Measurements of Net-Proton Fluctuation for p + p Collisions at $\sqrt{s} = 200$ GeV from the STAR Experiment

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Introduction

- Hadronic Gas $\rightarrow$ QGP
- Crossover @ $\mu_B=0$
- Critical point ?

Experimental search by Beam Energy Scan (BES) at RHIC-STAR

QCD phase diagram

Fluctuation = Cumulant, Moment

- n-th order moment is defined by
  \[ \langle m^n \rangle = \sum_m m^n P(m), \quad \langle \delta m^n \rangle = \langle (m - \langle m \rangle)^n \rangle \]

- Cumulants are extensive variables
  \[ C_n(X + Y) = C_n(X) + C_n(Y) \quad \text{X and Y are independent each other} \]

- Volume terms are cancelled by taking ratio
  \[ S = \frac{C_3}{C_2} = \frac{\chi_3}{\chi_2} \]
  \[ \kappa \sigma^2 = \frac{C_4}{C_2} = \frac{\chi_4}{\chi_2} \]

- \( C_6/C_2 = C_4/C_2 = 1 \) … Skellam baseline

  Skellam = Poisson - Poisson’
  Skellam : Difference between two independent Poission distributions

- Higher-order cumulants and ratios are sensitive to phase structure
The 4th-order fluctuation for critical point search

- Conserved quantity is sensitive to correlation length $\xi$

$$
C_2 = < (\delta N)^2 >_c \approx \xi^2 \\
C_3 = < (\delta N)^3 >_c \approx \xi^{4.5} \\
C_4 = < (\delta N)^4 >_c \approx \xi^7 \\
C_5 = < (\delta N)^5 >_c \approx \xi^{9.5} \\
C_6 = < (\delta N)^6 >_c \approx \xi^{12}
$$

$\xi$ diverges near the C.P.

M. A. Stephanov, Phys. Rev. Lett. 102, 032301 (2009)
M. A. Stephanov, Phys. Rev. Lett. 107, 052301 (2011)
STAR Collaboration, arXiv, 2101.12413 (2021)

Non-monotonic beam energy dependence of $\kappa \sigma^2$ has been observed for net-proton fluctuations

Possible signature of critical point

STAR Collaboration, arXiv, 2101.12413 (2021)
Sixth-order fluctuation and crossover search

STAR Collaboration, Nuclear Physics A, 1005, 121882 (2021)

From peripheral to central collisions, the values of $C_6/C_2$ change from positive to negative.

Lattice QCD calculations at $\mu_B = 0$ show negative $C_6/C_2$.
Why p+p?

- As a baseline to be compared with Au+Au collisions
- Statistics is 70 times larger than previous results
- Multiplicity / acceptance dependence would be available with high statistics dataset

STAR Detector

- Time Projection Chamber (TPC) : PID, Vertex
- Time Of Flight (TOF) : Additional PID

\[ |y| < 0.5, \quad 0.4 < p_T (\text{GeV/c}) < 2.0 \]
Multiplicity distributions

- Reference multiplicity is defined in $|\eta|<1.0$ excluding (anti)protons.
- Event-by-event net-proton distributions are measured at mid-rapidity.
Analysis method

Efficiency Correction

\[ q_{r,s} = \sum_{j=1}^{n_{\text{tot}}} \frac{a_j^r}{\varepsilon_j^s} \]

\[ a: \text{charge}, \varepsilon: \text{efficiency} \]


\[
\langle Q \rangle_c = \langle q_{(1,1)} \rangle_c,
\]
\[
\langle Q^2 \rangle_c = \langle q_{(1,1)}^2 \rangle_c + \langle q_{(2,1)} \rangle_c - \langle q_{(2,2)} \rangle_c,
\]
\[
\langle Q^3 \rangle_c = \langle q_{(1,1)}^3 \rangle_c + 3\langle q_{(1,1)}q_{(2,1)} \rangle_c - 3\langle q_{(1,1)}q_{(2,2)} \rangle_c + \langle q_{(3,1)} \rangle_c - 3\langle q_{(3,2)} \rangle_c + 2\langle q_{(3,3)} \rangle_c,
\]
\[
\langle Q^4 \rangle_c = \langle q_{(1,1)}^4 \rangle_c + 6\langle q_{(1,1)}q_{(2,1)}q_{(2,2)} \rangle_c - 6\langle q_{(1,1)}q_{(2,2)} \rangle_c + 4\langle q_{(1,1)}q_{(3,1)} \rangle_c + 3\langle q_{(2,1)}^2 \rangle_c + 3\langle q_{(2,2)}^2 \rangle_c - 12\langle q_{(1,1)}q_{(3,2)} \rangle_c
\]
\[ + 8\langle q_{(1,1)}q_{(3,3)} \rangle_c - 6\langle q_{(2,1)}q_{(2,2)} \rangle_c + \langle q_{(4,1)} \rangle_c - 7\langle q_{(4,2)} \rangle_c + 12\langle q_{(4,3)} \rangle_c - 6\langle q_{(4,4)} \rangle_c, \]

Centrality Bin Width Correction (CBWC)

- Event averaging for each multiplicity bin

\[
C'_n = \frac{\sum_i w_i C_{(n,i)}}{\sum_i w_i}, \quad i: \text{Multiplicity bin}
\]
\[
W_i: \text{Number of event}
\]

Error estimation

- Bootstrap method

A. Chatterjee, Y. Zhang, J. Zeng, N. R. Sahoo, X. Luo, PRC 101, 034902 (2020)
Multiplicty Dependence of Net-Proton Cumulants

- Cumulants increase with increasing multiplicity
- Deviations from Skellam* / Pythia become larger for higher-order

* Skellam = Poisson - Poisson’
**Multiplicity Dependence of Net-Proton Cumulant Ratios**

- $C_3/C_2$ is consistent with the Skellam expectations
- Deviations from Skellam* / Pythia become larger for higher-order
  
  *Skellam = Poisson - Poisson’

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**STAR Preliminary**

- $C_2/C_1$
- $C_3/C_2$
- $C_4/C_2$
- $C_6/C_2$
- $C_5/C_1$
Acceptance Dependence of Net-Proton Cumulant Ratios

- Deviations from Skellam baseline become large with increasing $|\Delta y|$ acceptance except for $C_3/C_2$
- $C_3/C_2$ is consistent with Skellam

$|\Delta y|$ dependence

$C_2/C_1$

$C_3/C_2$

$C_4/C_2$

$C_6/C_2$

$C_5/C_1$

STAR Preliminary

$p + p$ Collisions, $\sqrt{s} = 200$ GeV
$0.4 < p_T^p (\text{GeV}/c) < 2.0$
Net-Proton

Systematic uncertainties

Cumulant ratios

Skellam
Comparison between p+p and Au+Au Collisions

- The results from p+p collisions fit into the centrality dependence of Au+Au collisions
- C$_6$/C$_2$ > 0 for p+p collisions, while C$_6$/C$_2$ < 0 for Au+Au central collisions

Only statistical errors are shown for Au+Au results
Efficiency is not corrected for x-axis

Au+Au data taken from STAR Collaboration, arXiv, 2101.12413 (2021)

Au+Au data taken from STAR Collaboration, Nuclear Physics A, 1005, 121882 (2021)
Summary

• Multiplicity dependence of net-proton cumulant has been measured in p+p collisions at $\sqrt{s} = 200$ GeV

• Larger deviations from Skellam / Pythia expectations are observed for higher-order cumulants

• Larger deviations from Skellam expectations are observed for rapidity acceptance dependence of cumulant ratios

• $C_6/C_2 > 0$ for p+p collisions, while $C_6/C_2 < 0$ for Au+Au central collisions

• The results from p+p collisions fit into the centrality dependence of Au+Au collisions at the same energy. Lattice calculations imply chiral phase transition in the thermalized QCD matter. This is not the case in 200 GeV p+p collisions.
Backup
Acceptance Dependence of Net-Proton Cumulants

- Cumulants become large with increasing $|\Delta y|$ acceptance

$|\Delta y|$ dependence

$C_1$, $C_3$, $C_5$, $C_2$, $C_4$, $C_6$

$p+p$ Collisions
$\sqrt{s} = 200$ GeV
$0.4 < p_T (\text{GeV/c}) < 2.0$
Net-proton

STAR Preliminary
## Systematic uncertainties

Cuts on PID, track quality, and efficiencies were checked

<table>
<thead>
<tr>
<th>Variables</th>
<th>Default</th>
<th>Changed cuts</th>
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<tbody>
<tr>
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<tr>
<td>$</td>
<td>n_{d_0}</td>
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<tr>
<td>DCA[cm]</td>
<td>$&lt;1.0$</td>
<td>$&lt;1.5, &lt;1.3, &lt;1.1, &lt;0.9, &lt;0.7, &lt;0.5$</td>
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<tr>
<td>nHitsFit</td>
<td>$&gt;20$</td>
<td>$&gt;15, &gt;17, &gt;19, &gt;21, &gt;23, &gt;25$</td>
</tr>
<tr>
<td>$m^2$</td>
<td>$0.6&lt;m^2&lt;1.2$</td>
<td>$0.8$–$1.4, 0.7$–$1.3, 0.65$–$1.25, 0.75$–$1.35$</td>
</tr>
<tr>
<td>Efficiency</td>
<td>$+0%$</td>
<td>$+5%$, $+5%(\text{low})$&amp;$-5%(\text{high})$, $-5%(\text{low})$&amp;$+5%(\text{high})$</td>
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$\sigma_{sys} = Y_{\text{def}} \sqrt{\sum_j R_j^2}$, $R_j = \sqrt{\frac{1}{n} \sum_i \left[ \frac{Y_{i,j} - Y_{\text{def}}}{Y_{\text{def}}} \right]^2}$

※ The range has been determined based on the ±5% change of $C_1$

- **Efficiencies** are modified so that the corrected $C_1$ values become identical for each systematic cuts
- This will be checked again once we have large data of embedding (now producing)
- Barlow check has been done to remove statistical effects $\rightarrow$ Only a few cuts condition has passed

| $|y|<0.5, 0.4<|p_T|<2.0$ | $|y|<0.4, 0.4<|p_T|<2.0$ | $|y|<0.3, 0.4<|p_T|<2.0$ | $|y|<0.2, 0.4<|p_T|<2.0$ | $|y|<0.1, 0.4<|p_T|<2.0$ | $|y|<0.5, 0.4<|p_T|<1.7$ | $|y|<0.5, 0.4<|p_T|<1.4$ | $|y|<0.5, 0.4<|p_T|<1.1$ | $|y|<0.5, 0.4<|p_T|<0.8$ |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| $C_1$           | 0.067%          | 0.048%          | 0.086%          | 0.082%          | 0.144%          | 0.046%          | 0.060%          | 0.060%          | 0.046%          |
| $C_2$           | 1.466%          | 1.165%          | 0.851%          | 0.550%          | 0.255%          | 1.437%          | 1.272%          | 1.272%          | 1.020%          |
| $C_3$           | 3.202%          | 3.133%          | 3.001%          | 2.329%          | 1.490%          | 3.255%          | 3.556%          | 3.556%          | 3.264%          |
| $C_4$           | 2.889%          | 2.615%          | 2.142%          | 1.485%          | 0.812%          | 2.930%          | 2.979%          | 2.979%          | 2.674%          |
| $C_5$           | 20.646%         | 19.743%         | 18.317%         | 12.996%         | 7.696%          | 20.710%         | 21.282%         | 21.282%         | 16.808%         |
| $C_6$           | 13.121%         | 12.193%         | 9.979%          | 6.490%          | 3.435%          | 13.506%         | 13.826%         | 13.826%         | 11.059%         |
| $C_2/C_1$       | 1.253%          | 0.976%          | 0.678%          | 0.415%          | 0.646%          | 1.236%          | 1.171%          | 1.035%          | 0.752%          |
| $C_3/C_2$       | 2.391%          | 2.511%          | 2.607%          | 2.176%          | 1.595%          | 2.463%          | 2.554%          | 2.884%          | 2.976%          |
| $C_4/C_2$       | 1.566%          | 1.549%          | 1.362%          | 0.987%          | 0.577%          | 1.627%          | 1.706%          | 1.810%          | 1.741%          |
| $C_5/C_2$       | 12.545%         | 11.726%         | 9.664%          | 6.247%          | 3.271%          | 12.949%         | 13.357%         | 13.343%         | 10.642%         |
| $C_5/C_1$       | 21.531%         | 20.522%         | 18.728%         | 13.272%         | 7.948%          | 21.508%         | 21.188%         | 21.779%         | 17.305%         |