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A SEARCH FOR MULTIPLICITY FLUCTUATIONS IN HIGH ENERGY NUCLEUS-NUCLEUS COLLISIONS

The HELIOS-Emulsion Collaboration

T. Åkesson[4], S. Almehed[8], A.L.S. Angelis[8], S. Aoki[15], N. Armenise[2], H. Atherton[4], P. Aubry[12], G. Baroni[18], H.W. Bartels[7], G. Beaudoin[12], J.M. Beaulieu[12], H. Beker[4], O. Benary[23], D. Bettoni[4f], V. Bisi[25], I. Blevis[26], H. Bøggild[4b], A.C. Breslin[5], P. Cerello[25], W. Cleland[17], M. Clemen[17], B. Collick[17], F. Corriveau[11], S. Dagan[23], D.H. Davis[8], K. Dederichs[4d], S. Dell'Uomo[18], P. Depommier[12], R.C.E. Devenish[4e], N. DiGiacomo[9], S. Di Liberto[18], J.R. Dodd[8], B. Dolgoshein[14], A. Drees[7], H. En'yo[4], B. Erlandsson[22], M.J. Esten[8], C.W. Fabjan[4], P. Fischer[7], Z. Fraenkel[26], A. Gaidot[20], P. Giubellino[25], P. Glassel[7], U. Goerlach[4], G. Grella[21], R. Haglund[10], L.A. Hamel[11], H. van Hecke[9], V. Hedberg[4], R. Heifetz[23], A. Holscher[7], K. Hoshino[15], T. Ishigami[24], B. Jacak[9], G. Jarlskog[10], S. Johansson[10], M. Kazuno[24], H. Kitamura[15], M. Kobayashi[15], Y. Kobayashi[24], K. Kodama[1], H. Kraner[3], V. Kroh[7], F. Lamarche[11], C. Leroy[11], D. Lissauer[3,23], G. London[20], B. Lorstad[10], A. Lounis[12], A. Marzari-Chiesa[25], M. Masera[25], M.A. Mazzoni[4], E. Mazzucato[11], M.L. McCubbin[8], N.A. McCubbin[19], P. McGaughey[9], F. Meddi[18], M. Miyanishi[15], U. Mjornmark[10], M.T. Muciaccia[2], S. Muraviev[13], M. Murray[17], M. Nakamura[15], S. Nakanishi[15], K. Nakazawa[6], M. Neubert[7], S. Nilsson[22], K. Niu[15], K. Niwa[15], M. Nomura[15], L. Olsen[3], Y. Oren[23], J.P. Pansart[26], Y.M. Park[17], A. Pfeiffer[7], F. Piuz[4], V. Polychronakos[3], G. Poulard[4], M. Price[4], D. Rahm[3], L. Ramello[25], G. Romano[21], G. Rosa[18], L. Sandor[4], S. Sartori[25], J. Schukraft[4], M. Sekimoto[4g], B. Sellden[22], M. Seman[4c], H. Shibuya[24], A. Shmeleva[13], V. Sidorov[16], S. Simone[2], Y. Sirois[11], H. Sletten[4], S. Smirnov[14], J. Soltani[7], W. Sondheim[9], H.J. Specht[7], I. Stumer[3], J. Sunier[9], H. Tajima[15], H.H. Thodberg[4], J. Thompson[17], V. Tikhomirov[13], D.N. Tovee[8], I. Tserruya[26], K. Tsukagoshi[15], Y. Umezawa[24], N. Ushida[1], G. Vasseur[20], R. Veenhof[4a], S. Watanabe[24], R. Wigmans[4] and P. Yepes[11]

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1) Aichi University of Education, Kariya, Japan.
2) University of Bari and INFN, Bari, Italy.
3) Brookhaven National Laboratory, Upton, NY, USA.
4) CERN, Geneva, Switzerland.
5) University College, Dublin, Ireland.
6) Faculty of Education, Gifu University, Gifu, Japan.
7) University of Heidelberg, Heidelberg, Fed. Rep. Germany.
8) University College London, London, UK.
9) Los Alamos National Laboratory, Los Alamos, NM, USA.
10) University of Lund, Lund, Sweden.
11) McGill University, Montreal, Canada.
12) University of Montreal, Montreal, Canada.
13) Lebedev Institute of Physics, Moscow, USSR.
14) Institute of Physics and Engineering, Moscow, USSR.
15) Department of Physics, Nagoya University, Nagoya, Japan
16) Institute of Nuclear Physics, Novosibirsk, USSR.
17) University of Pittsburgh, Pittsburgh, PA, USA.
18) University of Rome 'La Sapienza' and INFN, Rome, Italy.
19) Rutherford Appleton Laboratory, U.K.
20) DPhPE, CEN-Saclay, Gif-sur-Yvette, France.
21) University of Salerno and INFN, Salerno, Italy.
22) University of Stockholm, Stockholm, Sweden.
23) University of Tel Aviv, Ramat Aviv, Israel.
24) Department of Physics, Toho University, Funabashi, Japan
25) University of Turin and INFN, Turin, Italy.
26) Weizmann Institute, Rehovot, Israel.
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e) Oxford University, Oxford, UK.
f) University of Syracuse, Syracuse, NY, USA.
g) Institute of Nuclear Study, Tokyo, Japan.

ABSTRACT

A search for non-statistical fluctuations was performed in 200 GeV per nucleon oxygen and sulphur ion-emulsion interactions selected by a high transverse energy trigger. No clear signal of dynamical correlations or of unusual fluctuations was found.

1. INTRODUCTION

In ultrarelativistic nucleus–nucleus collisions, the possibility that an enhancement in multiplicity fluctuations may indicate the formation of a quark–gluon plasma was suggested by many authors [1]. During hadronization, the formation of clusters of particles in restricted pseudorapidity intervals is expected as a signature of local deflagrations. The particles produced might therefore be expected to show correlations and unusual fluctuations in the rapidity density distributions.

Multiplicity fluctuations can also be directly related to the presence of possible dynamical correlations. Their study then allows a deeper insight into the behaviour of the strong interaction in a dense medium.

In this paper, we present a systematic search for non-statistical fluctuations in 200 GeV per nucleon ^{16}O and ^{32}S interactions on emulsion nuclei, selected according to transverse energy E_{T}. This selection defines samples of central interactions, i.e. those with small impact parameter b, and we therefore look for possible dynamical fluctuations in conditions where the effects of geometrical fluctuations, corresponding to large variations of b, are minimized.

Two different kinds of analyses were performed: one suitable for the study of possible collective effects separating the geometrical and the dynamical contributions to multiplicity fluctuations [2]; the other, mainly devoted to the search for possible 'intermittency' phenomena, uses the technique of factorial moments. This technique [3, 4] also permits the analysis of single events with large multiplicities.

2. SAMPLES OF EVENTS

The data were collected in emulsion stacks exposed to 200 GeV per nucleon ^{16}O and ^{32}S ions at the CERN Super Proton Synchrotron (SPS). The interactions were selected by means of multiplicity and transverse energy triggers in the HELIOS–NA34/2 apparatus; the experimental set-up and the general study of interactions is described in detail elsewhere [5]. For the purposes of the present work, we recall that tracks of close-to-minimum ionizing particles ($\beta > 0.6$) from the interactions were selected. The accuracy on the angular measurements was such that the uncertainty on the pseudorapidity ($\eta = -\ln \tan \theta/2$) of a single particle is less than 0.1 units within the range we use; this was obtained by repeated measurements [5].

The transverse energy E_{T} is defined by a calorimetric sum over all particles contained in the pseudorapidity range 0.1–3.0. From the E_{T} distributions obtained in HELIOS [6], it is seen that a sufficiently high cut-off on E_{T} efficiently selects central collisions produced in the heaviest target nucleus. The chosen value of $E_{\mathrm{T}}^{\mathrm{min}}$ corresponds, for each projectile, to the 'shoulder' of the $\mathrm{d}\sigma/\mathrm{d}E_{\mathrm{T}}$ distribution on silver. With this selection, it is mostly the central collisions with Ag nuclei that survive; interactions on Br nuclei are depressed by a factor of $\simeq 5$ with respect to Ag ones, whereas interactions on the light elements, H, C, N, O, are completely suppressed. The main features of the events in the selected samples are shown in Table 1.

Average charged-particle pseudorapidity densities

$$\rho = \frac{1}{N_{\mathrm{ev}}} \frac{\mathrm{d}n}{\mathrm{d}\eta} \tag{1}$$

as high as $\rho_{\mathrm{max}} \simeq 120$ and $\simeq 75$ for the ^{32}S–Ag and the ^{16}O–Ag central interactions, respectively, were observed. We note that, among the charged particles, there is a contribution from electron pairs owing to both Dalitz decays of π^0 and γ conversions close to the interaction vertex; the effect of this contamination will be discussed later.

3. GEOMETRICAL AND DYNAMICAL FLUCTUATIONS

According to a theoretical scheme [2], it is possible to classify non-statistical multiplicity fluctuations into geometrical and dynamical categories. The former refers to a sample of events with different impact parameters, which leads to an 'intrinsic' variation of the charged-particle multiplicity from one event to another; the latter includes fluctuations which can be present at all stages of the collision processes, and which arise from thermalization, hydrodynamical expansion, hadronization processes, and so on.

'New' physics could be contained in the dynamical fluctuations, so it is useful to separate these two contributions, as suggested in ref. [2]. In this scheme the normalized moments of the experimental multiplicity distribution C_i,

$$C_i = \frac{\langle n^i \rangle}{\langle n \rangle^i} \, , \tag{2}$$

are computed as a function of the charged-particle multiplicity n in different pseudorapidity intervals. The intervals are centred around the peak of the pseudorapidity distribution and increased symmetrically. This choice minimizes the contamination from particles produced in the fragmentation region and avoids problems arising from poor statistics in some of the bins. The second and third moments should depend on $\langle n \rangle$ and $\langle n \rangle^2$ as follows:

$$L_2 \equiv C_2 \langle n \rangle \; - \; 1 = S_2 \langle n \rangle \, , \tag{3}$$

$$L_3 \equiv C_3 \langle n \rangle^2 - 3 C_2 \langle n \rangle \; + \; 2 = S_3 \langle n \rangle^2 \, . \tag{4}$$

In this theoretical approach, geometrical (μ_i) and dynamical (ν_i) fluctuations are expected to contribute to the slopes: $S_i = \mu_i + \nu_i$. The former describes the dependence on the impact parameter: for a sample of collisions with fixed impact parameter, μ_i is equal to 1 by definition. Therefore by choosing an appropriate sample of central collisions, the dynamical fluctuations, being the only possible contribution to a value $S_i >$ 1, can be isolated.

This analysis was performed on our samples of central interactions (see Table 1), selected by E_T. The central value of η was chosen to be 2.8 for both samples of central O and S emulsion interactions. Figure 1 shows the quantities L_2 and L_3 as a function of $\langle n \rangle$ and $\langle n \rangle^2$, respectively. A fit of the data to a straight line gives

$$\begin{array}{lll} \text{Oxygen:} & S_2 = 1.010 \pm 0.004 \; , & S_3 = 1.031 \pm 0.012 \; , \\ \text{Sulphur:} & S_2 = 1.015 \pm 0.004 \; , & S_3 = 1.046 \pm 0.012 \; . \end{array}$$

The results are consistent with the behaviour of the parameters S_2 and S_3, which is independent of the pseudorapidity intervals. To avoid an underestimate of the errors, which arises from the strong correlation in the data, each sample was divided into several independent subsamples and the errors were computed from the dispersion.

The same analysis was performed on a different sample of S ion–emulsion collisions selected within a narrow window of E_T around a central value much lower than the previous cut-off. This sample is expected to show fewer dynamical fluctuations than that of central collisions. Within $110 < E_T < 120$ GeV, we obtained $S_2 = 1.011 \pm 0.005$. This value is also consistent with the absence of geometrical fluctuations and underlines the effectiveness of an E_T cut when selecting events with an almost fixed impact parameter.

In order to check the possible significance of the small values found for $S_i - 1$, the same analysis was also performed on a sample of 1000 S–Ag interactions generated by the IRIS code [7], by requiring an impact parameter $b < 3$ fm, corresponding to nearly complete overlap. The value thus obtained is $S_2 = 1.018 \pm 0.002$. Within the same sample, events selected in the tail of the transverse energy distribution gave $S_2 = 1.005 \pm 0.001$.

All this suggests that in our samples of central interactions, there is on the average no sign of large dynamical fluctuations, with possibly some residual geometrical fluctuations. The fact that a similar analysis performed by another group [8] provides values of S_2 consistently higher than 1 on samples of 'central' interactions that represent $\simeq 10\%$ of the total cross-section in emulsion is well explained, because their selection does not strictly retain events with nearly constant b.

4. STUDY OF NON-STATISTICAL FLUCTUATIONS IN THE MULTIPLICITY DISTRIBUTIONS

A different, more general approach was used to decide whether fluctuations observed in a rapidity density spectrum are statistically significant [3]. This analysis involves computation of the scaled factorial moments as a function of a varying $\delta\eta$ within a fixed pseudorapidity interval $\Delta\eta$.

Slightly different procedures were proposed [4] for the analysis of a sample of events. We will adopt the one suitable for an event-by-event analysis ('exclusive' moments).

For a given bin size $\delta\eta$, the i^{th} factorial moment F_i is defined for an event:

$$F_i(\delta\eta) = \frac{1}{M} \sum_{m=1}^{M} \frac{M^i}{n(n-1)...(n-i+1)} \cdot k_m \cdot (k_m - 1) \cdots (k_m - i + 1) \,, \tag{5}$$

where n is the multiplicity of the event within the pseudorapidity range $\Delta\eta$, $M = \Delta\eta/\delta\eta$, and k_m is the multiplicity within the m^{th} bin of width $\delta\eta$.

The scaled factorial moments averaged over the events ($\langle F_i \rangle$) must saturate as $\delta\eta$ decreases, if the fluctuations are purely statistical, or when a correlation exists with a range larger than the saturation width. However, if 'intermittency' is present, i.e. rapidity correlations of many different sizes, the following power law is expected [3]:

$$\langle F_i \rangle \simeq \left(\frac{\Delta\eta}{\delta\eta} \right)^{\phi_i} . \tag{6}$$

If the pseudorapidity density varies significantly over the range studied, the correction factor

$$R_i(\delta\eta) = \frac{(1/M) \sum_{m=1}^{M} \left[(1/\delta\eta_m) \int_{\delta\eta_m} \rho(\eta) \mathrm{d}\eta \right]^i}{\left[(1/\Delta\eta) \int_{\Delta\eta} \rho(\eta) \mathrm{d}\eta \right]^i} \tag{7}$$

should be included [4, 9], and the proper variable to be used in the analysis is $\langle F_i \rangle / R_i$ rather than $\langle F_i \rangle$. The values of $R_i(\delta\eta)$ have been computed, for each sample, from the average pseudorapidity distributions, appropriately smoothed.

The exclusive moments of each event were analysed in two different ways: i) for different values of $\delta\eta$, averages of the F_i over the samples were performed to fit a linear dependence of $\ln\langle F_i \rangle$ on $\ln\delta\eta$ with slope ϕ_i; ii) the slopes ϕ'_i were determined for each event from the values of $F_i(\delta\eta)$ and then averaged over the sample, $\langle \phi'_i \rangle$. In the first case, as the values of $\langle F_i \rangle$ from different choices of $\delta\eta$ are strongly correlated, errors on ϕ_i determined from the spread of the points around the fitted lines are likely to be underestimated. In the second case, reliable errors are computed from the spread of the ϕ'_i distributions.

When selecting events with an overall large multiplicity, these methods of analysis must be used with care in order to avoid generating large fluctuations that destroy the significance of the higher moments. For this reason we restricted the analysis to the pseudorapidity interval η = 1.2–4.8 and for $\delta\eta$ we used values ranging from 1.0 to 0.2. In this way, only very seldom does a single value of k_m turn out to be less than 10.

Table 2 shows the value of the slopes ϕ_i and $\langle\phi'_i\rangle$ for the different projectiles. Consistent values were also obtained in a smaller rapidity window, $\eta = 2.1$–3.9, where the factors R_i are much closer to 1. This confirms that the corrections introduced are efficient, and that they allow a meaningful comparison with results obtained with a different choice of the rapidity window.

All the values of ϕ_i from the oxygen sample appear to be systematically larger than the corresponding ones from the sulphur sample. The same trend in the ϕ_i results was observed in ref. [10], in samples of quasi-central interactions of 200 GeV per nucleon ^{16}O and ^{32}S on Ag(Br) nuclei of an emulsion target. Also, numerical values of ϕ_i seem to agree, within the errors, with those obtained in the present work, even if for the oxygen sample they appear to be some 20% higher than ours. In ref. [11], with the same beams and target and at the same energy, but with an analysis that apparently does not include the R_i factors, almost the same values of ϕ_i for oxygen and sensibly higher values for sulphur are found, when the same selection as in ref. [10] is used. Much higher values of the slopes are observed when a looser selection is applied. It is difficult to perform any more quantitative comparison because of our much more stringent selection of central interactions, which implies a much higher average multiplicity.

The values of $\langle\phi'_i\rangle$ are smaller than the corresponding ϕ_i, but the trend is less evident in the sulphur sample than in the oxygen one. This is to be expected because the method that computes $\langle\phi'_i\rangle$ performs the average as $\langle\ln F_i\rangle$, instead of the $\ln\ \langle F_i\rangle$ used to compute ϕ_i. The difference between the two averages becomes noticeable when the distributions are wide. As the F_i distributions for any $\delta\eta$ become larger with increasing i, but, for a given i, shrink when the multiplicity of the events increases, the result is readily explained. Figure 2, showing distributions of $F_i(\delta\eta = 0.2)$ and of ϕ'_i for the sample of sulphur ion–emulsion central interactions, illustrates this point. One could try to extract 'exceptional' events from these distributions by requiring single values of ϕ'_i in excess of three times the spread of the corresponding distribution. It is found that with the present multiplicities, this limit corresponds to a signal 10 to 20 times the average value. No such event was found in our sample.

From the results shown in Table 2 it is also seen that, as expected, the errors on $\langle\phi'_i\rangle$ are larger that those on ϕ_i, which are calculated from the linear fit. Assuming that the former can be taken as representative of the latter, the values of ϕ_i from both projectiles turn out to be two to three standard deviations different from zero. However, before drawing any conclusion on this point, it must be checked whether there are known sources leading to the same effect.

5. RESULTS FROM MONTE CARLO AND CONCLUSIONS

A Monte Carlo computation was performed in order to study the behaviour of moments and slopes when purely statistical fluctuations are present, or when some bias is introduced. One thousand events were generated for each sample with a multiplicity per pseudorapidity bin ($\delta\eta = 0.1$), computed according to a Poisson distribution with average value equal to the multiplicity in the same bin of the average event.

Table 2 shows the results from the Monte Carlo events, obtained by performing the same analyses as those carried out on the data samples. It is seen that the values of ϕ_i are nearly zero for any order; values of $\langle\phi_i'\rangle$, computed from single events, are negative for the highest order moments owing to the effect discussed in section 4.

In order to check if the observed signal can be explained with known sources of correlations, electron pairs were included in the simulated events. Electron pairs with pseudorapidity separation $\delta\eta < 0.1$ are in fact expected to be present in our sample owing to both Dalitz decays of π^0 and γ conversions so close to the interaction vertex as to be indistiguishable from other charged particles originating from the primary interaction.

Assuming that the π^0 average multiplicity is half that of the charged pions, Dalitz decays contribute with 0.006 pairs per charged particle; $\gamma \rightarrow e^+e^-$ are expected to be 0.025 per charged particle per millimetre path in emulsion (radiation length: $X_0 = 2.9$ cm). Assuming that the region 0.5 mm downstream from a primary interaction is too 'black' to recognize the conversion pairs, we expect on the average a total of 0.0185 electron pairs per charged particle. Their tracks were generated in our Monte Carlo events by randomly removing the corresponding number of tracks in proportion to the local multiplicity and by adding pairs of tracks (i.e. within the same $\delta\eta = 0.1$ bin) in the same way. In order to check the consistency of the results, further samples were generated with twice the above-considered rate of pairs.

The analyses performed on the new samples, again reported in Table 2, show that the addition of electron pairs leads to a clear signal of intermittency, comparable with that observed in the experimental samples. The same trend is found when considering $\langle\phi_i'\rangle$. Furthermore, the signal increases linearly with the rate of the added pairs, but more quickly ($\times 1.5$) for oxygen than for sulphur interactions. It is seen that if the electron pairs were the only source of the observed effect, in the sulphur sample a rate of $(2.6 \pm 1.1)\%$ would be required, consistent with the assumed one (1.85%). In the oxygen sample, where one would infer an even lower proportion of gamma-ray conversions due to the lower multiplicity, the required rate is $(3.7 \pm 1.6)\%$. In this sample one could therefore suspect the presence of an unexplained effect, e.g. real intermittency.

In conclusion, multiplicity fluctuations have been studied in central ^{16}O–Ag and ^{32}S–Ag interactions at 200 GeV per nucleon selected according to high values of E_T. On the average, no sign of dynamical correlation has been detected in either sample. The analysis performed by means of scaled factorial moments, however, gives some evidence of an 'intermittency' mechanism. The same analysis was performed on single events: we have shown that the same results can be obtained, on the average, for high enough multiplicities (this is not the case for oxygen), and that reliable errors can be estimated. Most of the signal can be readily explained by taking into account the effect of electron pairs from both Dalitz decays and conversion. The possibility of a small residual signal being left in the O–Ag sample of central interactions cannot be ruled out.

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Table 1

Main characteristics of the samples used in this work: N_{ev} is the number of events. $\langle E_T \rangle$ and $\langle n \rangle$ are the mean transverse energy and the mean charged multiplicity, respectively; σ_{E_T} and σ_n are their standard deviations; f is the fraction of the selected interaction cross-section on Ag nuclei and on the whole emulsion, respectively.

Beam	E_T $0.1 < \eta < 3.0$ (GeV)	N_{ev}	$\langle E_T \rangle$ (GeV)	σ_{E_T} (GeV)	$\langle n \rangle$	σ_n	f(Ag) (%)	f(emulsion) (%)
Oxygen	> 85	38	103	9	252	30	3.7	0.9
Sulphur	> 155	76	173	9	394	48	1.4	0.4

Table 2

Values of ϕ_i obtained from the samples of 200 GeV per nucleon ^{16}O and ^{32}S central interactions. MC shows the corresponding results from events generated by a Monte Carlo simulation, without and with added electron pairs (see text); $\langle \phi'_i \rangle$ represent averages of the slopes computed from each event, for the same samples.

Beam	N_{ev}	ϕ_2	ϕ_3	ϕ_4	ϕ_5
Oxygen	38	0.007 ± 0.002	0.021 ± 0.006	0.047 ± 0.013	0.090 ± 0.025
MC	1000	0.0005 ± 0.0004	0.002 ± 0.001	0.004 ± 0.003	0.008 ± 0.006
MC	1.85% e^+e^-	0.005 ± 0.001	0.015 ± 0.002	0.029 ± 0.005	0.048 ± 0.009
Sulphur	76	0.005 ± 0.001	0.014 ± 0.002	0.029 ± 0.005	0.050 ± 0.007
MC	1000	0.0003 ± 0.0003	0.001 ± 0.001	0.003 ± 0.002	0.006 ± 0.003
MC	1.85% e^+e^-	0.003 ± 0.001	0.010 ± 0.002	0.020 ± 0.004	0.034 ± 0.007
		$\langle \phi'_2 \rangle$	$\langle \phi'_3 \rangle$	$\langle \phi'_4 \rangle$	$\langle \phi'_5 \rangle$
Oxygen	38	0.006 ± 0.003	0.017 ± 0.010	0.029 ± 0.021	0.036 ± 0.034
MC	1000	0.0002 ± 0.0006	−0.001 ± 0.002	−0.005 ± 0.003	−0.018 ± 0.005
MC	1.85% e^+e^-	0.005 ± 0.001	0.012 ± 0.002	0.019 ± 0.004	0.020 ± 0.006
Sulphur	76	0.004 ± 0.002	0.012 ± 0.005	0.021 ± 0.011	0.029 ± 0.017
MC	1000	0.0001 ± 0.0004	0.000 ± 0.001	−0.001 ± 0.002	−0.004 ± 0.004
MC	1.85% e^+e^-	0.003 ± 0.0004	0.009 ± 0.001	0.016 ± 0.002	0.022 ± 0.004

Figure captions

Fig. 1 Values of L_2 as a function of $\langle n \rangle$ [line a, see Eq. (3)] and of L_3 as a function of $\langle n \rangle^2$ [line b, see Eq. (4)]. Straight lines represent the result of a fit to the experimental data.

Fig. 2 Distributions of F_i ($\delta\eta = 0.2$) (a) and ϕ'_i (b), for $i = 2$ to 5, from 200 GeV per nucleon ^{32}S–Ag(Br) central interactions.

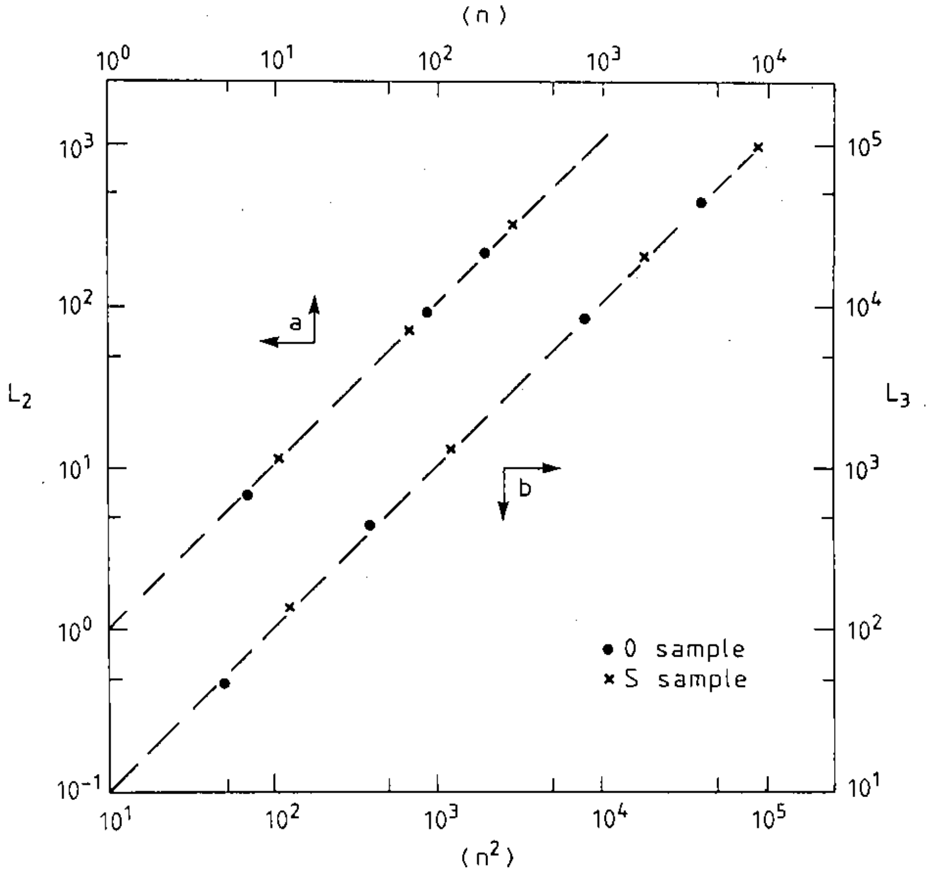

Fig. 1

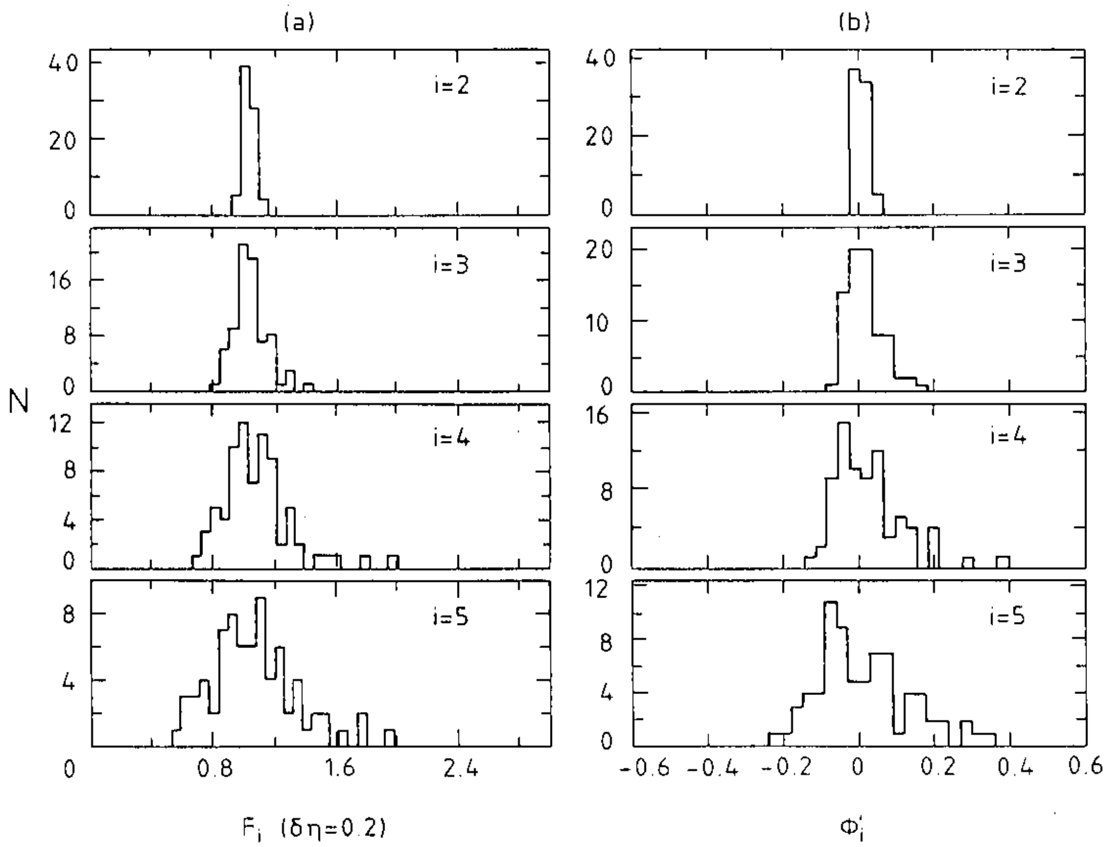

Fig. 2

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