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

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Supported by
U.S. DEPARTMENT OF ENERGY
Outline

1. Introduction & motivation
2. Analysis of $\sqrt{s_{NN}} = 200$ GeV isobaric collisions (Zr+Zr & Ru+Ru)
3. Net-proton cumulants & cumulant ratios
4. Summary & outlook
1. QCD calculation and model
   a. Lattice QCD: Cross over at $\mu_B = 0$ [1] and $T = 156.5 \pm 1.5$ MeV [2-5]
   b. QCD based Model: A critical point followed by first-order phase transition at high $\mu_B$ [6]

2. 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

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

\[ \delta N = N - \langle N \rangle \quad C_1 = \langle N \rangle, \quad C_2 = \left\langle (\delta N)^2 \right\rangle \]

\[ C_3 = \left\langle (\delta N)^3 \right\rangle, \quad C_4 = \left\langle (\delta N)^4 \right\rangle - 3 \left\langle (\delta N)^2 \right\rangle^2 \]

\[ C_2 = \sigma^2, \quad S = C_3/(C_2)^{3/2}, \quad \kappa = C_4/(C_2)^2 \]

2. The higher the cumulant order, the more sensitive to the correlation length

\[ C_2 \sim \xi^2, \quad C_3 \sim \xi^{4.5}, \quad C_4 \sim \xi^7 \quad [1\sim3] \]

3. The cumulant ratios can be directly compared to theoretical calculations

\[ \chi_q^{(n)} = \left( \frac{\partial^n p}{\partial \mu_q^n} \right)_T = \frac{1}{VT^3} \times C_q^n \]

Net-proton number is used as a proxy to net-B number

Fourth-order cumulant for critical point search

Talk by Yu Zhang (Tue T03-I)

Net-proton $\kappa \sigma^2$

- STAR
  - 0 - 5%
  - 70 - 80%
  - Stat. uncertainty
  - Syst. uncertainty
  - Projected BES-II
  - stat. uncertainty

Collision Energy $\sqrt{s_{NN}}$ (GeV)

STAR, Phys. Rev. Lett. 126, 092301 (2021)

$\kappa \sigma^2$ vs $\sqrt{s}$

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

- 4th order: predicts a non-monotonic energy dependence due to contribution from QCD critical point
Fifth- and Sixth-order cumulant

- Transition from QGP to hadronic matter is smooth crossover at $\mu_B \approx 0$.
- 6th order: first principle lattice QCD calculation predicts $C_6/C_2 < 0$


STAR Au+Au Collisions
- $|y| < 0.5$, $0.4 < p_T$ (GeV/c) $< 2.0$
- $|s_{NN}$ (GeV) $27, 54.4, 200$

Data

Theory
- UrQMD
- LQCD

Net-baryon
Net-proton

1. At \( \sqrt{s_{NN}} = 200 \text{ GeV} \): Zr+Zr and Ru+Ru (\( A = 96 \)), and Au+Au (\( A = 197 \)) with p+p averaged
2. Large statistics: 2.0B Zr+Zr and 1.9B Ru+Ru events taken at STAR in 2018
3. Inspect the systematic trend of multiplicity dependence of different collision systems (Zr, Ru, and Au) at the same collision energy

Solenoid Tracker At RHIC (STAR)

- Time Projection Chamber (TPC): vertexing & particle identification
- Time Of Flight (TOF) detector: improves proton purity at $0.8 < p_T < 2.0$ GeV/c

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

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
Efficiency uncorrected

Normalized Number of Events

Number of charged particles in $|\eta| < 1$ excluding (anti-)protons

$\sqrt{s_{NN}} = 200$ GeV

40% 30% 20% 10% 5%

Central collision
Mid-central collision

0-5%
5-10%
30-40%
70-80%

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Corrections

1. Detector efficiency correction [1~3]
   a. Binomial detector efficiency assumption
   b. TPC & TOF tracks

2. Centrality bin width correction [4]
   - Corrects finite bin width effect

1. The cumulants of net-proton in Zr+Zr, Ru+Ru and Au+Au collisions follow the same $\langle N_{\text{part}} \rangle$ trend at $\sqrt{s_{NN}} = 200$ GeV.

2. UrQMD overpredicts $C_1$ and $C_3$ while underpredicts $C_2$. In general, it shows a similar trend as the data.

UrQMD: hadronic transport model. Calculated in the STAR acceptance.

UrQMD centrality determined in a similar way to the data: measure charged-pion & charged-kaon multiplicity

$\langle N_{\text{part}} \rangle$: Average number of participating nucleons

Net-proton cumulants

$C_1$ (STAR Preliminary)
- Zr+Zr
- Ru+Ru
- Au+Au

$C_2$ (STAR Preliminary)

$C_3$ (STAR Preliminary)

$C_4$ (STAR Preliminary)

$C_5$ (STAR Preliminary)

$C_6$ (STAR Preliminary)

Net-proton cumulant ratios

1. The cumulant ratios $C_4/C_2$, $C_5/C_1$, and $C_6/C_2$ of net-proton in Zr+Zr, Ru+Ru and Au+Au collisions show the same $\langle N_{\text{part}} \rangle$ trend at $\sqrt{s_{NN}} = 200$ GeV.
2. UrQMD overpredicts $C_4/C_2$. In general, it shows a similar trend as the data.

$\langle N_{\text{part}} \rangle$: Average number of participating nucleons

UrQMD centrality determined in a similar way to the data: measure charged-pion & charged-kaon multiplicity

UrQMD: hadronic transport model. Calculated in the STAR acceptance

STAR Preliminary
High-order net-proton cumulant ratio comparison

1. Zr+Zr and Ru+Ru collision results fit into the p+p ⊕ AU+Au results at \( \sqrt{s_{NN}} = 200 \text{ GeV} \)
2. All cumulant ratios \( C_4/C_2, C_5/C_1, \) and \( C_6/C_2 \) decrease as the multiplicity increases
   → Most central AU+Au collision results become consistent with Lattice QCD prediction for the formation of thermalized QCD matter and smooth crossover transition
Summary and outlook

1. At $\sqrt{s_{NN}} = 200$ GeV: the highest precision data of Zr+Zr & Ru+Ru multiplicity-dependent cumulants and their higher order ratios fit into p+p and Au+Au results. All $C_4/C_2$, $C_5/C_1$, and $C_6/C_2$ show decreasing trend as multiplicity increases.

2. Comparison with model and lattice QCD calculations
   a. UrQMD over/underpredicts the results and in general, shows a similar trend as the data.
   b. Higher order cumulant ratios at high multiplicity (top Au+Au collision centrality) consistent with the lattice QCD calculation result (smooth crossover phase transition of thermalized medium).

3. Outlook: mixed cumulant ratios analysis to check a difference of B-field created in two isobar collisions
   a. Expect ~15% difference in the B-field between Zr+Zr & Ru+Ru collisions [1]
   b. Mixed cumulant ratios offer an opportunity to experimentally assess the background B-field in the late stage of heavy-ion collisions [2]

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