Searching for the QCD Critical Point Through Fluctuations at RHIC

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Introduction

- Event-by-event fluctuation of conserved quantities (Charge, Q / Baryon number, B / Strangeness, S) to study phase transition
  - Cross-over at small $\mu_B$
  - Critical point
  - First order at large $\mu_B$
- Experimental observables
  - Correlation functions of particles
Higher-order Fluctuations

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

\[ C_2 = \langle (\delta N)^2 \rangle \sim \xi^2; \quad C_3 = \langle (\delta N)^3 \rangle \sim \xi^{4.5}; \quad C_4 = \langle (\delta N)^4 \rangle \sim \xi^7 \]

- Connection to the susceptibility of the system

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

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

\[ \frac{\chi_q^{(4)}}{\chi_q^{(2)}} = \frac{C_{4,q}}{C_{2,q}} \quad \frac{\chi_q^{(6)}}{\chi_q^{(2)}} = \frac{C_{6,q}}{C_{2,q}} \]

- Theory → Experiment

\[ \delta N = N - \langle N \rangle \]

CIPANP 2018

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. 113 (2014) 092301
Based on factorial cumulants: T. Nonaka, M. Kitazawa and S. Esumi, PRC 95 064912(2017)
## Analysis details

<table>
<thead>
<tr>
<th></th>
<th>Net-Charge</th>
<th>Net-Proton</th>
<th>Net-Kaon</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Kinematic cuts</strong></td>
<td>0.2 &lt; ( p_T ) (GeV/c) &lt; 2.0,</td>
<td>0.4 &lt; ( p_T ) (GeV/c) &lt; 2.0,</td>
<td>0.2 &lt; ( p_T ) (GeV/c) &lt; 1.6,</td>
</tr>
<tr>
<td></td>
<td>(</td>
<td>\eta</td>
<td>&lt; 0.5 )</td>
</tr>
<tr>
<td><strong>Particle Identification</strong></td>
<td>Reject protons form spallation for ( p_T &lt; 0.4 ) GeV/c</td>
<td>0.4 &lt; ( p_T ) (GeV/c) &lt; 0.8 ( \rightarrow ) TPC</td>
<td>0.2 &lt; ( p_T ) (GeV/c) &lt; 0.4 ( \rightarrow ) TPC</td>
</tr>
<tr>
<td></td>
<td>( p_T &gt; 0.8 ) GeV/c &lt; 2.0 ( \rightarrow ) TPC+ToF</td>
<td>0.8 &lt; ( p_T ) (GeV/c) &lt; 2.0 ( \rightarrow ) TPC+ToF</td>
<td>0.4 &lt; ( p_T ) (GeV/c) &lt; 1.6 ( \rightarrow ) TPC+ToF</td>
</tr>
<tr>
<td><strong>Centrality definition, \rightarrow to avoid auto-correlations</strong></td>
<td>Uncorrected charged primary particles multiplicity distribution</td>
<td>Uncorrected charged primary particles multiplicity distribution, without (anti-)protons</td>
<td>Uncorrected charged primary particles multiplicity distribution, without (anti-)kaons</td>
</tr>
<tr>
<td></td>
<td>( 0.5 &lt;</td>
<td>\eta</td>
<td>&lt; 1.0 )</td>
</tr>
</tbody>
</table>

### Diagrams

1. **Proton Mass**
   - Mass (GeV/c^2) vs. \( p_T \) (GeV/c)

2. **Proton Rapidity**
   - Rapidity vs. \( p_T \) (GeV/c)

3. **Kaon Rapidity**
   - Rapidity vs. \( p_T \) (GeV/c)
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

Net-Charge

Net-Kaon

Net-Proton

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

\[
\begin{align*}
\hat{\kappa}_1 &= C_1 \\
\hat{\kappa}_2 &= C_2 - C_1 \\
\hat{\kappa}_3 &= C_3 - 3C_2 + 2C_1 \\
\hat{\kappa}_4 &= C_4 - 6C_3 + 11C_2 - 6C_1 \\
C_1 &= \langle N \rangle \\
C_2 &= \langle N \rangle + \hat{\kappa}_2 \\
C_3 &= \langle N \rangle + 3\hat{\kappa}_2 + \hat{\kappa}_3 \\
C_4 &= \langle N \rangle + 7\hat{\kappa}_2 + 6\hat{\kappa}_3 + \hat{\kappa}_4
\end{align*}
\]

Non-monotonic energy dependence is observed for 4\textsuperscript{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.
Non-binomial efficiency

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

- Multiplicity dependent efficiency

\[ \text{Au+Au @ } \sqrt{s_{NN}} = 200 \text{ GeV} \]

\[ p_T \text{ integrated efficiency} \]

\[ N_{ch} - N_p - N_p \]

\[ P(N) = \frac{(N)^N}{N!} e^{-(N)}, \]

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

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
Unfolding - an example

AMPT model with multiplicity-dependent efficiency for 0-5% central Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV

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

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

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.

BES-II at RHIC

More Data
RHIC Luminosity Upgrade for Low Energies

STAR Data: 0-5% Au+Au Collisions at 7.7 GeV

0.4 < p_T < 2.0 GeV (Prelim.)

BES-II

\( f = 1 - p_0^*x + p_1^*x^2 \)


iTPC upgrade extends the rapidity coverage to \( \Delta y = 1.6 \)
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!