第一届超子物理研讨会

高能重离子碰撞中的超核集体流研究

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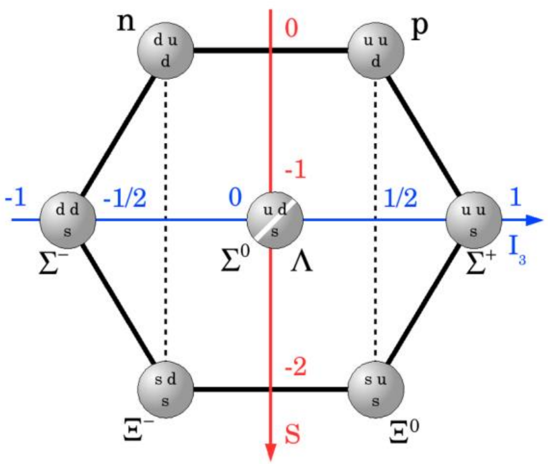
惠州，2024年4月12-16日

Outline

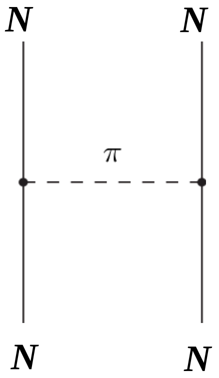
1) Hyperon-nucleon (YN) interaction
2) STAR Experiment for Fixed-target
3) ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$ reconstruction in 3 GeV Au+Au
4) Directed flow measurement of ${}^{3}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{H}$
5) Hypernuclei opportunity at HIAF
6) Summary

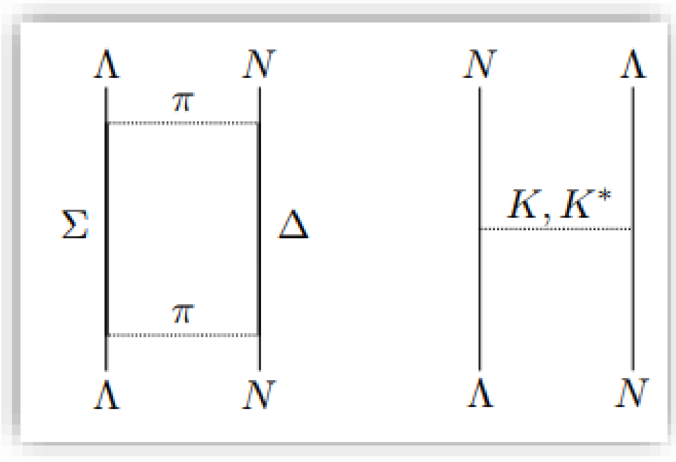
1. Hyperon and YN-interaction

SU(3) Baryon Octet



Baryon (Hyperon)	quarks	Isospin	Mass (MeV)
Λ	$u\ d\ s$	0	1115
Σ^+	$u\ u\ s$	1	1189
Σ^0	$u\ d\ s$	1	1193
Σ^-	$d\ d\ s$	1	1197
Ξ^0	$u\ s\ s$	1/2	1315
Ξ^-	$d\ s\ s$	1/2	1321



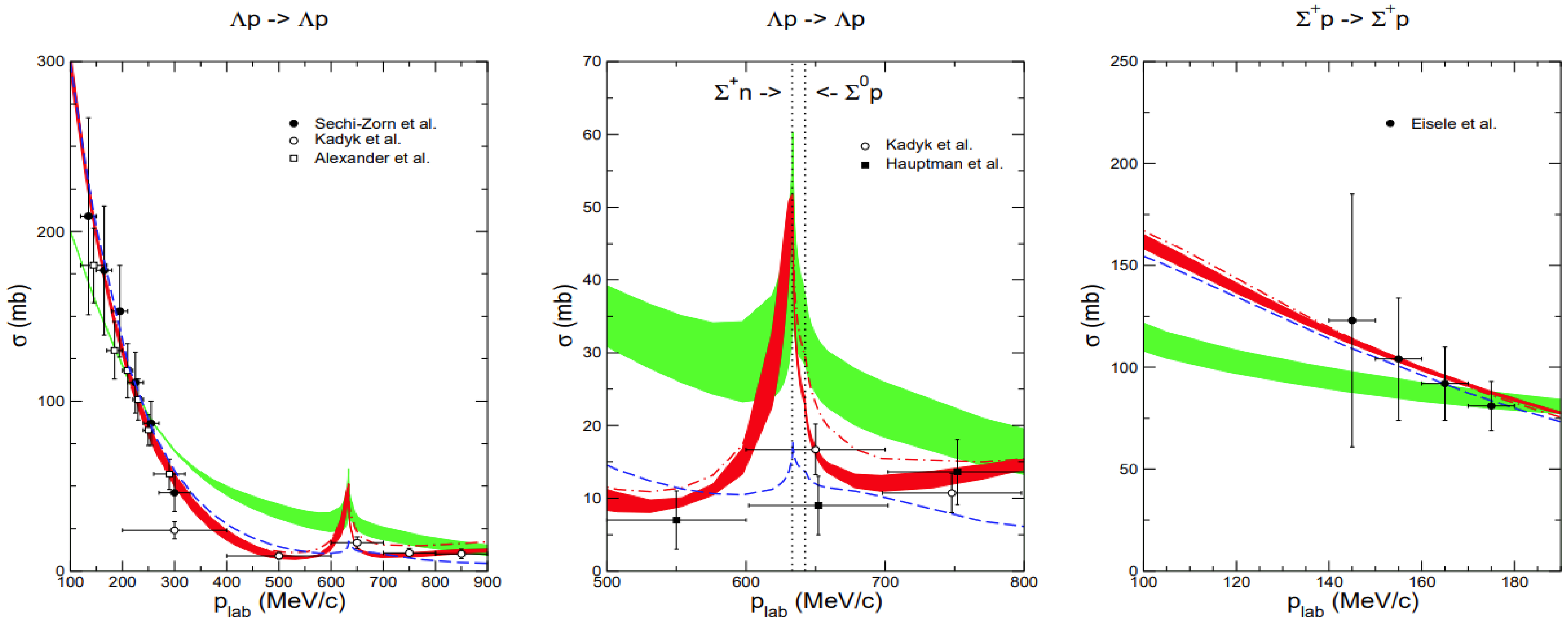


Hyperon-Nucleon interaction (YN)

- Understanding strong interaction
- Original of nuclear force
- Probe of nuclear structure
- Properties of neutron star
- … …

"The hyperon-nucleon interaction: conventional versus effective field theory approach", **Lect.NotesPhys.724:113-140,2007**, J. Haidenbauer, Ulf-G. Meißner, et al.

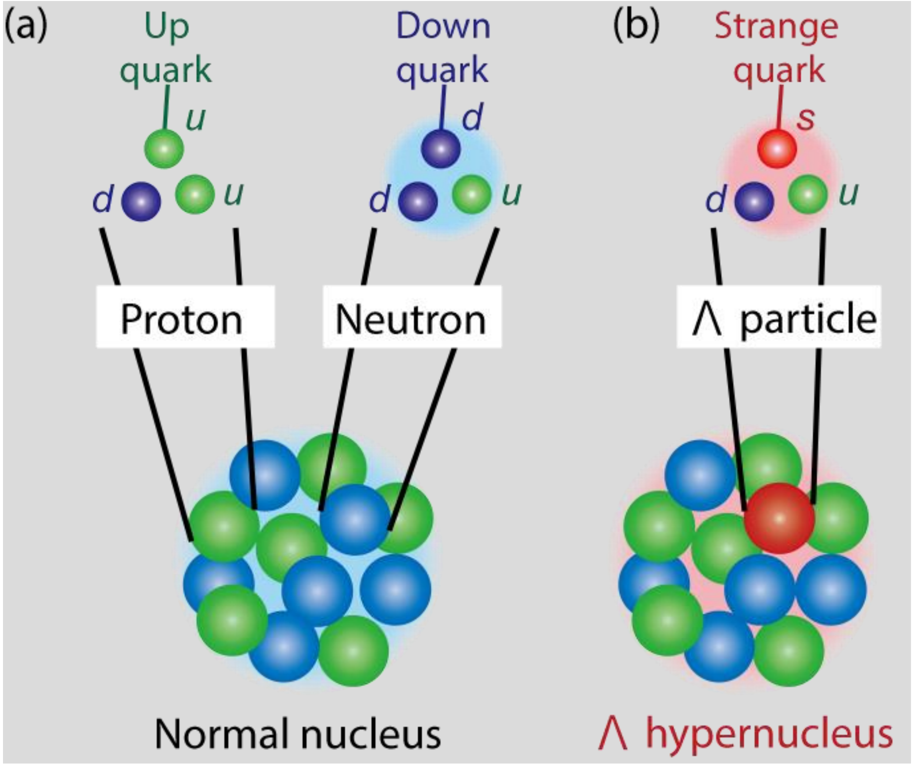
Chiral Effective Field Theory (χEFT) YN interaction



Review: Petschauer S, Haidenbauer J, Kaiser N, Meißner U-G and Weise W, Hyperon-Nuclear Interactions From SU(3) Chiral Effective Field Theory. Front. Phys. 8:12 (2020)

Hypernuclei and YN interaction

Hypernucleus: bound state of the Hyperon(s) and nucleons.



Properties of hypernuclei (i.e lifetime, binding energy, decay BR.) can be used to extract the strength of hyperon-nucleon (YN) interaction.

Binding energy of single-Λ Hypernuclei:

$$B_\Lambda({}^A_\Lambda Z) = \underbrace{M({}^{A-1}Z)}_{\text{Core mass}} + \underbrace{M(\Lambda)}_{\text{Free }\Lambda\text{ mass}} - \underbrace{M({}^A_\Lambda Z)}_{\text{Hypernuclei mass}}$$

Core mass

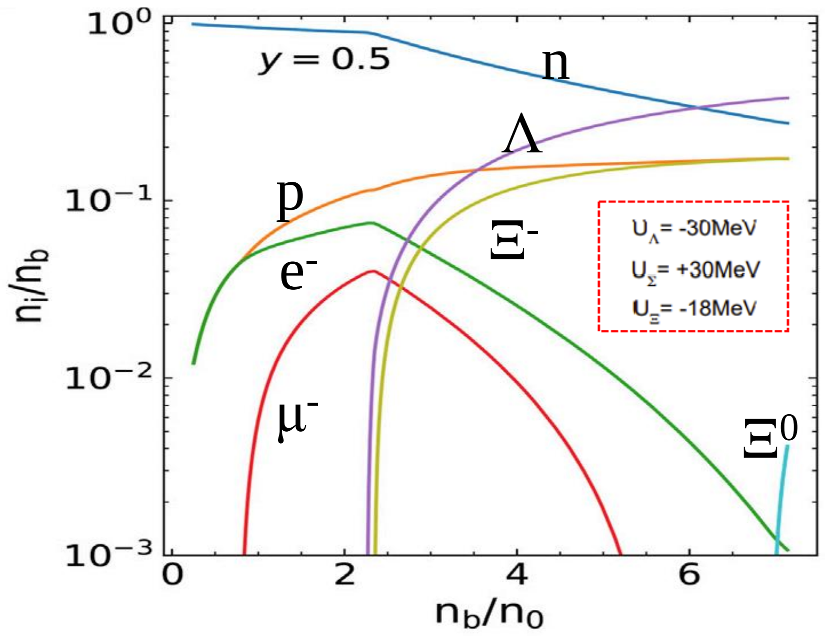
Free Λ mass

Hypernuclei mass

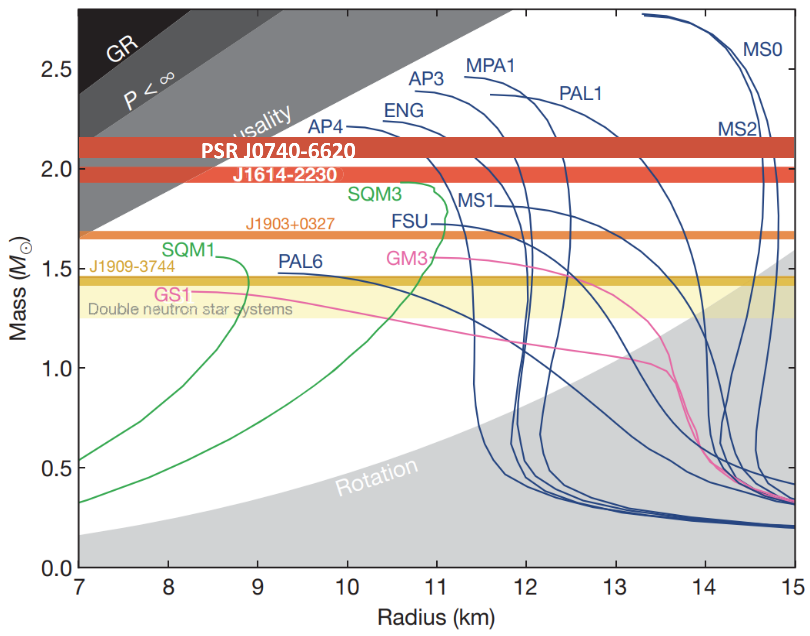
Neutron Star and YN-interaction

"Hyperon puzzle": the difficulty to reconcile the measured masses of neutron stars (NSs) with the presence of hyperons in their interiors

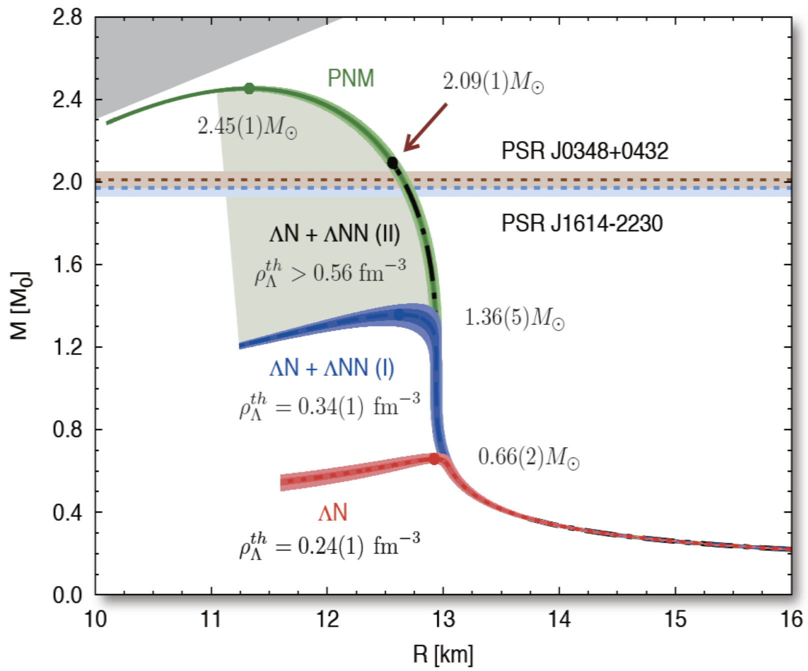
[Ignazio Bombaci, JPS Conf. Proc. 17, 101002 (2017)]; Phys. Rev. C 81, 035803 (2010)



Ghosh et al. Front. Astron. Space Sci. 9:864294 (2022)

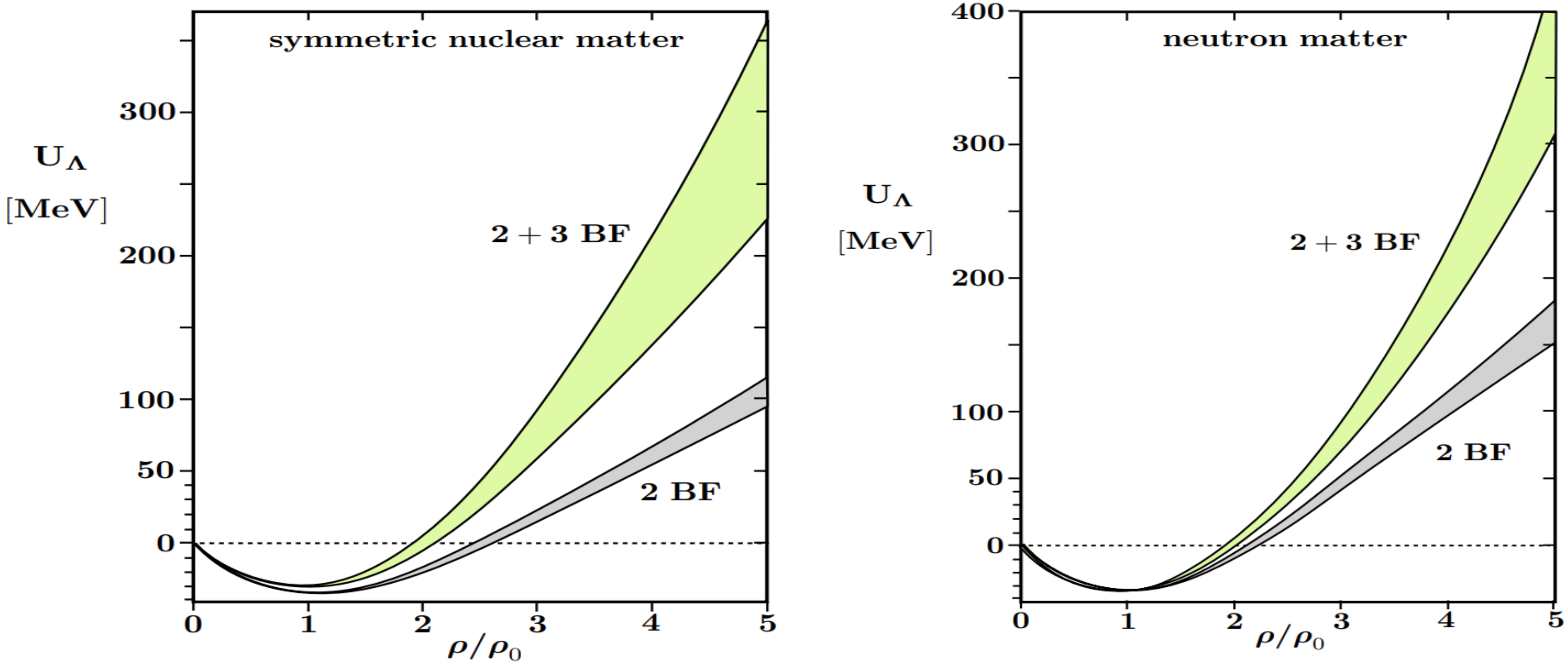


P. Demorest et al., Nature 467 (2010) 1081
NANOGrav Collaboration, Nature Astron. 4 (2019) 1, 72



D. Lonardoni et al, PRL 114, 092301 (2015)

χEFT: Density Dependent YN Interaction

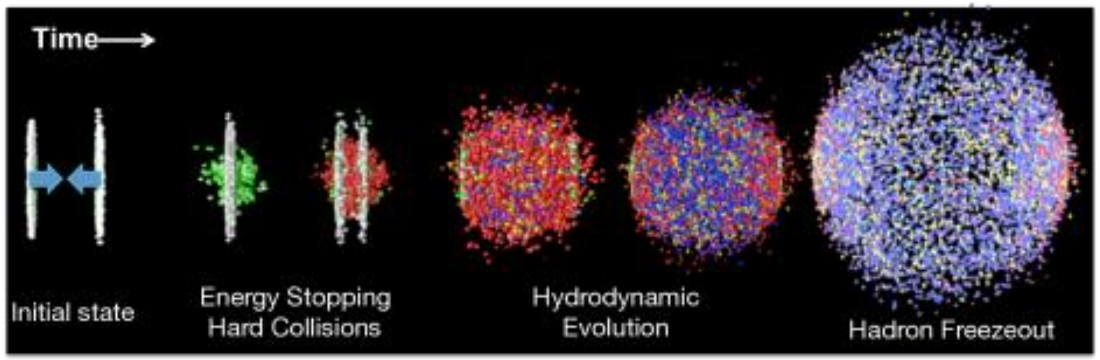


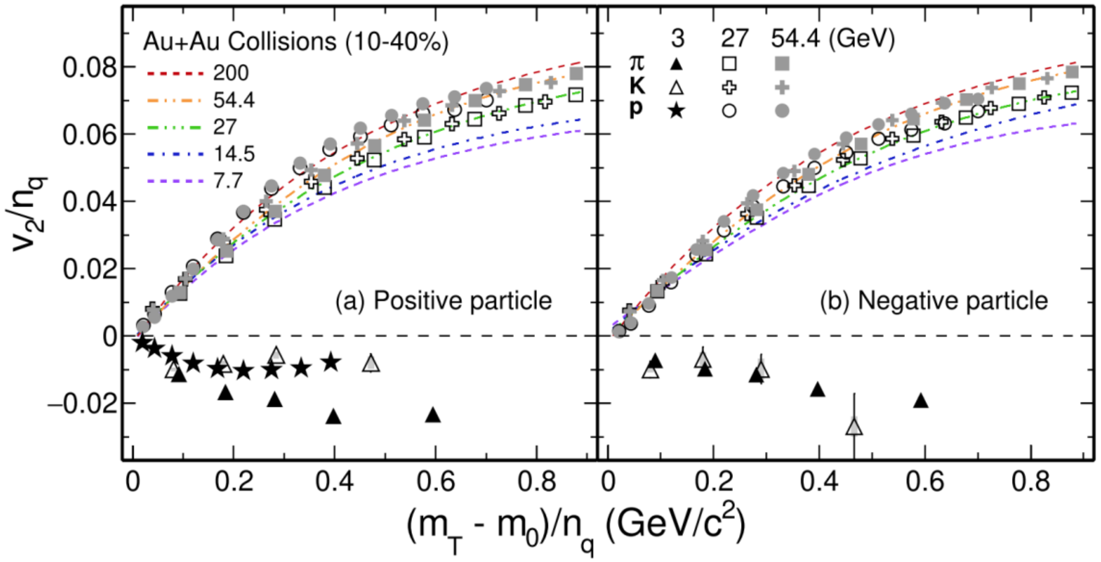
D. Gerstung, N. Kaisera , W Weise, Eur. Phys. J. A (2020) 56 :175

如何从实验上提取核介质依赖的YN和YY相互作用实验观测量？

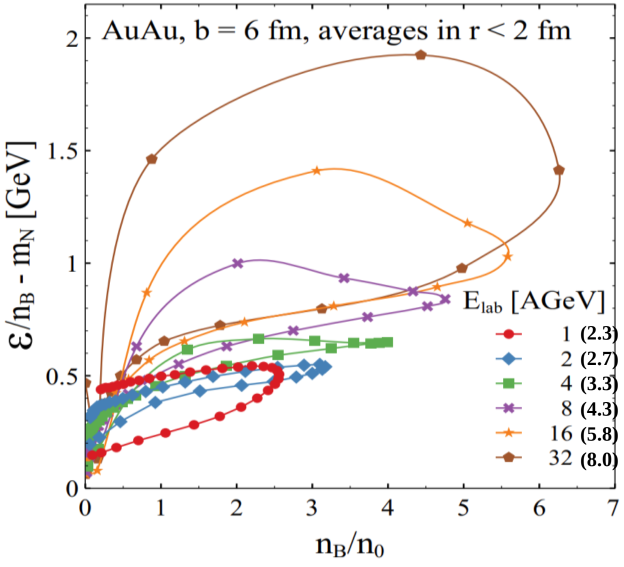
HICs at high baryon density region

Time Evolution of HICS

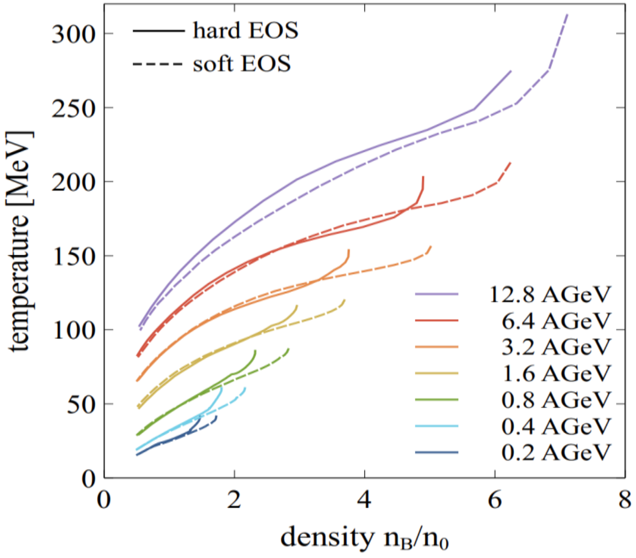




STAR Collaboration, PLB, 827, 137003 (2022)



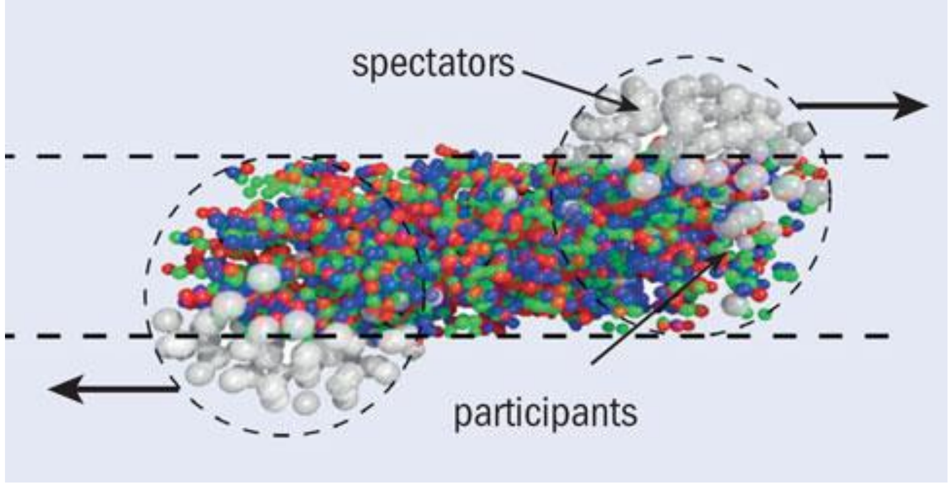
D. Oliinychenko et. al, arXiv:2208.11996v2

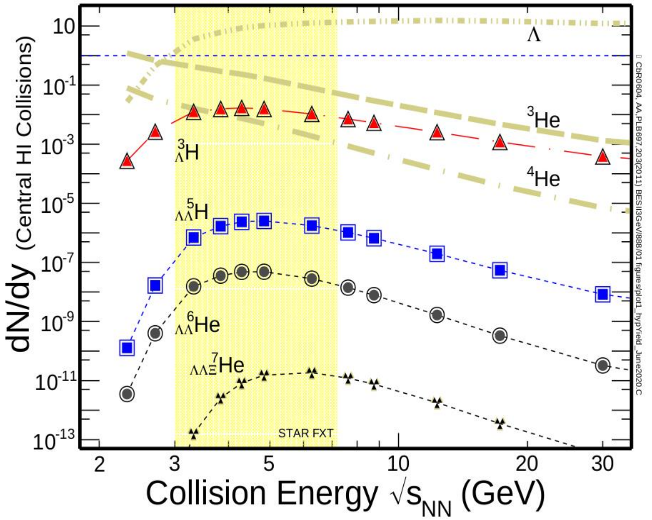


A. Sorensen et. al, arXiv:2301.13253v2

Due to strong baryon stopping, nuclear matter with high baryon density is expected to be created in HICs at medium energies

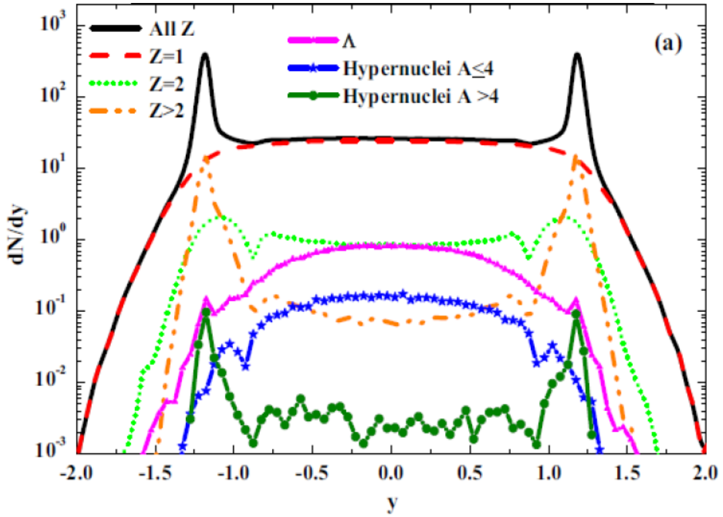
Hyper-nuclei Productions in HICs





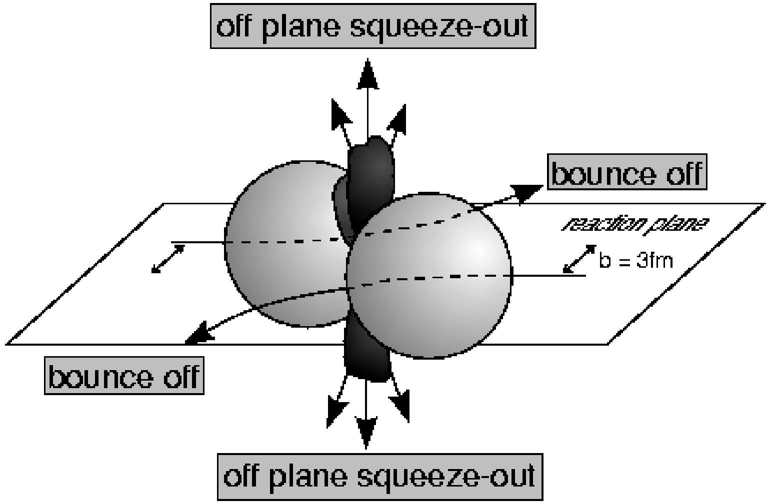
A. Andronic et al., Phys. Lett. **B697**, 203(2011) ;
B. J. Steinheimer et al., Phys. Lett. **B714**, 85(2012)

PHQMD model: Au+Au@4 A GeV



J. AICHELIN et al. PRC 101, 044905 (2020)

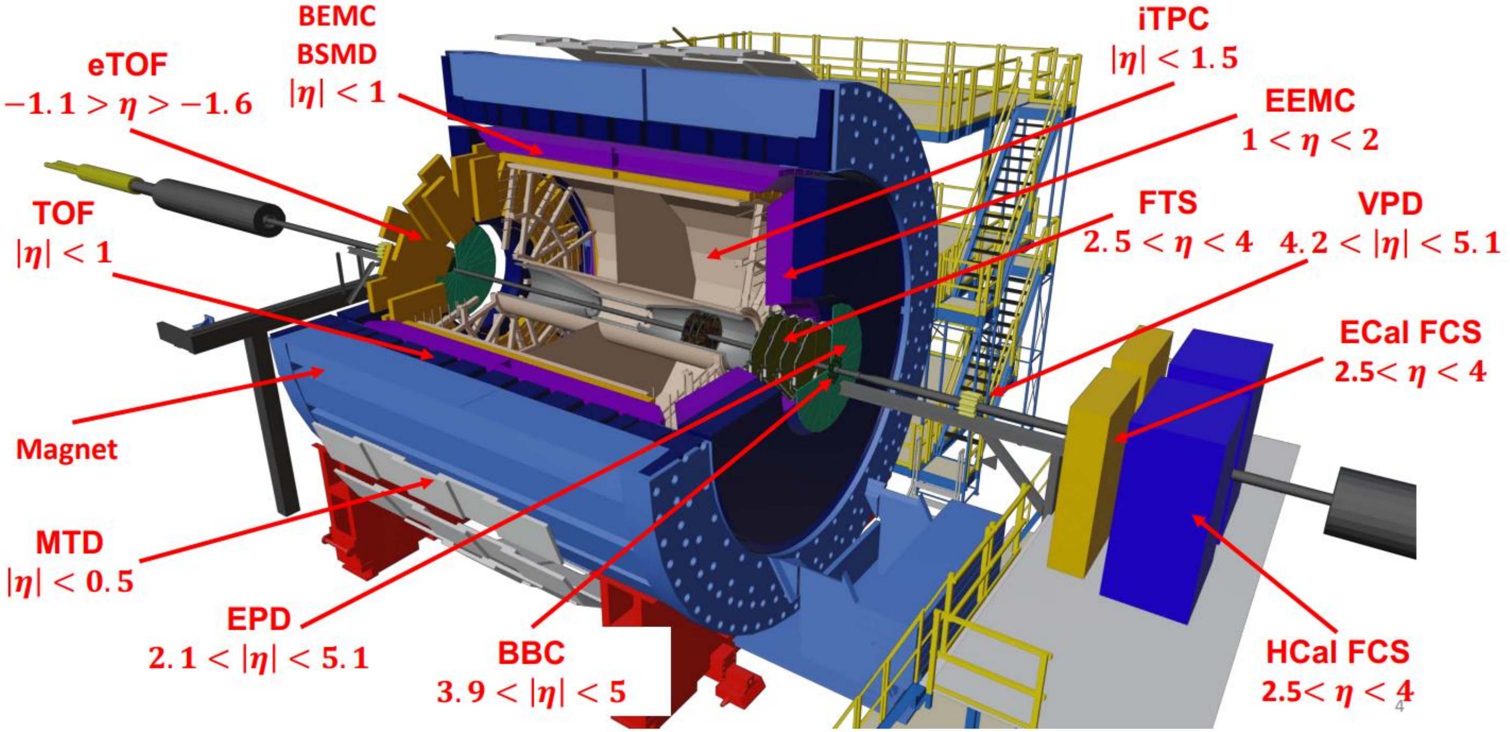
Rapidity: $y = \frac{1}{2}\ln(\frac{E - P_z}{E + P_z})$

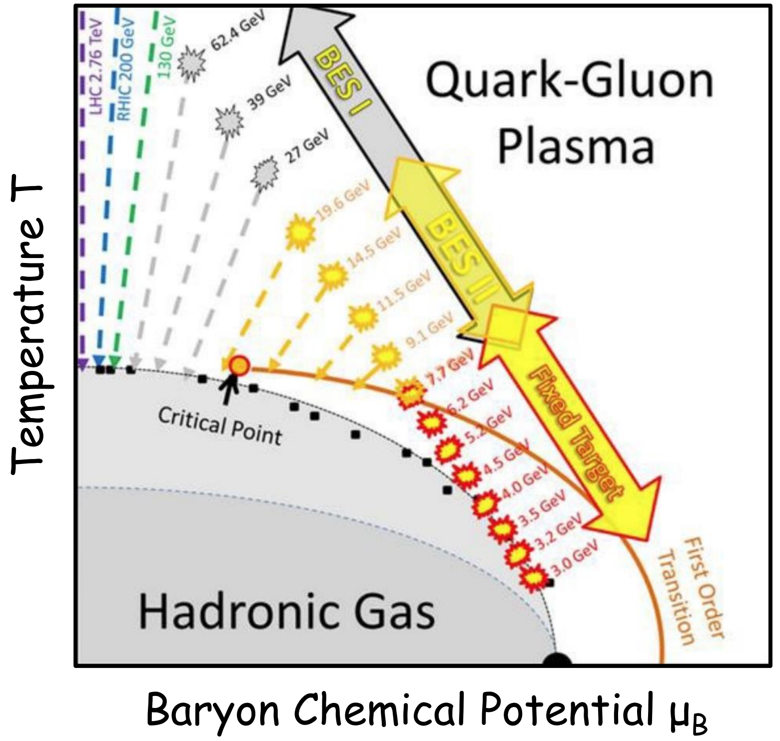


Possible connection with in-medium YN interaction

- Hypernuclei production
- Hypernuclei collectivity

2. Fixed-Target Runs at STAR





RHIC Beam Energy BES-II in 2018-2021:

- Fixed Target Run extends collision energy down to : $\sqrt{s_{NN}}$ = 3 - 7.7 GeV corresponding to chemical potential: 750 ≥ μ_B ≥ 420 MeV

Charged particle PID and ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ Reconstruction

2018 STAR FXT 3 GeV data set;
260M minimum biased events

1) Hyper-nuclei reconstruction channels:

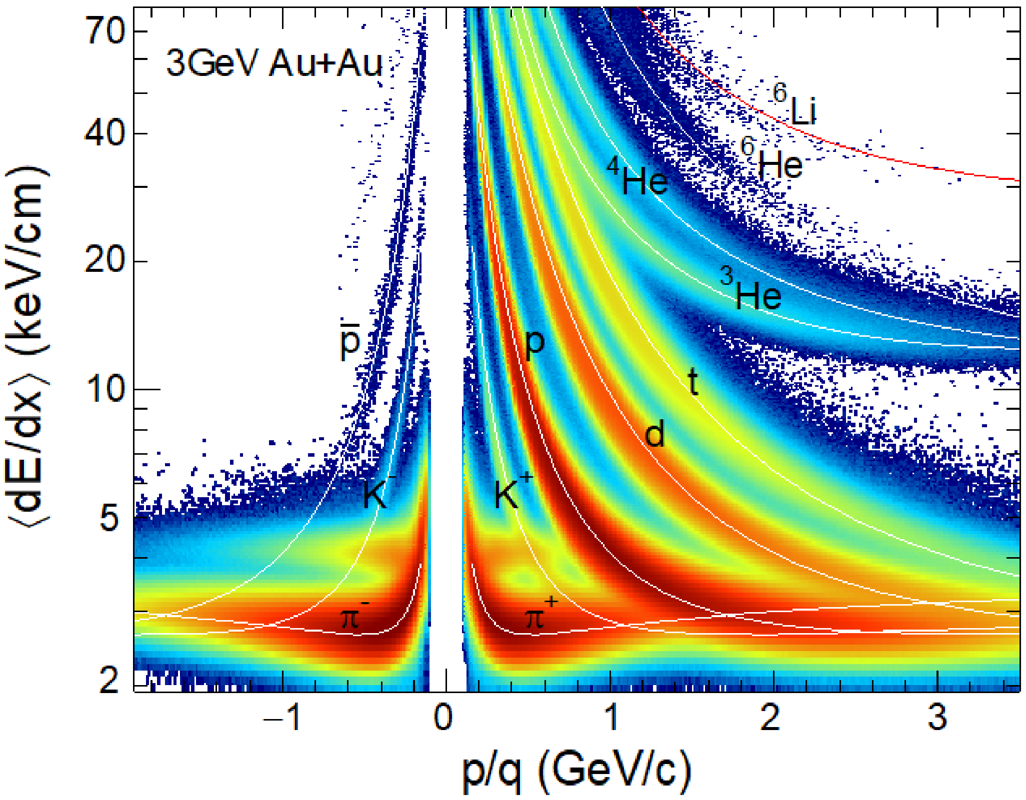
${}^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$ 2-body

${}^{3}_{\Lambda}H \rightarrow p + d + \pi^{-}$ 3-body

${}^{4}_{\Lambda}H \rightarrow {}^{4}He + \pi^{-}$ 2-body

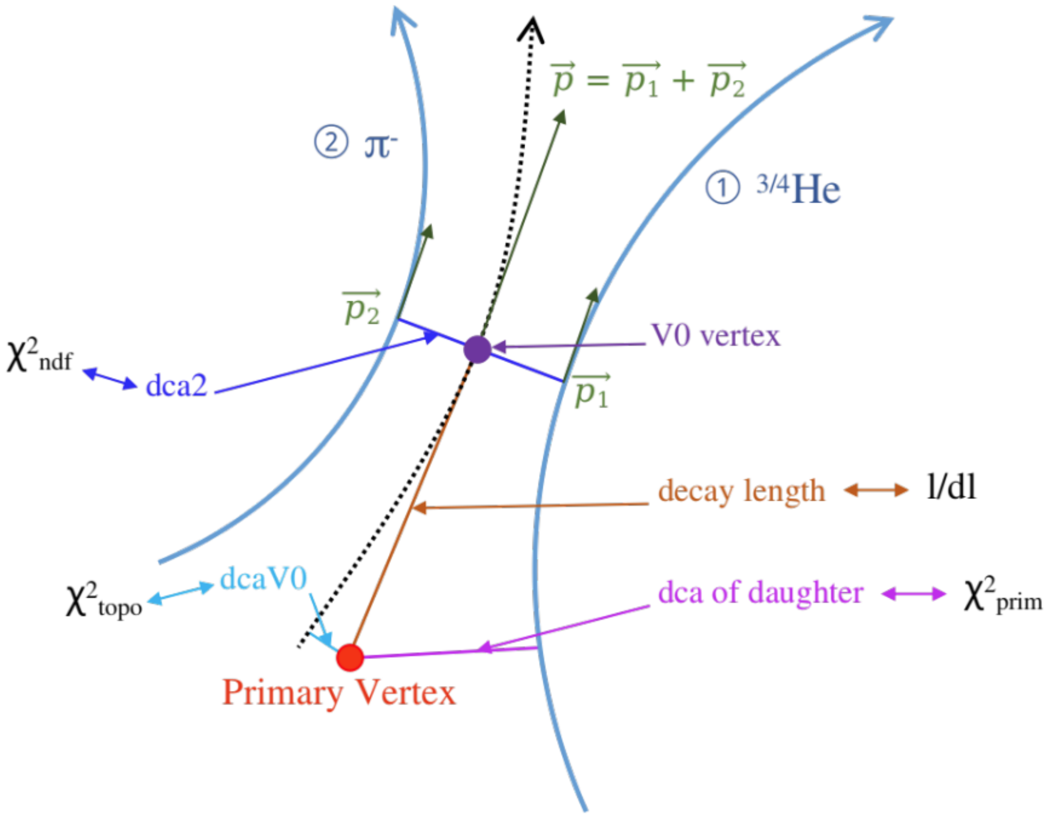
2) PID of p, d, t, ${}^{3}He$, ${}^{4}He$, π^{-} are made based on the dE/dx vs p/q distribution and particles are selected by $|n\sigma|$ method

STAR TPC Particle Identification

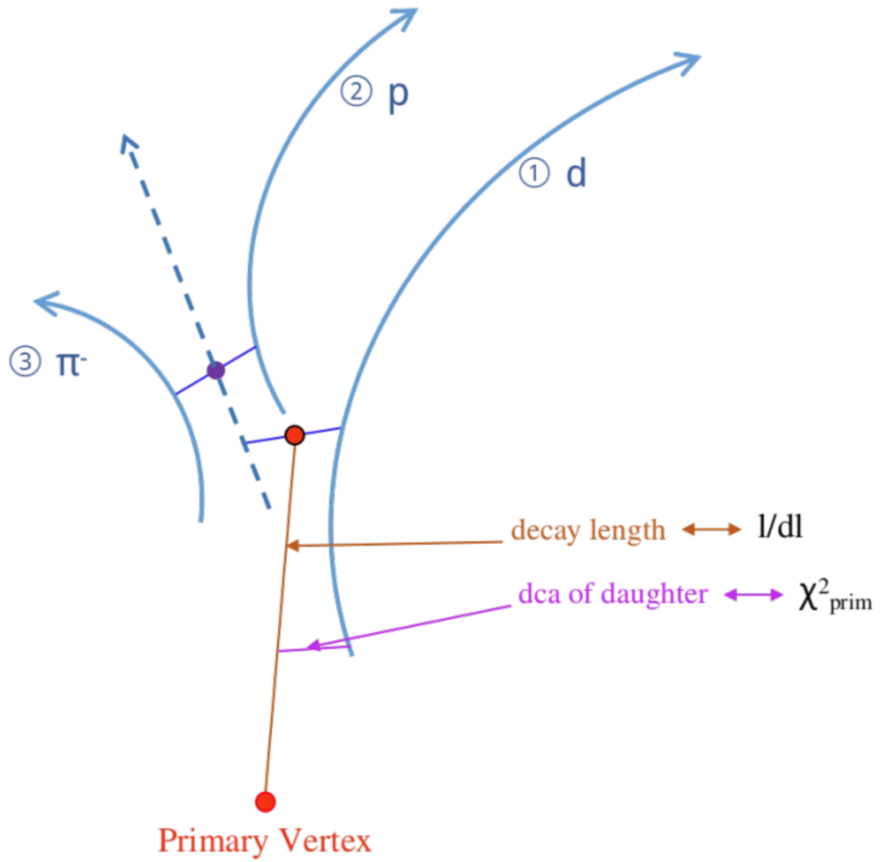


Reconstruction topology with KFParticle

Two-body decay

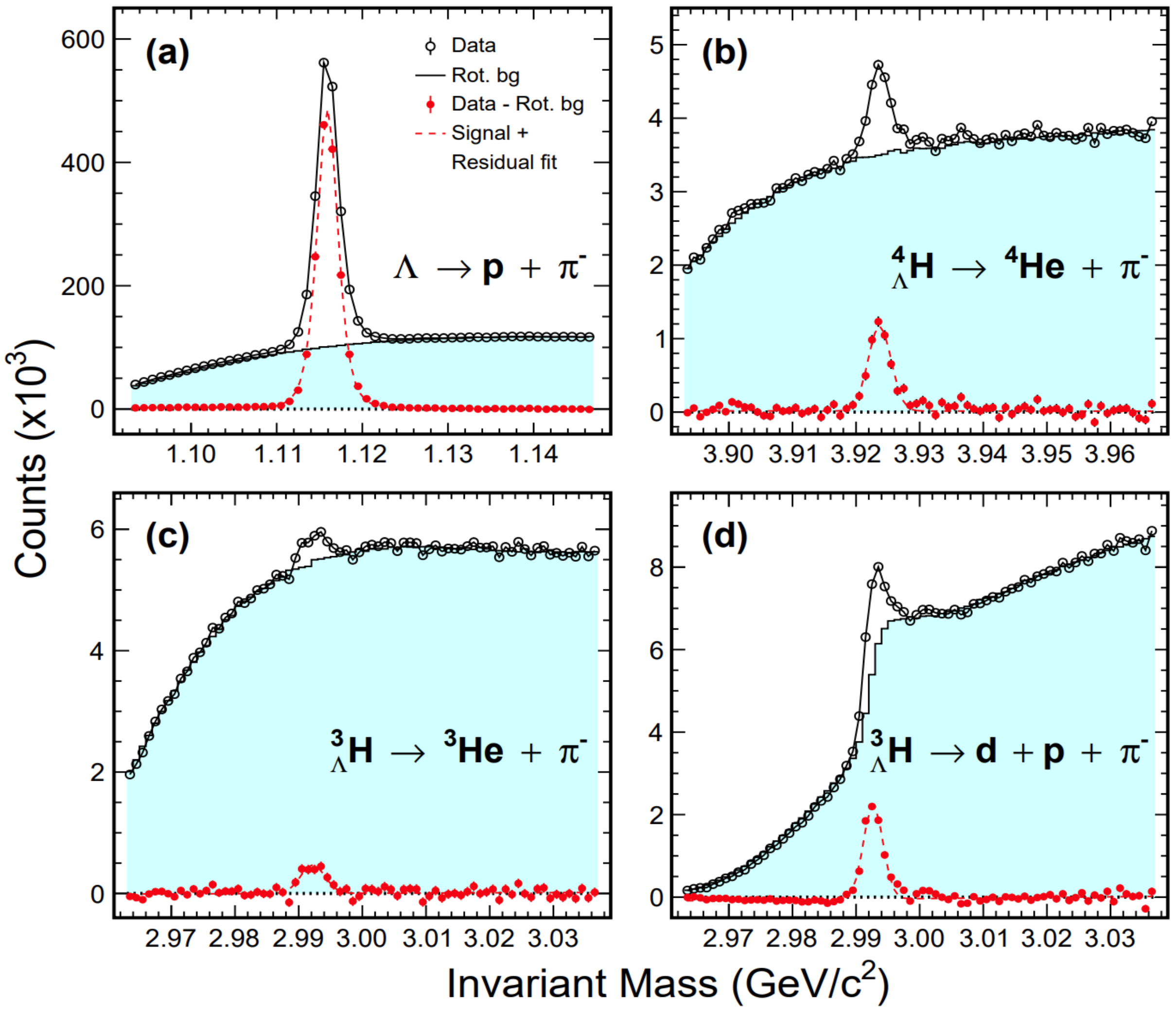


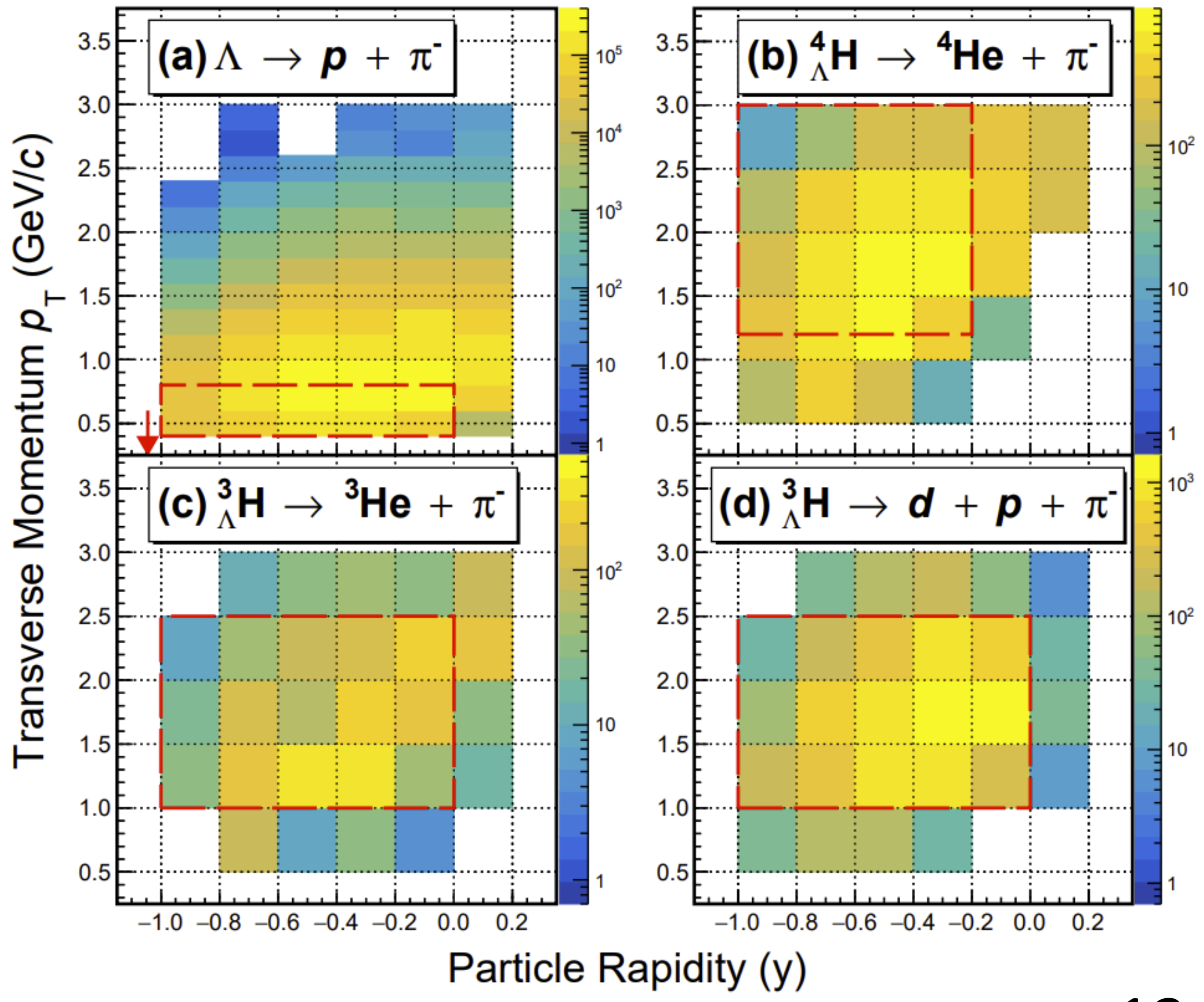
Three-body decay



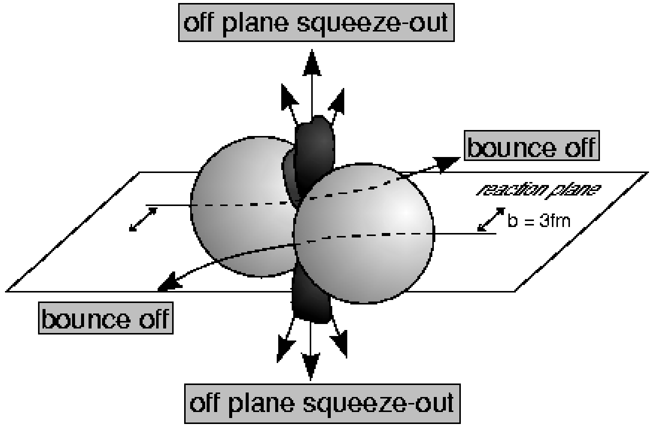
Λ, ${}^{3}_{\Lambda}H$ and ${}^{4}_{\Lambda}H$ Invariant Mass & Phase Space

$\sqrt{s_{NN}}$ = 3 GeV Au+Au collision (y_{target} ≈ -1.045)





4. Collective Flow with Event Plane Method



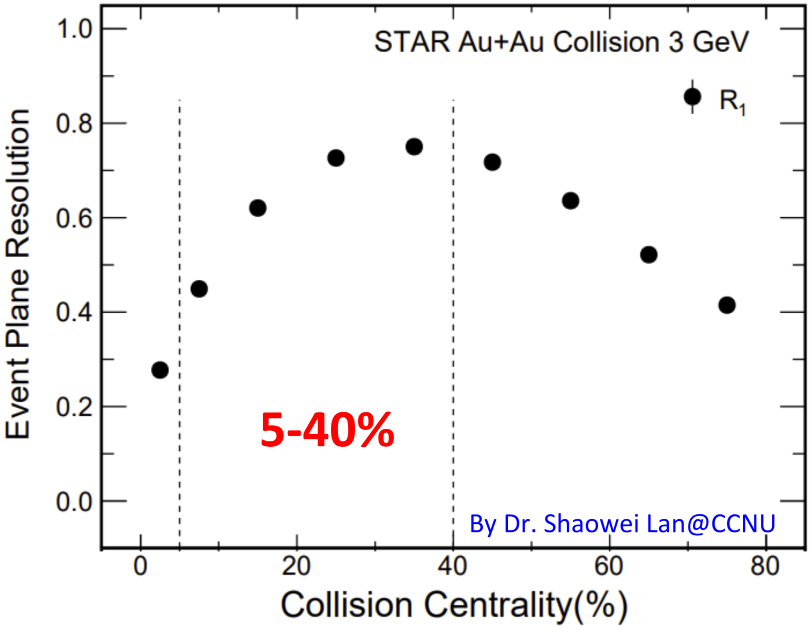
$$\frac{d^2N}{p_T dp_T d\varphi} = \frac{1}{2\pi}\frac{dN}{p_T dp_T}\left\{1 + \sum_{n=1}^{\infty} 2v_n(p_T)cos[n(\varphi - \Psi_R)]\right\}$$

$-\ v_1$ Directed flow; $-\ v_2$ Elliptic flow …

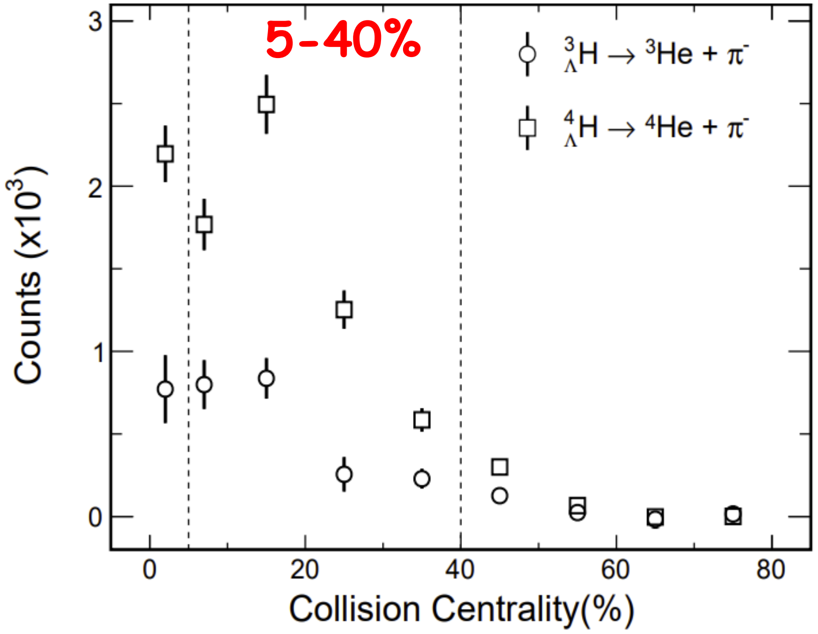
$$v_1 = \left\langle \frac{P_x}{P_t} \right\rangle$$

$$v_2 = \left\langle \frac{P_x^2 - P_y^2}{P_x^2 + P_y^2} \right\rangle$$

3-Sub-events with EPD A&B&TPC



Signal number Vs. Centrality



Collective flow in wide Centrality Range

$$v_1 = \frac{v_1^{obs}}{< \mathcal{R}_1 >}$$

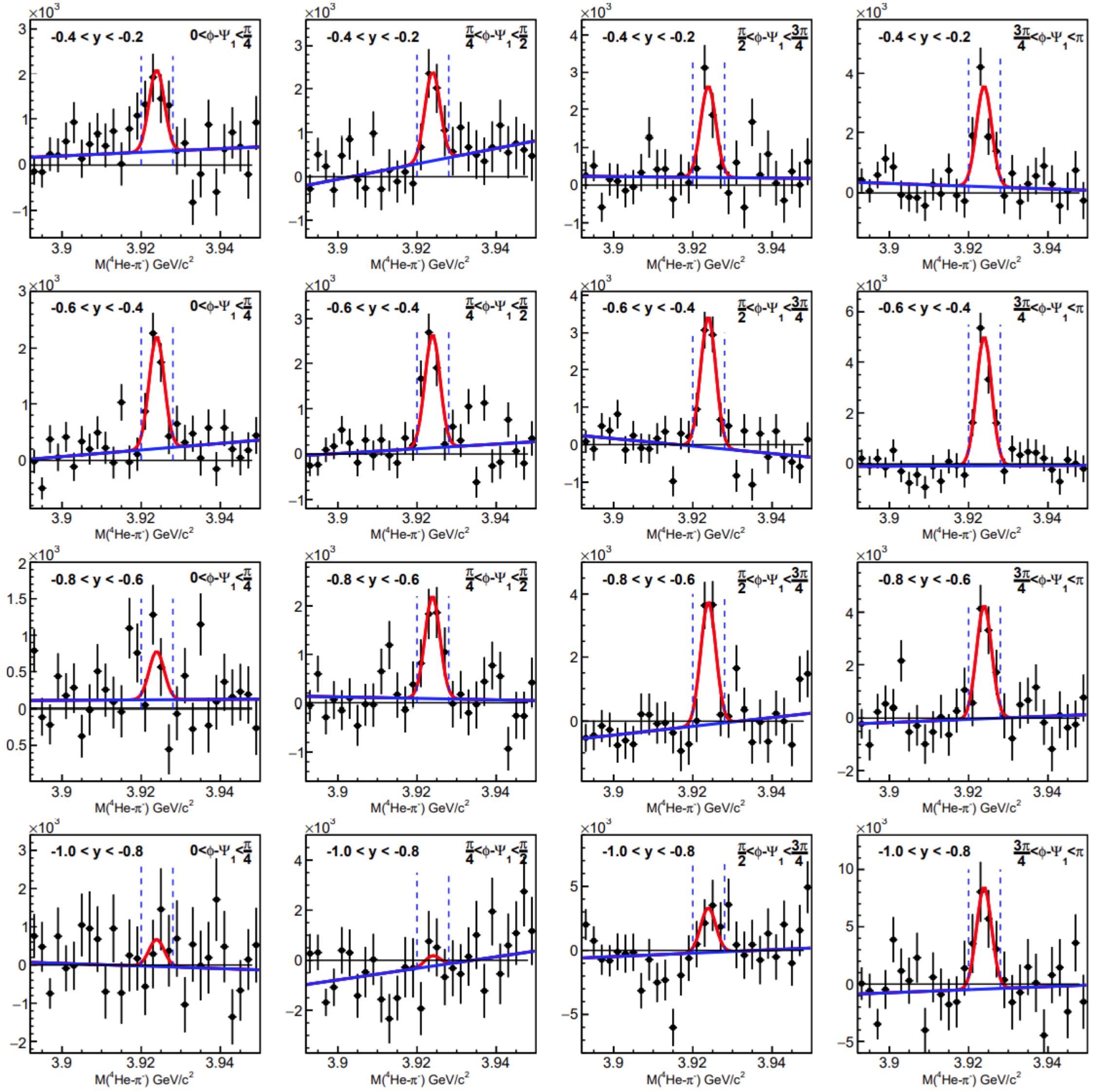
$$\frac{1}{< \mathcal{R}_1 >} = \frac{\Sigma_i (N_i \times \langle \frac{1}{\mathcal{R}_i} \rangle)}{\Sigma_i N_i}$$

Method: NIM.A 833 (2016) 181

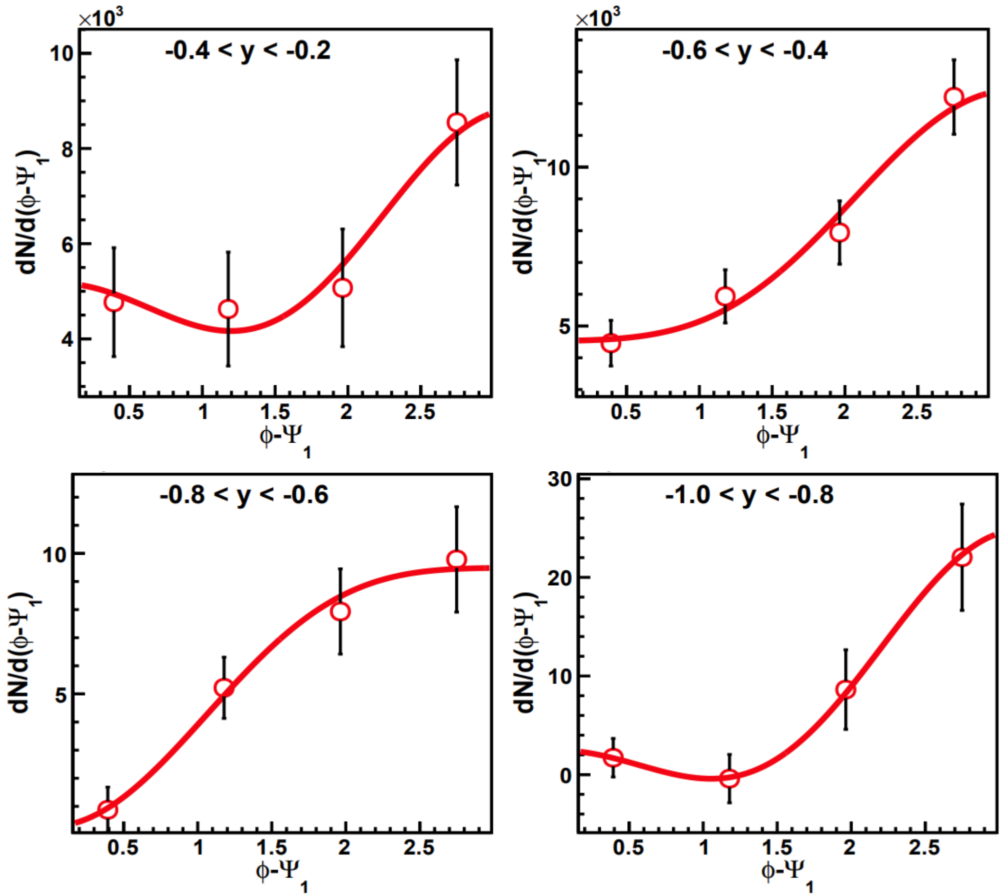
STAR Collaboration, PLB, 827, 137003 (2022)

Angular Distributions of Hypernuclei ${}^{4}_{\Lambda}\mathrm{H}$

p_T: (1.2, 3.0) GeV/c;   y: (-1.0, -0.2); Centrality: 5-40%



Angular ($\phi-\Psi_1$) Distributions

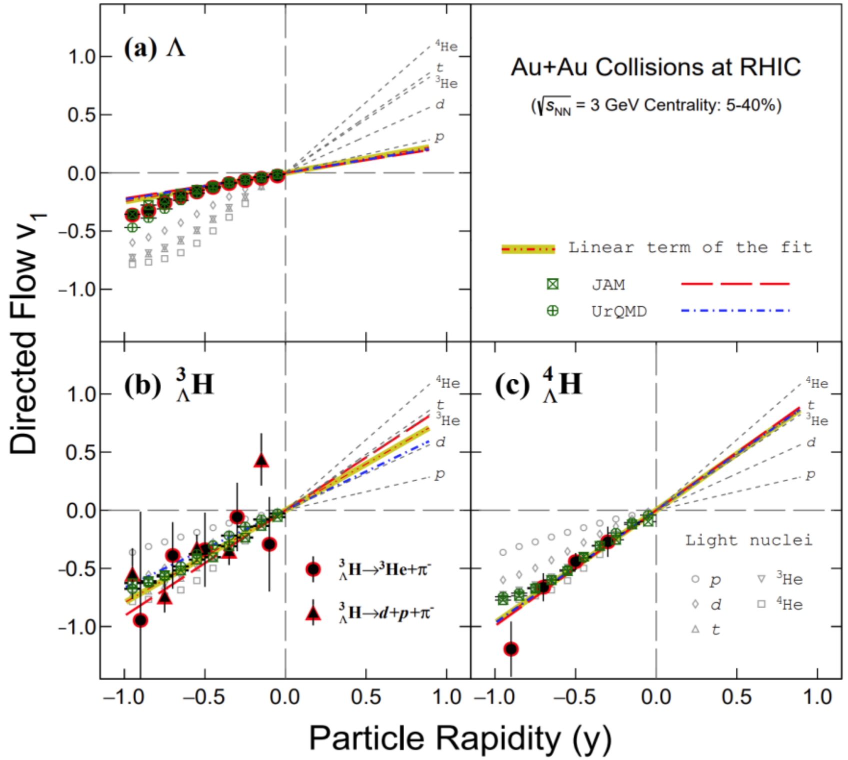


Fitting function:

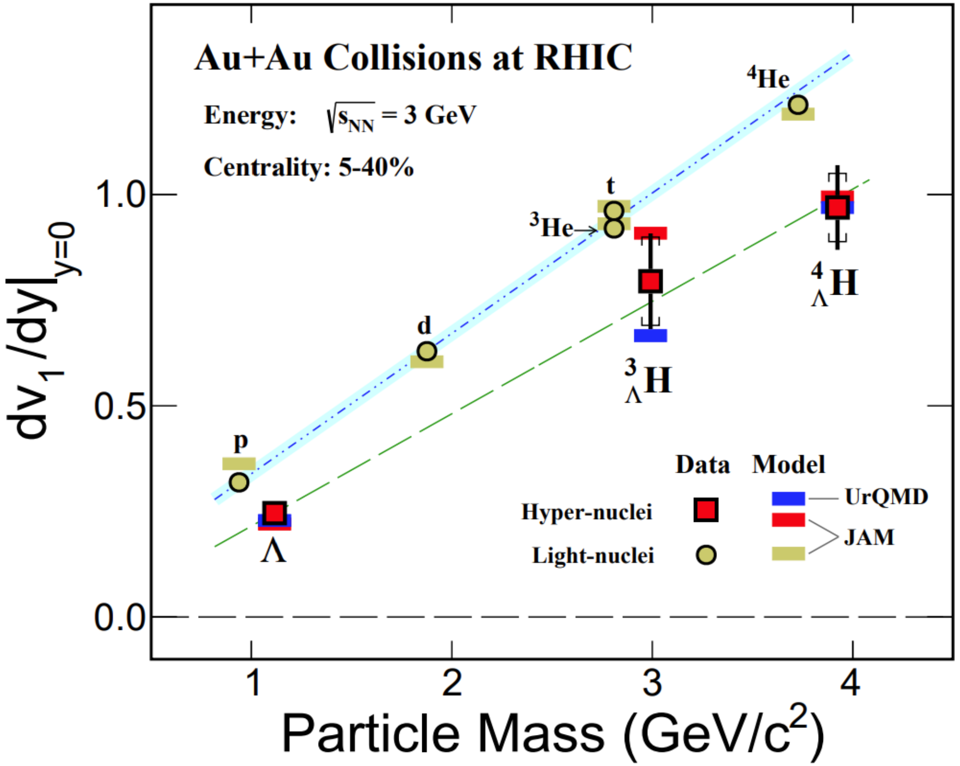
$$dN/d(\phi - \Psi 1) = p^0(1+2\mathbf{v_1}\cos(\phi-\Psi 1)+2v_2 \cos(2(\phi-\Psi 1)))$$

Experimental data Vs Transport+coalescence

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



$P_t/A \sim (0.4, 0.8)$ GeV/c



- The slopes of dv_1/dy Vs Mass for hyper-nuclei is similar to that of light nuclei
- Data and Simulation results are in a good agreement

Support: Coalescence is a dominant process for (hyper-)cluster formation

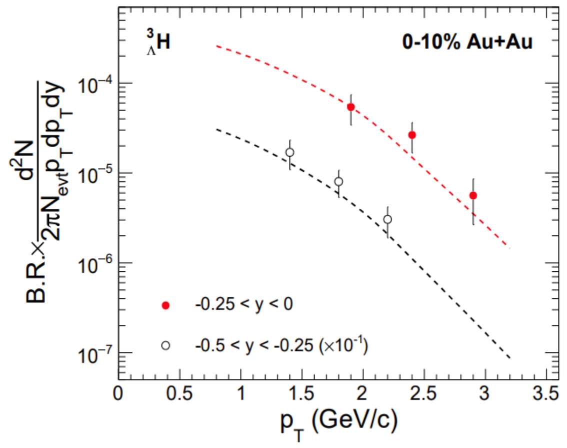
JAM/UrQMD + Coalescence

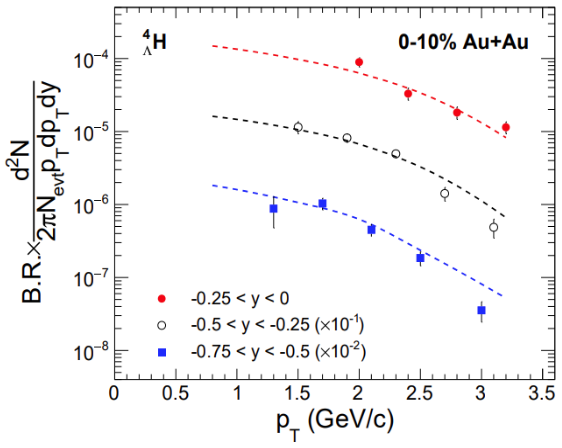
- Jet AA Microscopic Transport Model (JAM) simulation (κ = 380 MeV)

NARA et al, PRC, 61, 024901(2000)

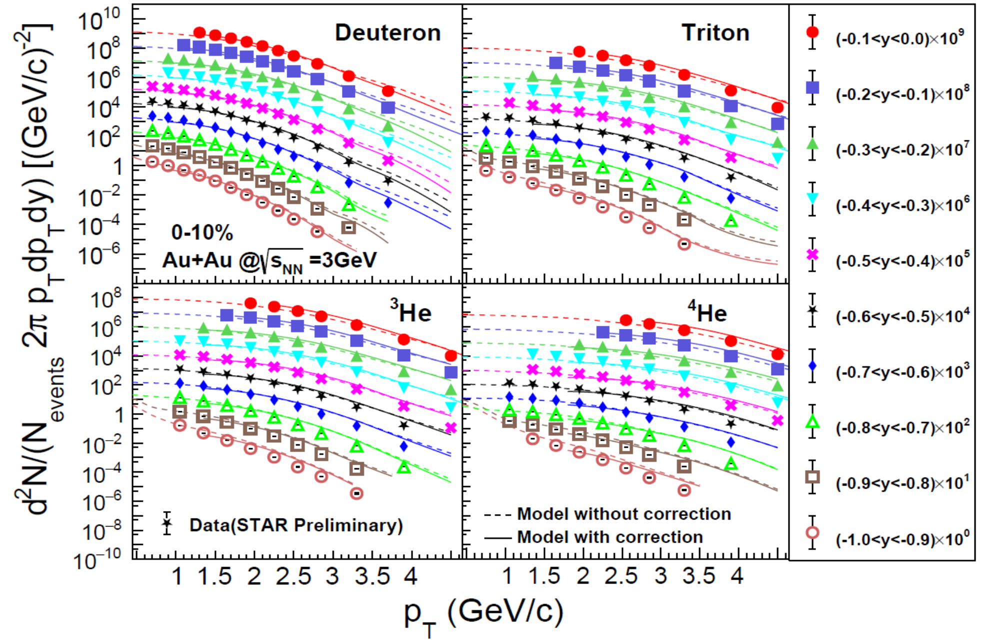
- Coalescence ($t_{freeze\text{-}out}$=50 fm/c)

$$E_A \frac{d^3N_A}{d^3p_A} \propto \left(E_p \frac{d^3N_p}{d^3p_p}\right)^Z \left(E_n \frac{d^3N_n}{d^3p_n}\right)^{A-Z} \approx \left(E_p \frac{d^3N_p}{d^3p_p}\right)^A$$





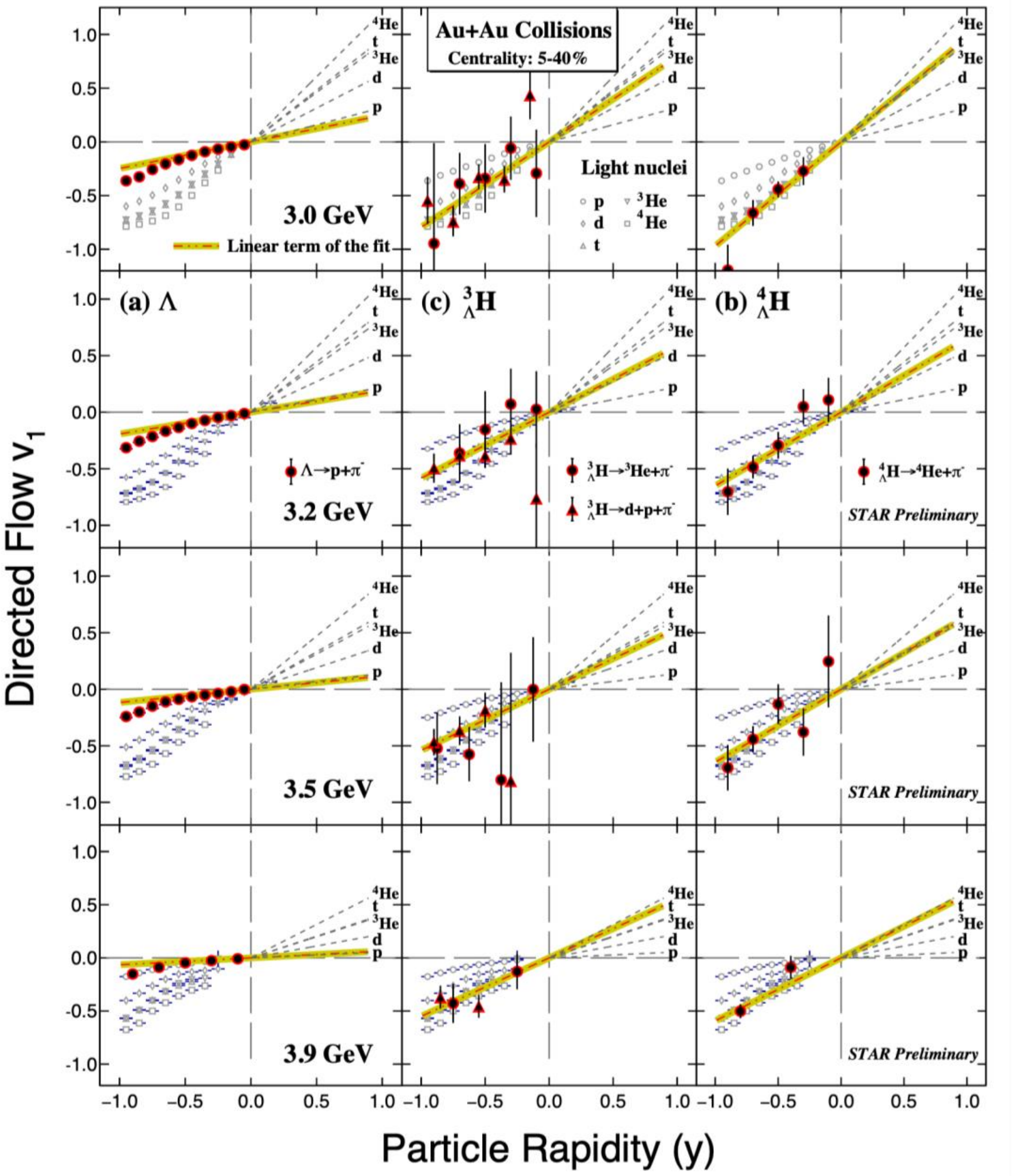
H. Liu (STAR Collaboration), SciPost Phys. Proc., 040 (2022)

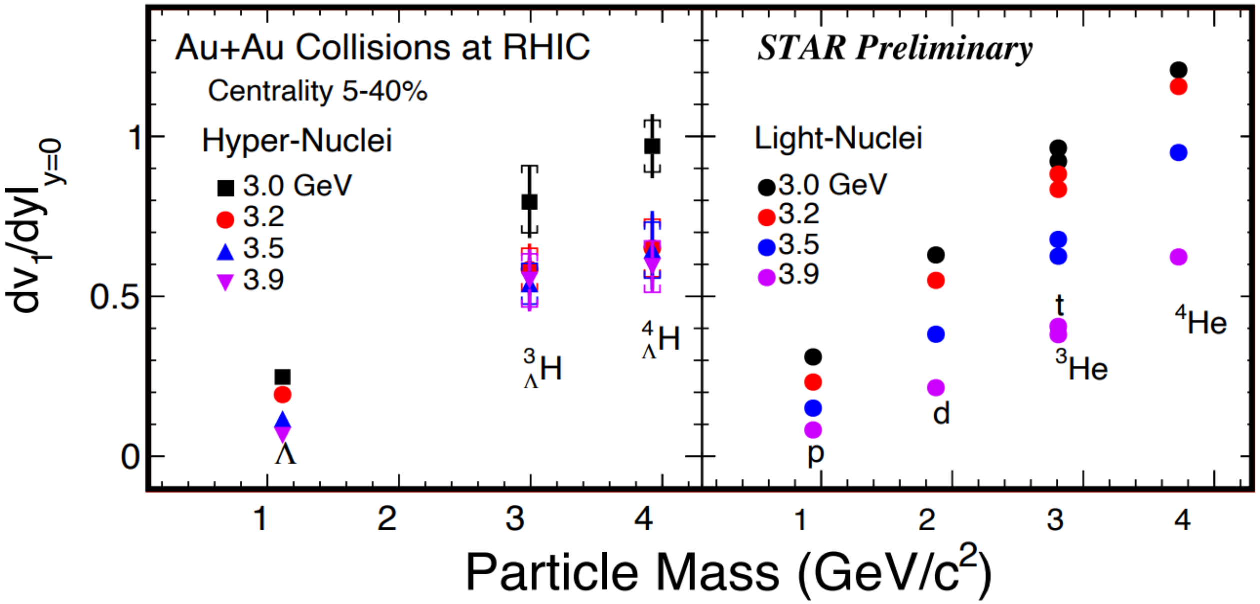


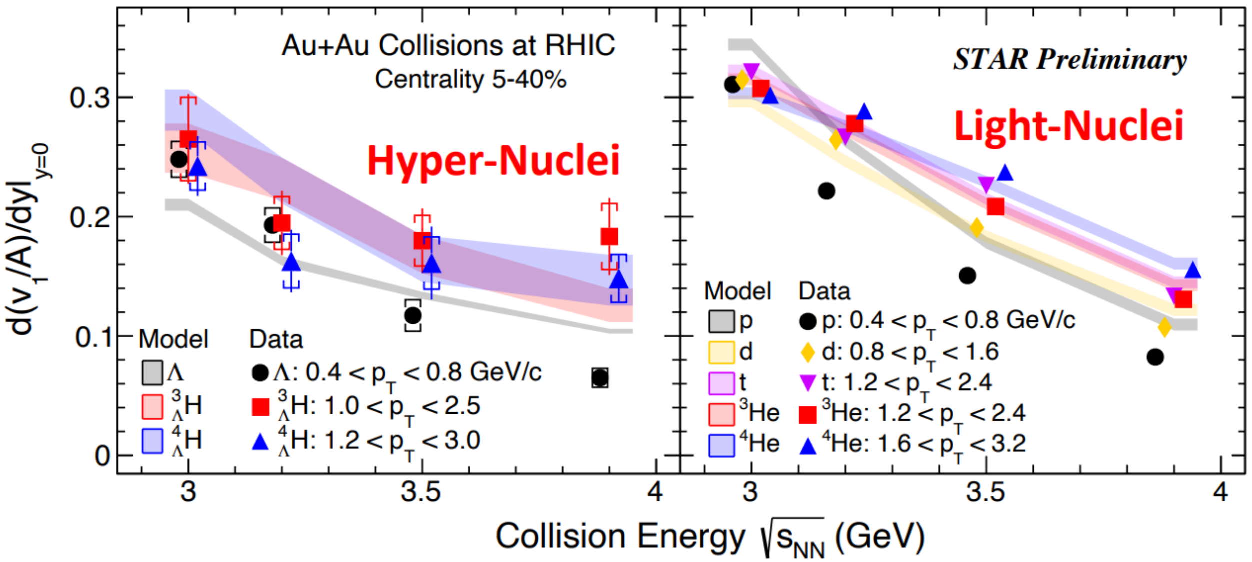
Particle	d	t, ^{3}He, ^{4}He	$^3_\Lambda$H	$^4_\Lambda$H
Δp (GeV/c)	0.3	0.3	0.12	0.3
Δr (fm)	4.5	4.0	4.0	4.0

Yue Xu, Xionghong He and Xu Nu, Chinese Physics C, 47, 074107 (2023)

Collective flow Vs. Colliding Energy

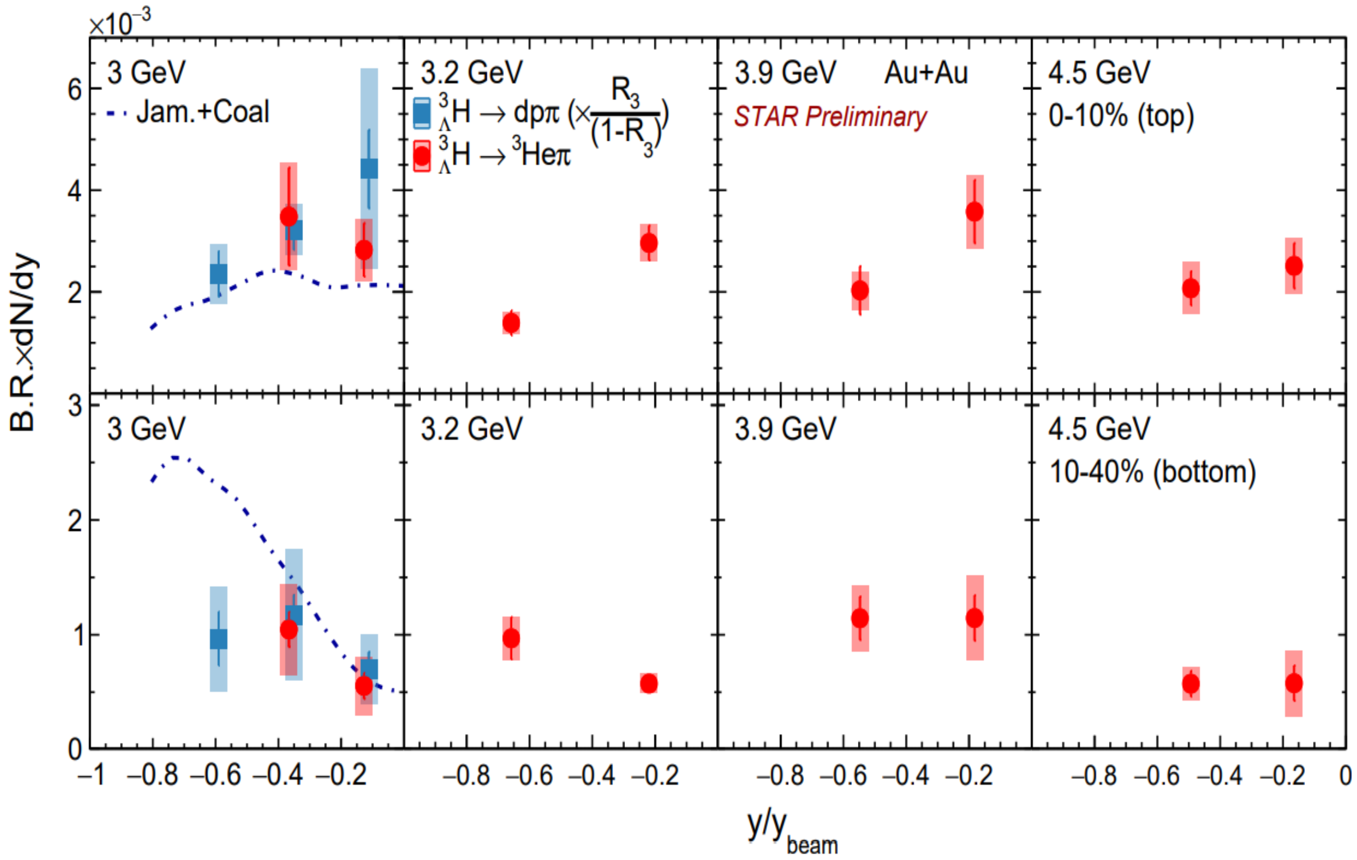


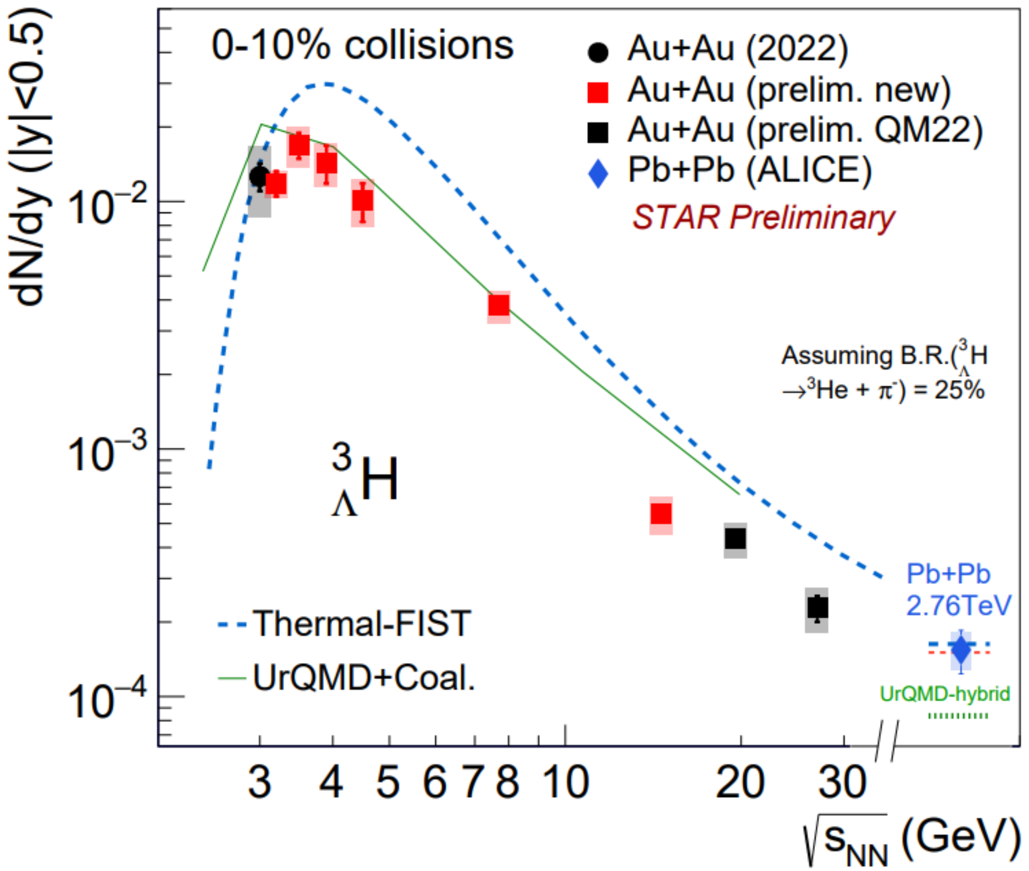




$^3_\Lambda H$ Production in HICs

中心碰撞(0-10%)/半中心碰撞：(10-40%) 超核产额 Vs 碰撞能量





J. Yuan@QM 2023

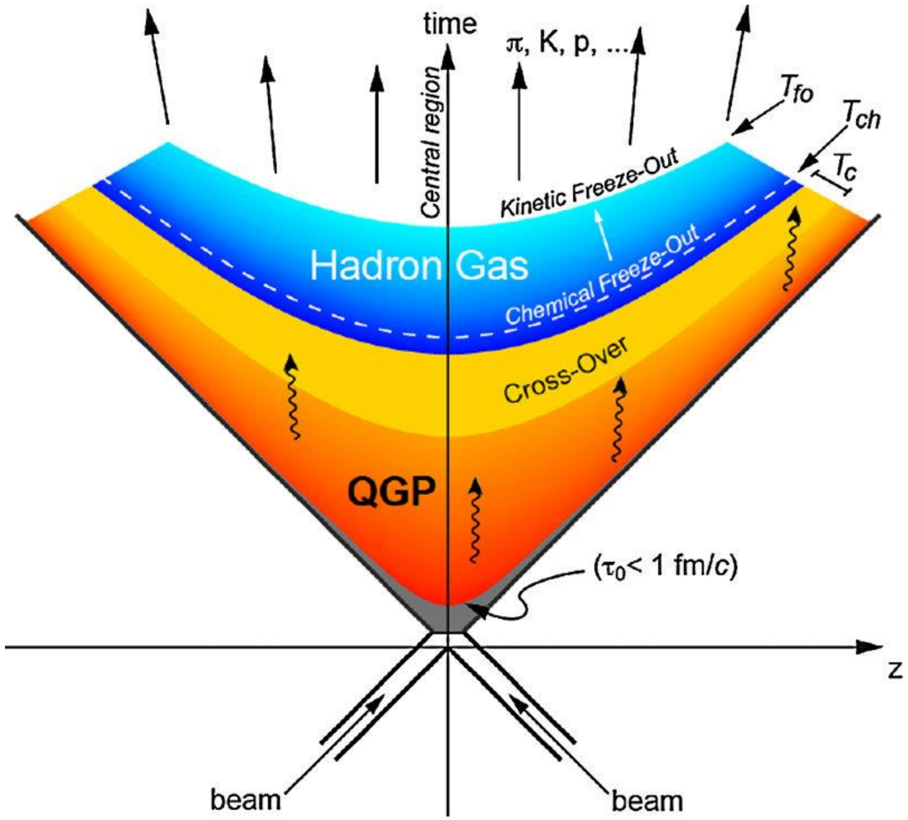
Hypernuclei:

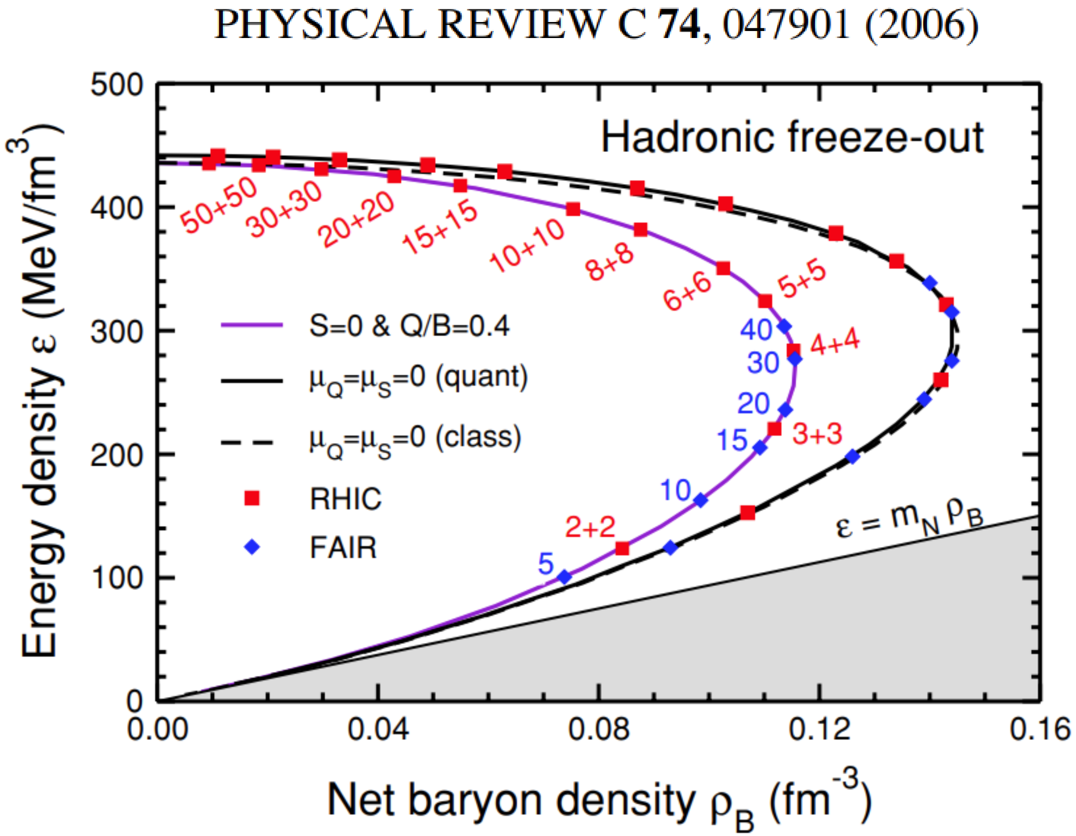
- Production
- Collectivity

??? ↔ YN (ρ)

When and how are the (hyper-)clusters formed?

Scenario I: Coalescence production at freeze-out

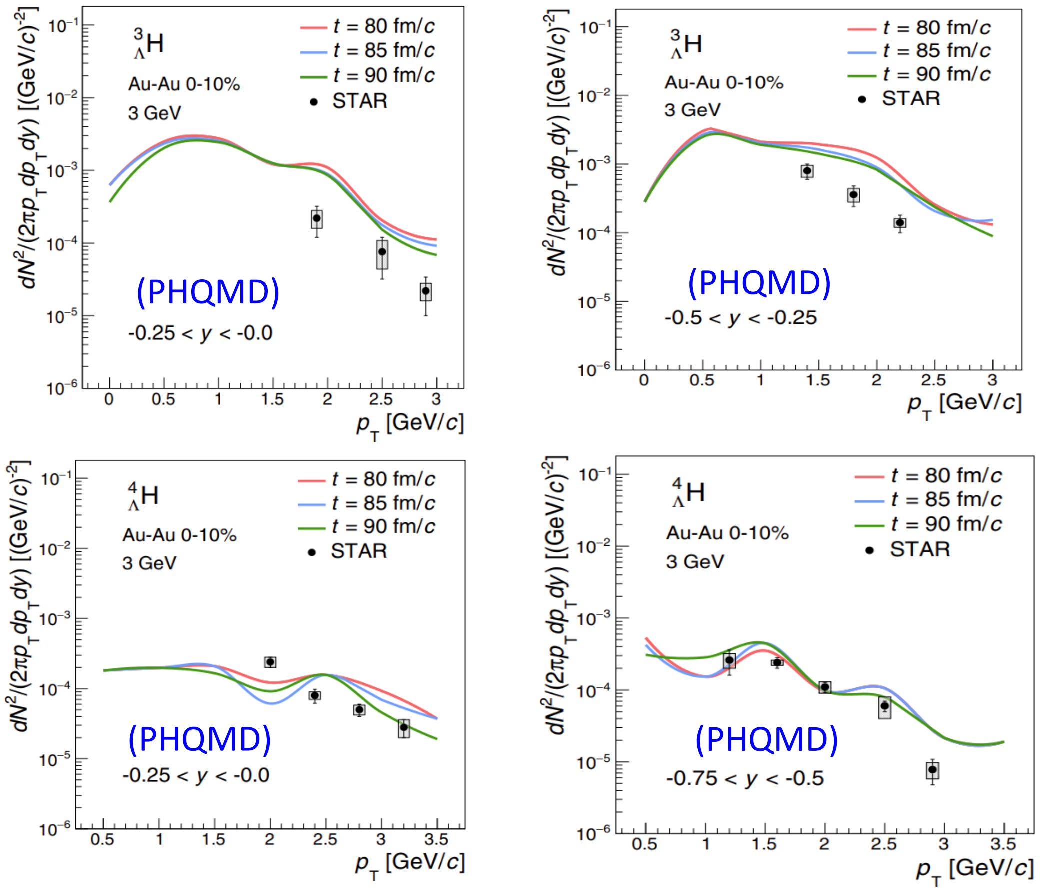




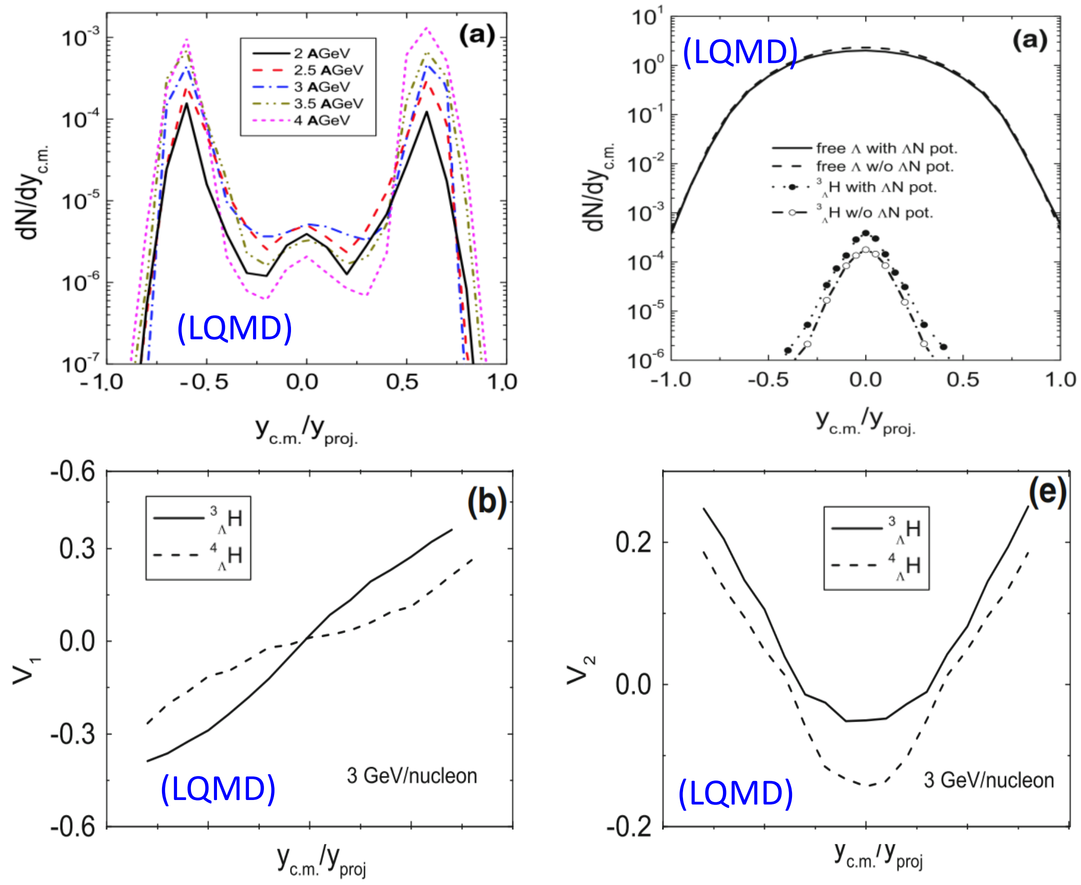
In picture of coalescence at freeze-out, hypernuclei collective flow would not probe YN interaction at high baryon density

Scenario II: Dynamical formation of (hyper-)clusters

Gleassel, PRC, 105, 014908 (2022)



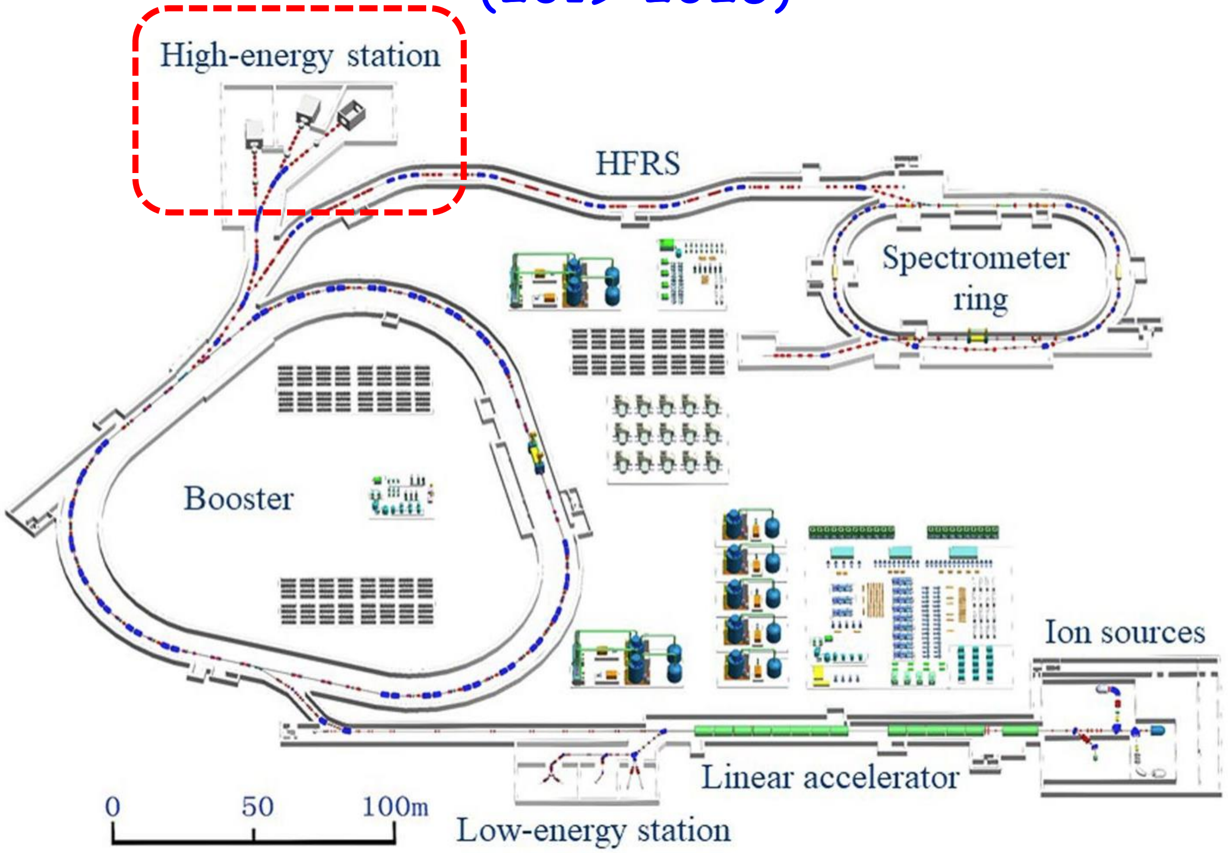
Zhao-Qing Feng, Eur. Phys. J. A (2021) 57



In dynamic formation scenario, hyper-nuclei collective flow and production may take the information of in-medium YN interaction

5. Hypernuclei opportunity at HIAF

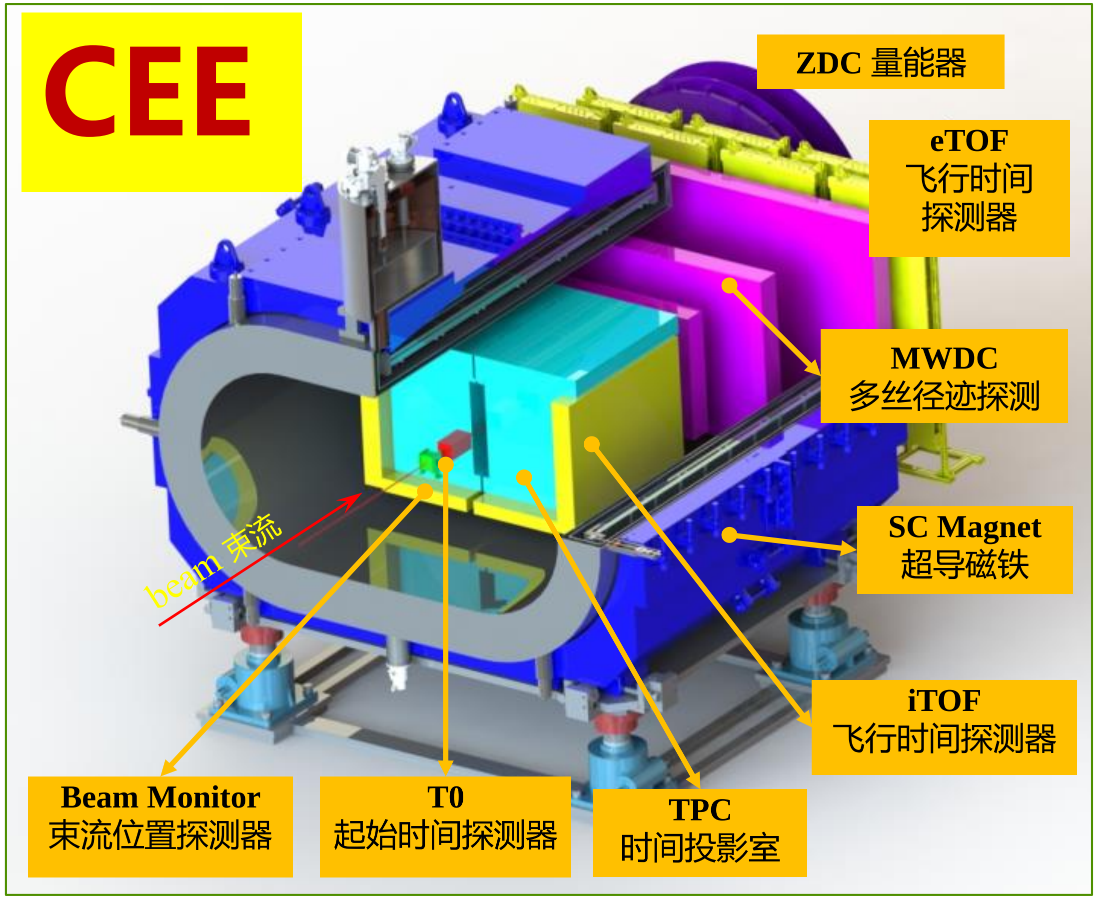
High Intensity Heavy-ion Accelerator Facility (HIAF) (2019-2025)



Heavy-ion beam: ~ 4.5 GeV/u
Proton beam: 9.3 GeV

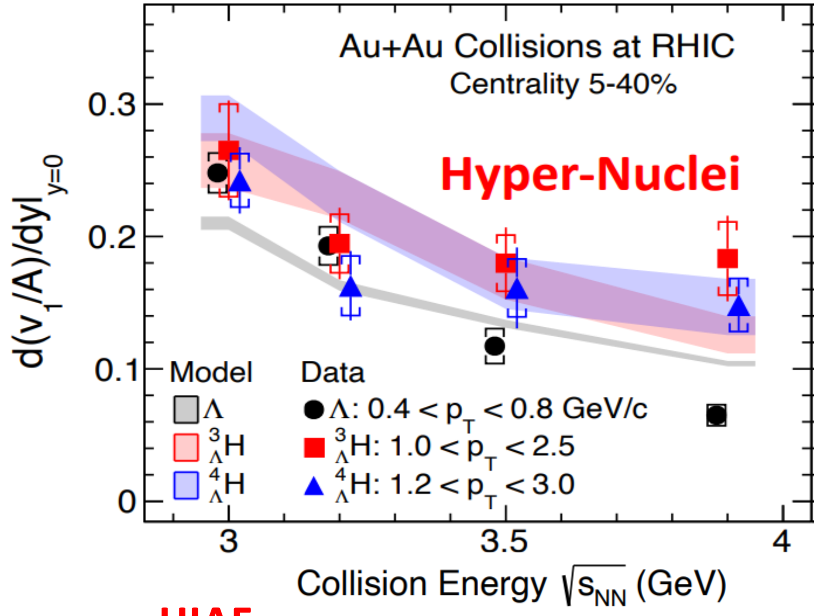
Zhou et al. AAPPS Bulletin (2022) 32

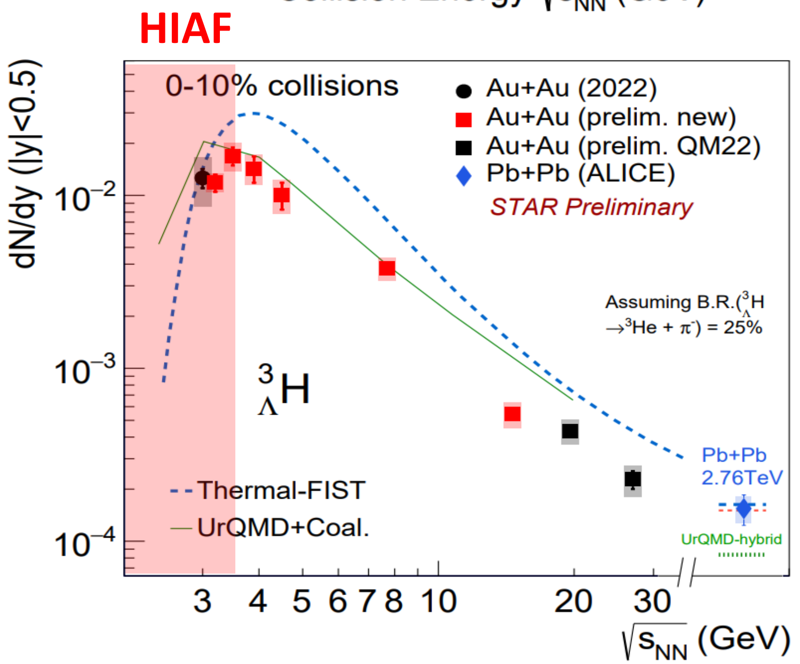
CSR-External target Experiment (CEE) (2020-2024)



总结

- 高能重离子碰撞中的超核产生和集体运动或是研究核介质依赖YN相互作用的独特手段；
- 基于STAR实验，在3 GeV金-金碰撞种观测到了最大统计量的$^{3}_{\Lambda}\mathrm{H}$ 和 $^{4}_{\Lambda}\mathrm{H}$ 的数据样本，并完成超核直接流和超核产额提取；超核集体流、产额与碰撞能量依赖(3.0-7.7 GeV)在进行中；
- HIAF位于超核产生的极大区域是发现新超核（丰质子和丰中子超核）、发现双超子超核、精确测量超核性质等来提取YN和YY的理想场所。





Thanks for your attention

Collaborators:

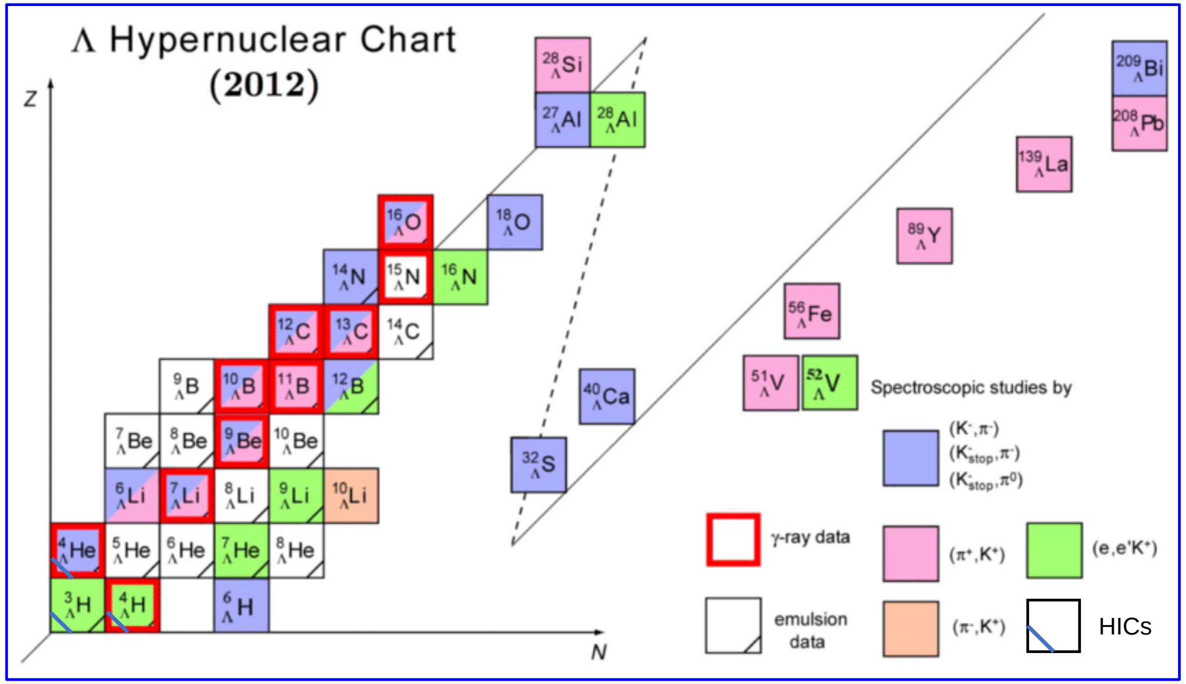
IMP: Xionghong He, Chenlu Hu (PhD), Nu Xu, Fengyi Zhao (PhD)

BNL: Xin Dong, Yuanjin Ji, Yue-Hang Leung

CCNU: Shusu Shi, Yaping Wang

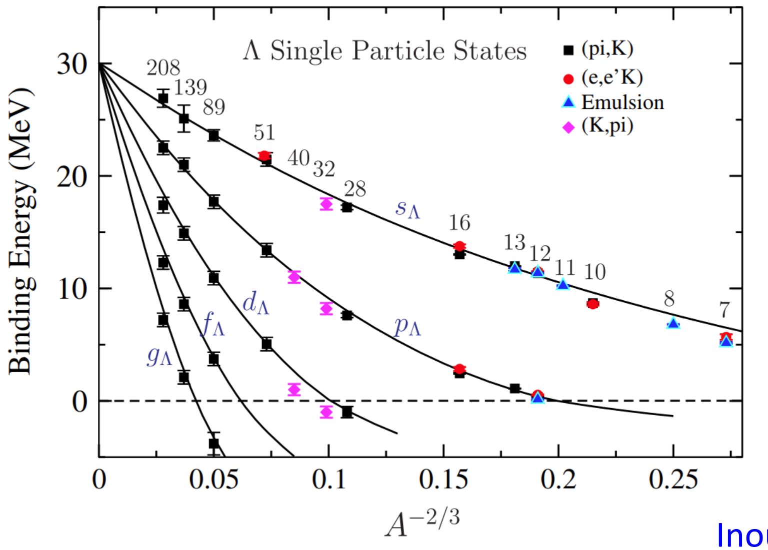
Lambda Hypernuclei chart

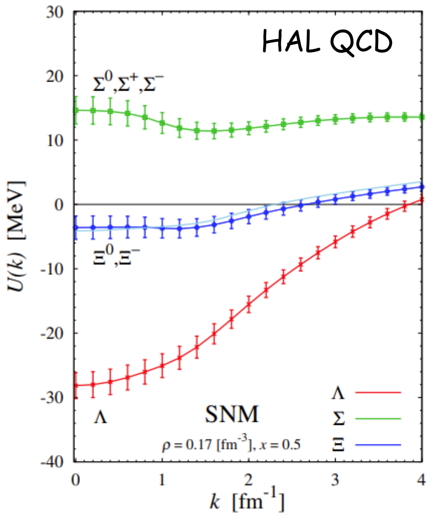
Single-Λ Hypernuclei chart



Updated from: Hashimoto, O., and H. Tamura
Prog. Part. Nucl. Phys. 57, 564(2006)

A. Gal et, al, RevModPhys, 88, 035004 (2016)
D. J. Millener, C. B. Dover, and A. Gal, RPC, 38, 2700 (1988)



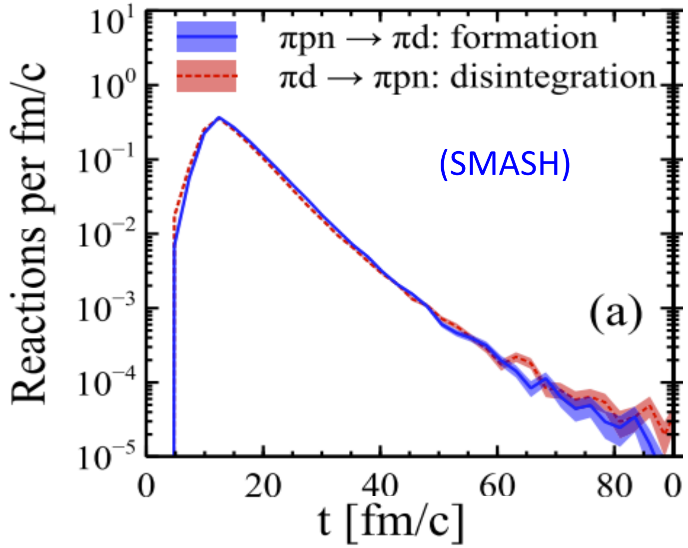


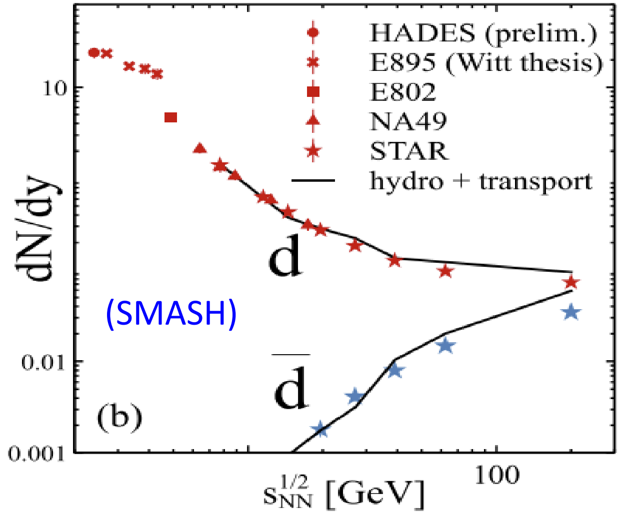
Inoue, Few-Body Syst (2021) 62:106

Woods-Saxon potential: $V(r) = V_0 \frac{1}{1 + e^{\frac{r-R}{a}}}$

Parameter	V_0 (MeV)	R (fm)	a (fm)
Nuclei	~ -53	1.25	0.65
Hyper-nuclei	~ -30	1.165	0.6

Scenario II: Dynamical formation of (hyper-)clusters





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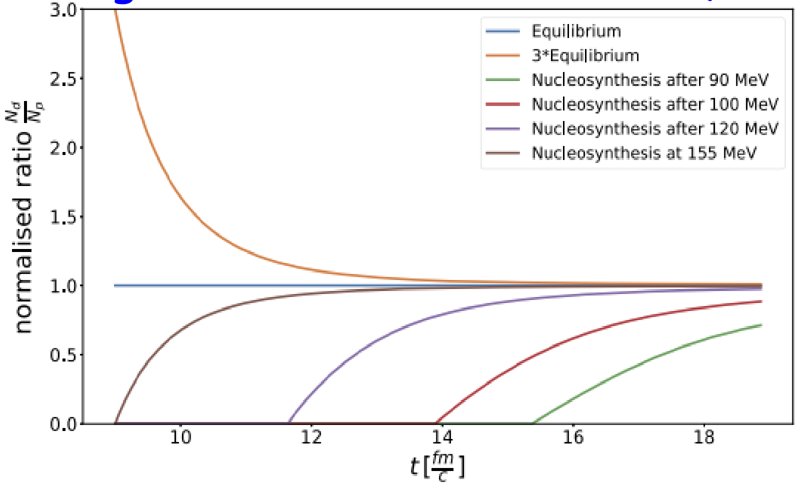

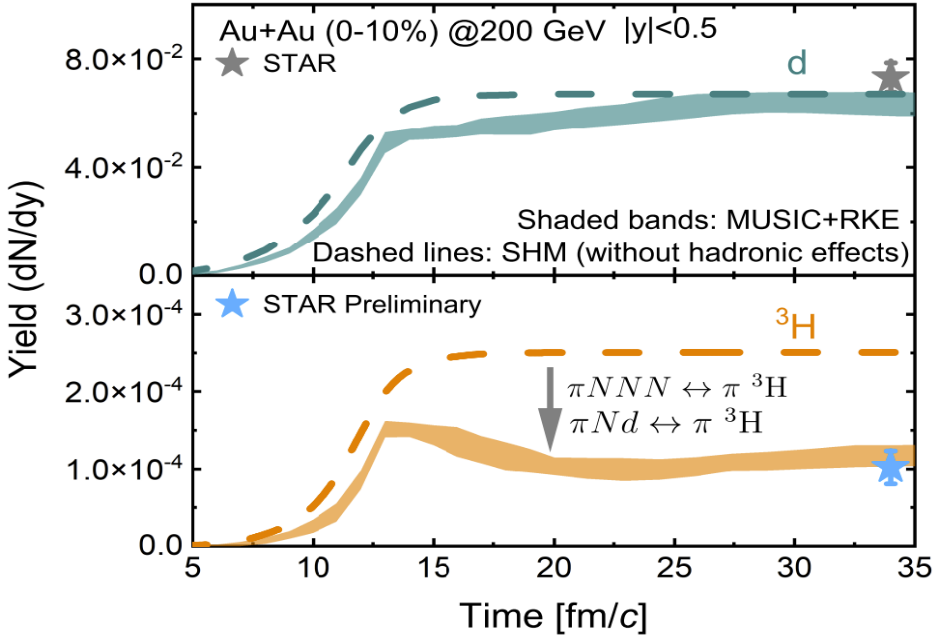

Kai-Jia Sun et al, arXiv:2207.12532 (2022)