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

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Outline
1. Introduction
2. Observable
3. The STAR Experiment
4. Higher Moment Analysis
5. Results
6. Summary
Introduction: QCD Phase Diagram & BES

Goal: Study the phase diagram of QCD.
BES: Varying beam energy varies Temperature (T) and Baryon Chemical Potential ($\mu_B$). 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

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

\[
\begin{align*}
C_1 &= <N> \\
C_2 &= <(\delta N)^2> \\
C_3 &= <(\delta N)^3> \\
C_4 &= <(\delta N)^4> - 3 <(\delta N)^2>^2
\end{align*}
\]

Higher order cumulants of conserved number distributions are sensitive observables.\(^*\) Related to the correlation length and susceptibilities.

\[
\begin{align*}
C_2 &\sim \xi^2 \\
C_4 &\sim \xi^7
\end{align*}
\]

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

Kurtosis of net-proton in the presence of CP

\[\sqrt{\bar{g}}\]

\[\omega_4\]

\(\mu_B\)

### The Sixth-Order Cumulant

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

<table>
<thead>
<tr>
<th>Freeze-out conditions</th>
<th>$\chi_4^B / \chi_2^B$</th>
<th>$\chi_6^B / \chi_2^B$</th>
<th>$\chi_4^Q / \chi_2^Q$</th>
<th>$\chi_6^Q / \chi_2^Q$</th>
</tr>
</thead>
<tbody>
<tr>
<td>HRG</td>
<td>1</td>
<td>1</td>
<td>~2</td>
<td>~10</td>
</tr>
<tr>
<td>QCD: $T_{\text{freeze}} / T_{pc} \leq 0.9$</td>
<td>$\geq 1$</td>
<td>$\geq 1$</td>
<td>~2</td>
<td>~10</td>
</tr>
<tr>
<td>QCD: $T_{\text{freeze}} / T_{pc} \approx 1$</td>
<td>$\sim 0.5$</td>
<td>$&lt; 0$</td>
<td>~1</td>
<td>$&lt; 0$</td>
</tr>
</tbody>
</table>

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

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**Data Set**

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

<table>
<thead>
<tr>
<th>Analysis</th>
<th>Particle Type</th>
<th>Transverse Momentum Range ($p_T$)</th>
<th>Rapidity (y)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net-proton</td>
<td>Protons and anti-protons ($p &amp; \bar{p}$)</td>
<td>0.4 to 2.0 GeV/c</td>
<td>$</td>
</tr>
<tr>
<td>Net-kaon</td>
<td>Kaons ($K^+ &amp; K^-$)</td>
<td>0.2 to 1.6 GeV/c</td>
<td>$</td>
</tr>
<tr>
<td>Net-charge</td>
<td>Protons and anti-protons ($p &amp; \bar{p}$) Kaons ($K^+ &amp; K^-$) Pions ($\pi^+ &amp; \pi^-$)</td>
<td>0.4 to 2.0 GeV/c 0.2 to 1.6 GeV/c 0.2 to 1.6 GeV/c</td>
<td>$</td>
</tr>
</tbody>
</table>
Centrality Selection

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

- 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.

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

Au+Au: $\sqrt{s_{NN}} = 54.4$ GeV
Event-by-Event Raw Net-Particle Distributions

- 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. $\frac{\sigma_r}{\sqrt{N_{evts}}}$
Analysis Techniques (Corrections And Uncertainties)

- Reconstruction efficiency correction - binomial model

Net-proton Cumulants

<table>
<thead>
<tr>
<th>Cumulant</th>
<th>$\sigma_{\text{stat}}$ (0-5%)</th>
<th>$\sigma_{\text{sys}}$ (0-5%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$C_1$</td>
<td>0.008%</td>
<td>6%</td>
</tr>
<tr>
<td>$C_2$</td>
<td>0.04%</td>
<td>5%</td>
</tr>
<tr>
<td>$C_3$</td>
<td>1%</td>
<td>7%</td>
</tr>
<tr>
<td>$C_4$</td>
<td>9%</td>
<td>22%</td>
</tr>
</tbody>
</table>

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

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.
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

$C_2/C_1$ 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 Preliminary
Net-proton
Au+Au collisions at RHIC
$0.4 < p_T < 2 \text{ GeV}/c$, $|y|<0.5$

- $0\text{-}5\%$
- $70\text{-}80\%$

---

STAR Preliminary
Net-charge
Au+Au collisions at RHIC

- $0\text{-}5\%$
- $70\text{-}80\%$

---

STAR Preliminary
Net-kaon
Au+Au collisions at RHIC

- $0\text{-}5\%$
- $70\text{-}80\%$

---

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

STAR: PRL, 113, 092301 (2014)
STAR: PLB, 785, 551 (2018)
Centrality Dependence of Cumulant Ratio $C_6/C_2$

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

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.

See Toshihiro Nonaka’s poster: id #586 (QF16)
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 distributions 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.
See Yi Yang’s Talk : id #388 (Tue 16:20)

Outlook: Beam Energy Scan Phase – II at RHIC

<table>
<thead>
<tr>
<th>√s (GeV)</th>
<th>Statistics (Millions) – BES-I</th>
<th>Statistics (Millions) – BES-II</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.7</td>
<td>~4</td>
<td>~100</td>
</tr>
<tr>
<td>9.1</td>
<td>~0.003</td>
<td>~160</td>
</tr>
<tr>
<td>11.5</td>
<td>~12</td>
<td>~230</td>
</tr>
<tr>
<td>14.5</td>
<td>~20</td>
<td>~300</td>
</tr>
<tr>
<td>19.6</td>
<td>~36</td>
<td>~400</td>
</tr>
<tr>
<td>27</td>
<td>~70</td>
<td>~500</td>
</tr>
</tbody>
</table>

iTPC
eTOF

<table>
<thead>
<tr>
<th>iTTPC</th>
<th>EPD</th>
<th>eTOF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Larger rapidity coverage</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Better dE/dx resolution</td>
<td>Centrality determination at forward rapidity</td>
<td>PID extended to forward rapidity</td>
</tr>
<tr>
<td>Lower momentum acceptance &gt; 0.1 GeV/c</td>
<td>Better event plane resolution</td>
<td>Better particle identification</td>
</tr>
</tbody>
</table>

Physics Impact: Higher moments and Dilepton

Centrality with the EPD
See Yuri Sato’s poster : id #644 (FF35)

STAR preliminary
Au+Au 27GeV in 2018

QM2019 - Ashish Pandav
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.