Can dileptons be observed in heavy ion collisions at RHIC?

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Abstract

Both dilepton and charm production at RHIC are considered to be important signatures for Quark-Gluon Plasma production. Recently it was argued by S.Gavin, P.L.McGaughey, P.V. Ruuskanen and R.Vogt \(^1\) that the background from semileptonic correlated charm decays is so large that it makes dilepton measurements virtually impossible. We show that this conclusion in fact is in fact reversed if the energy loss due to secondary interaction of charmed quarks is included.

Dileptons produced in highly excited hadronic matter provide valuable information about the hottest and the most dense stages of nuclear collisions. Together with photons, they are the so called penetrat\-ing probes \(^2\) which suffer very little secondary interaction. Consequently, dilepton measurements has attracted great deal of attention, both of theorists and experimentalists. Referring specifically to highest energies, let us remind that one of the major RHIC detectors, PHENIX, and ALICE at LHC plan dilepton measurements, both with electron and muon pairs.

Another potential QGP signature is thermal production of new quark flavors, especially of charm \(^3\) \(^4\) \(^5\) \(^6\) \(^7\) \(^8\) \(^9\). However, the ordinary partonic production of charm at the first impact is large, and whether it dominates the secondary (and thermal) charm production remains unclear. Nevertheless, charm signal will also be experimentally addressed at RHIC, by STAR and PHENIX collaborations.

Since charmed hadrons have substantial semileptonic decays, their simultaneous decay create a \(l^+l^-\) background for dilepton measurements. This issue was addressed recently by S.Gavin, P.L.McGaughey, P.V. Ruuskanen and R.Vogt (below GMRV) in a detailed paper \(^1\). Their conclusions are summarized in Fig.\(^1\), and they basically imply that the background from leptonic decays of charmed (and even b) quarks is so large, that implementation of the dilepton measurements is virtually impossible in the whole kinematic domain.

In this short paper we question those pessimistic conclusions, and suggest that it should be reversed. We show that a very important effect is missing from the GMRV

\(^1\) The expected highest temperatures at RHIC \(^2\) \(^3\) \(^4\) \(^5\) \(^6\) \(^7\) \(^8\) \(^9\) are \(T _i = 400 - 500 MeV\), so the mean energy per parton \(\approx 3T\) is comparable to charm quark mass. Note also that the mass of the strange quark is not large enough to suppress its production in the hadronic phase.
Figure 1: Contributions of different dilepton production mechanisms according to GMRV for central Au Au collisions at RHIC (a) and LHC (b). The curves correspond to: a correlated charm decays (dash-dots), b-quark decays (dash-double dots), Drell-Yan process (dashed curve), thermal dileptons (solid curve) and decays of thermally produced charm (dots).

analysis: unlike dileptons, the charmed quarks are not “penetrating probes”, and their spectra should be very different in pp and heavy ion collisions. Like any other quarks (and gluons), charmed ones are also subject to energy losses due to multiple secondary interactions in dense matter produced in the collisions. As we will show below, they are mostly stopped in matter.

Our first point is a purely geometrical observation. Consider collision of two heavy nuclei, and imagine that in it a $\bar{c}c$ pair is produced. The charmed quarks have to pass certain distances $d_1, d_2$ on their way out, and we point out that it is very improbable that the sum $d_1 + d_2$ is small because the quarks are mostly produced back-to-back.

If nuclei are approximated as spheres with a well-defined surface and radius R, one can easily quantify the relevant distributions. A distribution over a single quark path

\footnote{The commonly used terminology a \textit{correlated} and an \textit{uncorrelated} charm decay. The former is a simultaneous decay into $l^+$ and $l^-$ from a $\bar{c}c$ pair produced in one parton collisions, while the latter comes from the charm quarks produced \textit{independently}. In this note we concentrate on the correlated background only because the uncorrelated background can be statistically subtracted in a standard way.}
Figure 2: The histogram shows distribution of the transverse distance $d$ passed by a charm quark on the way out of nuclei (in units of its radius), while stars correspond to the sum $d_1 + d_2$ of distances for charmed quark and anti-quark.

$d$ (in units of the nuclei radius $R$) is shown by a histogram in Fig.2. Note that it is basically flat between $d \approx 2R$ (or 1 fm for heavy nuclei) and $2R$ (the diameter). However, the distribution of $(d_1 + d_2)/R$ (shown by stars in Fig.2) is quite different. It is sharply peaked at its largest value, but is very strongly suppressed at small ones. In order for both charmed quarks to escape, they not only should be created close to the surface, but also quarks should be emitted in a very small (tangent) solid angle. As we will show shortly, this simple observation is in fact responsible for a significant reduction of the correlated charm (and bottom)-induced background.

A dynamical ingredient of our analysis is $dE/dx$, the quark energy losses in QGP. We would not comment here on a complicated history of its discussion in theoretical and phenomenological papers. A consistent treatment (generalizing Landau-Pomeranchuck-Migdal approach to QCD) was recently developed by [7] (BDPS). The main qualitative
difference between QED and QCD cases can briefly be explained as follows. In QED an
electron is scattered and has a complicated zigzag-like trajectory, while its field go without
interaction by a straight line. In QCD it is the quark which is going by approximately
straight line, while its gluonic field suffer multiple rescatterings. The BDPS result for the
energy loss is

\[ \frac{dE}{dx} = C_R \alpha_s \left( \frac{E \mu^2}{\lambda_g} \right)^{1/2} \log \left( \frac{E}{\lambda_g \mu^2} \right) \] (1)

where \( C_R \) is Casimir for quark color representation, \( E \) is the collision energy, \( \lambda_g \) is gluonic
mean free path and \( \mu \) is the rms momentum transferred in each scatterings. Substituting
some “reasonable” parameters of QGP at RHIC (corresponding to “hot glue scenario, see
[3, 6]) we have estimated \( \frac{dE}{dx} \approx 2 \text{GeV/fm} \).

Our next step is Monte Carlo simulation of charm production. In order not to intro-
duce any additional points of discussion, we follow ref.[1] as close as possible. We have
ignore the “thermal charm” and assumed that each central AuAu collision at RHIC
produces \( \bar{c}c \) pairs with a very stiff \( p_t \) distribution\(^3\) generated by the leading order and
resummed next-to-leading-order QCD processes. This approach works in pp case, and
that is why GMRV has found that the correlated charm decay contributes so strongly at
large dilepton masses.

However, after the energy losses \( dE/dx \) are included, only very few of c or b quarks can
in fact escape, while most of them are stopped. Eventually, those should have \( p_t \) spectra
similar to all other hadrons, governed by low decoupling temperature \( T \sim 140 \text{MeV} \) and
hydro effects. Since both thermal and hydro velocities are not large, we have ignored
them.

We have simulated semileptonic decays of c and b quarks and show the resulting
invariant mass \( M = (p_{t+} + p_{t-})^2 \) spectrum in Figs.3, 4. In both cases the histogram shows
free decays, while stars include the effect of \( dE/dx \). Those two cases are very different:
while in free space the invariant mass distribution has a smooth and large tail toward
the large masses, with \( dE/dx \) one clearly see two distinct components: charm decay at
rest and the contribution of escaping ones. The boundary between two components is at
\( M_{t+/-} \approx 1.7 \text{GeV} \) for c and 4.5 GeV for b decays. Above it we have found a background
suppression, roughly by about 2 orders of magnitude. These features survive reasonable
modification of charm production spectra or of the chosen \( dE/dx \) value.

How important this reduction may be in practice? In order to answer this question,
one has to evaluate dilepton production, both primary (known as the Drell-Yan process)
and secondary (non-equilibrium \([3]\) and thermal \([8]\) ) ones. In this short note we will not go

\(^3\)An approximate parameterization used is \( dN/dp_t^2 \sim 1/(p_t^2 + 0.5)^{2.2} \), so the power of \( p_t \) is close to 4.
into discussion of it and simply return to GMRV estimates. As seen from Fig. 4, the ratio \( \frac{\text{dilepton yield}}{\text{correlated charm background}} \) is about 1/10 for \( M = 2 - 8 \text{GeV} \), while \( \frac{\text{dilepton yield}}{\text{b decay background}} \) is about 1/3 for \( M > 5 \text{GeV} \). Those are exactly the mass regions where our suppression discussed above appears! Thus we conclude that \( \frac{\text{dilepton yield}}{\text{correlated charm background}} \) is probably above 1; and that b-decays are simply negligible. More quantitative conclusion is difficult to get now: also one should consider acceptance of the particular detector, etc.

Since we are still in a situation with the signal/background ratio being around 1, additional experimental tools are needed in order to separate dileptons from charm decays. At least two are available: (i) dileptons are produced back-to-back in azimuthal angle, while leptons from charm decay are nearly isotropic in it; (ii) Drell-Yan pairs have the well known \( (1 + \cos^2 \theta) \) distribution where \( \theta \) is the polar angle between the dilepton direction in its CM frame and the beam. Also DY and direct charm should have simple scaling \( A^{4/3} \) from light nuclei (or peripheral collisions), so any excess over it is an indications for secondary processes.

\footnote{Let us only mention that GMRV make a very good job on DY, but do not include the non-equilibrium one. Also, they treat thermal in the leading order only. Both effects are expected to increase the secondary production substantially.}
In summary: in contrast to GMRV, we think that c and b quarks produced in high energy heavy ion collisions should be trapped in matter with very high probability. As a result, the background due to correlated semileptonic charm decay does not dominate the dilepton spectra for invariant masses above 2 GeV. Optimistically, by using various angular distributions, one may probably measure both dileptons and charm.

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