Experimental Overview Of Critical Fluctuations

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Outline
1. Introduction
2. Results
3. Future Prospects & Challenges
4. Summary

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CPOD2022
Probing the QCD Phase Diagram via Fluctuations
Introduction: QCD Phase Diagram

Experimental overview of critical fluctuations – Ashish Pandav
Introduction: QCD Phase Diagram

Test of QCD Thermodynamics:
Ordering of net-baryon ratios: $\frac{c_3}{c_1} > \frac{c_4}{c_2} > \frac{c_5}{c_1} > \frac{c_6}{c_2}$

Goal: Study of QCD Phase Diagram
Introduction: QCD Phase Diagram

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HotQCD: PRD101,074502 (2020)

Goal: Study of QCD Phase Diagram

Search for critical point (CP):
Non-monotonic trend for net-proton Kurtosis $C_4 / C_2$ vs $\sqrt{s_{NN}}$

M. Stephanov, PRL 107 (2011) 052301
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Search for crossover:
Negative net-baryon $\frac{c_6}{c_2}$

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Non-monotonic trend for net-proton Kurtosis \( \frac{C_4}{C_2} \) vs \( \sqrt{s_{NN}} \)

M. Stephanov, PRL 107 (2011) 052301

Search for crossover:
Negative net-baryon \( \frac{c_6}{c_2} \)

HotQCD: PRD101,074502 (2020)

Search for 1st order:
Bimodal proton distribution: Large proton factorial cumulants (\( \kappa_5 \) and \( \kappa_6 \)) with alternating sign.

A. Bzdak and V. Koch, PRC100, 051902(R) (2019)

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Introduction: QCD Phase Diagram

Varying beam energy varies Temperature (T) and Baryon Chemical Potential ($\mu_B$). Fluctuations of conserved quantities are sensitive to phase transition and critical point.
Observables

Higher-order cumulants of net-particle distributions (proxy for conserved charges).

\[ C_1 = < N > \]
\[ C_2 = < (\delta N)^2 > \]
\[ C_3 = < (\delta N)^3 > \]
\[ C_4 = < (\delta N)^4 > - 3 < (\delta N)^2 >^2 \]
\[ C_5 = < (\delta N)^5 > - 10 < (\delta N)^3 > < (\delta N)^2 > \]
\[ C_6 = < (\delta N)^6 > - 15 < (\delta N)^4 > < (\delta N)^2 > - 10 < (\delta N)^3 >^2 + 30 < (\delta N)^2 >^3 \]

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

Crossover (small \( \mu_B \))

First order (large \( \mu_B \))

\[ C_2 \sim \xi^2 \quad C_4 \sim \xi^7 \]

*Quantitative numbers - Model dependent

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

Skewness: Asymmetry

Kurtosis: Peakedness

M. A. Stephanov, Phys.Rev.Lett. 107 (2011) 052301,

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di of state Eq. (42) emerges from the parametric representation given by Eqs. (45) and (46), with parameters "universal scaling function. The correct scaling Eq. (43) is built into this representation and corresponds to subject of many classic textbooks (see, e.g., [82, 83]).

Significantly from the mean-field values. The role of fluctuations which are responsible for these deviations from fluid transitions. Critical points in ferromagnets and near liquid-gas critical points. It is characterized by the universal values of with specific values of

\[ R \]

Note that when scaling exponents are assigned their mean-field values

Thus the mean-field equation of state, while providing a simple and intuitive description of the phase transition, is

This is a ubiquitous critical universality class because it occurs in systems with a one-component (singlet) order parameter. For example, the

For a system evolving through the critical region with a

Critical exponent

Systematics provides an estimate of
determined experimentally using the chemical freezeout systematics extracted from the measured particle yields [95].

The position of the freezeout point on the curve depends on the collision energy shown in Fig. 13 superimposed on the density plot of the quartic cumulant of a critical order parameter, such as, e.g.,

Isospin blind. Thus cumulants of the fluctuations of proton number (or net proton number) show a similar pattern near

Which detect charge particles, leaving neutrons out of the acceptance. However, the fluctuations near the critical

Non-monotonic collision energy dependence with deviation below and above baseline fluctuations. → Existence of critical region

A. Bzdak et al, Phys. Rept. 853, 1-87 (2020)
$C_5, C_6$: negative for LQCD, FRG (Functional Renormalization Group) – crossover
$C_5, C_6$: positive for HRG (GCE) and UrQMD (No QCD transition)

$Lattice QCD$

$R_{62} = \frac{C_6}{C_2}$

$FRG$  

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 1st order Phase Transition

Multiplicity distribution bi-modal (contribution from two phases)

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

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

\[P(N) = (1 - \alpha)P_a(N) + \alpha P_b(N): \text{ Two Component/Bimodal Distribution}\]
Analysis Procedure

1/ Event and track selections, centrality selection

2/ Construct net-particle multiplicity distributions

3/ Perform measurement of cumulants

4/ Correct for volume fluctuation effect: perform centrality bin-width correction (CBWC) / VFC

5/ Correct for detector efficiency

6/ Comparison with models to draw conclusion
Analysis Methods and Corrections

**Particle Identification**

- Ensure high purity

**Correction for Efficiency and Volume Fluctuation**

- Binomial Efficiency correction
- Check for non-binomial effects: unfolding
- Centrality Bin Width Correction – data driven
- Volume Fluctuation Correction – model dependent

**Centrality Definition**

- Maximize resolution and minimize self correlation effects.

**Statistical and Systematic Uncertainties**

- Delta Theorem and Bootstrap method
- Vary PID, track selection cuts, background contamination

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Event-by-event Raw Net-proton Distributions

1) Net-proton distributions, top 5% central collisions, efficiency uncorrected.

2) Values of the mean increase as energy decreases, effect of baryon stopping.
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.
Cumulant Measurements at vanishing $\mu_B$

- Presence of long-range rapidity correlations ($\Delta y_{corr} > 0.5$) between protons and antiprotons. HIJING and EPOS reproduces qualitative trend but show quantitative differences.

- Vanishing third order cumulant observed – consistent with LQCD and HRG calculations.
Non-monotonic collision energy dependence observed for net-proton $C_4/C_2$ – consistent with CP expectation. Non-CP models fail to reproduce the observed trend.

Suppression observed at $\sqrt{s_{NN}} = 3$ GeV ($\mu_B = 750$ MeV), consistent with UrQMD – QCD matter created is dominantly hadronic.
Experimental overview of critical fluctuations

- **Net-Particle C_4/C_2 – Critical Point Search**

  ![Graph showing critical point search](image)

  - **Within large uncertainties monotonic energy dependence trend observed for net-charge and net-kaon fluctuations.**
  - **The statistical uncertainty:** \( \sim \frac{\sigma_m}{\sqrt{N} \epsilon^k} \)

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**Highlights from the NA61/SHINE experiment**

- Multiplicity and net-charge fluctuations in p+p, Be+Be and Ar+Sc collisions
- Net-charge fluctuations in p+p, Be+Be and Ar+Sc collisions
- STAR: PRL, 113 (2014) 092301
- STAR: PLB 785 (2018) 551-560

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- **Antoni Marcinek (IFJ PAN)**
- NA61/SHINE preliminary
- NA61/SHINE Collaborations, QM22
- Pandav, 113 (2014) 092301
- STAR Preliminary
- STAR Priliminary
- The net dependence trend observed for net kaon fluctuations.
- No structure indicating critical point
- Given collision energy
- Given collision energy
- Standard deviation; skewness; multiplicity; – kurtosis; – skewness; – multiplicity; – standard deviation
- Increasing difference between
- Increasing difference between
- =≠ 

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Within uncertainties, 7.7 and 200 GeV data consistent with predicted hierarchy. UrQMD does not follow the ordering. Positive for all the ratios.

At 3 GeV, violation of ordering is seen. Observed ordering reproduced by UrQMD.
Net-Proton $C_6/C_2$ – Crossover Search

- Increasingly negative $C_6/C_2$ (7.7 – 200 GeV) with decreasing energy at a level of $\lesssim 1.7\sigma$ observed for 0-40% centrality – lattice QCD calculations are consistent with observed trend in data.

- At 3 GeV, 0-40% measurement positive.

- $C_6/C_2(50-60\%),$ UrQMD $\geq 0$ for all energies.

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STAR: arXiv:2207.09837

Net-Proton $C_6/C_2$ – Crossover Search

- Decreasing trend of cumulant ratios observed with increase in system size. (p+p, Zr+Zr, Ru+Ru, and Au+Au collisions)
- Measurements at high charged multiplicity consistent with lattice QCD.
- Fifth and sixth order cumulant ratios grow progressively negative towards higher charged particle multiplicity – sign consistent with lattice QCD calculation with a crossover.

*STAR: PRL 127, 262301 (2021)
H.-S. Ko, STAR Collaboration, QM22*
For $\sqrt{s_{NN}} \geq 11.5$ GeV, the proton $\kappa_n$ within uncertainties does not support the two-component shape of proton distributions. Possibility of sign change at low energy.

Peripheral data and UrQMD calculations consistent with zero at all energies.
Summary

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Negative sign of $C_6/C_2$ observed

Search for critical point (CP):
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Search for 1st order:
Absence of bimodal structure at $\sqrt{s_{NN}} \geq 11.5$ GeV

Precision measurement at BES-II ongoing

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Future Prospects and Upcoming Experiments
Crossover Search and Probing Magnetic field in HIC

Extending fluctuations to $C_7$ and $C_8$ - more sensitive probes for crossover

Measuring BS, BQ, QS correlations to probe magnetic field in HIC

- STAR: Au+Au at $\sqrt{s_{NN}} = 200$ GeV: ~ 20 billion event (2023+2025)
- Au+Au at $\sqrt{s_{NN}} = 3$ GeV: ~ 2 billion events collected
- ALICE: Higher order measurements possible with high statistic LHC Run3

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Enlarged Phase Space

\[ \sqrt{s_{NN}} = 19.6 \text{ GeV collider mode} \]

BES-II: Precision measurement up to \( \mu_B = 750 \text{ MeV} \)

Full rapidity coverage at high \( \mu_B \) region

CBM: \( 2.7 < \sqrt{s_{NN}} < 4.9 \text{ GeV} \)
High interaction rates – large statistics

Energy scan and rapidity scan

Rapidity is a finer-resolution probe of the critical regime than \( \sqrt{s_{NN}} \)

Initial Volume Fluctuation Effect at High Baryonic Density Region

- Initial volume fluctuation effect significant at low $\sqrt{s_{NN}}$.
- Low collision energy: low charged particle multiplicity - poor centrality resolution.
- Look for alternate way to obtain $<N_{\text{part}}>$ in experiments.

**A new method:** A. Rastamov et al, arXiv:2211.14849

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Current Status of CP and Conclusion

Critical point unlikely to exist below $\frac{\mu_B}{T} < 2.5\ (\sqrt{s_{NN}} > 27\ \text{GeV})$ - lattice QCD

Measurements at $\sqrt{s_{NN}} = 3\ \text{GeV}$ strongly suggest QCD matter created is hadronic.

Critical region, if created in HIC is likely to be between $\sqrt{s_{NN}} = 3 - 27\ \text{GeV}$.

Measurements from BES-II, upcoming experiments: CBM at FAIR will be crucial.

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B. Mohanty, N. Xu, arXiv:2101.09210
A. Pandav, D. Mallick, B. Mohanty, PPNP. 125, 103960 (2022)
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Alphabetically: Xin Dong, ShinIchi Esumi, Yige Huang, Ho-San Ko, Xiaofeng Luo, Debasish Mallick, Bedangadas Mohanty, Dylan Neff, Risa Nishitani, Toshihiro Nonaka, Zachary Sweger, Nu Xu, Xin Zhang, Yu Zhang, and other STAR colleagues.

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