Charge and Isospin Fluctuations in High Energy pp-Collisions

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Charge and isospin event-by-event fluctuations in high-energy pp-collisions are predicted within the Unitary Eikonal Model, in particular the fluctuation patterns of the ratios of charged-to-charged and neutral-to-charged pions. These fluctuations are found to be sensitive to the presence of unstable resonances, such as $\rho$ and $\omega$ mesons. We predict that the charge-fluctuation observable $D_{UEM}$ should be restricted to the interval $8/3 \leq D_{UEM} \leq 4$ depending on the $\rho/\pi$ production ratio. Also, the isospin fluctuations of the DCC-type of the ratio of neutral-to-charged pions are suppressed if pions are produced together with $\rho$ mesons.

1 Introduction

In a single central ultrarelativistic collisions at RHIC and LHC more then 2400 hadrons are created \cite{1}, presenting remarkable opportunity to study event-by-event fluctuations of various hadronic observables. Such single event analysis with large statistics may reveal new physical phenomena usually hidden when averages over a large statistical sample of events are made \cite{2}. Recently, the study of event-by-event fluctuations of charged particles in high-energy pp and heavy-ion collisions has gained a considerable attention \cite{3, 4, 5, 6, 7}. The idea was to find an adequate measure that can differentiate a quark-gluon plasma (QGP) from a hadron gas (HG). So far, no consideration has been given to the fluctuations generated by the phase transition (PT) itself \cite{8}.

The number of particles produced in relativistic pp and heavy-ion collisions can differ dramatically from collision to collision due to the variation of impact parameter (centrality dependence), energy deposition (leading particle effect), and other dynamical effects \cite{9}. The fluctuations can also be influenced by novel phenomena such as the formation of disoriented chiral condensates (DCCs) \cite{10, 11, 18, 19, 20, 21, 22, 23} in consequence of the transient restoration of chiral symmetry. It is generally accepted that much larger
fluctuations of the neutral-to-charged pion ratio than expected from Poisson-statistics could be a sign of the DCC formation. However, such fluctuations are possible even without invoking the DCC formation if, for example, pions are produced semiclassically and constrained by global conservation of isospin [12, 13, 14, 15, 16]. In this paper, we present results of an event-by-event analysis of charged-charged and neutral-charged pion fluctuations as a function of the $\rho/\pi$ production ratio in pp-collisions. Our study of these fluctuations is performed within the Unitary Eikonal Model (UEM) [24, 27].

2 Coherent production of $\pi$ and $\rho$-mesons

At high energies most of the pions are produced in the nearly baryon-free central region of the phase space. The energy available for their production is

$$E_{had} = \frac{1}{2} \sqrt{s} - E_{leading}$$

which at fixed total c.m. energy $\sqrt{s}$ varies from event-to-event. Within the UEM the N-pion contribution to the s-channel unitarity in the central region can be written as an integral over the relative impact parameter $b$ between two incident leading particles:

$$\sigma_N(s) = \frac{1}{4s^2} \int d^2b \prod_{i=1}^N dq_i | T_N(s, b; q_1 \ldots q_N) |^2,$$  (2)

where $dq = d^2q_ydy/(2\pi)^3$. If the isospin of the incoming (outgoing) leading particle-system is $II_3$ ($I'I'_3$), then the N-pion production amplitude becomes cite24

$$iT_N(s, b; q_1 \ldots q_N) = 2s(I'I'_3; q_1 \ldots q_N | \hat{S}(s, b) | II_3),$$

where $\hat{S}(s, b)$ denotes the $\hat{S}$- matrix in the isospace of the leading particles.

The coherent emission of pions or clusters of pions, such as $\rho$ and $\omega$ mesons, in b-space of leading particles is described by the factorized form of the scattering amplitude, $T_N$. In that case the $\hat{S}(s, b)$-matrix has the following generic form:

$$\hat{S}(s, b) = \int d^2n_0 | n) \hat{D}(s, b) | n |,$$  (4)

where $| n )$ represents the isospin-state vector of the two-leading-particle system. The quantity $\hat{D}(s, b)$ is the unitary coherent-state displacement operator defined in our case as

$$D(s, b) = \exp[ a^\dagger(s, b) - a(s, b) ]$$

with

$$a^\dagger(s, b) = \sum_{c=\pi,\rho} \int dq J_c(s, b; q) n a^\dagger_c(q).$$  (6)
where, $J_c$ denotes a classical source function of the cluster $c$. The cluster decays into pions outside the region of strong interactions (i.e. the final-state interaction between pions is neglected).

The isospin $(I', I'_3')$ of the outgoing leading particle system varies from event-to-event. If the probabilities $\omega_{I', I'_3'}$ of producing $(I', I'_3')$ states are known, we can sum over all $(I' I'_3)$ to obtain a probability distribution of producing $N_+, N_-$ and $N_0$ pions from a given initial isospin state:

$$P_{II_3}(N_+N_-N_0 \mid N)C_{II_3}(N) = \sum_{I'_I, I'_3} \omega_{I', I'_3} \int d^2bdq_1dq_2 \ldots dq_N | \langle I' I'_3' , N_+ N_- N_0 \mid \hat{S}(s, b) \mid II_3 \rangle |^2 \quad (7)$$

where

$$N = N_+ + N_- + N_0$$
$$N_+ = n_{\pi^+} + n_{\rho^+} + n_{\rho^0}$$
$$N_- = n_{\pi^-} + n_{\rho^-} + n_{\rho^0}$$
$$N_0 = n_{\pi^0} + n_{\rho^+} + n_{\rho^-}$$  \hspace{1cm} (8)$$

and $C_{II_3}(N)$ is the corresponding normalization factor. This is now our basic equation for calculating various pion-multiplicity distributions, pion-multiplicities, and pion-correlations between definite charge combinations. In the following, we consider fluctuations of the $\pi^+/\pi^-$ and $\pi^0/N$ ratios in pp-collisions, $(I = I_3 = 1)$.

### 3 Charge and isospin fluctuations

A suitable measure of the charge fluctuations was suggested in [3]. It is related to the fluctuation of the ratio $R_{ch} = N_+/N_-$ and the observable to be studied is

$$D \equiv \langle N_{ch} \rangle < \delta R_{ch}^2 > = 4 \frac{< \delta Q^2 >}{< N_{ch} >} \quad (9)$$

where $N_{ch} = N_+ + N_-$, $Q = N_+ - N_-$ and $< \delta Q^2 > = < Q^2 > - < Q >^2$.

Our prediction of the $D$ quantity within the UEM, when both $\pi$ and $\rho$ mesons are produced is

$$D_{UEM} = \frac{8}{2 + \frac{n_{\pi^0}}{n_{\pi^+} + n_{\rho^+}}} \quad (10)$$

where $\pi_{\pi} = \int dq \mid J_{\pi}(q) \mid ^2$ denotes the average number of directly produced pions, and similarly $\pi_{\rho}$ denotes the average number of $\rho$ mesons which decay into two short-range correlated pions. The total number of emitted pions is
\[ N = \pi_\pi + 2\pi_\rho. \]  
\[ (11) \]

It was argued \cite{3} that the value of \( D \) may be used to distinguish the hadron gas (\( D_{\pi - \text{gas}} \approx 4 \)) from the quark-gluon plasma (\( D_{\text{QGP}} \approx 3/4 \)). It is expected that \( D_{\pi - \text{gas}} \approx 3 \) if appropriate corrections for resonance production are taken into account \cite{28}.

The UEM predicts \( D_{UEM} = 4 \) if \( n_\rho = 0 \). In that case the pion production is restricted only by the global conservation of isospin. However, if \( n_\pi = 0 \) the UEM predicts \( D_{UEM} = 8/3 \). This means that \( D \) is restricted to the interval \[ 8/3 \leq D_{UEM} \leq 4. \]

The preliminary results from CERES, NA49, and STAR collaboration \cite{29, 30, 31}, however, indicate that the measured value of \( D \) is close to that predicted for hadron gas and differs noticeably from that expected for QGP. This finding is somewhat disturbing since no effect of resonance production is visible in the fluctuations.

The formation of DCC in pp-collisions is expected to lead to different types of isospin fluctuations \cite{18, 19, 20, 21, 22}. Since pions formed in the DCC are essentially classical and form a quantum superposition of coherent states with different orientation in isospin space, large event-by-event fluctuations in the ratio \( R_0 = N_0/N \) are expected. The probability distribution of \( R_0 \) inside the DCC domain is \cite{15, 18, 19, 21}
\[ P_{DCC}(R_0) = \frac{1}{2\sqrt{R_0}}. \]  
\[ (12) \]

There are a variety of proposed mechanisms other than DCC formation which can also lead to the distribution \( P_{DCC}(R_0) \) \cite{23, 24, 25, 26}. The distribution \( P_{DCC}(R_0) \) is different from the generic binomial-distribution expected in normal events which assumes equal probability for production of \( \pi_+ \), \( \pi_- \) and \( \pi_0 \) pions.

Following the approach of our earlier papers \cite{24, 27}, we have calculated the probability distribution function, \( P^{\pi \rho}(N_0 \mid N) \) for producing \( N_0 \) neutral pions. For large \( N \) and \( N_0 \) such that \( R_0 \) is fixed, we find that only \( NP^{\pi}(N_0 \mid N) \) is of the form \( \sqrt{N/N_0} \) which resembles the DCC-type fluctuations and is typical for coherent pion production.

### 4 Conclusion

Our general conclusion is that within the UEM the large charge and isospin fluctuations depend strongly on the value of the \( \rho/\pi \) production ratio which fluctuate from event to event. Recent estimate of the \( \rho/\pi \) production ratio at accelerator energies, is \( \pi_\rho = 0.10\pi_\pi \) \cite{3}.

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