Higher-Order Cumulants of Net-Proton Multiplicity Distributions in $\sqrt{s_{\text{NN}}} = 200$ GeV Zr+Zr and Ru+Ru Collisions by the STAR Experiment

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Supported by
Outline

- Introduction & motivation
- Analysis information
  - $\sqrt{s_{NN}} = 200 \text{ GeV}$ isobaric collisions (mixed Ru and Zr data)
- Corrections
- Net-proton cumulants & cumulant ratios
- Summary
QCD phase diagram

- **QCD calculation**
  - Cross over at $\mu_B \sim 0$ [1] and $T \sim 150$ MeV [2-4]
  - A critical point followed by first-order phase transition at high $\mu_B$

- **Search for the possible signature of critical point by scanning $T$ vs $\mu_B$**:
  - By varying collision energy in heavy-ion collisions

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Fluctuation of conserved quantities

- Cumulants of conserved quantities (B, Q, S) are related to correlation length of the system

\[
\delta N = N - \langle N \rangle \quad C_1 = \langle N \rangle, \quad C_2 = \langle (\delta N)^2 \rangle \\
C_3 = \langle (\delta N)^3 \rangle, \quad C_4 = \langle (\delta N)^4 \rangle - 3 \langle (\delta N)^2 \rangle^2 \\
C_2 = \sigma^2, \quad S = C_3/(C_2)^{3/2}, \quad \kappa = C_4/(C_2)^2
\]

- The higher the order, the more sensitive

\[C_2 \sim \xi^2, \quad C_3 \sim \xi^{4.5}, \quad C_4 \sim \xi^7\]


- The cumulant ratios can be directly compared to theoretical calculations

\[
\chi_q^{(n)} = \frac{\partial^n(p/T^4)}{\partial(\mu_Q/T)^2} = \frac{1}{VT^3} \times C_q^m
\]

Net-proton number is used as a proxy to net-B number
Fourth-order fluctuations for critical point search

4th order: predicts a non-monotonic energy dependence due to contribution from QCD critical point.
Isobaric (Zr+Zr & Ru+Ru) collision data

\[ C_4/C_2 = \kappa \sigma^2 \]

- The number of nucleons per nucleus:
  - Proton: \( A = 1 \)
  - Isobar (Ru or Zr): \( A = 96 \)
  - Au: \( A = 197 \)
- Expect the same multiplicity dependence in different collision systems at the same collision energy
- Large statistics: 2.3B Zr+Zr and 2.2B Ru+Ru taken at STAR in 2018

\[ C_4/C_2 \text{ of net-proton for Au+Au collision at } \sqrt{s_{NN}} = 200 \text{ GeV} \]

\[ \text{Average Number of Participating Nucleons} \]

Solenoid Tracker at RHIC (STAR)

- Time Projection Chamber (TPC): Vertexing & particle identification
- Time Of Flight (TOF) detector: Ensures proton purity at $0.8 < p_T < 2.0 \text{ GeV/c}$

- Large, Uniform Acceptance at Mid-rapidity
- Excellent Particle Identification
(Anti) Proton identification:
- \(0.4 < p_T < 0.8 \text{ GeV/c}\): deviation from the red line (Bischel) < 2\(\sigma\)
- \(0.8 < p_T < 2.0 \text{ GeV/c}\): red line dev. < 2\(\sigma\) & \(0.6 < m^2 < 1.2 \text{ GeV}^2/c^4\)
- Purity: > 99%
Acceptance: \(|y| < 0.5 \& 0.4 < p_T < 2.0 \text{ GeV/c}\)
Net-proton distributions

Net-proton distribution (efficiency un-corrected)

STAR Preliminary

Ru+Ru & Zr+Zr mixed
$\sqrt{s_{NN}} = 200$ GeV

Net-proton
$|y| < 0.5$, $0.4 < p_T < 2.0$ GeV/c

Before detector efficiency correction
z-axis normalized
Moments analysis corrections

- Detector efficiency correction [1~3]
  - Binomial detector efficiency correction
  - Efficiency corrected to each particle track
    - TOF matching + TPC tracking efficiency corrections
- Statistical uncertainty calculated based on Delta theorem [4]
- Centrality bin width correction [5]
  - Corrects finite bin width effect

Centrality: a measure of geometric overlap of two colliding nuclei → determined by charged-particle multiplicity

\[ C_n = \frac{\sum_i n_i C_{n,i}}{\sum_i n_i} = \sum_i \omega_i C_{n,i} \]

- Measured
- Detector response
- Actual distribution

\[ p(n) = \sum_{N} \text{Binomial}(n; N, \epsilon) \times P(N) \]

"N" detector bins with efficiency \( \epsilon \)

\( s_{NN} = 200 \text{ GeV} \)

charged-particle multiplicity: number of charged particles in \( |\eta| < 1 \) excluding (anti-)protons per event

\[ n_i : \text{number of events in multiplicity bin } i \]

TOF matching efficiency & TPC tracking efficiency maps

- TOF matching efficiency: Number of protons identified by TPC vs TPC+TOF
- TPC tracking efficiency: Number of protons identified by TPC vs generated both in MC simulation with realistic geometry (embedding)
- Do interpolation between bins to overcome the low statistics of the MC simulation events
Net-proton cumulants and ratios

UrQMD: hadronic transport model calculation with the same acceptance of the STAR

UrQMD results show discrepancies. However, in general, show a similar trend as the data

Au+Au collision at $\sqrt{s_{NN}} = 200$ GeV plotted

- Systematic shift in cumulant ratios
- Overall trends are consistent

$<N_{\text{part}}>$: Average Number of participating nucleons per event
1. For p+p collision, the entire centrality classes are merged to one and shown with light blue
   a. p+p collision’s multiplicity dependence is the opposite from the heavy-ion collision’s
2. Isobaric collisions (Ru+Ru, Zr+Zr combined) fit into the p+p (averaged) and Au+Au collision results at $\sqrt{s_{NN}} = 200$ GeV
3. $C_4/C_2$ lowers as the charged particle multiplicity $\rightarrow$ consistent with the lattice QCD result at high multiplicity region: approaching thermalized medium in the most central collisions
Summary and outlook

1. Net-proton cumulants and their ratios from $\sqrt{s_{\text{NN}}} = 200$ GeV isobaric collisions (mixed Ru and Zr data)

2. Net-proton cumulants and their ratios of the isobaric collision compared with the Au+Au collision results at $\sqrt{s_{\text{NN}}} = 200$ GeV
   a. Systematic shift in cumulant ratios. However, overall trends are consistent
   b. p+p collisions show the opposite multiplicity dependency from the heavy-ion collisions
   c. $C_4/C_2$ from the different collision systems fit one another in collision centrality dependence

3. Net-proton cumulant ratios compared with HRG, UrQMD models, and lattice QCD
   a. UrQMD results qualitatively show the same trends as the data
   b. $C_4/C_2$ consistent with the lattice QCD calculation result at high multiplicity
      i. approaching thermalized medium in the most central collisions

4. Working on higher order cumulants