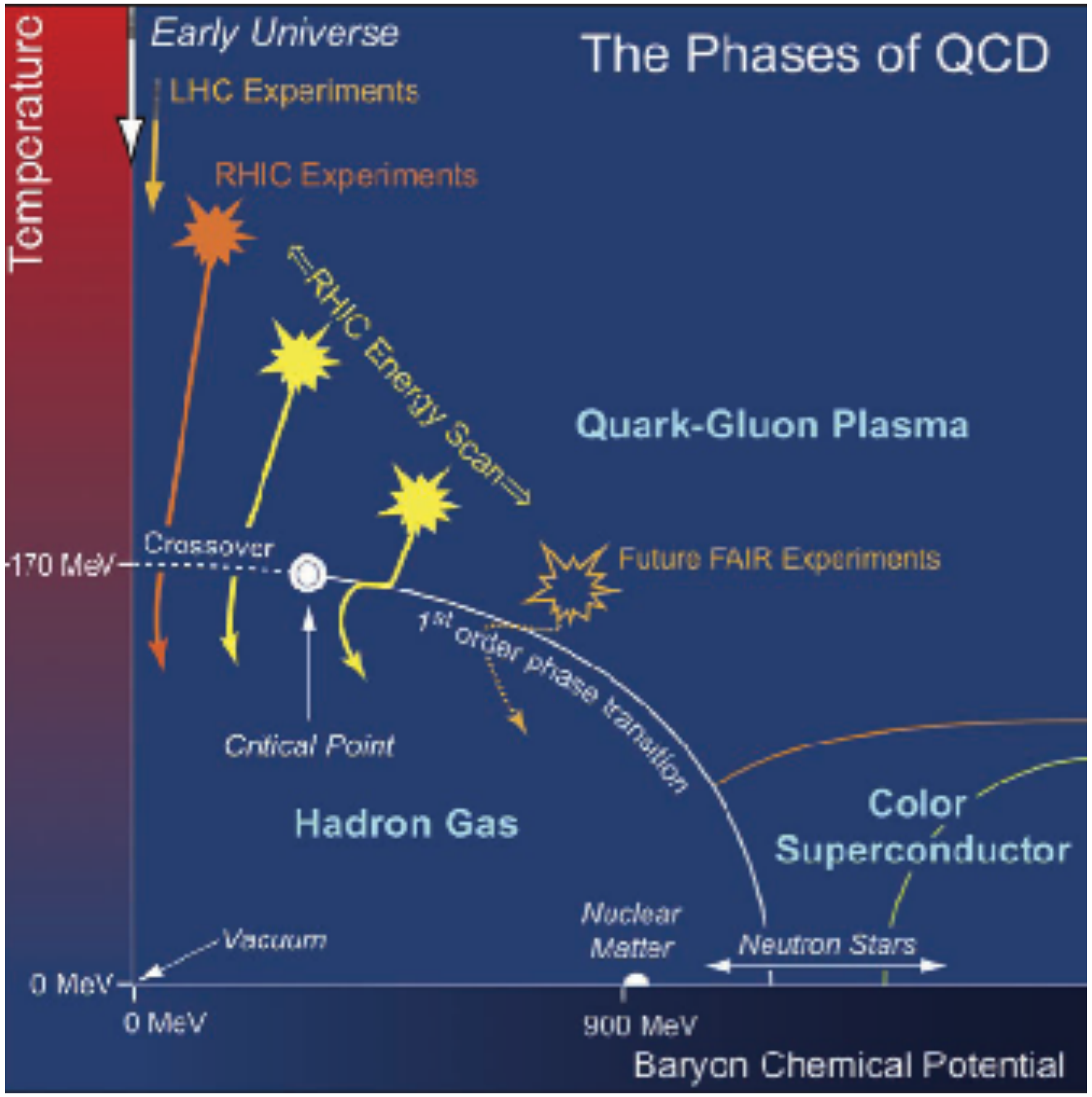
Searching for the QCD Critical Point Through Fluctuations at RHIC

Roli Esha
University of California, Los Angeles

UCLA

Introduction

- Event-by-event fluctuation of conserved quantities (Charge, Q / Baryon number, B / Strangeness, S) to study phase transition
  - Cross-over at small μ_B
  - Critical point
  - First order at large μ_B
- Experimental observables
  - Cumulants of event-by-event net-particle multiplicity distributions - Net charge / net-proton (proxy for net-baryon) / net-kaon (proxy for net-strangeness)
  - Correlation functions of particles



Higher-order Fluctuations

- Higher order cumulants are more sensitive to signatures of phase transition

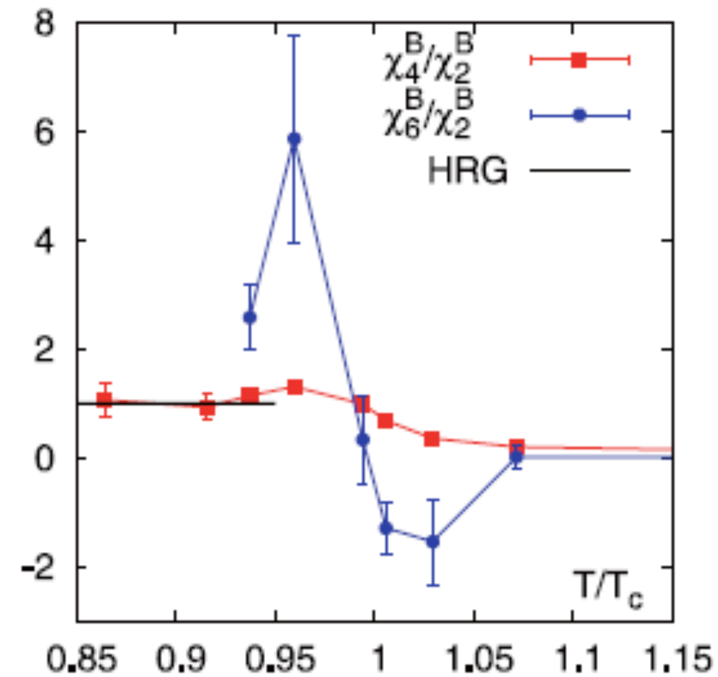
$$C_2 = \langle(\delta N)^2\rangle \sim \xi^2;\ C_3 = \langle(\delta N)^3\rangle \sim \xi^{4.5};\ C_4 = \langle(\delta N)^4\rangle \sim \xi^7 \qquad \delta N = N - \langle N\rangle$$

- Connection to the susceptibility of the system

$$\chi_q^{(n)} = \frac{1}{VT^3} \times C_{n,q} = \frac{\partial^n (p/T^4)}{\partial(\mu_q/T)^n} \qquad q = B, Q, S$$

$$\frac{\chi_q^{(4)}}{\chi_q^{(2)}} = \frac{C_{4,q}}{C_{2,q}} \qquad \frac{\chi_q^{(6)}}{\chi_q^{(2)}} = \frac{C_{6,q}}{C_{2,q}}$$

Theory ⟷ Experiment



- Correlation functions have the same power law dependence as the cumulants

M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009).
M. Asakawa, S. Ejiri and M. Kitazawa, Phys. Rev. Lett. 103, 262301 (2009).
M. A. Stephanov, Phys. Rev. Lett. 107, 052301 (2011).
Cheng et al, Phys. Rev. D 79, 074505 (2009).
B. Ling, M. Stephanov, Phys. Rev. C 93, 034915 (2016);
A. Bzdak, V. Koch, N. Strodthoff, arXiv:1607.07375;
A. Bzdak, V. Koch, V. Skokov, arXiv:1612.05128

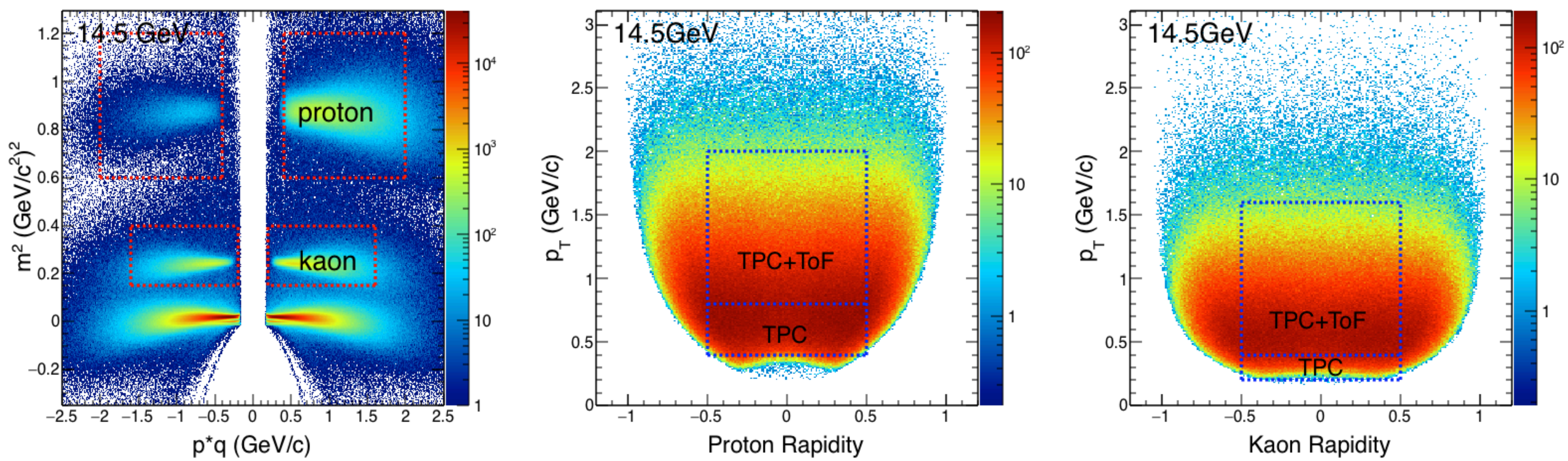
Analysis methods

- Centrality re-definition to exclude particle of interest to avoid auto-correlation
- Centrality bin width correction to suppress volume fluctuation
- Statistical error estimation using Bootstrap technique or Delta theorem
- Detector efficiency correction assuming Binomial efficiencies.

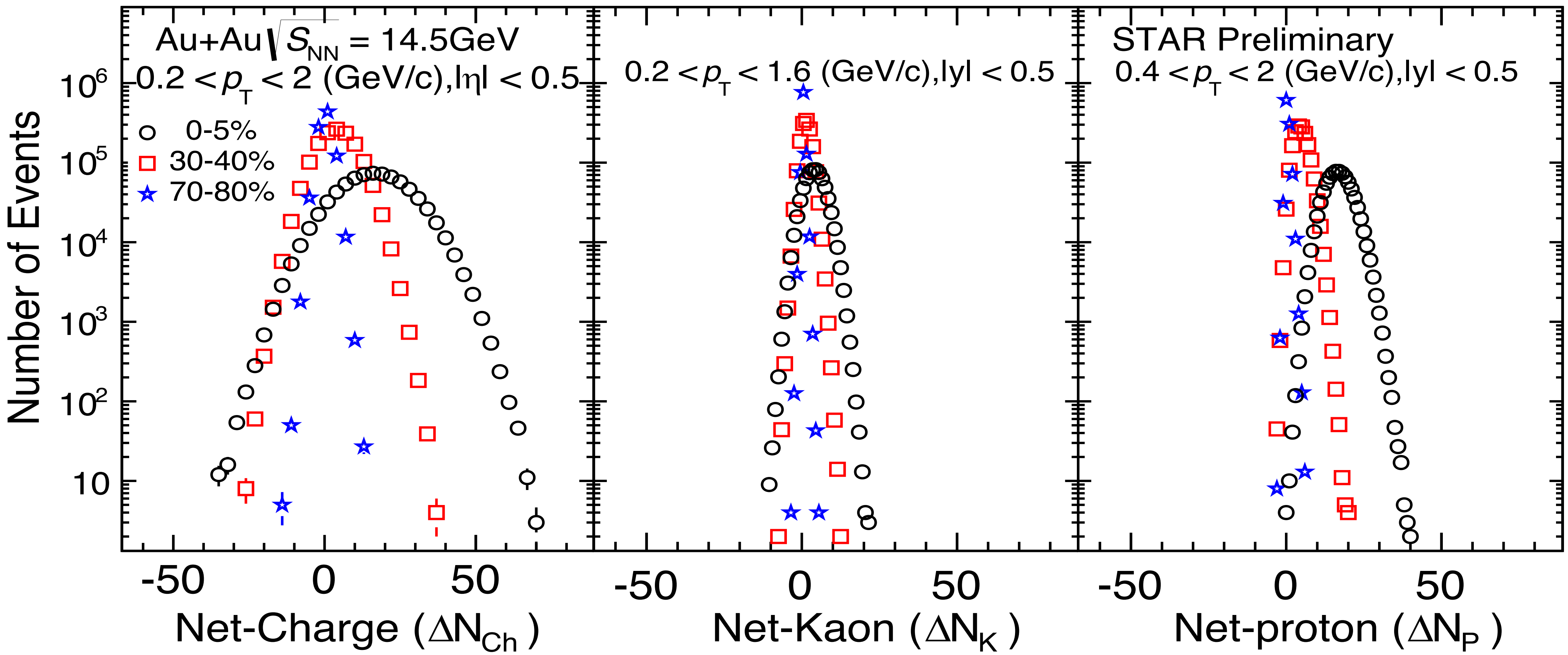
X. Luo and N. Xu, arXiv:1701.02105
STAR Collaboration, Phys.Rev.Lett. 105 (2010) 022302.
STAR Collaboration, Phys.Rev.Lett. 113 (2014) 092301
B. Efron et al. An Introduction to Bootstrap, Chapman & Hill (1993).
X. Luo, J. Xu, B. Mohanty, N. Xu, J. Phys. G 40, 105104 (2013)
Based on factorial cumulants: T. Nonaka, M. Kitazawa and S. Esumi, PRC.95 064912(2017)
Based on factorial moments: A. Bzdak and V. Koch, PRC91, 027901 (2015). X. Luo, PRC91, 034907(2015).

Analysis details

	Net-Charge	Net-Proton	Net-Kaon
Kinematic cuts	$0.2 < p_T$ (GeV/c) < 2.0 $\|\eta\| < 0.5$	$0.4 < p_T$ (GeV/c) < 2.0 $\|y\| < 0.5$	$0.2 < p_T$ (GeV/c) < 1.6 $\|y\| < 0.5$
Particle Identification	Reject protons form spallation for $p_T < 0.4$ GeV/c	$0.4 < p_T$ (GeV/c) < 0.8 → TPC $0.8 < p_T$ (GeV/c) < 2.0 → TPC+TOF	$0.2 < p_T$ (GeV/c) < 0.4 → TPC $0.4 < p_T$ (GeV/c) < 1.6 → TPC+TOF
Centrality definition, → *to avoid auto-correlations*	Uncorrected charged primary particles multiplicity distribution	Uncorrected charged primary particles multiplicity distribution, without (anti-)protons	Uncorrected charged primary particles multiplicity distribution, without (anti-)kaons
	$0.5 < \|\eta\| < 1.0$	$\|\eta\| < 1.0$	$\|\eta\| < 1.0$

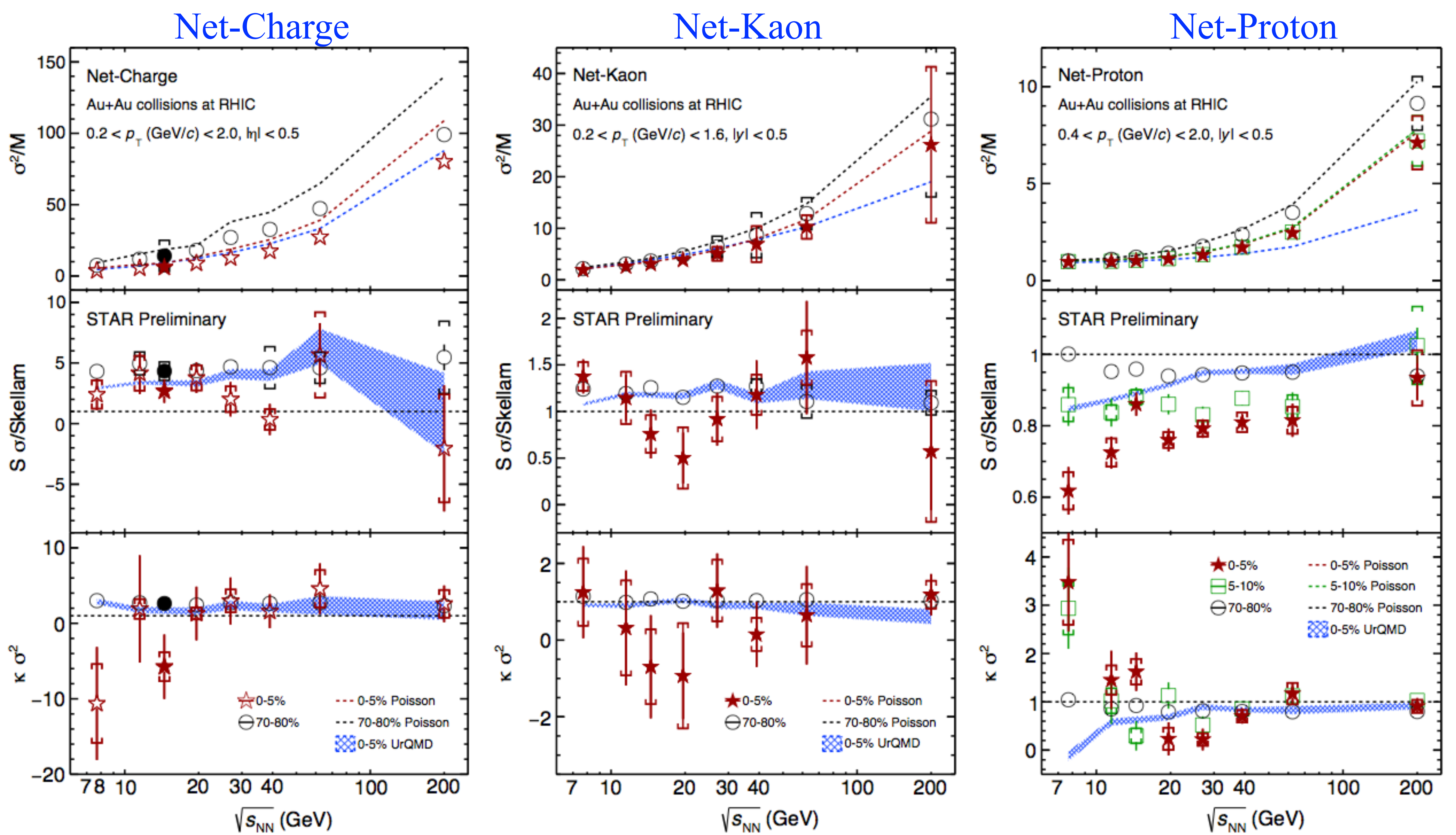


Raw Distributions



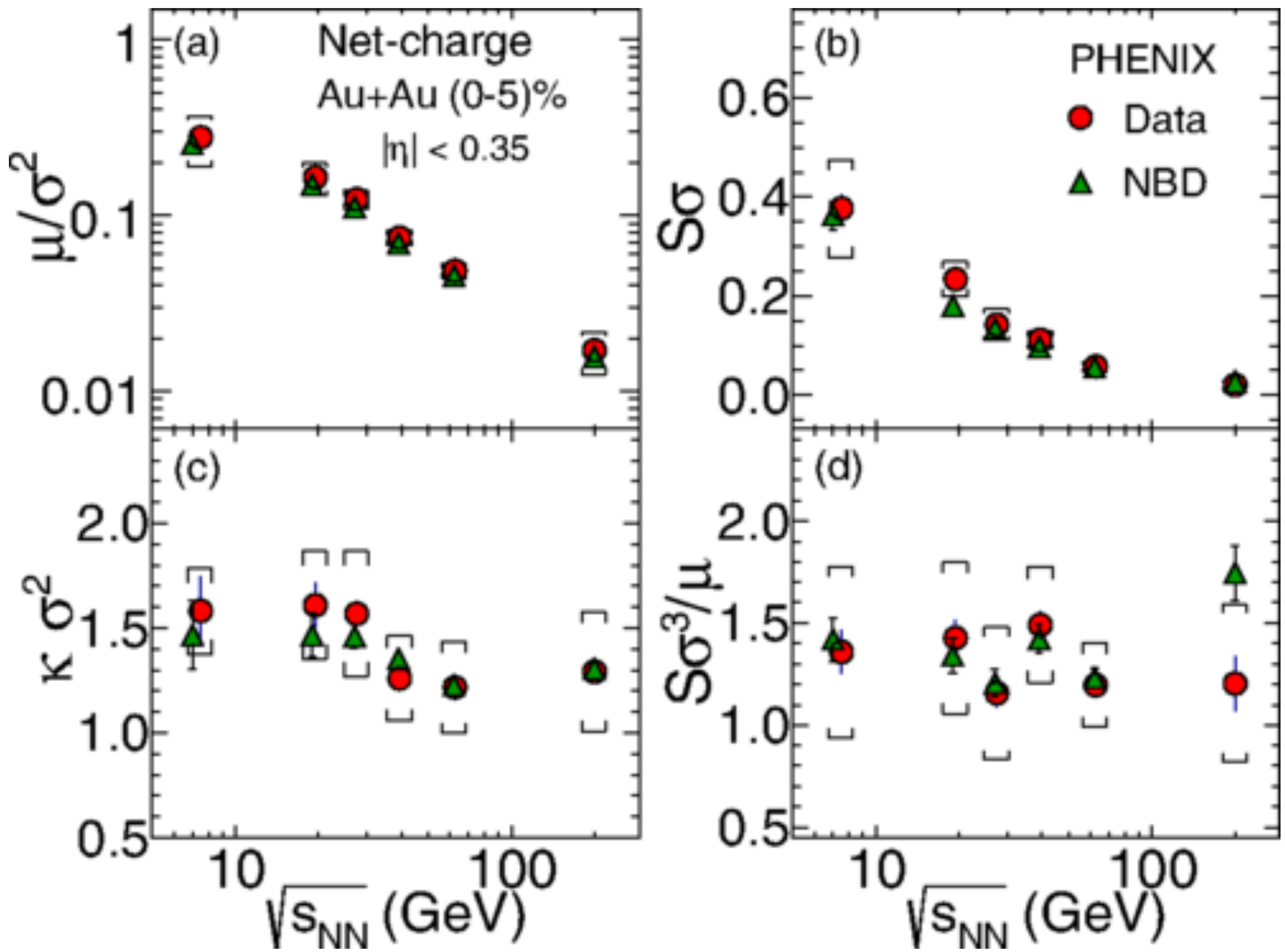
Uncorrected raw event-by-event net-particle multiplicity distribution for Au+Au collisions at $\sqrt{s_{NN}}$ = 14.5 GeV

Corrected cumulant ratios from STAR



J. Thaeder (for the STAR Collaboration), Quark Matter 2015

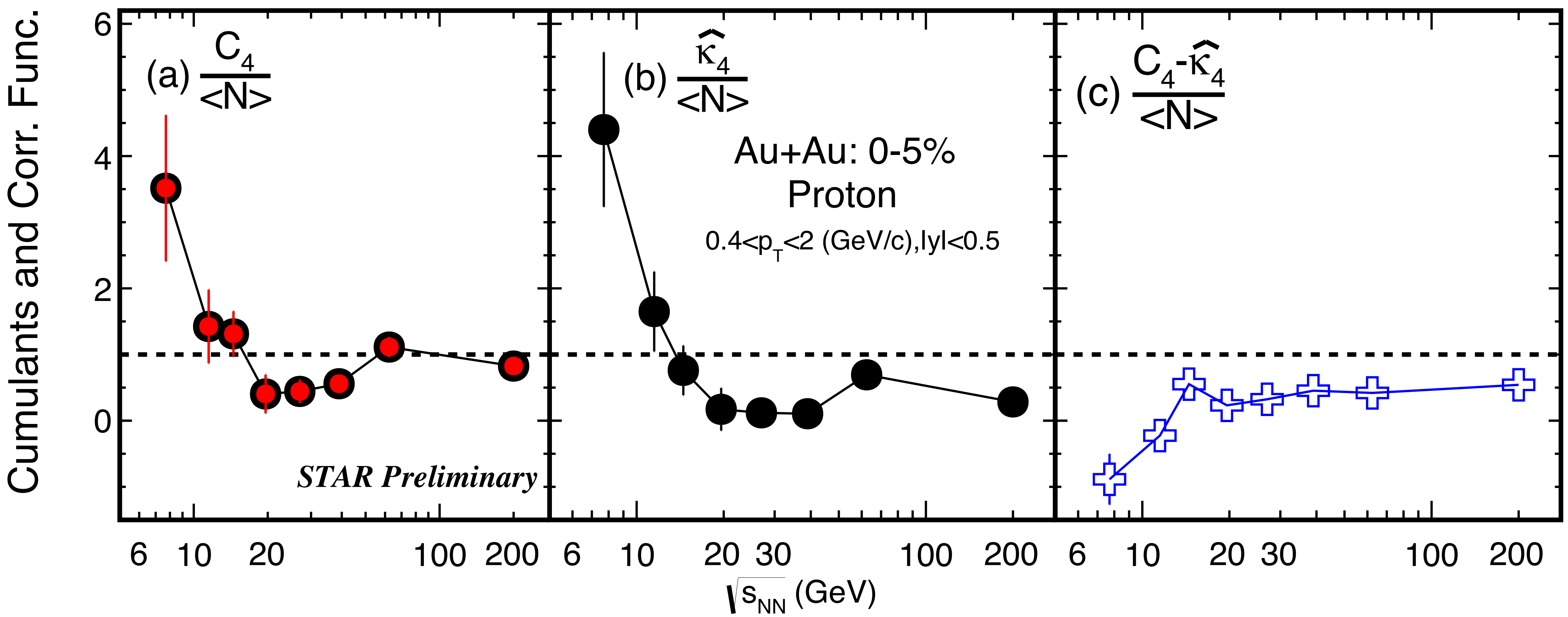
Corrected cumulant ratios from PHENIX



- Within errors, the results of net-charge show flat energy dependence.
- More statistics are needed at low energies.

A. Adare et al. (PHENIX Collaboration) Phys. Rev. C 93, 011901

Correlation function



$\hat{\kappa}_1 = C_1$

$\hat{\kappa}_2 = C_2 - C_1$

$\hat{\kappa}_3 = C_3 - 3C_2 + 2C_1$

$\hat{\kappa}_4 = C_4 - 6C_3 + 11C_2 - 6C_1$

$C_1 = < N >$

$C_2 = < N > + \hat{\kappa}_2$

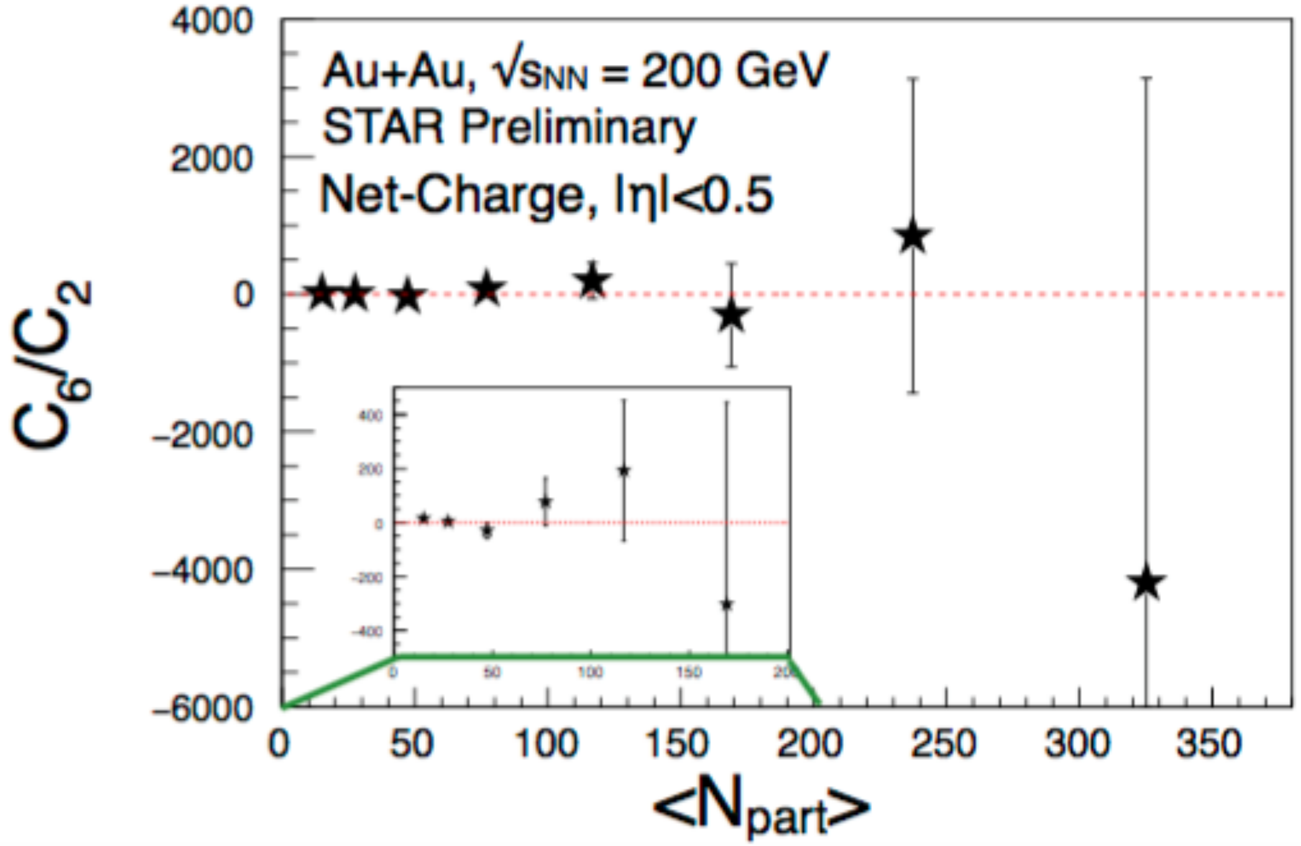
$C_3 = < N > + 3\hat{\kappa}_2 + \hat{\kappa}_3$

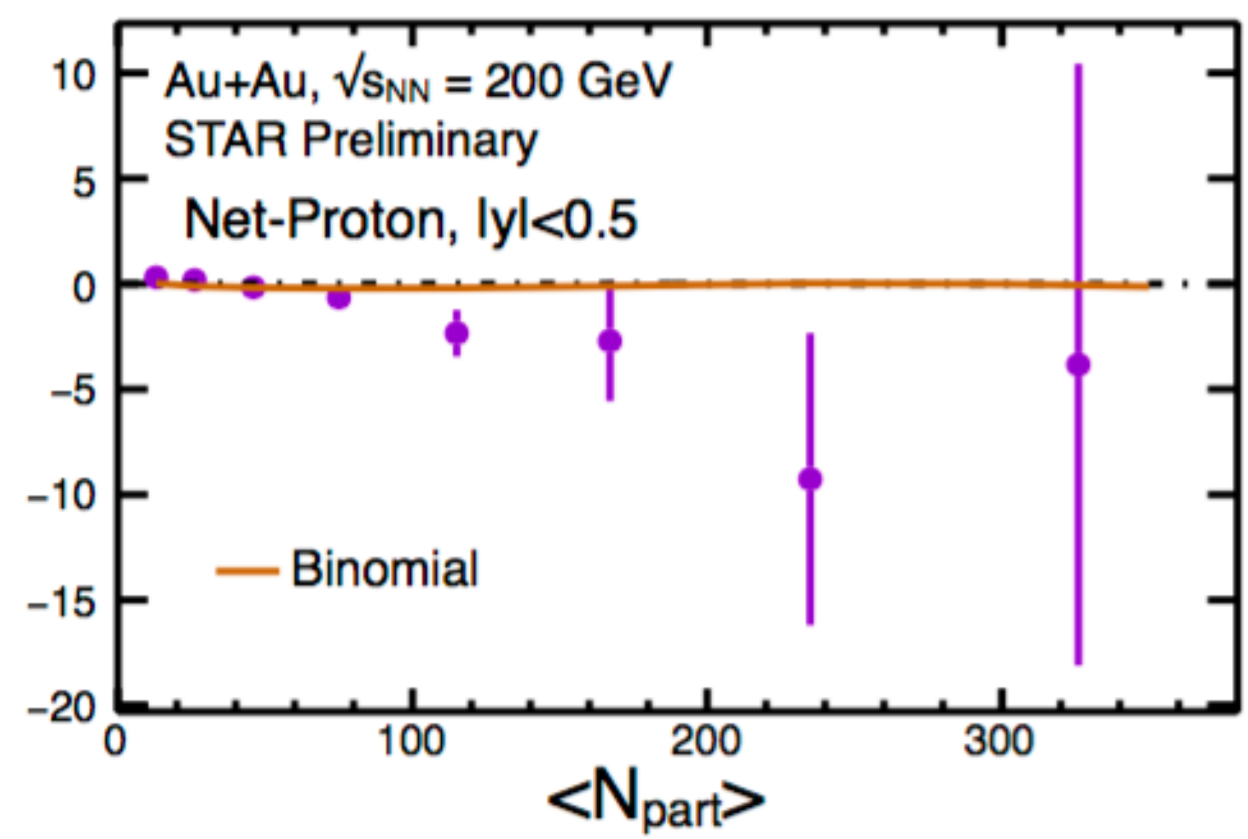
$C_4 = < N > + 7\hat{\kappa}_2 + 6\hat{\kappa}_3 + \hat{\kappa}_4$

Non-monotonic energy dependence is observed for 4^{th} order net-proton and proton fluctuations in most central Au+Au collisions.

R. Esha (for the STAR Collaboration), Quark Matter 2017

Sixth-order cumulants





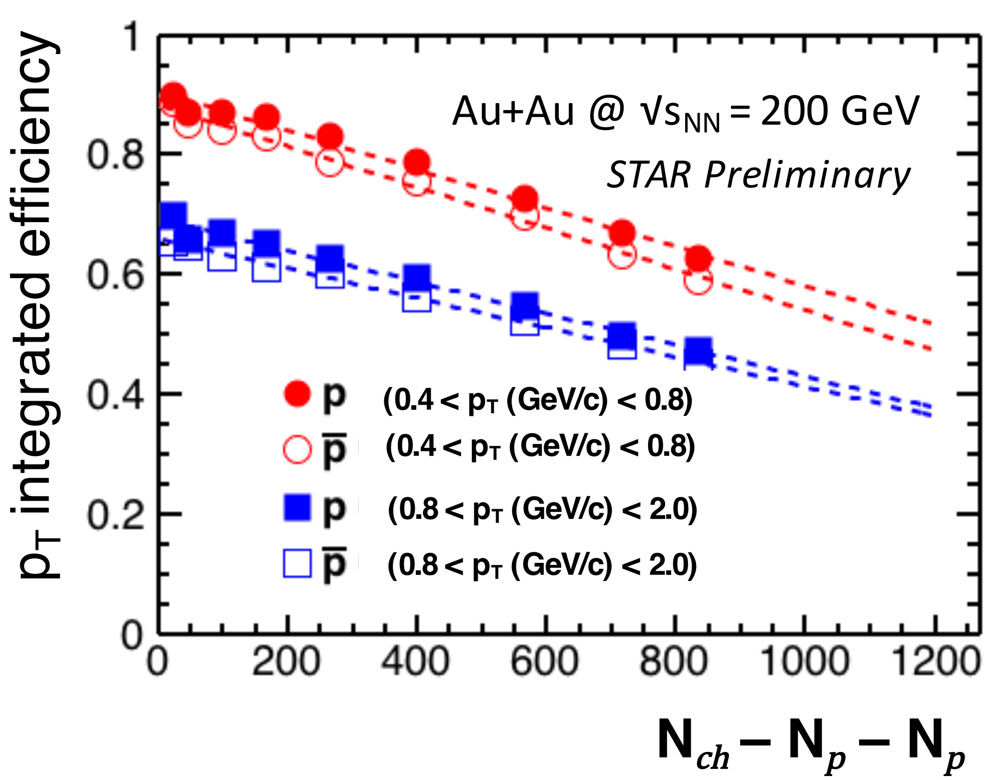
- Sixth-order cumulants of net-charge and net-baryon distributions are predicted to be negative if the chemical freeze-out is close enough to the phase transition.
- C_6/C_2 for net-charge is consistent with zero with large statistical errors
- Negative values are observed for C_6/C_2 of net-proton systematically from peripheral to central collisions.

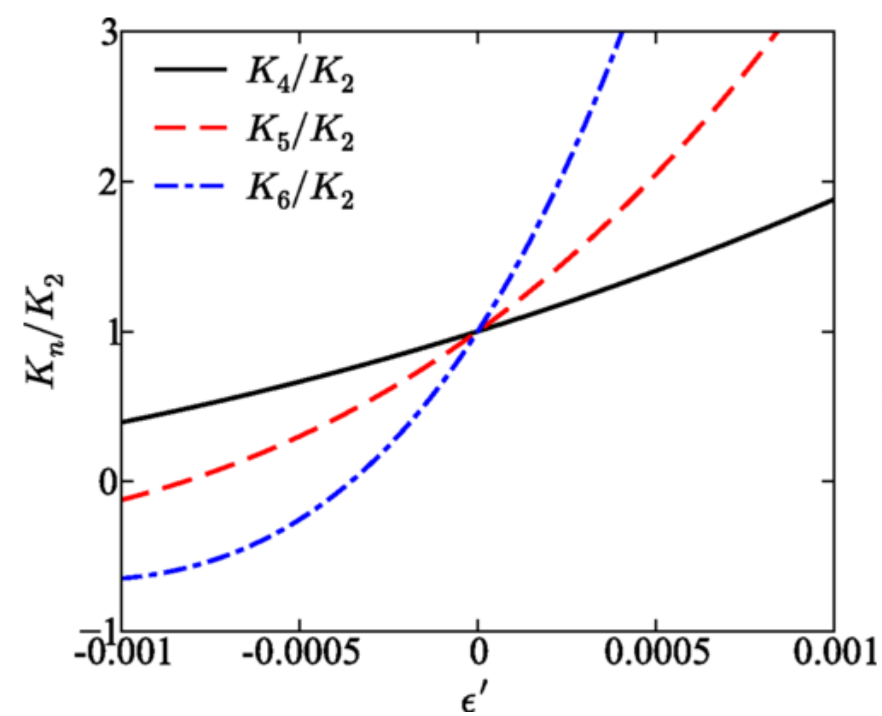
R. Esha (for the STAR Collaboration), Quark Matter 2017
T. Nonaka (for the STAR Collaboration), Quark Matter 2018

Non-binomial efficiency

- Experimental effects — particle mis-identification, track splitting/merging etc.

- Multiplicity dependent efficiency



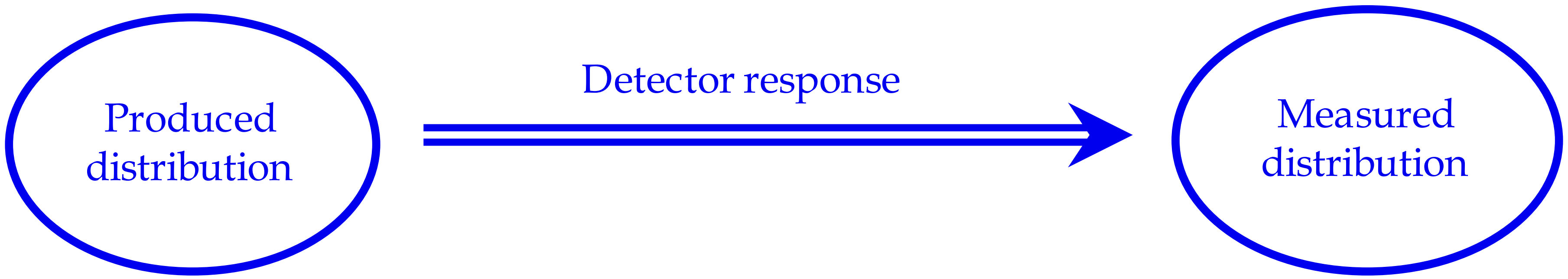


$$P(N) = \frac{\langle N \rangle^N}{N!} e^{-\langle N \rangle},$$

$$\epsilon(N) = \epsilon_0 + \epsilon'(N - \langle N \rangle),$$

A. Bzdak, R. Holzmann and V. Koch, Phys.Rev. C 94, 064907 (2016)

Unfolding



- Correlation histogram
  - Contains the number correlation between measured protons and anti-protons
- Response histogram
  - Contains the distribution of produced particles for every detected number of particles; these are obtained from embedding

- Schemes
  - Unfolding with initial proton and anti-proton distributions assumed to be Poisson distributions
  - Unfolding with iterations

R. Esha, CPOD 2017
T. Nonaka (for the STAR Collaboration), Quark Matter 2018

Unfolding - an example

AMPT model with multiplicity-dependent efficiency for 0-5% central Au+Au collisions at √sNN = 200 GeV

Efficiency for protons = 0.8 - 0.0003*(Ncharge - Nproton - Nantiproton)
Efficiency for antiproton = 0.7 - 0.0003*(Ncharge - Nproton - Nantiproton)

Cumulant for net-proton distribution	True distribution	Efficiency corrected (2D response matrix)	Efficiency corrected (1D response matrix)	Efficiency corrected (factorial moment method)
C_1	2.7990$\pm$ 0.0017	2.7994 $\pm$ 0.0019	2.8001$\pm$ 0.0020	2.5502$\pm$ 0.0011
C_2	31.436$\pm$ 0.015	31.435 $\pm$ 0.014	49.777$\pm$ 0.019	12.632$\pm$ 0.012
C_3	8.43 $\pm$ 0.15	8.45 $\pm$ 0.14	9.33$\pm$ 0.24	2.58$\pm$ 0.04
C_4	91.33 $\pm$ 1.57	90.95 $\pm$ 1.98	88.89$\pm$ 3.49	12.49$\pm$ 0.28

2D response matrix : Protons and anti-protons are corrected simultaneously
1D response matrix : Protons and anti-protons are corrected separately
Factorial moment method assumes binomial efficiency correction. CBWC is applied.

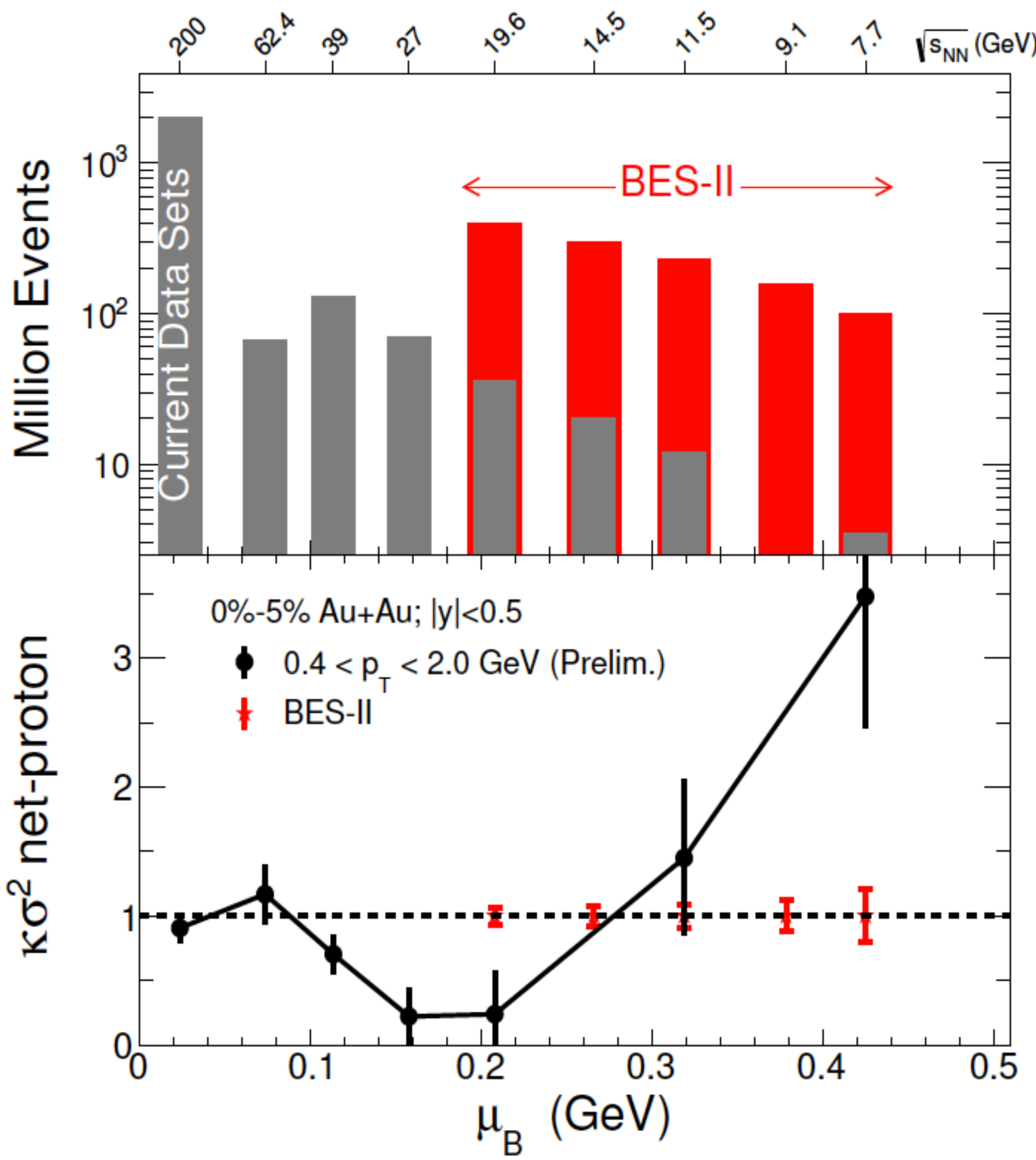
Even a seemingly small non-binomial effect could have a noticeable consequence on higher-order cumulants -- Pointed out by A. Bzdak et al.

A. Bzdak, R. Holzmann and V. Koch, Phys.Rev. C 94, 064907 (2016)

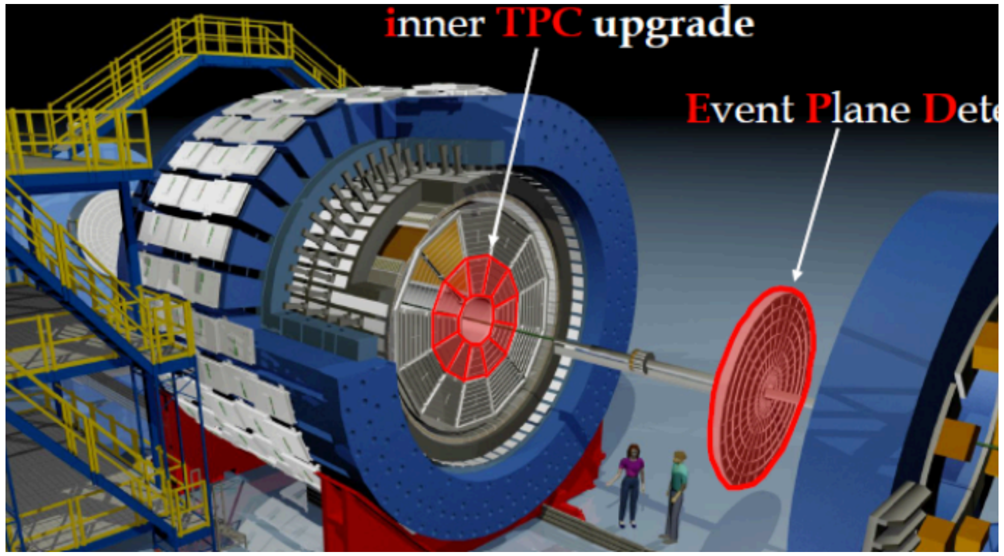
BES-II at RHIC

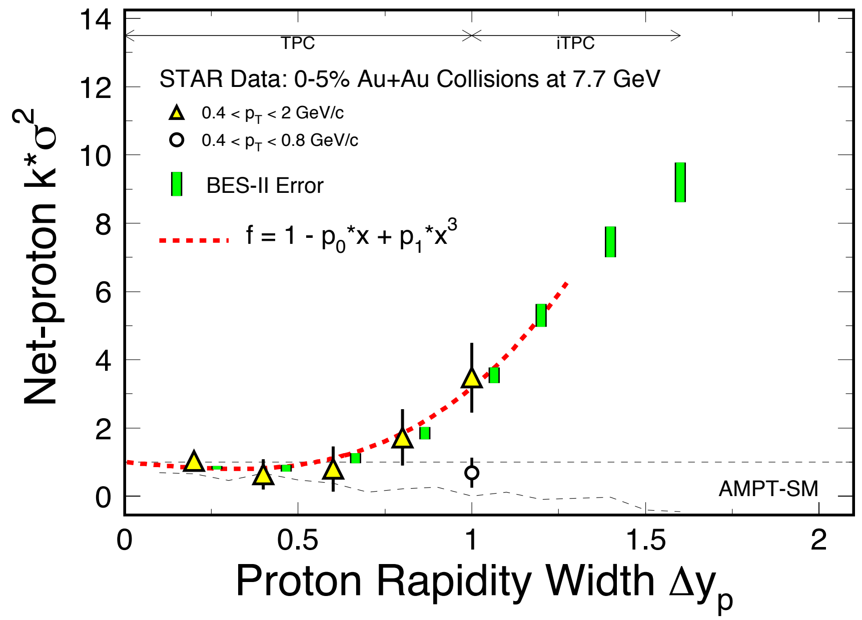
More Data

RHIC Luminosity Upgrade for Low Energies



iTPC upgrade extends the rapidity coverage to $\Delta y = 1.6$





STAR Collaboration, https://drupal.star.bnl.gov/STAR/starnotes/public/sn0619

Summary

- Non-monotonic energy dependences of net-proton and proton C_4/C_2 are observed for 0 - 5% central Au+Au collisions.
- Four-particle correlations contribute dominantly to the observed non-monotonicity.
- C_6/C_2 is negative for net-protons for central collisions with large statistical uncertainties.
- Efficiency correction is an important ingredient in order to reliably calculate the higher-order cumulants. We need to develop an approach to explore these issues adequately, which we have not done previously in our data analyses.
- More data will be collected in BES-II at $\sqrt{s_{NN}}$ = 7.7 – 19.6 GeV in 2019–2020 with detector upgrades.

Thank you!