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Current Topics in Heavy Quarkonium Physics

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I review some recent progress, open puzzles and future opportunities in heavy quarkonium physics in the framework of effective field theories.

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1. Quarkonium

Heavy Quarkonia are systems composed by two heavy quarks, with mass m larger than the "QCD confinement scale" $\Lambda_{\rm QCD}$, so that $\alpha_{\rm s}(m) \ll 1$ holds. They are multiscale systems. Being nonrelativistic, quarkonia are characterized by another small parameter, the heavy-quark velocity v, ($v^2 \sim 0.1$ for $b\bar{b}$, $v^2 \sim 0.3$ for $c\bar{c}$, $v^2 \sim 0.01$ for $t\bar{t}$), and by a hierarchy of energy scales: m (hard), the relative momentum $p \sim mv$ (soft), and the binding energy $E \sim mv^2$ (ultrasoft). For energy scales close to $\Lambda_{\rm QCD}$, perturbation theory breaks down and one has to rely on nonperturbative methods. Regardless of this, the nonrelativistic hierarchy $m \gg mv \gg mv^2$ persists also below the $\Lambda_{\rm QCD}$ threshold. While the hard scale m is always larger than $\Lambda_{\rm QCD}$, different situations may arise for the other two scales depending on the considered quarkonium system. The soft scale, proportional to the inverse quarkonium radius r, may be a perturbative ($\gg \Lambda_{\rm QCD}$) or a nonperturbative scale ($\sim \Lambda_{\rm QCD}$) depending on the physical system in consideration. The first case is likely to happen only for the lowest charmonium and bottomonium states. We do not have direct information on the radius of the quarkonia systems, and thus the attribution of some of the lowest bottomonia and charmonia states to the perturbative or the nonperturbative soft regime is at the moment still ambiguous [4]. Only for $t\bar{t}$ threshold states the ultrasoft scale may be considered still perturbative.

All these quarkonium scales get entangled in a typical amplitude involving a quarkonium observable. In particular, quarkonium annihilation and production take place at the scale m, quarkonium binding takes place at the scale mv, which is the typical momentum exchanged inside the bound state, while very low-energy gluons and light quarks (also called ultrasoft degrees of freedom) live long enough that a bound state has time to form and, therefore, are sensitive to the scale mv^2. Ultrasoft gluons are responsible for phenomena similar to the the Lamb shift in QCD.

The existence of many scales in quarkonium makes it a unique system to study complex environments. Quarkonium probes all the regimes of QCD, from the high energy region, where an expansion in the the coupling constant is possible, to the low energy region, where nonperturbative effects dominate. It probes also the intermediate region between the two regimes. In particular for quarkonium system with a very small radius the interaction turns out to be purely perturbative while for system with a large radius with respect to the confinement scale the interaction turns out to be nonperturbative. Therefore quarkonium is an ideal and to some extent unique laboratory where our understanding of nonperturbative QCD and its interplay with perturbative QCD may be tested in a controlled framework. The fact that the quarkonium interaction is dominated by the glue contribution makes it a particularly precious system to test models of physics beyond the Standard Model (BSM) where a treatment of confinement and nontrivial low energy configurations is introduced. The large mass, the clean and known decays mode make quarkonium an ideal probe of new physics in some well defined window of parameters of beyond the Standard Model (BSM), in particular for some dark matter candidates search [2, 3, 5].

In the complex environment of heavy ion collisions quarkonium suppression constitutes a unique probe of deconfinement and quark gluon plasma formation [2, 3]. The different radius of the different quarkonia states induces the phenomenon of sequential suppression, allowing to use quarkonium as a kind of thermometer for the measurement of the temperature of the formed medium. On similar ground quarkonium may constitute a special probe to be used in the study of a nuclear medium [6].

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The diversity, quantity and accuracy of the data collected at experiments in the last few years is impressive and includes data on quarkonium formation from BES and BESIII at BEPC and BEPC2, KEDR at VEPP-4M, and CLEO-III and CLEO-c at CESR; clean samples of charmonia produced in B-decays, in photon-photon fusion and in initial state radiation from the B-meson factory experiments BaBar at SLAC and Belle at KEK, including the unexpected observation of large associated $(c\bar{c})(c\bar{c})$ production; heavy quarkonia production from gluon-gluon fusion in $p\bar{p}$ annihilations at 2 TeV from the CDF and D0 experiments at Fermilab; charmonia production in heavy-ion collisions from the PHENIX and STAR experiments at RHIC. These experiments have largely operated as quarkonium factories producing large data sample on quarkonium spectra, decays and production with high statistics. New states and exotics, new production mechanisms, new transitions and unexpected states of an exotic nature have been observed. The study of quarkonium in media has also undergone crucial developments, the suppression of quarkonium production in the hot medium remaining one of the cleanest and most relevant probe of deconfined matter. New data are already copiously coming from LHC experiments and new facilities will become operational (Panda at GSI, a much higher luminosity B factory at KEK, possibly a SuperB) adding challenges and opportunities to this research field.

From the theory point of view, effective field theories (EFTs) as HQET (Heavy Quark Effective Theory), NRQCD (Non Relativistic QCD), pNRQCD (potential Non Relativistic QCD), SCET (Soft Collinear Effective Theory)..., for the description of quarkonium processes have been newly developed and are being developed, providing a unifying description as well as a solid and versatile tool giving well-defined, model independent and precise predictions [2, 3, 1]. They rely on one hand on high order perturbative calculations and on the other hand on lattice simulations, the recent progress in both fields having added a lot to the theory reach.

The progress in our understanding of nonrelativistic EFTs makes it possible to move beyond phenomenological models (at least for states below threshold) and to provide in this case a systematic description inside QCD of heavy-quarkonium physics. On the other hand, the recent progress in the measurement of several heavy-quarkonium observables makes it meaningful to address the problem of their precise theoretical determination. In this situation quarkonium becomes a special system to advance our theoretical understanding of the strong interactions, also in special environments (e.g. quarkonium in media) and in several production mechanisms, as well as our control of some parameters of the Standard Model

The International Quarkonium Working Group (QWG) (www.qwg.to.infn.it) created in 2002 has supplied ad adequate platform for discussion and common research work between theorists and experimentalists, producing also two large reviews of state of the art, open problems, perspective and opportunities of quarkonium physics in 2010 and 2004 [2]. In particular at the end of [2] is presented a list of 65 priorities in experiments and in theory. Some of the results appeared in the last few months already challenged such list. In the following I will address some aspects of this research field which is at the moment in great evolution.

2. Theory: the effective field theory description

A hierarchy of EFTs may be constructed by systematically integrating out modes associated to high energy scales not relevant for quarkonium [1]. Such integration is made in a matching

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procedure enforcing the equivalence between QCD and the EFT at a given order of the expansion in v. The EFT realizes a factorization at the Lagrangian level between the high energy contributions, encoded into the matching coefficients, and the low energy contributions, carried by the dynamical degrees of freedom. Poincaré symmetry remains intact in a nonlinear realization at the level of the nonrelativistic (NR) EFT and imposes exact relations among the matching coefficients [7].

By integrating out the hard modes Nonrelativistic QCD (NRQCD) is obtained [8, 9, 10], making explicit at the Lagrangian level the expansions in mv/m and mv^2/m. The effective Lagrangian is organized as an expansion in $1/m$ and $\alpha_s(m)$. It is is similar to HQET, but with a different power counting and accounts also for contact interactions between quarks and antiquark pairs (e.g. in decay processes), hence having a wider set of operators.

Quarkonium annihilation and production happen at the scale m: at this scale m, the suitable EFT is NonRelativistic QCD (NRQCD). In NRQCD soft and ultrasoft scales remain dynamical and their mixing may complicate calculations, power counting and do not allow to obtain a Schrödinger formulation in terms of potentials. One can go down one step further and integrate out the soft scale in a matching procedure to the lowest energy EFT, where only ultrasoft degrees of freedom are dynamical. Such EFT is called potential NonRelativistic QCD (pNRQCD) [11, 12, 1]. In this case the matching coefficients encode the information on the soft scale and represent the potentials. pNRQCD is making explicit at the Lagrangian level the expansion in mv^2/mv. It is close to a Schrödinger-like description of the bound state, the bulk of the interaction being carried by potential-like terms, but non-potential interactions, associated with the propagation of low-energy degrees of freedom ($Q\bar{Q}$ colour singlets, $Q\bar{Q}$ colour octets and low energy gluons), may still be present in general. They start to contribute at NLO (next-to-leading order) in the multipole expansion of the gluon fields and are typically related to nonperturbative effects [12] like gluon condensates.

Quarkonium formation happens at the scale mv. At the scales mv and mv^2 the suitable EFT is pNRQCD.

In this EFT frame, it is important to establish when $\Lambda_{\rm QCD}$ sets in, i.e. when we have to resort to non-perturbative methods. For low-lying resonances, it is reasonable to assume $mv^2 \gtrsim \Lambda_{\rm QCD}$. Then, the system is weakly coupled and we may rely on perturbation theory, for instance, to calculate the potential. In this case, we deal with weak coupling pNRQCD. The theoretical challenge here is performing higher-order perturbative calculations, resum large logarithms in the ratio of the scales and the goal is precision physics.

Given that for system with a small radius precision calculations are possible, in this case quarkonium may become a benchmark for our understanding of QCD, in particular the transition region between perturbative and nonperturbative QCD, and for the precise determination of relevant Standard Model parameters e.g. the heavy quark masses m_c, m_b, m_t and α_s. For example, using the new CLEO data on radiative $\Upsilon(1S)$ decay, the improved lattice determination of the NRQCD matrix elements and their perturbative pNRQCD calculation, it has been possible to obtain in [13] a determination of α_s at the Υ mass $\alpha_s(M_\Upsilon(1S)) = 0.184^{+0.015}_{-0.014}$ giving a value $\alpha_s(M_z) = 0.119^{0.006}_{-0.005}$ in agreement with the world average.

In weak coupling pNRQCD the soft scale is perturbative and the potentials are purely perturbative objects. Nonperturbative effects enter energy levels and decay calculations in the form of local or nonlocal electric and magnetic condensates [14]. We still lack a precise and systematic knowledge of such nonperturbative purely glue dependent objects and it would be important to have for them lattice determinations or data extraction (see e.g. [15]) or calculation in models of low energy QCD. Notice that the leading electric and magnetic nonlocal correlators (that are gauge invariant quantities) may be related to the gluelump masses [12] and to some existing lattice (quenched) determinations [1].

However, since the nonperturbative contributions are suppressed in the power counting it is possible to obtain good determinations of the masses of the lowest quarkonium resonances with purely perturbative calculations in the cases in which the perturbative series is convergent after that the appropriate subtractions of renormalons have been performed and large logarithms in the scales ratios are resummed [16]. The potentials are matching coefficients that undergo renormalization, develop a scale dependence and satisfy renormalization group equations.

The static singlet $Q\bar{Q}$ potential is pretty well known. The three-loop correction to the static potential is now completely known: the fermionic contributions to the three-loop coefficient [17] first became available, and more recently the remaining purely gluonic term has been obtained [18, 19].

The first log related to ultrasoft effects arises at three loops [20] . Such logarithm contribution at N^{3}LO and the single logarithm contribution at N^{4}LO may be extracted respectively from a one-loop and two-loop calculation in the EFT and have been calculated in [21, 22].

The perturbative series of the static potential suffers from a renormalon ambiguity (i.e. large β_0 contributions) and from large logarithmic contributions. The singlet static energy, given by the sum of a constant, the static potential and the ultrasoft corrections, is free from ambiguities of the perturbative series. By resumming the large logs using the renormalization group equations and comparing it (at the NNLL) with lattice calculations of the static energy one sees that the QCD perturbative series converges very nicely to and agrees with the lattice result in the short range (up to 0.25 fm) and that no nonperturbative linear ("stringy") contribution to the static potential exist [23, 21].

In particular, the recently obtained theoretical expression [21] for the complete QCD static energy at NNNLL precision has been used to determine $r_0\Lambda_{\overline{MS}}$ by comparison with available lattice data, where r_0 is the lattice scale and $\Lambda_{\overline{MS}}$ is the QCD scale, obtaining $r_0\Lambda_{\overline{MS}} = 0.622^{+0.019}_{-0.015}$ for the zero-flavor case. This extraction was previously performed at the NNLO level (including an estimate at NNNLO) in [24]. The same procedure can be used to obtain a precise evaluation of the unquenched $r_0\Lambda_{\overline{MS}}$ value after short distance unquenched lattice data for the $Q\overline{Q}$ exist [25].

The static octet potential is known up to two loops [26], see also [27]. Relativistic corrections to the static singlet potential have been calculated over the years and are summarized in [1].

In the case of QQq baryons, the static potential has been determined up to NNLO in perturbation theory [28] and recently also on the lattice [29]. Terms suppressed by powers of $1/m$ and r in the Lagrangian have been matched (mostly) at leading order and used to determine, for instance, the expected hyperfine splitting of the ground state of these systems.

In the case of QQQ baryons, the static potential has been determined up to NNLO in perturbation theory [28] and also on the lattice [30]. The transition region from a Coulomb to a linearly raising potential is characterized in this case also by the emergence of a three-body potential apparently parameterized by only one length. It has been shown that in perturbation theory a smooth genuine three-body potential shows up at two loops.

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For higher resonances $mv \sim \Lambda_{\rm QCD}$. In this case, we deal with strongly coupled pNRQCD. We need nonperturbative methods to calculate the potentials and one of the goal is the investigation of the QCD low energy dynamics [31].

Then the potential matching coefficients are obtained in the form of expectation values of gauge-invariant Wilson-loop operators. In this case, heavy-light meson pairs and heavy hybrids develop a mass gap of order $\Lambda_{\rm QCD}$ with respect to the energy of the $Q\overline{Q}$ pair, the second circumstance being apparent from lattice simulations. Thus, away from threshold, the quarkonium singlet field is the only low-energy dynamical degree of freedom in the pNRQCD Lagrangian (neglecting ultrasoft corrections coming from pions and other Goldstone bosons). The singlet potential can be expanded in powers of the inverse of the quark mass; static, $1/m$ and $1/m^2$ terms were calculated long ago [32, 43]. They involve NRQCD matching coefficients (containing the contribution from the hard scale) and low-energy nonperturbative parts given in terms of static Wilson loops and field-strength insertions in the static Wilson loop (containing the contribution from the soft scale). Such expressions correct and generalize previous finding in the Wilson loop approach [33] that were typically missing the high energy parts of the potentials, encoded into the NRQCD matching coefficients and containing the dependence on the logarithms of m_Q, and some of the low energy contributions. The nonperturbative QQQ potentials (static and relativistic corrections) have been obtained in terms of Wilson loops and field strengths insertions in [34] and in the second reference of [28].

In this regime of pNRQCD, we recover the quark potential singlet model. However, here the potentials are calculated in QCD by nonperturbative matching. Their evaluation requires calculations on the lattice or in QCD vacuum models. For calculations inside different QCD vacuum/string models see [31, 35]. Recent progress includes new, precise lattice calculations of these potentials obtained using the Lüscher multi-level algorithm [36].

As mentioned, which quarkonium state belongs to which regime is an open issue and no clear cut method exist to decide this a priori, in the lack of a direct way to determine the quarkonium radius [4]. Typically the lowest states $\Upsilon(1S), \eta_b$, B_c and possibly $J\psi$ and η_c are assumed to be in the weakly coupled regime (for what concerns the soft scale).

3. Quarkonium spectra, decays, exotics and production

An enormous set of the most updated phenomenological applications of the EFT framework outlined above to quarkonium spectra, decays and production is presented and discussed in relation to the experimental data in [2, 1, 3].

Here I can only briefly recall some selected results.

The energy levels have been calculated at order $m\alpha_s^5$ [14, 37]. Decays amplitude [51, 2, 1] and production and annihilation [50] have been calculated in perturbation theory at high order. Since for systems with a small radius the nonperturbative contributions are suppressed in the power counting it is possible to obtain good determinations of the masses of the lowest quarkonium resonances with purely perturbative calculations in the cases in which the perturbative series is convergent (after that the appropriate subtractions of renormalons have been performed) and large logarithms in the scales ratios are resummed. For example in [52] a prediction of the B_c mass has been obtained. The NNLO calculation with finite charm mass effects [55] predicts a mass that well matches the Fermilab measurement [2] and the lattice determination [53]. The same procedure has been applied at NNLO even for higher states [55]. A NLO calculation reproduces in part the $1P$ fine splitting [54]. Including logs resummation at NLL, it is possible to obtain a prediction for for the B_c hyperfine separation $\Delta = 65 \pm 24^{+19}_{-16}$ MeV [56] and for the hyperfine separation between the $\Upsilon(1S)$ and the η_b the value of $41 \pm 11(\mathrm{th})^{+9}_{-8}(\delta\alpha_s)$ MeV (where the second error comes from the uncertainty in α_s) [38]. This last value turned out to undershoot the experimental measurement of BABAR by about two standard deviation. This is an open puzzles in theory. NRQCD lattice calculations [59] obtains a value close to the experimental one but do not include the one loop matching coefficients of the spin-spin term that is large nad may give a negative correction of up to -20 MeV [60]. Recent lattice calculations [61] aims at including the NRQCD matching coefficients in the NRQCD lattice calculation and will help to settle this issue. Another explanation would be related to the presence of a CPlight odd higgs which mixes with the η_b [5].

An effective field theory of magnetic dipole transition has been given in [62], allowed magnetic dipole transitions between $c\bar{c}$ and $b\bar{b}$ ground states have been considered in pNRQCD at NNLO in [62]. The results are: $\Gamma(J/\psi \to \gamma\eta_c) = (1.5 \pm 1.0)$ keV and $\Gamma(\Upsilon(1S) \to \gamma\eta_b) = (k_\gamma/39\ \mathrm{MeV})^3$ (2.50 ± 0.25) eV, where the errors account for uncertainties coming from higher-order corrections. The width $\Gamma(J/\psi \to \gamma\eta_c)$ is consistent with the PDG value. The quarkonium magnetic moment is explicitly calculated and turns out to be very small in agreement with a recent lattice calculation [39]; the M1 transition of the lowest quarkonium states at relative order v^2 turn out to be completely accessible in perturbation theory [62]. A description of the η_c line shape has been given in [57]. and effective field theory calculation of electric dipole transitions is currently in elaboration [48]. Using pNRCD and Soft Collinear EFT (SCET) a good description of the $\Upsilon(1S)$ radiative decay have been obtained [47].

For what concerns decays, recently, substantial progress has been made in the evaluation of the NRQCD factorization formula at order v^7 [40], in the lattice evaluation of the NRQCD matrix elements [49], in the higher order perturbative calculation of some NRQCD matching coefficients [41, 42] and in the new, accurate data on many hadronic and electromagnetic decays [2]. The data are clearly sensitive to NLO corrections in the Wilson coefficients and presumably also to relativistic corrections. Improved theory predictability would entail the lattice calculation or data extraction of the NRQCD matrix elements and perturbative resummation of large contribution in the NRQCD matching coefficients. Inclusive decay amplitudes have been calculated in pNRQCD in [43] and the number of nonperturbative correlators appears to be sizeably reduced with respect to NRQCD so that new, model independent predictions have been made possible [15]. Still, the new data on hadronic transitions and hadronic decays pose interesting challenging to the theory. Exclusive decays mode are more difficult to be addressed in theory [44, 46, 45].

For the excited states masses away from threshold, phenomenological applications of the QCD potentials obtained in [32] are ongoing [58]. For a full phenomenological description of the spectra and decays it would be helpful to have updated, more precise and unquenched lattice calculation of the Wilson loop field strength insertions expectation values and of the local and nonlocal gluon correlators [1]. For recent lattice results on the spectroscopy see [63].

In the most interesting region, the region close to threshold where many new states, conceivably of an exotic nature have been recently discovered, a full EFT description has yet been constructed nor the appropriate degrees of freedom clearly identified [64, 2]. An exception is constituted by the $X(3872)$ that displays universal characteristics related to its being so close to threshold, reason for which a beautiful EFT description could be obtained [66, 67].

The threshold region remains troublesome also for the lattice, althought several excited states calculations have been recently being pionereed.

Lattice results about the crosstalk of the static potential with a pair of heavy-light mesons in the lattice have recently appeared [65] but further investigations appear to be necessary. Several model approaches and predictions for the exotics properties are summarized and described in [2]. For a sum rules review see [68]. The recent discovery at BELLE of two new exotic charged bottomonium-like resonance [69] suggests that many new exotics states will be soon discovered [70].

The field of quarkonium production has seen terrific progress in the last few years both in theory and in experiments, for a review see [2, 3, 71, 72, 73]. Particularly promising seem to be the recent full NLO NRQCD calculation of $J\psi$ photoproduction [76] and hadroproduction [74, 75], the consequent phenomenological applications to the study of $J\psi$ production at Hera, Tevatron, RHIC and LHC [77] with the possibility to extract the color octet matrix elements from the combined fits. The quarkonium polarization remains a very hot topic with theory predictions and approaches [78, 2] to be soon validated at the LHC. A calculation of triply heavy baryons production at LHC just appeared [79].

4. Quarkonium in media

The suppression of quarkonium production in the hot medium remains one of the cleanest and most relevant probe of deconfined matter.

However, the use of quarkonium yields as a hot-medium diagnostic tool has turned out to be quite challenging for several reasons. Quarkonium production has already been found to be suppressed in proton-nucleus collisions by cold-nuclear-matter effects, which themselves require dedicated experimental and theoretical attention. Recombination effects may play an additional role and thus transport properties may become relevant to be considered. Finally, the heavy quark-antiquark interaction at finite temperature T has to be obtained from QCD.

For observables only sensitive to gluons and light quarks, a very successfull EFT called Hard Thermal Loop (HTL) effective theory has been derived in the past by integrating out the hardest momenta proportional to T from the dynamics. However, considering also heavy quarkonium in the hot QCD medium, one has to consider in addition to the thermodynamical scales in T also the scales of the nonrelativistic bound state and the situation becomes more complicate.

In the last few years years, there has been a remarkable progress in constructing EFTs for quarkonium at finite temperature and in rigorously defining the quarkonium potential. In [80, 81], the static potential was calculated in the regime $T \gg 1/r \gtrsim m_D$, where m_D is the Debye mass and r the quark-antiquark distance, by performing an analytical continuation of the Euclidean Wilson loop to real time. The calculation was done in the weak-coupling resummed perturbation theory. The imaginary part of the gluon self energy gives an imaginary part to the static potential and hence a thermal width to the quark-antiquark bound state. In the same framework, the dilepton production rate for charmonium and bottomonium was calculated in [82, 83]. In [84], static particles in real-time formalism were considered and the potential for distances $1/r \sim m_D$ was derived for a hot

QED plasma. The real part of the static potential was found to agree with the singlet free energy and the damping factor with the one found in [80]. In [85], a study of bound states in a hot QED plasma was performed in a non-relativistic EFT framework. In particular, the hydrogen atom was studied for temperatures ranging from $T \ll m\alpha^2$ to $T \sim m$, where the imaginary part of the potential becomes larger than the real part and the hydrogen ceases to exist. The same study has been extended to muonic hydrogen in [86], providing a method to estimate the effects of a finite charm quark mass on the dissociation temperature of bottomonium.

An EFT framework in real time and weak coupling for quarkonium at finite temperature was developed in [88] working in real time and in the regime of small coupling g, so that $gT \ll T$ and $v \sim \alpha_s$, which is expected to be valid for tightly bound states: $\Upsilon(1S)$, J/ψ, ...

Quarkonium in a medium is characterized by different energy and momentum scales; there are the scales of the non-relativistic bound state that we have discussed at the beginning,

and there are the thermodynamical scales: the temperature T, the inverse of the screening length of the chromoelectric interactions, i.e. the Debye mass m_D and lower scales, which we will neglect in the following.

If these scales are hierarchically ordered, then we may expand physical observables in the ratio of such scales. If we separate explicitly the contributions from the different scales at the Lagrangian level this amounts to substituting QCD with a hierarchy of EFTs, which are equivalent to QCD order by order in the expansion parameters. As it has been described in the previous sections at zero temperature the EFTs that follow from QCD by integrating out the scales m and mv are called respectively Non-relativistic QCD (NRQCD) and potential NRQCD (pNRQCD). We assume that the temperature is high enough that $T \gg gT \sim m_D$ holds but also that it is low enough for $T \ll m$ and $1/r \sim mv \gtrsim m_D$ to be satisfied, because for higher temperature the bound state ceases to exist. Under these conditions some possibilities are in order. If T is the next relevant scale after m, then integrating out T from NRQCD leads to an EFT that we may name $\text{NRQCD}_{\text{HTL}}$, because it contains the hard thermal loop (HTL) Lagrangian [89]. Subsequently integrating out the scale mv from $\text{NRQCD}_{\text{HTL}}$ leads to a thermal version of pNRQCD that we may call $\text{pNRQCD}_{\text{HTL}}$. If the next relevant scale after m is mv, then integrating out mv from NRQCD leads to pNRQCD. If the temperature is larger than mv^2, then the temperature may be integrated out from pNRQCD leading to a new version of $\text{pNRQCD}_{\text{HTL}}$ [90]. Note that, as long as the temperature is smaller than the scale being integrated out, the matching leading to the EFT may be performed putting the temperature to zero.

The derived potential V describes the real-time evolution of a quarkonium state in a thermal medium. At leading order, the evolution is governed by a Schrödinger equation. In an EFT framework, the potential follows naturally from integrating out all contributions coming from modes with energy and momentum larger than the binding energy. For $T < V$ the potential is simply the Coulomb potential. Thermal corrections affect the energy and induce a thermal width to the quarkonium state; these may be relevant to describe the in medium modifications of quarkonium at low temperatures. For $T > V$ the potential gets thermal contributions, which are both real and imaginary.

General findings in this picture are:

- The thermal part of the potential has a real and an imaginary part. The imaginary part of the potential smears out the bound state peaks of the quarkonium spectral function, leading to their dissolution prior to the onset of Debye screening in the real part of the potential (see, e.g. the discussion in [87]). So quarkonium dissociation appears to be a consequence of the appearance of a thermal decay width rather than being due to the color screening of the real part of the potential; this follows from the observation that the thermal decay width becomes as large as the binding energy at a temperature at which color screening may not yet have set in.

- Two mechanisms contribute to the thermal decay width: the imaginary part of the gluon self energy induced by the Landau-damping phenomenon (existing also in QED) [80] and the quark-antiquark color singlet to color octet thermal break up (a new effect, specific of QCD) [91]. Parametrically, the first mechanism dominates for temperatures such that the Debye mass m_D is larger than the binding energy, while the latter dominates for temperatures such that m_D is smaller than the binding energy.

- The obtained singlet thermal potential, V, is neither the color-singlet quark-antiquark free energy nor the internal energy. It has an imaginary part and may contain divergences that eventually cancel in physical observables [91].

- Temperature effects can be other than screening, typically they may appear as power law corrections or a logarithmic dependence [91, 85].

- The dissociation temperature goes parametrically as $\pi T_{\rm melting} \sim m g^{\frac{4}{3}}$ [85, 87].

The EFT provides a clear definition of the potential and a coherent and systematical setup to calculate masses and widths of quarkonium at finite temperature. In [93] heavy quarkonium energy levels and decay widths in a quark-gluon plasma, below the melting temperature at a temperature T and screening mass m_D satisfying the hierarchy $m\alpha_s \gg \pi T \gg m\alpha_s^2 \gg m_D$, have been calculated at order $m\alpha_s^5$. This situation is relevant for bottomonium $1S$ states ($\Upsilon(1S)$, η_b) at the LHC. It has been found [93] that: at leading order the quarkonium masses increase quadratically with T which in turn implies the same functional increase in the energy of the dileptons produced in the electromagnetic decays; a thermal correction proportial to T^2 appears in the electromagnetic quarkonium decay rates; at leading order a decay width linear with the temperature is developed which implies a tendency to dissolve by decaying to the continuum of the colour-octet states.

In [94] the leading-order thermal corrections to the spin-orbit potentials of pNRQCD$_{\rm HTL}$ has been calculated and it has been shown how Poincaré invariance is broken by the presence of the medium. In [95] the propagation of a nonrelativistic bound state moving across a homogenoeus thermal bath have been studied.

In [91, 92] the Polyakov loop and the correlator of two Polyakov loops at finite temperature has ben calculated at next-to-next-to-leading order in the weak coupling regime and at quark-antiquark distances shorter than the inverse of the temperature and for Debye mass larger than the Coulomb potential. The calculation has been performed also the in EFT framework [91] and a relation between the Polyakov loop correlator and the singlet and octet quark-antiquark correlator has been established in this setup.

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First attempts to generalize this new picture to the nonperturbative regime have been undertaken in [96].

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