Dilepton Production from Heavy Quark Decays at RHIC

(I. Sarcevic, Z. Huang, D. Fein and P. Valerio)

Dilepton emission in high energy heavy-ion collisions provides an excellent probe of the property of dense hadronic matter such as the quark-gluon plasma and the hot hadronic gas. Due to the small cross sections of electromagnetic interactions, these dileptons once produced can escape the strong interacting volume of sizes which might be produced in heavy-ion collisions. The dilepton invariant mass spectrum holds the most promising signatures of the quark-gluon plasma such as thermal dileptons [1] and the J/ψ suppression [2]. However, the use of the dilepton probe is difficult for an obvious reason: it is sensitive to many different sources. In the low mass region, the resonance decays from the light hadrons constitute the main background. In the intermediate and high mass regions, the Drell-Yan dilepton production from the initial hard scattering is important. In high energy heavy-ion colliders such as RHIC and LHC, the heavy flavor quark production can be quite substantial and its subsequent decay can lead to a large combinatorial background for the dilepton spectrum. Therefore it is crucial to make a solid theoretical prediction on the contribution from heavy quark decays.

We have studied the dimuon emission as the decay product of the heavy quarks (charm and bottom) produced in an initial hard scattering and in a thermalized quark-gluon plasma at RHIC energy [3]. In our calculation we have included the next-to-leading order radiative corrections and nuclear shadowing effects and we have examined various components of the heavy quark spectra and their role in the dilepton production in an extended dilepton mass region. We have also studied the sensitivities of the perturbative calculation on the choices of the relevant physical scale and the heavy quark fragmentation function. The heavy parton production was calculated using the explicit next-to-leading order matrix elements, while the parton fragmentation and the heavy hadron decay are handled by the ISAJET Monte Carlo model [4]. The cascade decay of the bottom quark, $b \to c \to s$ is included in this model [3].

Theoretical calculations of heavy quark differential and total cross sections to the next-to-leading order $O(\alpha_s^3)$ at RHIC and LHC energies for the initial hard scattering indicate that higher order radiative corrections are important and the theoretical K-factor ranging from $1 \sim 3$ has strong transverse momentum dependence [5]. The nuclear shadowing effect is also non-negligible even at RHIC energy. Therefore, it is crucial to include full next-to-leading order corrections when one evaluates the dilepton production from heavy-quark decay.

The production of heavy hadrons is based on the factorization theorem, which states that the cross section for the production process of a hadron with an energy-momentum $(E, \mathbf{k})$ can be written in a factorized form

$$E\frac{d\sigma}{d^3k} = \sum_i \int E'\frac{d\sigma_i}{d^3k'}(k', \mu) D_i^{(h)}(z, \mu)\frac{E}{E'}\frac{dz}{z^3} \ , \tag{1}$$

where $k' = k/z$, $D_i^{(h)}(z, \mu)$ is the fragmentation function for producing the hadron h from the parton i and $d\sigma_i$ is the short-distance cross section for producing the parton i from the colliding hadrons. Clearly if i is a light parton, the cross section $d\sigma_i$ is not finite and the prescription for subtracting the collinear singularity has to be employed. However, in the case of heavy quark production, $d\sigma_i$ is an infrared safe quantity because the heavy quark mass acts as a cutoff for final state collinear singularities. Thus, the heavy quark mass sets the scale for a perturbative expansion in the strong coupling constant. In the limit when the mass can be considered much larger than the typical hadronic scale, the fragmentation function $D_i^{(h)}(z,\mu)$ is also calculable in perturbation theory. As long as the transverse momentum of the produced heavy quark is not much larger than its mass, perturbation theory predicts $D_i^{(h)}(z) \sim \delta(1-z)$. On the other hand, the finite mass and energy transfer (ΔE) in the fragmentation process suggests that the breakup amplitude $\sim 1/\Delta E$, where

$$\begin{aligned} \Delta E &= (m_Q^2 + z^2k^2)^{1/2} + (m_q^2 + (1-z)^2k^2)^{1/2} - (m_Q^2 + k^2)^{1/2} \\ &\propto 1 - 1/z - \epsilon_Q/(1-z) \; . \end{aligned} \tag{2}$$

This leads to a Peterson form [6]

$$D_Q^{(H)} = \frac{N}{z[1-(1/z)-\epsilon_Q/(1-z)]^2} \; , \tag{3}$$

where $\epsilon_c = 0.15$ and $\epsilon_b = 0.016$. The normalization constant N is fixed by the sum rule $\int dz D_Q^H(z) = 1$: $N = 1.28,\ 0.25$ for c and b respectively. Such a parameterization has been shown to be appropriate in e^+e^- reactions and fit well the MARK-II data [6]. For hadronic collisions or an even heavier quark decay, it is known that there are no universal fragmentation functions. The double differential cross sections for (all) charmed hadrons (mainly D-mesons) as well as (all) b-hadrons (mainly B-mesons) are calculated (assuming that there is no energy loss for the produced parton before hadronization) and the results are plotted in Fig. 1 in Ref. 3 against the distributions for the heavy partons.

The initial parton differential distributions are calculated using the next-to-leading-order (NLO) matrix elements provided by Nason, Dawson and Ellis in [7]. We have taken $m_c = 1.5$ GeV, $m_b = 4.7$ GeV, the factorization and renormalization scale μ to be the transverse mass $2m_t$. The nucleon structure function is parameterized by MRS A and the nuclear shadowing parametrization fits the EMC, NMC and E665 data [8]. The total cross sections (per initial nucleon) are $\sigma_{c\bar{c}}^{\rm tot} = 153\mu$b and $\sigma_{b\bar{b}}^{\rm tot} = 1.5\mu$b for Au+Au collisions at $\sqrt{s} = 200$ GeV/n. The choice of a smaller charm quark mass $m_c = 1.2$ GeV increases the total cross section by a factor of 2 (see Vogt in [5]). As is evident from Fig. 1 in Ref. 3, the leading order (in heavy quark mass) fragmentation function $D(z) \sim \delta(1-z)$ seems to be a reasonable approximation for heavy quarks. There is some noticeable softening of heavy mesons at large p_t and an enhancement of B-meson at very small p_t due to the finite heavy quark mass and the heavy quark-hadron mass splitting. The semileptonic decay of the heavy meson can be conveniently handled by Monte Carlo simulations such as ISAJET or JETSET.

Thermal Charm Production

At sufficiently high temperatures, a thermal system of light partons can create a charm pair which will decay into leptons and should also be included. The thermal charm production has been calculated so far at the leading order matrix element level [9]. To estimate the reliability of the leading-order result, one has to perform a full NLO calculation. At the next-to-leading order, there are additional $2 \rightarrow 3$ processes and loop diagrams. Formally, the differential production rate is given by the convolution of the parton level differential cross sections with the initial light parton phase space densities (distribution functions) $f_i(p)$

$$\begin{aligned} E\frac{dR}{d^3k} &= \int \frac{d^3p_1}{(2\pi)^3 2E_1}\frac{d^3p_2}{(2\pi)^3 2E_2} F(p_1,p_1)\left[\frac{g_{gg}}{2} f_g(p_1) f_g(p_2) E\frac{d\hat{\sigma}_{gg}}{d^3k} + \right. \\ & \left. g_{q\bar{q}} f_q(p_1) f_{\bar{q}}(p_2) E\frac{d\hat{\sigma}_{q\bar{q}}}{d^3k} + g_{qg} f_q(p_1) f_g(p_2) E\frac{d\hat{\sigma}_{qg}}{d^3k}\right] , \end{aligned} \tag{4}$$

where $g_{gg} = 16^2$, $g_{q\bar{q}} = 6^2 N_f$ and $g_{qg} = 6 \cdot 16 N_f$ are the degeneracy factors, and $F(p_1,p_2) = 4p_1p_2$ is the inverse flux factor.

At the leading order, the $d\hat{\sigma}_{qg}$ term is absent. At the next-to-leading order, these parton level differential cross sections contain $2 \to 3$ processes and loop diagrams and they are not infrared finite quantities. Braaten and Pisarski [10] have shown that a resummation technique has to be employed to take into account the so-called "hard thermal loops" which give the same order of magnitude contributions as the leading order terms when the external momenta of the amplitude are soft. As a result of the resummation, the infrared singularities are shielded by a Debye screening effect, and the screening masses of gluons and quarks provide an infrared cutoff. The perturbative resummation can only regularize the electric part of the propagators and so far the magnetic screening mass has to come from the unknown nonperturbative effect. To obtain a qualitative result for the NLO thermal charm production, we use the Debye screening mass [11]

$$\mu_D^2 = \frac{6g^2}{\pi^2}\int p f(p) dp = 4\pi\alpha_s T^2 , \tag{5}$$

to regularize all singularities in the radiative cross sections. This amounts to a "massive gluon scheme" where the μ_D^2 sets the scale for the parton level cross sections in Eq.(4). Certainly, this calculation is not entirely consistent, and the results thus obtained can only be taken as an qualitative indication on the reliability of the leading-order result. We have evaluated the thermal charm yield at RHIC energy by integrating over the space-time evolution of the quark-gluon plasma. We assume a fully equilibrated thermal system with an initial temperature $T_0 = 0.55$ GeV and a Bjorken ideal-fluid scaling $T(\tau)/T_0 = (\tau_0/\tau)^{1/3}$ with $\tau_0 = 0.7$ fm/c and $T_c = 0.2$ GeV. A spatial rapidity cutoff $\eta_{\max} = 3$ is assumed. The differential distributions are plotted in Fig. 2 in Ref. 3 for the leading order and the next-to-leading order calculations using the Debye screening scale in (5). We also compare the result for a choice of the scale $\mu = m_t$. As in the initial hard scattering case, the higher order corrections are sizable with an effective K-factor ranging from 1.7 to 2.5 as p_t varies from 1 GeV to 10 GeV. We use the leading order kinematics to generate the heavy quark momenta and multiply the weights uniformly by an average value $K = 2$ to account for the radiative corrections. The calculated dimuon spectra from the decay of heavy quarks produced in a hard scattering and in an idealized quark-gluon plasma are plotted in Fig. 1. The dimuon spectrum from thermal charm quark production is considerably softer than the initial hard scattering results as can be inferred from the p_t distribution in Fig. 2 in Ref. 3. However, it dominates the dilepton production in the low mass region ($M < 2$ GeV). This can be a important background at RHIC for the dilepton signature for the low lying vector resonances such as ρ and ϕ. It is important to note that the calculated thermal

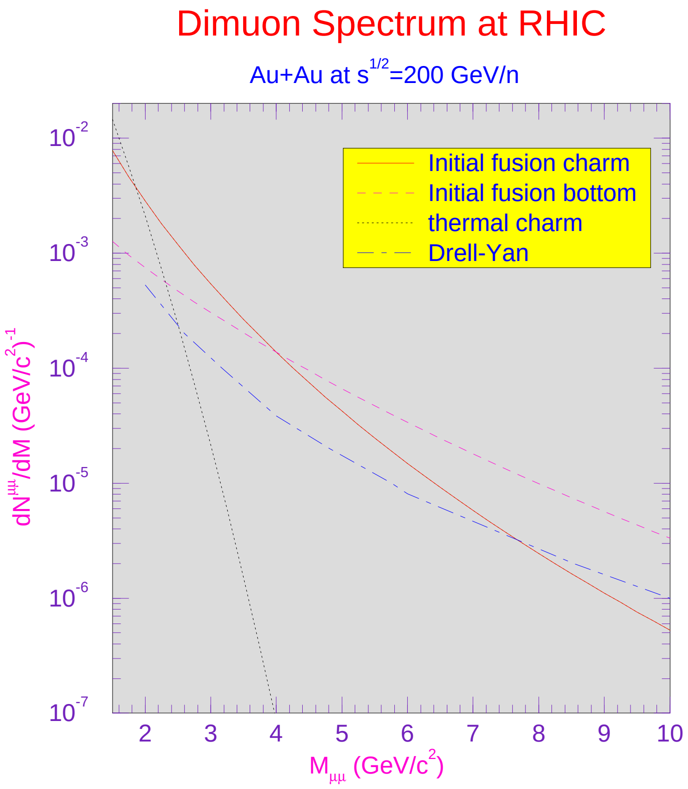

Figure 1: The dimuon invariant mass spectra from the correlated heavy quark decays.

charm contribution corresponds to a very ideal case where the quarks and gluons are fully equilibrated. The result may be considerably smaller in the plasma where the chemical process is not in equilibrium [9]. The thermal production of the bottom quark is negligible and is not included. The cascade decay of B-mesons, $b \to c \to s$ is also included in the curve for the initial fusion bottom production. We have not assumed any secondary interactions in the medium produced in the collision. Although the production rate for the initial bottom quark is much smaller than the charm, the dilepton production from B-meson decay is non-negligible in the large invariant mass region due to the large rest mass of the B-meson. It becomes the dominant contribution when the dimuon invariant mass is above ~ 4 GeV. If the fast charm suffers the significant energy loss before it hadronizes, the dimuon spectrum from the initial fusion charm can be considerably softened. In fact, it becomes very similar to that of the thermal charm and falls off rapidly as M gets bigger than 2 GeV, as demonstrated by Shuryak [12]. In this case, the bottom dominance is more prominent and starts at a smaller value of $M \sim 2$ GeV because two B-mesons at rest can produce an energetic lepton pair. In Fig. 2 in Ref. 3 we include the Drell-Yan dimuon production from [13] for comparison. The thermal charm from an ideal quark-gluon plasma dominates the dilepton emission in the low dilepton invariant mass region (< 2 GeV). The correlated heavy mesons produced from the initial hard scattering constitutes the major contribution to the intermediate and high mass dileptons. If there is significant energy loss for the fast charm, the bottom decay is by far the dominant component in the intermediate and high dimuon mass regions. In any case, we are likely to find more bottom than charm in the high mass dilepton channel in central Au+Au collisions at RHIC.

Future Plans: We plan to improve calculation of the thermal charm production by performing self-consistent next-to-leading order calculation. The result should be free of infrared singularities. Current results for thermal charm have the infrared cut off put in by hand and the predictions are very sensitive to its values. This calculation is crucial in order to have firm predictions for charm and/or dilepton enhancement as a signal for the quark-gluon plasma formation at RHIC.

We will also calculate the energy loss of the charm quark in a dense medium similar to the light-quark case done by Baier et al. [14]. We discuss this topic further in a section on QCD Energy Loss. Currently there are interesting phenomenological studies of this effect for heavy quarks [12].

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