Energy loss of quarks in deconfined matter at RHIC: photon-tagged jets, single electron and dilepton spectra from open charm

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We report a first attempt (i) to derive constraints on the energy loss of charm quarks in a deconfined medium from the recent PHENIX data of single-electron transverse momentum spectra and (ii) to estimate the resulting suppression of dileptons from correlated semi-leptonic decays of open charmed mesons. The momentum imbalance of photon-tagged light-quark jets is also considered.

1. INTRODUCTION

Induced gluon radiation of a fast quark propagating through a deconfined medium of quarks and gluons causes an energy loss which should considerably modify various observables in relativistic heavy-ion collisions compared to pp collisions. In such a way the properties of the deconfined medium (parton composition and space-time dependent densities etc.) can be probed. The QCD based theory of the energy loss has been elaborated by various groups; a few key references are [1–4] from which other relevant publications can be traced back. As pointed out in [5] the modified transverse momentum spectrum of final hadrons at midrapidity appears as a convolution of the energy loss distribution and the primary spectrum. To enable a comparison with earlier work [6,7], we employ here a simplified version by using a Monte Carlo averaging over traversed path lengths and by shifting the transverse momentum of a quark with energy E and mean free path λ before hadronizing by the mean energy loss according to [2]

$$\Delta E = -\frac{\alpha_s}{3}\zeta \begin{cases} 0 & : \quad L < \lambda \text{ or in hadron matter} \\ \hat{q}(T_f)L^2 & : \quad L < L_c \\ \sqrt{\hat{q}(T_f)E}L & : \quad L > L_c \end{cases} \tag{1}$$

where L is the traversed path inside the deconfined medium, $L_c = \sqrt{E/\hat{q}(T_f)}$, and $\hat{q}$ encodes the transport properties of the medium. Remarkable is the apparent independence of the initial state, i.e. the energy loss depends on the temperature T_f at which the quark leaves the medium. As we show below, however, due to life time and geometrical size effects, a sensitivity on the initial conditions occurs.

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2. SINGLE ELECTRONS FROM OPEN CHARM DECAYS

Using the PYTHIA version 6.206 with charm quark mass parameter $m_c = 1.5$ GeV, intrinsic parton transverse momentum distribution $\sqrt{\langle k_\perp^2 \rangle} = 2.5$ GeV,[1] default Q scale and K factor $\mathcal{K} = 5.7$ one gets the charm cross section $\sigma_{c\bar{c}}^{NN} = 404$ μb at $\sqrt{s_{NN}} = 130$ GeV. With the hybrid fragmentation scheme (Peterson fragmentation function with $\epsilon = 0.06$) and the electron/positron decay channels of charmed hadrons within PYTHIA the resulting inclusive transverse momentum spectrum agrees fairly well ($\chi_{d.o.f.}^2 = 0.27$ (0.39)) with the PHENIX data [8] when using the appropriate thickness functions $T_{AA} = 6.2$ (22.6) mb^{-1} for minimum bias (central) collisions, see Figure 1.
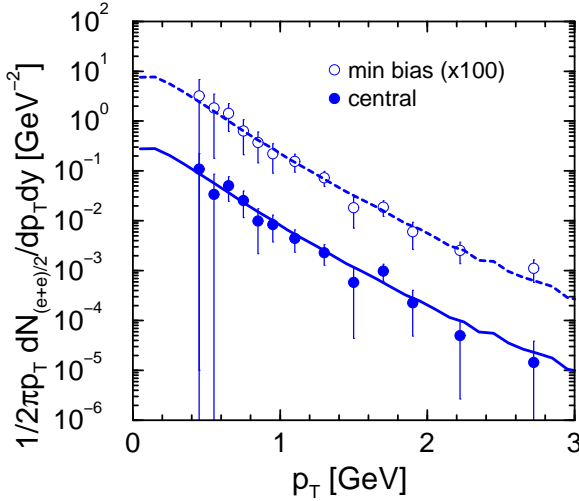

Figure 1. Comparison of our PYTHIA results with the PHENIX data [8] (statistical and systematical errors are quadratically added).
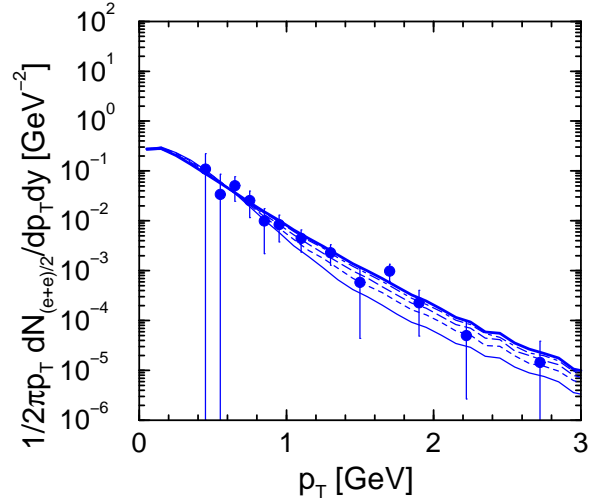
Figure 2. Comparison of various energy loss strengths $\zeta = 0$, 0.2, 0.5, 1.0, 2.0 (from top to bottom) with PHENIX data [8] of central collisions.

To see which space is left for an energy loss we use the above described scheme with Bjorken symmetries (transverse radius $R_A = 7$ fm, no transverse expansion, full chemical equilibrium, initial time $\tau_i = 0.2$ fm/c) and initial temperature $T_i = 550$ MeV. The final temperature T_f depends on the creation point and propagation direction of the charm quarks; the minimum of T_f is given by the chiral transition temperature of 170 MeV. We parameterize different energy loss strengths by ζ. The results of our Monte Carlo sampling are exhibited in Figure 2. An optimum description of the data is accomplished by $\zeta = 0.2 \cdots 0.5$, as quantified by $\chi_{d.o.f.}^2 = 0.32 \cdots 0.31$. It turns out, however, that larger energy losses are also compatible with data (e.g., $\chi_{d.o.f.}^2 = 0.43$ (0.76) for $\zeta = 1.0$ (2.0)), as no energy loss does ($\chi_{d.o.f.}^2 = 0.39$ for $\zeta = 0$). Insofar, the present data do not constrain significantly the energy loss of charm quarks. Our neglect of the dead cone effect [4] and the use of the mean energy loss instead of the proper distribution [5] overestimates the theoretical energy loss. We are aware that it would be better to compare pp data with central AA data because the minimum bias data might be contaminated by energy losses.

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[1]This choice describes the charged hadron and π^0 spectra measured by PHENIX in peripheral collisions and is compatible with UA1 data [K. Gallmeister, C. Greiner, Z. Xu, to be published].

3. DILEPTON SUPPRESSION

As pointed out in [9] and quantified in [6,10], energy loss effects can suppress the dileptons from charm decays. This is a potentially important effect since these charm contributions compete with the Drell-Yan yield [11] and hide the interesting thermal contribution. Given the above parameterization of the modifications of inclusive single electrons by energy losses of charm quarks, we proceed to estimate the possible suppression of dileptons from correlated semi-leptonic decays of open charm mesons. Our predictions are displayed in Figure 3 for various values of the strength parameter ζ. Indeed, the dilepton spectra are quite sensitive to energy losses, however, assuming a small loss, as suggested by the above analysis, the corresponding suppression is small. This implies that without subtracting the charm component in dilepton spectra, an identification and quantification of the thermal yield will hardly be possible. Otherwise, as shown in [12] the thermal dilepton contribution allows a very concise characterization of the highly excited strongly interacting matter. Therefore, it would be very useful to get experimental dilepton spectra with identified charm contribution.
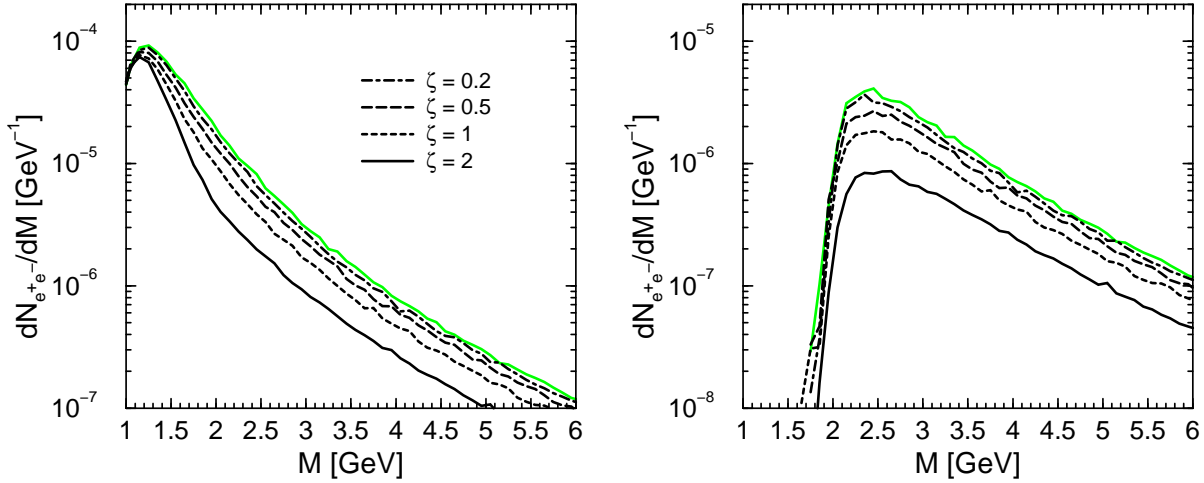

Figure 3. Predicted dilepton spectra from open charm mesons for various strength parameters of the energy loss within the PHENIX acceptance. $T_{AA} = 31/\text{mb}$, $\sqrt{s_{NN}} = 200$ GeV. Left (right) panel: single-lepton $p_\perp^{\min} = 0.5$ (1.0) GeV/c.

4. MOMENTUM IMBALANCE OF PHOTON-TAGGED JETS

Following the suggestion in [13] one can try to extract information on energy losses from photon-tagged jets. After the hard reaction $g + q \rightarrow \gamma + q$ the outgoing photon does not suffer any noticeable modification by the ambient medium. Therefore, the momentum imbalance $p_\perp^\gamma - \langle p_\perp^q \rangle$ may serve as a sensible quantity to characterize the energy loss of the outgoing quark q which can be identified in a jet by selecting a sufficiently narrow cone [7]. Within the above described scheme the resulting momentum imbalance is depicted in Figure 4. Clearly seen is the dependence on the initial condition which essentially comes from life time effects. For $T_i = 550$ MeV the two-regime behavior from Eq. (1) is evidenced. For more details consult [7].
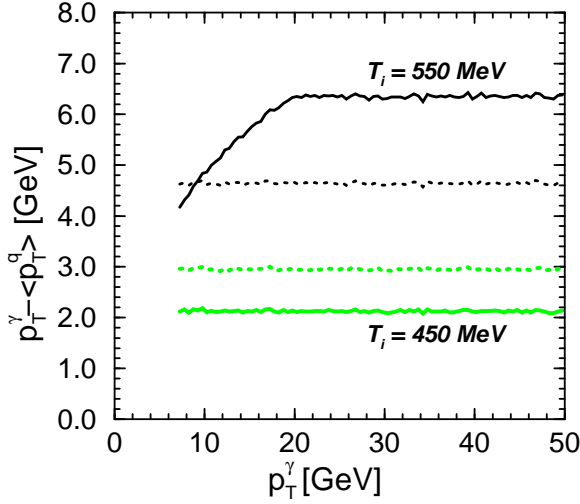
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Figure 4. Momentum imbalance of photon-tagged jets at midrapidity for two initial temperatures. $\zeta = 2$ in the energy loss scheme according to Eq. (1) is used (solid curves). The dotted curves are for a constant energy loss $dE/dx = -1$ GeV/fm.

5. SUMMARY

The present inclusive single-electron spectra [8] from open charm decays in Au + Au collisions at $\sqrt{s_{NN}} = 130$ GeV seem to point to tiny energy losses. More quantitative conclusions can be drawn after the release of the data of Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV which have better statistics and better centrality selection [14]; also the release of the pp data at the same energy will be very helpful.

Photon-tagged jets are considered useful to accomplish the goal of jet tomography of deconfined matter.

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