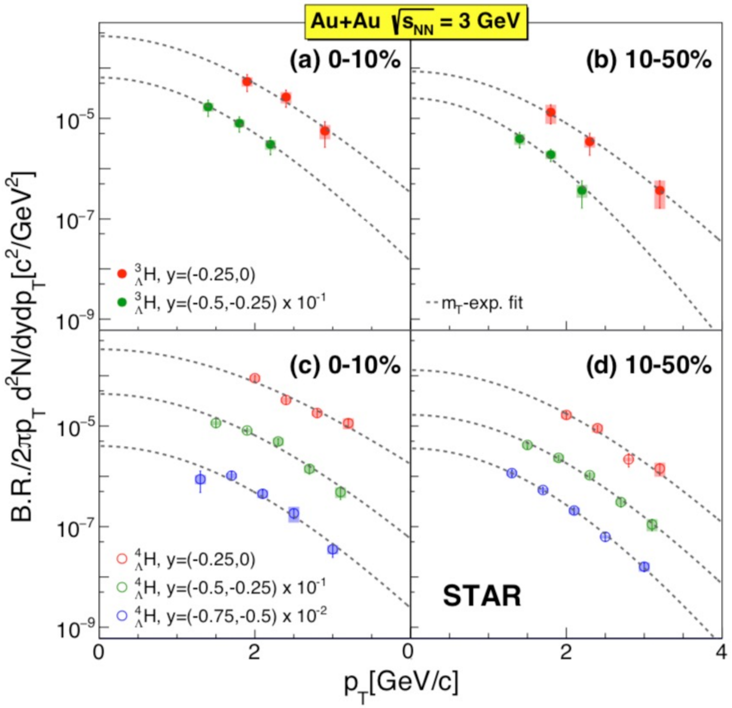
- Decay channels:

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

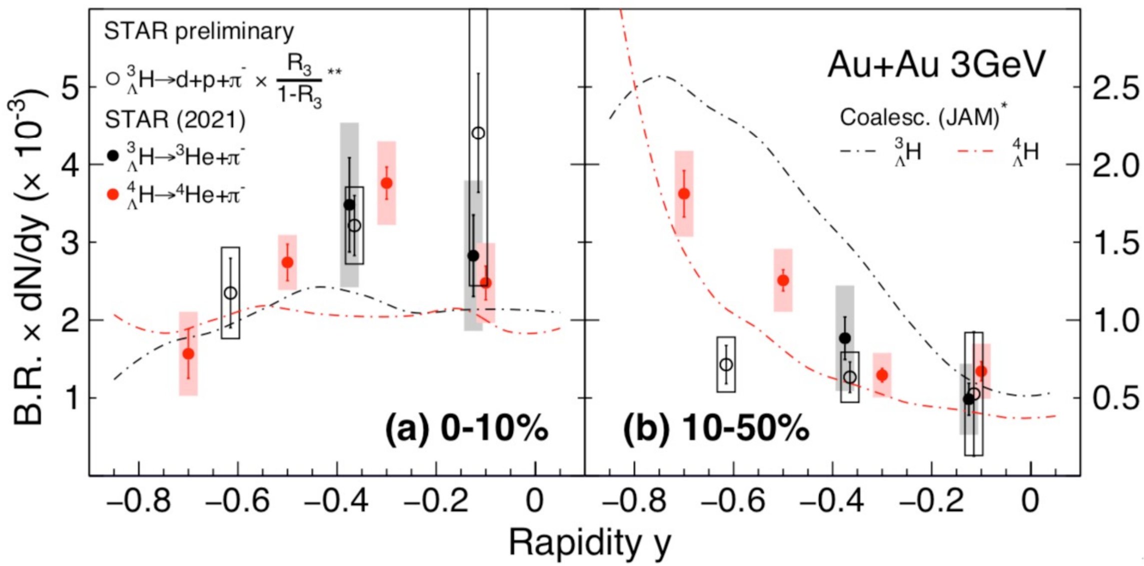
  $^{4}_{\Lambda}\mathrm{H} \rightarrow {}^{4}\mathrm{He} + \pi^{-}$ $\quad$ $^{4}_{\Lambda}\mathrm{He} \rightarrow {}^{3}\mathrm{He} + \mathrm{p} + \pi^{-}$

- Combinatorial background estimated via rotating pion tracks or event mixing

Hypernuclei production yields at 3 GeV

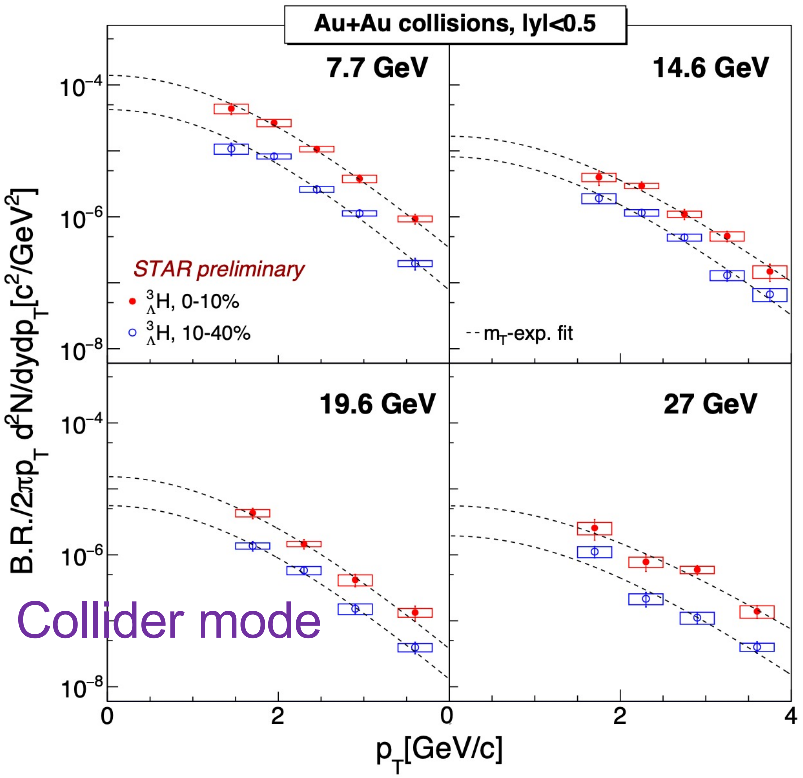


PRL 128, 202301(2022)



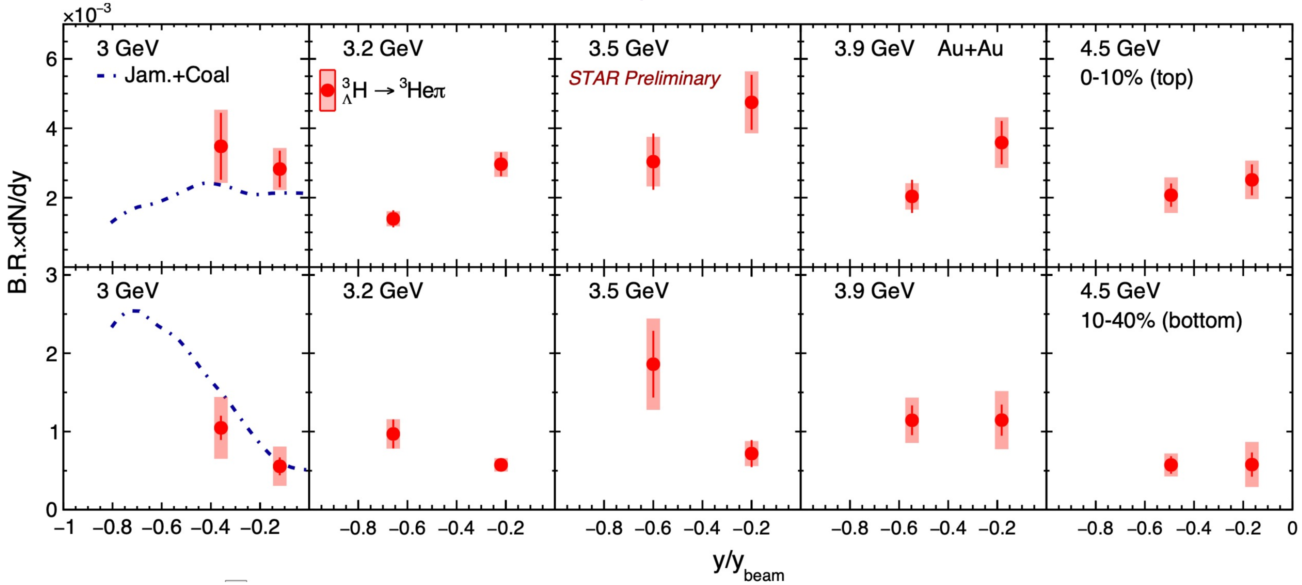
- First measurement of dN/dy of light hypernuclei in heavy-ion collisions.
- Different trends in the $^4_\Lambda$H rapidity distributions in central (0-10%) and semi-central (10-50%) collisions.
- Transport model (JAM) with coalescence reproduces trends of $^4_\Lambda$H but failed to describe $^3_\Lambda$H.

Hypertriton production yields at BES-II energies



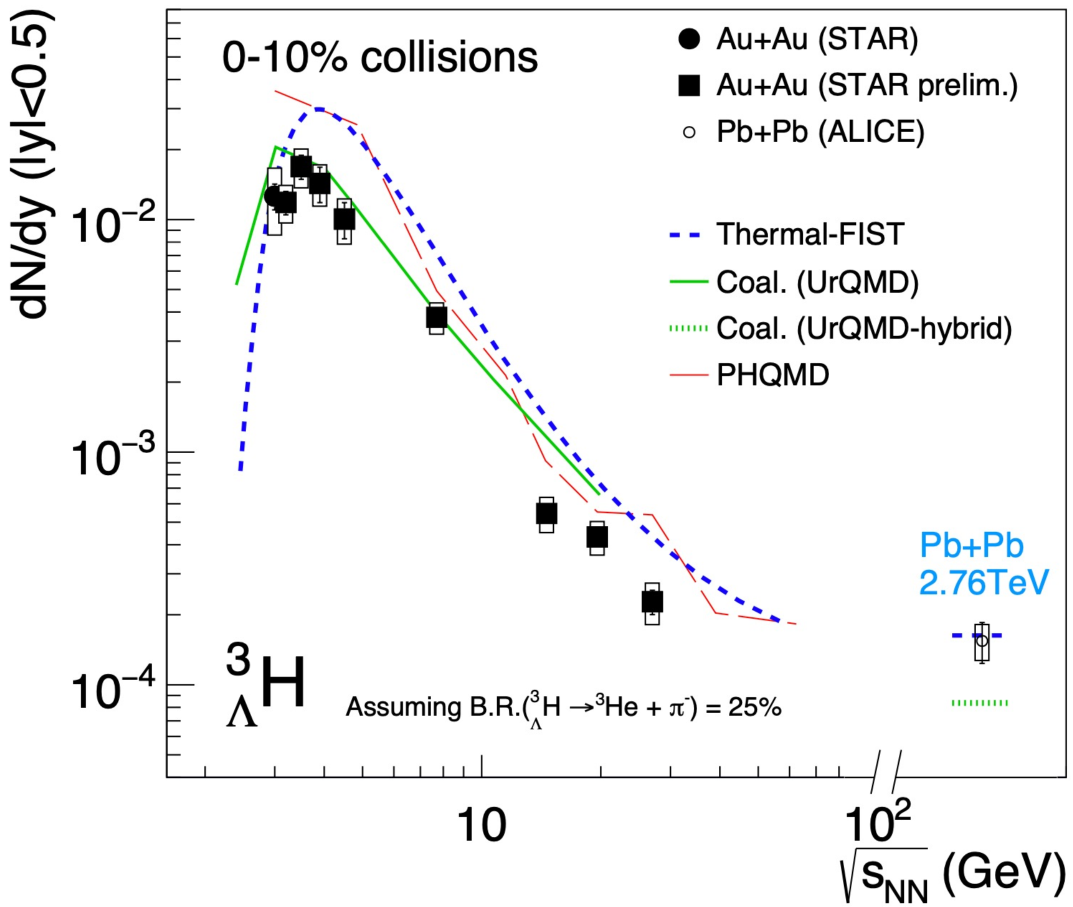
Collider mode

Fixed-target mode



- Comprehensive measurements using fixed-target and collider data with high statistics.

Hypertriton excitation function



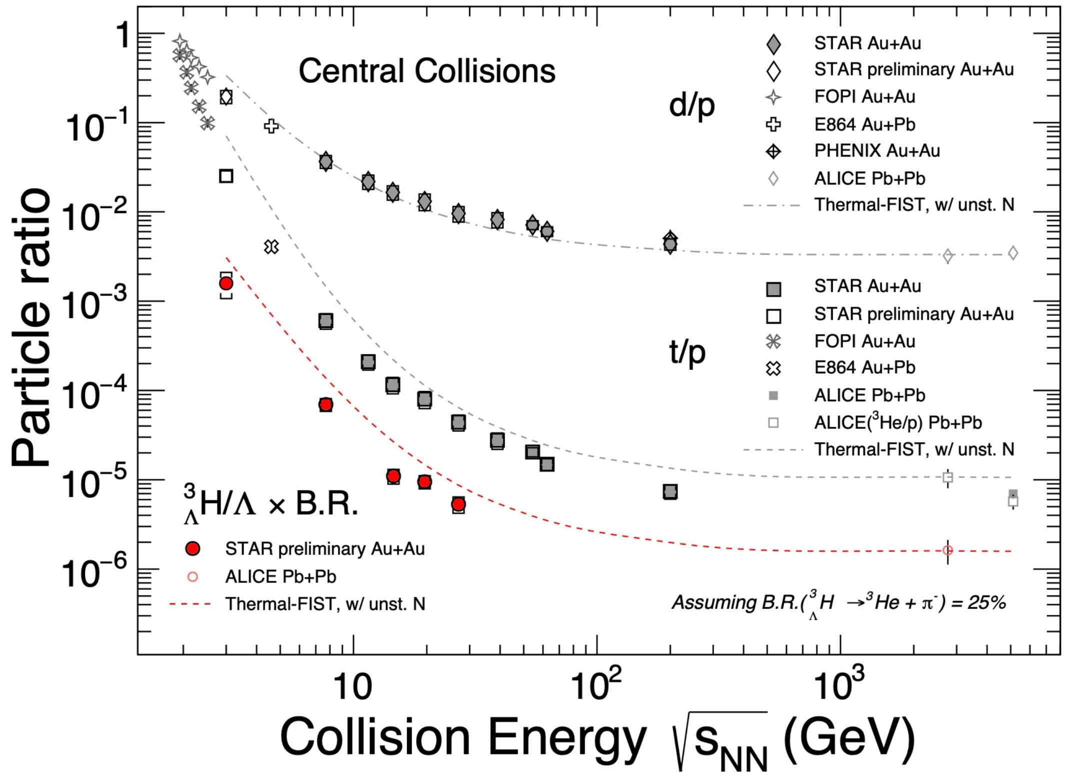
- Yield increases strongly from 27 - 7.7 GeV
- Maximum is reached at ~3-4 GeV
- Qualitatively consistent with thermal and coalescence models

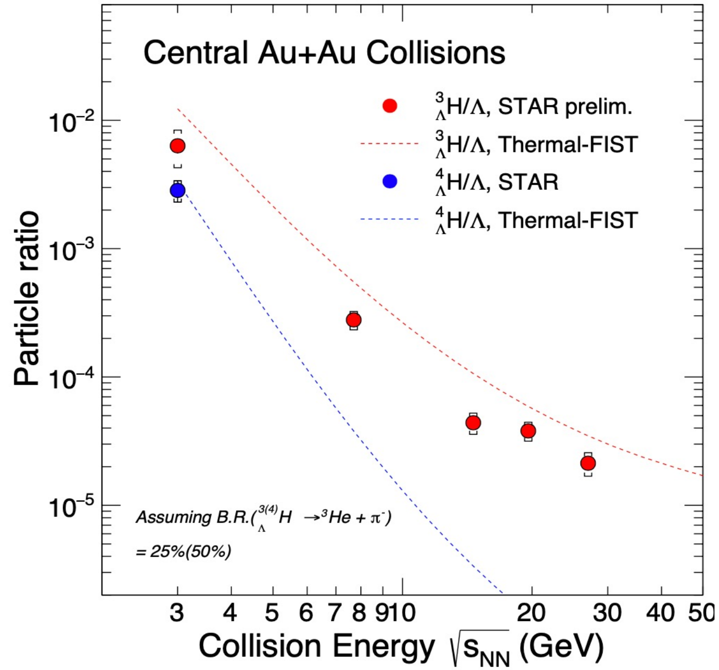
Trend in data can be interpreted as an interplay b/w

increasing baryon density and **stronger strangeness canonical suppression**

towards low energies

Nuclei-to-Hadron Ratios

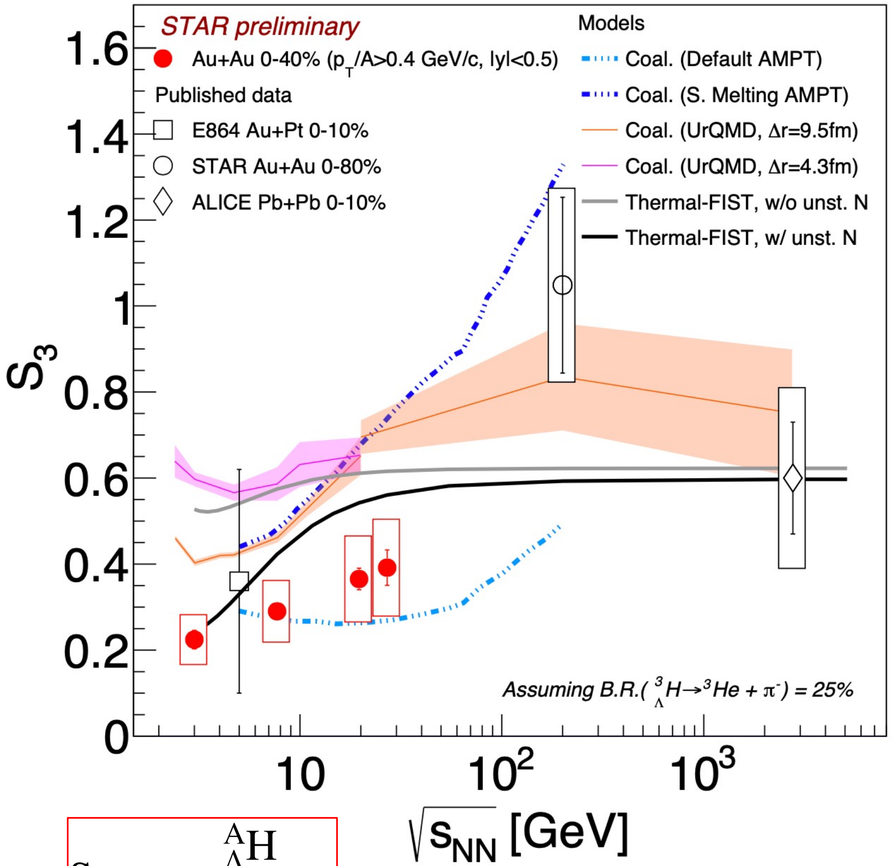




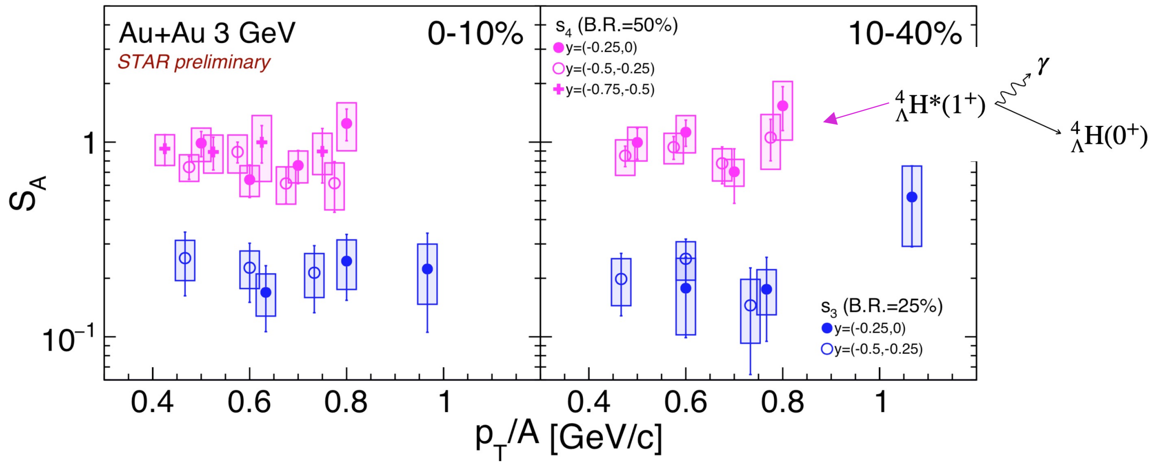
- At RHIC energies, similar to t/p
- $^3_\Lambda$H/Λ is overestimated by a factor of ~2 by the thermal model.
- $^4_\Lambda$H/Λ consistent with thermal model, feeddown effect?

Data are **in contradiction** to the scenario where $^3_\Lambda$H is **in equilibrium and frozen** at the **conventional chemical freezeout**

Strangeness Population Factor (S_A)



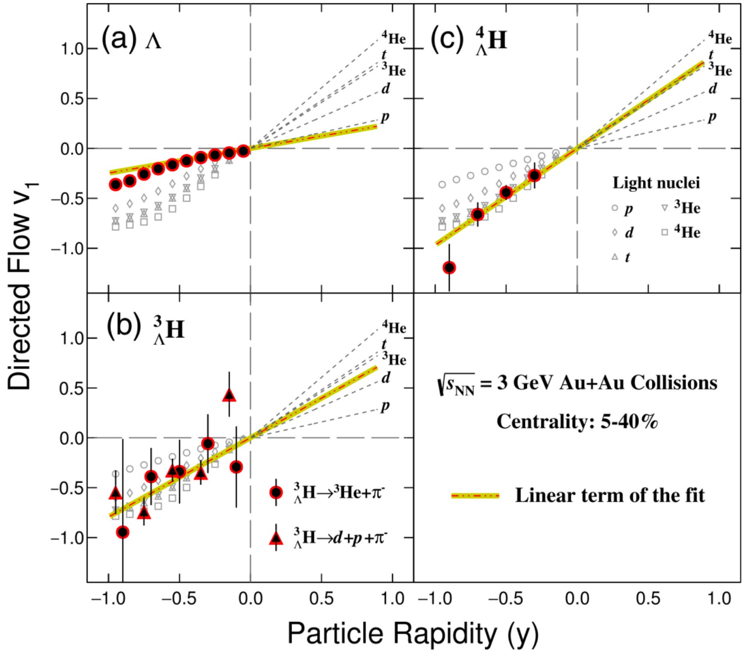
$$S_A = \frac{{}^{A}_{\Lambda}\mathrm{H}}{{}^{A}\mathrm{He} \times \frac{\Lambda}{p}}$$

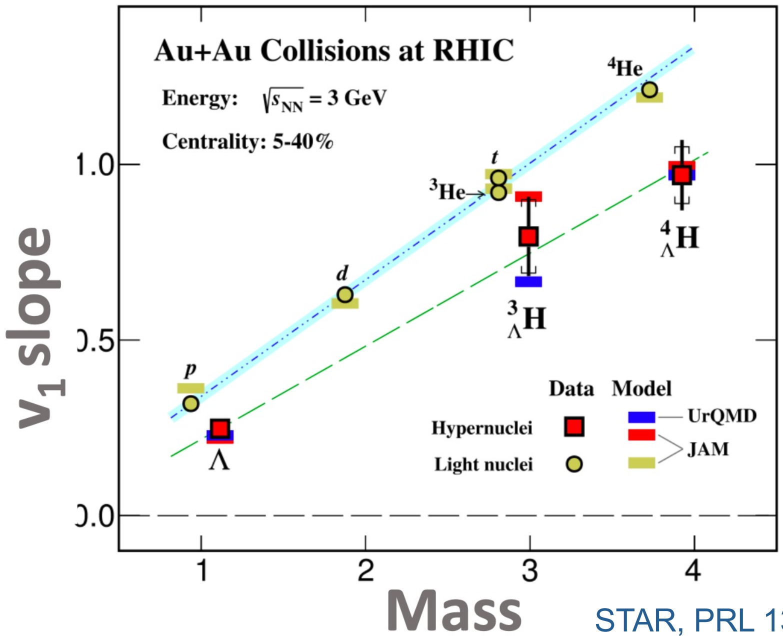


- S_A: Ratio of hypernuclei yield compared to light nuclei.
- S_A vs p_T/A, expect ~ 1 if no suppression naively,
  - $S_3 < 1 \longrightarrow$ suppression of ${}^{3}_{\Lambda}\mathrm{H}$ to ${}^{3}\mathrm{He}$ due to larger size.
  - $S_4 > S_3 \longrightarrow$ enhanced ${}^{4}_{\Lambda}\mathrm{H}$, feeddown from excited states.
- No clear centrality dependence.
- None of the models describe the S_3 data quantitatively.

Increasing trend of S_3 originally proposed as a signature of onset of deconfinement PLB 684 (2010) 224

Hypernuclei directed flow at 3 GeV





STAR, PRL 130, 212301 (2023)

- 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**

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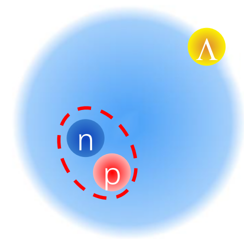
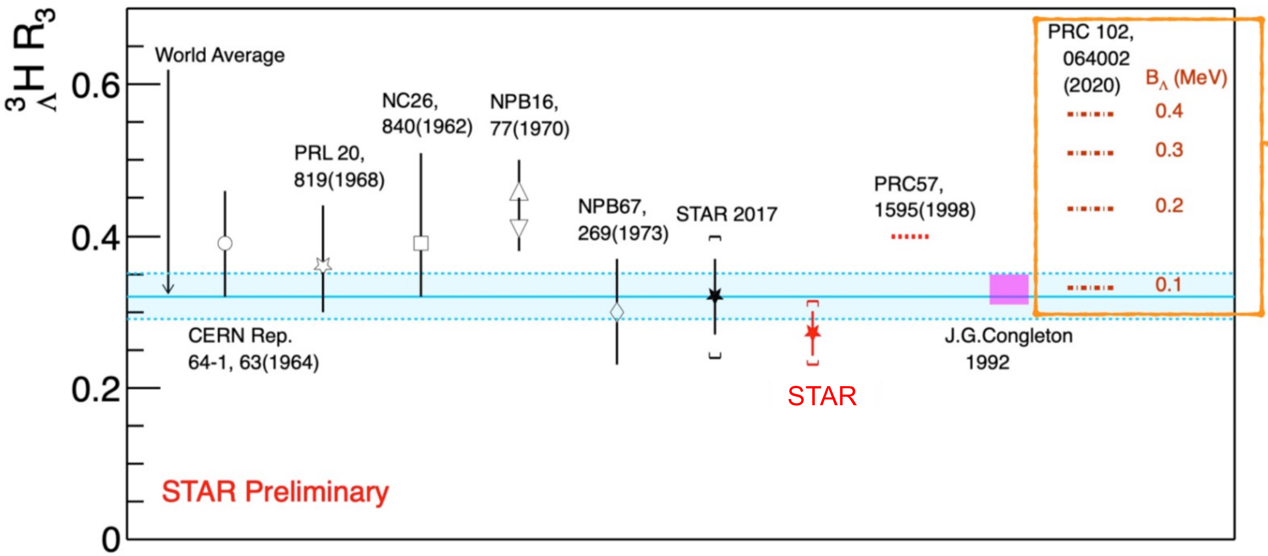
Hypertriton relative branching ratio (R_3)

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





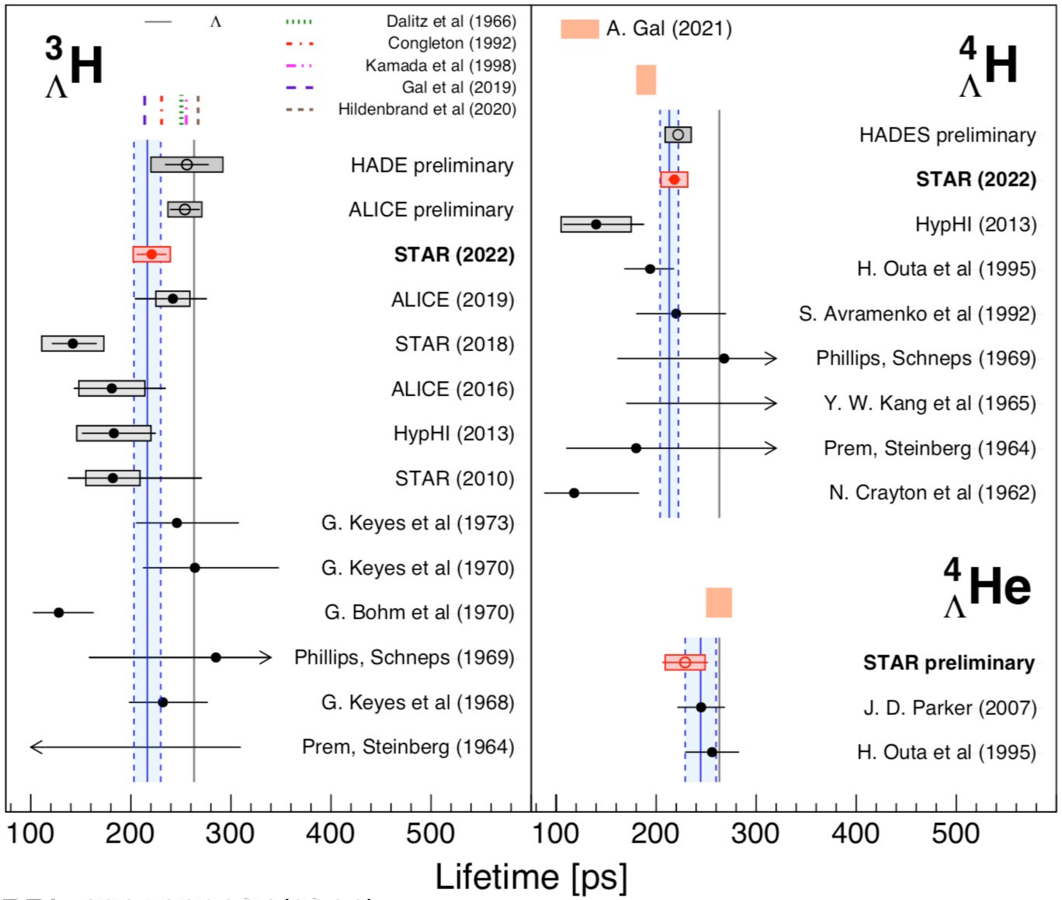
R_3 may be sensitive to the binding energy of ${}^3_\Lambda H$

- 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)

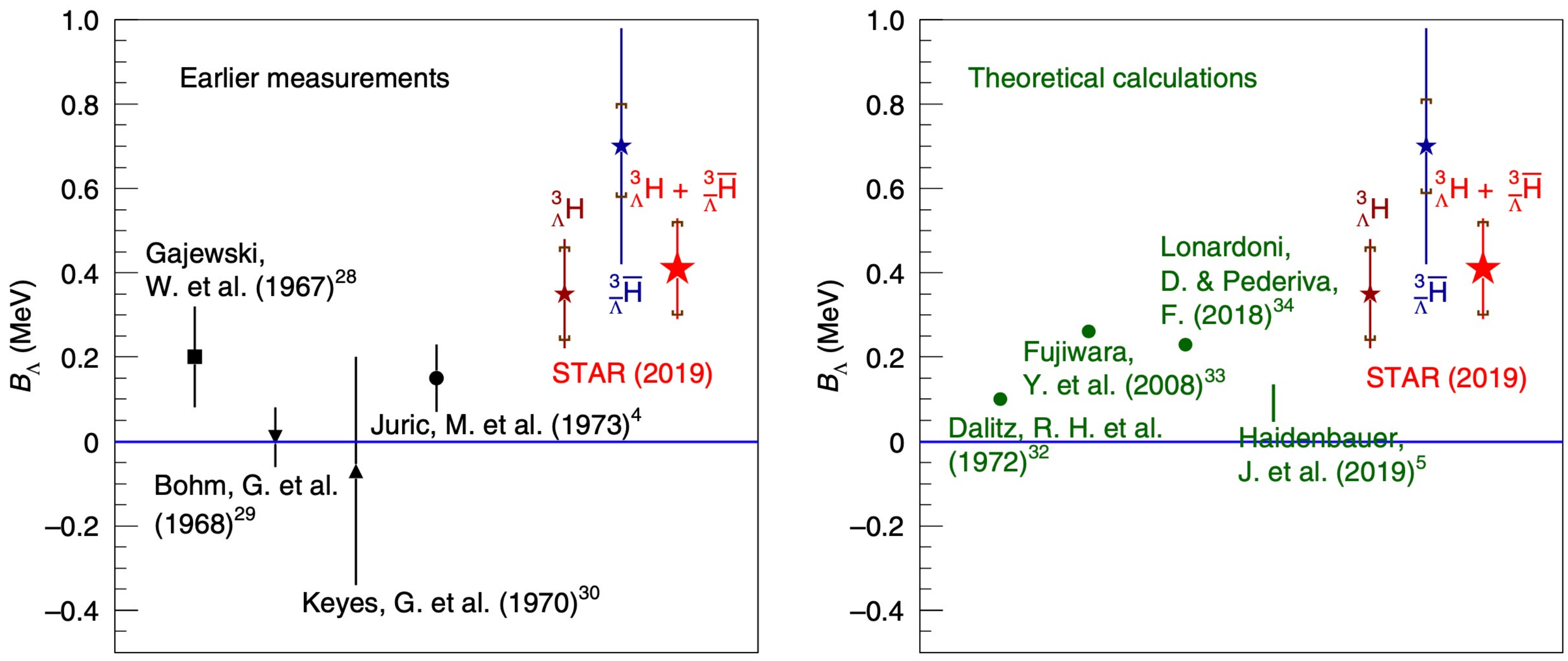
$^{3}_{\Lambda}\mathrm{H}: \tau = 221 \pm 15(\mathrm{stat.}) \pm 19(\mathrm{syst.})[\mathrm{ps}]$

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

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

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

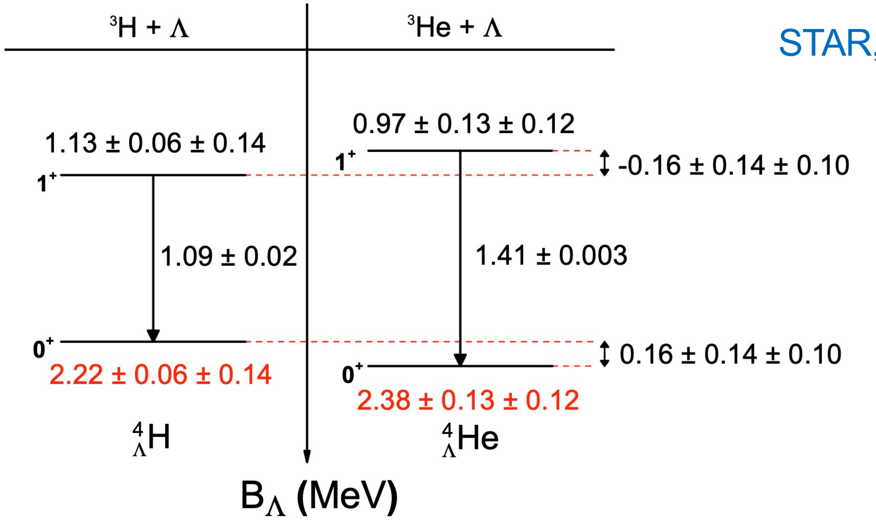


STAR Col, Nat. Phys. 16 (2020) 409

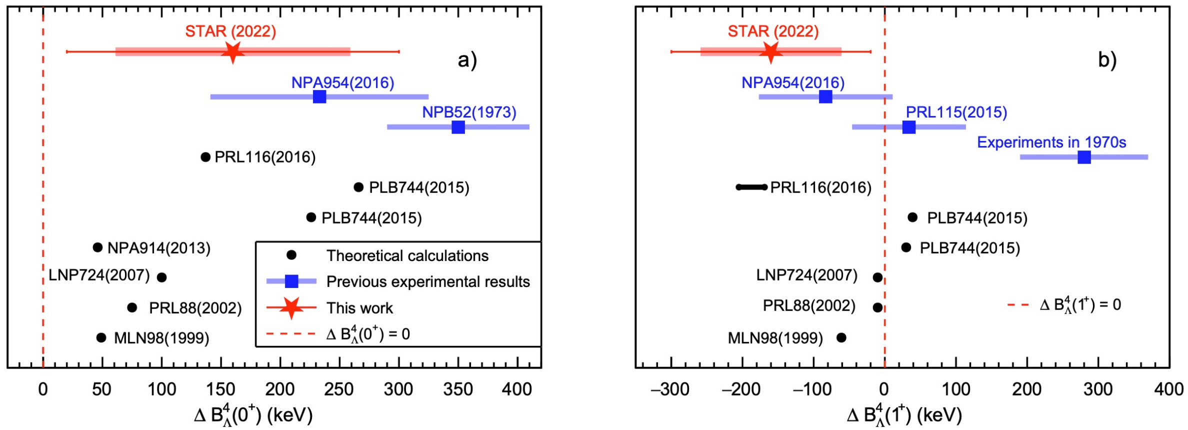
$$B_\Lambda = 0.41 \pm 0.12(\mathrm{stat.}) \pm 0.11(\mathrm{syst.})\ \mathrm{MeV}$$

- STAR data differs from zero (3.4σ) and larger than the prior measurements from 1973
- Theoretical calculations span in a wide range

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



STAR, PLB 834 (2022) 137449



- 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.

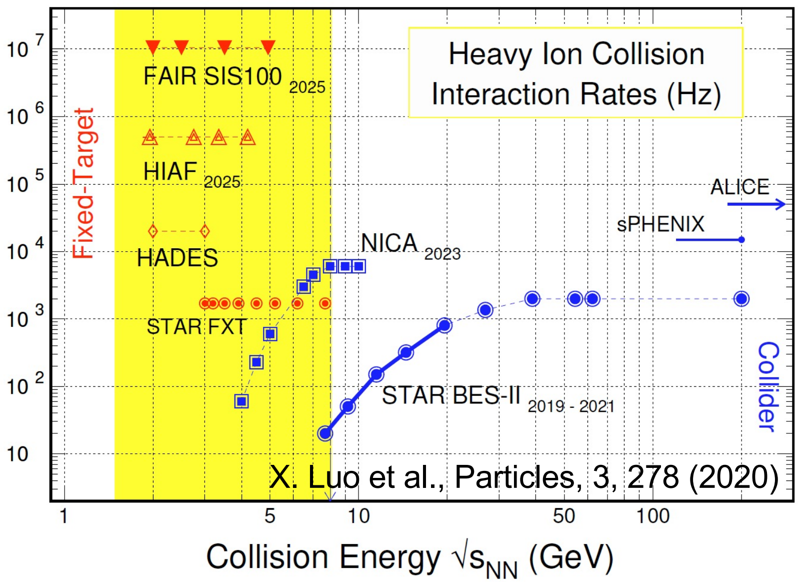
Summary

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

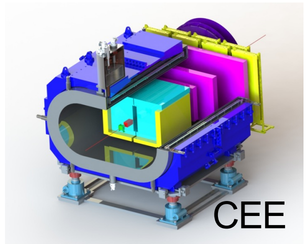
- First measurement of ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$ collectivity v_1
  - Mass number scaling is observed for the light hypernuclei → qualitatively consistent with coalescence
- First measurement of ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$ dN/dy vs y in heavy-ion collisions. Excitation functions and S_A.
  - Provide first constraints to hypernuclei production models @ high μ_B

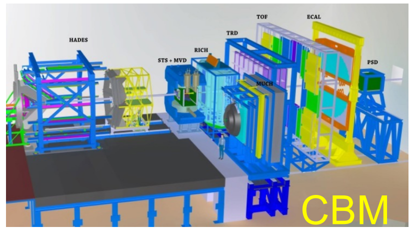
- ${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}$ lifetimes measured with improved precision
- Relative branching ratio R_3 of ${}^{3}_{\Lambda}\mathrm{H}$ with improved precision
  - Precision lifetime and R_3 provide stronger constraints on hyper nuclear interaction models
- Λ binding-energy difference between ${}^{4}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{He}$
  - Hint of CSB effect at A=4

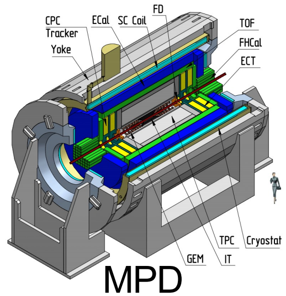
Outlook: High baryon density frontier

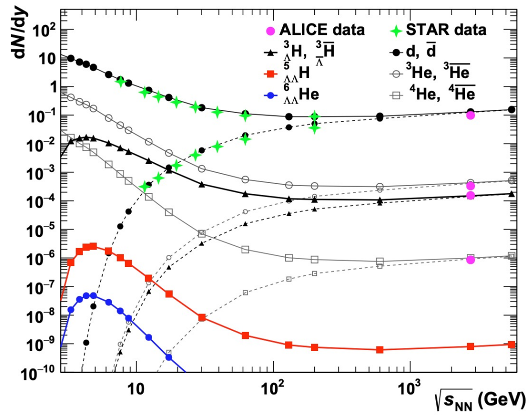


Year	$\sqrt{s_{NN}}$ (GeV)	Events
2020	11.5	235 M
	7.7	113 M
	4.5	108 M
	6.2	118 M
	5.2	103 M
	3.9	117 M
	3.5	116 M
	9.2	162 M
	7.2	317 M
2021	7.7	101 M
	3.0	2103 M
	9.2	54 M
	11.5	52 M
	13.7	51 M
	17.3	256 M
	7.2	89 M









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 !

Feed-down effect

- Relative branching ratio:

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

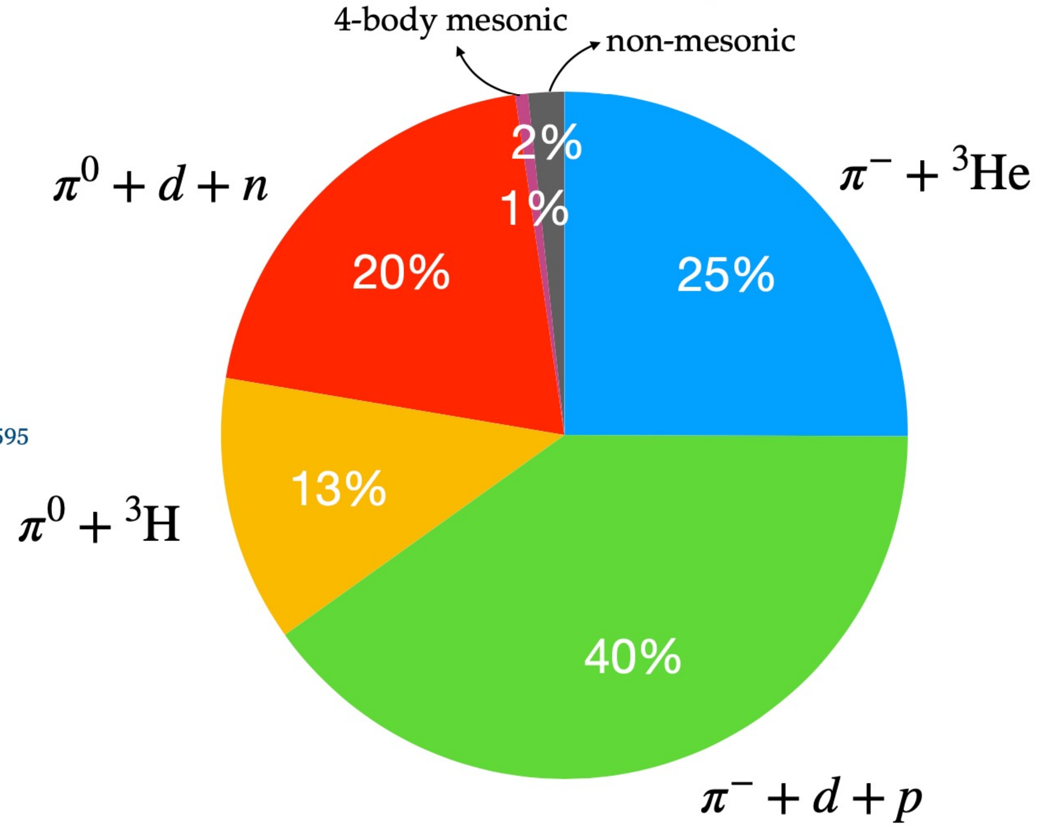
- The 2-body and 3-body mesonic decay channels are expected to contribute ~97% of the total decay rate

Kamada et al, Phys. Rev. C 57 (1998) 1595

- $\pi^- : \pi^0$ decay rates expected to follow isospin rule (2:1)

- Suggested to be sensitive to the radius of the hypertriton   Hildenbrand et al, Phys. Rev. C 102 (2020) 064002

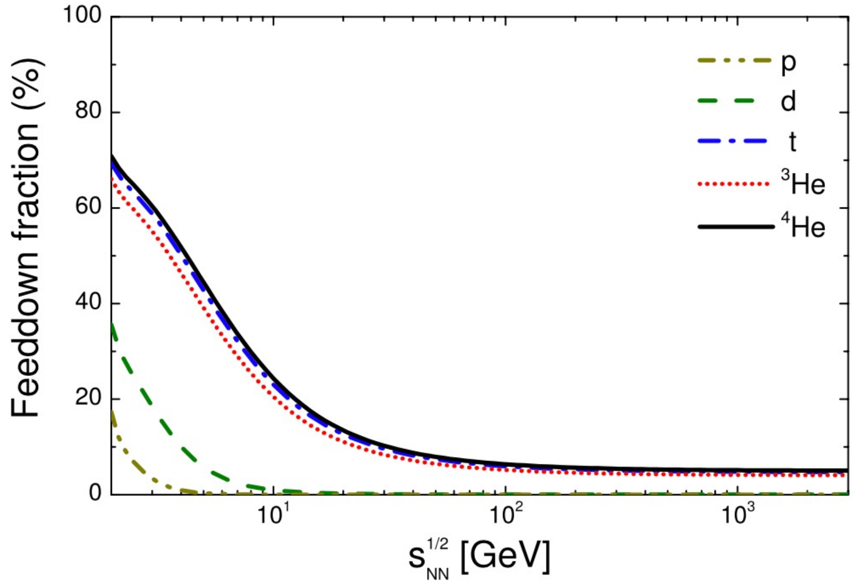
Calculated decay B.R. from Kamada et al



- Give constraints to **the absolute branching ratio**, crucial for yield measurements

Feed-down effect

- Thermal-FIST also suggest increasing trend
  - Unstable nuclei breakup enhance ^{3}He yields? $e.g.\,{}^4\mathrm{Li} \rightarrow {}^3\mathrm{He} + p$



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