Dileptons from $\eta_c$ in Nucleus-Nucleus collisions

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Abstract

Preliminary estimates suggest that excess dimuon production with invariant mass in the range 1.5 – 2.5 GeV in nucleus-nucleus collisions can be explained on the basis of $\eta_c$ production. This appears to be consistent with all the peripheral and central collision data with various nuclei such as S-U at 200 GeV/nucleon except for the central collision data on Pb-Pb at 158 GeV/nucleon. Some explanations based on glueball production for Pb-Pb data are discussed.

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Over the past decade many different experiments in Nucleus-Nucleus (A-A) collisions \cite{1} have consistently shown excess dilepton production with dimuon invariant mass in the range 1.5-2.5 GeV for \( \mu^+\mu^- \) pairs. These data sets were interpreted by appropriately scaling proton-nucleus (p-A) data. Essentially in all these data sets the dilepton sources are either Drell-Yan pairs or decays of \( J/\psi \) or \( D\bar{D} \). The bulk of the data appears to agree in general by consideration of these sources alone. However there is a significant departure between the observed dilepton pairs and the theoretical estimate based on the above sources, in the intermediate mass range (IMR) (i.e. \( \mu^+\mu^- \) invariant mass in the range 1.5-2.5 GeV).

In the literature there have been several attempts to explain this discrepancy. Some of these explanations are based on decrease in \( \rho \) meson mass due to thermal effects in \( e^+e^- \) data \cite{4}, D-rescattering \cite{2}, enhanced \( D\bar{D} \) production, in-flight \( \pi^+\pi^- \) decaying to \( e^+e^- \) \cite{3}, and so on. Many of these physical processes suggested as an explanation are interesting in their own right but in all of these the explanation for excess dileptons in the IMR is at best partial and generally tend to be relevant in a regime different from the IMR. Fireball hydrodynamics with adjustable parameters however seem to contribute in the IMR regime in Pb-Pb at 158 GeV/nucleon central collisions \cite{5}.

Present data for di-leptons from p-A and A-A collisions over the entire kinematic regime upto 5 GeV agrees with the conventional QCD explanation in terms of Drell-Yan process and vector mesons except for the IMR region mentioned above. The overall picture involving charm quarks \cite{6} is that when there is sufficient energy exchange in a collision, protons have non-negligible charm content (\( c\bar{c} \) pairs), and substantial high energy gluons which in turn can decay to \( c\bar{c} \) pairs. These \( c\bar{c} \) pairs occassionally form bound states such as \( J/\psi \) by emitting a soft gluon to maintain color balance, or can further polarize \( uu \) or \( dd \) from the surrounding medium to form \( D\bar{D} \) pairs. Although the present theoretical understanding cannot predict absolute numbers for these processes it is possible to check the consistency of this picture with various p-A and A-A data. By and large the data agrees with various quantitative checks.

This picture however, also suggests that other charm meson bound states such as \( \eta_c, \psi' \) and \( \chi'' \)'s are produced as well. The relative abundance of each of these mesons is expected to be constrained by their sizes. In particular the larger the size of the charm meson the less likely it is to get formed in the hadronic plasma \cite{6}. This expectation is clearly borne out by the data, viz. in any experimental setup \( J/\psi \) which is a 1S orbital state is produced about 100 times more than \( \psi' \) which is a 2S orbital state. Both these resonance peaks are clearly visible in the dimuon data.
In this paper we are concerned about the production of the $\eta_c$ meson. This is a 1S orbital state and is expected to have the same size as a $J/\psi$; furthermore it has almost the same mass. They differ only in their spin and hence it is expected that in any collision where $c\bar{c}$ quarks are produced these can form $\eta_c$ with about $1/3$ probability as $J/\psi$. In fact, any suppression mechanisms [7, 8] due to the hot hadronic medium will equally affect both the mesons. Consequently it is fair to expect that in any of the experimental setups the production cross sections of $J/\psi$ and $\eta_c$ are similar. The $\eta_c$’s once produced will typically decay into lighter hadrons, which makes the direct detection of $\eta_c$ virtually impossible. However there is a small (estimable) cross section for it to decay into $\gamma\mu^+\mu^-$ or $\gamma e^+e^-$. The relative decay probabilities of $\eta_c$ to $\gamma\mu^+\mu^-$ and that of $J/\psi$ to $\mu^+\mu^-$ is essentially determined by the electromagnetic interaction of the charm quark. The reason for this is clear from Fig. 1 which shows $J/\psi$ decay in Fig 1a and that of $\eta_c$ in Fig 1b where $\gamma^*$ in turn decays into a $\mu^+\mu^-$ pair. If we restrict ourselves to large invariant mass for the $\gamma^*$ ($> 1$ GeV in Fig1b), it is reasonable to expect the charm quark inside the loop to be almost free. In other words, if the $J/\psi$ spin dependent wave function is $\gamma\mu\phi$ and the $\eta_c$ wave function is $\gamma_5\phi$ where $\phi$ refers to the remaining spin and spatial part of the wave function, then (ref. Fig 1a. and Fig 1b.) when the mass of $\gamma^*$ is above 1 GeV, we can take $\phi$ to be well approximated by free quark and anti-quark propagators upto an overall constant. Hence in the ratio of these processes this constant is irrelevant. In Fig 1b. we integrate the kinematic space for physical $\gamma$ and find the $\eta_c$ contribution to $\mu^+\mu^-$ pair is given by [9] (for $M^2 \leq M_{\eta}^2$)

$$
\frac{dN}{dM} = \frac{1}{3} \frac{N_{\psi}}{N_{\eta_c}} \frac{1}{\alpha \pi m_{\psi}^2} \frac{M_{\eta_c}^2}{M_{\psi}^2 - 1} \left| \int_0^1 \frac{dx}{x} \ln \left( \frac{m_{\psi}^2 - x(1-x)M_{\eta_c}^2}{M_{\psi}^2 - x(1-x)M_{\psi}^2} \right)^2 \right| \left| \int_0^1 dx (1-x) \ln \left( \frac{m_{\psi}^2 - x(1-x)M_{\psi}^2}{\Lambda^2} \right)^2 \right|^{-2}
$$

where $m_c$ is the mass of the charm quark and $M_{\eta}$ and $M_{\psi}$ are the masses of the $\eta_c$ and $J/\psi$ mesons. $\Lambda$ is a cut-off parameter which regulates the
logarithmic divergence in Fig.1a. Here $N_{\psi}$ is the number of $J/\psi$ events per unit mass around the $J/\psi$ peak. In reality, in the p-A and A-A experiments, the $J/\psi$ peak is broadened due to detector resolution. Consequently, we interpret $N_{\psi}$ as the total number of $J/\psi$ events under the broadened peak.

Now we would like to remark on the limitations of this preliminary analysis. In any experimental set up the detection of $\mu^+\mu^-$ is limited by various cuts - in particular, rapidity and Collins-Soper [10] angle cuts. It is with these constraints that the experiment determines $N_{\psi}$, the number of $J/\psi$ events seen. $J/\psi$ undergoes a two body decay to dimuons and hence will have different acceptance ratios to that of the three body decay of $\eta_c$. These differences can be taken into account in detail, by doing a Monte Carlo simulation of the experiment using PYTHIA, for instance. In this preliminary analysis we shall ignore these details. Consequently we are assuming that the acceptance ratios of $J/\psi$ and $\eta_c$ events are about the same. It is known, for example, that the experimental acceptance ratio is about 15% for $J/\psi$ events. For $\eta_c$ we expect that when most of the energy is carried away by the dimuons alone and in addition, we also do not detect the real photon, it is possible that the acceptance ratio for $\eta_c$ may not be very different. However, for sufficiently small invariant mass ($< 1$ GeV) this assumption will fail. In spite of ignoring these details, we feel that the qualitative features of our analysis can be of importance in understanding the excess dimuon production in the IMR.

The data on S-U collisions at 200 GeV/nucleon [10] is one of the best studied experimentally in terms of statistics and comparisons between central vs peripheral collisions. Furthermore, most of the features of the earlier experiments with different nuclei are essentially contained, with better statistics, in this data. We therefore take the S-U data as the typical example for doing our analysis and take $\Lambda = .85$ GeV to reproduce the excess dimuon events in the central S-U collisions as shown in Fig.2a. Using the same value for $\Lambda$ we then check with the peripheral collision data, as shown in Fig.2b. Both appear to be reasonably satisfactory. It shows, for example, that in the IMR nearly 10 - 14% of events (depending on peripheral or central), appear to come from $\eta_c$. Taking $m_c = 1.6$ GeV, it turns out that the logarithm in the denominator in Eq.(1) is very sensitive to the choice of $\Lambda$. This is only to be expected since the $J/\psi$ mass is very close to $c\bar{c}$ threshold. We further notice that after choosing $\Lambda$, the exact choice of $m_c$ in the range 1.1 to 1.8 GeV is insignificant to our estimates.

For the chosen values of $\Lambda$ and $m_c$, we can check the p-A data against the corresponding $N_{\psi}$. We find that in these data sets the $\eta_c$ contribution, although substantial in IMR, is still less than the background as estimated by the experimental groups [10]. In fact, both in p-A and A-A the $\eta_c$ contribution is less than the $D\bar{D}$ contribution (see Fig. 2). From [10] it is clear
that in the p-A data the $D\bar{D}$ contribution is an order of magnitude lower than the combinatorial background. Hence the $\eta_c$ contribution is also much below the background.

Next, data for Pb-Pb at 158 GeV/nucleon data is fitted with the same parameters $m_c$ and $\Lambda$ obtained earlier from the S-U data. $N_\psi$ here is taken from the Pb-Pb data (for central or peripheral collisions as the case may be). This is shown in Fig. 3a and 3b (central and peripheral). Peripheral data is reasonably well accounted for with our $\eta_c$ production mechanism. (This peripheral data can be sensitive to the experimental cuts and therefore this agreement should be re-examined in a more detailed analysis incorporating all the experimental cuts). However in the central collision data Fig. 3a the discrepancy between our explanation and the data is still about 40% in the IMR. This discrepancy in the total number of events is rather less sensitive to the experimental cuts. Consequently it is fair to infer that our explanation in terms of $\eta_c$ production for central collisions of Pb-Pb at 158 GeV/nucleon is not complete.

For $e^+e^-$ data we have not redone this analysis since the corresponding $N_\psi$ is not quoted by the experimental group. It is clear from the analysis however, that there can be substantial contribution here as well from $\eta_c$.

The net result of this analysis is that the $\eta_c$ contribution to IMR of dimuon events is substantial and can fit the data satisfactorily in all A-A
Figure 3: Pb-Pb data - a)central and b) peripheral collisions. The solid line is the total contribution excluding $\eta_c$. The dot-dashed line is the total contribution including $\eta_c$. The individual contributions are also shown.

data excepting central Pb-Pb at 158 GeV/nucleon. There is substantial other evidence which suggests that in this data the hadronic plasma may have undergone QGP transition; consequently the hydrodynamic evolution parameters can play an important role [5].

Finally we would like to speculate over what other candidates from QCD phenomenology may play a role in the dilepton data. It has long been suspected that QCD has glueballs, although experimentally there is as yet no strong evidence - only some candidate events. In the context of A-A collisions, we can expect that a gluon-rich medium either hadronic or QGP in nature can produce such particles. These in turn can form glueballs of various spin, which again decay into standard mesons and baryons. This makes the detection of glueballs extremely tricky. Occassionally due to electromagnetic interaction through quark loops they do decay into photons and lepton pairs. Estimates of these processes is essentially hampered by our lack of understanding of glueball production. Noting that most of A-A collision data other than Pb-Pb are well explained by our $\eta_c$ scenario, it would not be out of place to surmise that perhaps some glueballs may be produced after QGP in Pb-Pb collision. Let us now expand on this scenario.

From Fig.3a, after accounting for $\eta_c$, the major discrepancy in the data occurs in the narrow region 1.7 - 2.3 GeV. Scalar or pseudoscalar glueballs, lighter than 2 GeV cannot contribute to the above region as their decay
goes through a $\gamma^*\gamma$ process. Thus only heavier than 3 GeV glueballs will contribute over the IMR. Since our present theoretical prejudices coming from either lattice [11,12,13] or sum rule techniques [14,15] suggest that the lightest glueballs are around 1.5 - 2 GeV, these light scalar or pseudoscalars cannot contribute to the discrepancy in Fig.3a. On the other hand the range 1.7- 2.3 GeV is reasonably narrow, which suggests that perhaps this is due to the $1^-\pi$ vector glueball with a mass of about 2 GeV decaying to dimuons. The production rate of this vector glueball is not estimable. If we presume that all the discrepancy is to be accomodated by the $1^-\pi$ vector glueball then we can infer from Fig. 3a that about $3 - 4 \times 10^3$ dimuon events are due to this glueball.

Finally a word of caution. It is clear that in central Pb-Pb at 158 GeV/nucleon some interesting different physics such as the hydrodynamic fireball expansion model as envisaged by [5] may be at work. In such a case our association of all the extra events to glueballs alone would be incorrect. It would be worthwhile therefore if there were other corroborative evidence in the data to support glueball production.

Keeping this in mind, we can speculate that in RHIC, where the QGP phase is produced and lasts longer, the effects of glueballs would be enhanced. The net effect of this in the dimuon spectrum in the IMR would be an enhancement of the bump in that region, thereby increasing the discrepancy between the data and present explanations by much more than 40%.

To summarize, the standard QCD explanation for the dimuon spectrum naturally involves the $\eta_c$ contribution as well. Interestingly, this contribution can be self-consistently estimated and the inclusion of this effect explains the various experimental data. However, central Pb-Pb data which is believed to undergo perhaps a QGP phase transition continues to show a discrepancy which perhaps needs explaining through a qualitatively new mechanism.

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