# Measurement of Intermittency for Charged Particles in Au + Au Collisions at $\sqrt{s_{\rm NN}}$ = 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 $\sqrt{s_{\rm NN}}$ = 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 $\sqrt{s_{\rm NN}}$ = 20-30 GeV in central Au + Au collisions.**

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## Contents



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## 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 GeV from the NA49 experiment [6]. Meanwhile, studies based on a critical Monte Carlo with self-similar property [7] and transport model with hadronic potentials [8] demonstrate that the intermittency could be visible in Au + Au collisions at RHIC energies.

## 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:

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

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]:

$$F_q(M) \propto F_2(M)^{\beta q}. \quad (2)$$

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

$$\beta_q \propto (q-1)^{\nu}. \quad (3)$$

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].

The data reported here were obtained from Au + Au collisions at $\sqrt{s_{\mathrm{NN}}} = 7.7$, 11.5, 14.5, 19.6, 27, 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 $0.5 <\mid \eta \mid< 1$, which was chosen to be beyond the analysis window of $\mid \eta \mid< 0.5$.

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., $\Delta F_q(M) = F_q(M)^{data} - F_q(M)^{mix}$ [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.

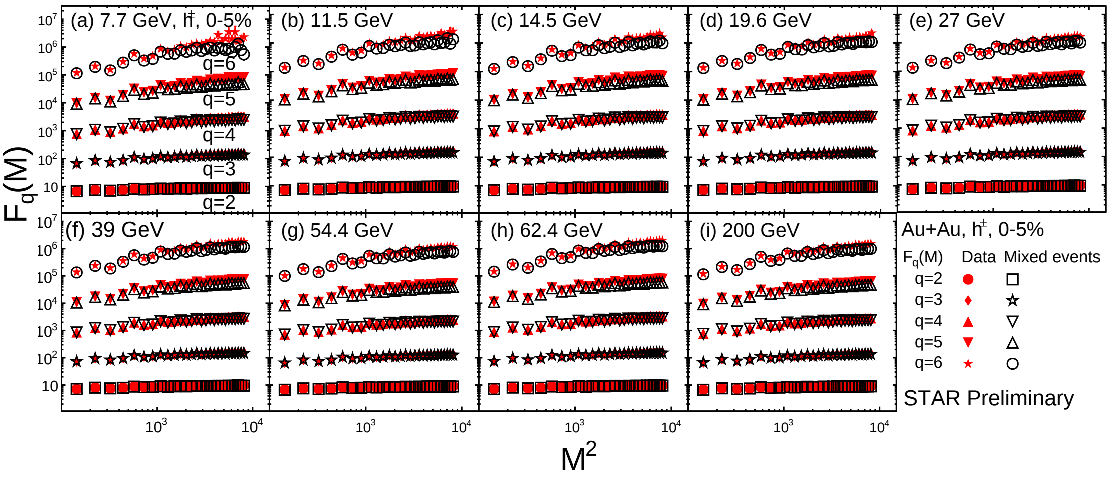


Figure 1: $F_q(M)$ (up to sixth order) of charged particles in transverse momentum space for the most central (0-5%) Au + Au collisions at $\sqrt{s_{\rm NN}}$ = 7.7-200 GeV in double-logarithmic scale.

## 3 Results and Discussion

Figure 1 shows $F_q(M)^{data}$ and $F_q(M)^{mix}$, from the second order to the sixth order in the most central (0-5%) collisions for various $\sqrt{s_{\rm NN}}$. 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 $F_q(M)^{data}$ is larger than $F_q(M)^{mix}$ at large $M^2$ region for various $\sqrt{s_{\rm NN}}$, thus a deviation of $\Delta F_q(M)$ from zero is present in central Au + Au collisions.

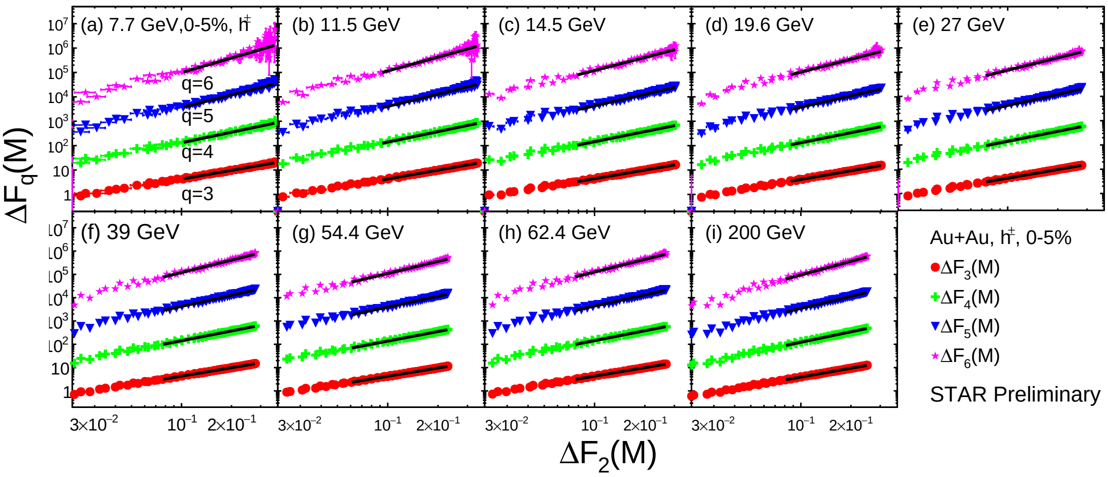


Figure 2: $\Delta F_q(M)$ (q=3-6) as a function of $\Delta F_2(M)$ in the most central (0-5%) Au + Au collisions at $\sqrt{s_{\rm NN}}$ = 7.7-200 GeV in double-logarithmic scale.

Figure 2 shows $\Delta F_q(M)$ (q=2-6), as a function of $\Delta F_2(M)$ in the most central (0-5%) collisions for various $\sqrt{s_{\rm NN}}$. 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 $\sqrt{s_{\rm NN}}$ = 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 $\langle N_{part}\rangle$ in central Au + Au collisions at various $\sqrt{s_{\rm NN}}$. 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 $\sqrt{s_{\rm NN}}$ = 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 $\sqrt{s_{\rm NN}}$ = 20-30 GeV. Higher statistics data from BES-II will help to confirm the trend of energy dependence of $\nu$.

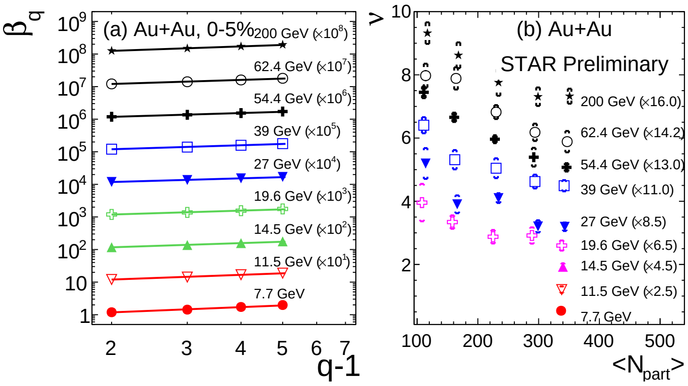


Figure 3: (a) $\beta_q$ (q=3-6) as a function of q-1 in most central Au + Au collisions at $\sqrt{s_{\rm NN}}$ = 7.7-200 GeV. (b) $\nu$ as a function of $\langle N_{part}\rangle$ in central Au + Au collisions.

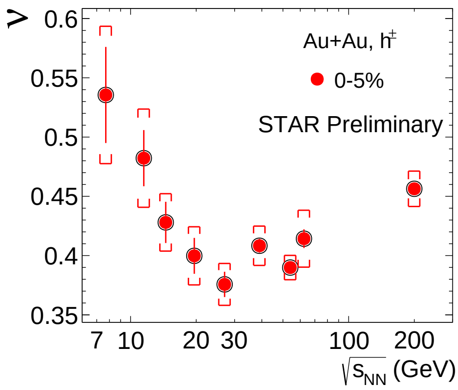


Figure 4: Energy dependence of $\nu$ for charged particles in Au + Au collisions at $\sqrt{s_{\rm NN}}$ = 7.7- 200 GeV. The statistical and systematic errors are shown in bars and brackets, respectively.

## 4 Summary

In summary, we report the first measurements of intermittency for charged particles in Au + Au collisions at $\sqrt{s_{\rm NN}}$ = 7.7-200 GeV from the STAR experiment. Scaled factorial moments (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 $\sqrt{s_{\rm NN}}$ 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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