

Heavy-Quark Diffusion, Flow and Recombination at RHIC

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Abstract. We discuss recent developments in assessing heavy-quark interactions in the Quark-Gluon Plasma (QGP). While induced gluon radiation is expected to be the main energy-loss mechanism for fast-moving quarks, we focus on elastic scattering which prevails toward lower energies, evaluating both perturbative (gluon-exchange) and nonperturbative (resonance formation) interactions in the QGP. The latter are treated within an effective model for D - and B -meson resonances above T_c as motivated by current QCD lattice calculations. Pertinent diffusion and drag constants, following from a Fokker-Planck equation, are implemented into an expanding fireball model for Au-Au collisions at RHIC using relativistic Langevin simulations. Heavy quarks are hadronized in a combined fragmentation and coalescence framework, and resulting electron-decay spectra are compared to recent RHIC data. A reasonable description of both nuclear suppression factors and elliptic flow up to momenta of ~ 5 GeV supports the notion of a strongly interacting QGP created at RHIC. Consequences and further tests of the proposed resonance interactions are discussed.

1. Introduction: The Virtue of Heavy Quarks in Heavy-Ion Collisions

The observed suppression of high-momentum particles in central Au-Au collisions is one of the most exciting discoveries made at the Relativistic Heavy-Ion Collider (RHIC) to date. It has been interpreted as a large energy loss of energetic partons traveling through an almost opaque partonic medium, the “strongly-interacting Quark-Gluon Plasma” (sQGP). The underlying microscopic mechanism has been attributed to medium-induced radiation of gluons. However, recent data at RHIC, showing a strong nuclear suppression (small R_{AA}) [1, 2] and elliptic flow (large v_2) [3] of “non-photonic” single electrons (attributed to the semileptonic decay of charm and beauty hadrons) in semi-/central Au-Au, have posed challenges to the radiative energy-loss picture within perturbative QCD (pQCD). The importance of elastic interactions of heavy quarks (HQs) in the QGP in this context has been pointed out in Refs. [4, 5, 6, 7, 8]. Within pQCD, radiative and elastic energy-loss mechanisms turn out to be equally important in the currently accessible momentum range at RHIC, and their combined effect reduces the discrepancy with the measured electron R_{AA} in central Au-Au (but does not eliminate it) [7].

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However, even when using upscaled transport coefficients within pQCD energy-loss calculations [9], the maximal single-electron (e^\pm) v_2 is limited to 2-3% in semicentral Au-Au, while the experimental values reach up to 10% around $p_T^e=2$ GeV [3]. Significantly larger theoretical v_2 values can only be obtained if the quarks interact strongly enough to become part of the collectively expanding medium, implying that not only energy-loss but also energy-gain processes (detailed balance) need to be accounted for. This has recently been studied employing Langevin simulations of HQs in an expanding QGP based on elastic reinteractions [4, 5, 6, 8]. Since at RHIC energies, secondary production of HQs is suppressed [10], the latter are also valuable probes of the soft (collective) properties of the putative sQGP, and can provide tests of hadronization mechanisms, e.g., quark coalescence [11]. HQ-momentum distributions furthermore have important impact on secondary production (regeneration) of heavy quarkonium states [12, 13, 14].

In the present paper, we report on our studies [4, 6] of HQ properties in the sQGP and applications to RHIC, based on non-perturbative interactions. We will address pertinent uncertainties, open problems and consequences of our findings thus far.

2. Heavy-Flavor Baseline Spectra at RHIC

The interpretation of semileptonic e^\pm -spectra in A - A collisions requires a reliable estimate of baseline spectra in p - p , in particular their decomposition into contributions of charm and bottom decays (bottom quarks are much more inert to changes in their momentum spectra). Current pQCD predictions expect the transition from charm to bottom at around $p_T^e \simeq 4$ -5 GeV, albeit with significant uncertainty [15]. This rather early onset of a bottom component constitutes part of the difficulty in explaining the large suppression observed in the e^\pm -spectra in Au-Au collisions. In Refs. [6, 16], we have adopted a model-independent procedure to determine e^\pm baseline spectra, by first reproducing available data on D and D^* spectra, evaluating their contribution to the e^\pm spectrum at low(er) p_T , and then adjusting the bottom contribution to fill the high-

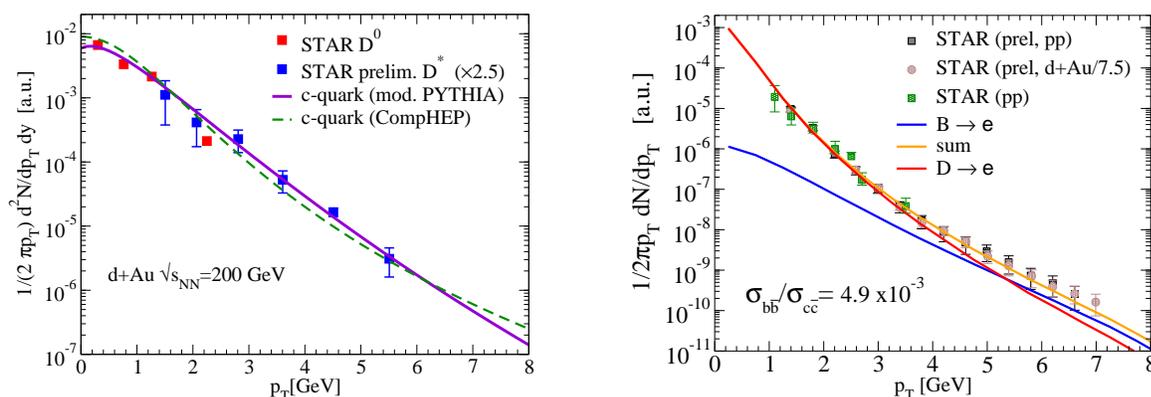


Figure 1. Left panel: D and D^* p_T -spectra in $\sqrt{s_{NN}}=200$ GeV d-Au collisions [17]; right panel: composition of semileptonic electron-decay spectra based on the charm spectra in the left panel in p - p and d-Au at RHIC[18].

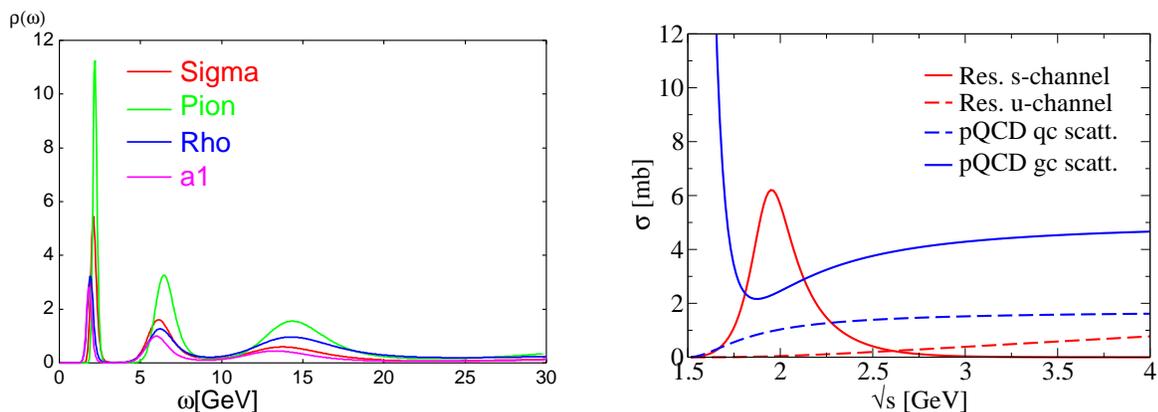


Figure 2. Left panel: mesonic spectral functions in the $q\bar{q}$ channel for "strange" quarks [21]; note the approximate degeneracy of the chiral multiplets. Right panel: total cross sections for a c quark scattering off partons within LO QCD (blue curves), and off antiquarks in the resonance model (red curves).

p_T part of the spectrum, cf. Fig. 1. Our result confirms the crossing of the c and b contributions at about $p_T \simeq 5$ GeV.

3. Elastic Heavy-Quark Scattering in the QGP

We evaluate (elastic) interactions of HQs in the QGP using Brownian motion of a heavy particle in a thermal background of light partons, as encoded in a Fokker-Planck equation [19, 20, 4, 5],

$$\frac{\partial f}{\partial t} = \gamma \frac{\partial(pf)}{\partial p} + D \frac{\partial^2 f}{\partial p^2}, \quad (1)$$

for the HQ distribution function, f . $\gamma = \tau_Q^{-1}$ and D_p are the corresponding drag and (momentum) diffusion constants which determine the approach to equilibrium and satisfy the Einstein relation, $T = D_p / \gamma M_Q$. They are typically calculated from elastic $2 \leftrightarrow 2$ scattering processes, $p + Q \rightarrow p + Q$ ($p = q, \bar{q}, g$; $Q = c, b$). In leading-order (LO) pQCD these are dominated by t -channel gluon exchange (regulated by a Debye mass). E.g., at a temperature $T = 300$ MeV, and for a strong coupling constant $\alpha_s = 0.4$, the thermal relaxation time for charm is $\tau_c \simeq 15$ fm/ c , well above expected QGP lifetimes of $\tau_{QGP} \lesssim 5$ fm/ c at RHIC. On the other hand, lattice QCD suggests that hadronic resonance (or bound) states in both $Q\bar{Q}$ and $q\bar{q}$ channels might survive up to temperatures of $\sim 2T_c$ [21, 22], cf. left panel of Fig. 2. In Ref. [4] we therefore suggested that D - and B -meson resonances in the $Q\bar{q}$ channel could accelerate the thermal relaxation of HQs. Based on an effective Lagrangian for the $\bar{q}\text{-}Q\text{-}\Phi$ interaction ($\Phi = D, B$),

$$\mathcal{L} = Q \frac{1 + \not{p}}{2} \Phi \Gamma \bar{q} + \text{h.c} \quad (2)$$

we evaluated elastic $Q + \bar{q} \rightarrow Q + \bar{q}$ scattering amplitudes via Φ exchange in s -, t and u -channel. Assuming the existence of one Φ state (e.g., a pseudoscalar $J^P = 0^-$), and

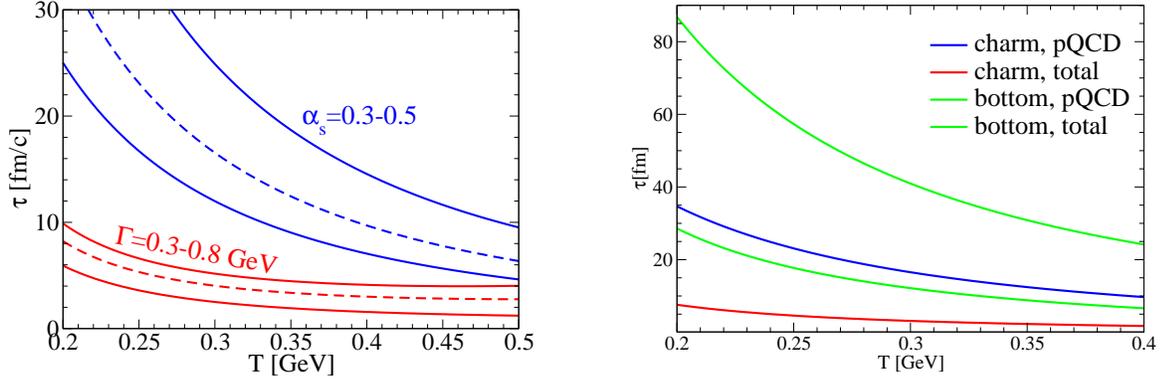


Figure 3. Left panel: thermalization times of c quarks in a QGP using LO pQCD (upper band) and resonance interactions (lower band); right panel: c - and b -quark thermalization times for LO pQCD interactions ($\alpha_s=0.4$, upper green and blue curve) and when adding resonance interactions ($\Gamma_\Phi=0.5$ GeV, lower green and red curve).

a minimal degeneracy following from chiral and HQ symmetries (with Dirac matrices $\Gamma=1, \gamma_5, \gamma^\mu, \gamma_5\gamma^\mu$ in Eq. (2)), the τ_Q 's are reduced by a factor ~ 3 over pQCD scattering (cf. Fig. 3), with moderate sensitivity to the unknown coupling at the effective $c\bar{q}-D$ ($b\bar{q}-B$) vertex. While the total cross sections for LO pQCD and resonance scattering are not very different in magnitude (right panel in Fig. 2), the angular distributions are: forward-dominated pQCD scattering is much less efficient in isotropizing the momentum distributions compared to the isotropic resonance scattering, since the (angular-averaged) "transport cross section" carries a weight of $1 - \cos\theta$ (θ : scattering angle in the center of mass).

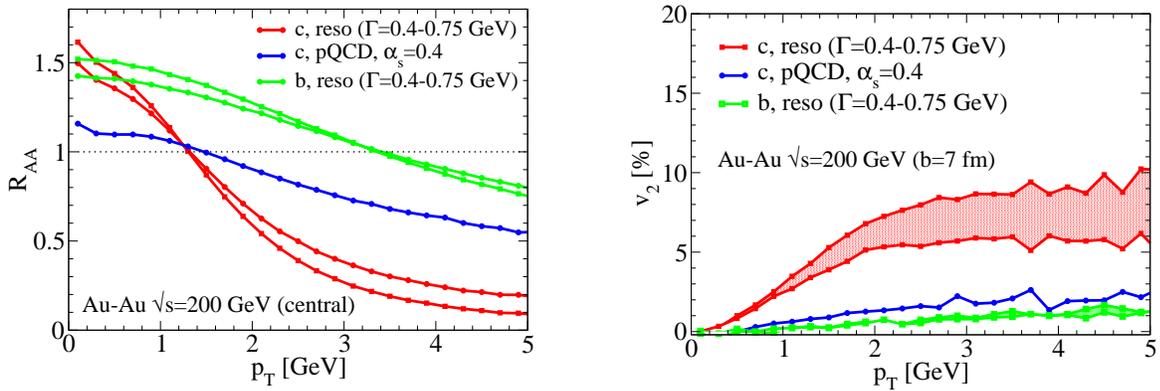


Figure 4. HQ nuclear suppression factor (left panel) and elliptic flow (right panel) following from relativistic Langevin simulations for an expanding QGP in Au-Au at RHIC; red (green) lines: c (b) quarks using resonance+pQCD interactions; blue lines: c quarks with LO pQCD scattering only.

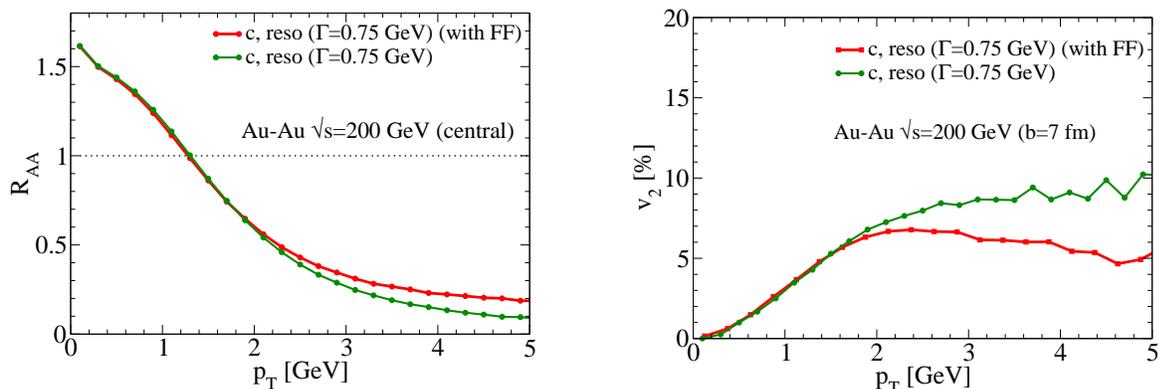


Figure 5. Comparison of the c -quark R_{AA} and v_2 following from Langevin simulations at RHIC when using effective \bar{q} - c - D vertices with renormalization (green curves) or monopole form factors with cutoff $\Lambda=1$ GeV (red curves).

4. Heavy-Quark and Single-Electron Spectra at RHIC

Using the initial c - and b -quark spectra as discussed in Sec. 2, the diffusion and drag coefficients as evaluated in Sec. 3 have been implemented into a relativistic Langevin simulation for an expanding QGP fireball at RHIC [6]. As expected, resonance interactions have a much larger effect on the nuclear suppression factor (R_{AA}) and elliptic flow (v_2) of c quarks in semi-/central Au-Au collisions than pQCD interactions (cf. Fig. 4), while b quarks are less affected. The leveling-off of the c -quark elliptic flow characterizes the transition from a quasi-thermal to a kinetic regime.

Fig. 5 illustrates the sensitivity of the Langevin results to the regularization procedure applied to the Q - \bar{q} loops [4]: at quark momenta above 3 GeV a renormalized interaction (point-like vertices) leads to somewhat stronger effects compared to finite-size vertices (form factor with cutoff $\Lambda=1$ GeV and identical resonance widths).

To compare to e^\pm observables, the HQs have been hadronized and decayed semileptonically [11, 6]. If the hadronization is performed by using δ -function fragmentation only, the resulting e^\pm R_{AA} and v_2 do not describe the data very well, cf. Fig. 6. The situation improves when allowing for coalescence of the HQs with light quarks [11, 6] at T_c which preferentially occurs at lower momenta (the remaining HQs are again δ -function fragmented). Consequently, we find an increase in *both* R_{AA} and v_2 mostly for momenta up to $p_T \simeq 4$ -5 GeV, leading to fair agreement with experiment, cf. Fig. 7. At higher p_T , contributions from radiative energy-loss (which have been neglected here) are expected to become important. Note that at high p_T the data for R_{AA} stay small, while the v_2 tends to (much) reduced values, which is suggestive for substantial energy loss with small collectivity. Such a feature is indeed consistent with perturbative energy-loss mechanisms. We also recall that the Langevin results in Figs. 6 and 7 presumably overestimate the suppression and v_2 at high p_T somewhat, due to the assumptions of (i) point-like vertices (cf. Fig. 5), and (ii) a thermal background medium even at high p_T (while from light hadron spectra of RHIC one infers that full

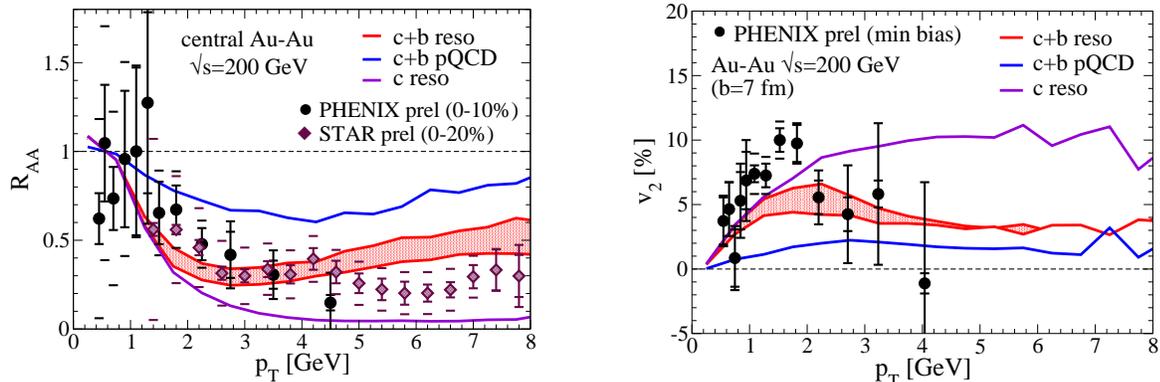


Figure 6. Nuclear suppression factor (left panel) and elliptic flow (right panel) for non-photon single-electron spectra in semi-/central Au-Au collisions at RHIC. Data [1, 2, 3] are compared to theory predictions [6] using Langevin simulations with elastic c - and b -quark interactions in an expanding QGP fireball and δ -fragmentation at T_c ; red band: LO pQCD + resonance interactions (with $\Gamma_\Phi=0.4-0.75$ GeV), blue line: LO-pQCD only, purple line: c quarks only for LO pQCD and resonances.

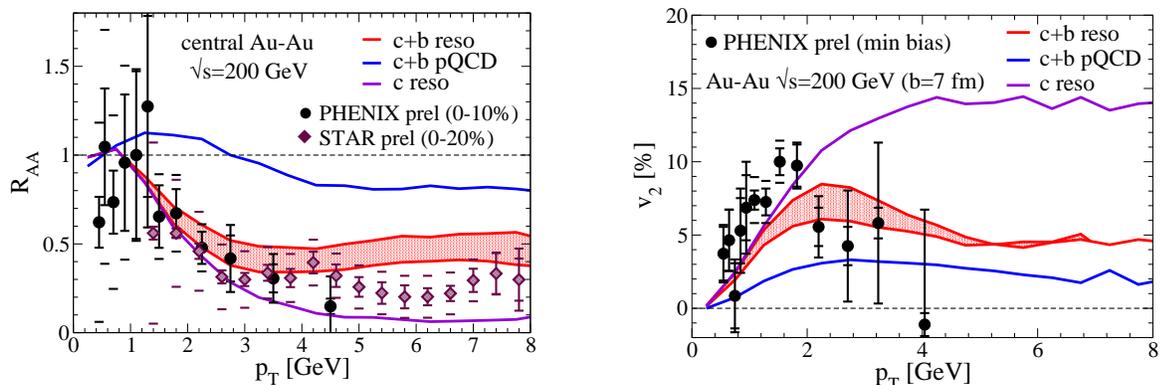


Figure 7. Same as Fig. 6 but including heavy-light quark-coalescence at hadronization.

thermalization for light partons reaches to about $p_T \simeq 1$ GeV).

5. Discussion and Further Tests

The small R_{AA} and the large v_2 in the e^\pm data require strong interactions of heavy quarks in the QGP, (well) beyond radiative energy-loss. While elastic pQCD scattering reduces the discrepancy in the R_{AA} , a sufficient collectivity to explain the v_2 can only be obtained for (unrealistically!?) large coupling constants [5]. Resonance scattering is a promising candidate for a microscopic explanation of the apparently large diffusion constant (for an estimate of energy loss due to $3 \leftrightarrow 3$ scattering, cf. Ref. [23]).

An important feature that distinguishes resonance contributions from pQCD relates to the chemical composition of the QGP. While the resonances as implemented here require the presence of anti-/quarks (here we have assumed QGP in chemical equilibrium for 2+1 flavors, amounting to ~ 25 anti-/quark and 16 gluon degrees of freedom),

pQCD approaches typically assume a gluon plasma by saturating the bound on the produced entropy in central Au-Au at RHIC with $dN_g/dy=1000$; this maximizes the color charge and thus the interaction strength in both radiative (gluon emission) and elastic (gluon exchange) channels. Thus, if RHIC indeed produces a gluon plasma, resonance scattering could be severely suppressed (much less is known about the presence of colored composites [24]). However, if quark-pair production occurs early in the collision resulting in an approximately chemically equilibrated QGP [25], more than half of the partons are anti-/quarks and the pQCD transport coefficient is appreciably reduced, increasing the importance of non-perturbative effects.

While the existence of resonances needs to be scrutinized theoretically (e.g., by lQCD calculations of heavy-light correlators, or effective models based on lQCD potentials [24, 26]), one should also search for experimental means of discrimination. The relative quark content of the colliding nuclear system can be increased by lowering the center-of-mass energy, while antiquarks (and possibly gluons) become suppressed. Thus, one would expect stronger rescattering of \bar{c} quarks compared to c quarks, resulting in larger v_2 and smaller R_{AA} for D^- and \bar{D}^0 relative to D^+ and D^0 -mesons. Whether such an effect is detectable at lower RHIC energies, or whether one has to await the (higher luminosities at the fixed-target) Compressed Baryonic Matter (CBM) experiment at the future GSI facility, needs to be checked in quantitative studies. We also note that diquark-like c - q interactions could diminish the differences between D and \bar{D} mesons (or even charm-exchange reactions in the hadronic phase [27]).

Finally, it is important to keep in mind the consistency of open and hidden charm. As has been emphasized by several authors [28, 12, 13, 14], secondary production (regeneration) of charmonia is much facilitated by a softening (thermalization) of the c - and \bar{c} -quark momentum distributions (for bottom/onia, this interplay appears to be less pronounced, even at the LHC [29]).

6. Conclusions

Heavy-quark probes at RHIC have posed new challenges to the theoretical understanding of parton-energy loss at high momenta and (the approach to) equilibration at moderate and low momenta. Currently, the severeness of this problem hinges on the interpretation of (semileptonic-decay) electron spectra, and in particular their relative decomposition into charm- and bottom-decay contributions (obviously, explicit D -meson measurements would remove this ambiguity). If their crossing in baseline p - p spectra occurs around $p_T \simeq 5$ GeV, the combination of radiative and elastic pQCD interactions of heavy quarks is apparently too weak to generate a suppression and collectivity consistent with the observed spectra in semi-/central Au-Au collisions. We have presented a scenario based on resonance exchange to introduce nonperturbative elastic interactions of heavy quarks in the sQGP at moderate temperatures (relevant for RHIC). When treated within a Brownian motion scheme for an expanding QGP fireball, a fair description of the single- e^\pm spectra up to $p_T \simeq 4$ -5 GeV emerges (especially if hadronization is supplemented with

heavy-light-quark coalescence); at higher p_T , induced gluon radiation (not included here) is expected to take over and become the main source of heavy-quark energy loss. A consistent implementation of the latter in the Fokker-Planck approach, which requires the integration of coherence effects, is not an easy task. We have also emphasized the importance of the chemical composition of the (early) QGP which affects the diffusion constants in the perturbative and nonperturbative sectors (as evaluated here) in a rather opposite way and may thus help to disentangle the two. An excitation function could provide a valuable handle to explicitly vary the quark-to-gluon ratio to further illuminate the nature of heavy-quark diffusion in the QGP.

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