Event-by-event fluctuations of the kaon to pion ratio in central Pb+Pb collisions at 158 GeV per Nucleon

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We present the first measurement of fluctuations from event to event in the production of strange particles in collisions of heavy nuclei. The ratio of charged kaons to charged pions is determined for individual central Pb+Pb collisions. After accounting for the fluctuations due to detector resolution and finite number statistics we derive an upper limit on genuine non-statistical fluctuations, perhaps related to a first or second order QCD phase transition. Such fluctuations are shown to be very small.

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Quantum Chromodynamics predicts that at sufficiently high energy density strongly interacting matter will undergo a phase transition from hadronic matter to a deconfined state of quarks and gluons, the quark gluon plasma (QGP) [1]. To create and study this state of matter in the laboratory collisions of heavy ions are studied at the CERN SPS which provides lead (^{208}Pb) beams of 158 GeV per nucleon. Recent data suggest that conditions consistent with the creation of a QCD phase transition are indeed reached in central Pb+Pb collisions [2]. Whereas the position of the phase transformation in temperature, energy density and baryon density may thus be located we are lacking information as to the nature and order of that transition. These might be reflected by the presence or absence of fluctuations that are characteristic for a first or second order phase transition. An early theoretical investigation by Kapusta and Mekjian [3] suggested such fluctuations in the kaon-to-pion total-yield ratio, due to supercooling-reheating fluctuations produced by a predicted large enthalpy difference in the two phases.The K/π ratio was shown to fluctuate by about 10%, over the domain of conceivable hadronization temperatures, i.e. 140 $<$T$<$200 MeV [4]. This prediction would be experimentally testable if the K/π ratio or related quantities could be quantified for individual central collision events [5].

In a single central Pb+Pb collision at 158 GeV per nucleon about 2400 hadrons are created [6], permitting a statistically significant determination of momentum space distributions and particle ratios on an event-by-event basis. Using the NA49 large acceptance hadron spectrometer, which detects about 70% of all charged particles, we are able to study event-by-event fluctuations of hadronic observables. In a previous publication [7] we have presented results concerning the fluctuations of the eventwise mean transverse momentum. We showed that these fluctuations are very small in central Pb+Pb collisions, and that the data are consistent with a hadronic gas in thermal equilibrium [8].

In this letter fluctuations in the eventwise ratio of the number of charged kaons to the number of charged pions ($[K^{+}+K^{-}]/[\pi^{+}+\pi^{-}]$) are investigated, yielding information on fluctuations in hadrochemical composition [9] and on the strangeness-to-entropy ratio [3]. We shall show that, similar to the $\langle p_T \rangle$ study, the event-by-event fluctuations of the K/π ratio exhibit no significant large-scale fluctuation signal. We discuss fluctuations predicted in a thermodynamical resonance-gas model, which was previously used in a study of transverse momentum fluctuations [8], and those expected in various microscopic descriptions of the collision evolution.

A detailed description of the NA49 experiment can be found in [10]. We used a data set of central Pb+Pb collisions that were selected by a trigger on the energy deposited in the NA49 forward calorimeter. The trigger accepted only the 5% most central events, corresponding to an impact parameter range $b < 3.5$ fm. The event vertex was reconstructed using information from beam position detectors and a fit to the measured particle trajectories. Only events uniquely reconstructed at the known target position were used. In this analysis particles were selected that had at least 30 measured points in one of the two Main Time Projection Chambers (MTPC) outside the magnectic field.

A cut on the extrapolated impact parameter of a particle track at the primary vertex was used to reduce the contribution of non-vertex particles originating from weak decays and secondary interactions. We estimate that about 60 % of such particles are rejected by the vertex cuts. No further acceptance cuts were made, thus maximising the statistical significance of the event-by-event particle ratio measurement.

The particle identification (PID) in this analysis was based on the measured specific energy loss (dE/dx) in the MTPC using a truncated mean algorithm. Details of the dE/dx measurement can be found in [10] and in particular in [11]. As the event-by-event particle identification depends crucially on the stability of the dE/dx measurement with respect to time, event multiplicity and possible backgrounds, only the energy loss of the track in the MTPC was used in this analysis, making use of correction algorithms developed for this detector [11]. In particular we observed a significant multiplicity dependence due to the high charge load on the TPC readout chambers in central Pb+Pb events. The procedure we employed to correct these effects are based on detailed measurements of the electronics response using laser tracks. They perform a channel-by-channel iterative correction of the raw TPC charge measurements taking into account the charge history of sets of neighbouring channels, which are coupled via crosstalk effects through the sense wires of each TPC readout chamber. These corrections improved the average dE/dx resolution by about 30% from $\sigma_{dE/dx}/\langle dE/dx\rangle$ = 5-6% to the final value of 3.9% for central Pb+Pb collisions. More importantly, the multiplicity dependence of the dE/dx measurement was reduced by more than 90%, leaving a change of less than 0.3% in the multiplicity range used in this analysis.

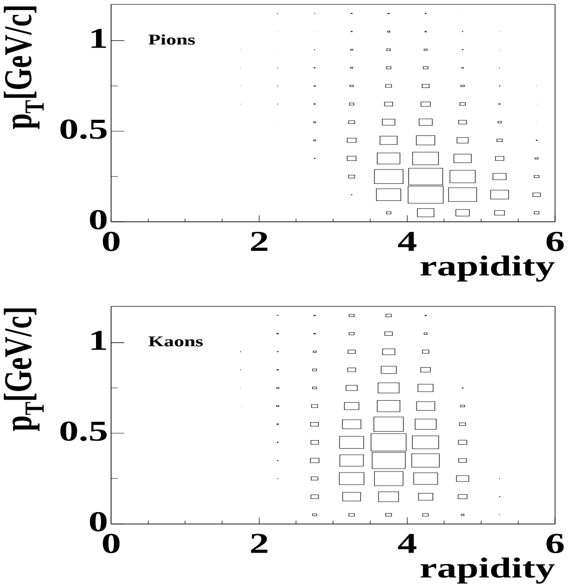

FIG. 1. Phase-space distribution of accepted charged particles pions (above) and kaons (lower plot). No acceptance correction was applied to the kaon to pion ratios reported here.

Within our acceptance window for kaons and pions (shown in Fig. 1) the dE/dx resolution translates into an average separation of pions from kaons of about 2.1 sigma and of kaons from protons of about 1.8 sigma. Obviously, given the accepted multiplicity of about 40 kaons per event, it becomes crucial to make maximum use of the available information when constructing an estimator for the event-by-event kaon-to-pion ratio. In particular a simple counting of particles is not possible under these conditions. In our analysis we use a PID method closely related to that proposed in [12].

Combining the information from all events, the momentum distributions normalized to unity, $F_m(p)$, were determined for each particle species (m = kaons, pions, protons, electrons). We also evaluated the normalized probability density functions for the truncated mean energy loss, $f_m(\vec{p};\ dE/dx)$, as a function of particle momentum for each species. The relative yield of different particle species is characterized by parameters Θ_m, such that $\sum_m \Theta_m = 1$. These parameters, with the ratio Θ_K/Θ_π giving the K/π ratio of interest here, were determined for every single event by maximizing the likelihood function

$$L = \prod_{i=1}^{n} [\sum_m \Theta_m F_m(p_i) f_m(p_i; (dE/dx)_i)] \tag{1}$$

using directly the observed momentum p_i, and specific energy loss $(dE/dx)_i$, for each particle i in the event. The use of fixed momentum distributions $F_m(p)$, implying small changes in the particle momentum distributions from event to event, is justified by the result of our analysis of event-by-event fluctuations in transverse momentum [7] which were found to be in the range of 1% or smaller. The resulting distribution of event-by-event K/π ratios is shown in Fig. 2 (points). The shape of the distribution can be understood as the result of three main contributions:

Firstly, due to the finite number of particles produced and observed per event, the ratio of particle multiplicities measured event-by-event will exhibit statistical fluctuations with a width dictated by the individual particle multiplicities.

Secondly, due to non-ideal particle identification these pure number fluctuations will be smeared by the experimental dE/dx resolution and the event-by-event fitting procedure outlined above.

Finally, superimposed on the statistical and experimental fluctuations we expect to observe any true non-statistical fluctuations. The characterization of the strength of these non-statistical fluctuations is the goal of this analysis.

In order to isolate the strength of non-statistical fluctuations in the event-by-event K/π distribution, we need to establish a reference providing us with the size of the contributions from finite number statistics and experimental resolution, but not containing any further correlations between particles. This was achieved using a mixed-event reference sample. The mixed events were constructed by combining particles randomly selected from different real events, reproducing the multiplicity distribution of the real events. Only one track of each event was used in the mixing to exclude any residual correlations. Within our central event sample no further selection on impact parameter was made. By construction, the mixed events on average have the same kaon to pion ratio as the real events, but no internal correlations. Due to the constraint on the overall multiplicity distribution they give an accurate estimate of finite-number fluctuations in the kaon and pion multiplicities. Equally importantly, each track in the mixed events represents an actual dE/dx measurement.

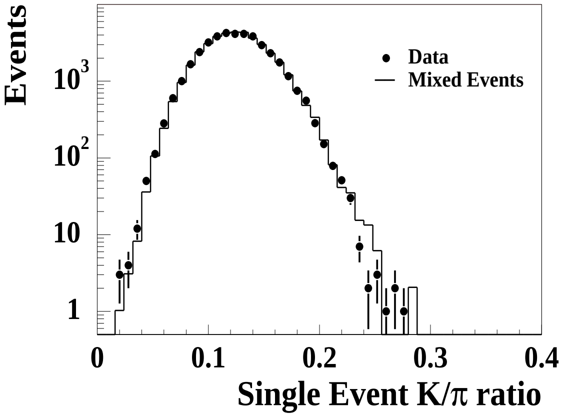

FIG. 2. Distribution of the event-by-event kaon to pion ratio estimated using a maximum likelihood method (points). As a reference, the same procedure was applied to a mixed event sample (histogram).

The mixed events therefore automatically include all the effects of detector resolution. They are subjected to the same maximum likelihood fit procedure as the real events, allowing a direct comparison with the data. Any deviation of the distribution for the data from the purely statistical mixed-event distribution would indicate the presence of non-statistical fluctuations in the production of kaons and pions. The result of this comparison is shown in Fig. 2, showing the distribution of the K/π ratio for data (points) and for mixed events (histogram). The small difference between data and statistical reference immediately illustrates that any correlations or anti-correlations in the final multiplicities are small. In particular no significant number of events with unusually small or large strangeness content is present in our data sample.

The observed relative width of the data distribution is $\sigma_{data} = 23.27\%$. The width of the mixed event distribution is $\sigma_{mixed} = 23.1\%$. A more detailed analysis of the latter [11] shows that it is composed of contributions from finite number statistics of $\sigma = 15.9\%$ and the dE/dx resolution plus fitting procedure of $\sigma = 16.7\%$ which add in quadrature to the observed width. Note that the average eventwise K/π ratio shown in Fig. 2 does not necessarily correspond to the true ratio in 4π acceptance [6], since no corrections for efficiency and y, p_T acceptance were included in the analysis presented.

To quantify the remaining difference between data and mixed events we define the strength of non-statistical fluctuations as

$$\sigma_{non-stat} = \sqrt{\sigma^2_{data} - \sigma^2_{mixed}} \tag{2}$$

In general, processes leading to a correlated production of one or the other particle species or to a correlation in their multiplicities would result in $\sigma_{non-stat} > 0$.

For our data set we obtain

$$\sigma_{non-stat} = 2.8\% \pm 0.5\%. \tag{3}$$

The fluctuations observed in the data are very small compared to the scale given by the observed two-fold enhancement of strangeness in nucleus-nucleus collisions relative to nucleon-nucleon collisions [6]. To a very good accuracy we can conclude that the mechanism responsible for the enhancement of strangeness is therefore active in each central Pb+Pb collision.

The observed value of $\sigma_{non-stat}$ also allows us to establish a limit on event-by-event fluctuations as a function of the frequency of occurrence of these fluctuations. In establishing this limit at the 90% confidence level we took into account our estimated systematical uncertainties in determining the event-by-event K/π ratio. As mentioned previously, all systematic uncertainties considered tend to increase the observed value. According to our measurement fluctuations of a relative amplitude of $\sigma_{non-stat} > 4.0\%$ can be ruled out in case all events of the sample exhibit the fluctuation pattern, whereas fluctuations occurring in 5% of the events can only be ruled out for $\sigma_{non-stat} > 15.0\%$ (still small compared to the strangeness enhancement).

Finally, we would like to compare our measurement to the FRITIOF model of nucleus-nucleus collisions. This microscopic model quantitatively reproduces the correlations observed in nucleon-nucleon collisions and predicts a value of $\sigma_{non-stat}^{FRITIOF} = 9\%$ for central Pb+Pb collisions. Clearly the fluctuations in the data are much smaller. The disappearance of fluctuations when going to central nucleus-nucleus collisions can be interpreted as evidence for statistical particle production, as opposed to the highly correlated processes observed in nucleon-nucleon collisions.

This observation lends further support to the interpretation of particle ratios in nucleus-nucleus collisions using statistical hadronization models [2], with the added information that the statistical distribution is actually realized in every individual event and not just on an ensemble basis.

The observed fluctuations can also be compared to the results of an equilibrium hadron gas calculation [13] which includes correlations induced by many-body decays of resonances into pions and kaons. This calculation predicts non-statistical fluctuations $\sigma_{non-stat} \approx 2\%$, in good agreement with the data.

In conclusion we have presented the first event-by-event measurement of particle ratios in ultra-relativistic heavy ion collisions. Using particle identification by dE/dx in the NA49 TPCs the fluctuations in strangeness production were studied using the ratio of charged kaons to pions. No non-statistical fluctuations are observed and we deduce an upper limit of $\sigma_{non-stat} < 4.0\%$ for fluctuations occurring in every event at the 3σ-level. The fluctuations are therefore very small relative to the two-fold strangeness enhancement, indicating that the dynamical evolution of individual events proceeds in a very similar fashion. As in our previous study of transverse momentum fluctuations in Pb+Pb collisions [7], we find no evidence of fluctuations that might indicate a strong first-order phase transition or freeze-out near a proposed QCD critical end point.

On the contrary, the fluctuations observed in Pb+Pb collisions are significantly smaller than those expected for an indepedent superposition of nucleon-nucleon collisions. This supports the interpretation of flavor ratios in terms of statistical hadronization models, combined with a smooth transition from a possible partonic state to the final state hadronic particle composition. In fact, the minimal fluctuations expected due to resonance production of the final state hadrons seem to completely exhaust the observed strength of non-statistical fluctuations.

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