Collision Energy Dependence of Hypertriton Production in Au+Au Collisions at RHIC

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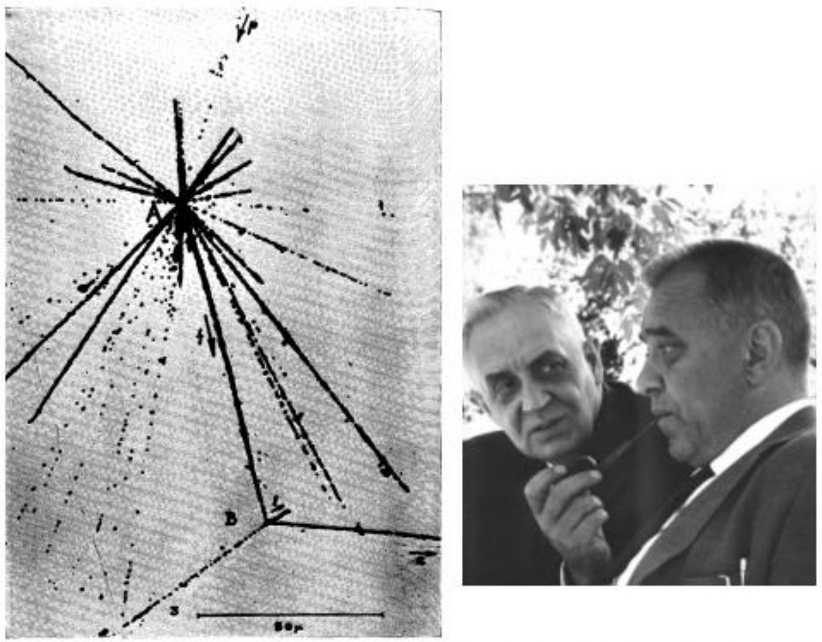
Introduction: hypernuclei

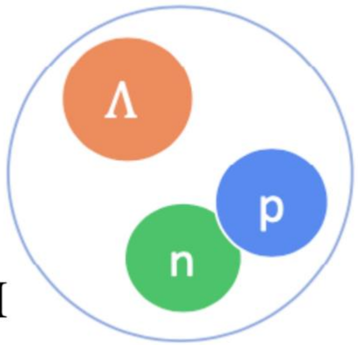
- Hypernuclei : bound nuclear systems of non-strange and strange baryons

  -Natural hyperon-baryon correlation system



The first discovery of hypernucleus by Marian Danysz (right) and Jerzy Pniewski (left) in 1952

M. Danysz, J. Pniewski, Philos. Mag. 44 (1953) 348.

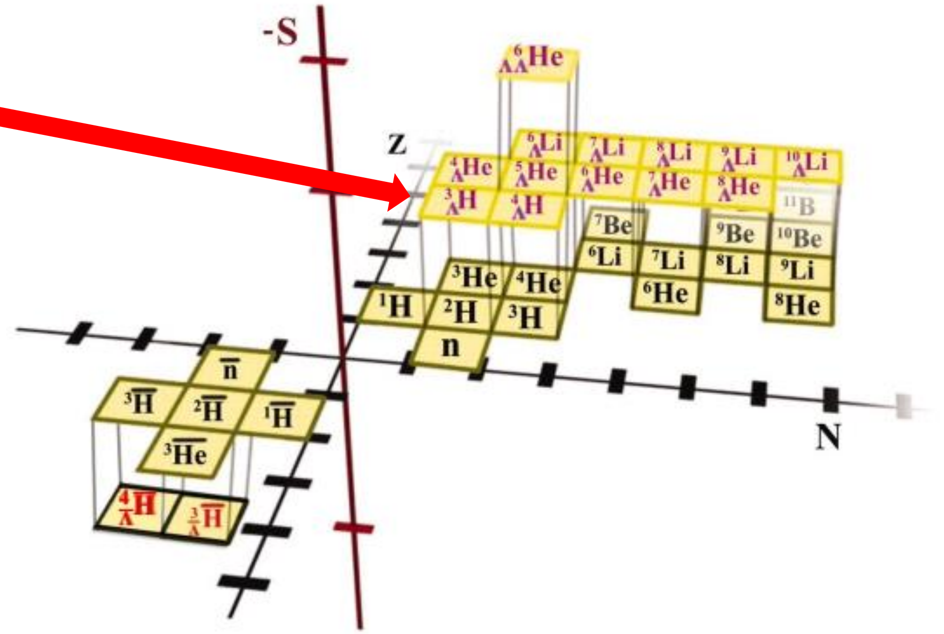


$^{3}_{\Lambda}\mathrm{H}$

lightest hypernucleus

$B_{\Lambda} \sim 0.15\mathrm{MeV}$

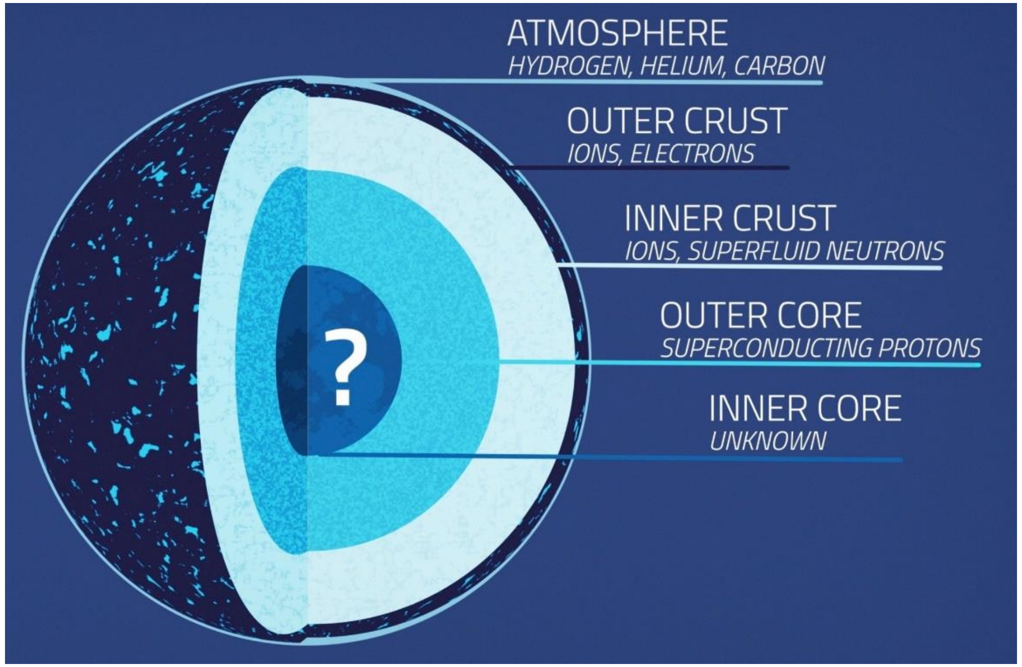
RMS radius $5 \sim 10$ fm



Introduction: YN interaction in dense matter

- Hypernuclei serve as a laboratory to study the hyperon−nucleon (YN) interaction
  - YN interaction is essential in probing neutron star inner core

- **Hyperon puzzle**: do hyperons exist in the dense inner core of neutron stars?
  - No direct probe method
  - Rely on theoretical models
  - Lack of direct experimental data of YN, YNN, YY interactions to constrain theoretical models of the dense matter equation of state (EoS)

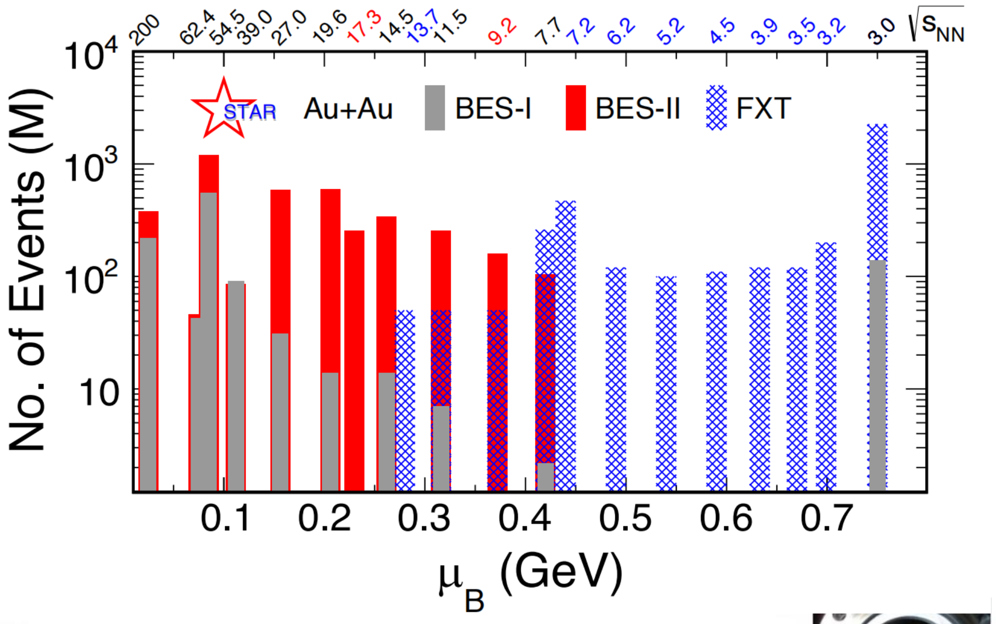


Introduction: RHIC BES-II

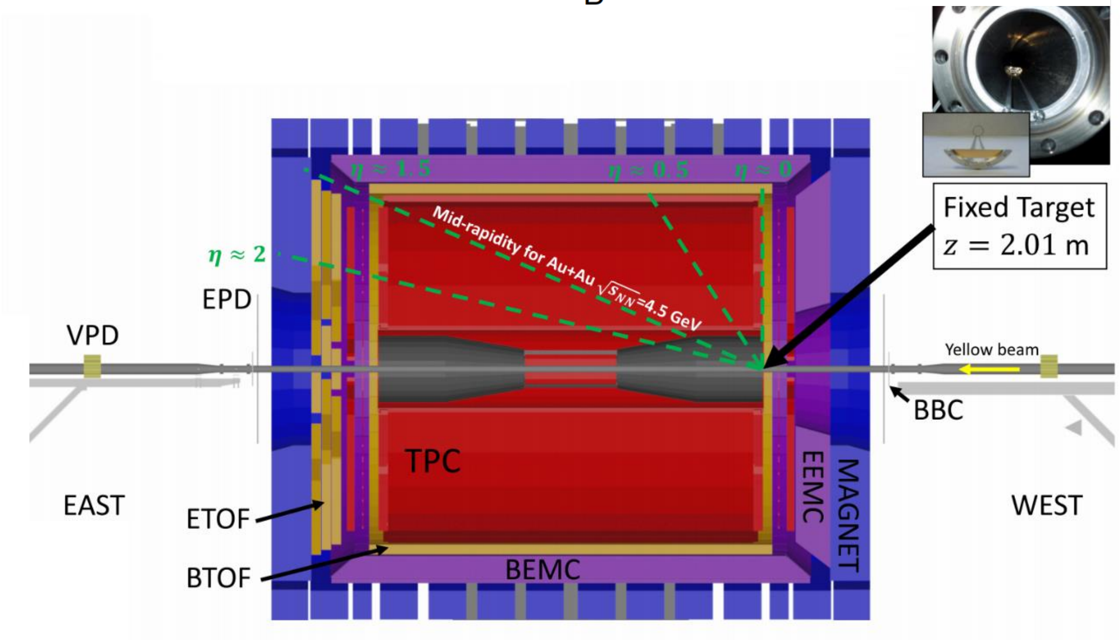
- RHIC beam energy scan Phase II (BES-II)
  - Specific focus on low $\sqrt{s_{NN}}$

    Include fixed target (FXT) mode extends down to 3.0 GeV, increase μ_B range from ~400 MeV to ~700 MeV

  - High statistics data
  - Improve systematics
    - Detector upgrade: iTPC, EPD, eTOF



Enhances the capability of various measurements with excellent precision



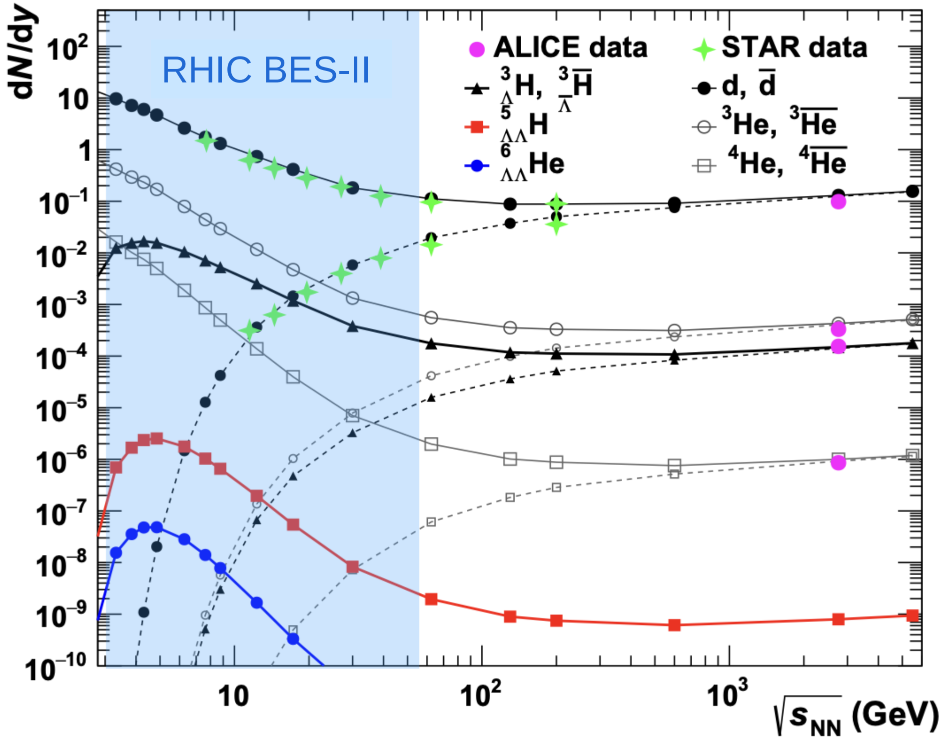
Production mechanism of hypernuclei is still not well understood.

Hypernuclei formation process in relativistic heavy-ion (HI) collisions can be studied through measurements related to **spectra and collective flow.**

- Hypernuclei measurements are scarce in HI collision experiments

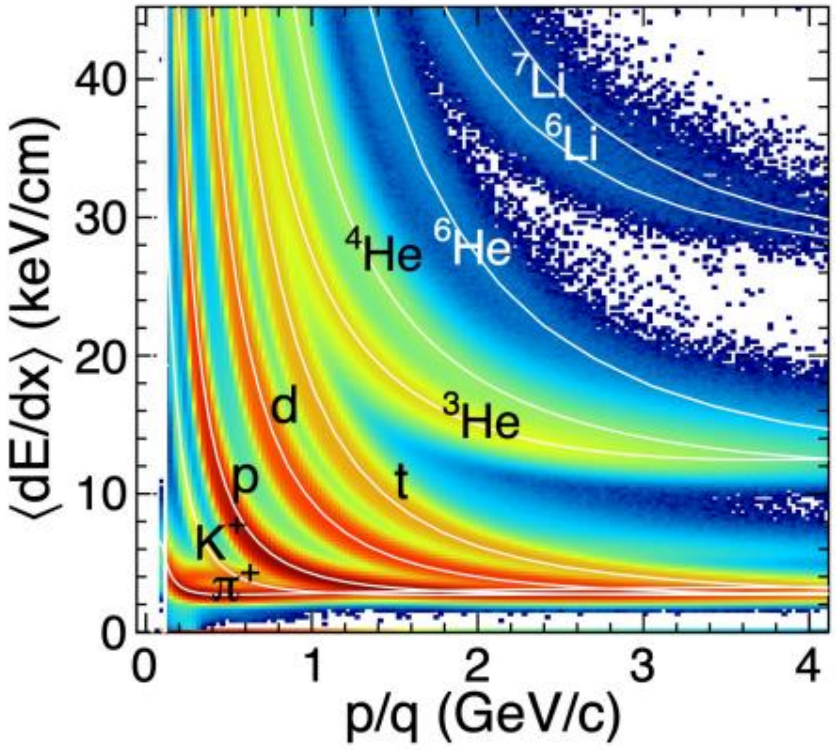
- At **low beam energies**, hypernuclei production is expected to be **enhanced** due to high baryon density

RHIC BES-II offers great opportunity for hypernuclei measurements.

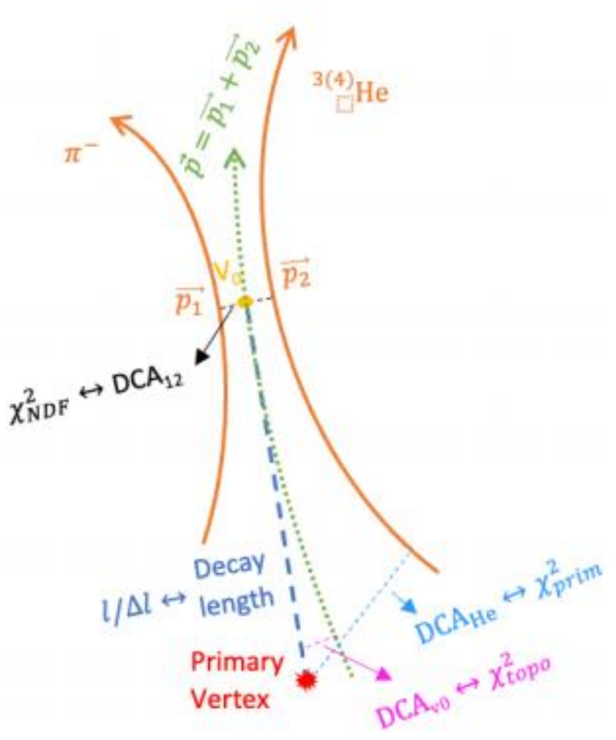


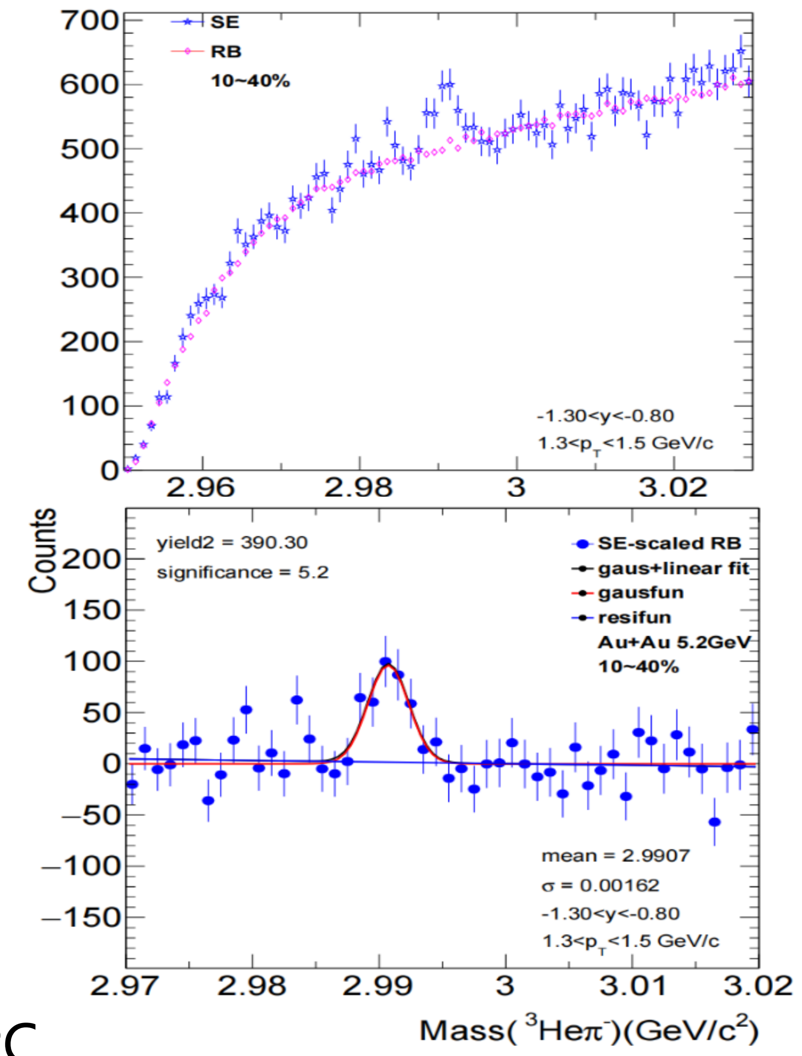
B. Dönigus, Eur. Phys. J. A (2020) 56:280
A. Andronic et al. PLB (2011) 697:203–207

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



${}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + \pi^{-}$

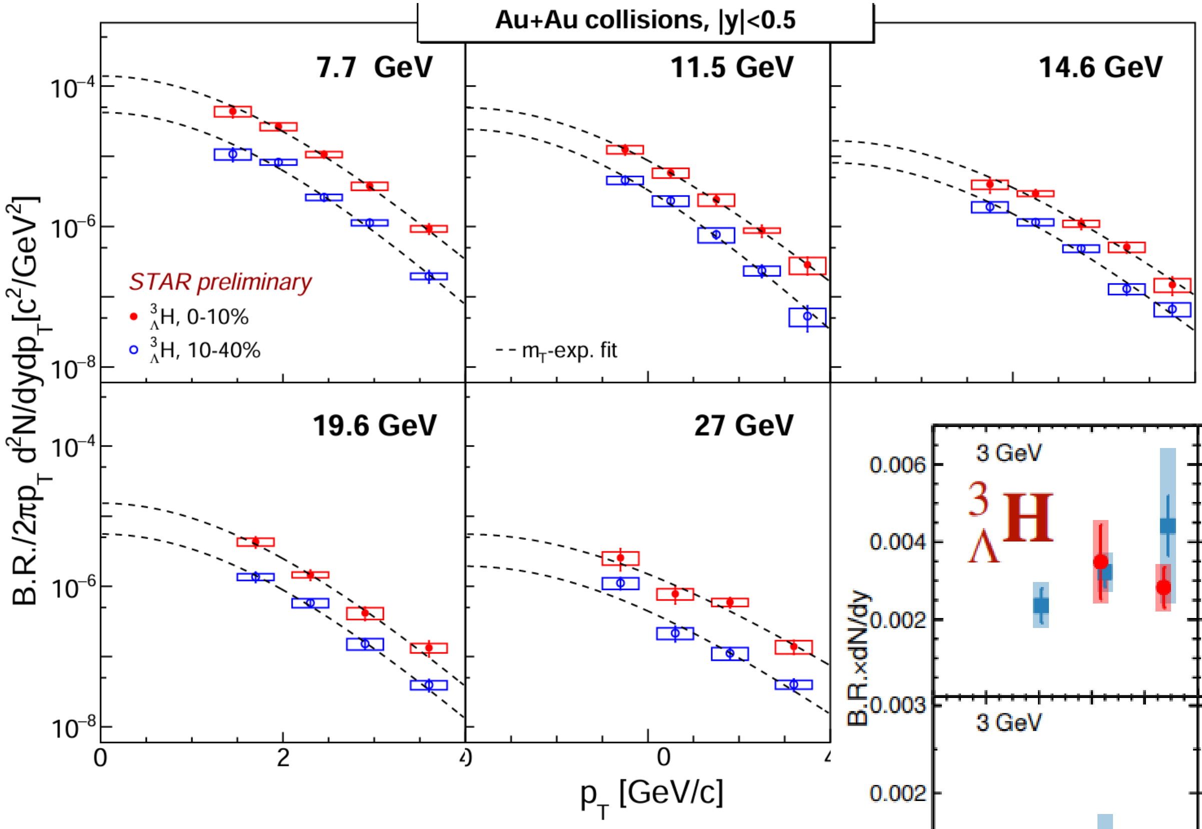




- Reconstruction channel: ${}^{3}_{\Lambda}\mathrm{H} \rightarrow {}^{3}_{2}\mathrm{He} + \pi^{-}$
- Particle identification from energy loss measurement using TPC
- KF particle package * is used for signal reconstruction

* XY. Ju et al. Nucl.Sci.Tech. 34 (2023) 10, 158

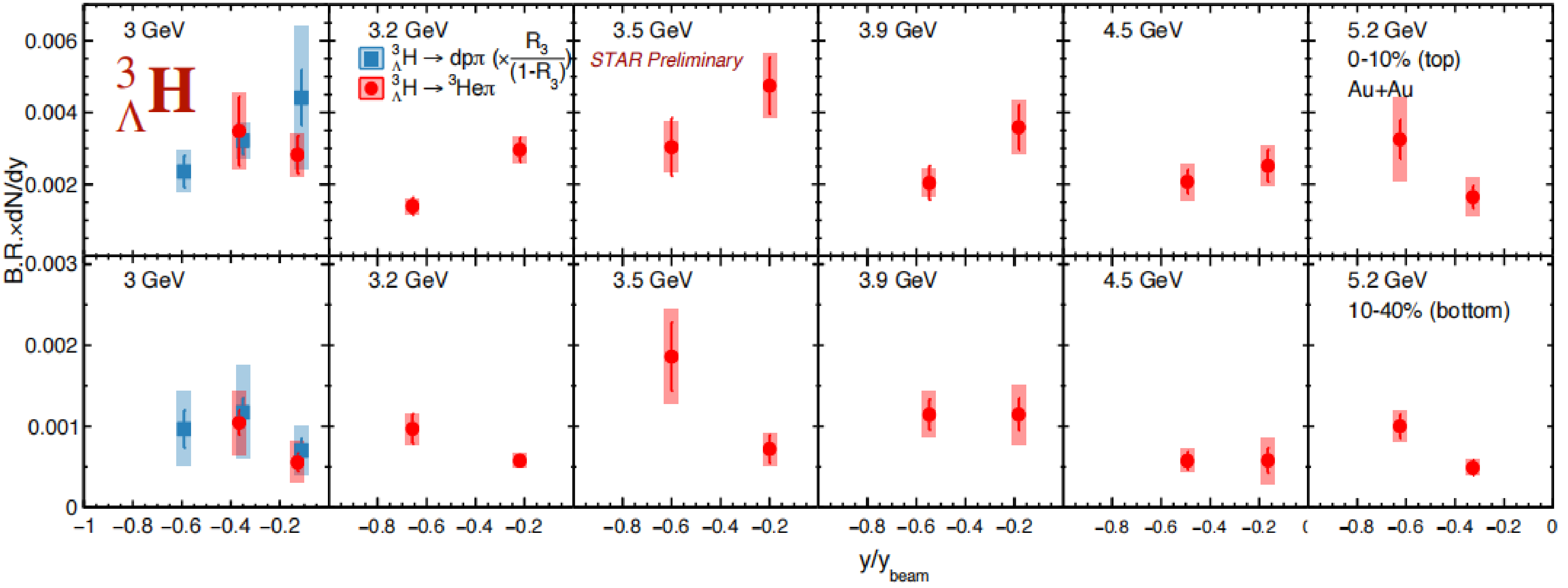
${}^{3}_{\Lambda}H$ rapidity and p_T spectra



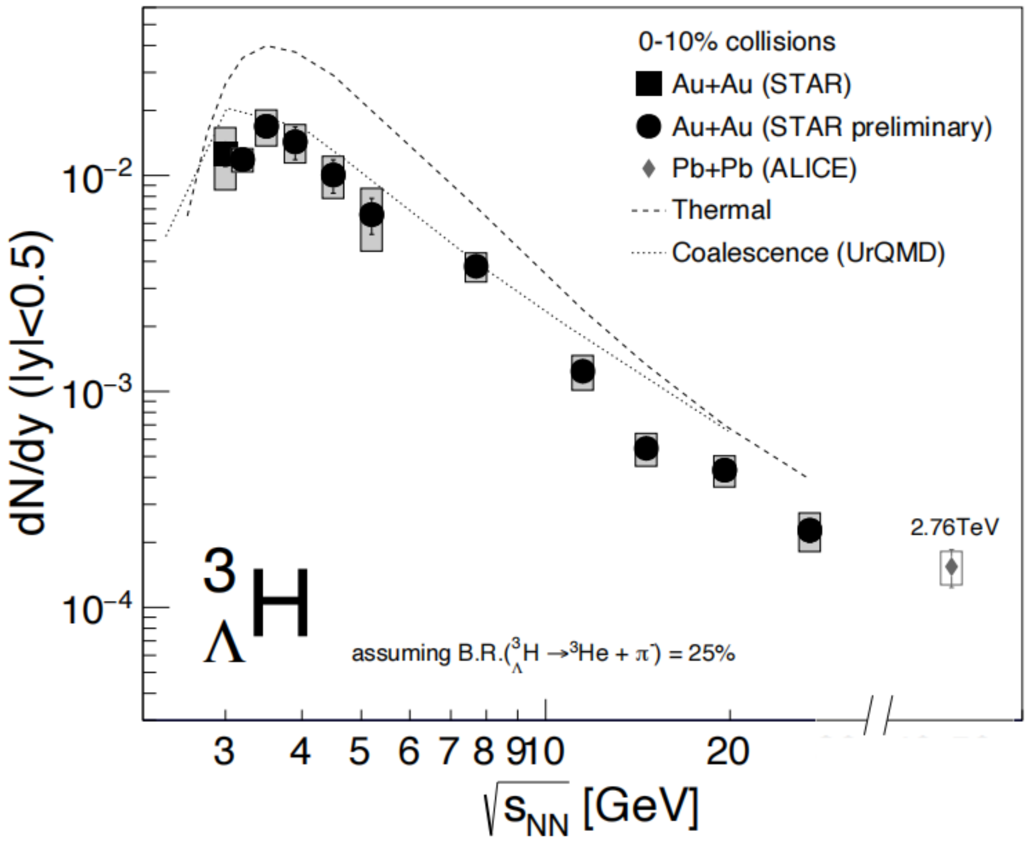
- Measurements cover 11 different energies

Collider: 7.7, 11.5, 14.6, 19.6, 27 GeV

Fixed Target: 3.0, 3.2, 3.5, 3.9, 4.5, 5.2 GeV



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

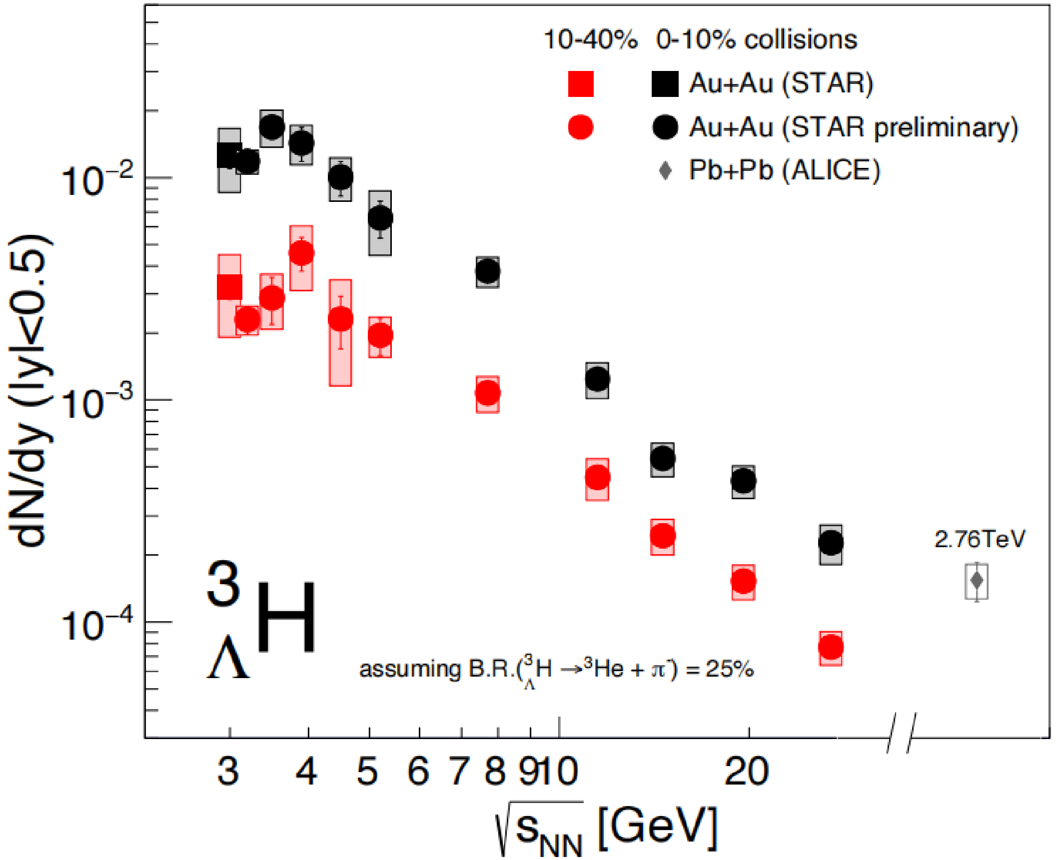


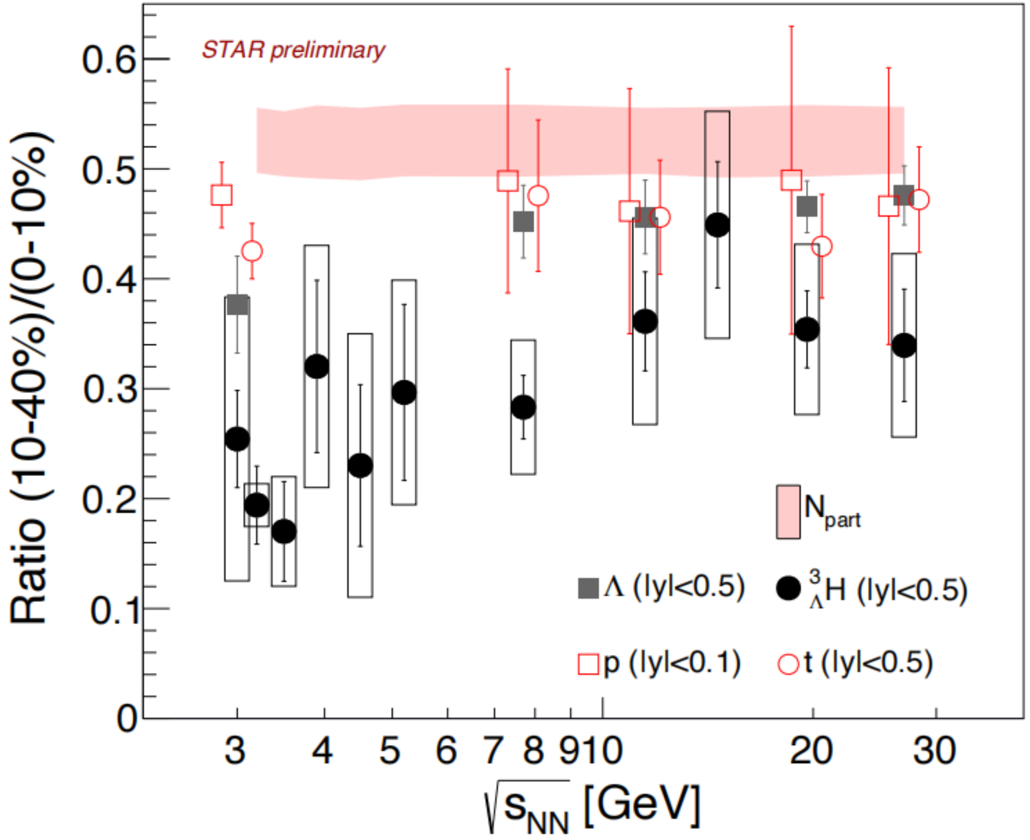
- Yields increase strongly from $\sqrt{S_{NN}} = 27$ GeV to ~4GeV
- Peak at 3-4 GeV
- Hadronic transport + coalescence models qualitatively describe the data
- Thermal model overestimates the data

First energy dependence of $^{3}_{\Lambda}\mathrm{H}$ production yields in the high-baryon-density region

STAR, PRL 128 (2022) 202301
ALICE, PLB 754 (2016) 360
T. Reichert, et al, PRC 107 (2023) 014912

Centrality dependence of $^3_\Lambda H$ production



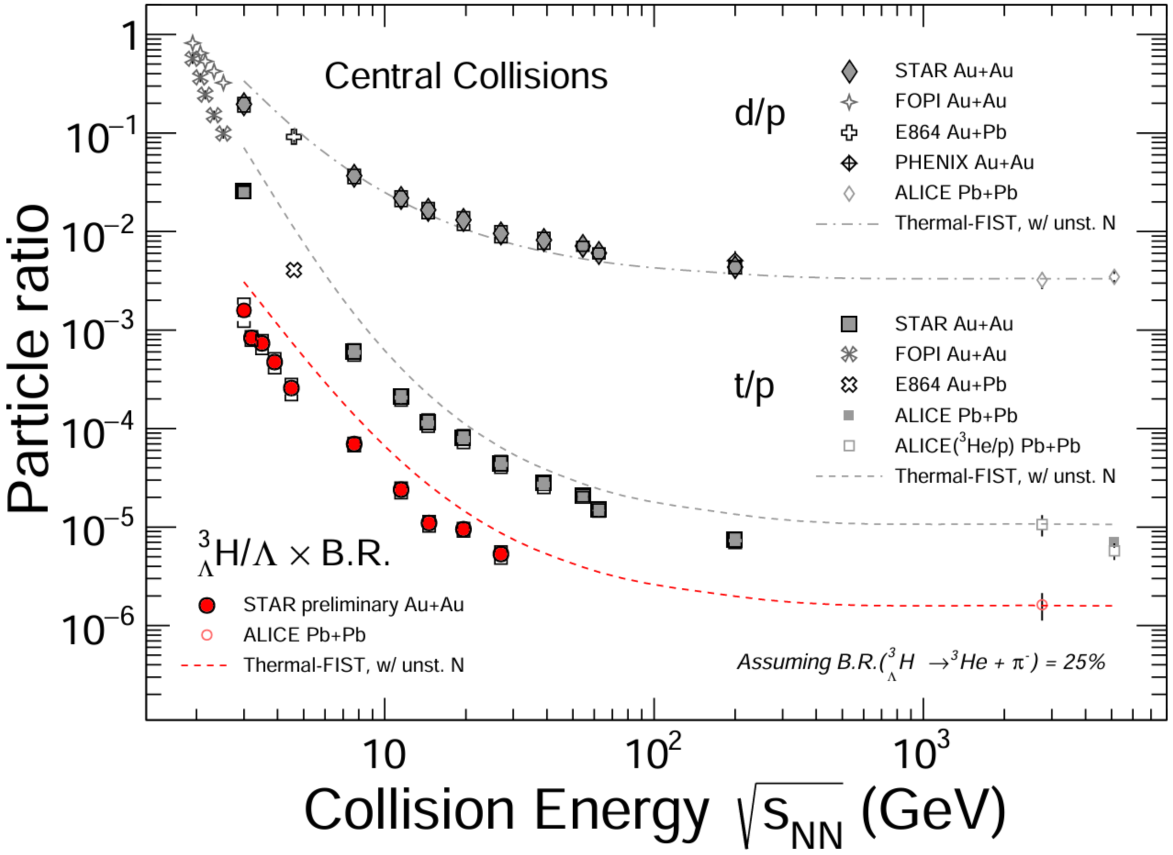


- Similar trend in central (0-10%) and mid-central (10-40%) collisions
- Suppression of mid-central/central $^3_\Lambda H$ yield ratio seems more apparent below $\sqrt{S_{NN}} = 7.7$ GeV
- $^3_\Lambda H$ yield ratio tends to increase more steeply than proton, Λ, triton at low energies

Suppression of $^3_\Lambda H$ production in mid-central collisions at low energies compared to central collisions

STAR, PRL 128 (2022) 202301
ALICE, PLB 754 (2016) 360

Nuclei-to-Hadron ratios



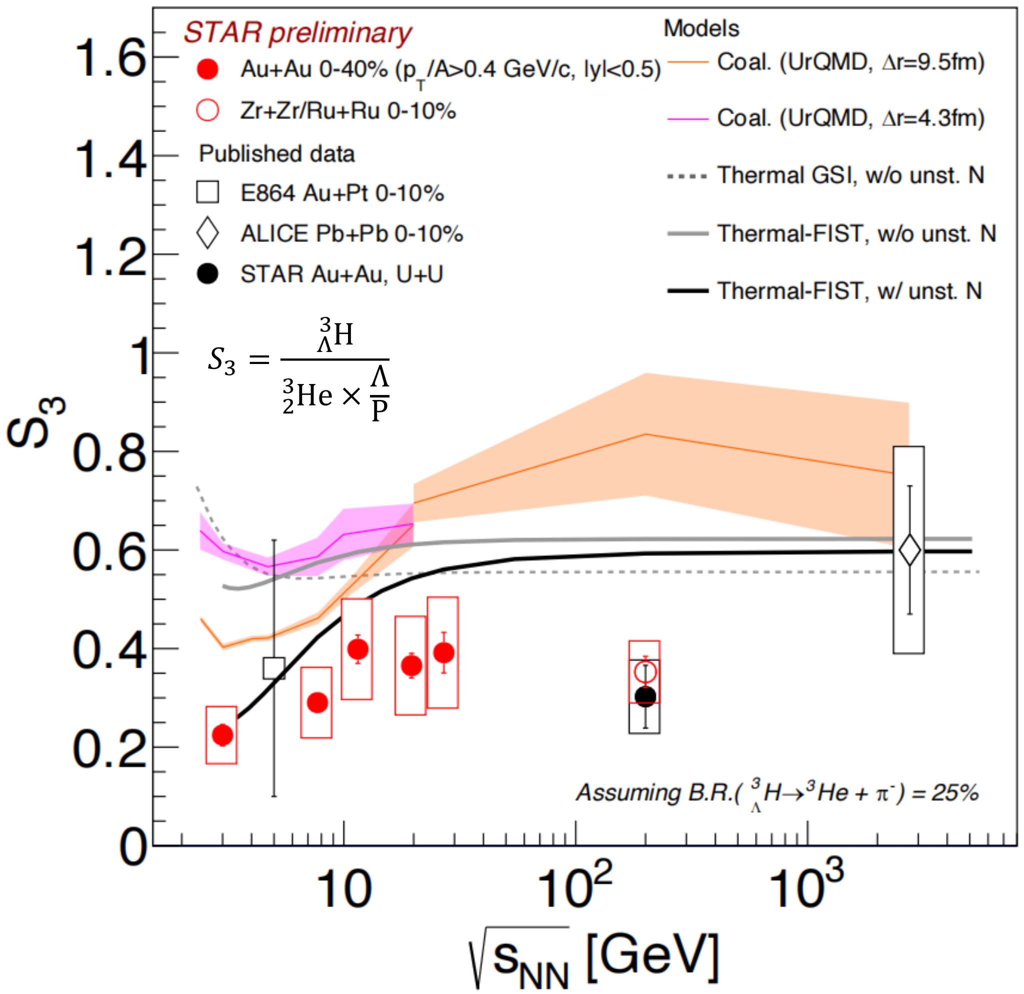
- Thermal model, assuming that chemical freeze-out of light/ hypernuclei happens at same time with hadrons, **overestimates** $^{3}_{\Lambda}\mathrm{H}/\Lambda$ by a factor of ~2, as well as **t/p**

- In thermal model, particle yield ratio is independent of volume. $^{3}_{\Lambda}\mathrm{H}/\Lambda$ yield ratio is dependent of strangeness correlation length

Might suggest $^{3}_{\Lambda}\mathrm{H}$ and t yields are not in equilibrium and fixed at chemical freeze-out simultaneously with other hadrons

STAR, PRL 130 (2023) 202301
STAR, arXiv: 2311.11020
T. Reichert, et al, PRC 107 (2023) 014912

Energy dependence of S_3

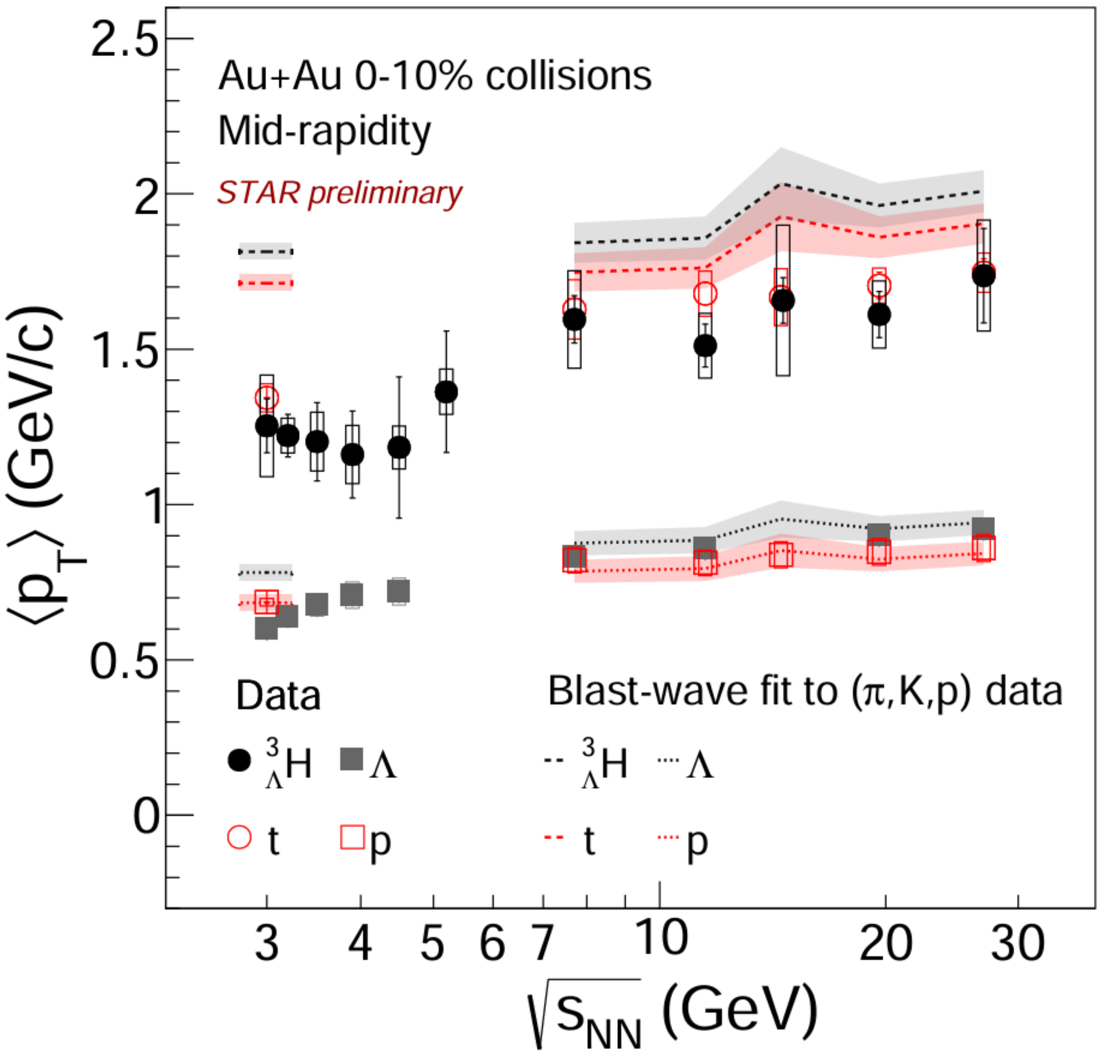


- A prominent enhancement of S_3 was proposed as a probe for deconfinement
- Data shows a mild increasing trend from $\sqrt{S_{NN}} = 3.0$ GeV to 2.76 TeV
- For coalescence(UrQMD) models, the energy dependence is sensitive to the **source radius** (Δr)
  - Data favor larger radius
- Thermal-FIST, which includes **feed-down** from unstable nuclei to stable p, ^3_2He , describes the S_3 data better
  - Possible feed-down should be accounted

STAR, Science 328 (2010) 58
STAR, arXiv: 2310.12674
ALICE, PLB 754 (2016) 360
E864, PRC 70 (2004) 024902

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

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



- Similar $\langle p_T \rangle$ for ${}^3_\Lambda\mathrm{H}$ and t
- Hint of ${}^3_\Lambda H$ and t $\langle p_T \rangle < \langle p_T \rangle^{BW}$ >7.7GeV

Blast-wave expectation calculated using measured kinetic freeze-out parameters from light hadrons (π, K, p)spectra

${}^3_\Lambda\mathrm{H}$ and t might do not follow same collective expansion as light hadrons. Can be interpreted as ${}^3_\Lambda\mathrm{H}$ and t decoupling at different times compared to light hadrons

- Different trend around $\sqrt{S_{NN}} = 4.5$ GeV

  ⟹ Suggest different expansion dynamics?

Summary

- First measurements of ${}^{3}_{\Lambda}\mathrm{H}$ yields vs. energy at high baryon density region presented, consistent with coalescence model

- Suppression of ${}^{3}_{\Lambda}\mathrm{H}$ in 10-40% collisions at low collisions energies observed

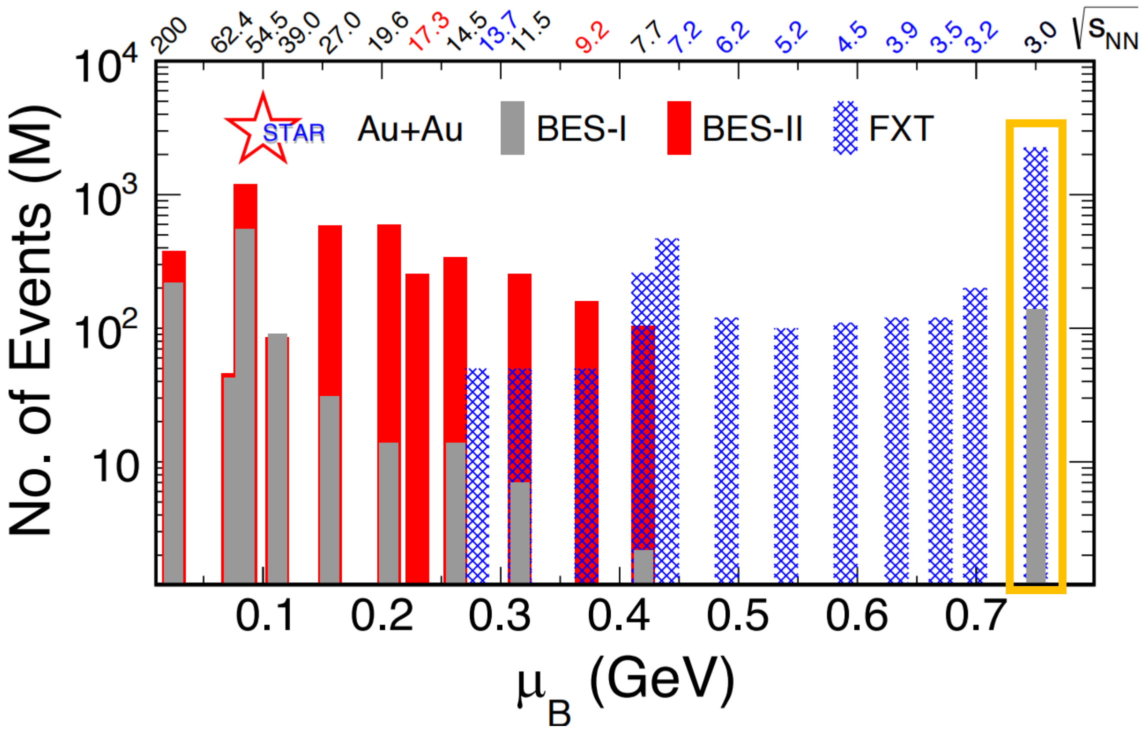
- ${}^{3}_{\Lambda}\mathrm{H}/\Lambda$ ratio vs. energy seems in contradiction to that ${}^{3}_{\Lambda}\mathrm{H}$ freeze out at the same time as light hadrons

- S_3 vs. collision energy favor large ${}^{3}_{\Lambda}\mathrm{H}$ radius

- ${}^{3}_{\Lambda}\mathrm{H}$ $\langle p_T \rangle$ overestimated by Blast-wave fit parameterization from light hadrons

  ⇒ ${}^{3}_{\Lambda}\mathrm{H}$ are likely formed at or decouples from the system at a different time compared to the light hadrons

Outlook



- Huge datasets enable precision hypernuclei measurements
  - **Run 21, Au+Au 3 GeV, ~2 billion events**
  - Run 18, Isobar 200 GeV, ~6 billion events

- Opportunities for heavier hypernuclei: $\boldsymbol{^{4}_{\Lambda}H}$, $\boldsymbol{^{4}_{\Lambda}He}$, $^{5}_{\Lambda}He$, $^{6}_{\Lambda}H$, $^{A}_{\Lambda\Lambda}H$, $^{A}_{\Lambda\Lambda}He$

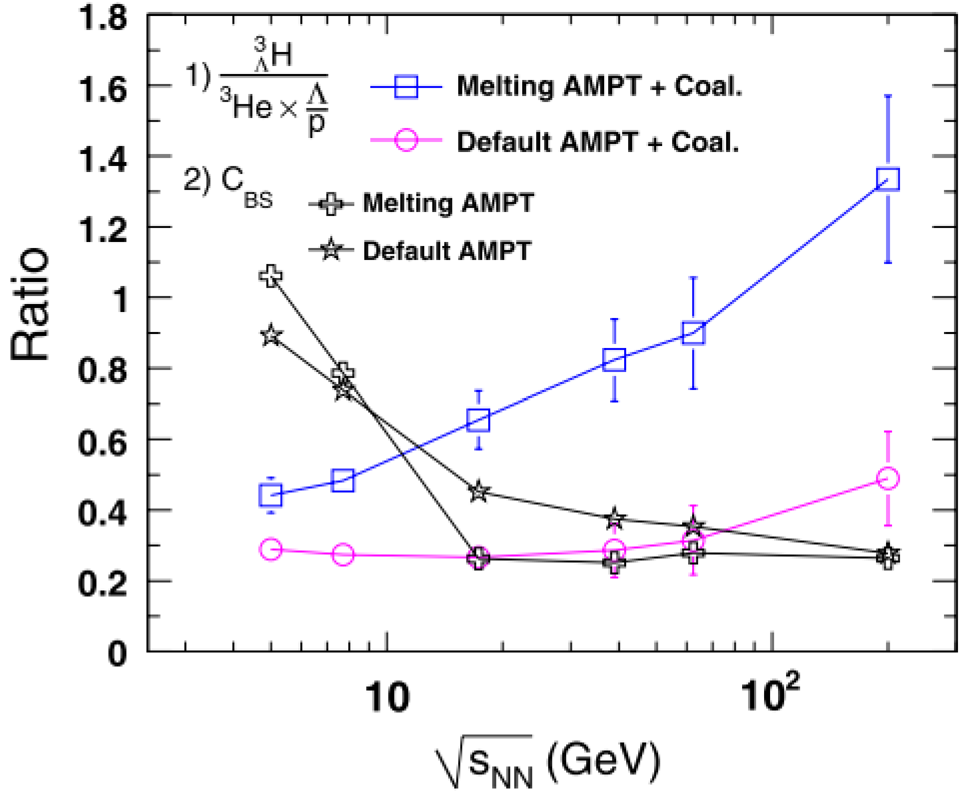
Back up

Introduction: the strangeness population factor S_3

- S_3 may be sensitive to the onset of deconfinen

$$S_3 = \frac{{}^{3}_{\Lambda}\mathrm{H}}{{}^{3}_{2}\mathrm{He} \times \frac{\Lambda}{\mathrm{P}}}$$

  - S_3 maybe enhanced in a system involving partonic interactions
  - Models suggest S_3 is more sensitive to the local baryon-strangeness correlation than the global baryon-strangeness correlation coefficient (C_{BS})

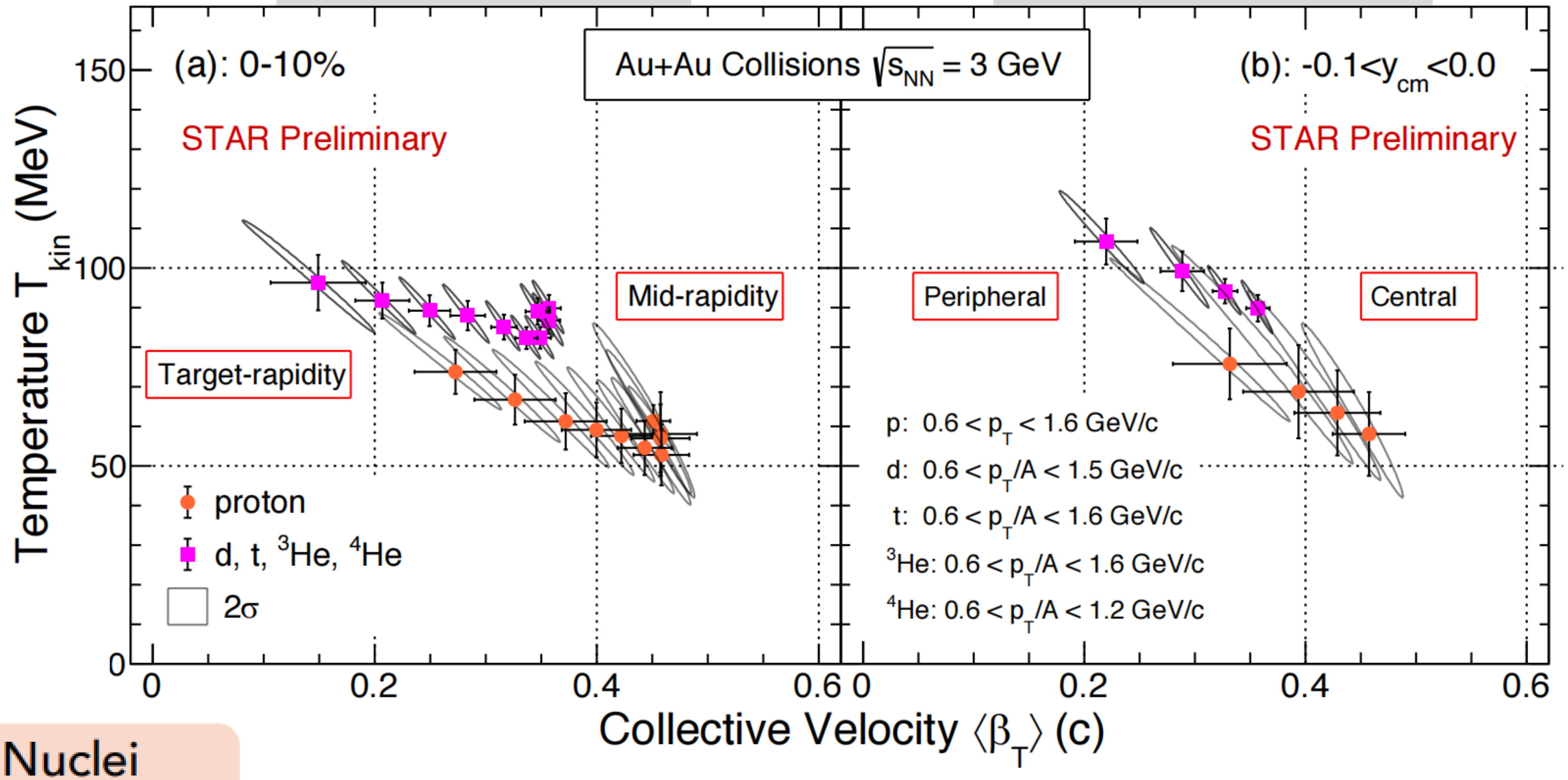


S. Zhang et al. PLB 684 (2010) 224–227

Kinetic Freeze-out Dynamics at 3 GeV

Rapidity Dependence

Centrality Dependence



Light Nuclei freeze out earlier?

J. Adams et al. [STAR Collaboration] Nucl.Phys.A 757 (2005) 102-183

- The kinetic freeze-out parameters (T_{kin} and ⟨β_T⟩) show rapidity and centrality dependence
- The freeze-out parameter (T_{kin}) of the light nuclei is systematically higher than that of the protons

Hui Liu, QM2022 @ Krakow, Poland