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Quarkonia in Medium and Transport in Heavy-Ion Collisions

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The transport and spectral properties of heavy quarkonia in hot QCD matter are a central ingredient to describe their observables in high-energy heavy-ion collisions. We review recent activity in evaluating these properties, including a nonperturbative quantum many-body approach where the basic two-body interaction kernel is constrained by quantities that can be computed with good precision in thermal lattice QCD. We then give a brief overview of quarkonium transport approaches to heavy-ion collisions. Focusing on the semiclassical approach we discuss the current interpretation of charmonium and bottomonium observables at RHIC and the LHC, including excitation functions that started with J/ψ and ψ' data from the heavy-ion program at the SPS.

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1. Introduction

Ultrarelativistic heavy-ion collisions (URHICs) are an excellent way to unleash the partonic degrees of freedom that are confined inside the protons and neutrons of the incoming nuclei and produce a universal form of strong-interaction matter known as quark-gluon plasma (QGP). Pertinent campaigns over the last four decades at the CERN-SPS, BNL-RHIC and CERN-LHC have provided remarkable insights into the QGP. For example, its transport properties, as deduced from hydrodynamic simulations of the expanding fireball and the diffusion of heavy charm and bottom quarks within it [1–3], have revealed the QGP to be a "nearly perfect liquid", with transport coefficients close to lower bounds conjectured from quantum mechanics. However, the microscopic origin of this highly nonperturbative behavior has not been fully elaborated yet.

Since their discovery in the 1970's, bound states of a heavy quark and its antiquark have provided key insights into the nonperturbative dynamics of Quantum Chromodynamics (QCD). The Cornell potential, originally introduced on phenomenological grounds to describe the observed quarkonium spectra [4], has been an effective tool in a systematic description of the bound-state properties. Nowadays, it is confirmed by lattice-QCD computations and can be understood as a matching coefficient in an effective theory, potential non-relativistic QCD, based on a $1/m_Q$ expansion of the QCD lagrangian. In the color-singlet channel, it is usually expressed as

$$V(r) = -\frac{4}{3}\frac{\alpha_s}{r} + \sigma r \;, \tag{1}$$

which amounts to a combination of a color-Coulomb term from perturbative one-gluon exchange at small distances and a string term with a force of $\sigma \simeq 1$ GeV/fm $\sim 10^5 N$ prevalent at large distances. While the microscopic origin of the string term remains a matter of debate (*e.g.*, via a condensation of color-magnetic monopoles causing a dual Meissner effect that contracts the color-electric field [5, 6]), in practice it is one of the most direct manifestations of confinement. Consequently, it was suggested that Debye screening in a QGP, dissolving quarkonia and suppressing their production in URHICs, can serve as a signature of deconfinement [7], which triggered intense theoretical and experimental activity. Transport approaches have been developed that systematically treat the kinetics of different quarkonia as they evolve through the fireballs of hot QCD matter formed in URHICs [8]. This not only includes dissociation mechanisms in the QGP but also for (re-) generation reactions of quarkonia once the ambient temperature allows for their re-binding.

In this paper, we survey contemporary approaches and progress in evaluating quarkonium properties in the QGP (Sec. 2), implementations into transport models (Sec. 3) and the phenomenology of heavy-quarkonium production in URHICs (Sec. 4). We conclude and give an outlook in Sec. 5.

2. Quarkonia at Finite Temperature

Substantial theory efforts have been undertaken to extend the potential approach to finite temperature. While early works have focused on the effects of screening, it has become clear that large collisional rates of charm and bottom quarks in the strongly-coupled QGP (sQGP) need to be included in calculating pertinent spectral functions in the QGP [3]. The interplay of various scales, including a large range of binding energies, heavy-quark (HQ) momenta, temperature, screening lengths, and collision rates, renders this a challenging problem, especially in the presence of

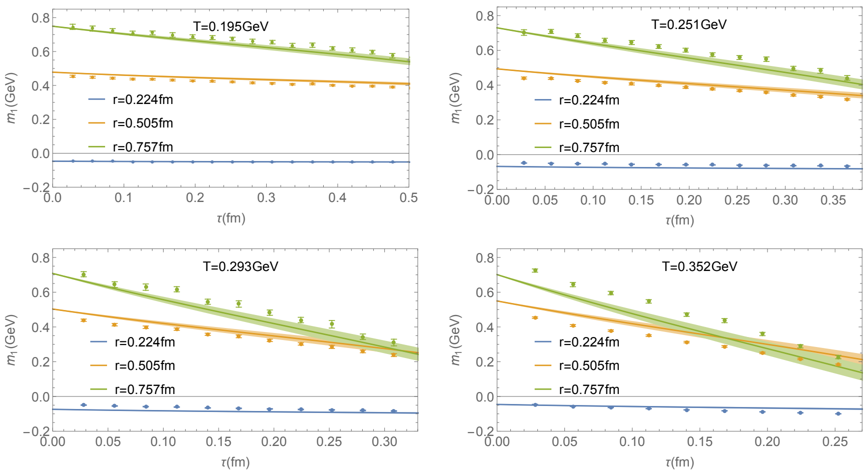

Figure 1: Effective quarkonium "masses" (relative to the $Q\bar{Q}$ threshold) from the first moment of static WLCs computed in thermal lQCD [10] (symbols), compared to selfconsistent T-matrix calculations (bands) [11] with input potentials from Fig. 2.

nonperturbative interactions. A powerful quantum many-body theory that has been widely applied in other contexts is the thermodynamic T-matrix approach. It's applicability to the HQ sector is well motivated, since a large mass suppresses the energy transfer in two-body scattering enabling a reduction of the 4D Bethe Salpeter equation to a 3D Lippmann Schwinger equation,

$$T(E;p',p) = V(p',p) + \int \frac{d^3k}{(2\pi)^3} V(p',p) G_2(E,k) T(E;k,p) \ . \tag{2}$$

The central input is the two-body potential which not only governs the in-medium binding properties but also allows to evaluate the (complex) selfenergies of the individual heavy quarks in the QGP (figuring in the two-body propagator, G_2) in a selfconsistent framework. The main idea is now to constrain the potential by first-principle information from thermal lattice-QCD (lQCD). In the past, this has been done by employing free- or internal-energy proxies, as well as euclidean correlators of quarkonia. However, the results remained ambiguous, supporting both strong and weak in-medium potentials [9], although the former are usually preferred by phenomenology. More

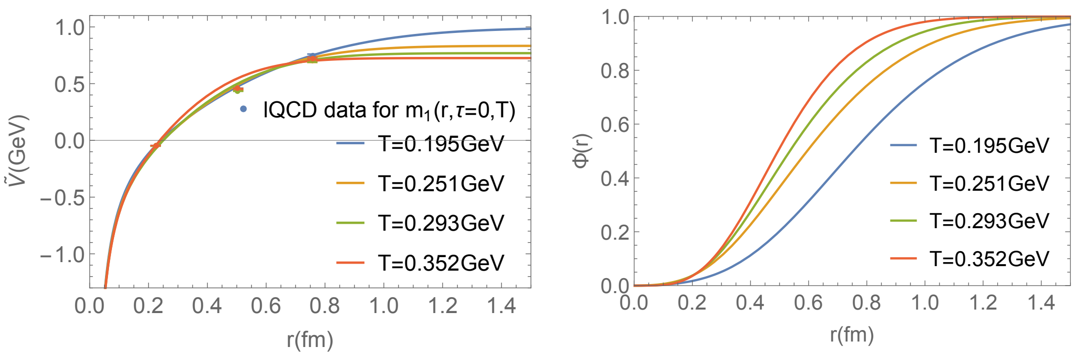

Figure 2: Input potentials for the T-matrix approach inferred from fits to the static WLCs [11] shown in Fig. 1. Left panel: real part; right panel: interference function multiplying the two-body selfenergy.

powerful constraints turn out to come from static Wilson line correlators (WLCs) [10] which can be related the quarkonium spectral function in energy-coordinate space via a Laplace transform. In particular, perturbative calculations with hard-thermal-loop resummations were not unable to describe pertinent lQCD data. In Fig. 1 we show the selfconsistent results of the T-matrix approach with suitably constrained in-medium potentials as shown in Fig. 2. The resulting potential (left panel) exhibits surprisingly little screening even at relatively large distances, suggesting that QCD strings in the QGP are more robust than previously expected. One also finds significant effects in the "imaginary part" of the potential [12]: while the individual HQ collision widths are very large (in excess of 0.5 GeV, compatible with the notion of nearly perfect liquid), the distance dependence of the $Q\bar{Q}$ selfenergy, which can be characterized by an interference function (right panel), substantially suppresses the in-medium quarkonium widths at small $Q\bar{Q}$ separation.

3. Quarkonium Transport in QCD Matter

The theoretical description of the kinetics of quarkonium dissociation and (re-) generation through the course of URHICs is a formidable problem, as sketched in Fig. 3. Pertinent approaches can be roughly divided in 3 classes, with an increasing level of complexity (see Ref. [8] for a more detailed recent survey): (i) Statistical Hadronization Model (SHM) at the QCD phase boundary [13], asserting that quarkonia are dissolved in the QGP of a heavy-ion collision and re-form from the deconfined heavy anti-/quarks that are present in the fireball as the medium hadronizes; (ii) Semiclassical transport models [14, 15], usually based on the Boltzmann equation, which evolve the quarkonium phase distribution using inelastic reaction rates that initially suppress the quarkonia that would be produced in the primordial nucleon-nucleon collisions, but also regenerate them from the diffusing quarks in the medium once bound-state formation is supported by the potential; (iii) Quantum transport approaches [16] that are usually based on the evolution of density matrices using the framework of open quantum systems and implemented using a Lindblad equation. While the latter are the most fundamental approach, their practical applications are not without difficulty,

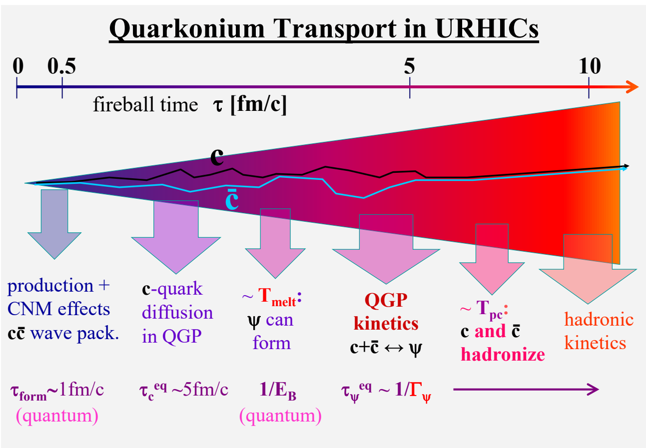

Figure 3: Schematic depiction of different stages of quarkonium transport in URHICs along with relevant time scales, starting from initial production of a $Q\bar{Q}$ wave package to a coupled transport of heavy quarks and their bound states through the QGP, hadronization and hadronic matter.

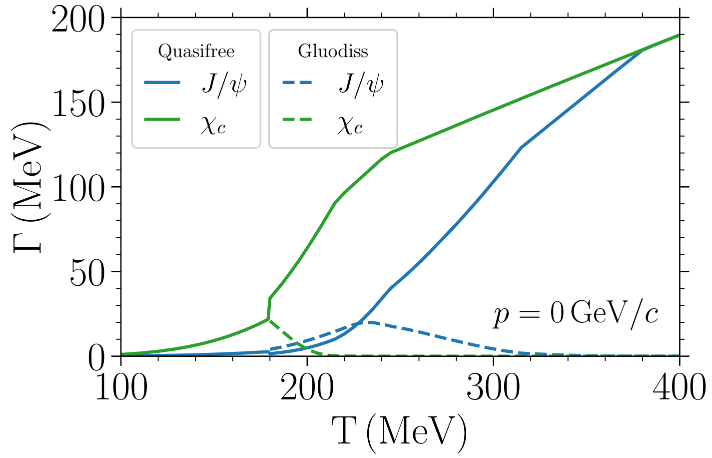

Figure 4: Comparison of inelastic reaction rates of the J/ψ and χ_c in QCD matter. In the QGP ($T > T_c$=180 MeV) a perturbative coupling to the medium is combined with in-medium binding energies from the T-matrix [15]. One clearly recognizes the effect of the binding energy, and that gluo-dissociation (dotted line) is negligible compared to inelastic scattering (solid lines), except in regions where the rates are small.

e.g., with respect to their kinetic equilibration or the presence of a clear scale hierarchy in the presence of nonperturbative interactions. In the semiclassical approaches the equilibrium limit is manifest, as can be readily seen when integrating out the momentum dependence in the Boltzmann equation to obtain a kinetic rate equation of the type $dN_\psi/dt = -\Gamma_\psi(N_\psi - N_{\rm eq}^\psi(T)$. This equation contains two transport parameters, the inelastic reaction rate, Γ_ψ, and the chemical equilibrium limit, $N_{\rm eq}^\psi(T)$, which controls regeneration processes once the medium becomes conducive to bound-state formation. It also shows that the SHM corresponds to equilibration at the phase boundary based on large reactions rate in the QGP which are assumed to be small in the hadronic medium shutting off further quarkonium kinetics. On the other hand, the semiclassical approach becomes problematic when the reaction rates are larger then the binding energy in which case the equilibrium limit will be more involved as the thermodynamic weight of a broad bound state is usually suppressed compared to the narrow-width limit. In the language of quantum transport this is referred to as the Brownian motion limit where the intrinsic time scale of the bound state is larger than the relaxation time scale of the environment which is small in a strongly coupled system; in this regime quantum effects in the evolution of the $Q\bar{Q}$ wave package are expected to be relevant.

The original idea of sequential dissociation of quarkonium bound states according to their binding energies still leaves its footprint in the reaction rates. This is illustrated in Fig. 4 where the reaction rates of J/ψ and and χ_c show a clear hierarchy until the binding has vanished for both states. The figure of merit of the width for the kinetics to shut off is typically ~50 MeV, *i.e.*, a relaxation time of roughly 5 fm/c, corresponding to the timescale of the (remaining) fireball evolution.

4. Phenomenology of Quarkonia in Heavy-Ion Collisions

Quarkonium transport approaches started to be developed in the context of the SPS heavy-ion program. A substantial suppression of J/ψ production in Pb-Pb($\sqrt{s}$=17.3 GeV) collisions was observed [17], relative to the yield expected from a mere superposition of initial nucleon-nucleon collisions. It was soon realized that most of the suppression was caused by "cold-nuclear matter" (CNM) effects present already in proton-nucleus collisions: incoming nucleons can dissociate the bound state, leaving room for only a relatively small portion for a QGP-induced dissociation in central Pb-Pb collisions. In retrospect, and in view of Fig. 4, this is plausible given initial fireball temperatures of about $T_0 \leq 250\,\mathrm{MeV}$ at the SPS. On the other hand, a large $\psi(2S)$ suppression was observed [18], with a $\psi(2S)/J/\psi$ ratio in central collisions which agrees with the SHM. In Au-Au($\sqrt{s}$=200 GeV) collisions at RHIC, J/ψ suppression turns out to be quite comparable to that at the SPS [19], despite a much larger $T_0 \simeq 350\,\mathrm{MeV}$. Transport models suggest that a stronger suppression in the QGP is offset by a smaller CNM suppression and a significant regeneration contribution; the latter is supported by the relatively soft p_T spectra observed for the J/ψ. A critical test of this interpretation came with the LHC data, where the charm-anticharm quark ($c\bar{c}$) production cross section is about an order of magnitude larger than at RHIC, resulting in multiple $c\bar{c}$ pairs in causally connected regions of the fireball available for regeneration in semi-/central Pb-Pb(5.02 TeV) collisions. The measurements confirm this expectation, with a marked increase of the suppression factor relative to the RHIC results, cf. left panel of Fig. 5 for forward-rapidity data from ALICE [20]. At mid-rapidity, where the $c\bar{c}$ density is another ~ 50% larger, the nuclear modification

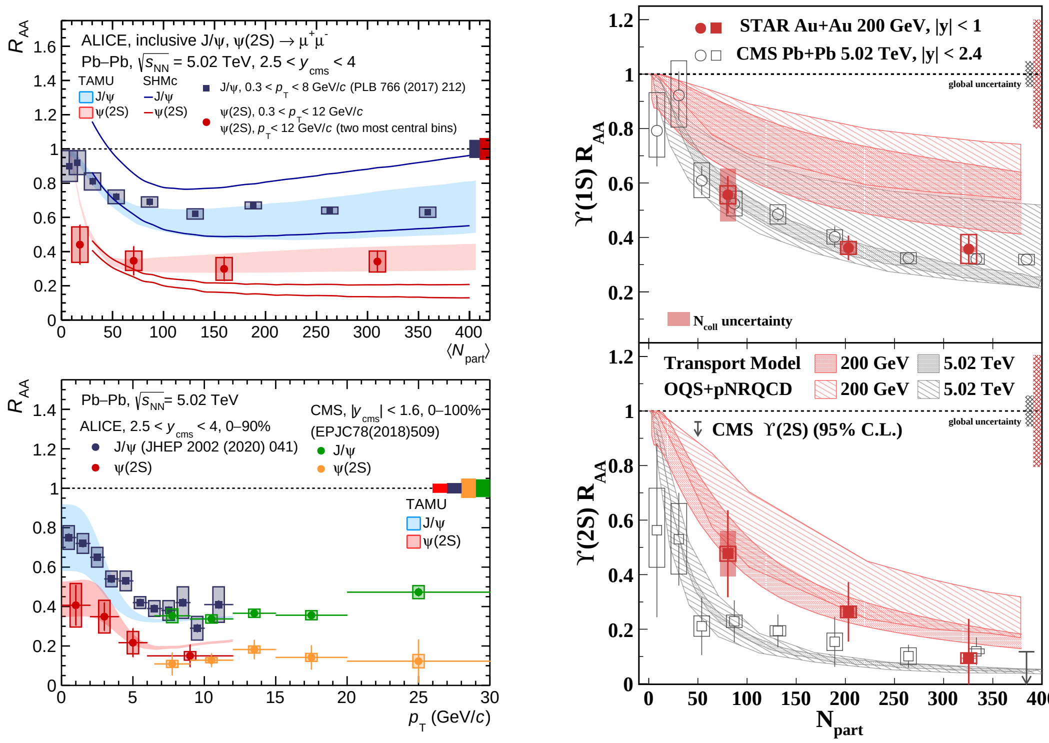

Figure 5: Nuclear modification factors for quarkonium production in URHICs. Left column: ALICE data [20] for the centrality (upper panel) and p_T dependence (lower panel) for J/ψ (blue) and ψ' compared to transport (bands) and SHM (lines) calculations. Right column: STAR (red) [24] and CMS [25] (gray) data for $\Upsilon(1S)$ (upper panel) and $\Upsilon(2S)$ compared to semiclassical [26] and quantum transport [27] calculations; figures taken from Refs. [20, 24].

factor reaches around one [21]. A striking feature of the J/ψ enhancement is its concentration at low p_T, as predicted by transport models and the SHM. Further evidence for regeneration as the dominant source in Pb-Pb collisions comes form measurements of the so-called elliptic flow of J/ψ mesons, which was found to be quite large [22], consistent with a recombination of anti-/charm quarks that are dragged along with the elliptic expansion of the strongly coupled QGP liquid in non-central Pb-Pb collisions [3]. Recent efforts succeeded in measuring $\psi(2S)$ production down to low p_T in Pb-Pb collisions at the LHC [20]. Here the data tend to be underestimated by the equilibrium limit obtained from the SHM. They agree with transport model predictions [15] where the $\psi(2S)$ is regenerated at later times due to larger reaction rates at lower temperatures ("sequential regeneration") [23], recall Fig. 4.

Finally, let us turn to bottomonium production, with a snapshot from RHIC and LHC data in the right panel of Fig. 5. For the $\Upsilon(2S)$, one finds strong suppression, which increases at higher collision energies and is readily explained by both semiclassical and quantum transport calculations. Note that the $\Upsilon(2S)$ has a binding energy comparable to the J/ψ, but the calculations predict a much smaller regeneration contribution due to a much fewer $b\bar{b}$ pairs in the system, typically no more than one pair per collision per unit rapidity. The $\Upsilon(1S)$ exhibits markedly less suppression which, however, is very comparable at RHIC and LHC energies, which evades current model calculations. It is currently unclear what the reason for that could be, and precision data from sPHENIX will be very valuable in this regard [28].

5. Conclusions

The synergy of results from lattice-QCD with effective theories of in-medium quarkonium properties have provided new insights in recent years. In particular, significant progress has been made in understanding the role of the HQ potential in quantum many-body theory, where it is defined as the driving kernel of an in-medium scattering equation. The off-shell properties of the HQ propagation inside the bound state incorporate the collisional effects underlying HQ diffusion and thereby explicitly connect the transport coefficients of heavy quarks and quarkonia. Quantitatively, the most recent indications are that the in-medium HQ potential is subject to a rather weak screening, providing a long-range force that is a prime candidate for generating the remarkable transport properties of the sQGP. Semiclassical quarkonium transport models in URHICs have enabled a rather consistent understanding of most of quarkonium data in AA collisions to date (with some exceptions), suggesting that the ground states can survive rather deep into the QGP. Significant challenges remain to fully implement the nonperturbative physics generated by a strong potential into quarkonium kinetics and to improve the understanding of the relation between semiclassical and quantum approaches. Work in these directions is in progress.

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References

[1] E. Shuryak, *Physics of Strongly coupled Quark-Gluon Plasma*,' Prog. Part. Nucl. Phys. **62** (2009) 48-101 [arXiv:0807.3033 [hep-ph]].

[2] U. Heinz and R. Snellings, *Collective flow and viscosity in relativistic heavy-ion collisions*, Ann. Rev. Nucl. Part. Sci. **63** (2013) 123-151 [arXiv:1301.2826 [nucl-th]].

[3] M. He, H. van Hees and R. Rapp, *Heavy-quark diffusion in the quark–gluon plasma*, Prog. Part. Nucl. Phys. **130** (2023) 104020 [arXiv:2204.09299 [hep-ph]].

[4] E. Eichten, K. Gottfried, T. Kinoshita, K. D. Lane and T. M. Yan, *Charmonium: Comparison with Experiment*, Phys. Rev. D **21** (1980) 203.

[5] G. 't Hooft, *A Property of Electric and Magnetic Flux in Nonabelian Gauge Theories*, Nucl. Phys. B **153** (1979) 141-160.

[6] A. Di Giacomo, M. Maggiore and S. Olejnik, *Confinement and Chromoelectric Flux Tubes in Lattice QCD*, Nucl. Phys. B **347** (1990) 441-460.

[7] T. Matsui and H. Satz, *J/ψ Suppression by Quark-Gluon Plasma Formation*, Phys. Lett. B **178** (1986) 416-422.

[8] A. Andronic, P. B. Gossiaux, P. Petreczky, R. Rapp, M. Strickland, *et al.*, *Comparative study of quarkonium transport in hot QCD matter*, Eur. Phys. J. A **60** (2024) 88 [arXiv:2402.04366 [nucl-th]].

[9] S. Y. F. Liu and R. Rapp, *T-matrix Approach to Quark-Gluon Plasma*, Phys. Rev. C **97** (2018) 034918 [arXiv:1711.03282 [nucl-th]].

[10] D. Bala *et al.* [HotQCD], *Static quark-antiquark interactions at nonzero temperature from lattice QCD*, Phys. Rev. D **105** (2022) 054513 [arXiv:2110.11659 [hep-lat]].

[11] Z. Tang, S. Mukherjee, P. Petreczky and R. Rapp, *T-matrix analysis of static Wilson line correlators from lattice QCD at finite temperature*, Eur. Phys. J. A **60** (2024) 92 [arXiv:2310.18864 [hep-lat]].

[12] M. Laine, O. Philipsen, P. Romatschke and M. Tassler, it Real-time static potential in hot QCD, JHEP **03** (2007) 054 [arXiv:hep-ph/0611300].

[13] A. Andronic, P. Braun-Munzinger, K. Redlich and J. Stachel, *Statistical hadronization of heavy quarks in ultra-relativistic nucleus-nucleus collisions*, Nucl. Phys. A **789** (2007) 334 [arXiv:nucl-th/0611023].

[14] Y. Liu, K. Zhou and P. Zhuang, *Quarkonia in high energy nuclear collisions*, Int. J. Mod. Phys. E **24** (2015) 1530015

[15] B. Wu and R. Rapp, *Charmonium Transport in Heavy-Ion Collisions at the LHC*, Universe **10** (2024) 244 [arXiv:2404.09881 [nucl-th]].

[16] Y. Akamatsu, *Quarkonium in quark–gluon plasma: Open quantum system approaches re-examined*, Prog. Part. Nucl. Phys. **123** (2022) 103932 [arXiv:2009.10559 [nucl-th]].

[17] M. C. Abreu *et al.* [NA50], *Evidence for deconfinement of quarks and gluons from the J/ψ suppression pattern measured in Pb + Pb collisions at the CERN SPS*, Phys. Lett. B **477** (2000) 28-36

[18] B. Alessandro *et al.* [NA50], *ψ' production in Pb-Pb collisions at 158-GeV/nucleon*, Eur. Phys. J. C **49** (2007) 559-567 [arXiv:nucl-ex/0612013].

[19] Z. Tang *et al.*, *An experimental review of open heavy flavor and quarkonium production at RHIC*, Nucl. Sci. Tech. **31** (2020) 81 [arXiv:2105.11656 [nucl-ex]].

[20] S. Acharya *et al.* [ALICE], *ψ(2S) Suppression in Pb-Pb Collisions at the LHC*, Phys. Rev. Lett. **132** (2024) 042301 [arXiv:2210.08893 [nucl-ex]].

[21] S. Acharya *et al.* [ALICE], *Measurements of inclusive J/ψ production at midrapidity and forward rapidity in Pb–Pb collisions at sNN = 5.02 TeV*, Phys. Lett. B **849** (2024) 138451 [arXiv:2303.13361 [nucl-ex]].

[22] S. Acharya *et al.* [ALICE], *Studies of J/ψ production at forward rapidity in Pb-Pb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV*, JHEP **02** (2020) 041 [arXiv:1909.03158 [nucl-ex]].

[23] X. Du and R. Rapp, *Sequential Regeneration of Charmonia in Heavy-Ion Collisions*, Nucl. Phys. A **943** (2015) 147-158 [arXiv:1504.00670 [hep-ph]].

[24] B. Aboona *et al.* [STAR], *Observation of sequential Υ suppression in Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 200 GeV with the STAR experiment*, Phys. Rev. Lett. **130** (2023) 112301 [arXiv:2207.06568 [nucl-ex]].

[25] A. M. Sirunyan *et al.* [CMS], *Measurement of nuclear modification factors of Υ(1S), Υ(2S), and Υ(3S) mesons in PbPb collisions at $\sqrt{s_{\rm NN}}$ = 5.02 TeV*, Phys. Lett. B **790** (2019) 270-293 [arXiv:1805.09215 [hep-ex]].

[26] X. Du, M. He and R. Rapp, *Color Screening and Regeneration of Bottomonia in High-Energy Heavy-Ion Collisions*, Phys. Rev. C **96** (2017) 054901 [arXiv:1706.08670 [hep-ph]].

[27] N. Brambilla, M. Á. Escobedo, A. Islam, M. Strickland, A. Tiwari, A. Vairo and P. Vander Griend, *Heavy quarkonium dynamics at next-to-leading order in the binding energy over temperature*, JHEP **08** (2022) 303 [arXiv:2205.10289 [hep-ph]].

[28] Z. Shi [sPHENIX], *Heavy Flavor Physics at the sPHENIX Experiment*, Universe **10** (2024) 126 [arXiv:2401.11036 [nucl-ex]].