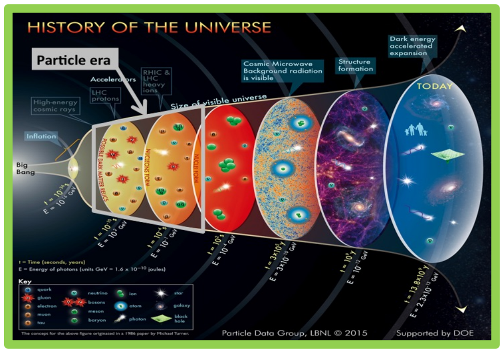
Results on Hyper-Nuclei Productions in High-Energy Nuclear Collisions

Nu Xu (LBNL)

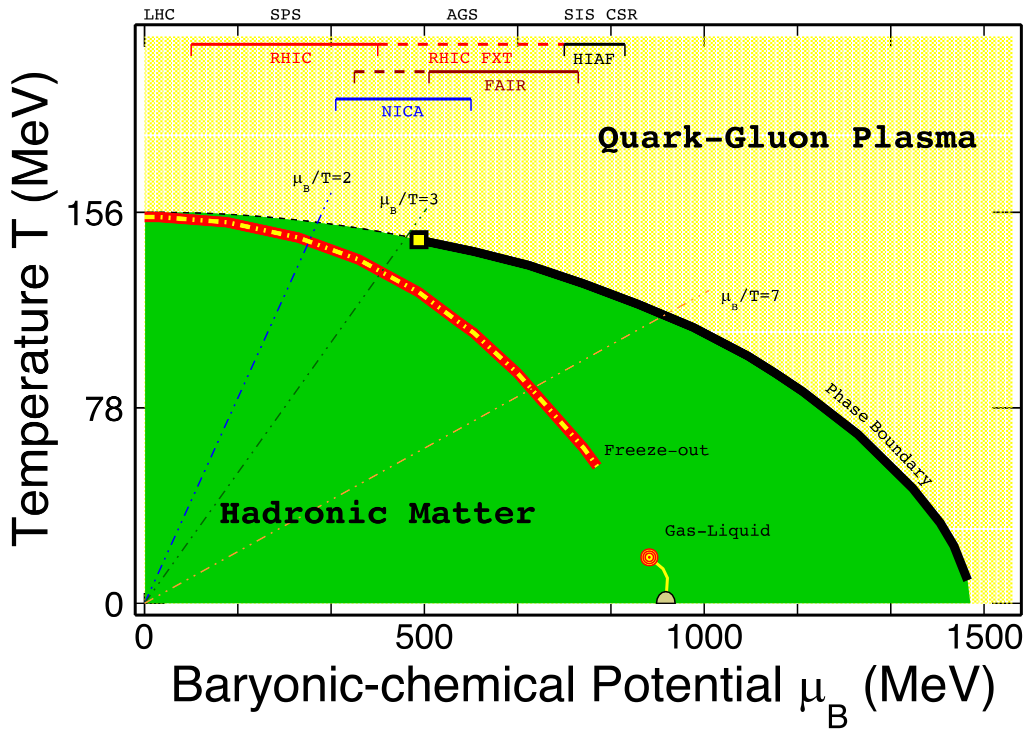
1) Introduction
2) Lifetime
3) Rapidity Density and Collectivity

High-Energy Nuclear Collisions and QCD Phase Diagram

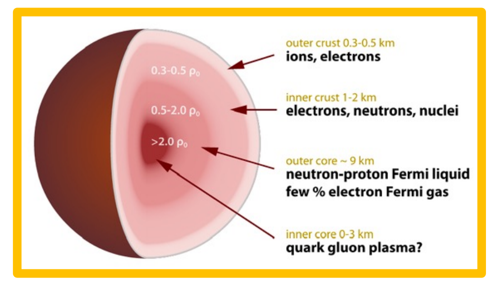
LHC | RHIC BES | FAIR, NICA, …



High temperature:
Early Universe evolution



High baryon density:
Inner structure of
compact stars



1) At $\mu_B = 0$, smooth crossover (LGT + data) ;

2) Large μ_B, 1st order phase transition → **QCD critical point**

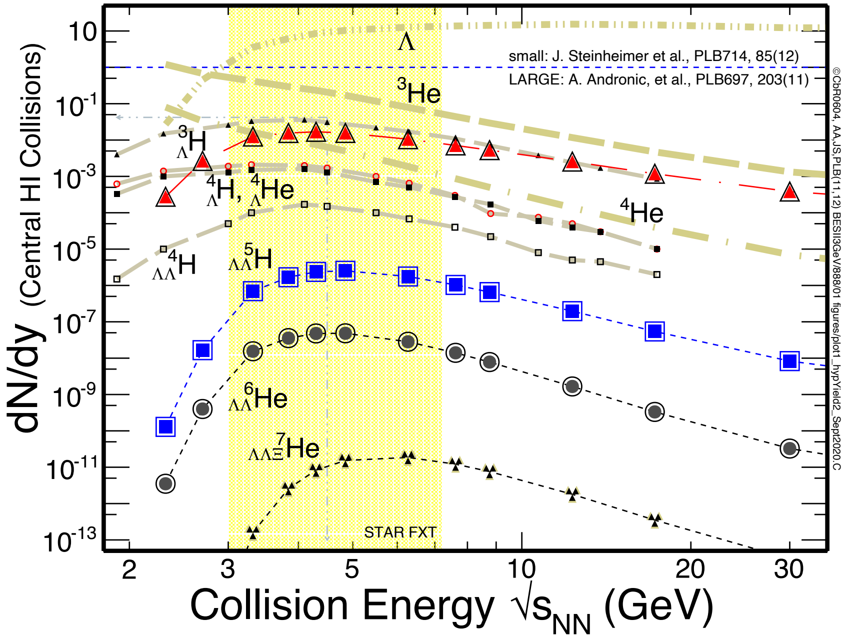
BES-I and BES-II Data Sets

Au+Au Collisions at RHIC											
Collider Runs						Fixed-Target Runs					
	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run		$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	run
1	**200**	380 M	**25** MeV	5.3	Run-10, 19	1	13.7 (100)	50 M	280 MeV	-2.69	Run-21
2	62.4	46 M	75 MeV		Run-10	2	**11.5 (70)**	50 M	320 MeV	-2.51	Run-21
3	54.4	1200 M	85 MeV		Run-17	3	**9.2 (44.5)**	50 M	370 MeV	-2.28	Run-21
4	39	86 M	112 MeV		Run-10	4	**7.7 (31.2)**	260 M	420 MeV	-2.1	Run-18, 19, 20
5	27	585 M	156 MeV	3.36	Run-11, 18	5	7.2 (26.5)	470 M	440 MeV	-2.02	Run-18, 20
6	19.6	595 M	206 MeV	3.1	Run-11, 19	6	6.2 (19.5)	120 M	490 MeV	1.87	Run-20
7	17.3	256 M	230 MeV		Run-21	7	5.2 (13.5)	100 M	540 MeV	-1.68	Run-20
8	14.6	340 M	262 MeV		Run-14, 19	8	4.5 (9.8)	110 M	590 MeV	-1.52	Run-20
9	**11.5**	157 M	316 MeV		Run-10, 20	9	3.9 (7.3)	120 M	633 MeV	-1.37	Run-20
10	**9.2**	160 M	372 MeV		Run-10, 20	10	3.5 (5.75)	120 M	670 MeV	-1.2	Run-20
11	**7.7**	104 M	420 MeV		Run-21	11	3.2 (4.59)	200 M	699 MeV	-1.13	Run-19
						12	**3.0** (3.85)	250 + 2000 M	**750** MeV	-1.05	Run-18, 21

Precision data to map the QCD phase diagram

$$3 < \sqrt{s_{NN}} < 200 \text{ GeV}; \quad 760 < \mu_B < 25 \text{ MeV}$$

Hyper-Nuclei Production at High Baryon Density



high ρ_B + the E_Λ threshold

→ **coalescence** ←

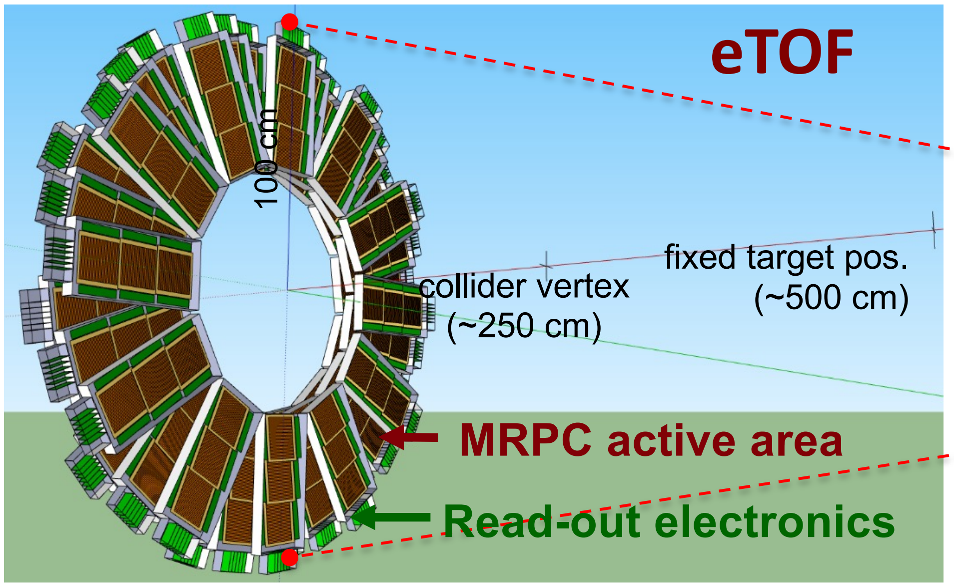
hyper-nuclei production

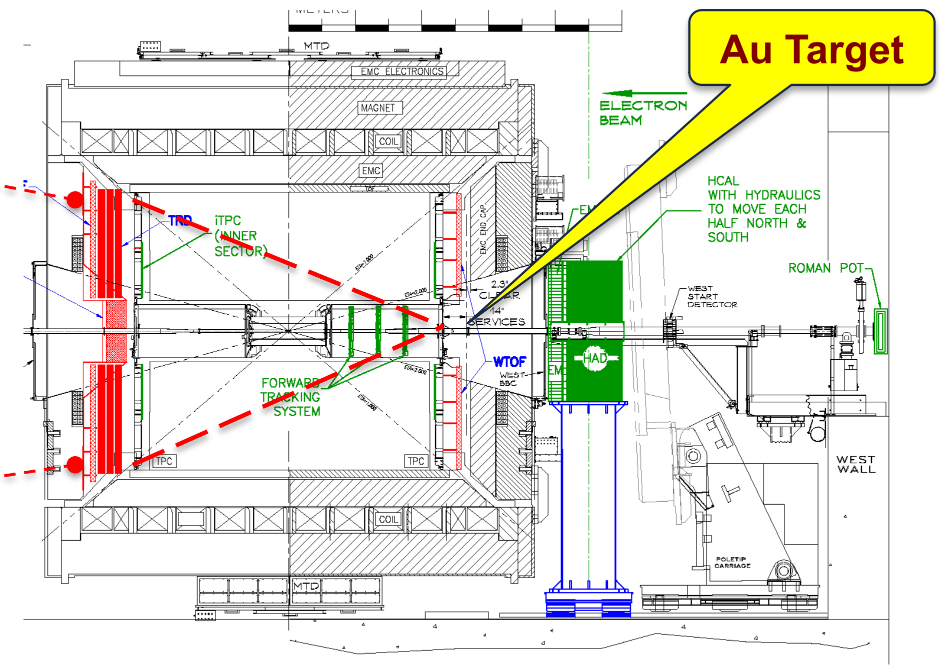
under density and pressure

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

1) Unlike e- and meson-induced interactions, high-energy nuclear collisions are unique for studying hyper-nuclei collectivity (v_0, v_1, v_2) ;
2) In-medium EOS parameter under *pressure,* important for understanding the inner dynamics of compact stars

BES-III Started with CBM TOF at STAR

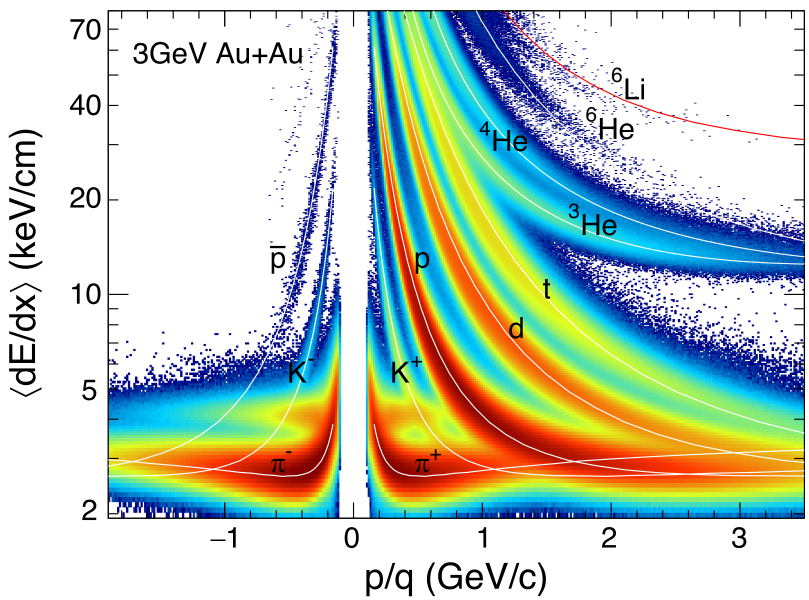


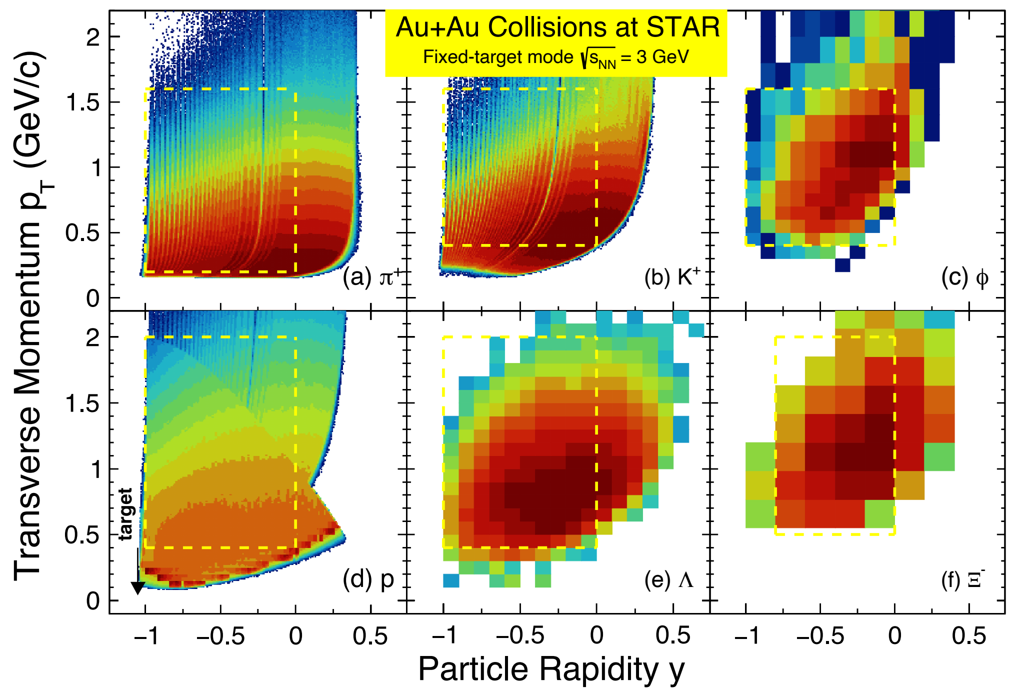


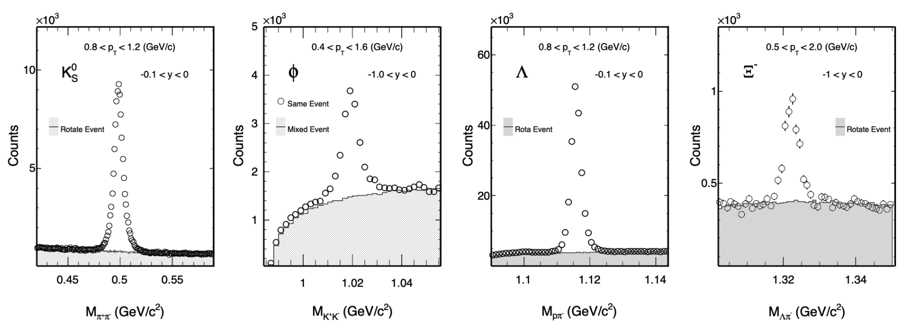
CBM participates in RHIC BES-II in 2019 – 2021:

- Complementary to CBM program: $\sqrt{s_{NN}}$ = 3 - 7.2 GeV (**760 ≥ μ_B ≥ 420 MeV**)
- Strange-hadron, hyper-nuclei and fluctuation at the high baryon density region

Fixed-Target Collisions: PID and Acceptances







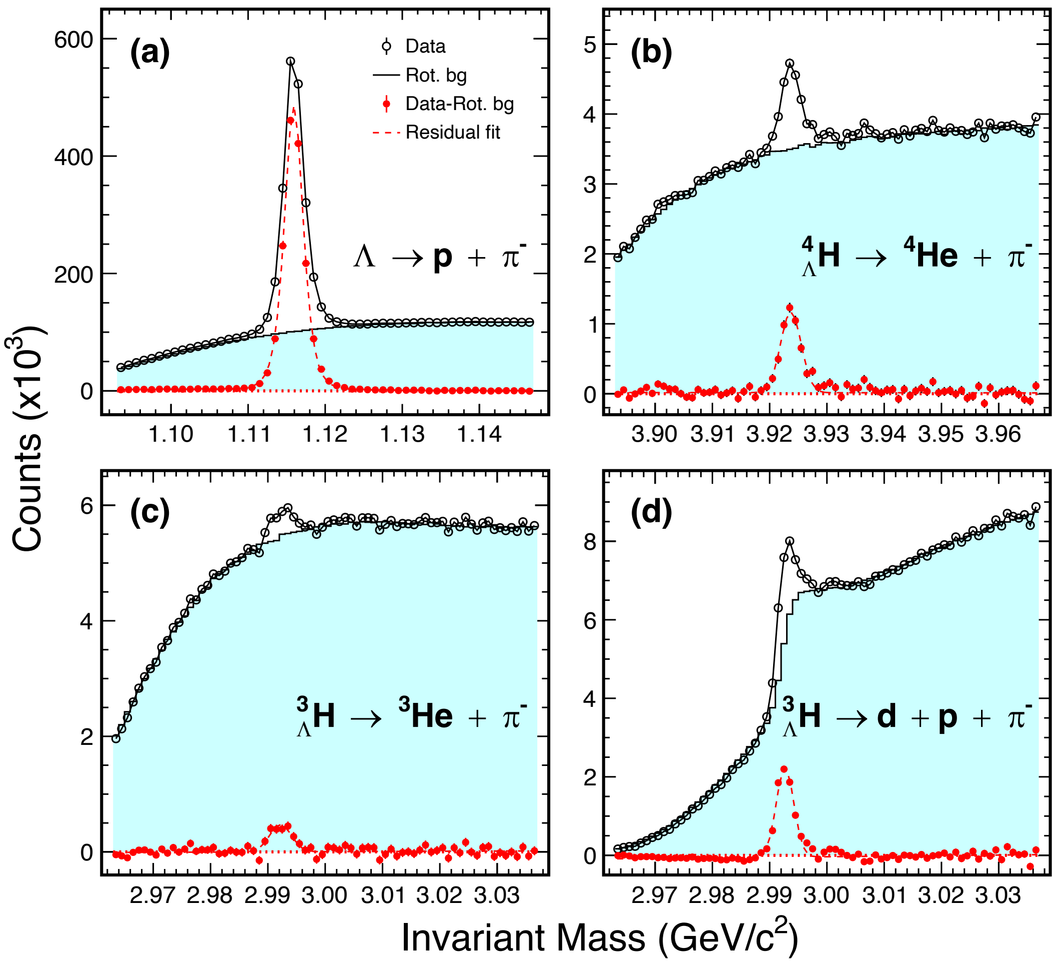
1) 160M minimum biased events

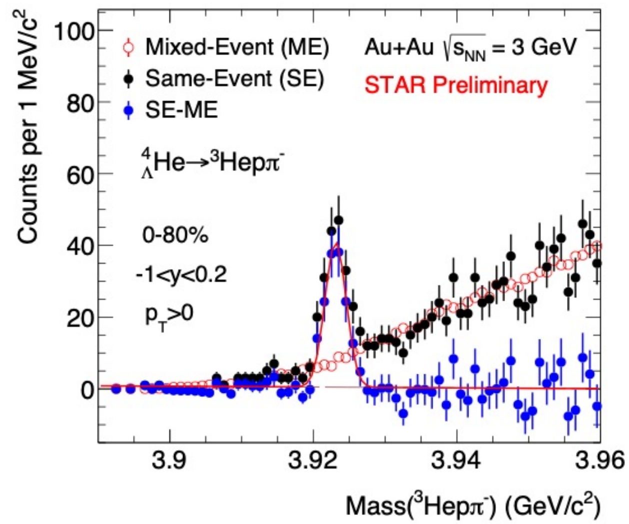
2) Longer tracks, better dE/dx, good PID at mid-y

3) Hyper-nuclei production is abundant!

$^{7}_{\Lambda}Li \rightarrow {}^{6}Li + p + \pi^{-}$ $\quad$ $^{6}_{\Lambda}He \rightarrow {}^{6}Li + \pi^{-}$

Particle Identifications in Au+Au Collisions at 3 GeV



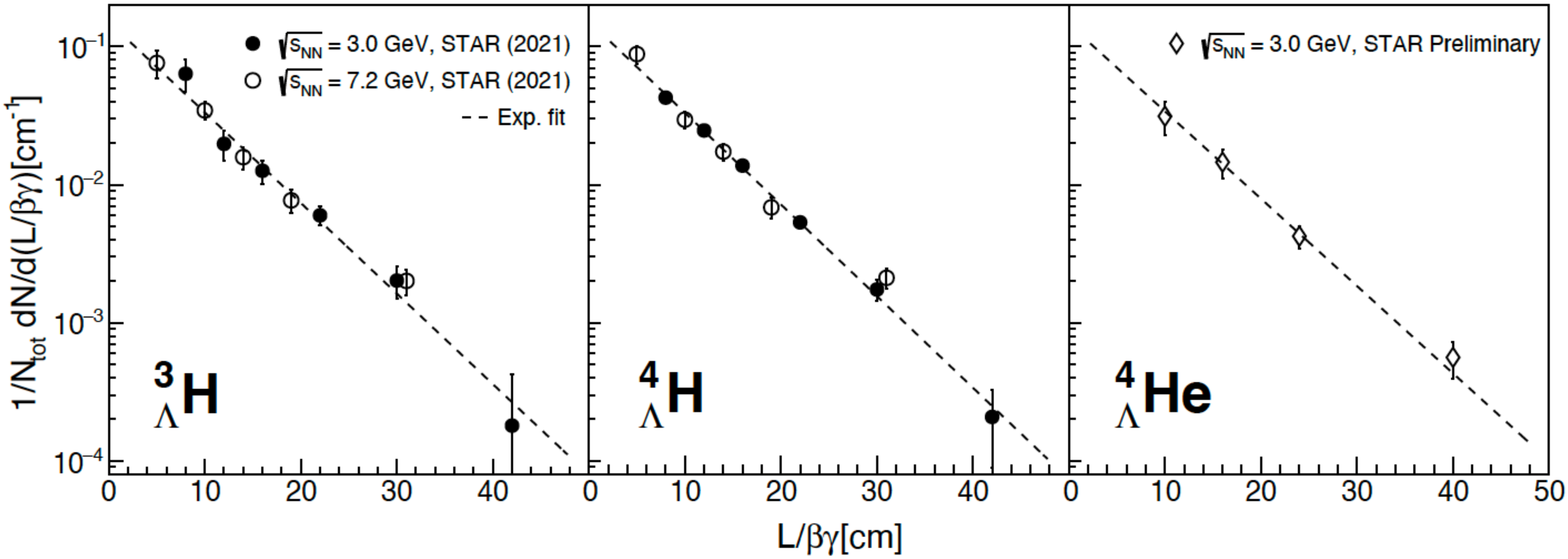


${}^{3}_{\Lambda}H \rightarrow {}^{3}He + \pi^{-}$ and
${}^{3}_{\Lambda}H \rightarrow d + p + \pi^{-}$

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

${}^{4}_{\Lambda}H_{e} \rightarrow {}^{3}He + p + \pi^{-}$

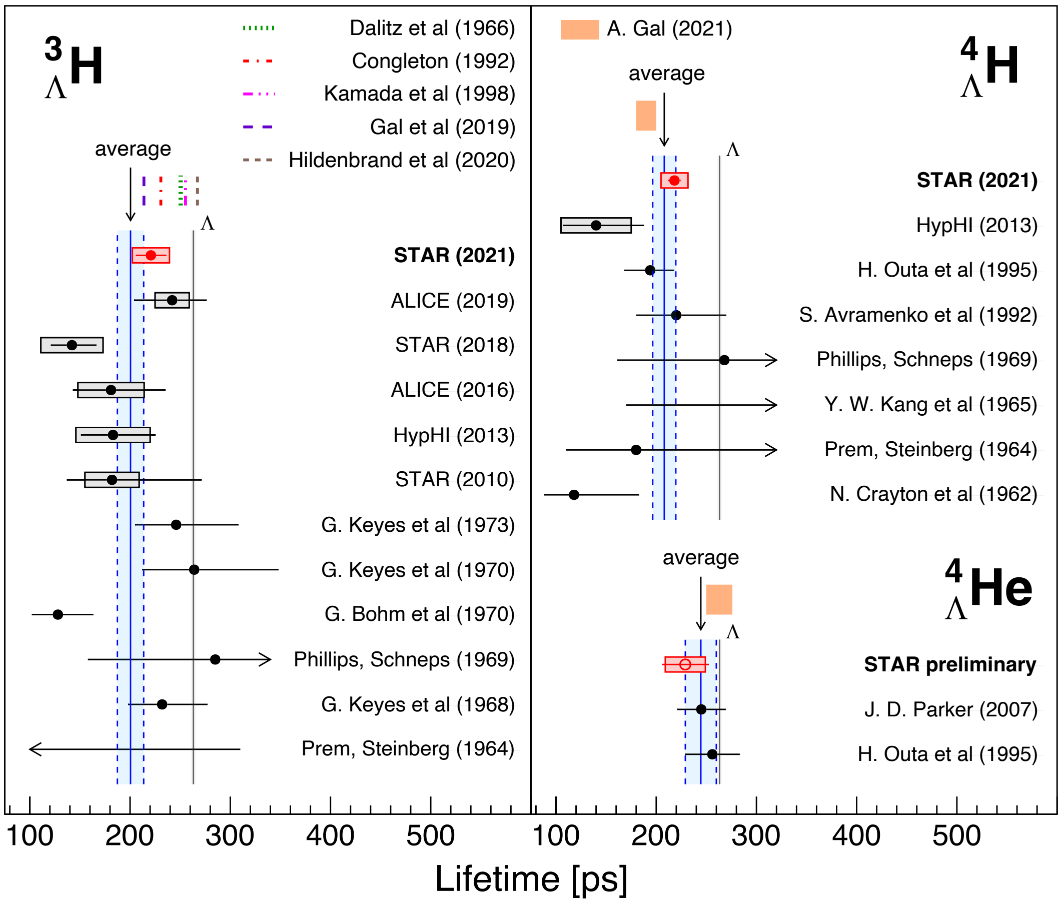
Lifetime Measurements: $^{3}_{\Lambda}H$, $^{4}_{\Lambda}H$, $^{4}_{\Lambda}He$



1) Results of $^{3}_{\Lambda}H$ and $^{4}_{\Lambda}H$ lifetime are consistent from 3 and 7.2 GeV Au+Au collisions;
2) The 3 GeV data has been published;
3) Results of $^{4}_{\Lambda}H_e$ are preliminary

STAR: Y-H. Leung, **HYP2022**
Phys.Rev.Lett. 128 (2022) 202301

Lifetime Measurements: $^{3}_{\Lambda}H$, $^{4}_{\Lambda}H$, $^{4}_{\Lambda}He$



STAR beam energy scan program provided the precision results of the lifetime data :

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

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

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

$\tau(\Lambda)[ps] = 267 \pm 4(stat)$ (PDG: 264± 2)

No more puzzle on hyper-nuclei lifetime!

STAR: Y-H. Leung, **HYP2022**
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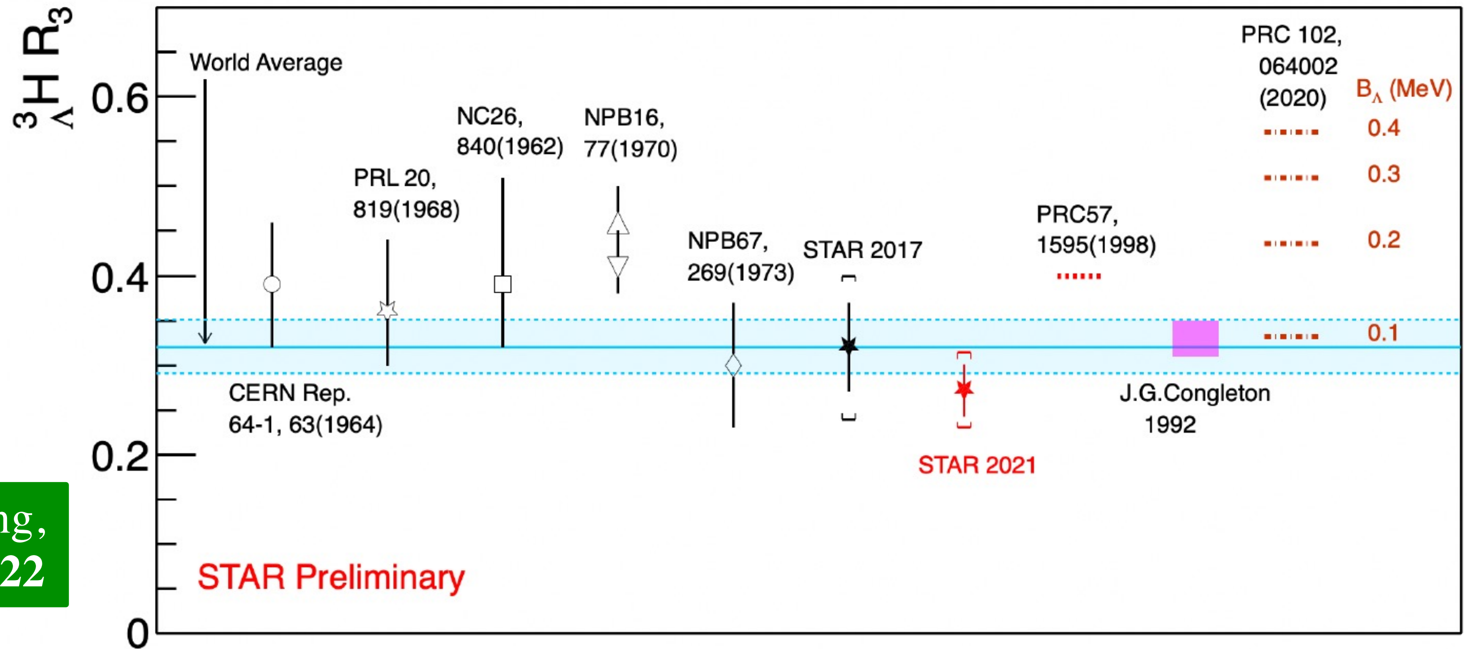
${}^{3}_{\Lambda}$H Relative Branching Ratio R_3

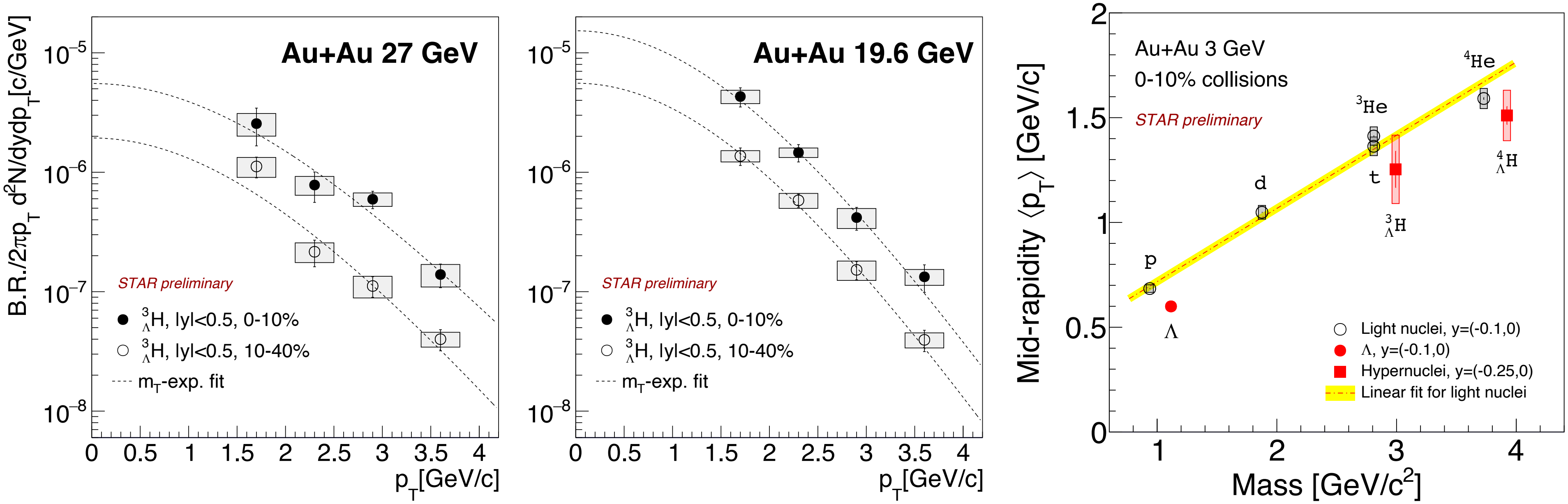


STAR: Y-H. Leung, **HYP2022**

1) $R_3({}^{3}_{\Lambda}\mathrm{H}) = BR(\rightarrow\ {}^{3}He + \pi^{-}) / \left[BR(\rightarrow\ {}^{3}He + \pi^{-}) + BR(\rightarrow d + p + \pi^{-})\right]$
$= 0.27 \pm 0.03(stat.) \pm 0.04(syst.)$

2) Consistent with previous results and lifetime measurement.

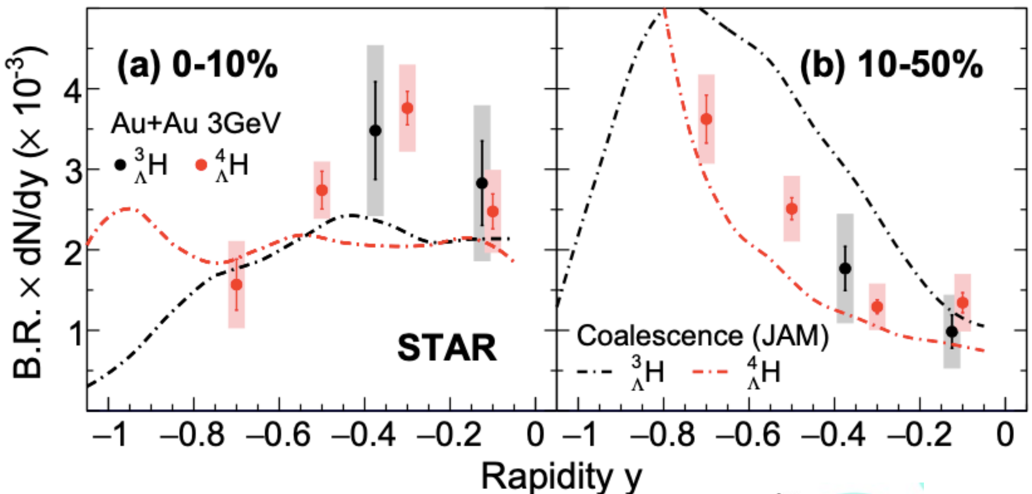
Hyper-Nuclei Transverse Momentum Distributions



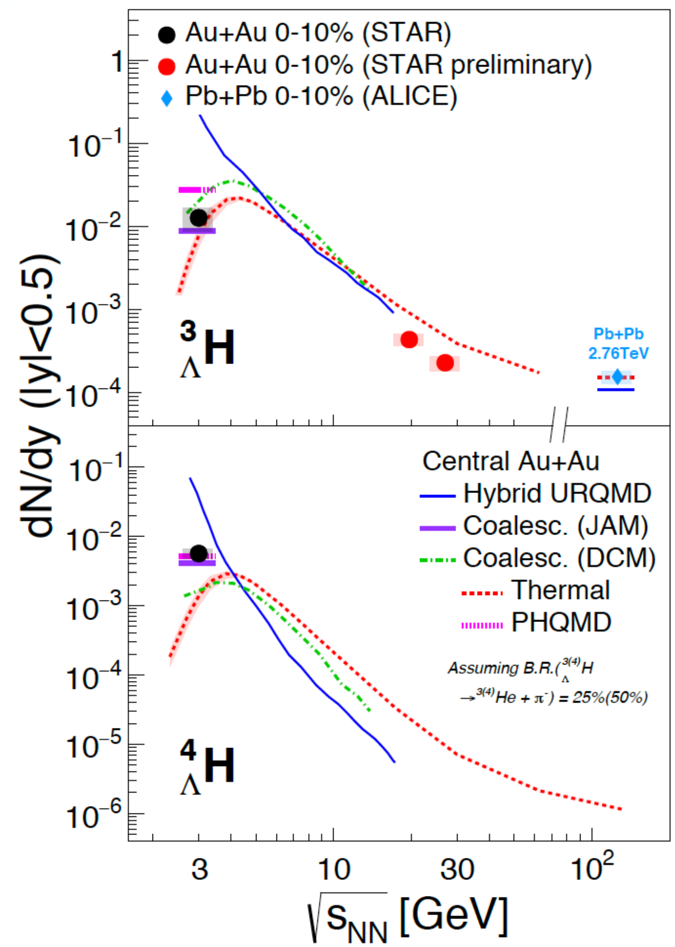
1) Mass dependent in $\langle p_T \rangle$ of hyper-nuclei → collective motion (transverse expansion)
2) Within uncertainties, very similar to that of light nuclei
Similar production mechanism?

STAR:
Y-H. Leung, **HYP2022**

Rapidity Density of Hyper-Nuclei in HIC

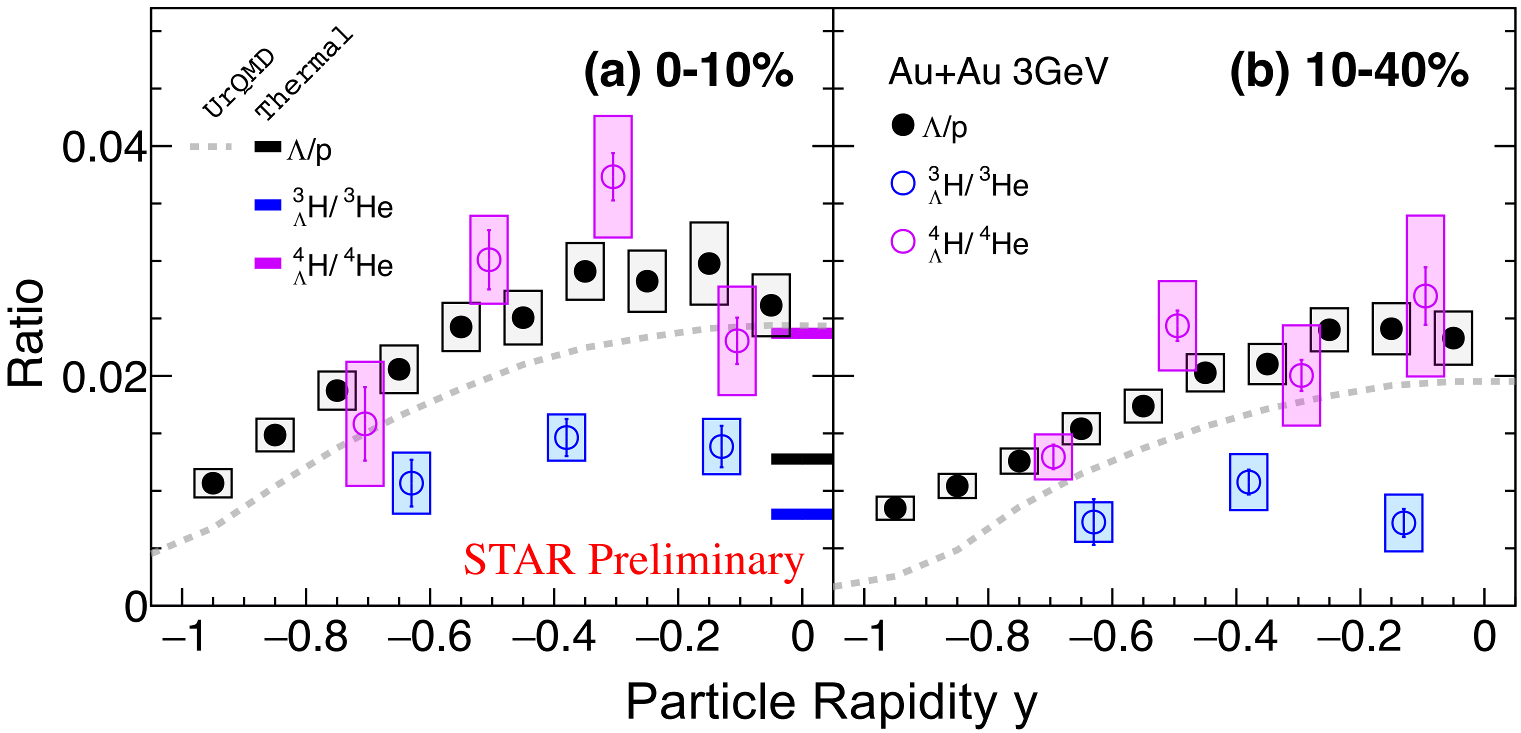


Phys. Rev. Lett. **128**, 202301(2022)



1) At 3 GeV, thermal model w/ CE consistent with ${}^{3}_{\Lambda}H$, but underestimate ${}^{4}_{\Lambda}H$
2) Transport models (JAM or PHQMD) consistent with data, within uncertainties

Hyper-Nuclei Production in HIC



$$R^A = \frac{n^A_\Lambda}{n^A}$$

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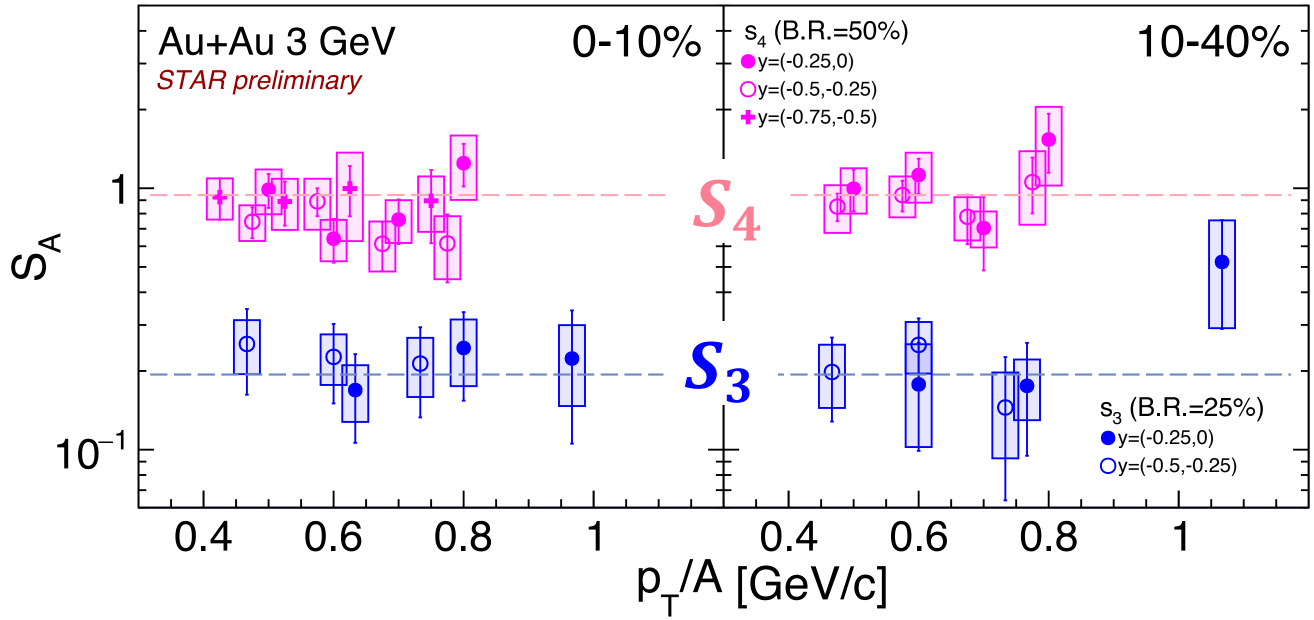
1) First results on the rapidity dependence of the hyper-nuclei production;
2) R^1 ~ R^4 ~ $2R^3$: Enhanced production of Λ and hyper-nuclei at mid-rapidity;
3) UrQMD and thermal model *underpredict* those ratios at mid-rapidity

Hyper-Nuclei Production in HIC

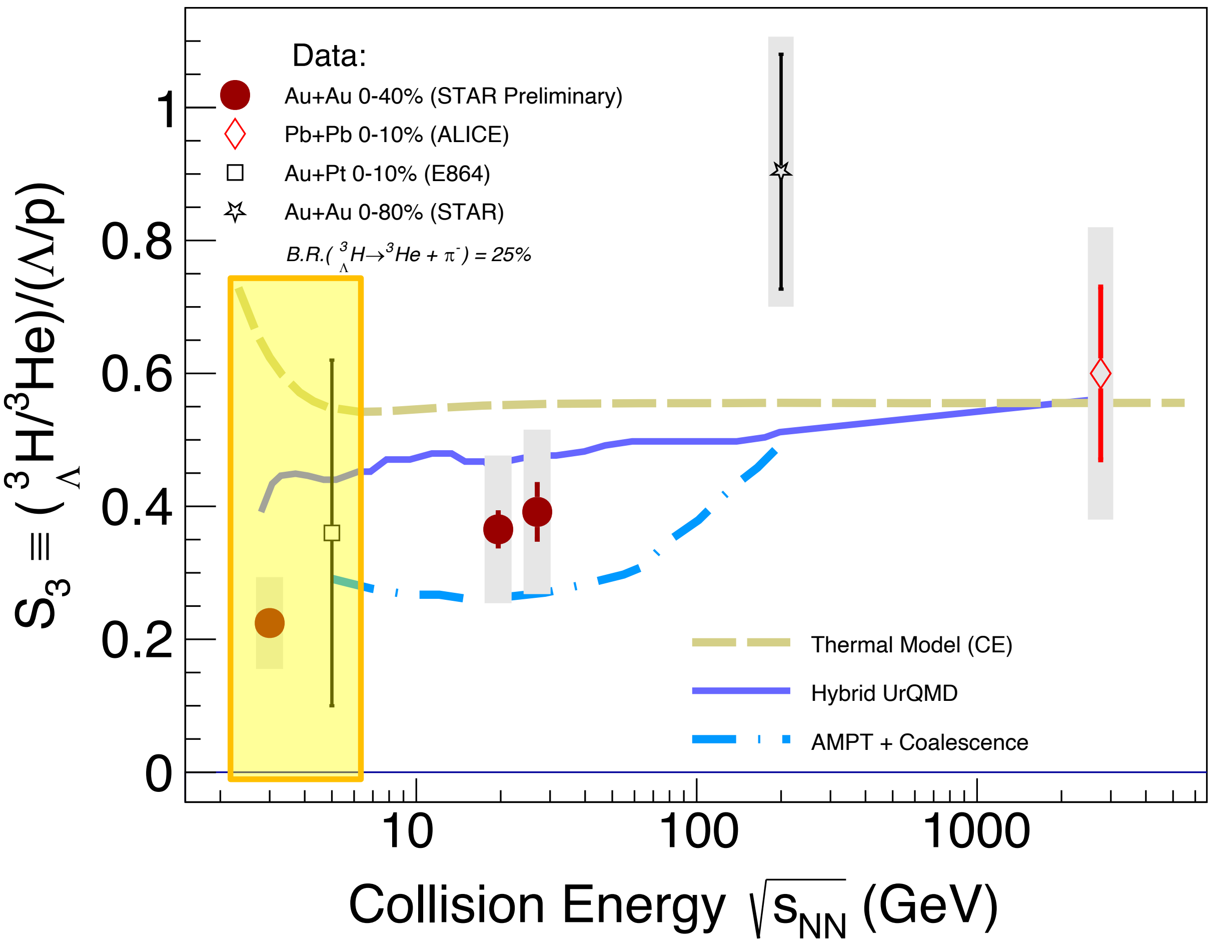


$$S_A = \frac{{}^{\mathrm{n}}_{\Lambda}\mathrm{A}}{{}^{\mathrm{n}}\mathrm{A}} \frac{p}{\Lambda} = R^A \frac{p}{\Lambda}$$

STAR: Y-H. Leung, **HYP2022**

1) S_3 and S_4: ***No effects of mass and threshold for strangeness***.
   Constants versus centrality, rapidity and p_T; $S_4 \sim$ unity $\sim 5\ S_3$?
2) Theory inputs needed to understand the results.

Hyper-Nuclei Production in HIC



$$S_A = \frac{n_\Lambda A}{n_A A}\frac{p}{\Lambda} = R^A \frac{p}{\Lambda}$$

Energy Dependence:

1) S_3 is suppressed in high baryon density region approaching to thermal production;
2) At high baryon density, model over predict the ratios

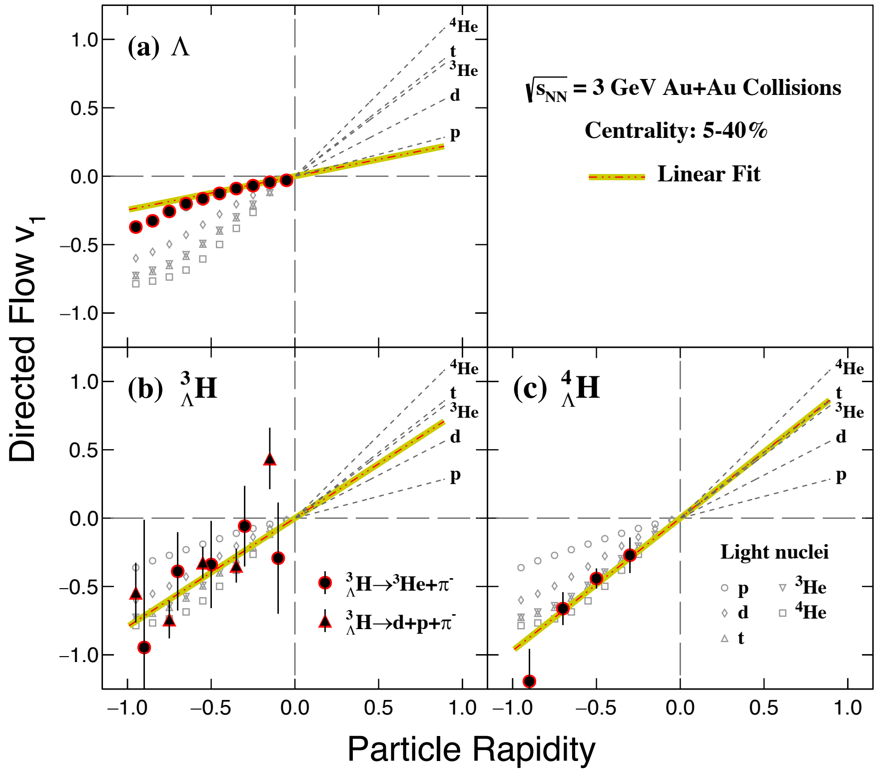
Collectivity

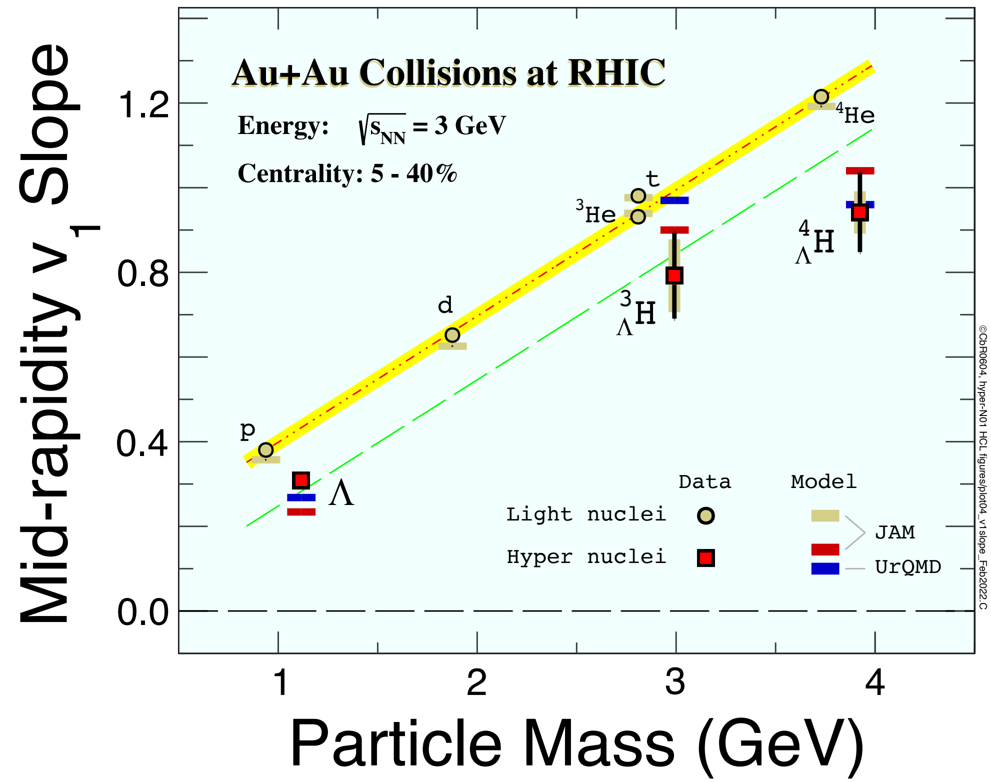
$$\partial_\mu [(\varepsilon + p) u^\mu u^\nu - p g^{\mu\nu}] = 0$$
$$\partial_\mu [s\, u^\mu] = 0$$

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

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

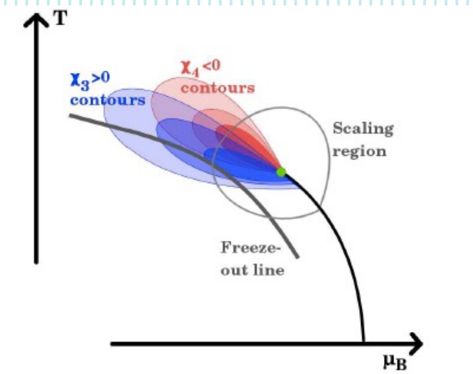
Hyper-Nuclei v_1 Distributions

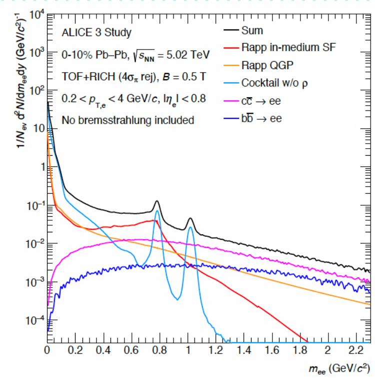


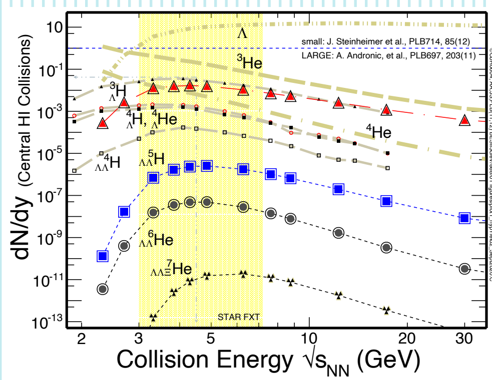


1) First measurements on v_1 and clear mass dependent;
2) Within uncertainties, similar to that of light nuclei and model prediction.

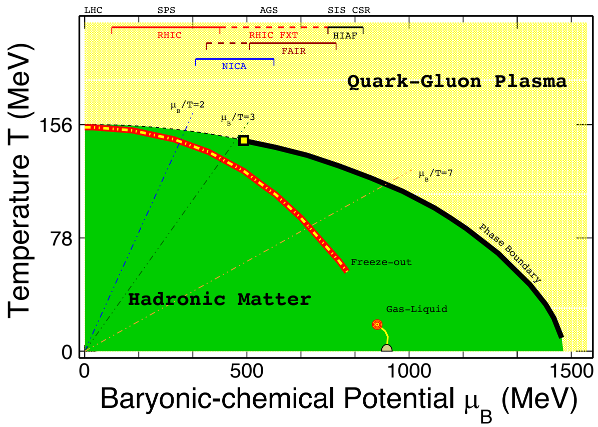
Future Programs







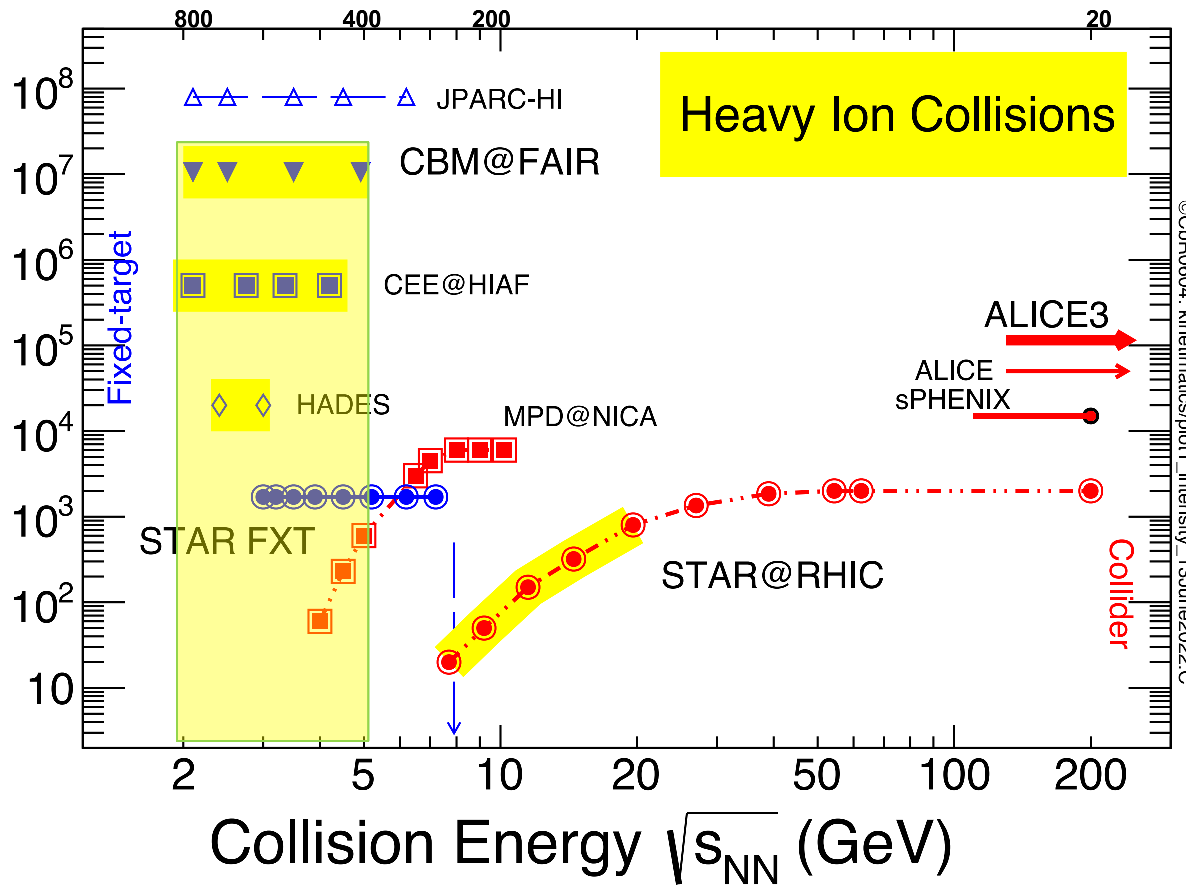
Future Facilities for Heavy-Ion Collisions



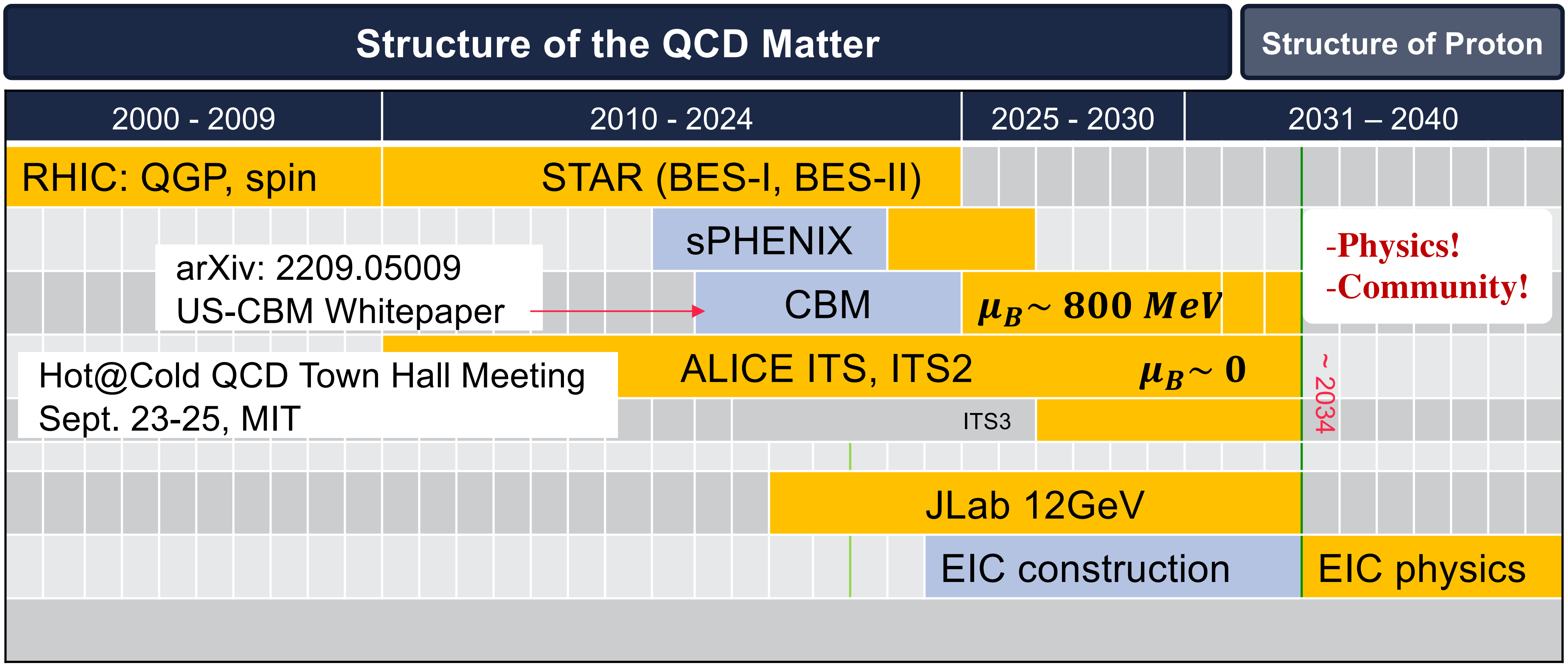
CBM at FAIR

(μ_B = 760MeV)

1) Phase boundary and QCD CP;
2) Hyper-Nuclei and Y-N interactions
3) Dileptons



US NSAC Long Range Plan Discussions



《论语·卫灵公》：“子曰: ‘人无远虑，必有近忧’ ”

Summary

Abundant light hyper-nuclei production at 3GeV Au+Au collisions, the high baryon density region:

1) Precision lifetime results for ${}^{3}_{\Lambda}\mathrm{H}$, ${}^{4}_{\Lambda}\mathrm{H}$ and ${}^{4}_{\Lambda}\mathrm{He}$;

2) First observations of the rapidity yields and collectivity of ${}^{3}_{\Lambda}\mathrm{H}$, and ${}^{4}_{\Lambda}\mathrm{H}$ hyper-nuclei;

3) Both yields and collectivity are consistent with coalescence predictions, making the production mechanism *trivial*!

4) More data from RHIC BES-II and future CBM experiment are expected.

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// YELLOW: Theory // **WHITE**: Exp. //

Thanks for Your Attention!
Many Thanks to Organizers!

EMMI