

# Novel heavy flavor suppression mechanisms in the QGP

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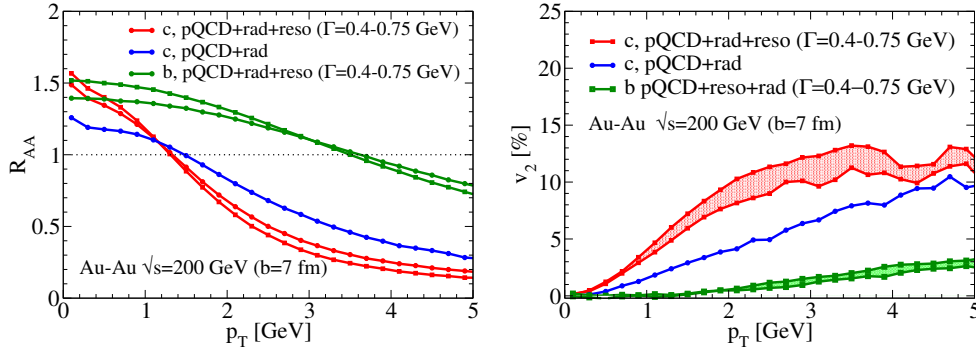
**Abstract.** We revisit the question of the measured, unexpectedly large, heavy flavor suppression,  $R_{AA}(p_T) \ll 1$ , in nucleus-nucleus collisions at RHIC and compare two new theoretical approaches to the  $D$ - and  $B$ -meson quenching. In the first model, radiative energy loss, collisional energy loss and heavy quark-resonance interactions are combined to evaluate the drag and diffusion coefficients in the quark-gluon plasma and the mixed phase. These are applied in a relativistic Fokker-Planck equation to simulate the heavy  $c$ - and  $b$ -quark suppression rate and elliptic flow  $v_2(p_T)$ . In the second model, the fragmentation probability for heavy quarks and the medium-induced decay probability for heavy hadrons are derived. These are implemented in a set of coupled rate equations that describe the attenuation of the observable spectra from the collisional dissociation of heavy mesons in the QGP. An improved description of the non-photonic electron  $R_{AA}(p_T)$  at RHIC can be obtained. In contrast to previous results, the latter approach predicts suppression of  $B$ -mesons comparable to that of  $D$ -mesons at transverse momenta as low as  $p_T \sim 10$  GeV.

## 1. Introduction

The detailed suppression pattern,  $R_{AA}(p_T)$ , and elliptic flow,  $v_2(p_T)$ , of high-transverse-momentum hadrons is an important experimental signature of the quark-gluon plasma creation in heavy ion collisions [1]. Jet quenching for light mesons, such as  $\pi$ ,  $K$  and  $\eta$ , at RHIC is well explained by radiative energy loss calculations [2]. It also gives the dominant contribution to the azimuthal asymmetry of hard probes [1]. In contrast, models [5] with a physically reasonable set of QGP temperatures and densities, predict a QCD heavy-quark energy loss which is too small compared to the measured suppression of single non-photonic electrons [3, 4]. Therefore, it is critical to investigate new interaction mechanisms in the QGP that may be specific to heavy flavor [6, 7, 10, 11].

## 2. Heavy-flavor suppression in a combined transport + quenching approach

Thermalization of heavy quarks in the QGP-heat bath has been recently studied in the framework of the parton-transport approach [6, 7, 8]. Large nuclear suppression



**Figure 1.** Left panel: preliminary results on the nuclear modification  $R_{AA}(p_T)$  for heavy  $c$ - and  $b$ -quarks [10] from collisional [5] and radiative energy loss [9] and quark-resonance interactions [6, 7]. For charm quarks, the PQCD  $\Delta E$  contribution is shown separately. Right panel: elliptic flow  $v_2(p_T)$  for heavy  $c$ - and  $b$ -quarks for the same physics mechanisms [10].

and elliptic flow  $v_2$  result when employing a Fokker-Planck equation,

$$\frac{\partial f(\vec{p}, t)}{\partial t} = \frac{\partial}{\partial p_i} \left[ p_i A(\vec{p}, t) + \frac{\partial}{\partial p_j} B_{ij}(\vec{p}, t) \right] f(\vec{p}, t), \quad (1)$$

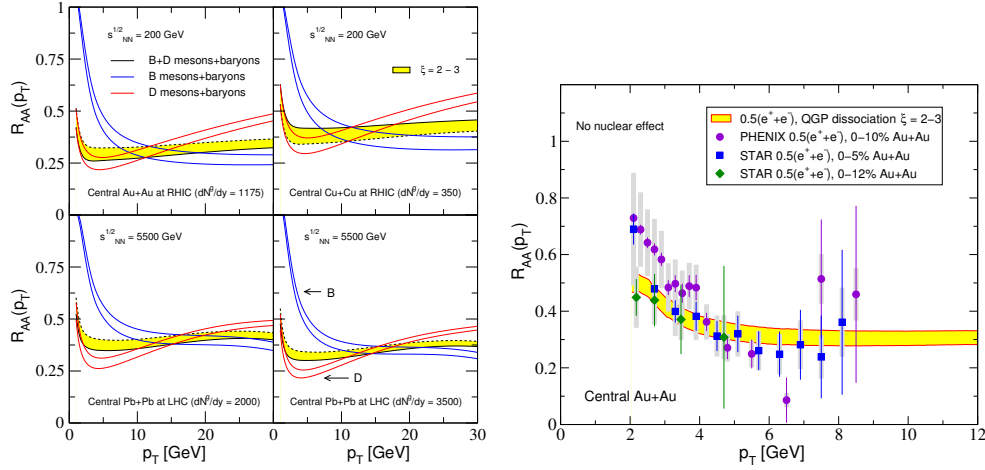
solved via an equivalent Langevin simulation. In Eq. (1)  $f(\vec{p}, t)$  is the distribution of  $c$ - and  $b$ -quarks and  $A(\vec{p}, t), B(\vec{p}, t)$  are the drag / diffusion coefficients, respectively. It has been argued that strong coupling between the  $c$ - and  $b$ -quarks and the QGP medium may be generated via quark-resonance interactions near the QCD-phase transition,  $T \sim T_c$  [6]. It is, therefore, important to study the interplay between such non-perturbative effects and the radiative [9] and collisional [5] heavy-quark energy loss. We evaluate [10] the contribution of these processes to the drag and diffusion coefficients,

$$A(\vec{p}, t) = \frac{1}{p_i} \frac{\langle \delta p_i \rangle}{\delta t}, \quad B_{ij}(\vec{p}, t) = \frac{1}{2} \frac{\langle \delta p_i \delta p_j \rangle}{\delta t}, \quad (2)$$

which are then applied in the relativistic Fokker-Planck equation.

Results on the  $p_T$ -dependent suppression pattern of heavy quarks,  $R_{AA}(p_T)$ , are shown in the left panel of Fig. 1. Drag coefficients are easily evaluated from the fractional momentum loss of heavy quarks, see Eq. (2). The diffusion coefficients in this preliminary study were constrained from the fluctuation-dissipation relation. We observe that the suppression of charm quarks can be very large even in minimum-bias reactions of large nuclei and  $R_{AA}(\text{charm}) \ll R_{AA}(\text{bottom})$ . The high- $p_T$  azimuthal asymmetry for minimum-bias Au+Au collisions is shown in the right panel of Fig. 1. We note that the generated  $v_2$  for  $b$ -quarks is much smaller than that for  $c$ -quarks.

One of the reasons for the large suppression in our current energy-loss implementation is that the Einstein fluctuation-dissipation relation induces minimal Gaussian fluctuations. These are significantly different from the ones in the probabilistic treatment of PQCD-energy loss [1, 2, 5]. Future Langevin simulations of  $c$ - and  $b$ -quark diffusion should include momentum fluctuations beyond the Einstein's relation and the decay of the heavy quark / hadron spectra into  $(e^+ + e^-)$  for direct comparison to the non-photonic electron observables at RHIC [10].



**Figure 2.** Left panel: suppressions of  $D$ - and  $B$ -meson production via collisional dissociation in the QGP in central Au+Au and Cu+Cu reactions at RHIC [11] for gluon rapidity densities  $dN^g/dy = 1175$  and  $350$ , respectively [2]. Right panel: quenching of the non-photonic electrons from the softened  $D$ - and  $B$ -meson spectra in central Au+Au collisions [11]. Data is from PHENIX [3, 14] and STAR [4, 12, 13].

### 3. QGP-induced dissociation of heavy mesons

In the perturbative QCD-factorization approach, the cause of the limited single non-photonic electron quenching is identified as the small suppression of  $B$ -mesons, which dominate the high- $p_T$   $e^+e^-$  yields. Such models assume that the hard jet hadronizes in vacuum, having fully traversed the region of hot and dense nuclear matter,  $L_T^{\text{QGP}} \leq 6$  fm, and lost energy via radiative and collisional processes [1, 2, 5]. In Ref. [11] we examined the validity of this assumption for different species of final-state partons and decay hadrons. For a  $p_T = 10$  GeV pion at mid-rapidity  $\tau_{\text{form}} \approx 25$  fm  $\gg L_T^{\text{QGP}}$ , consistent with the jet-quenching assumptions [1, 2]. In contrast,  $B$ - and  $D$ -mesons of the same  $p_T$  have formation times  $\tau_{\text{form}} \approx 0.4, 1.6$  fm, respectively,  $\ll L_T^{\text{QGP}}$ . Therefore, at the finite  $p_T$  range accessible at RHIC and LHC a conceptually different approach to the description of  $D$ - and  $B$ -meson quenching in A+A collisions is required, when compared to light hadrons.

Motivated by this finding, in the framework of the GLV theory, we derive the collisional dissociation probability of heavy mesons in the QGP [11]:

$$P_d(\chi\mu^2\xi) = [1 - P_s(\chi\mu^2\xi)] \geq 0, \quad P_d(\chi\mu^2\xi = 0) = 0. \quad (3)$$

In Eq. (3)  $2\chi\mu^2\xi = 2(\mu^2L/\lambda)\xi$  is the cumulative 2D transverse momentum squared per parton. The dissociation probability also depends on the detailed heavy meson light cone wave function. The dynamics of open heavy flavor production and modification in this model is represented by a set of coupled rate equations that describe the competition between  $b$ - and  $c$ -quark fragmentation and  $D$ - and  $B$ -meson dissociation [11]:

$$\partial_t f^Q(p_T, t) = -\frac{f^Q(p_T, t)}{\langle\tau_{\text{form}}(p_T, t)\rangle} + \frac{1}{\langle\tau_{\text{diss}}(p_T/\bar{x}, t)\rangle} \int_0^1 dx \frac{1}{x^2} \phi_{Q/H}(x) f^H(p_T/x, t), \quad (4)$$

$$\partial_t f^H(p_T, t) = -\frac{f^H(p_T, t)}{\langle\tau_{\text{diss}}(p_T, t)\rangle} + \frac{1}{\langle\tau_{\text{form}}(p_T/\bar{z}, t)\rangle} \int_0^1 dz \frac{1}{z^2} D_{H/Q}(z) f^Q(p_T/z, t). \quad (5)$$

In Eqs. (4) and (5)  $f^i(p_T, t) = d\sigma^i/dyd^2p_T$ . For further details, see [11].

We solve this system of coupled rate equations numerically, using the same initial soft-gluon rapidity density  $dN^g/dy$  as in the calculation of the  $\pi^0$  quenching [2] in central Au+Au and Cu+Cu collisions at RHIC. Our results, including a study of a range of anticipated QGP densities at the LHC, are shown in the left panel of Fig. 2. Contrary to calculations that emphasize radiative and collisional heavy quark energy loss [5, 7, 10], QGP-induced dissociation predicts  $B$ -meson suppression comparable to or larger than that of  $D$ -mesons at transverse momenta as low as  $p_T \sim 10$  GeV [11]. The heavy meson spectra are decayed into electrons ( $e^+ + e^-$ ) using the PYTHIA event generator. Our results are shown in the right panel of Fig. 2. The predicted  $R_{AA}(p_T)$ , which does not neglect the large  $B$ -meson contribution, describes well the most recent heavy flavor quenching measurements at RHIC [12, 13, 14]. We emphasize that such agreement between theory and experiment is not achieved at the cost of neglecting the contribution of the  $B$ -mesons to the non-photonic  $e^+e^-$  spectra.

#### 4. Conclusions

In these proceedings, we compared two new theoretical approaches [10, 11] to open heavy flavor modification in the QGP. Preliminary results on Langevin simulations of heavy quark diffusion, which include radiative energy loss, collisional energy loss and quark-resonance interactions, were shown. While an improved implementation of momentum fluctuations is required for quantitative comparison between data [3, 4] and theory [10], we find normal suppression,  $R_{AA}(c) \ll R_{AA}(b)$ , and elliptic flow,  $v_2(c) \gg v_2(b)$ , hierarchies as function of the heavy quark mass. Results on QGP-induced collisional dissociation of heavy mesons [11] were also shown. A good description [12, 13, 14] of the large quenching of the inclusive non-photonic electrons [3, 4] is achieved by this model. A natural consequence of the approach developed in Ref. [11] is that  $B$ -mesons are attenuated as much as  $D$ -mesons at transverse momenta as low as  $p_T \sim 10$  GeV. We conclude that robust experimental determination of the dominant mechanism for in-medium modification of open heavy flavor would require direct and separate measurements of the  $B$ - and  $D$ -meson  $R_{AA}$  and  $v_2$  distributions versus  $p_T$  and centrality in collisions of heavy nuclei.

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