Feasibility studies of conserved charge fluctuations in Au-Au collisions with CBM

Subhasis Samanta (for the CBM Collaboration)

National Institute of Science Education and Research, HBNI, Jatni, India

Outline

★ Introduction
★ CBM experiment
★ Analysis details
★ Results
  ■ Net-proton cumulants
  ■ Net-charge cumulants
★ Summary
Study QCD phase diagram at high net-baryon density

- At high net-baryon density and low temperature, first order phase transition is expected which will end at a critical point (CP)
- CBM program supplements the Beam Energy Scan Program at RHIC, NA61 at SPS, NICA at JINR

Ref: CBM: EPJA 53, 60 (2017); PRC 74, 047901 (2006)
Observables for CP search

**Cumulants**

\[
C_1 = \langle N_q \rangle, \quad C_2 = \langle (\delta N_q)^2 \rangle, \quad C_3 = \langle (\delta N_q)^3 \rangle, \\
C_4 = \langle (\delta N_q)^4 \rangle - 3 \langle (\delta N_q)^2 \rangle^2
\]

\(N_q = N_q^+ - N_q^-\) and \(\delta N_q = N_q - \langle N_q \rangle\)

\(q\) can be any conserved quantum number

- (net-baryon, net-charge, net-strangeness etc.)

**Mean, variance, skewness, kurtosis**

\[
M = C_1, \quad \sigma^2 = C_2, \quad S = \frac{C_3}{\sigma^3}, \quad \kappa = \frac{C_4}{\sigma^4}
\]

- Higher moments of conserved quantities are sensitive to correlation length
  \(\langle (\delta N_q)^2 \rangle \sim \zeta^2 \quad \langle (\delta N_q)^3 \rangle \sim \zeta^{4.5} \quad \langle (\delta N_q)^4 \rangle \sim \zeta^7\)

- Non-monotonic variations of \(S\sigma = C_3/C_2, \quad \kappa\sigma^2 = C_4/C_2\) with beam energy are believed to be good signatures of CP

Ref: STAR: PRL 112, 032302 (2014); PRL 102, 032301 (2009)

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CBM experiment

- Fixed target experiment
- SIS 100: Au + Au collision, $\sqrt{s_{NN}} = 2.7 - 4.9$ GeV
- High interaction rate
- High statistics data
- Density in the center of the fireball expected to exceed few times greater than density of nucleus

Challenges of higher moments measurements at CBM

- Particle identification
- Non-trivial variations of efficiency $\times$ acceptance with $p_T$ and rapidity (proper method of corrections needed)
- Proper vertex identification in multiple collisions

Simulation details

- Event generators: UrQMD
- Collision: Au+Au
- Energy: $E_{lab} = 10$ AGeV ($\sqrt{s_{NN}} = 4.72$ GeV)
- Events: 5 M (minimum bias)

**Detectors used:**
- MVD, STS, RICH, TOF
- MVD: Vertex information
- STS: Momentum information
- RICH: Electron identification
- TOF: Hadron identification

**Detector acceptance:**
$1.5 < \eta < 3.8$ ($25^\circ > \theta > 2.5^\circ$)
Particle identification using TOF

Centrality selection using STS

- Clean particle identification for bulk properties studies
- To remove auto correlation in net-proton study, charge particles selected excluding $p, \bar{p}$
Proton (anti-proton) selection

**Mass square cut:**
\[ 0.6 < m^2 < 1.2 \text{ GeV}^2/c^4 \]

**Rapidity acceptance:**
\[ \Delta y = 1 \ (y_{\text{mid}} = 1.58) \]

**\( p_T \) acceptance:**
\[ 0.2 < p_T < 2 \text{ GeV/c} \]

\[ \begin{array}{c}
\text{Au + Au, } E_{\text{lab}} = 10 \text{ AGeV} \\
\text{UrQMD + CBM GEANT3}
\end{array} \]

\[ 1.08 < y < 2.08 \]

\[ \begin{array}{c}
\text{Purity} \\
\text{Efficiency}
\end{array} \]

\[ \begin{array}{c}
\text{0} \quad 0.1 \quad 0.2 \quad 0.3 \quad 0.4 \quad 0.5 \quad 0.6 \quad 0.7 \quad 0.8 \quad 0.9 \quad 1.0 \\
\text{0} \quad 0.1 \quad 0.2 \quad 0.3 \quad 0.4 \quad 0.5 \quad 0.6 \quad 0.7 \quad 0.8 \quad 0.9 \quad 1.0
\end{array} \]

\[ \begin{array}{c}
\text{0} \quad 0.5 \quad 1 \quad 1.5 \quad 2 \quad 2.5 \quad 3 \quad 3.5 \quad 4 \\
\text{0} \quad 0.5 \quad 1 \quad 1.5 \quad 2 \quad 2.5 \quad 3 \quad 3.5 \quad 4
\end{array} \]

\[ \begin{array}{c}
\text{y} \\
\text{p}_{T} \ (\text{GeV/c})
\end{array} \]

\[ \begin{array}{c}
\text{p}_{T} \ (\text{GeV/c}) \\
\text{y}
\end{array} \]

\[ \begin{array}{c}
\text{Purity} > 96 \%
\text{Efficiency decreases at high } p_T \text{ due to the detector acceptance}
\text{Efficiency for 0-5 \% and 70 -80 \% centralities are } \simeq 62 \% \text{ and } \simeq 46 \%
\end{array} \]
Proton (anti-proton) multiplicity distributions

Uncorrected distributions for efficiency and acceptance

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Quark Matter - 2019, Wuhan, China
Proton (anti-proton) multiplicity distributions

(Uncorrected distributions for efficiency and acceptance)

- Proton multiplicities follow negative binomial distribution
- Number of $\bar{p}$ is very less compared to $p$
  \[ \frac{\bar{p}}{p} = 7.8 \times 10^{-5} \text{ (0 -5 \%)}, \quad \frac{\bar{p}}{p} = 2.5 \times 10^{-4} \text{ (70 - 80 \%)} \text{ from UrQMD) } \\
- Proton distributions are skewed more to the right side of the mean
Net-proton multiplicity distributions

Uncorrected for efficiency and acceptance

☆ Mean and variance decreases from central towards the peripheral collisions
☆ Distributions are skewed more to the right side of the mean

<table>
<thead>
<tr>
<th>Centrality (%)</th>
<th>N_{ch} (m^2 &lt; 0.4 \text{GeV}^2/c^4)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-5</td>
<td>N_{ch} \geq 71</td>
</tr>
<tr>
<td>5-10</td>
<td>60 \leq N_{ch} &lt; 71</td>
</tr>
<tr>
<td>10-20</td>
<td>44 \leq N_{ch} &lt; 60</td>
</tr>
<tr>
<td>20-30</td>
<td>32 \leq N_{ch} &lt; 44</td>
</tr>
<tr>
<td>30-40</td>
<td>23 \leq N_{ch} &lt; 32</td>
</tr>
<tr>
<td>40-50</td>
<td>16 \leq N_{ch} &lt; 23</td>
</tr>
<tr>
<td>50-60</td>
<td>10 \leq N_{ch} &lt; 16</td>
</tr>
<tr>
<td>60-70</td>
<td>6 \leq N_{ch} &lt; 10</td>
</tr>
<tr>
<td>70-80</td>
<td>4 \leq N_{ch} &lt; 6</td>
</tr>
</tbody>
</table>

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$C_n$ of net-proton vs centrality (%)

**Centrality bin width correction**

$$C_n = \sum_r w_r C_{n,r}$$

$$w_r = \frac{n_r}{\sum_r n_r}$$

$\sum_r w_r = 1$

sum is over multiplicity bins

- CBWC done to suppress volume fluctuations
- Statistical error estimation is done using Delta theorem

Correction of cumulants of net-proton using Unfolding method

**Algorithm used:** RooUnfoldBayes

Relationship between measured and true distribution: \( y = Rx \)

\( y = \) measured, \( x = \) true, \( R = \) response matrix

• 50% events are used to construct \( R \)

We are able to get back cumulants of 'True', even if the efficiency is non-binomial and has non-trivial dependence on \( p_T \) and rapidity


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Net-charge multiplicity distributions and cumulants of net-charge

Uncorrected for efficiency and acceptance

We are able to get back cumulants of 'True', except $C_4$ in 0 – 5 %

More statistics needed

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Summary

★ Studied the feasibility of doing fluctuation analysis with conserved charges in Au+Au collisions at 10 AGeV with CBM detector using simulated events from UrQMD.
★ Clean proton identification with high purity is possible and hence one can study the net-proton (proxy for net-baryon) higher order moments using CBM detector.
★ Centrality selection using charged particles other than proton and anti-protons is possible.
★ Efficiency and detector effects were corrected for using unfolding techniques and original distributions and cummulants recovered. This shows that using the CBM detector, higher moments of net-proton and net-charge can be studied.

Outlook

★ Similar studies in other SIS100 energies
★ Look forward to data from CBM at SIS100 energies in the year 2025
Thank you