IJNRD.ORG ISSN : 2456-4184
INTERNATIONAL JOURNAL OF NOVEL RESEARCH AND DEVELOPMENT (IJNRD) | IJNRD.ORG
An International Open Access, Peer-reviewed, Refereed Journal

Erraticity of Rapidity Gaps in ^{32}S – Ag/Br Interaction at 200 A GeV/c

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Abstract: An analysis of data on angular distribution of shower tracks coming out of ^{32}S-Ag/Br interactions at 200A GeV/c has been presented in this paper in terms of the phase-space variable gaps between neighbouring particles in a single event. The event-to-event fluctuation of multiparticle production has been investigated using moments of the gap distribution. The results suggest that such fluctuations of nonstatistical origin are present in the data.

***Key words*:** Relativistic heavy-ion collisions, Multiparticle production, Fluctuation phenomena

1. INTRODUCTION

During the last couple of decades a growing interest has been observed in detecting clusters and voids in the distribution of produced particles in high-energy heavy ion interactions. It is generally believed that, the particles belonging to final states of such interactions may be an outcome of a second order phase transition from an exotic state e.g., the quark-gluon plasma to the normal hadronic state of matter. As a result, one can expect various time-integrated patterns of clusters within narrow regions of phase space, as well as sharp voids in the phase space distribution. The fluctuation observed in a small interval of phase space may be purely a matter of chance, or it may be due to some dynamical reason, or both. Therefore, it is important to identify the presence of such fluctuations in the density distribution of produced particles beyond trivial statistical contributions. Different methods have been suggested for this purpose. One such method is the computation of normalized horizontal factorial moments [1]. This method has so far been extensively applied to various data on multiparticle production [2-6]. While the normalized horizontal factorial moments (F_q) are suitable to characterize the multiplicity fluctuation in an event, they are insensitive to the event-to-event fluctuation because of the averaging done over event space. Moreover, these moments are incapable to locate the position of a spike or a sharp void in an event. When the study is made over a limited region of phase space, and only a few phase space intervals contribute to the final value of the moment because of finite multiplicity in an event, very little information about that event is contained in the value of F_q. Recently, a few alternative methods have been suggested [7,8] to overcome the abovementioned limitations of F_q, and this has sparked some interest to investigate event-to-event fluctuation in multiparticle production. In one of these methods the erraticity moments C_{pq} of the phase space variable [7] were introduced. These are nothing but the moments of F_q in event space, and they are connected with an entropy index μ_q that directly measures the chaotic behavior of particle production mechanism. If the analysis can be made with a cut on a variable like the transverse momentum (p_T) of the produced particles, it can also be checked whether the chaotic behavior is due to some kind of phase transition or not. The method has already been successfully applied to hadron-hadron, nucleon-nucleon and nucleus-nucleus interactions at high energy [9-12]. The other method [8] involves computing the erraticity moments of phase space variable gaps. To some extent this method is complimentary to the one suggested in [7]. When the average multiplicity of event sample is high, erraticity moments C_{pq} are suitable to investigate. On the other hand, if the average multiplicity of produced particles is small or the analysis is made in such a restricted region of phase space that the average multiplicity is not very large, the method of rapidity gaps [8] is a useful tool to investigate chaotic behavior. This method has also been tested for hadron-hadron and nucleus-nucleus interactions [11, 13], though a complete analysis of all gap moments, cannot be found in either of these works. In this paper I have presented a study on all the moments of pseudorapidity gaps as suggested in [8], of produced charged hadrons in ^{32}S-Ag/Br interactions at 200A GeV/c.

2. EXPERIMENTAL DETAILS

The data presented in this paper were collected by scanning Ilford G-5 nuclear photographic emulsion plates irradiated with ^{32}S ions with an incident momentum of 200A GeV/c. The ^{32}S beam was obtained from the super proton synchrotron (SPS) at CERN. Before development each emulsion pellicle was of dimension of 18cm x 7 cm x 600μm, and after development and mounting on glass plates the sensitivity these emulsion plates was around 20 grains per 100μm for the minimum ionizing particles. The emulsion plates were volume scanned with the help of Leitz Metalloplan microscopes under a total magnification of 300x. To minimize any bias that may be present in collected data the plates were scanned by two independent observers. Only those events were chosen for analysis, for which the interactions occurred within 20μm either from the top or from the bottom surface of the emulsion pellicle. This criterion would ensure less error in angle measurement of tracks as well as minimum loss in counting the number of secondary tracks coming out of an event. The measurement of emission angle was performed under a total magnification of 1500x using oil immersion objectives. The emission angle (θ), and the azimuthal angle (Φ) of each secondary track of an event was measured with respect to the incident projectile track by taking into account the three-dimensional Cartesian coordinates of three points namely, (i) the point of interaction, (ii) a point on the linear portion of the track of secondary particle for which the angles are going to be measured, and (iii) a point on the track of the ^{32}S projectile that caused the interaction.

According to the emulsion terminology, the tracks produced in an interaction are classified into three main categories namely shower tracks, grey tracks and black tracks [14]. The shower tracks are due to the charged hadrons, mainly pions and a few strange mesons. They have a very high velocity ($\geq 0.7c$), and consequently a low ionization ($I \leq 1.4I_0$), where I_0 is the minimum ionization produced by any singly charged particle in a plate. The no of shower tracks produced in an interaction will henceforth be denoted by n_s. The grey tracks are mainly due to knocked out protons with an energy range of 30-400 MeV, and the ionization of these particles is between $1.4I_0$ and $6.8I_0$. In emulsion plates a grey track has a range greater than 3 mm and the particle velocity lies between 0.3c and 0.7c. The number of grey tracks in an interaction will be denoted by n_g. The tracks having ionization $I \geq 6.8I_0$, energy ≤ 30 MeV and velocity $\leq 0.3c$ are called the black tracks. These tracks are mainly due to the fragments of target nuclei, and the number of such tracks in an event will be leveled as n_b. The number of heavy tracks in an event is denoted by n_h, and this is equal to the sum of the number of black and grey tracks in an event. If in an event $n_h > 8$, then the interaction has certainly taken place between the incident nucleus and either a Silver (Ag) or a Bromine (Br) nucleus, which are two of the constituent atoms of emulsion material. For the heavy ion induced interactions, there is another category of tracks called the projectile fragments, and their number in an event will be denoted by n_{pf}. These tracks are confined within a forward cone of semi-vertex angle $\theta_{pf} \approx 0.2/p_{lab}$, where p_{lab} is the momentum per nucleon of the incident nucleus in the laboratory frame. The projectile fragments are mainly due to the spectator part of the incident nucleus. If in an event there is no projectile fragment with charge $Z \geq 2$ within the forward cone, it is said that total fragmentation of the incident nucleus has taken place.

3. METHODOLOGY

The pseudorapidity (η) of a shower track is related to its emission angle (θ) by the relation, $\eta = -\ln(\tan\frac{\theta}{2})$, and along with the azimuthal angle (Φ), this variable is used to locate the position of a particle in phase space. Pseudorapidity of a particle is a suitable replacement of the rapidity variable where the energy or momentum of the particle cannot be easily measured. The pseudorapidity distribution of the shower particles can be converted to a distribution of the cumulative variable $\chi(\eta)$ defined as [15],

$$\chi(\eta) = \int_{\eta_{\min}}^{\eta} \rho(\eta) d\eta \Big/ \int_{\eta_{\min}}^{\eta_{\max}} \rho(\eta) d\eta \cdot \tag{1}$$

Here, $\rho(\eta) = \frac{1}{N}\frac{dn}{d\eta}$ is the single particle pseudorapidity density of the shower particles, and $\eta_{\max}$ ($\eta_{\min}$) are the maximum (minimum) pseudorapidity values within which the analysis is performed. The $\chi(\eta)$ values vary between 0 and 1, and the single particle density distribution in terms of this cumulative variable, irrespective of the shape of the distribution from which it is derived, is always uniform. Consider an event with n particles, where the gap (x_i) is defined as the difference of cumulative variables of two neighbouring particles in the same event,

$$x_i = \chi_{i+1} - \chi_i, \qquad i = 0,1,2\ldots\ldots,n. \tag{2}$$

Note that $\chi_{i+1} \rangle \chi_i$ and $\chi_0 = 0$, $\chi_{N+1} = 1$ are the boundaries. For a single event the gap moments G_q and H_q are defined as,

$$G_q = \frac{1}{n+1}\sum_{i=0}^{n} x_i^q, \tag{3}$$

and

$$H_q = \frac{1}{n+1}\sum_{i=0}^{n}(1-x_i)^{-q}, \text{ where } n \ge q+1. \tag{4}$$

These moments provide us with a quantitative characteristic of a single event. Here the order of the moment q is an integer, and it is clear that G_q is always less than unity whereas, H_q is always greater than unity. As the moments G_q and H_q fluctuate from event to event, Hwa and Zhang proposed to consider the event sample averages s_q and σ_q as,

$$s_q = -\langle G_q \ln G_q \rangle, \tag{5}$$

and

$$\sigma_q = -\langle H_q \ln H_q \rangle \tag{6}$$

as description of event-to-event fluctuations in the sample. In both cases the statistical fluctuations are not excluded. In order to minimize the contribution from statistical fluctuations one may calculate-

$$s_q^{st} = -\langle G_q^{st} \ln G_q^{st} \rangle, \tag{7}$$

and

$$\sigma_q^{st} = -\langle H_q^{st} \ln H_q^{st} \rangle, \tag{8}$$

Where, G_q^{st} and H_q^{st} are obtained using eq. (3) and eq. (4) from a purely statistical distribution i.e., when all n particles in an event are randomly distributed in χ-space within a limit of 0 to 1. The multiplicity distribution of the generated sample within the phase space interval under consideration, matches with that of the experiment. Finally one can define S_q and Σ_q as:

$$S_q = \frac{s_q}{s_q^{st}}, \tag{9}$$

and

$$\Sigma_q = \frac{\sigma_q}{\sigma_q^{st}}, \tag{10}$$

that indicate how much the moments s_q and σ_q stand out above the corresponding statistical contributions. As we are also interested to calculate the deviation of G_q and H_q from the event sample averaged quantities $\langle G_q \rangle$ and $\langle H_q \rangle$, respectively, another set of variables $\bar{s}_q$ and $\bar{\sigma}_q$ can be defined as a measure of such deviations in the following manner,

$$\bar{s}_q = -\left\langle \frac{G_q}{\langle G_q \rangle} \ln \frac{G_q}{\langle G_q \rangle} \right\rangle \tag{11}$$

and

$$\bar{\sigma}_q = -\left\langle \frac{H_q}{\langle H_q \rangle} \ln \frac{H_q}{\langle H_q \rangle} \right\rangle. \tag{12}$$

These parameters can once again be normalized by the corresponding statistical contributions as, $\bar{S}_q = \bar{s}_q / \bar{s}_q^{st}$ and $\bar{\Sigma}_q = \bar{\sigma}_q / \bar{\sigma}_q^{st}$, respectively, to provide another set of erraticity moments.

4. Data and results

In the present analysis angular distribution of shower tracks emitted from ^{32}S-Ag/Br interactions obtained from a sample of 195 events has been used by putting a cut on the no of heavy fragments i.e., $n_h > 8$. Also these events do not have any projectile fragment with charge $Z \geq 2$ inside the forward cone of the interaction as defined earlier in the experiment section. This means that total fragmentation of the incident ^{32}S ion has taken place in each such interaction. The average no of shower tracks for the event sample used is $\langle n_s \rangle = 217.79 \pm 6.16$. The no density of shower tracks in the central pseudorapidity region is a good measure of the average centrality or the impact parameter for the sample of events. Following a method suggested by Wong [16], an estimate of the average impact parameter for the sample of events used in the analysis has been obtained. In this method the peak value of the pseudorapidity density of produced charged particles in nucleus-nucleus collision at an impact parameter b, and at a particular incident momentum per nucleon, is related to the same density for pp interaction at the same momentum by the following formula,

$$\frac{dn_{AB}}{d\eta}(b)\Big|_{peak} \approx 1.28 \frac{AB}{A^{2/3}+B^{2/3}} \frac{1}{1+a(A^{1/3}+B^{1/3})} e^{-b^2/2\beta^2} \frac{dn_{pp}}{d\eta}\Big|_{paek}. \tag{13}$$

In present case, the peak value of pseudorapidity density for the nucleus-nucleus interaction at an impact parameter b, has been obtained from a Gaussian fit to experimental data as, $\frac{dn_{AB}}{d\eta}(b)\Big|_{peak} = 55.54$. The corresponding density for pp interaction at laboratory momentum 200 GeV/c ($\sqrt{s}$=19.4 GeV) $\frac{dn_{pp}}{d\eta}\Big|_{paek} = 1.38$ [17]. It should however be noted that in the above equation pseudorapidity densities of secondary charged particles are used in place of rapidity densities, as for high energy interactions they are not much different from each other. 'A' and 'B' are the mass no of interacting nuclei, and 'a' (=0.09) is a parameter obtained from fitting the values of $\frac{dn}{d\eta}\Big|_{peak}$ against $A^{1/3}$ for nucleus-nucleus collisions at 200A GeV/c [16]. For our case A = 32, whereas B = 94, is the weighted average mass no of Ag and Br nuclei. In the above formula, $\beta^2 = \beta_A^2 + \beta_B^2 + \beta_p^2$ and $\beta_A = r_0 A^{1/3}/\sqrt{3}$, where r_0 (= 1.05 fm) is the radius parameter and β_p (=0.68 fm) is a thickness parameter for nucleon-nucleon collision. Substitution of these values in eq. (13) resulted in an estimated average value of impact parameter for our sample of events as, b = 3.78 fm. The value of impact parameter obtained in this manner gives us only an idea of the average centrality of event sample used, so that experimental results can be compared with events simulated by computer codes based on models of heavy-ion interaction. Also, while studying dynamical fluctuation, it is imperative to restrict all other trivial sources of fluctuation coming out of e.g., widely varying collision geometry or widely fluctuating no of particles from one pseudorapidity bin to the other. Both of these sources of fluctuations contribute marginally to our results, because of a high value of average shower multiplicity, and total fragmentation of incident projectile (n_{pf}=0) in all events.

As mentioned above, the erraticity analysis of gaps provides information that is complimentary to the analysis of spikes. But gap analysis is not very effective for events with very high multiplicity. For heavy-ion interaction in most cases the event multiplicity is high. Therefore, one needs to make a severe cut on the domain of analysis, so that the average multiplicity under consideration is never too large. In the present case the analysis has been performed in a central region of pseudorapidity given by, $\eta_{peak} - 1 \leq \eta \leq \eta_{peak} + 1$. The peak of a Gaussian fit to the experimental pseudorapidity distribution of shower tracks occurs at η_{peak} = 3.30. The phase space domain has further been reduced by partitioning the azimuthal angle (Φ) space into four quadrants namely, (i) $0 \leq \Phi < \pi/2$, (ii) $\pi/2 \leq \Phi < \pi$, (iii) $\pi \leq \Phi < 3\pi/2$, and (iv) $3\pi/2 \leq \Phi \leq 2\pi$. After pseudorapidity cut, the average shower multiplicity in these quadrants came out to be (i) 25.37±0.84, (ii) 26.65±0.98, (iii) 26.43±0.1.00, (iv) 25.89 ± 0.94 respectively – values that are not too large to make the gap analysis ineffective. Values of the cumulative variable $\chi(\eta)$ have been obtained for the shower tracks belonging to each quadrant separately.

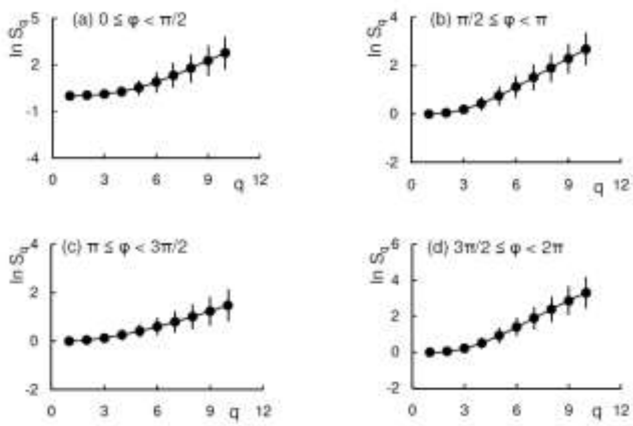

Fig. 1. Plot of $\ln S_q$ against q in four quadrants of azimuthal angle - (a) $0 \leq \Phi < \pi/2$, (b) $\pi/2 \leq \Phi < \pi$, (c) $\pi \leq \Phi < 3\pi/2$, and (d) $3\pi/2 \leq \Phi \leq 2\pi$. The analysis has been performed in a pseudorapidity interval $2.3 \leq \eta \leq 3.3$. The solid curves are best fit of experimental values to a quadratic function as given by eq. (14).

The results of erraticity analysis on gap distribution of shower tracks from ^{32}S-Ag/Br interactions at 200A GeV/c starts with a graphical representation of the S_q moments. In Fig. 1, $\ln S_q$ has been plotted against q for all four quadrants of azimuthal angle (Φ), and for q = 2 to 10 in each case. The error associated with each data point is statistical in nature. They are computed by following standard methods with an assumption, since no bin is considered to compute G_q, it is a number with very small statistical error. Though the experimentally obtained values of S_q are associated with large statistical errors, one can see from the graphs that, $\ln S_q$ values are deviating more and more from zero with increasing values of q. The change of $\ln S_q$ with q has been parameterized by using a quadratic form,

$$\ln S_q = \alpha + \beta q + \gamma q^2 \quad \text{for, } 2 \leq q \leq 10. \tag{14}$$

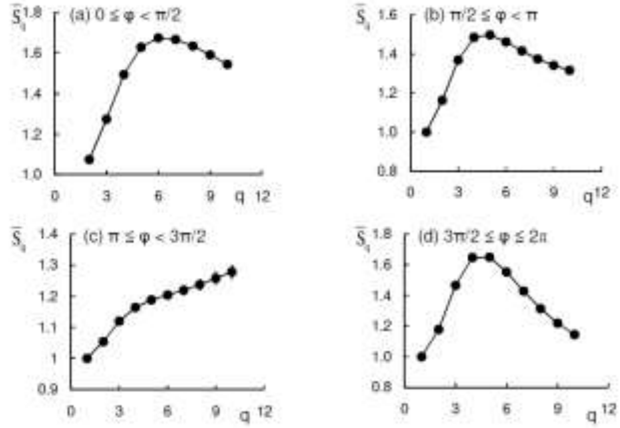

Fig. 2. Plot of $\bar{S}_q$ against q in four quadrants of azimuthal angle - (a) $0 \le \Phi < \pi/2$, (b) $\pi/2 \le \Phi < \pi$, (c) $\pi \le \Phi < 3\pi/2$, and (d) $3\pi/2 \le \Phi \le 2\pi$. The solid curves joining the experimental points are drawn to guide the eye.

Table 1. Values of the fit parameters α, β and γ as in eq.(14) and the values of R^2 showing the goodness of fit.

Quantity plotted against order q	Interval of azimuthal angle (Φ)	Value of α	Value of β	Value of γ	Value of R^2
$\ln S_q$	$0 \le \Phi < \pi/2$	-0.07±0.09	-0.03±0.03	0.03±0.003	0.998
	$\pi/2 \le \Phi < \pi$	-0.40±0.10	0.16±0.04	0.15±0.03	0.998
	$\pi/2 \le \Phi < 3\pi/2$	-0.14±0.02	0.06±0.01	0.01±0.0007	1.000
	$3\pi/2 \le \Phi \le 2\pi$	-0.54±0.15	0.22±0.06	0.02±0.005	0.997
$\ln \Sigma_q$	$0 \le \Phi < \pi/2$	-0.05±0.02	-0.10±0.08	0.06±0.007	0.994
	$\pi/2 \le \Phi < \pi$	0.13±0.04	-0.13±0.02	0.04±0.001	0.999
	$\pi/2 \le \Phi < 3\pi/2$	0.07±0.02	-0.05±0.01	0.01±0.001	0.994
	$3\pi/2 \le \Phi \le 2\pi$	0.13±0.06	-0.15±0.03	0.05±0.002	0.998

The values of α, β and γ along with the R^2 values are listed in table 1, showing that the fit is reasonably good in each case. In Fig. 2, the $\bar{S}_q$ moments are plotted against q for all four quadrants of (Φ) for q = 2 to 10. One can see that the values of these moments always deviate from unity beyond statistical uncertainties, which are always very small in this case. The variation of $\bar{S}_q$ with q does not follow any unique pattern. While for the first, second and fourth quadrants maxima in $\bar{S}_q$ values are observed at around q = 4 ~ 6, in the third quadrant only a monotonic rise of $\bar{S}_q$ with increasing q can be seen. Fig. 3 shows the graphical plots of erraticity moments Σ_q against q for all four quadrants of azimuthal angle and for q = 1 to 10. Like S_q, comparatively larger statistical errors can also be seen in this case, particularly in higher q region. The variation of Σ_q with q has been parameterized in the same way as has been done

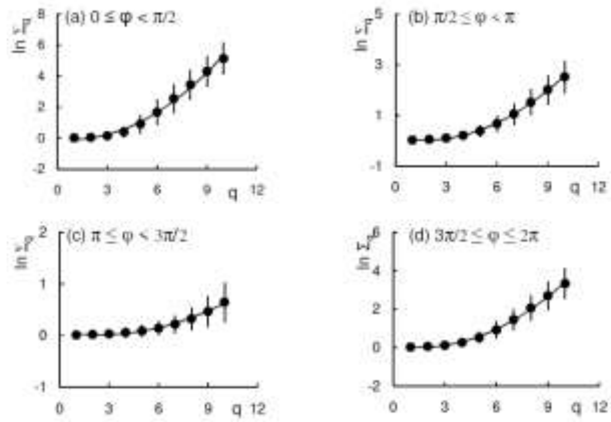

Fig. 3. Plot of $\ln \Sigma_q$ against q in four quadrants of azimuthal angle - (a) 0 ≤ Φ < π/2, (b) π/2 ≤ Φ <π, (c) π ≤ Φ < 3π/2, and (d) 3π/2 ≤ Φ ≤ 2π. The solid curves are best fit of experimental values to a quadratic function like that of eq. (14).

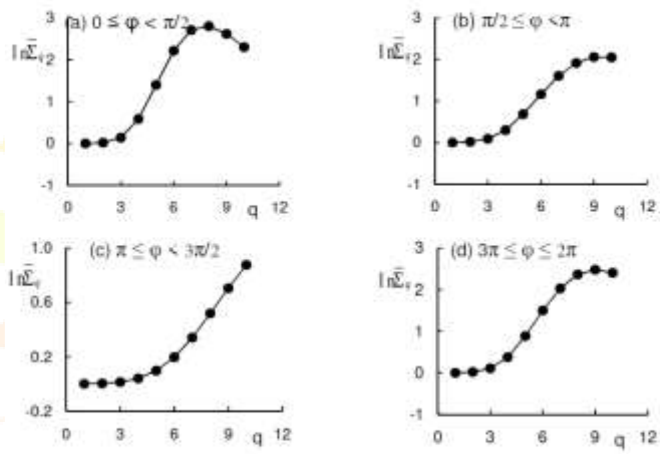

Fig. 4. Plot of $\ln \overline{\Sigma}_q$ against q in four quadrants of azimuthal angle - (a) 0 ≤ Φ < π/2, (b) π/2 ≤ Φ <π, (c) π ≤ Φ < 3π/2, and (d) 3π/2 ≤ Φ ≤ 2π. The solid curves joining the experimental points are drawn to guide the eye.

in the case of S_q using eq. (13). The values of the parameters as well as the R^2 values are given in table 1. One can see that in this case also the fit of a quadratic curve to experimental data has always been good. In fig. 4 the last set of erraticity moments $\overline{\Sigma}_q$ has been graphically represented by plotting $\ln \overline{\Sigma}_q$ against q for q = 1 to 10, and for each of the four quadrants of Φ. Once again no definite pattern in the variation of these moments is observed, except the fact that, in the region 1 ≤ q ≤ 7, the increase of $\ln \overline{\Sigma}_q$ with q in each quadrant is quadratic in nature. Once again like in the case of $\overline{S}_q$, very small statistical errors are associated with $\ln \overline{\Sigma}_q$ values.

5. Discussion

The above analysis on gap distribution of shower tracks emitted from ^{32}S-Ag/Br interactions at 200A GeV/c shows that, event-to-event fluctuation of gap moments G_q and H_q, exists over the corresponding statistical contribution. The conclusion is based on the fact that, all entropy-like erraticity parameters suggested by Hwa and Zhang [8] namely, $S_q, \overline{S}_q, \Sigma_q$ and $\overline{\Sigma}_q$ deviate significantly from unity beyond standard errors. In general the erraticity parameters behave in a more or less similar way in all four quadrants of the azimuthal angle within the central region of pseudorapidity space 2.3≤ η ≤3.3. In view of comparatively smaller errors associated with $\overline{S}_q$ and $\overline{\Sigma}_q$, it may conclude that in the present case these parameters provide a better measure of erraticity than S_q or Σ_q. It should be noted that, $\overline{S}_q$ and $\overline{\Sigma}_q$ contain information about how much the gap moments, G_q and H_q deviate from their average values $<G_q>$ and $<H_q>$, respectively. The other two parameters S_q and Σ_q have been found to increase with increasing q, showing a quadratic variation in each case. The exact nature of these variations or the exact values of fit parameters α, β and γ is not much important. It would however be interesting to compare the present experimental results on erraticity analysis of gap distribution of produced charged hadrons with those obtained from other experiments, as well as with the results from event sample generated by computer codes based on some realistic model on relativistic heavy-ion interactions, that takes into account all possible sources of fluctuations. As far as erraticity of rapidity gaps is concerned, event generators like PYTHIA or ECOMB underestimate the experimental on hadronic interactions, even after the Bose-Einstein correlation has been taken into account as a possible source of dynamical fluctuation [13]. Such a comparison is yet to be made in case of heavy-ion interactions, where the collision mechanism is much more complex involving a large number of hadrons, and the number of participating nucleons being dependent on the collision geometry. By choosing only those interactions where complete break-up of the projectile nucleus has taken place, an effort has certainly been made in the present investigation to restrict the collision geometry within a certain limit as can be seen above, from the estimated average value of the impact parameter for the event sample.

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