Can Recent Charge Fluctuation Calculations Be a Reliable Signal for a QGP at RHIC?

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Abstract

The recent papers of Jeon and Koch[1] and Asakawa, Heinz and Muller[2] propose that the event by event fluctuations of the ratio of the positively charged and negatively charged pions could provide a distinct signal for a QGP at RHIC/LHC due to differences in those from the QGP phase, and the Hadron Gas Phase. In this paper we point out that aside from the questionability of the many assumptions in the treatment used, even following their approach there are other effects not considered, e.g. color charge fluctuations which we show could signifiantly or completely wash out the proposed signal. Therefore lack of observation of these charge flucuation signals cannot lead one to conclude that a QGP is not formed at RHIC. A general discussion of experimental requirements for observation of such signals (if they exist) and how to interpret them is included.

1 Introduction

The recent papers of Jeon and Koch[1] and Asakawa, Heinz, and Muller[2] argue that the event by event fluctuations of the ratio of the positively charged and negatively charged pions provide a distinct signal for Quark-Gluon Plasma at RHIC and eventually at LHC. Since the size of the average fluctuations of electric charge differ widely in the confined and deconfined phases, it is possible that these initial state fluctuations survive until freezeout and thus appear differently in the final state for pions arising from a QGP and those from normally confined processes.

This is a complex process and thus their novel work involves many assumptions and approximations which one can question whether they lead to a reliable conclusion. However, a second perhaps more relevant question is following their approach, are there effects they have not considered which may significantly or even totally wash out the predicted signals? In this paper we point out that fluctuations in color and anti-color if taken into account may significantly or even more or less totally wash out the predicted effects.

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2 Calculation of Charge Fluctuations Following [1] and [2]

We now follow the arguments made in [1] and [2] and then consider the case with the addition of our arguments.

If as discussed one can assume that conditions are such that the expansion is too fast for local fluctuations to follow the mean thermodynamic evolution of the system, and concern ourselves with locally conserved quantities that show large differences in a hadron gas (HG), and a Quark-Gluon Plasma (QGP), the different fluctuations in these quantities may survive the freezout. If sub-volumes are considered which move rapidly away from one another, conditions which one expects, due to a strong differential flow pattern[3], and thus these fluctuations would reflect the phase, HG or QGP from which the pions came from. At RHIC, mesons dominate the hadronic particles, and the baryonic chemical potential μ is much less than the temperature. The final state hadrons are mostly pions, although approximately 30-50% of these pions are estimated to come from resonance decay in calculations in [[1] and [2] respectively.

Let us now consider charge fluctuations of pions in an HG compared to a QGP: Both [1] and [2] use ideal gases in equilibrium for their estimates. However, [1] also uses the lattice calculations of [4] to determine D as approximately 1 for a QGP, and [2] obtains a similar effect. Following [1] and [2] we will use the ideal gas approximation in our considerations. Take a phase space sub-volume which has N hadrons. Let us assume that we have only light quark mesons and meson resonances which decay. Jeon and Koch define a parameter $D =< N_{ch} >< \delta R^2 >$ which measures the mean charge multiplicity times the fluctuation of the ratio R, where

$$R = \frac{N_+}{N_-}. \tag{1}$$

N_+ and N_- are the positive and negative particle (pion) multiplicities The fluctuation of R is shown to be

$$< \delta R^2 >=< R^2 > - < R >^2 . \tag{2}$$

¿From [1], we have

$$D =< N_{ch} >< \delta R^2 > . \tag{3}$$

where

$$< N_{ch} >= N_+ + N_-. \tag{4}$$

The net charge Q is

$$Q = N_+ - N_-. \tag{5}$$

Reference [1] also shows that $< \delta Q^2 >$ is purely Poisson, using thermal distributions and disregarding correlations, is approximately for a pion gas equal to $< N_{ch} >$, thus we have

$$< \delta Q^2 > \approx < N_{ch} > \tag{6}$$

Reference 1 then shows that D becomes

$$D \approx 4 \frac{< \delta Q^2 >}{N_{ch}}, \tag{7}$$

thus

$$D \approx 4. \tag{8}$$

The value of D for that coming from a thermal light quark meson and meson resonance system, the resonances of which decay into charged pions (for example the neutral ρ which decays into a positive and negative pion), reduces the observed D to

$$D \approx 3 \text{ from [1], and perhaps as low as 2 from [2].} \tag{9}$$

Therefore, D is reduced because there are some neutral meson resonaces (ρ, etc.) which decay into π^+ and π^-, thus decreasing the fluctuations. Hence for a thermal light quark resonace meson system

$$D = 4 \frac{< \delta Q^2 >}{< N_{\rm meson} >} = \approx 3 - 2 \tag{10}$$

as estimated by references[1] and [2] respectively.

In references [1] and [2] for a QGP they both estimate D approximately 1. Thus the D signal for mesons decreases by a factor of 2-3 for those pions which come from a QGP.

3 Taking into Account Color Fluctuations

In the calculation that follows we will take into account color charge $< \delta Q^2_{\rm color} >$ fluctuations and, anti-color charge $< \delta Q^2_{\rm anti-color} >$ fluctuations, since it appears there is no reason these fluctuations would not occur in the sub-volume before passing from the QGP to the meson system. At this stage of the system the color charge degree of freedom is active and important. These color and anti-color fluctuations should be frozen out just like the charge fluctuations (as [1] and [2] have done for electric charge flucuations). Their reduction is not expected to be local since, for example, if it's done by the movement of quarks and anti-quarks in and out of the sub-volume in order to eliminate the color and anti-color charge fluctuations. In our subsequent treatment of color charge fluctuations, and the fragmentation process, we will find the D_{QGP} can become approximately equal to the D_{HG} if the fragmentation size is large enough to mix the sub-volumes. Thus the signal for the QGP could be washed out.

As we have stated, this problem is a difficult and very complex one, and we do not claim to have solved it. However the questions regarding color charge fluctuations, etc. that we are raising should be addressed, and a critical evaluation of the reliability of fluctuation calculations made.

4 A Model of Charge Fluctuations Including Color Charge Fluctuations and Hadronization

The following model is not claimed to be unique or even a reasonable representation of the real physical situation. Its purpose is merely to show that color charge fluctuations could drastically affect the charge fluctuation calculations of [1] and [2]. In addition we beleive the physical situation can be much more complex than any of the models treating it.

Let us consider the quark gluon plasma, following the approach of [1] and [2]. The inital number of quarks, anti-quarks, and gluons is equal to the number of mesons after hadronization, assuming conservation of entropy[1, 2]. For a given sub-volume $< \delta Q^2 >$ is fixed and will not change in the final hadronization of the quark qluon plasma. Thus one would expect a $< \delta Q^2 >$ for the QGP. Reference [1] calculated D to be a factor of approximately 3 smaller than for a hadron gas, while Ref.[2] also claimed a similar though smaller (factor of ≈ 2) result using the same conserved $< \delta Q^2 >$ when the QGP hadronizes.

If we redefine equations (7 and 10), it becomes easier to keep track of the steps in hadronization in the system. We generalize D as

$$D = 4\frac{< \delta Q^2 >}{< N_{\text{particles}} >} \tag{11}$$

With this new definition of D, entropy conservation which is assumed will not mean that D stays the same as in Ref.[1] which shows that for a QGP, D is approximately 1 and that $< \delta Q^2 > \approx \frac{1}{4} < N_{\text{particles}} >$ where $N_{\text{particles}}$ is the number of quarks, anti-quarks and gluons. Thus in moving from the QGP to the meson system $< \delta Q^2 >$ remains the same and the number of mesons are equal to the number of quarks, anti-quarks and gluons, therefore our generalized D is unchanged like the old D of reference [1].

We will now reconsider our classic meson light quark system. If we recalculate (10) using the quarks and anti-quarks which make up the mesons D becomes equal to 1.5, because $< \delta Q^2 >$ remained the same and $N_{\text{particles}}$ doubled.

In the hadronization process of making mesons the gluons in the QGP, which contain $\sim \frac{1}{2}$ of the degrees of freedom, in our model we will create quark and anti-quark pairs, which would increase the number of quarks and anti-quarks to double the total number. We believe that this is the final stage in which $< \delta Q^2 >$ is conserved in any hadronization process. Our new D has dropped by a factor two, but entropy has not changed. This is because there is a one to one mapping of the degrees of freedom from quark anit-quark color-singlet pairs to mesons. However additional quarks and anti-quarks have to be formed by the gluons in the fragmentation of the QGP. In the intial QGP before hadronization the quarks, anti-quarks and gluons are equal to the number of final mesons. The sub-volume also has color charge fluctuations $< \delta Q^2_{\rm color} >$ and $< \delta Q^2_{\rm anti-color} >$. At this stage the color charge degree of freedom is active and very important. In passing from QGP to the meson system these fluctuations get frozen out and become part of the process leading to the increased number of quarks and anti-quarks just before forming the mesons. In this way entropy is conserved through the hadronization process. The reduction of $< \delta Q^2_{\rm color} >$ and $< \delta Q^2_{\rm anti-color} >$ is achieved through gluon fragmentation into quark, anti-quarks and gluons. This fragmentation is not local because quarks and anti-quarks move in and out of the sub-volume in order to get rid of the color and anti-color charge fluctuations. When the gluons fragment and before the movement and rearrangement of color charge, the quarks and anti-quarks are expected to be approximately doubled. Since the $< \delta Q^2 >$ is the same as its value in the QGP, the value of D drops from ≈ 1.0 to approximately 0.5 because N is approximately equal to double the initial particles. However the movement of quarks and anti-quarks into and out of the sub-volume, which reduces the $< \delta Q^2_{\rm color} >$ and $< \delta Q^2_{\rm anti-color} >$ will increase the electric charge fluctuation. How effective the color charge fluctuations are at increasing $< \delta Q^2 >$ depends on the size of the gluon fragmentation region. We have studied how the size of gluon fragmentation increases the random mixing of quarks and antiquarks from zero size where color fluctuations are removed by soft gluon teleportation, to larger sizes where color singlets are formed by rearrangment. The maxium transfer of color fluctuation happens in our calculations at $3.5fm$ gluon fragmentation size (see Fig. 1), where the value of color fluctuations becomes equal to the value of charge fluctuations. At increasing fm beyond 3.5 the the transfer of color fluctuation remains approximately the same. Thus we get a half unit increase in D for the reduction of $< \delta Q^2_{\rm color} >$ and another half unit increase in D for $< \delta Q^2_{\rm anti-color} >$ reduction. This causes D to increase to the value of 1.5. The quarks and the anti-quarks form mesons and the value of D goes from ≈ 1.5 to ≈ 3.0, (see Fig .1) which is the value for a light quark resonance system.[2] Thus in this approach the value of D for a QGPis approximately equal to the same value as for pions which came from the Hadron Gas (i.e. there is no QGP signal). Underlying the above discussion are the assumptions that the make up of the meson system from a thermal and a QGP hadronization are very similar. This may not be the case for strange particles and baryons anti-baryons. It is also assumed that fragmentation of gluons producing quarks and anti quarks occurs, and that quarks and anti-quarks rearrange to take care of color. What if gluons only fragment into gluons and they rearange into color-singlet glueballs, then there would not be the random walk of some electric charge to participate in the elimination of color charge fluctuations. We feel that this would not happen if the masses of glueballs remain large like lattice gauge predictions for formation in the normal vacuum. This seems to be the case for Glueballs calculated on the lattice since the very striking evidence for at least one 2^{++} glueball[5] can only be explained by a 2^{++} glueball, while all alternative explanations over a period of almost two decades have been shown to be incorrect or not viable[6]. This 2^{++} glueball has the approximate mass of lattice guage calculations[7]. If on the other hand some new medium rescaling of the glueball mass occurred or for some other reason the gluons in the QGP formed mostly glueballs then in our treatment a reduction in charge fluctuations could occur.

[2] The next section (5) discusses the gluon fragmentation region size.

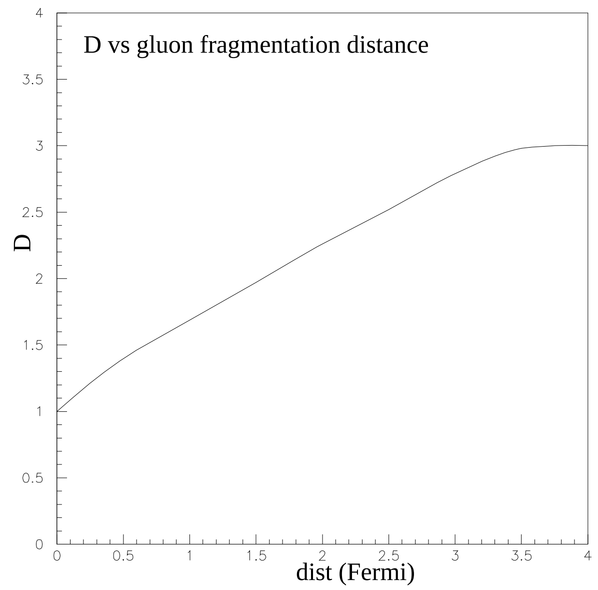

Figure 1: We plot D for a QGP as defined in the text (Eq. 7 or 11) for a sub-volume versus the gluon fragmentation size dist(fermi). The size is the separation distance between pairs of quarks created from gluons.

5 Experimental Considerations

It is clear that a measurement of charge fluctuations from a sub-volume of the final hadronic system is a important measurement. The experimental question is how can one make such a measurment? If the QGP would proceed through the formation of a plasma (spherical or not greatly longitudinally expanded) bubble as Van Hove had proposed, then even small infrequent suppresed local charge fluctuations would be isolated to a rapidity bump which would only spread out over two units. Within this signal one could possibly observe the charge fluctuation due to a QGP. However, if the bubble expands longitudinally, then the bubble could spread out to about six units in rapidity[8] and the local charge fluctuation would increase. For relativistic heavy ion collisions of ($\sqrt{s_{NN}} = 130$) Au on Au at RHIC, produced pions at mid-rapidity and lower transverse momentum (p_t) show a source size of a radius up to about six fm[8]. This means that inside a given sub-volume pions that are moving along the beam endup in different rapidity intervals. Thus at a given rapidity we see low p_t pions coming from different sub-volumes. Since the pions are a random sample of the sub-volume the charge fluctuation at a given rapidity would increase due to this kinematic mixing. For the quarks and gluons used to form the light meson system which was used to calculate charge fluctuations shown in Fig. 1, we gave each parton the kinematics such that the final pions coming from low p_t would see a six Fermi source which decreased in size as one increased the p_t. For p_t above 600 MeV/c the size became 2 Fermis. The slope of the pion m_t spectrum was 290 MeV. We then calculated D for mid-rapity for a bin of $\Delta Y = 1.0$ and $\Delta Y = 2.0$ (see Fig. 2). In Fig. 2 we show D as a function of gluon fragmentation size

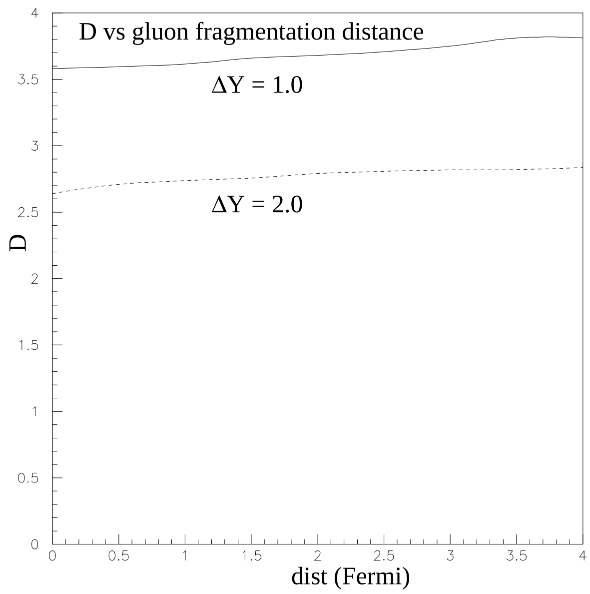

Figure 2: We plot D for a QGP as defined in the text (Eq. 11) for particles lying in a δY range versus the gluon fragmentation size dist(fermi). The size is the separation distance between pairs of quarks created from the gluons.

for each ΔY bin. Even though the charge fluctuation for each sub-volume decreases with smaller fragmentation size, the D is not changed much due to kinematic mixing. It is clear that the bigger the ΔY bin the smaller the D, and how D varies with ΔY is considerably complex and model dependent.

6 Finding Possible Charge Fluctuations: If They Exist

If one assumes suppressed charge fluctuations exists in some events containing sufficient amounts of QGP, we need a way to select those events and the rapidity intervals in which the plasma is contained. Large and universal QGP production, which considering the dynamics involved as discussed in a recent paper[9] is not in our opinion likely. Therefore some QGP selector (e.g. QGP "Bubbles" [9]), is necessary to select an appropriate set of events. Then if there are statistically significant reductions of charge fluctuations in that sample that would be a significant dicovery.

This discovery would be consistent with some present ideas of a QGP, however one could not conclude that this is a unique explanation of the effect due to the crudeness and incompleteness of the arquements made for it. In order to establish a QGP, numerous supporting additional evidence must accompany this signal. Furthermore, perhaps most importantly no other viable explanation of the data other than a QGP must exist.

COVERSELY THE LACK OF DISCOVERY OF REDUCED CHARGE FLUCTUA-

TIONS AT RHIC DOES NOT IMPLY THAT QGP IS NOT FORMED AT RHIC. THE OVERLY SIMPLIFIED AND INCOMPLETE CALCULATIONS WHICH PREDICT THIS CAN VERY EASILY BE MISLEADING IN REGARD TO THE ACTUAL PHYSICAL SITUATION. FURTHERMORE THE QGP SIGNALS (if they exist) MAY NOT HAVE BEEN STRONG ENOUGH TO HAVE BEEN ISOLATED AND OBSERVED BY THE METHODS USED.

7 Conclusions and Summary

In this paper we raised the question "Can Recent Charge Fluctuations Calculations Be A Reliable Signal For A QGP at RHIC?"

We pointed out that the approximations and simplifications used in [1] and [2] raises the question of their reliability in treating this complex process.

We then asked even following the methods of this simple treatment, what was left out which could change the conclusions? We pointed out that color charge flucuations, which were not even considered could possibly drastically change or even wash out the predicted effects. We used a simple model to evaluate these possible effects, We do not claim that any credence should be placed in our very simplistic model, or that it is even correct. Our purpose was merely to point out that color fluctuations and perhaps other effects should be carefully addressed.

We further pointed out that the lack of discovery of reduced charge fluctuations at RHIC does not imply that QGP is not formed at RHIC, since the overly simplified and incomplete calculations which predict this can easily be misleading in regard to the actual physical situation. Furthermore the QGP signals may not have been strong enough to have been isolated and observed by the methods used. On the other hand if reduced charge fluctuations are observed this would be an important observation. However, by itself this would not be conclusive evidence for its origin in a QGP, unless there is convincing other general strong supporting evidence, and perhaps most importantly no other viable explanation of the data.

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