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Higher-Order Proton Cumulants in Au+Au Collisions at $\sqrt{s_{NN}}$ = 3 GeV from STAR Fixed-Target Experiment

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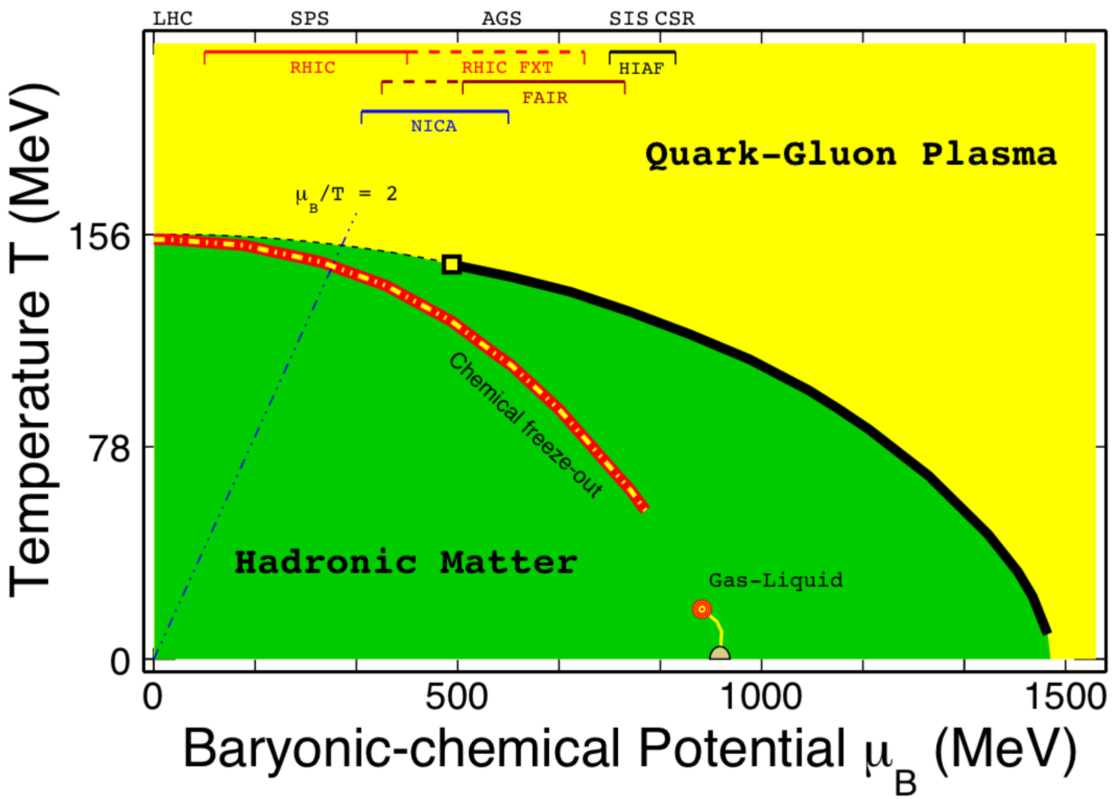
Outline

- Motivation
- Analysis Details
- Results
  - 3 GeV Proton Cumulant
  - Energy Dependence
- Summary and Outlook

QCD Phase Diagram

Figure, courtesy of Nu Xu



- Smooth crossover at μ_{B} = 0 MeV

  Y. Aoki et al, Nature 443, 675(2006)

- 1st-order phase transition is predicted at large μ_{B} by various models
- Possible QCD critical point and 1st-order phase boundary ?
- Vary T, μ_{B} by varying collision energy to scan phase diagram

Higher-order Cumulants

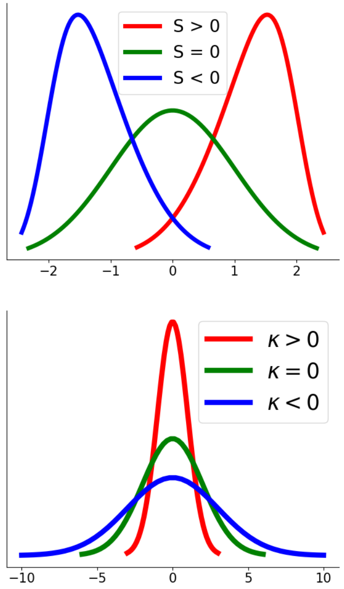
Higher-order cumulants of conserved charges (B, Q, S) are promising observables to search for the QCD critical point and 1st-order phase transition boundary.

- Cumulant definition

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

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

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



- Sensitive quantities to system correlation length ξ

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

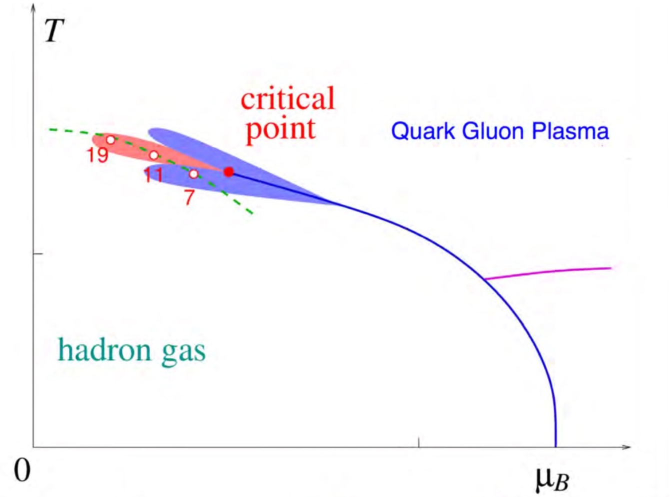
M. A. Stephanov, PRL 102, 032301 (2009)
M. Asakawa, S. Ejiri and M. Kitazawa, PRL 103, 262301 (2009)
M. A. Stephanov, PRL 107, 052301 (2011)

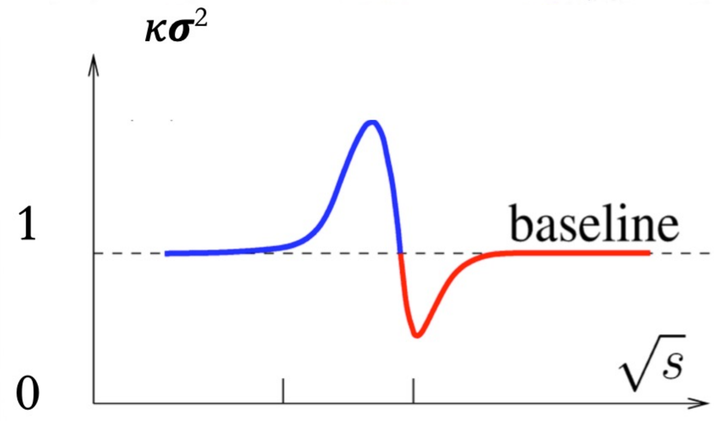
- Directly connected to susceptibility χ of different charges (B, Q, S)

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

S. Ejiri et al, PLB 633, 275 (2006)
M. Cheng et al, PRD 074505 (2009)
B. Friman et al, EPJC 71, 1694 (2011)
F. Karsch and K. Redlich, PLB 695, 136 (2011)
S. Gupta et al, Science 332, 1525(2012)
A. Bazavov et al, PRL 109, 192302(2012)
S. Borsányi et al, PRL 111, 062005(2013)

Signature of QCD Critical Point

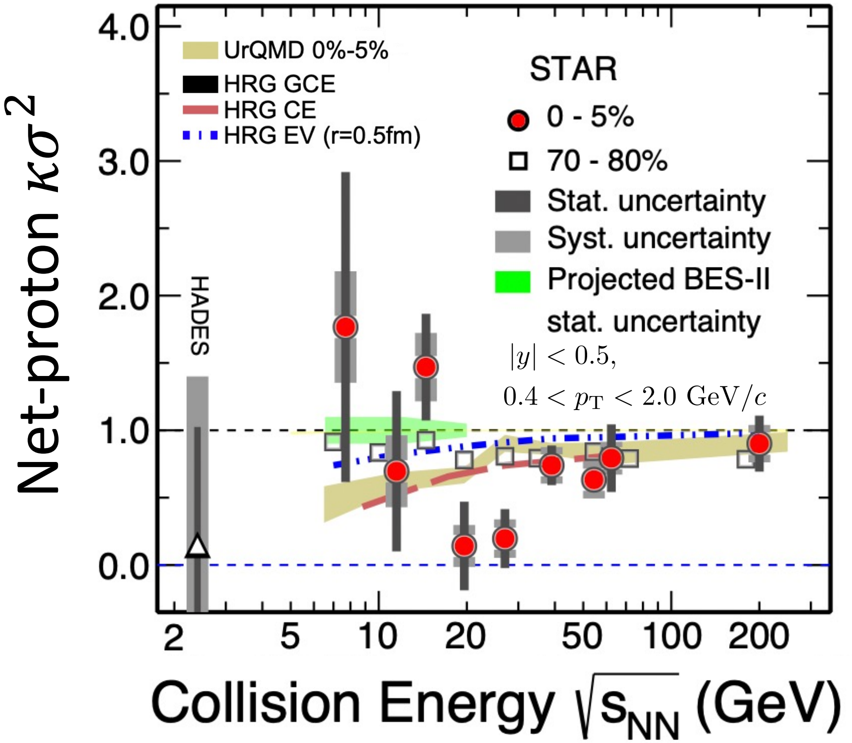




$\kappa\sigma^2 = 1$ (Poisson Fluctuations)

M. A. Stephanov, PRL 107,052301(2011).
Schaefer, Wanger, PRD 85, 034027 (2012)
JW Chen et al., PRD93, 034037 (2016); PRD 95, 014038 (2017).

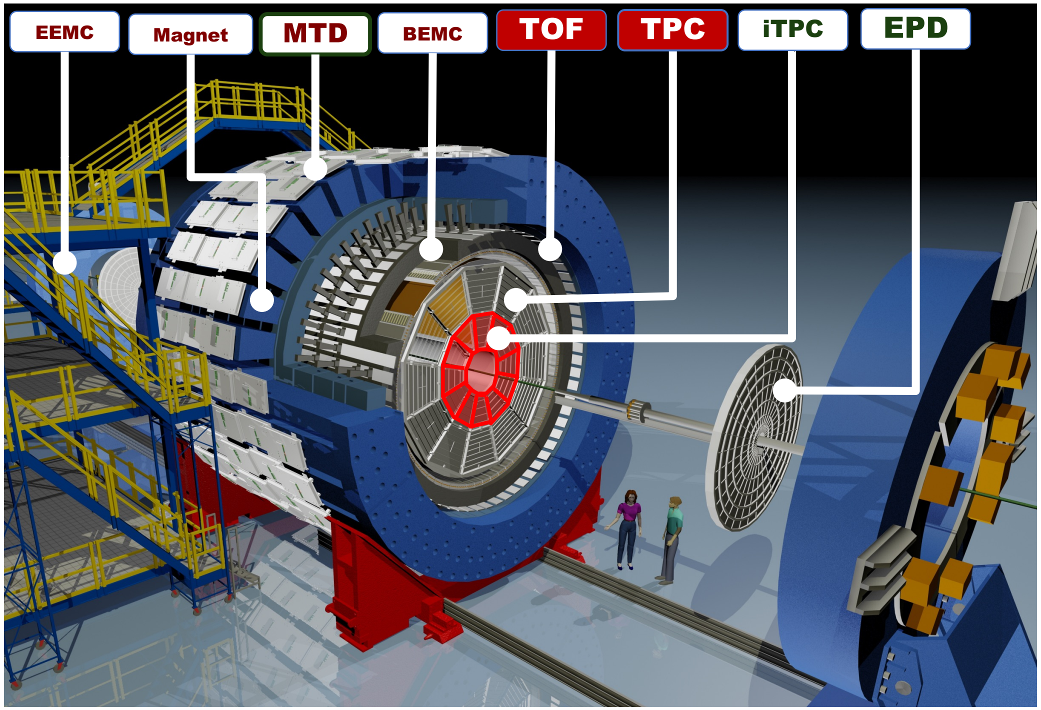
(STAR) PRL 126, 092301 (2021); PRC 104, 024902 (2021)



- Non-monotonic energy dependence of net-proton $\kappa\sigma^2$ with 3.1σ significance is shown in top 5% central collisions from BES-I data which is consistent with theoretical expectation with a critical point.

STAR Fixed Target Experiment Setup

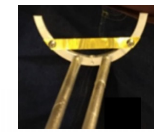
STAR Detector System

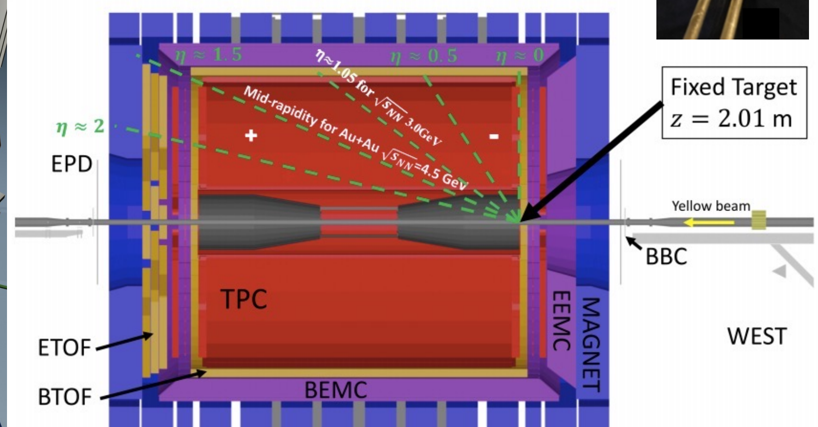


- Large, uniform acceptance at mid-rapidity (2π azimuthal, |η|<1)
- Excellent particle identification

Fixed Target Setup (Run 18)

250 μm gold foil

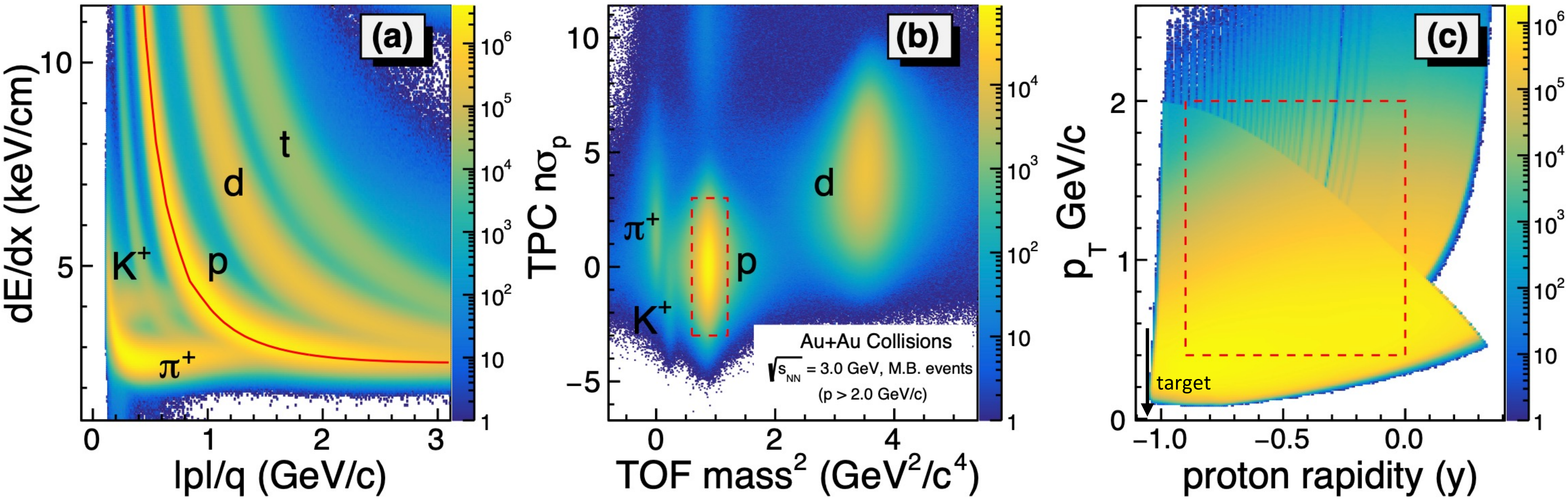




- STAR fixed target experiment extends the coverage of baryon chemical potential μ_{B} to 750 MeV !

Particle Identification

TPC PID **TOF PID** **Proton Phase Space**



p_{lab} < 2 GeV/c: TPC

p_{lab} > 2 GeV/c: TPC + TOF

- High-purity protons are selected with the combination of TPC and TOF PID
- The analysis covers rapidity window -0.9 < y < 0

Correction Methods

Detector Efficiency Correction

A. Bzdak and V. Koch, PRC 86, 044904 (2012)
A. Bzdak and V. Koch, PRC 91, 027901 (2015)
X. Luo, PRC 91, 034907 (2015)
T. Nonaka et al, PRC 95, 064912 (2017)
X. Luo, T. Nonaka , PRC 99, 044917 (2019)

↓

Pileup Correction

T. Nonaka et al, NIM A 984, 164632 (2020)
Y. Zhang et al, NIM A 1026, 166246 (2022)

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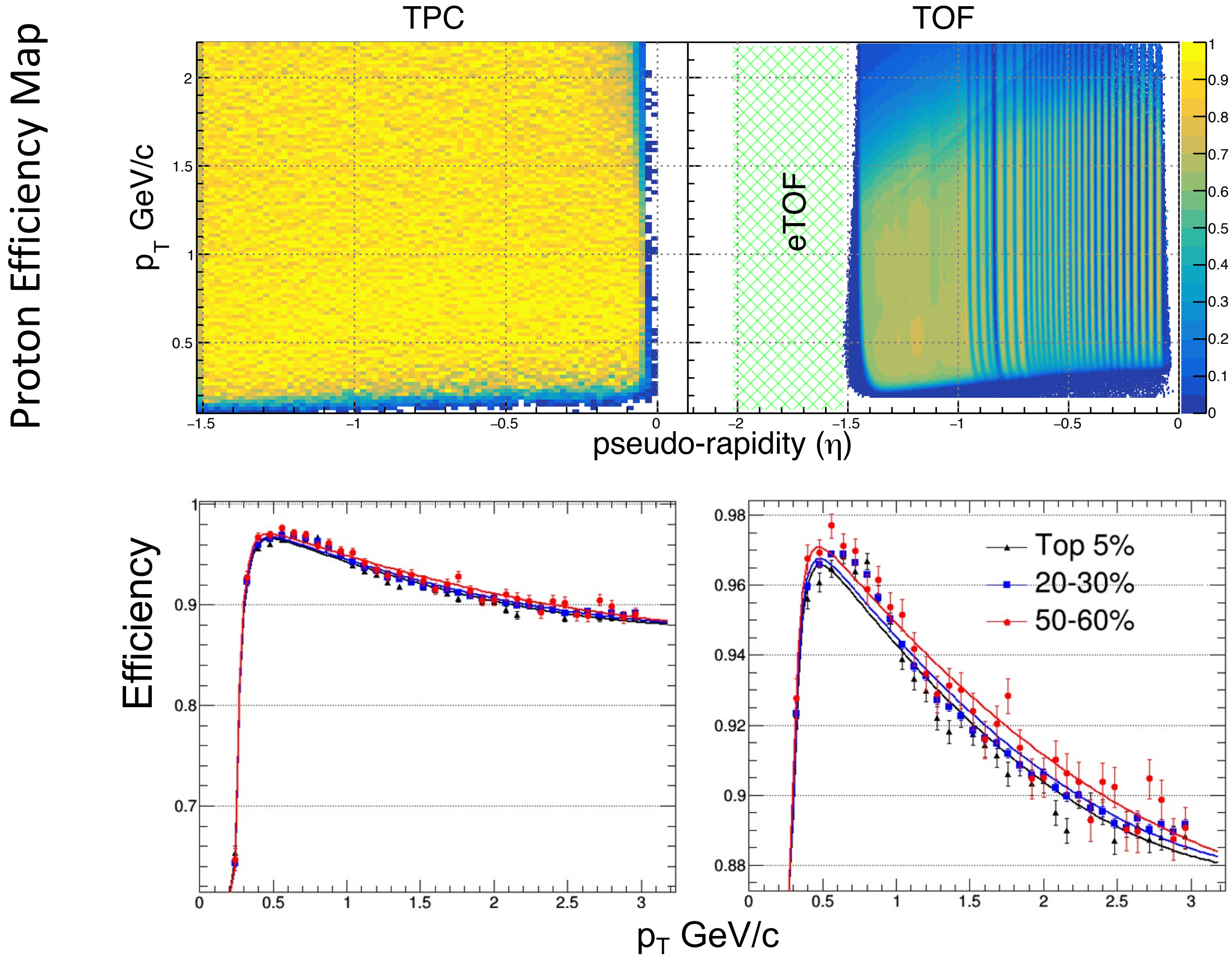
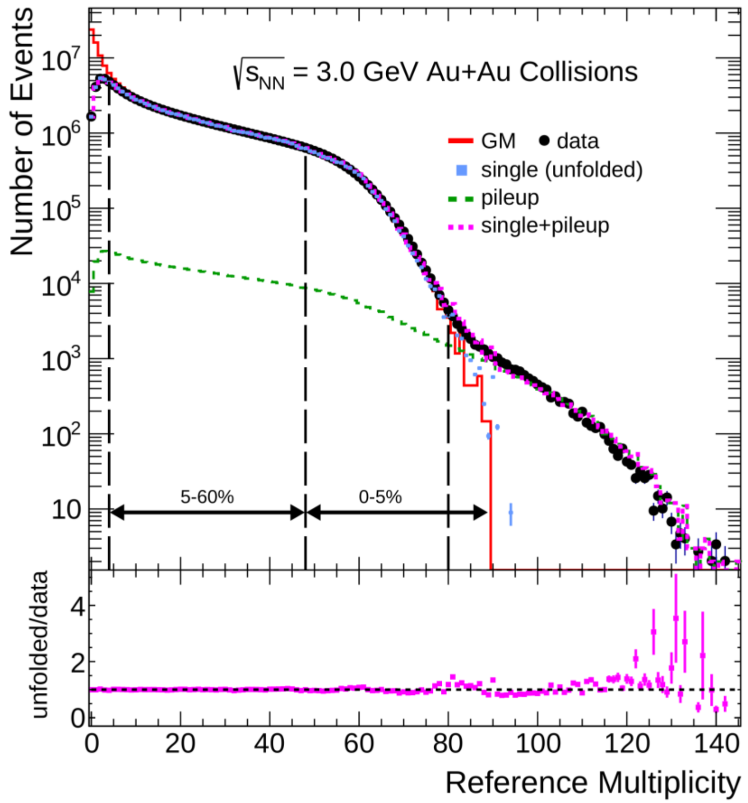
Centrality Bin Width Correction

X.Luo et al, J. Phys. G: Nucl. Part. Phys. 40 (2013)
X. Luo, PRC 91, 034907 (2015)



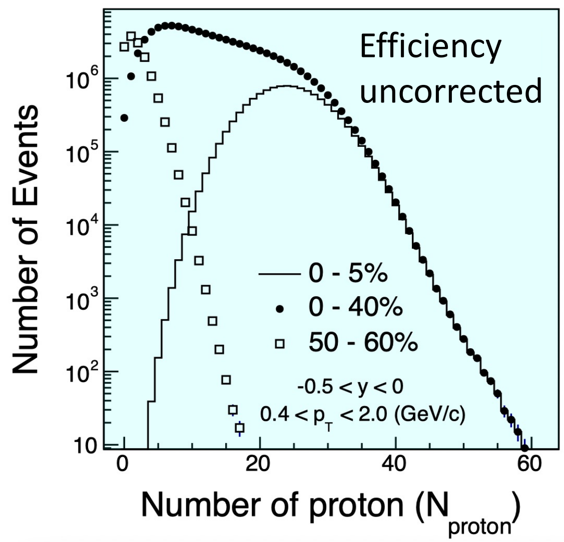
- The efficiency response is assumed to be binomial
- p_T and rapidity dependence are considered in track-by-track efficiency correction

Centrality & Pileup



Centrality	RefMult cut	$\langle N_{part} \rangle$	estimated pileup fraction (%)
0-5%	48 - 80	326	2.32
5-10%	38	282	1.47
10-20%	25	219	1.28
20-30%	16	157	1.07
30-40%	10	107	0.90
40-50%	6	70	0.75
50-60%	4	47	0.64

- Charged particle multiplicity excluding protons within $0 < \eta < 2$ is used as reference multiplicity.
- Reference multiplicity distribution is compared to Monte Carlo Glauber model to determine centrality.



Pileup Correction

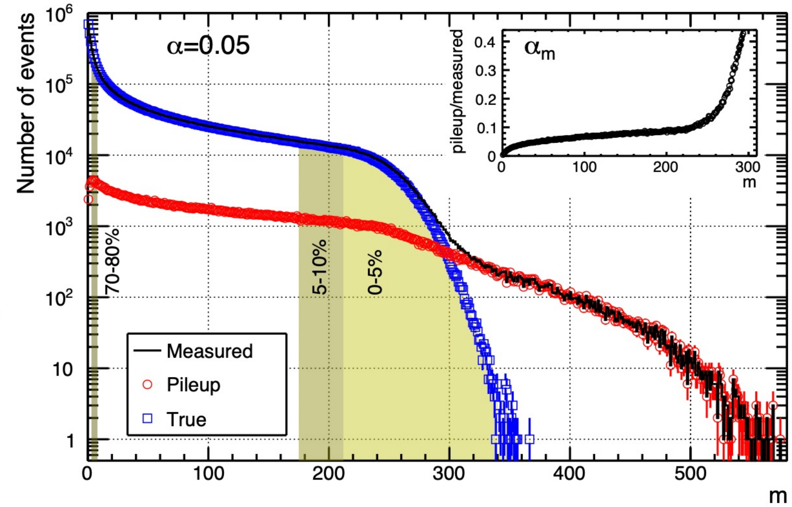
- Assume multiple-collision events are independent combination of single-collision one
- Statistically suppress contributions from pileup events

$$P_m(N) = (1-\alpha_m)P_m^{\mathrm{single}}(N) + \alpha P_m^{\mathrm{pileup}}(N)$$

$P(N)$: probability distribution

α : pileup fraction

m : reference multiplicity

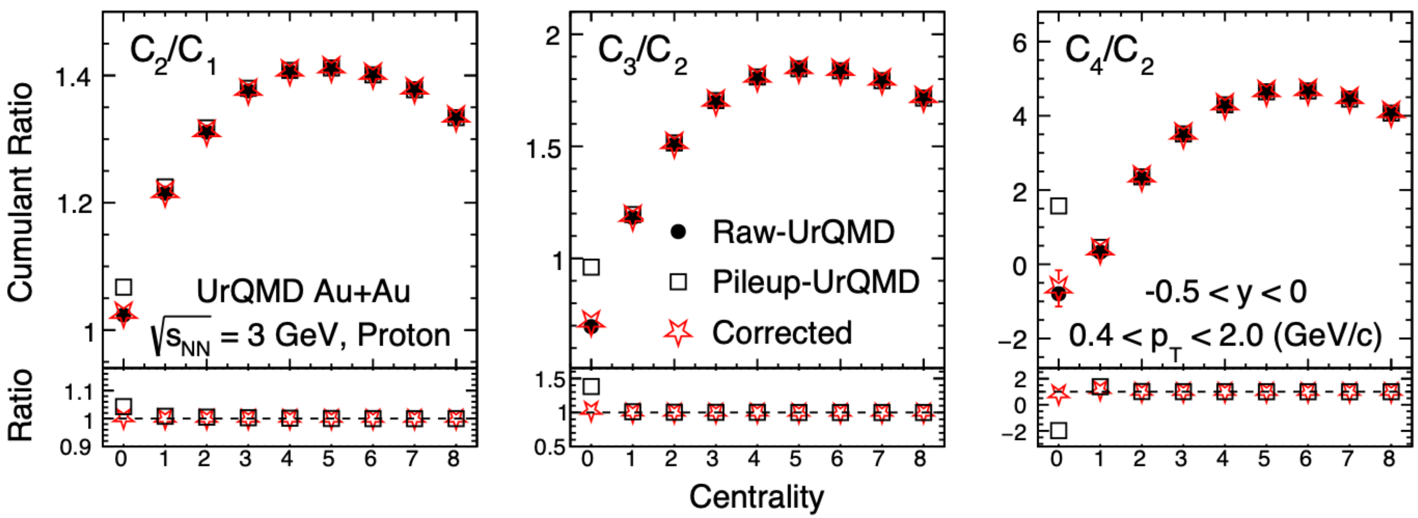


corrected moments: $\langle N^r\rangle_m^{\mathrm{t}} = \dfrac{\langle N^r\rangle_m - \alpha_m C_m^{(r)}}{1-\alpha_m+2\alpha_m w_{m,0}}$,

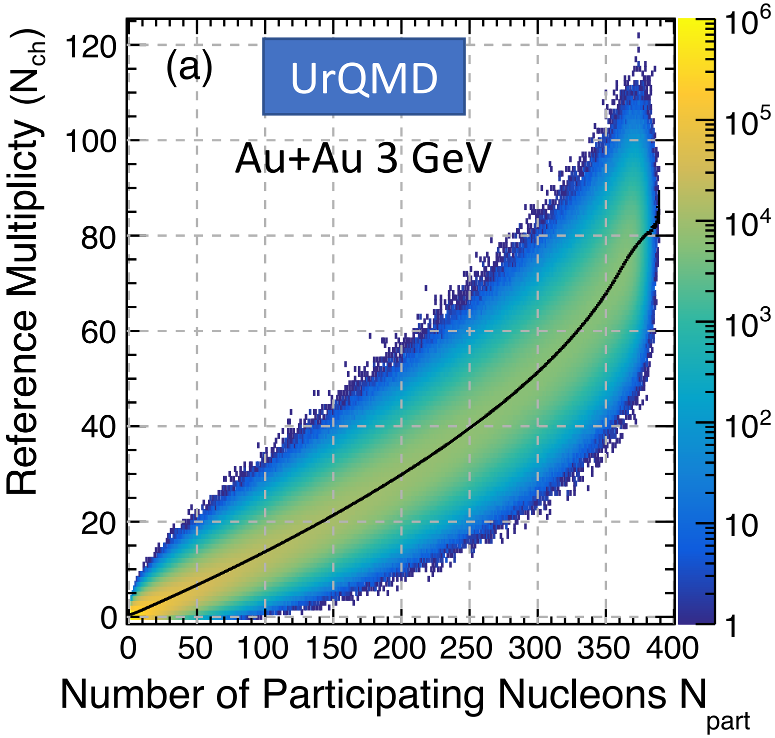
where

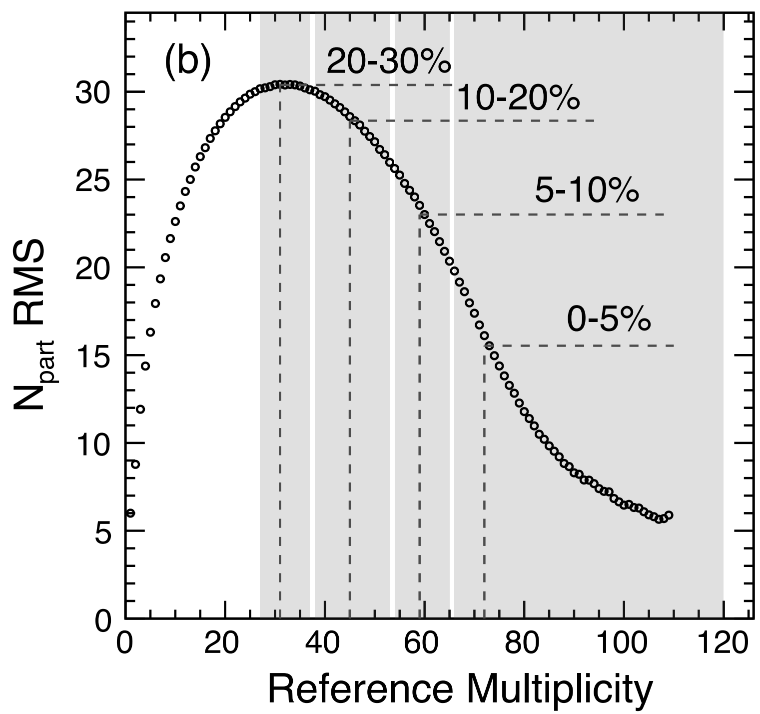
$$C_m^{(r)} = \mu_m^{(r)} + \sum_{i,j>0} \delta_{m,i+j} w_{i,j} \langle N^r\rangle_{i,j}^{\mathrm{sub}}, \quad \mu_m^{(r)} = \begin{cases} 2w_{m,0}\sum_{k=0}^{r-1}\binom{r}{k}\langle N^{r-k}\rangle_0^{\mathrm{t}}\langle N^k\rangle_m^{\mathrm{t}} & (m>0), \\ \sum_{k=1}^{r-1}\binom{r}{k}\langle N^{r-k}\rangle_0^{\mathrm{t}}\langle N^k\rangle_0^{\mathrm{t}} & (m=0). \end{cases}$$

T. Nonaka et al, NIM A 984, 164632 (2020)
Y. Zhang et al, NIM A 1026, 166246 (2022)



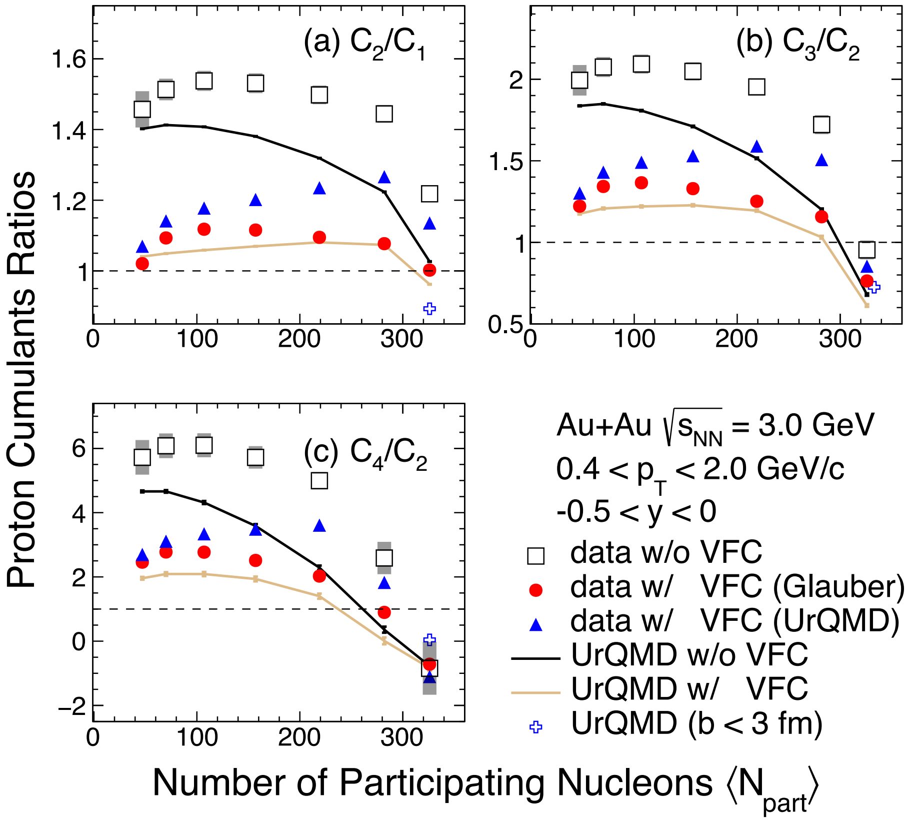
Volume Fluctuation



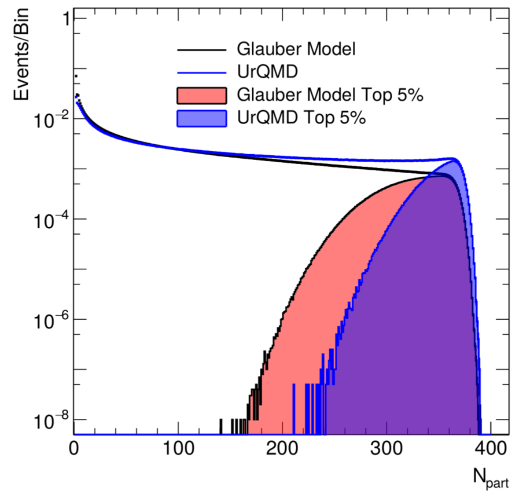


- Due to weak correlation between N_{ch} and N_{part} at low energies, there is large volume fluctuation effect
- Most central and peripheral centrality bins are less affected by volume fluctuation

Volume Fluctuation Correction



STAR, arXiv:2112.00240

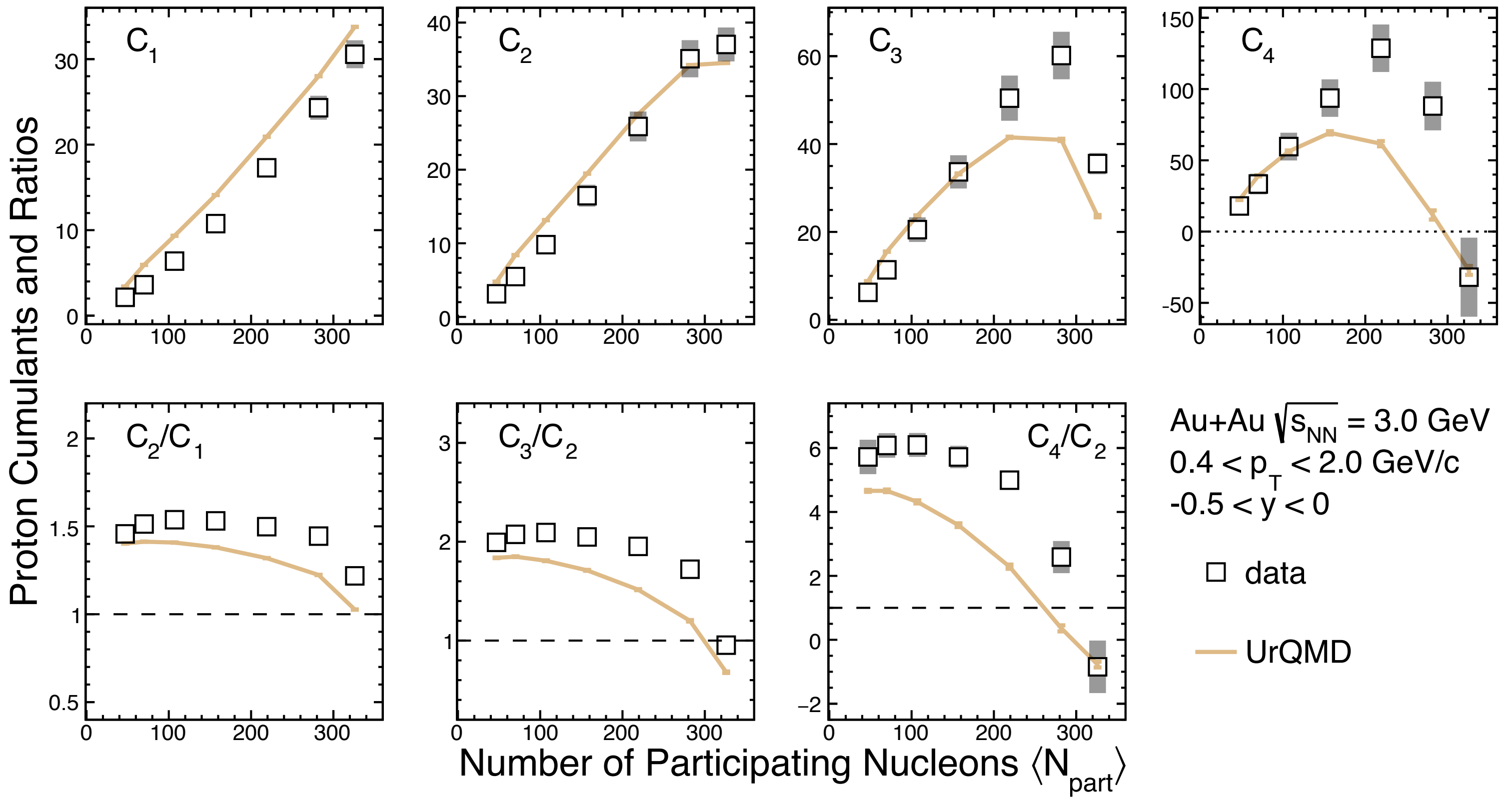


$$
\begin{aligned}
C_1(\Delta N) &= \langle N_W \rangle C_1(\Delta n), \\
C_2(\Delta N) &= \langle N_W \rangle C_2(\Delta n) + \langle \Delta n \rangle^2 C_2(N_W), \\
C_3(\Delta N) &= \langle N_W \rangle C_3(\Delta n) + 3\langle \Delta n \rangle C_2(\Delta n) C_2(N_W) \\
&\quad + \langle \Delta n \rangle^3 C_3(N_W), \\
C_4(\Delta N) &= \langle N_W \rangle C_4(\Delta n) + 4\langle \Delta n \rangle C_3(\Delta n) C_2(N_W) \\
&\quad + 3C_2^2(\Delta n) C_2(N_W) + 6\langle \Delta n \rangle^2 C_2(\Delta n) C_3(N_W) \\
&\quad + \langle \Delta n \rangle^4 C_4(N_W), \quad N_W \equiv N_{part}.
\end{aligned}
$$

V. Skokov et al, PRC 88, 034911 (2013)
P. Braun-Munzinger et al, NPA 960, 114 (2017)

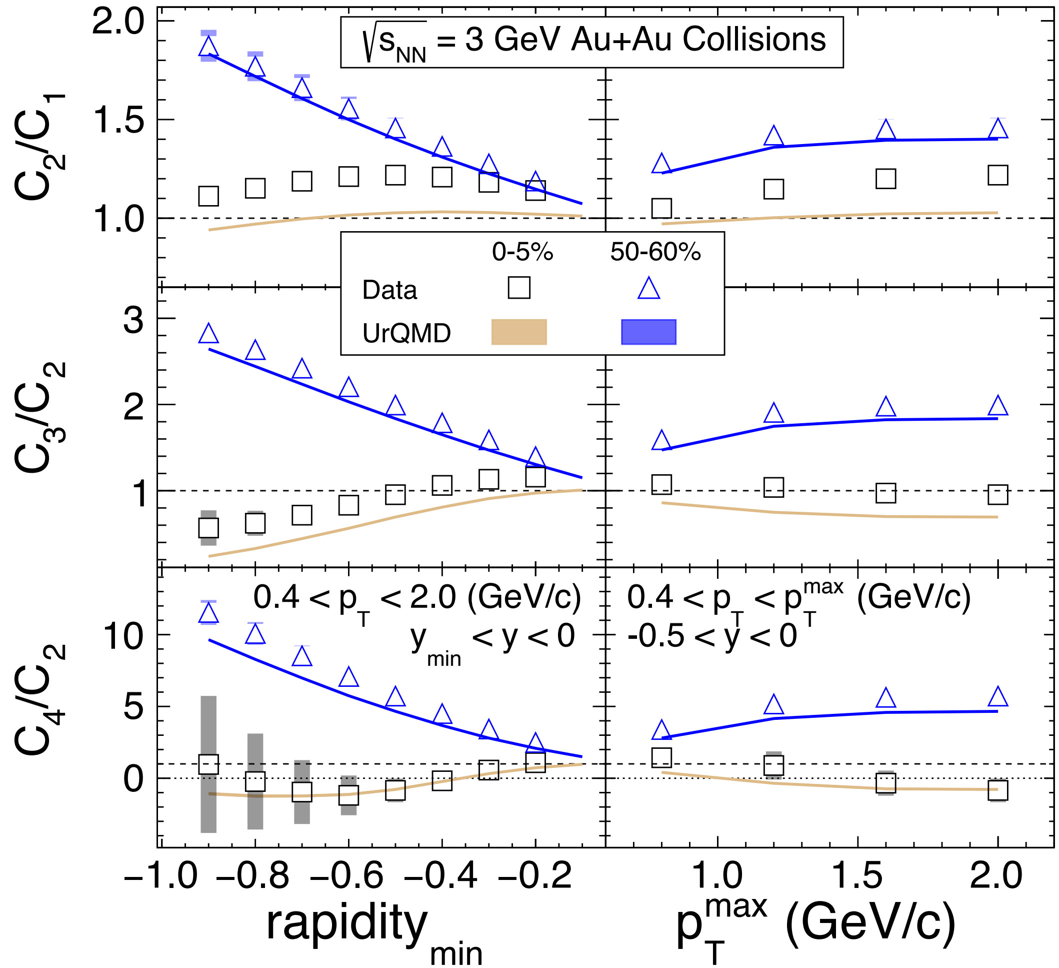
- A volume fluctuation correction method is tested on data
- Most central centrality is least affected by volume fluctuation correction
- The correction strongly depends on N_{part} fluctuation from models, thus it is not used in the STAR data analysis

Centrality Dependence



- Results are corrected for detector efficiency and pileup effect
- Centrality bin width correction applied to extract centrality binned cumulants
- Data is qualitatively reproduced by calculation from hadronic transport model UrQMD

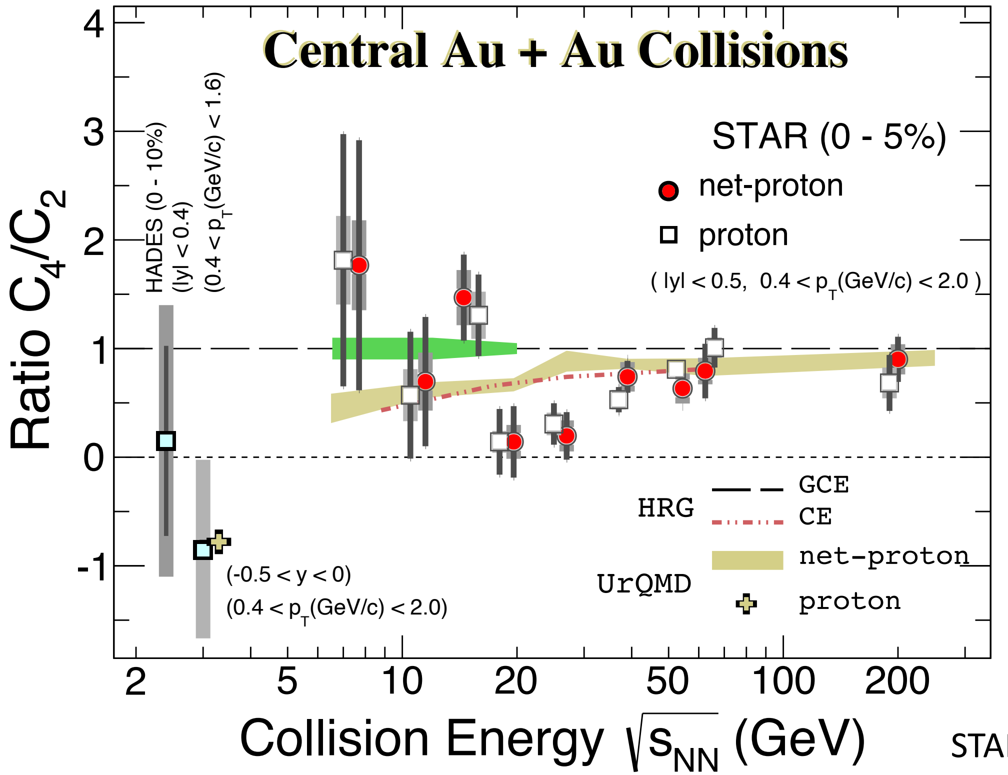
Acceptance Dependence



STAR, arXiv:2112.00240

- The C_4/C_2 ratio is close to unity in small acceptance and seems to be saturated in large acceptance for 5% central collisions within uncertainty
- Acceptance dependence of cumulant ratios are also qualitatively reproduced by UrQMD calculation!

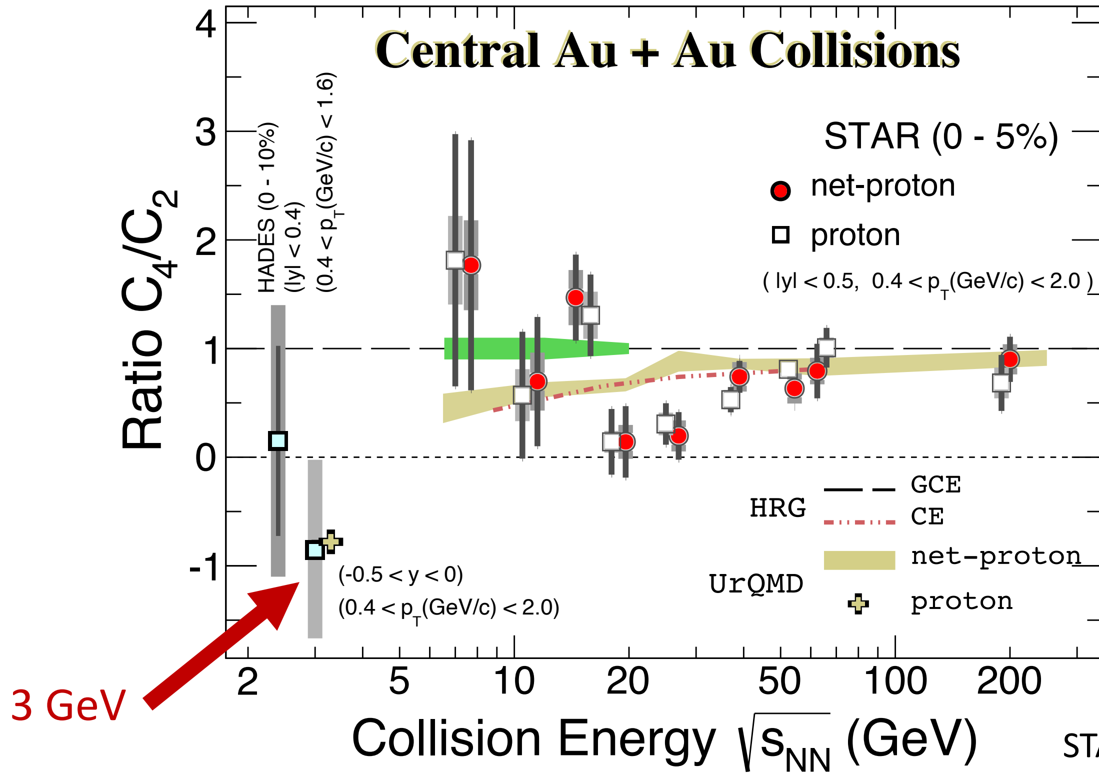
Energy Dependence of C_4/C_2



STAR, arXiv:2112.00240

- The suppression of C_4/C_2 is consistent with fluctuations driven by baryon number conservation which indicates a hadronic interaction dominated region in the top 5% central Au+Au collisions at 3 GeV
- The QCD critical point, if exists in heavy-ion collisions, could likely be at energy higher than 3 GeV

Energy Dependence of C_4/C_2



STAR, arXiv:2112.00240

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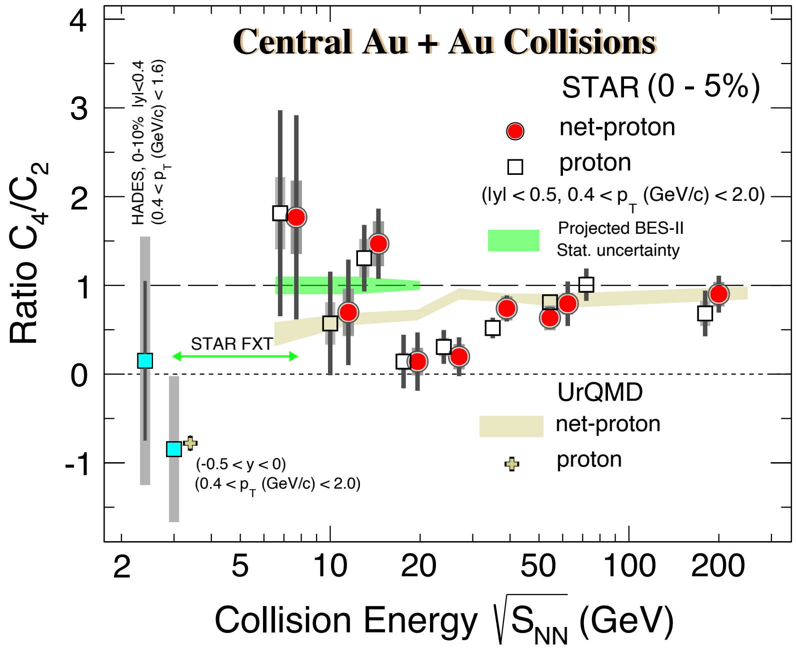
Summary

1. We report proton C_4/C_2 = -0.85 $\pm$ 0.09(stat.) $\pm$ 0.82(sys.) for the top 5% central Au+Au collisions within acceptance window $-0.5 < y < 0$ and $0.4 < p_T < 2.0$ GeV/c.
2. The most central event class is least affected by volume fluctuation.
3. The consistency of proton C_4/C_2 with fluctuation driven by baryon number conservation implies a hadronic interaction dominated region in the top 5% central Au+Au collisions at 3 GeV.
4. The QCD critical point, if exists in heavy-ion collisions, could likely be at collision energies higher than 3 GeV.

Outlook of BES-II Higher Moments Analysis

Statistics of Au+Au Collisions in BES	
$\sqrt{s_{NN}}$ (GeV)	BES–II / BES-I (million)
19.6	478 / 36
17.3	256
14.6	324 / 24
11.5	235 / 12
9.2	162
7.7	100 / 4
3.2 (FXT)	200
3 (FXT)	2100

STAR also collected FXT data at $\sqrt{s_{NN}}$ = 3.5, 3.9, 4.5, 4.8, 5.2, 6.2, 7.2, 7.7, 9.1, 11.5 and 13.7 GeV.



STAR, arXiv:2112.00240
PRL 126,092301; PRC 104, 024902

- BES-II collected 10-20 times larger statistics than BES-I in $\sqrt{s_{NN}}$ = 3 - 19.6 GeV Au+Au collisions
- Measurements on those datasets are crucial to search for the QCD critical point at high baryon density region
- Stay tuned for the exciting results from RHIC BES-II

Thank you for your attention!