Experimental Study on the QCD Critical Point from STAR

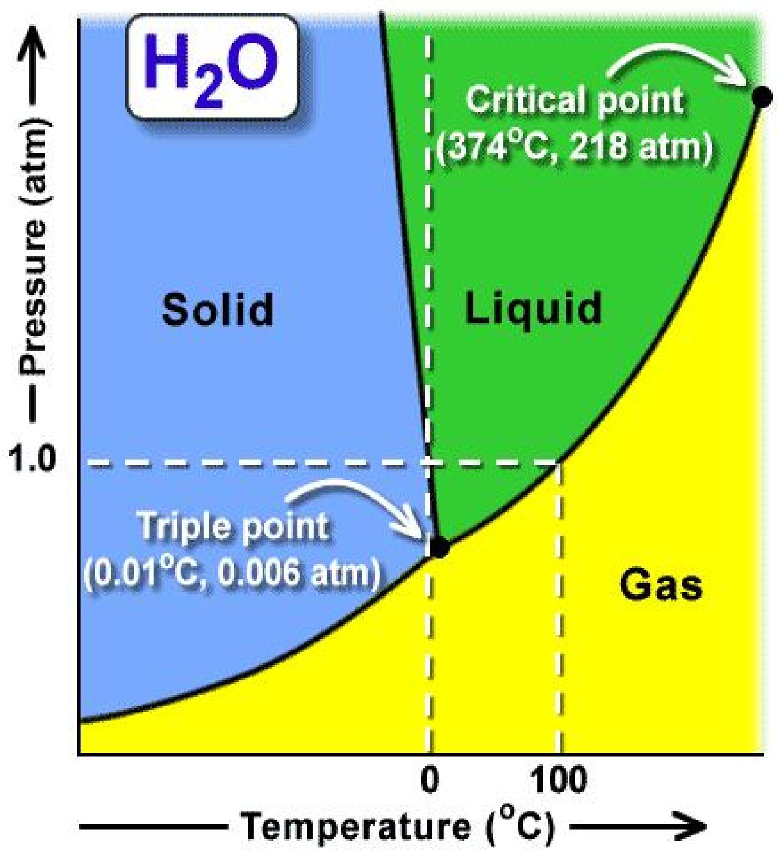
Yu Zhang

2025/11/30

Guangxi Normal University

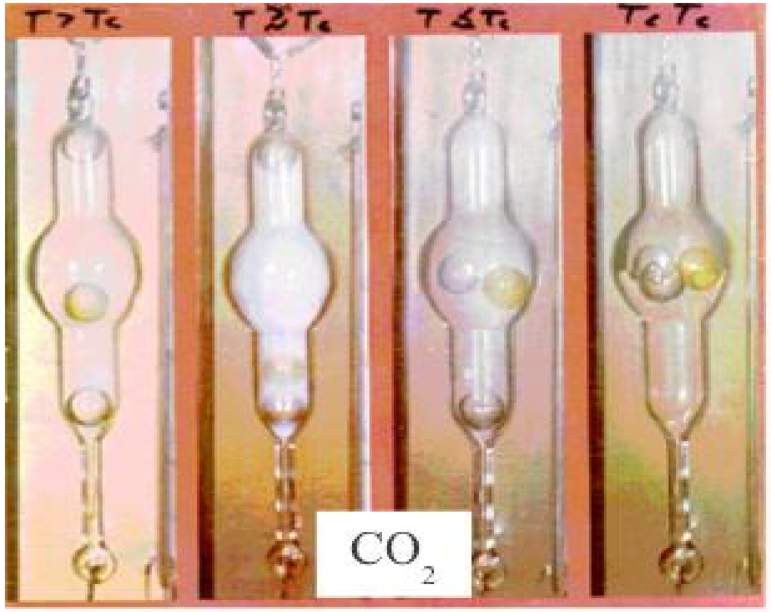
惠州强子谱仪HHas合作组年会

Critical Point and Critical Phenomena



Thermal motion Vs. Interactions

critical opalescence of CO_2



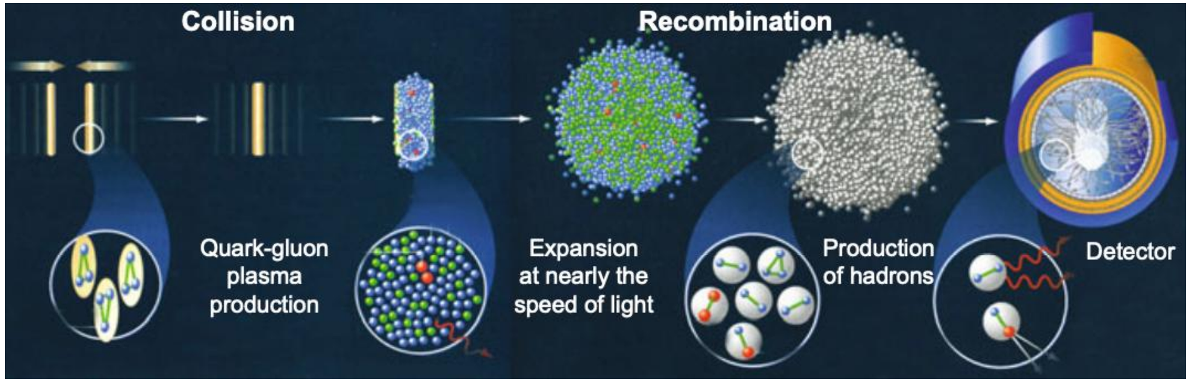
T. Andrews.Phil. Trans. Royal Soc., 159:575 (1869).

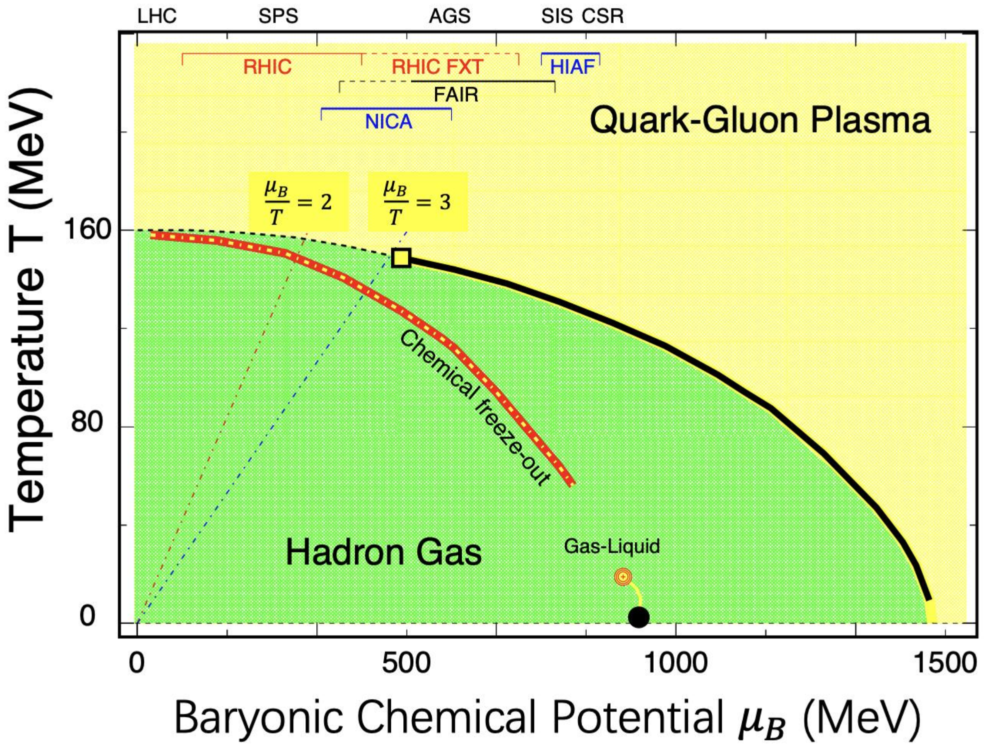
First critical point was discovered in 1869 for CO_2 by Andrews. $\mathbf{T_c = 31}$°C

Explained by Van der Waals (1873)

Nobel Prize 1910.

QCD Phase Diagram

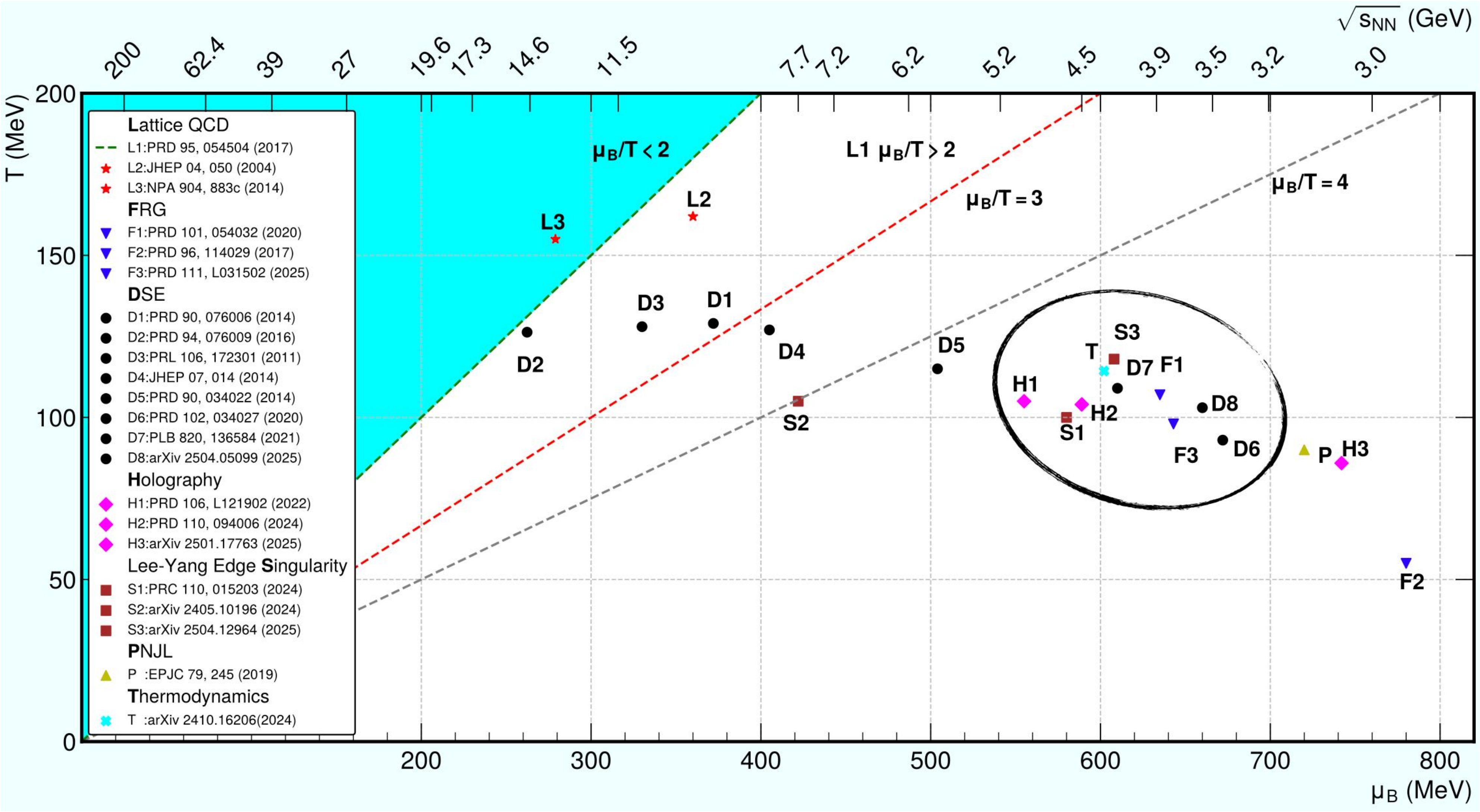




1. QGP formed in heavy-ion collisions under extreme conditions
2. Smooth crossover at μ_B = 0 MeV
3. 1st-order phase transition predicted at large μ_B by theory
4. Does QCD critical point exist?

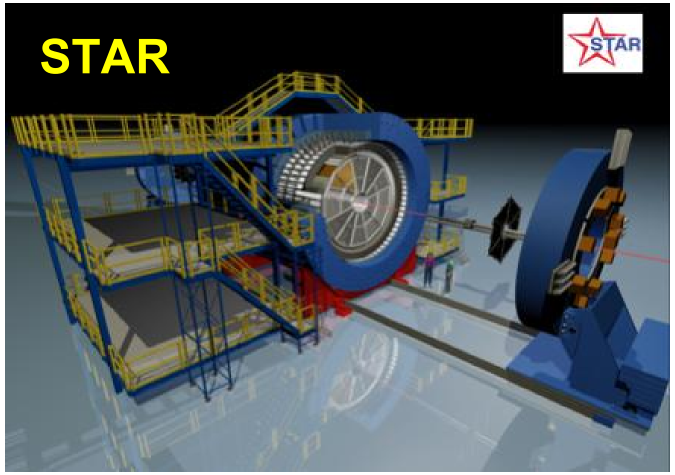
Y. Aoki et al, Nature 443, 675(2006)
A. Bzdak et al, Physics Reports 853,1-87(2020)
X. Luo, N. Xu, Nucl. Sci. Tech. 28, 112 (2017)

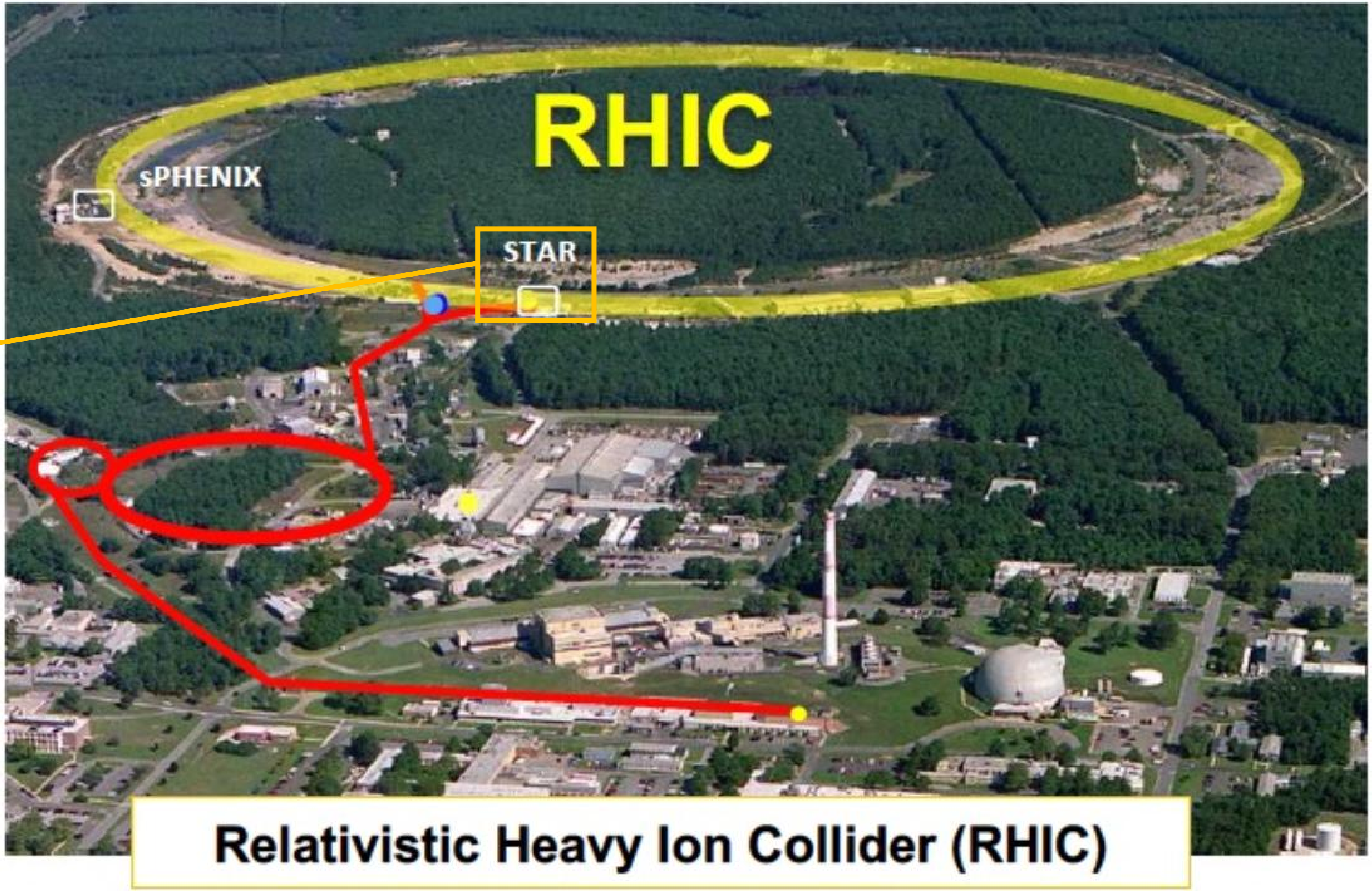
QCD Phase Diagram



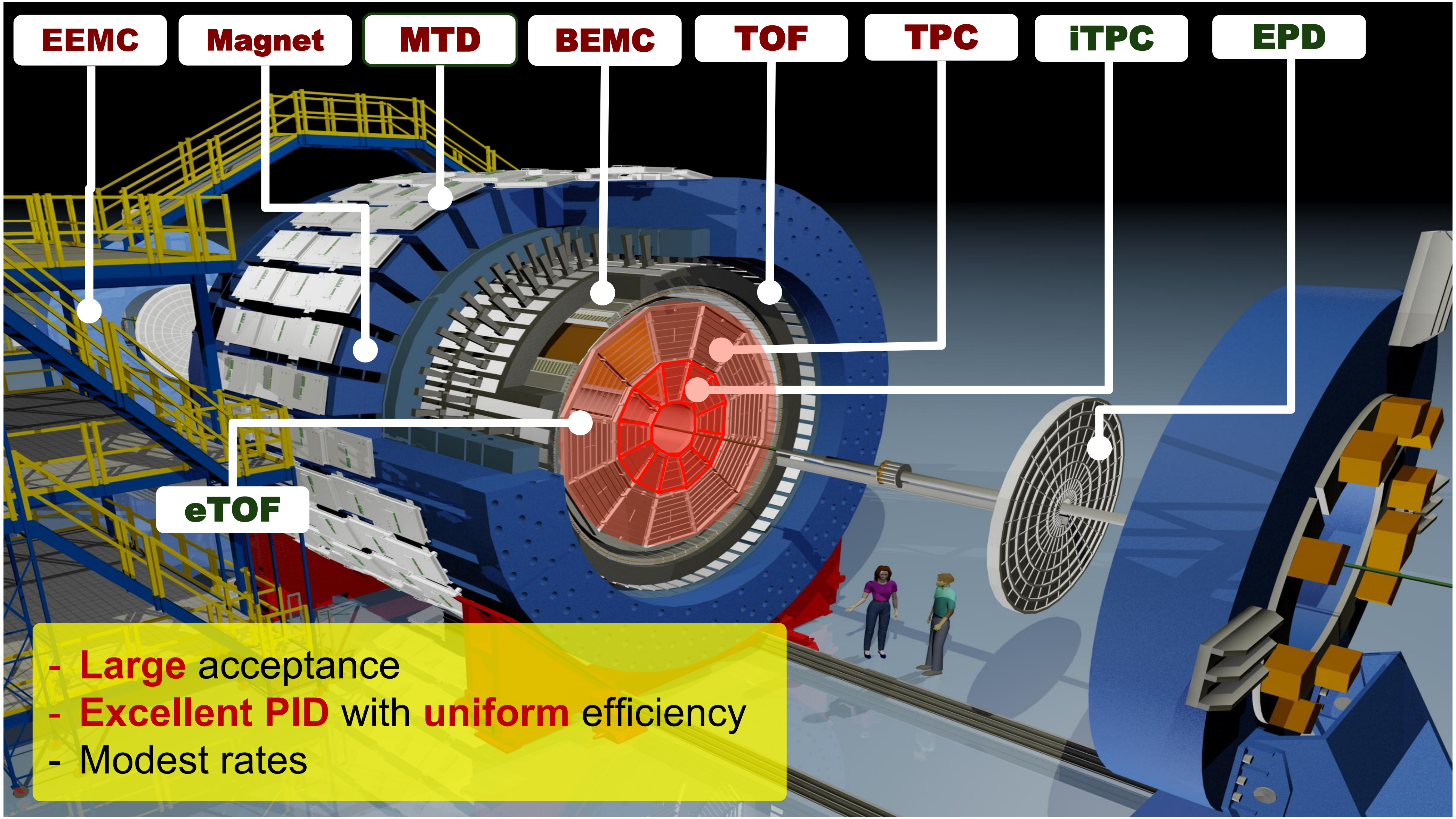
Latest estimation from different methods: μ_B^{CEP}: ~ 420 – 750 MeV, T^{CEP}: ~ 90 – 120 MeV

Relativistic Heavy-ion Collisions



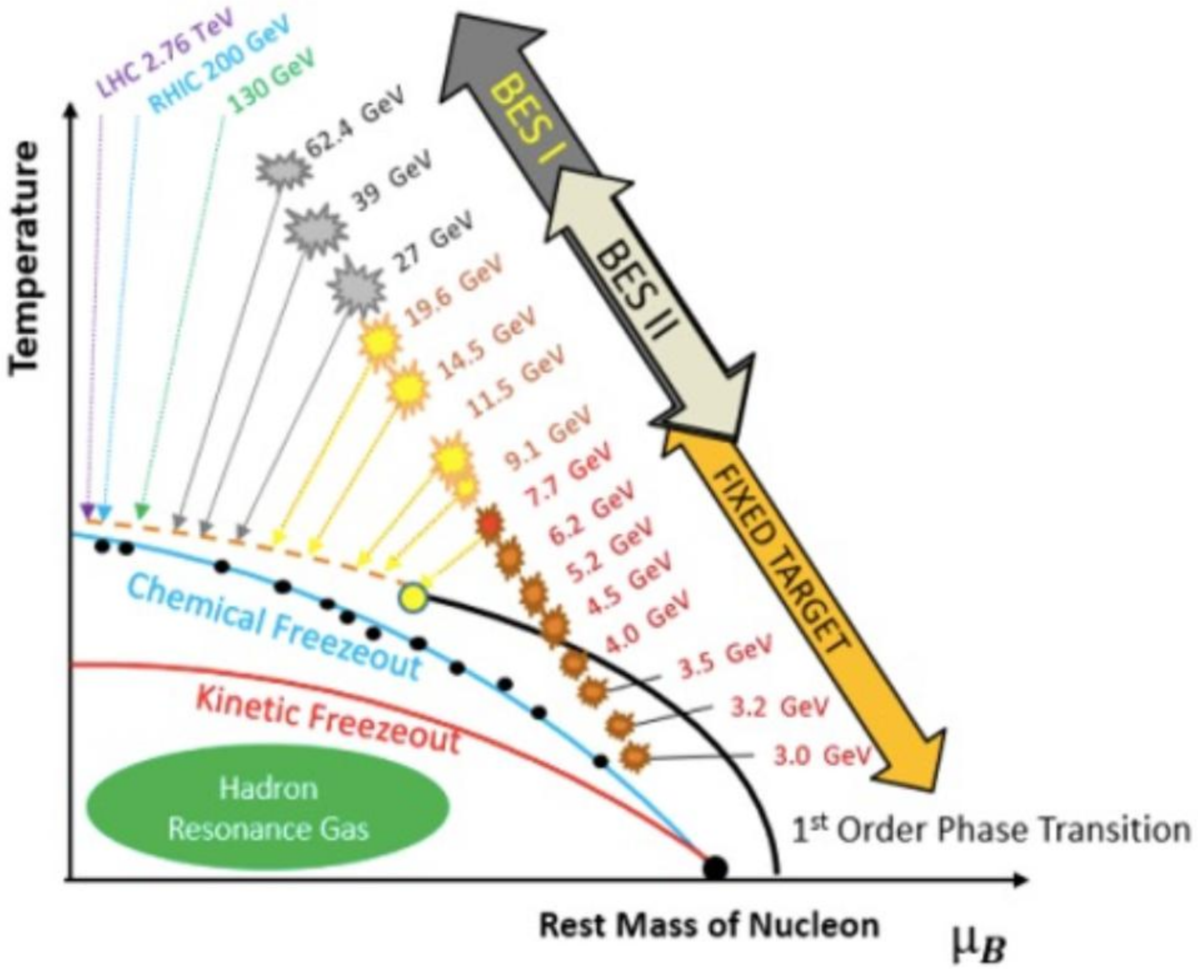


STAR Detector System



- **Large** acceptance
- **Excellent PID** with **uniform** efficiency
- Modest rates

RHIC Beam Energy Scan Program



RHIC Beam Energy Scan program provides an excellent oppotunity for QCD critical point search.

Au+Au Collisions at RHIC			
Collider Runs			
	$\sqrt{s_{NN}}$ / GeV	events / million	μ_B / MeV
1	200	380	25
2	62.4	46	75
3	54.4	1200	85
4	39	86	112
5	27	585	156
6	19.6	595	206
7	17.3	256	230
8	14.6	340	262
9	11.5	257	316
10	9.2	160	372
11	7.7	104	420

Multiplicity Fluctuation of Conserved Quantities

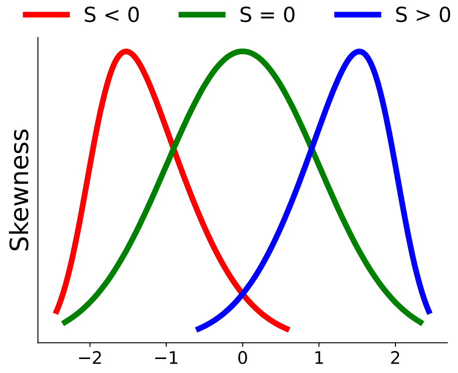
- Cumulants of conserved quantities

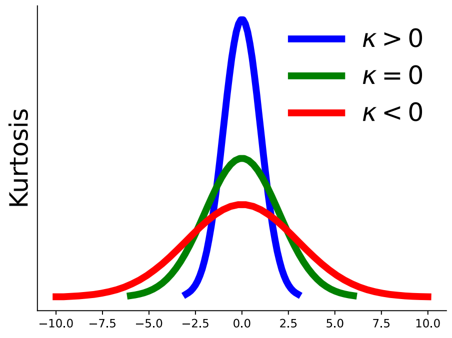
Net-baryon (B) (net-proton as proxy)
Net-electric charge (Q)
Net-strangeness (S) (net-kaon as proxy)

$$\delta N = N - \langle N \rangle$$
$$C_1 = \langle N \rangle = M$$
$$C_2 = \langle (\delta N)^2 \rangle = \sigma^2$$
$$C_3 = \langle (\delta N)^3 \rangle$$
$$C_4 = \langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle^2$$

$$\frac{C_2}{C_1} = \frac{\sigma^2}{M}, \quad \frac{C_3}{C_2} = S\sigma$$
$$\frac{C_4}{C_2} = \kappa\sigma^2$$

N : event-wise net-particle multiplicity





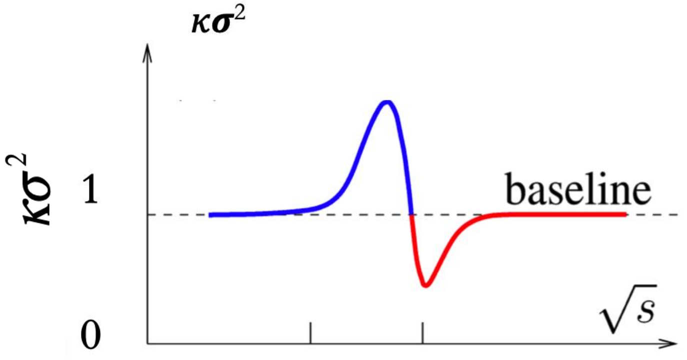
1. Sensitive to correlation length

$$C_3 = \langle (\delta N)^3 \rangle \sim \xi^{4.5}$$
$$C_4 = \langle (\delta N)^4 \rangle - 3\langle (\delta N)^2 \rangle \sim \xi^7$$

2. Related to susceptibility

$$\frac{\chi_4^q}{\chi_2^q} = \kappa\sigma^2 = \frac{C_4^q}{C_2^q}, \quad \frac{\chi_3^q}{\chi_2^q} = S\sigma = \frac{C_3^q}{C_2^q}$$
$$\chi_n^q = \frac{1}{VT^3} \cdot C_n^q = \frac{\partial^n (p/T^4)}{\partial(\mu^q)^n}, \quad q = B, Q, S$$

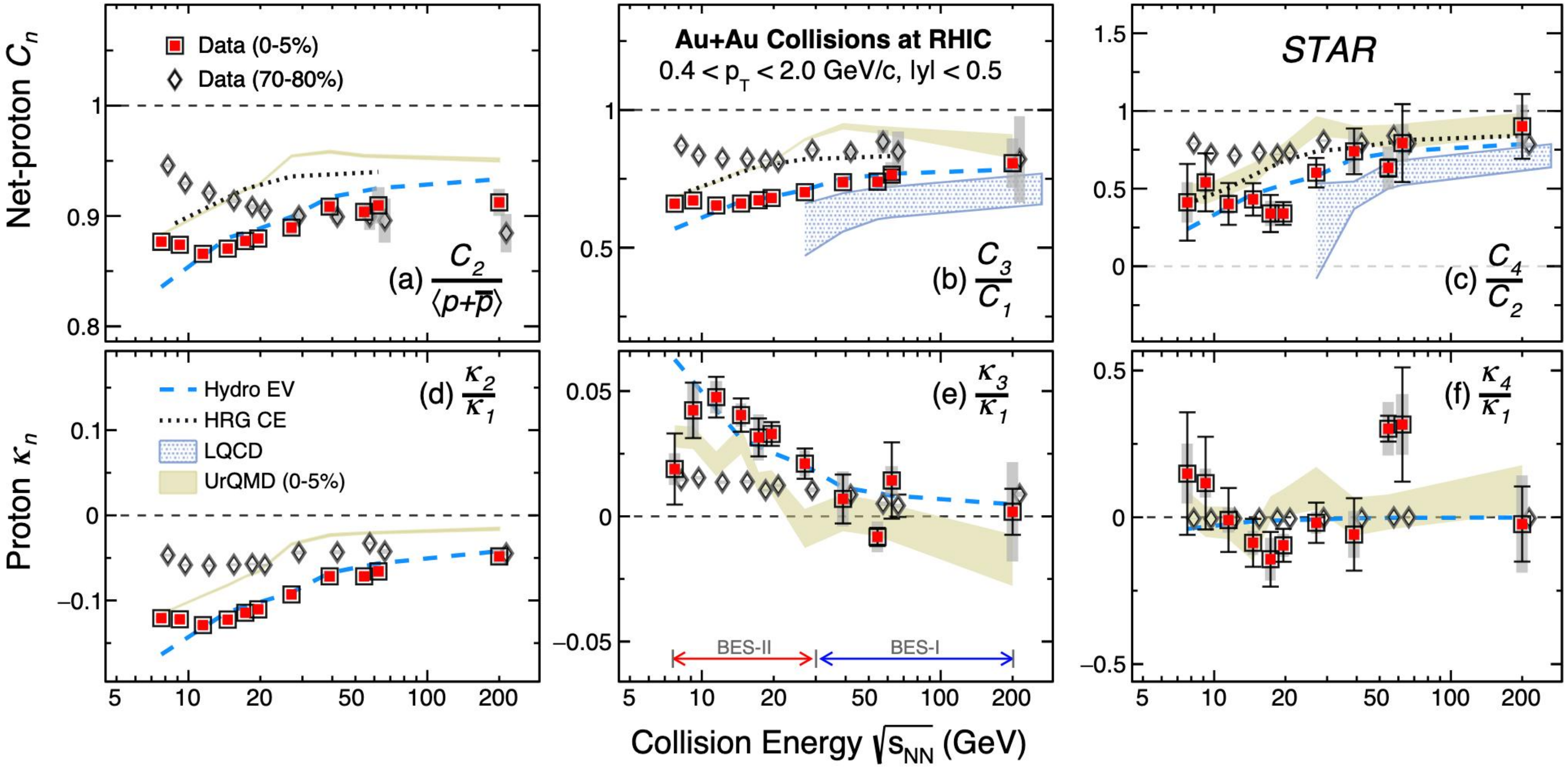
3. Non-monotonic behavior of C_4/C_2 indicates the existence of the QCD critical point



$\kappa\sigma^2 = 1$ (Poisson Fluctuations)

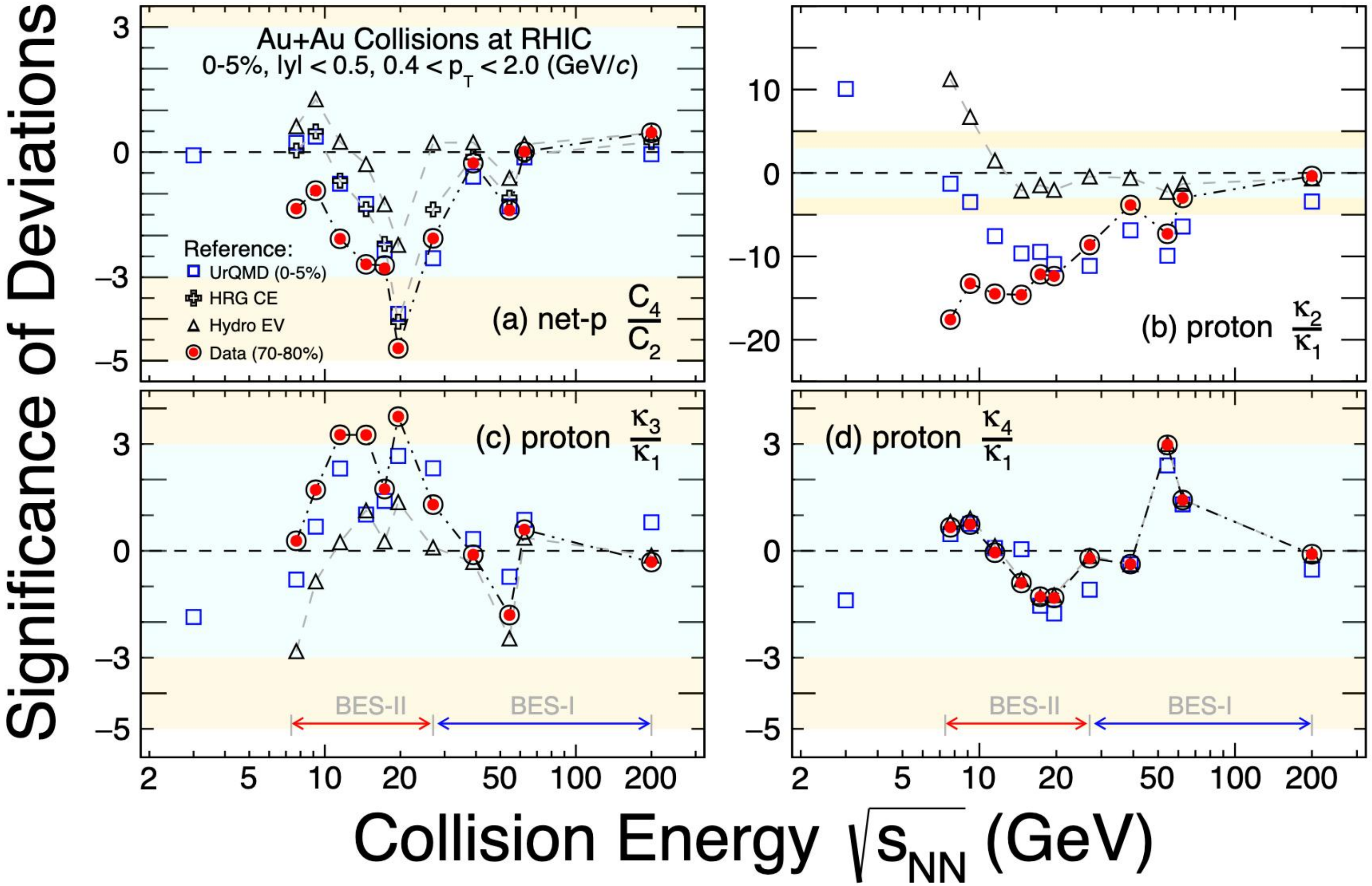
M. A. Stephanov, PRL 102, 032301 (09);
M. Asakawa, S. Ejiri and M. Kitazawa, PRL 103, 262301 (09)
S.Ejiri et al, PLB 633, 275(06);
M. A. Stephanov, PRL 107, 052301 (11); F. Karsch and K. Redlich, PLB 695, 136 (11)

Energy dependence of cumulant ratios



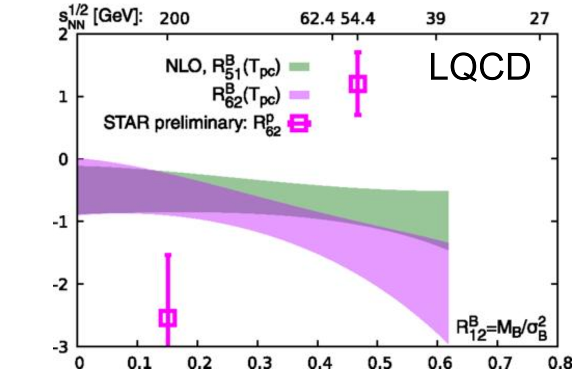
1. In 0-5% central Au+Au collisions, net-proton C_4/C_2 shows deviation from non-critical references at around 20 GeV
2. Net-proton $C_2/\langle p+\bar{p}\rangle$, C_3/C_1 and proton κ_2/κ_1 , κ_3/κ_1 also show deviations from non-critical models too, especially below 11.5 GeV

Deviations from non-critical baselines

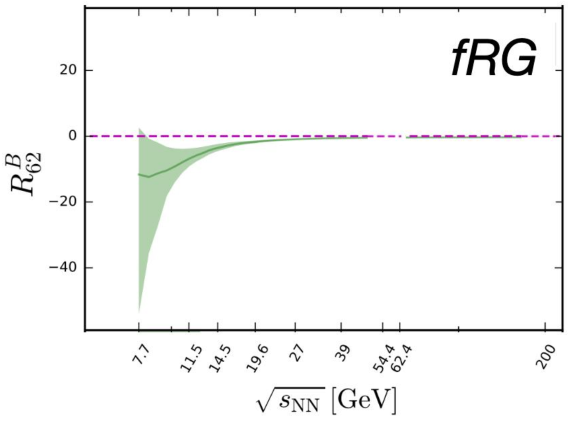


1. C_4/C_2 shows a minimum at ~20 GeV comparing to non-critical models or 70-80% data
   - Maximum deviation: 2 – 5σ at 20 GeV (1.3 – 2σ at BES-I)
2. Are the deviations due to critical fluctuations?

Hyper-order fluctuations in Au+Au collisions

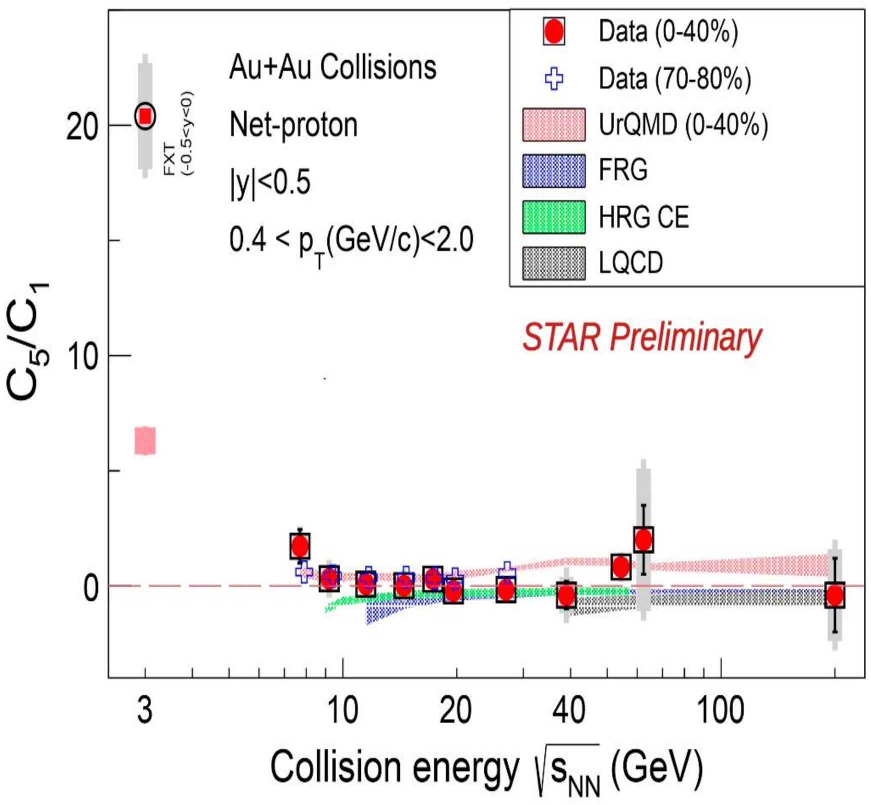


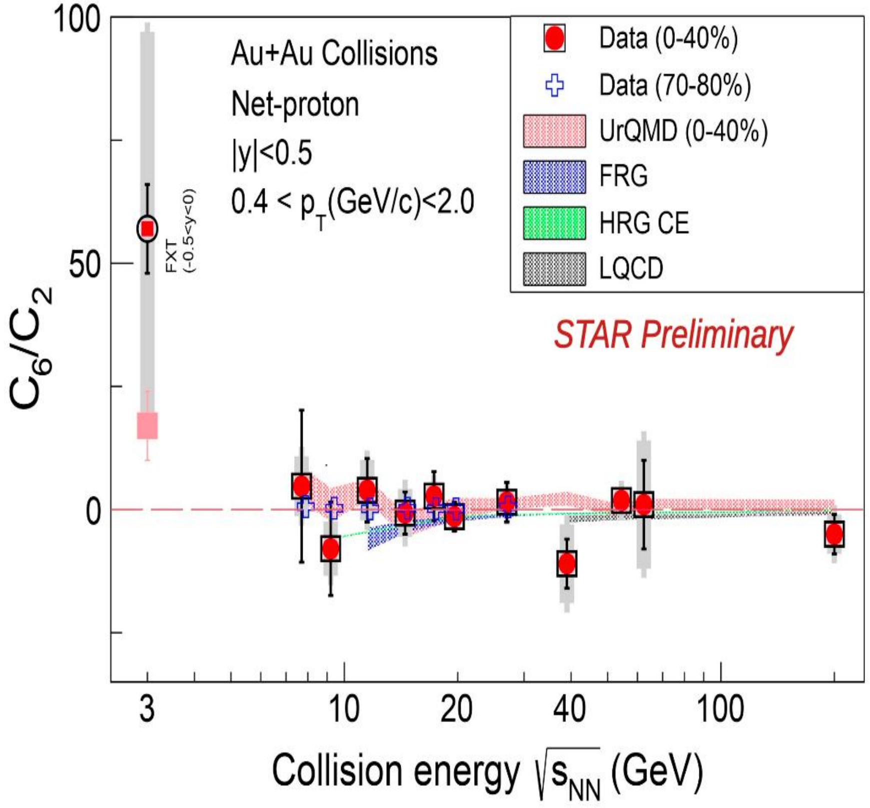
A. Bazavov et al. Phys. Rev. D 101, 074502



W. Fu, et al: PRD 104 094047 (2021)

Negative sign in hyper-order cumulants indicates crossover transitions

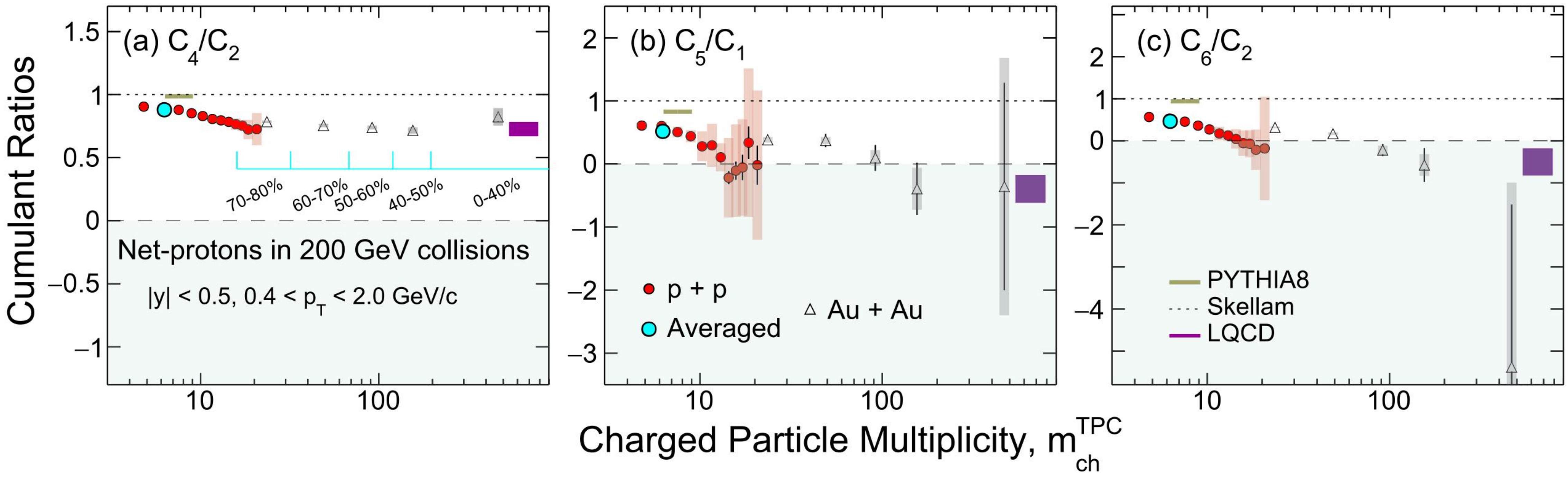




1. Hyper-order cumulants are data-hungry measurement
2. C_6/C_2 in 0-40% fluctuate in collider energies around zero within uncertainties

Hyper-order across collision system

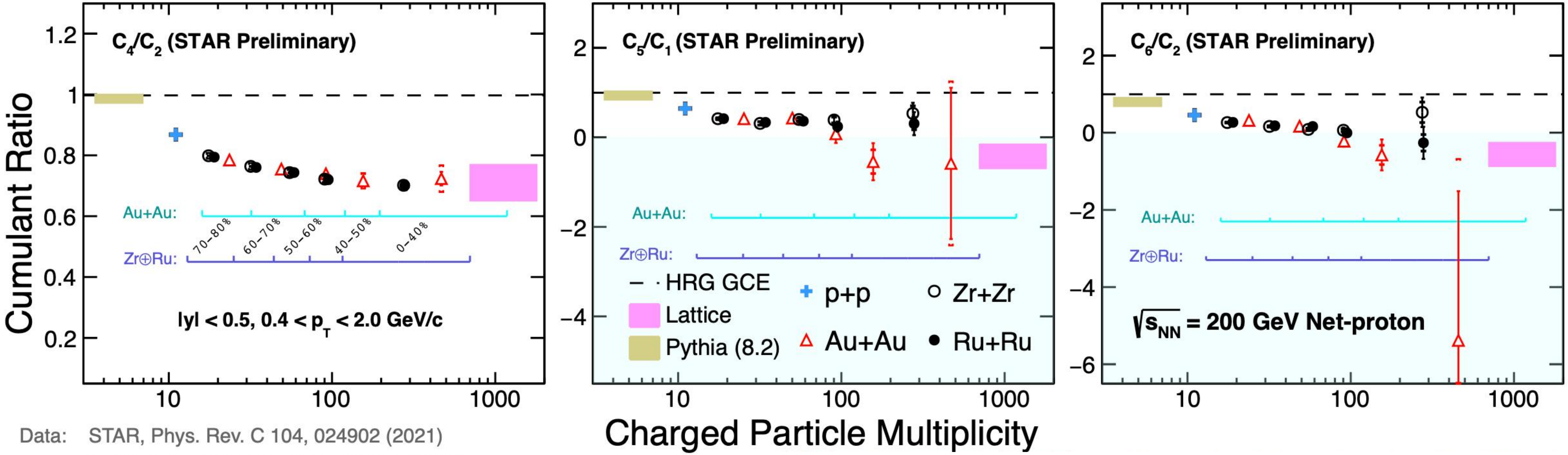
STAR, Phys. Lett. B 857 (2024) 138966



1. Negative C_5/C_1 and C_6/C_2 observed in central Au+Au collisions at 200 GeV
2. C_5/C_1 and C_6/C_2 in p+p gradually approach negative when it goes to higher multiplicity
3. The result could indicate QGP created at highest multiplicity in p+p

Hyper-order across collision system

STAR Preliminary, Ho-San Ko, QM 2022

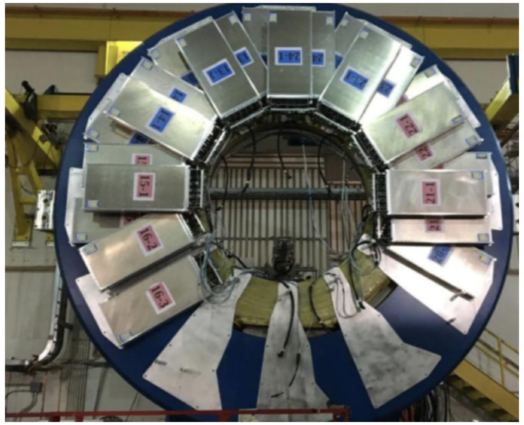


Data: STAR, Phys. Rev. C 104, 024902 (2021)
STAR, Phys. Rev. Lett. 127, 262301 (2021)

1. Overall, isobar data show decreasing trends towards negative in C_4-C_6 ratios as a function of multiplicity
2. Deviations from decreasing trend is seen in central Zr+Zr collisions

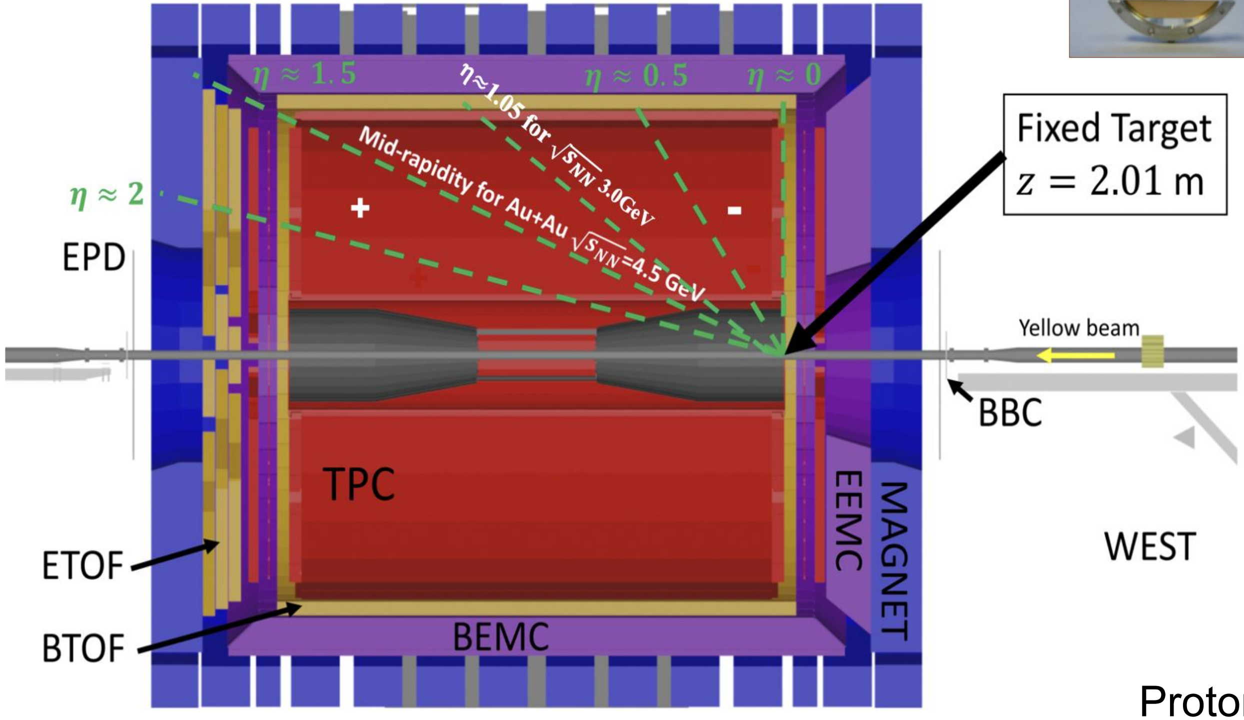
STAR Fixed-target experiment

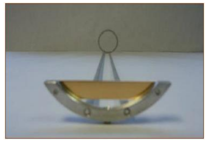
eTOF detector



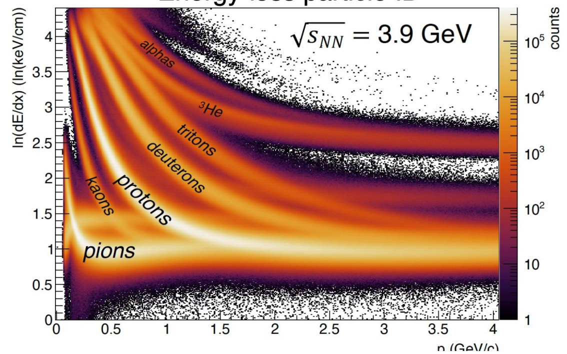
Forward rapidity coverage
PID at η = 0.9 to 1.5
Provided by FAIR-CBM

Fixed-target setup

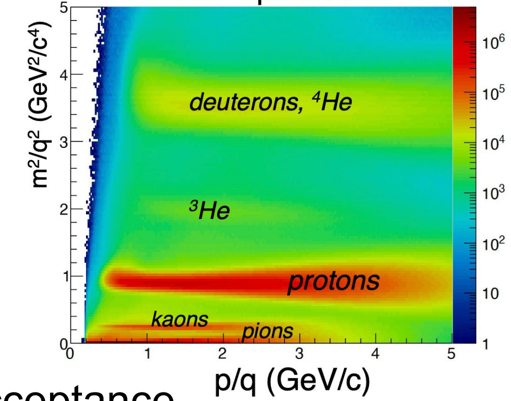




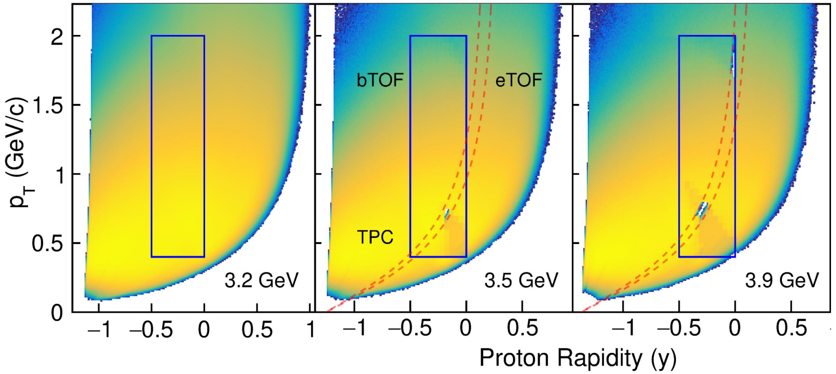
Energy-loss particle ID



ETOF particle ID



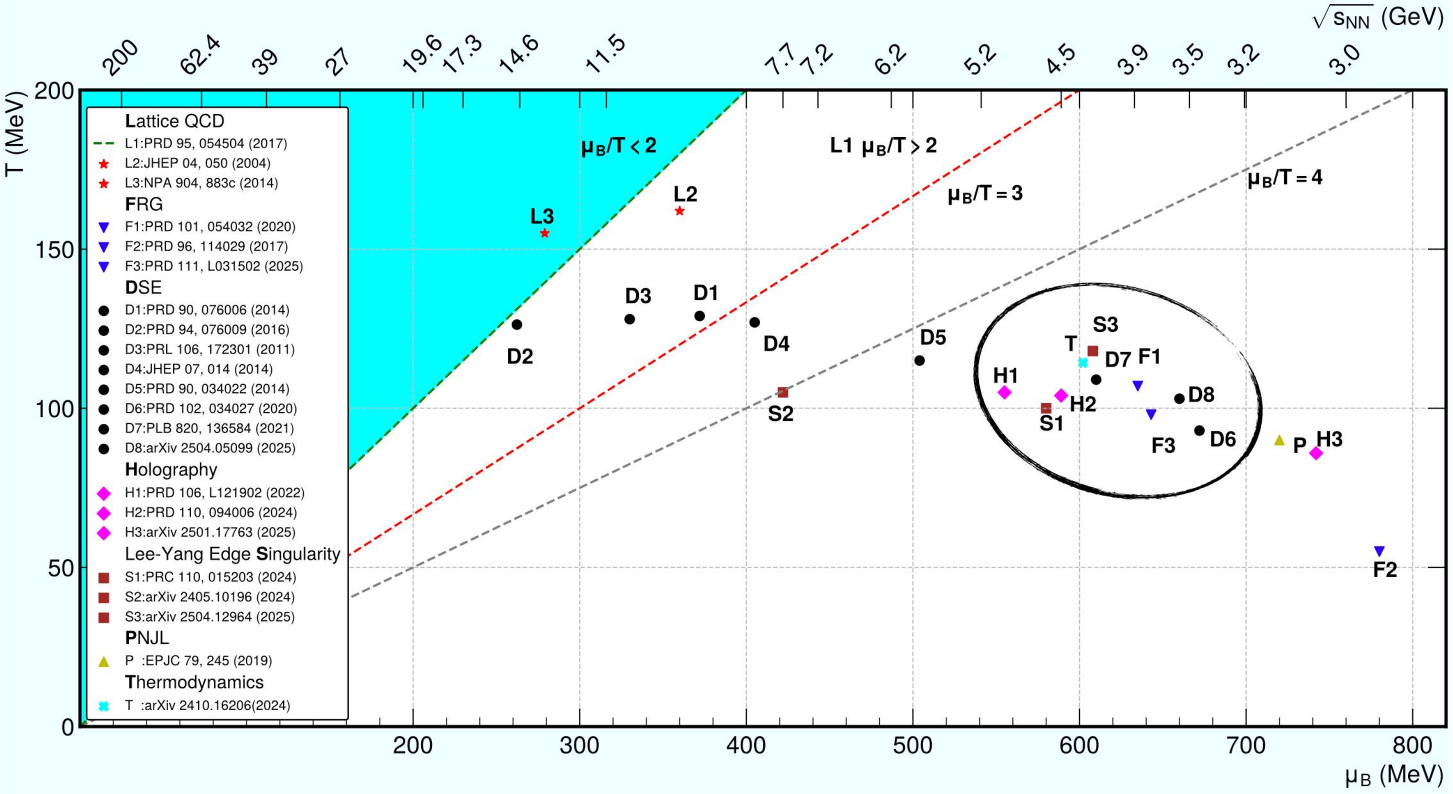
Proton Acceptance



1. STAR detector also runs in fixed-target mode.
2. eTOF provides forward coverage during data-taking
3. While not dedicated for fixed-target runs, mid-rapidity of interest is coverd by half when going to high FXT energy (>4.5 GeV)

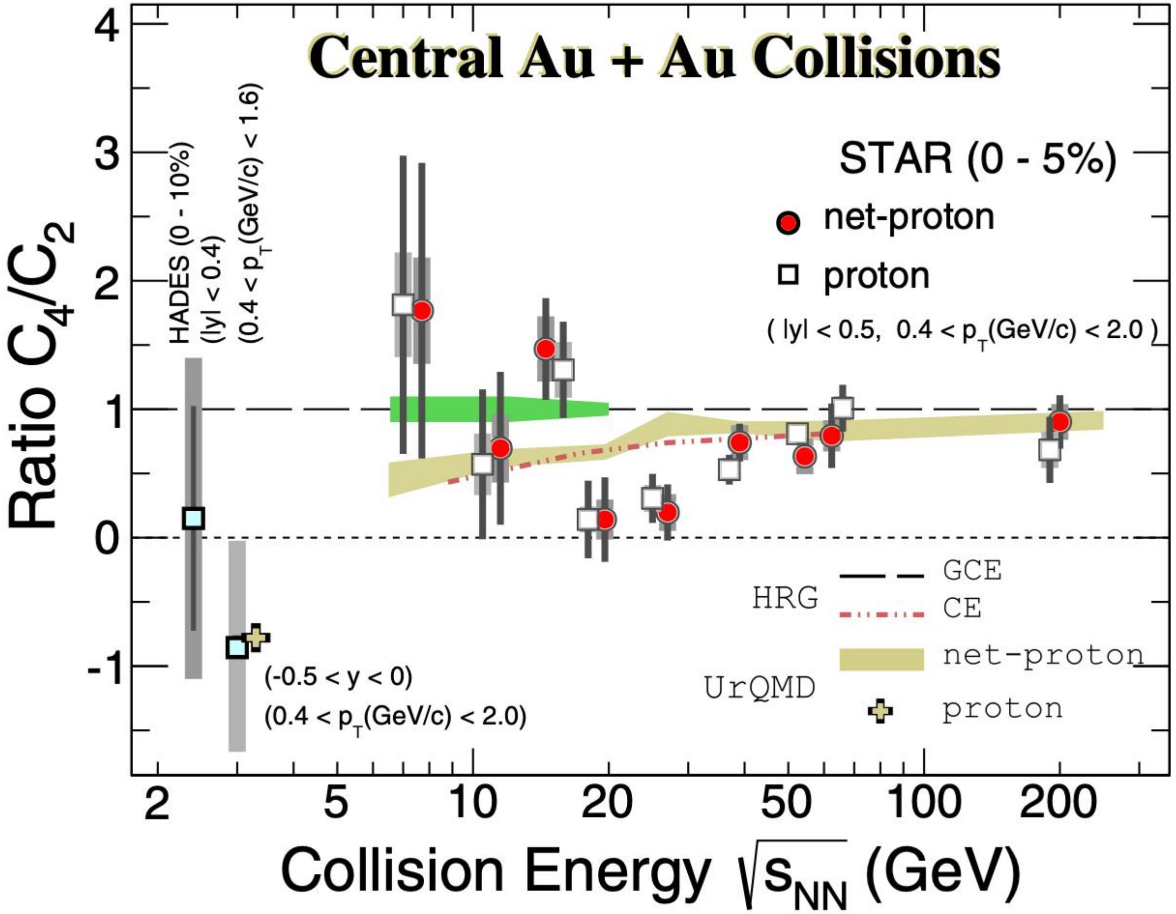
High baryon density is important for critical point search

STAR Fixed-Target Runs			
	$\sqrt{s_{NN}}$ / GeV	event / million	μ_B / MeV
1	13.7 (100)	50	280
2	11.5 (70)	50	316
3	9.2 (44.5)	50	372
4	7.7 (31.2)	260	420
5	7.2 (26.5)	470	440
6	6.2 (19.5)	120	490
7	5.2 (13.5)	100	540
8	4.5 (9.8)	110	590
9	3.9 (7.3)	120	633
10	3.5 (5.75)	120	670
11	3.2 (4.59)	200	699
12	3.0 (3.85)	260+2000	750



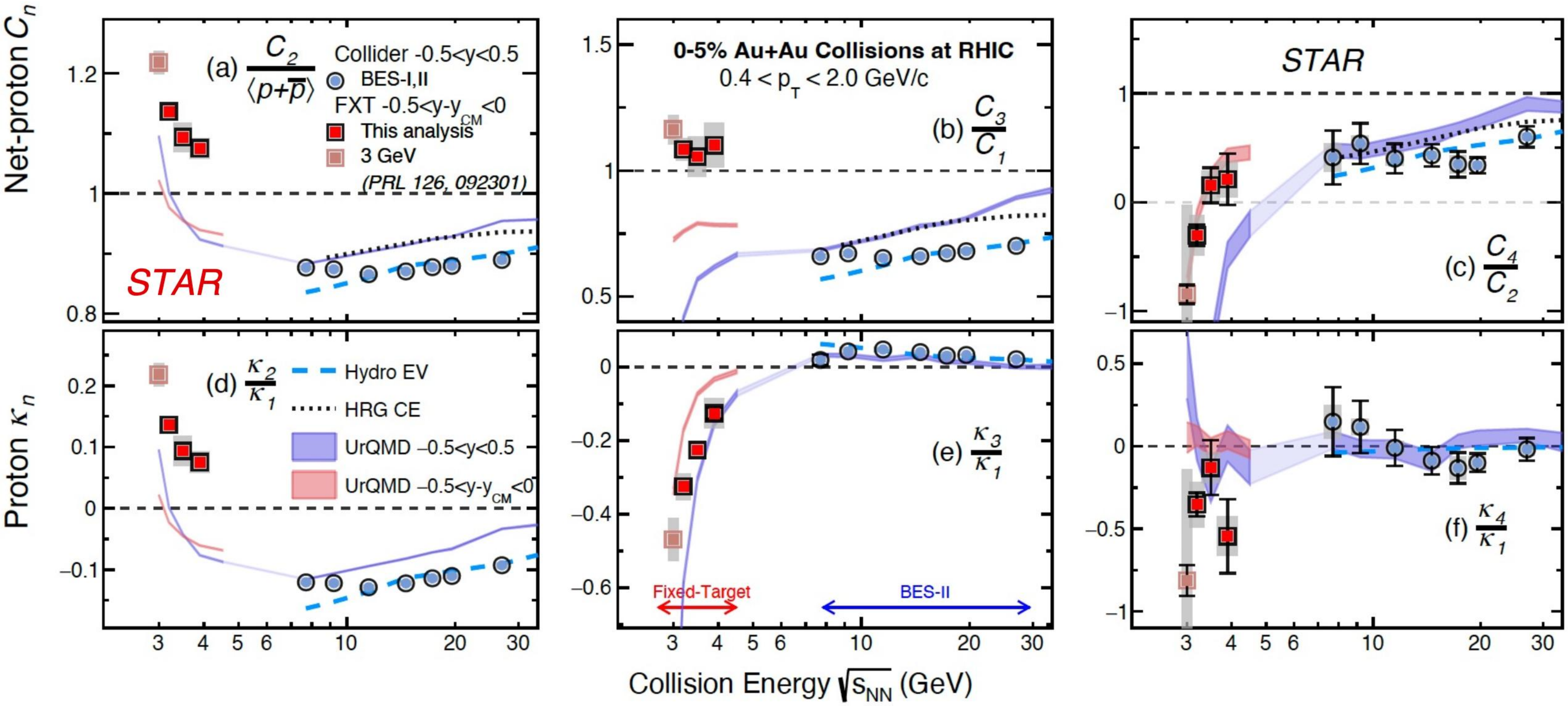
STAR fixed-taget experiment extends research to high baryon density region.

Measurement from Fixed-target energies



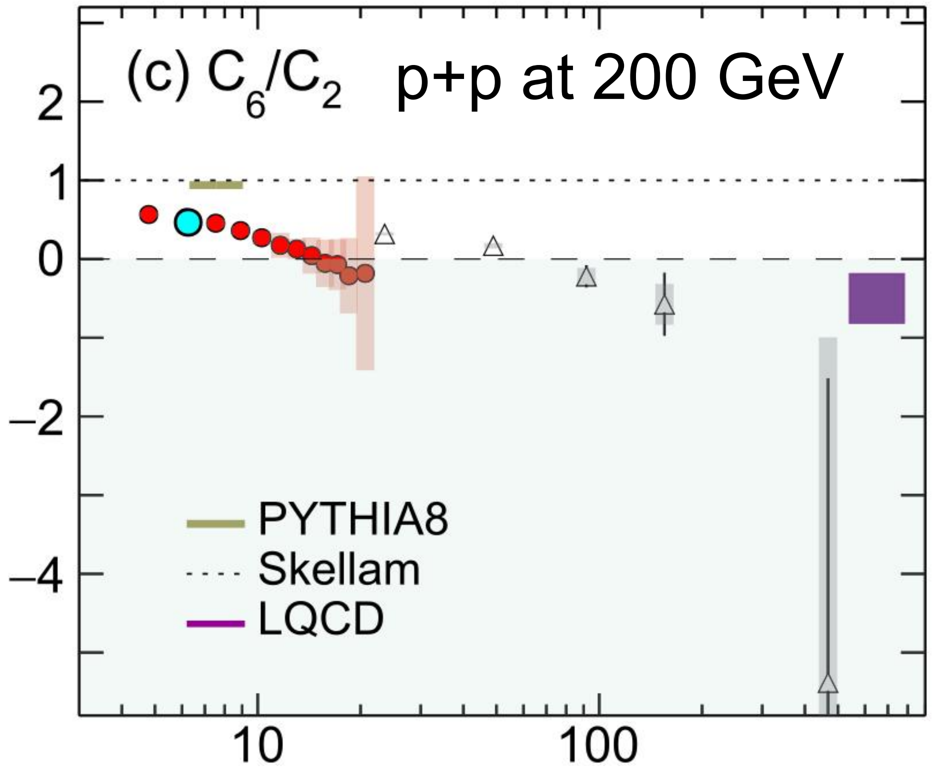
1. First measurement from STAR fixed-target experiment.
2. The 3GeV result is consistent with hadronic transport calculation which indicates QCD critical point could exist at energy higher than 3 GeV.

Preliminary results at 3.2-3.9 GeV from STAR FXT

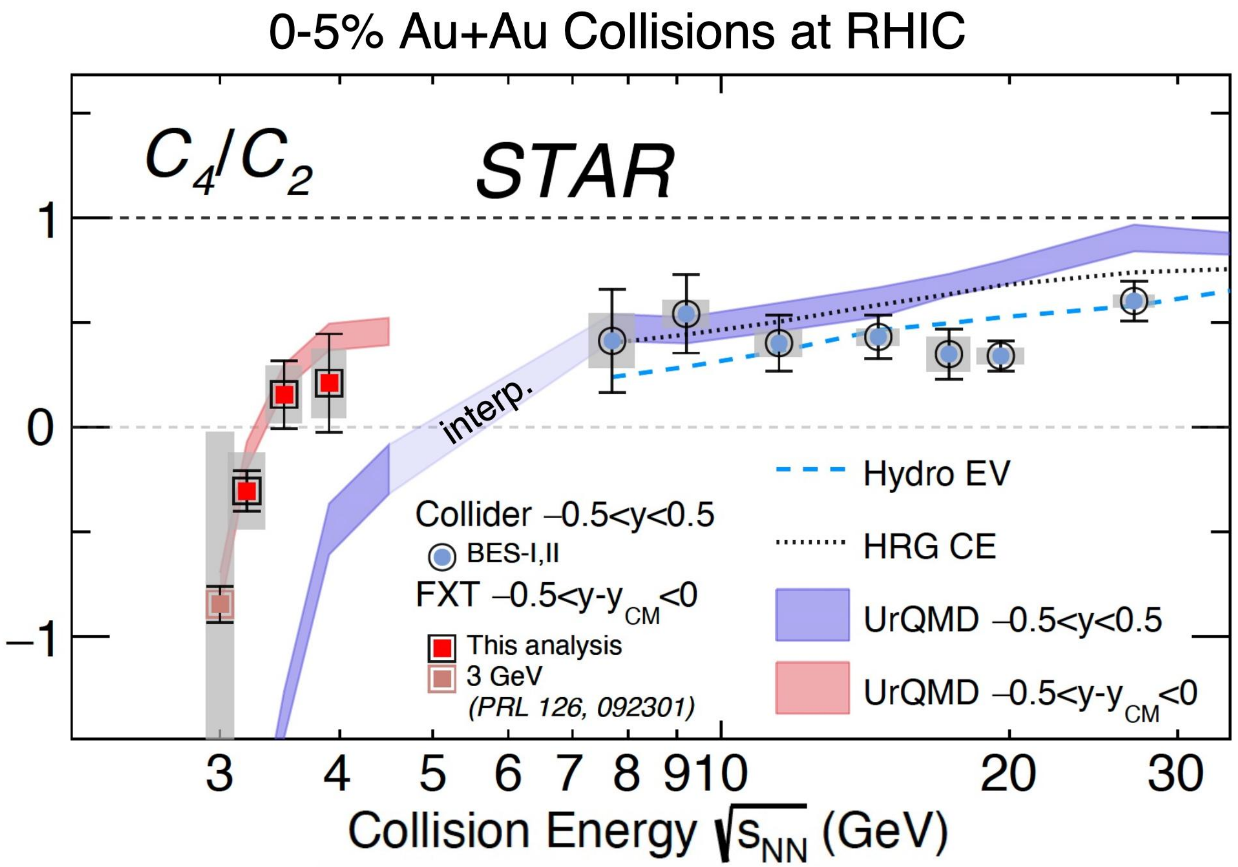


1. Results at high baryon density region are important
2. Be careful when interpreting data at low energy: large volume fluctuation

Possible Measurements at HHaS



Hyper-order fluctuations to probe the onset of QGP in small systems



Heavy-ion collisions to search for QCD critical point at high baryon density region

Summary

1. A maximum deviation of C_4/C_2 at 19.6 GeV from non-critical baselines
2. Deviations from non-critical baselines of 2nd, 3rd-order below 11GeV
3. Measurements at high baryon density region are needed for the search of QCD critical point

Thank you very much!