Heavy Quark Production from Jet Conversions in a Quark-Gluon Plasma

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Recently, it has been demonstrated that the chemical composition of jets in heavy ion collisions is significantly altered compared to jets in the vacuum. This signal can be used to probe the medium formed in nuclear collisions. In this study we investigate the possibility that fast light quarks and gluons can convert to heavy quarks when passing through a quark gluon plasma. We study the rate of light to heavy jet conversions in a consistent Fokker-Planck framework and investigate their impact on the production of high-p_T charm and bottom quarks at RHIC and LHC.

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I. INTRODUCTION

In heavy ion collisions, energetic jets are expected to lose a significant amount of energy when passing through the surrounding quark gluon plasma (QGP) [1, 2, 3, 4]. This jet quenching phenomenon leads to a large suppression of the yield of high-p_T hadrons in Au+Au collisions compared to the yield expected from a superposition of $p+p$ collisions [5, 6] at the same center-of-mass energy. Induced gluon radiation was expected to be the largest contributor to the momentum degradation of the leading jet parton. However, experimental results on the quenching of heavy flavors [7] has led to new efforts to revisit elastic energy loss [8, 9, 10] and non-perturbative mechanisms [11]. Jet quenching measurements deliver important information about the medium in terms of the average squared momentum transfer to the jet per unit path length, $\hat{q} = \mu^2/\lambda$. Besides quenching as a manifestation of energy loss of the leading high-p_T parton, the chemical composition of a jet can also change through flavor changes of the leading parton. This is an unavoidable consequence of collisions of the high-p_T parton with thermal partons. The probability of conversion is related to the path length through the medium and the collisional conversion widths. Thus by tracking the flavor of jets (defined as the flavor of the leading parton) throughout their interaction with the medium, transport properties of the medium which are independent of and complementary to $\hat{q}$ can be obtained. Eventually, the flavor changes will be reflected by the hadron composition of the jet.

Flavor changing processes were first studied in the context of light quarks and gluons [12], and parton to photon conversions [13]. More recently, we unified these two processes and discussed new observables which could be measured at the Relativistic Heavy Ion Collider (RHIC) or the Large Hadron Collider (LHC) [15]. In Ref. [12] it was found that conversions of light quarks to gluons could help solve the puzzle of very similar nuclear modification factors R_{AA} for pions and protons observed by the STAR experiment [14]. These seemed to be incompatible with a relative energy loss of 9/4 for gluons and light quarks. However, as we discussed in more detail in [15], the concept of a fixed flavor for the leading jet parton is ill-defined in a medium. Conversions to real or virtual photons are just other examples of what can happen to a fast quark or gluon traversing a quark gluon plasma. Although much rarer than conversions to strongly interacting partons, it has been shown that these photons can make a significant contribution to the direct photon or dilepton spectrum at intermediate p_T.

In [15] it was shown that strange hadrons might be the ideal probe for flavor conversions at RHIC energies. This is due to the strong gradient between the very small initial strange quark content of jets at RHIC, and the almost full chemical equilibration of strangeness in the plasma. Jets coupling to the medium will be driven toward chemical equilibrium and thus kaons and Λ-hyperons have to be enhanced relative to pions and protons at large p_T when compared to naive expectations from $p+p$ collisions. Measurements of this enhancement could shed light on the mean free path of fast gluons and light quarks in the medium. At LHC, the value of strangeness as a high-p_T probe is diminished through the large initial strangeness content of jets at larger energies. When translating leading particle flavor into hadrons it has to be kept in mind that the hadron chemistry can also be altered through the increased multiplicity in a jet cone interacting with the medium as studied in [16].

Two important questions emerge from the discussion of high-p_T strangeness enhancement at RHIC. First, can heavy quarks, in particular charm, play a similar role as a probe for the average mean free path at LHC? And secondly, is the suppression of charm found at RHIC compatible with the mechanism proposed here which boosts the yields of rare particle species at intermediate and high p_T? In this Report, we answer these questions by studying the production of high-p_T heavy quarks from jet conversions in heavy ion collisions. We compute the contributions from leading order (LO) processes in perturbation theory multiplied by a K-factor. The heavy quarks can be produced from the annihilation process $g+g \to Q+\bar{Q}$ that converts a gluon jet and a thermal gluon to a pair of heavy quarks, and also through the Compton processes $g(q)+Q \to Q+g(q)$ by transferring the momentum of the incoming jet to that of a slow moving heavy quark in the medium. We follow the method introduced in Ref. [15] to study the propagation of the high p_T heavy quark in the expanding fireball within the framework of a Fokker-Planck equation.

This work is organized as follows. In the next section we discuss the transport coefficients of heavy quarks and the collisional widths for the conversion of light partons to heavy quarks. We then proceed to present numerical results for charm and bottom quarks at RHIC and LHC in Sec.III using a consistent model based on rate equations for conversions and a Fokker-Planck equation for energy loss. Finally, a summary is presented in Sec. IV.

II. HEAVY QUARK SCATTERING IN A QGP

First we discuss the propagation of heavy quarks in a partonic medium. It can be described in the framework of a Fokker-Planck equation [11, 17]

$$\frac{\partial f(\mathbf{p},t)}{\partial t} = \frac{\partial}{\partial \mathrm{p_i}}\left[A_\mathrm{i}(\mathbf{p}) + \frac{\partial}{\partial \mathrm{p_j}} B_\mathrm{ij}(\mathbf{p})\right] f(\mathbf{p},t) \tag{1}$$

where $f(\mathbf{p},t)$ is the distribution function of heavy quarks. The drag and diffusion coefficients are

$$\begin{aligned} A_\mathrm{i}(\mathbf{p}) &= \mathrm{p_i}\gamma(|\mathbf{p}|), \\ B_\mathrm{ij}(\mathbf{p}) &= \left(\delta_\mathrm{ij} - \frac{\mathrm{p_i p_j}}{|\mathbf{p}|^2}\right) B_0(|\mathbf{p}|) + \frac{\mathrm{p_i p_j}}{|\mathbf{p}|^2} B_1(|\mathbf{p}|), \end{aligned} \tag{2}$$

with

$$\begin{aligned} \gamma(|\mathbf{p}|) &= \langle 1\rangle - \frac{\langle \mathbf{p}\cdot\mathbf{p}'\rangle}{|\mathbf{p}|^2}, \\ B_0(|\mathbf{p}|) &= \frac{1}{4}\left[\langle |\mathbf{p}|^2\rangle - \frac{\langle(\mathbf{p}\cdot\mathbf{p}')^2\rangle}{|\mathbf{p}|^2}\right], \\ B_1(|\mathbf{p}|) &= \frac{1}{2}\left[\frac{\langle(\mathbf{p}\cdot\mathbf{p}')^2\rangle}{|\mathbf{p}|^2} - 2\langle\mathbf{p}\cdot\mathbf{p}'\rangle + \mathbf{p}^2\langle 1\rangle\right]. \end{aligned} \tag{3}$$

Here $\mathbf{p}$ and $\mathbf{p}'$ label the momenta of the heavy quark before and after each collision, respectively. We define the thermal averaging $\langle Y(\mathbf{p}')\rangle$ in the elastic process $Q + g(q) \to Q + g(q)$ as

$$\begin{aligned} &\langle Y(\mathbf{p}')\rangle \\ &= \frac{1}{2E_p}\int \prod_{Q=p',q,q'} \frac{d^3Q}{(2\pi)^3 2E_Q}\delta^{(4)}(p+q-p'-q') \\ &\times\frac{1}{\gamma_Q}(2\pi)^4|\mathcal{M}_{p+q\to p'+q'}|^2 f(q)[1\pm f(q')]Y(\mathbf{p}'). \end{aligned} \tag{4}$$

where $\mathcal{M}$ is the scattering amplitude and $\gamma_Q = 6$ is the spin and color degeneracy factor for heavy quark.

Using a fixed coupling constant $\alpha_s = 0.3$ and masses $m_g = gT/\sqrt{2}$ for thermal gluons and $m_q = gT/\sqrt{6}$ for thermal quarks [18], we calculate the transport coefficients for both charm (m_c=1.2 GeV) and bottom (m_b=4.5 GeV) quarks numerically at leading order accuracy for the Compton processes $Q + g(q) \to Q + g(q)$.

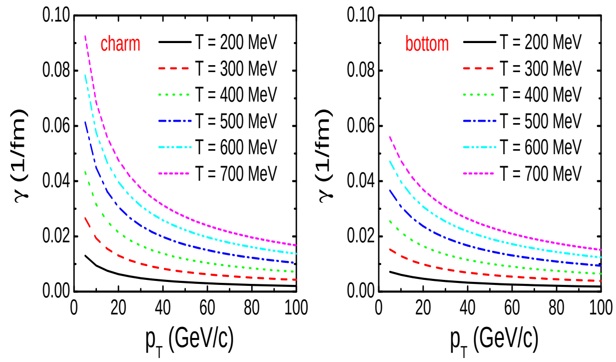

FIG. 1: (Color online) Transport coefficients γ of charm (left) and bottom quarks (right) in a QGP as functions of transverse momentum p_T at different temperatures T.

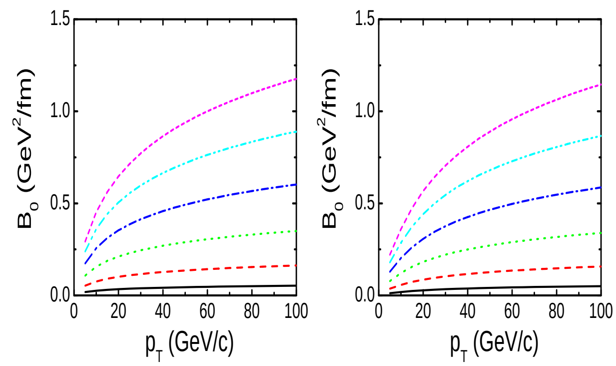

FIG. 2: (Color online) Transport coefficients B_0 of charm (left) and bottom (right) quarks in a QGP as functions of transverse momentum p_T at different temperatures T.

We show the results in Figs. 1, 2, and 3. The drag coefficients γ decrease with increasing momentum of the incoming jets while diffusion coefficients behave the opposite way.

To study the dynamics of heavy quark in an expanding QGP medium, we focus on the degradation of transverse momentum of heavy quark jets, which can be taken into account using a Langevin equation [19, 20] obtained from the Fokker-Planck equation in (1) by calculating the first and second modes,

$$\begin{aligned} \Delta x &= \frac{\vec{p}}{E}\Delta\tau, \\ \Delta\vec{p} &= -\gamma(T,\vec{p}+\Delta\vec{p})\vec{p}\Delta\tau + \Delta\vec{W}(T,\vec{p}+\Delta\vec{p}). \end{aligned} \tag{5}$$

Here $\Delta\vec{W}$ is the random force according to the normal distribution

$$f_{rf}(\Delta\vec{W}) \sim \frac{1}{\sqrt{4\pi\Delta\tau}}\exp\left[-\frac{\hat{B}_{ij}\Delta W^i\Delta W^j}{4\Delta\tau}\right] \tag{6}$$

and $\hat{B}_{ij}$ is the inverse of the diffusion-coefficient matrix B_{ij} defined in Eq. (2).

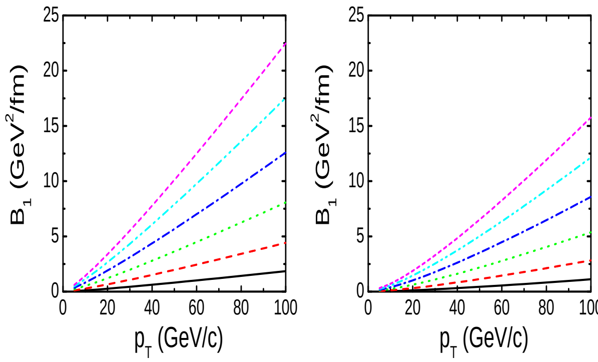

FIG. 3: (Color online) Transport coefficients B_1 of charm (left) and bottom (right) quarks in a QGP as functions of transverse momentum p_T at different temperatures T.

Now we discuss the implementation of the conversion of light quarks (u,d,s) and gluons into heavy quarks through the processes $g + g \to Q + \bar{Q}$ and $g(q) + Q \to Q + g(q)$. The dynamics is governed by the rate equation

$$\frac{dN^a}{d\tau} = -\sum_b \Gamma^{a\to b}(p_T) N^a + \sum_c \Gamma^{c\to a}(p_T) N^c \, . \qquad (7)$$

The collisional conversion widths can be estimated as $\Gamma(p) = \langle 1 \rangle$ in the notation defined in Eq. (4).

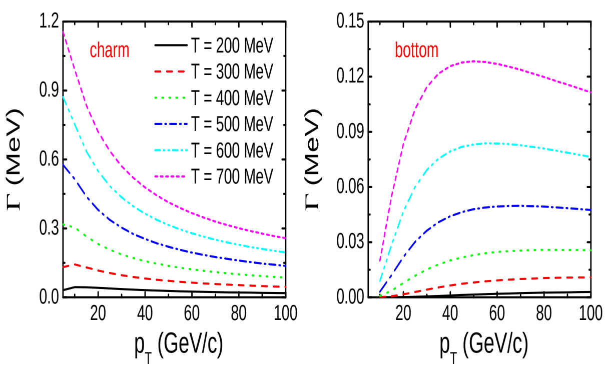

FIG. 4: (Color online) Conversion widths for charm (left panel) and bottom (right panel) in a QGP due to the process $g + g \to Q + \bar{Q}$ as functions of transverse momentum p_T of the incoming gluon jets at different temperatures T.

In Fig. 4, we plot the width of a gluon jet converting to charm and bottom via the process $g + g \to Q + \bar{Q}$. We have introduced a constraint on the momentum of the outgoing heavy quark jet. We only count the heavy quark as a jet particle if it carries the larger momentum of the two final state partons. The conversion will also cause effective energy loss since the final momentum is usually smaller than the initial gluon jet momentum due to the mass threshold. This is different from the case of light flavor conversions which can occur with 100% efficiency. The resulting average momentum of the heavy quark after conversion from a gluon, $p_Q = \langle p_Q \rangle / \langle 1 \rangle$, as a function of the incoming gluon momentum p are shown in Fig. 5. $\langle p_Q \rangle$ has an almost linear dependence on p only depends very weakly on temperature.

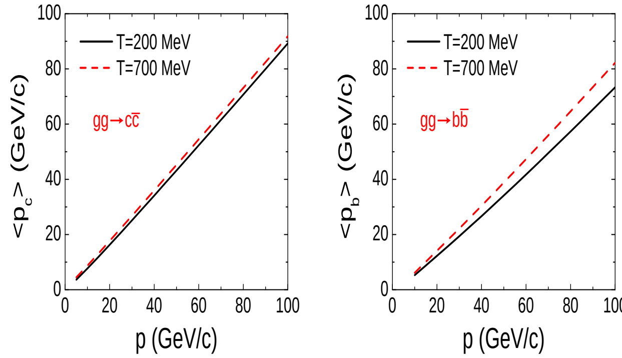

FIG. 5: (Color online) Average final state momentum of the heavy quark for charm (left panel) and bottom (right panel) after conversion from gluons with momentum p for two different temperatures.

As mentioned above there are two more elastic processes, $g+Q \to Q+g$ and $q+Q \to q+Q$, which contribute to the enhancement of high-p_T heavy quarks by accelerating slowly moving heavy quarks from the medium. We use the distribution function of heavy quarks obtained from perturbative QCD calculations in Pb+Pb collisions at $\sqrt{s_{NN}}$=5.5 TeV (shown in the next section) to estimate the conversion width for a quark or gluon into a heavy quark via these Compton-like processes. It turns out that their contribution to high-p_T heavy quark production is two orders of magnitude smaller than that from the gluon annihilation process $g + g \to Q + \bar{Q}$ due to the mass mismatch in the initial state. This is true when we require the momentum of the outgoing heavy quark to be larger than half of the momentum of the incoming light flavor jet. When this constraint is lifted a much larger conversion rate is obtained, however, with a much smaller average momentum gain for the final state heavy quark which seems irrelevant for the high-p_T sector. Thus we neglect the contributions from Compton-like elastic processes in the following.

In this work we follow the procedure outlined for light quark and gluons in [12]. The leading order matrix elements are scaled by a factor $K = 4$ which was needed to reproduce the observed p/π^+ and $\bar{p}/\pi^-$ ratios. Ultimately, however, the drag and diffusion coefficients have to be extracted from data and compared to a variety of perturbative and non-perturbative predictions. A large K-factor as used here, if found compatible with data, might rather hint toward a much stronger jet-medium coupling than expected from perturbation theory.

III. HEAVY QUARK CONVERSIONS AT RHIC AND LHC

Now we turn to charm and bottom production in Au+Au collisions at RHIC with a center-of-mass energy $\sqrt{s_{NN}} = 200$ GeV. The initial p_T spectra of charm and bottom quarks at mid-rapidity are taken from Ref. [21]. Both are obtained by multiplying the heavy quark p_T-spectra from $p+p$ collisions at the same energy by the number of binary collisions (~ 960) in central Au+Au collisions.

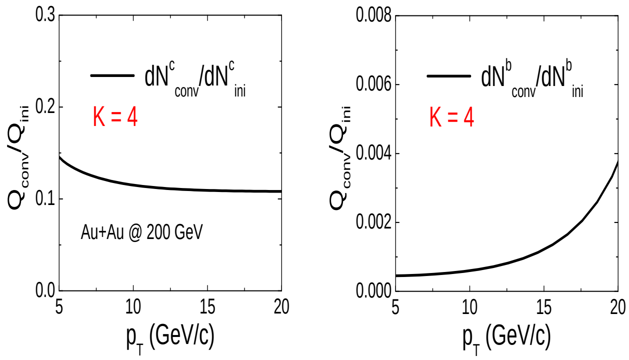

FIG. 6: (Color online) The ratio of heavy quarks from jet conversions to heavy quarks from initial production with energy loss included for charm (left panel) and bottom (right panel) as functions of transverse momentum p_T in Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV.

For the dynamics of the fireball, we assume that it evolves boost invariantly in the longitudinal direction but with an accelerated transverse expansion. Specifically, its volume expands in the proper time τ according to $V(\tau) = \pi R(\tau)^2\tau$, where $R(\tau) = R_0 + a/2(\tau - \tau_0)^2$ is the transverse radius with an initial value R_0=7 fm, τ_0=0.6 fm is the QGP formation time, and $a = 0.1c^2$/fm is the transverse acceleration [12, 21, 22]. With an initial temperature $T_i = 350$ MeV and using thermal masses for quarks and gluons, this model gives a total transverse energy comparable to that measured in experiments. The time dependence of the temperature is then obtained from entropy conservation, and the critical temperature $T_c = 175$ MeV is reached at proper time $\tau_c \sim 5$ fm.

To solve Eq. 5, we follow the test particle methods introduced in Ref. [12] for the propagation of light flavored jets and heavy quarks in the QGP medium. The light flavors can convert into each other or into heavy quarks according to the probabilities discussed above in [15]. The conversion of heavy quarks into light flavors is suppressed and not taken into account, except for the process $Qg(q) \to g(q)Q$ which is included in the drag coefficient. In Fig. 6 we show the ratio of heavy quarks obtained from jet conversions to that obtained from initial hard collisions with energy loss included. The jet conversions contribute about 10% to the spectrum of charm quarks at high p_T, and only 0.3% to that of bottom quarks in central Au+Au collisions at RHIC.

For LHC energies we take the initial p_T spectra of charm and bottom quarks at midrapidity from the perturbative calculation in Refs. [23, 24] multiplied by the number of binary collisions ($\langle N_{coll}\rangle \approx 1700$ [25]). The spectra are parametrized as

$$\begin{aligned}\frac{dN_c}{d^2p_T} &= 2497\left(1+\frac{p_T}{1.95}\right)^{-5.5}\left(p_T\left[1+\left(\frac{4}{0.1+p_T}\right)^2\right]\right)^{-1}\\ \frac{dN_b}{d^2p_T} &= 38\left(1+\frac{p_T}{2.0}\right)^{-5.6}\left[1+\left(\frac{10}{0.8+p_T}\right)^3\right]^{-1}, \qquad (8)\end{aligned}$$

The parameters of the fireball are taken from Ref. [26] where thermal charm production at LHC was studied. Specifically, we choose initial proper time $\tau_0 = 0.2$ fm/c for the formation of the equilibrated QGP with initial temperature $T_0 = 700$ MeV. In Fig. 7, we show the ratio of heavy quark yields from jet conversions to that from initial hard collisions with energy loss included. The ratios are similar in magnitude magnitude to what has been obtained for RHIC.

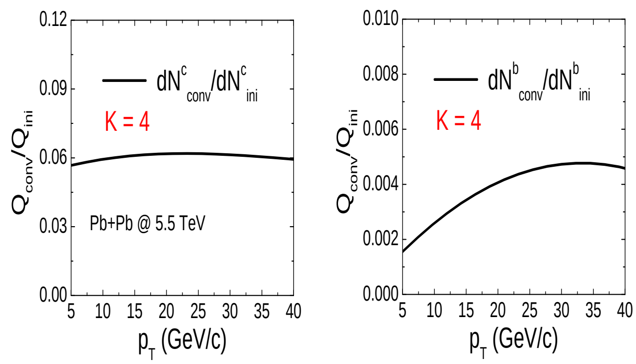

FIG. 7: (Color online) The ratio of heavy quark spectrum from initial production to that from jet conversions for charm (left panel) and bottom (right panel) as functions of transverse momentum in Pb+Pb collisions at $\sqrt{s_{NN}} = 5.5$ TeV.

We can now answer the two questions that we have posed at the beginning. First, the promotion of heavy quarks from the medium to high p_T is not an effective mechanism for the production of high-p_T charm and bottom quarks. This is compatible with the experimental observations [7]. Note that we have used the same framework and K-factors which led to the prediction of a sizable strange quark excess at high-p_T at RHIC. On the other hand, we have found that the corresponding process for charm quarks at LHC is not efficient. This can be traced back to the relatively large amount of initial charm in jets produced at LHC and the missing chemical equilibration of charm in the QGP. Note that some authors have argued recently that thermal charm production might occur at the temperatures reached at LHC [26]. We have chosen not to include this scenario here.

IV. DISCUSSION

We have studied the impact of jet conversions on the production of high-p_T heavy quarks in heavy ion collisions. Based on leading order perturbative QCD, we calculated transport coefficients of heavy quarks, and studied their propagation in an expanding QGP medium. We find that the dominant conversion process is pair production off gluon jets in the medium, $g + g \rightarrow Q + \bar{Q}$. However, the contribution of jet conversions to the total yields of heavy quarks at high p_T is rather small both at RHIC and LHC. This is consistent with measurements of single electrons at moderate values of p_T at RHIC. On the other hand, it implies that high-p_T charm quarks at LHC as a probe for the mean free path in the medium might not be as useful as strangeness is at RHIC energies.

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