Production of Light Nuclei and Hypernuclei in Heavy-Ion Collisions

Guannan Xie (Yue-Hang Leung)

University of Chinese Academy of Sciences (University of Heidelberg)

2026/03/26

The 22nd International Conference on Strangeness in Quark Matter, UCLA

Contents

Light Nuclei & Hypernuclei (What)

- Hypernuclei are nuclei containing at least one hyperon
- Light (hyper)nuclei show strong structural diversity

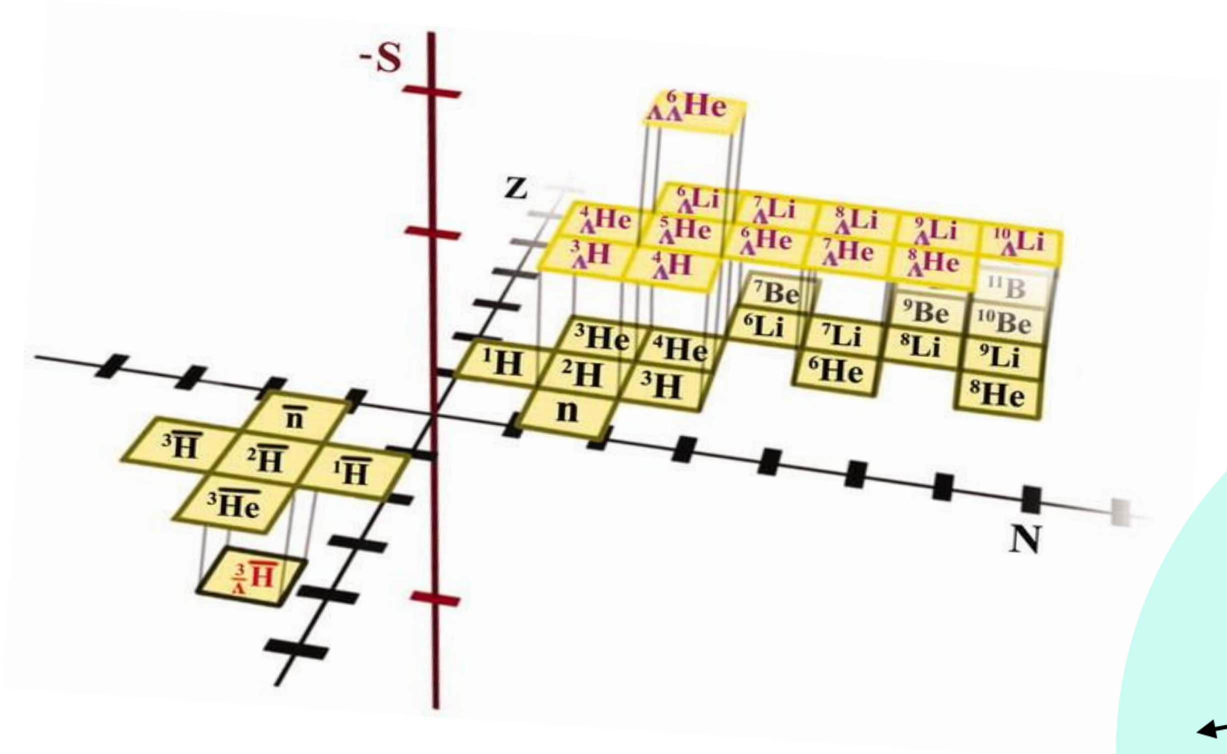


Figure from Science 328 (2010) 58-62

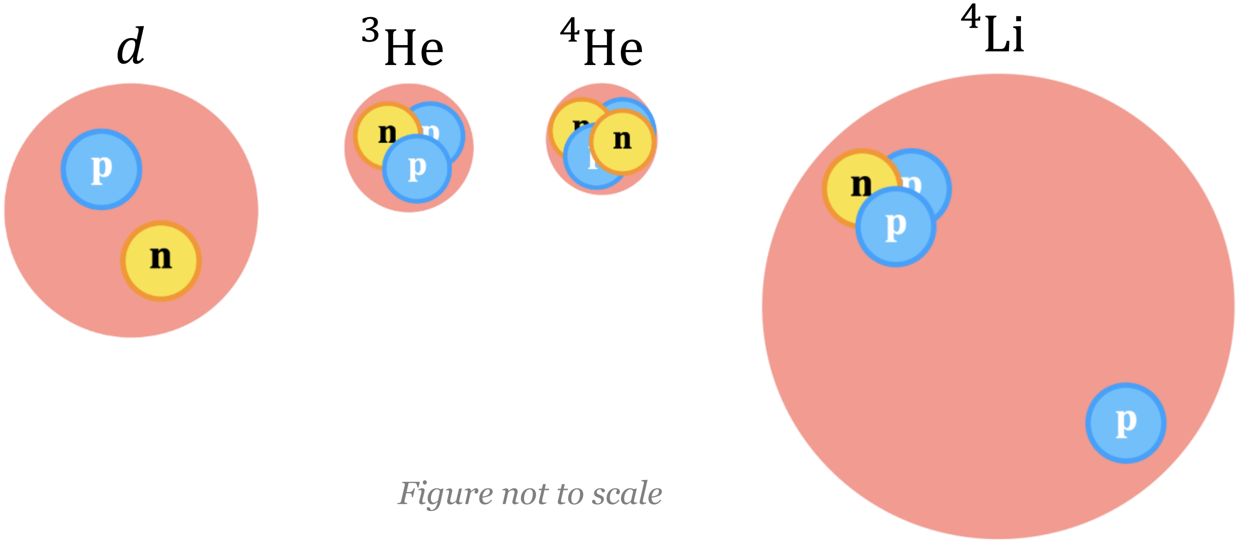
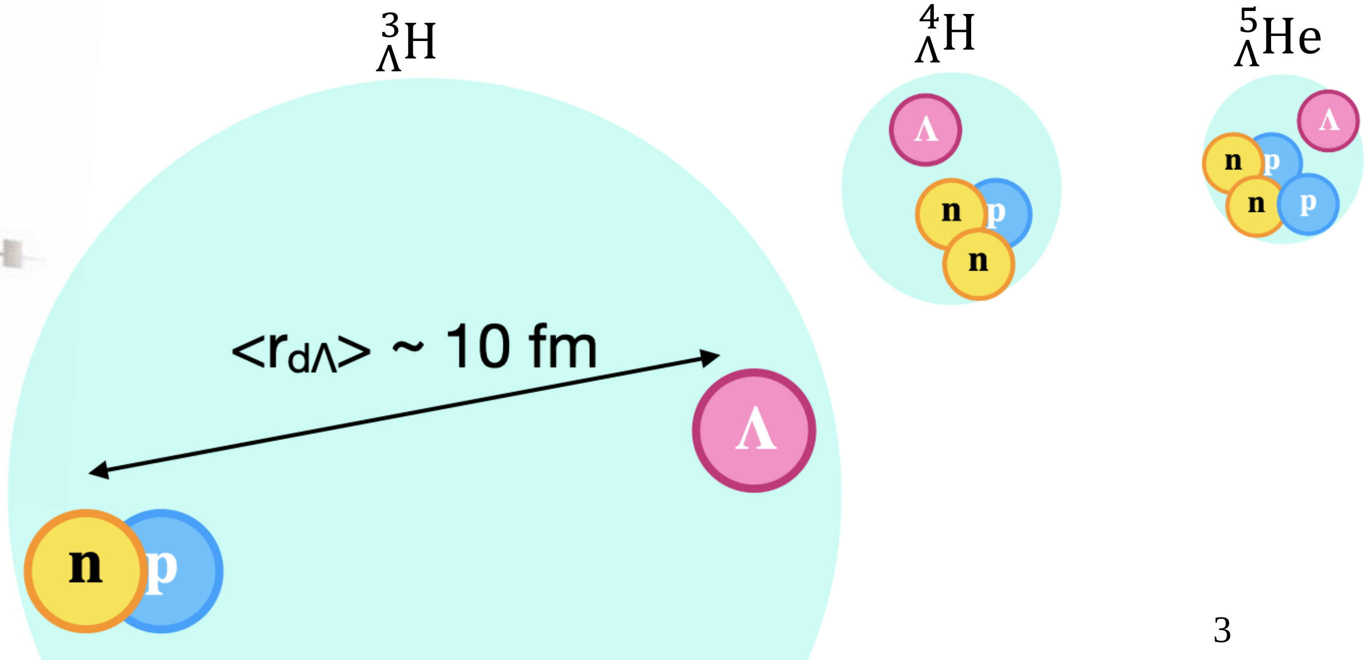


Figure not to scale



Light Nuclei & Hypernuclei (Why)

1. What can (hyper)nuclei production in heavy-ion collisions tell us about the QCD phase diagram and the nuclear equation-of-state?

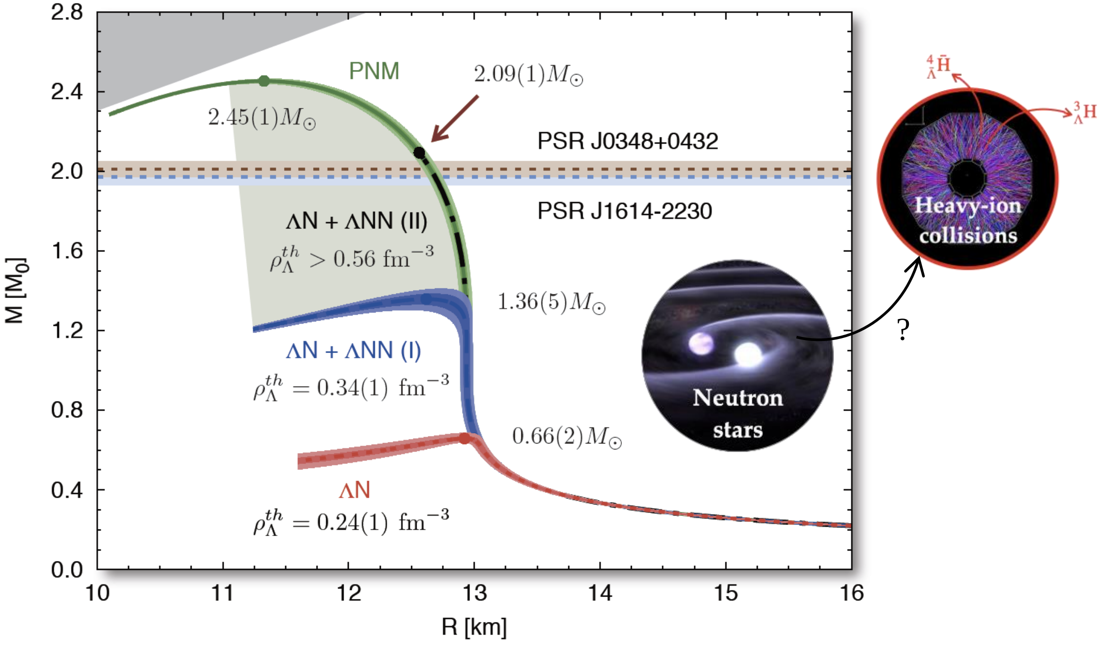
- Sensitive to critical fluctuations and the onset of deconfinement

S. Zhang et al., Phys. Lett. B 684 (2010) 224
K. Sun et al., Phys. Lett. B 781 (2018) 499

$$\frac{t \times p}{d^2} \qquad \frac{{}^{3}_{\Lambda}\mathrm{H}}{{}^{3}\mathrm{He} \times \frac{\Lambda}{p}}$$

2. What is the role of hyperon-nucleon (Y-N, Y-N-N) and hyperon-hyperon (Y-Y) interaction in the equation-of-state of high baryon density matter?

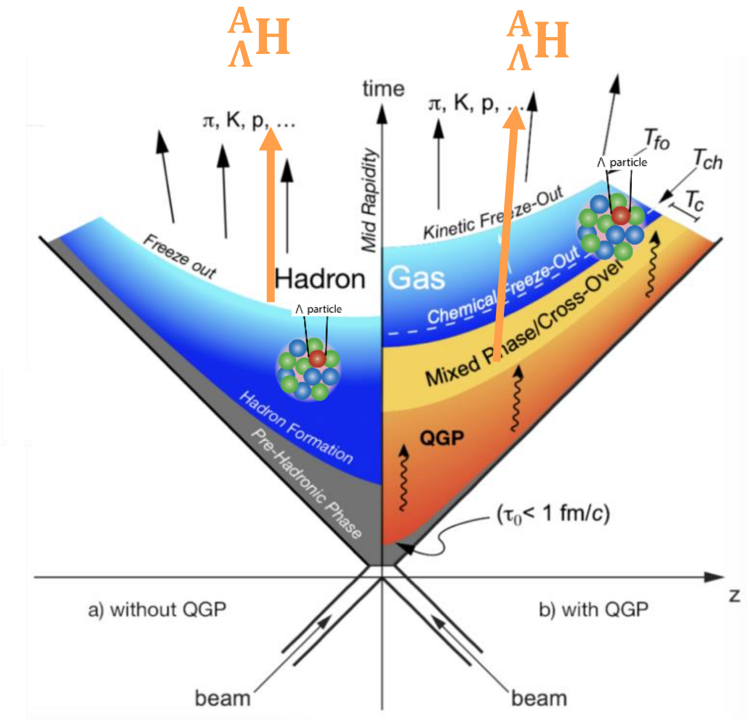
- Hyperon Puzzle: difficulty to reconcile the measured masses of neutron stars with the presence of hyperons in their interiors



D Lonardoni et al., Phys. Rev. Lett. 114, 092301 (2015)

Light Nuclei & Hypernuclei (How)

1. When and how are (hyper)nuclei formed?



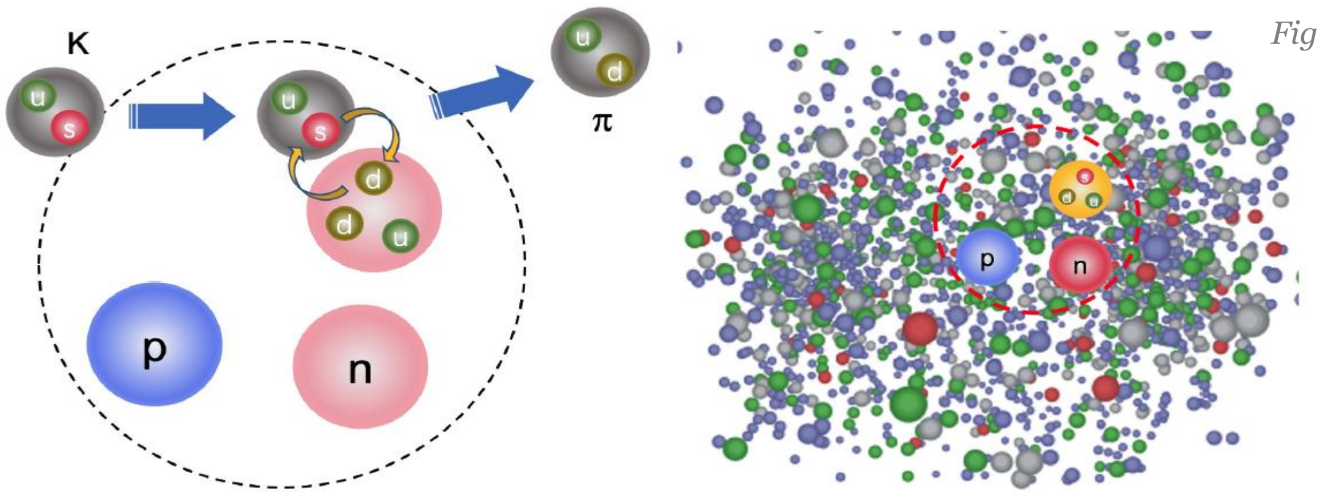


Fig. from Yifei Zhang

- Observables related to nuclei production:
  p_T spectra, yields, flow, **correlation functions**

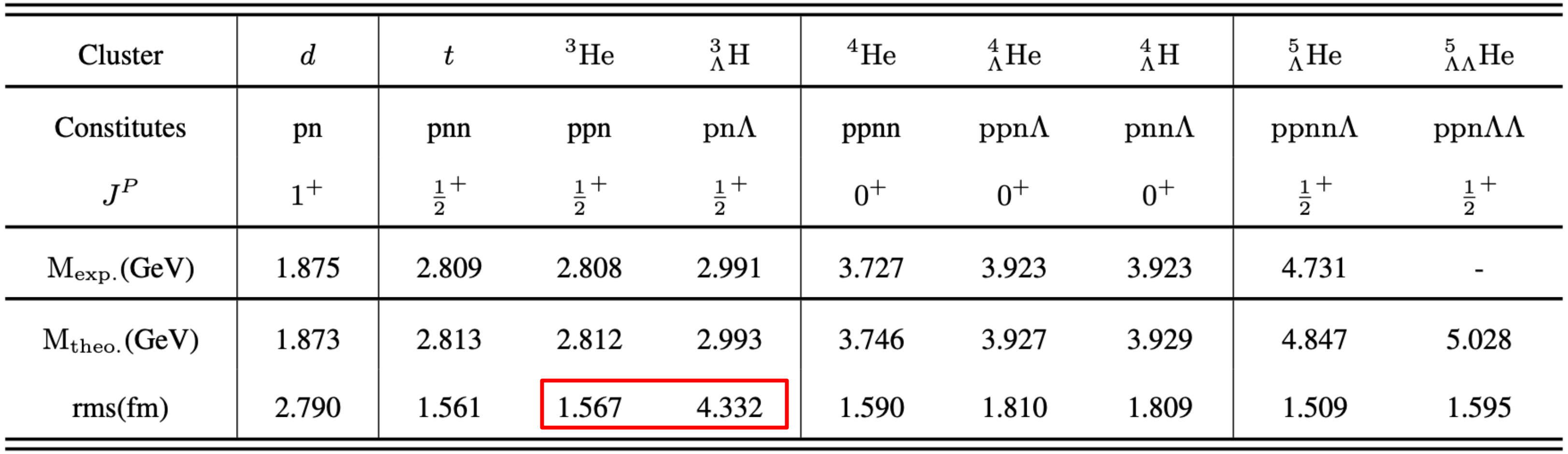
Light Nuclei & Hypernuclei (How)

2. Is the production yield of (hyper)nuclei sensitive to their internal structure?

- Observables related to hypernuclear structure: Binding energy, lifetime, … **(yield?)**
- Compare production yields of (hyper)nuclei with large and small radii, e.g.:

1. ${}^{3}_{\Lambda}\mathrm{H}$ vs ${}^{3}\mathrm{He}$
2. ${}^{4}\mathrm{Li}$ vs ${}^{4}\mathrm{He}$

Jiaxing Zhao, 24/03 afternoon



Cluster	d	t	${}^{3}\mathrm{He}$	${}^{3}_{\Lambda}\mathrm{H}$	${}^{4}\mathrm{He}$	${}^{4}_{\Lambda}\mathrm{He}$	${}^{4}_{\Lambda}\mathrm{H}$	${}^{5}_{\Lambda}\mathrm{He}$	${}^{5}_{\Lambda\Lambda}\mathrm{He}$
Constitutes	pn	pnn	ppn	pnΛ	ppnn	ppnΛ	pnnΛ	ppnnΛ	ppnΛΛ
J^P	1^+	$\frac{1}{2}^+$	$\frac{1}{2}^+$	$\frac{1}{2}^+$	0^+	0^+	0^+	$\frac{1}{2}^+$	$\frac{1}{2}^+$
$\mathrm{M}_{\mathrm{exp.}}$(GeV)	1.875	2.809	2.808	2.991	3.727	3.923	3.923	4.731	-
$\mathrm{M}_{\mathrm{theo.}}$(GeV)	1.873	2.813	2.812	2.993	3.746	3.927	3.929	4.847	5.028
rms(fm)	2.790	1.561	1.567	4.332	1.590	1.810	1.809	1.509	1.595

Jiaxing Zhao et al., Phys.Rev.C 112 (2025) 6, 064902

Clusterization mechanism

Jiaxing Zhao, 24/03 afternoon

- **Statistical hadronization model**
  - Nuclei are in thermal equilibrium on the chemical freeze-out surface
  - **Yields not related to nuclear structure**

A. Andronic, et al. Phys.Lett.B 697 (2011) 203-207
J. Steinheimer, et al. Phys.Lett.B 714 (2012) 85-91

- **Coalescence model**
  - Nuclei are formed from nucleons (hyperons) that are close together in phase space.
  - In the Wigner Function formalism, formation probability given by overlap b/w:
    - Nucleon distributions at freeze-out
    - **Nuclear wave function**

J. I. Kapusta Phys.Rev.C 21 (1980) 1301
R. Scheibl and U. Heinz, Phys. Rev. C 59, 1585 (1999)
K. Sun and C. Ko, Phys. Rev. C 103, 064909 (2021)
F. Bellini, et al. Phys. Rev. C 103, 014907 (2021)

- **“Potential” model**
  - Nuclei are identified during the dynamical evolution of the system by the Minimum Spanning Tree (MST and aMST)

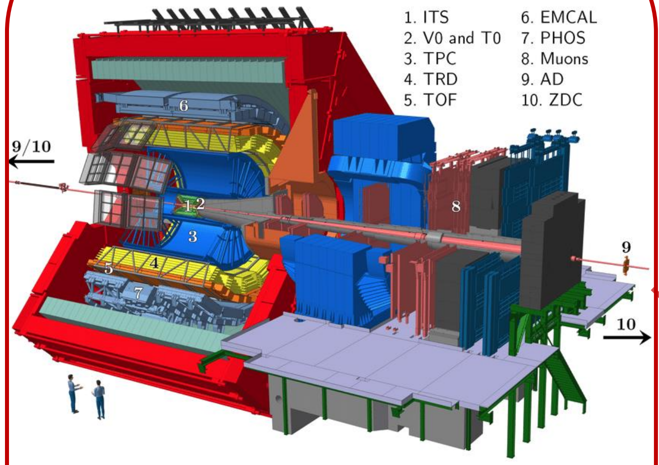
J. Aichelin, Phys. Rept. 202, 233 (1991)
J. Aichelin, et al, Phys. Rev. C 101, 044905 (2020) (PHQMD)

- **Kinetic model**
  - Nuclei are formed dynamically via reactions e.g.: $NNN \rightarrow dN$; $NN\pi \rightarrow d\pi$

D. Oliinychenko, et al. Phys.Lett.B 714 (2012) 85-91 (SMASH)
G. Coci et al. Phys. Rev. C 108, 014902 (2023) (PHQMD)

Experimental Facilities

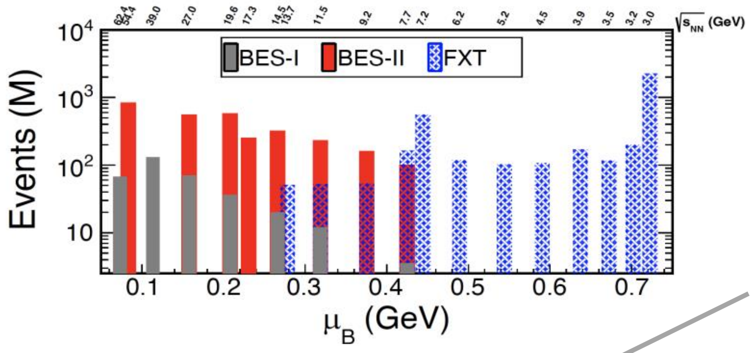
ALICE LHC, CERN

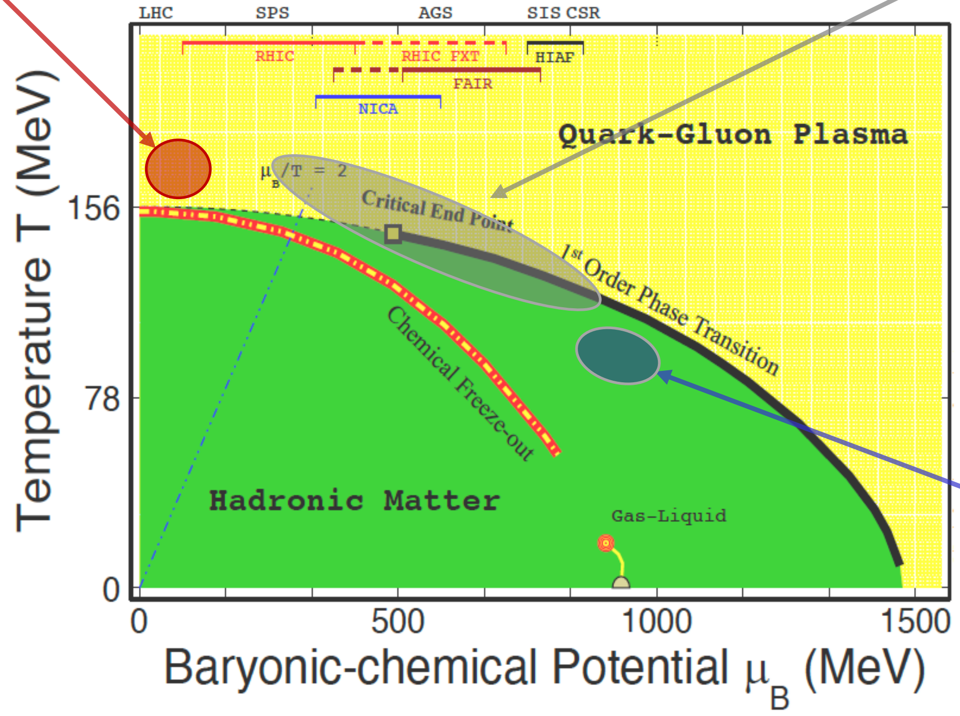


- Pb+Pb, p+p, p+Pb, …
- $\sqrt{s_{NN}}$ = 2.76 – 5.02 TeV (Pb+Pb)

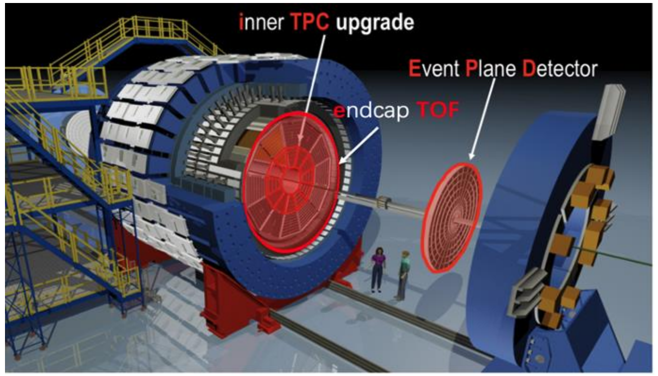
- Advantage at low $\sqrt{s_{NN}}$: high $\mu_B \rightarrow$ enhanced yields
- Advantage at high $\sqrt{s_{NN}}$: anti-particles

RHIC BES-II, $3 < \sqrt{s_{NN}} < 200$ GeV



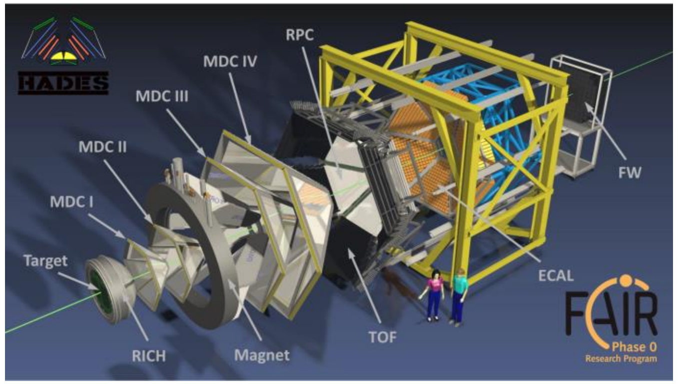


STAR RHIC, BNL



- Au+Au,p+p, p+Au, …
- $\sqrt{s_{NN}}$ = 3.0 – 200 GeV (Au+Au)

HADES SIS18, GSI

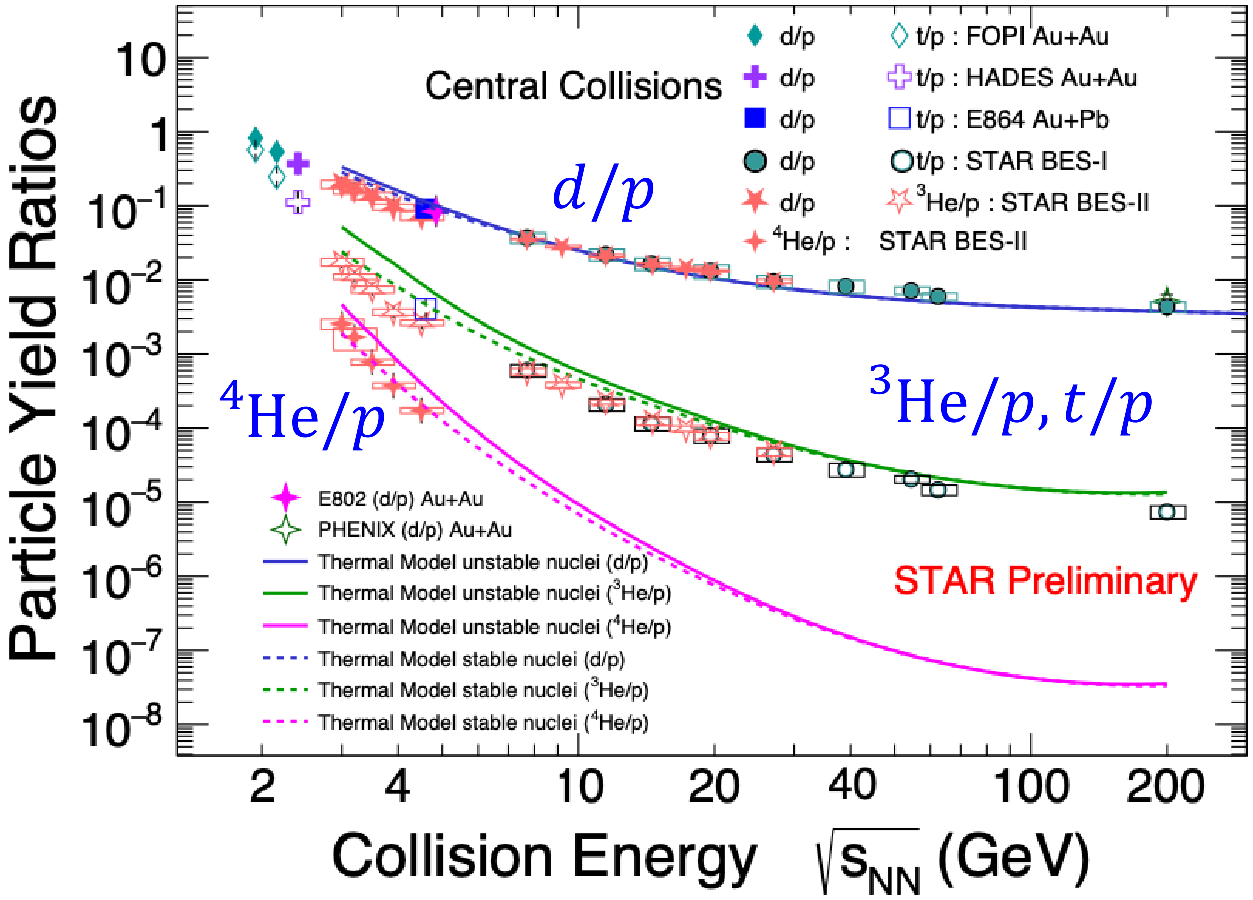


- Au+Au, Ag+Ag, …
- $\sqrt{s_{NN}}$ = 2.55 GeV (Ag+Ag)

Nuclei Yield Ratios from RHIC-BES

Y. Jin, STAR, QM2025

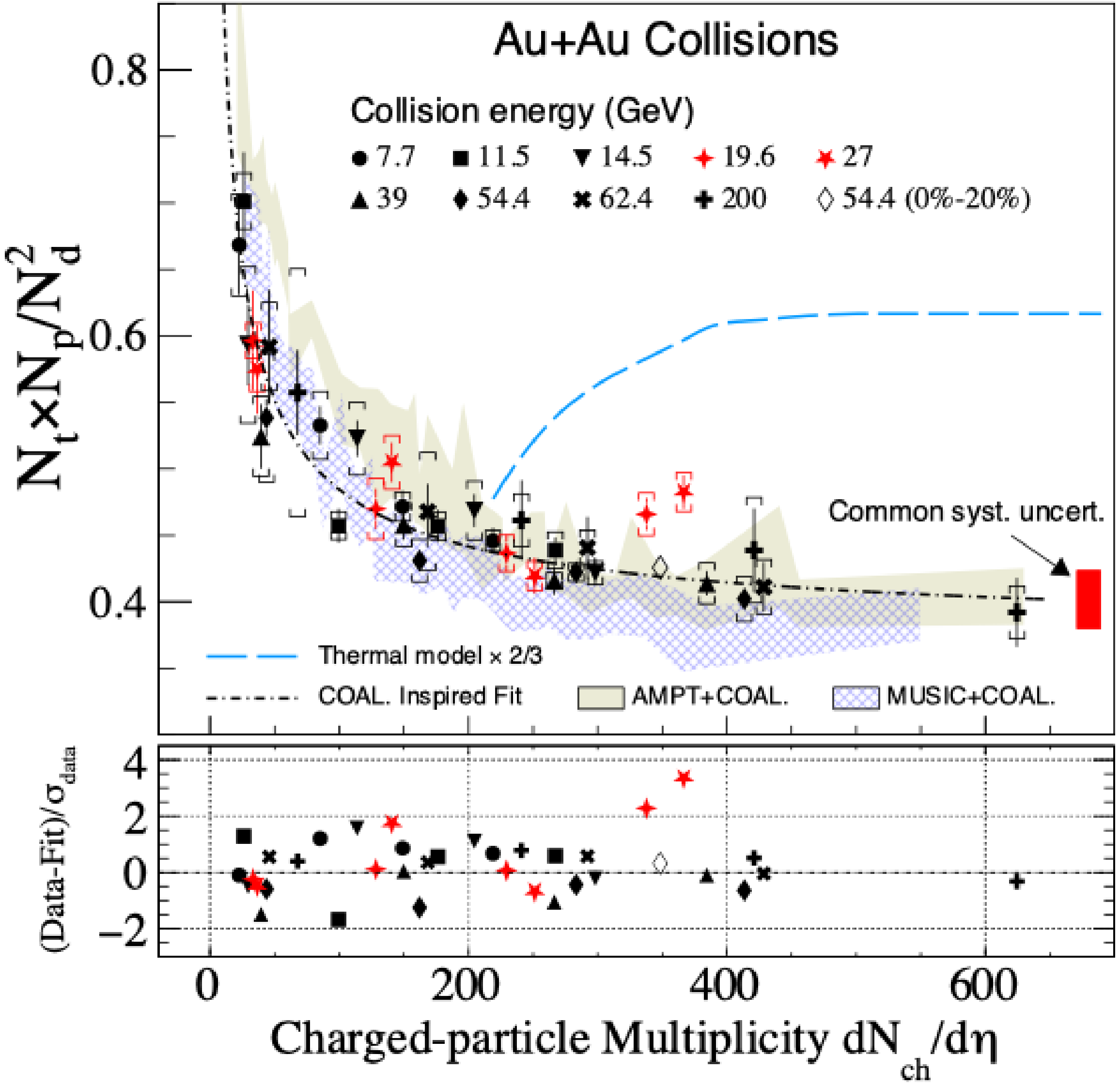
Thermal-FIST: V. Vovchenko, Comput. Phys. Commun. 244, 295 (2019)



- d/p fairly well described by thermal model
- $^3\mathrm{He}/p, t/p$ overestimated by approx. factor of 2
- For $^4\mathrm{He}/p$, the results depend on whether we consider unstable nuclei feed-down decays

Compound Ratio (tp/d^2)

STAR, Phys. Rev. Lett. 130 (2023) 202301
K. Sun et al., Phys. Lett. B 781 (2018) 499

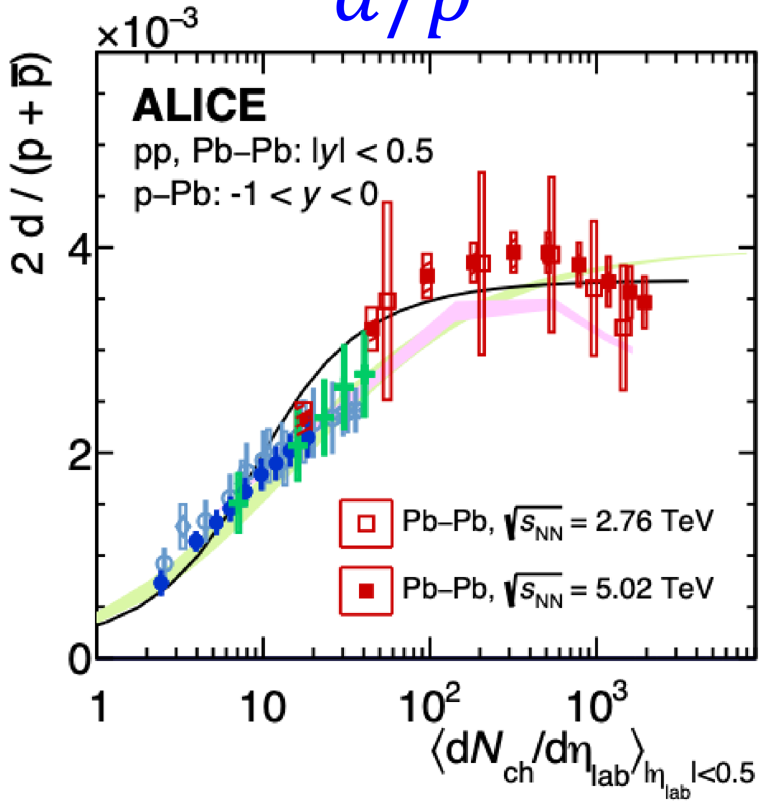


- Data follows a common decreasing trend
- Thermal model predicts an increasing trend and is inconsistent with data
- Compound ratio can be described by coalescence calculations

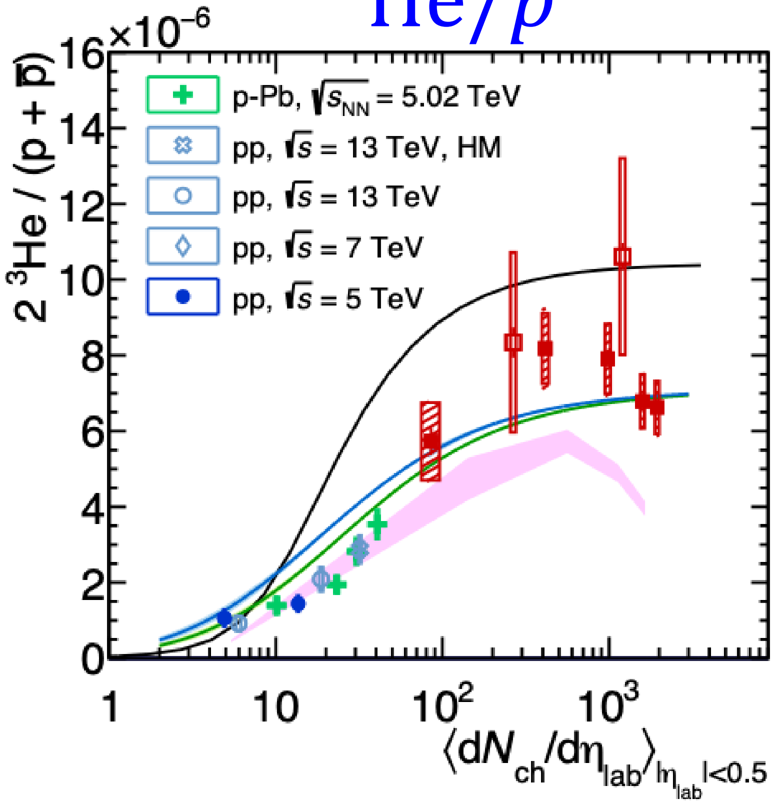
Nuclei Ratios from LHC

ALICE, Phys. Lett. B 858 (2024) 138943

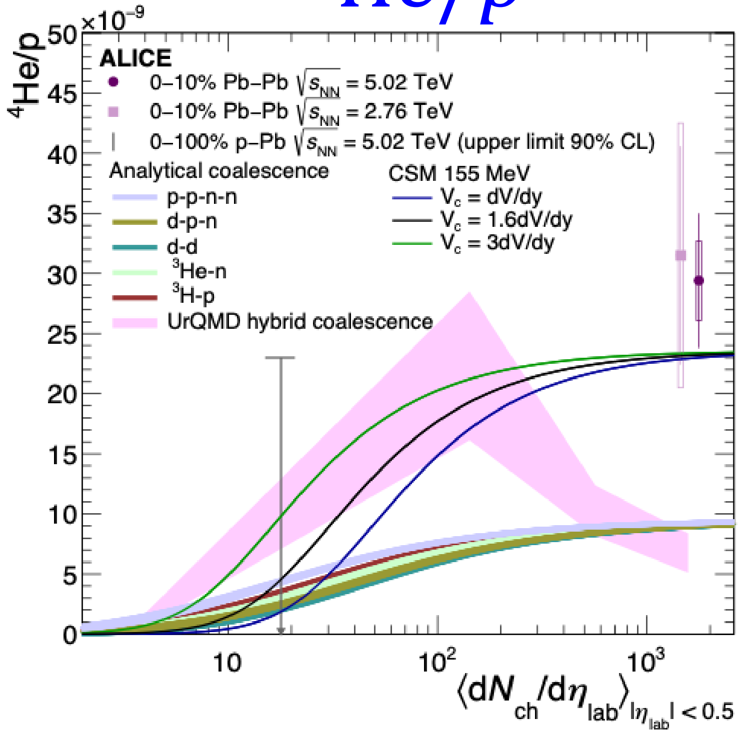
d/p



$^{3}\mathrm{He}/p$



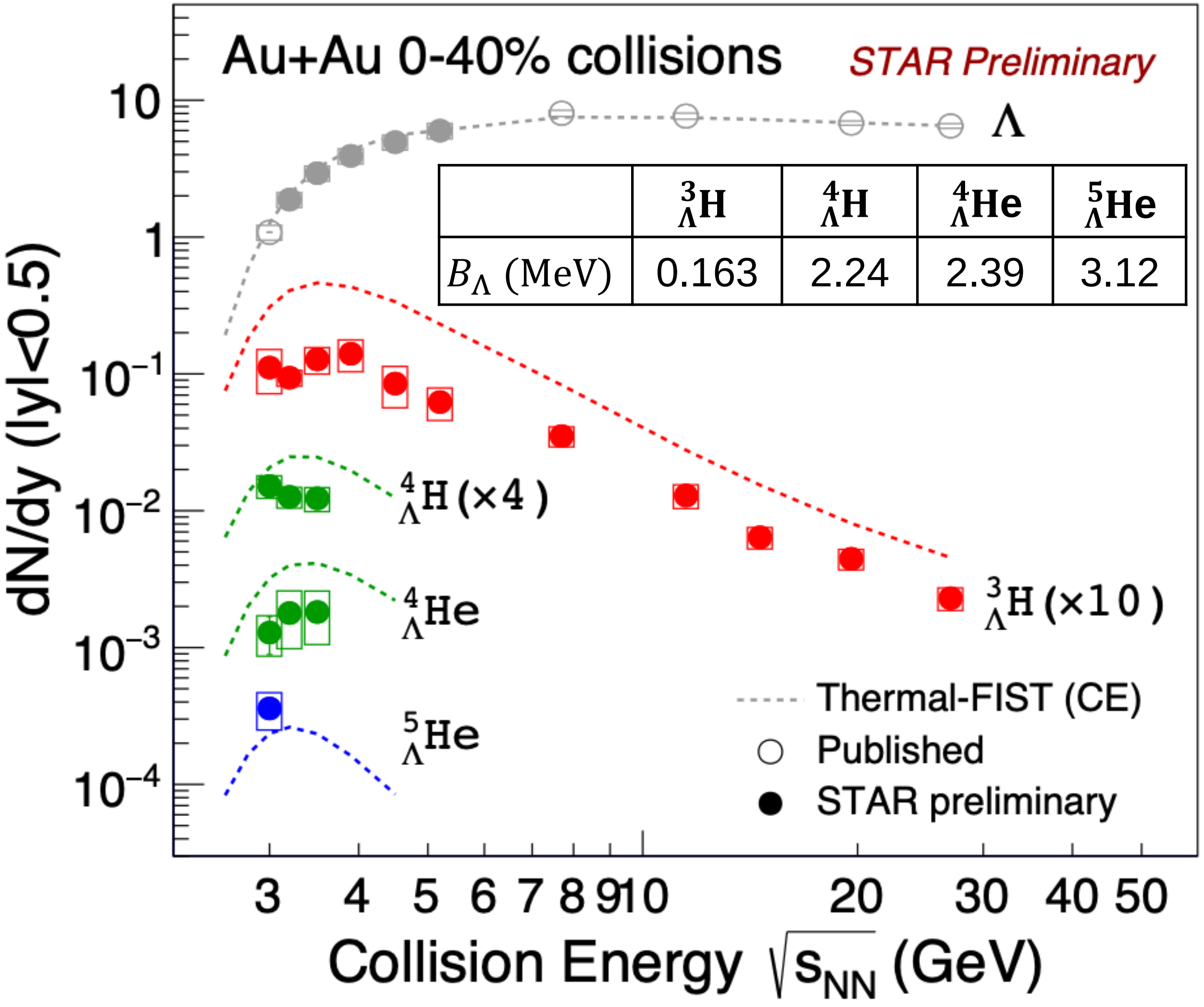
$^{4}\mathrm{He}/p$



- Thermal: $A = 2{,}4$: fairly well described; A=3: strongly overpredicted
- Coalescence: $A = 2{,}3$: fairly well described; A=4: underpredicted
- Similar trends in data–model comparisons across RHIC and LHC

For nuclei with A < 4, coalescence models provide a good description, while thermal models do not consistently describe all species

Hypernuclei Excitation Functions in Au+Au collisions



	$^{3}_{\Lambda}$H	$^{4}_{\Lambda}$H	$^{4}_{\Lambda}$He	$^{5}_{\Lambda}$He
B_{Λ} (MeV)	0.163	2.24	2.39	3.12

STAR, Phys. Rev. Lett 128, 202301 (2022)

- $^{3}_{\Lambda}$H yields peak at $\sqrt{s_{NN}}$= 3-4 GeV then decrease toward higher energies
  - Increasing baryon density at lower energies ↑
  - Stronger strangeness canonical suppression at low energies ↓

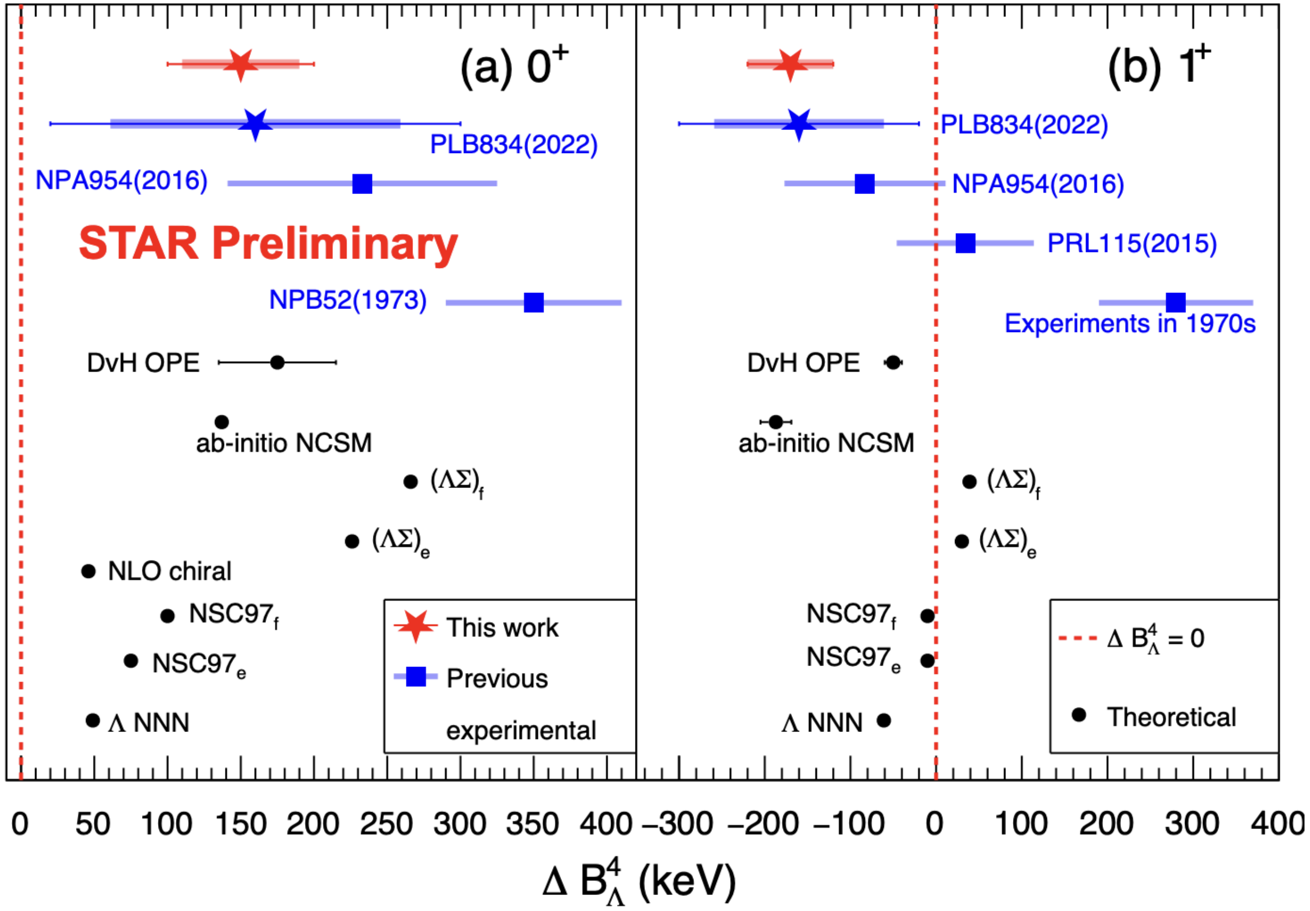
- Similar to ^{3}He, $^{3}_{\Lambda}$H is overestimated by thermal model across all energies
- As the mass number increases, the discrepancy with the thermal model decreases

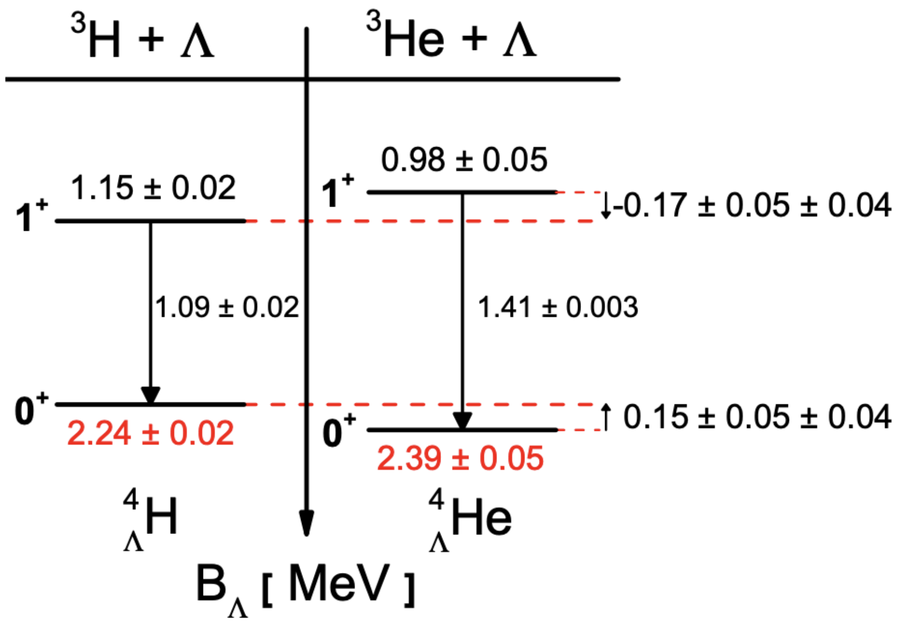
May indicate larger survival probability for more tightly bound hypernuclei

- Need dynamical models coupling formation and dissociation of (hyper)nuclei

Aside: Charge Symmetry Breaking in A = 4 hypernuclei

Tianhao Shao, 24/03 afternoon





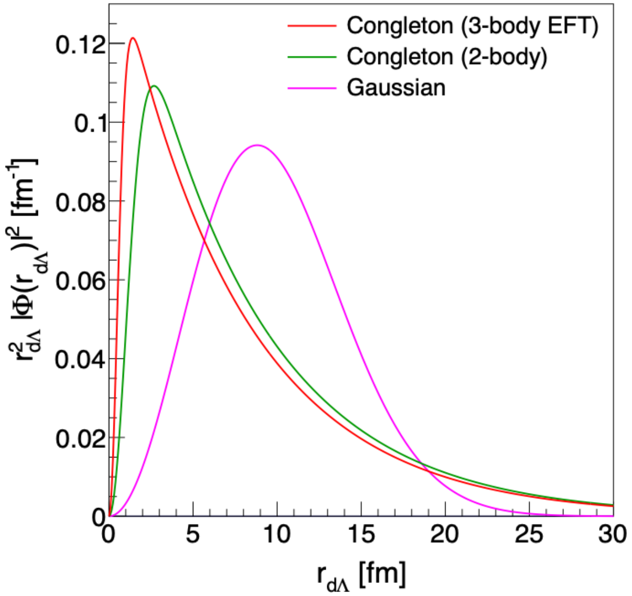
Precise constraints on YN and YNN interactions

- Precise measurement of $^4_\Lambda$H and $^4_\Lambda$He ground state binding energies
- Charge Symmetry Breaking is comparable in magnitude but opposite in sign for ground and excited states
- Consistent with ab-initio no-core shell model calculation

Strangeness Population Factor S_3 vs. $dN_{ch}/d\eta$

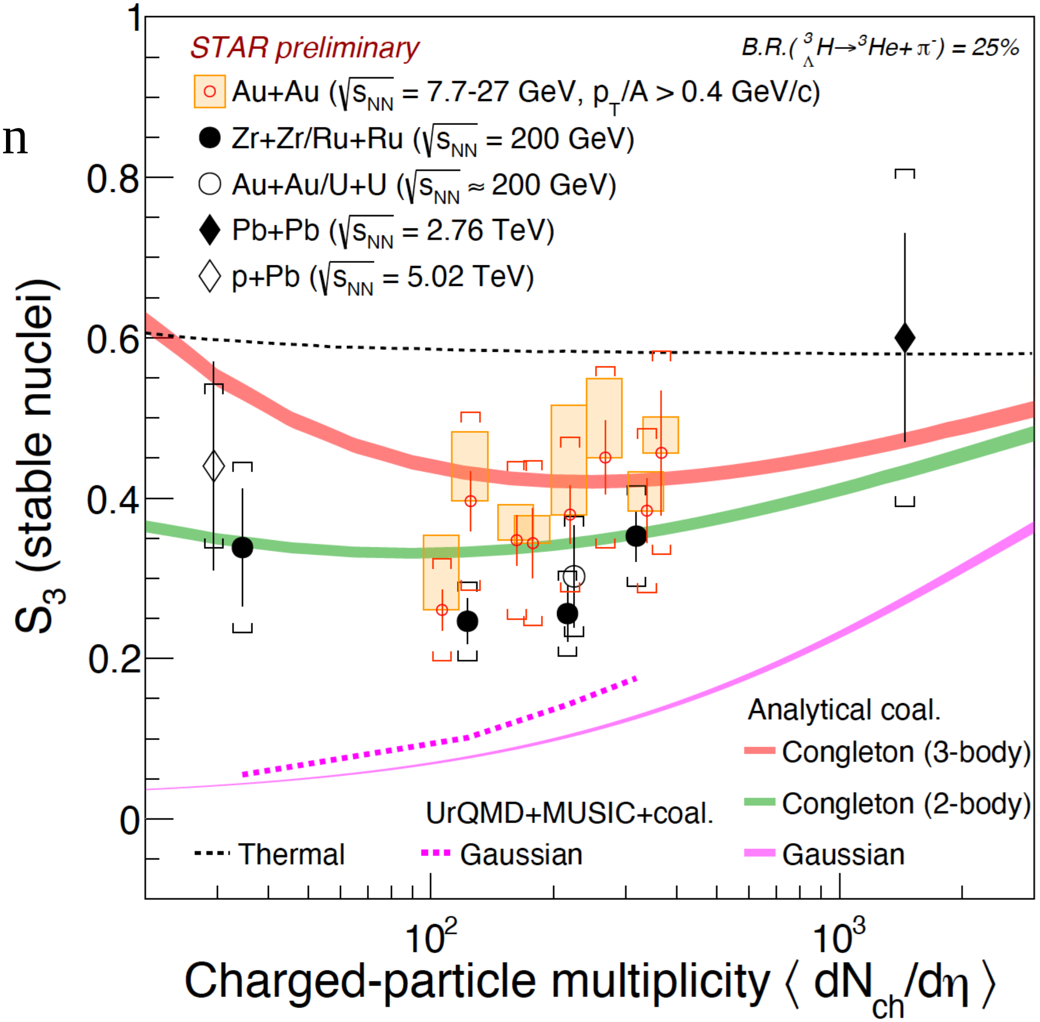
$$S_3 = \frac{{}^{3}_{\Lambda}\mathrm{H}}{{}^{3}\mathrm{He} \times \frac{\Lambda}{p}}$$

removes the difference of Λ and proton density
→ direct comparison b/w ${}^{3}_{\Lambda}$H and ^{3}He production



	${}^{3}_{\Lambda}$H	^{3}He
Mass (GeV)	2.991	2.809
rms (fm)	4.332	1.567

- $S_3 < 1$ → suppression of ${}^{3}_{\Lambda}$H relative to ^{3}He due to wider wave function in coalescence
- Coalescence using Gaussian wave function underestimates the data
- Coalescence using Congleton wave function describes across different energies/systems



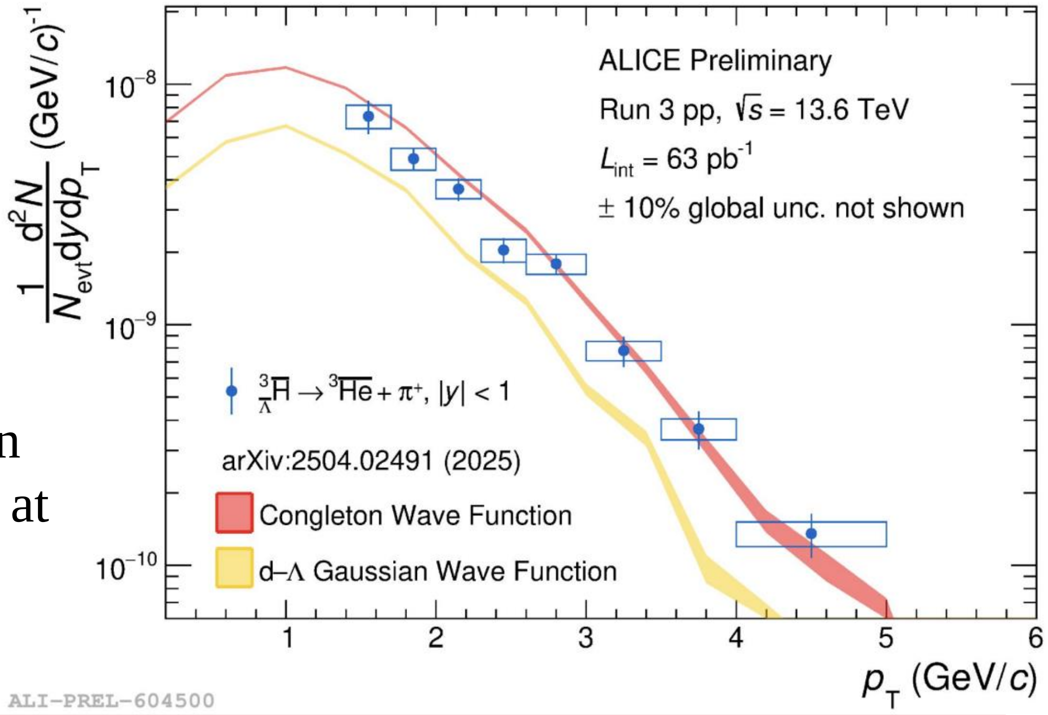
F. Bellini et al., Phys. Rev. C 103 (2021) 1, 014907
YHL et al., Phys.Rev.C 113 (2026) 3, 034912
K. Sun et al., PLB 820(2021)136571
V .Vovchenko et al., Phys. Let. B 809 (2020) 135746
ALICE, Phys. Rev. Lett. 128 (2022) 252003
ALICE, Phys. Lett. B 754 (2016) 360

Strangeness Population Factor S_3 vs. $dN_{ch}/d\eta$

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

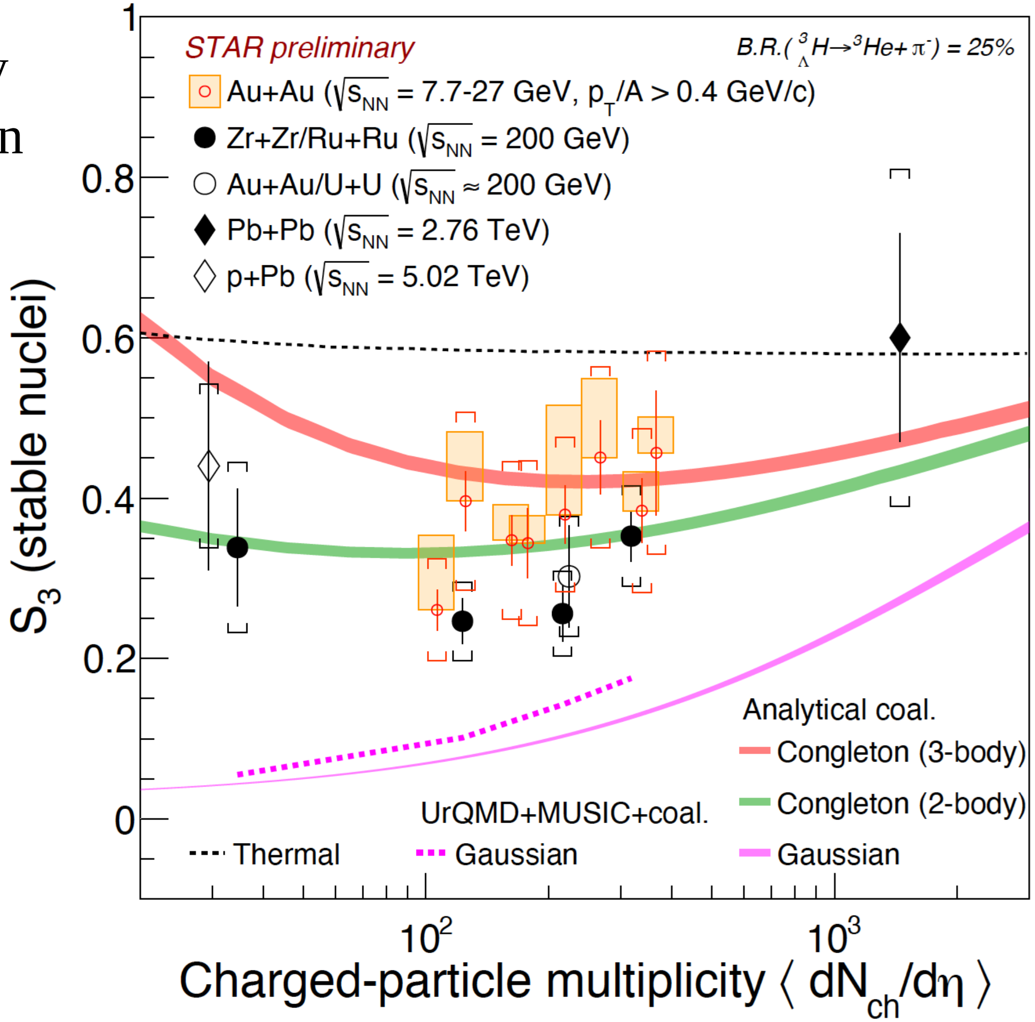
removes the difference of Λ and nucleon density
→ direct comparison b/w $^{3}_{\Lambda}$H and ^{3}He production

ALICE, QM2025



- Similar observations in p+p collisions at 13.6 TeV

S_3 provides access to the short distance behavior of the $^{3}_{\Lambda}$H wave function

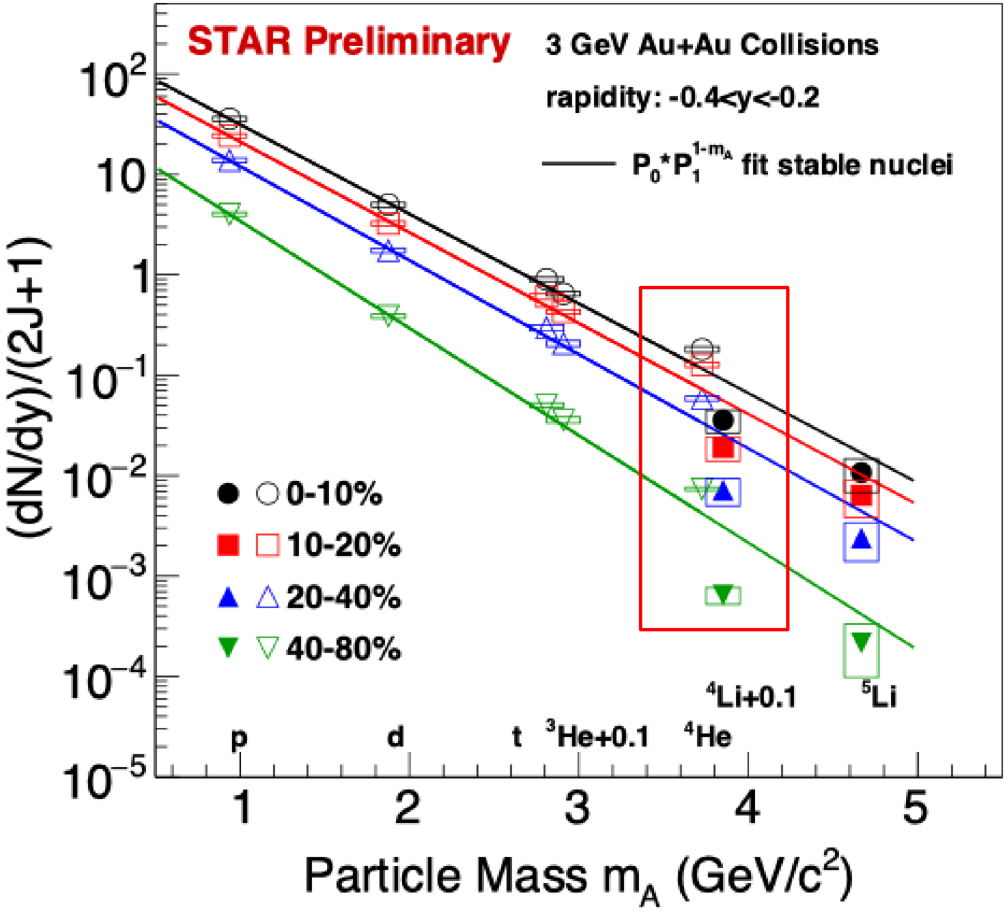


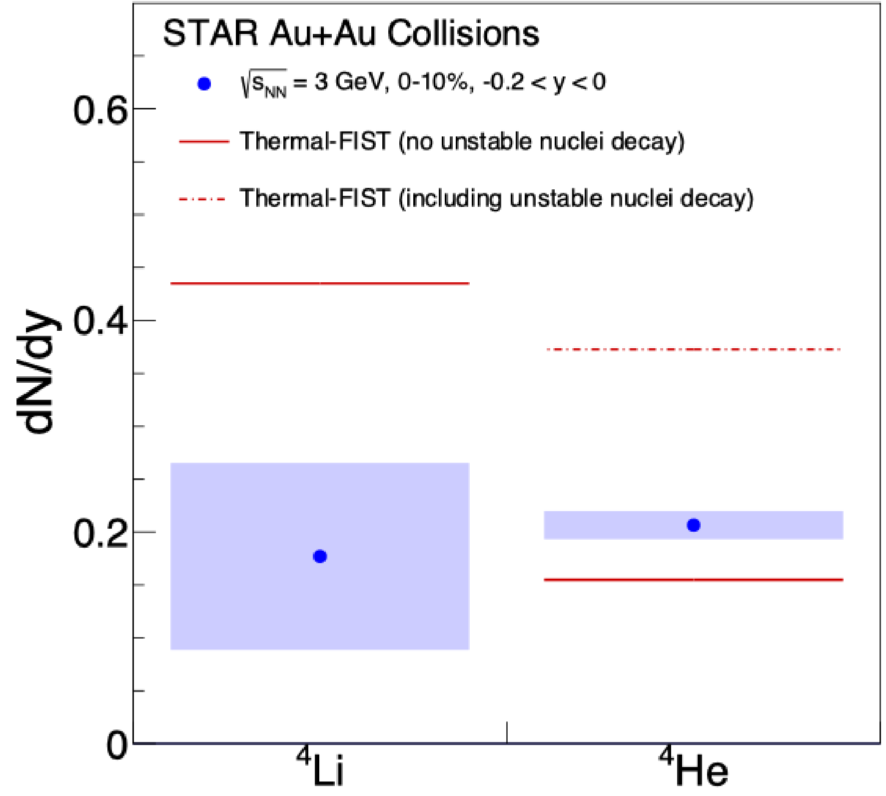
F. Bellini et al., Phys. Rev. C 103 (2021) 1, 014907
YHL et al., Phys.Rev.C 113 (2026) 3, 034912
K. Sun et al., PLB 820(2021)136571
V .Vovchenko et al., Phys. Let. B 809 (2020) 135746
ALICE, Phys. Rev. Lett. 128 (2022) 252003
ALICE, Phys. Lett. B 754 (2016) 360

^{4}Li & ^{5}Li yields in $\sqrt{s_{NN}}$ = 3 GeV Au+Au collisions

Chenlu Hu, Junlin Wu, 24/03 afternoon

Fig. from STAR preliminary + STAR, Phys. Rev. C 110 (2024) 54911





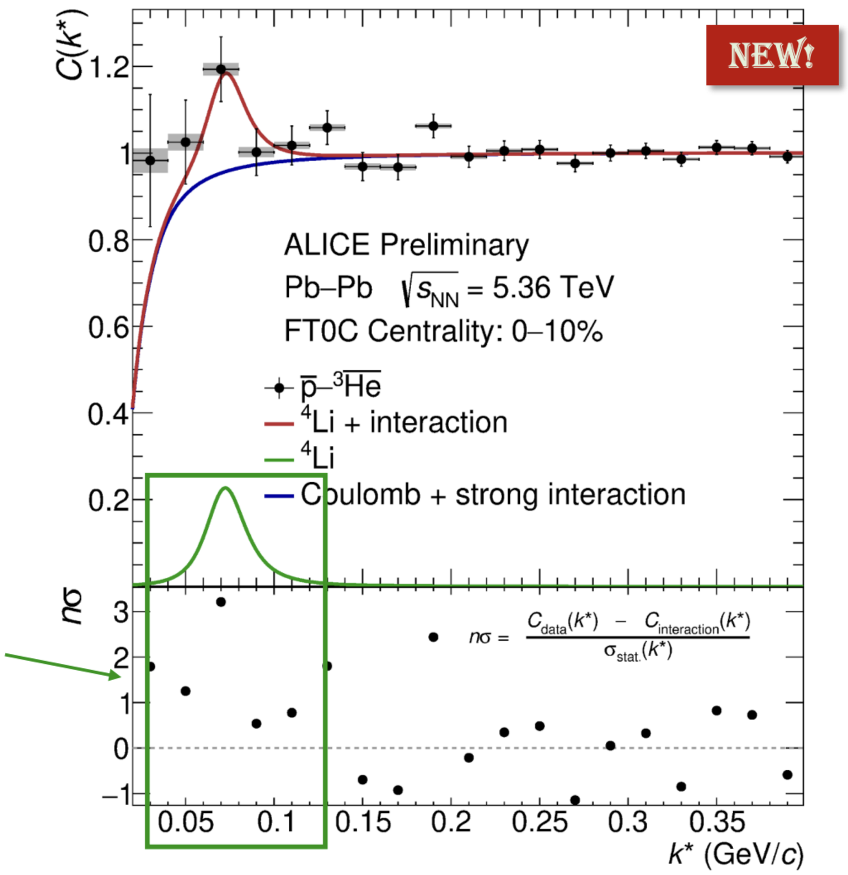
	^{4}Li	^{4}He
Mass (GeV)	3.749	3.727
rms (fm)	?	1.590

- Yield of ^{4}Li /(2J+1) is significantly lower than that of ^{4}He
- Thermal model overestimates ^{4}Li yield
- Thermal model (including unstable nuclei feed-down) overestimates ^{4}He yield

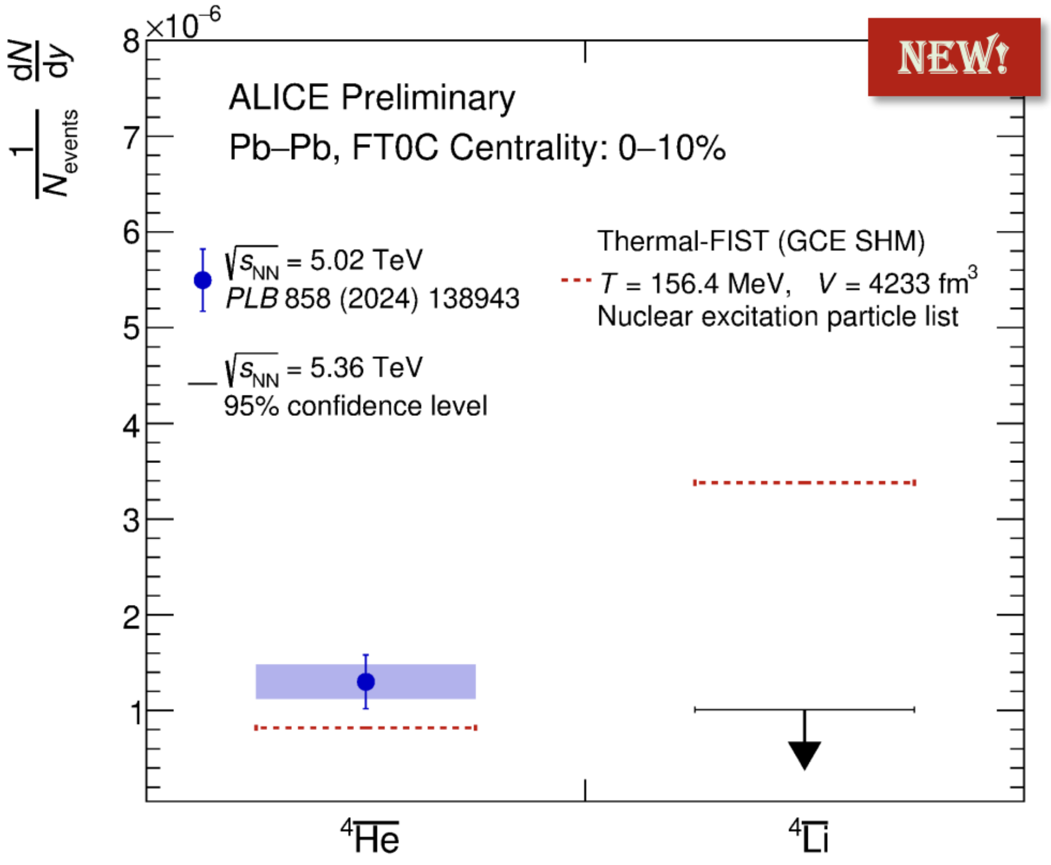
Search for $^{4}\overline{\mathrm{Li}}$ in Pb+Pb collisions at 5.36 TeV

Giorgio Lucia, 24/03 afternoon

Significance: 2.1σ



ALI-PREL-621440

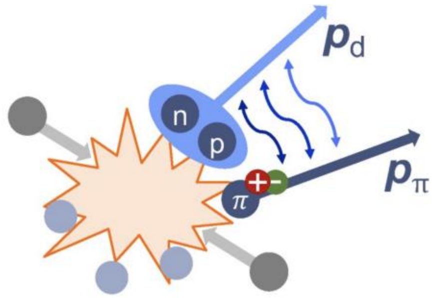


- Search for $^{4}\overline{\mathrm{Li}}$ in Pb+Pb at $\sqrt{s_{NN}} = 5.36$ TeV
- Upper limit on $^{4}\overline{\mathrm{Li}}$ yield obtained, significantly below SHM prediction

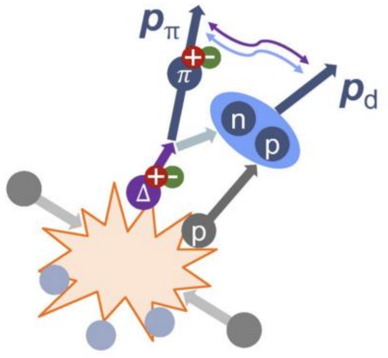
^{4}Li suppressed relative to ^{4}He , possibly reflecting its resonant nature and extended spatial structure

Studying deuteron production via femtoscopy

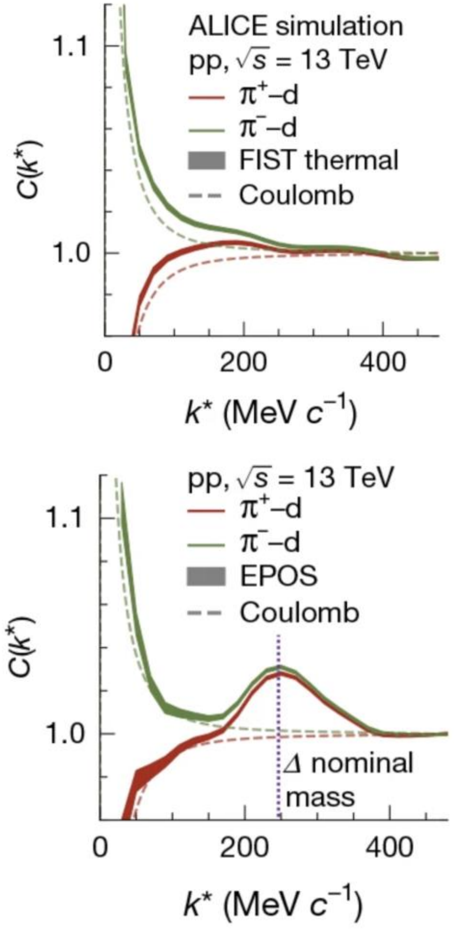
Luca Barioglio, 24/03 afternoon



1. Prompt production



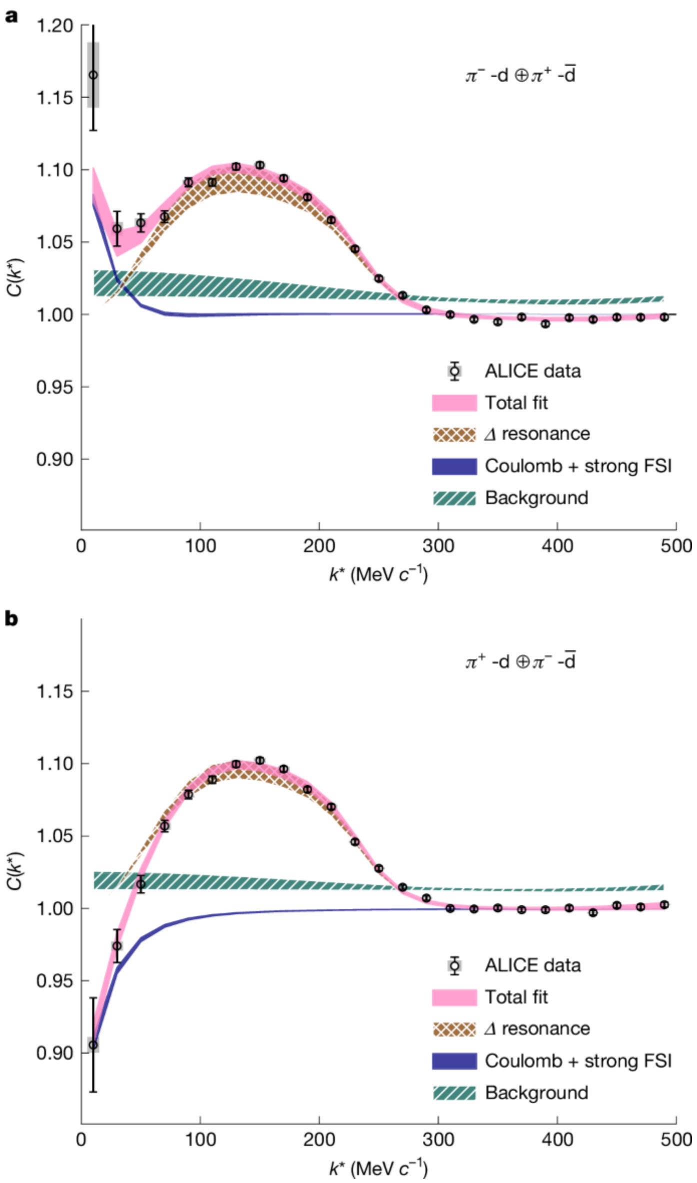
2. Coalescence



ALICE, Nature 648 (2025) 8093, 306-311

- The correlation function of π-d can provide information about deuteron production

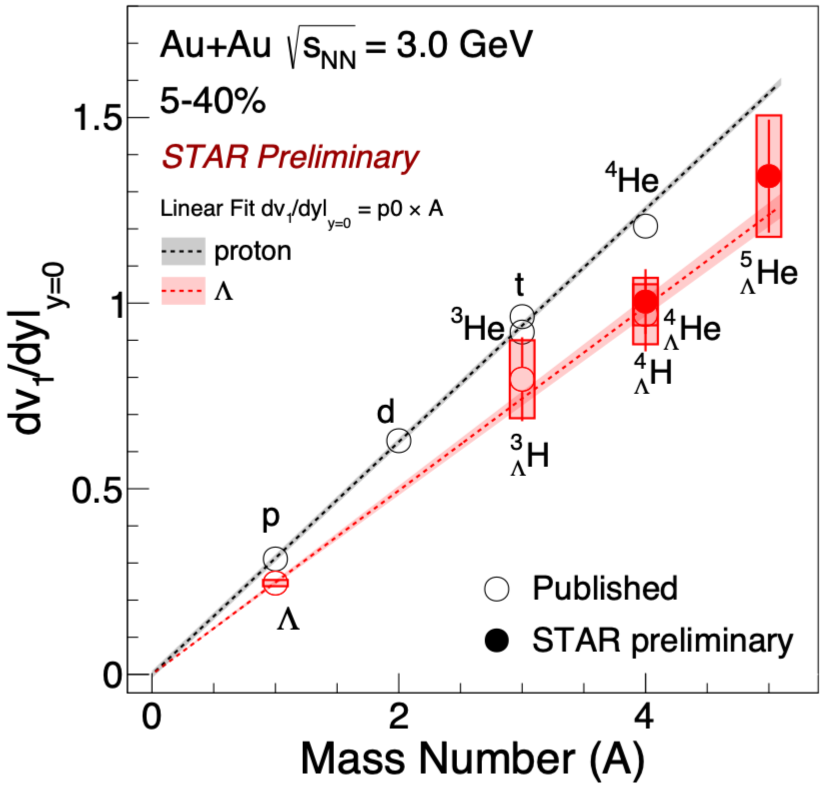
- Aim: to distinguish between two scenarios
  - Prompt production
  - Coalescence (occurs after resonance decay)

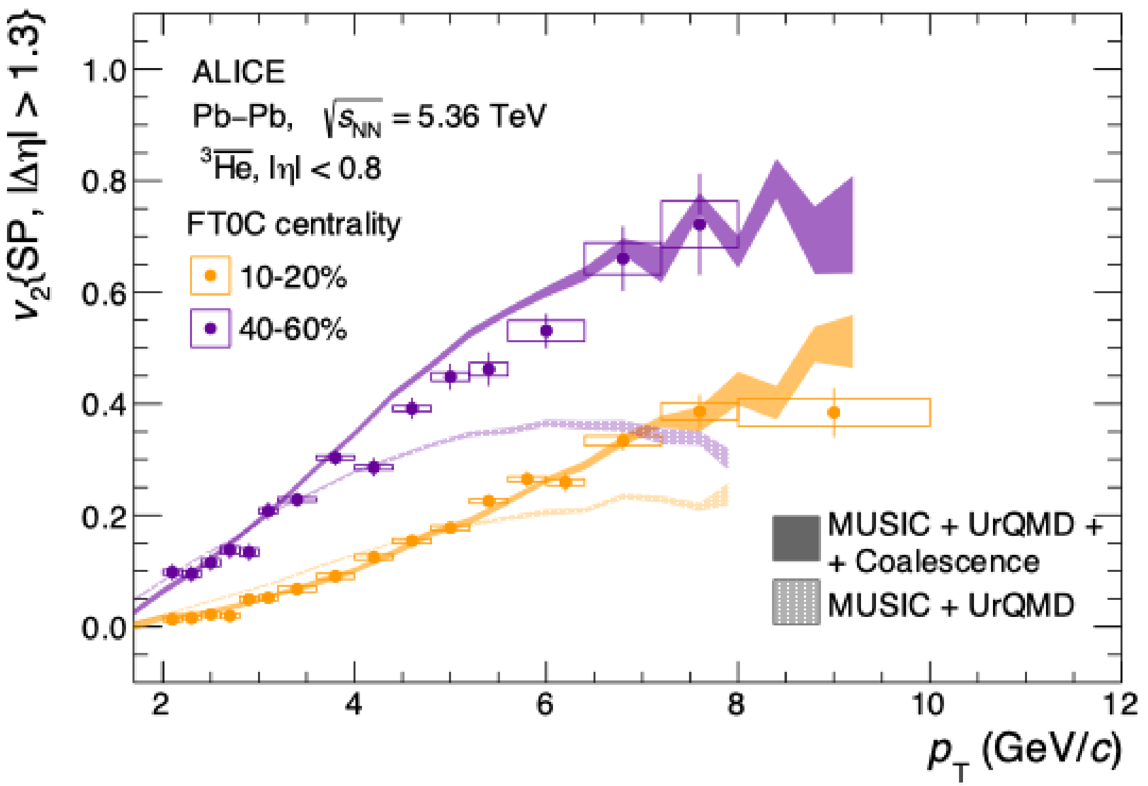


Large fraction of deuteron formed via coalescence following the strong decay of short-lived resonances

Nuclei and hypernuclei Flow

Luca Barioglio, 24/03 afternoon





- Nuclei and hypernuclei dv_1/dy follows mass number scaling up to $A = 5$ in $\sqrt{s_{NN}} = 3$ GeV Au+Au collisions
- $^3\overline{\mathrm{He}}$ v_2 in $\sqrt{s_{NN}} = 5.36$ TeV Pb+Pb collisions, consistent with hydrodynamic models paired with coalescence

STAR, Phys. Rev. Lett. 130 (2023) 212301, QM2025
ALICE, arXiv:2603.19398

Nuclei flow measurements support the coalescence picture

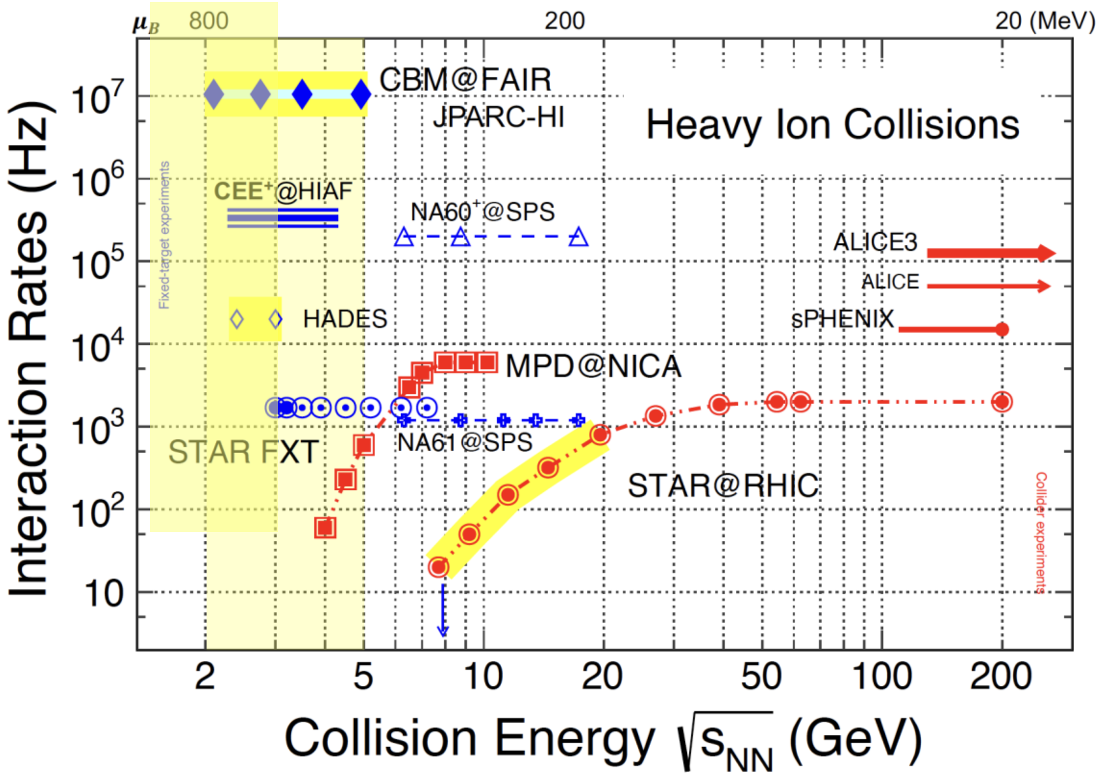
$$E\frac{d^3N}{dp^3} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{1}^{\infty} 2v_n \cos\left[n\left(\phi - \psi_{RP}\right)\right]\right)$$

Summary

- ✓ Data suggest that (hyper)nuclei yields are sensitive to their internal structure, and models that neglect this cannot consistently describe all observables
  - ✓ (Hyper)nuclei with larger spatial extent (${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}\mathrm{Li}$) suppressed w.r.t. those with smaller (${}^{3}\mathrm{He}$, ${}^{4}\mathrm{He}$)
  - ✓ ${}^{3}_{\Lambda}\mathrm{H}$ production is sensitive to its internal wave function.
    - ✓ Gaussian ansatz fail, while more realistic (Congleton-type) wave functions describe data

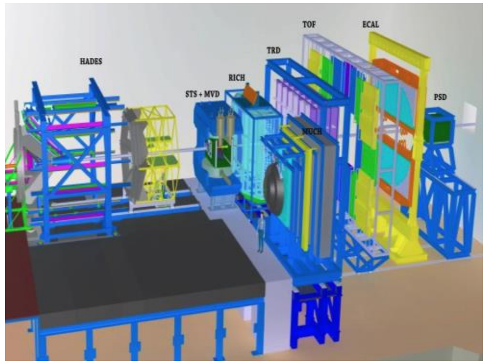
- ✓ Data for bound nuclei with $A < 4$ consistent with coalescence during late stage of collision
  - ✓ Coherent description of yield ratios, flow, and correlation observables **across datasets**
  - ✓ Correlation function indicates majority of deuterons produced after resonance decay
  - ✓ Thermal model works reasonably well for A=4–5 non-resonant (hyper)nuclei
    - ✓ May be due to stronger binding and larger survival probability in the hot medium

Future Prospects



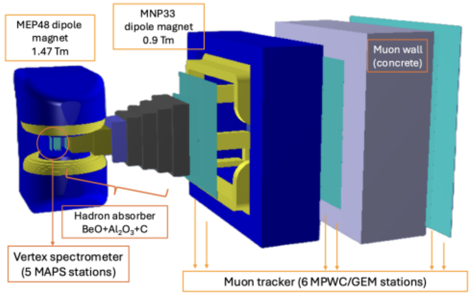
- Double-Λ hypernuclei (YY): $^{A}_{\Lambda\Lambda}$H?
  - Constrain ΛΛ interaction
- Heavier single-Λ hypernuclei
  - Further explore CSB, in-medium ΛN, etc.
- Hypernuclei polarization, etc.

CBM@FAIR

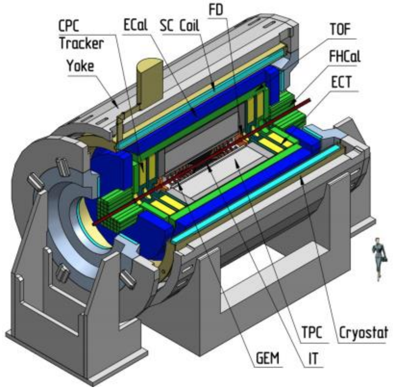


HIAF

NA60+/DICE



NICA



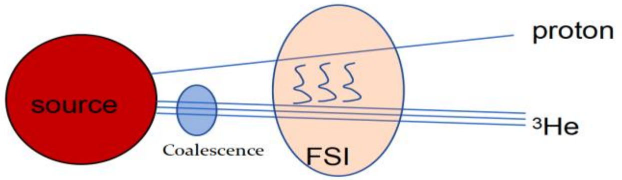
中国科学院大学
University of Chinese Academy of Sciences

Thank you for your attention!

Backup slides follow

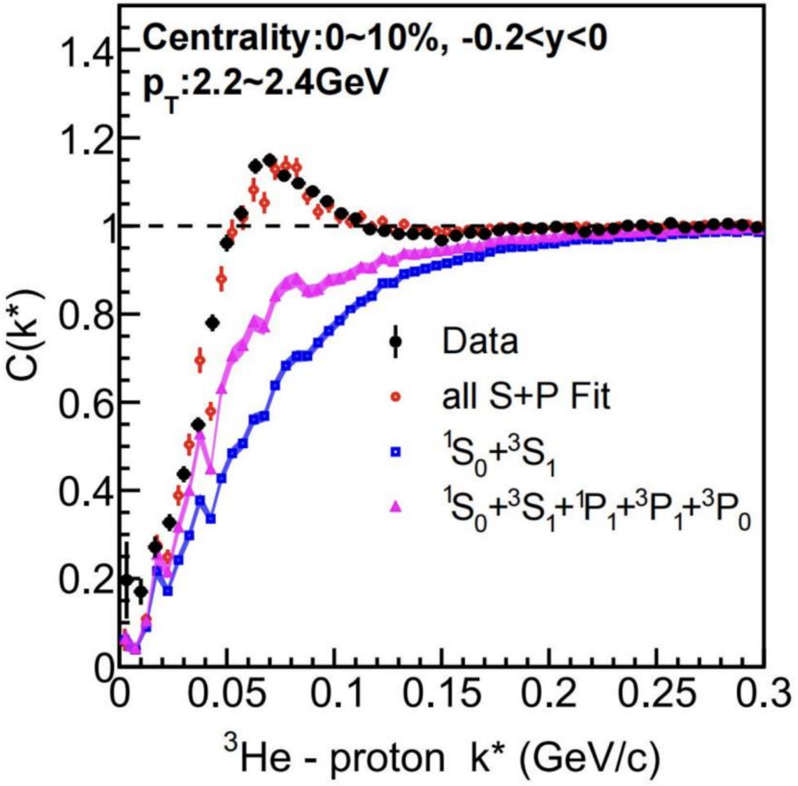
Unstable and Resonant Light Nuclei (^{4}Li &^{5}Li)

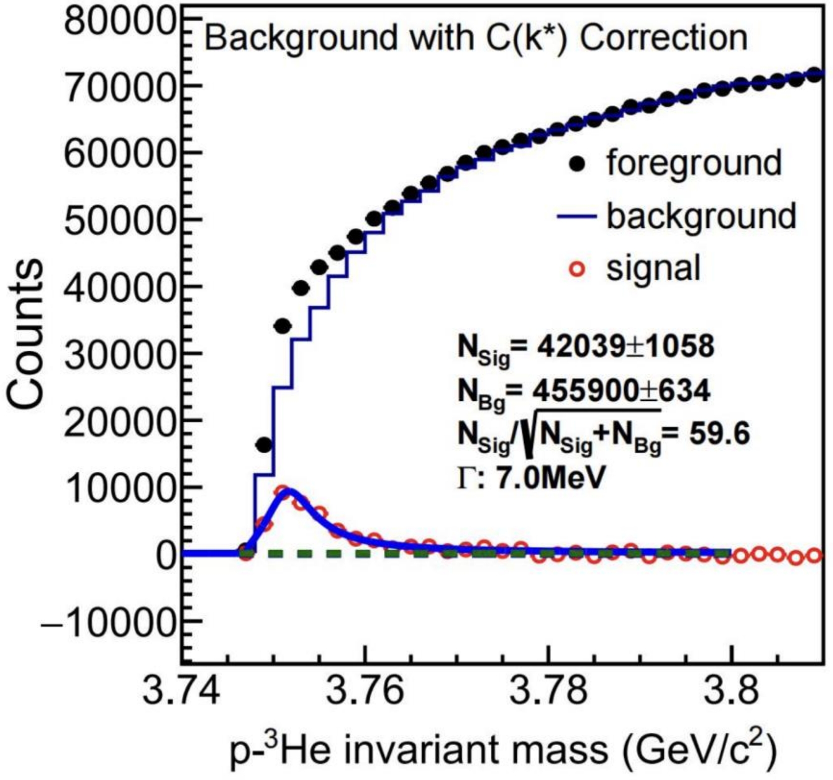
Chenlu Hu, Junlin Wu, 24/03 afternoon



$^{4}\mathbf{Li}\ (^{3}P_{2}) \rightarrow \boldsymbol{p} + {}^{3}\mathrm{He}\ (\tau{\sim}30\ \mathrm{fm/c})$

$^{5}\mathbf{Li}\ (\,P_{3/2}) \rightarrow \boldsymbol{p} + {}^{4}\mathrm{He}\ (\tau{\sim}120\mathrm{fm/c})$

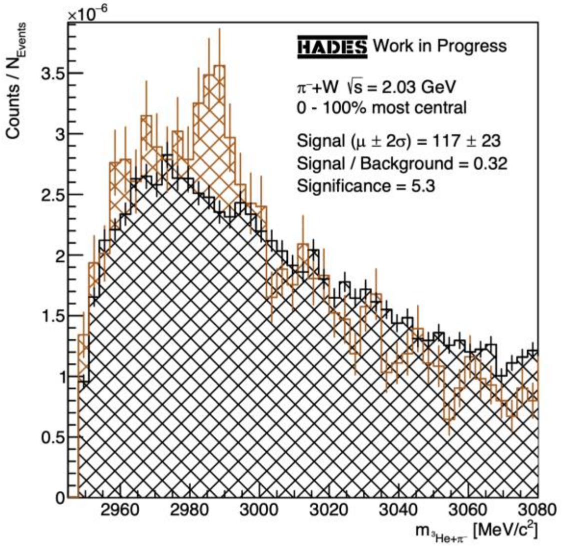




- Femtoscopic correlations provide a unique bridge between heavy-ion collisions and low-energy nuclear scattering
- Novel method: Partial-wave + phase-shift data + LL model enables the extraction of near-threshold resonances, ^{4}Li &^{5}Li

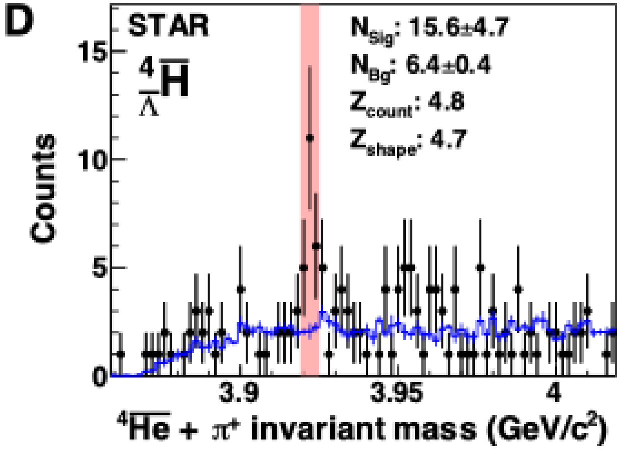
Hypernuclei Reconstruction

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



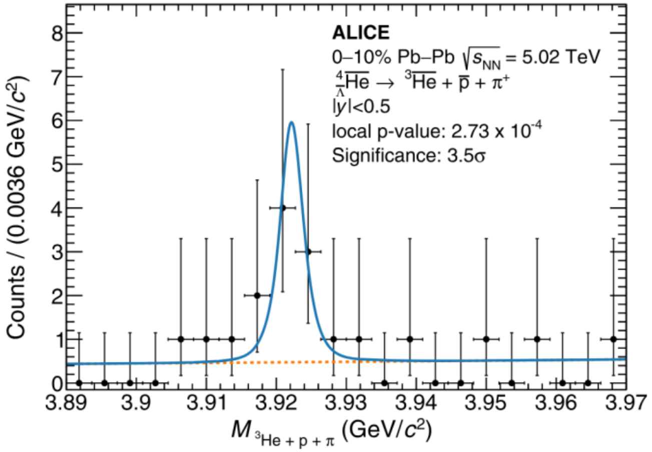
$^{3}_{\Lambda}\mathrm{H} \rightarrow\ ^{3}\mathrm{He}\,\pi^{-}$

$^{4}_{\Lambda}\overline{\mathrm{H}}$



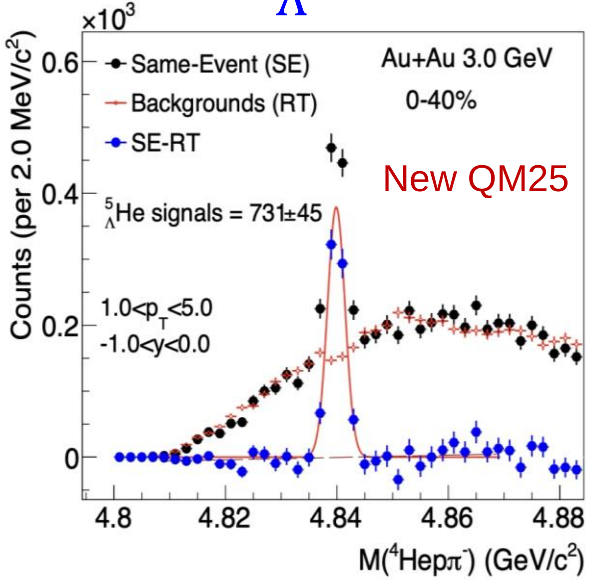
$^{4}_{\Lambda}\overline{\mathrm{H}} \rightarrow\ ^{4}\overline{\mathrm{He}}\,\pi^{+}$

$^{4}_{\Lambda}\overline{\mathrm{He}}$



$^{4}_{\Lambda}\overline{\mathrm{He}} \rightarrow\ ^{3}\overline{\mathrm{He}}\,\bar{p}\,\pi^{+}$

$^{5}_{\Lambda}\mathrm{He}$



$^{5}_{\Lambda}\mathrm{He} \rightarrow\ ^{4}\mathrm{He}\,p\,\pi^{-}$

- Various hypernuclei reconstructed using 2- and 3-body mesonic decay channels
- Discovery of $^{4}_{\Lambda}\overline{\mathrm{H}}$ (STAR, 2024) and $^{4}_{\Lambda}\overline{\mathrm{He}}$ (ALICE, 2025) *STAR, Nature 632 (2024) 8027* *ALICE, Phys. Rev. Lett. 134 (2025) 16, 162301*
- Observation of the heaviest hypernucleus in heavy-ion collisions to date, $^{5}_{\Lambda}\mathrm{He}$ *Y. Zhou, STAR, QM2025*

Data-Driven Semi-Analytical Coalescence Model *(YHL et al., Phys.Rev.C 113 (2026) 3, 034912)*

- Define B_3 as ratio of hypernuclei yields to the product of constituent yields:

$$B_3({}^3_\Lambda\mathrm{H}) = \boxed{\frac{E_{{}^3_\Lambda\mathrm{H}}\dfrac{d^3N_{{}^3_\Lambda\mathrm{H}}}{d^3p_{{}^3_\Lambda\mathrm{H}}}}{\left(E_p\dfrac{d^3N_p}{d^3p_p}\right)\left(E_n\dfrac{d^3N_n}{d^3p_n}\right)\left(E_n\dfrac{d^3N_\Lambda}{d^3p_\Lambda}\right)}}$$

p and Λ yields from data

- In the Wigner-function coalescence formalism (ignoring momentum dependence of the nucleon source):

F. Bellini et al., Phys. Rev. C 103 (2021) 014907

$$B_3({}^3_\Lambda\mathrm{H}) \approx \frac{3}{m^2}\frac{2s_{{}^3_\Lambda\mathrm{H}}+1}{(2s_N+1)^3}(2\pi)^6\int d^3r_{pn}\int d^3r_\Lambda \boxed{|\Phi_{{}^3_\Lambda\mathrm{H}}(r_{pn}, r_\Lambda)|^2}\,\boxed{\mathcal{S}_3(r_{pn}, r_\Lambda)}$$

nuclei wave function

nucleon source

- Assume an isotropic Gaussian nucleon source:

$$\mathcal{S}_3(r_{12}, r_3) = \frac{1}{(12\pi^2R_{\mathrm{inv}}^4)^{3/2}}\exp\left(-\frac{r_{12}^2+\frac{4}{3}r_3^2}{4R_{\mathrm{inv}}^2}\right)$$

- R_{inv} is estimated using deuteron data
- **No free parameters for once ${}^3_\Lambda\mathrm{H}$ wave function is specified**

The Hypertriton Wave Function

- ${}^{3}_{\Lambda}$H: loosely bound hypernuclei
- Gaussian:

$$\Phi_{{}^{3}_{\Lambda}\mathrm{H}}(r_{pn}, r_{\Lambda}) = \left(\frac{1}{3\pi^2 b_{pn}^2 b_{\Lambda}^2}\right)^{\frac{3}{4}} e^{-\frac{r_{pn}^2}{4b_{pn}^2}-\frac{r_{\Lambda}^2}{3b_{\Lambda}^2}}$$

$b_{\Lambda} = 7.2\mathrm{fm}$

F. Bellini et al., Phys. Rev. C 103 (2021) 014907

- Congleton:

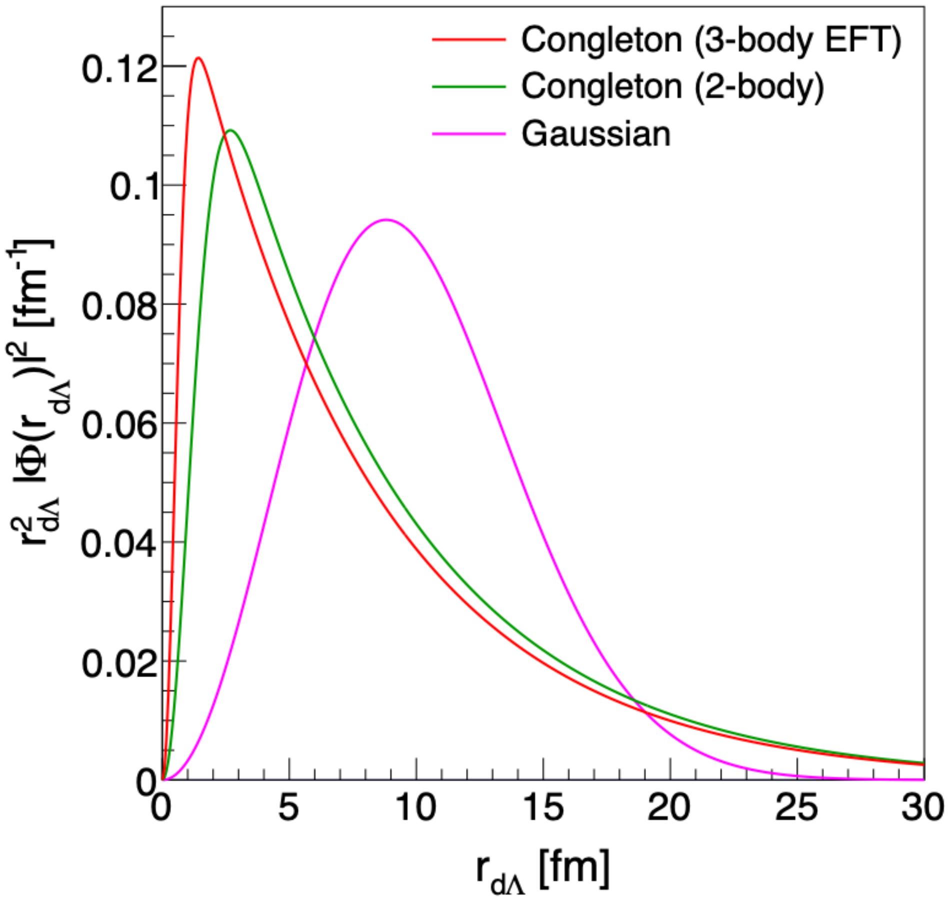
$$\hat{\Phi}_{{}^{3}_{\Lambda}\mathrm{H}(d\Lambda)}(q) = A\frac{e^{-\frac{-q^2}{Q_{\Lambda}^2}}}{q^2+\alpha_{\Lambda}^2}$$

  - 2-body model of ${}^{3}_{\Lambda}$H: $(Q_{\Lambda}, \alpha_{\Lambda}) = (1.17, 0.068)\mathrm{fm}^{-1}$

J. Congleton, J.Phys.G 18 (1992)339-357

  - 3-body effective field theory: $(Q_{\Lambda}, \alpha_{\Lambda}) = (2.5, 0.068)\mathrm{fm}^{-1}$

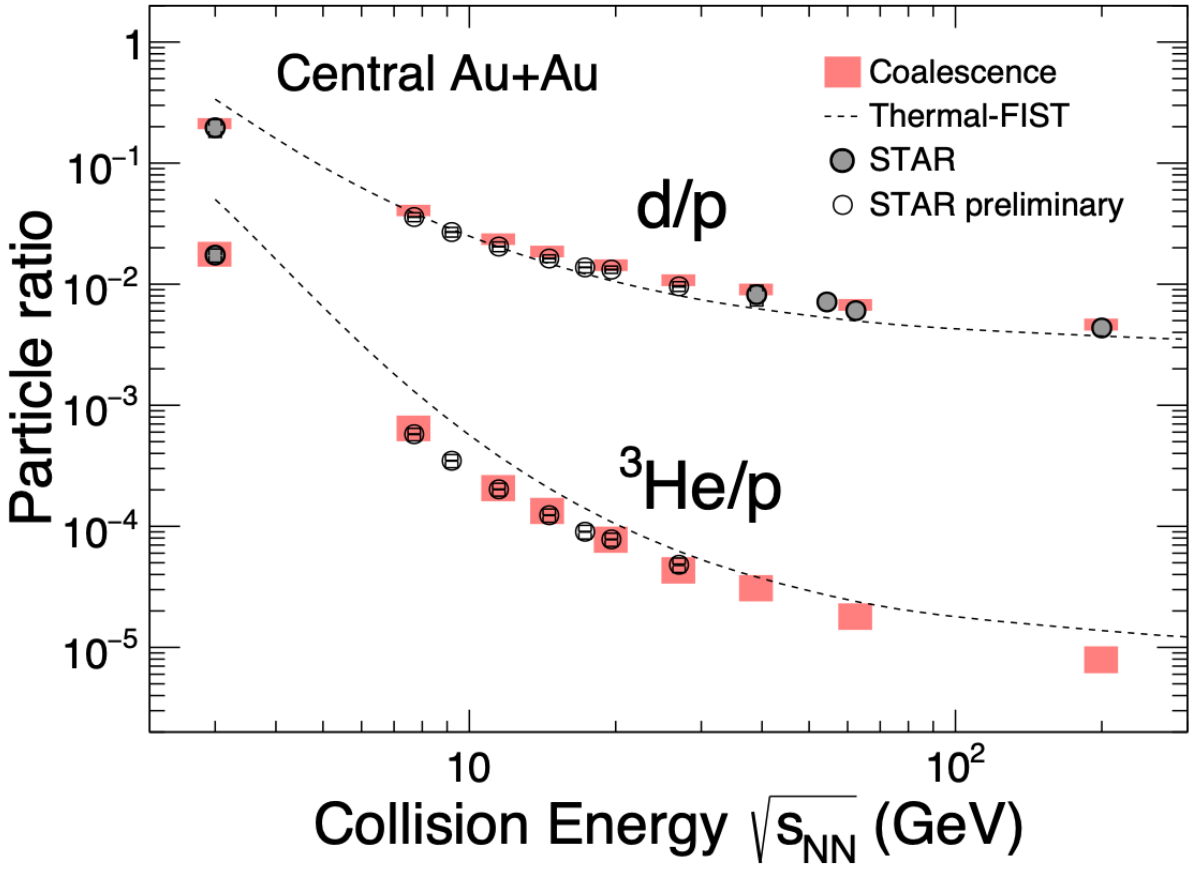
F. Hildenbrand, H.-W. Hammer, Phys. Rev. C 100(2019)034002

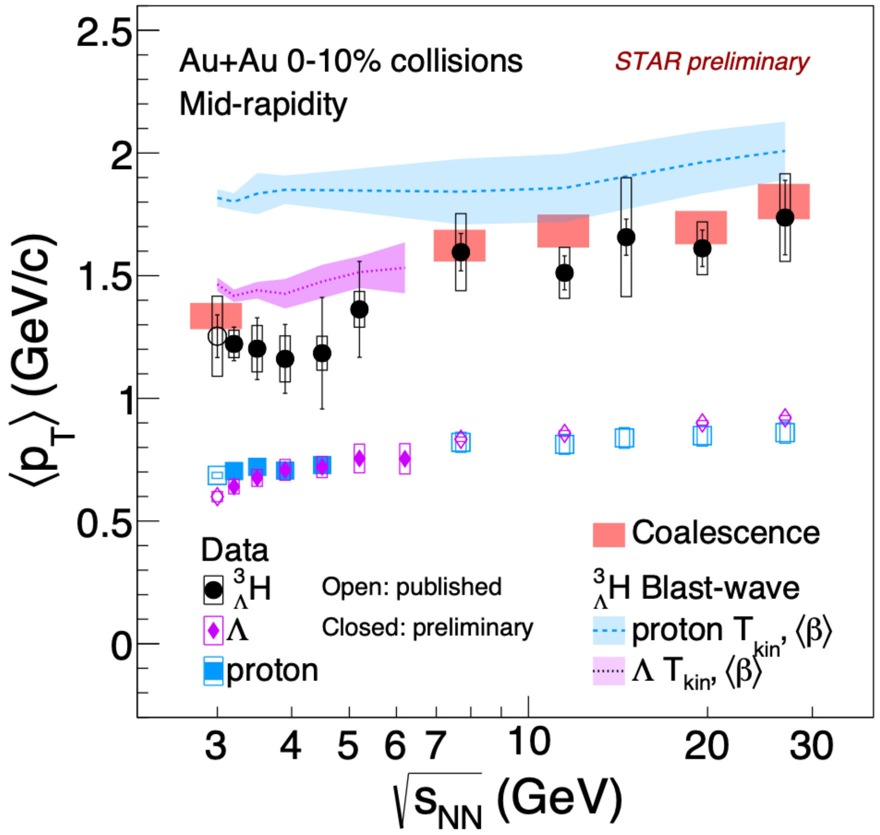


- **${}^{3}_{\Lambda}$H wave function is an active field of research**

Jiaxing Zhao et al., Phys.Rev.C 112 (2025) 6, 064902
Z. Zhang et al., Phys.Lett.B 874 (2026) 140285

Nuclei yields in BES

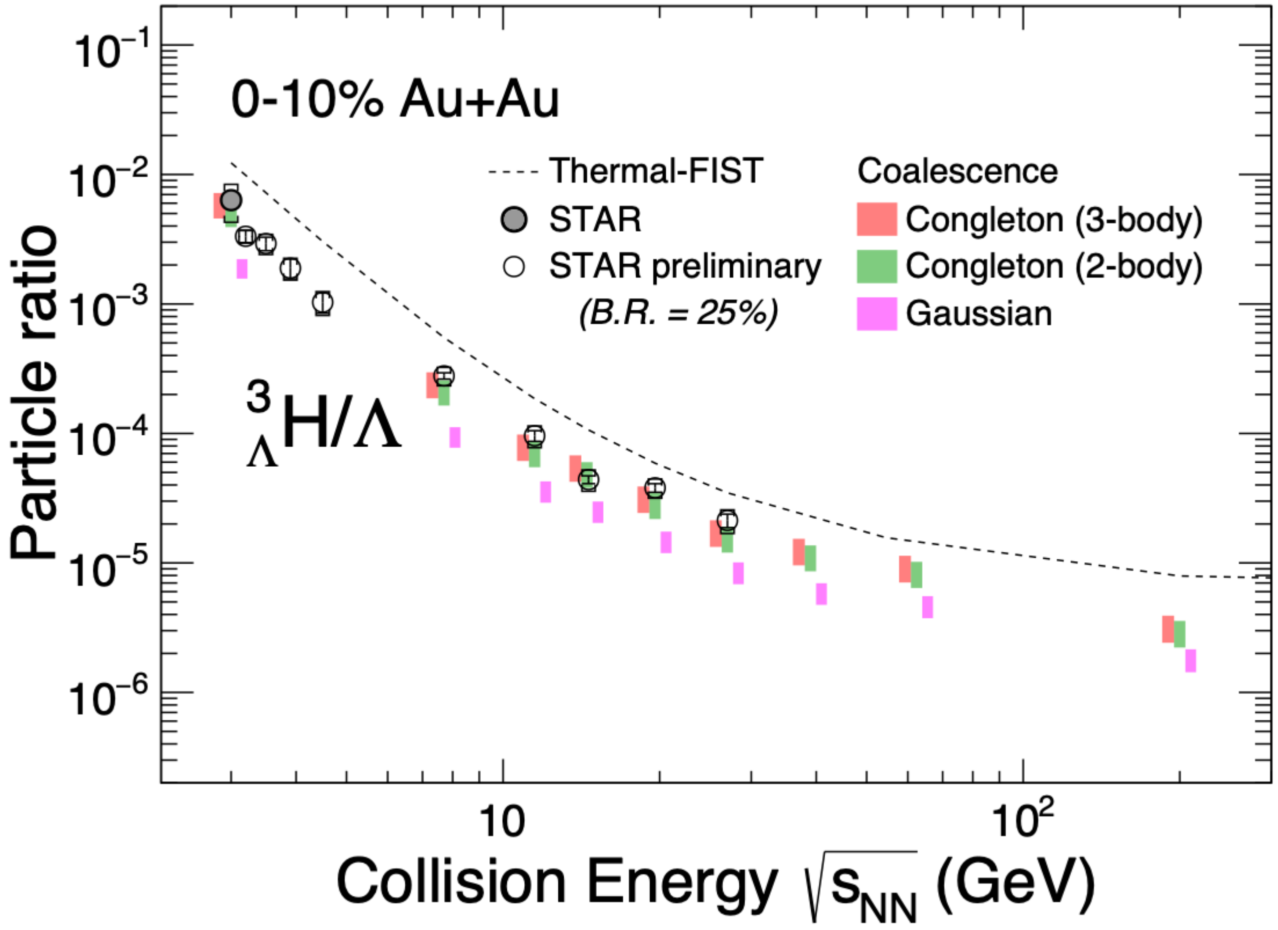


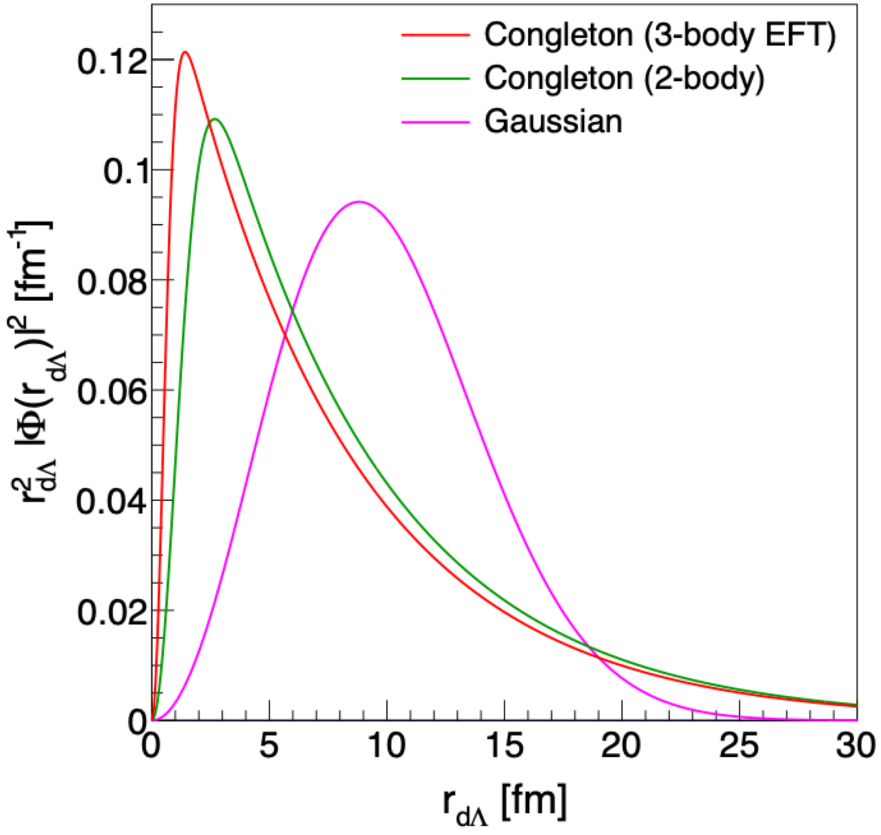


- Coalescence gives a reasonable description of $A < 4$ nuclei data

V. Vovchenko, et al, Comput. Phys. Commun. 244 (2019) 295
YHL et al., Phys.Rev.C 113 (2026) 3, 034912
STAR, Phys. Rev. Lett. 130 (2023) 202301

Hypernuclei yields in BES



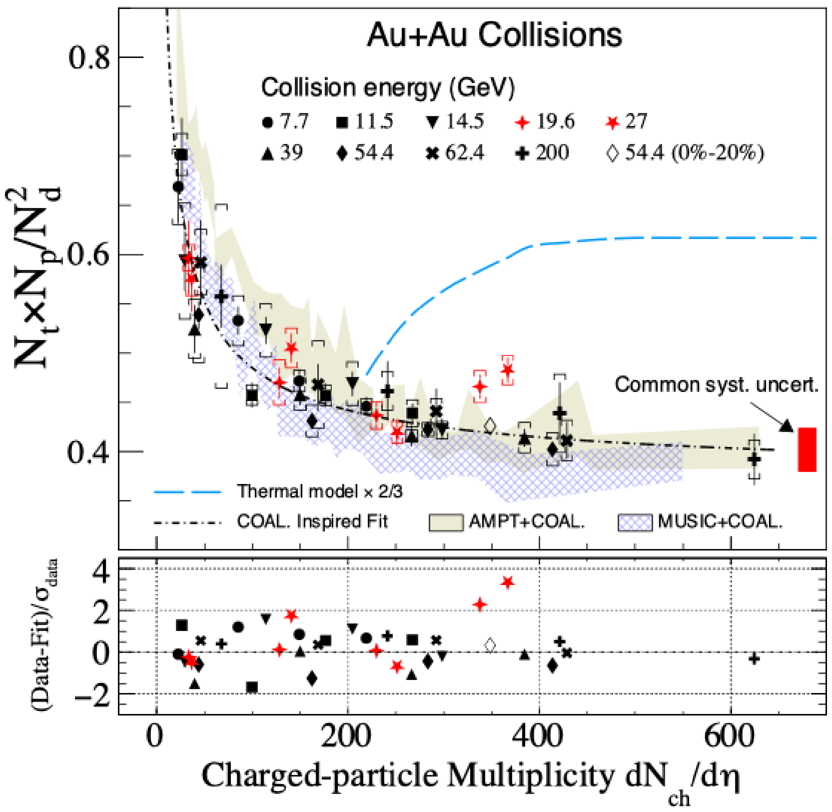


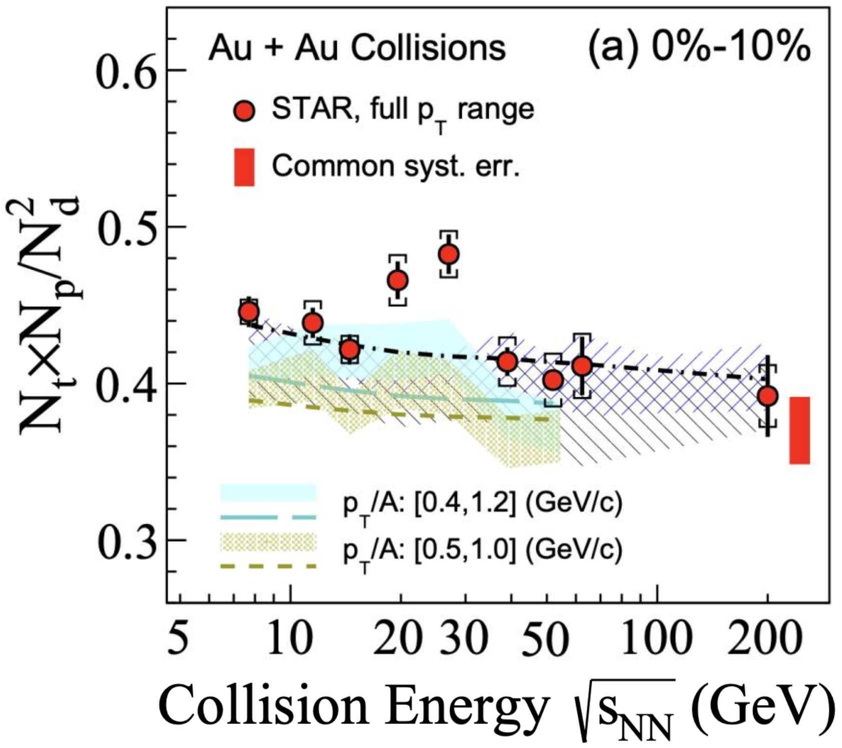
V. Vovchenko, et al, Comput. Phys. Commun. 244 (2019) 295
YHL et al., Phys.Rev.C 113 (2026) 3, 034912

- Coalescence gives a reasonable description of $A < 4$ hypernuclei data

Compound Ratio (tp/d^2) vs. $\sqrt{s_{NN}}$

STAR, Phys. Rev. Lett. 130 (2023) 202301
K. Sun et al., Phys. Lett. B 781 (2018) 499





Yield ratios have been suggested to be sensitive to neutron density fluctuations

$$\boxed{\frac{t \times p}{d^2} = g(1 + \Delta n)}$$

Δn: Neutron Density Fluctuation

- Compound ratio can be described by coalescence calculations
- Enhancements around 19.6/27 GeV w.r.t. baseline observed, but they decrease with decreasing p_T acceptance
- Analyses with STAR BES-II (with extended low p_T coverage) is in progress.