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EVENT-BY-EVENT FLUCTUATIONS IN HEAVY ION COLLISIONS*

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We discuss the physics underlying event-by-event fluctuations in relativistic heavy ion collisions. We will argue that the fluctuations of the ratio of positively over negatively charged particles may serve as a unique signature for the Quark Gluon Plasma.

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1. Introduction

Any physical quantity measured in experiment is subject to fluctuations. In general, these fluctuations depend on the properties of the system under study (in the case at hand, on the properties of a fireball created in a heavy ion collision) and may contain important information about the system.

The original motivation for Event-by-Event (E-by-E) studies in ultra relativistic heavy ion collisions has been to find indications for distinct event classes. In particular it was hoped that one would find events which would carry the signature of the Quark Gluon Plasma (QGP). First pioneering experiments in this direction have been carried out by the NA49 collaboration [1]. They analyzed the E-by-E fluctuations of the mean transverse momentum as well as the kaon to pion ratio. Both observables, however, did not show any indication for two or more distinct event classes. Moreover, the observed fluctuations in both cases were consistent with pure statistical fluctuations.

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On the theoretical side, the subject of E-by-E fluctuations has recently gained considerable interest. Several methods to distinguish between statistical and dynamic fluctuations have been devised [2, 3]. Furthermore, the influence of hadronic resonances and possible phase transitions has been investigated [4–8]. All these theoretical considerations assume that the observed fluctuations will be Gaussian and thus the physics information will be in the width of the Gaussian, which is controlled by 2-particle correlations [9].

2. Event-by-event fluctuations

Fluctuations have contributions of different nature. Besides the statistical fluctuations due to a finite number of particles in case of heavy ion collisions, there are also fluctuations of the volume. Both these fluctuations are trivial and add to the dynamical fluctuations which carry the real information about the properties of the system. The dynamical fluctuations are controlled by the appropriate susceptibilities, which are the second derivative of the free energy with respect to the appropriate conjugate variable. For example the fluctuations of the charge are given by

$$\left\langle (\delta Q)^2 \right\rangle = -T \frac{\partial^2 F}{\partial \mu_Q^2} = -VT\chi_Q \,, \tag{1}$$

where μ_Q is the charge chemical potential, T the temperature and V the volume of the system. χ_Q is the charge susceptibility. It is interesting to note that the very same susceptibility also controls the response of the system to an external electric field. The properties of a macroscopic system are studied by investigating its response, *i.e.* its susceptibility, to external forces. This is, of course, impossible for the mesoscopic systems created in a heavy ion collision. However, the same property can also be accessed via fluctuations.

Since we will mostly concentrate on the charge susceptibility, let us point out that it is directly related to the electric mass, which is given by the zero momentum limit of the static current–current correlation function [10] $\Pi_{00}(\omega = 0, \vec{k} \to 0)$.

$$\left\langle (\delta Q)^2 \right\rangle = -VT\Pi_{00}(\omega = 0, \vec{k} \to 0)\,. \tag{2}$$

This object has been evaluated in Lattice QCD [11, 12] as well as in effective hadronic models (see below and [10, 13, 15]). Note also that this is the same current–current correlation function, which controls dilepton and photon production in heavy ion collisions [16, 17].

2.1. Fluctuations of particle ratios

In order to avoid volume fluctuations one needs to study observables which are independent of the volume of the system. Among others the ratio of particle multiplicities will have this property. This is certainly true if one looks at similar particles such as π^+ and π^-, where the freeze out volumes are expected to be the same. Some residual volume fluctuations may be present if one considers ratios of particles with different quantum numbers such as the K/π ratio, but they still should be small. Let us define the particle ratio R_{12} of two particle species N_1 and N_2

$$R_{12} = \frac{N_1}{N_2} \,. \tag{3}$$

The fluctuations of this ratio are then given by [2, 5, 6]

$$\frac{(\delta R_{12})^2}{\langle R_{12} \rangle^2} = \left(\frac{\langle (\delta N_1)^2 \rangle}{\langle N_1 \rangle^2} + \frac{\langle (\delta N_2)^2 \rangle}{\langle N_2 \rangle^2} \frac{\langle \delta N_1 \delta N_2 \rangle}{\langle N_1 \rangle \langle N_2 \rangle} \right) . \tag{4}$$

The last term in Eq. (4) takes into account correlations between the particles of type 1 and type 2. This term will be important if both particle types originate from the decay of one and the same resonance. For example, in case of the π^+/π^-ratio, the ρ_0, ω *etc.* contribute to these correlations. Also this term is responsible for canceling out all volume fluctuations [5].

Let us note that the effect of the correlations introduced by the resonances should be most visible when $\langle N_1 \rangle \simeq \langle N_2 \rangle$. On the other hand, when $\langle N_2 \rangle \gg \langle N_1 \rangle$, as in the K/π ratio, the fluctuations are dominated by the less abundant particle type and the resonances feeding into it. The correlations are then very hard to extract. In [5] it was shown that in case of the K/π ratio resonances and quantum statistics give rise to deviations from the statistical value of at most 2 %, in agreement with experiment [1].

As pointed out in [5] the measurement of particle ratio fluctuations can provide important information about the abundance of resonances at chemical freeze out, and thus provides a crucial test for the picture emerging from the systematics of single particle yields [18]. In particular the fluctuations of the π^+/π^- ratio should be reduced by about 30 % as compared to pure statistics due to the presence of hadronic resonances with decay channels into a π^+–π^- pair at chemical freeze out. About 50 % of the correlations originate from the decay of the ρ_0 and the ω mesons. Thus the fluctuations provide a complementary measurement to the dileptons.

3. Fluctuations and correlations

As already pointed out in the previous section, the fluctuations are sensitive to correlations among the particles of concern. In case of charge fluctuations which we will discuss below, the relation between the charge fluctuations and the 2-particle correlation function C_2 for a system of unit charged particles is given by [20, 23]

$$\left\langle (\delta Q)^2 \right\rangle = C_2(+,+) + C_2(-,-) - 2C_2(+,-) + \rho_1(+) + \rho_1(-)\,, \tag{5}$$

where the correlation function C_2 is defined as

$$C_2(\pm,\pm) = \int\limits_{\Delta y} dy_{1,\pm} dy_{2,\pm} \frac{d^2N}{dy_{1,\pm}dy_{2,\pm}} - \frac{dN}{dy_{1,\pm}} \frac{dN}{dy_{2,\pm}}\,. \tag{6}$$

The single particle density $\rho_1(\pm)$ is defined as

$$\rho_1(\pm) = \int\limits_{\Delta y} dy_{\pm} \frac{dN}{dy_{\pm}}\,. \tag{7}$$

Here Δy denotes the range of acceptance *e.g.* in rapidity, over which the particles are measured. This expression can easily be extended to a system of particles with charge states different from unity [20].

Thus, an alternative way to access charge fluctuations is the measurement of the one and two particle densities. However, in this case the effect of volume fluctuations still needs to be removed. This can be achieved by defining appropriate modifications of the correlation functions as discussed in [21]. Also the so-called balance functions introduced in Ref. [22] can be viewed as another way of analyzing these correlation functions and a relation between the ratio fluctuations discussed here has been made in [23].

4. Charge fluctuations

Measuring the charge fluctuations or more precisely the charge fluctuations per unit degree of freedom of the system created in a heavy ion collision would tell us immediately if we have created a system of quarks and gluons [24] (see also [25]). The point is that in the QGP phase, the unit of charge is 1/3 while in the hadronic phase, the unit of charge is 1. The net charge, of course, does not depend on such subtleties, but the fluctuation in the net charge depends on the *squares* of the charges and hence is strongly dependent on which phase it originates from. However, as discussed in the previous section, measuring the charge fluctuation itself is plagued by systematic uncertainties such as volume fluctuations, which can be avoided if one considers ratio fluctuations. The task is then to find a suitable ratio whose fluctuation is easy to measure and simply related to the net charge fluctuation.

As shown in [24] the fluctuation of the ratio $R = N_+/N_-$ serves this purpose and the observable to investigate is

$$D \equiv \langle N_{\rm ch}\rangle \left\langle \delta R^2 \right\rangle = 4\frac{\left\langle \delta Q^2 \right\rangle}{\langle N_{\rm ch}\rangle}\,, \tag{8}$$

which provides a measure of the charge fluctuations per unit entropy.

In order to see how this observable differs between a hadronic system and a QGP let us compare the value for D in a pion gas and in a simple model of free quarks and gluons. Ignoring small corrections due to quantum statistics a simple calculation gives for a pion gas

$$D_{\pi-{\rm gas}} \approx 4\,. \tag{9}$$

In the presence of resonances, this value gets reduced by about 30 % due to the correlations introduced by the resonances, as discussed in Section 2.1.

For a thermal system of free quarks and gluons we have in the absence of correlations and ignoring small correction due to quantum statistics [24]

$$D_{\rm QGP} \simeq 3/4\,. \tag{10}$$

Actually the charge fluctuations $\left\langle (\delta Q)^2 \right\rangle$ have been evaluated in lattice QCD along with the entropy density [11]. Using these results one finds

$$D_{\rm Lattice-QCD} \simeq 1 - 1.5\,, \tag{11}$$

where the uncertainty results from the uncertainty of relating the entropy to the number of charged particles in the final state. Actually the most recent lattice result [12] for the charge fluctuations, which was obtained in the quenched approximation, is somewhat lower then the result of [11].

But even using the larger value of $D = 1.5$ for the Quark Gluon Plasma, there is still a factor of 2 difference between a hadronic gas and the QGP, which should be measurable in experiment.

The key question, of course, is how can these reduced fluctuations survive the hadronic phase. This has been addressed in [24] and in more detail in [26]. The essential point why this signal should survive is that the charge is conserved which fact leads to a very slow relaxation of the initial fluctuations.

Finally, one needs to take into account that the total charge of the system is conserved and thus does not fluctuate. This has been addressed in [27] and a corrected observable $\tilde{D}$ has been derived.

In Fig. 1 the importance of these corrections, in particular the charge conservation correction is demonstrated. There we compare the uncorrected observable D with the corrected observable $\tilde{D}$ as a function of the width of the rapidity window based on a URQMD [28] simulation. The effect of the charge conservation is clearly visible. With increasing rapidity window the charge fluctuation are suppressed. Once the charge conservation corrections are applied, the value for $\tilde{D}$ remains constant at the value for a hadron gas of $\tilde{D} \simeq 3$. This is to be expected for the URQMD model, which is of hadronic nature and does not have quark–gluon degrees of freedom.

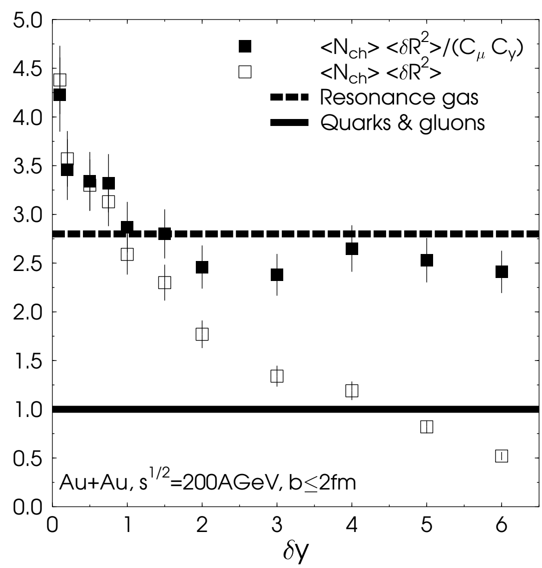

Fig. 1. Charge fluctuations as a function of the size of the rapidity window.

Also for small Δy the value is $\tilde{D} \simeq 4$ before it drops to $\tilde{D} \simeq 3$ for $\Delta y > 1.5$. This effect, which was already predicted in [5], is simply due to the fact that the correlation introduced by the resonances gets lost if the acceptance window becomes too small.

Recently an interesting comparison [29] between predictions for $\tilde{D}$ by different event generators has been made. The authors find that indeed a parton cascade model leads to small values for $\tilde{D}$ provided hadronic rescattering is turned off. This is in line with the predictions of [24]. However, the authors also report substantial corrections due to hadronic rescattering, which appear quite large given the arguments presented in [24,26]. But none of the event generators gave result larger than $\tilde{D} \simeq 3$.

5. Effects of particle interactions

So far we have discussed the fluctuations of free, noninteracting particles only. Of course, by considering resonances as well, some of the interactions are taken into account [14,15]. To address the effect of interactions we have calculated the electromagnetic current–current correlator Π^{00} as well as the entropy to the first order of the interaction for a system of pions interacting via ρ-meson exchange. For simplicity, we have assumed that the ρ-mass is infinite, which leads to point-like interaction among the pions, and is governed by the following effective Lagrangian

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}^2 - m_\pi^2|\phi|^2 + \frac{1}{2}\Big((\partial_\mu\phi_0)^2 - m_\pi^2\phi_0^2\Big) + |D_\mu\phi|^2 - \frac{g^2}{2m_\rho^2}\Big(\phi^\star \overleftrightarrow{D}_\mu \phi\Big)^2 + \frac{g^2}{m_\rho^2}\left(\phi_0 D_\mu\phi - \phi\partial_\mu\phi_0\right)\left(\phi_0\left(D^\mu\phi\right)^\star - \phi^\star\partial^\mu\phi_0\right) . \quad (12)$$

The two-loop diagrams for the corrections to Π^{00} are shown in Fig. 2.

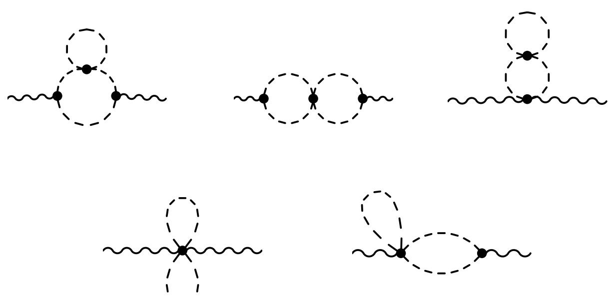

Fig. 2. Two-loop diagrams contributing to Π^{00} to order g^2.

The ratio $\Pi^{00}(T)/S(T)$ for the entropy $S(T)$ and the self energy $\Pi^{00}(T)$ is shown in Fig. 3.

The effect of the interactions is to *increase* the charge fluctuations per entropy. At temperature of $\sim 140\,\mathrm{MeV}$ the corrections are quite large, in line with the findings of [15], where chiral perturbation theory has been used. However, in the same paper [15] the effect of the charge fluctuations have also been evaluated in a virial expansion, leading to much smaller (but still positive) corrections. Therefore, it appears that at least dynamical ρ-mesons need to be taken into account before any quantitative conclusion can be made.

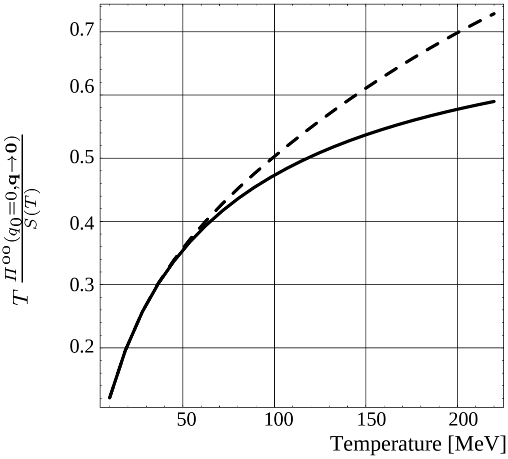

Fig. 3. Ratio of charge fluctuations over entropy for free particles (full line) and with interactions (dashed line).

6. Conclusions

We have discussed event-by-event fluctuations in heavy ion collisions. These fluctuations may provide useful information about the properties of the matter created in these collisions, as long as the trivial volume fluctuations, inherent to heavy ion collisions, can be removed. We have argued that the fluctuations of particle ratios is not affected by volume fluctuations.

In particular the fluctuations of the ratio of positively over negatively charged particles measures the charge fluctuation per degree of freedom. Due to the fractional charge of the quarks, these are smaller in a QGP than in a hadronic system.

A measurement of our observable $\tilde{D} \simeq 1$ would provide strong evidence for the existence of a QGP in these collisions. A measurement of $\tilde{D} \simeq 3$ on the other hand does not rule out the creation of a QGP. There are a number of caveats (see [24]), which could destroy the signal, such as unexpected large rapidity shifts during hadronization.

At this workshop first preliminary results for the observable $\tilde{D}$ have been reported by the STAR, CERES and NA49 collaboration [30]. They all find a value which is consistent with $\tilde{D} \simeq 4$. This finding is somewhat surprising since not even the effect of resonances seems to be visible in the fluctuations. At the same time STAR reports that the measured number of K^* mesons is well in line with the expectations of the thermal model [19, 31]. So where are the correlations? Could it be that the interactions among the resonances are indeed so strong that they entirely compensate the reduction of $\tilde{D}$ due to resonances? Also, as already mentioned, in the study presented in [29] *none* of the event generators finds a value of $\tilde{D} > 3$ for rapidity windows $\Delta y > 2$. This certainly needs further investigation.

Finally, let us note that fluctuations of the baryon number in principle can also be utilized since in the QGP quarks carry fractional baryon number [25]. This, however, would require the measurement of neutrons on an event by event basis.

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