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Evidence of centrality dependent fractal behavior in high energy heavy ion interactions: Hint of two different sources

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ABSTRACT

Studies on large density fluctuations in produced particle spectra in high energy interactions provide enough information regarding the dynamics of the process of particle production. Various analyses have revealed self-similarity in particle production process. The concept of self-similarity is indicative of fractal geometry. The present analysis reports an exhaustive study on centrality dependence of event-by-event fluctuation of pions produced in^{16}O-AgBr interactions at 60 A GeV using a non conventional tool based on complex network analysis, viz. visibility graph method. The analysis reveals different fractal behaviour as well as different clustering property for different centrality events and the amount of fractality and average clustering coefficient decrease with the increase of centrality. Estimation of Hurst exponent hints towards two different sources of fluctuation, fractional Brownian motion (fBm) and fractional Gaussian noises (fGn) for two different centrality classes.

1. Introduction

Complex network and time series are two generic ways to describe complex systems. Dynamical properties of time series can usually be preserved in network topological structures. Lots of methods have been developed to capture the geometrical structure of time series from complex network aspect such as cycle network [1], correlation network [2], visibility graph [3], recurrence network [4] and isometric network [5] as well as to monitor evolutionary behaviors of complex systems stored in different time series [6-9].

Visibility graph maps a time series into a network. This network inherits several properties of the time series, and the study of the network reveals nontrivial information about the series itself. It has been reported that the periodic time series can be transformed into regular graphs and random series corresponding to random graphs [10] and fractal series into scale-free graphs [3,11-14].

The visibility graph method has a wide range of applicability. It has been applied in searching for the hidden geometry of traffic jamming [15], in studying energy dissipation rates in three-dimensional fully developed turbulence [16], in analyzing exchange rate series [17], in searching for fluctuation and geometrical structure of magnetisation time series of two-dimensional Ising model around critical point [18], in investigating human heartbeat dynamics [19-21], in searching for multifractal nature of multiparticle production in high energy collisions [22-27].

Over the last few decades, the physics of high energy collisions has been in the frontier of the Basic Science research activities throughout the world. According to the acceptable theory, the tiny Universe of high energy-density and temperature, immediately after the Big Bang, evolved through a state of an exotic phase of partonic (comprises of quarks and gluons - the elementary particles) matter, called the Quark-Gluon Plasma (QGP) [28], that survived for some microseconds only. It was predicted that QGP - the plasma state in quantum chromodynamics (QCD) can be created also in the laboratory [29].

However, since the QGP phase is very short lived, it is not possible to detect its direct signal. Physicists have to depend on indirect signals. Existence of large dynamical fluctuation in produced particle spectra is one of the signals of QGP.

To search for the dynamical fluctuation Bialas and Peschanski [30,31] coined a method named intermittency, which refers to the power-law behaviour of factorial moments with respect to the size of phase-space interval in the process of multipion production in heavy-ion interaction. This indicates self-similar fluctuation in this process and self-similarity indicates fractal behaviour. From this analysis, a conjecture has been raised that multipion production process might show fractal behaviour and also there might be a relationship between intermittency and fractality. Multipion produc-

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tion process has an existing cascading mechanism which reflects fractal structure in the hadronization process.

To analyze the fractal structure in multipion production process, several methods have been proposed using techniques based on the fractal theory. The most popular of them have been developed by Hwa (Gq moment) [32] and Takagi (Tq moment) [33]. After considering advantages and disadvantages, both methods are extensively applied to analyze the multipion emission process [34,35]. Then rigorous techniques like Detrended Fluctuation Analysis (DFA) method [36] and multifractal-DFA (MF-DFA) method [37] have also been studied [20,38-41]. Diffusion entropy analysis (DE) is proposed to overcome several shortcomings of variance-based tools [42]. This method is further improved to Balanced Estimator of Diffusion Entropy [43-46] and Factorial Moment Based diffusion Entropy [47] to evaluate scaling exponents in very short time series. To search for multifractals embedded in short time series, a factorial-moment-based estimation of probability moments has also been suggested [48].

However, the latest addition in this kind of analysis is Power of Scale-freeness of Visibility Graph – PSVG. The special feature of this method is that it does not demand infinite time series. In real life time series is always finite, therefore, visibility graph analysis has a wide range of applicability as we have already discussed.

Here we intend to apply the rigorous method of visibility graph in the domain of high energy collisions. It is well known that two types of fluctuations exist in any high energy collision, namely, spatial fluctuation and event–to-event fluctuation. For complete information about the fluctuation pattern and related dynamics one needs to probe both the fluctuations simultaneously. Most of the analyses on multiparticle production using visibility graph algorithm utilize event averaged (pseudorapidity or void probability) distribution to search for scaling behavior [23], whereas, Mali et al. [27] have adopted event wise distribution as input to the horizontal visibility graph [49,50]. However, no such event-by-event analysis is reported till date adopting natural visibility graph algorithm proposed by Lacasa et al. [3].

In this paper we have attempted to search for the evidence of fractality in multipion production process using the multipion data obtained from Illford G5 emulsion stacks exposed to ^{16}O beam of energy 60 AGeV from CERN SPS [51]. We have mapped the event-by-event pseudorapidity distributions into scale-free network and investigated fractal property and clustering property of the constructed network in detail.

We further studied the centrality dependence of fluctuation phenomena by separating the experimental data of ^{16}O-AgBr interactions at 60 A GeV into two sub-samples depending on the number of grey particles (n_g) produced in the interaction (n_g is considered as an indirect measure of the collision centrality in any high energy interactions [52]) and investigated the possible sources of fluctuations for different centrality event samples.

The rest of the paper is organized as follows. The experimental data details are presented in Section 2. The method of visibility graph technique is described in Section 3. Power of Scale-freeness property of Visibility Graph (PSVG) is elaborated in Section 3.1 and Network Average Clustering Coefficient is defined in Section 3.2. The details of our data analysis and results are presented in Section 4. The paper is concluded in Section 5.

2. Experimental data details

The data are obtained from Illford G5 emulsion stacks exposed to ^{16}O beam of energy 60 AGeV from CERN SPS [51]. Detection of charged particles using Nuclear emulsion technique is an age old method, the details of which can be found in Ref. [53]. A Leitz Metaloplan microscope with a 10X objective and 10X ocular lens provided with a semi-automatic scanning stage is used to scan the plates. Each plate is scanned by two independent observers to increase the scanning efficiency. The final measurements are done using an oil-immersion 100X objective. The measuring system fitted with it has 1μ m resolution along the X and Y axes and 0.5 μm resolution along the Z axis.

After scanning, the events are chosen according to the following criteria:

I. The incident beam track should not exceed more than 3° from the main beam direction in the pellicle. It is done to ensure that we have taken the real projectile beam.
II. Events showing interactions within 20 μm from the top and bottom surface of the pellicle are rejected. It is done to reduce the loss of tracks as well as to reduce the error in angle measurement.
III. The tracks of the incident particle, which induce interactions, are followed in the backward direction to ensure that it is a projectile beam starting from the beginning of the pellicle.

According to the emulsion terminology [54] the particles emitted after interactions are classified as:

A. Black particles: Black particles consist of both single and multiple charged fragments. They are target fragments of various elements like carbon, lithium, beryllium etc. with ionization greater or equal to $10I_0$, I_0 being the minimum ionization of a singly charged particle. Ranges of them are less than 3 mm and velocity less than 0.3c and energy less than 30 MeV. c is the velocity of light in vacuum. In the emulsion experiments it is very difficult to measure the charges of the fragments. So identification of the exact nucleus is not possible.
B. Grey particles: -They are mainly fast target recoil protons with energy upto 400 MeV. They have ionization $1.4\ I_0 \leq I < 10\ I_0$. Their ranges are greater than 3 mm and having velocities $0.7c \geq V \geq 0.3c$.
C. Shower particles: -The relativistic shower tracks with ionization $\leq 1.4\ I_0$ are mainly produced by pions and are not generally confined within the emulsion pellicle. These shower particles have energy in GeV range.

For the present analysis, only the shower tracks resulting from singly charged particles (mostly pions) moving with relativistic speeds ($v \geq 0.8c$), are taken into consideration. According to the above selection procedure we have chosen 250 events of ^{16}O- AgBr interactions at 60 AGeV. For the present analysis, only the shower tracks resulting from singly charged particles (mostly pions) moving with relativistic speeds ($v \geq 0.8c$), are taken into consideration. The emission angle (θ) and azimuthal angle (ϕ) are measured for each tracks by taking readings of the coordinates of the interaction point (X_0,Y_0,Z_0), coordinates (X_1,Y_1,Z_1) at the end of the linear portion each secondary track and coordinate (X_i,Y_i,Z_i) of a point on the incident beam. In case of shower particles the variable used is pseudorapidity (η) which is defined as $= -\ln\tan\frac{\theta}{2}$. The accuracy in pseudorapidity in the region of interest is of the order of 0.1 pseudorapidity units. Nuclear emulsion covers 4π geometry and provides very good accuracy in the measurement of emission angles of pions due to high spatial resolution and thus, is suitable as a detector for the study of fluctuations in the fine resolution of the phase space considered.

3. Visibility graph technique

The visibility graph algorithm maps time series X to its visibility graph [3]. Let ith point of the time series is X_i. Each data value is considered to be a node. Two nodes are connected if they can see each other, namely, a straight visibility line exists between them.

Formally, two arbitrary data values (t_a,X_a) and (t_b,X_b) are visible to each other if any other point (t_c,X_c) between them satisfies