Indian Journal of Pure & Applied Physics
Vol. 46, February 2008, pp. 93-99

Self-affine multiplicity fluctuation of grey tracks in π^--AgBr interactions at 350 GeV/c

Dipak Ghosh, Argha Deb, Sitaram Pal* & Jayita Ghosh

Nuclear and Particle Physics Research Centre, Department of Physics, Jadavpur University, Kolkata 700 032

Received 31 July 2006; revised 20 September 2007; accepted 17 December 2007

Fluctuation characteristics of protons produced in π^--AgBr interactions at 350 GeV/c have been investigated in cosθ, ϕ and $X_{\cos\theta}$–X_ϕ phase spaces. Xcosθ and Xϕ Factorial moment methodology has been used for the analysis. In two-dimensional analysis, fluctuation characteristics have been studied both in self-similar and self-affine space. No scaling behaviour is observed in the full bin-range. For in-depth study, full bin range is divided into different sub-bins. Fluctuation analysis into different sub-bins confirms the scaling law in a particular bin only. The analysis provides an indication of self-affine fluctuation pattern in this bin. $X_{\cos\theta}$ and X_ϕ

Keywords: Proton fluctuation, Grey particle, Self-affine scaling, π^--AgBr interactions

1 Introduction

In high energy interactions, the study of multiparticle production entered into a remarkable era particularly when Bialas and Peschanski[1] introduced a completely new methodology to find out the non-statistical fluctuation in pseudorapidity space in place of analyzing the average features of multiparticle production. The idea of studying the intermittent pattern of particle production was introduced for explaining the statistical significance of unusual events[2-4] having sharp spikes in pseudorapidity spectra. Generally, the study of particle density fluctuation in variable phase space domains can throw light on the underlying dynamics of multi hadron production process. The statistical counting variable called the scaled factorial moment (SFM) F_q is the main tool for studying intermittency. Scaled factorial moments are designed for extraction of non-statistical fluctuation after eliminating the statistical part. In high energy physics, concept of intermittency was first propounded by Bialas and Peschanski[1]. It has been shown that the average SFM is equal to the moment of a true probability distribution of particle density, without any statistical bias. Bialas and Peschanski[1] have investigated the development of these moments as a function of space-time resolution. According to them, power law growth of the factorial moments with decreasing phase space interval size signals the onset of intermittency in the context of high-energy interactions. The idea of searching for intermittent pattern of fluctuation gathered tremendous momentum from experimental data analysis. Various types of interaction data were published confirming power law singularities in particle spectra[5-8].

To explain intermittency, a number of suggestions like self-similar random cascading mechanism[1,9], formation of jets and minijets[10], B-E interference[11], conventional short range correlation[12] etc are available, but none of them is accepted universally. Different data sets prefer different explanation.

Experimental data on intermittency do not rule out the possibility of something non-trivial. The theoretical interpretation has not been able to take a concrete shape. In fact, the quest for the proper dynamics, which can produce such chaotic structure, is still in its infancy. Such a situation demands more and more data analyses from different angles.

Most of the investigations on these anomalous fluctuations were performed in one-dimensional space only. But the real process occurs in three dimensions. So one dimensional analysis is not sufficient enough for extracting the proper fluctuation pattern of the real three dimensional process[13]. The analysis should be done in higher dimension to reduce the error due to dimensional reduction. The usual procedure for calculating the higher dimensional factorial moments is to divide phase space into sub-cells with the same M (where M is the number of sub-cells in three dimensional phase space) in each direction assuming that the phase spaces are isotropic in nature. This is called self-similar analysis. However, phase space in high-energy multiparticle production is anisotropic as indicated by Van Hove[14]. The experimental observation regarding momentum values in different directions also supports this notion. The longitudinal momentum values are large. On the contrary, momentum in the transverse direction is small. Thus, it is expected that the fluctuations or the scaling properties if exist should also be anisotropic and the scaling behaviour at the same time should also be different in longitudinal and transverse directions (i.e scaled anisotropically). In most of the previous analyses, researchers overlooked this anisotropic nature of phase space. Only a few research works have been reported so far where the evidence of self-affine multiparticle production is indicated by the data[15-23].

According to nuclear emulsion terminology[24], the particles emitted in high energy interactions are classified as:

(a) *Black particles* — They are target fragments with ionization greater than or equal to 10 I_0, I_0 being the minimum ionization of a singly charged particle. Their ranges are less than 3 mm. Their velocity is less than 0.3*c* and their energy is less than 30 MeV, where *c* is the velocity of light in free space.
(b) *Grey particles* — They are mainly fast target recoil protons with energy up to 400 MeV. The ionization power of grey particles lies between 1.4 to 10 I_0. Their ranges are greater than 3 mm and they have velocities between 0.3*c* to 0.7*c*.
(c) *Shower particles* — They are mainly pions with ionization ≤ 1.4 I_0. These particles are generally not confined within the emulsion pellicle.

To find the proper dynamics of the multiparticle production process, the characteristics of relativistic shower particles has already been studied, though the medium energy (30-400 MeV) knocked out protons, which manifest themselves as grey particles in nuclear emulsion, may also play an important role in this regard. The importance of investigating the grey particles is due to the fact that the time scale of emission of these particles is of the same order as that of the produced shower particles and hence, it is expected to remember a part of the history of these reactions. Therefore, the grey particles are supposed to carry relevant information about the multiparticle production mechanism. Still only some elementary investigations have been done[25-29] and even the emission process of these protons has not yet been fully explained theoretically. Therefore, in this paper, we have carried out an in-depth study of the fluctuation characteristics of protons in π^--AgBr interactions at 350 GeV/c both in one and two dimensional phase spaces. This type of fluctuation analysis is done for the first time in case of emitted protons.

2 Experimental Details

We study the hadron-nucleus interaction data of π^--AgBr at 350 GeV/c. A stack of G5 nuclear emulsion plate was exposed horizontally to π^-beam at CERN with 350 GeV/c. The nuclear emulsion covers 4π geometry and provides very good accuracy, even less than 0.1 mrad in angle measurements due to high spatial resolution and thus, is suitable as a detector to study the fluctuations in fine resolution intervals of the phase space. The emulsion plates were area scanned with a Leitz Metalloplan Microscope fitted with a semiautomatic scanning device, having a resolution along the X and Y axes of 1μm while that along the Z axis is 0.5 μm. A sample of 569 events of π^--AgBr at 350 *GeV/c* was chosen, following the usual emulsion methodology for selection criteria of the events. The average multiplicity of the shower particles is 11.7 and that of the grey particles is 4.63. The details of scanning and measurement including selection of events are described in our earlier papers[30].

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_i, y_i, z_i) at any point on the linear portion of each secondary track and coordinate (x_1, y_1, z_1) of a point on the incident beam.

Let us suppose that the beam track is along the Y axis.

$$dx = x - x_0$$
$$dz = z - z_0$$

where (x_0, y_0, z_0) is the space coordinate of the vertex. (*x, y, z*) is the space coordinate of any point on a particular track.

The azimuthal angle ϕ is defined as:

$$\phi = \tan^{-1}\frac{dx}{dz}$$

3 Method of Analysis

(a) One dimensional analysis

Mathematically a scaled factorial moment F_q (1) of order q for one event is defined as:

$$F_q = M^{q-1} \sum_{j=1}^{M} \frac{n_j(n_j-1)..................[n_j-(j-1)]}{\langle N\rangle^q} \quad \ldots(1)$$

where the full phase space range x is divided into M equal bins of size $\delta x = x/M$, n_j is the number of particles in the j th bin in a single event, $<N>$ is the average multiplicity in phase range x. For given q and M values, F_q's are calculated for all events and then averaged over events to obtain $<F_q>$.

It was suggested by Fialkowski, Wosiek[31] that the calculated SFMs should be corrected due to non-uniform shape of particle distribution in the specified phase space by dividing by the factor:

$$R_q = \frac{1}{M} \sum_{j=1}^{M} \frac{M^q\langle n_j\rangle^q}{\langle N\rangle^q}$$

Thus we can write the corrected scaled factorial moment of order q as:

$$<F_q>^{corr} = <F_q>/R_q \quad \ldots(2)$$

In the presence of non-statistical fluctuations, an increase of SFM with decreasing bin size is observed. However, if the fluctuation is self- similar in nature, then increase of SFM is well represented by a power law, which can be defined as:

$$< F_q >^{corr} \propto (1/M)^{-\alpha_q}$$

as $(1/M) \to 0$

$$\text{i.e } \ln < F_q >^{corr} = \alpha_q \ln M + C \quad \ldots(3)$$

This power law dependence is known as intermittency. Here, α_q is defined as the intermittency index which represents the degree of fluctuations or the strength of the intermittency signal. The intermittency exponent α_q is obtained from linear fittings according to Eq. (3).

(b) Two -dimensional analysis

The method of factorial moment is used here to analyse the intermittent type of fluctuations of emitted particles in two-dimensional space. Denoting the two-phase space variables as x_1 and x_2, factorial moment[1] of order q may be defined as:

$$F_q(\delta x_1, \delta x_2) = \frac{1}{M} \sum_{m=1}^{M} \frac{\langle n_m(n_m-1)...........(n_m-q+1)\rangle}{\langle n_m\rangle^q} \quad \ldots(4)$$

where $\delta x_1\ \delta x_2$ is the size of a two dimensional cell. $\langle\rangle$ Indicates the average over the whole ensemble of events. n_m is the multiplicity in the m[th] cell**.** M is the number of two-dimensional cells into which the considered phase space has been divided.

A problem is how to fix $\delta x_1\delta x_2$ and M. As the starting point to solve this problem, let us fix a two dimensional region $\Delta x_1\Delta x_2$ and divide it into sub cells of width $\delta x_1 = \Delta x_1/M_1$ and $\delta x_2 = \Delta x_2/M_2$. Where M_1 be the number of bins along $x_1$direction and M_2 be the number of bins along x_2 direction. Cell size dependence of factorial moment is studied by shrinking the bin widths in both directions. There are two ways of doing it. Widths may be shrinked equally ($M_1=M_2$) or unequally ($M_1\neq M_2$) in the two dimensions. The shrinking ratios along x_1 and x_2 directions are characterised by a parameter $H=\ln M_1/\ln M_2$. where $0<H\leq 1$ is called the roughness or Hurst exponent[32]. If and only if the shrinking ratios along the two directions satisfy the above relation with a particular H value the function $F_q(\delta x_1, \delta x_2)$ will have a well defined scaling property. H=1 signifies that the phase space is divided isotropically and consequently fluctuations are self-similar. When $H < 1$, it is clearly understood that the phase spaces along x_1 and x_2 directions are divided anisotropically consequently the fluctuations are self-affine in nature.

The intermittent behaviour of multiplicity distribution manifests itself as a power law dependence of factorial moment on the cell size as cell size$\to$ 0.

$$<F_q> \propto M^{\alpha_q} \quad \ldots(5)$$

The exponent α_q is the slope characterising the linear rise of $\ln<F_q>$ with $\ln M$. The strength of intermittency is characterized by this exponent α_q α_q can be obtained from a linear fit of the form:

$$\ln<F_q>=\alpha_q \ln(M)+a \quad \ldots(6)$$

where a is a constant.

4 Results and Discussion

(a) One dimensional analysis

In our experimental data cosine of emission angle ($\cos\theta$) space and azimuthal angle (ϕ) space are divided into M bins where M = 2, 3, 4……..20. The corrected Scaled Factorial Moment (SFM) $< F_q >^{corr}$ of order q= 2, 3, 4 and 5 are calculated according to

Eqs (1 and 2) for the full bin range. In Figs (1 and 2) $\ln < F_q >^{corr}$ is plotted as a function of ln *M* for both cosθ space and ϕ space for the considered bin interval. The errors shown are nothing but standard statistical errors calculated from the standard deviation of the event wise Factorial moments. A linear rise of $\ln < F_q >^{corr}$ with ln*M* is observed that clearly exhibits intermittent behaviour of particle production. The intermittency indices α_q obtained from linear fitting of the data points are shown in Table 1 for phase space variables cosθ and ϕ for protons. It is observed that the intermittency exponent α_q increases with order of moment for the interaction as expected.

(b) Two- dimensional analysis

Ochs and Wosiek[10, 13] proposed that intermittency effect should be stronger if the fluctuations are analyzed in higher dimensions. This has been observed in several experimental investigations where stronger intermittency is seen in higher dimensional phase spaces as compared to a lower dimensional phase space[33-36]. But most of the earlier analyses are done in self-similar space where the phase spaces are divided equally in both the directions assuming that the phase spaces are isotropic in nature. Consequently, self-similar fluctuations are expected. But it may happen that the fluctuations are anisotropic and the scaling behaviour is different in different directions giving rise to self-affine scaling. Here, we investigate the scaling behaviour in two-dimensional phase space considering anisotropic phase space.

We have performed our study in two-dimensional cosine of emission angle- azimuthal angle (with respect to the beam direction) space. The cosine of emission angle region used is −1 to +1 and the azimuthal region is 0 to 2π. As the non-uniform shape of single particle density distribution influences the scaling behaviour of the factorial moments, we have used the cumulative variables[37,38] $X_{\cos\theta}$ and X_ϕ instead of cosθ and ϕ. The corresponding region of investigation for both the variables then becomes [0-1]. New cumulative variable X_z is related to the original single- particle density distribution[38] ρ(z) as:

$$X_z = \int_{z_{min}}^{z} \rho(z')\partial z' / \int_{z_{min}}^{Z_{max}} \rho(z')\partial z'$$

where z_{min} and z_{max} are the two extreme points of the distribution. The variable X_z is uniformly distributed between 0 and 1. In the $X_{\cos\theta}$ (X_ϕ) space, we divided

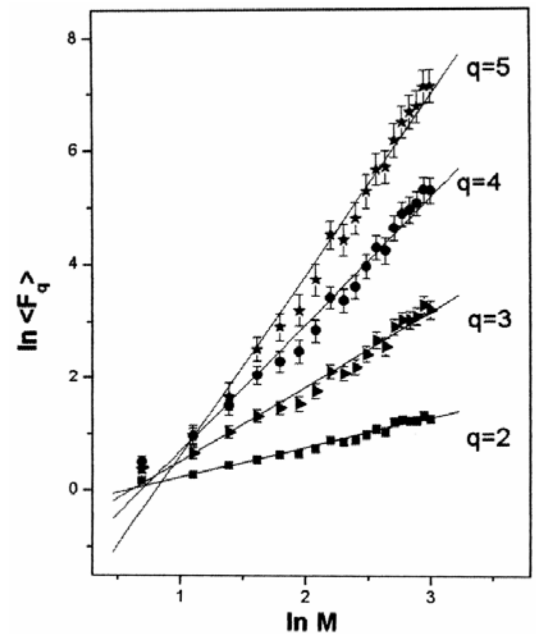

Fig. 1 — Plot of $\ln < F_q >^{corr}$ as a function of ln *M* in cosθ phase space for 2≤ *M*≤ 20

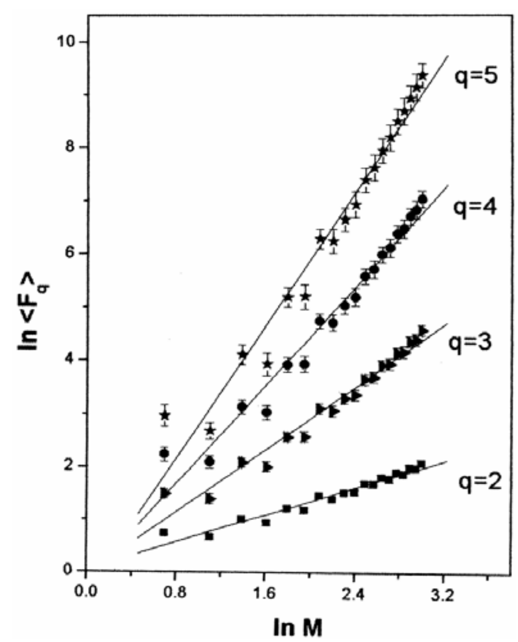

Fig. 2 — Plot of $\ln < F_q >^{corr}$ as a function of ln*M* in ϕ phase space for 2≤ *M*≤ 20

Table 1 — Values of intermittency exponent α_q in emission angle (cosθ) and azimuthal angle phase space (ϕ) for 2≤ *M*≤ 20

Bin Range *M*	*q*	α_q	
		cosθ space	ϕ space
2 ≤ M ≤ 20	2	0.532±0.02	0.646±0.033
	3	1.319±0.051	1.48±0.068
	4	2.233±0.078	2.319±0.104
	5	3.175±0.102	3.132±0.146

the region [0, 1] into $M_{\cos\theta}$ and M_{ϕ} bins respectively. The partioning was taken as $M_{\cos\theta} = M^{H}_{\phi}$.where we choose the partition number along ϕ direction as M_{ϕ} = 2, 3, 4……………….., 20. In the Factorial moment analysis usually the maximum number of bins is chosen considering the resolution of the variable. In some cases, at higher resolutions statistical errors become very high, yielding unreliable results. We have chosen the bin ranges considering the above features. The $X_{\cos\theta}$-X_{ϕ} space is divided into $M = M_{\cos\theta} \times M_{\phi}$ bins and calculation is done in each bin independently.

To analyze the anisotropic nature of the $X_{\cos\theta}$–X_{ϕ} phase space factorial moment of different orders for different Hurst exponents starting from 0.3 to 0.7 in steps of 0.1 and for H=1 are calculated for grey multiplicity distribution data set. We have studied the variation of average factorial moment $\langle F_q \rangle$ against the number of the two-dimensional cell M in a log-log plot for different orders (q=2, 3 and 4) and for the considered H values. In order to find the partition condition at which the anisotropic behaviour is best revealed, we have performed the linear best fits. From the linear best fits intermittency exponents (α_q) are extracted. We have also estimated confidence level of fittings from the χ^2 values. The values of χ^2 per degree of freedom and the confidence level of fittings are presented in Table 2. The fittings are very poor (Table2) which reflects that scaling behaviour does not hold good for any value of H in the bin range $2 \leq M_{\phi} \leq 20$.

Since the analysis in the full bin range does not predict anything, in-depth study is necessary in this context. In order to see whether scaling behaviour exists in sub-bins, the full bin range is divided into different sub-bins e.g. $2 \leq M_{\phi} \leq 10$, $11 \leq M_{\phi} \leq 20$. The analysis is repeated for the sub-bin ranges. The variation of ln$\langle F_q \rangle$ with ln M has been studied for all sub-bin ranges. Interesting results have been observed for the two sub-bins. Scaling properties do not hold good for the sub-bin $2 \leq M_{\phi} \leq 10$ also as is evident from the Table 3. But totally different scaling behaviour is observed in the other sub-bin $11 \leq M_{\phi} \leq 20$. The average factorial moment $\langle F_q \rangle$ is observed to depend linearly on the number of the two-dimensional cell M in a log-log plot for the all considered H values. In order to find the partition condition at which the anisotropic behaviour is best revealed, we have performed the linear best fits which occurs at H= 0.3 and shows that the anisotropic behaviour is best revealed at H= 0.3. The best linear fit is shown in the Fig. 3(a). From the linear best fits, intermittency exponents (α_q) are extracted and presented in Table 4. The values of χ^2 per degree of freedom and the confidence level of fittings are presented in Table 4. The minimum value of χ^2 per degree of freedom indicates the best linear behaviour which occurs at H=0.3. The confidence level of fittings are more than 99% for q=2, 3 and 4 at H=0.3.

To compare the self- affine behaviour with the self-similar one, the variation of ln$\langle F_q \rangle$ against ln M corresponding to H=1 is shown in Fig. 3(b). For H=1 also χ^2 per degree of freedom values are calculated and presented in Table 4 along with corresponding confidence level of fittings. From the Table 4, it is seen that confidence level of fittings are about 90%

Table 2 — Values of χ^2/d.o.f. and confidence level of fittings for $2 \leq M_{\phi} \leq 20$ in cosθ−ϕ phase space

Bin range M_{ϕ}	H	χ^2 /d.o.f.			Confidence level of fittings		
		Q = 2	Q = 3	q=4	Q = 2	Q = 3	Q = 4
$2 \leq M_{\phi} \leq 20$	0.3	2.25	3.95	5.02	0.23%	0%	0%
	0.4	2.48	3.53	3.78	0.06%	0%	0%
	0.5	3.05	4.74	5.84	0%	0%	0%
	0.6	2.54	4.11	5.23	0.05%	0%	0%
	0.7	2.47	3.72	4.65	0.07%	0%	0%
	1	2.54	4.35	4.62	0.05%	0%	0%

Table 3 — Values of χ^2 /d.o.f. and confidence level of fittings for $2 \leq M_{\phi} \leq 10$ in cosθ−ϕ phase space

Bin range M_{ϕ}	H	χ^2 /d.o.f.			Confidence level of fittings		
		q=2	q=3	q=4	q=2	q=3	q=4
$2 \leq M_{\phi} \leq 10$	0.3	1.41	1.83	2.49	19.4%	7.69%	1.46%
	0.4	2.71	4.10	4.55	0.83%	0.02%	0%
	0.5	3.77	5.43	7.01	0.04%	0%	0%
	0.6	3.73	6.57	9.17	0.05%	0%	0%
	0.7	4.87	7.34	9.92	0%	0%	0%
	1	3.13	5.20	5.89	0.26%	0%	0%

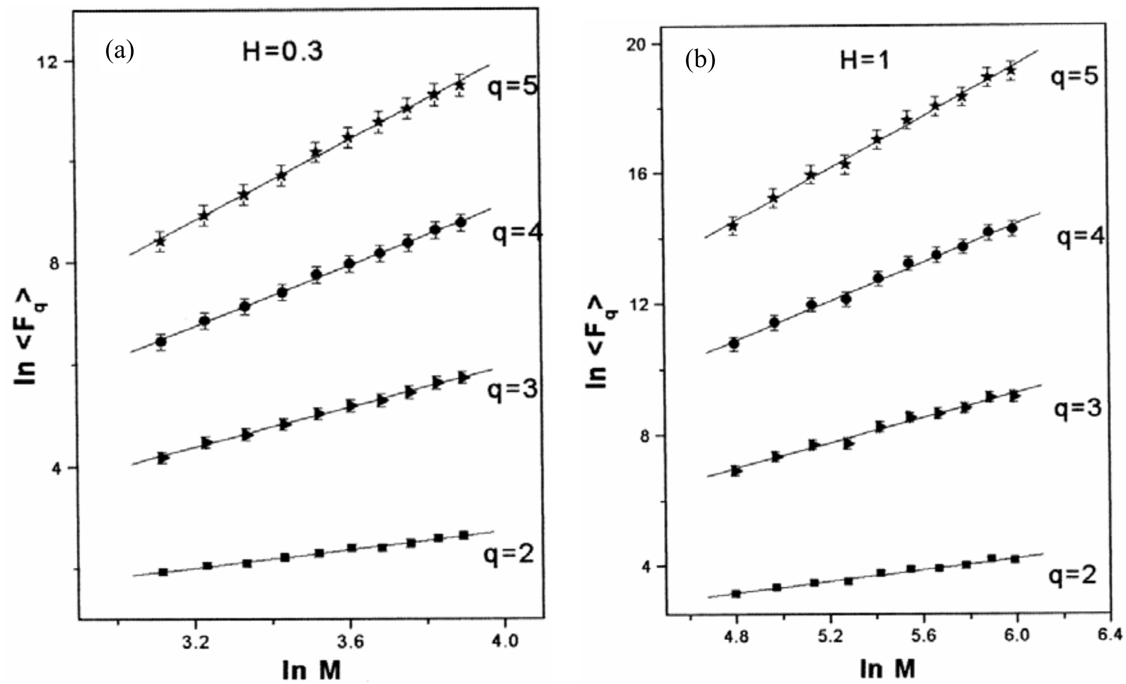

Fig. 3— Plot of ln < F_q> as a function of ln$M$ in the bin range 11≤ M_ϕ≤ 20 (a) at H= 0.3 and (b) at H= 1 in cosθ−ϕ phase space

Table 4 — Values of intermittency exponent, χ^2 /d.o.f. and confidence level of fittings α_q for 11 ≤ M_ϕ ≤ 20 in cosθ-ϕ phase space

Bin range M_ϕ	H	α_q			χ^2 / d.o.f.			Confidence level of fittings		
		q=2	q=3	q=4	q=2	q=3	q=4	q=2	q=3	q=4
11≤M_ϕ≤20	0.3	0.90±0.03	1.96±0.04	2.98±0.05	0.10	0.06	0.05	99.9%	99.9%	99.9%
	1	0.87±0.05	1.91±0.08	2.94±0.09	0.45	0.40	0.25	89%	91.9%	98.1%

for q= 2, 3 and 98% for q= 4. So confidence level of fittings are good in self-affine space at q=2 and 3 than that of self-similar space. Therefore, the analysis gives an indication of self-affine fluctuation in this sub-bin. It is to be noted that this sub-bin scaling law holds well where in the full bin and sub-bin 2≤ M_ϕ ≤ 10 scaling law does not hold good at all.

In our analysis, sometimes the χ^2 per degree of freedom values are too low. The small values of χ^2 per degree of freedom may be attributed to a few points whose errors are comparatively large.

In our analysis, the χ^2 per degrees of freedom values are obtained considering the statistical errors calculated independently of each point and they form the diagonal terms of the full covariance matrix. The off-diagonal terms of the covariance matrix arise due to the correlation between the data points. To have a detailed idea of the full-covariance matrix, this correlation between the data points should be taken into account. However, it is seen in different studies[39] that contributions to χ^2 per degree of freedom mainly come from the diagonal term of the full-covariance matrix. The changes of χ^2 per degrees of freedom values are insignificant when the effects of the off-diagonal terms are taken into account.

This work reports the observation of scaling of multiplicity fluctuation in case of target protons ---- whereas we may mention that this behaviour has already been observed in case of pions. This scaling behaviour of protons may shed some light on dynamics of production mechanism of target protons. In this context, we may recall the works of Anderson *et al.*[40] who made some basic assumptions about the dynamics of proton production which were later established by them in the same work.

(i) Initially an inelastic encounter inside the nucleus results in a primary recoil nucleon with a phenomenological momentum distribution; (ii) The primary recoil particle may start an elastic cascade during its motion through the nuclear matter; (iii) Some nucleons may escape from the target nucleus, namely those that by chance do not undergo subsequent elastic scattering. The escaping nucleons are assigned charge according to the proton to neutron ratio. If the emerging particle is a proton and in the kinetic energy range 40-400 MeV, it will be recognized as a recoil proton (grey prong in emulsion studies).

One of the possible origins of the observed self-similarity of the pions has been attributed to self-similar cascadings[1,9]. This present observation of self-similar proton fluctuation may hint at possible similar cascading type of phenomena in case of proton emission also. Further detail investigations are essential for arriving at firmer conclusion.

5 Conclusions

The following interesting conclusions can be obtained from the present analysis:

1 A linear dependence of ln $< F_q >$ with ln M is observed indicating intermittent behaviour in particle production in one dimensional phase space (cosθ and ϕ phase space). However, in two dimensions (cosθ-ϕ phase space) linear dependence is not observed in the full bin. But in the second sub-bin ($11 \leq M_\phi \leq 20$) linear dependence is well observed.

2 Intermittency exponent α_q, which measures the strength of intermittency, are greater in two-dimension than that of one dimension suggesting more fluctuation in distribution of protons in two dimension.

3 In one dimension, larger α_q values are obtained in ϕ space than in cosθ space for any order of moment (except for q=5).

4 In two-dimension scaling law is not established in the full bin range. But in-depth analysis into sub-bins confirms the scaling law in a particular bin ($11 \leq M_\phi \leq 20$). The analysis provides an indication of self-affine scaling in this sub-bin.

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