High moments of net-proton and the QCD phase structure

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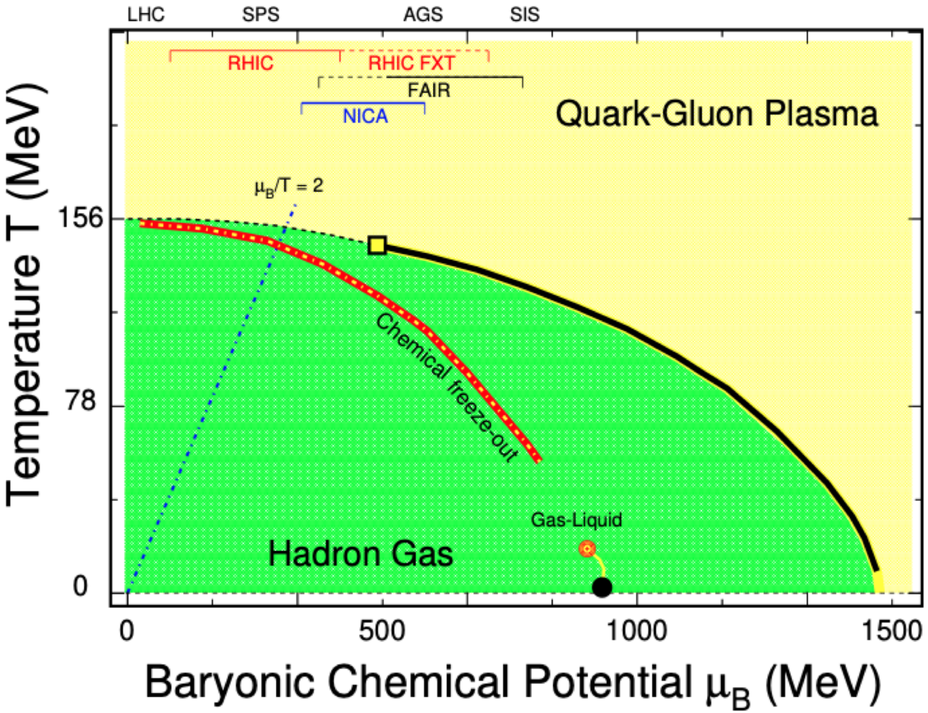
Supported by

Outline

- Introduction & motivation
- Fluctuation of conserved quantities
- Experimental status
- Near future interests
- Future experiments and summary

QCD phase diagram



STAR, Phys. Rev. Lett. 126, 092301 (2021)

1. QCD calculation and model
   Lattice QCD: Cross over at $\mu_B = 0$ [1] and T = 156.5 ± 1.5 MeV [2].
   QCD based Model: A critical point followed by first-order phase transition at high μ_B [3]
2. Search for the possible signature of critical point and 1st order transition by scanning T vs μ_B:
   - by varying collision energy in heavy-ion collisions

[1] Y. Aoki, Nature 443, 675 (2006)
[2] HotQCD, Phys. Lett. B 795, 15 (2019)
[3] M. A. Halasz, Phys. Rev. D 58, 096007 (1998)

Fluctuation of conserved quantities

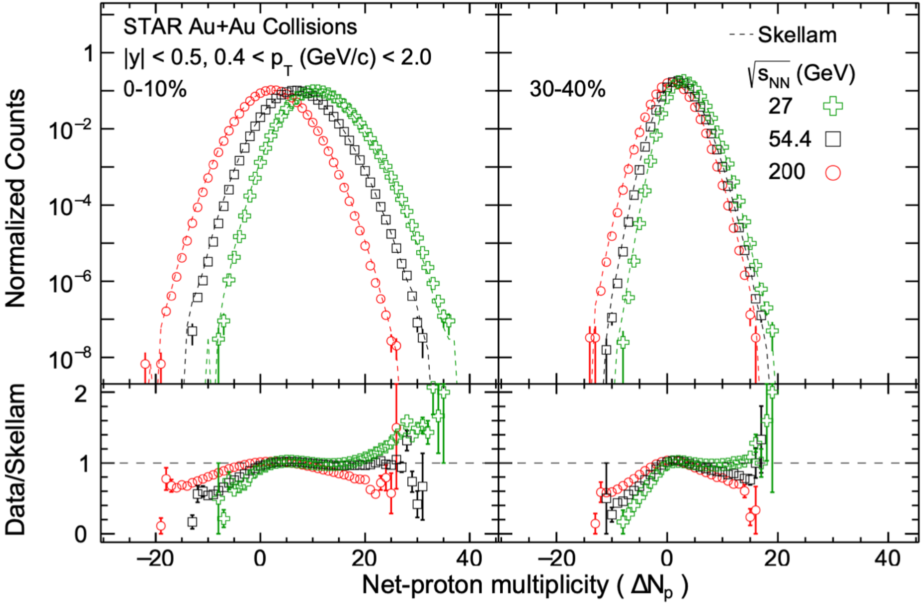
1. Fluctuation of conserved quantities (B, Q, S)
   e.g. Net-B: "Baryon number" – "anti-Baryon number"
   net-proton number is used as a proxy to net-B number [1,2]

2. Moment analysis of net-B: cumulants

3. When particles are not correlated, the particle distribution becomes Skellam (Poisson distribution – Poisson distribution)

$$C_n = \langle N_B \rangle + (-1)^n \langle N_{\bar{B}} \rangle$$

STAR Collaboration, Phys. Rev. Lett. **127** (2021) 262301



[1] Y. Hatta, M.A. Stephanov, PRL 91 102003 (2003)
[2] M. Kitazawa, M. Asakawa, Phys. Rev. C 86, 024904 (2012)

Fluctuation of conserved quantities

1. Cumulants of conserved quantities (B, Q, S) are related to correlation length of the system

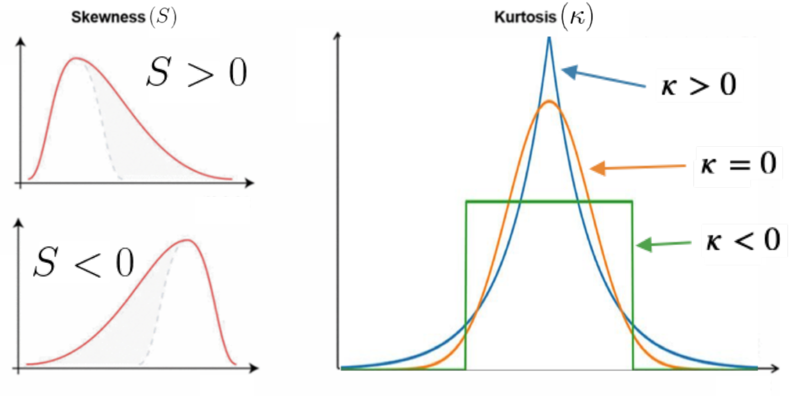
$$\delta N = N - \langle N \rangle$$

$$S = C_3/(C_2)^{3/2}, \kappa = C_4/(C_2)^2$$

$$C_1 = \langle N \rangle \quad C_2 = \langle (\delta N)^2 \rangle \quad C_3 = \langle (\delta N)^3 \rangle$$

$$C_4 = \langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle^2 \quad C_5 = \langle (\delta N)^5 \rangle - 10\langle (\delta N)^2 \rangle \langle (\delta N)^3 \rangle$$

$$C_6 = \langle (\delta N)^6 \rangle + 30\langle (\delta N)^2 \rangle^3 - 15\langle (\delta N)^2 \rangle \langle (\delta N)^4 \rangle - 10\langle (\delta N)^3 \rangle^2$$



The higher the cumulant order, the more sensitive to the correlation length

$$C_2 \sim \xi^2, C_3 \sim \xi^{4.5}, C_4 \sim \xi^7$$ [1~3]

2. The cumulant ratios can be directly compared to theoretical calculations

$$\chi_q^{(n)} = \left(\frac{\partial^n p}{\partial \mu_q^n} \right)_T = \frac{1}{VT^3} \times C_q^n$$

Directly linked to the EoS

[1] M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009)
[2] M. Asakawa, Phys. Rev. Lett. 103, 262301 (2009)
[3] M. A. Stephanov, Phys. Rev. Lett. 107, 052301 (2011)

Corrections for the analysis

1. Detector efficiency corrections

   A. Bzdak and V. Koch, Phys. Rev. C86, 044904 (2012)
   X. Luo and T. Nonaka, Phys. Rev. C99, 044917 (2019)
   STAR Collaboration, Phys. Rev. Lett. **126** (2021) 92301
   STAR Collaboration, Phys. Rev. Lett. **128** (2022) 202303

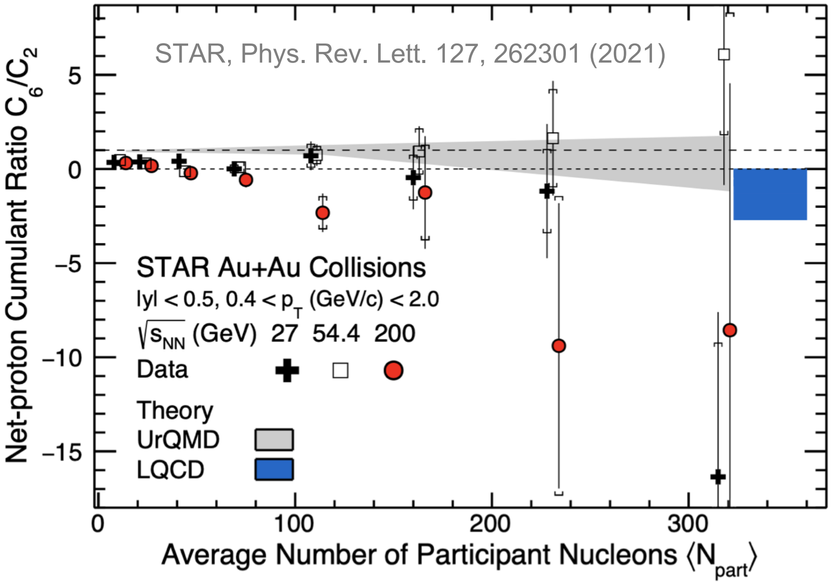
2. Pileup corrections

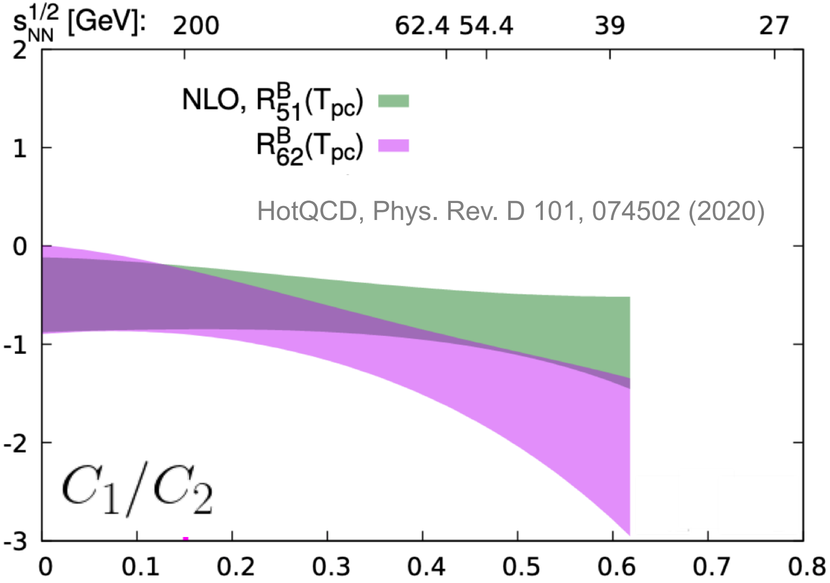
   T. Nonaka, M. Kitazawa, and S. Esumi, Nucl. Instrum. Meth. A 984, 164632 (2020)
   Y. Zhang, Y. Huang, T. Nonaka, and X. Luo, Nucl. Instrum. Meth. A 1026 (2022) 166246
   STAR Collaboration, Phys. Rev. Lett. **128** (2022) 202303

3. Volume fluctuation correction

   X. Luo, J. Xu, B. Mohanty, and N. Xu, J. Phys. G40, 105104 (2013)
   A. Chatterjee, Y. Zhang, J. Zeng, N. R. Sahoo, and X. Luo, Phys. Rev. C101, 034902 (2020)
   S. He and X. Luo, Chin. Phys. C42, 104001 (2018)
   V. Skokov, B. Friman, and K. Redlich, Phys. Rev. C88, 034911 (2013)
   P. Braun-Munzinger, A. Rustamov, and J. Stachel, Nucl. Phys. A960, 114 (2017)
   HADES Collaboration, Phys. Rev. C 102, 024914 (2020)
   STAR Collaboration, Phys. Rev. Lett. **128** (2022) 202303

Fifth- and Sixth-order cumulants





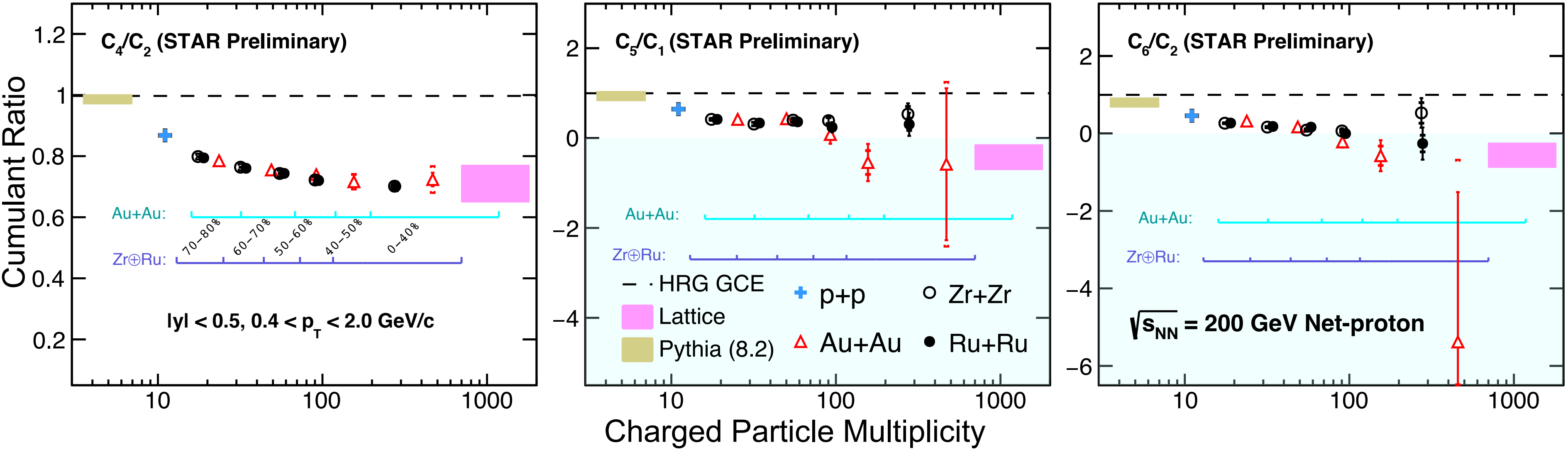
1. Transition from QGP to hadronic matter is smooth crossover at $\mu_B \approx 0$
2. 6th order: first principle lattice QCD calculation predicts $C_6/C_2 < 0$

Smooth cross over at $\sqrt{s_{NN}}$ = 200 GeV

Net-proton fluctuation in different collision system

STAR Collaboration, Phys. Rev. C 104, 024902 (2021)
STAR Collaboration, Phys. Rev. Lett. 127, 262301 (2021)

R. Nishitani, STAR Collaboration, CPOD21
H.-S. Ko, STAR Collaboration, QM22

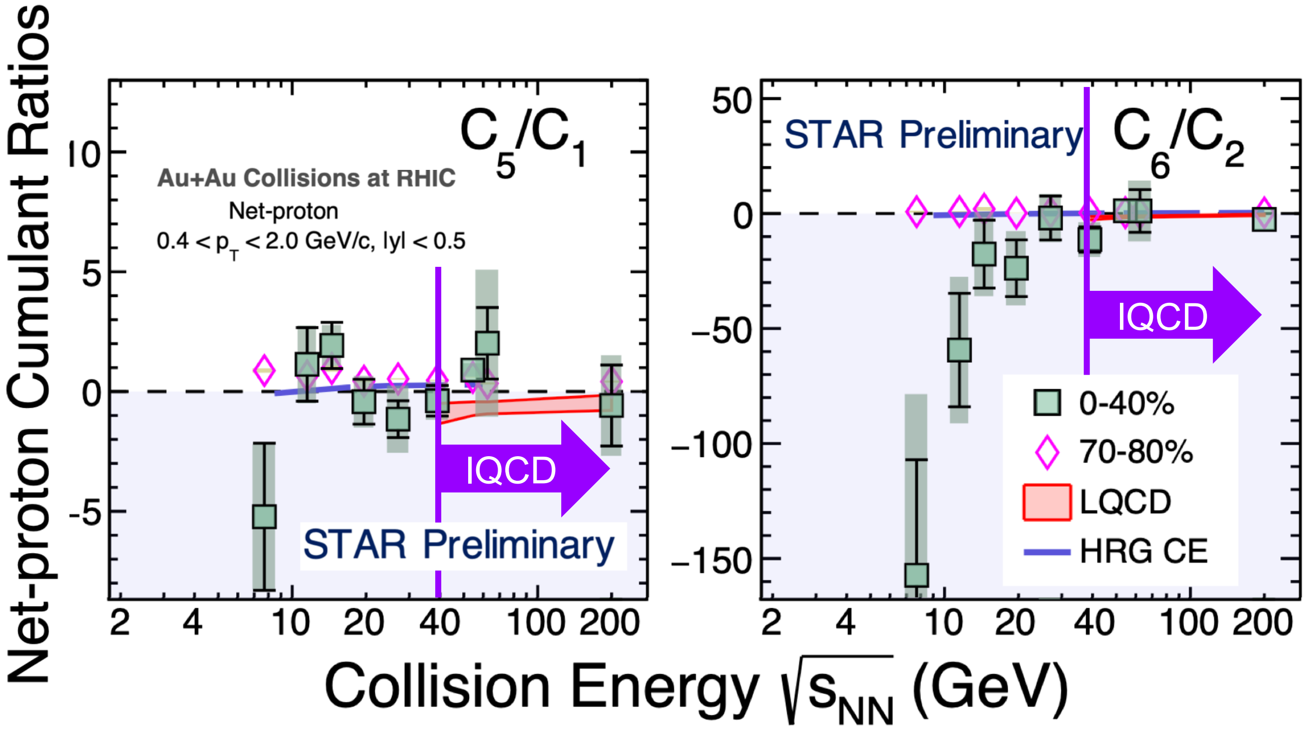


1. p+p, Zr+Zr and Ru+Ru, and Au+Au results agree among each other at $\sqrt{s_{NN}}$ = 200 GeV
2. All cumulant ratios C_4/C_2, C_5/C_1, and C_6/C_2 decrease as the multiplicity increases

→ Most central Au+Au collision results become consistent with Lattice QCD prediction for the formation of thermalized QCD matter and smooth crossover transition

Smooth cross over at $\sqrt{s_{NN}} = 200$ GeV

Fifth- and Sixth-order cumulants

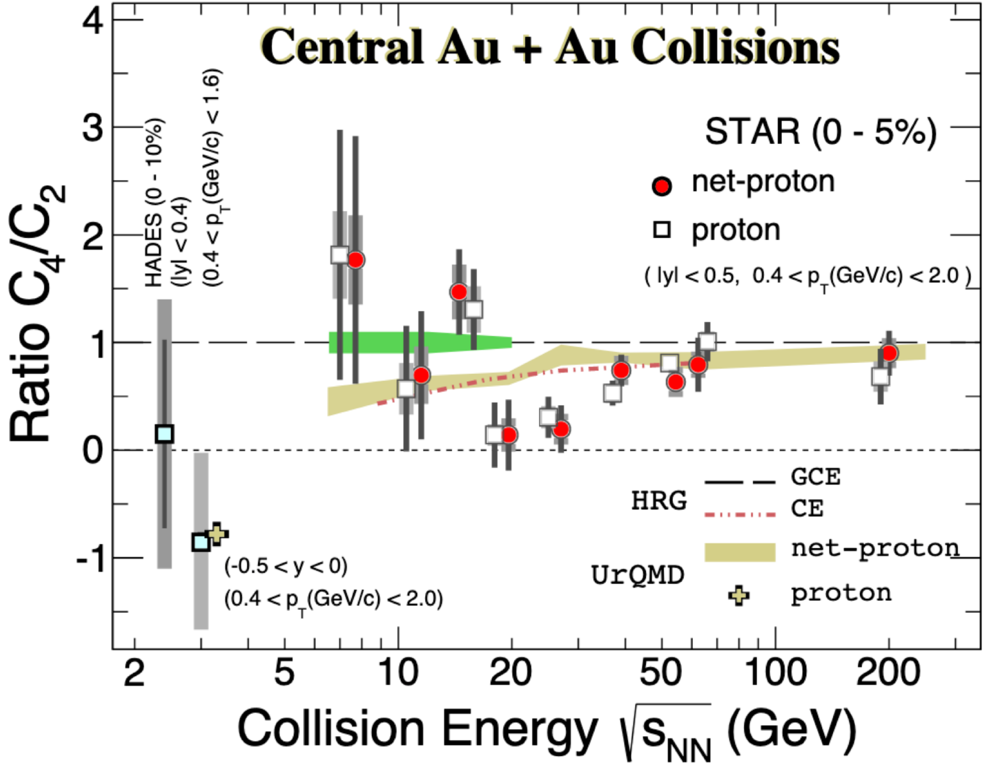


1. C_5/C_1 (0-40%) fluctuates around zero
2. C_6/C_2 progressively negative with decreasing collision energy: consistent with lattice QCD (μ_B < 110 MeV)

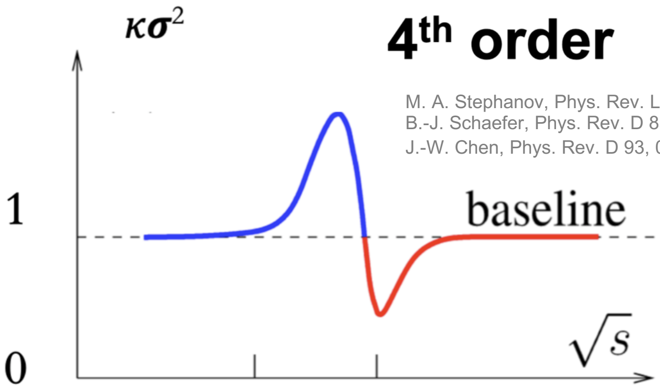
lattice QCD & fRG [1]: C_5/C_1 & $C_6/C_2 < 0$ & $C_5/C_1 > C_6/C_2$
HRG, UrQMD & 70-80%: C_5/C_1 & $C_6/C_2 \geq 0$

[1] W.-j. Fu, X. Luo, J. M. Pawlowski, F. Rennecke, R. Wen et al. Phys. Rev. D 104, 094047 (2021)

Fourth-order cumulant for critical point search



STAR Collaboration, Phys. Rev. Lett. 128 (2022) 202303
HADES Collaboration, Phys. Rev. C 102 (2020) 024914



M. A. Stephanov, Phys. Rev. Lett. 107, 052301 (2011)
B.-J. Schaefer, Phys. Rev. D 85, 034027 (2012)
J.-W. Chen, Phys. Rev. D 93, 034037 (2016)

1. 4th order shows hints of non-monotonic energy dependence which could be attributed to the critical fluctuation in the vicinity of CP [1]
2. New data points from STAR (@ $\sqrt{s_{NN}}$ = 3 GeV) and HADES (@ $\sqrt{s_{NN}}$ = 2.4 GeV)

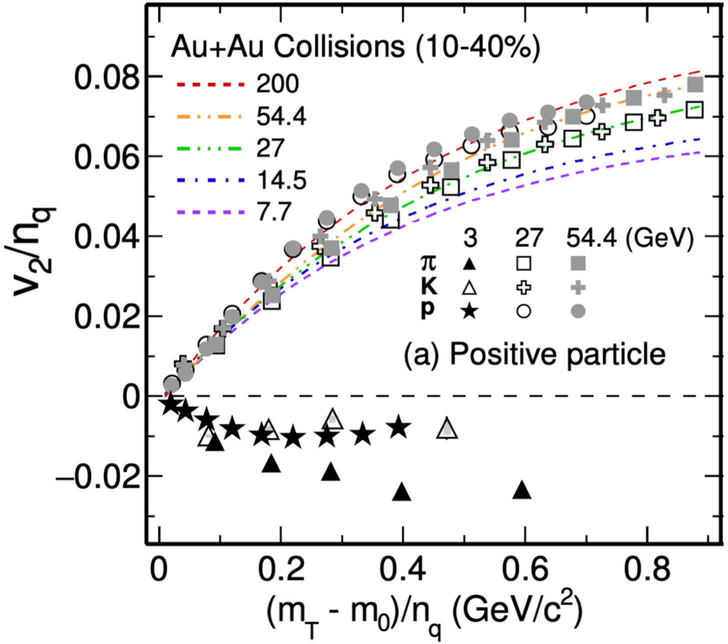
→ consistent with fluctuations driven by baryon number conservation

Hadronic interaction dominant at $\sqrt{s_{NN}} \leq 3$ GeV

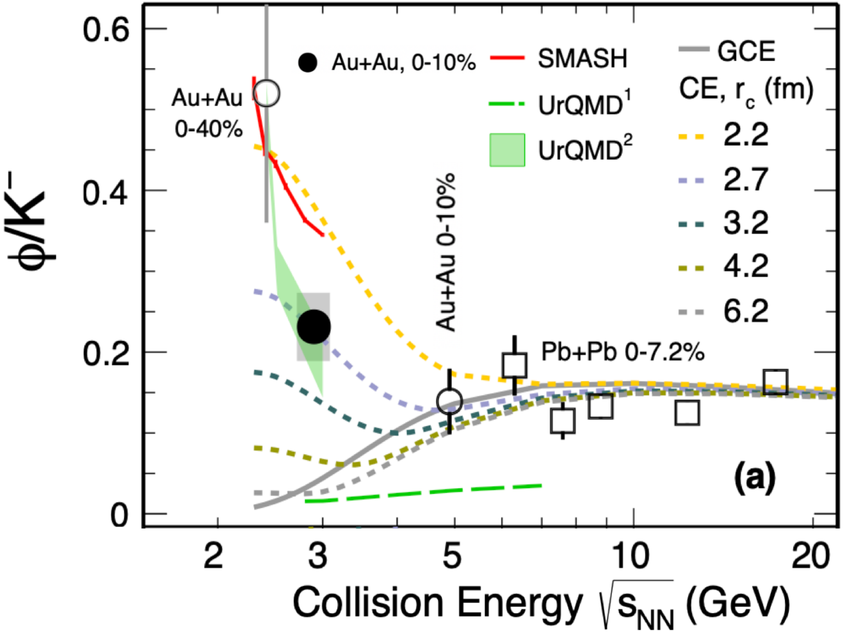
[1] STAR Collaboration, Phys. Rev. Lett. **126** (2021) 092301

Other measurements at $\sqrt{s_{NN}}$ = 3 GeV

[1] STAR, Phys. Lett. B 827, 137003 (2022)
[2] STAR, doi.org/10.1016/j.physletb.2022.137152
[3] HADES, Phys. Lett. B 778, 403 (2018)



[1]



[2,3]

1. $v_2/n_q > 0 \rightarrow v_2/n_q < 0$ as the collision energy decreases to 3 GeV

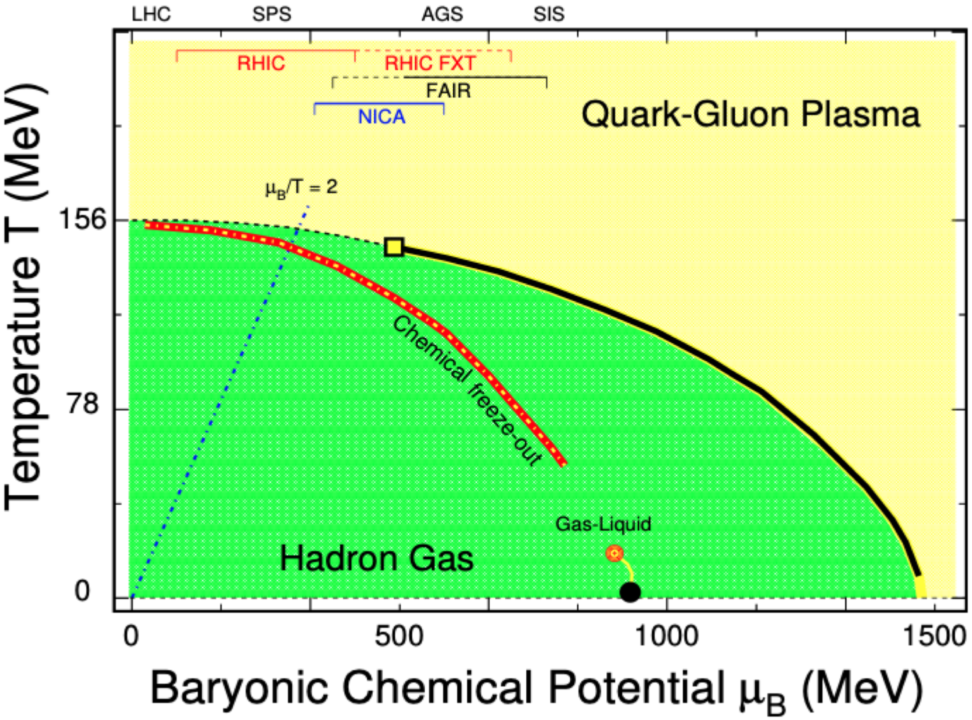
→ vanishing of partonic collectivity and a new EOS, likely dominated by baryonic interactions

2. ϕ/K^- favor Canonical Ensemble model at 3 GeV & transport models describe the data

→ change of medium properties

$\sqrt{s_{NN}}$ = 3 GeV and below: hadronic interaction dominant

Where are we?

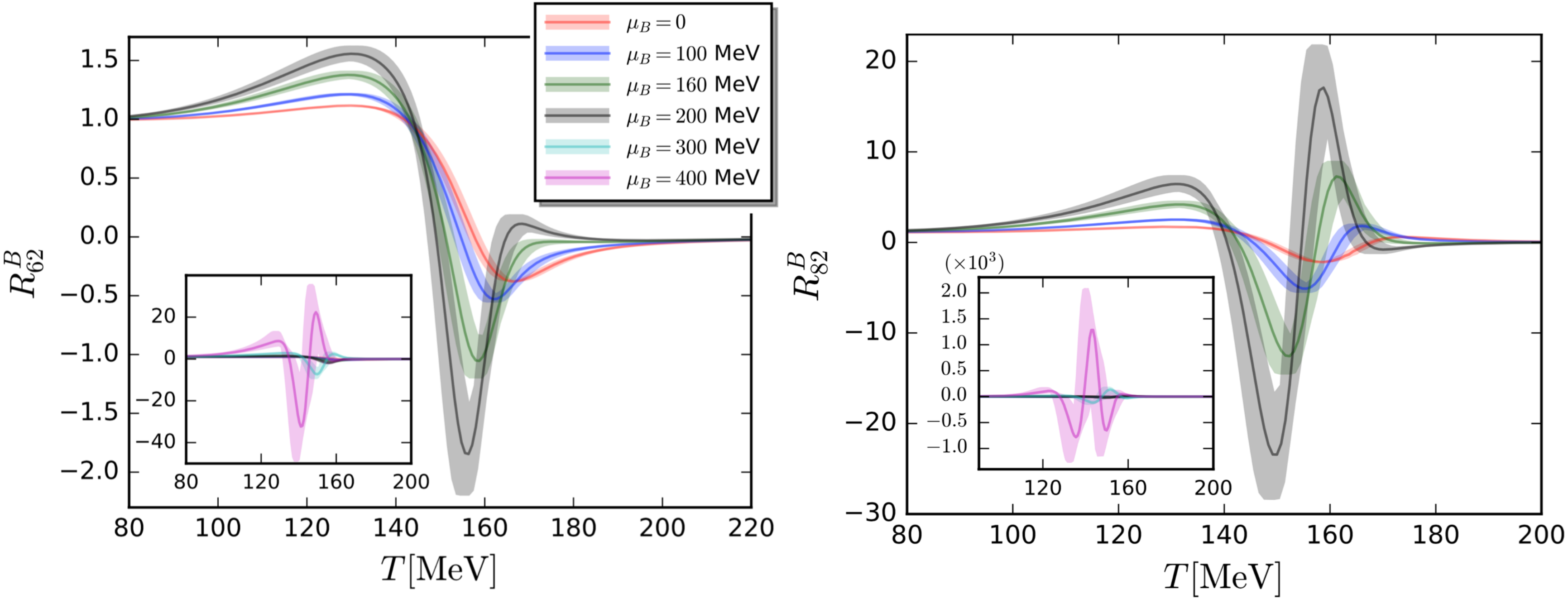


STAR, Phys. Rev. Lett. 126, 092301 (2021)

1. $\sqrt{s_{NN}}$ = 200 GeV (and above, LHC): Thermalized QGP matter and smooth crossover
2. $\sqrt{s_{NN}}$ = 3 GeV: hadronic interaction dominant

If QCD critical point exists, likely $3 < \sqrt{s_{NN}} < 27$ GeV

Even higher order cumulant analysis

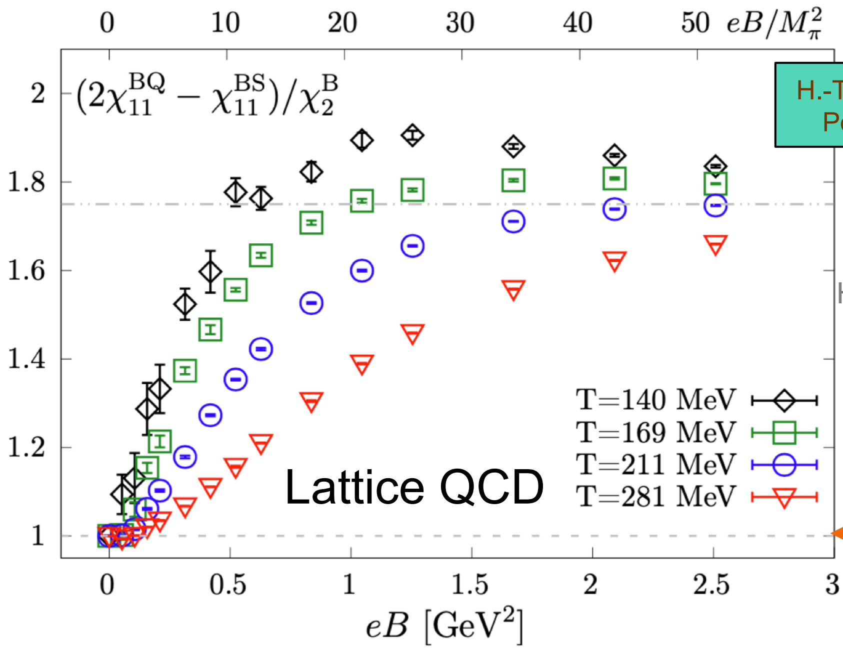


$$\chi_q^{(n)} = \left(\frac{\partial^n p}{\partial \mu_q^n}\right)_T = \frac{1}{VT^3} \times C_q^n$$

1. Provides additional μ_B and T (energy) dependence
2. Statistic hungry & more vulnerable to backgrounds

W.-j. Fu, X. Luo, J. M. Pawlowski, F. Rennecke, R. Wen et al. Phys. Rev. D 104, 094047 (2021)

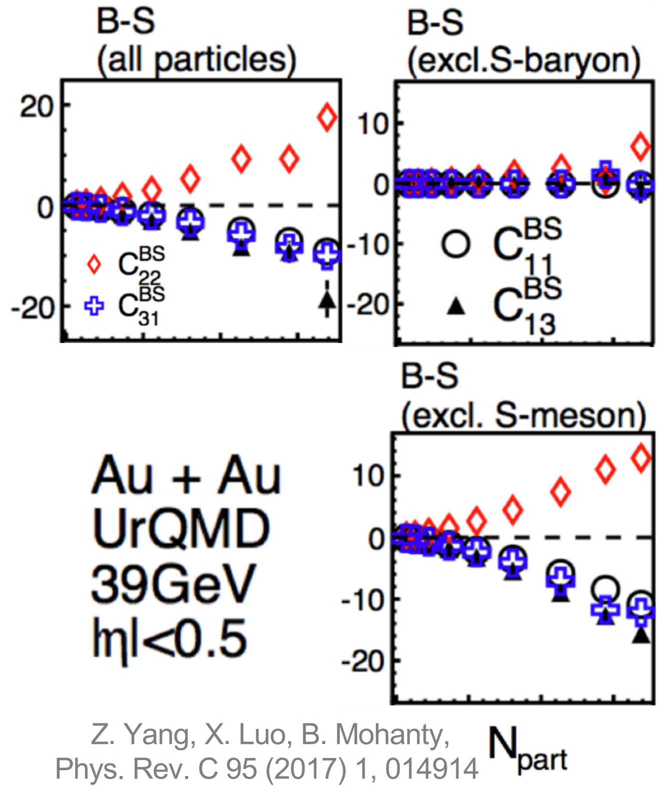
Probe magnetic field in HIC



H.-T. Ding / Jun-Hong Liu, Poster, 6/14, 5:10 PM

H.-T. Ding, S.-T. Li, Q. Shi, X.-D. Wang, Eur. Phys. J. A 57 (2021) 6, 202

Isospin symmetric



Z. Yang, X. Luo, B. Mohanty, Phys. Rev. C 95 (2017) 1, 014914

1. Off-diagonal (mixed) term maybe sensitive to the initial stage B-field
2. Strange baryons are important for the mixed term analysis

Future experiments: STAR BES-II

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 (+25B)	**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)	2000 M	**760** MeV	-1.05	Run-18, 21

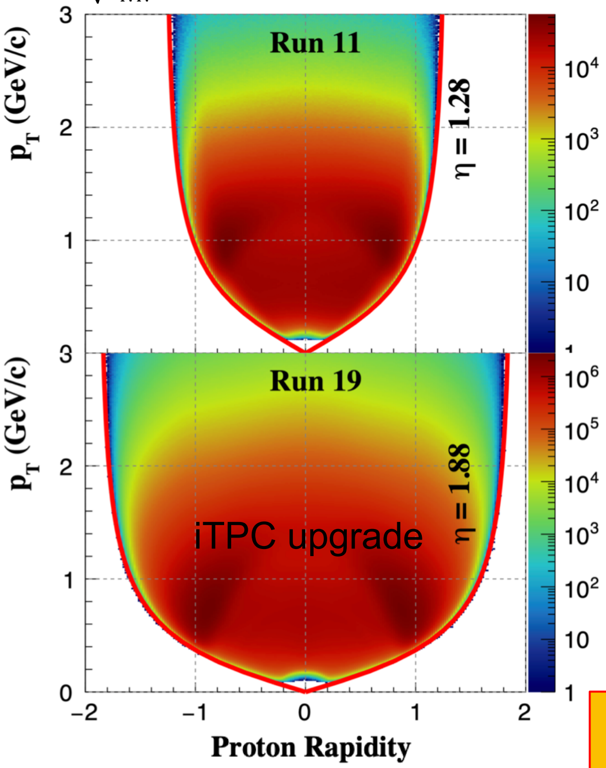
1. Higher statistics for 7 <= $\sqrt{s_{NN}}$ <= 27 GeV
2. Detector upgrades help also reduce systematic uncertainties

Most precise data to map the QCD phase diagram

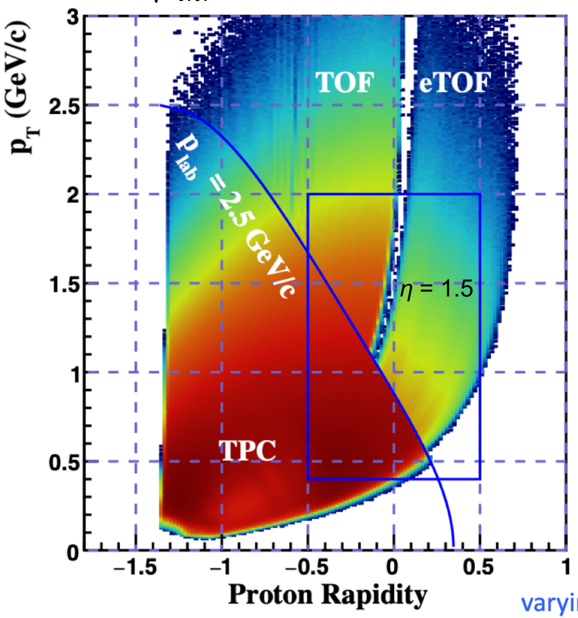
Future experiments: STAR BES-II

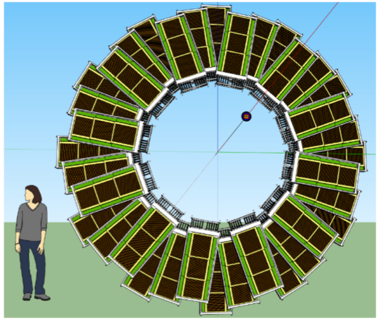
BES-II whitepaper:
https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

Proton, STAR Au+Au
$\sqrt{s_{NN}}$ = 19.6 GeV collider mode



Proton, STAR Au+Au
$\sqrt{s_{NN}}$ = 3.9 GeV FXT mode

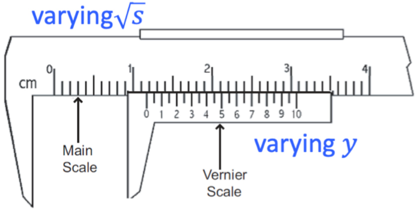


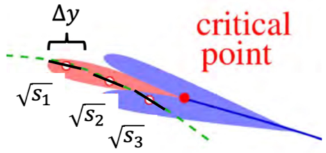


CBM TOF

- New detectors enable larger coverage of acceptance
  → rapidity window scan

Rapidity scan: sensitive probe of the critical region

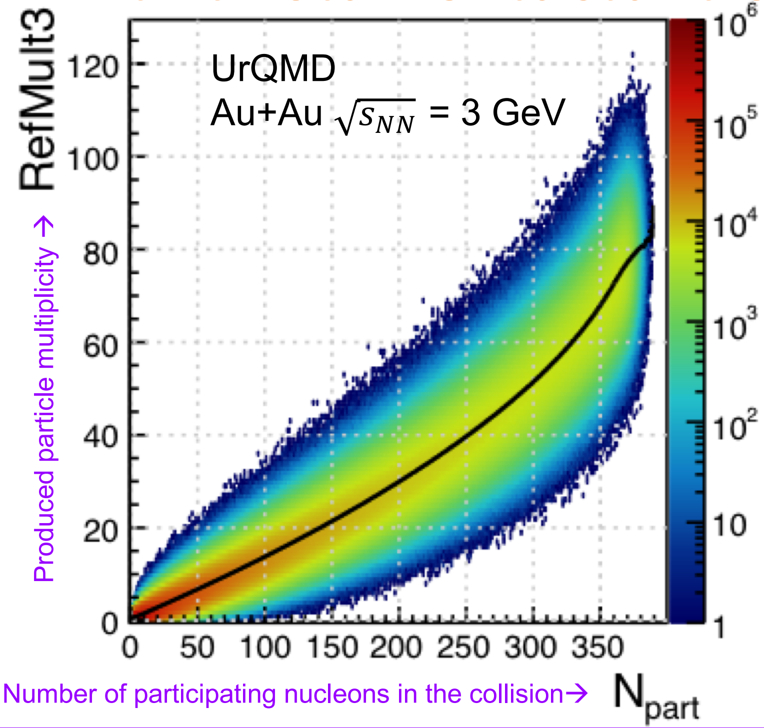


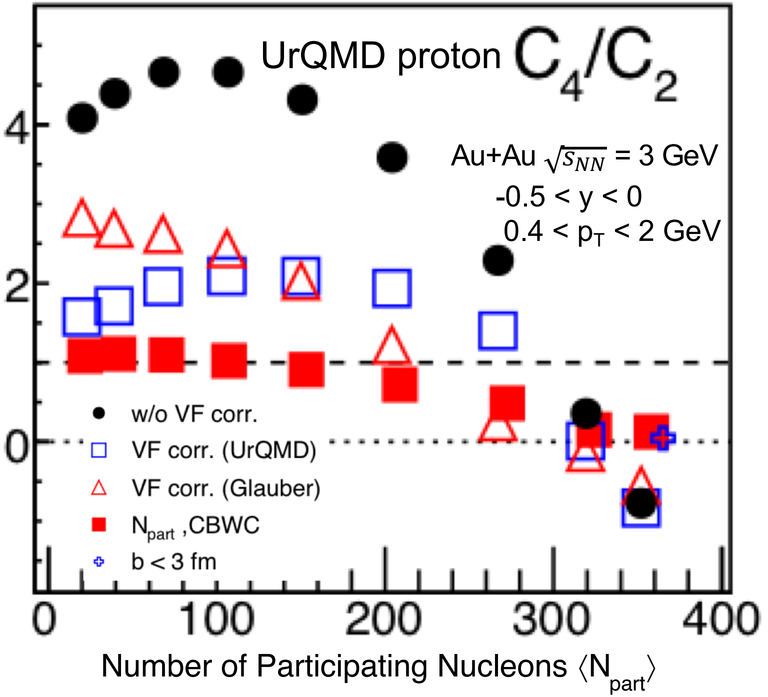


J. Brewer, BEST Collaboration, CPOD2018

Initial volume fluctuation at high baryon density

Ph.D thesis, Yu Zhang



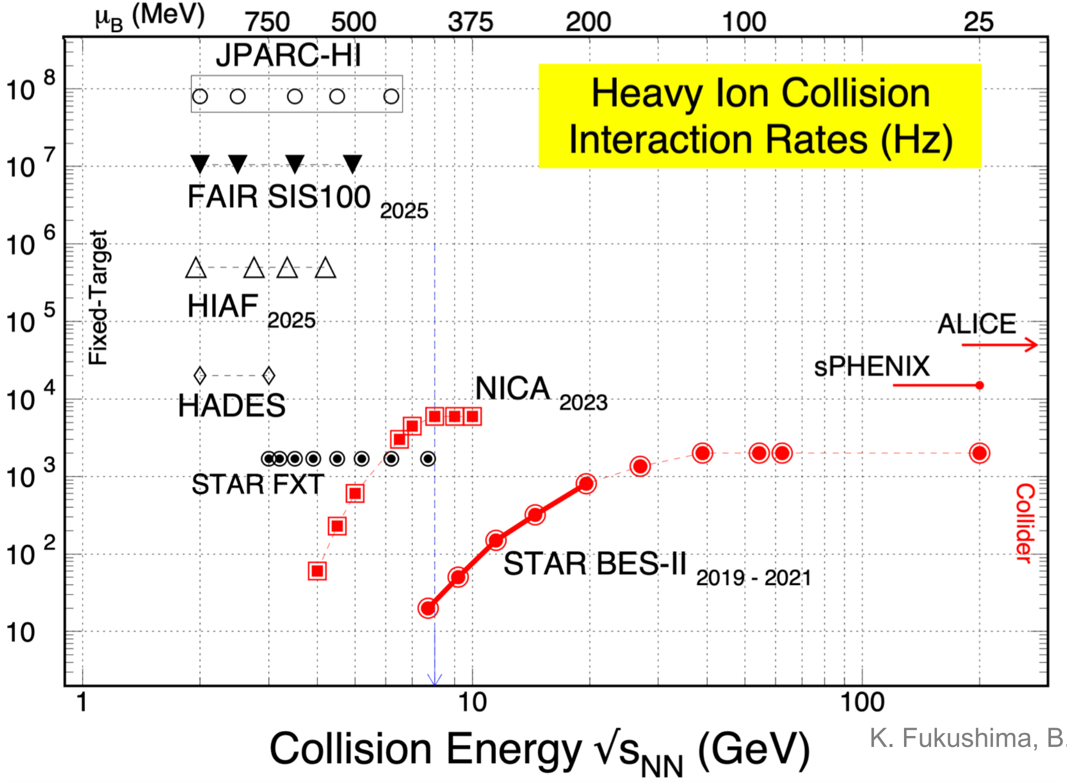


At lower collision energy, number of produced particle reduces → N_{part} resolution decreases

Resulting effect from the initial volume fluctuation is prominent in lower collision energy

We need to measure Npart independently and precisely!!

Summary and future experiments



K. Fukushima, B. Mohanty, N. Xu, AAPPS Bull. 31 (2021) 1

Cumulants analysis of conserved quantities are expected to locate the position of CP of the QCD

→ net-proton analysis: if QCD critical point exists, it is likely $\sqrt{s_{NN}} > 3$ GeV

1. Higher statistics:
2. Higher baryon densities: NICA, STAR BES-II, HADES, HIAF, FAIR, and JPARC-HI

Initial volume fluctuation challenge!

Many experimental challenges and new results are waiting for us

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Alphabetically: Daniel Cebra, Xin Dong, ShinIchi Esumi, ***Yige Huang****, Xiaofeng Luo,*
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