Event-by-event fluctuations of particle ratios in central Pb+Pb collisions at 20–158 A GeV

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Abstract
Recent results of the NA49 energy scan programme show a sharp maximum of the ratio of K\textsuperscript{+} to π\textsuperscript{+} yields in central Pb+Pb collisions at beam energies of 20–30 A GeV. This observation has been interpreted as an indication of a phase transition at low SPS energies. We present results on event-by-event fluctuations of the kaon to pion and proton to pion ratios at beam energies close to this maximum. A significant increase of the fluctuation signal of the kaon to pion ratio with deceasing beam energy is observed.

Heavy-ion collisions at relativistic energies are investigated to study the creation and properties of a deconfined state of quarks and gluons, the quark–gluon plasma (QGP). One of the difficulties of the search for the QGP is the insensitivity of inclusive observables to the phase transition itself. It was realized, however, that event-by-event fluctuations could provide a direct probe of the existence and nature of the phase transition [1].

An early theoretical investigation [2] suggested that if the free enthalpy difference between the hadronic and the plasma phase was high, marked overheating–supercooling fluctuations might set in at about the critical temperature $T_c$, to be reflected in a broadening of the event-by-event kaon to pion total yield ratio. More recent calculations on the nature of the QCD phase diagram suggest the existence of a tricritical point. Thus, fluctuation patterns of event-by-event observables are expected to be altered in the vicinity of the QCD phase boundary [3, 4] and especially in the vicinity of a tricritical point. Thus, a scan of event-by-event observables over a wide range of collision scenarios, probing the properties of nuclear matter in various regions of the $\mu_B$ versus $T$ phase diagram, is used to search for the location of the tricritical point and provide information directly related to the nature of the phase transition. Experimentally, the energy density achieved in the reaction can be controlled by varying the incident energy of the colliding system.

Recently, the energy scan programme at the CERN SPS, providing Pb+Pb collisions at beam energies of 20, 30, 40, 80 and 158 A GeV, has been completed. The NA49 experiment

\textsuperscript{1} A list of all members of this Collaboration is given at the end of this issue.
was conceived to measure event-by-event fluctuations in heavy-ion collisions and is well suited for a measurement of particle ratios in single Pb+Pb collisions at all available beam energies. A detailed description of the NA49 experiment can be found in [5]. In this paper, the event-by-event particle ratios $[K^+ + K^-]/[\pi^+ + \pi^-]$ and $[p + \bar{p}]/[\pi^+ + \pi^-]$ are presented. The analysis method is described in [6–9]. At all five available beam energies, the 3.5% most central Pb+Pb collisions were selected based on projectile spectator energy. For illustration, the distributions of the two studied particle ratios at 20, 40 and 158 A GeV are shown in figures 1 and 2. The relative width $\sigma$, defined as $\sigma = \text{rms}/\text{mean} \times 100(\%)$, of the measured event-by-event particle ratio distributions can be decomposed into three contributions:

(i) 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.

(ii) Due to non-ideal particle identification, these statistical fluctuations will be smeared by the experimental $dE/dx$ resolution and the event-by-event fitting procedure.

(iii) Superimposed on the background of statistical and experimental fluctuations, we may observe genuine non-statistical fluctuations.

The contributions due to finite number fluctuations in the particle multiplicities and effects of detector resolution are estimated using a mixed event technique. Mixed events are constructed by randomly selecting measured particles from different events and combining them to artificial events, while reproducing the multiplicity distribution of the real events. By construction, mixed events have on an average the same particle ratios as the real events, but no internal correlations. These mixed events are then subjected to the same fit procedure as the real
events and the rms width $\sigma_{\text{mix}}$ of the mixed event particle ratio distribution is obtained. The contribution of dynamical fluctuations to the width of the distribution of particle ratios in data events can be estimated by subtracting the width of the mixed event distribution of particle ratios:

$$\sigma_{\text{dyn}} = \text{sign} \left( \sigma_{\text{data}}^2 - \sigma_{\text{mixed}}^2 \right) \sqrt{|\sigma_{\text{data}}^2 - \sigma_{\text{mixed}}^2|}. \quad (1)$$

The systematic error of the fluctuation measurement is estimated by comparing the fluctuation signals obtained in two different analyses using varying sets of track quality cuts. Track samples selected with a stringent set of track quality cuts are compared to samples obtained with lose track cuts. The track selection using lose track quality cuts yields 15–20% more tracks per event to drive the event-by-event particle ratio estimation, but also increases the contamination of the track sample with non-primary and background particles. The values of the fluctuation signal presented here are calculated as the arithmetic mean of both results. Note that even though the absolute difference in the width of data and mixed events is small, it can be measured with high precision given the large number of analysed events. The significance of the measurement is reflected in the systematic error. The contribution from dynamical fluctuations obtained from equation (1) is plotted in figure 3.

The observed fluctuations of the $K/\pi$ ratio are positive and decrease with beam energy. In the case of the $[p + \bar{p}]/\pi$ ratio, the width of the data distribution is smaller than the width of the distribution of mixed events. The dynamical fluctuations are negative. A negative fluctuation signal of the eventwise $[p + \bar{p}]/\pi$ ratio can be understood, if resonance decays into pions and protons are considered. The magnitude of the negative fluctuation signal in the $[p + \bar{p}]/\pi$ channel may be related to the relative contribution of resonance decay products in the final state of the collision. In order to estimate the significance of the observed fluctuation signals of the two ratios considered, we compare the data to a string-hadronic cascade model UrQMD [10]. In this model, by construction, no fluctuations due to a potential phase transition are present, while resonance decays are included as well as effects of correlated particle production due to quantum number and energy/momentum conservation laws. For this study, samples of 50,000 UrQMD events were generated at all five beam energies and then subjected to an acceptance filter modelling the NA49 detector system. The accepted final-state particles were counted and the corresponding ratios were formed. The energy dependence of the event-by-event $[p + \bar{p}]/\pi$ ratio in UrQMD closely matches the energy dependence observed in the data, as...
shown in figure 3. This lends further support to interpreting the negative fluctuation signal as resulting from resonance decays. In the case of the fluctuations of the eventwise K/π ratio, the energy dependence of the signal cannot be reproduced in the cascade model. UrQMD gives an energy-independent fluctuation signal. Since the relative contribution of resonances changes dramatically with incident beam energy [12], we conclude that in the K/π ratio resonances do not give a significant contribution to the fluctuation signal. The finite fluctuation signal in the UrQMD model can be attributed to correlated particle production due to conservation laws. In the data, we observe a significantly smaller fluctuation signal at highest beam energies than in the cascade model.

In the data taken at 158 A GeV incident energy, the fluctuation signal is consistent with calculations performed assuming a grand canonical ensemble without enforcing local conservation laws [11]. Towards lower beam energies, a steep increase of the fluctuation signal is observed as shown in the left panel of figure 3. The increase of the signal goes significantly beyond the value seen in a hadronic cascade model, indicating the onset of a new source of fluctuations. The largest fluctuation signal in the event-by-event K/π ratio is observed at the lowest beam energies available at the SPS. This domain coincides with the range where the properties of the inclusive particle spectra also suggest the presence of phenomena possibly related to a deconfined phase in the early stage of the collision [12].

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