Beam energy and centrality dependence of the statistical moments of the net-charge and net-Kaon multiplicity distributions in Au+Au collisions at STAR

Daniel McDonald for the STAR Collaboration
Rice University
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QCD phase diagram

- Top RHIC energies
- baryochemical potential is small
- crossover transition

Various indirect suggestions of 1st order phase transition. Under discussion in the theory community.

Lattice QCD is difficult (different actions, numerical sign problem).

However, this topic can be addressed experimentally!

STAR, arXiv:1007.2613 [nucl-ex]

Thus, a critical point (CP) might exist somewhere in between these extremes at the end of the 1st order phase transition…
- Varying the beam energy results in different trajectories through this space. Decreasing the beam energy results in larger $\mu_B$ values, as shown in the cartoon below.

| $\sqrt{s_{NN}}$ (GeV) | MB Events in $10^6$ | $\mu_B$ (MeV) |
|------------------------|---------------------|---------------|
| 7.7                    | 4.3                 | 421           |
| 11.5                   | 11.7                | 316           |
| 19.6                   | 35.8                | 206           |
| 27                     | 70.4                | 156           |
| 39                     | 130.4               | 112           |
| 62.4                   | 67.3                | 73            |
| 200                    | 587                 | 24            |

- We will be describing data collected by the STAR experiment at: $\sqrt{s_{NN}} = 7.7, 11.5, 19.6, 27, 39, 62.4, 200$ GeV

Cleymans et al. PRC 73,034905 (2006)
Correlation length divergence near the critical point

At the critical point the correlation length, $\xi$, should diverge.

- “critical opalescence”

For $T \sim T_c$, substance becomes “cloudy,” indicating long-range density fluctuations.

T. Andrews, Phil. Trans. Royal Soc., 159:575, 1869
A. Einstein, Annalen der Physik, 33 (1910) 1275-1298

At the critical point, the susceptibility, $\chi$, should diverge.

$$\chi_n^B = -\frac{1}{3^n} \frac{\partial^n f / T^4}{\partial \mu_q^n}$$

Susceptibility is the derivative of free energy vs. baryochemical potential

Susceptibilities
Z. Fodor, PoS, 11, 2007
Pure SU(3) Gauge Theory, Polyakov Loop

Different volumes (lattice sizes) in different colors

Full QCD, Lattice
$\beta \sim$ temperature
Electric charge susceptibility

Charge susceptibility, $\chi^Q$, may be sensitive to the chiral phase transition. 
Skokov et al, PLB, 708, 2012, 179-185.

Fluctuations of $\chi^Q$ are related to net-baryon ($\chi^B$) and isospin ($\chi^I$) fluctuations.
Gavai, Gupta. PLB, 696 (2011), 459-463

Charge susceptibility ratios are related to the correlation length, $\xi$:

$\sim \chi^Q_3/\chi^Q_2 \sim \xi^{5/2}$

$\sim \chi^Q_4/\chi^Q_2 \sim \xi^5$

Strong dependence on $\xi$, so may reflect long-range correlations near the critical point.

HRG = Hadron Resonance Gas. 
FRG = Functional Renormalization Group 
Andronic et al. PLB, 571 (2003).
Experiment observables

We measure the multiplicity distributions of particles and the multiplicity cumulants.

**“deviate”**

\[ \delta x \equiv x - \langle x \rangle \]

**“cumulants”**

- \[ \kappa_{2x} \equiv \langle x^2 \rangle \equiv \langle (\delta x)^2 \rangle \]
- \[ \kappa_{3x} \equiv \langle x^3 \rangle \equiv \langle (\delta x)^3 \rangle \]
- \[ \kappa_{4x} \equiv \langle x^4 \rangle \equiv \langle (\delta x)^4 \rangle - 3 \langle (\delta x)^2 \rangle^2 \]

**skewness** = \[ \frac{\kappa_3}{\kappa_2^{3/2}} \]

**kurtosis** = \[ \frac{\kappa_4}{\kappa_2^2} \]

- S = \[ \frac{\kappa_3}{\kappa_2} \]
- K = \[ \frac{\kappa_4}{\kappa_2} \]

**Final observables**

\[ S \sigma = \kappa_3/\kappa_2 \]

\[ K \sigma^2 = \kappa_4/\kappa_2 \]

These cumulants of conserved charge are related not only to \( \xi \), but also to \( \chi^Q \):

- \[ \kappa_{3} / \kappa_{2} \sim \chi_{3}^{Q} / \chi_{2}^{Q} \sim \xi^{5/2} \]
- \[ \kappa_{4} / \kappa_{2} \sim \chi_{4}^{Q} / \chi_{2}^{Q} \sim \xi^{5} \]

Near the critical point, the cumulants will diverge with large powers of the correlation length (\( \xi \)). Higher moments scale with higher powers of the correlation length.

- \[ \kappa_{2x} = \langle (\delta x)^2 \rangle \sim \xi^{2} \]
- \[ \kappa_{3x} = \langle (\delta x)^3 \rangle \sim \xi^{9/2} \]
- \[ \kappa_{4x} = \langle (\delta x)^4 \rangle - 3 \langle (\delta x)^2 \rangle^2 \sim \xi^{7} \]

Gavai, Gupta. *PLB*, 696 (2011), 459-463

Stephanov PRL 102, 032301 (2009)
Sensitivity to critical phenomena

Lattice implies $K\sigma^2 = \chi_4^Q/\chi_2^Q$ increases by an order of magnitude ($\sim 5/0.6$).

Non-linear sigma model predicts enhancements to the proton and pion cumulants of order 10-100.

Both lattice and a phenomenological field theory model predict factor $> \sim 10$ enhancements in $\kappa_4$ and $K\sigma^2$. 

\begin{align*}
\omega_4^p &\quad \sim \kappa_4^p/\langle N_p \rangle \\
\chi_2^Q &\quad \sim 0.6 \\
\chi_4^Q &\quad \sim 5
\end{align*}

Athanasiou et al. arXiv: 1006.4636v2 [hep-ph]

Y. Hatta et al. PRD 67, 014028 (2003)
Third and fourth moments may be very sensitive to possible critical fluctuations, but are also very sensitive to experiment effects (background, drift, etc). It is important to remove these experimental effects via careful data QA and cuts.

Good event cuts:
- all beam energies: $|Z_{vtx}| < 30 \text{ cm, } R_{vtx} < 2 \text{ cm, and other cuts on global observables}$
- careful bad run and bad event rejection performed

Good track cuts:
- $N_{hitsfit} > 20, N_{hitsdE/dx} > 10, |\eta| < 0.5, \text{ globaldca } < 1.0 \text{ cm, } N_{hitsratio} > 0.52$
- $0.2 < p_t < 2.0 \text{ GeV, } p < 1.6 \text{ GeV/c for K (TPC+TOF)}$  
- $0.2 < p_t < 2.0 \text{ GeV/c for charge}$

Numbers of events surviving cuts in the 0-80% centrality range

| Energy  | # events |
|---------|----------|
| 7.7 GeV | 1.4 M    |
| 11.5 GeV| 2.4 M    |
| 19.6 GeV| 15.5 M   |
| 27 GeV  | 24.1 M   |
| 39 GeV  | 55.8 M   |
| 62.4 GeV| 31.4 M   |
| 200 GeV | 74.6 M   |
Moments are corrected for centrality bin-width effects by using track-multiplicity weighted average of the moments inside each centrality bin.

Centrality definition separated from analysis region to avoid autocorrelations between the centrality definition and the multiplicity moments.

Error bars are statistical only and calculated using the Delta Theorem.

Will show moments products for 2 particle groups:

- $K^+ - K^-$ “net-Kaons”
- pos-neg “net-charge”

...see also Amal Sarkar's poster
...see also Nihar Sahoo's poster

Will compare to “baselines” from Poisson statistics and HRG model.

**HRG model**

Moments are functions of thermodynamic parameters.

- \[ S\sigma = \tanh(Q_i\mu_i/T) \quad Q_i = \text{electric charge} \]
- \[ K\sigma^2 \sim 1.8 \quad (\text{very weakly dependent on } \sqrt{s_{NN}}) \]

Karsch & Redlich, *PLB* 695, 136 (2011).
A. Andronic, *et al.*, Nucl. Phys. A 772 (2006) 167

**Poisson Statistics**

Moments are functions only of the mean values

- \[ S\sigma = (M^+ - M^-)/(M^+ + M^-) \]
- \[ K\sigma^2 = 1 \quad M = \text{mean value} \]
S\sigma, K\sigma^2 net-Kaons, 0-5% centrality

No significant enhancement relative to Poisson baseline observed.
$S\sigma$, net-Kaons, centrality dependence

- $S\sigma$ is independent of centrality to within $\sim 15\%$.
- $S\sigma$ is greater than the Poisson baseline.
$\mathbf{K\sigma^2}$, net-Kaons, centrality dependence

- $\mathbf{K\sigma^2}$ is independent of centrality to within $\sim 10\%$.
- $\mathbf{K\sigma^2}$ is generally greater than the Poisson baseline.
$S\sigma$, $K\sigma^2$ net-charge, 0-5% centrality

- In 0-5% central collisions, $S\sigma$ is greater than the Poisson baseline and less than the HRG prediction.
$S\sigma$, net-charge, centrality dependence

- $S\sigma$ is independent of centrality to within $\sim10\%$.
- $S\sigma$ is generally greater than the Poisson baseline.
$K\sigma^2$ net-charge, centrality dependence

$K\sigma^2$ is generally independent of centrality and is above the Poisson baseline at all $\sqrt{s_{NN}}$. 

STAR Preliminary
Summary

- Critical point might result in non-monotonic changes to the statistical moments of the multiplicity distributions of specific groups of identified charged particles.

- Studied Au+Au collisions for beam energies, $\sqrt{s_{NN}}$, from 7.7 - 200 GeV ($\sim 20 < \mu_B < \sim 420$ MeV).
  - Care taken to obtain clean data and to avoid autocorrelations

- Showed moments products $S\sigma$ and $K\sigma^2$ for two particle groups: net-charge and net-Kaons.
  - Compared to Poisson baselines and the Hadron Resonance Gas model
  - Moments products do not depend significantly on the centrality of the collision
  - For both net-charge and net-Kaons, $S\sigma$ and $K\sigma^2$ are above or near the Poisson baseline
  - Net-charge $K\sigma^2$ values in central collisions are close to the HRG predictions
  - Net-charge $S\sigma$ values in central collisions are below the HRG predictions

- At the presently available beam energies, of order 10-100 enhancements of the moments products was not observed.

Thank you!