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

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Outline

Introduction
  • Higher-order fluctuations
  • Recent STAR results

Data analysis
  • Particle identification
  • Efficiency correction
  • Centrality bin width correction

Results
  • Multiplicity dependence
  • Acceptance dependence
  • Comparison with Au+Au collisions

Summary
Introduction

- **QCD phase diagram**
- **Hadronic Gas → QGP**
- **Crossover @ $\mu_B=0$**
  

- **Critical point?**

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

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STAR Collaboration, Nuclear Physics A 982, 899-902 (2019)
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
  \[ C_n(X + Y) = C_n(X) + C_n(Y) \]
  X and Y are independent each other

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

- \( C_6/C_2 = C_4/C_2 = 1 \) … Skellam baseline
  Skellam = Poisson - Poisson’
  Skellam : Difference between two independent Possion distributions

- Higher-order cumulants and ratios are sensitive to phase structure
Fourth-order fluctuations for critical point search

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

Possible signature of critical point
Sixth-order fluctuations for crossover search

- 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) : Extend proton PID up to $p_T = 2$ GeV/c

Full azimuthal angles, $|\eta| < 1.0$

Protons and Antiprotons are identified by

- TPC for $0.4 < p_T (\text{GeV/c}) < 0.8$
- TPC and TOF for $0.8 < p_T (\text{GeV/c}) < 2.0$
Multiplicity distributions

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

- Cumulants are corrected for detector efficiencies by assuming they follow the binomial distribution.
- Efficiency variations on acceptance and multiplicity are taken into account.

\[
B_{p,N}(n) = \frac{N!}{n!(N-n)!}p^n(1-p)^{n}
\]

\[
C_1 = \langle Q \rangle_c = \langle q_{(1,1)} \rangle_c, \quad q_{(r,s)} = \sum_{j=1}^{n_{\text{tot}}} \frac{a_j^r}{\varepsilon_j^s}
\]

\[
C_2 = \langle Q^2 \rangle_c = \langle q_{(1,1)}^2 \rangle_c + \langle q_{(2,1)} \rangle_c - \langle q_{(2,2)} \rangle_c,
\]

\[
C_3 = \langle Q^3 \rangle_c = \langle q_{(1,1)}^3 \rangle_c + 3\langle q_{(1,1)}q_{(2,1)} \rangle_c - 3\langle q_{(1,1)}q_{(2,2)} \rangle_c + \langle q_{(3,1)} \rangle_c - 3\langle q_{(3,2)} \rangle_c + 2\langle q_{(3,3)} \rangle_c,
\]

\[
C_4 = \langle Q^4 \rangle_c = \langle q_{(1,1)}^4 \rangle_c + 6\langle q_{(1,1)}q_{(2,1)}^2 \rangle_c - 6\langle q_{(1,1)}q_{(2,2)} \rangle_c + 4\langle q_{(1,1)}q_{(3,1)} \rangle_c + 3\langle q_{(2,1)}^2 \rangle_c + 3\langle q_{(2,2)}^2 \rangle_c - 12\langle q_{(1,1)}q_{(3,2)} \rangle_c
\]

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

M. Kitazawa, PRC.86.024904 (2012),
M. Kitazawa and M. Asakawa, PRC.86.024904 (2012)
A. Bzdak and V. Koch, PRC.86.044904 (2012), PRC.91.027901 (2015),
X. Luo, PRC.91.034907 (2015)
T. Nonaka et al, PRC.94.034909 (2016), T. Nonaka, M. Kitazawa, S. Esumi,
PRC.95.064912 (2017)
A. Bzdak, R. Holzmann, V. Koch, PRC.94.064907 (2016)
Centrality bin width correction

- Cumulants are calculated for each multiplicity bin, and averaged for each centrality class in AuAu collisions.
- Effects of initial volume fluctuations are suppressed in a data-driven way.

\[ C'_{n} = \frac{\sum_{i} w_{i} C(n,i)}{\sum_{i} w_{i}} \]

- \( i \): Multiplicity bin
- \( w_{i} \): Number of event

There is no initial volume fluctuations by construction, thus CBWC is just to take averaging.

A. Chatterjee, Y. Zhang, J. Zeng, N. R. Sahoo, X. Luo, PRC 101, 034902 (2020)
Multiplicity dependence of net-proton cumulants

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

\* Skellam = \((\text{Poisson})_{\text{proton}} - (\text{Poisson})_{\text{antiproton}}\)

**STAR Preliminary**
Multiplicity dependence of net-proton cumulant ratios

- $C_3/C_2$ is consistent with the Skellam expectations
- Deviations from Skellam and Pythia become larger for higher-order

$\text{p + p Collisions, } \sqrt{s} = 200 \text{ GeV}$

$0.4 < p_T \text{ (GeV/c)} < 2.0, |y| < 0.5$

Net-Proton Multiplicity bin

$\text{RefMult3} < 50$

$\text{CBWC (5}$ $\text{ RefMult3} < 50)$

$\text{Skellam}$

$\text{Systematic uncertainties}$

$\text{Pythia 8}$

$\text{Average of Pythia 8}$

$\text{STAR Preliminary}$

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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

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

STAR Preliminary

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Acceptance dependence of net-proton cumulant ratios

- Deviations from Skellam baseline become large with increasing $p_T$ acceptance except for $C_3/C_2$
- $C_3/C_2$ is consistent with Skellam
Comparison between p+p and Au+Au collisions

- The results from p+p collisions fit into the centrality dependence of Au+Au collisions
- \( \frac{C_5}{C_1} \) and \( \frac{C_6}{C_2} > 0 \) for p+p collisions, while \( \frac{C_5}{C_1} \) and \( \frac{C_6}{C_2} < 0 \) for Au+Au central collisions

![Cumulant Ratios](image)

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

**STAR Collaboration, arXiv, 2101.12413 (2021)**


**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

• Cumulant ratios decrease with increasing rapidity acceptance

• $C_5/C_1$ and $C_6/C_2 > 0$ for p+p collisions, while $C_5/C_1$ and $C_6/C_2 < 0$ 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
STAR results for net-charge and net-kaon


STAR Collaboration, 1709.00773 (2017)

Monotonic beam energy dependence
Acceptance Dependence of Net-Proton Cumulants

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

**STAR Preliminary**
Acceptance Dependence of Net-Proton Cumulant

Δp_T dependence

- Cumulants become large with increasing p_T acceptance

STAR Preliminary

$0.4 < p_T < x$ (GeV/c)

Net-Proton Cumulants

$C_1$ $C_3$ $C_5$

$C_2$ $C_4$ $C_6$

$p+p$ Collisions

$\sqrt{s} = 200$ GeV

$|y| < 0.5$

Net-proton

Skellam baseline

Systematic uncertainties

Acceptance Dependence of Net-Proton Cumulant

$Δp_T$ dependence

- Cumulants become large with increasing $p_T$ acceptance

STAR Preliminary

$0.4 < p_T < x$ (GeV/c)
# Systematic uncertainties

Cuts on PID, track quality, and efficiencies were checked

<table>
<thead>
<tr>
<th>Variables</th>
<th>Default</th>
<th>Changed cuts $\ast$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>n_{\sigma_0}</td>
<td>$</td>
</tr>
<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>
</tr>
<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<del>1.4, 0.7</del>1.3, 0.65<del>1.25, 0.75</del>1.35</td>
</tr>
<tr>
<td>Efficiency</td>
<td>+0%</td>
<td>+5%, +5%(low)&amp;-5%(high), -5%(low)+5%(high)</td>
</tr>
</tbody>
</table>

$\ast$ The range has been determined based on the ±5% change of C1

- **Efficiencies** are modified so that the corrected C1 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 → Only a few cuts condition has passed

\[ \sigma_{sys} = Y_{def} \sqrt{\sum_j R_j^2}, \quad R_j = \sqrt{\frac{1}{n} \sum_i \left[ \frac{Y_{i,j} - Y_{def}}{Y_{def}} \right]^2} \]

- $Y_{def}$: default cuts results
- $Y_{ij}$: ith change of the cut on jth variable

|       | $|y|<0.5$, 0.4<$pT$<2.0 | $|y|<0.4$, 0.4<$pT$<2.0 | $|y|<0.3$, 0.4<$pT$<2.0 | $|y|<0.2$, 0.4<$pT$<2.0 | $|y|<0.1$, 0.4<$pT$<2.0 | $|y|<0.5$, 0.4<$pT$<1.7 | $|y|<0.5$, 0.4<$pT$<14 | $|y|<0.5$, 0.4<$pT$<1.1 | $|y|<0.5$, 0.4<$pT$<0.8 |
|-------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| $C_1$ | 0.067% | 0.049% | 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% |
| $C_6/C_1$ | 1.253% | 0.976% | 0.678% | 0.415% | 0.646% | 1.236% | 1.171% | 1.171% | 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% |
| $C_6/C_2$ | 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% |