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PARTICLE PRODUCTION AND FLUCTUATIONS IN 158-GeV/n Pb COLLISIONS WITH NUCLEAR TARGETS [1]

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and the KLMM Collaboration

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ABSTRACT

Results from the CERN EMU13 experiment on particle multiplicities and pseudorapidity distributions are shown for semi-central Pb-Ag/Br and Pb-Pb collisions. Superposition models provide a good description of these global observables. However, the analysis of fluctuations revealed the presence of dynamical fluctuations, in contrast to the VENUS model expectations. The investigation of fluctuations in individual high multiplicity events is presented.

1. Introduction

A beam of lead nuclei of an energy of 158 GeV/nucleon was conveyed to experiments at the CERN SPS in December 1994, providing a unique opportunity to study strongly interacting matter in the true high-energy heavy-ion regime. Here, we report on the results obtained from the EMU13 experiment, performed by the Krakow-Louisiana-Minnesota-Moscow (KLMM) Collaboration as a part of a long-term program, started more than a decade ago. The KLMM Collaboration employs detectors using nuclear emulsions which due to their good spatial resolution and a large geometrical acceptance are suitable for measuring charged particle multiplicities, angular distributions and density fluctuations for high multiplicity events. The results for ^{208}Pb interactions are compared to the data obtained from previous experiments with lighter projectiles at 200 GeV/n and to the ^{197}Au collisions at 10.6 GeV/n, as well as to the predictions of models based on incoherent superposition of nucleon-nucleon collisions. After a brief description of the experiment, we first show the results of measurements of charged particle multiplicities, pseudorapidity distributions and energy densities. The results of the analysis of fluctuations via factorial

moments in samples of events and in individual events are then discussed.

2. The experiment

Conventional stacks composed of horizontal BR-2 emulsion pellicles were exposed to a beam of lead ions of 158 GeV/n, in order to study ^{208}Pb interactions with heavy components of the emulsion, Ag and Br nuclei. In addition the KLMM Collaboration has exposed, perpendicular to the beam, a set of emulsion chambers which consist of lead target foils and thin emulsion plates for studying the symmetric Pb-Pb collisions. In emulsion stacks, the emulsion serves both as target and detector, thus a full 4π coverage is attained. The chamber technique limits the geometrical acceptance to the forward hemisphere, i.e. the range of measurable pseudorapidities to $\eta \geq 2.9$. The analysis of events recorded in the chambers has been fully automated [1], which provided a significant increase of measuring rate as compared to the manual measurements in emulsion stacks.

In this analysis we have concentrated on a relatively central collisions, which have been selected from the visual scan in the stacks for the events with the highest multiplicities. In the chambers, the emulsion plates directly below the Pb target were scanned for high multiplicity events. We present the results of the analysis of the 28 highest multiplicity Pb-Ag/Br interactions and of 40 high multiplicity Pb-Pb collisions. More results on the symmetric Pb-Pb collisions can be found in [1].

3. Particle production

Table 1 gives the global characteristics of the samples used in this study. The data for ^{32}S and ^{16}O projectiles were obtained from the CERN EMU07 experiment [2] while those for Au-Ag/Br collisions come from the BNL 868 experiment [3]. All samples consist of semi-central collisions, i.e., the highest multiplicity events, and the selected fractions of inelastic cross sections are about 20 %. The mean multiplicities of produced charged particles, $< N >$, for interactions with heavy emulsion nuclei were corrected for the electrons originating from photon conversions (see section 4). The average multiplicities listed in Table 1 do not include protons and fragments released from the projectile nucleus. The charged particle multiplicity measured for Pb-Pb events in the restricted pseudorapidity range was scaled to the full phase space [1] and Table 1 gives the estimated produced charged particle multiplicity.

One can see that in the selected Pb collisions with heavy targets on average about a thousand secondaries are produced, considerably more than in the collisions of lighter projectiles or in the low energy Au-Ag/Br collisions. The same increase is also observed for the particle densities $< dN/d\eta >_{max}$, that is the average multiplicities within a window of one pseudorapidity unit centered on the position, η_{peak}, of the peak in $dN/d\eta$ distribution. In the last column of Table 1 the average energy densities

Table 1. Incident energy, fraction of the inelastic cross section, event statistics, N_{ev}, average multiplicity, and pseudorapidity and energy densities for different data samples.

Sample	E GeV/n	% σ_{inel}	N_{ev}	$< N >$	$< dN/d\eta >_{max}$	$< \epsilon >$ GeV/fm^3
Pb-Pb	158	22± 3	40	1098± 55	277±12	0.78
Pb-Ag/Br	158	20±5	28	866±23	235± 8	1.12
S-Ag/Br	200	22±2	106	298± 5	78± 2	0.76
O-Ag/Br	200	20±2	95	198± 3	52± 1	0.81
Au-Ag/Br	11	21±2	97	217± 4	102± 2	0.49

are listed, calculated from the formula [4]:

$$\epsilon = \frac{3}{2}\frac{\sqrt{< p_T >^2 + m^2} < dN/d\eta >_{max}}{\pi A^{2/3}(2\tau_0)}, \tag{1}$$

where $< p_T >= 390$ MeV/c [5], $\tau_0 = 1$ fm/c, m is the pion mass and A denotes the mass of the lighter nucleus involved in the collision. One can notice that energy densities for Pb collisions are not large and may still be smaller than the densities required for a quark gluon plasma formation [a]. However, one should not put too much significance on the absolute values of energy densities due to the questionable applicability of the formula used at energies where no clear longitudinal invariance is observed and also due to the uncertainty in the τ_0 value. We quote these values only as a useful parameterization of particle densities measured in different collision systems. We observe no significant dependence of the energy density on the projectile mass for collisions at similar incident energies. On the other hand, for the same collision systems (Pb-Ag/Br and Au-Ag/Br), the energy density increases by a factor of about 2 with the primary energy increasing by about an order of magnitude.

In Fig.1a the pseudorapidity distribution of all singly charged particles for Pb-Ag/Br collisions is compared to the VENUS 4.10 model predictions [6]. From the model, events with multiplicities similar to those measured experimentally were generated. The shape of the measured distribution agree with the model calculations in almost the entire η range, except for the very forward region, $\eta > 6.5$, where the data show the expected contributions from spectator protons which are not accounted for in the model calculations. It seems, however, that the VENUS events have a slightly

[a]For our selection of semi-central Pb-Pb collisions the energy density evaluated from Eq.1 is underestimated by about 10 % (due to the incomplete overlap of the colliding Pb nuclei) as compared to the estimate based on the effective number of participants [1].

narrower $dN/d\eta$ distribution than the measured one. In Fig.1b the $dN/d\eta$ distribution measured for the symmetric Pb-Pb collisions is compared to the FRITIOF 7.02 model predictions [7]. Also in this case the events with similar multiplicities as observed in the data have been generated from the FRITIOF code. The shape of the measured distribution is well reproduced by the FRITIOF model calculations, except of the very forward spectator region. The highest multiplicity event observed is the Pb-Pb interaction in which 1729 $\pm$100 secondary particles is produced. The charged particle density for this event, $(dN/d\eta)_{max}$ is 410, giving the energy density of 1.16 GeV/fm^3.

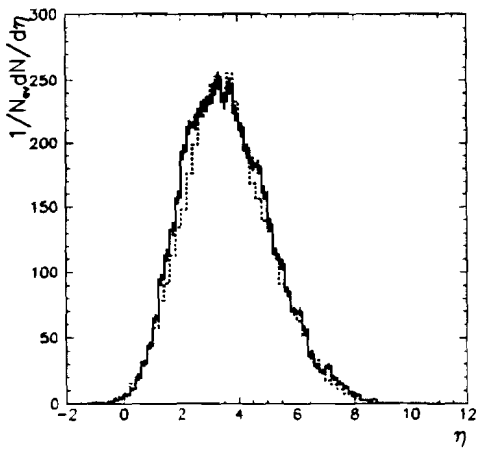

Fig.1a The pseudorapidity distribution for Pb-Ag/Br interactions (solid line) and for VENUS simulated events (dotted line).

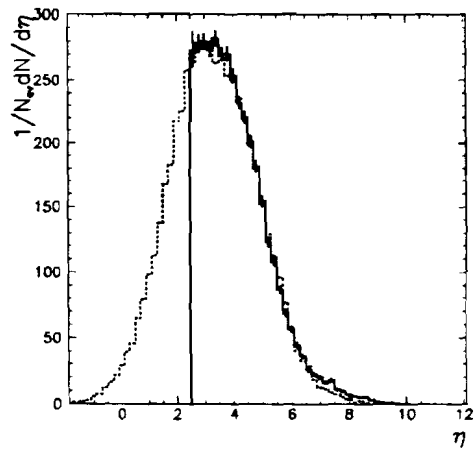

Fig.1b The pseudorapidity distribution for Pb-Pb interactions (solid line) and for FRITIOF simulated events (dotted line).

Comparing in Fig.2 the pseudorapidity distributions measured for collisions of different incident nuclei, ^{16}O, ^{32}S and ^{208}Pb, with the same Ag/Br target at approximately the same energy (200 GeV/n for ^{16}O and ^{32}S and 158 GeV/n for ^{208}Pb) we see that with increasing mass of the projectile the position of the peak moves slightly towards larger η's. This effect is due to the different projectiles and different asymmetries of colliding systems. As it was already shown in Table 1, the height of the peak increases with increasing mass of the projectile, A_p. This increase is consistent with a power-law rise ,$< dN/d\eta >_{max} \propto A_p^{\alpha}$, where $\alpha = 0.61 \pm 0.02$ (see Fig.3).

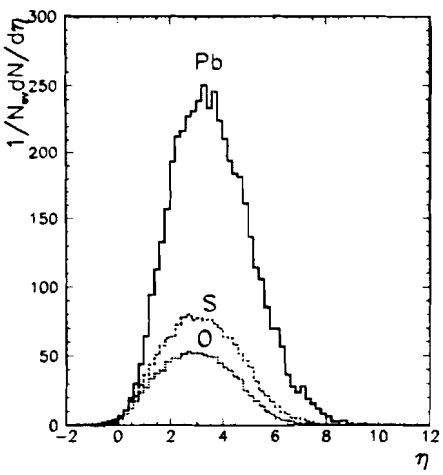

Fig.2 Pseudorapidity distributions for ^{16}O, ^{32}S and ^{208}Pb interactions with the Ag/Br target.

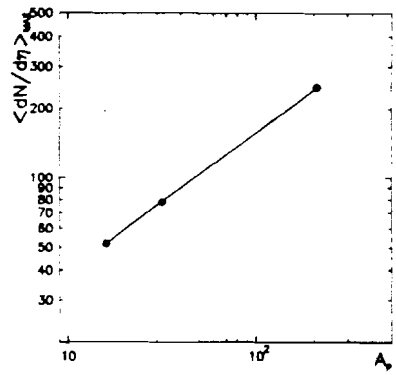

Fig.3 Particle pseudorapidity densities in ^{16}O, ^{32}S and ^{208}Pb interactions with the Ag/Br target at 200 GeV/n as a function of A_p. The density for ^{208}Pb was rescaled to 200 GeV/n by a factor of 1.05= ln 200/ ln 158.

4. Fluctuations in sample of events

The analysis of fluctuations was performed for the sample of Pb-Ag/Br collisions. For this data a special effort was made to exclude e^+e^- pairs from photon conversions. The number of measured charged particles and the distances of their measurement points from the primary vertex were used to estimate the number of electron pairs in each event. The applied off-line procedure ensured the rejection of an appropriate number of closest pairs of particles with the correct dependence on emission angles. The percentage of excluded particles, assumed to be electrons, was in average 9 % per event.

To search for the presence of nonstatistical fluctuations we have studied factorial moments of the particle density distributions in phase space domains of varying sizes [8]. The procedure to calculate factorial moments is the following: A d-dimensional overall phase space region, V, is divided into the number, M, of non-overlapping smaller cells of size $v = V/M$. For each partition the factorial moment of the order q, averaged over all events in the sample, is calculated according to [8,9]:

$$F_q(M) = \frac{\frac{1}{N_{ev}}\frac{1}{M}\sum_{j=1}^{N_{ev}}\sum_{k=1}^{M} n_{jk}(n_{jk}-1)...(n_{jk}-q+1)}{\frac{1}{N_{ev}^q}\frac{1}{M}\sum_{k=1}^{M} N_k(N_k-1)...(N_k-q+1)}, \tag{2}$$

where n_{jk} denotes the number of particles in the $k-th$ phase space cell of the $j-th$ event and $N_k = \sum_{j=1}^{N_{ev}} n_{jk}$. In the case of purely statistical fluctuations, F_q are independent of the size of phase space cell. On the other hand, any rise of the factorial moments with decreasing cell size indicates the presence of dynamical fluctuations. Furthermore, if this increase follows a simple power law, $F_q(M) \propto (M)^{\alpha_q} = (V/v)^{\alpha_q}$,

it signals intermittent or self-similar behaviour of particle density distributions, where α_q, the intermittency index, measures the strength of the intermittency effect.

For Pb-Ag/Br collisions we have investigated the phase space region covering 6 units in pseudorapidity ($\eta = 0 \div 6$) and 2π in the azimuthal angle, φ. The studied bin sizes in η varied from $\delta\eta = 1$ down to the experimental resolution, $\delta\eta = 0.12$. For the azimuth the largest bin was $\delta\varphi = 90\,\mathrm{deg}$ and the smallest 5 deg. The moments were calculated in η and φ bins (one-dimensional analysis) and in two-dimensional $\eta - \varphi$ cells (d=2).

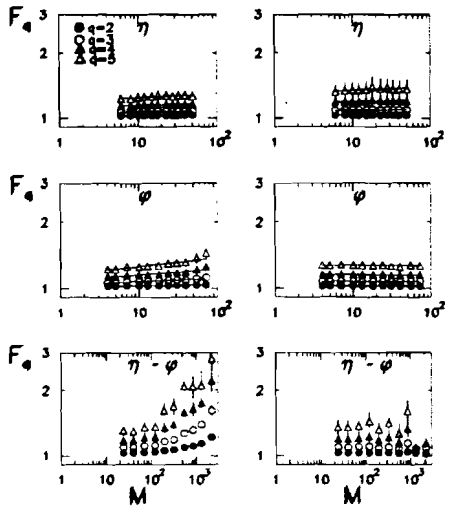

Fig.4 Log-log plots of the factorial moments F_q vs the number M of cells for Pb-Ag/Br collisions in the one-dimensional η (upper) and φ (middle) space and in the two-dimensional $\eta - \varphi$ space (lower). Lines show the best fits to power law functions.

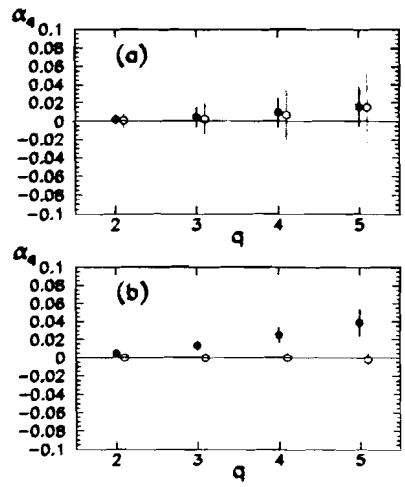

Fig.5 Intermittency indices α_q vs the order of the moments for the Pb-Ag/Br data (full circles) and the VENUS similations (open circles) for the analysis of η (a) and φ (b) bins. Values of q are slightly displaced for clarity.

Double logarithmic plots of the factorial moments as a function of the number of subdivisions for Pb-Ag/Br collisions are shown in Fig.4. The left-side plots show the data, the right-side plots represent the calculations for the VENUS generated events. Factorial moments calculated from the model are found to be independent of the size of the phase space domain in the one dimensional analysis in η and φ as well as in the two-dimensional $\eta - \varphi$ phase space. Thus, there is no evidence for the dynamical fluctuations in the VENUS model. The data show no rise of the moments in pseudorapidity while in the azimuth the moments rise like a power law. In the two-dimensional phase space the long range correlations seem to be suppressed and for smaller cells an increase faster than a power law is observed. A power law dependence has been fitted to the one-dimensional factorial moments. The fitted intermittency indices, α_q, are plotted in Fig.5 as a function of the order of the moment, for the data

and Monte Carlo simulations. Clear evidence for dynamical fluctuations is seen in the azimuth, contrary to the model predictions.

The extensive studies of the factorial moments in different high energy collision processes, pursued over the last 10 years, revealed that the effect of dynamical fluctuations decreases with increasing complexity of the colliding system [10]. We see the same weakening of the effect when comparing the results obtained for collisions of different projectiles with the Ag/Br target [11]. Such a comparison is shown in Fig.6. Indeed, the weakest rise of the moments is observed for the heaviest projectile nucleus. Consequently, the fitted intermittency indices are smallest for primary Pb nuclei as it is shown in Fig.7.

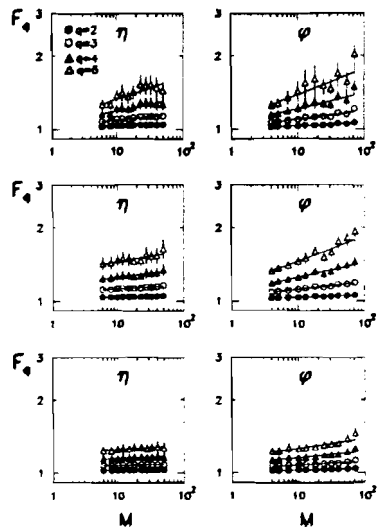

Fig.6 Double logarithmic plots of the factorial moments F_q vs M for ^{16}O (upper), ^{32}S (middle) and ^{208}Pb (lower) collisions with the Ag/Br target.

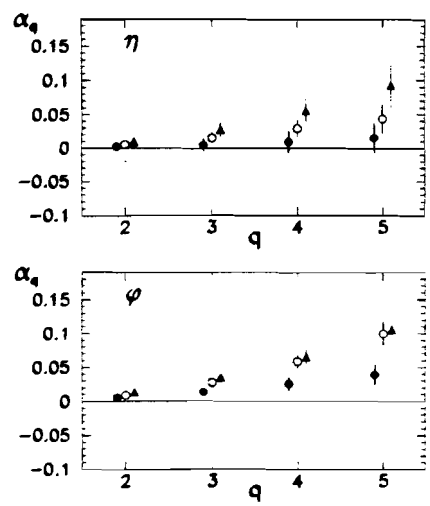

Fig.7 Intermittency indices as a function of the order of the moment for ^{16}O (full triangles), ^{32}S (open circles) and ^{208}Pb (full circles) projectiles.

The weakening of the intermittency effect for complex collisions is usually attributed to the mixing of independent particle sources [12]. Such a reduction of fluctuations was observed for hadron-hadron collisions where the intermittency indices were found to decrease roughly linearly with increasing particle density, $\alpha_q \propto < dN/d\eta >^{-1}$ [13]. In Fig.8 we show the dependencies of α_2 and α_3 on the particle density for O, S and Pb collisions with the Ag/Br target, and the decrease of α_q with increasing $< dN/d\eta >_{max}$ can be seen. For comparison, dashed lines in Fig.8 represent the extrapolation to large densities of the α_q vs. $< dN/d\eta >$ dependencies measured for $p-\overline{p}$ collisions [13]. Interestingly, at the same $dN/d\eta$ the slopes are significantly larger in nuclear collisions than those expected from the extrapolation of $p-\overline{p}$ data. Similar observations have been shown for the collisions of lighter projectiles [10] and were interpreted as evidence for the appearance of collective effects in nuclear collisions. Here, we show that for very heavy nuclei, like Pb, although the overall effect is very

small as compared to hadronic collisions, it is significantly stronger when compared at the same particle density.

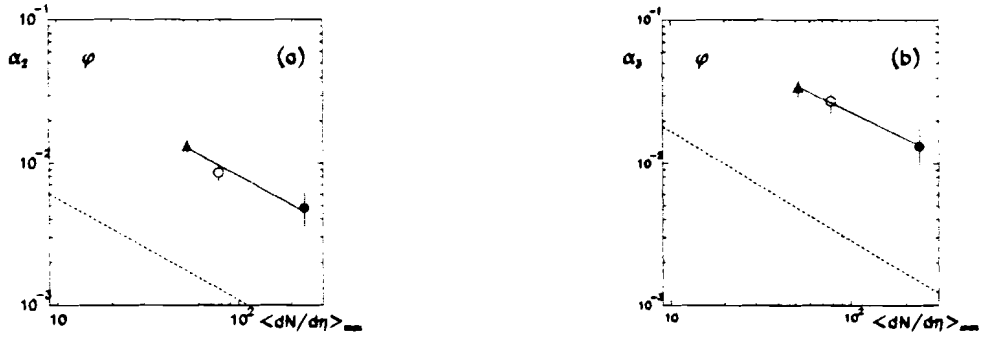

Fig.8 Dependence of α_2 (a) and α_3 (b) obtained from fitting the factorial moments, $F_q(\delta\varphi)$, as a power function on the particle densities. Symbols (see Fig.7) correspond to different projectiles.

5. Fluctuations in individual events

Almost a decade ago Białas and Peschanski [8] showed that factorial moments calculated for a single high multiplicity JACEE event [14] exhibit a power law rise with increasing resolution in pseudorapidity. Now, with Pb data, the events with a multiplicity of the order of 1000 secondaries are prevalent, and the analysis of individual events can be carried out in a more systematic way. We have calculated factorial moments in one-dimensional η and φ bins for each event in the sample of Pb-Ag/Br interactions. For a given event, the factorial moment of the order q is defined:

$$F_q^{ev} = S\frac{f_q^{ev}}{B} = S\frac{\frac{1}{M}\sum_{k=1}^{M} n_k(n_k-1)...(n_k-q+1)}{\frac{1}{N_{ev}^q}\frac{1}{M}\sum_{k=1}^{M} N_k(N_k-1)...(N_k-q+1)}, \tag{3}$$

where n_k is the number of particles in the k-th bin of an event. In order to reduce statistical errors we have taken for the normalization, B, the average over all events in the analyzed data set (see Eq.(2)). The scaling factor, S, was introduced to account for the difference between an event multiplicity and the average multiplicity of the sample:

$$S = \frac{< f_q^{ev}(M=1) >}{f_q^{ev}(M=1)}, \tag{4}$$

where brackets, <>, denote the averaging over all events.
It is not evident, however, how to calculate the errors of moments measured for a single event. Here, we propose to estimate the errors from the spread in F_q^{ev} values calculated for slightly different η ranges. Namely, we keep the full η interval

fixed, $\Delta\eta = \eta_{max} - \eta_{min} = 6$, and we vary the η_{min} and adequately η_{max} limits in 11 steps each corresponding to the shift of $\Delta\eta$ interval by 0.1 pseudorapidity units: $\eta_{min,i} = -0.5+(i-1)0.1$, $\eta_{max,i} = 5.5+(i-1)0.1$. The errors are then estimated from the maximal spread of the moments calculated for i=1,...,11. For illustration, we show in Fig.9 the dependencies of the factorial moments on M for four randomly selected events. One can see that they exhibit a different behavior: e.g. in an event # 4 the fluctuations are strongly suppressed in φ as compared to the events # 6 and # 12. For all events shown, except event # 11, the fluctuations in η are negligible. Among all investigated events, we do not observe an event with extremly large fluctuations. Particularly, the fitted event slopes, α_q^{ev}, averaged over all events are consistent with the slope, α_q, obtained from fitting the averaged factorial moments considered in the preceding section, see Table 2.

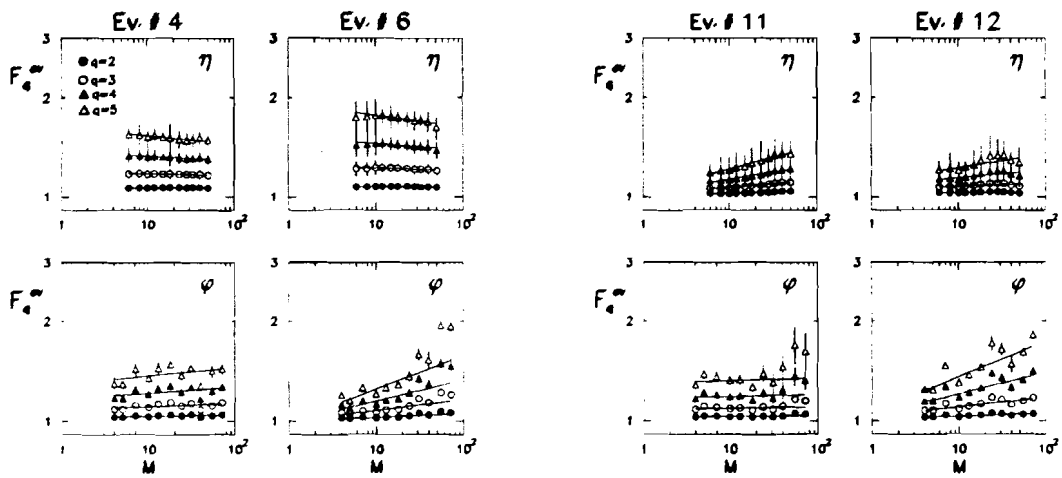

Fig.9 Log-log plots of the factorial moments F_q^{ev} calculated for a four Pb-Ag/Br events vs M in η (upper plots) and φ (lower plots) bins.

Table 2. Comparison of the mean event slopes with the slopes obtained from the averaged factorial moments for the analysis of the azimuth.

q	2	3	4	5
$< \alpha_q^{ev} >$	.005 ± .001	.014 ± .003	.028 ± .006	.045 ± .011
α_q	.005 ± .001	.013 ± .005	.025 ± .010	.039 ± .015

6. Summary

Charged particle multiplicities and pseudorapidity distributions have been measured in semi-central Pb-Ag/Br and Pb-Pb collisions at 158 GeV/n. The shapes of

the pseudorapidity distributions are in good agreement with the results from superposition models. We do not observe events with extremly high multiplicities. The estimated energy densities are also not very large and may be still insufficient for a quark-gluon plasma formation.

A search for dynamical fluctuations has been performed for the sample of Pb-Ag/Br collisions. The intermittency effect is seen in one-dimensional azimuthal angle space, however, it is weaker than in the O and S data. The VENUS model is unable to describe the observed nonstatistical fluctuations. Intermittency indices for Pb-Ag/Br collisions are considerably larger than those expected from the extrapolation of $p-\overline{p}$ data to the same pseudorapidity densities, confirming the earlier observations, and indicating for the presence of collective phenomena in nuclear collisions.

An attempt was made to investigate nonstatistical fluctuations in single high multiplicity events. Although the present analysis revealed no event with unusually large density fluctuations, its feasibility has been tested. In future, at RHIC or LHC experiments, such an analysis can be used as an effective triggering for interesting events, e.g. quark-gluon plasma candidates.

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