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Energy dependence of kaon-to-proton ratio fluctuations in central Pb+Pb collisions from $\sqrt{s_{NN}} = 6.3$ to 17.3 GeV

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Abstract

Kaons and protons carry large parts of two conserved quantities, strangeness and baryon number. It is argued that their correlation and thus also fluctuations are sensitive to conditions prevailing at the anticipated parton-hadron phase boundary. Fluctuations of the $(\mathrm{K}^+ + \mathrm{K}^-)/(\mathrm{p} + \bar{\mathrm{p}})$ and K^+/p ratios have been measured for the first time by NA49 in central Pb+Pb collisions at 5 SPS energies between $\sqrt{s_{NN}}$= 6.3 GeV and 17.3 GeV. Both ratios exhibit a change of sign in σ_{dyn}, a measure of non-statistical fluctuations, around $\sqrt{s_{NN}} = 8$ GeV. Below this energy, σ_{dyn} is positive, indicating higher fluctuation compared to a mixed event background sample, while for higher energies, σ_{dyn} is negative, indicating correlated emission of kaons and protons. The results are compared to UrQMD calculations which which give a good description at the higher SPS energies, but fail to reproduce the transition to positive values.

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Heavy-ion collisions serve as the laboratory to study hadronic matter under extreme energy density and temperature conditions. They surpass critical values of energy density where lattice QCD calculations predict a phase transition from hadronic to deconfined matter (the "quark-gluon plasma") [1]. A multitude of relevant physics observables provides indication [2, 3, 4, 5, 6, 7, 8] that this phase transition takes place onward from the energy range of the CERN SPS (6.3 GeV $\leq \sqrt{s_{NN}} \leq$ 17.3 GeV): the domain of the present study.

While the above evidence is based on inclusive observables, additional insight can be obtained by looking at event-by-event fluctuations. Enhanced fluctuations are a general feature of phase transitions. Recent lattice QCD calculations report indications of a QCD critical point at finite baryo-chemical potential, reflected in a steep rise of quark number density fluctuation (quark "susceptibility") [9, 10, 11]. In addition, the changed correlation patterns in particle production, expected where new degrees of freedom emerge, are accessible via fluctuation observables [12].

Numerous such observables have been explored previously [12, 13, 14], in part with non-conclusive outcome. This resulted from uncontrolled sources of background fluctuations, notably variation of the reaction volume due to concurrent impact geometry fluctuations, finite number statistics, or from an obliteration of the signals during the hadron-resonance expansion phase that follows hadron formation at the parton-hadron phase boundary (notably so for electric charge correlations [13, 14]).

The present study of hadron ratio fluctuations overcomes the mentioned difficulties to a certain extent. Effects from volume fluctuations are minimized, as a particle ratio is an intensive quantity and the average hadron ratios change only marginally in the analysed centrality interval. Fluctuations from finite number statistics, as well as effects of the limited detector resolution in the particle identification (PID) method are removed by subtracting a mixed event reference. Thus, *dynamical* fluctuations are studied.

For kaon-to-proton number ratio fluctuations, the conserved charges strangeness and baryon number are carried by heavy particles, making their dispersion in momentum space smaller compared to the case of electric charge fluctuations, where the Q-value of resonance decays creates a noticeable difference between the original charge distribution and that of the finally observed pions [13]. No such transport process (as, e.g. a resonance feeding into $\mathrm{K}^+ + \mathrm{p}$) is known in the case discussed here.

The results presented here are the first attempt to experimentally probe the baryon number-strangeness correlation, which undergoes a massive change at the deconfinement phase transition. Above that transition, where strange quarks ($S = -1$, $B = 1/3$) are the relevant degrees of freedom, strangeness

S can only exist in direct conjunction with baryon number B. In a hadronic medium, kaons ($S = -1$, $B = 0$) allow for strangeness production unrelated to baryon number. An appropriate correlation coefficient C_{BS} [15] has been proposed which is related to the above mentioned quark number density susceptibililties at finite baryo-chemical potential μ_B recently predicted by lattice QCD [9, 10, 11]. The latter exhibit steep maxima at $T = 150$ MeV and $\mu_B \approx 400$ MeV, conditions that are reached in A+A collisions in the energy range under investigation in this analysis. An important contribution to this coefficient are the kaon-proton correlations, that were experimentally probed for the first time in the present data analysis.

The following analysis is based on data from Pb+Pb collisions recorded at the CERN SPS at five energies, $\sqrt{s_{_{NN}}} = 6.3, 7.6, 8.7, 12.3$ and 17.3 GeV. The 3.5% most central events were selected, also avoiding an influence of the change in the inclusive $\langle \mathrm{K} \rangle / \langle \mathrm{p} \rangle$ ratio with centrality.

The NA49 detector [16] uses 4 large volume time projection chambers (TPC) for tracking and particle identification (PID) via their specific energy loss ($\mathrm{d}E/\mathrm{d}x$) in the TPC gas. During the SPS energy scan program, care was taken to keep the acceptance approximately constant with respect to midrapidity by setting the magnetic field strength proportional to the beam momentum. To ensure best resolution and stability of the $\mathrm{d}E/\mathrm{d}x$ measurement, only tracks within the acceptance of the large main TPCs were accepted for the analysis. Further quality cuts are applied on the distance of closest approach of the extrapolated particle trajectory back to the main vertex and on the number of measured $\mathrm{d}E/\mathrm{d}x$ samples on the track. The resulting acceptance as a function of center-of-mass rapidity normalized by beam rapidity, and transverse momentum p_{T} is depicted in Fig. 1. The azimuthal acceptance is described in [17] and the comprehensive acceptance tables to be used in simulations can be found in [18]. Average uncorrected multiplicities within this acceptance range from $\langle \mathrm{K}^+ + \mathrm{K}^- \rangle = 6$ and $\langle \mathrm{p} + \bar{\mathrm{p}} \rangle = 28$ at $\sqrt{s_{_{NN}}} = 6.3$ GeV to 54 and 75 at $\sqrt{s_{_{NN}}} = 17.3$ GeV.

The analysis procedure is similar to the one employed by NA49 in the study of fluctuations of the K/π and p/π ratios [17]. The $\mathrm{d}E/\mathrm{d}x$ resolution of approximately 4% allows for a statistical determination of the inclusive particle yields through a χ^2 fit to the $\mathrm{d}E/\mathrm{d}x$ spectra in momentum space bins. Probability density functions (PDFs) f_m for $\mathrm{d}E/\mathrm{d}x$ and momentum F_m from this inclusive analysis are then used as input for the event-wise particle ratio determination. The $\mathrm{d}E/\mathrm{d}x$ distributions overlap for different hadron species m, making a simple particle counting impossible. Therefore, an unbinned likelihood method as introduced in [19, 20] is used.

In each event, the likelihood function L is obtained by multiplying the probabilities of the n particles in the event ($\langle n \rangle \approx 60$ at $\sqrt{s_{_{NN}}} = 6.3$ GeV

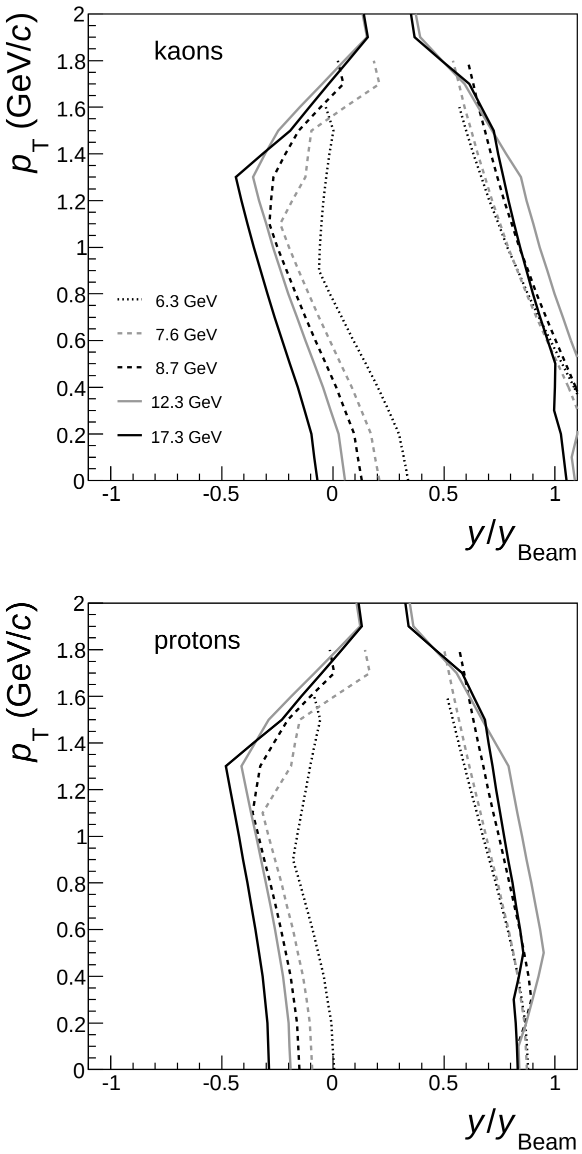

Figure 1: (Color online) The acceptance for kaons and protons, as used in the present analysis, as a function of transverse momentum and the center-of-mass rapidity, normalized by the corresponding beam rapidity, for all analysed energies. Lines delimit the regions in which particles can be identified. Limits are due to geometric acceptance and available statistics, the latter predominantly at large momenta p and transverse momenta p_{T}.

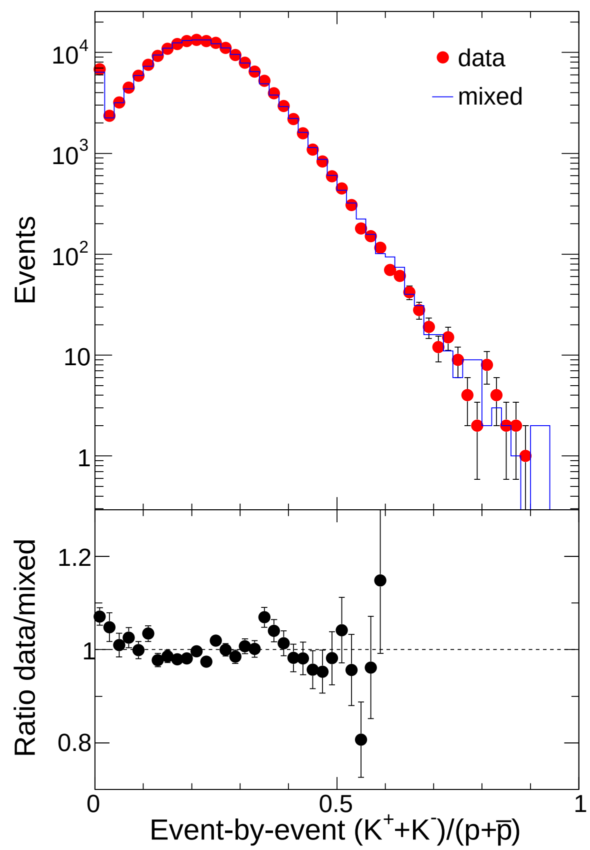

Figure 2: (Color online) Event-by-event distribution of the $(\mathrm{K}^+{+}\mathrm{K}^-)/(\mathrm{p}{+}\bar{\mathrm{p}})$ ratio at $\sqrt{s_{_{NN}}}$= 6.3 GeV for real data events compared to the mixed event reference. The lower panel shows the ratio data/mixed, where the concave shape indicates positive dynamical fluctuations.

and $\langle n\rangle \approx 600$ at $\sqrt{s_{_{NN}}} = 17.3$ GeV):

$$L = \prod_{i=1}^{n} \left[\sum_{m} \Theta_m F_m\left(\vec{p_i}\right) f_m\left(\vec{p_i}, (\mathrm{d}E/\mathrm{d}x)_i\right) \right], \tag{1}$$

where Θ_m are the relative abundances, constructed such that $\sum_m \Theta_m = 1$. They are the only free parameters in the subsequent likelihood maximization. The event-wise hadron ratios are then calculated from the fitted values of Θ_m.

The fluctuations of the event-wise K/p ratio are quantified using the scaled dispersion $\sigma := \sqrt{\mathrm{Var}(\mathrm{K/p})}/\langle\mathrm{K/p}\rangle$. The measured value in the data is denoted σ_{data}. Figures 2 and 3 show the event-by-event distribution of the $(\mathrm{K}^+ + \mathrm{K}^-)/(\mathrm{p} + \bar{\mathrm{p}})$ ratio for $\sqrt{s_{_{NN}}}$= 6.3 GeV and 17.3 GeV. To quantify finite-number statistics and PID resolution effects, a reference sample

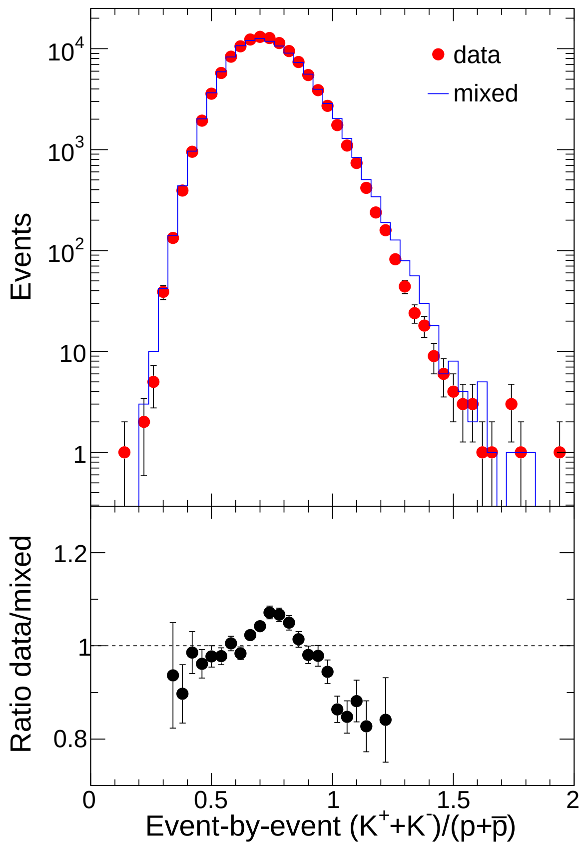

Figure 3: (Color online) Event-by-event distribution of the $(K^{+}+K^{-})/(p+\bar{p})$ ratio at $\sqrt{s_{NN}}$= 17.3 GeV for real data events compared to the mixed event reference. The lower panel shows the ratio data/mixed, where the convex shape indicates negative dynamical fluctuations.

of mixed events is constructed. This sample is made such as to preserve the original multiplicity distribution, with no two tracks in a mixed event taken from the same physical event. As described in detail in [17], the mixed events contain no correlation due to physical processes, but effects from finite number statistics remain. The measured $\mathrm{d}E/\mathrm{d}x$ information is still attached to the individual particles, so that the likelihood method can be applied to the mixed events in the same way as to the original events. Thus, the effect of the $\mathrm{d}E/\mathrm{d}x$ resolution on the extracted particle ratios is reproduced by the mixed events. The event-by-event distribution from mixed events is also displayed in Figs. 2 and 3. Their scaled dispersion is denoted σ_{mix}.

The dynamical fluctuations can now be constructed as the quadratic difference [17, 19, 20]:

$$\sigma_{\mathrm{dyn}} := \mathrm{sign}\left(\sigma_{\mathrm{data}}^2 - \sigma_{\mathrm{mix}}^2\right)\sqrt{|\sigma_{\mathrm{data}}^2 - \sigma_{\mathrm{mix}}^2|}. \tag{2}$$

At $\sqrt{s_{_{NN}}}$= 6.3 GeV (Fig. 2) the data show a broader distribution compared to mixed events. This is demonstrated in the lower panel of Figs. 2 and 3, showing the ratio between data and mixed event distributions. Only in these ratio plots, for better readability, statistically insignificant bins are not shown. The larger fluctuations in the data result in a positive value of σ_{dyn}. For $\sqrt{s_{_{NN}}}$= 17.3 GeV (Fig. 3), the opposite is true. The mixed event distribution is wider, leading to $\sigma_{\mathrm{dyn}} < 0$.

The method described above has been successfully used and thoroughly tested in the analysis of K/π and $(\mathrm{p}+\bar{\mathrm{p}})/\pi$ fluctuations [17], and the same extensive quality checks were applied in the present analysis. For instance, outlying events with very small or high K/p ratios were found to contribute only modestly to the reported fluctuation signal: Consistent with [17], the signal changes by less than 1% when removing the high or low tails of the K/p distributions that correspond to 1% of the events. Special care was taken in the present analysis to check whether a correlation remains from the fit when extracting the K/p ratio, as the $\mathrm{d}E/\mathrm{d}x$ based kaon-proton separation is smaller than for the kaon-pion case. To exclude such an influence, events generated in the hadronic transport model UrQMD [21, 22, 23] were used to study the effect of the $\mathrm{d}E/\mathrm{d}x$ resolution. The results of a direct model calculation are in agreement with those obtained using in addition a simulation of the NA49 TPC $\mathrm{d}E/\mathrm{d}x$ response and employing the fit procedure described above. The difference between the two methods amounts to 1.5% at most and is taken into account in the systematic error.

The stability of the results was tested under variation of the track selection criteria, acceptance and event selection, as described in detail in [17]. The changes due to these variations are also represented in the systematic

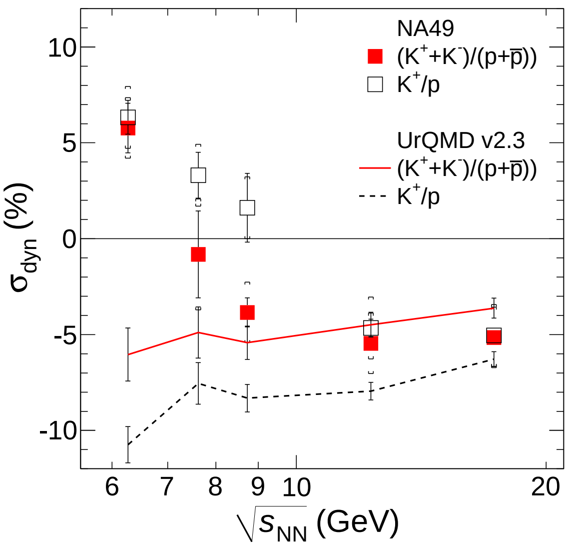

Figure 4: (Color online) Energy dependence of the event-by-event dynamical fluctuations of the $(\mathrm{K}^+ + \mathrm{K}^-)/(\mathrm{p} + \bar{\mathrm{p}})$ and the K^+/p ratios. Symbols represent the NA49 measurements with statistical and systematic (braces) uncertainties. Calculations within the UrQMD transport model, processed through an NA49 acceptance filter are represented by lines.

errors. The results proved to be stable under small variations of the chosen acceptance. However, the acceptance tables provided in [18] should be used for model comparisons.

The excitation function of σ_{dyn} for $(\mathrm{K}^+ + \mathrm{K}^-)/(\mathrm{p} + \bar{\mathrm{p}})$ and K^+/p is shown in Fig. 4. For both cases, the dynamical ratio fluctuations change from positive (enhanced fluctuations compared to mixed events) at low SPS energies to negative values at the higher SPS energies. At high and low energies, σ_{dyn} agrees for the two studied ratios, but disagrees at $\sqrt{s_{NN}} = 7.6$ and 8.7 GeV. Recent preliminary results from the STAR collaboration [24] also find negative values and indicate a weak energy dependence between $\sqrt{s_{NN}} = 17.3$ and 200 GeV.

Calculations with the hadronic transport model UrQMD [21, 22, 23] are shown for comparison. The NA49 experimental acceptance was used in the model studies. The resulting σ_{dyn} is negative, and shows only a weak energy dependence. In contrast to the data, both charge combinations have a constant difference over the studied energy range. The striking change to positive values at low $\sqrt{s_{NN}}$, as seen in the data, is also not present in the hadronic model.

In contrast to the previous results on K/π and $(\mathrm{p}+\bar{\mathrm{p}})/\pi$ fluctuations, for which attempts of an explanation exist, the present data can not easily be understood. We recall that the $(\mathrm{p}+\bar{\mathrm{p}})/\pi$ fluctuations were explained in hadronic models as a result of the proton-pion correlation due to resonance decay [17, 25] and that the rise in σ_{dyn} for K/π was suggested to be due to scaling properties of the observable σ_{dyn} itself [26] or might even be connected to the onset of deconfinement [27].

As no known resonance feeds into positively charged kaons and protons, another source of correlation has to change at the energy where σ_{dyn} abruptly switches sign and starts to deviate from the UrQMD calculations. The deviation from a scaling as described in [26] is indicative of a change in the underlying correlation physics.

In the baryon-strangeness correlation, a rapid change is expected at the deconfinement phase transition [28, 29] for which indications were found in the same energy region in rapid changes of several hadron production properties [5, 6, 7]. Thus the observed energy dependence qualitatively supports the scenario of a change in the baryon-strangeness correlation. But the exact contribution to C_{BS} of $\sigma_{\mathrm{dyn}}((\mathrm{K}^{+}+\mathrm{K}^{-})/(\mathrm{p}+\bar{\mathrm{p}}))$ and $\sigma_{\mathrm{dyn}}(\mathrm{K}^{+}/\mathrm{p})$, respectively is still under discussion [30].

In summary, we present a first measurement of the dynamical fluctuations of the kaon-to-proton number ratio at the SPS energies. Both $(\mathrm{K}^{+}+\mathrm{K}^{-})/(\mathrm{p}+\bar{\mathrm{p}})$ and $\mathrm{K}^{+}/\mathrm{p}$ fluctuations show a non-trivial excitation function that is not reproduced in the hadronic model UrQMD, and may point to a change in the baryon number-strangeness correlation at $\sqrt{s_{NN}} \approx 8$ GeV. Although a connection between the kaon-to-proton ratio and C_{BS} seems reasonable, and the latter is suggested as a unique test for the basic degrees of freedom in the probed matter, the detailed connection between our measurement and C_{BS} and its interpretation requires further theoretical studies.

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