

Recent Results on Hypernuclei Production at RHIC

HENPIC Seminar

Yue Hang Leung

University of Heidelberg

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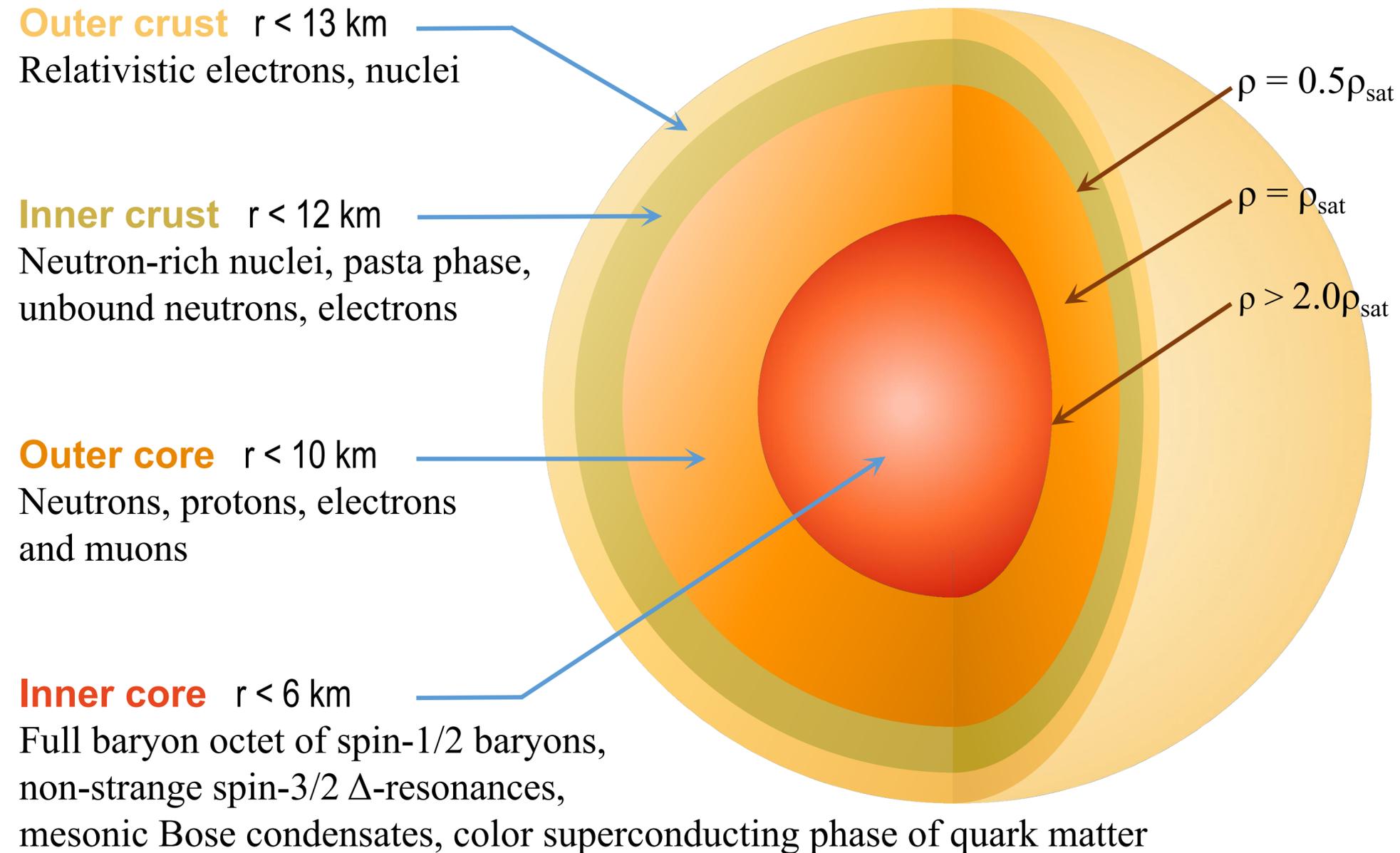


Outline

- Introduction: Hyperon Puzzle
- Results
 - $A=3$ (Hypertriton)
 - Wave function dependence
 - $A=4, 5$
 - Binding energy dependence
- Summary and outlook

Neutron Stars

A. Sedrakian, et al., PPNP 131, 104041 (2023)



- Neutron stars are among the **densest known massive** objects in the universe
- Density at inner core can reach several times the **nuclear matter saturation density** ($\rho_{\text{sat}} \approx 0.16 \text{ fm}^{-3}$)

Tolman–Oppenheimer–Volkoff (TOV) equation

- TOV equation is the general-relativistic version of **hydrostatic equilibrium**

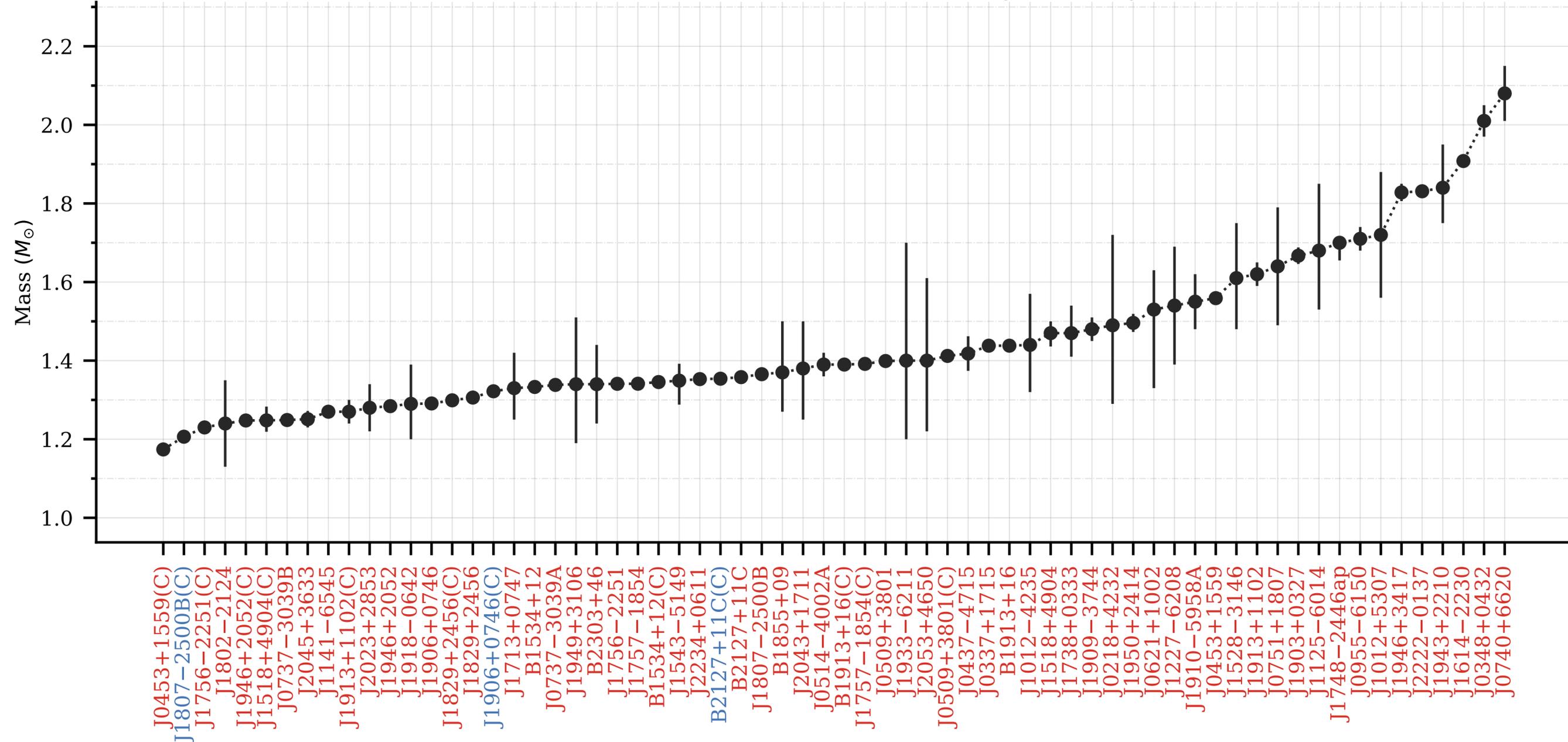
$$\frac{dP(r)}{dr} = - \frac{G \left(\rho(r) + \frac{P(r)}{c^2} \right) \left(m(r) + 4\pi r^3 \frac{P(r)}{c^2} \right)}{r^2 \left(1 - \frac{2Gm(r)}{rc^2} \right)}$$

- The **equation-of-state (EOS)**, which relates pressure to density $P = P(\rho)$ is needed to solve the equation, and obtain a mass-radius relationship
- Key ingredients to the **EOS**:
 1. Degrees of freedom
 2. Quantum statistics
 3. Thermodynamic conditions
 4. **Interactions**

Neutron Star Masses

Mass distribution of neutron stars in binary pulsar systems

figure from Vivek V. Krishnan



- Massive pulsars observed recently: **PSR 0740+6620** with $M = 2.08(7)M_{\odot}$ (Fonseca et al. 2021) and **PSR 0348+0432** $M = 2.01(4)M_{\odot}$ (Antoniadis et al. 2013)

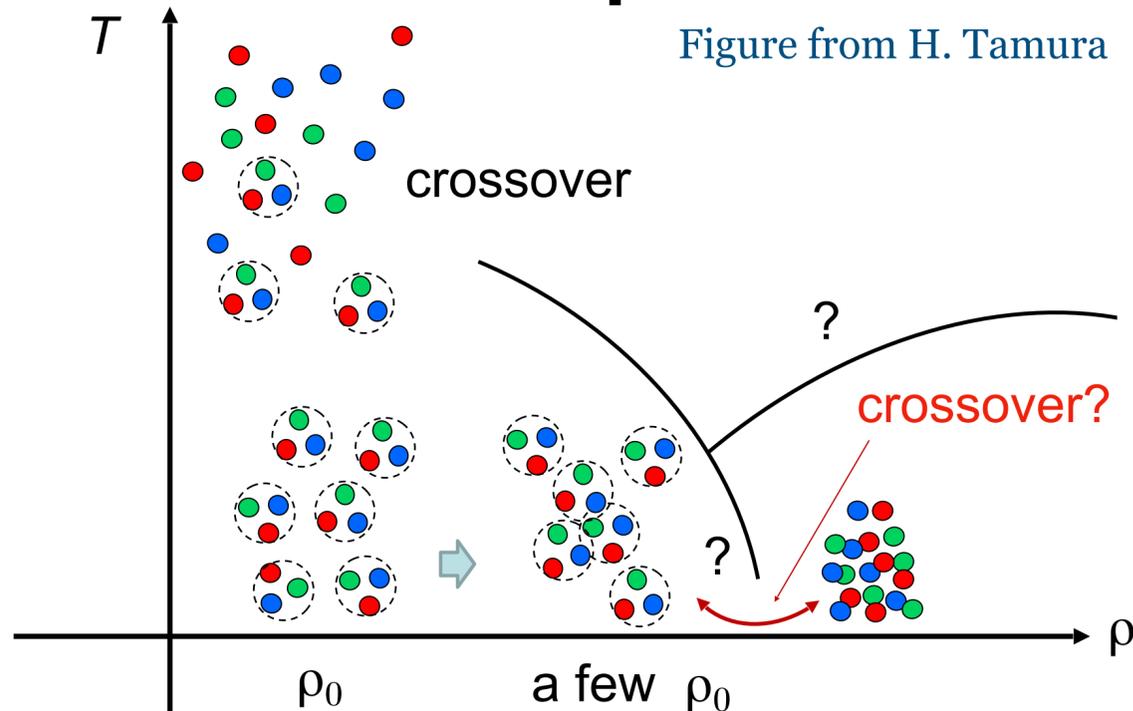
The Hyperon Puzzle

- Hyperons are expected to appear in the core of neutron stars

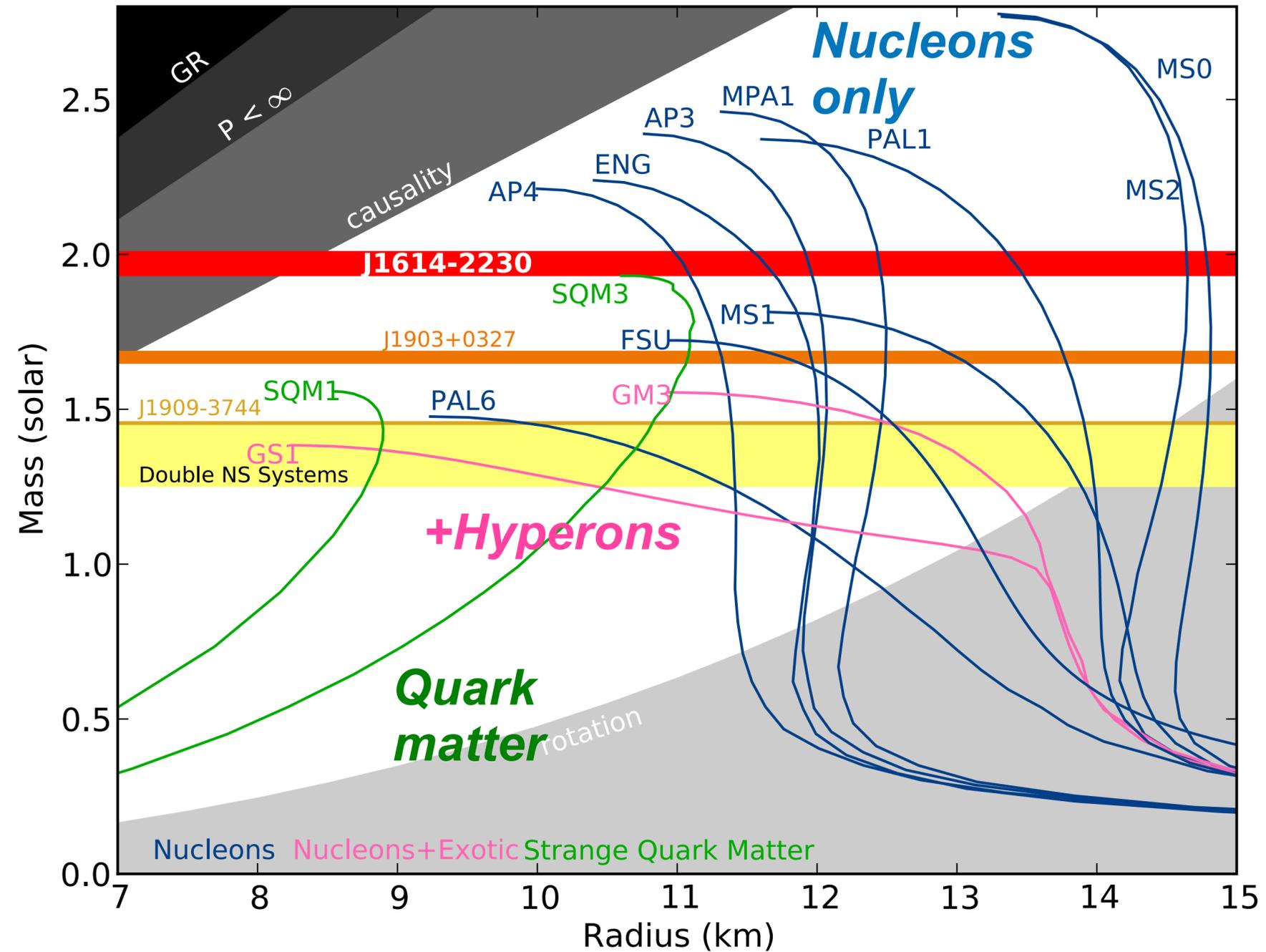
- Hyperon puzzle:** EoS's with hyperons are too soft to support massive neutron stars of $>1.5 M_{\odot}$

- Repulsive **three-body force** in NNN. What about hyperon (Y)-nucleon (N) and hyperon (Y)-hyperon (Y) forces, **YNN, YYN, YYY?**

- Deconfined quark matter?**



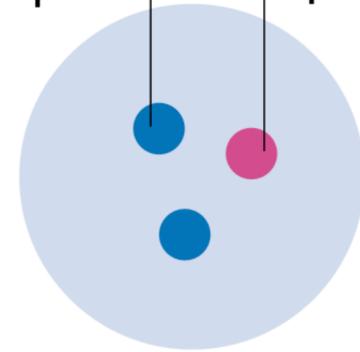
P. Demorest et al., Nature 467(2010)1081



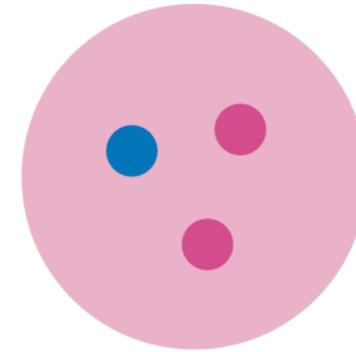
Hypernuclei

- Hypernuclei are nuclei containing at least one hyperon
- First discovered in 1952 by M. Danysz and J. Pniewski

Down quark Up quark

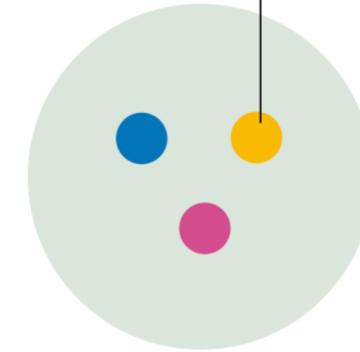


Neutron

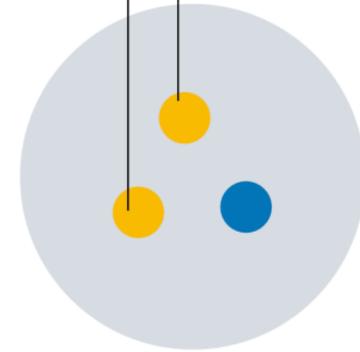


Proton

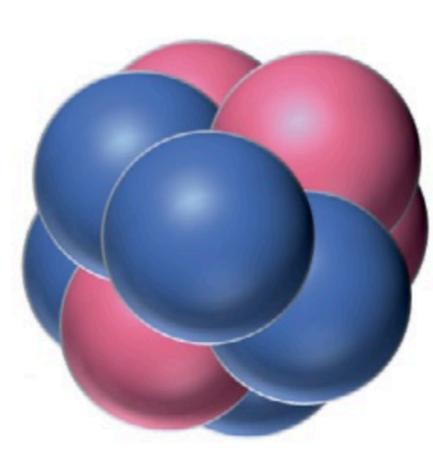
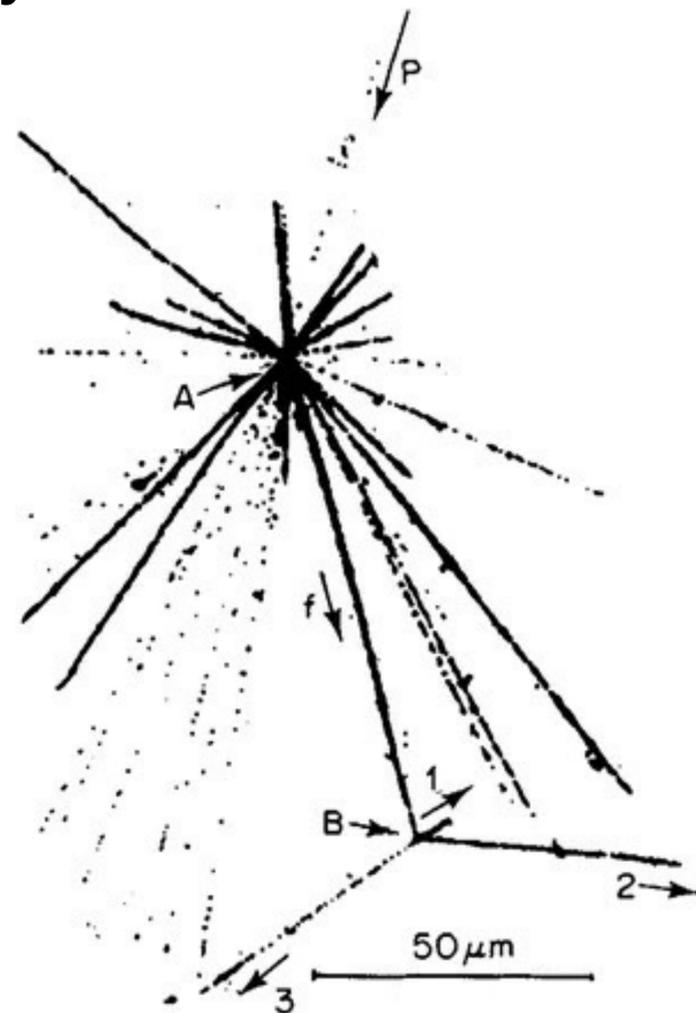
Strange quark



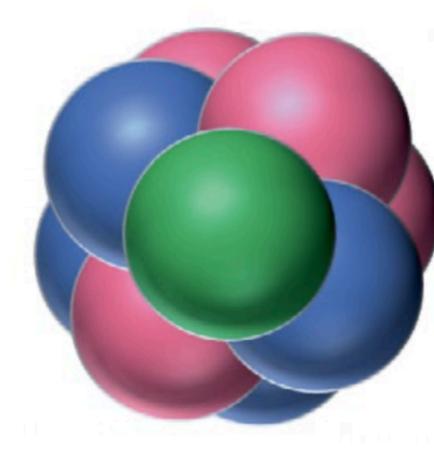
Λ Hyperon



Ξ Hyperon



Ordinary nucleus

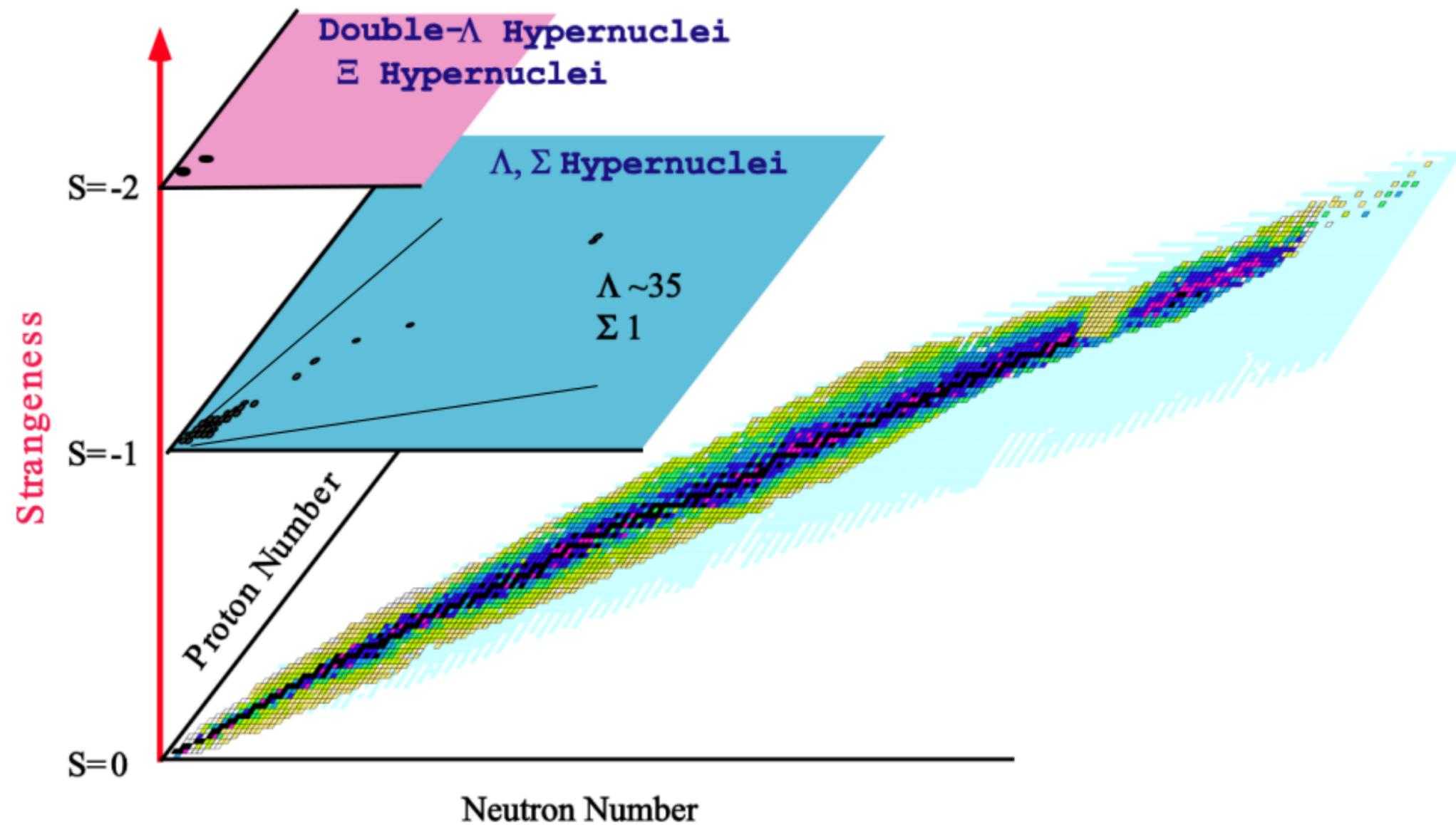


Single Λ -hypernucleus

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

Hypernuclei

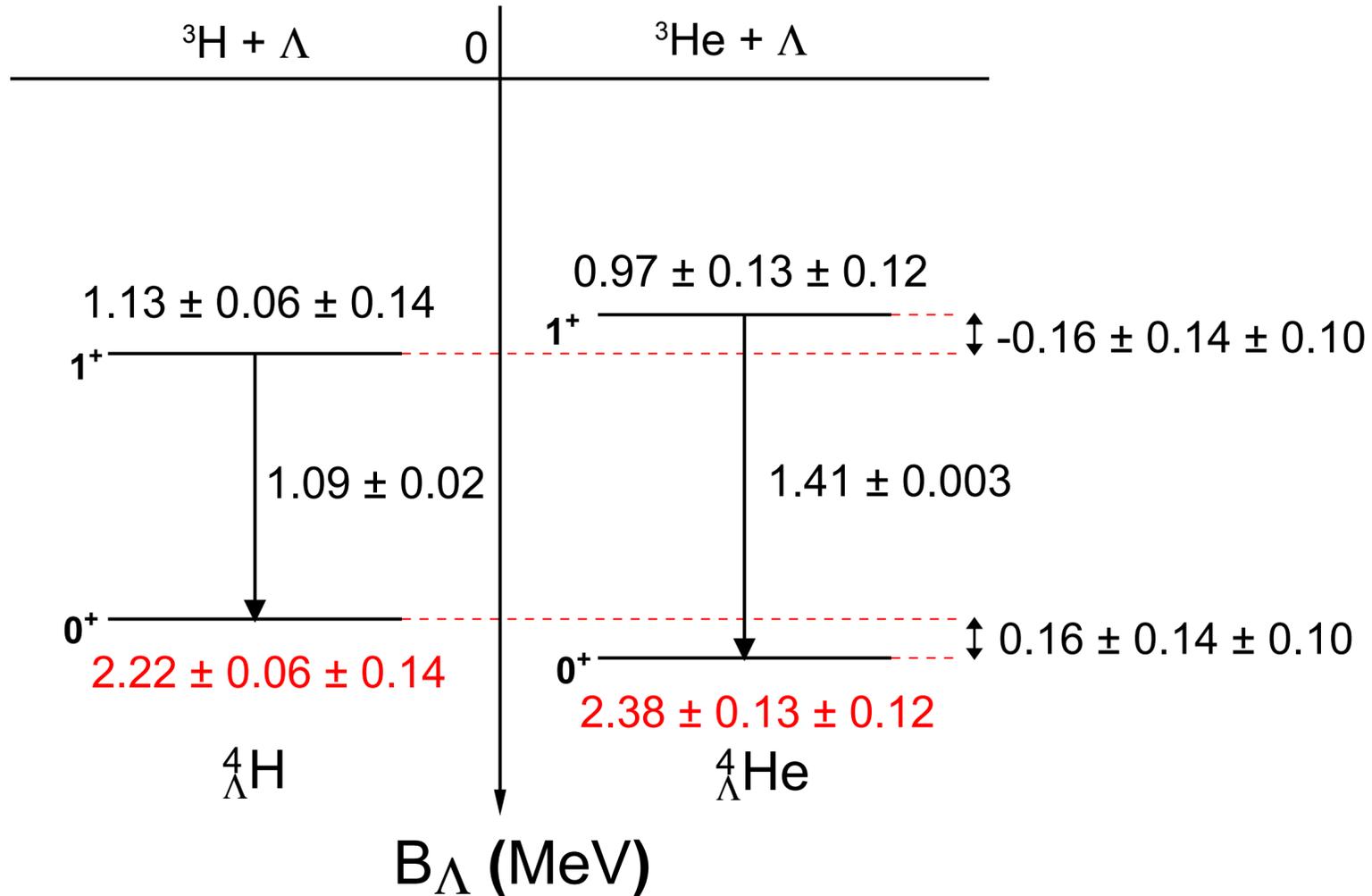
- Hypernuclei are nuclei containing at least one hyperon
- First discovered in 1952 by M. Danysz and J. Pniewski
- Goal: to understand baryon-baryon interactions
- Scattering experiments
 - Nucleon (N) - Nucleon (N) data: ~ 4000
 - Hyperon (Y) - Nucleon (N) data: ~ 40



- Determine YN interaction from **hypernuclear structure**

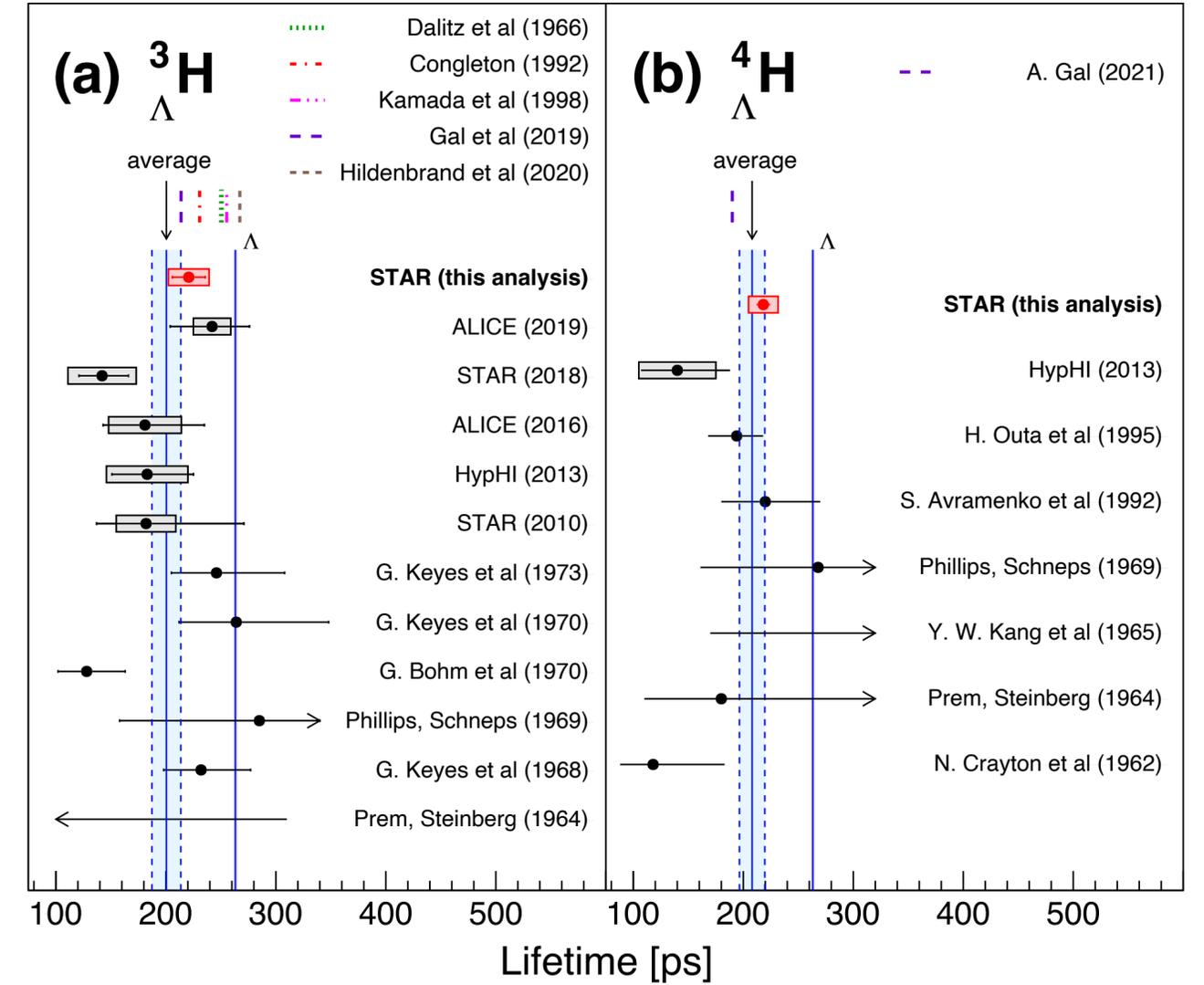
Constraining the YN Interaction through Hypernuclei

- Binding energy



STAR, Phys.Lett.B 834 (2022) 137449

- Lifetime



STAR, Phys.Rev.Lett. 128 (2022) 20, 202301

- Can the **production yields and flow** of hypernuclei in heavy-ion collisions tell us anything about the **YN interaction**?

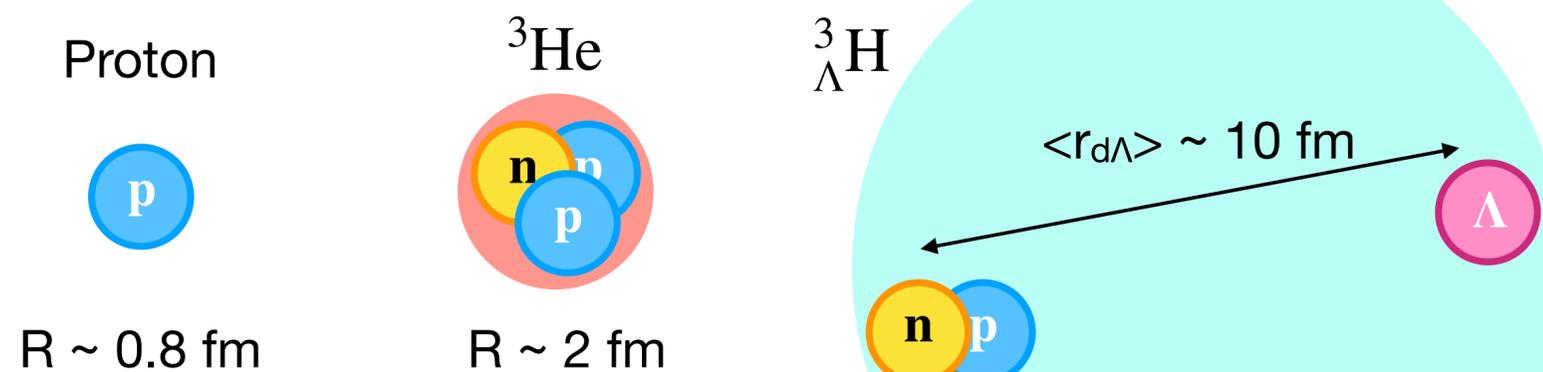
Hypernuclei Production Models in Heavy-Ion Collisions

Thermal

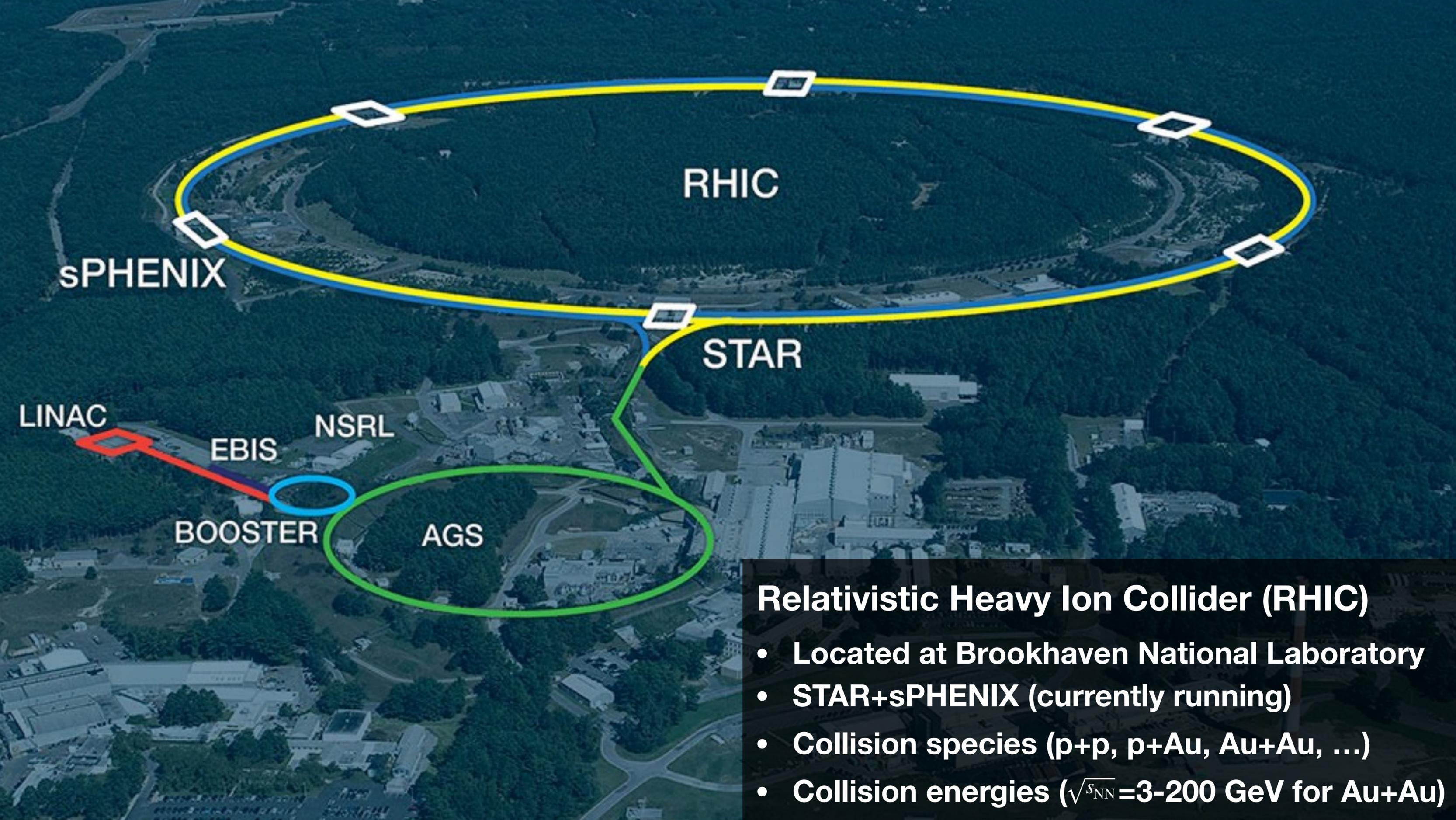
- Particle yields predicted with thermal equilibrium assumptions
 - *Chemical freeze-out temperature* T_{ch}
 - *Baryo-chemical potential* μ_B
 - *Volume* V
 - *Strangeness correlation length* r_C

Coalescence

- Formed by nucleons (and hyperons) which are nearby in phase space after kinetic freeze-out
- Formation probability given by overlap b/w:
 - *Nucleon distributions at freeze-out*
 - *Nuclear wave function*



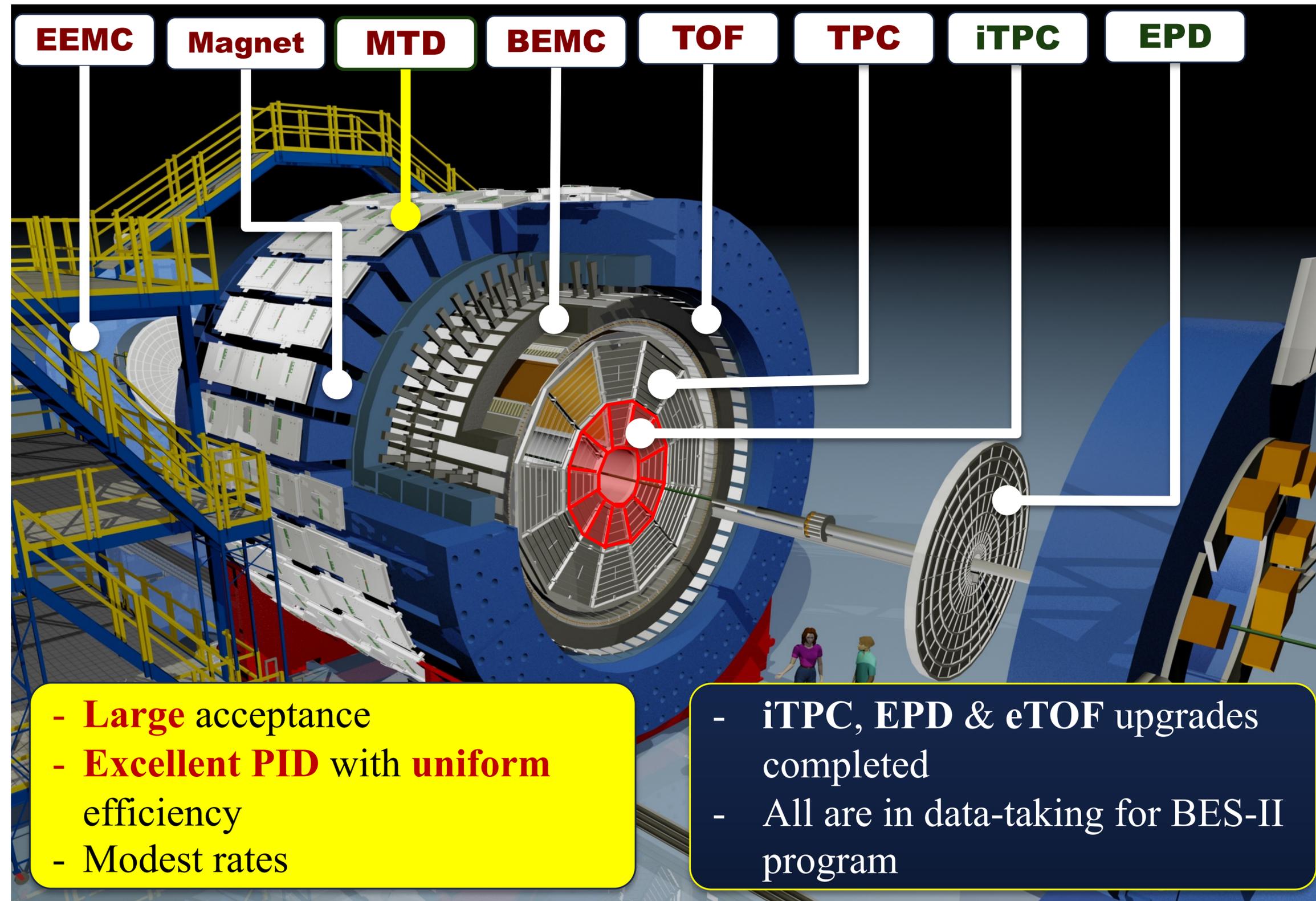
- ${}^3_{\Lambda}\text{H}$ production is the ultimate test:
 - **Thermal**: insensitive to size of ${}^3_{\Lambda}\text{H}$
 - **Coalescence**: yield suppressed



Relativistic Heavy Ion Collider (RHIC)

- Located at Brookhaven National Laboratory
- STAR+sPHENIX (currently running)
- Collision species (p+p, p+Au, Au+Au, ...)
- Collision energies ($\sqrt{s_{NN}}=3-200$ GeV for Au+Au)

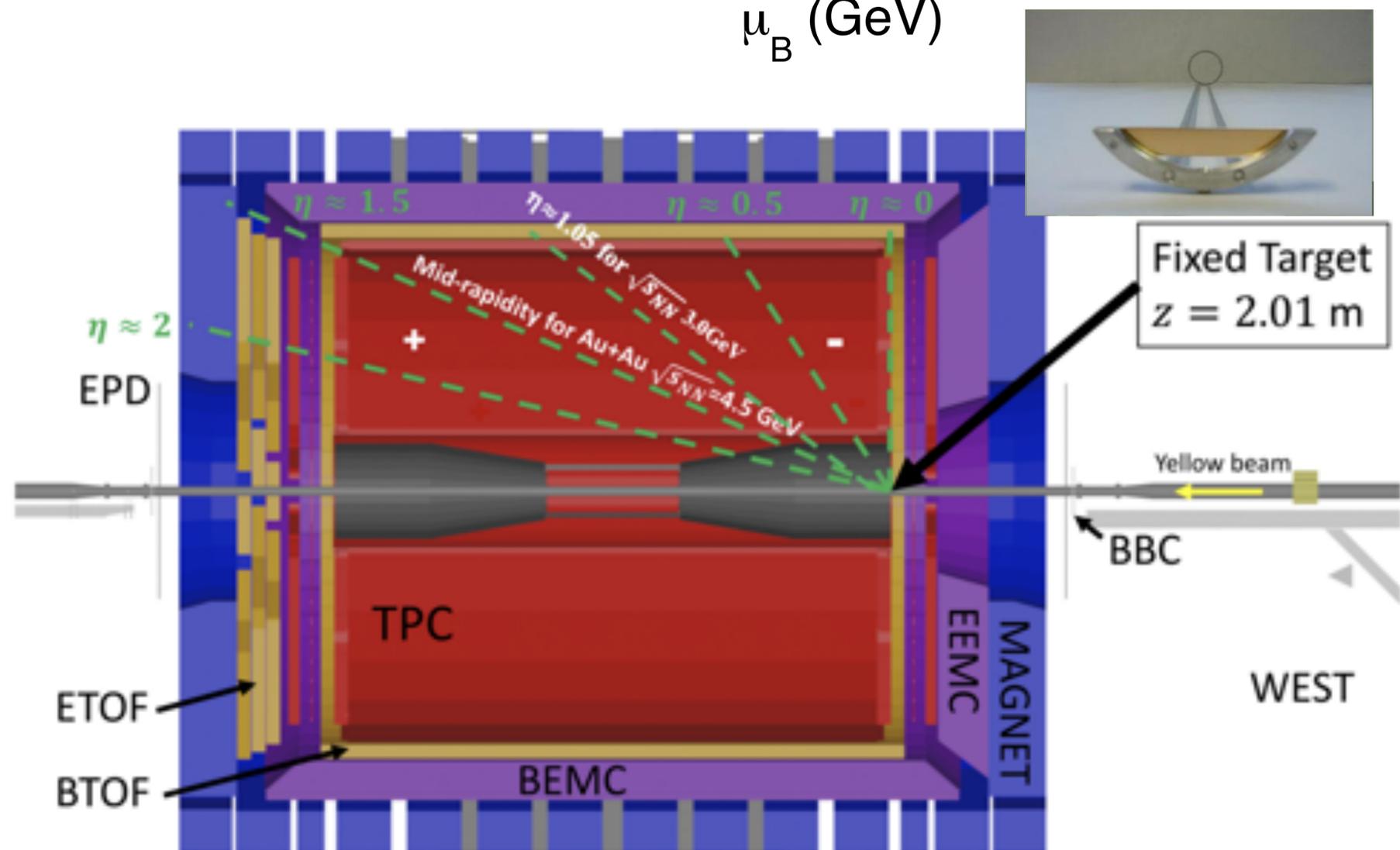
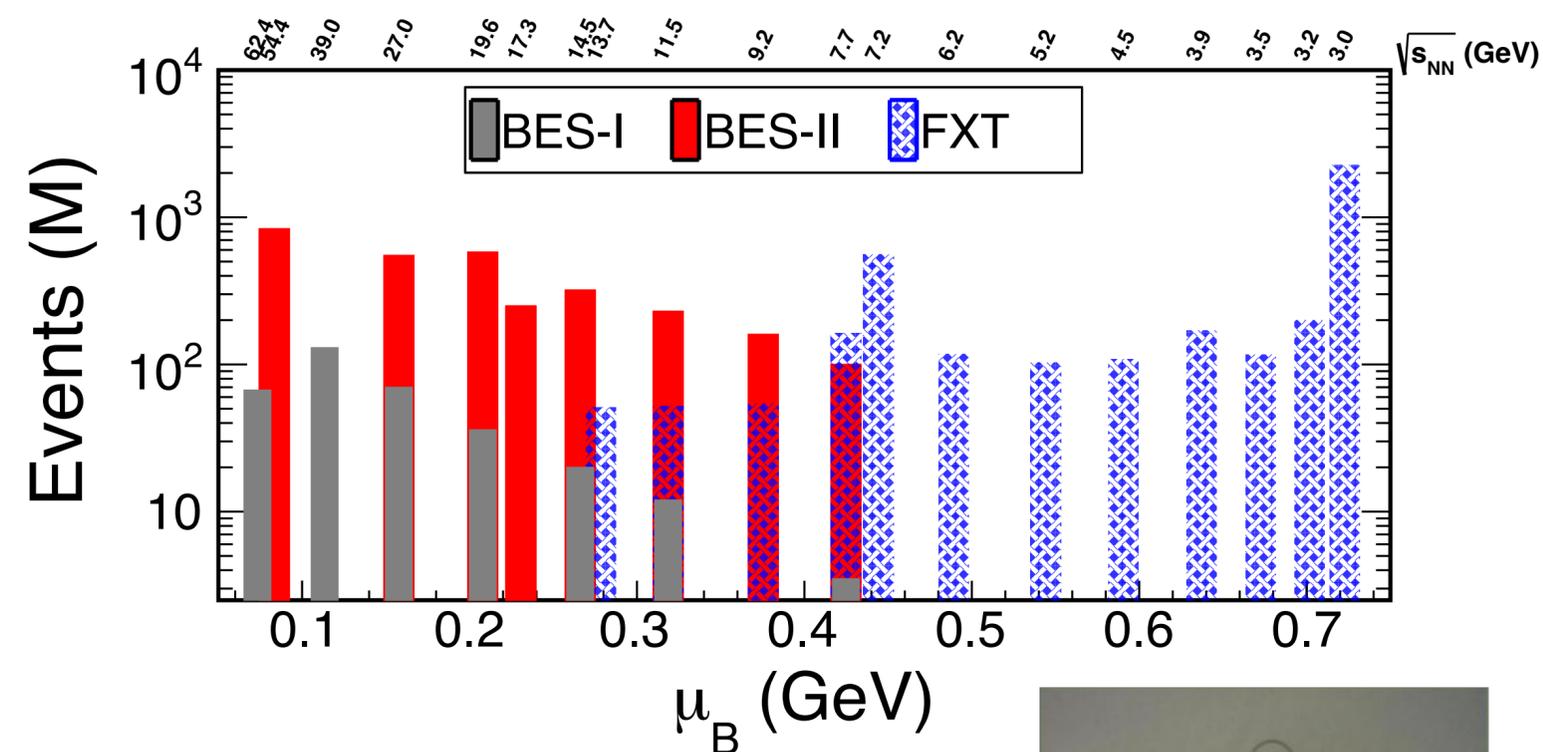
The STAR (Solenoidal Tracker At RHIC) Detector



- Solenoidal magnet with 0.5T uniform field
- Time projection chamber (TPC)
- Time-of-flight detectors (TOF)
- Electromagnetic calorimeters (BEMC, EEMC)

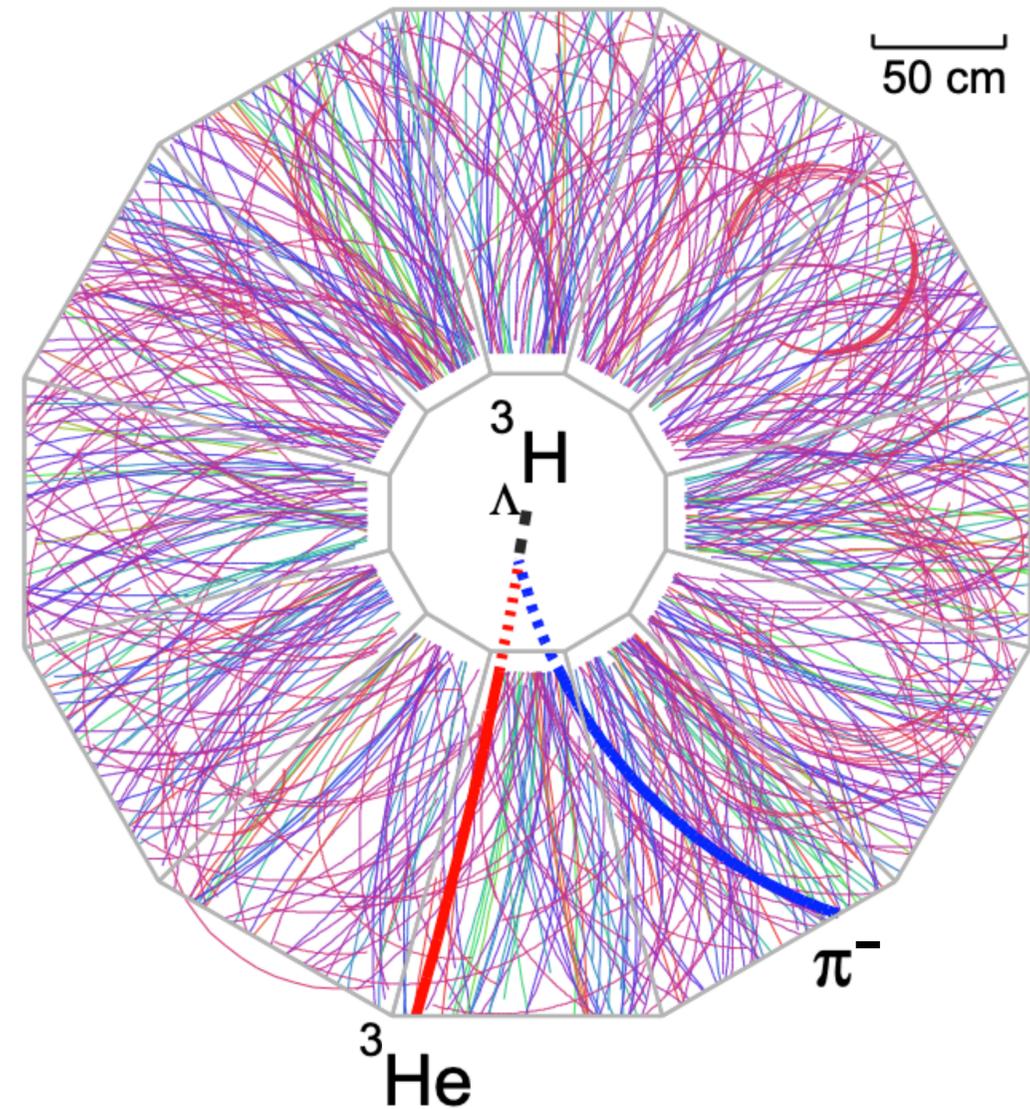
Beam Energy Scan (BES)

- BES-I (2009-2011)
 - Au+Au collisions $\sqrt{s_{NN}} = 7.7-62.4$ GeV
 - Search for onset of deconfinement
 - Search for critical end point
- BES-II (2018-2021)
 - High statistics Au+Au collisions $\sqrt{s_{NN}} = 3-54.4$ GeV
 - Fixed target (FXT) collisions extend energy reach down to 3 GeV
 - Search for possible formation and investigate properties of dense baryonic matter

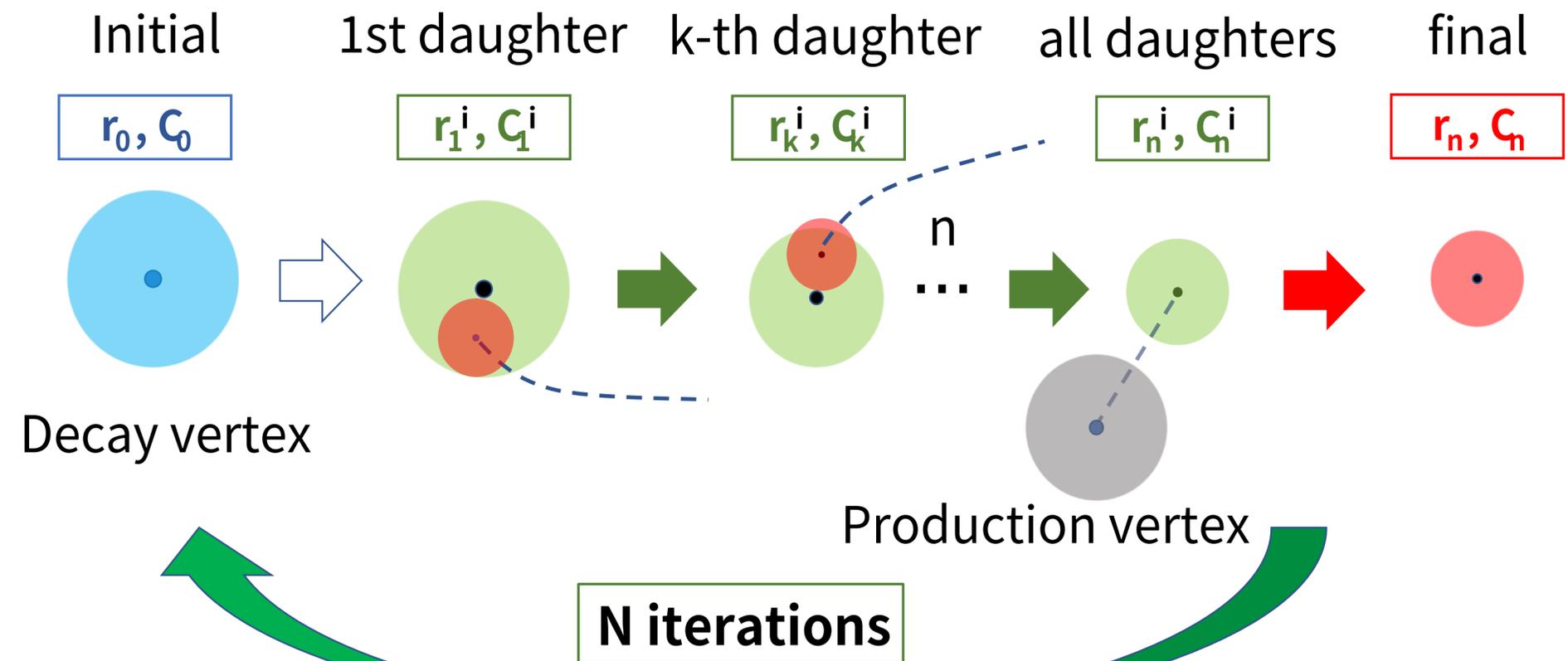


KFParticle Package

STAR collaboration, Science 328(2010)58



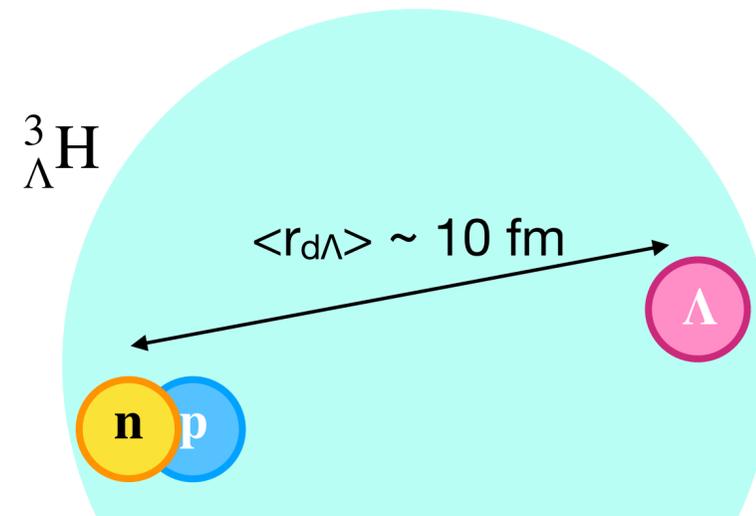
X. Ju, et al, NST 34(2023)10,158



- *KFParticle*: a **Kalman Filter** package for secondary vertex finding and fitting
- Utilize information from error matrices to improve signal significance
→ important for rare signals

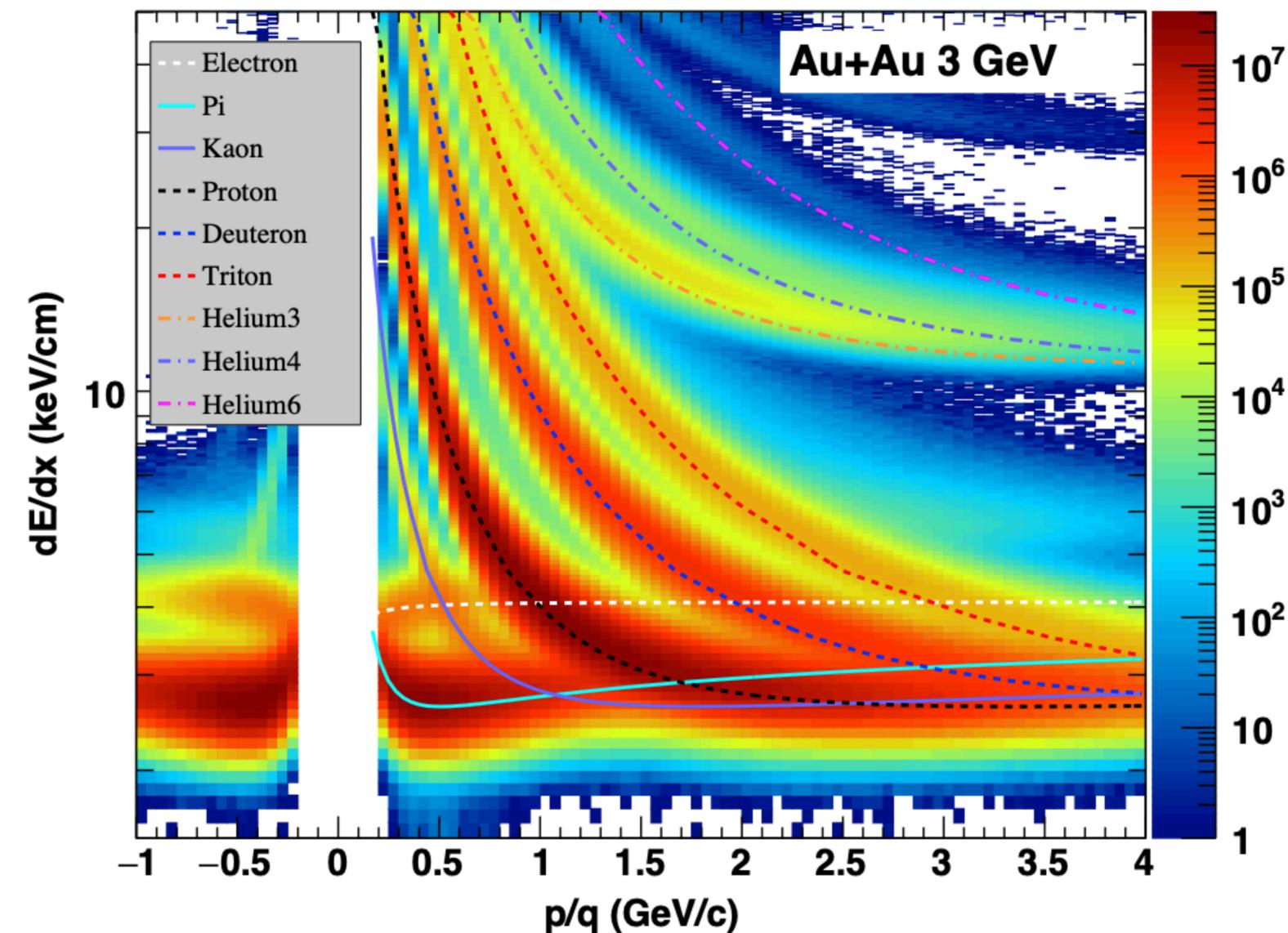
	${}^3_{\Lambda}\text{H}$	${}^4_{\Lambda}\text{H}, {}^4_{\Lambda}\text{He}$	${}^5_{\Lambda}\text{He}$
Mass number	3	4	5
Constituents	pn Λ	pnn Λ , ppn Λ	ppnn Λ
Excited states	/	${}^4_{\Lambda}\text{H}^*(1^+) \rightarrow {}^4_{\Lambda}\text{H}(0^+) + \gamma$ ${}^4_{\Lambda}\text{He}^*(1^+) \rightarrow {}^4_{\Lambda}\text{He}(0^+) + \gamma$	/
Λ binding energy (MeV)	0.163 \pm 0.036	2.16 \pm 0.08 2.38 \pm 0.03	3.12 \pm 0.02
Rms radii (fm)	4.332	1.809, 1.810	1.509

J. Zhao et al., arXiv:2508.05814

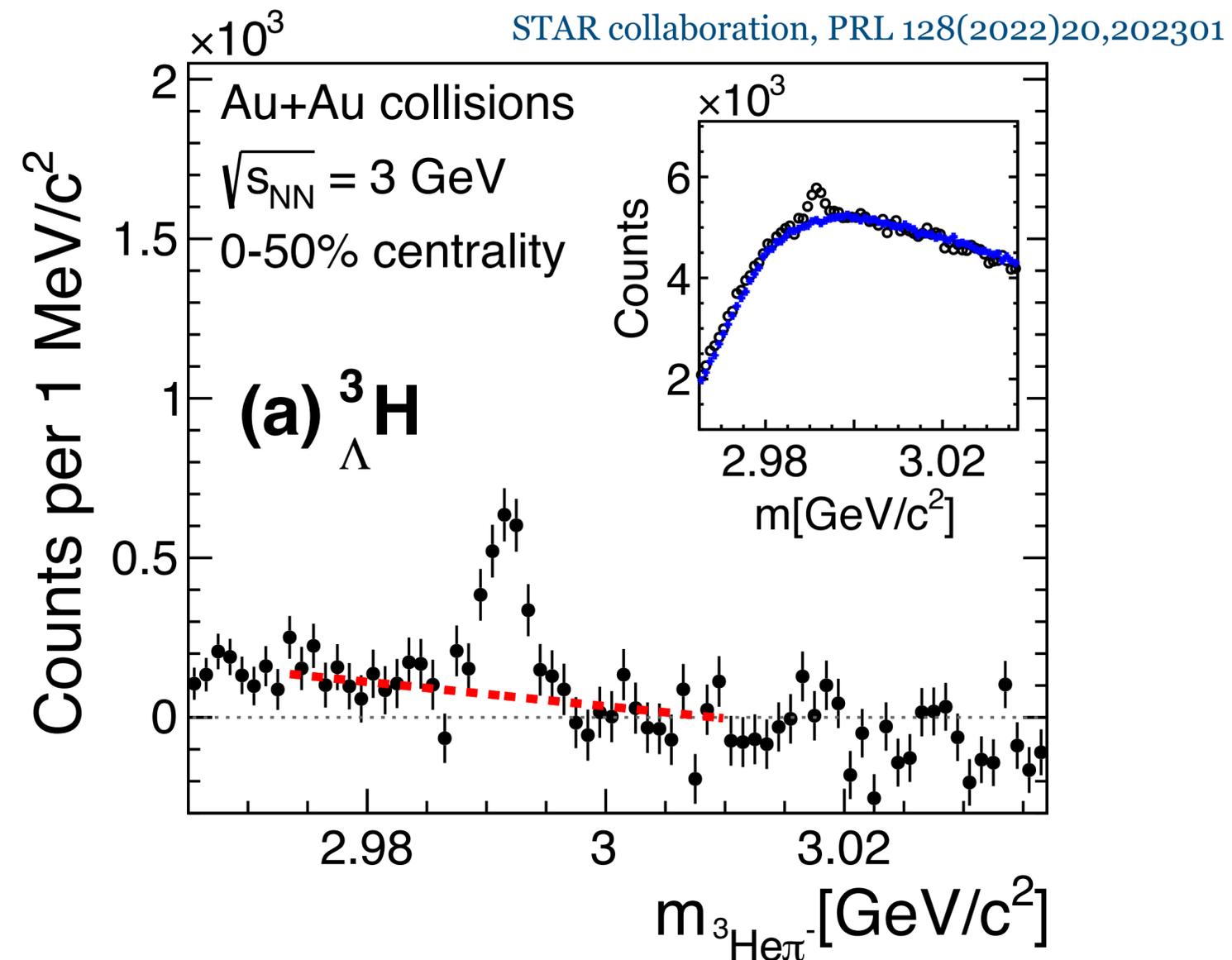


${}^3_{\Lambda}\text{H}$: **Characterized by loose binding and large radius**

Particle Identification (PID) and Reconstruction



- TPC ionization energy loss used for PID of daughter tracks



- Reconstructed via weak decay channel ${}^3_{\Lambda}\text{H} \rightarrow {}^3\text{He} + \pi^-$
- Combinatorial background estimated via track rotation method

Hypernuclei Yields at $\sqrt{s_{NN}}=3$ GeV

STAR, Phys. Rev. Lett. 128(2022)20,202301

- Hypertriton yield per participant is **significantly enhanced at 3 GeV** relative to LHC energies

Establishes low energy heavy-ion collisions as a promising tool to study exotic strange matter

- Thermal model
 - Strangeness correlation length from educated guess only
- Coalescence model
 - Huge difference using different methodologies

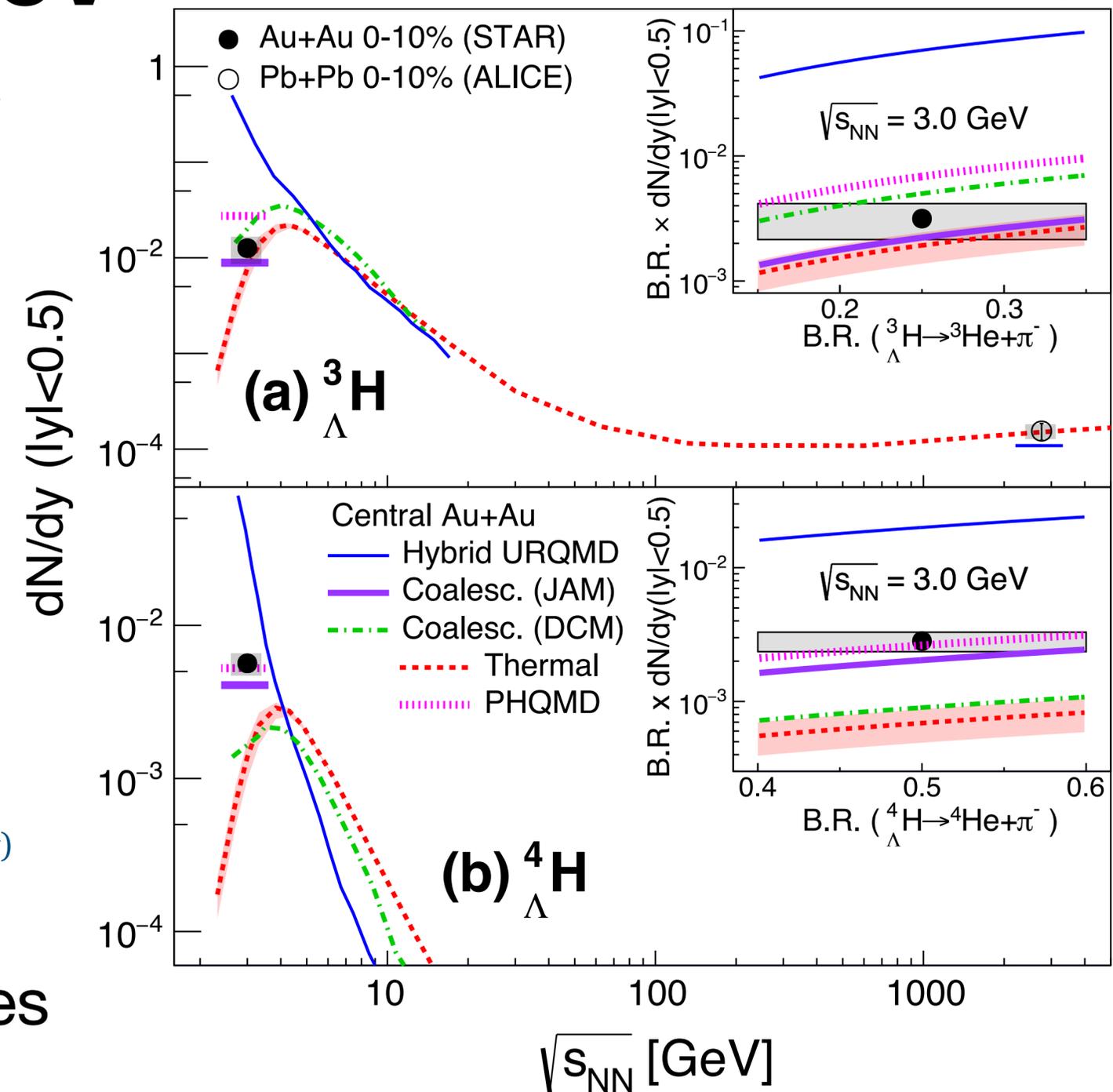
A. Andronic et al., Phys. Lett. B 697(2011)203 (update, preliminary)

J. Steinheimer et al., Phys. Lett. B 714(2012)85

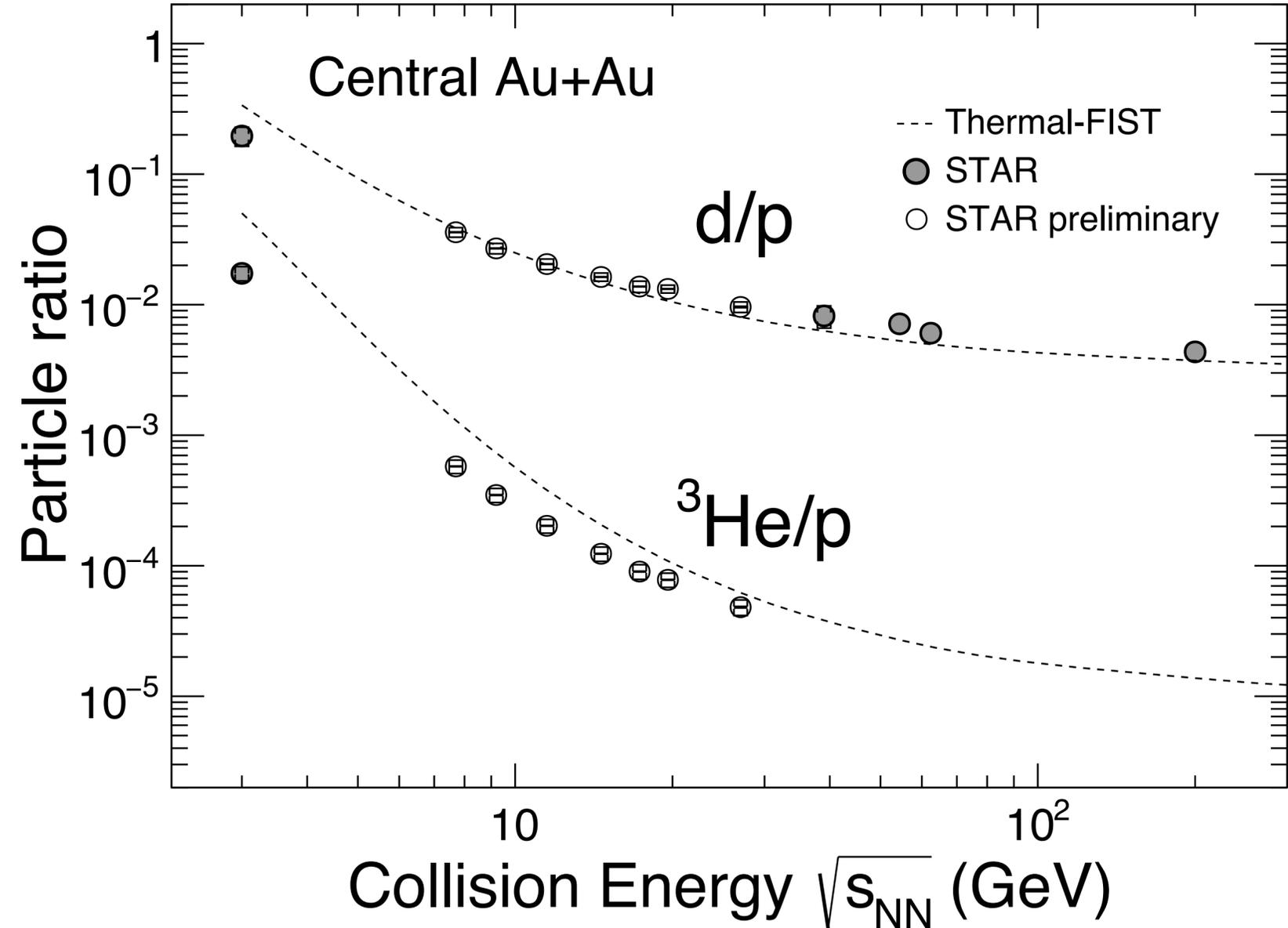
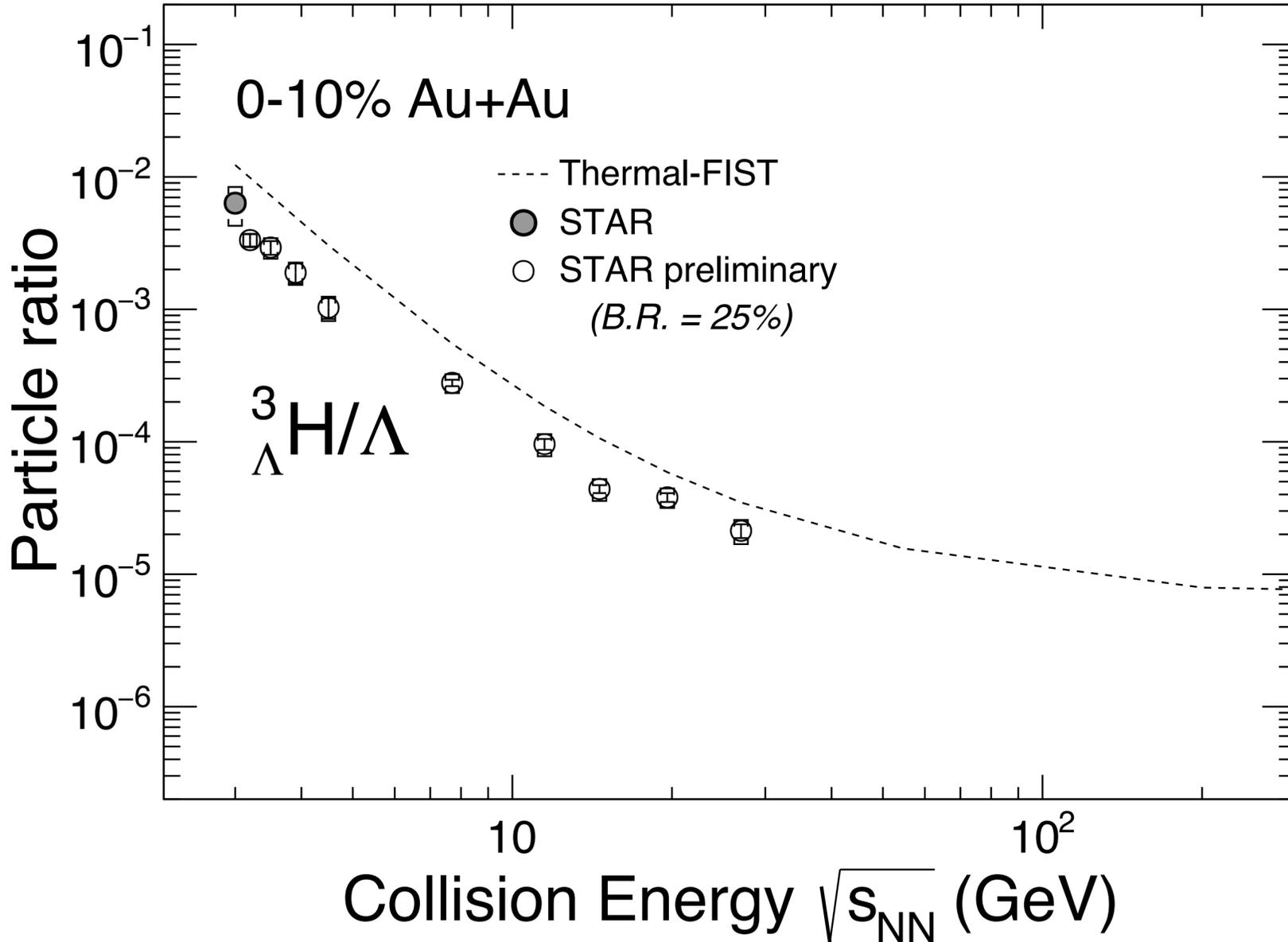
H. Liu et al., Phys. Lett. B 805(2020)135452

V. Kireyeu et al., Bull. Russ. Acad. Sci. Phys. 84(2020)957

- Robust conclusions on the microscopic production mechanism require tighter control and systematic validation of the coalescence approach



Nuclei-to-Nucleon Ratios



- Effects of strangeness correlation length and volume are **cancelled in yield ratios** in thermal model
- Thermal model describes deuteron well, but **overestimates both ${}^3_{\Lambda}\text{H}$ and ${}^3\text{He}$**

Data-Driven Semi-Analytical Coalescence Model

- Define $B_3({}^3_{\Lambda}\text{H})$ as ratio of hypernuclei yields to the product of constituent yields:

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

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](#)

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

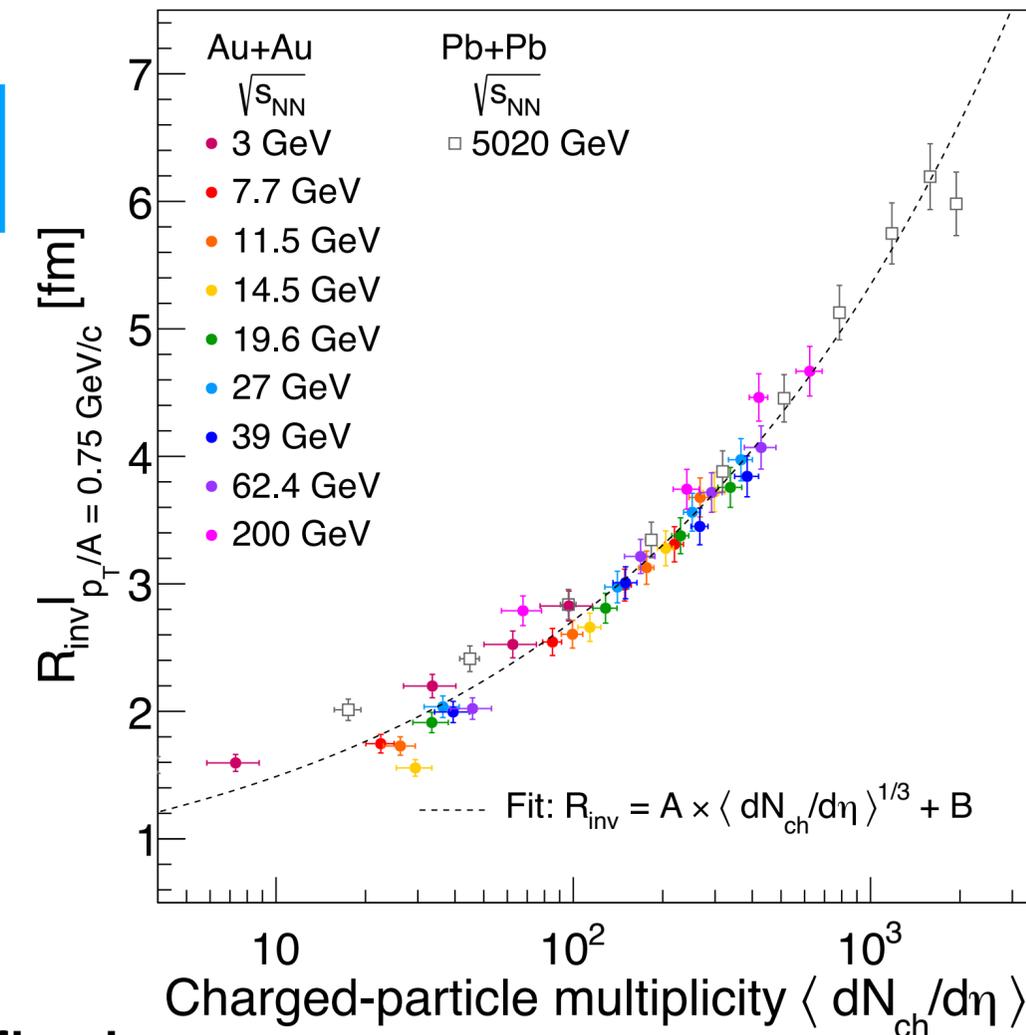
Nuclei wave function Nucleon source

- Assume an isotropic Gaussian nucleon source:

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

- R_{inv} is estimated using deuteron data [YHL et al., arXiv:2510.06758](#)

- No free parameters** for ${}^3_{\Lambda}\text{H}$ once **wave function** is specified



The Hypertriton (${}^3_{\Lambda}\text{H}$) Wave Function

YHL et al., arXiv:2510.06758

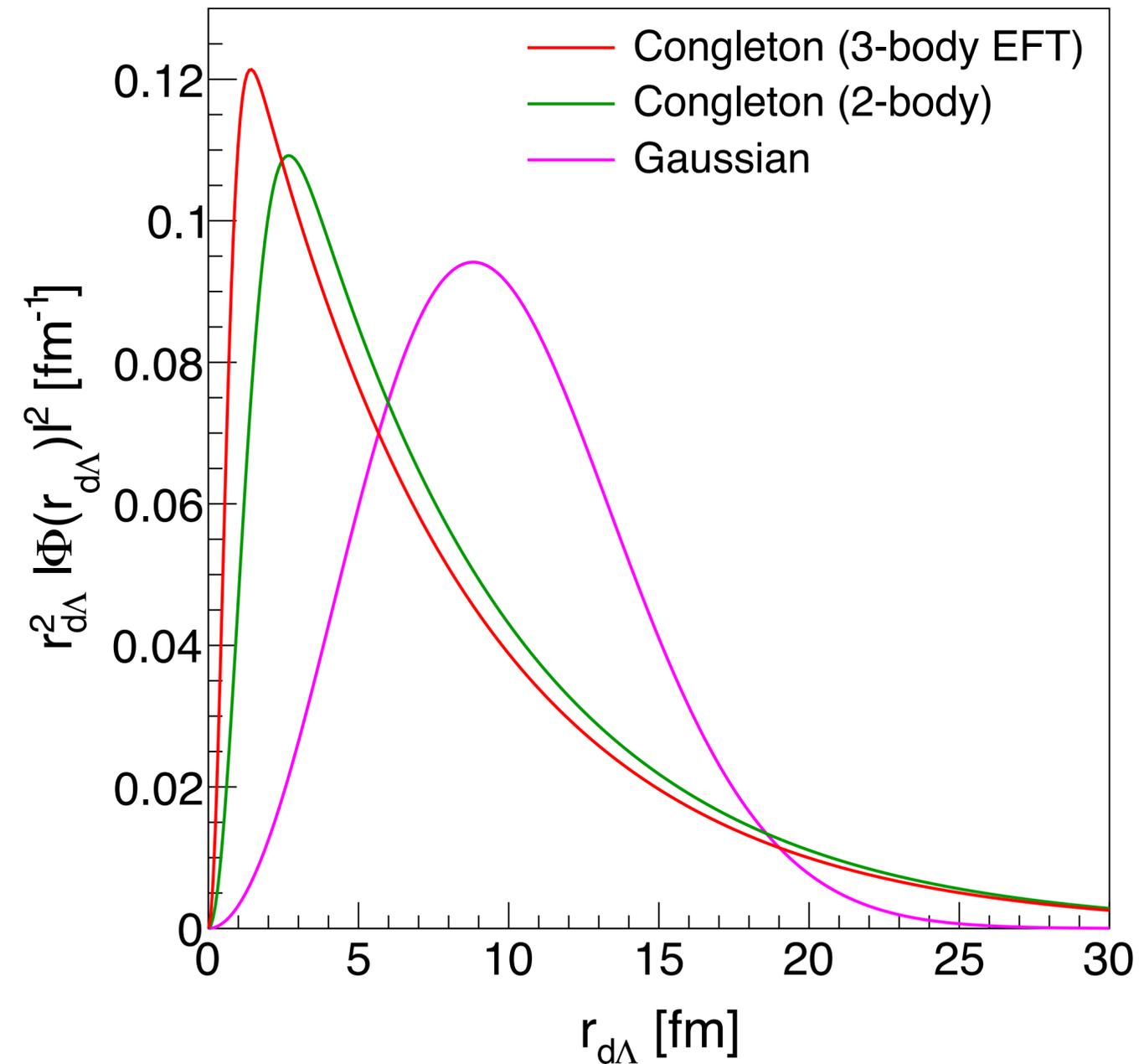
- ${}^3_{\Lambda}\text{H}$: loosely bound hypernuclei
($B_{\Lambda} = 0.163 \pm 0.036$ MeV)

- Gaussian: $\Phi_{{}^3_{\Lambda}\text{H}}(r_{pn}, r_{\Lambda}) = \left(\frac{1}{3\pi^2 b_{pn}^2 b_{\Lambda}^2} \right)^{\frac{3}{4}} e^{-\frac{r_{pn}^2}{4b_{pn}^2} - \frac{r_{\Lambda}^2}{3b_{\Lambda}^2}}$
 $b_{\Lambda} = 7.2$ fm
F. Bellini et al., *Phys. Rev. C* 103 (2021) 014907

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

- 2-body model of ${}^3_{\Lambda}\text{H}$
($Q_{\Lambda}, \alpha_{\Lambda}$) = (1.17, 0.068) fm⁻¹
J. Congleton, *J. Phys. G* 18 (1992) 339-357

- 3-body effective field theory
($Q_{\Lambda}, \alpha_{\Lambda}$) = (2.5, 0.068) fm⁻¹
F. Hildenbrand, H.-W. Hammer, *PRC* 100(2019)034002

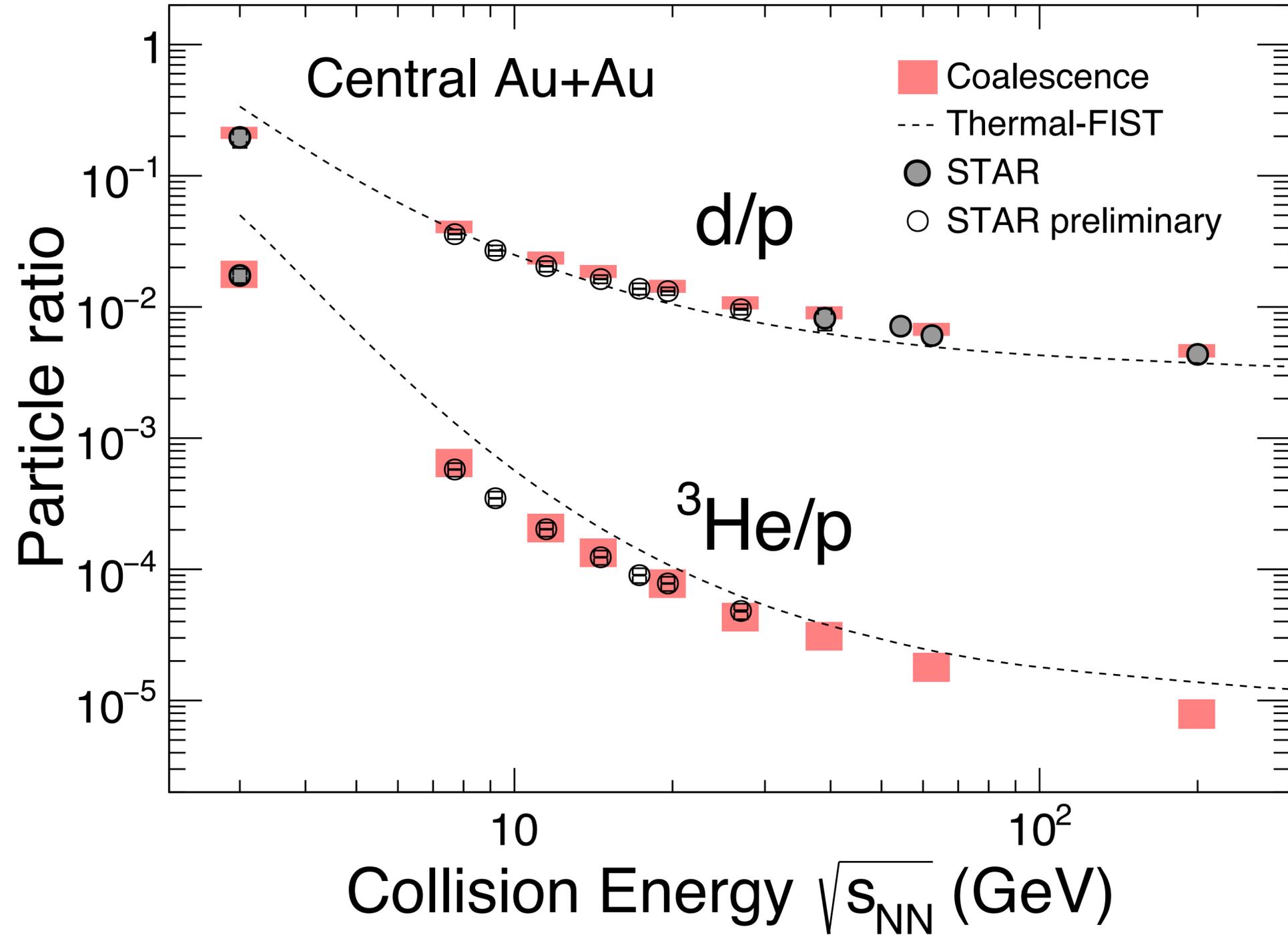


Wave function of the ${}^3_{\Lambda}\text{H}$ remains is an active field of research

J. Zhao et al. arXiv:2508.05814 (2025)
Z. Zhang et al., arXiv:2508.03575 (2025)

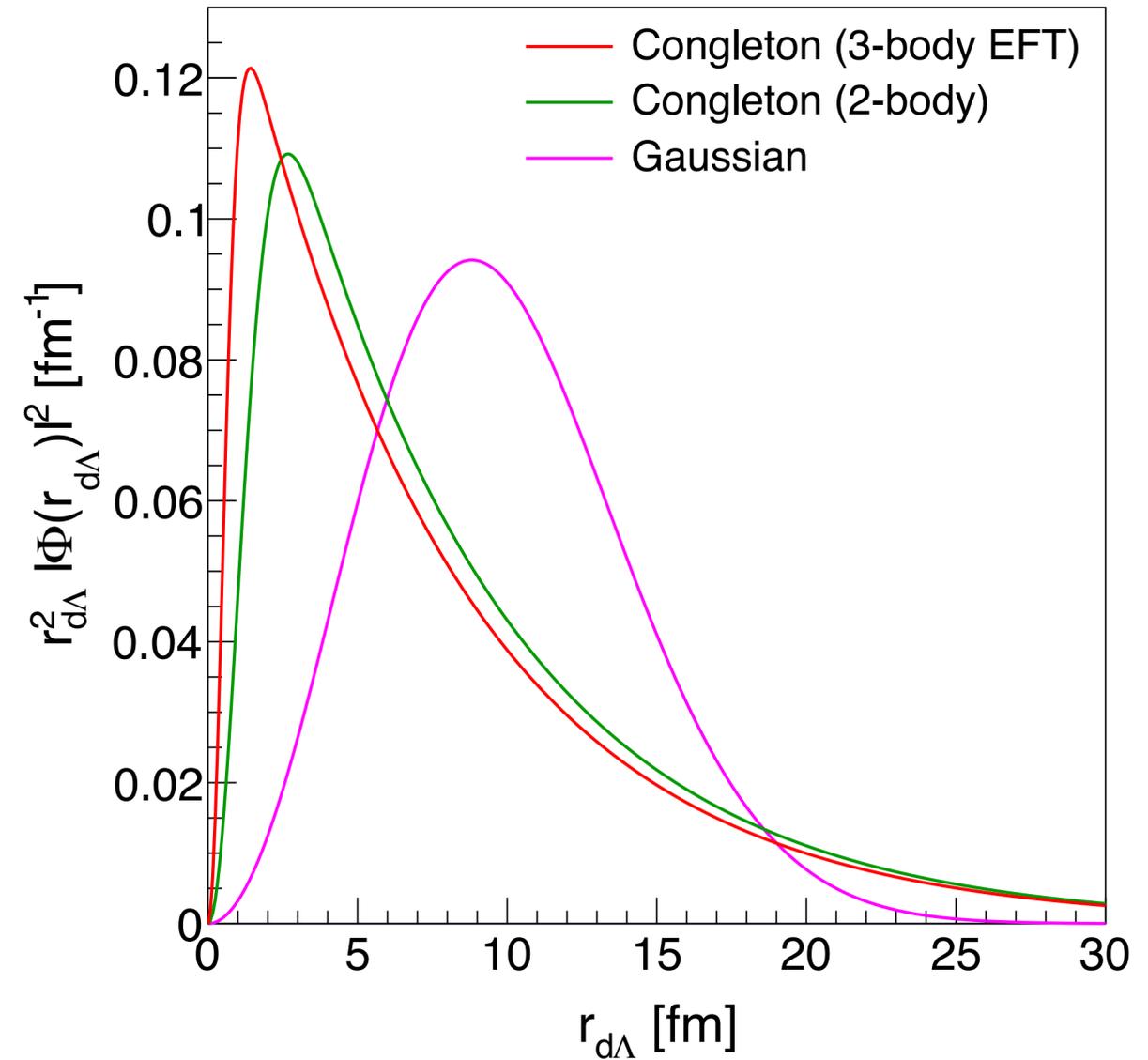
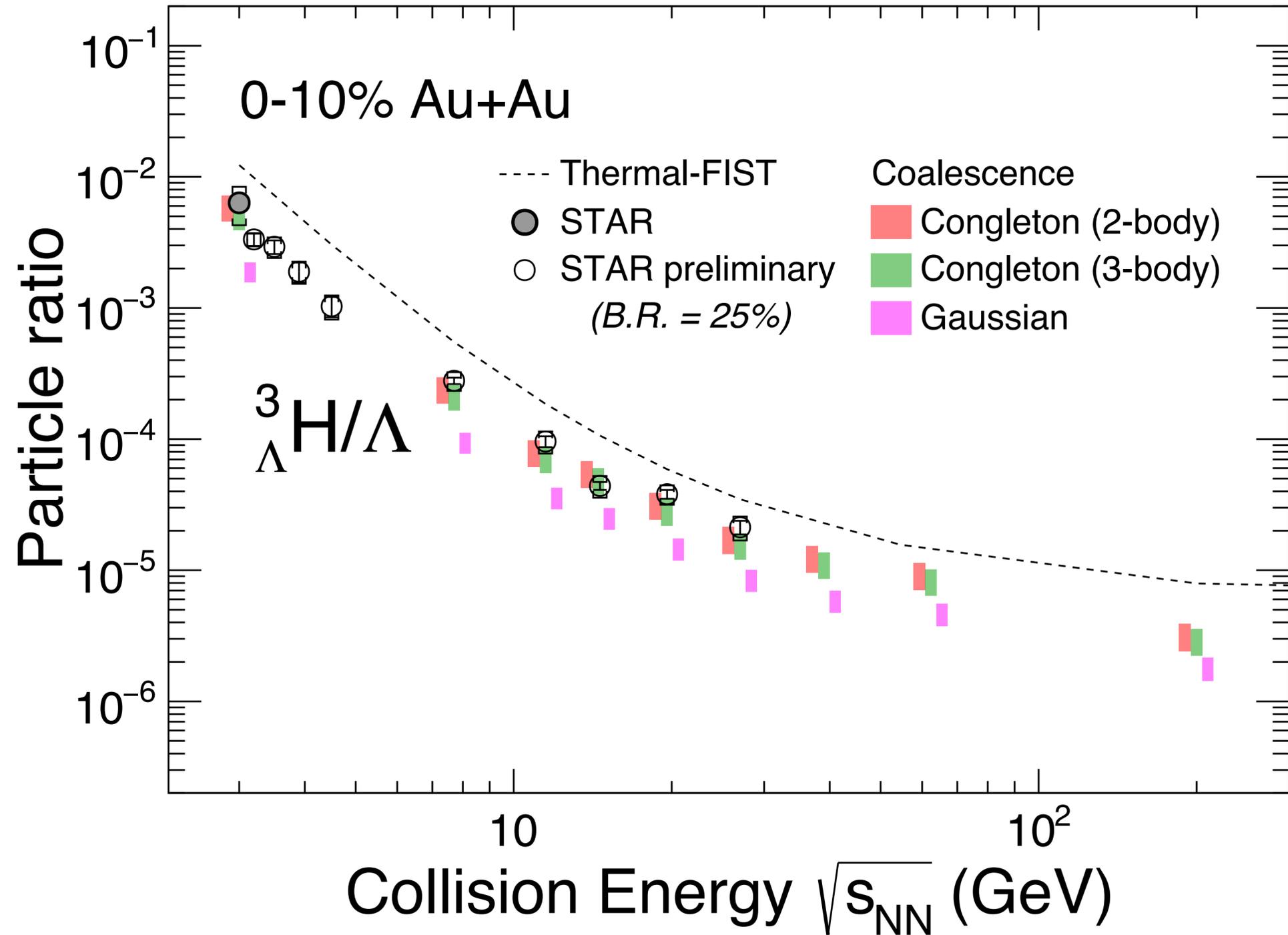
Comparison with Coalescence: Nuclei

YHL et al., arXiv:2510.06758
V. Vovchenko, et al, Comput. Phys. Commun. 244 (2019) 295
STAR, Phys. Rev. Lett. 130 (2023) 202301



- Coalescence gives a reasonable description of the nuclei-to-nucleon data

Comparison with Coalescence: Hypernuclei



YHL et al., arXiv:2510.06758

V. Vovchenko, et al, Comput. Phys. Commun. 244 (2019) 295

STAR, Phys. Rev. Lett. 128(2022)20,202301

- The Gaussian wave function underestimates ${}^3_{\Lambda}H/\Lambda$, while the Congleton wave function provides a quantitatively consistent description

Strangeness Population Factor S_3

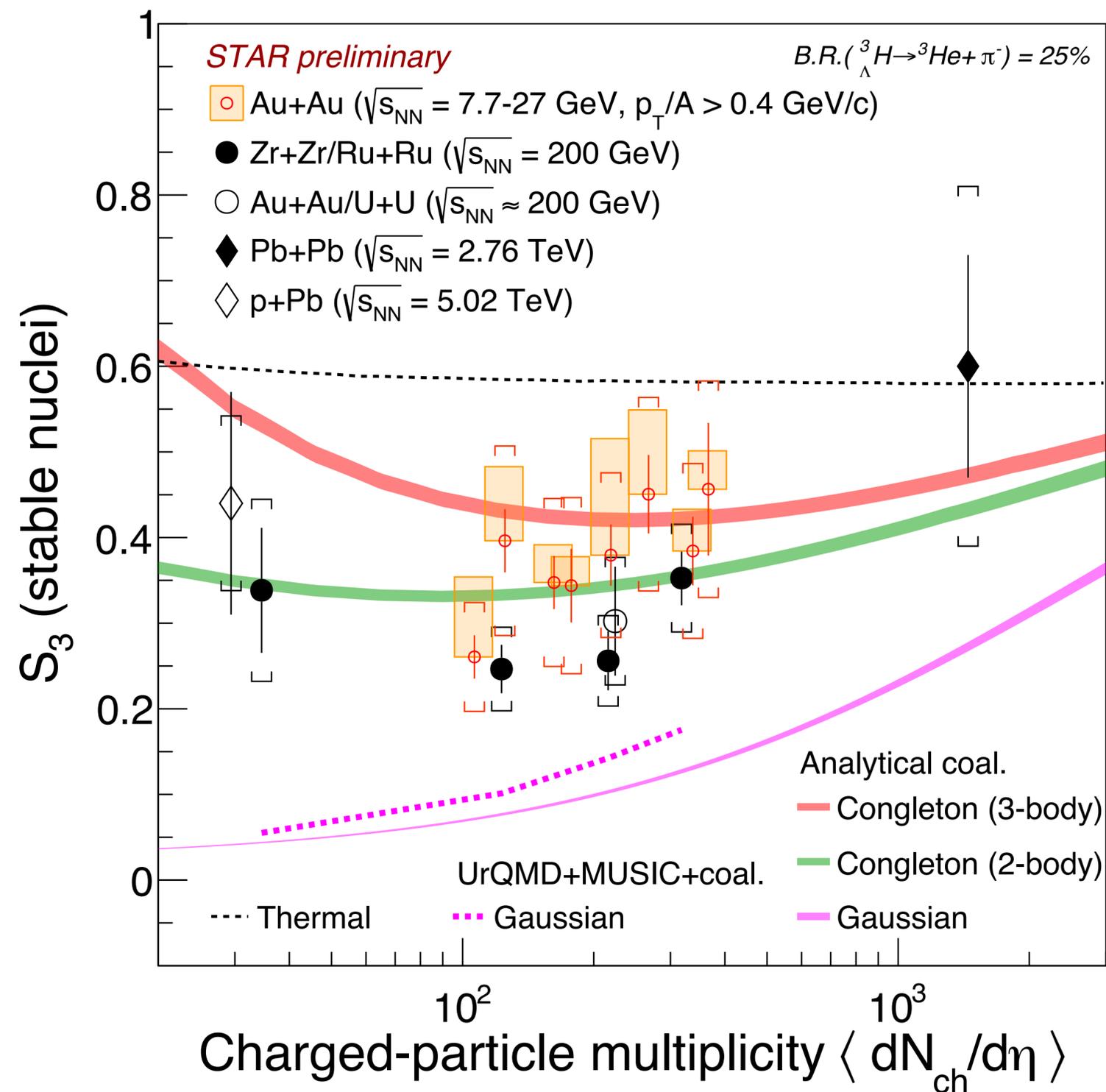
STAR, Nature 2024(2024)77
 ALICE, PRL 128(2022)252003, PLB 754(2016)360
 Thermal: V. Vovchenko et al., CPC 244(2019)295
 UrQMD+MUSIC coal.: K. Sun et al., PLB 820(2021)136571
 ana. coal.: F. Bellini et al, PRC 103(2021)014907
 YHL et al, arXiv:2510.06758

- $S_3 = \frac{{}^3_{\Lambda}\text{H}}{{}^3\text{He} \times \frac{\Lambda}{p}}$ compares ${}^3_{\Lambda}\text{H}$ production to ${}^3\text{He}$

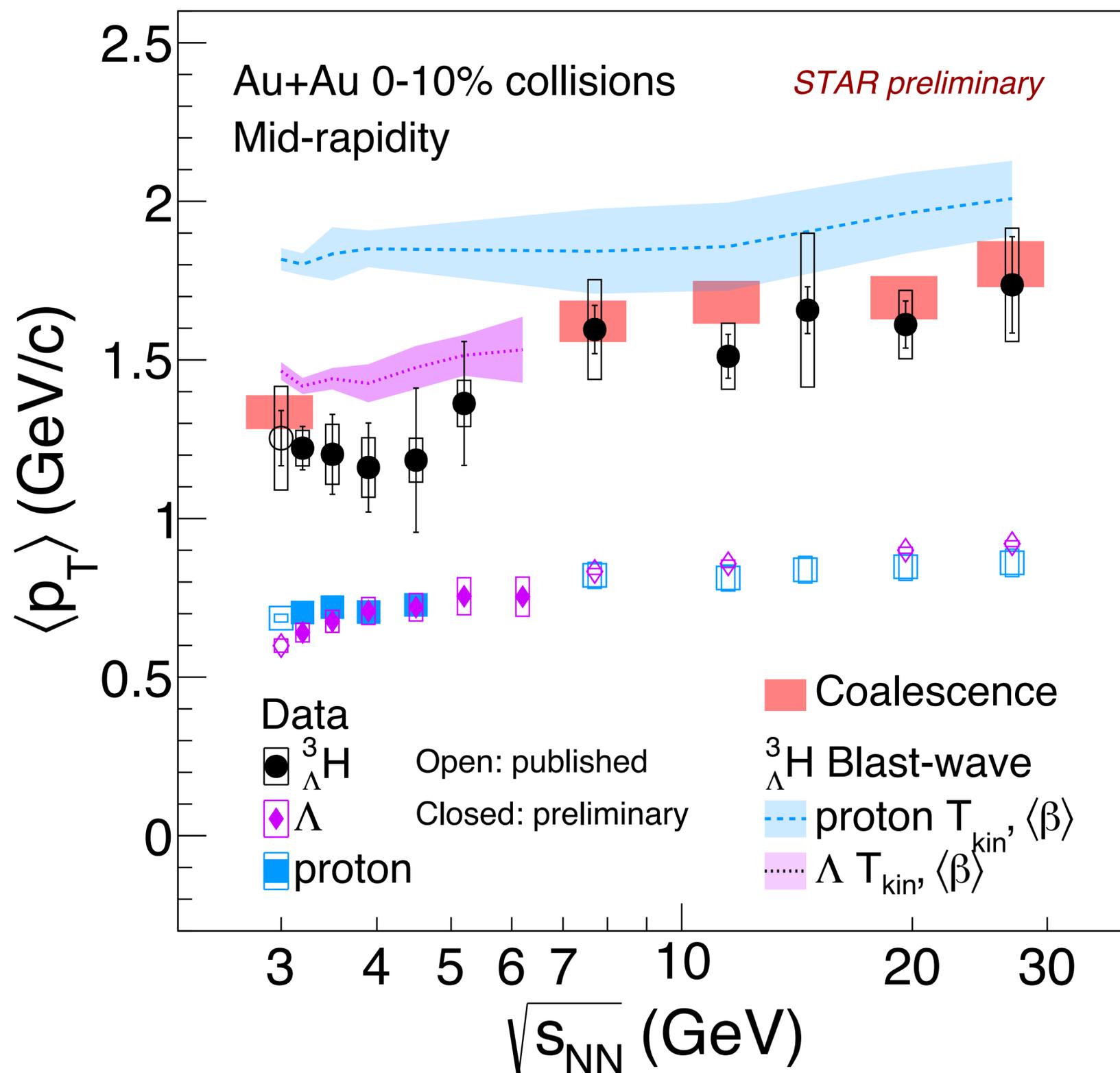
- Coalescence using **Congleton wave function** describes S_3 across different energies/systems

- Suppression of ${}^3_{\Lambda}\text{H}$ relative to ${}^3\text{He}$ due to coalescence mechanism confirmed by data

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



Energy Dependence of Mean Transverse Momentum



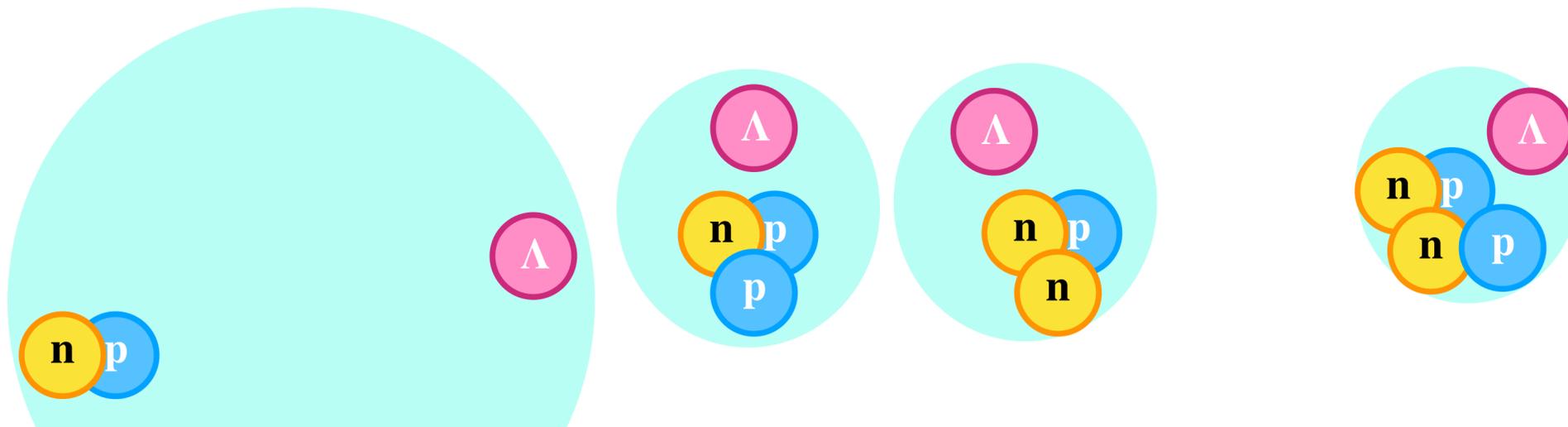
- Hydrodynamic-inspired Blast-wave model: assumes particles are emitted thermally from an expanding source with **common T_{kin} and $\langle \beta_T \rangle$**
 - **Vary mass** to construct blast-wave predictions using p or Λ freeze-out parameters

Deviation from blast-wave picture observed for ${}^3_{\Lambda}\text{H}$ particularly below 7.7 GeV

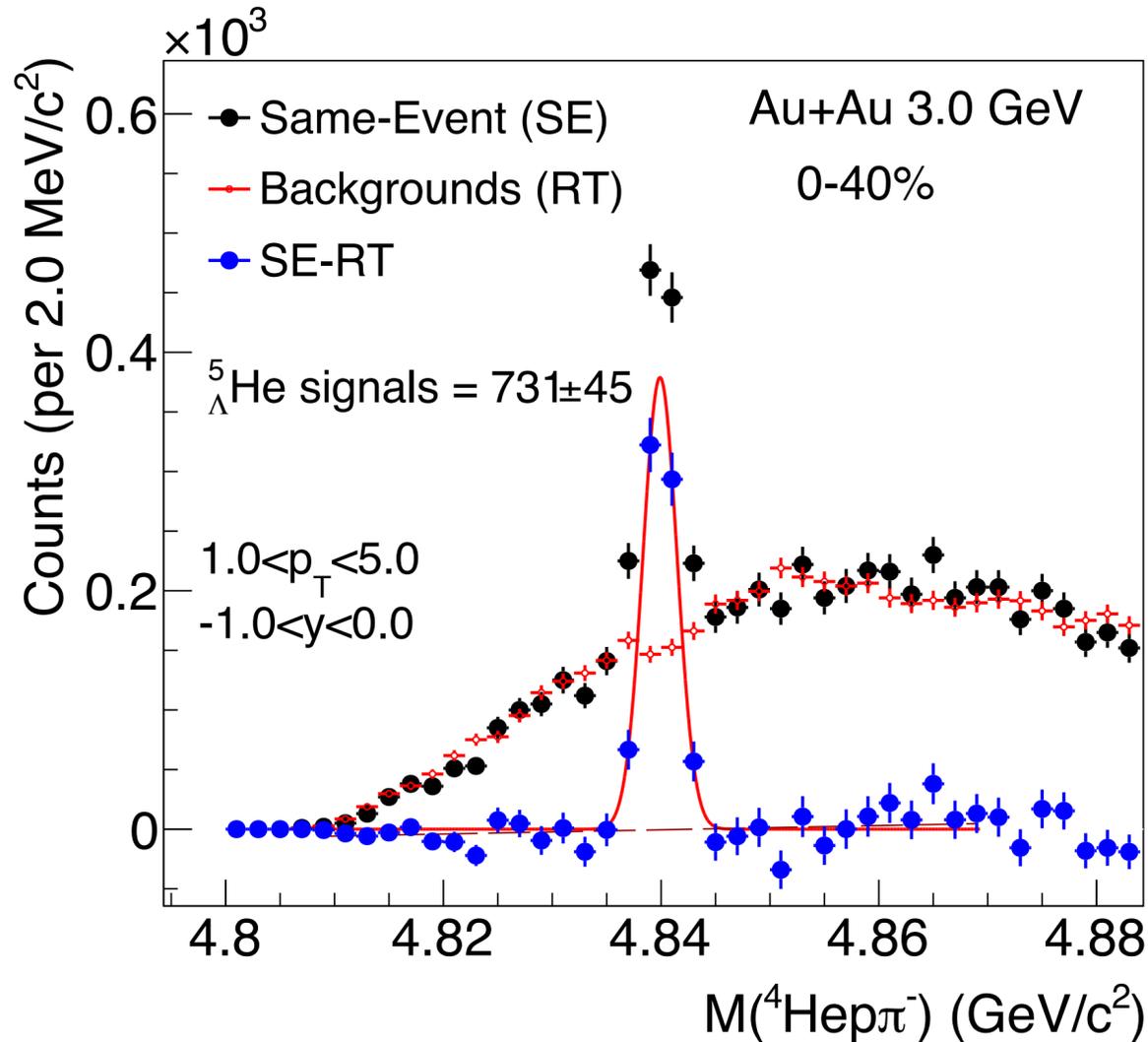
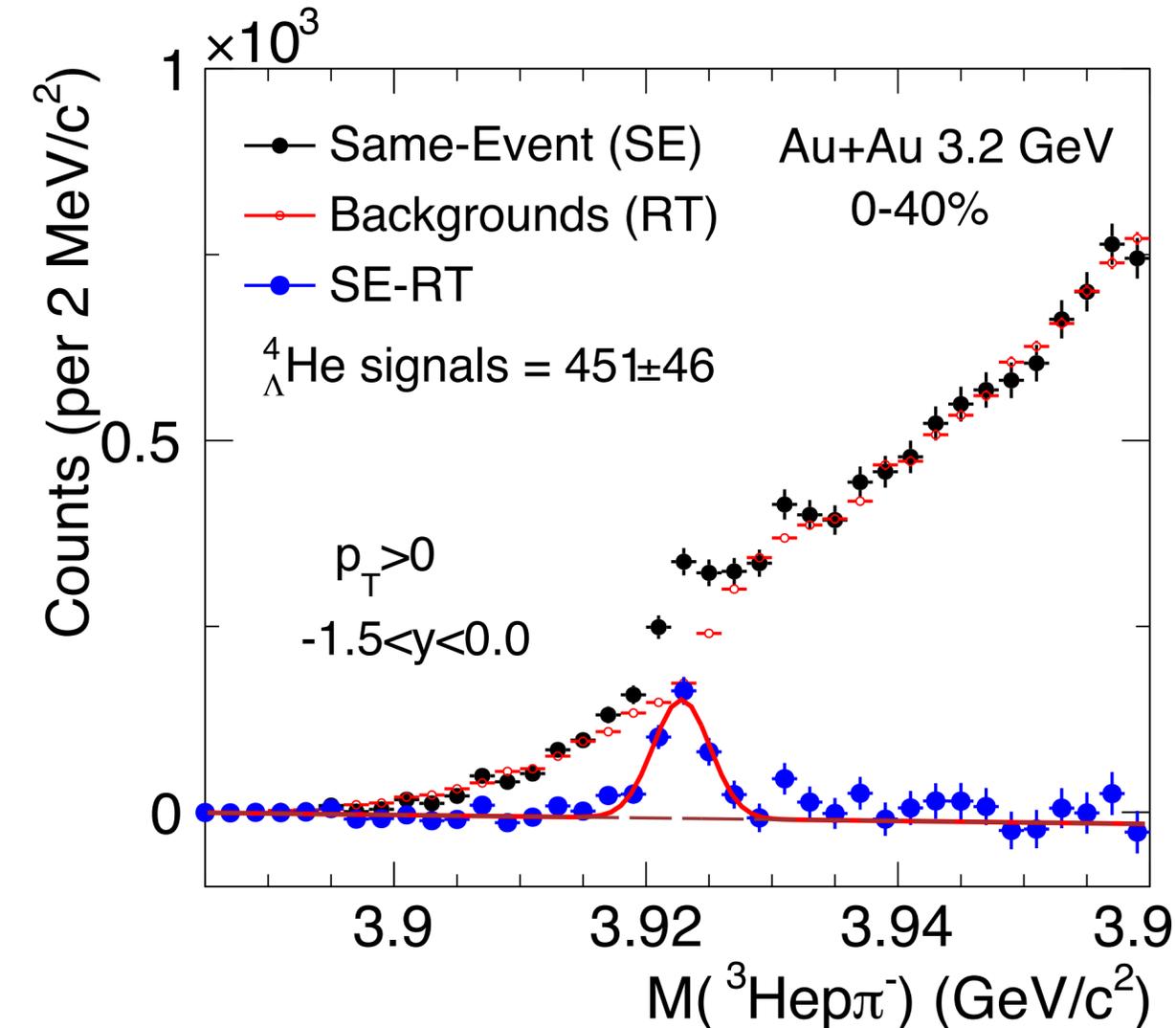
- Coalescence provides a reasonable description of the energy dependence of $\langle p_T \rangle$

	${}^3_{\Lambda}\text{H}$	${}^4_{\Lambda}\text{H}, {}^4_{\Lambda}\text{He}$	${}^5_{\Lambda}\text{He}$
Mass number	3	4	5
Constituents	pn Λ	pnn Λ , ppn Λ	ppnn Λ
Excited states	/	${}^4_{\Lambda}\text{H}^*(1^+) \rightarrow {}^4_{\Lambda}\text{H}(0^+) + \gamma$ ${}^4_{\Lambda}\text{He}^*(1^+) \rightarrow {}^4_{\Lambda}\text{He}(0^+) + \gamma$	/
Λ binding energy (MeV)	0.163 ± 0.036	2.16 ± 0.08 2.38 ± 0.03	3.12 ± 0.02
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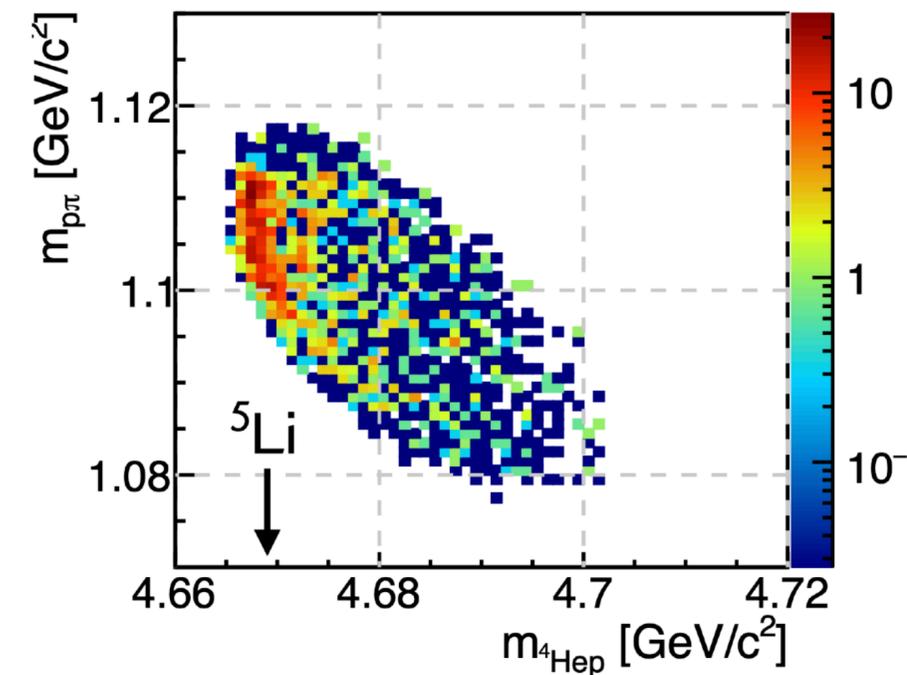
Binding energy dependence of hypernuclei production



Hypernuclei Reconstruction with 3-body Decays



Yingjie Zhou, QM25



- The 3-body decay phase space reflects the underlying **decay kinematics** and **final-state interactions**
- Embedding simulations are weighted to reproduce the measured kinematic distributions, ensuring **realistic efficiency corrections**

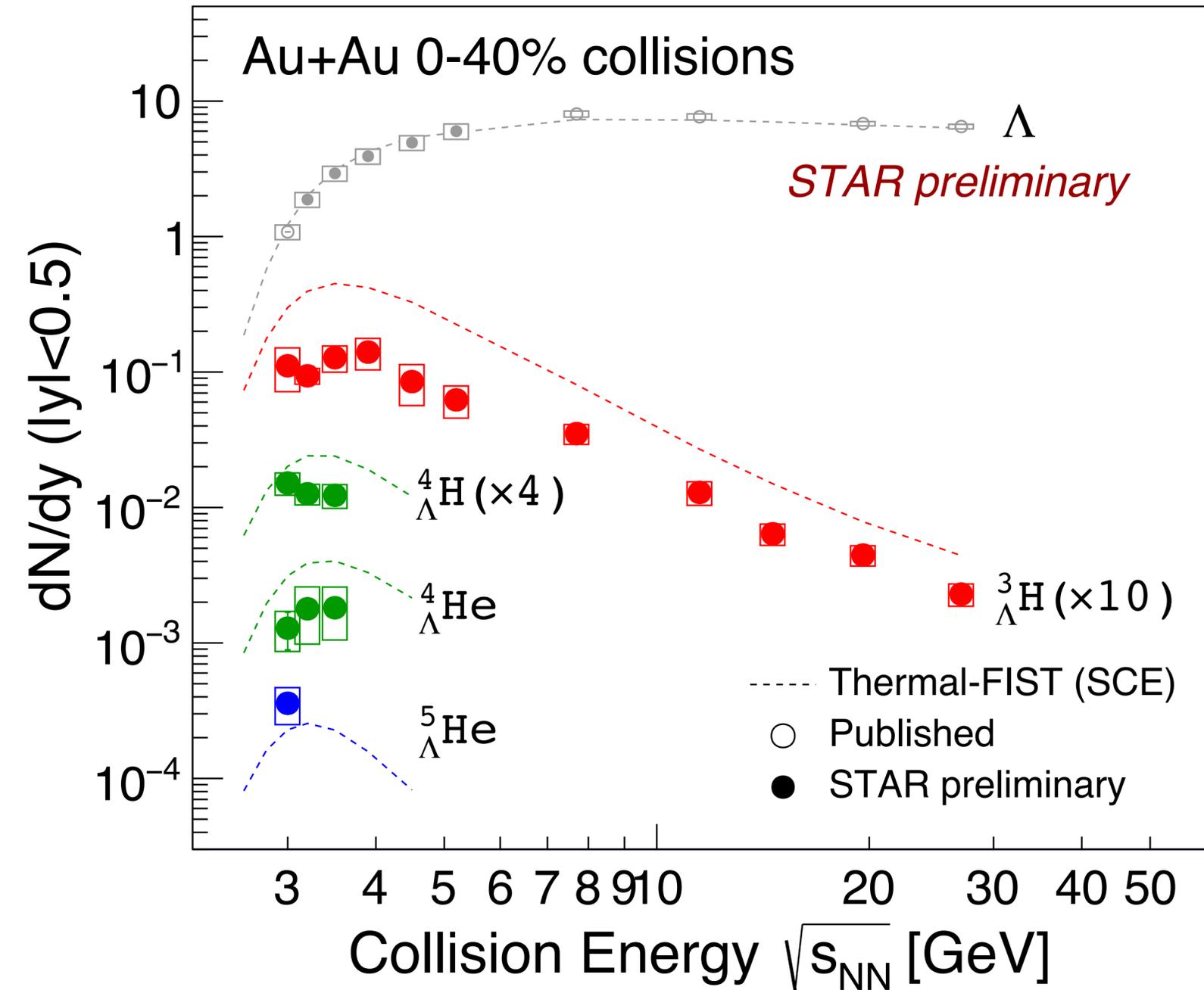
Hypernuclei Excitation Functions

STAR, Phys. Rev. Lett. 128 (2022) 202301
STAR, Phys. Rev. C 102 (2020) 34909
STAR, JHEP 2024 (2024) 139

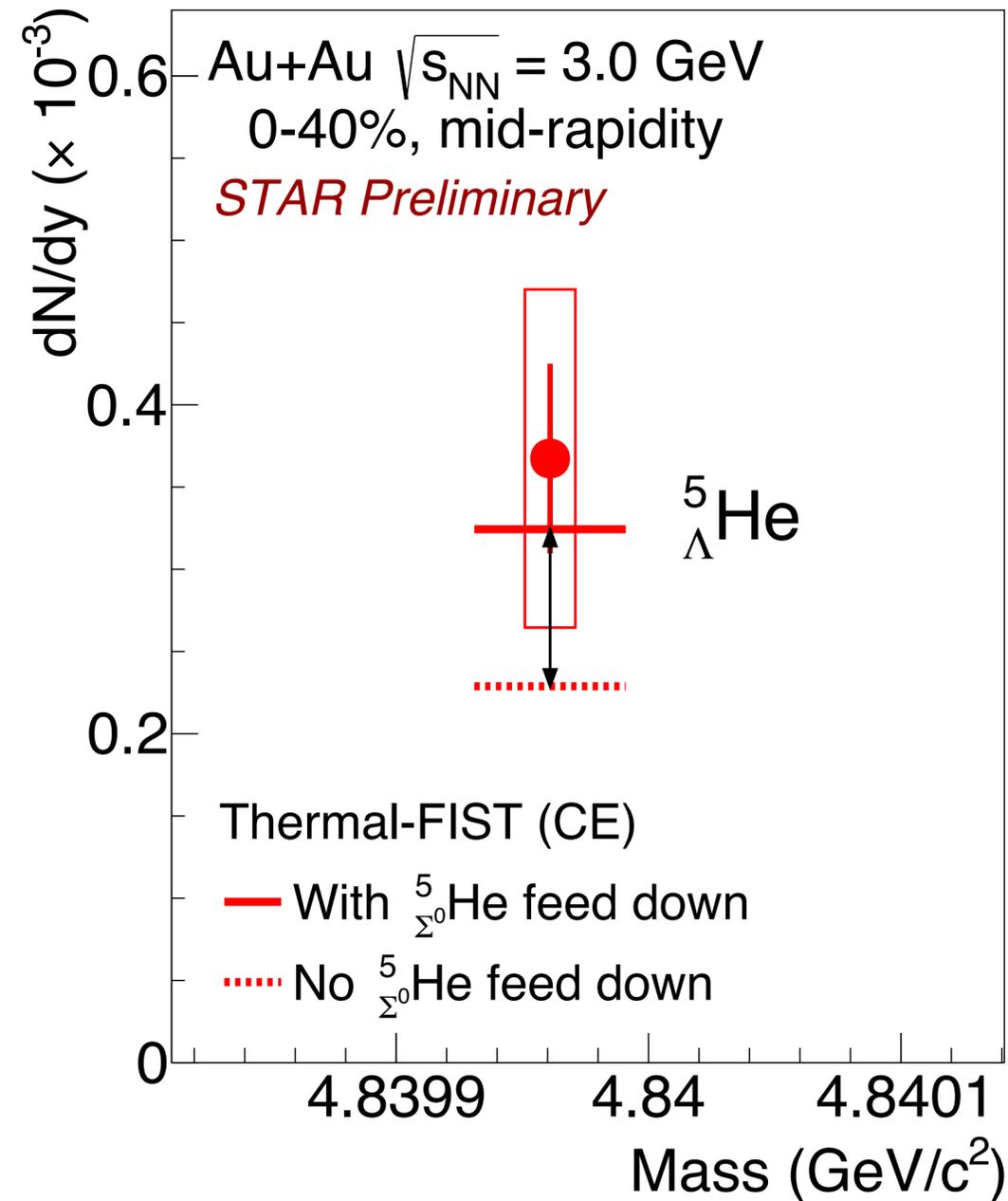
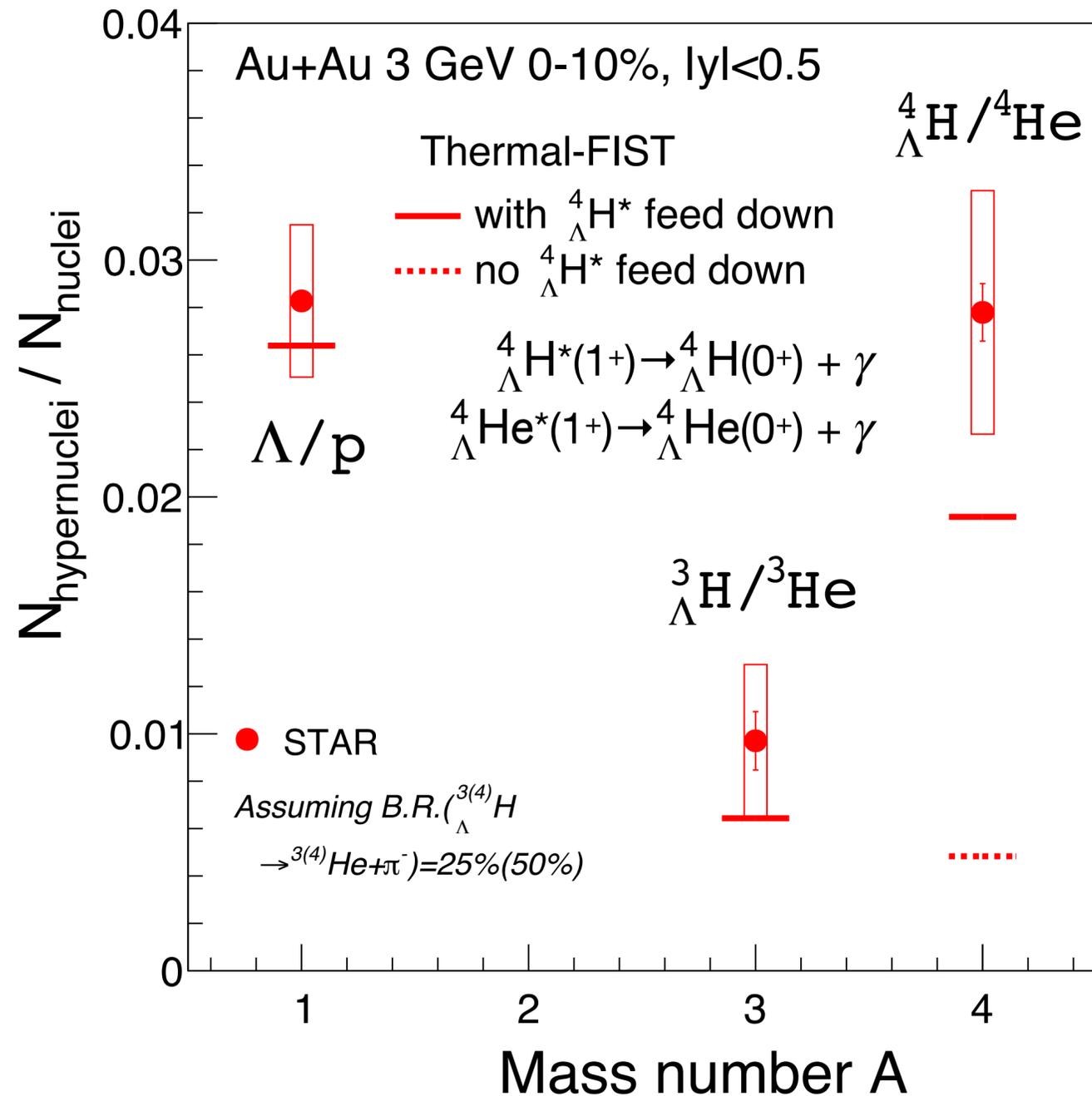
- As the mass number increases, the discrepancy with the thermal model decreases

Larger survival probability for more tightly bound hypernuclei?

- Coalescence with realistic Wigner functions for $A > 3$ hypernuclei is crucial to interpret the data



Excited-State Effects in Hypernuclei Production at $\sqrt{s_{NN}}=3$ GeV



Excited hypernuclear states play a crucial role in accurately modeling production yields

- **Non-monotonic** trend in hypernuclei-to-nuclei ratios can be explained by **excited state feed-down**

- Possible feed-down from ${}^5_{\Sigma^0}He \rightarrow {}^5_{\Lambda}He + \gamma$

J. Johnstone et al., JPG 8, L105 (1982)

Rapidity Dependence of Hypernuclei Production

- Significant hypernuclei production near target rapidity

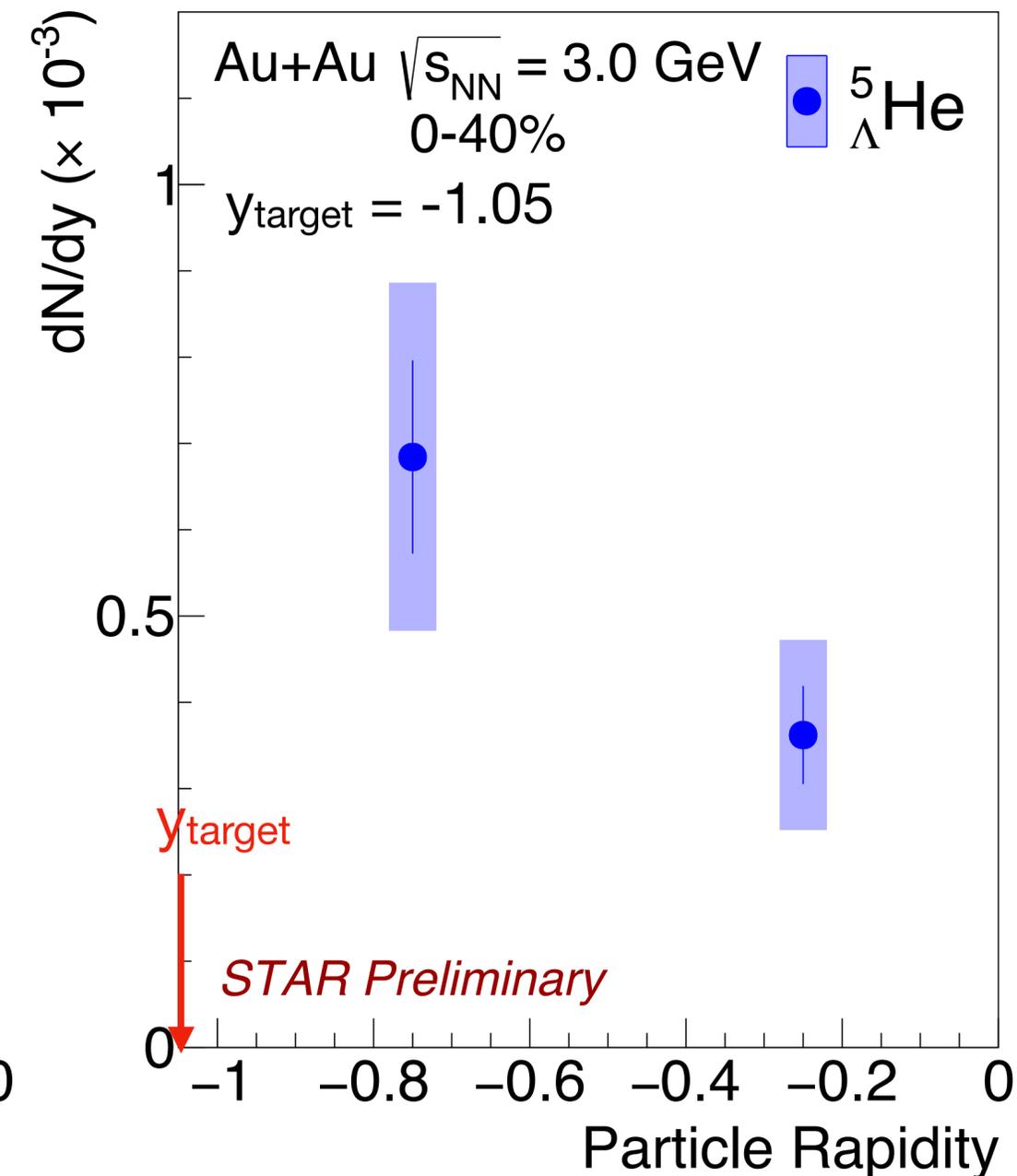
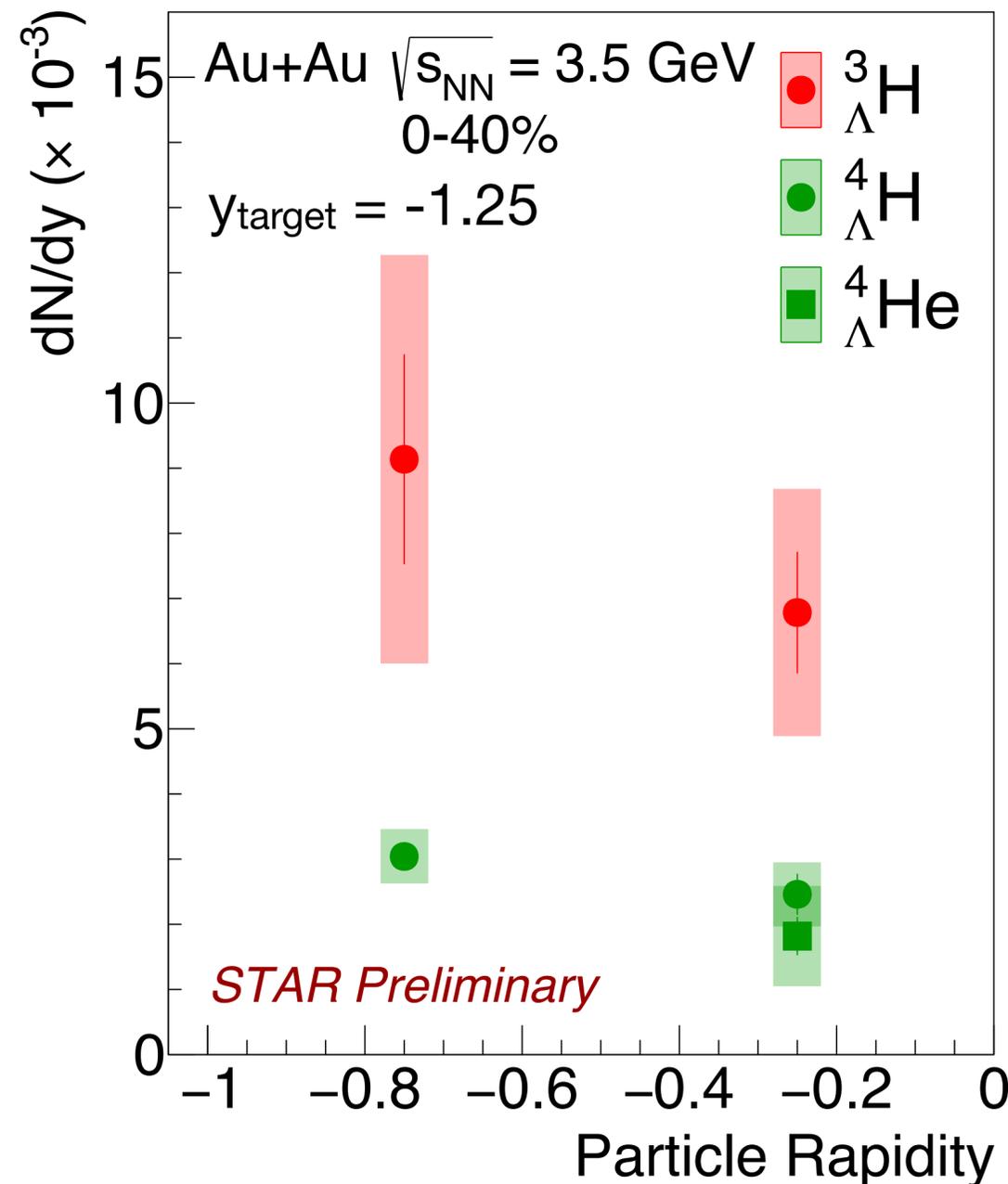
Spectator matter plays an important role in hypernuclei production

- Not “thermal”-like
- Coalescence
- Multifragmentation

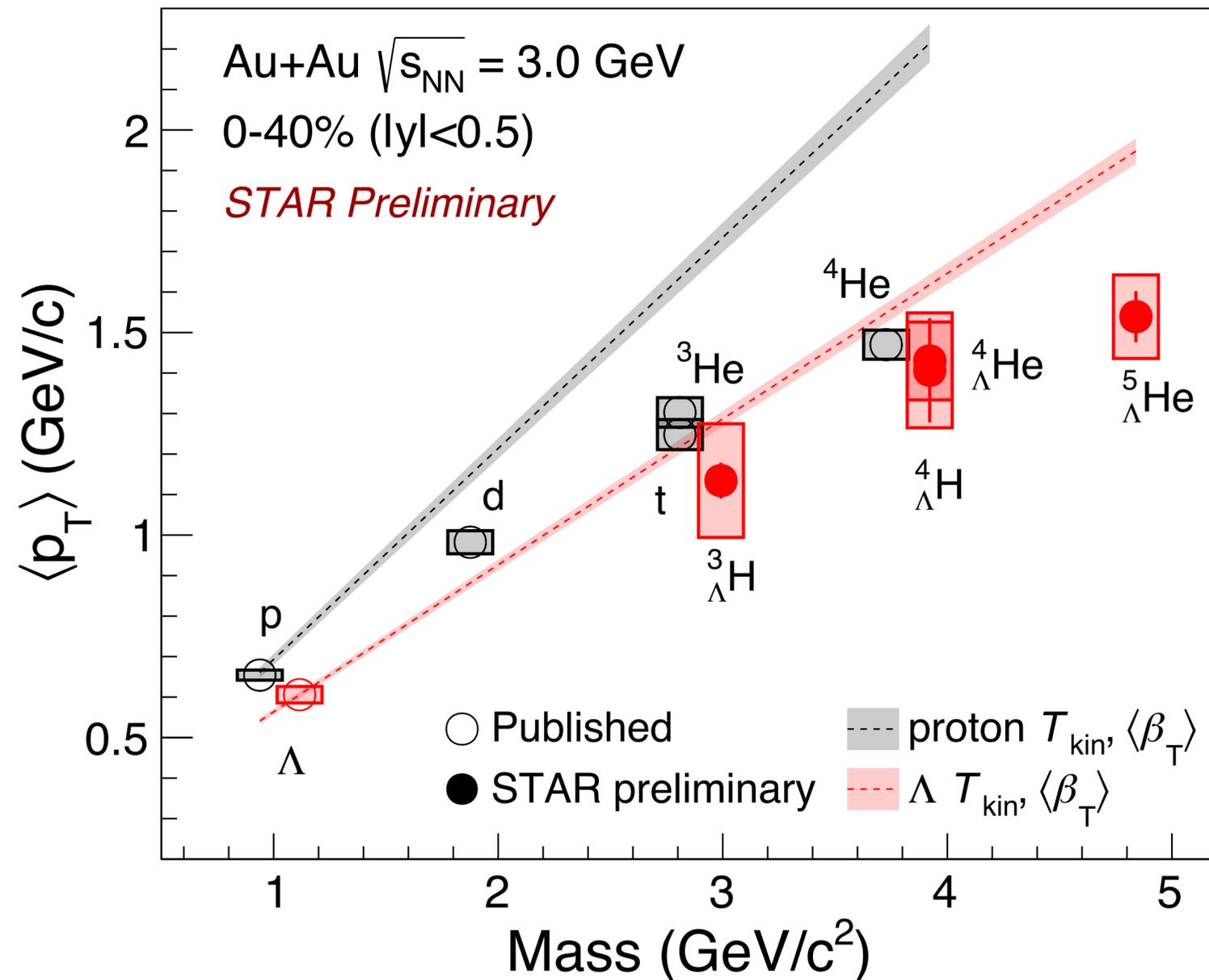
Liquid-gas phase transition in hypermatter

Phys.Rev.C 76, 024909 (2007)

- *More differential measurements underway!*



Mean Transverse Momentum $\langle p_T \rangle$ at $\sqrt{s_{NN}}=3$ GeV



- Vary mass to construct blast-wave predictions using $p(\Lambda)$ freeze-out parameters

	p	Λ
$\langle \beta_T \rangle$ (c)	0.43	0.33
T_{kin} (GeV)	0.065	0.076

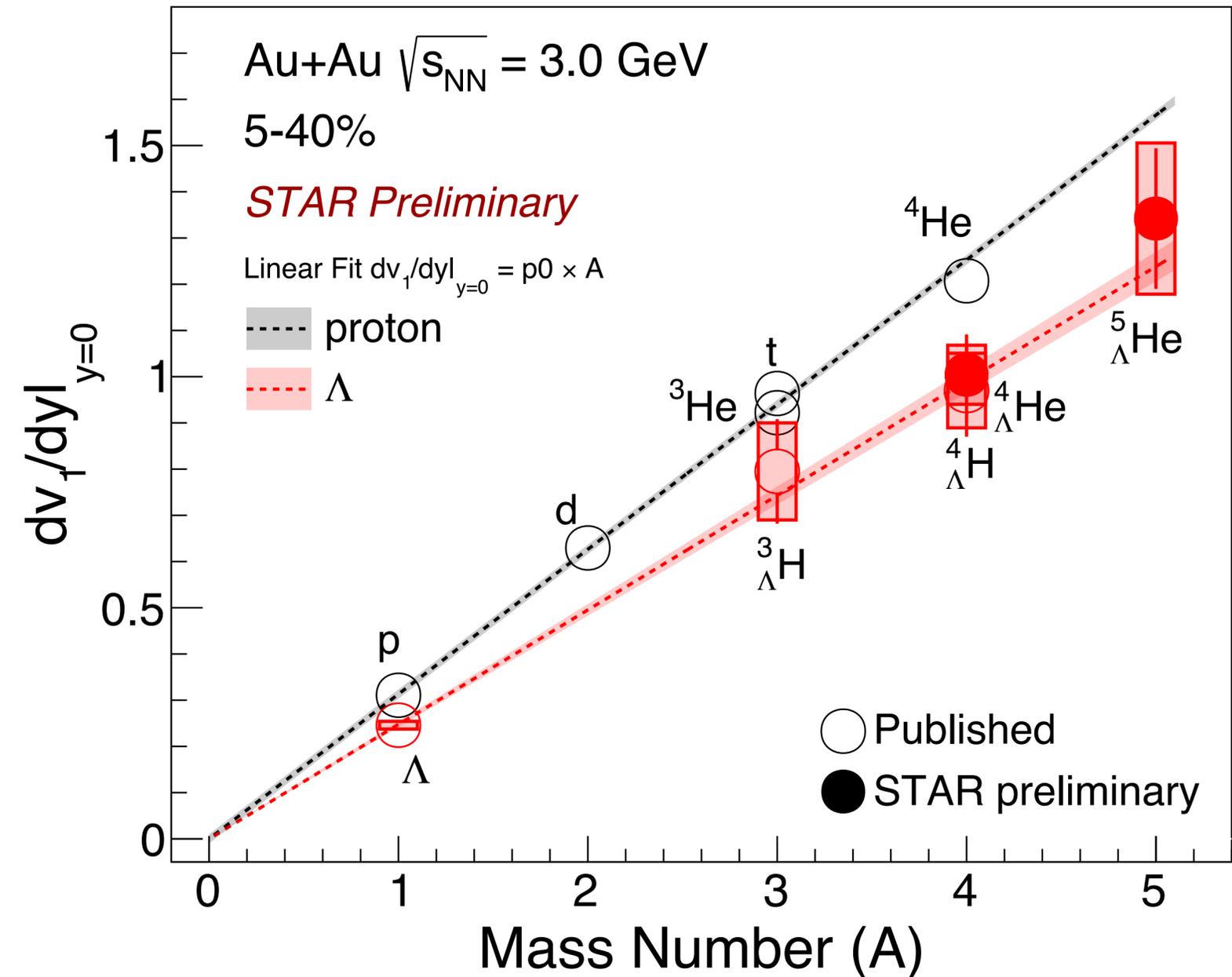
- Larger deviation from blast-wave ansatz for heavier (hyper)nuclei

(Hyper)nuclei do not follow the same collective expansion of the bulk matter

Mass Number Scaling of Directed Flow at $\sqrt{s_{NN}}=3$ GeV

- Mid-rapidity v_1 slope of nuclei increase linearly with mass number A
- Hypernuclei v_1 slope compatible with **Λ atomic mass number scaling**
- In the coalescence picture, nuclei inherits flow from constituents

A scaling of v_1 qualitatively consistent with coalescence at mid-rapidity



STAR, Phys. Rev. Lett. 130, 212301 (2023)

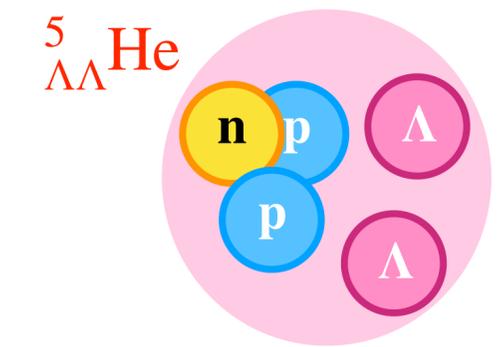
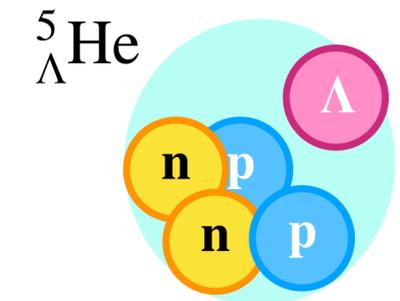
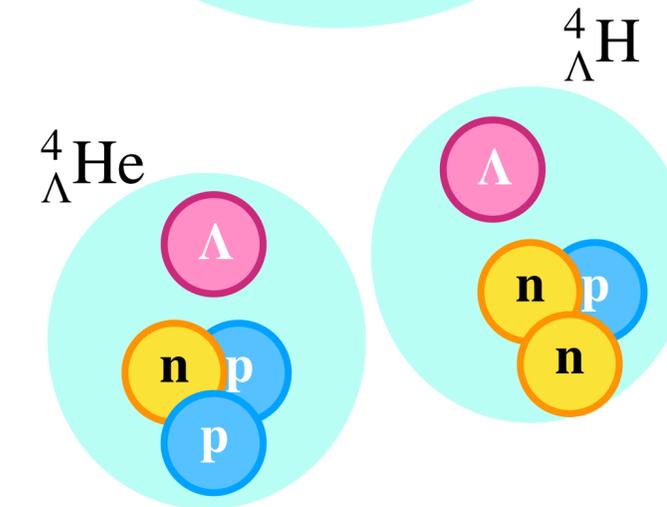
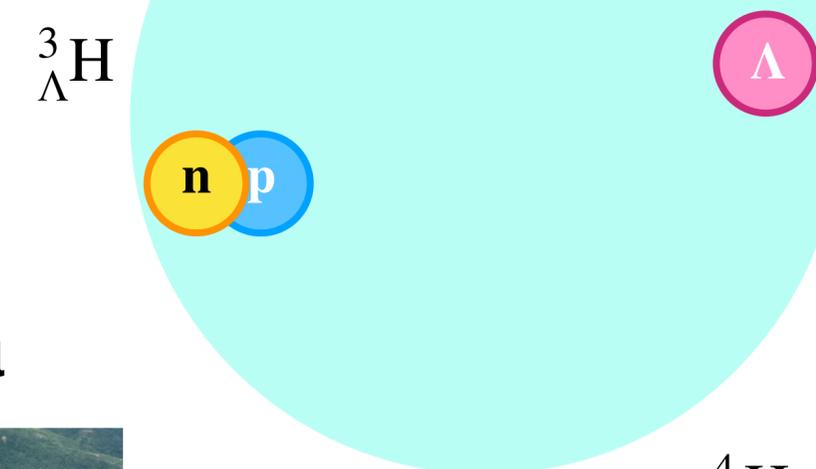
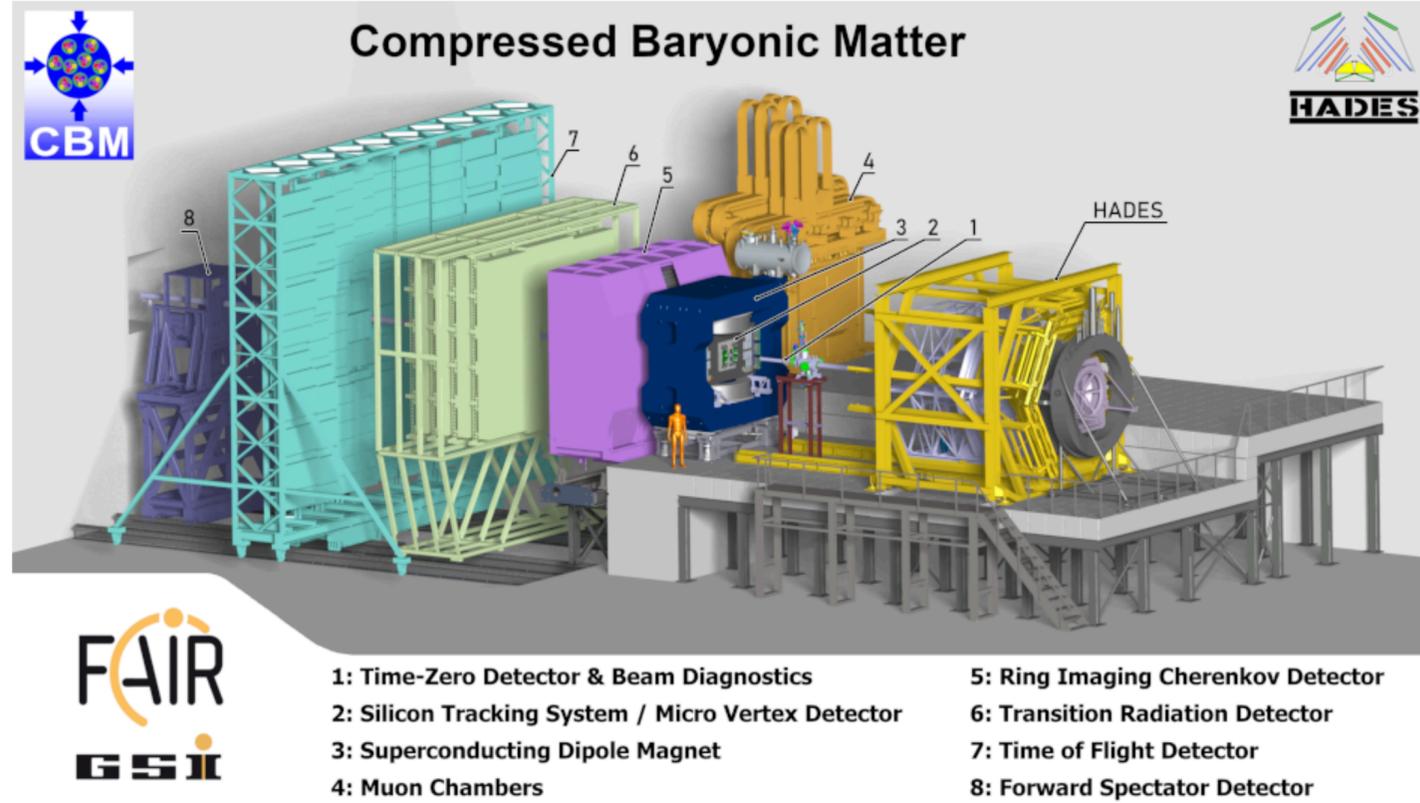
Summary

- **Hypernuclei yields provide experimental access to their internal structure,** and models that ignore this cannot describe the data consistently.
- **Thermal model** works reasonably well for $A=4-5$ hypernuclei, but fails for the loosely bound hypertriton (${}^3_{\Lambda}\text{H}$).
 - **May be due to stronger binding and larger survival probability in the hot medium**
- ${}^3_{\Lambda}\text{H}$ production is sensitive to its internal wave function. In a coalescence approach:
 - Gaussian ansatz fail
 - More realistic (Congleton-type) wave functions describe data
 - ${}^3_{\Lambda}\text{H}$ yield provides experimental access to its internal structure and subsequently the YN interaction
- **Directed flow** and **mean transverse momentum** measurements support the **coalescence** picture
- **Excited hypernuclear states** and **spectator matter** play a crucial role in hypernuclei production

Outlook

GSI/FAIR @ Darmstadt, Germany

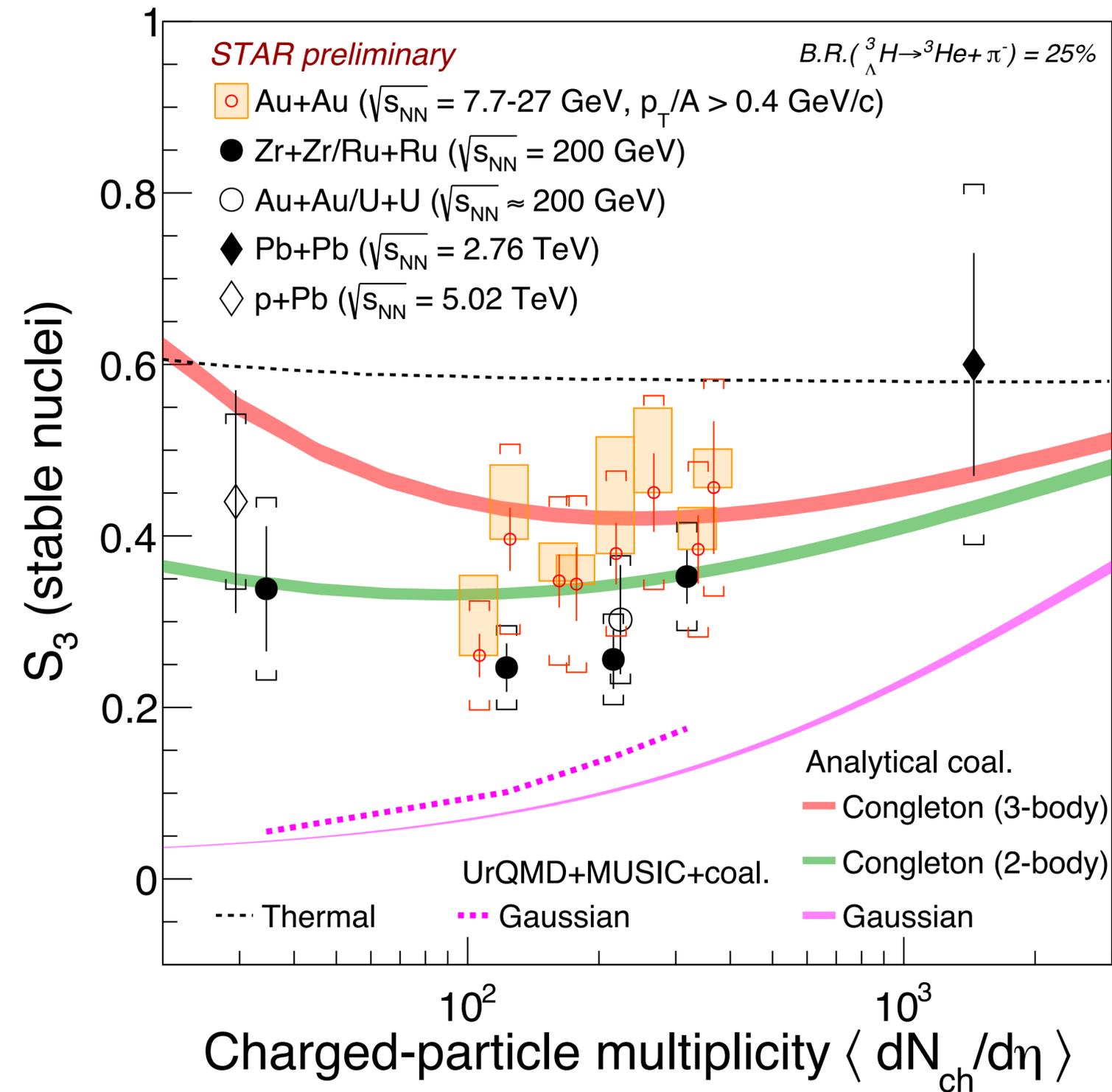
HIAF @ Huizhou, China



- **Λ interaction:** key missing ingredient of the hyperon puzzle
- **$A \geq 5$:** onset of possible Λ binding
- Λ hypernuclei searches at **HIAF & GSI/FAIR** access to Λ interactions

Thank you for listening!!

Strangeness Population Factor



Bracket:
syst. unc.

Line:
stat. unc.

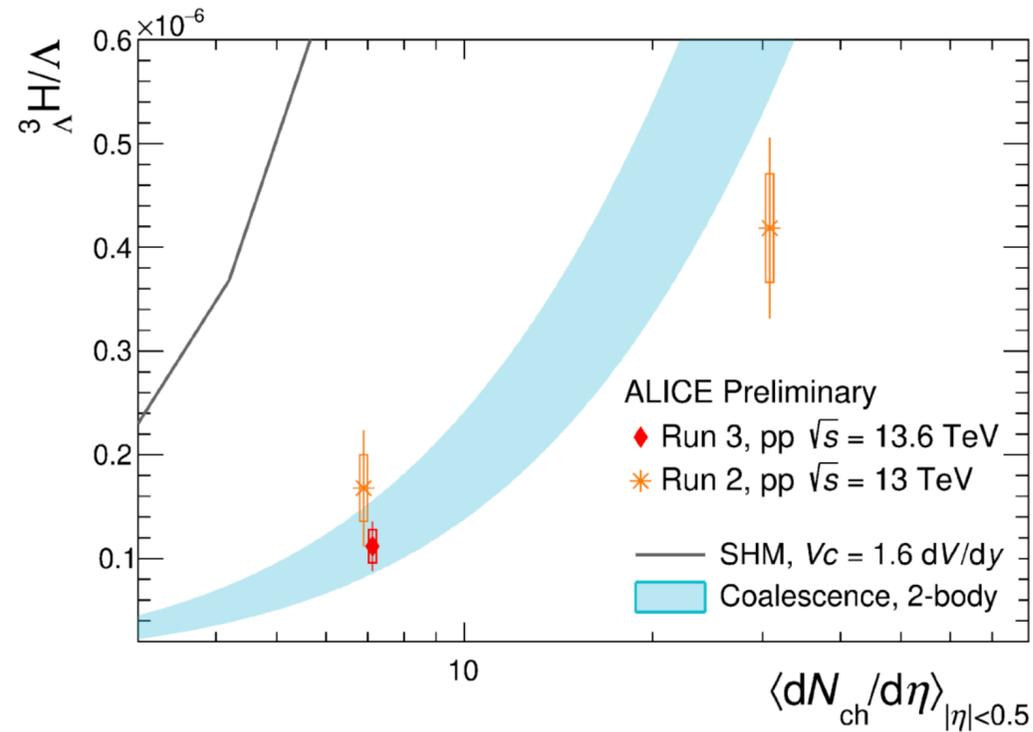
Upper edge of box:
 S_3 value **corrected**
for feed-down from
thermal model

Lower edge of box:
 S_3 value **uncorrected**
for feed-down

- Unstable nuclei production are suppressed relative to stable nuclei
- The true value of S_3 (stable nuclei) very likely lies between the upper and lower limits

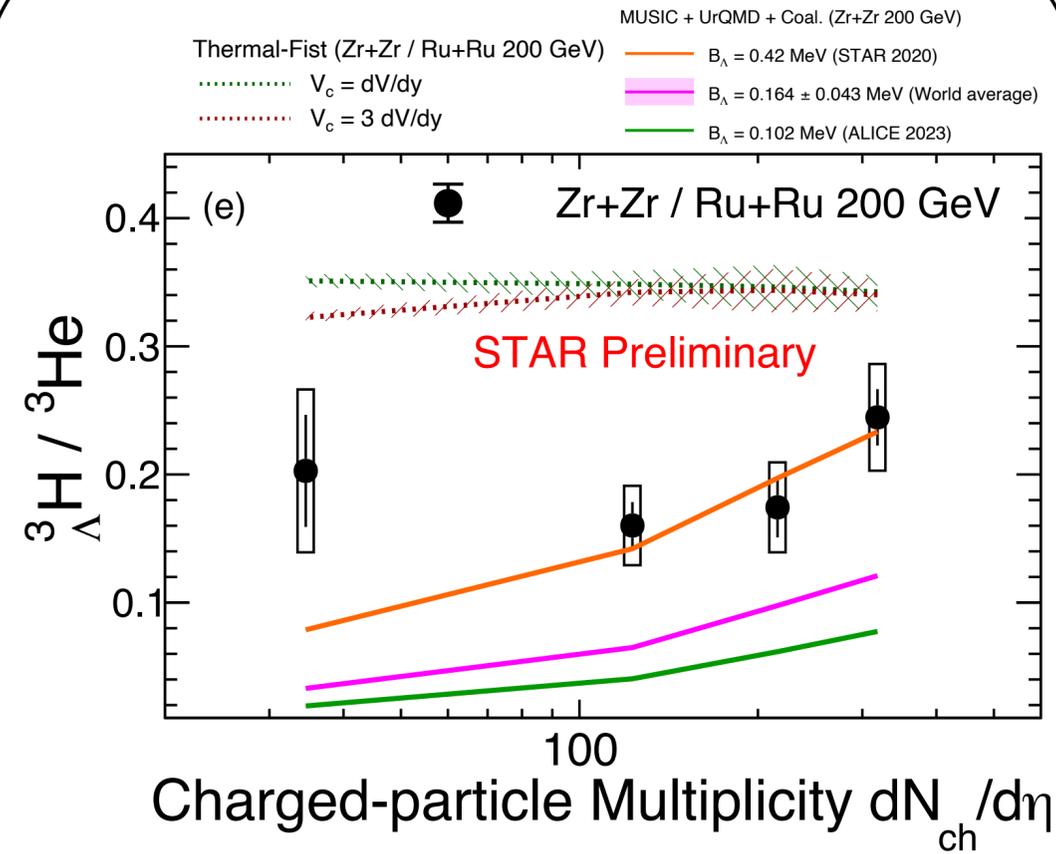
System Size Dependence at High Collision Energies

J. Ditzel (ALICE), QM2025



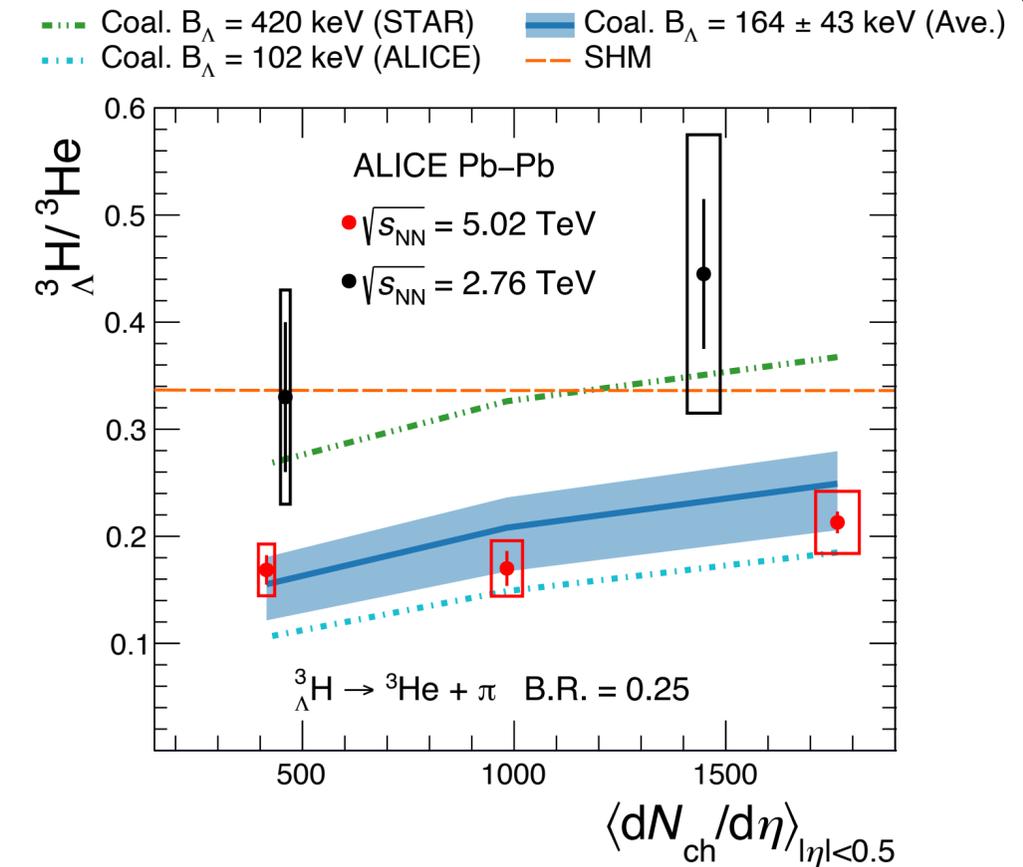
p+p @ $\sqrt{s} = 13, 13.6$ GeV
 $dN_{ch}/d\eta \sim O(10)$

D. Li (STAR), SQM2024



Ru/Zr+Ru/Zr @ $\sqrt{s_{NN}} = 200$ GeV
 $dN_{ch}/d\eta \sim O(100)$

ALICE, Phys.Lett.B 860 (2025) 139066



Pb+Pb @ $\sqrt{s_{NN}} = 2.76, 5.02$ TeV
 $dN_{ch}/d\eta \sim O(1000)$

Small systems

Large systems

- Across all systems, thermal model overestimates ${}^3_{\Lambda}\text{H}$ production

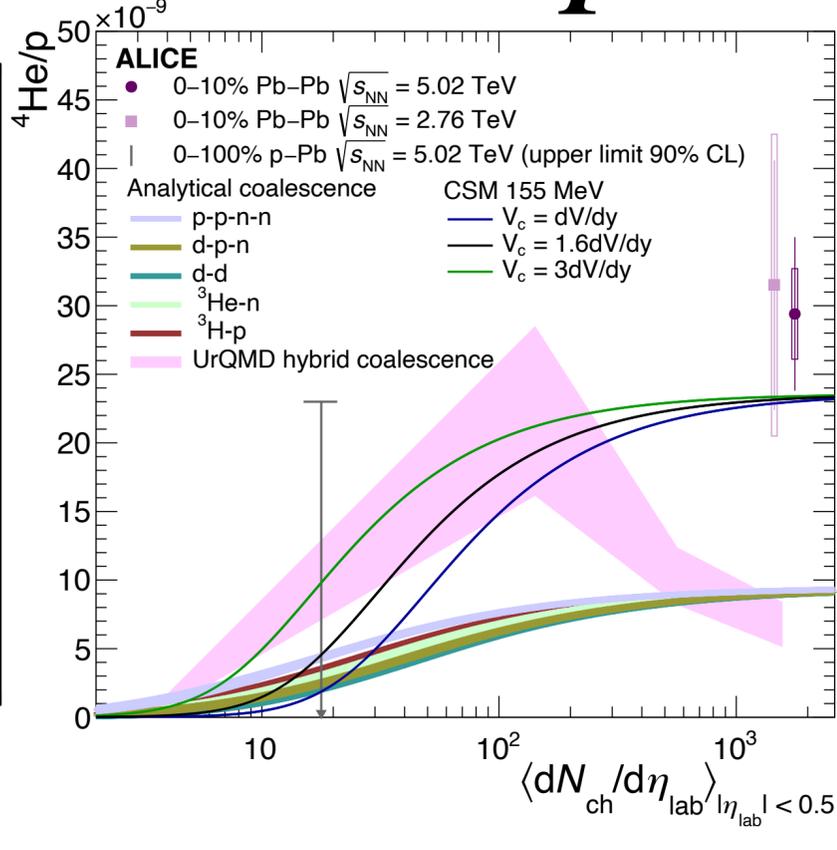
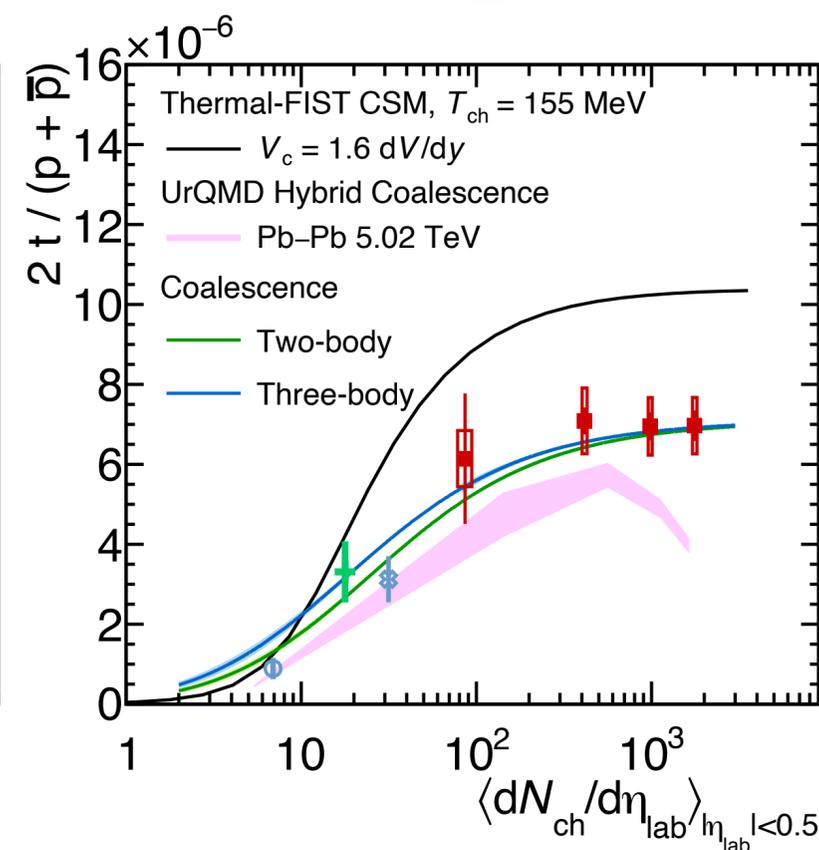
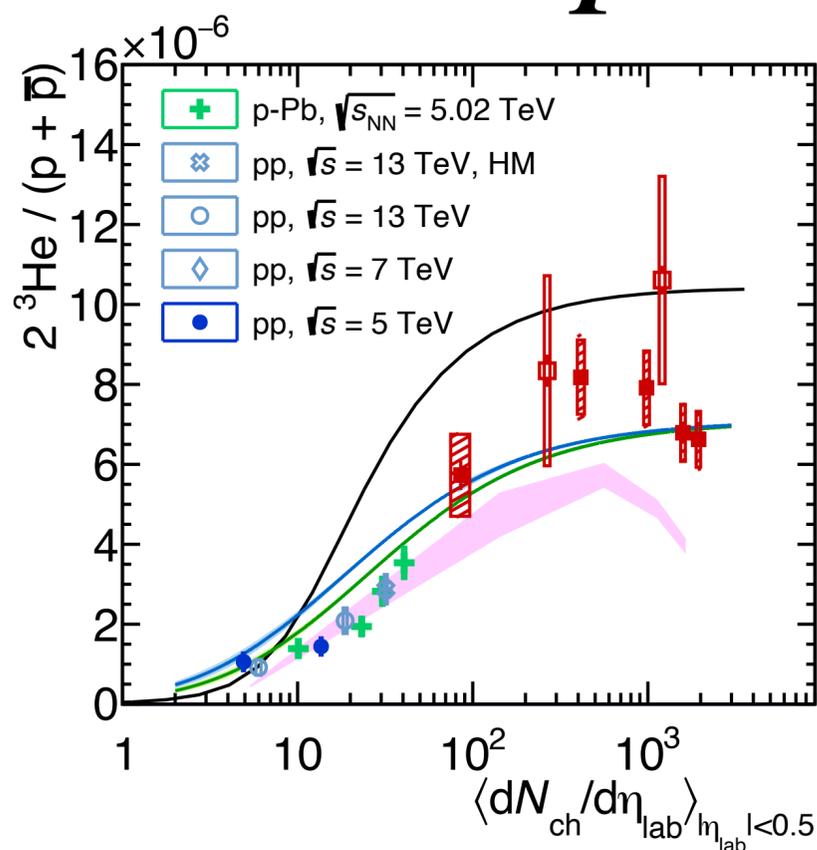
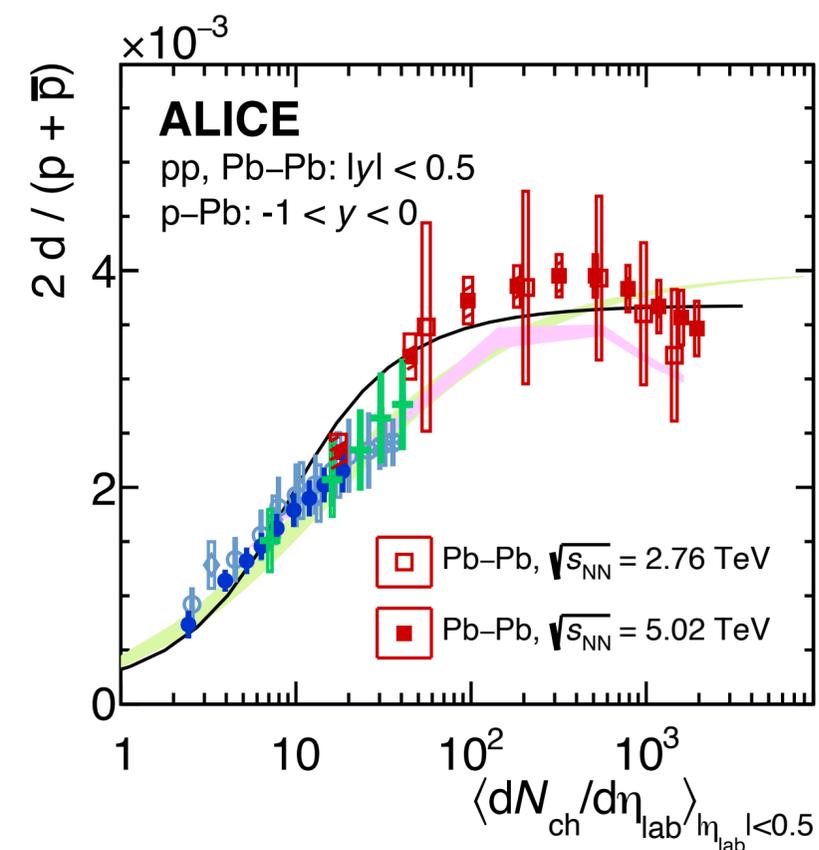
Nuclei Production at the LHC

d/p

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

t/p

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



- $A=2,4$: fairly well described; $A=3$ nuclei: strongly overpredicted

Semi-Analytical Data-Driven Coalescence (arXiv:2510.06758)

- Use deuteron data to estimate R_{inv} for **BES energies**
- Calculate B_2 as function for pT and centrality using data

- Use coalescence formula with Argonne v_{18} wave function to obtain R_{inv}
- $$B_2(d) \approx \frac{2(2s_d + 1)}{m(2s_N + 1)^2(2\pi)^3} \int d^3r |\Phi_d(r)|^2 \mathcal{S}_2(r)$$

