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Multiplicity fluctuations of pions and protons at SPS energy – An in-depth analysis with factorial correlator

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Abstract. We compute the factorial correlators to study the dynamical fluctuations of pions and a combination of pions and protons (compound multiplicity) in ^{32}S–AgBr interactions at 200 A GeV. The study reveals that for both pion and compound multiplicity the correlated moments increase with the decrease in bin–bin separation D, following a power-law, which suggests the self-similarity of multiplicity fluctuation in each case. The results of the analysis also show a consistency with the prediction of α-model for the existence of intermittency in both cases.

Keywords. Dynamical fluctuations; pions; compound multiplicity; nucleus–nucleus interactions; factorial correlator study.

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1. Introduction

Several experimental investigations over the last few years have revealed non-statistical fluctuation in multiparticle production process in all types of interactions (lepton–lepton, lepton–nucleus, hadron–hadron, hadron–nucleus and nucleus–nucleus) at relativistic and ultra-relativistic energies. The most commonly used technique to investigate the origin of non-statistical fluctuations was introduced by Bialas and Peschanski [1] through the analysis of the distribution of produced particles from cosmic ray event [2]. Their technique seems to be one of the most powerful and promising technique for the analysis of event-by-event basis data in terms of intermittency. This technique involves the computation of scaled factorial moments (SFMs) as a function of the decreasing phase space cells and this intermittent type of non-statistical fluctuation was thought to be the outcome of the transition from the quark-gluon plasma to normal hadronic matter and interest was centred around self-similarity studies. Later on, analyses of various accelerator-based data [3–17] were found to be consistent with the power-law and the results are not enough for the interpretation. Analysis of the experimental data in almost all the cases has been performed as SFMs which is the main tool for intermittency in different phase space variables. But the results from different types of interactions are not enough for an unambiguous interpretation of the intermittency effect. A number of alternative suggestions such as conventional short-range correlations [18], formation of jets and mini-jets [19], self-similar random cascading mechanism [20], Bose–Einstein (B–E) interference [21] etc. have also been proposed but none of them can explain all the datasets simultaneously. Besides these, Hwa [22,23] suggested an alternative moment G_q which is used to investigate the large density fluctuations in terms of multifractal formalism. But the dynamical origin of such fluctuations is still controversial.

Recently, WA98 Collaboration has performed a detailed event-by-event fluctuation study in the multiplicities of charged particles and photons and the total transverse energy in 158 A GeV Pb+Pb collisions [24]. It was observed that the relative fluctuations increase with the increase in the impact parameter interval. The fluctuations in multiplicities and transverse energy were found to increase from central to peripheral events.

The multiplicity fluctuation has been studied in terms of scaled variances for most central Pb+Pb collisions at 20 A, 30 A, 40 A, 80 A and 158 A GeV as measured by the NA49 experiment at CERN SPS. The scaled variance of multiplicity distribution was found to increase with decreasing rapidity and transverse momenta [25].

The STAR experiment at RHIC has measured the dynamical net charge fluctuations in Au+Au collisions at $\sqrt{S_{NN}} = 19.6$, 62.4, 130, 200 GeV, Cu+Cu collisions at $\sqrt{S_{NN}} = 62.4$, 200 GeV and P+P collisions at $\sqrt{S} = 200$ GeV using a robust observable $\nu_{+-,\mathrm{dyn}}$ [26]. It was observed that the dynamical net charge fluctuations are non-vanishing at all energies and exhibit a modest dependence on beam energy for Au+Au as well as Cu+Cu collisions. Recent investigations of NA49 data at CERN SPS have revealed the fact that the behaviour of multiplicity fluctuation with collision centrality is non-monotonic [27] in nature.

Meanwhile, Bialas and Peschanski [28] suggested a new approach for the test of intermittency in terms of factorial correlators (FCs). This important tool measures not only the non-statistical local density fluctuation but also provides information about the correlation between these local density fluctuations in the phase space. The results from the analysis of data in terms of SFMs compared to analysis in terms of FCs is relatively scarce. Over the last few years, some investigations [29–33] have been done on 'factorial correlators'. In these studies fluctuations in pion production process have been probed with the help of factorial correlators. In all the cases the results suggest self-similar fluctuation pattern in pionization process. The result also supports the α-model of particle production. Investigations in high energy nuclear collisions are generally carried out on the produced pions because these particles are believed to be most informative about the collision dynamics. Limited attention has been paid to the medium energy (30–400 MeV) knocked out target protons. These target protons are also supposed to carry some information about the interaction dynamics. This is because the time-scale of emission of these particles is the same ($\approx 10^{-22}$ s) as that of the produced particles. These target protons, which are known as grey tracks in nuclear emulsion, are the low energy part of the internuclear cascade formed in high energy interactions. If the number of fast target fragments, generally known as the grey particles in emulsion media is combined with the produced pions, known as the shower tracks in the same media, in a collision, a new parameter named as 'compound multiplicity' ($n_{\rm c} = n_{\rm g} + n_{\rm s}$ where $n_{\rm c}$ = compound multiplicity, $n_{\rm g}$ = number of grey tracks and $n_{\rm s}$ = number of shower tracks) is formed which can play an important role in understanding the reaction dynamics in high energy nuclear interactions. The first investigation of compound multiplicity was done by Jurak *et al* [34]. The behaviour of the compound multiplicity spectra is to be probed thoroughly with the available sophisticated tools. So far only limited attempts have been made with this parameter [35–39].

In view of the above, fluctuation study in terms of factorial correlators (FCs) for both pions and compound multiplicity emitted from ^{32}S–AgBr interactions at 200 A GeV in $\cos\theta$ space has been the subject of investigation in the present paper. This study reveals self-similarity in pion production as well as in compound hadron production process and also supports α-model of intermittency as indicated in the previous works [29,30].

2. Experimental details

The data used in this present analysis were obtained by exposing G5 nuclear emulsion plates by ^{32}S beam with 200 A GeV incident energy at CERN SPS.

The scanning of the plates is carried out with the help of a high resolution Leitz metalloplan microscope provided with semi-automatic scanning and measuring system. The scanning is done using objective 10× in conjunction with a 25× ocular lens. To increase the scanning efficiency, two independent observers scanned the plates independently. For measurement, 100× oil immersion objective is used in conjunction with 25× ocular lens. The measuring system fitted with it has 1 μm resolution along the X- and Y-axes and 0.5 μm resolution along the Z-axis.

Events are scanned according to the following criteria:

(a) The beam track should lie within 3° to the mean beam direction of the pellicle.
(b) The events, which are within 20 μm thickness from the top or bottom surface of the plate, should be rejected.
(c) The events, primary beam tracks of which are observed to be a secondary track of other interactions should not be analysed and should be rejected.

According to the emulsion technique 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 such as carbon, lithium, beryllium etc. with ionization greater than or equal to $10I_0, I_0$ being the minimum ionization of a singly charged particle. These black particles having maximum ionizing power are less energetic and consequently they are short-ranged. Their range is less than 3 mm in emulsion medium. They have velocities 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 charge of the fragments. So identification of the exact nucleus is not possible.

(b) Grey particles: They are mainly fast target recoil protons with energy up to 400 MeV. They have ionization $1.4I_0 \leq I < 10I_0$. These particles have range greater than 3 mm in emulsion medium and have velocities $0.7c \geq V \geq 0.3c$.

(c) Shower particles: The relativistic shower tracks with ionization I less than or equal to $1.4I_0$ are mainly produced by pions and are not generally confined within the emulsion pellicle. These shower particles have energy in the GeV range.

(d) Projectile fragments: Along with these tracks there are a few projectile fragments. In high energy nuclear collisions, the projectile beam which collides with the target nucleus also undergoes fragmentation. These particles have constant ionization, long range and small emission angle. They generally lie within 3° with respect to the main beam direction. Great care should be taken to identify these projectile fragments.

3. Target selection

We have chosen only the events with at least eight heavy ionizing tracks of (black+grey) particles so that the targets chosen are silver or bromine. (The events that have heavy tracks less than eight, are due to the collision of the projectile beam with carbon, nitrogen and oxygen nucleus present in the emulsion. These types of events are called CNO events). For our present analysis we have considered the combination of grey and shower tracks for compound multiplicity. Following the above selection procedure we have chosen 150 events of ^{32}S–AgBr interactions at 200 A GeV. In our data sample the average number of pions is 95.8±3.68 and the average number of grey tracks is 5.3±0.21. The emission angle $\cos\theta$ is measured for each track by taking the readings of the coordinates (X_0, Y_0, Z_0) of the interaction point, the coordinates (X_1, Y_1, Z_1) at any point on each secondary track and the coordinates (X_i, Y_i, Z_i) of a point on the incident beam.

The uncertainty in the measurement of emission angle which is very essential for this study never exceeds 0.1 mrad. Nuclear emulsion covers 4π geometry and provides very good accuracy in the measurements of the angles of the produced particles due to high spatial resolution and thus, is suitable as a detector for the study of factorial correlators in emission angle space.

4. Factorial correlator analysis

The factorial correlator study has been performed in the emission angle space for both pions and compound multiplicity. We have considered the emission angle interval $\Delta\cos\theta$ which is subdivided into M bins of width $\delta\cos\theta = \Delta\cos\theta/M$. Two bins, the mth and lth, having a separation D are chosen so that $D = d \times \delta\cos\theta$, where $d = |m - l|$. D is known as the correlation length. The factorial correlator F_{ij} of order $i \times j$ between the mth and lth bins is defined as [28]

$$F_{ij}^{m,l}(\delta\cos\theta) = \frac{\langle n_m(n_m-1)\cdots(n_m-i+1)n_l(n_l-1)\cdots(n_l-j+1)\rangle}{\langle n_m(n_m-1)\cdots(n_m-i+1)\rangle\langle n_l(n_l-1)\cdots(n_l-j+1)\rangle}, \qquad (1)$$

where n_m and n_l are the number of particles in the mth and lth bins respectively and $\langle\ \rangle$ denotes an averaging over the whole sample of events.

In order to increase statistics, the average is calculated for all bin combinations with a given distance D. Thus,

$$\begin{aligned} C_{ij}(D, \delta\cos\theta) &= \frac{1}{[2(M-d)]} \\ &\quad\times \left(\sum_{m=1}^{M-d} F_{ij}^{m,m+d}(\delta\cos\theta) + \sum_{l=1}^{M-d} F_{ij}^{l+d,l}(\delta\cos\theta) \right) \\ &= \frac{1}{[2(M-d)]} \sum_{m=1}^{M-d} (F_{ij}^{m,m+d}(\delta\cos\theta) + F_{ji}^{m,m+d}(\delta\cos\theta)) \end{aligned} \tag{2}$$

as $F_{ij}^{m,l}(\delta\cos\theta) = F_{ji}^{l,m}(\delta\cos\theta)$. The correlators, C_{ij}, can now be studied as a function of bin–bin separation D and binwidth $\delta\cos\theta$.

The α-model [28] for intermittency gives the following predictions:

(i) C_{ij} should show a power-law dependence on the bin–bin separation D, $C_{ij} \propto D^{\alpha_{ij}}$ which can also be written as

$$\ln C_{ij} = -\ln(D) \times \alpha_{ij} + \text{constant}. \tag{3}$$

(ii) At fixed D, the correlators C_{ij} should be independent of $\delta\cos\theta$.

5. Results and discussions

The $\cos\theta$ region used is -1 to $+1$ both for pions and compound multiplicity. As the shape of the distribution curve influences the scaling behaviour of the factorial correlators, we have used the cumulative variable [33] $X_{\cos\theta}$ instead of $\cos\theta$. The corresponding region of investigation then becomes 0 to 1. The cumulative variable X_y is given by the relation as below:

$$X_y = \frac{\int_{y_1}^{y} \rho(y')\partial y'}{\int_{y_1}^{y_2} \rho(y')\partial y'}, \tag{4}$$

where y_1 and y_2 are the two extreme points in the distribution $\rho(y)$, between which X_y varies from 0 to 1. The $\cos\theta$ distributions for both pions and compound multiplicity are shown in figures 1a and 1b respectively.

To study the characteristics of the factorial correlators at different binwidths, we have considered the total emission angle space $\Delta X_{\cos\theta} = 1$ and it has been subdivided into 10, 20, 30 and 40 bins of widths $\delta X_{\cos\theta} = 0.100$, 0.050, 0.033 and 0.025 respectively. Factorial correlators of order (1,1), (2,1), (2,2), (3,1), (3,2) and (3,3) have been calculated using eq. (2) for each binwidth. The power-law dependences have been studied for different binwidths $\delta X_{\cos\theta} = 0.100$, 0.050, 0.033 and 0.025 using eq. (3) and the variations of $\ln C_{ij}$ as a function of $-\ln D$ are

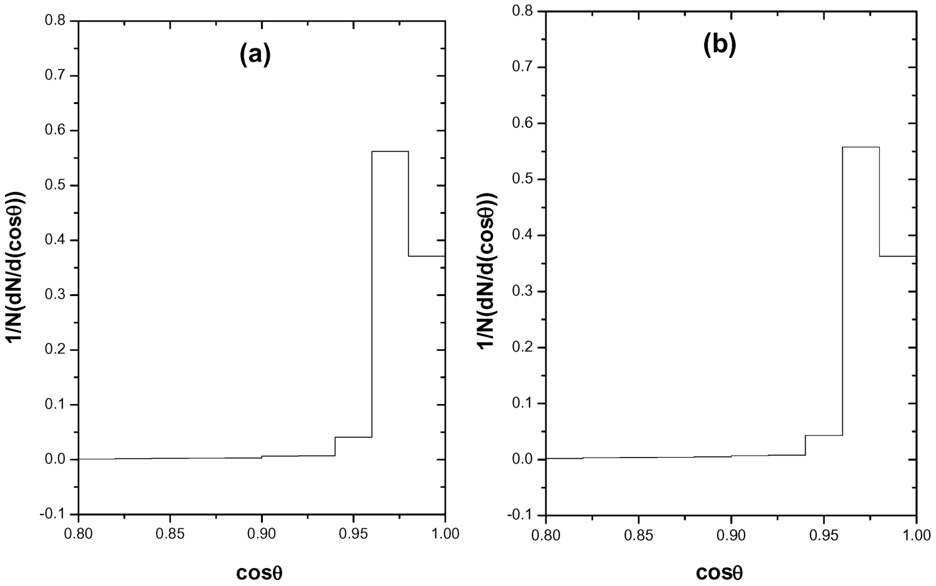

Figure 1. The $\cos\theta$ distributions for (**a**) pions and (**b**) compound multiplicity.

shown in figures 2a and 2b for $\delta X_{\cos\theta} = 0.050$ and 0.033 respectively for pions. If the relation between the two ($\ln C_{ij}$ and $-\ln D$) are linear then it suggests an intermittent type of fluctuation. The error bars shown in the figures are nothing but the statistical errors obtained from the dispersion of the F_{ij} values for different bin combinations. The increase in $\ln C_{ij}$ with $-\ln D$ is not linear in the full D range as predicted by the α-model of intermittency. However, our analysis shows that the relationship between $\ln C_{ij}$ and $-\ln D$ is almost linear in restricted D region where $D \leq 0.299$ ($\ln D \leq -1.207$). The behaviour of correlated moments at large D is largely controlled by the long-range correlations. The exponents α_{ij} are calculated by performing the best linear fits in the selected regions $0.099 \leq D \leq 0.299$ ($-2.312 \leq \ln D \leq -1.207$), $0.049 \leq D \leq 0.299$ ($-3.015 \leq \ln D \leq -1.207$), $0.033 \leq D \leq 0.200$ ($-3.411 \leq \ln D \leq -1.609$) and $0.024 \leq D \leq 0.200$ ($-3.729 \leq \ln D \leq -1.609$) for bins 10, 20, 30 and 40 respectively. The maximum and minimum values of D range depends on $\delta X_{\cos\theta}$. These D values are different for different binwidths. Table 1 shows the slope values (α_{ij}) for different binwidths for pions.

The error bars shown in the figures are standard statistical errors. For the fitted parameters, the errors shown are the values returned by the fitting procedure. Electron pairs produced by Dalitz decay or photon conversion, may be counted as hadrons in this experiment. This is a possible source of systematic error. Special care has been taken to avoid such contamination. However, Dalitz production alone is negligible and it was shown by Adamovich and his collaborators [40] that the results of intermittency analyses is negligible as the percentage of gamma conversion is too small. Generally, this systematic error is lesser than the quoted statistical errors.

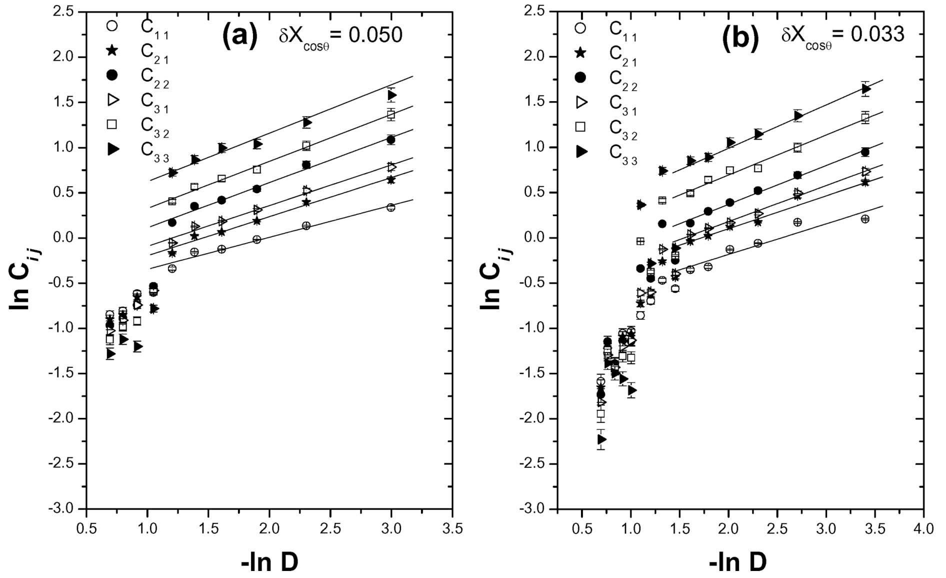

Figure 2. The dependence of $\ln C_{ij}$ on $-\ln D$ for binwidths (**a**) $\delta X_{\cos\theta} = 0.050$ and (**b**) $\delta X_{\cos\theta} = 0.033$ for pions.

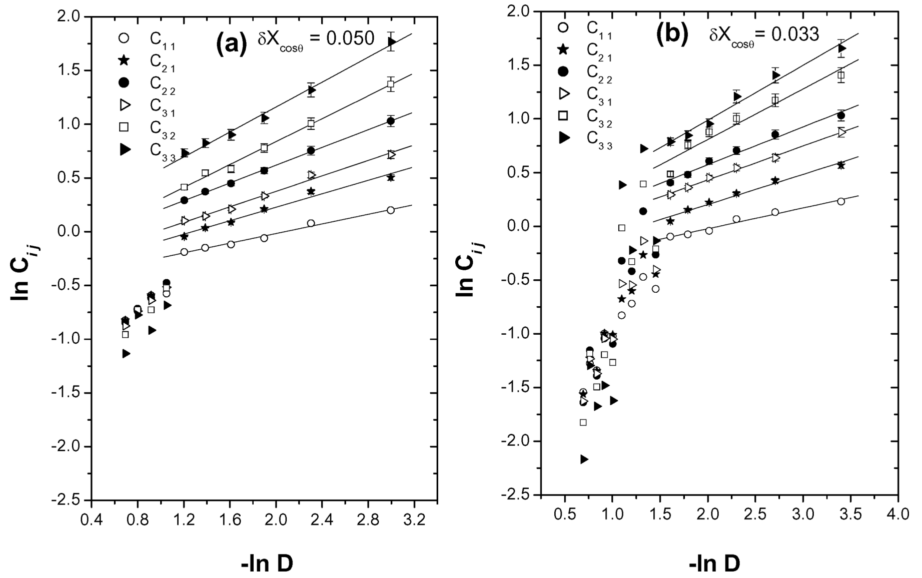

Figure 3. The dependence of $\ln C_{ij}$ on $-\ln D$ for binwidths (**a**) $\delta X_{\cos\theta} = 0.050$ and (**b**) $\delta X_{\cos\theta} = 0.033$ for compound multiplicity.

We have performed similar analysis for compound multiplicity. The power-law dependences have been studied for different binwidths ($\delta X_{\cos\theta} = 0.100$, 0.050, 0.033 and 0.025). The variations of $\ln C_{ij}$ with $-\ln D$ are shown in figures 3a and 3b for

Table 1. The slope values (α_{ij}) of the best-fitted points from the plot of $\ln C_{ij}$ vs. $-\ln D$ in the region $D \leq 0.299$ for different binwidths for pions.

Order of correlator (ij)	$\delta X_{\cos\theta} = 0.100$ $0.099 \leq D \leq 0.299$	$\delta X_{\cos\theta} = 0.050$ $0.049 \leq D \leq 0.299$	$\delta X_{\cos\theta} = 0.033$ $0.033 \leq D \leq 0.200$	$\delta X_{\cos\theta} = 0.025$ $0.024 \leq D \leq 0.200$
11	0.365±0.017	0.353±0.030	0.338±0.027	0.329±0.029
21	0.470±0.013	0.432±0.029	0.363±0.014	0.352±0.027
31	0.485±0.012	0.450±0.027	0.397±0.017	0.375±0.043
22	0.508±0.013	0.499±0.028	0.428±0.019	0.392±0.033
32	0.530±0.015	0.520±0.021	0.441±0.030	0.422±0.031
33	0.564±0.019	0.535±0.035	0.452±0.016	0.433±0.036

Table 2. The slope values (α_{ij}) of the best-fitted points from the plot of $\ln C_{ij}$ vs. $-\ln D$ in the region $D \leq 0.299$ for different binwidths in compound multiplicity.

Order of correlator (ij)	$\delta X_{\cos\theta} = 0.100$ $0.099 \leq D \leq 0.299$	$\delta X_{\cos\theta} = 0.050$ $0.049 \leq D \leq 0.299$	$\delta X_{\cos\theta} = 0.033$ $0.033 \leq D \leq 0.200$	$\delta X_{\cos\theta} = 0.025$ $0.024 \leq D \leq 0.200$
11	0.233±0.053	0.224±0.013	0.193±0.016	0.150±0.009
21	0.349±0.059	0.314±0.023	0.281±0.021	0.210±0.021
31	0.380±0.012	0.360±0.018	0.316±0.011	0.258±0.039
22	0.439±0.030	0.413±0.005	0.351±0.023	0.289±0.050
32	0.588±0.068	0.533±0.019	0.470±0.060	0.334±0.064
33	0.613±0.031	0.580±0.025	0.511±0.038	0.418±0.056

$\delta X_{\cos\theta} = 0.050$ and 0.033 respectively for compound multiplicity spectrum. Table 2 shows the slope values (α_{ij}) in different binwidths for compound multiplicity. The positive slope values α_{ij} clearly indicate that the correlated moments increase with the decreasing correlation length, D. From tables 1 and 2, it is clear that for both pions and compound multiplicity, the exponent values (α_{ij}) decreases with the decreasing bin size ($\delta X_{\cos\theta}$) for any particular order of moment ($i \times j$). It is also evident from tables 1 and 2 that for a given binwidth, $\delta X_{\cos\theta}$, the slope values increase with the increase of the order of moments ($i \times j$). It is observed from tables 1 and 2 that for all the binwidths ($\delta X_{\cos\theta} = 0.100$, 0.050, 0.033 and 0.025) the values of correlated moments for pions are more than those of compound multiplicity for the order of moments (1,1), (2,1), (2,2) and (3,1). But for higher orders (3,2) and (3,3), it is clear that the values of correlated moments are more in the case of compound multiplicity than for pions in different binwidths ($\delta X_{\cos\theta} = 0.100$, 0.050 and 0.033) except for the binwidth $\delta X_{\cos\theta} = 0.025$. This result suggests that the strength of non-statistical fluctuations for lower orders are more in the case of pions than those from compound multiplicity, whereas for higher orders there occurs reverse result. This point has been discussed in summary section.

The intermittency exponent values are expected to satisfy the following relation [28]:

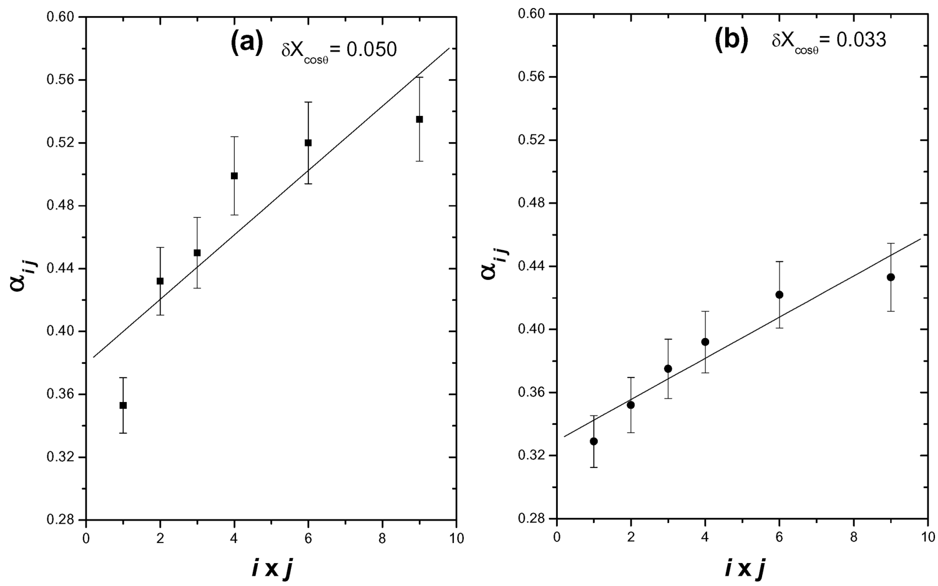

Figure 4. The plot of α_{ij} against $(i \times j)$ for binwidths (**a**) $\delta X_{\cos\theta} = 0.050$ and (**b**) $\delta X_{\cos\theta} = 0.033$ for pions.

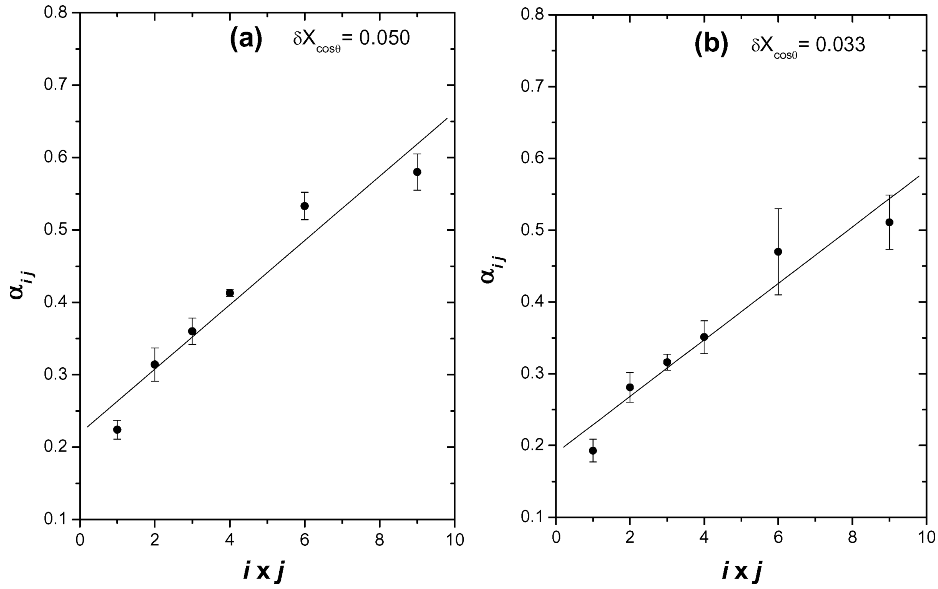

Figure 5. The plot of α_{ij} against $(i \times j)$ for binwidths (**a**) $\delta X_{\cos\theta} = 0.050$ and (**b**) $\delta X_{\cos\theta} = 0.033$ for compound multiplicity.

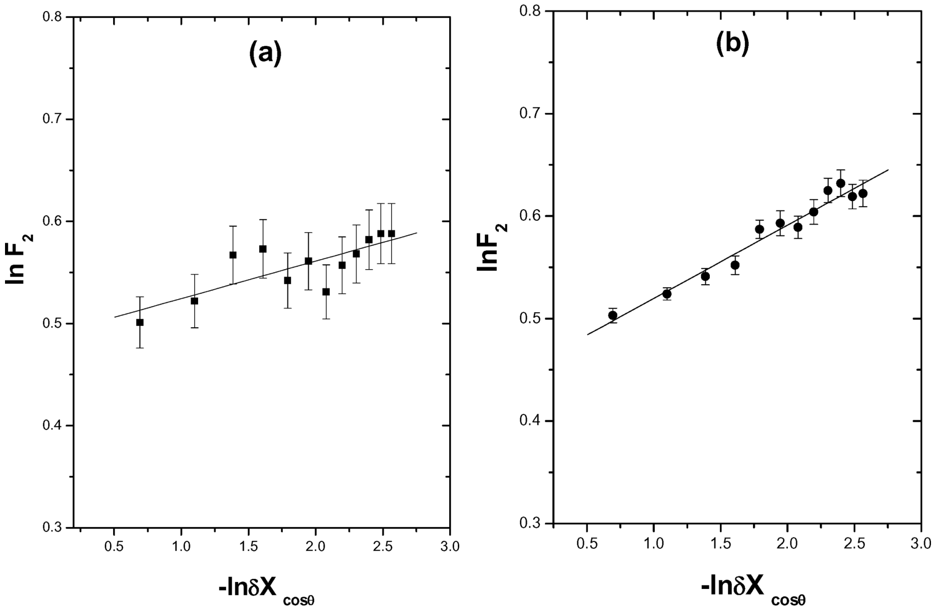

Figure 6. The variation of $\ln F_2$ against $-\ln \delta X_{\cos\theta}$ for (**a**) pions and (**b**) compound multiplicity.

$$\alpha_{ij} = ij\alpha_2, \tag{5}$$

where the equality sign is due to the log-normal approximation. To verify the above relation, we have plotted α_{ij} as a function of the product $(i \times j)$ for different binwidths. Figures 4a and 4b represent the plot of α_{ij} vs. $(i \times j)$ for $\delta X_{\cos\theta} =$ 0.050 and 0.033 respectively for pions. Similar plots for compound multiplicity are shown in figures 5a and 5b for $\delta X_{\cos\theta} = 0.050$ and 0.033 respectively. For each binwidth the plot is consistent with the linear growth of the exponent values as predicted by the log-normal approximation [28]. Though the slope values of the curves, i.e. $\Delta\alpha_{ij}/\Delta(i \times j)$, are not exactly equal to the intermittency exponent of second order (α_2), they are comparable. The plots of $\ln F_2$ against $-\ln \delta X_{\cos\theta}$ are shown in figures 6a and 6b for pions and compound multiplicity respectively. The slope values α_2 are extracted by performing the best linear fits of those plots.

F_2 values are obtained using the following relation:

$$F_2 = \frac{1}{M} \sum_{m=1}^{M} \frac{\langle n_m(n_m - 1)\rangle}{\langle n_m\rangle^2}, \tag{6}$$

where the total emission angle space region $\Delta X_{\cos\theta}$ is divided into M equal bins of size $\delta X_{\cos\theta}$, n_m is the number of particles in the mth bin for a particular event.

$\langle\ \rangle$ denotes the average over all the events. The values of $\Delta\alpha_{ij}/\Delta(i \times j)$ for different binwidths ($\delta X_{\cos\theta} = 0.100$, 0.050, 0.033 and 0.025) and α_2 are tabulated in tables 3 and 4 for pions and compound multiplicity respectively. The slope values of the curves ($\Delta\alpha_{ij}/\Delta(i \times j)$) are different in different binwidths of the

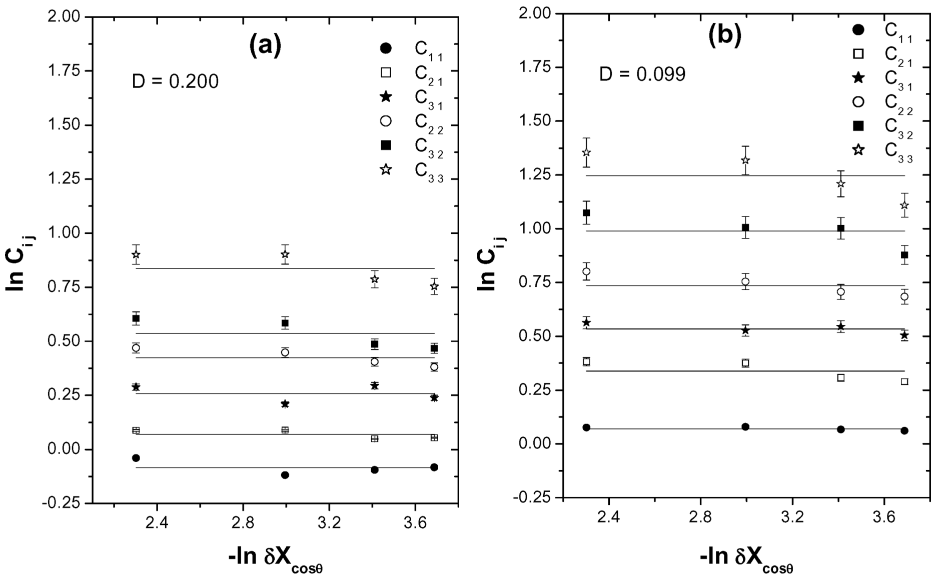

Figure 7. The plot of $\ln C_{ij}$ against $-\ln \delta X_{\cos\theta}$ for (**a**) $D = 0.200$ and (**b**) $D = 0.099$ for compound multiplicity.

Table 3. The comparison of α_2 with slope values of α_{ij} vs. $(i \times j)$ plots for different binwidths for pions.

$\delta X_{\cos\theta}$	$\Delta\alpha_{ij}/\Delta(i\times j)$	$\langle\Delta\alpha_{ij}/\Delta(i\times j)\rangle$	α_2
0.100	0.020±0.005		
0.050	0.020±0.005	0.016±0.004	0.034±0.009
0.033	0.014±0.003		
0.025	0.013±0.002		

Table 4. The comparison of α_2 with slope values of α_{ij} vs. $(i \times j)$ plots for different binwidths in compound multiplicity.

$\delta X_{\cos\theta}$	$\Delta\alpha_{ij}/\Delta(i\times j)$	$\langle\Delta\alpha_{ij}/\Delta(i\times j)\rangle$	α_2
0.100	0.047±0.007		
0.050	0.044±0.005	0.040±0.004	0.072±0.003
0.033	0.039±0.005		
0.025	0.031±0.002		

correlated moments but the average of these slopes $\langle\Delta\alpha_{ij}/\Delta(i\times j)\rangle$ is really comparable with the intermittency exponent of second order (α_2). This analysis reveals a scale invariant property of the correlated non-statistical fluctuations in different regions of emission angle space indicating the intermittent nature of particle production in both pions and compound multiplicity. From table 3 for pions and from table 4 for compound multiplicity it is clear that the intermittency exponent of second order (α_2) is more in the case of compound multiplicity than that in the case of pions. According to the α-model for fixed D, the correlators should be independent of the binwidth $\delta X_{\cos\theta}$. Figures 7a and 7b represent the variation of $\ln C_{ij}$ against $-\ln \delta X_{\cos\theta}$ for $D = 0.200$ and 0.099 respectively for compound multiplicity. The horizontal lines are drawn through the average values to facilitate observations.

6. Summary

Thus the present analysis reveals the following interesting features of the multiparticle production process.

(1) The correlated moments for the pions and compound multiplicity in emission angle space follow a power-law behaviour within a restricted D region where $D \leq 0.299$ indicating self-similar behaviour of both pions and compound hadrons.

(2) This power-law type D-dependence of the FCs and the binwidth independence of the FCs at fixed D, support the α-model of intermittency in both the cases.

(3) It is further interesting to note that the strength of non-statistical fluctuations is less for compound multiplicity than those of pions. However, the lower-order results are taken to be more informative and this supports the fact that the fluctuation decreases with the increase of the number of hadrons.

(4) $D < 0.299$ does not have any special significance. This value was obtained from the data which were taken for straight line fit.

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