

## Heavy Flavor in the sQGP

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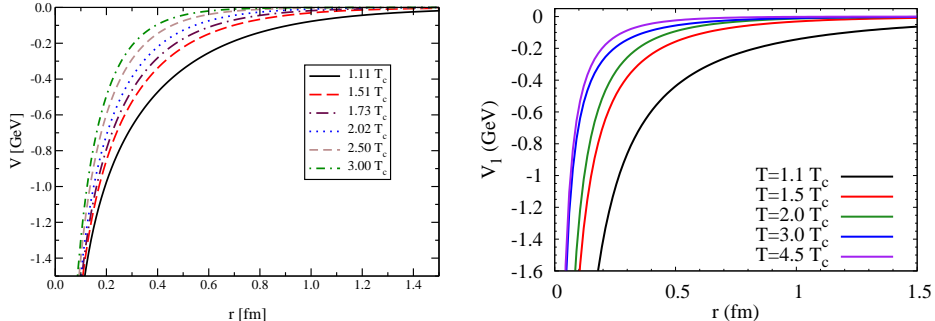
**Abstract.** We attempt a unified treatment of heavy quarkonia and heavy-quark diffusion in the Quark-Gluon Plasma. Our approach is based on finite-temperature  $T$ -matrices with interaction potentials estimated from the heavy-quark internal energy computed in thermal lattice QCD (lQCD). In the charmonium sector  $S$ -wave bound states ( $J/\psi$ ,  $\eta_c$ ) survive up to temperatures of  $\sim 2T_c$ , not inconsistent with constraints from euclidean correlation functions in lQCD. In the open-heavy flavor sector, the  $T$ -matrix interaction reduces heavy-quark diffusion substantially, leading to fair agreement with single-electron spectra at RHIC and suggestive for a small viscosity-to-entropy ratio close to  $T_c$ .

*Keywords:* Quark-Gluon Plasma, Heavy Quarks, Heavy-Ion Collisions

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### 1. Introduction

The properties of the strong-interaction matter produced in Au-Au collisions at RHIC are under intense debate. The empirical evidence collected thus far suggests a liquid-like medium which (i) quickly establishes, and then maintains, local thermal equilibrium for low transverse-momentum particles ( $p_t \leq 2$  GeV), (ii) is largely opaque to high  $p_t \geq 5$  GeV particles, (iii) exhibits constituent quark-scaling properties in hadron production at intermediate  $p_t \simeq 2$ -5 GeV. A key question is if and how



**Fig. 1.** Color-singlet heavy-quark internal energies at finite temperature (with the asymptotic value,  $U_\infty \equiv U(r \rightarrow \infty, T)$  subtracted) extracted from 3-flavor [ 8] (left panel) [ 4] and quenched IQCD [ 9] (right panel) [ 10].

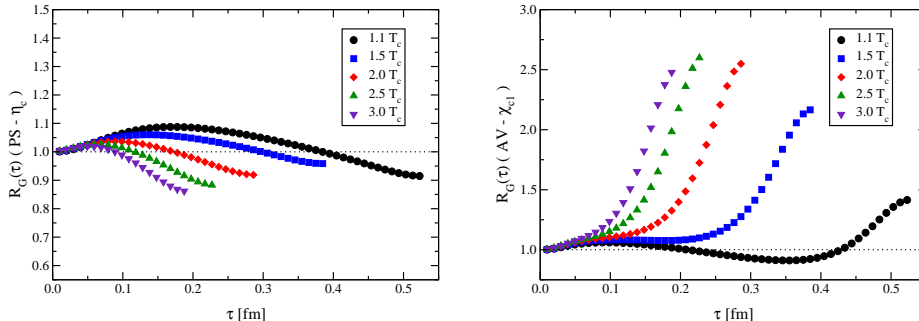
these phenomena are related [ 1, 2] and what the relevant interactions are (e.g., radiative or elastic, perturbative or nonperturbative, gluon- or quark-driven, etc.). In this article we approach this problem via the heavy-quark (HQ) sector. For heavy quarkonia, the hope has emerged that, using potential models, one can quantitatively analyze in-medium quarkonium properties based on input from lattice QCD (IQCD), which is discussed in Sec. 2. The question arises whether similar interactions could be relevant for low-momentum properties of individual heavy quarks in the Quark-Gluon Plasma (QGP), i.e., for HQ diffusion; this is studied in Sec. 3, including applications to observables. We conclude in Sec. 4.

## 2. Heavy Quarkonia

Our starting point is a two-body scattering equation for the in-medium  $T$ -matrix of a heavy quark ( $Q$ ) and antiquark ( $\bar{Q}$ ) [ 3, 4],

$$T(E, q, q') = V(q, q') + \int d^3k V(q, k) G(E, k) T(E, k, q'). \quad (1)$$

It represents a “ladder” resummation of a suitably defined HQ potential,  $V$ , and is widely used in the nuclear many-body problem as well as in the study of electromagnetic plasmas [ 5];  $G$  denotes the intermediate  $Q$ - $\bar{Q}$  propagator including selfenergy insertions due to interactions with the surrounding medium particles. The main approximations are neglecting (i) virtual  $Q$ - $\bar{Q}$  excitations, and (ii) retardation effects in the interaction; both should be reasonable for large quark masses,  $m_Q$ . The  $T$ -matrix provides a uniform treatment of bound and scattering states which is particularly important for situations involving dissolving bound states, such as for atoms in plasma physics or quarkonia in the QGP. The precise relation between the HQ potential and free energy,  $F = U - TS$ , computed in thermal IQCD, is an open problem. We here adopt the internal energy,  $U$ , as the potential, but other choices

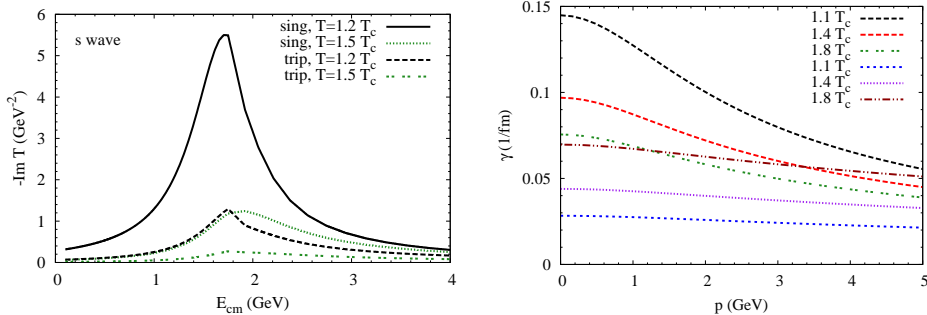


**Fig. 2.** Euclidean correlators for  $\eta_c$  (left) and  $\chi_{c1}$  (right) in the QGP computed within the  $T$ -matrix approach [ 4] using the HQ internal energy extracted from  $N_f=3$  IQCD [ 8]. The correlators are normalized to a reconstructed one based on the vacuum  $T$ -matrix. The increase in the  $\chi_c$  correlator is largely driven by zero-mode contributions [ 11] implemented in quasi-particle approximation.

are possible [ 6, 7]. Figure 1 shows that different extractions of  $U$  still imply up to  $\sim 40\%$  uncertainty. In either case, the increased color-screening leads to a reduction in charmonium binding with increasing temperature. However, when including an in-medium reduction of the  $c$ -quark mass governed by the asymptotic value of the internal energy,  $m_c^* = m_c^0 + U_\infty/2$ , the bound-state mass is almost stable. Together with the lowering of the  $c\bar{c}$  threshold,  $E_{\text{thr}} = 2m_c^*$ , and nonperturbative rescattering strength generated by the  $T$ -matrix [ 4], the pertinent  $\eta_c$  correlator is rather stable (cf. left panel of Fig. 2), similar to the findings in IQCD [ 12, 13]. The underlying spectral functions show that the bound state “melts” slightly above  $\sim 2T_c$ . Smaller melting temperatures are found in Refs. [ 6, 7] based on different input potentials, but the IQCD correlators can be well reproduced, due to the above-mentioned interplay between binding and threshold effects. An independent determination of the in-medium HQ mass, an improved definition of the potential, a quantitative implementation of finite width effects, as well as a coupled channel treatment to account for gluonic excitations, may be required to make further progress.

### 3. Heavy-Flavor Transport and Observables

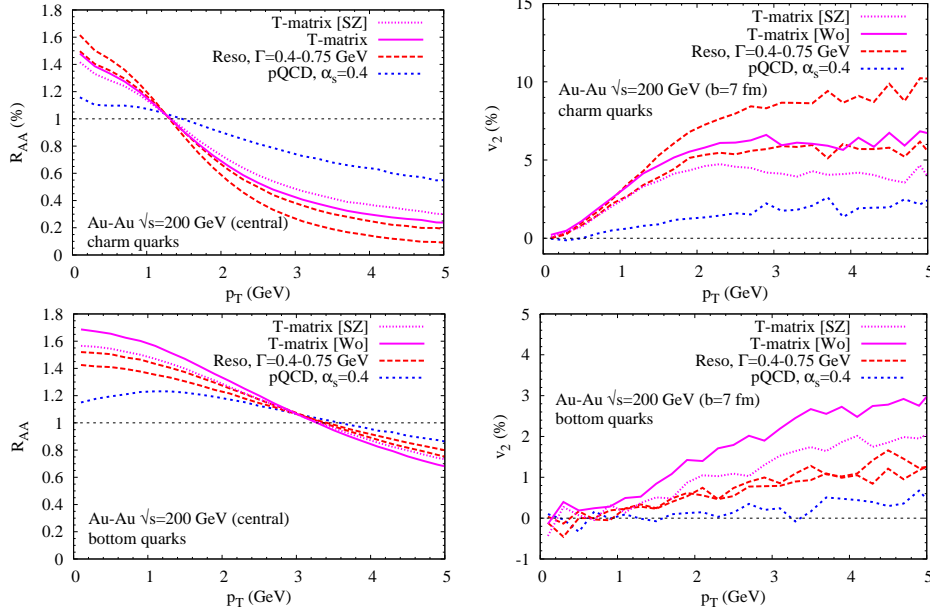
In Ref. [ 14] the exchange of effective meson resonances in scattering of heavy quarks in the QGP has been introduced and found to reduce charm- and bottom-quark thermalization times by a factor of  $\sim 3$  compared to elastic perturbative QCD (pQCD) scattering. When implemented into relativistic Langevin simulations for Au-Au collisions at RHIC [ 15], the predictions for semileptonic electron ( $e^\pm$ ) spectra from HQ decays turned out to be in fair agreement with experiment [ 16, 17]. In Ref. [ 18], nonperturbative HQ interactions in the QGP have been evaluated by employing the same  $T$ -matrix approach as discussed in the previous section,



**Fig. 3.** Left panel: Imaginary part of the  $T$ -matrix for  $c$ -quark scattering of light quarks and antiquarks in the QGP. Right panel: thermal relaxation rates for  $c$ -quarks following from the nonperturbative heavy-light  $T$  matrices (upper curves at  $p=0$ ) and from LO pQCD scattering off quarks and gluons with  $\alpha_s=0.4$ .

including all color channels (1,  $\bar{3}$ , 6, 8) as well as  $S$ - and  $P$ -waves in heavy-light quark scattering. The pertinent  $T$ -matrices exhibit (“pre-hadronic”) resonance-like  $D$ -meson and diquark correlations up to temperatures of  $\sim 1.5$  and  $1.2 T_c$ , respectively, cf. left panel of Fig. 3 (using the potential in the right panel of Fig. 1; in the bottom sector, the dissolution temperatures are slightly larger). The repulsive sextet and octet channels, as well as  $P$ -waves, are suppressed. The dissolution of the resonances leads to a *decrease* of the thermalization rate with increasing temperature, opposite to the standard behavior as found, e.g., in pQCD, cf. right panel of Fig. 3.

The heavy-light quark  $T$  matrices (supplemented by pQCD interactions with gluons) have been used to compute HQ diffusion in a Fokker-Planck approach and applied to Au-Au collisions at RHIC utilizing relativistic Langevin simulations in an expanding fireball. The resulting nuclear modification factor and elliptic flow are quite comparable to the effective resonance model [14, 15] (see Fig. 4), with slightly smaller (larger) effects for  $c$  ( $b$ ) quarks (which is qualitatively similar to the dissociation model of Ref. [19]). Uncertainties due to different extractions of the lQCD internal energy [10, 20] amount to  $\sim 30\%$ . The HQ spectra have been hadronized into  $D$  and  $B$  mesons in a combined coalescence/fragmentation framework [21, 15], with subsequent semileptonic (3-body) decays into single electrons. The relative weight of charm and bottom contributions is estimated from  $d$ -Au data [22], crossing at about  $p_t^e \simeq 5$  GeV, (cf. also Ref. [23]). Note that quark coalescence at  $T_c$  naturally emerges from the “pre-hadronic” resonant correlations in the  $T$ -matrix [24]. The electron spectra in Au-Au collisions [18], which do not involve adjustable parameters, compare well to the most recent RHIC data [16, 17, 23], see left panel of Fig. 5. The HQ diffusion coefficient at  $p=0$  can be used for a schematic estimate of the viscosity-to-entropy ratio ( $\eta/s$ ) in the QGP [1]; evaluating their relation in both weak- and strong-coupling limits leads to the pink band in the right



**Fig. 4.** HQ spectra in Au-Au collisions at RHIC utilizing relativistic Langevin simulations with nonperturbative HQ interactions [ 15, 18].

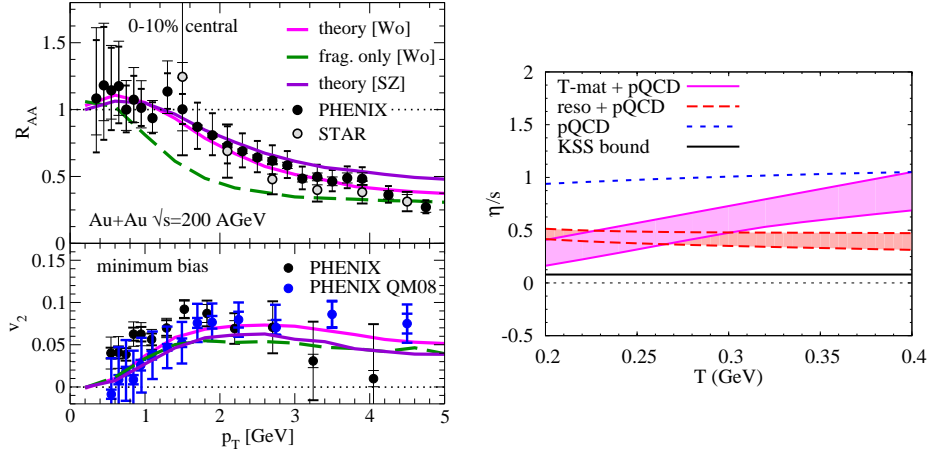
panel of Fig. 5: it rises with temperature and is indicative for a strongly coupled QGP close to  $T_c$ .

#### 4. Conclusions

An in-medium  $T$ -matrix approach (utilizing potentials estimated from thermal lattice QCD) has been applied to evaluate HQ interactions in the QGP. For charmonia,  $S$ -wave ground state can survive up to  $\sim 2T_c$ , roughly in line with lQCD correlators. For open heavy flavor, resonance-like correlations induce a small HQ diffusion coefficient which allows to describe  $e^\pm$  data and suggests a small  $\eta/s$  ratio. Several open problems remain, e.g., a proper definition of the potential, corrections to the  $T$ -matrix approach including radiative ones, and in-medium mass and width effects.

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**Fig. 5.** Left:  $e^\pm$  spectra in Au+Au collisions at RHIC following from the HQ spectra in Fig. 4 after hadronization and decay [18], compared to data [16, 17, 23]. Right: estimates of  $\eta/s$  [1] for pQCD, resonance model and  $T$ -matrix approach.

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