Probing the QCD Phase Diagram via Higher Order Net-particle Fluctuation Measurements from STAR-BES

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Outline
1. Introduction
2. Physics Motivation
3. Data Analysis
4. Results

From RHIC to EIC
At the QCD Frontiers
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In part supported by
Introduction: QCD Phase Diagram

Goal: Study the phase diagram of QCD.
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Is there a critical point?

B. Mohanty, N. Xu, arXiv:2101.09210
A. Pandav, D. Mallick, B. Mohanty, PPNP. 125, 103960 (2022)
Introduction: QCD Phase Diagram

Goal: Study the phase diagram of QCD.

Is there a critical point?
To what extent is the crossover in $T - \mu_B$ plane?
Is there a first-order transition at finite $\mu_B$?

B. Mohanty, N. Xu, arXiv:2101.09210
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Goal: Study the phase diagram of QCD.

Varying collision energy varies Temperature (T) and Baryon Chemical Potential ($\mu_B$). Fluctuations in various observables are sensitive to phase transition and critical point.
Higher order cumulants of net-proton distributions (proxy for net-baryon).

\[ C_1 = < N > \]
\[ C_2 = < (\delta N)^2 > \]
\[ C_3 = < (\delta N)^3 > \]

Here, \( \delta N = N - < N > \)

\[ C_4 = < (\delta N)^4 > - 3 < (\delta N)^2 >^2 \]
\[ C_5 = < (\delta N)^5 > - 10 < (\delta N)^3 > < (\delta N)^2 > \]
\[ C_6 = < (\delta N)^6 > - 15 < (\delta N)^4 > < (\delta N)^2 > - 10 < (\delta N)^3 >^2 + 30 < (\delta N)^2 >^3 \]

Higher order cumulants: sensitive probe for CP and the nature of phase transition.

\[ C_2 \sim \xi^2 \quad C_4 \sim \xi^7 \quad \text{*Quantitative numbers - Model dependent} \]

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

Search for CP

Non-monotonic energy dependence of kurtosis of net-proton in presence of CP

Observables

Higher order cumulants of net-proton distributions (proxy for net-baryon).

\[ C_1 = \langle N \rangle \]
\[ C_2 = \langle (\delta N)^2 \rangle \]
\[ C_3 = \langle (\delta N)^3 \rangle \]
\[ C_4 = \langle (\delta N)^4 \rangle - 3 \langle (\delta N)^2 \rangle^2 \]
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Goal: Identification of O(4) chiral criticality on the phase boundary.

\[ C_5, C_6: \text{negative for LQCD, FRG, PQM – crossover} \]
\[ C_5, C_6: \text{positive for HRG and UrQMD (No QCD transition)} \]

Ordering of ratios: \[ \frac{C_3}{C_1} > \frac{C_4}{C_2} > \frac{C_5}{C_1} > \frac{C_6}{C_2} \] - LQCD, FRG

Search for First-order Phase Transition

Multiplicity distribution becomes bi-modal (contribution from two phases)

Proton factorial cumulants $\kappa_n$: with increasing order, increase rapidly in magnitude with alternating sign

$$
\begin{align*}
\kappa_1 &= C_1 \\
\kappa_2 &= -C_1 + C_2 \\
\kappa_3 &= 2C_1 - 3C_2 + C_3 \\
\kappa_4 &= -6C_1 + 11C_2 - 6C_3 + C_4 \\
\kappa_5 &= 24C_1 - 50C_2 + 35C_3 - 10C_4 + C_5 \\
\kappa_6 &= -120C_1 + 274C_2 - 225C_3 + \\
&\quad 85C_4 - 15C_5 + C_6
\end{align*}
$$

$P(N) = (1 - \alpha)P_a(N) + \alpha P_b(N)$: Two Component/Bimodal Distribution
Analysis Procedure

1/ Event Selection

3/ Track selection and PID

5/ Calculate Cumulants

7/ Correct for Centrality Bin Width Effect

2/ Centrality Selection

4/ Construct Multiplicity Distributions

6/ Correct for Efficiency

8/ Compute Statistical Errors

9/ Compute Systematic Errors

10/ Comparison with models
Goal: to map the QCD phase diagram $20 < \mu_B < 750$ MeV

J. Cleymans et. al, PRC. 73, 034905 (2006)
1) Net-proton distributions, top 5% central collisions, efficiency uncorrected.
2) Values of the mean increase as energy decreases, effect of baryon stopping. Larger width $\rightarrow$ larger stat. errors: $\text{err}(C_r) \propto \frac{\sigma^r}{\sqrt{N_{\text{evts}}}}$
Analysis Techniques (Corrections and Uncertainties)

- **Reconstruction efficiency**

![Graph showing reconstruction efficiency vs. average number of participant nucleons.](image)

- **Statistical uncertainties:**
  - Bootstrap method

- **Sources of systematic uncertainties:**
  - Particle identification
  - Background estimates (DCA)
  - Track quality cuts
  - Efficiency variation

- **Centrality bin width correction**

\[ C_n = \sum_r w_r C_{n,r} \text{ where } w_r = n_r / \sum_r n_r, \ n=1,2,3,4... \]

Here, \( n_r \) is no. of events in \( r^{th} \) multiplicity bin

Net-proton Cumulant Measurements

Cumulants $C_1$ and $C_3$ decrease with collision energy for 0-5% centrality.

$C_2$ and $C_4$ (0-5%) show non-monotonic collision energy dependence.

Peripheral measurements close to zero.
Measurements and QCD Thermodynamics

Ordering of ratios (Net-baryon): \( \frac{C_3}{C_1} > \frac{C_4}{C_2} > \frac{C_5}{C_1} > \frac{C_6}{C_2} \) - LQCD, FRG

Within uncertainties, experimental data consistent with predicted hierarchy.

UrQMD does not follow the ordering. Positive for all the ratios.
Net-Proton $C_4/C_2$ – CP Search

Non-monotonic collision energy dependence observed.

UrQMD model fails to reproduce the observed non-monotonic dependence.

STAR: PRL 126, 092301 (2021)
STAR: PRL. 128, 202303 (2022)
Net-Proton $C_4/C_2$ – CP Search

Non-monotonic collision energy dependence observed.

Precision measurements in the range: $7.7 < \sqrt{s_{NN}} < 27$ GeV ongoing at BES-II

the observed non-monotonic dependence.

STAR: PRL 126, 092301 (2021)
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Net-Proton $C_4/C_2$ – CP Search

Non-monotonic collision energy dependence observed.

Precision measurements in the range: $7.7 < \sqrt{s_{NN}} < 27$ GeV ongoing at BES-II.

New measurement at 3 GeV ($\mu_B=720$ MeV).

Consistent with UrQMD.

QCD matter is hadronic at 3 GeV.

If CP exists, it exists at $\sqrt{s_{NN}} > 3$ GeV.

Most Central Au+Au collisions
Net-proton
$0.4 < p_T < 2.0$ GeV/c, $|y| < 0.5$

HADES, Proton
$(0.4 < p_T < 1.6$ GeV/c, $|y| < 0.4)$

STAR Data
Projected BES-II
stat. uncertainty

Collision Energy $\sqrt{s_{NN}}$ (GeV)
Net-Proton $C_4/C_2$ – CP Search

Net-charge

Net-kaon

No such non-monotonic trend observed.

Large uncertainties.

Precision measurement at BES-II needed.

If CP exists, it exists at $\sqrt{s_{NN}} > 3$ GeV.
Net-Proton $C_5/C_1$ and $C_6/C_2$ – Search for Crossover

- $C_5/C_1 (0-40\%)$ fluctuates around zero as a function of $\sqrt{s_{NN}}$. $C_6/C_2 (0-40\%)$ increasingly negative with decreasing $\sqrt{s_{NN}}$ - consistent with expectation from LQCD, FRG model.
- Peripheral data, UrQMD, HRG model calculation are positive or consistent with zero.
Zr+Zr and Ru+Ru data follows the multiplicity trend shown by p+p and Au+Au.

Cumulant ratios decrease with increasing multiplicity. $C_5/C_1$ and $C_6/C_2$ from Au+Au results becomes negative: consistent with LQCD.
Proton $\kappa_5$ and $\kappa_6$ – Search for First-order Phase Transition

- $\kappa_5$ (0-5%) consistent with two component model expectation within uncertainties while $\kappa_6$ (0-5%) remains 1.8$\sigma$ away.
Summary and Outlook

- Higher-order cumulants are important observable in the study of QCD phase structure. Sensitive to CP, crossover and first-order phase transition.

- Net-proton cumulant ratios seem to follow hierarchy predicted by QCD thermodynamics.

- Non-monotonic collision energy dependence observed for net-proton $C_4/C_2$. Hint of CP in the collision energy range $7.7 \leq \sqrt{s_{NN}} \leq 27$ GeV. Recent data at 3 GeV suggests QCD matter is hadronic at such low energies, indicating that if critical region is created in heavy-ion collisions, it should exist at $\sqrt{s_{NN}} > 3$ GeV.

- Net-proton $C_6/C_2$ is increasingly negative with decreasing $\sqrt{s_{NN}}$. Multiplicity dependence studies at $\sqrt{s_{NN}} = 200$ GeV suggest $C_6/C_2$ becomes negative with increasing multiplicity. Observations are consistent with sign predicted by lattice QCD for crossover.

- Proton $\kappa_n$ measurement at 7.7 GeV have large uncertainties. Precision measurements at low $\sqrt{s_{NN}}$ from BES-II will be interesting for the search of first-order phase transition.

- Measurements with high statistic BES-II data (~10 – 20 times of current statistics) ongoing.
BES-II at RHIC

High statistics collected for $\sqrt{s_{NN}} = 7.7 - 27$ GeV: Precision measurement

STAR FXT: Extend precision measurements to $\mu_B=750$ MeV


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STAR Internal Note: https://drupal.star.bnl.gov/STAR/starnotes/public/sn0598

T. Nonaka (for STAR Collaboration) : 3rd workshop on Physics performance studies at FAIR and NICA, 2021
High statistics collected for $\sqrt{s_{NN}} = 7.7 - 27$ GeV: Precision measurement

STAR FXT: Extend precision measurements to $\mu_B = 750$ MeV


Stay Tuned For BES-II Results

**THANK YOU ALL FOR YOUR ATTENTION**

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