Open heavy flavor and quarkonium - theoretical overview

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Abstract. This is a theoretical overview of the new results regarding open heavy flavor and quarkonium presented in the Quark Matter 2023 conference.

1 Introduction

Hard probes play a crucial role in heavy-ion collisions. These probes are only generated at the onset of a collision because they require significant energy for their creation. Nevertheless, they undergo substantial modifications due to the presence of the medium, and they are relatively easy to detect. In our discussion, the focus revolves around probes associated with heavy quarks. Heavy quarks are good probes of the medium because their mass, m, is much larger than Λ_{QCD}. This implies that the production or annihilation of heavy quarks is a perturbative process. Furthermore, the temperature (T) of the medium is considerably smaller than the heavy quark mass. As a result, the medium's influence on the production of heavy quarks is minimal. However, the medium does play a crucial role in governing the diffusion of heavy quarks and influencing the likelihood of the formation of bound states. In the case of quarkonium, additional energy scales, such as the inverse of the typical radius ($\frac{1}{r}$) and the binding energy (E), come into play. Importantly, utilizing heavy quarks as probes allows exploring the medium's properties across various energy scales, offering valuable insights into its behavior and characteristics.

Open heavy quarks and quarkonia share many similarities but, at the same time, have important differences. Both are formed by heavy quarks, and they are sensitive to correlators of the chromoelectric field. Moreover, the theoretical tools that can be used to describe both systems are quite similar. For example, Boltzmann and Langevin equations and the T-matrix approach have been used to study these systems. On the other hand, differences arise in the way they respond to a collision with a medium constituent. A quarkonium state colliding with a medium parton will typically change the color state of the heavy quark pair from a color singlet to an octet, destroying the bound state. However, if we consider a single heavy quark in the medium, a collision with a parton will certainly change its color but would not imply a dramatic change. Additionally, heavy quarks undergo hadronization to particles of a size on the order of $1/\Lambda_{QCD}$, with each quarkonium species possessing a distinct size that can be much smaller. Another notable difference is that heavy quarks carry color while quarkonium bound states are globally color-neutral, rendering them less affected by infrared physics. Finally, heavy quarks at very large momentum exhibit similarities to jets, albeit with the consideration of the dead-cone effect.

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2 Open heavy flavor

Heavy quarks undergo momentum exchange with the surrounding medium particles, leading to a characteristic Brownian motion. This dynamic can be modeled by either a Langevin or a Boltzmann equation. Each has advantages and disadvantages. On one hand, the Boltzmann equation requires a more detailed understanding of the microscopic degrees of freedom. On the other hand, in the Langevin equation all the information about the medium is encoded in the momentum diffusion coefficient κ [1]. However, this description is only valid when the heavy quark's momentum is much larger than the medium's temperature. κ can be written as an expectation value of gauge fields

$$\kappa = \frac{g^2}{6N_c}\mathrm{Re}\int_{-\infty}^{\infty} dt \langle E^{i,a}(t,\mathbf{0})E^{i,a}(0,\mathbf{0})\rangle\,. \tag{1}$$

In fact, many of the results presented in this conference have to do with new determinations of κ. In [2], κ was computed in the pre-equilibrium phase using Effective Kinetic Theory. They found that in this regime κ is within 30% of its corresponding equilibrium value. In this environment, there is no rotational invariance because the beam axis represents a preferred direction. Therefore, κ has different values in the longitudinal and in the transverse direction. It was observed that transverse κ is enhanced at small times and converges to longitudinal κ at large times.

In the conference, it was also presented a new unquenched lattice QCD determination of κ [3]. A comparison with previous quenched determinations show that unquenched results are significantly larger. The new results agree with AdS/CFT determinations at low temperatures while they are also compatible with Next-to-leading order (NLO) perturbative results. They are also close to determinations based on the T-matrix approach. In summary, these unquenched results seem quite compatible with determinations using other approaches.

In [4] it was reported a computation based on the Boltzmann approach in which it was possible to define a mass dependent generalization of κ, being eq. (1) the infinite mass limit. However, within their approach they see that there is a significant difference between the values of kappa at the charm mass, at the bottom mass and at infinity. It happens that the value they obtain for kappa using the charm mass is compatible with previous quenched lattice QCD evaluations.

Another aspect of the interaction of heavy quarks with a medium that we have not discussed is radiation. A heavy quark traversing a medium might radiate gluons, producing an energy loss. This is the energy loss mechanism that dominates at large momentum. At moderate momentum, we might need to consider also collisional energy loss. The more significant difference between the radiation pattern of a heavy quark and that of a large momentum massless parton is the so-called dead-cone effect. A heavy quark can only emit gluons at an angle larger than M/E where E is the energy of the emitted particle. Recently, this effect has been observed directly for the first time [5].

Another aspect relevant for the study of open heavy flavor that we have not yet discussed is hadronization. As the fireball expands and cools down after the collision, the medium goes through a phase transition from a quark-gluon plasma to a hadron gas. At this point, the heavy quark must combine with some light quarks and gluons in order to form a meson. This affects the momentum of the observed heavy meson distribution and, therefore, it needs to be considered in a phenomenological analysis. Various models attempt to describe hadronization. We expect that at high-momentum, hadronization is well-described by fragmentation models and is not affected by the presence of the medium. However, at low momentum, the hadronization process is influenced by the surrounding medium. In this conference, it was presented a study, [6], showing that high multiplicity proton-proton collisions hadronization might already exhibit medium-like characteristics, similar to what is observed in heavy-ion collisions. Another model used to describe hadronization is the Statistical Hadronization Model (SHM). In this model, it is assumed that a thermal distribution of hadrons is found after the phase transitions. In [7] it was discussed how SHM is able to reproduce *pp* data and how the same model, combined with b quark diffusion within the plasma, can also describe reasonably heavy-ion data.

Finally, let us discuss the new theoretical approach presented in [8]. In this model, the heavy quarks are assumed to be in local thermal equilibrium. Then, the number of $Q\bar{Q}$ pairs is treated as an additional conserved charge within a hydrodynamical description of the medium. It is observed that this approach can accurately describe charm quarks, but has some difficulties describing bottom data. We can take this as an indication that charm is thermalized in nowadays heavy-ion collisions, while bottom is not.

3 Heavy quarkonium suppression

First, let us review the mechanism how the medium might modify the formation of bound states. The initial mechanism under consideration is color screening, as proposed by Matsui and Satz [9]. They suggested that the suppression of heavy quarkonium serves as a signal for QGP formation, attributing this suppression to the screening of chromoelectric fields at large distances. From a perturbative perspective, the potential at short distances undergoes a transition from a Coulomb potential at zero temperature to a Yukawa potential in the QGP. This implies the existence of a Debye radius, such that heavy quarks separated by a distance greater than the Debye radius cannot form a bound state. Another dissociation mechanism involves inelastic scattering with medium partons. Collisions with constituents of the medium lead to a transition from a color singlet to a color octet state, resulting in a finite thermal decay width. This mechanism, responsible for the imaginary part of the potential, was initially discussed in [10] and, although recognized before, gained significance through subsequent studies. It became apparent that it could be as crucial as screening, or even the dominant factor.

Now, let us discuss recombination—a process where two unbound heavy quarks join to create a new bound state within the medium. Recombination can be categorized into two types: uncorrelated and correlated. In the context of correlated recombination, the two heavy unbound quarks were initially part of the same bound state. Uncorrelated recombination, when the unbound heavy quarks were initially not part of the same bound state, dominates when the density of heavy quarks is high. At LHC energies, this implies that uncorrelated recombination significantly influences charmonium but plays a less significant role in bottomonium.

Now that we have discussed the relevant phenomena, let us briefly review the different theoretical approaches. We can classify them according to how they model the evolution of quarkonium. One possibility is to consider that the state of the quark-antiquark pair can be encoded in a probability distribution. This is the case for the approaches based in the rate or Boltzmann equation. In this case a decay width can be assigned to every quarkonium state and thermalization is achieved by construction due to the structure of the collision term. There are several mechanisms that can be responsible for this decay width as, for example, the absorption of a medium gluon (gluo-dissociation) or inelastic scattering with medium partons.

Alternatively, we can regard quarkonium as an open quantum system interacting with an environment (the medium). The state of quarkonium at a given time is encoded in its reduced density matrix. The equation that describes the evolution of the density matrix is called the master equation. The master equation for QCD has been derived using perturbation theory and HTL [11] and EFTs in the regime $Tr \ll 1$ [12, 13]. If the temperature is much larger than the binding energy $T \gg E$, the interaction of quarkonium with the medium is very fast compared to the time scales of the evolution of quarkonium. Then, from the point of view of the quarkonium, the interaction is instantaneous and, therefore, the evolution is Markovian. It is well-known that all Markovian master equations that maintain some basic properties of density matrices (trace equal to unity, being hermitian and complete positivity) are so-called Lindblad equations

$$\frac{d\rho}{dt} = -i[H,\rho] + \sum_n \left(C_n \rho C_n^\dagger - \frac{1}{2}\{C_n^\dagger C_n, \rho\} \right) , \tag{2}$$

where H is an Hermitian Hamiltonian and C_n's are so-called collapse operators.

In [12] it was found that in the regime $1/r \gg T \gg E$ (being E quarkonium's binding energy) all the information about the medium that enters quarkonium's evolution can be encoded in two transport coefficients, γ and κ. In fact, we should have been more precise when writing eq. (1) since there should be a Wilson line joining the two chromoelectric fields in order to make the expectation value gauge-invariant. This can be done either with a fundamental or an adjoin Wilson line. It happens that in the case of heavy quark diffusion we are interested in κ_{fund} while quarkonium's decay width is proportional to κ_{adj}. The differences between these two definitions of κ were discussed in [14]. Although both transport coefficients are equal at LO and NLO perturbative QCD there were found to be quite different in strongly-coupled $\mathcal{N} = 4$ Super Yang-Mills. More specifically, in this theory, $\kappa_{adj} = 0$ while κ_{fund} was previously known to have a finite value.

The Remmler's approach was also discussed in *Quark Matter 2023*, see [15]. This approach is based on the open quantum system framework, but one works with the Wigner distribution instead of the density matrix. Then the distribution is approximated by assuming that it has a classical phase space. The advantage of this approach is that it is possible to simulate a large quantity of heavy quarks in the medium, something that is challenging for the open quantum system approach and that is needed to include uncorrelated recombination.

Many recent studies within the open quantum system approach are related with thermalization. At the moment, fully quantum evolutions of the density matrix require that $T \gg E$. Otherwise, we would have a non-Markovian evolution that requires a much larger computational cost. However, we can get closer to thermalization by performing an expansion in E/T. Previous QED results suggest that not many orders in this expansion are needed to achieve a master equation that leads approximately to thermalization. The one-dimensional approximation has been studied in [16, 17]. In [16] it was found that the master equation at this order always leads to a density matrix that is almost diagonal in the coordinate basis. This implies that a Langevin-like approach is a good approximation for the evolution at large times [18]. However, it was also seen in [16] that there is a surviving non-diagonal structure around $r = 0$. In the complementary study of [17] it was found that thermalization is approximately achieved in the one-dimensional approximation, however, the time it takes to thermalize is large. This is an indication that bottomonium does not have time to thermalize in a heavy-ion collision.

Let us also discuss the EFT-based approach to these E/T corrections, that was presented in [20]. The master equation used is valid in the regime in which the medium sees quarkonium as a small color dipole $rT \ll 1$. The impact of E/T has been studied with a focus on obtaining phenomenological results for bottomonium's R_{AA} and a discussion of thermalization has been postponed to future work. The study uses a three-dimensional master equation that takes into account the non-Abelian nature of QCD. It has been found that up to temperatures lower than $190\,MeV$ the corrections induced by the first E/T correction is smaller than 50%. Another

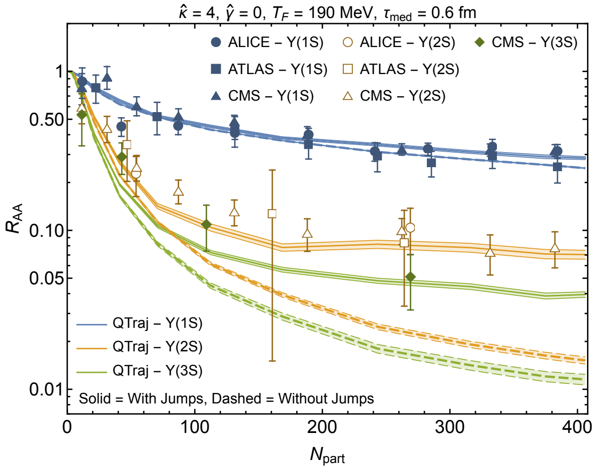

Figure 1. Figure taken from [19]. Results for R_{AA} at $\sqrt{s} = 5.02\,TeV$ obtained within the pNRQCD approach are compared to experimental results. We can clearly see the need of recombination (jumps) to reproduce experimental results. Circles represents Alice data for $\Upsilon(1S)$ and $\Upsilon(2S)$ with $2.5 < y < 4.0$. Squares are Atlas data for $\Upsilon(1S)$ and $\Upsilon(2S)$ with $|y| < 1.5$. Triangles and rhombuses are CMS data for $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ with $|y| < 2.4$.

important result is that correlated recombination is needed to reproduce experimental results for excited states, even if it is a very small correction for $\Upsilon(1S)$. A summary of the results for R_{AA} can be seen in fig. 1, where it can be observed the need of recombination to reproduce excited state data.

Another interesting development in the theory of quarkonium suppression in recent years has to do with the appearance of new unquenched results on quarkonium's potential at finite temperature. New results in [21] and references therein show that there is no significant screening in the real part of the potential. However, an imaginary part of the potential is observed. This indicates that, as is also the case in perturbation theory, the leading mechanism leading to dissociation in the medium-induced is the decay width. These results have an important impact in phenomenological analyses that use the finite temperature potential as input. In *Quark Matter 2023*, it was presented a study on how these new results affect computations based on the T-matrix approach [22].

4 Conclusions

Heavy quarks and quarkonium serve as valuable probes for studying the properties of the medium. Throughout recent studies, significant insights have been gained, particularly in understanding transport coefficients, including both κ_{fund} and κ_{adj}. Recent unquenched results suggest a trend towards increased dissipation (indicated by κ and the imaginary potential) and reduced screening compared to previous assumptions. Additionally, intriguing relationships between proton-proton (pp) and heavy-ion physics have emerged, particularly in the context of hadronization. Furthermore, the incorporation of E/T corrections to the master equation of quarkonium yields results consistent with observations, with indications that these corrections enhance the approach to equilibrium.

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