Measurement of cumulants of conserved charge multiplicity distributions in Au+Au collisions from the STAR experiment

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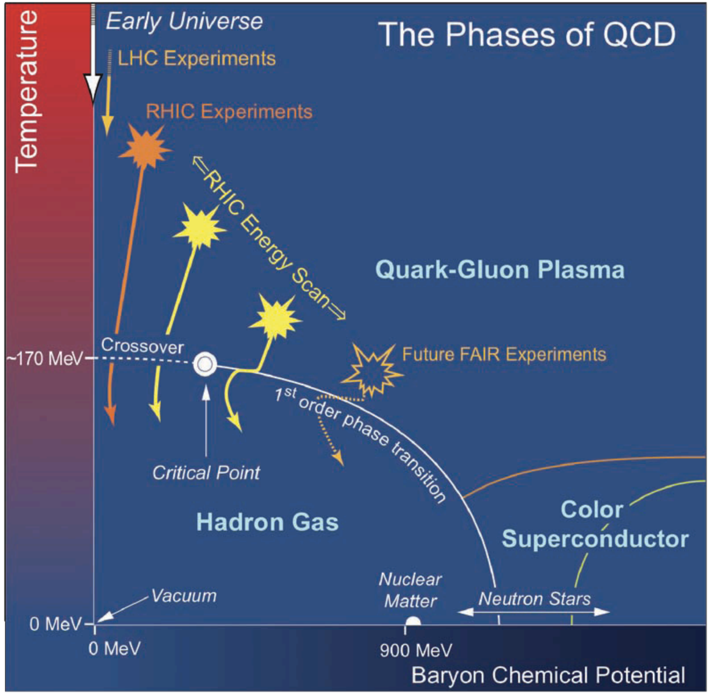
STAR

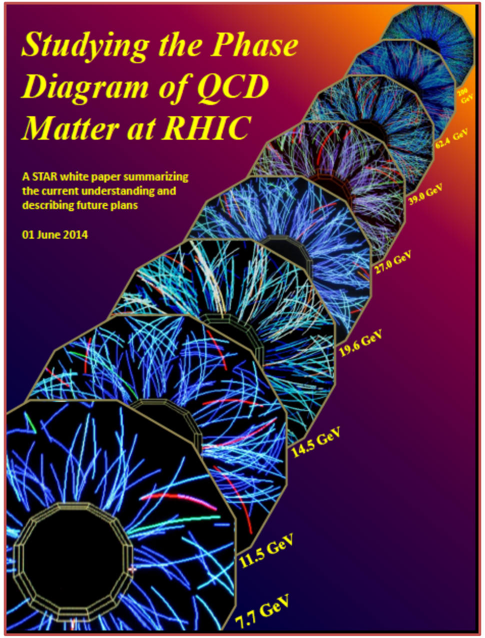
In part supported by

Outline
1. Introduction
2. Observable
3. The STAR Experiment
4. Higher Moment Analysis
5. Results
6. Summary

NISER

Introduction: QCD Phase Diagram & BES





https://drupal.star.bnl.gov/STAR/starnotes/public/sn0493
https://drupal.star.bnl.gov/STAR/files/BES_WPII_ver6.9_Cover.pdf

Goal: Study the phase diagram of QCD.
BES: Varying beam energy varies Temperature (T) and Baryon Chemical Potential (μ_B).
Fluctuations in various observables are sensitive to phase transition and critical point.

Results from new data : Au+Au collisions at $\sqrt{s_{NN}}$ = 54.4 GeV

Observables

- Higher moments or cumulants of net-particle distributions (B, Q, S).

$$C_1 = < N >$$
$$C_2 = < (\delta N)^2 >$$
$$C_3 = < (\delta N)^3 >$$
$$C_4 = < (\delta N)^4 > -3 < (\delta N)^2 >^2$$

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

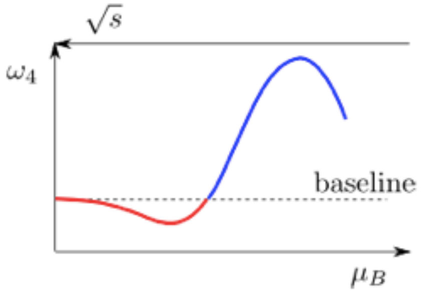
- Higher order cumulants of conserved number distributions are sensitive observables.* Related to the correlation length and susceptibilities.

$C_2 \sim \xi^2$ $C_4 \sim \xi^7$ *Quantitative numbers - Model dependent

$$\frac{\chi_q^{(4)}}{\chi_q^{(2)}} = \kappa\sigma^2 = \frac{C_{4,q}}{C_{2,q}} \qquad \frac{\chi_q^{(3)}}{\chi_q^{(2)}} = S\sigma = \frac{C_{3,q}}{C_{2,q}}$$

M. A. Stephanov, Phys.Rev.Lett. 107 (2011) 052301
M.A Stephanov, Phys.Rev.Lett. 102 (2009) 032301
Y. Hatta et al, Phys.Rev.Lett. 91 (2003) 102003

Kurtosis of net-proton in the presence of CP



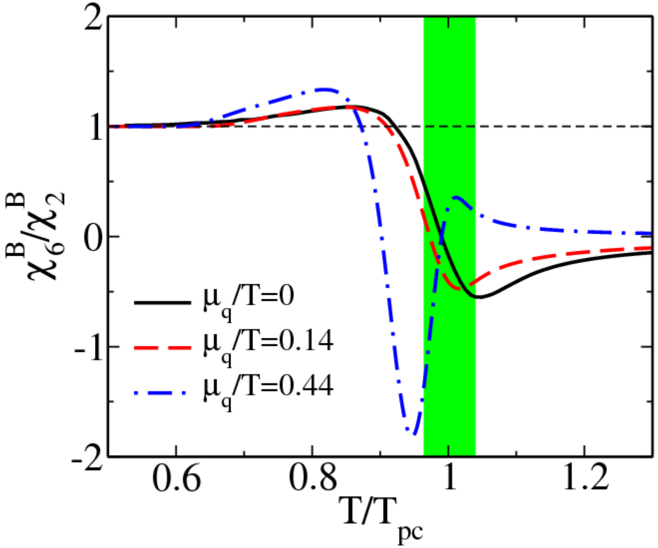
M.A Stephanov et al, Phys.Rev.Lett. 81 (1998) 4816-4819
M. A. Stephanov et al, Phys.Rev. D82 (2010) 074008
B. Berdnikov et al, Phys.Rev. D61 (2000) 105017
M. Asakawa et al, Phys.Rev.Lett. 103 (2009) 262301

The Sixth-Order Cumulant

Goal: Identification of O(4) chiral criticality on the phase boundary.

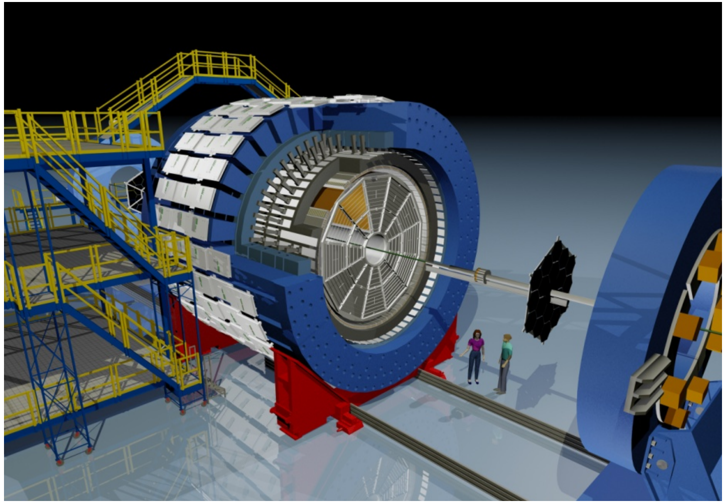
Freeze-out conditions	χ_4^B/χ_2^B	χ_6^B/χ_2^B	χ_4^Q/χ_2^Q	χ_6^Q/χ_2^Q
HRG	1	1	~2	~10
QCD: $T^{freeze}/T_{pc} \lesssim 0.9$	$\gtrsim 1$	$\gtrsim 1$	~2	~10
QCD: $T^{freeze}/T_{pc} \simeq 1$	~0.5	<0	~1	<0

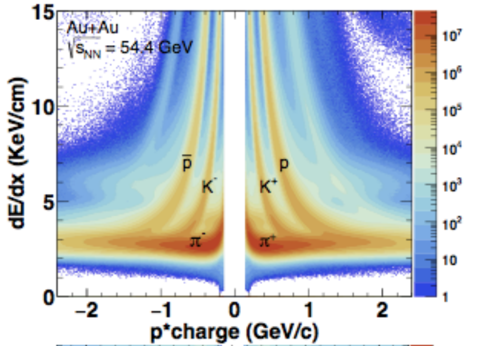
B. Friman et al, Eur.Phys.J. C71 (2011) 1694

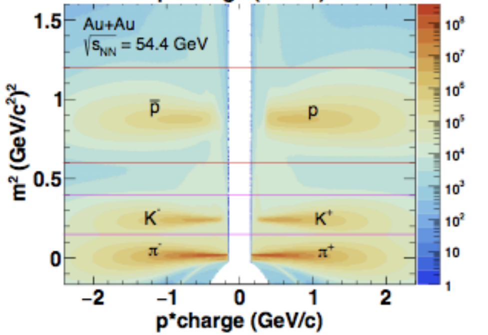


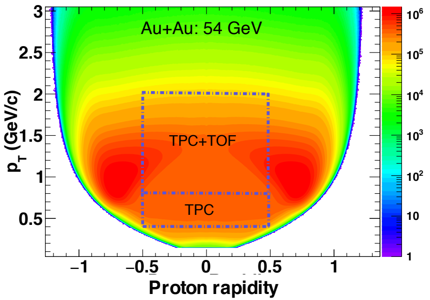
The C_6 of baryon number and electric charge fluctuations remain negative at the chiral transition temperature.

The STAR Detector









Main Detectors: Time Projection Chamber and Time-of-Flight. **Full azimuthal angle coverage.**
$|\eta|<1$ coverage.
Uniform acceptance in p_T vs. rapidity at midrapidity for all particles.

K. H. Ackermann et al. Nucl. Instrum. Meth. A 499, 624 (2003)

Data Set

Collision system and energy	Au+Au at $\sqrt{s_{NN}}$ = 54.4 GeV
Baryon Chemical Potential	~ 83 MeV
No. of events	~ 550 Millions
Collision centrality	0-5%, 5-10%, 10-20%, 20-30%, 30-40%, 40-50%, 50-60%, 60-70%, 70-80%
Centrality	Using charged particle multiplicity
Z Vertex	+/- 30 cm
Vertex radial position	2 cm
Detectors for PID	Time Projection Chamber and Time-of-Flight

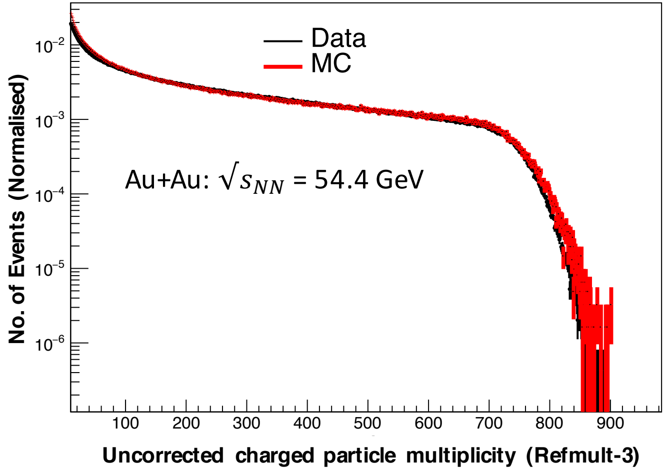
Analysis	Particle Type	Transverse Momentum Range (p_T)	Rapidity (y)
Net-proton	Protons and anti-protons (p & $\bar{p}$)	0.4 to 2.0 GeV/c	$\|y\| < 0.5$
Net-kaon	Kaons (K^+ & K^-)	0.2 to 1.6 GeV/c	$\|y\| < 0.5$
Net-charge	Protons and anti-protons (p & $\bar{p}$) Kaons (K^+ & K^-) Pions (π^+ & π^-)	0.4 to 2.0 GeV/c 0.2 to 1.6 GeV/c 0.2 to 1.6 GeV/c	$\|\eta\| < 0.5$

Centrality Selection

- Use charged particle multiplicity excluding particles of interest to avoid autocorrelation effects.

A.Chatterjee et al, arXiv:1910.08004

- Charged particle multiplicity for net-proton analysis (Refmult-3) fitted with Glauber MC Model.



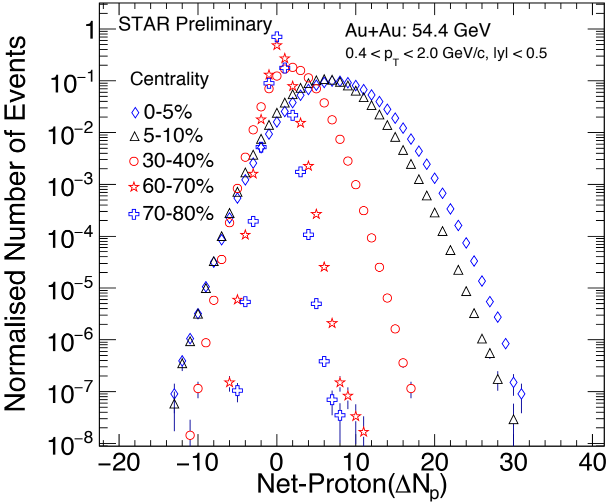
- Corrected for luminosity and Z-vertex effects.

- Compared to the MC Glauber model.

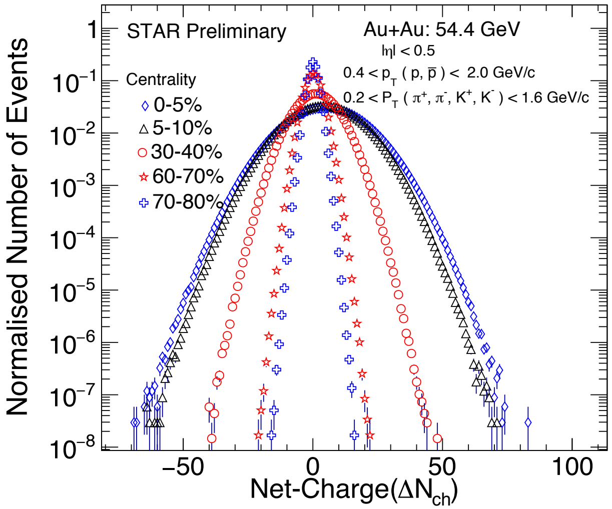
Centrality	Refmult-3 cuts	<Npart>	Events (Millions)
0-5%	621	346	33
5-10%	516	292	34
10-20%	354	228	70
20-30%	237	161	69
30-40%	151	111	69
40-50%	90	73	67
50-60%	50	45	64
60-70%	24	26	60
70-80%	10	13	57

Event-by-Event Raw Net-Particle Distributions

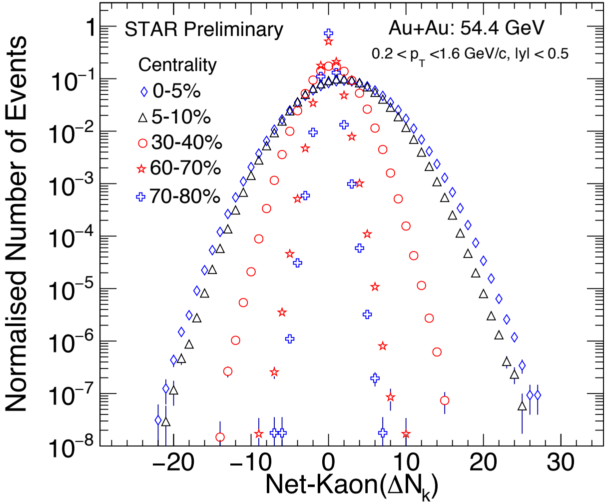
Net-Proton



Net-Charge



Net-Kaon

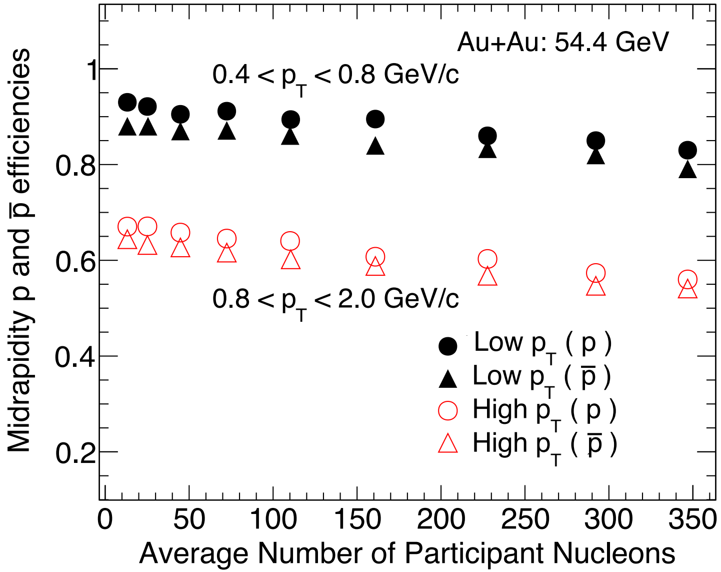


- ➢ From peripheral to central collisions:
- ❑ Mean of net-particle distributions increase.
- ❑ Width (or the sigma) of the distributions also increase.

- ➢ Net-charge distribution has the largest width for a given centrality. $\boldsymbol{err}(\boldsymbol{C_r}) \propto \frac{\boldsymbol{\sigma^r}}{\sqrt{\boldsymbol{N_{evts}}}}$

Analysis Techniques (Corrections And Uncertainties)

- Reconstruction efficiency correction - binomial model



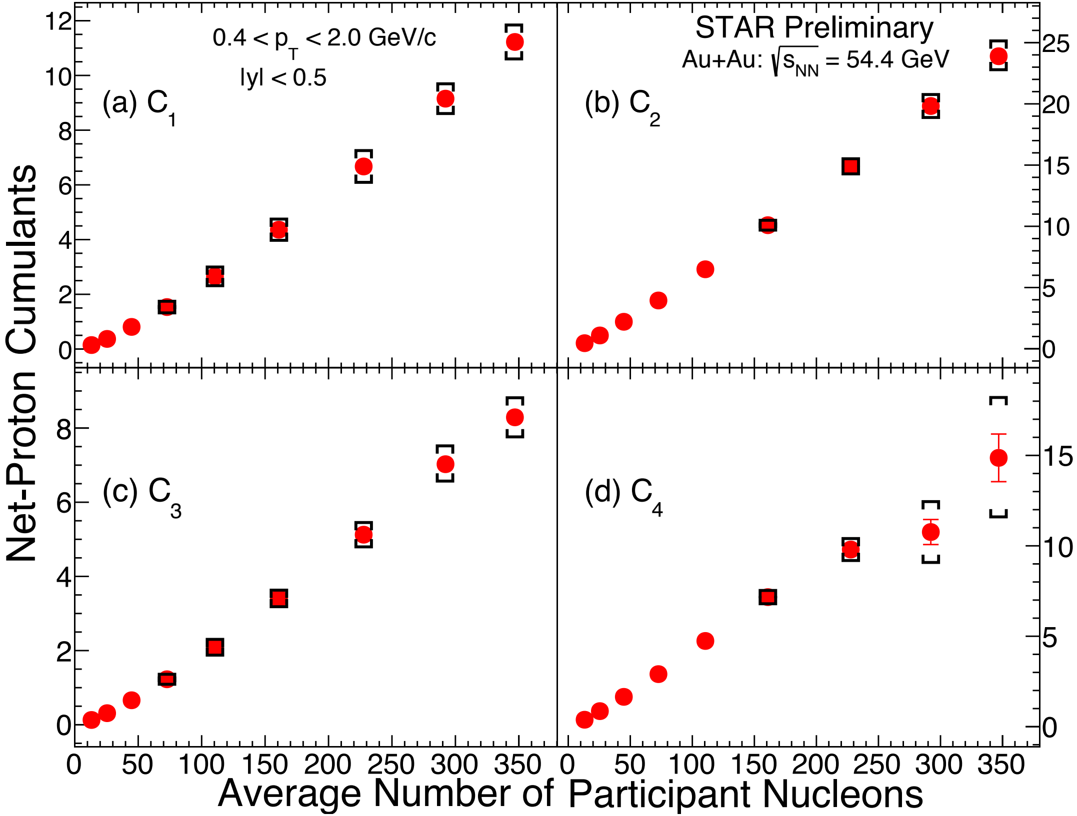
Net-proton Cumulants

Cumulant	σ_{stat} (0-5%)	σ_{sys} (0-5%)
C_1	0.008%	6%
C_2	0.04%	5%
C_3	1%	7%
C_4	9%	22%

- Centrality bin width correction
- Statistical uncertainties:
  - Bootstrap method
  - Delta theorem method
- Sources of systematic uncertainties:
  - Particle identification
  - Background estimates (DCA)
  - Track quality cuts
  - Efficiency variation

X. Luo , Phys. Rev. C 91, (2015) 034907
T. Nonaka et al, Phys. Rev. C 95, (2017) 064912
X. Luo et al, J.Phys. G 40, 105104 (2013)
X. Luo, J. Phys. G 39, 025008 (2012)
X.Luo et al, Phys.Rev. C99 (2019) no.4, 044917
A.Pandav et al, Nucl. Phys. A 991, (2019)121608

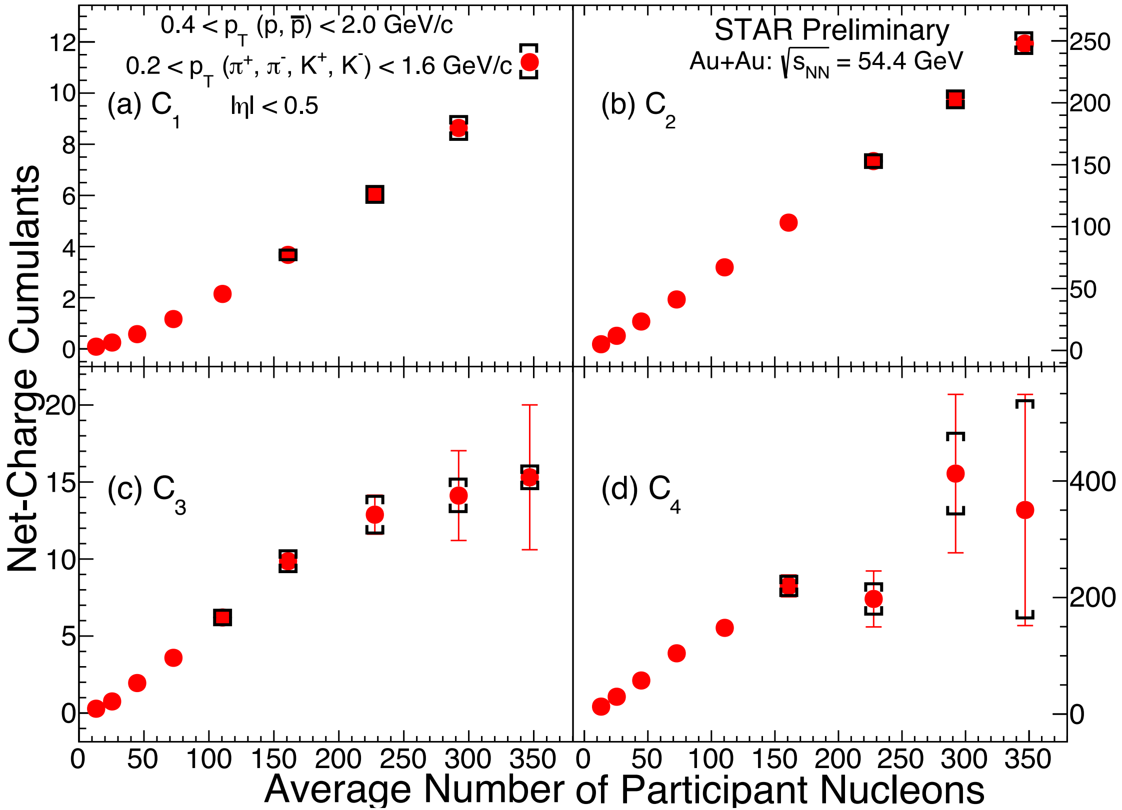
Centrality Dependence of Net-Proton Cumulants



Bars and brackets are statistical and systematic uncertainties respectively.

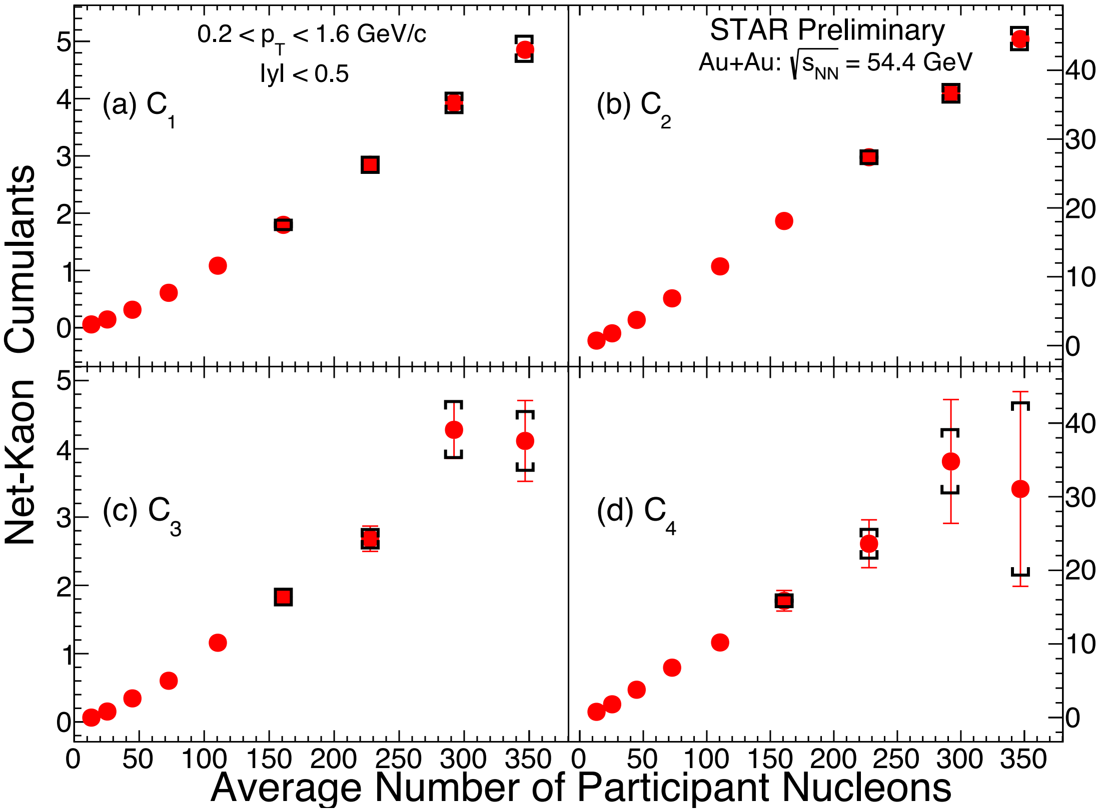
Net-proton cumulants up to the fourth order increases with average number of participant nucleons.

Centrality Dependence of Net-Charge Cumulants



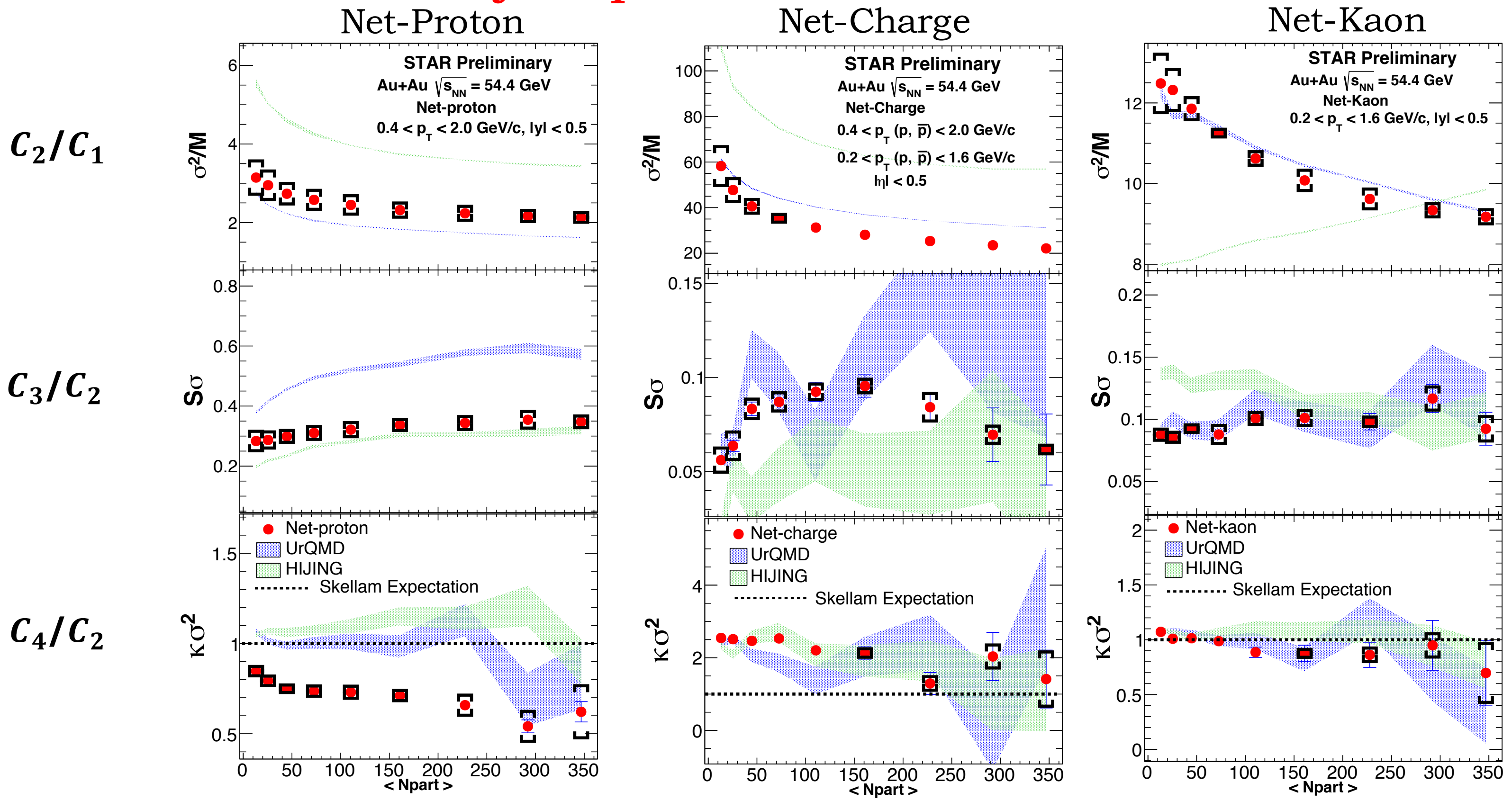
Net-charge cumulants up to the fourth order increases with average number of participant nucleons.

Centrality Dependence of Net-Kaon Cumulants



Net-kaon cumulants up to the fourth order increases with average number of participant nucleons.

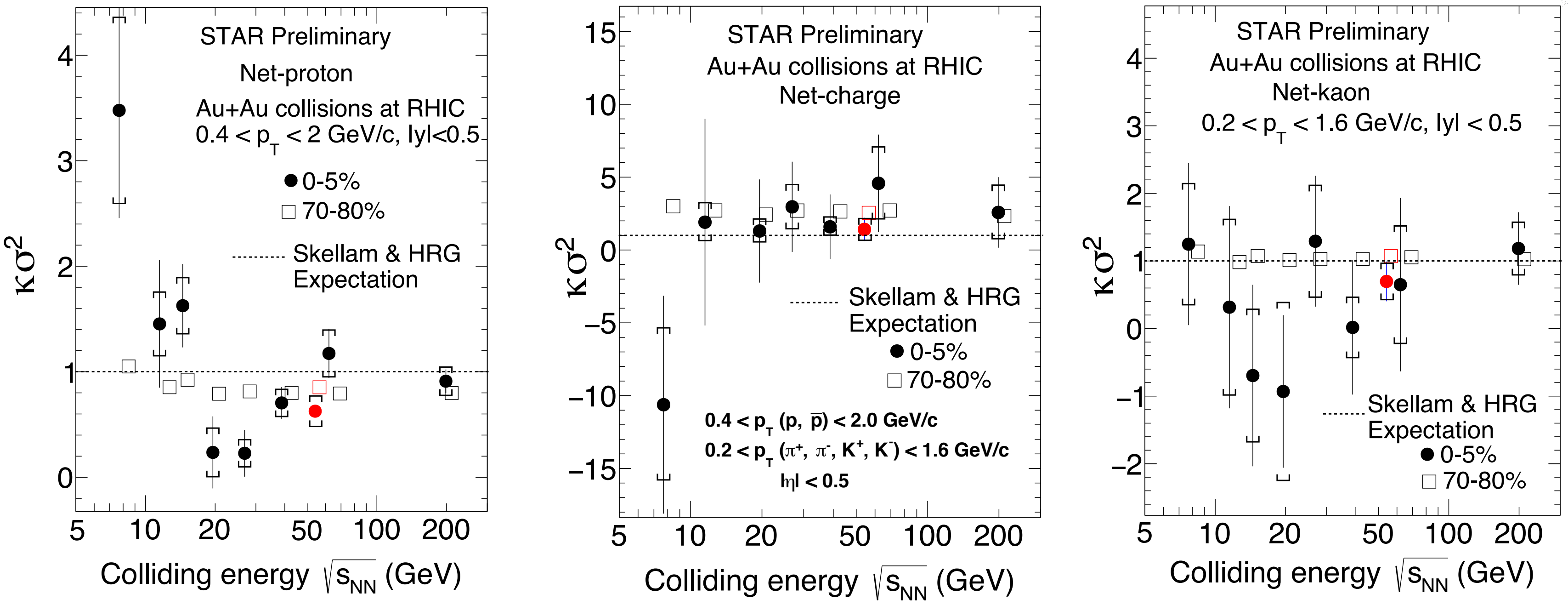
Centrality Dependence of Cumulant Ratios



S. A. Bass et al., Prog.Part. Nucl. Phys. 41, 255 (1998) *M. Gyulassy et al, Comput. Phys.Commun. 83, 307 (1994)*

C_2/C_1 decreases from peripheral to central collisions. C_3/C_2 and C_4/C_2 show weak dependence on centrality. Only qualitative agreement with models expectations observed.

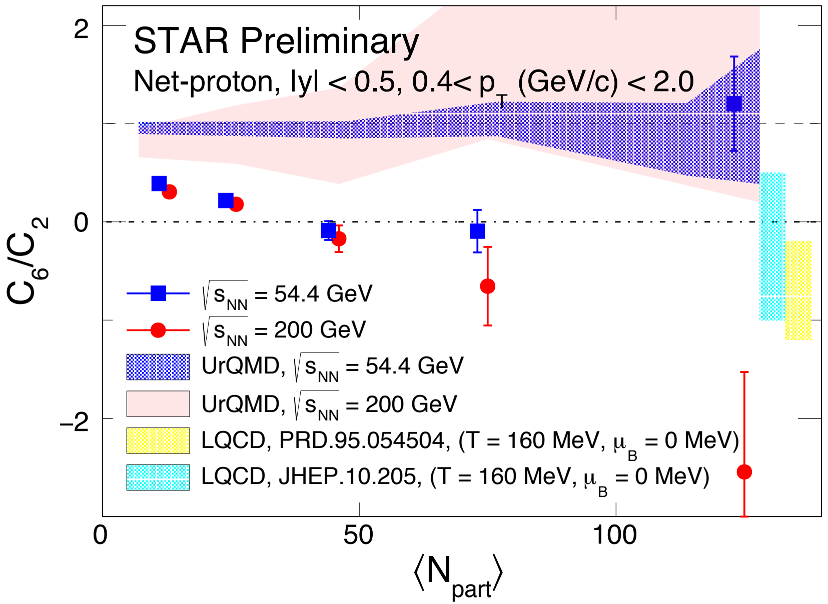
Energy Dependence of Cumulant Ratios



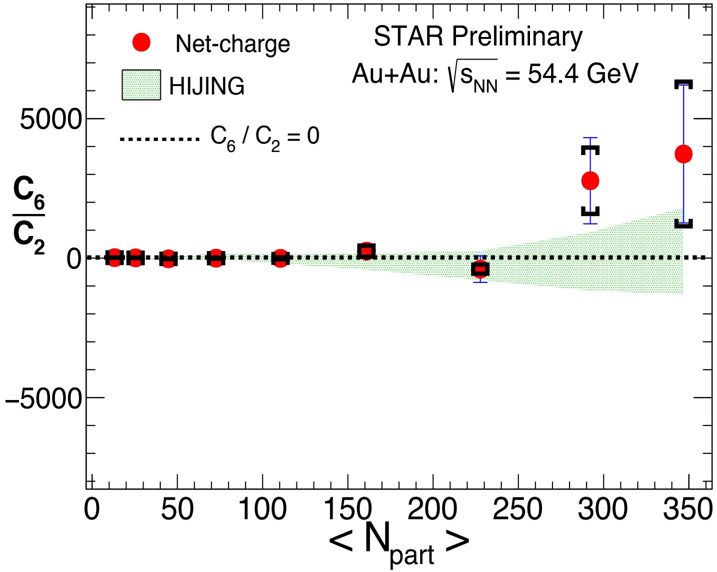
STAR: PoS CPOD2014 (2015) 019
STAR: PRL, 113, 092301 (2014)
STAR: PLB, 785, 551 (2018)

$\kappa\sigma^2$ measurement at 54.4 GeV agrees with the trend from BES-I results. Form precise baseline for critical fluctuation measurements at lower beam energies.

Centrality Dependence of Cumulant Ratio C_6/C_2



See Toshihiro Nonaka's poster : id #586 (QF16)



For most central collisions (0-40%)
$C_6/C_2 < 0$ at 200 GeV
$C_6/C_2 > 0$ at 54.4 GeV

$C_6/C_2 > 0$ at 54.4 GeV at 0-5% and 5-10% collision classes.

Observation of negative sign of C_6/C_2 of net-proton distribution for most central collisions at 200 GeV. Could be the experimental evidence of crossover phase transition.

Summary

STAR

- The first measurements of net-proton, net-kaon and net-charge cumulants (up to the fourth order) presented for Au+Au collisions at $\sqrt{s_{NN}}$ = 54.4 GeV.

- The cumulants of net-proton, net-charge and net-kaon up to the fourth order increase with average number of participant nucleons.

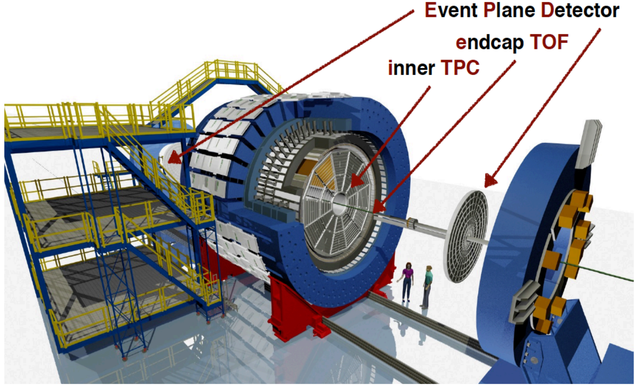
- The cumulant ratios of net-particle:
  - C_2/C_1 shows a strong centrality dependence.
  - C_3/C_2 , C_4/C_2 and C_6/C_2 have a weak centrality dependence.

- The centrality dependence of cumulant ratios is only qualitatively reproduced by the UrQMD and HIJING models. Quantitative differences exist.

- The C_6/C_2 of net-proton and net-charge distribuions for central Au+Au collisions at 54.4 GeV are positive while that for 200 GeV, C_6/C_2 of net-proton distribution is negative (most central). The observed negative sign of C_6/C_2 at 200 GeV could be experimental evidence of cross-over phase transition.

Outlook: Beam Energy Scan Phase – II at RHIC

See Yi Yang's Talk : id #388 (Tue 16:20)

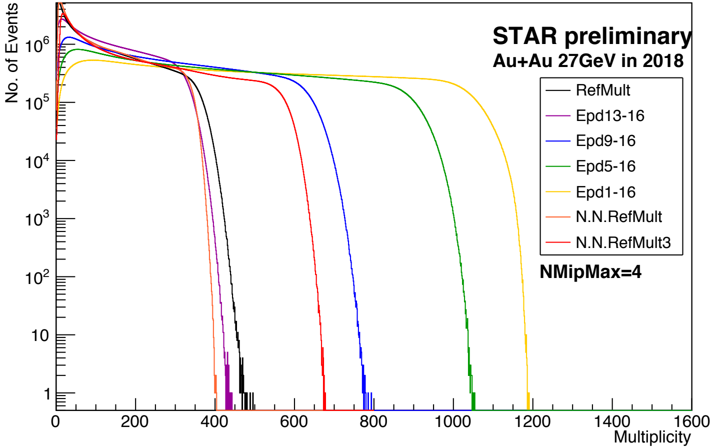


√s (GeV)	Statistics (Millions) – BES-I	Statistics (Millions) – BES-II
7.7	~4	**~100**
9.1	~0.003	**~160**
11.5	~12	**~230**
14.5	~ 20	**~300**
19.6	~36	**~400**
27	~70	**~500**

iTPC	EPD	eTOF
Larger rapidity coverage $|\eta| < 1.5$	$2.1 < |\eta| < 5.1$	$-1.6 < \eta < 1.0$
Better dE/dx resolution	Centrality determination at forward rapidity	PID extended to forward rapidity
Lower momentum acceptance > 0.1 GeV/c	Better event plane resolution	Better particle identification
Physics Impact: Higher moments and Dilepton	Physics Impact: Higher moments, v_n	Physics Impact: Fixed target program and all analysis with PID

Centrality with the EPD

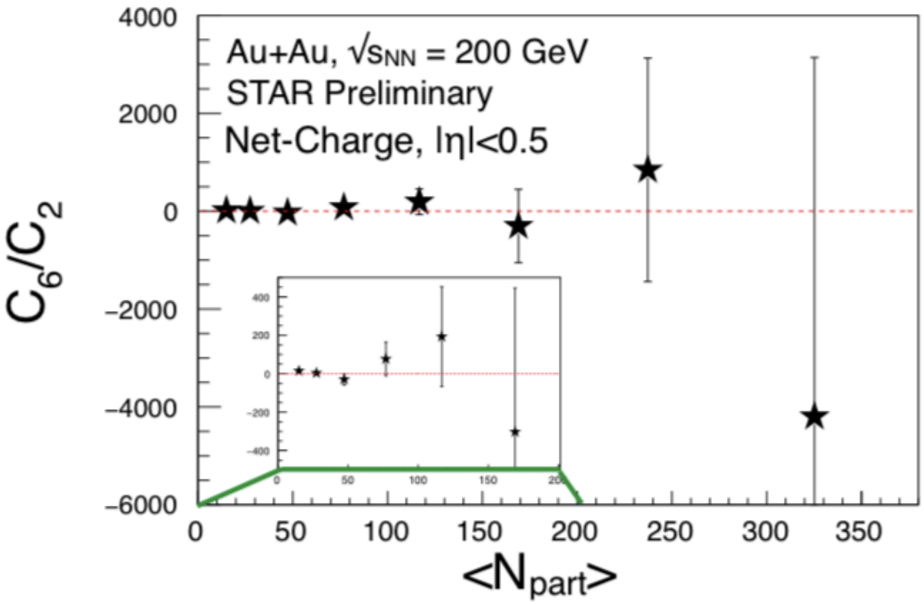
See Yuri Sato's poster : id #644 (FF35)



THANK YOU

BACK UP

Centrality Dependence of Cumulant Ratio C_6/C_2 of Net-Charge Distribution for Au+Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV



C_6/C_2 of net-charge at 200 GeV is negative for most central collisions (0-10% centrality). Consistent with zero with statistical uncertainty.