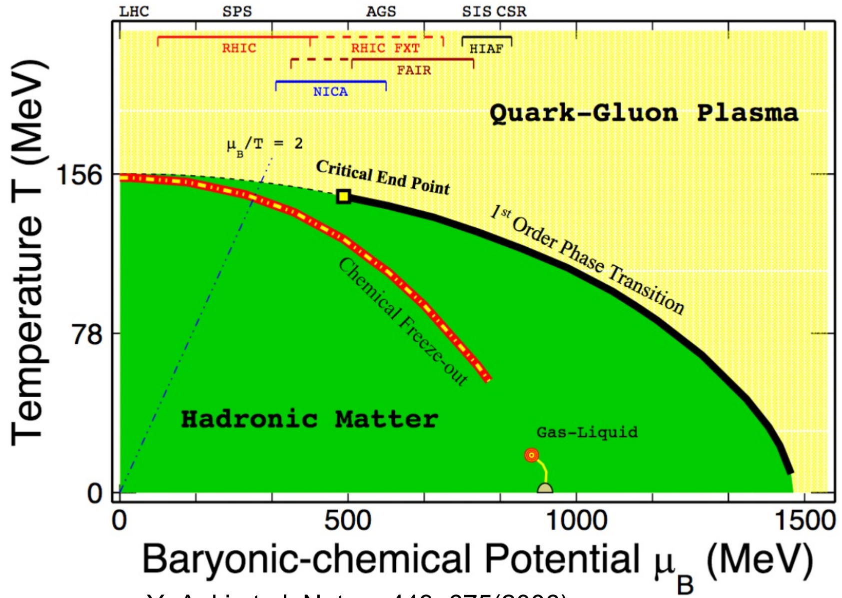
QCD Critical Point and Net-proton Fluctuations

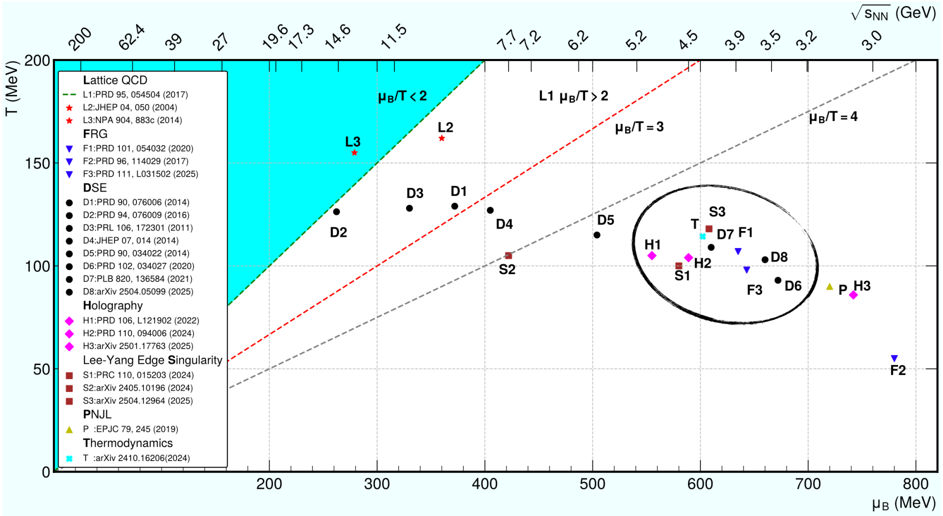
Yu Zhang
Guangxi Normal University

QPT 2025/10/24-28

QCD Phase Diagram



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)



1. Recent theoretical predictions converge around high baryon density region
2. Experimental result from STAR in this talk
   a. Net-proton at BES-II collider energies
   b. Proton at STAR fixed-target energies

Observable: cumulants

At around critical point, correlation length should diverge

Moments of Net-B, Net-Q, Net-S are

a) sensitive to correlation length

b) directly related to susceptibility ratios

$$\frac{\chi_4^q}{\chi_2^q} = \kappa\sigma^2 = \frac{C_4^q}{C_2^q}, \quad \frac{\chi_3^q}{\chi_2^q} = S\sigma = \frac{C_3^q}{C_2^q}$$

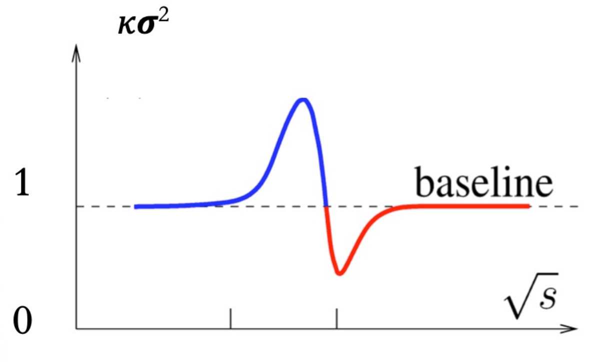
$$\chi_n^q = \frac{1}{VT^3} \cdot C_n^q = \frac{\partial^n (p/T^4)}{\partial(\mu^q)^n}, \quad q = B, Q, S$$

Cumulants:

$$\boxed{\begin{aligned} &\text{mean: } M && = \langle N \rangle && = C_1 \\ &\text{variance: } \sigma^2 && = \langle (\delta N)^2 \rangle && = C_2 \\ &\text{skewness: } S && = \langle (\delta N)^3 \rangle / \sigma^3 && = C_3 / C_2^{\frac{3}{2}} \\ &\text{kurtosis: } \kappa && = \langle (\delta N)^4 \rangle / \sigma^4 - 3 && = C_4 / C_2^2 \end{aligned}}$$

Factorial cumulants:

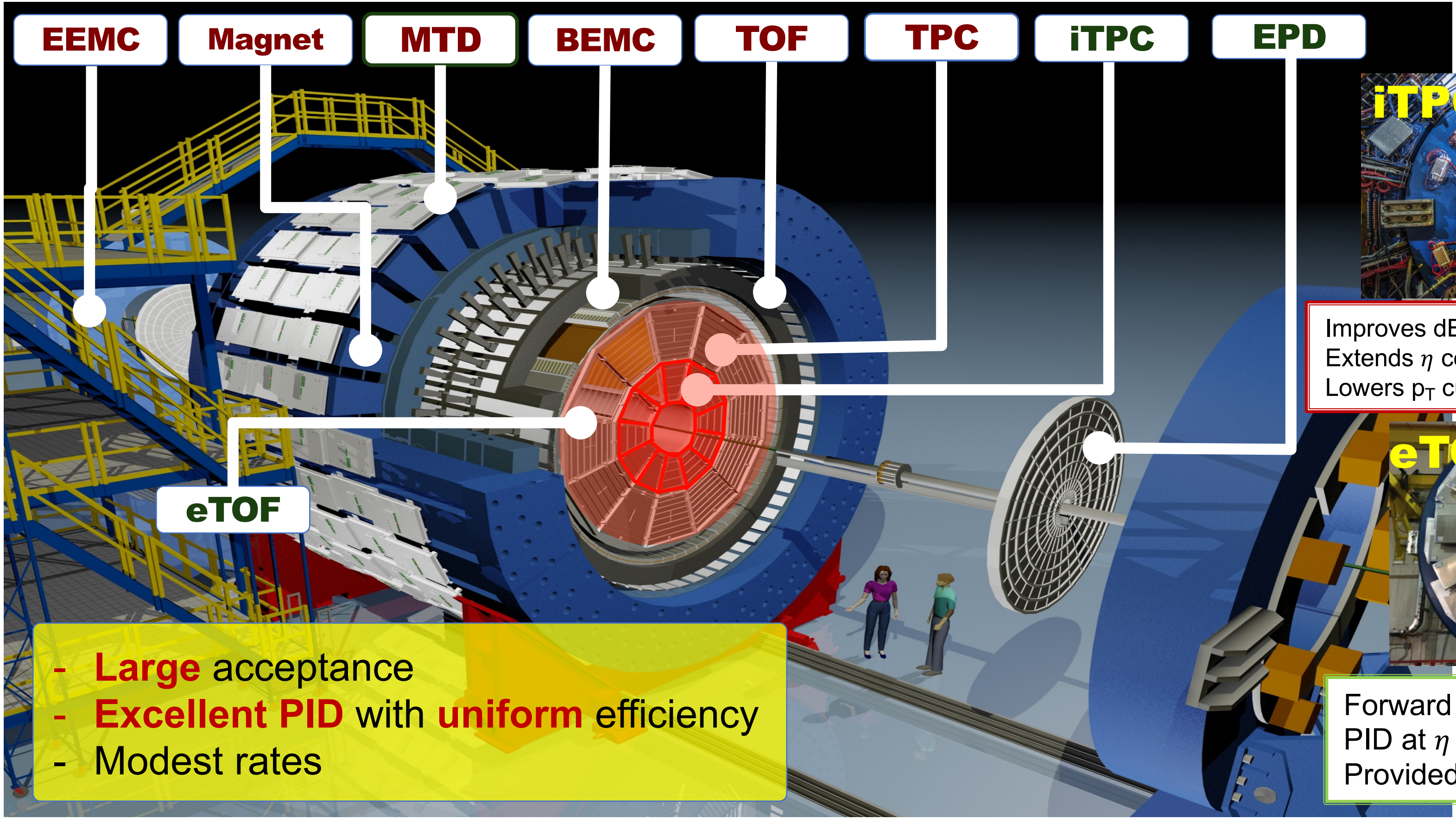
$$\boxed{\begin{aligned} \kappa_1 &= C_1 \\ \kappa_2 &= C_2 - C_1 \\ \kappa_3 &= C_3 - 3C_2 + 2C_1 \\ \kappa_4 &= C_4 - 6C_3 + 11C_2 - 6C_1 \end{aligned}}$$



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

M. A. Stephanov, PRL 102, 032301 (2009)

STAR detector in BES-II

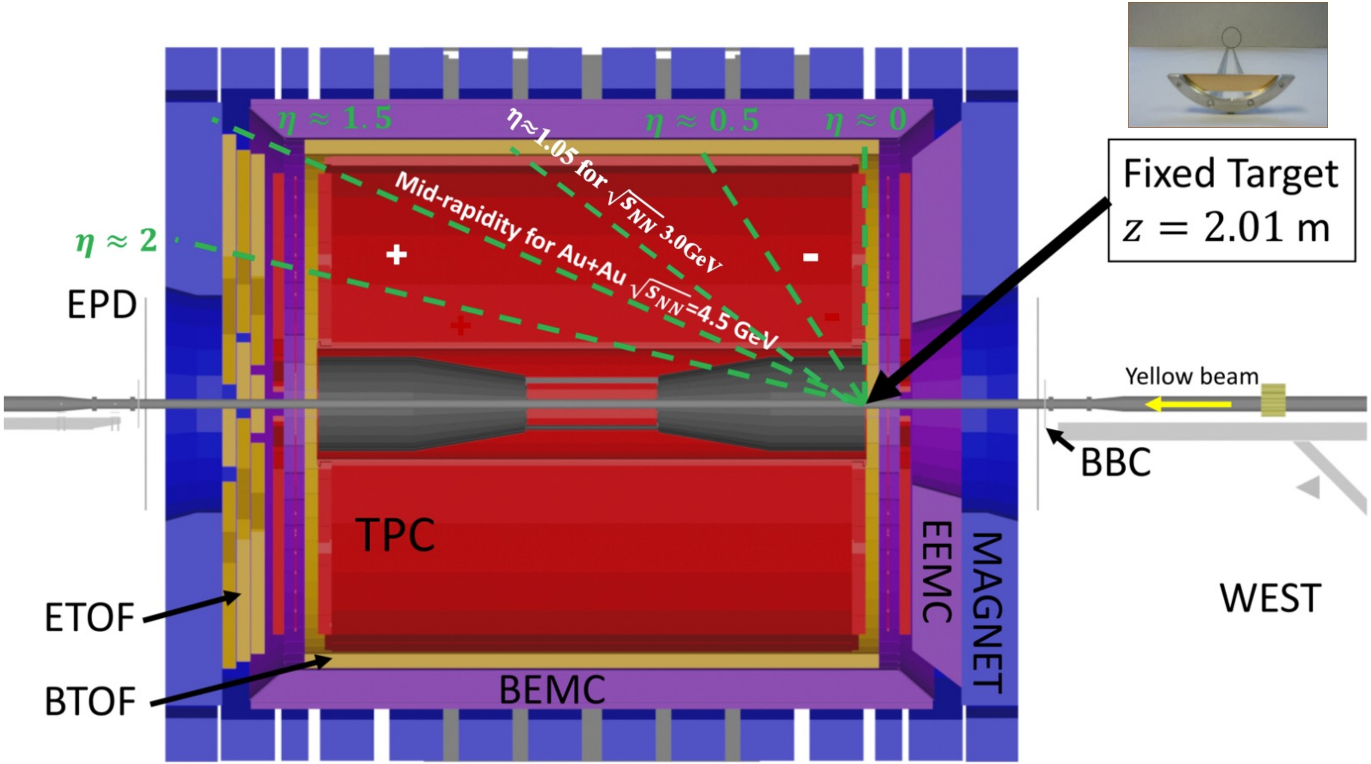


Improves dE/dx
Extends η coverage from 1.0 to 1.5
Lowers p_T cut-in from 125 to 60 MeV/c

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

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

STAR Fixed-target (FXT) mode



Fixed Target
$z = 2.01$ m

Extend μ_B coverage to 750 MeV by FXT

High statistics data from BES-II (2019-2021)

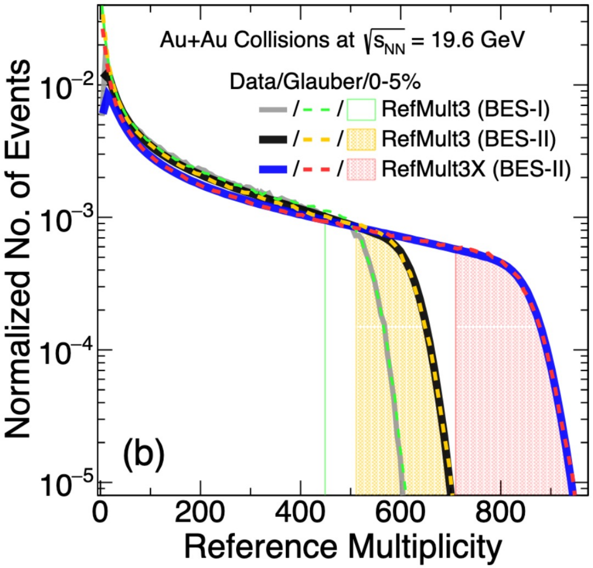
Au+Au Collisions at RHIC							
Collider Runs				Fixed-Target Runs			
	$\sqrt{s_{NN}}$ / GeV	events / million	μ_B / MeV		$\sqrt{s_{NN}}$ / GeV	event / million	μ_B / MeV
1	200	380	25	1	13.7 (100)	50	280
2	62.4	46	75	2	11.5 (70)	50	316
3	54.4	1200	85	3	9.2 (44.5)	50	372
4	39	86	112	4	7.7 (31.2)	260	420
5	27	585	156	5	7.2 (26.5)	470	440
6	19.6	595	206	6	6.2 (19.5)	120	490
7	17.3	256	230	7	5.2 (13.5)	100	540
8	14.6	340	262	8	4.5 (9.8)	110	590
9	11.5	257	316	9	3.9 (7.3)	120	633
10	9.2	160	372	10	3.5 (5.75)	120	670
11	7.7	104	420	11	3.2 (4.59)	200	699
				12	3.0 (3.85)	260+2000	750

BES-II events used in analysis

FXT events used in analysis

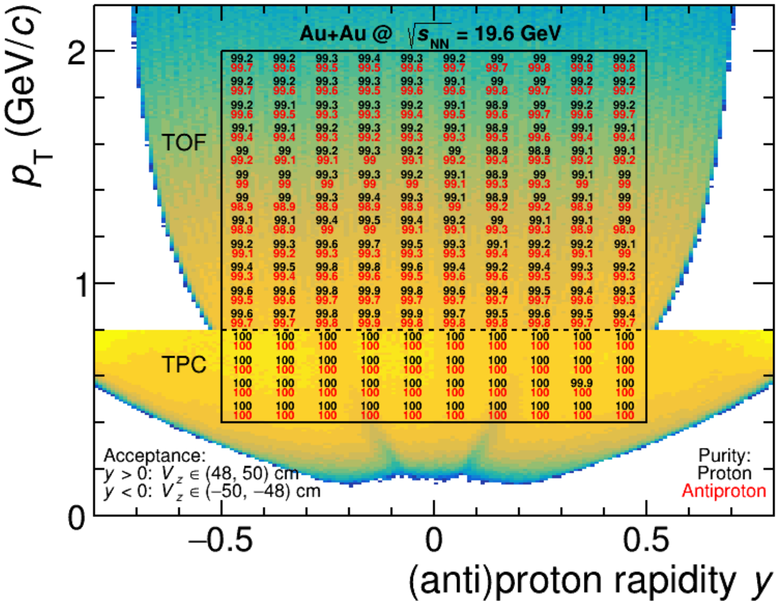
Analysis in BES-II collider energies

Collision Centrality



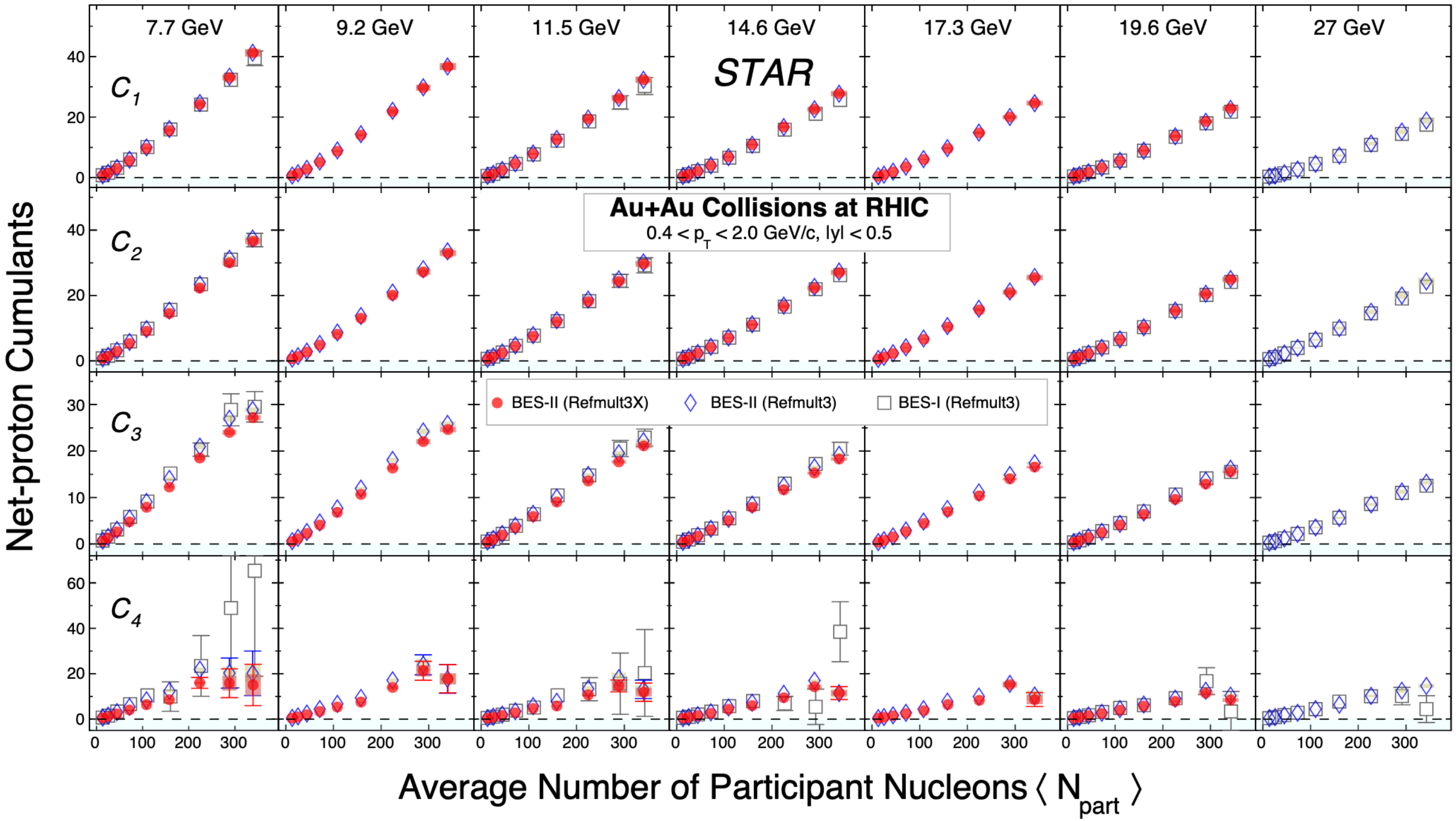
1. Charged particle multiplicity fit to MC Glauber to determine centrality
2. Better centrality resolution in BES-II analysis with extended detector coverage from $|\eta| \leq 1.0$ (BES-I) to $|\eta| \leq 1.6$ (BES-II)

Proton Selection

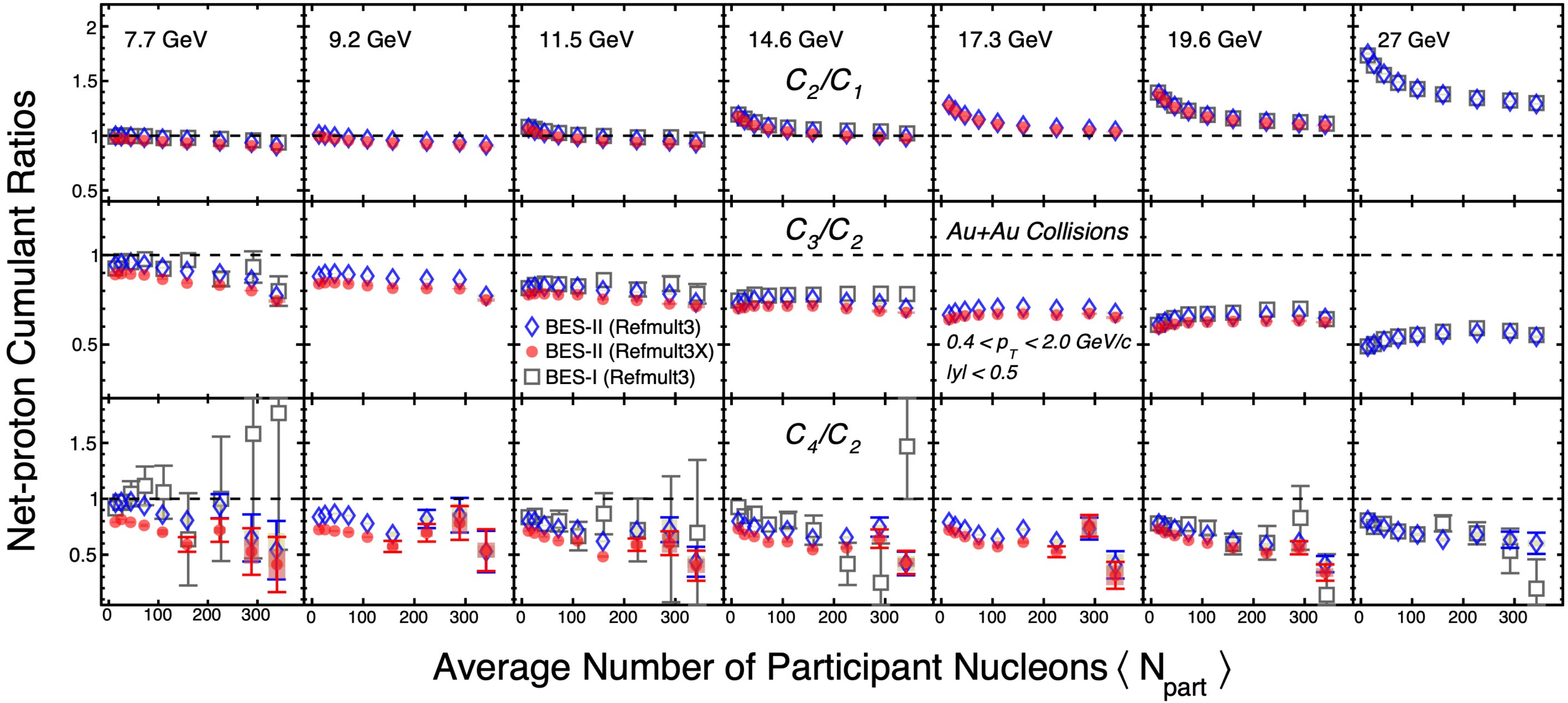


1. Uniform acceptance for (anti-) protons |y|<0.5
2. (anti-)protons identified using TPC dE/dx + TOF
3. Bin-by-bin purity > 99% in the full acceptance range and all energies

Net-proton cumulants from BES-II

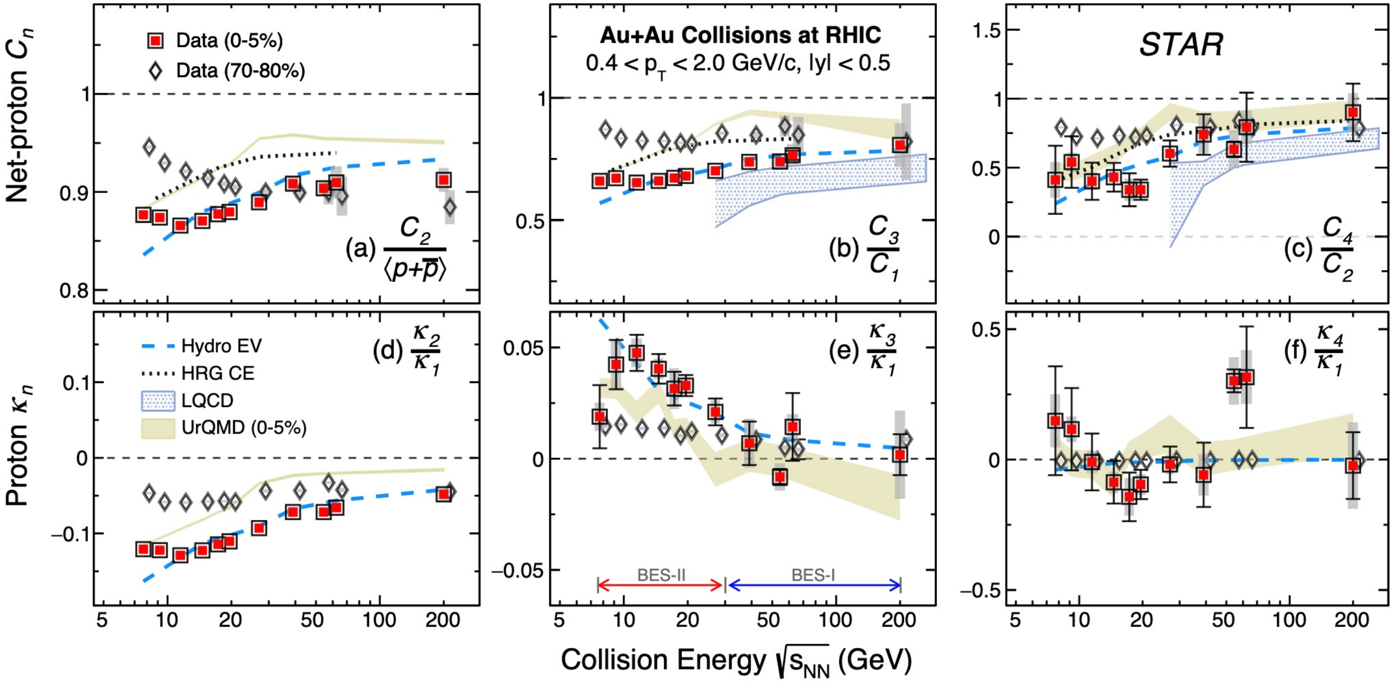


Net-proton cumulant ratios from BES-II



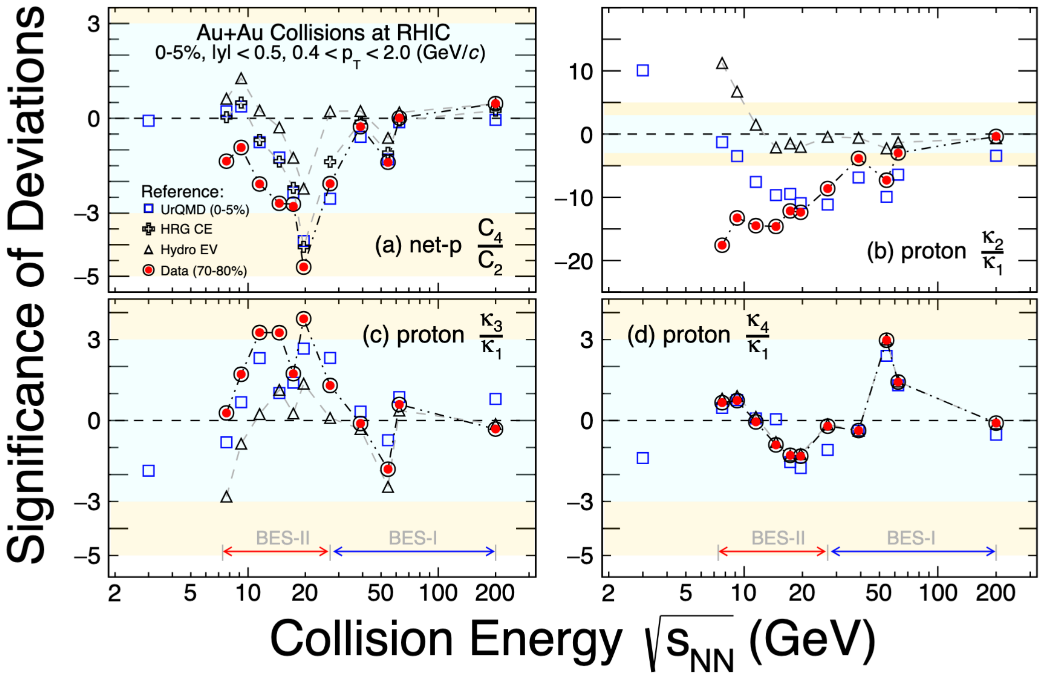
1. Significantly improved precision in BES-II measurements
2. C_4/C_2 in 0-5% centrality, results are consistent – weak centrality resolution effect

Energy dependence of cumulant ratios



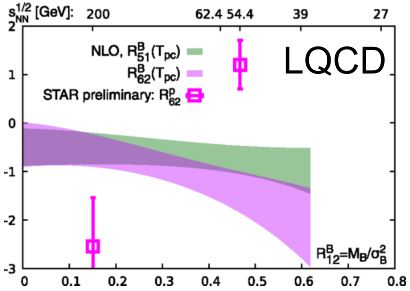
1. In 0-5% central Au+Au collisions, net-proton C_4/C_2 shows deviation from non-critical references at around 20 GeV
2. Net-proton $C_2/\langle p+\bar{p}\rangle$, C_3/C_1 and proton κ_2/κ_1, κ_3/κ_1 also show deviations from non-critical models too, especially below 11.5 GeV

Deviations from non-critical baselines

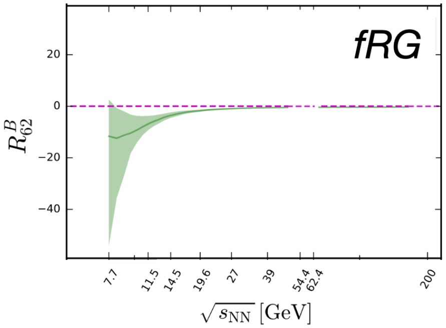


1. C_4/C_2 shows a minimum at ~20 GeV comparing to non-critical models or 70-80% data
    - Maximum deviation: 2 – 5σ at 20 GeV (1.3 – 2σ at BES-I)
2. Are the deviations due to critical fluctuations?

Hyper-order cumulants C_5, C_6



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

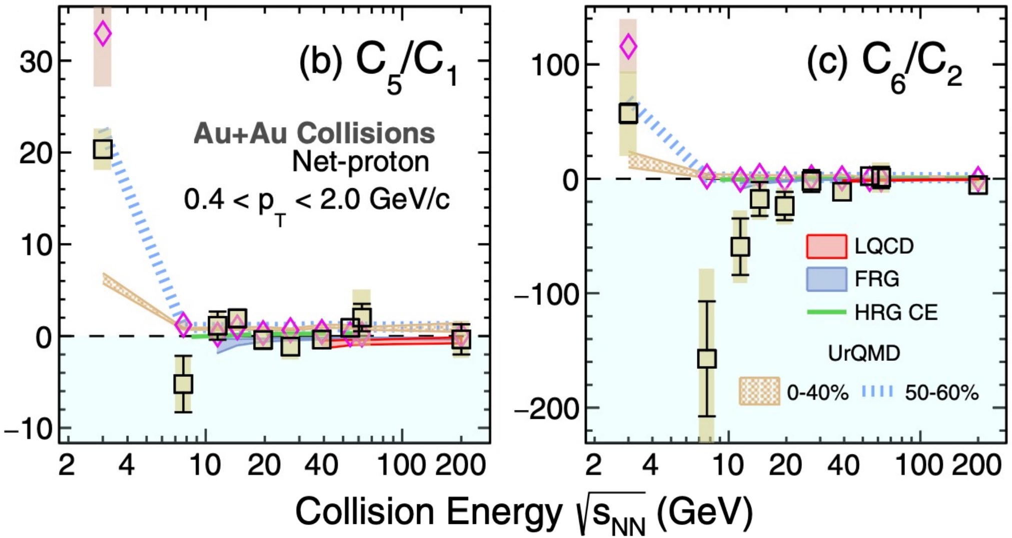


W. Fu, et al: PRD 104 094047 (2021)

- Negative sign in hyper-order cumulants for crossover transitions predicted by Lattice QCD and FRG

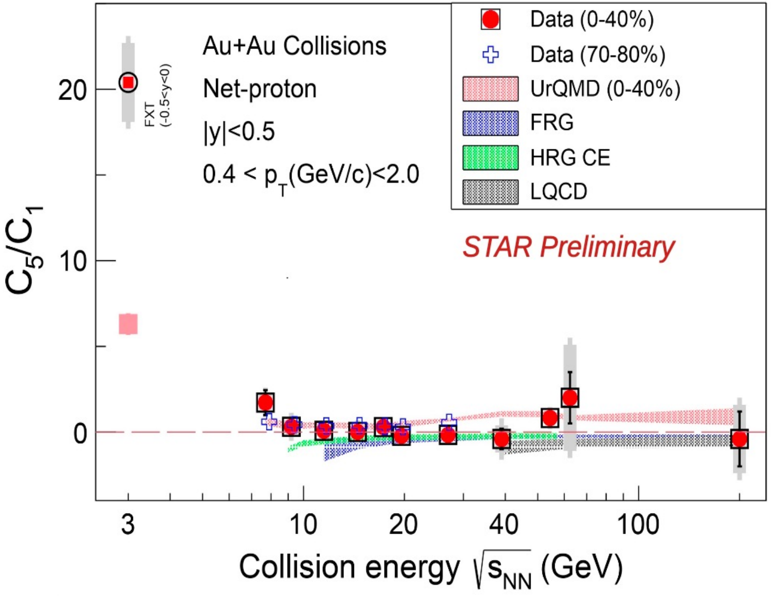
BES-I Measurement

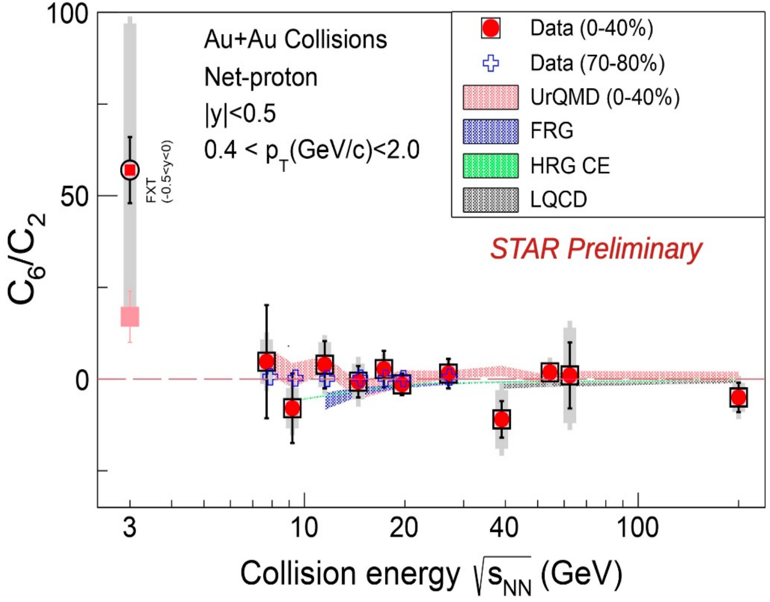
STAR, PRL 130,082301(2023)



1. Hyper-order cumulant are data-hungry
2. C_6/C_2 in 0-40% on BES-I data show progressively negative trend with decreasing energy but with large uncertainty

Hyper-order cumulants in BES-II



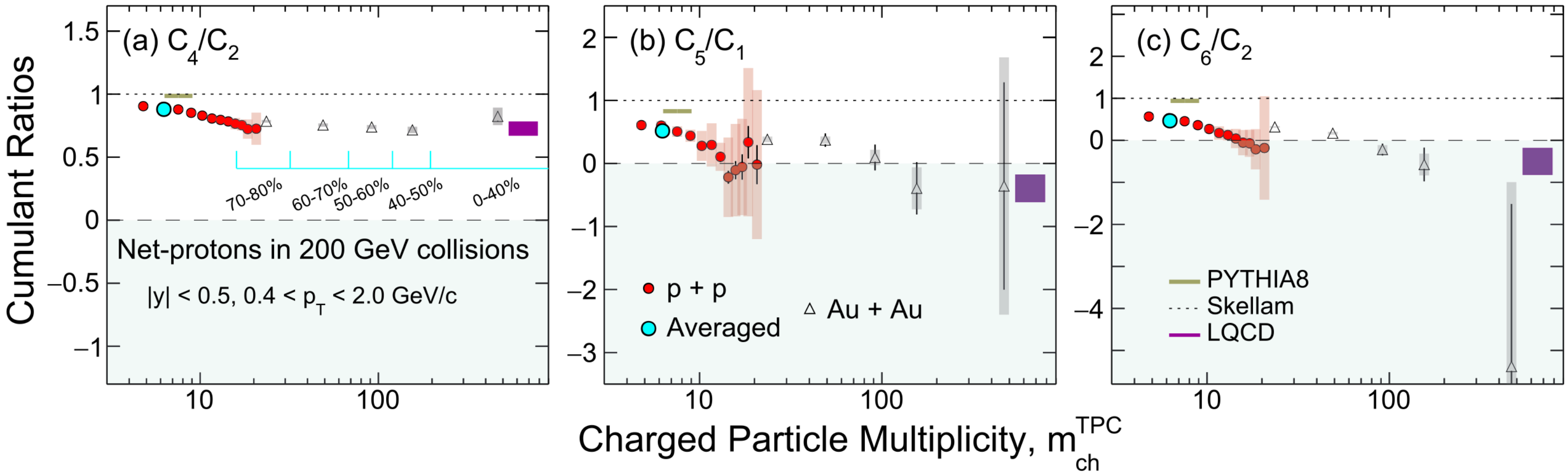


1. Hyper-order cumulants are measured on BES-II high-statistics data (7.7-27 GeV)
2. Cumulant ratios in collider energies fluctuate around zero within uncertainties

Hyper-order across collision system

Is it possible to see negative C_5, C_6 in smaller system, p+p, isobar ?

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

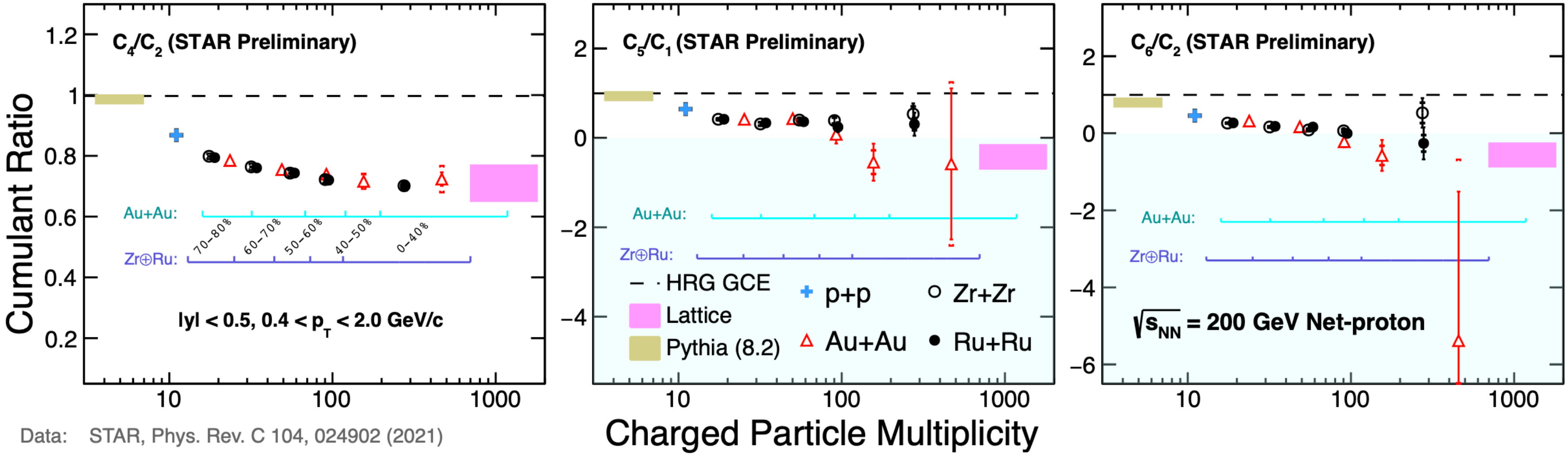


1. Negative C_5/C_1 and C_6/C_2 observed in central Au+Au collisions at 200 GeV
2. C_5/C_1 and C_6/C_2 in p+p gradually approach negative when it goes to higher multiplicity
3. The result could indicate QGP created at highest multiplicity in p+p

Hyper-order across collision system

Is it possible to see negative C_5, C_6 in smaller system, p+p, isobar ?

STAR Preliminary, Ho-San Ko, QM 2022

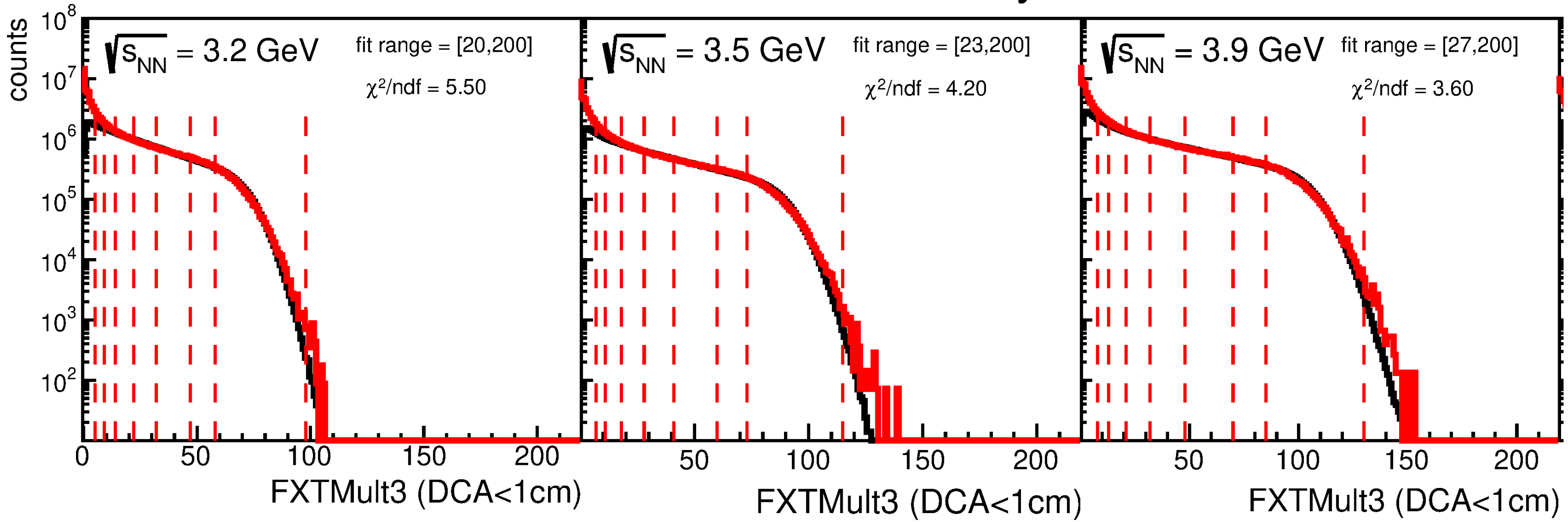


Data: STAR, Phys. Rev. C 104, 024902 (2021)
STAR, Phys. Rev. Lett. 127, 262301 (2021)

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

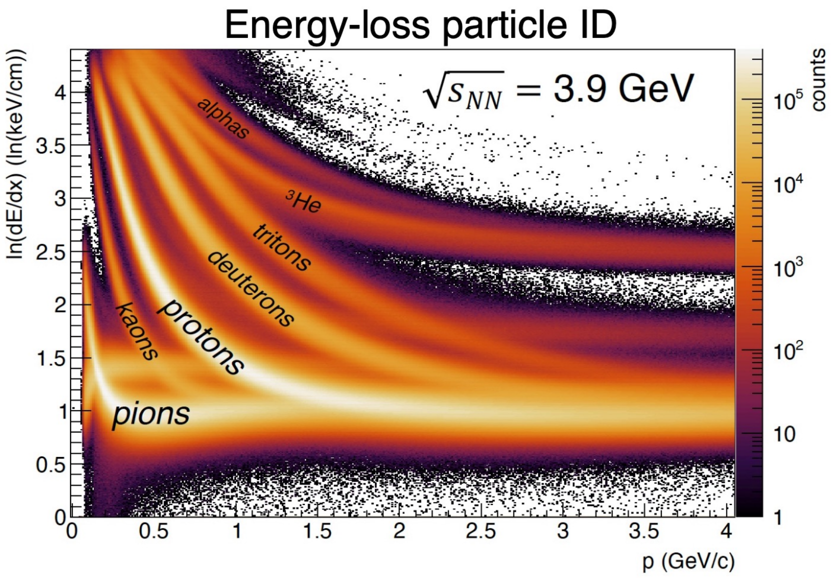
Analysis in FXT energies

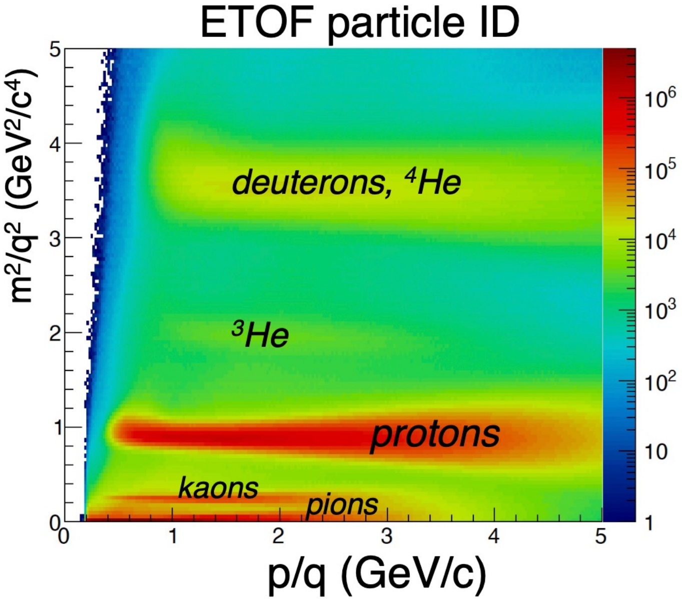
Collision Centrality

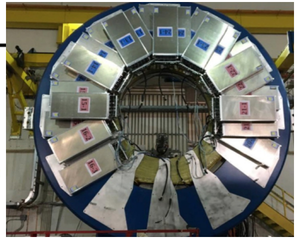


1. FXTMult3: All charged hadrons except protons within STAR detector
2. Smaller FXTMult3 with decreasing energy → worse centrality resolution

Analysis in FXT energies



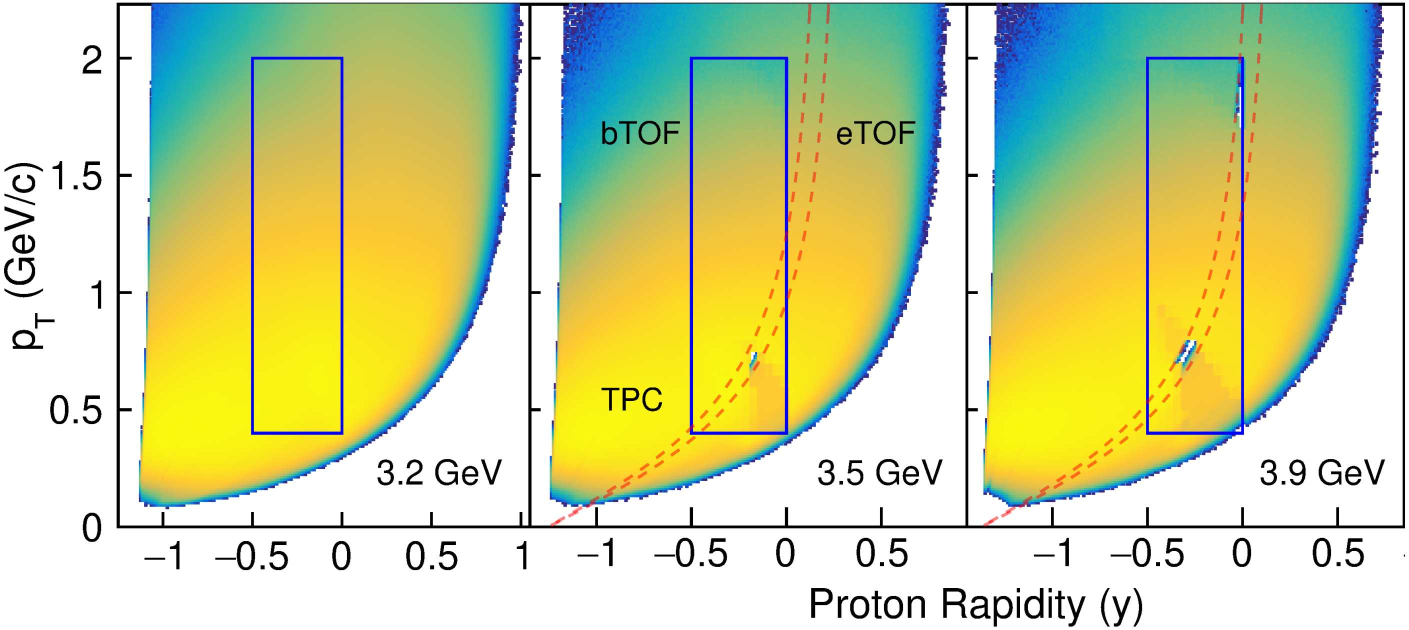




eTOF

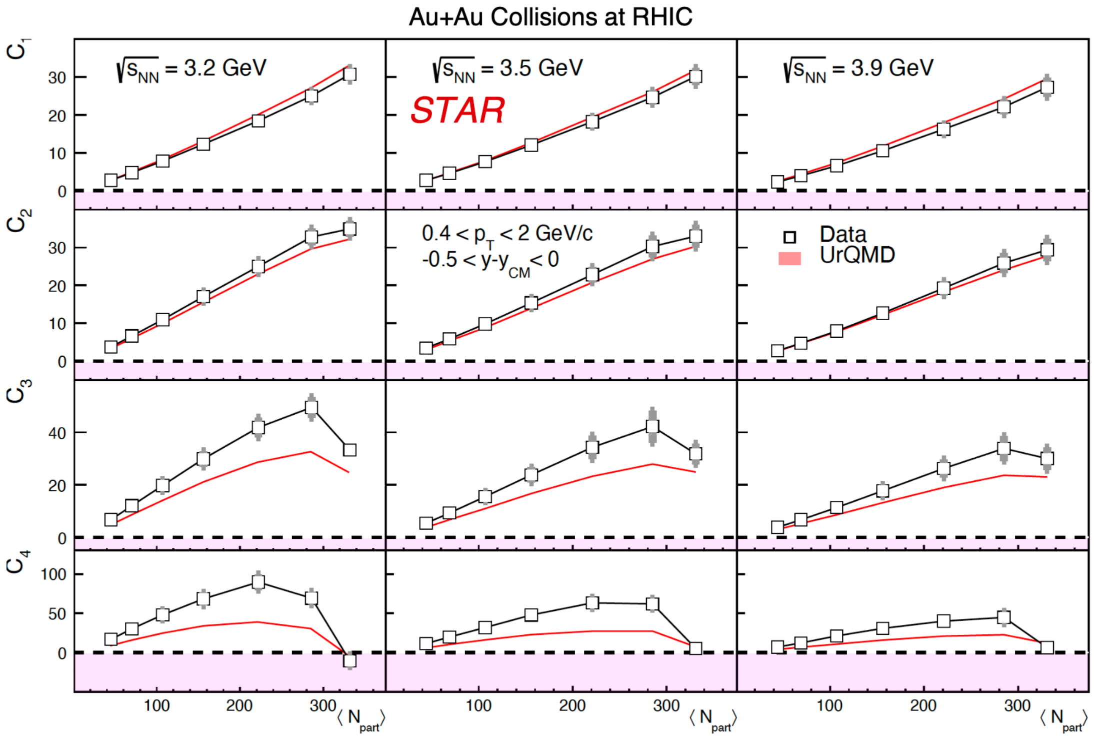
1. eTOF modules constructed for CBM-TOF detector
2. Crucial for hadron/light nuclei identification at FXT energies
3. Good detector performance (timing resolution, matching efficiency, stability)

Proton acceptance



1. Combining TPC, bTOF/eTOF for PID, centrality, pileup
2. Evolving proton acceptance in different collision energies
3. Acceptance gaps between detector boundaries

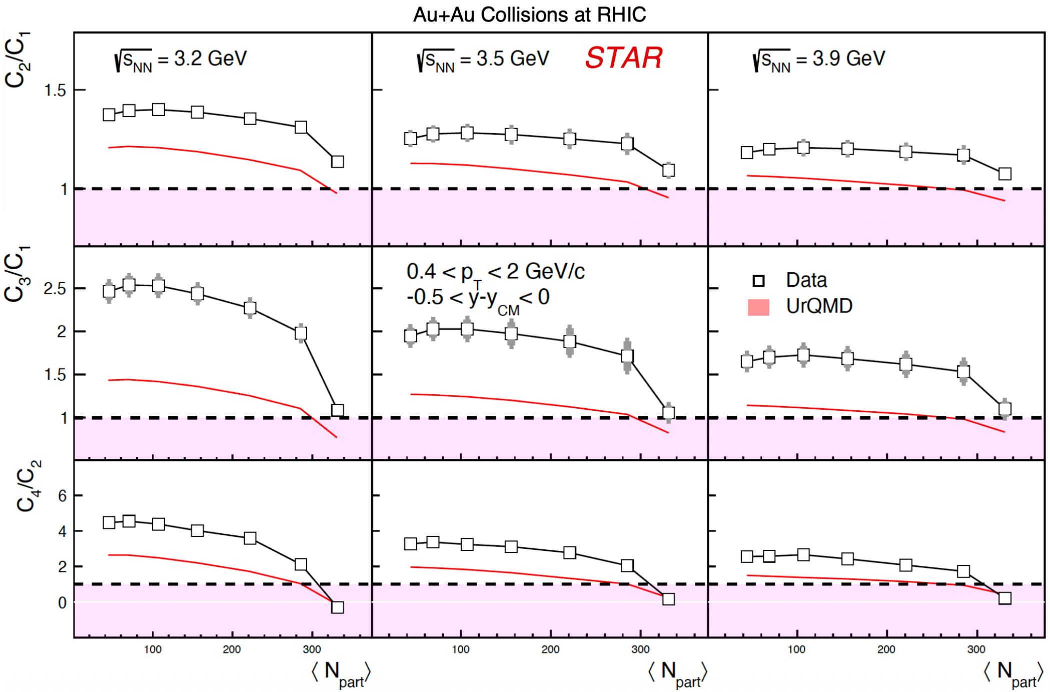
Proton Cumulants in FXT Energies



STAR Preliminary
Zachary Sweger, QM 2025

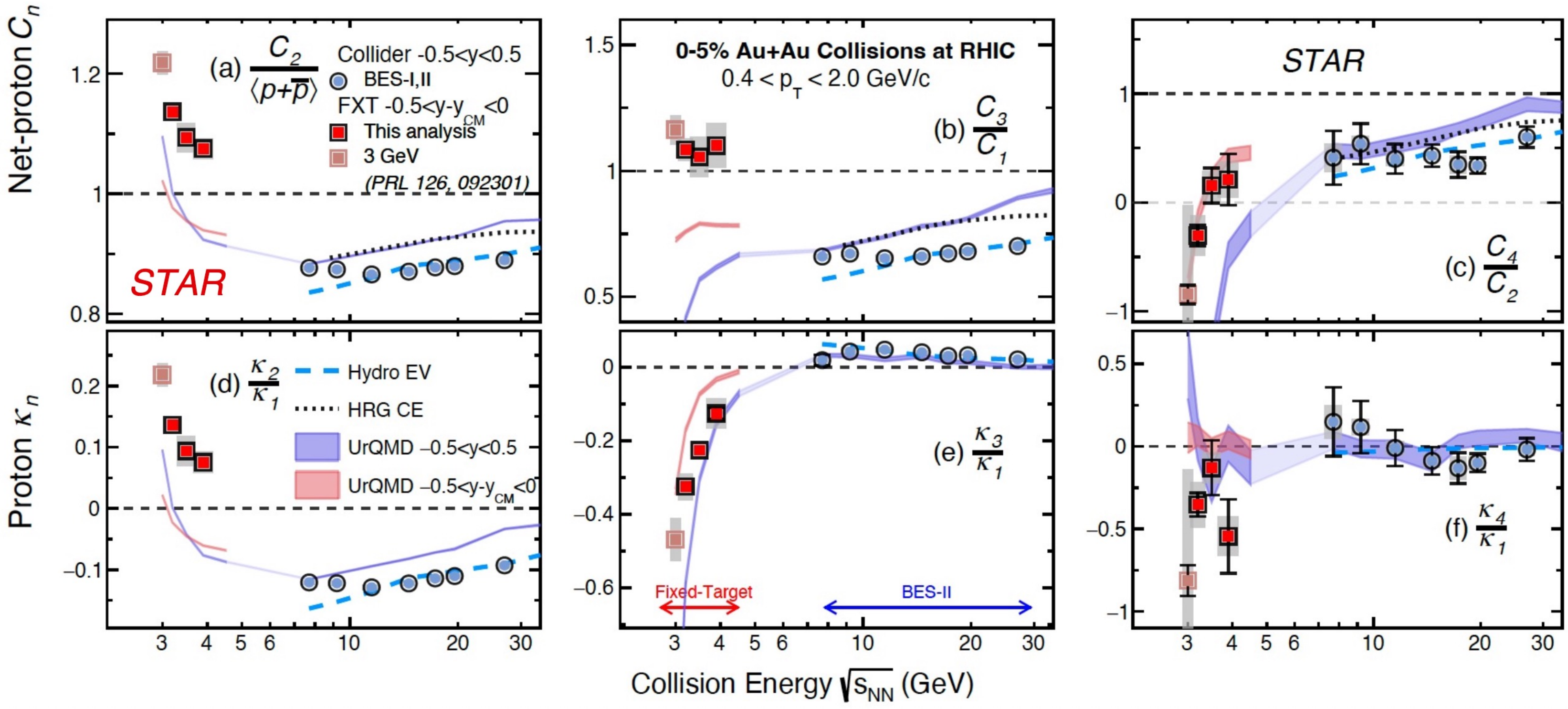
1. We performed calculations using events from UrQMD simulations using a same manner with data
2. Data are qualitatively described by UrQMD
3. While not a fully fair comparison between data and UrQMD due to different centrality resolution

Proton Cumulants in FXT Energies



1. The observed increase in ratios in peripheral collisions with decreasing collision energy suggests a growing influence of volume fluctuations at lower energies
2. The 0-5% most central collisions are the least affected by volume fluctuations, while caution is required when interpretating data

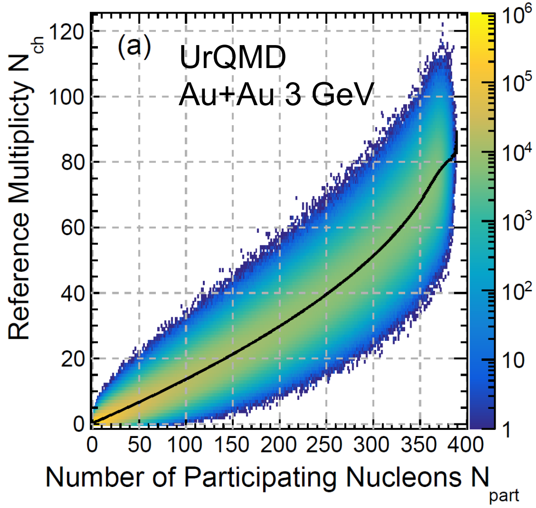
Combing with collider data



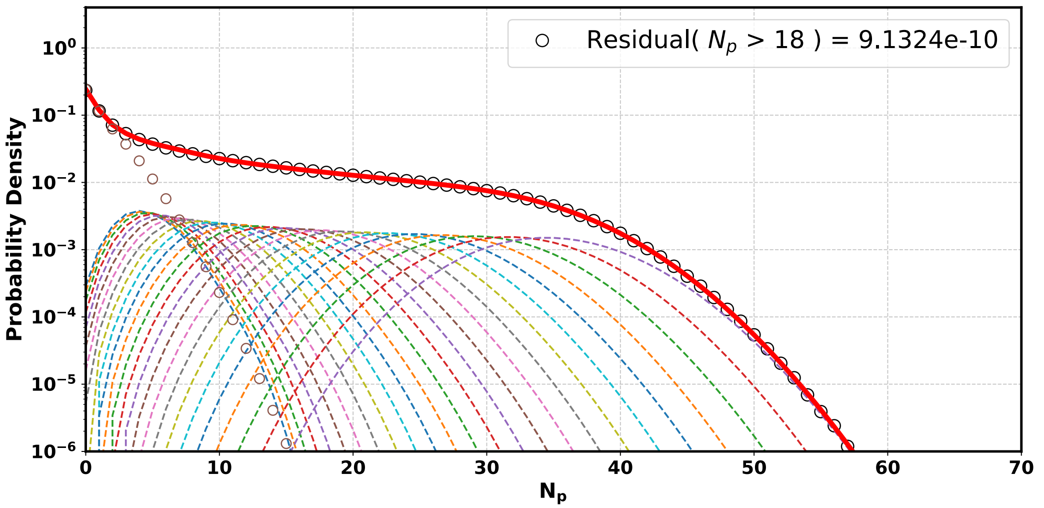
1. We are finishing the analysis at 3.2 – 4.5 GeV
2. Data will be compared with various models.

Centrality independent analysis in FXT

Zhaohui Wang, Xiaofeng Luo
arXiv:2505.03666, PLB accepted

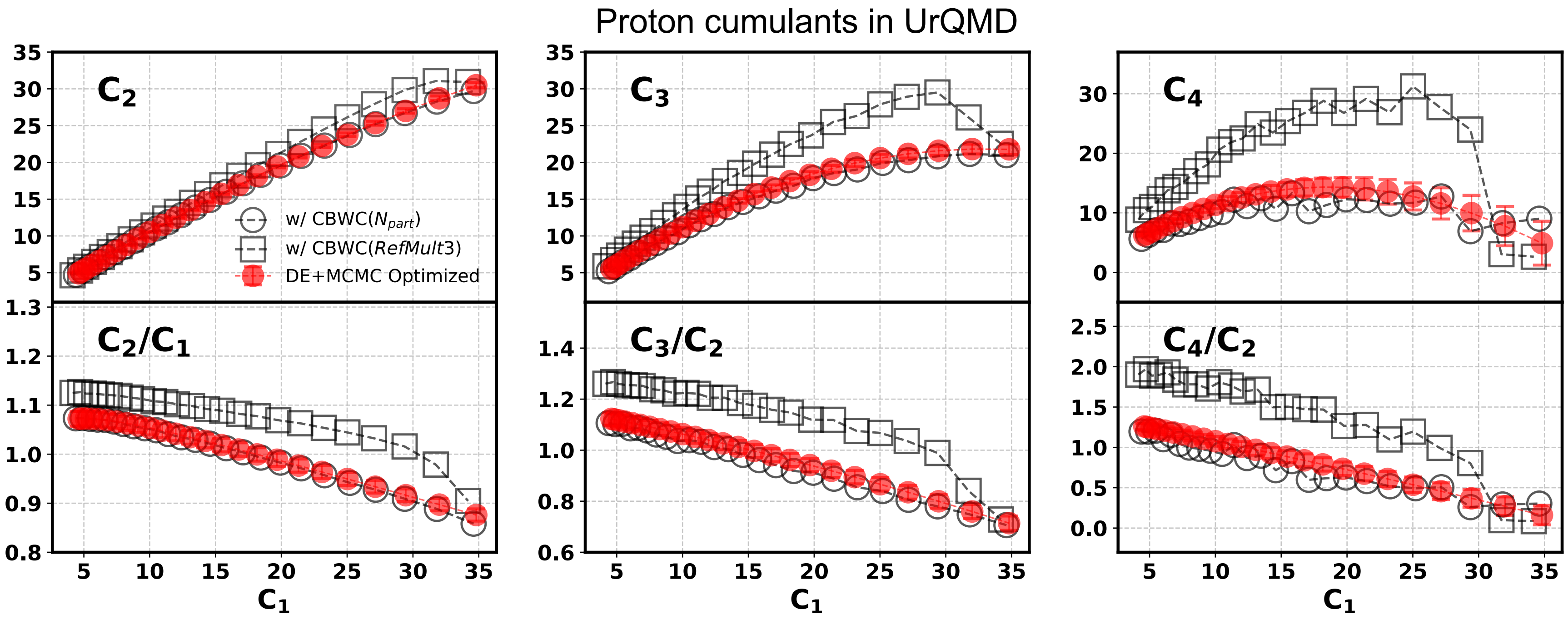


Proton distribution



1. Whenever a centrality reference is used in data analysis, volume fluctuation effect involved in measurements
2. Use Edgeworth expansion to reconstruct proton distribution in finer centrality bins

Centrality independent analysis in FXT



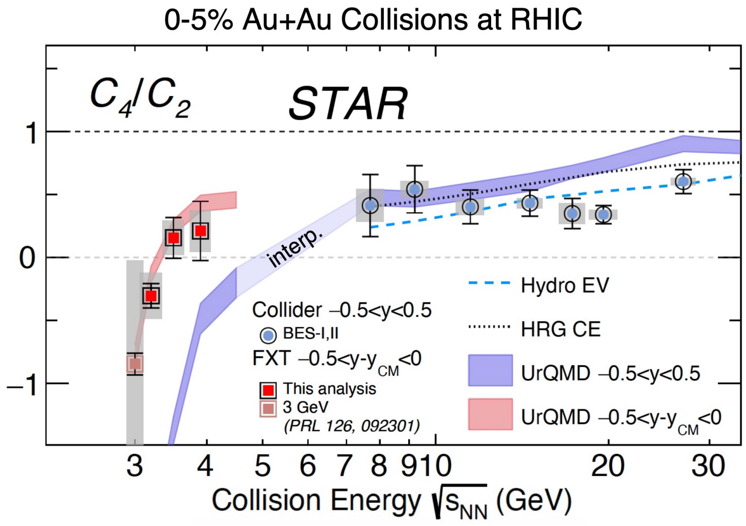
1. Model test shows good consistency with results binning on N_{part}
2. Being tested in FXT data to overcome volume fluctuation effect

Summary

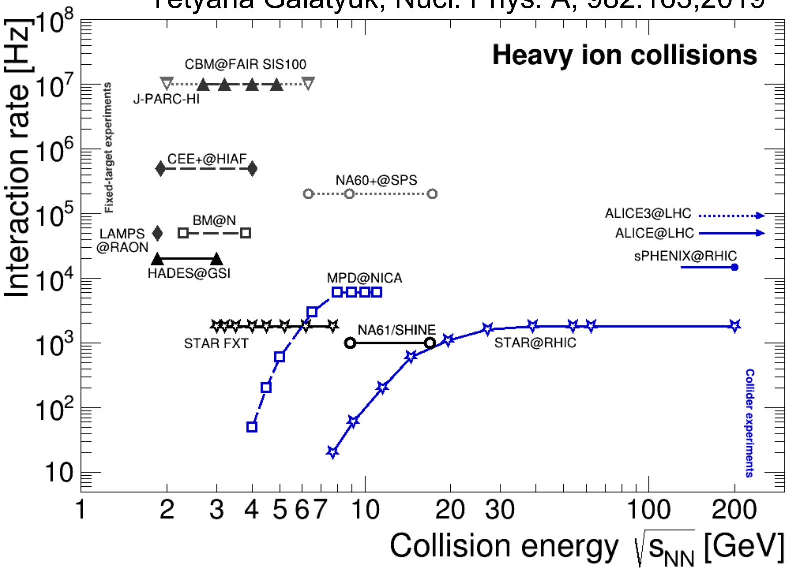
- Collider energies in BES-II:
  1. Significantly improved precision in measurements
  2. A maximum deviation of C_4/C_2 at 19.6 GeV from non-critical baselines

- FXT energies:
  1. We are finalizing the analysis at 3.2 to 4.5 GeV.
  2. Caution is required when interpretating data due to volume fluctuation

Outlook



Tetyana Galatyuk, Nucl. Phys. A, 982:163,2019



Looking forwarding to future experiment to explore the signature of QCD critical point at high baryon density!

Many thanks to:

Daniel Cebra, Xin Dong, ShinIchi Esumi, Yige Huang, Xiaofeng Luo, Bedanga Mohanty, Bappaditya Mondal, Toshihiro Nonaka, Ashish Pandav, Zachary Sweger, Fan Si, Zhaohui Wang, Nu Xu, Yongcong Xu, Yifei Zhang, Xin Zhang

STAR Collaboration and Theory Colleagues!

Thank you for your attention!