The Cumulants of Net-proton Multiplicity Distribution at STAR

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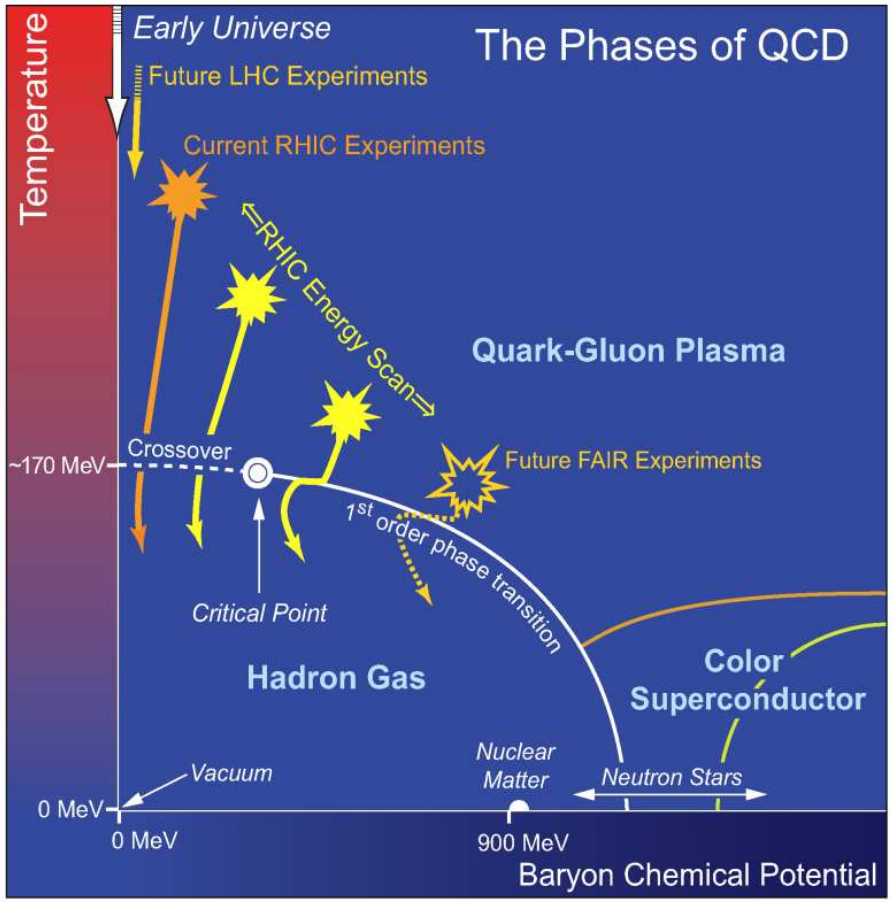
Outline

- **Motivation**
- **STAR Detecting System**
- **Results and Discussions**
  - Centrality dependence
  - Energy dependence
- **Summary**

Motivation



- Lattice QCD: $\mu_B = 0$, Crossover.
  Y. Aoki et al., Nature 443, 675-678(2006).

- QCD based Model,
  T≈0 and large μ_B , first order transition.
  eg: S. Ejiri, Phys. Rev. D 78, 074507 (2008); H. Saito, et al., (WHOT-QCD Collaboration). hep-lat/1106.0974.

- Experiment approach:
  ✓RHIC Beam Energy Scan Program: The search for signatures of phase boundary and critical point.
  http://drupal.star.bnl.gov/STAR/starnotes/public/sn0493. arXiv: 1007.2613.

  ✓High event statistics collected at RHIC top energy.

Important observable: The cumulants ratios of conserved quantities.

Direct connection between theory calculation and experiment.

Ratios of cumulants of net-proton multiplicity

1:The net-proton multiplicity fluctuation can reflect the net-baryon number fluctuation.

Y. Hatta et al,PRL 91, 102003 (2003)

2: Related to the ratios of the susceptibilities directly.

$$\chi_3^B / \chi_2^B \approx \left(\frac{1}{VT^3} C_3\right) / \left(\frac{1}{VT^3} C_2\right) = S\sigma$$

$$\chi_4^B / \chi_2^B \approx \left(\frac{1}{VT^3} C_4\right) / \left(\frac{1}{VT^3} C_2\right) = C_4 / C_2 = \kappa\sigma^2$$

$$\chi_6^B / \chi_2^B \approx \left(\frac{1}{VT^3} C_6\right) / \left(\frac{1}{VT^3} C_2\right) = C_6 / C_2$$

✓Cancel the volume effect.

3: Hadron Resonance Gas expectation:

$$\frac{C_{2n+1}}{C_2} = \tanh(\mu_B / T), \quad \frac{C_{2n}}{C_2} = 1 \quad (n = 1, 2, 3 \cdots)$$

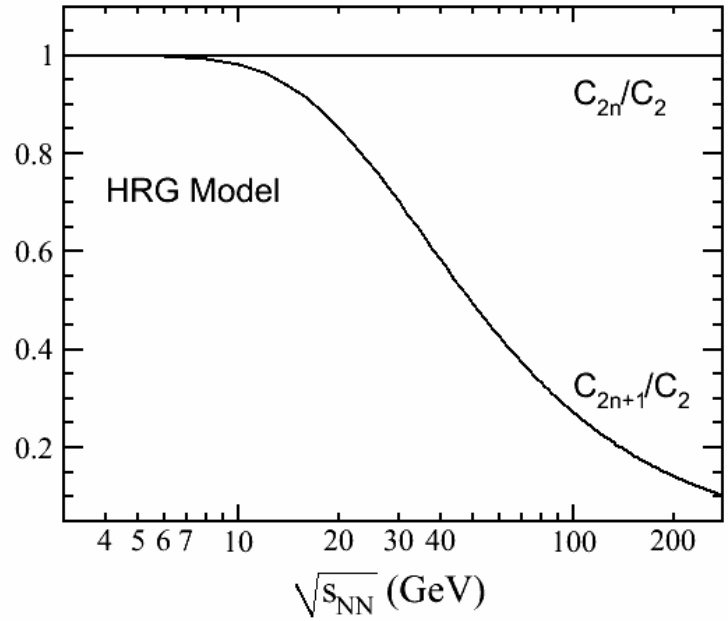
F. Karsch and K. Redlich, Phys. Lett. B 695, 136 (2011)

$$C_2 = \langle \delta N_{p-\bar{p}}^2 \rangle$$

$$C_3 = \langle \delta N_{p-\bar{p}}^3 \rangle$$

$$C_4 = \langle \delta N_{p-\bar{p}}^4 \rangle - 3 \langle \delta N_{p-\bar{p}}^2 \rangle^2$$

$$C_6 = \langle \delta N_{p-\bar{p}}^6 \rangle - 15 \langle \delta N_{p-\bar{p}}^4 \rangle \langle \delta N_{p-\bar{p}}^2 \rangle - 10 \langle \delta N_{p-\bar{p}}^3 \rangle^2 + 30 \langle \delta N_{p-\bar{p}}^2 \rangle^3$$



Ratios of cumulants of net-proton multiplicity

4: Sensitive to the correlation length

$$\langle \delta N^k \rangle \sim \xi^{2.5k-3} \longrightarrow \begin{array}{l} \langle \delta N^3 \rangle \sim \xi^{4.5} \\ \langle \delta N^4 \rangle - 3\langle \delta N^2 \rangle^2 \sim \xi^7 \end{array}$$

M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009).
arXiv:1104.1627

✓ The correlation length away from the CP (Critical Point): $\xi \sim 0.5 - 1\, fm$

✓Near the CP, due to the critical slowing down:
Magnitude of ξ is limited: $\xi \sim 2 - 3\, fm$

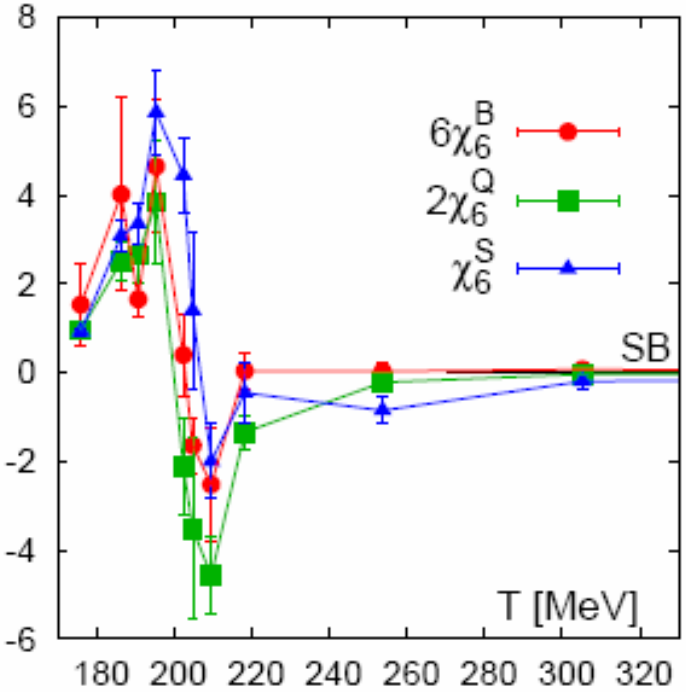
B. Berdnikov, K. Rajagopal, Phys. Rev. D 61, 105017 (2000).

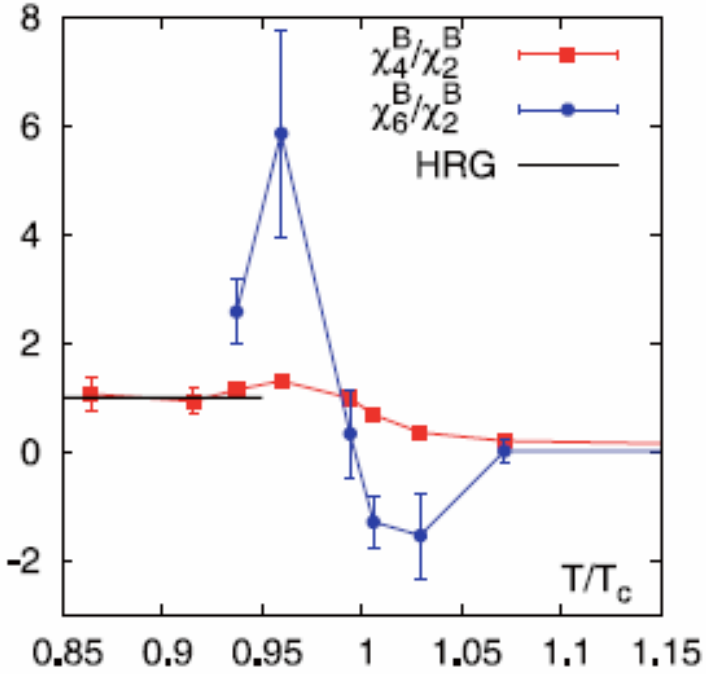
✓Higher moments are more sensitive to the critical point.

✓ **Non-monotonic signal as function of energy is expected to be observed near CP.**

Ratios of cumulants of net-proton multiplicity

5: Sensitive to the QCD Critical Temperature Tc

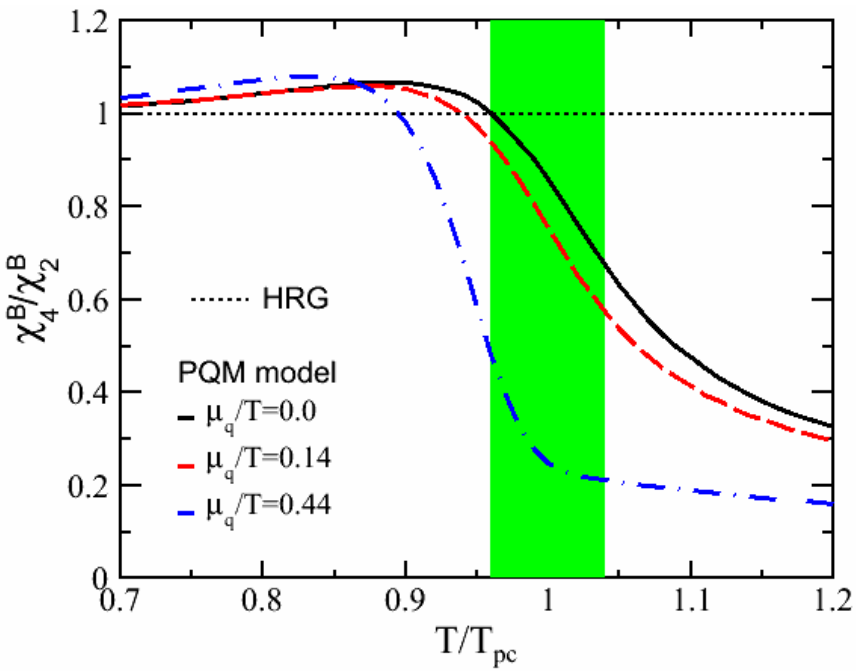


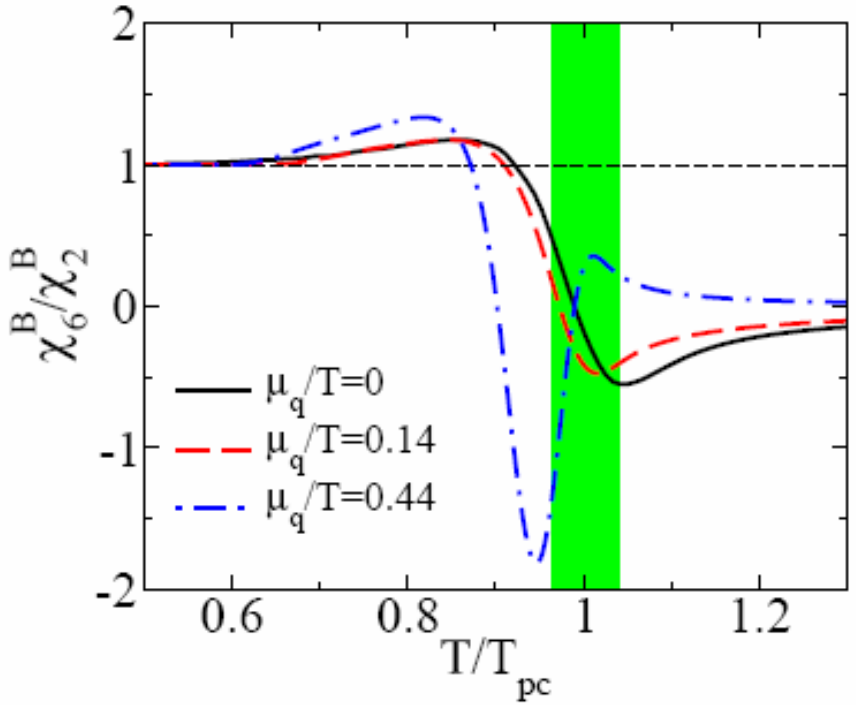


Cheng et al, Phys.Rev. D79 (2009) 074505，Prog.Theor.Phys.Suppl. 186 (2010) 563-566

- Both χ_6^B/χ_2^B and χ_4^B/χ_2^B deviate from unity near the Tc.
- The χ_6^B/χ_2^B are much more sensitive to the Tc.
- Lattice Prediction: At LHC and RHIC high energy, the experiment may observe the negative χ_6^B/χ_2^B if the freeze-out curve close to the phase transition line.

Ratios of cumulants of net-proton multiplicity



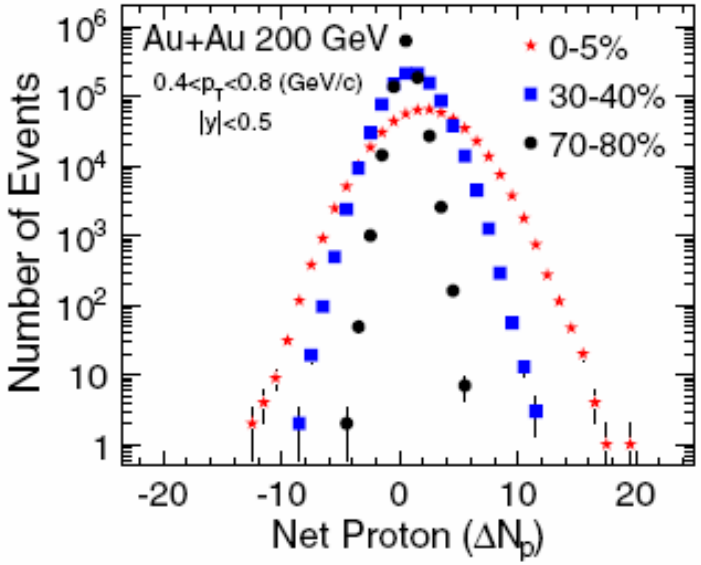


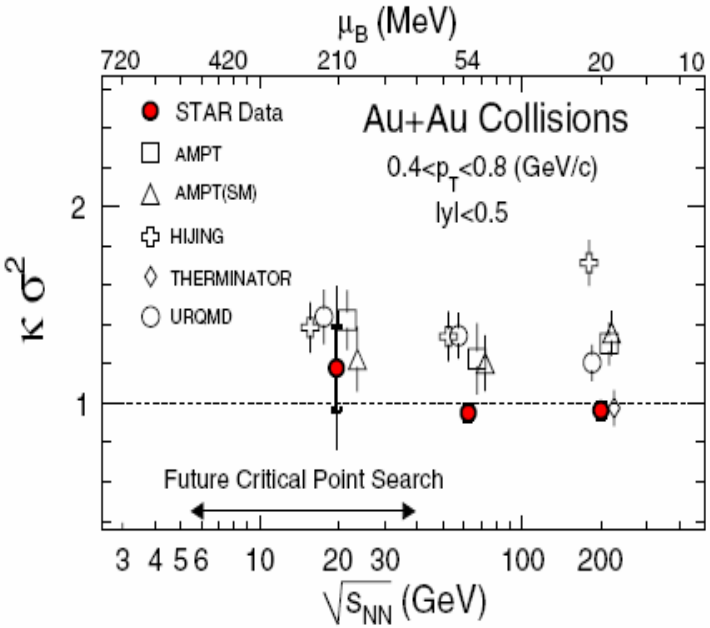
- The Polyakov loop extended quark meson (PQM) model is an effective model to study the thermodynamics near the chiral phase transition.

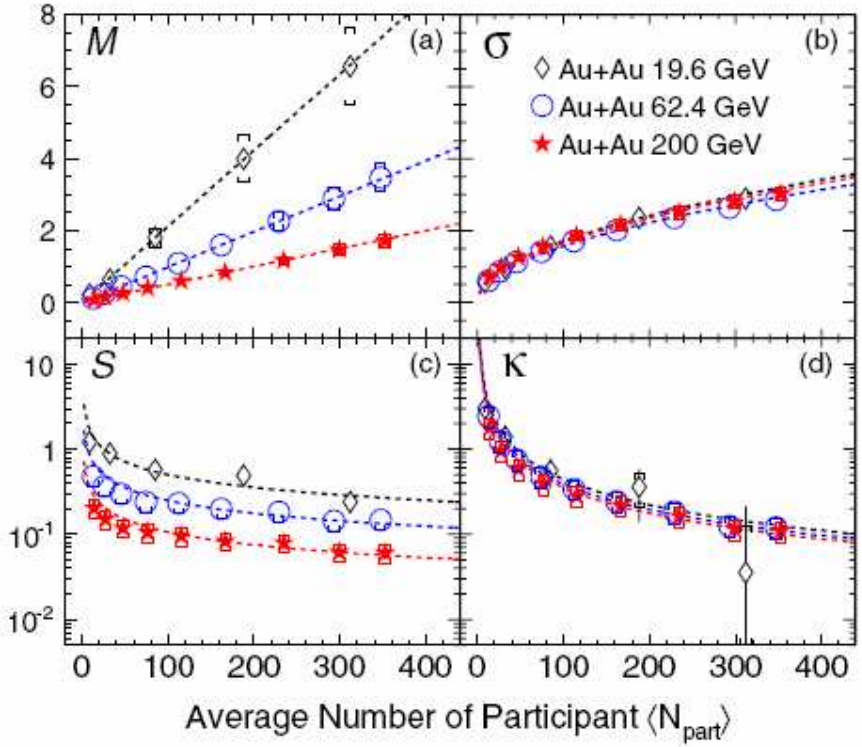
- The structure of the fluctuation in PQM model are similar with Lattice QCD for both χ_6^B/χ_2^B and χ_4^B/χ_2^B .

B. Friman, F. Karsch, K. Redlich and V. Skokov. Eur. Phys. J. C71, 1694 (2011)

First result on higher moments of net-proton



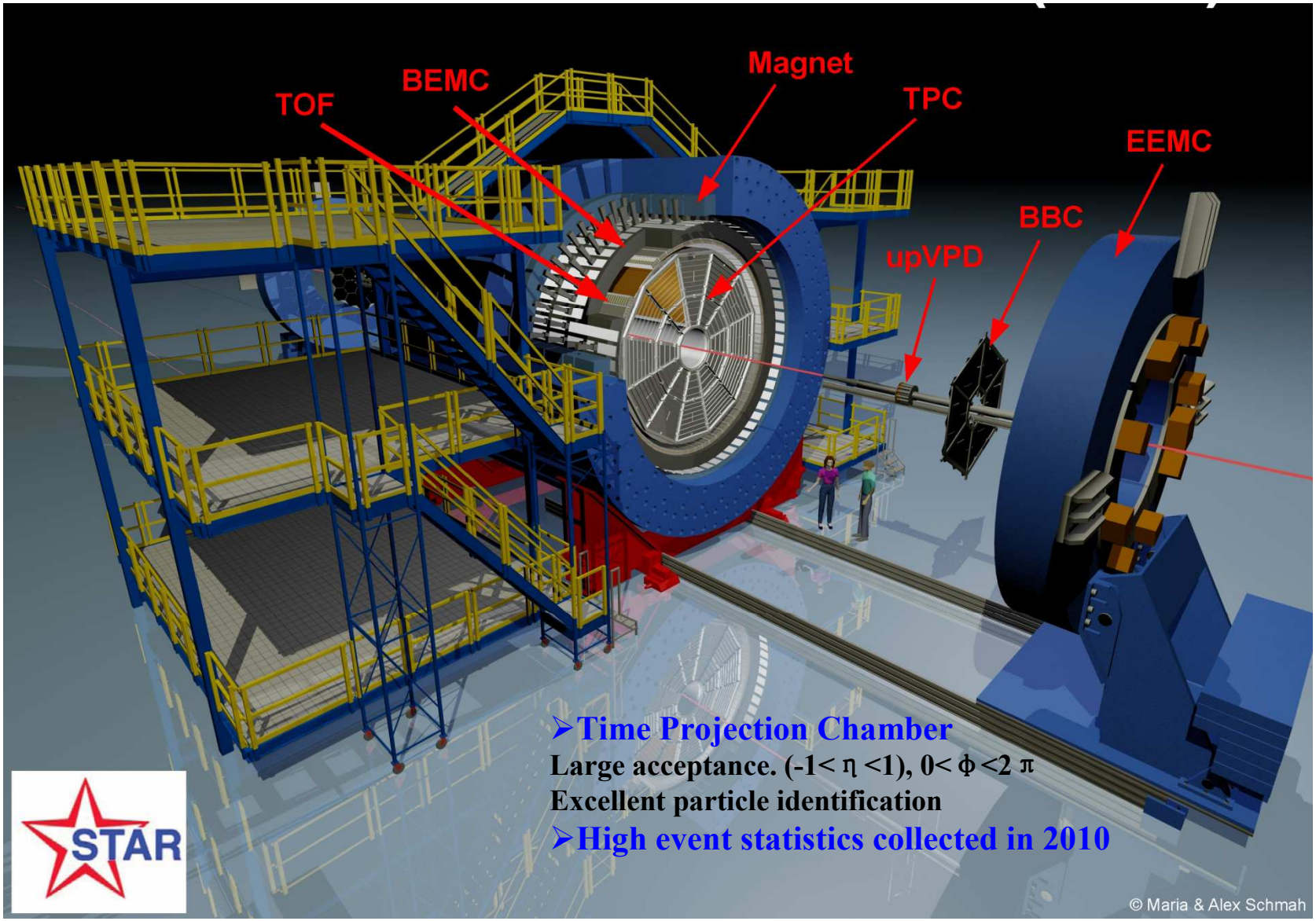




STAR Collaboration, PRL 105 (2010) 022302.

- STAR first results on higher moments analysis are up to fourth order.
- Using ratios used to establish base line measurements for the QCD critical point search.
- **This talk: C_6 / C_2 and C_4 / C_2.**

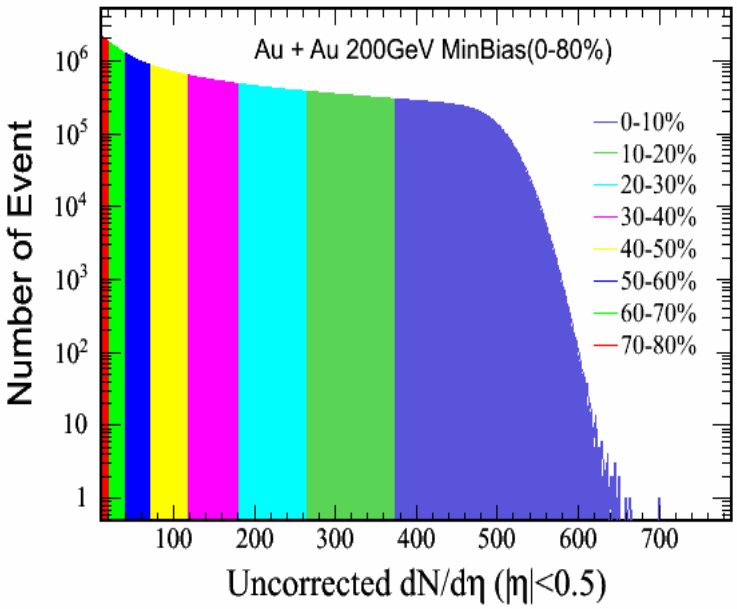
STAR Detecting System



- **Time Projection Chamber**
  Large acceptance. ($-1< \eta <1$), $0< \phi <2\pi$
  Excellent particle identification
- **High event statistics collected in 2010**

Analysis Detail

➢ The centrality definition and data collection



- ✓ 200 GeV: 404 Million totally*
- ✓ 39 GeV: 125 Million MB
- ✓ 11.5 GeV: 14 Million MB
- ✓ 7.7 GeV: 4.2 Million MB

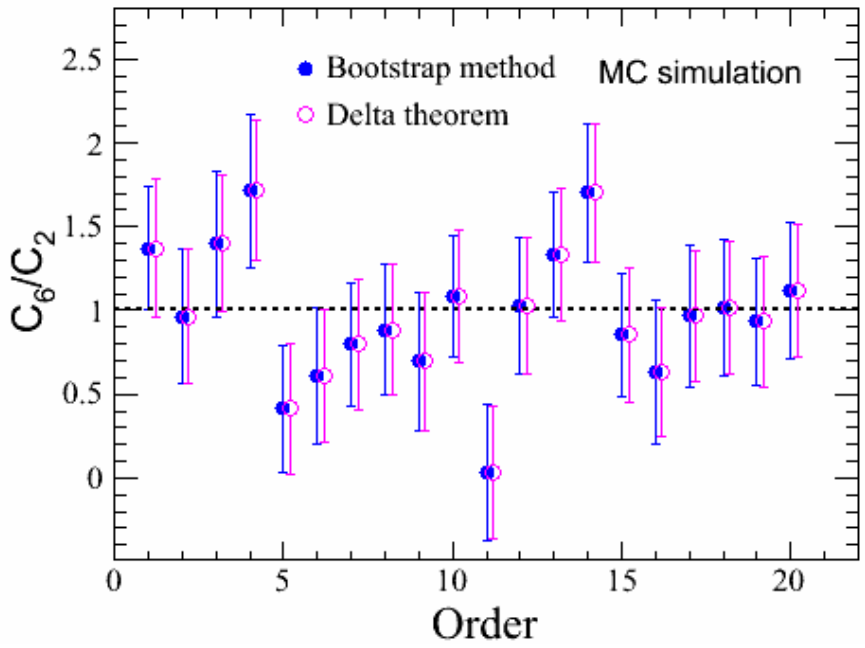
*For Central collisions of 200 GeV, the data are from MinBias and central-triggered datasets.

Kinematic range of protons:

- Midrapidity: $|y| < 0.5$
- p_T : 0.4 - 0.8 GeV/c

Analysis Detail

➢ Statistical error propagation method study



(a): The 20 samples are from MC simulation based on the Skellam distribution.
(b): Input parameter for MC simulation:
mean value: $\mu_1 = 4.0, \mu_2 = 3.0,$
Number of event for each sample: 30 Million.

- Trying different methods for data analysis
  (a) Sub-group method.
  (b) Bootstrap method .
  (c) Delta theorem method.

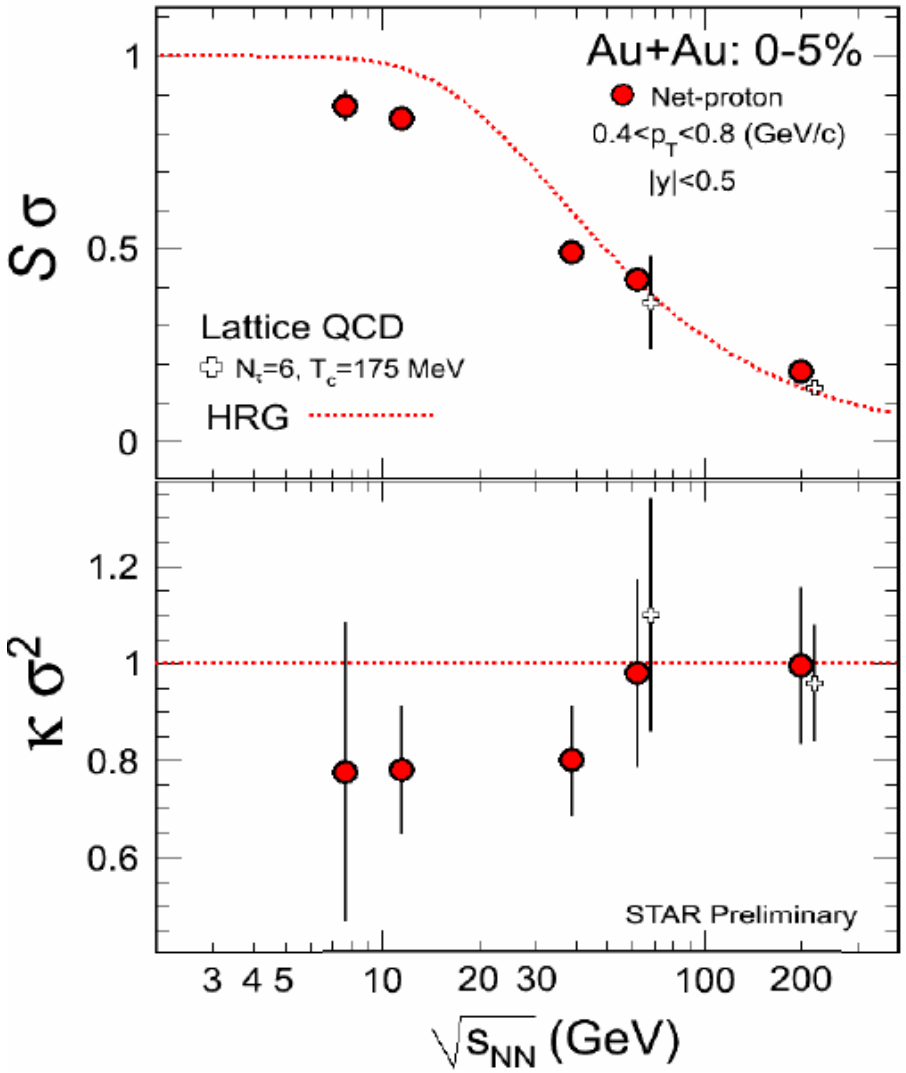
- The statistical error estimated by sub-group method is unstable.

- The bootstrap method and delta theorem give the consistent result for statistical error estimation.

- Using bootstrap method for data analysis.

Bradley Efron,http://www.jstor.org/pss/2030104.
X. Luo, arXiv:1109.0593

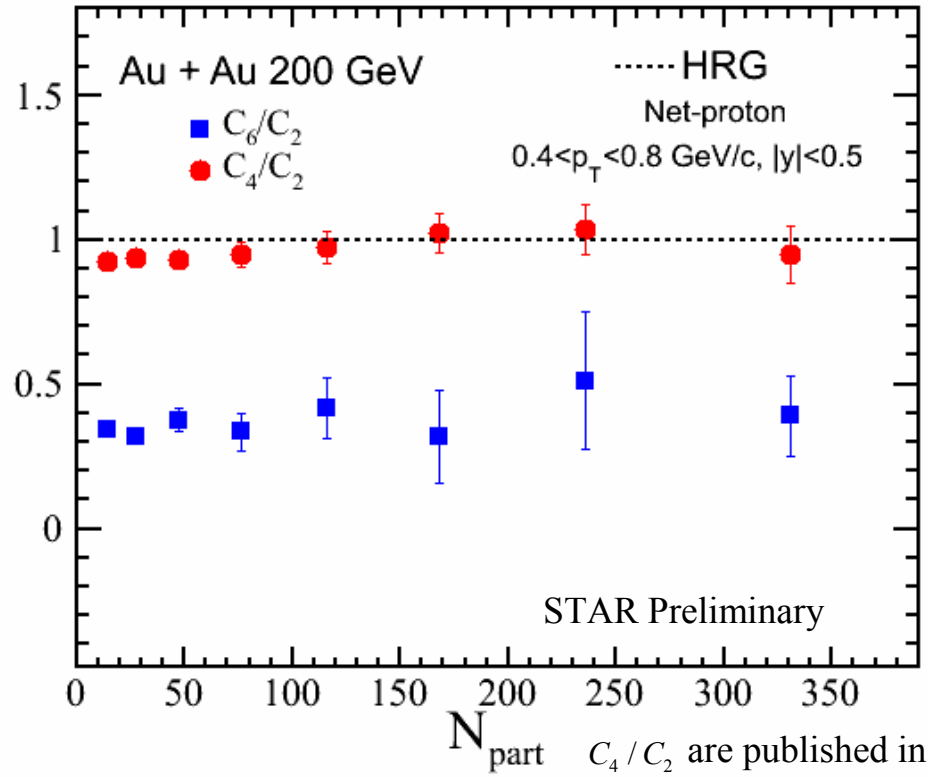
Results (I): Energy dependence of product moments



X. Luo, SQM 2011

- Data are compared with HRG and Lattice QCD.

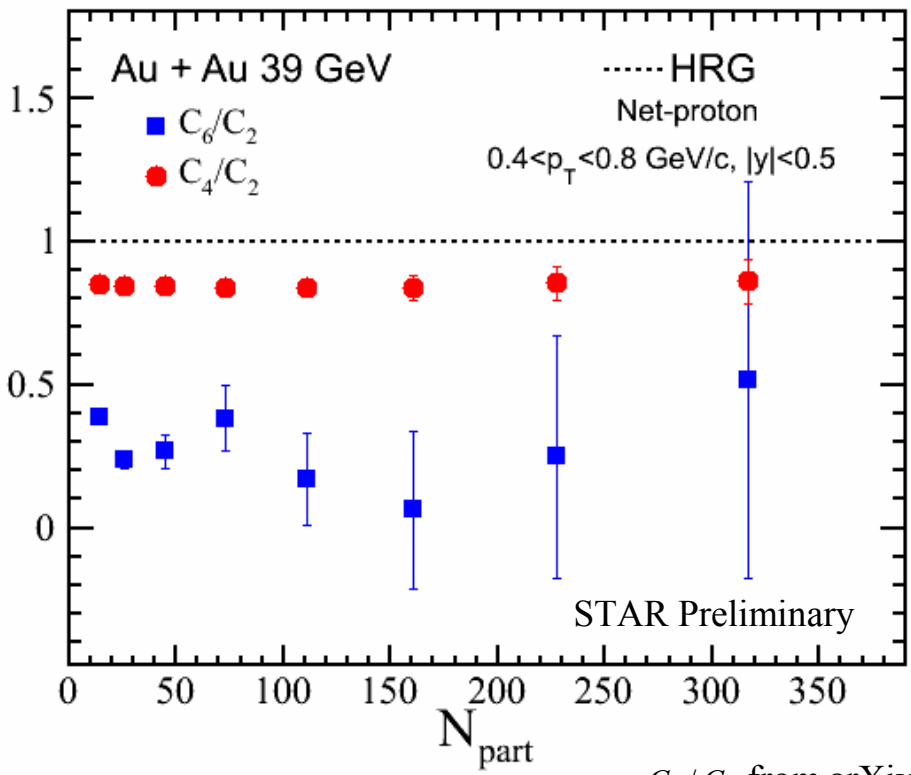
Results (II): Au + Au 200 GeV



C_4/C_2 are published in PRL 105 (2010) 022302.

- Central collisions, MinBias Trigger and Central Trigger datasets.
- The centrality dependence is small.
- C_4/C_2 are consistent with unity for central collisions.
- First results of C_6/C_2

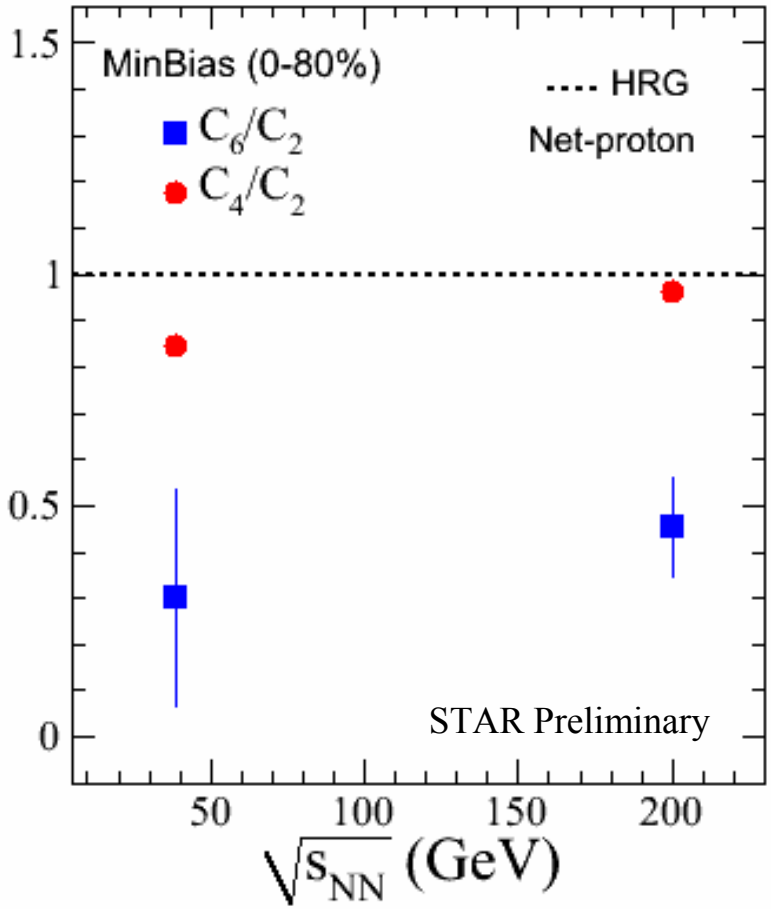
Results (III): Au + Au 39 GeV



C_4/C_2 from arXiv:1106.2926

- C_4/C_2 deviate from the unity.
- C_6/C_2 show similar trends with Au + Au 200 GeV. But larger error in central collisions.

Results (IV): Energy dependence



- Data:
  The deviation for C_4/C_2 from HRG at lower energy.

- Theory:
  The deviation from the HRG results grow with increasing energy.

P. Braun-Munzinger, B. Friman, et al. arXiv: 1107.4267

Summary

- The cumulant ratio of conserved quantities provide a directly connection between theory calculation and experiment. It is an important observable for studying the QCD phase diagram.

- We report the first results of net-proton C_6/C_2 in Au + Au collisions at 39 and 200 GeV .

Outlook: Au + Au Collisions at 19.6, 27 and 62.4 GeV data are under analysis.