

Light Cluster Production and Baryon Correlation at High Baryon Density

- Selected Results from RHIC Beam Energy Scan

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Outline

1) Introduction

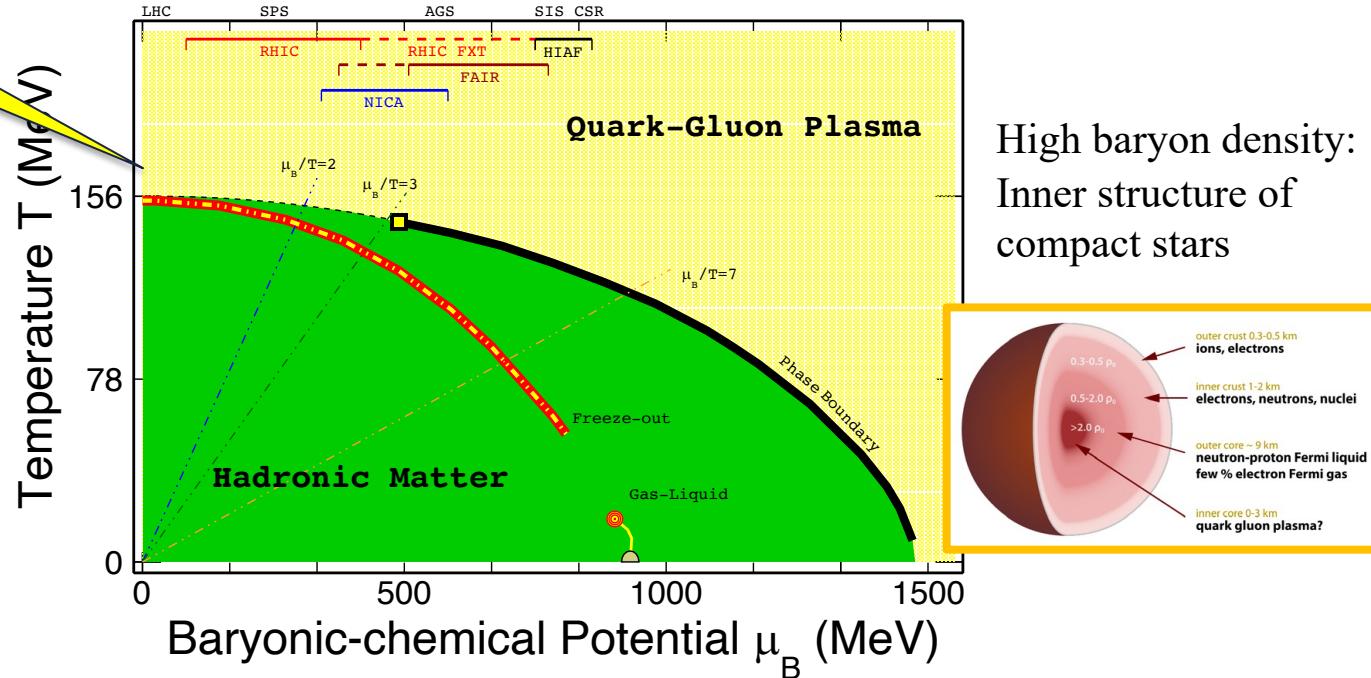
2) Recent results from 3 GeV Au+Au Collisions

- i. Light- and Hyper-Nuclei Production and Collectivity
- ii. Baryon Correlation Functions

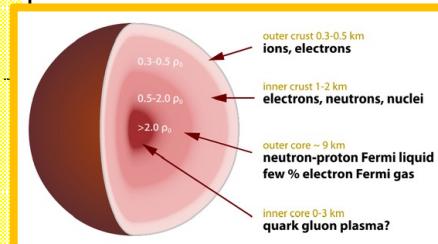
3) Summary and Outlook

High-Energy Nuclear Collisions and QCD Phase Diagram

Early Universe

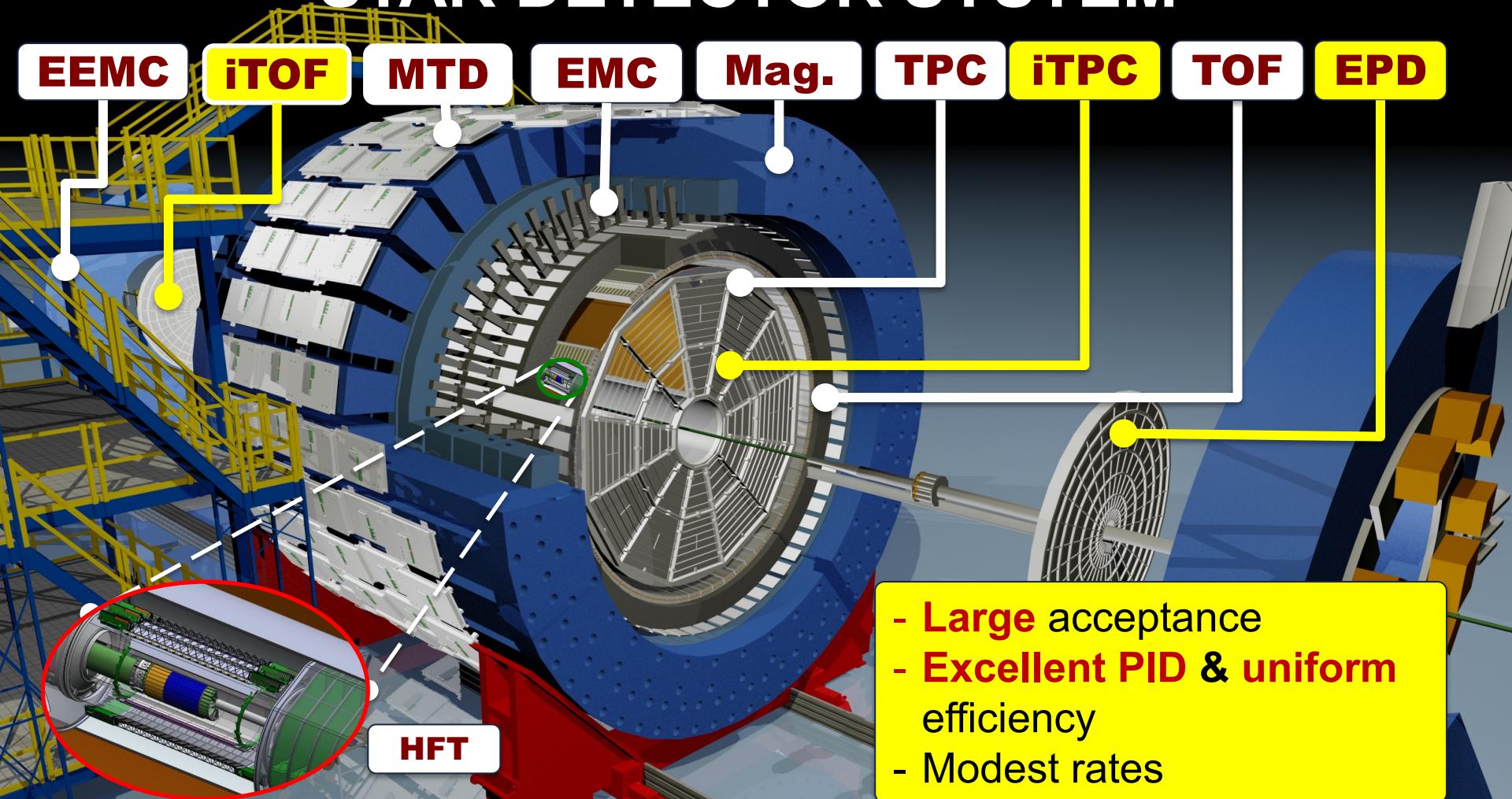


High baryon density:
Inner structure of
compact stars



- 1) RHIC BES: → search for 1st-order phase transition and **QCD critical point**;
- 2) Baryon interactions (e.g. $N - N$, $Y - N$) → inner structure of compact stars

STAR DETECTOR SYSTEM



Major Upgrades for BES-II



iTPC:

- Improves dE/dx
- Extends η coverage from 1.0 to 1.5
- Lowers p_T cut-in from 125 to 60 MeV/c
- Ready in 2019

eTOF:

- Forward rapidity coverage
- PID at $\eta = 0.9$ to 1.5
- **Borrowed from CBM-FAIR**
- Ready in 2019

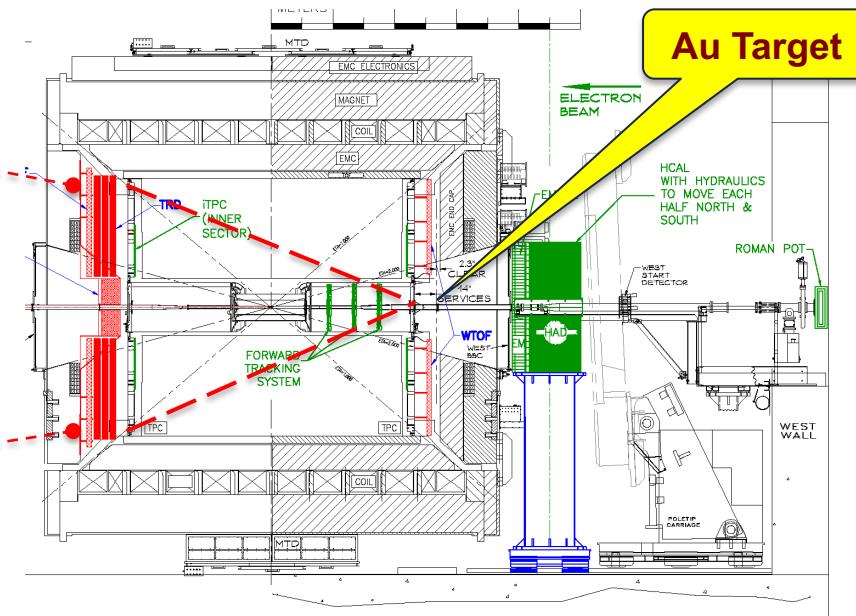
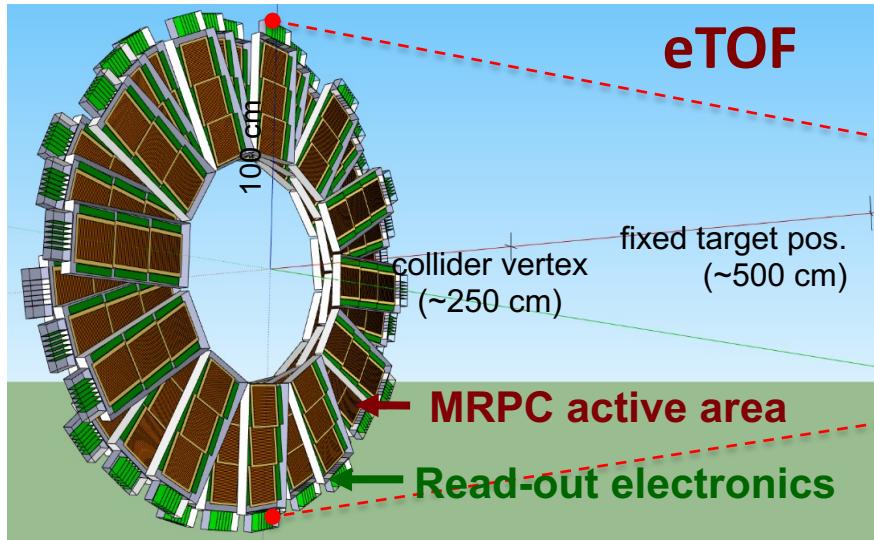
EPD:

- Improves trigger
- Better centrality & event plane measurements
- Ready in 2018

- 1) Enlarge rapidity acceptance
- 2) Improve particle identification
- 3) Enhance centrality/event plane resolution

iTPC: <https://drupal.star.bnl.gov/STAR/starnotes/public/sn0619>
eTOF: STAR and CBM eTOF group, arXiv: 1609.05102
EPD: J. Adams, et al. NIM **A968**, 163970 (2020)

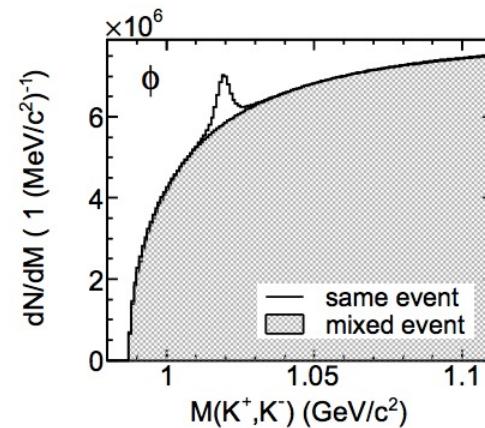
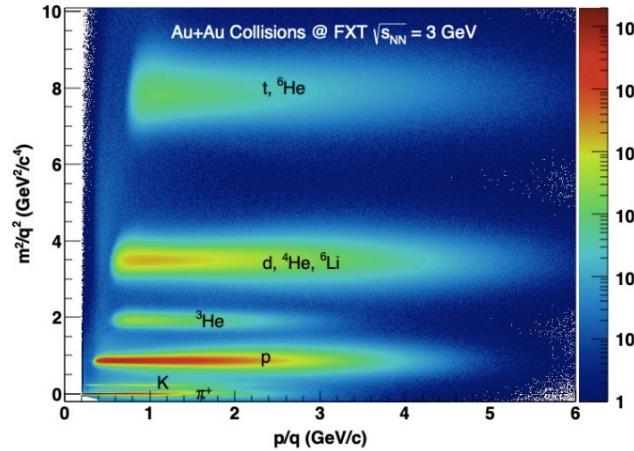
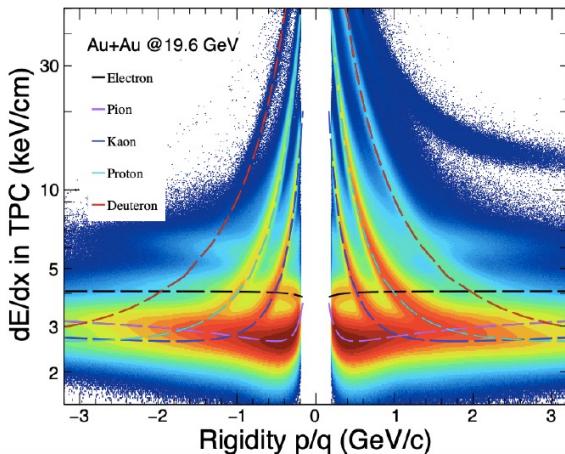
CBM Time of Flight Detectors at STAR



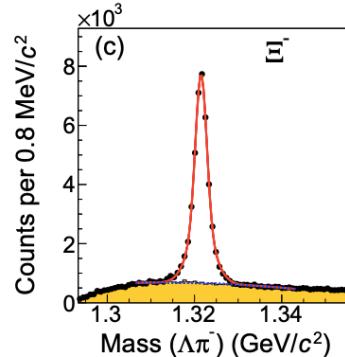
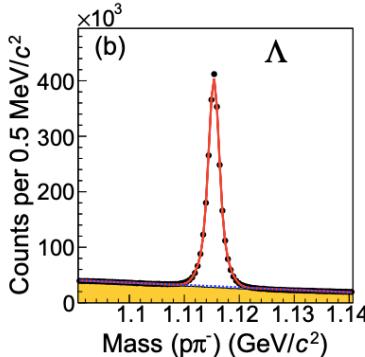
CBM participates in RHIC BES-II in 2019 – 2021:

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

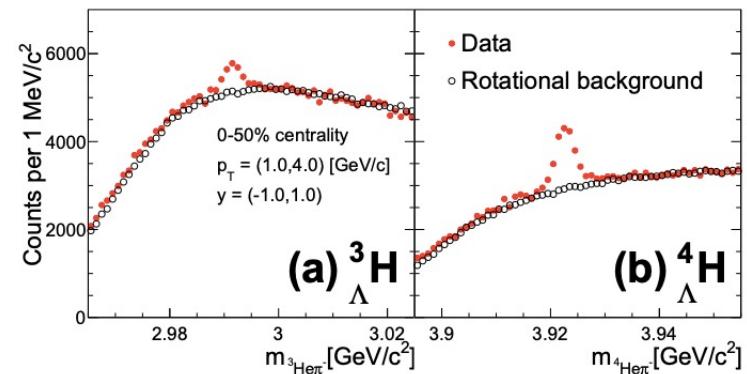
Particle Identifications



STAR, $\sqrt{s_{NN}} = 7.7$ GeV Au+Au (0-80%), $|y| < 0.5$



Au+Au Collisions at $\sqrt{s_{NN}} = 3.0$ GeV



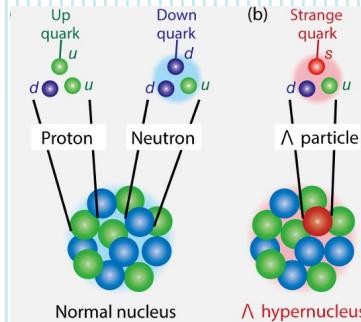
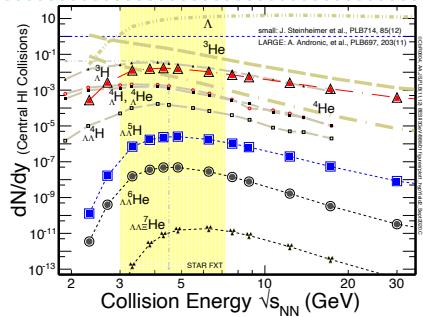
STAR BES-I and BES-II Data Sets

Au+Au Collisions at RHIC											
Collider Runs						Fixed-Target Runs					
	$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	runs		$\sqrt{s_{NN}}$ (GeV)	#Events	μ_B	y_{beam}	runs
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	57 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)	260 + 2000 M	760 MeV	-1.05	Run-18, 21

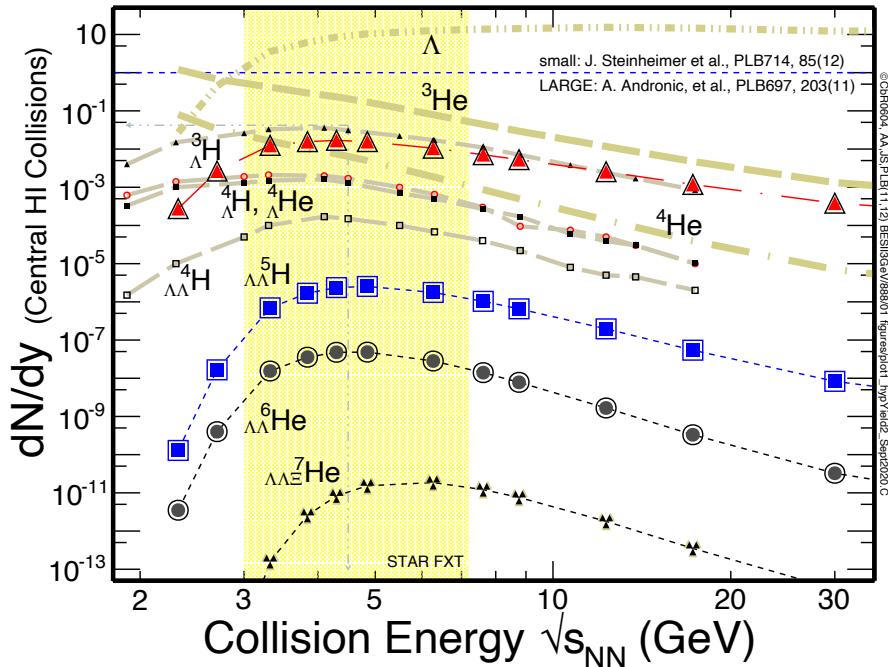
Most precise data to map the QCD phase diagram

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

Light- and Hyper-Nuclei Production



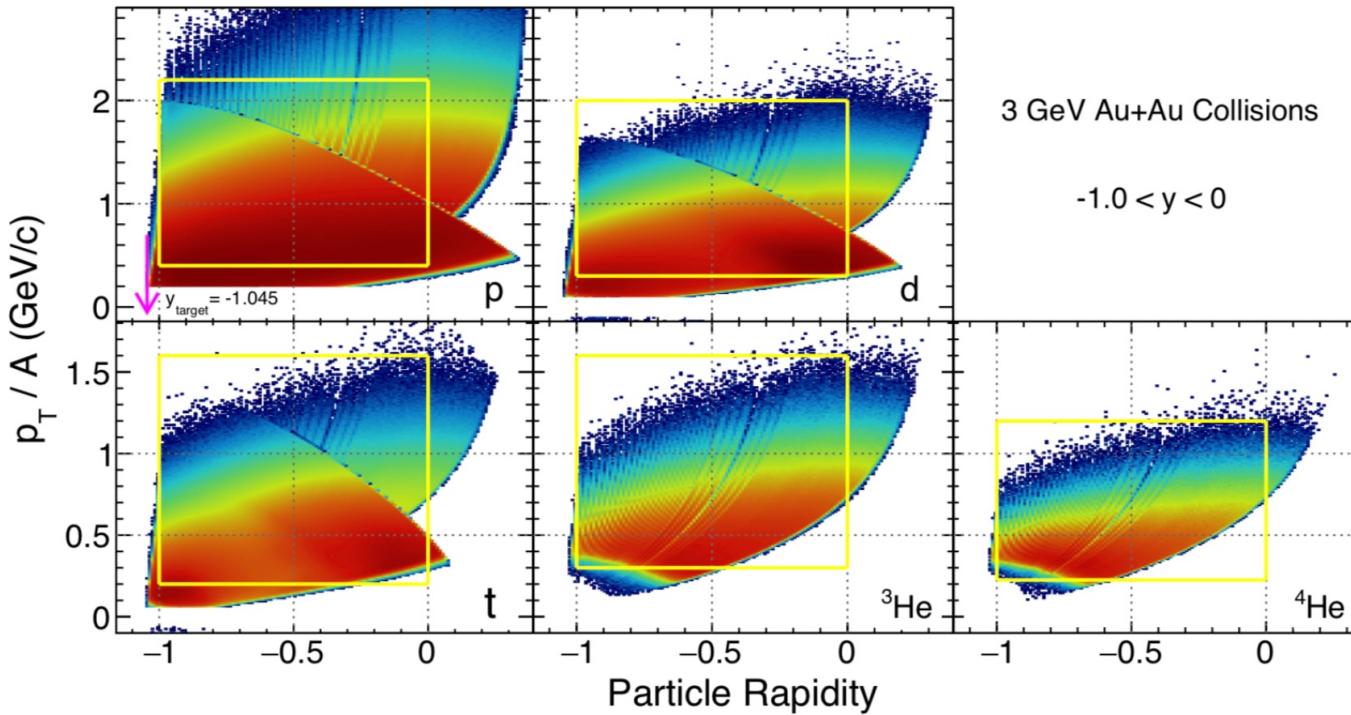
Light- and Hyper-nuclei Productions



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

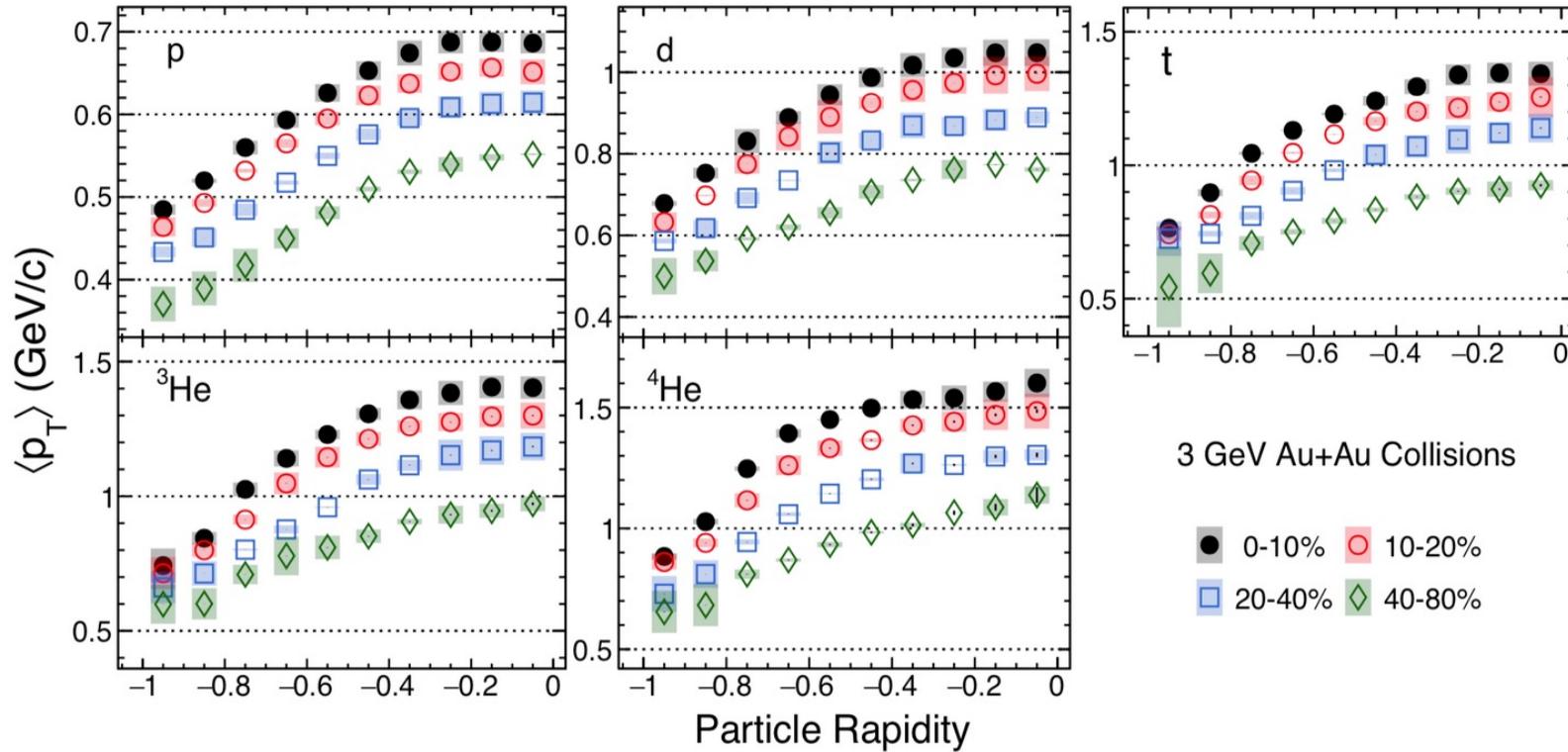
- 1) Light- and hyper-nuclei are abundantly produced at high density region;
- 2) Light-nuclei carry information about local baryon density fluctuations at freeze-out; offers insights on the Final State Interaction (FSI): **N-N**;
- 3) Hyper-nuclei provide access to the hyperon–nucleon interaction: **Λ -N**;
- 4) Light nuclei formation might help to understand hadronization: **nucleon coalescence vs. quark coalescence**

Acceptances from FXT Runs

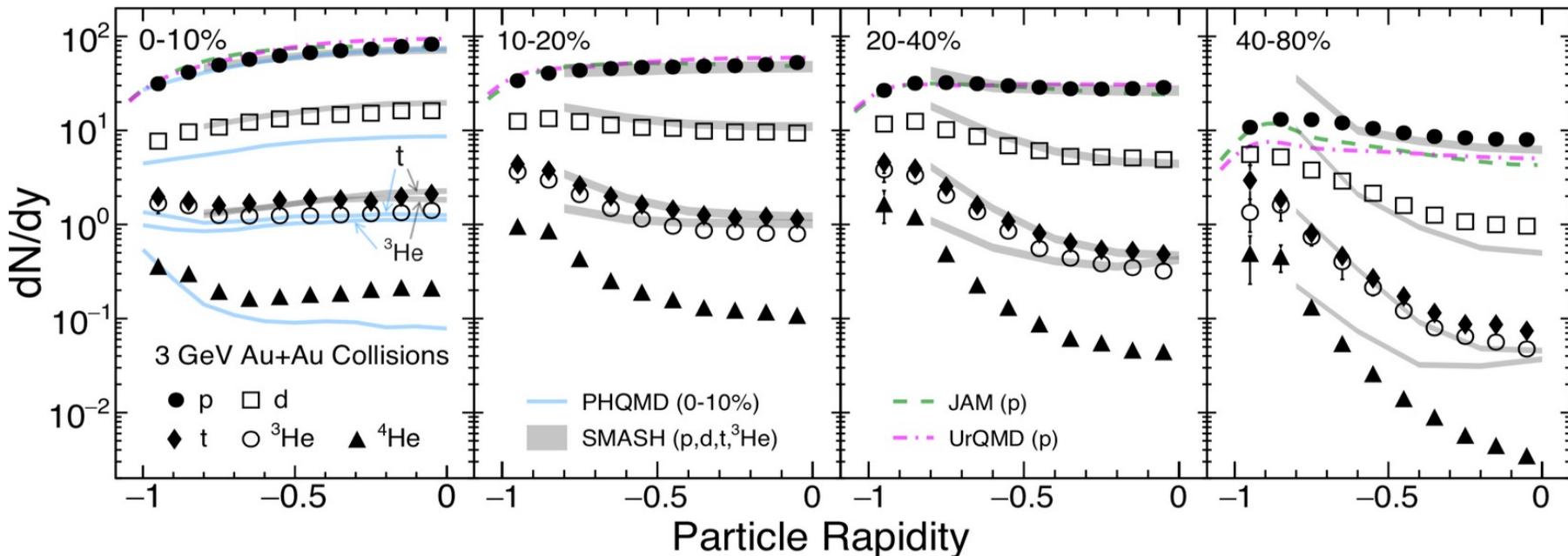


In the FXT mode, strong energy and mass dependence

Transverse Expansion $\langle p_T \rangle$ at 3 GeV

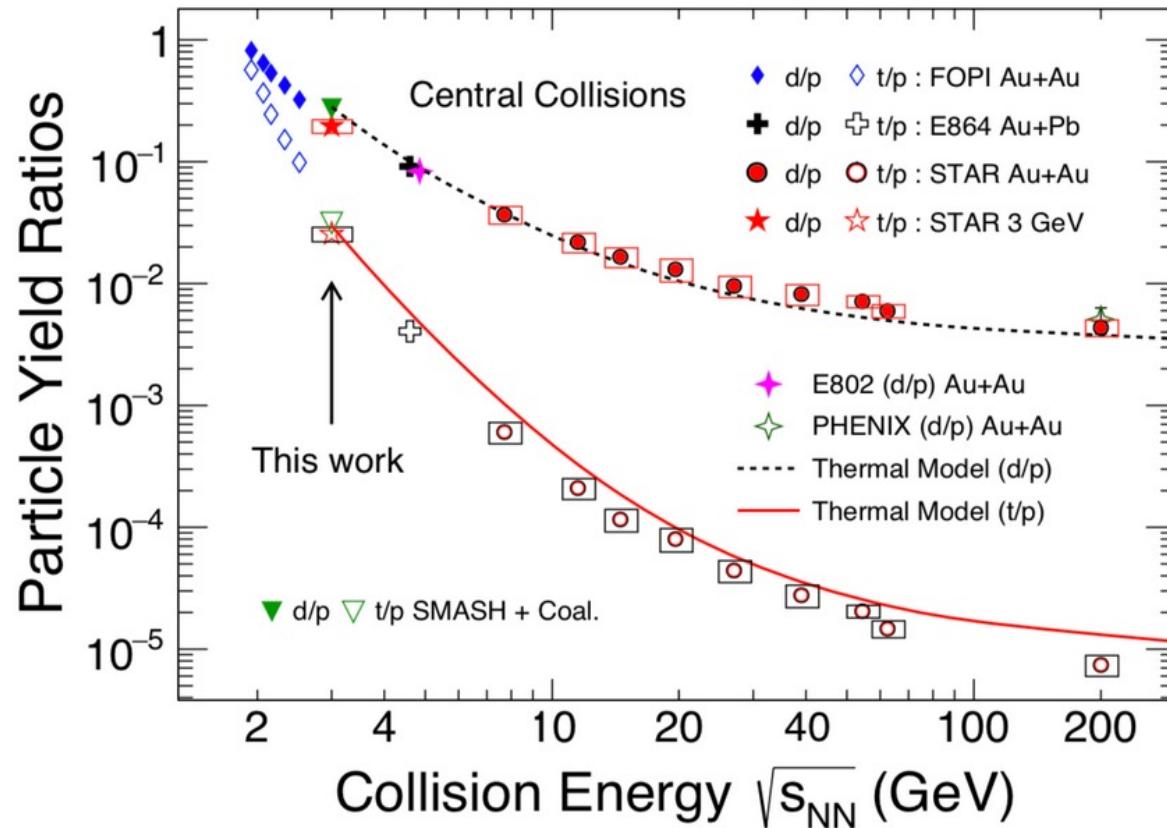


Full Rapidity Distributions for $p, d, t, {}^3He, {}^4He$



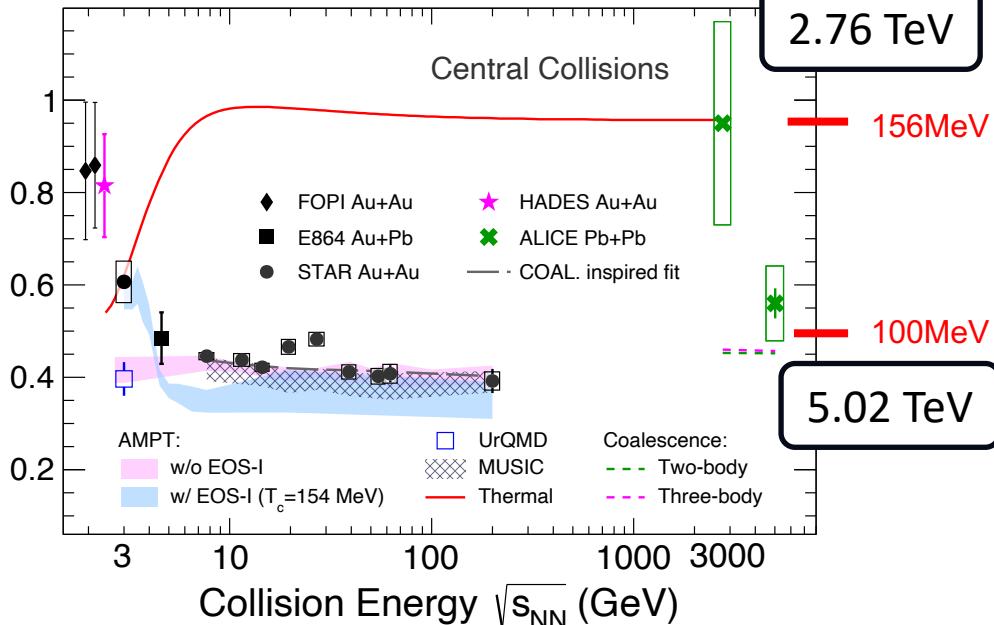
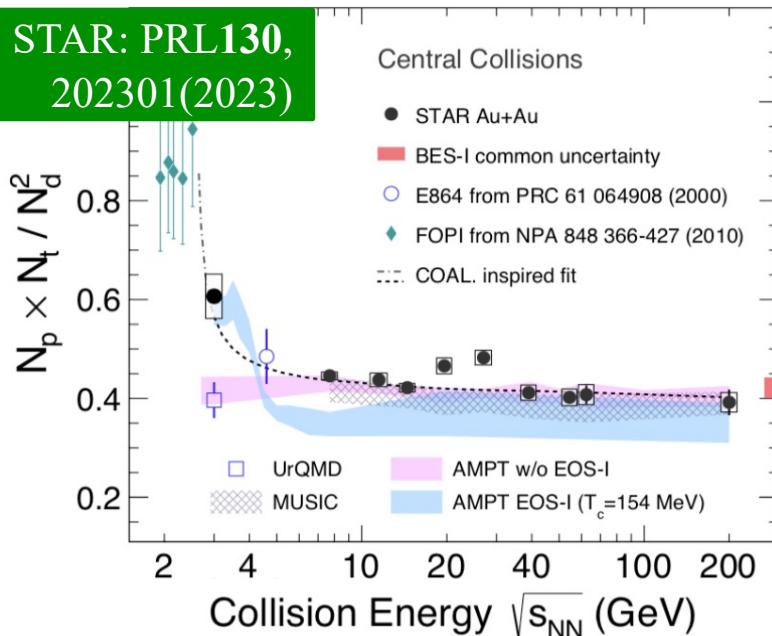
- 1) Proton rapidity distributions can be reproduced by JAM, PHQMD*, SMASH, UrQMD. Except PHQMD, in which light-nuclei are formed dynamically, all other calculations are using coalescence after-burner approach;
- 2) But only SMASH can reproduce d and t distributions.

Light-nuclei Ratios



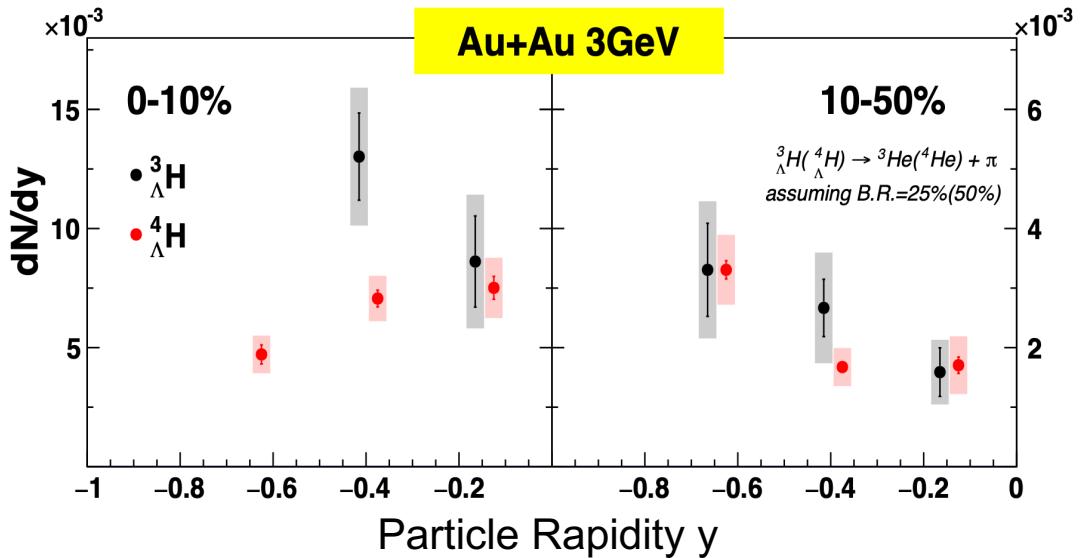
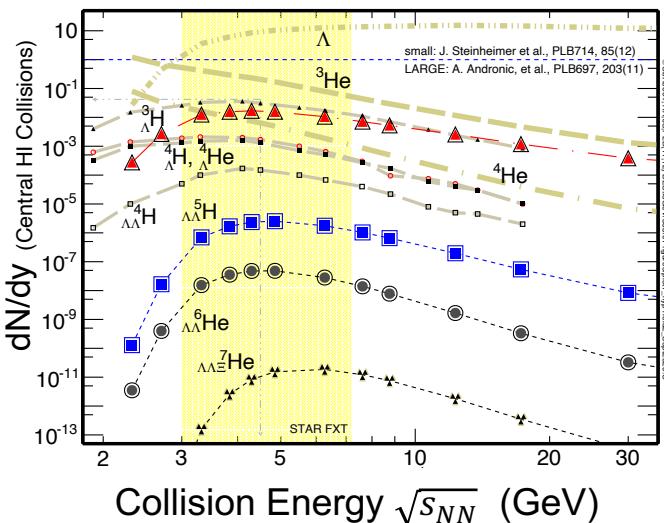
More Light-nuclei Ratios

STAR: PRL130,
202301(2023)



- 1) In 3 – 200 GeV Au+Au collisions, the coalescence approach seems reproduce the energy dependent data;
- 2) HRG calculations at freeze-out may not be appropriate for light-nuclei

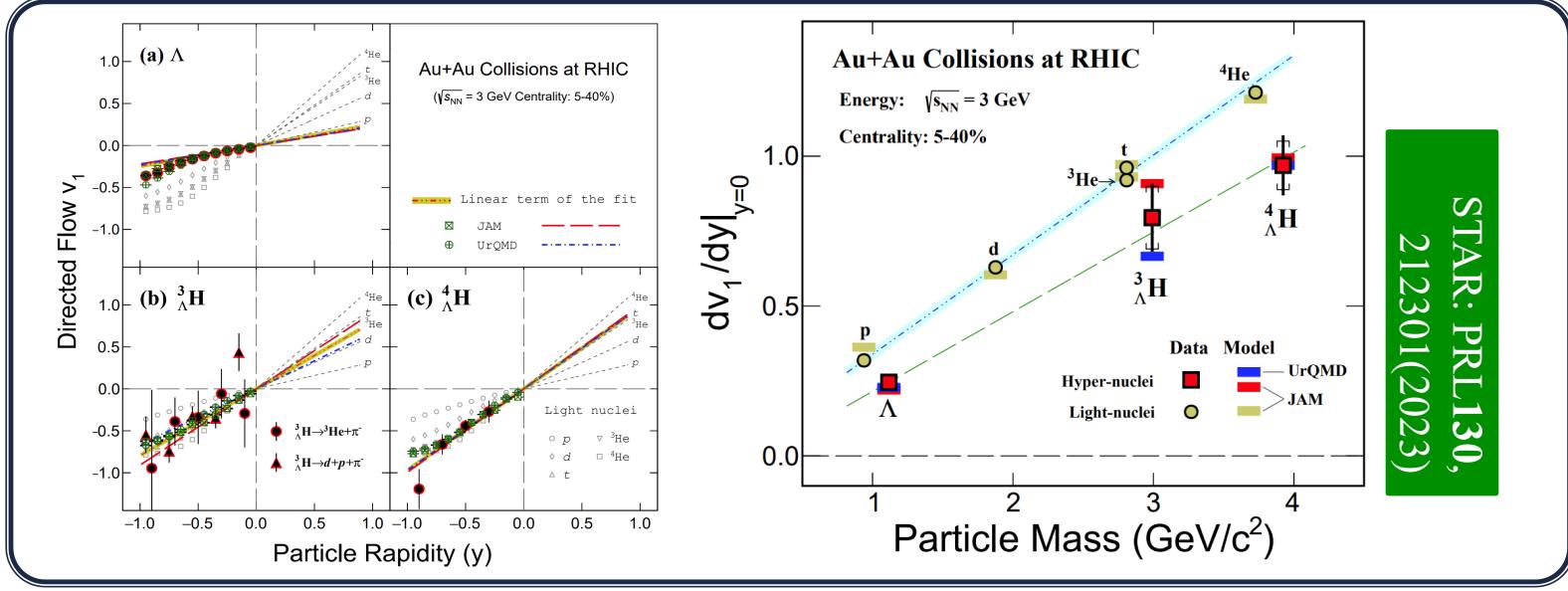
Hyper-nuclei Production



- 1) Abundant hyper-nuclei at the high baryon density region. First measurements of the rapidity distributions of hyper-nuclei
- 2) Coalescence also works for hyper-nuclei within uncertainties

STAR: PRL128 202301(2022)

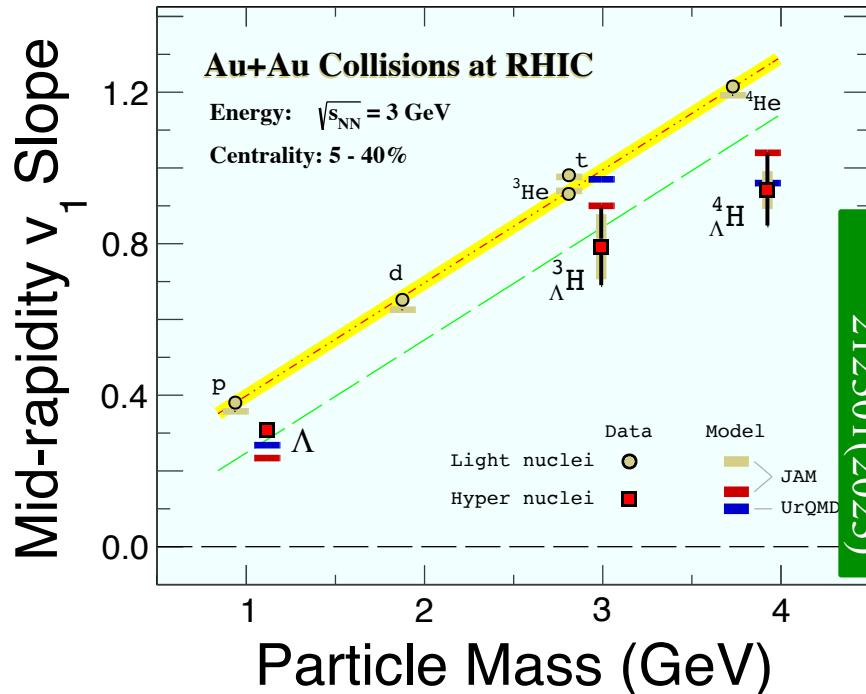
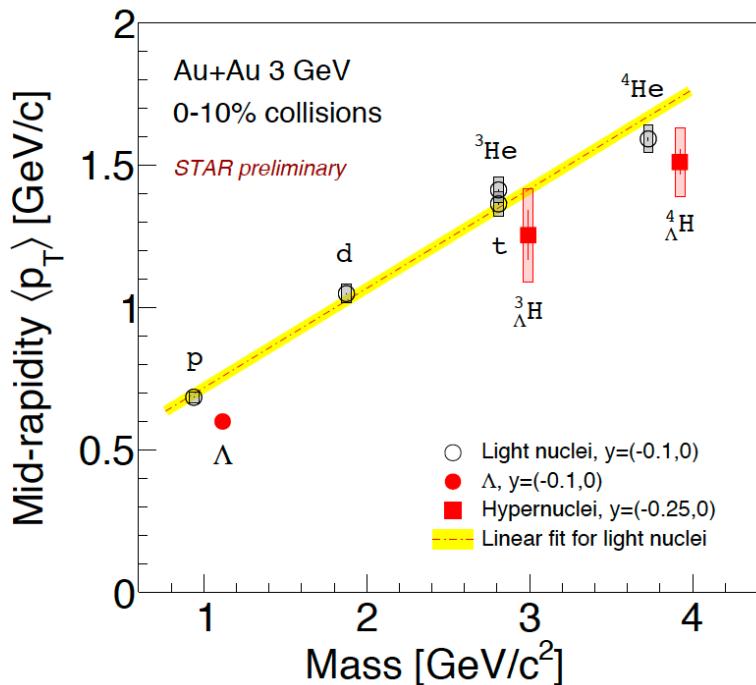
Collectivity of Hyper-nuclei



STAR: PRL130,
212301(2023)

- Coalescence: the dominant procedure for hyper-nuclei production;
- Hyper-nuclei collectivity (e.g. v_1 and v_2) \rightarrow $Y-N$ and $Y-Y$ interactions under finite pressure gradient;
- **Questions:** Connection to the EOS of compact stars? Effect of isospin?

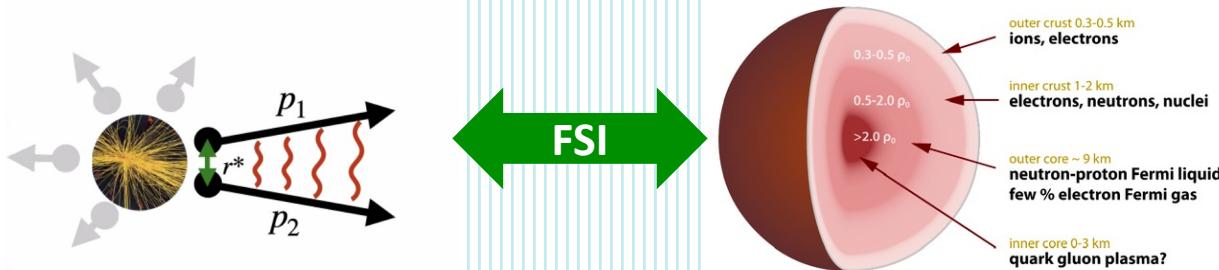
Hyper-nuclei Collectivity



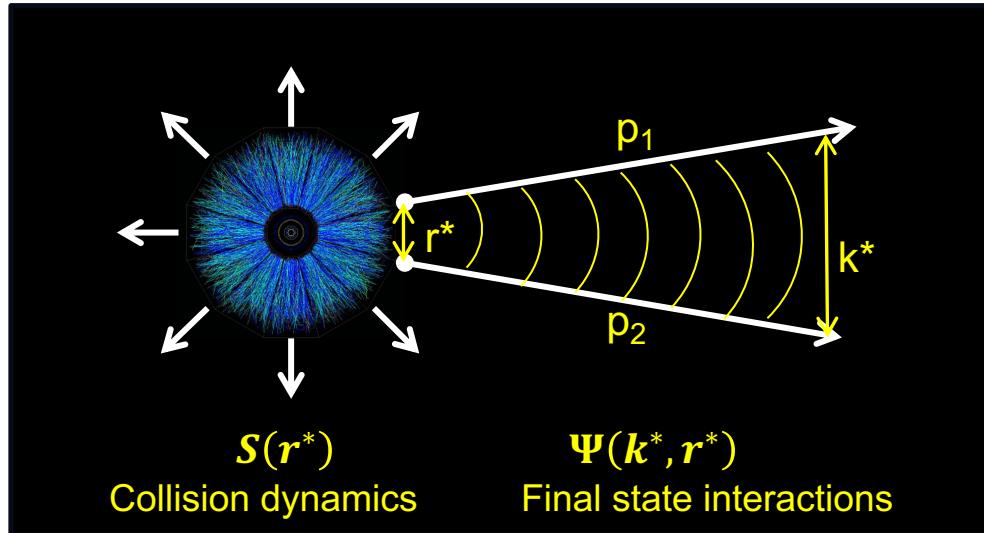
STAR: PRL130,
212301(2023)

- 1) First observation of **hyper-nuclei collective flow**. Allowing study Y-N interactions under finite baryon density and pressure gradients;
- 2) Coalescence procedure for production for both light- and hyper-nuclei

Baryon Correlations



Baryon Correlation Functions



STAR:

(1) Meson HBT: $\pi - \pi$, $K - K$;

(2) **Baryon correlations:**

$p - p$		reference
$p - \Lambda$,	$p - \Xi^-$	YN
$p - d$,	$d - d$	NNN
$d - \Lambda$		YNN

Source

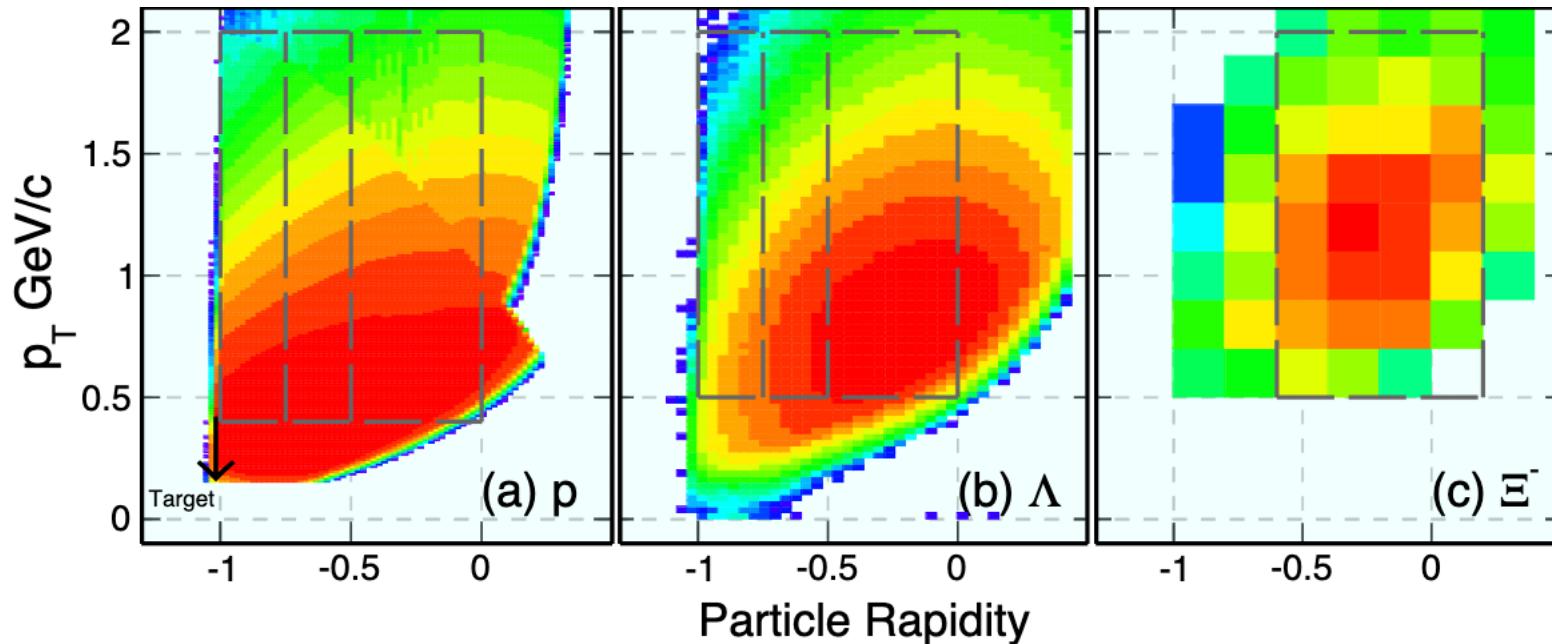
Interaction potential

$$C_{the}(k^*) = \int d^3r^* S(r^*) |\Psi(r^*, k^*)|^2$$

$$C_{exp}(k^*) = \lambda \frac{N_{same}(p_1, p_2)}{N(p_1)N(p_2)} \rightarrow \text{Source and FSI}$$

$$k^* = \frac{1}{2} |p_1^* - p_2^*|$$

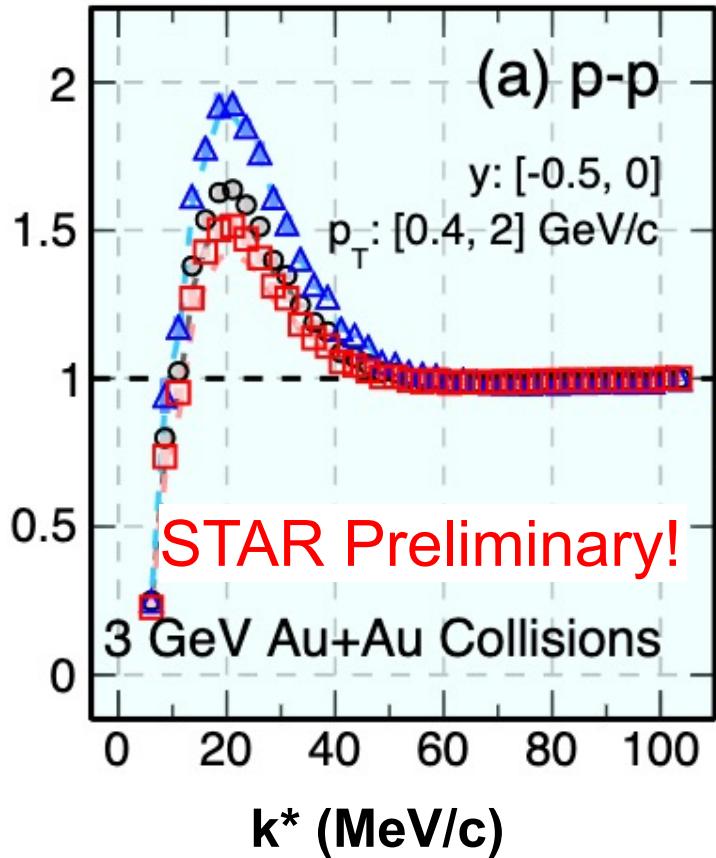
$p - p, p - \Lambda, p - \Xi^-$ Correlation Functions



3 GeV Au+Au Collisions at RHIC:
Full rapidity coverage for p and Λ with STAR;

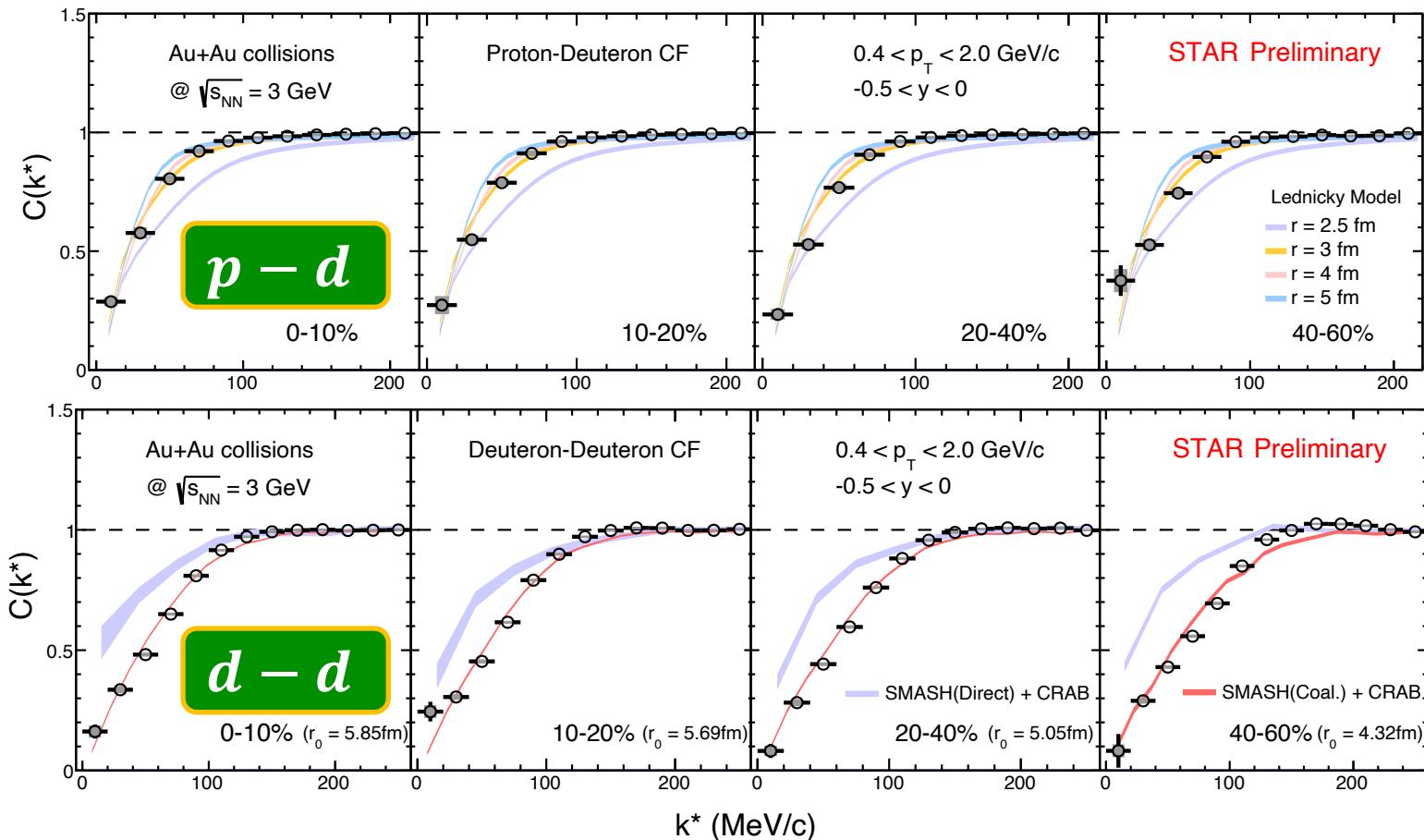
$p - p$ Correlation Functions

Correlation Function



- 1) Centrality and rapidity dependence of the $p - p$ CFs are reproduced by calculations of transport model (UrQMD). Extracted source radii r_G are systematically smaller than the RMS values from the transport model results;
- 2) LL calculations are used to extract FSI parameters ():
 - f_0 is consistent with known data.
 - d_0 is less constrained;
 - *no collision centrality nor rapidity dependence is observed*

$p - d$, $d - d$ Correlation Functions



$p - d$, $d - d$ Correlation Functions

- 1) Both $p - d$ and $d - d$ CFs can be reproduced by calculations of transport model (SMASH) plus coalescence after-burner. Consistent with the coalescence procedure for deuteron production;
- 2) LL calculations are used to extract FSI parameters:
 - $f_0 < 0$ is observed
 - *no collision centrality dependence is observed*

Summary and Outlook

3GeV Au+Au collisions:

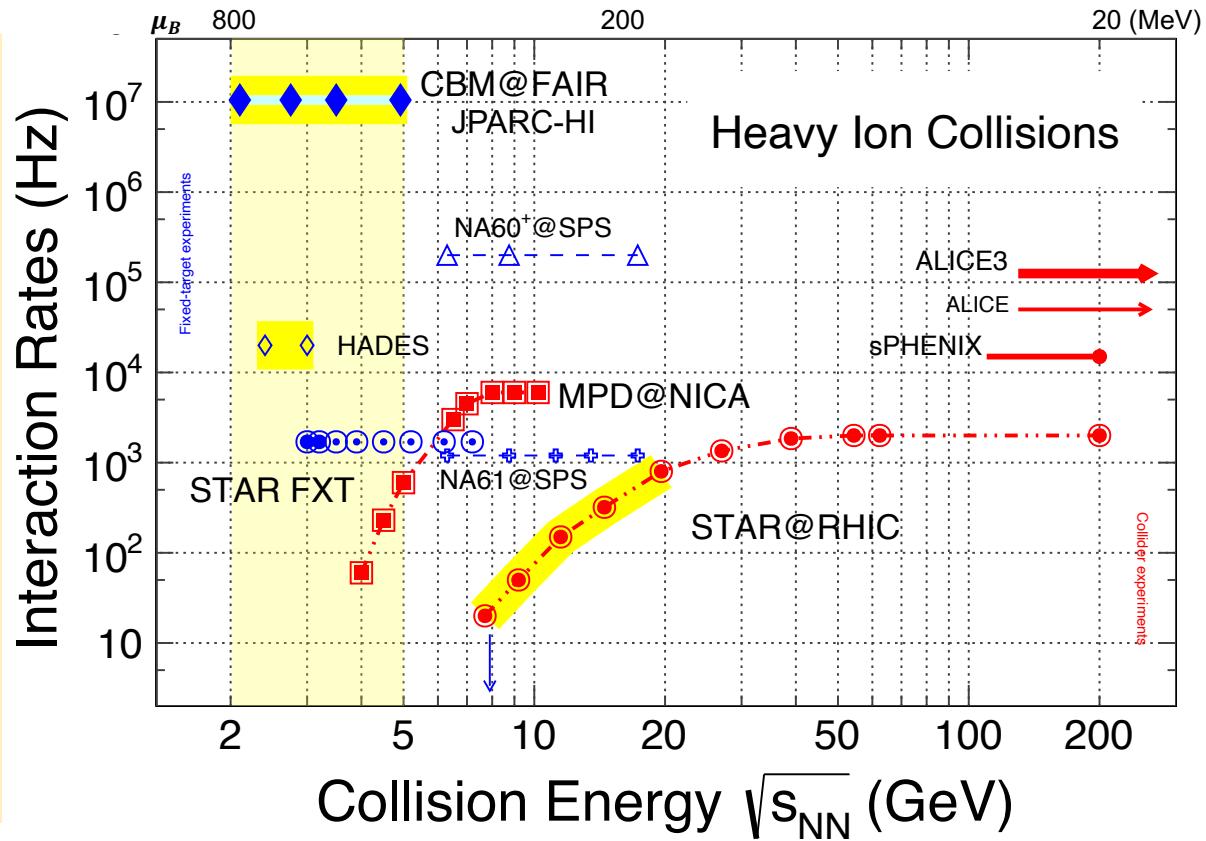
- 1) STAR: wide rapidity acceptance for p , Λ , d , ${}^3_{\Lambda}H$, ${}^4_{\Lambda}H$, ${}^4_{\Lambda}He$
- 2) Calculations with coalescence reproduce yields, $\langle p_T \rangle$, v_1 for light nuclei as well as hyper nuclei; The same is true for baryon correlation functions: $p - d$, $d - d$;
- 3) Spin-averaged FSI (f_0 , d_0) extracted

Outlook:

- 1) 2B data on tape: 3GeV Au+Au collisions;
- 2) **Compressed Baryonic Matter (CBM) experiment is the future!**

Future is the CBM Experiment!

- Unprecedented rate capability at CBM;
 - Necessary for precision measurements and search for exotics
- 1) High order baryon fluctuation and correlation;
 - 2) 3D di-lepton spectra (collision centrality, pair mass and p_T);
 - 3) Hyper-nuclei production and Y-N interactions



Acknowledgements:

P. Braun-Munzinger, **C. Fu**, X. Dong, S. Esumi, X.H. He, **C.L. Hu**, **H. Liu**, **K. Mi**, V. Koch, X.F. Luo, B. Mohanty, S. Pratt, S.S. Shi, J. Stroth, K.J. Sun, **Y. Xu**, **D.W. Zhang**, Y.P. Zhang

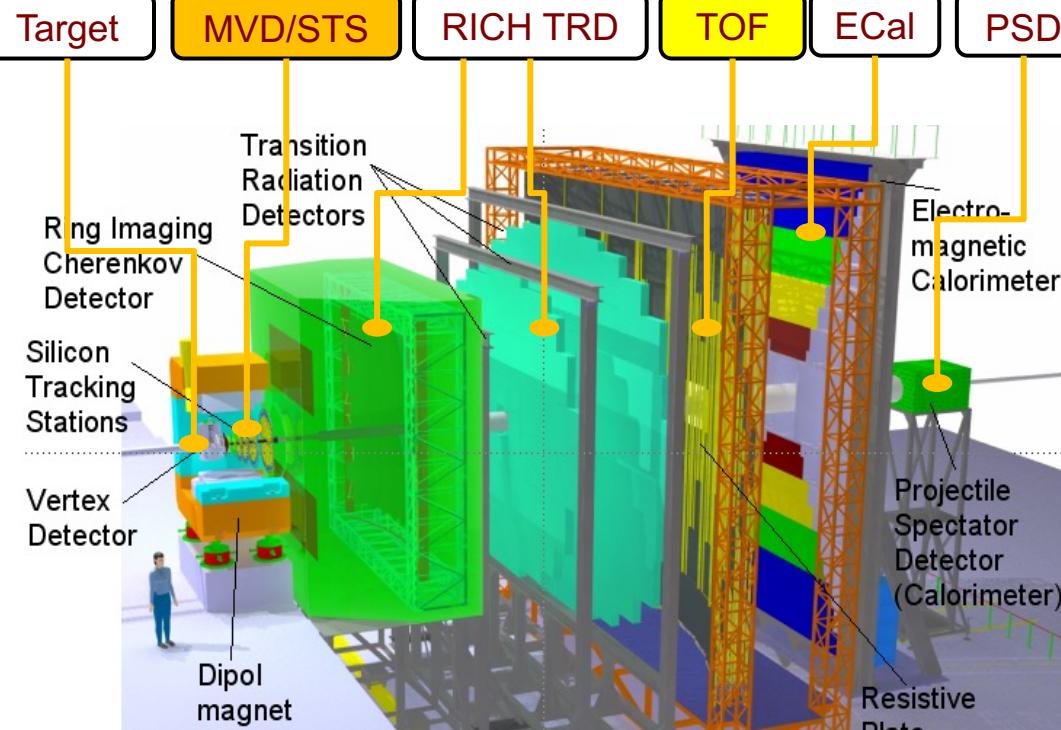
// BLUE: Theory // RED: Exp. //

Alexander von Humboldt Foundation



Thank you for your attention!

CBM Experiment at FAIR



- FAIR: One of the brightest accelerator complexes
- Precision measurements at high baryon density region:
 - (i) Dileptons (e, μ);
 - (ii) High order correlations;
 - (iii) Flavor productions (s, c) and hyper-nuclei