Event-by-event fluctuations at SPS

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Results on event-by-event fluctuations of the mean transverse momentum and net charge in Pb-Au collisions, measured by the CERES Collaboration at CERN-SPS, are presented. We discuss the centrality and beam energy dependence and compare our data to cascade calculations.

1. Introduction

In collisions of heavy nuclei at high energies, the creation of hot and dense matter consisting of deconfined quarks and gluons is expected. If thermalization is achieved in the early stage of the collision, a phase transition to a Quark-Gluon-Plasma (QGP) may occur, as indicated by QCD calculations on the lattice. The experimental verification of the phase transition based on the final state distribution of the produced hadrons is, however, rather circumstantial. Non-statistical fluctuations of intensive quantities, such as the event-by-event mean transverse momentum $M_{\text{pt}}$ of hadrons, have been proposed as a possible signature for critical phenomena connected with the passage of the system through the
phase boundary, and may therefore serve as an important tool for the exploration of the QCD phase diagram [1, 2]. The formation of an equilibrated QGP may also lead to reduced fluctuations of the net electric charge in the hadronic final state [3, 4]. This expectation arises from the smaller charge units of quarks compared to pions and the large contribution to charged particle production by gluons, which are electrically neutral and do not contribute to fluctuations.

In this contribution, results on event-by-event fluctuations are presented from Pb-Au collisions at 40, 80, and 158 A GeV. The data are recorded with the TPC of the CERES experiment at CERN-SPS. The TPC covers the polar angle range $8^\circ < \theta < 15^\circ$, corresponding to about half a unit in pseudorapidity close to mid-rapidity.

1.1. Fluctuations of the mean transverse momentum

Fluctuations of the event-by-event mean transverse momentum $M_{pt,j}$ are composed of statistical fluctuations arising from the finite number of tracks per event, and a possible non-statistical (dynamical) contribution. The mean transverse momentum $M_{pt,j}$ of event $j$ with $N_j$ charged particles is defined as

$$M_{pt,j} = \frac{\sum_{i=1}^{N_j} p_{t,i}}{N_j}.$$ 

As a measure for event-by-event fluctuations, we employ the quantity $\Sigma_{pt}$ [5, 6] which is dimensionless and specifies the dynamical contribution to event-by-event $M_{pt}$ fluctuations in fractions of the inclusive mean transverse momentum $\overline{p_t}$. In the case of independent particle emission from a single parent distribution, $\Sigma_{pt}$ is zero.

The finite two-track separation of the TPC leads to a suppression of particle pairs with small momentum difference and consequently to a slight anti-correlation of particles in momentum space. In the case of the CERES-TPC, the effect on $\Sigma_{pt}$ is negligible [6], hence no correction has been applied. Positive correlations may arise due to quantum statistics, flow, jets, and other physics effects which have also not been corrected for.

In Fig. 1 (left) the results for $\Sigma_{pt}$ in minimum bias Pb-Au collisions at 40 and 158 A GeV/c are shown as function of $\langle N_{part} \rangle$. Also shown are results from an analysis [6] of central data sets at 40, 80, and 158 A GeV/c. At all beam energies, a significant centrality dependence of $\Sigma_{pt}$ is observed. The magnitude of the fluctuations does not depend on beam energies. In the most central events, $\Sigma_{pt}$ is about 1% of $\overline{p_t}$, consistent with previously reported results from SPS and RHIC [6, 7].

As a reference, we employ an extrapolation from p-p data. At ISR, event-by-event fluctuations of $M_{pt}$ have been measured in p-p collisions at $\sqrt{s}$ between 30.8 and 63 GeV [8]. For $\Sigma_{pp}^{pt}$, a value of 12% was found, with no significant dependence on beam energy. Implying that particle production at SPS is approximately proportional to $N_{part}$, fluctuations may scale with the number $\langle N_{part} \rangle$ of participating nucleons:

$$\Sigma_{pt}^{AA} = \Sigma_{pt}^{pp} (\langle N_{part} \rangle / 2)^{-1/2}.$$ 

As demonstrated in Fig. 1, the data agree with this extrapolation for very peripheral and central events. In contrast, a pronounced deviation is observed in semi-central events. In the right panel of Fig. 1, the product $\langle N_{part} \rangle \Sigma_{pt}^2$ is plotted as function of $\langle N_{part} \rangle$. In this representation, the p-p extrapolation becomes a constant, while the data exhibit a broad maximum around $N_{part} = 120$. This observation is in qualitative agreement with previous findings at SPS and RHIC [7, 9, 10, 11].
Non-statistical $M_{pt}$ fluctuations may be caused by momentum space correlations which arise due to resonance decays. Moreover, the correlation strength is expected to increase with the average transverse momentum of the decaying resonances. We have therefore performed a comparison of our results at 158 AGeV/$c$ to the cascade models RQMD and UrQMD. The UrQMD model does not describe the observed increase of $\langle p_T \rangle$ with centrality, as demonstrated in Fig.2 (right). Also, neither the magnitude nor the centrality dependence of the $M_{pt}$ fluctuations can be reproduced by UrQMD (Fig.2 left). In contrast, RQMD gives a rather good description of $\langle p_T \rangle$ and of the observed centrality dependence of $M_{pt}$ fluctuations. This indicates that resonance decay kinematics combined with the centrality dependent increase of $p_T$ may give an important contribution to $M_{pt}$ fluctuations. Further studies are needed, in particular regarding the failure of UrQMD.

1.2. Fluctuations of net charge

As a measure for fluctuations of the net electric charge $Q = N_+ - N_-$ we evaluate the expression $\nu_{+} = \langle \left( \frac{N_+}{(N_+ + N_-)} - \frac{N_-}{(N_+ + N_-)} \right)^2 \rangle$ and its statistical limit $\nu_{stat} = \left( \frac{1}{(N_+ + N_-)} \right)$ [12]. Fig.3 shows the centrality dependence of $\nu_{dyn} = \nu_{+} - \nu_{stat}$ multiplied by the mean multiplicity $\langle N \rangle$ of accepted particles at different beam energies. The results at 40 AGeV/$c$ are consistent with the expected contribution from global charge conservation (GCC). With increasing beam energy $\langle N \rangle \cdot \nu_{dyn}$ decreases, indicating an increased correlation between positive and negative particles. At 158 AGeV/$c$, we note a decrease of $\langle N \rangle \nu_{dyn}$ in peripheral collisions which is connected to the narrowing of the charge balance function in central collisions at SPS and at RHIC [7,12,13].

In Fig.4 is shown the beam energy dependence of $\nu_{dyn}$ in central collisions, corrected for the contribution from GCC. The result at top SPS energy is very similar to measurements
Figure 3. The measure $\langle N \rangle \cdot \nu_{\text{dyn}}$ as function of centrality at different energies. Also shown is the GCC contribution.

Figure 4. Beam energy dependence of $\nu_{\text{dyn}}$ after GCC correction.

at RHIC \cite{7, 14, 15}. The good agreement of RQMD and URQMD with the data indicates that the kinematics of resonance decays combined with the finite acceptance of the experiment may be sufficient to account for the observed charge fluctuations. At all energies, the data exceed by far the expectation from an equilibrated QGP of $\langle N \rangle \nu_{\text{dyn}} \approx -3.5$. It was, however, pointed out that in the framework of a constituent quark coalescence model without gluons, the expected net charge fluctuations as well as the evolution of the balance function are compatible with the data \cite{16}.

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