Measurement of intermittency for charged particles in Au + Au collisions at $\sqrt{s_{NN}} = 7.7$-200 GeV from STAR

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Abstract

Local density fluctuations near the QCD critical point can be probed by intermittency analysis of scaled factorial moments in relativistic heavy-ion collisions. We report the first measurement of intermittency for charged particles in Au + Au collisions at $\sqrt{s_{NN}} = 7.7$-200 GeV from the STAR experiment at RHIC. We observe scaling behaviors in central Au + Au collisions, with the extracted scaling exponent decreasing from mid-central to the most central Au + Au collisions. Furthermore, the scaling exponent exhibits a non-monotonic energy dependence with a minimum around $\sqrt{s_{NN}} = 20$-30 GeV in central Au + Au collisions.

1 Introduction

The major goal of the Beam Energy Scan (BES) at the Relativistic Heavy Ion Collider (RHIC) is to explore the phase diagram of quantum chromodynamics (QCD) [1, 2]. An important landmark of the QCD phase structure is the critical point (CP), which is the end point of first-order phase boundary between quark-gluon and hadronic phases [3]. In the thermodynamic limit, the correlation length diverges at the CP and the system becomes scale invariant and fractal [4]. It is shown that the density fluctuations near the QCD critical point form a distinct pattern of power-law or intermittent behavior in the matter produced in high energy heavy-ion collisions [5].

In analogy to the critical opalescence observed in conventional matter near the critical point, the related fractal and self-similar geometry of QCD matter will lead to local density fluctuations that obey intermittent behavior [5]. Based on the effective action belonging to three-dimensional Ising universality class, the intermittency of QCD matter is revealed in transverse momentum spectra as a power-law (scaling) behavior of scaled factorial moment (SFM) in heavy-ion collisions [5]. An intermittent behavior has observed in Si + Si collisions at 158A
2 Analysis Details

In high-energy experiments, local power-law fluctuations can be detectable through the measurements of scaled factorial moment (SFM) which is defined as:

\[ F_q(M) = \frac{\langle \frac{1}{M^D} \sum_{i=1}^{M^D} n_i(n_i - 1) \cdots (n_i - q + 1) \rangle}{\langle \frac{1}{M^D} \sum_{i=1}^{M^D} n_i \rangle^q}, \]  

(1)

where \( M^D \) is the number of cells in D-dimensional momentum space, \( n_i \) is the measured multiplicity in the \( i \)-th cell, and \( q \) is the order of moment.

Another expected power-law behavior that describes relationship between \( F_q(M) \) and \( F_2(M) \) is defined as \([9, 10]\):

\[ F_q(M) \propto F_2(M)^{\beta_q}. \]  

(2)

Moreover, the scaling exponent \( \nu \) quantitatively describes the values of \( \beta_q \):

\[ \beta_q \propto (q - 1)^\nu. \]  

(3)

Here \( \nu \) specifies scaling (power-law) behavior of \( F_q(M) \). According to Ginzburg-Landau (GL) theory, the critical \( \nu \) is equal to 1.304 in entire space phase \([9]\), while it is equal to 1.0 from the two-dimensional Ising model \([10]\).

![Figure 1: \( F_q(M) \) (up to sixth order) of charged particles in transverse momentum space for the most central (0-5%) Au + Au collisions at \( \sqrt{s_{NN}} = 7.7\)–200 GeV in double-logarithmic scale.](image)

The data reported here were obtained from Au + Au collisions at \( \sqrt{s_{NN}} = 7.7, 11.5, 14.5, 19.6, 39, 54.4, 62.4 \) and 200 GeV, which were recorded by the STAR experiment at RHIC from 2010 to 2017. Protons (\( p \)), antiprotons (\( \bar{p} \)), kaons (\( K^\pm \)) and pions (\( \pi^\pm \)) are analyzed as charged particles, and their identifications are carried out using the Time Projection Chamber (TPC) and the Time-of-Flight (TOF) detectors. To avoid the self-correlation, the centrality was determined from uncorrected charged particles within a pseudo-rapidity window of \( 0.5 < |\eta| < 1 \), which was chosen to be beyond the analysis window of \( |\eta| < 0.5 \).
To subtract the background at the level of SFM, a correlator $\Delta F_q(M)$ is defined in terms of original and mixed events, i.e., $\Delta F_q(M) = F_q(M)^{\text{data}} - F_q(M)^{\text{mix}}$ [6]. In addition, a cell-by-cell method is proposed for efficiency correction on SFM [11]. The statistical uncertainties are estimated by Bootstrap method, and the systematic uncertainties are estimated by varying the experimental requirements for tracks in the TPC and TOF.

3 Results and Discussion

Figure 1 shows $F_q(M)^{\text{data}}$ and $F_q(M)^{\text{mix}}$, from the second order to the sixth order in the most central (0-5%) collisions for various $\sqrt{s_{NN}}$. Based on the statistics of BES-I data, $F_q(M)$ can be calculated in the range of $M^2$ from 1 to 100$^2$ and up to the sixth order ($q=6$). It is observed that $F_q(M)^{\text{data}}$ is larger than $F_q(M)^{\text{mix}}$ at large $M^2$ region for various $\sqrt{s_{NN}}$, thus a deviation of $\Delta F_q(M)$ from zero is present in central Au + Au collisions.

![Figure 2: $\Delta F_q(M)$ ($q=3-6$) as a function of $\Delta F_2(M)$ in the most central (0-5%) Au + Au collisions at $\sqrt{s_{NN}} = 7.7-200$ GeV in double-logarithmic scale.](image)

Figure 2 shows $\Delta F_q(M)$ ($q=3-6$), as a function of $\Delta F_2(M)$ in the most central (0-5%) collisions for various $\sqrt{s_{NN}}$. We clearly observe that the correlators $\Delta F_q(M)$ ($q=3-6$) exhibit scaling behavior with $\Delta F_2(M)$.

The value of $\beta_q$ is obtained through a power-law fit of Eq. (2) as shown in Figure 2, and its statistical error is determined by the fit. Figure 3(a) shows $\beta_q$ as a function of $q - 1$ in the most central Au + Au collisions for $\sqrt{s_{NN}} = 7.7-200$ GeV. Consistent with theoretical expectation, $\beta_q$ also obeys a good scaling behavior with $q$, thus $\nu$ can be obtained through a power-law fit of Eq. (3). Figure 3(b) shows the extracted $\nu$ as a function of $(N_{\text{part}})$ in central Au + Au collisions at various $\sqrt{s_{NN}}$. We find that $\nu$ decreases from mid-central (30-40%) to the most central (0-5%) Au + Au collisions.

Figure 4 shows the energy dependence of $\nu$ of charged particles in central Au + Au collisions at $\sqrt{s_{NN}} = 7.7-200$ GeV. It is observed that the $\nu$ exhibits a non-monotonic behavior on collision energy and seems to reach a minimum around $\sqrt{s_{NN}} = 20-30$ GeV. Higher statistics data from BES-II will help to confirm the trend of energy dependence of $\nu$.

4 Summary

In summary, we report the first measurements of intermittency for charged particles in Au + Au collisions at $\sqrt{s_{NN}} = 7.7-200$ GeV from the STAR experiment. Scaled factorial moments
Figure 3: (a) $\beta_q$ (q=3-6) as a function of $q^{-1}$ in most central Au + Au collisions at $\sqrt{s_{NN}} = 7.7$-200 GeV. (b) $\nu$ as a function of $\langle N_{part} \rangle$ in central Au + Au collisions.

Figure 4: Energy dependence of $\nu$ for charged particles in Au + Au collisions at $\sqrt{s_{NN}} = 7.7$-200 GeV. The statistical and systematic errors are shown in bars and brackets, respectively.

(up to the sixth order) for $p$, $\bar{p}$, $K^\pm$ and $\pi^\pm$ within $|\eta| < 0.5$, have been measured in available transverse momentum space. Scaling behavior is clearly visible in Au + Au collisions which is consistent with theoretical predictions. The scaling exponent is related to the critical component, and we observe that it shows a non-monotonic behavior on $\sqrt{s_{NN}}$ with a dip around 20-30 GeV in the most central (0-5%) Au + Au collisions. This non-monotonic behavior needs to be understood with more theoretical inputs. With significantly improved statistics, the RHIC BES Phase-II program will allow for a more precise measurement of intermittency in heavy-ion collisions.

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