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Bottomonia physics at RHIC and LHC

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The physics of Υ-mesons in the hot quark-gluon plasma (QGP) is investigated in heavy-ion collisions at energies reached at the Relativistic Heavy Ion Collider (RHIC) and the Large Hadron Collider (LHC). Our model for Υ suppression encompasses screening, collisional damping and gluodissociation in the QGP. It provides $p_{\perp}$- and centrality-dependent results for the six states involved. Most of the $\Upsilon(1S)$-suppression at LHC energies is found to be due to reduced feed-down, whereas the $\Upsilon(2S)$-suppression is mainly caused by hot-medium effects in the collectively expanding QGP. The previously predicted $\Upsilon(1S)$-suppression in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV agrees with recent CMS data. At RHIC energies, comparisons with 200 GeV AuAu data from STAR are shown. In the asymmetric pPb system at $\sqrt{s_{NN}} = 8.16$ TeV, both cold-matter and and hot-medium effects contribute substantially. Model comparisons with LHCb, and preliminary ALICE data are discussed.

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1. Introduction

Heavy mesons such as J/ψ or Υ provide sensitive probes for the properties of the quark-gluon plasma (QGP) that is generated in relativistic heavy-ion collisions. They are produced in hard collisions at very short formation times, typically at $\tau_F = 0.3 - 0.6$ fm/c. Since the spin-triplet Υ(1S)-state is particularly stable, it has a sizeable probability to survive as a color-neutral state in the colored hot quark-gluon medium of light quarks and gluons that is generated in a central heavy-ion collision at LHC energies, even at initial medium temperatures of the order of 400 MeV or above.

There exists a considerable literature on the dissociation of quarkonia, in particular of the Υ meson [1, 2, 3, 4], in the hot quark-gluon medium; see [5] and references therein for a review. In minimum-bias PbPb-collisions at LHC energies of $\sqrt{s_{NN}} = 2.76$ TeV in the midrapidity range, the $\Upsilon(1S)$-state is found to be suppressed down to about 45% as compared to the expectation from scaled pp collisions at the same energy. The Υ(2S)-state has a smaller binding energy and is even more suppressed, down to 11.9% [6]. At the higher centre-of-mass energy of 5.02 TeV, the suppression is more pronounced by a factor of $\simeq 1.2$, although the values are compatible with the ones at 2.76 TeV, within the experimental uncertainties.

Regarding bottomonia physics at RHIC energies of 200 GeV, the STAR collaboration has results for AuAu and UU collisions [3, 4]. The AuAu data [4] show more suppression for the $\Upsilon(1S)$ state compared to our hot-medium model, indicating that cold nuclear matter (CNM) effects are relatively more pronounced as compared to PbPb at LHC energies. We will briefly discuss these results in the RHIC energy domain.

The asymmetric pPb system at $\sqrt{s_{NN}}$ = 8.16 TeV has been investigated theoretically in great detail with respect to CNM effects in Ref. [7]. In addition, we have recently considered the hot-medium contribution to Υ suppression as functions of transverse momentum, centrality, and rapidity, and I report some of the results of our multiparticle dynamics group, and comparisons with recent LHCb and ALICE data from Ref. [8] in this conference contribution.

2. The model

In [9, 10, 11] we have devised a model that accounts for the screening of the real part of the potential, the gluon-induced dissociation of the various bottomonium states in the hot medium (gluodissociation), and the damping of the quark-antiquark binding due to the presence of the medium which generates an imaginary part of the temperature-dependent potential. Screening is less important for the strongly bound $\Upsilon(1S)$ ground state, but it is relevant for the b$\bar{\text{b}}$ excited states, and also for all c$\bar{\text{c}}$ bound states.

Due to screening and depopulation of the excited states in the hot medium, the subsequent feed-down cascade towards the $\Upsilon(1S)$ ground state differs considerably from what is known based on *pp* collisions. The LHCb collaboration has measured a feed-down fraction of $\Upsilon(1S)$ originating from $\chi_b(1P)$ decays in *pp* collisions at $\sqrt{s} = 7$ TeV of 20.7% [12], and the total feed-down from excited states to the ground state is estimated to be around 40% [13] at LHC energies. If feed-down was completely absent because of screening and depopulation of excited states in the hot medium, a suppression factor of $R_{AA}(\Upsilon(1S)) \simeq 0.6$ would thus result, whereas the measured suppression factor of the $\Upsilon(1\mathrm{S})$ state in minimum-bias PbPb collisions at 2.76 TeV is 0.453 ± 0.014 (stat) ± 0.046 (syst) [6], and 0.378 ± 0.013 (stat)± 0.035 (syst) at 5.02 TeV [14]. Hence, there clearly exist in-medium suppression mechanisms for the strongly bound $\Upsilon(1\mathrm{S})$ state which we aim to account for in detail, together with the suppression of the excited states, and the reduced feed-down.

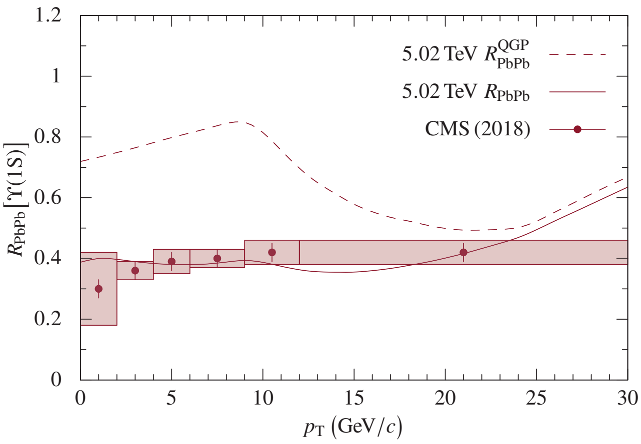

Figure 1: Transverse-momentum dependence of the suppression factor R^{QGP}_{PbPb} in the medium (dashed curve), and of the total suppression R_{PbPb} including reduced feed-down (solid curve) as calculated previously in Ref. [11] for the $\Upsilon(1S)$ state in minimum-bias PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV ($T_0 = 513$ MeV). Recent CMS data from Ref. [14] are compared with our theoretical prediction from Ref. [11].

In our model calculation [11], we thus determine the respective contributions from in-medium suppression, and from reduced feed-down for the $\Upsilon(1\mathrm{S})$ ground state, and the $\Upsilon(2\mathrm{S})$ first excited state in PbPb collisions at both LHC energies, 2.76 TeV and 5.02 TeV. The p_T-dependence and the role of the relativistic Doppler effect on the measured transverse-momentum spectra is discussed. For the $\Upsilon(2\mathrm{S})$ state, the QGP effects are expected to be much more important with respect to reduced feed-down. We compare in Ref. [11] with centrality-dependent CMS data [1, 6] for the $\Upsilon(1\mathrm{S})$ and $\Upsilon(2\mathrm{S})$ states in 2.76 TeV PbPb collisions. The $p_\perp$- and centrality-dependent suppression at the higher LHC energy of $\sqrt{s_{NN}} = 5.02$ TeV has also been predicted in Ref. [11].

For symmetric systems such as AuAu at RHIC or PbPb at LHC, we do not include an explicit treatment of CNM effects such as shadowing in the present study. These are, however, important in asymmetric collisions such as pPb where most of the system remains cold during the interaction time, and we have considered them in our corresponding calculations [8] shown at the end of this note. Statistical recombination of the heavy quarks following bottomonia dissociation is, however, disregarded: Although this is certainly a relevant process in the J/ψ case, the significantly smaller cross section for Υ production allows us to neglect it.

The anisotropic expansion of the hot fireball is accounted for using hydrodynamics for a perfect fluid that includes transverse expansion. Such a simplified nonviscous treatment [10, 11] of the bulk evolution appears to be tolerable because conclusions on the relative importance of the in-medium suppression versus reduced feed-down are not expected to depend much on the details of the background model. When calculating the in-medium dissociation, we consider the relativistic Doppler effect that arises due to the relative velocity of the bottomonia with respect to the expanding medium. It leads to more suppression at high $p_\perp$, and to an overall flat dependence of R_{AA} on $p_\perp$.

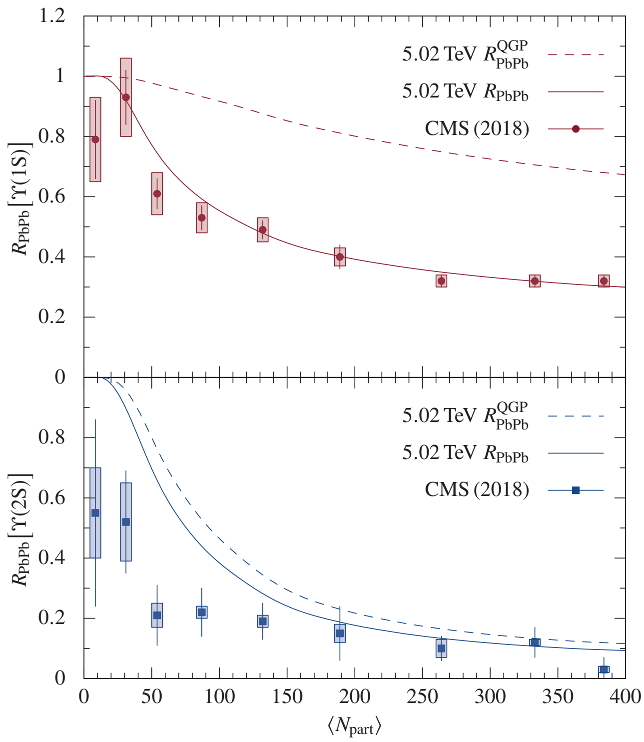

Figure 2: Top: Predicted suppression factor $R_{PbPb}\big(\Upsilon(1\mathrm{S})\big)$ in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (solid curve, calculation from [11]) together with centrality-dependent data from CMS ($|y| < 2.4$, [14]) as function of the number of participants $\langle N_{part} \rangle$ (averaged over centrality bins). The suppression factor R_{PbPb}^{QGP} in the QGP-phase without the effect of reduced feed-down is shown as dashed (upper) curve. The formation time is $\tau_F = 0.4$ fm/c, the initial central temperature $T_0 = 513$ MeV. Bottom: Predicted suppression factor (solid curve, from [11]) for the first excited state $R_{PbPb}\big(\Upsilon(2\mathrm{S})\big)$ in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (solid line) together with data from CMS [14]. The suppression factor R_{PbPb}^{QGP} in the QGP-phase (dashed) accounts for most of the calculated total suppression (solid) of the $\Upsilon(2\mathrm{S})$. Calculations from [11], plot by Hoelck.

3. Results and comparison with data

In Ref. [11] we had calculated predictions for the $p_\perp$-dependent Υ-suppression in 5.02 TeV PbPb collisions, which are shown to be in agreement with recent CMS data [14] in Fig. 1; see the caption for details. For the $\Upsilon(1S)$ state, a substantial fraction of the suppression, in particular at low $p_\perp$, is due to reduced feed-down. The corresponding centrality-dependent suppression (integrated over $p_\perp$) is shown in Fig. 2, in agreement with the data [14] for the $\Upsilon(1S)$ state. Related ALICE data at more forward rapidities $2.5 < y < 4$ are roughly consistent within the error bars [15].

The suppression of the $\Upsilon(2S)$ state is mostly in-medium, with only a small contribution due to reduced feed-down. The prediction shows less suppression than the data in peripheral collisions.

Fig. 3 displays calculated results for the $\Upsilon(1S)$-suppression in AuAu collisions at RHIC energies of 200 GeV in comparison with recent STAR data [4]. Here the initial central temperature has been estimated from the charged-hadron yields as $T_0 = 356$ MeV. The in-medium suppression of the $1S$-state is not very pronounced, the contribution from reduced feed-down is larger, but not suf-

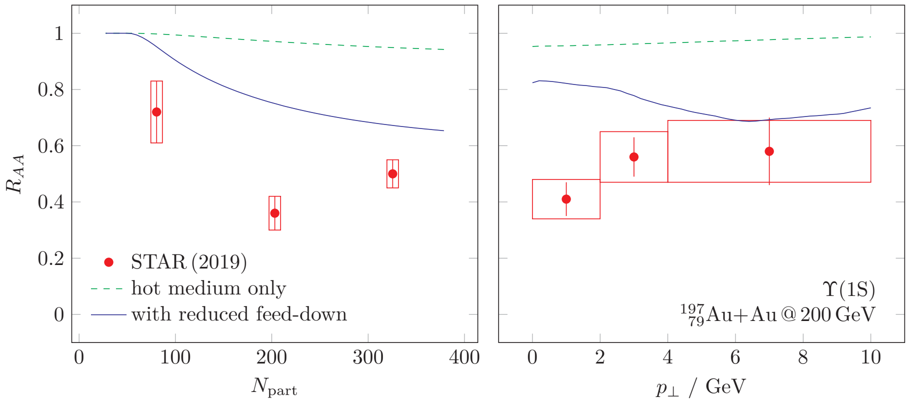

Figure 3: Bottomonia suppression at RHIC energies in AuAu collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Our calculation is as in Ref. [11] for PbPb, with the same bottomonium formation time $t_F = 0.4$ fm/c. The initial central temperature is estimated from the charged-hadron yield as $T_0 = 356$ MeV. Centrality-dependent results are shown on the left, transverse-momentum-dependent results (for 0-60% centrality) on the right. Dashed curves are for in-medium suppression only, solid curves include the feed-down reduction. In contrast to LHC results, the in-medium suppression plus reduced feed-down is not sufficient to account for the STAR data [4]. CNM effects could explain the discrepancy. From Hoelck and Wolschin, priv. comm. (2019).

ficient to account for the data. The likely reason is the neglect of CNM-effects, which are expected to be relatively more important at RHIC energies as compared to the higher LHC energies.

For bottomonia in asymmetric collisions, pPb at $\sqrt{s_{NN}} = 8.16$ TeV has been investigated experimentally by the LHCb [16] and ALICE [15] collaborations, and cold nuclear matter predictions had been published by a group of theorists [7]. Clearly, CNM effects are much more relevant than in symmetric systems, because the bulk of the hadronic matter remains cold during the interaction. There is, however, a spatially small hot zone (fireball) with an initial central temperature that is comparable to the one in a symmetric system, and during its expansion and cooling, it contributes to bottomonia dissociation. We have investigated the respective cold-matter and hot-medium effects on Υ-dissociation in 8.16 pPb collisions in [8]. A representative result from this work is shown in Fig. 4, which displays CNM (blue, upper bands) and CNM plus QGP (red, lower bands) effects on the $\Upsilon(1\text{S})$ and $\Upsilon(2\text{S})$ yields in 8.16 TeV pPb collisions at the LHC.

The forward/backward asymmetric shape of the nuclear modification factors as functions of rapidity arises from the different cold-matter effects in the forward and backward regions (in particular, shadowing/ antishadowing of the parton distribution functions, but also energy loss in the relatively cold medium). The additional suppression due to the dissociation in the hot fireball is shown in the lower (red) curves, which are in better agreement with the data for the $\Upsilon(1S)$ ground state. The substantial role of the hot-medium effects is even more pronounced for the $\Upsilon(2S)$ first excited state, where the CNM-calculation shows enhancement in the backward region, whereas the full calculation with in-medium dissociation displays a suppression down to almost 70% - in agreement with the preliminary ALICE data point from Ref. [15].

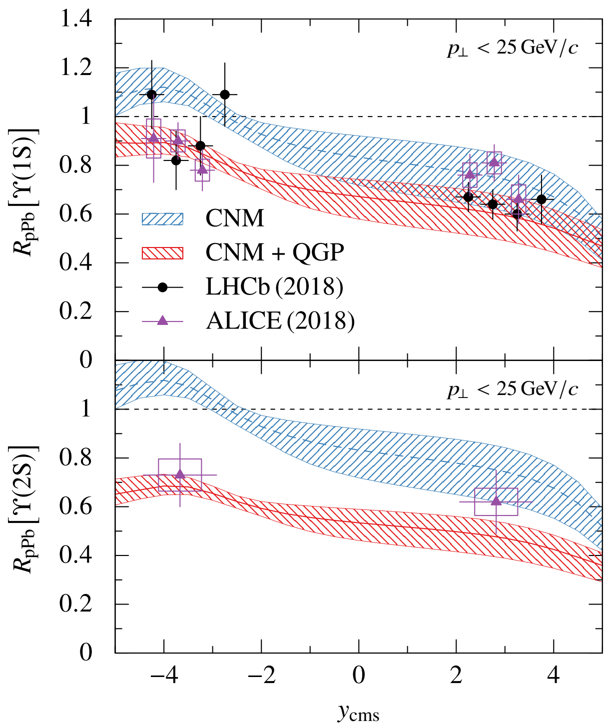

Figure 4: Calculated rapidity-dependent nuclear modification factors R_{pPb} for the $\Upsilon(1S)$ (top) and $\Upsilon(2S)$ state (bottom) in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV with preliminary ALICE data, triangles [15], and with LHCb data, circles [16]. Results for cold nuclear matter (CNM) effects that include shadowing, energy loss, and reduced feed-down (dashed curves, blue) are shown together with calculations that incorporate also QGP effects (solid curves, red). The error bands result from the uncertainties of the parton distribution functions that enter the calculations. The initial central temperature in the fireball region is $T_0 \simeq 460$ MeV. From Dinh, Hoelck and Wolschin [8].

4. Conclusions

Our phenomenological model for Upsilon suppression in relativistic heavy-ion collisions incorporates gluodissociation, damping, and reduced feed-down. It has been shown to predict [11] the $\Upsilon(1S)$-suppression in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV accurately when compared to recent CMS data [14]. Screening is unimportant for the $\Upsilon(1S)$ state, whereas reduced feed-down is responsible for a considerable part of the suppression.

In contrast, for the excited $\Upsilon(2S)$ state the model reveals substantial screening effects and – together with the other dissociation processes that we consider – more suppression than for $\Upsilon(1S)$, with only a small contribution from reduced feed-down. In very peripheral collisions, however, the current CMS data for $\Upsilon(2S)$ [14] show more suppression than the model, leaving room for future improvement. Electromagnetic field effects [17] are, however, unlikely to be the origin of the discrepancy. We have also calculated the Υ-suppression in AuAu collisions at RHIC energies of $\sqrt{s_{NN}} = 200$ GeV. Here, the in-medium suppression is less pronounced, and CNM effects are expected to be more important.

Regarding bottomonia in asymmetric systems, we have investigated pPb collisions at LHC energies of 8.16 TeV [8], with the result that for a proper understanding of the data not only the well-established CNM effects need to be considered, but also the hot-medium suppression in the spatially small, but rapidly expanding fireball.

Acknowledgments

This work was performed in collaboration with Johannes Hölck (ITP Heidelberg), who had previously investigated in his MSc. thesis electromagnetic field effects on the Upsilon suppression. Viet Hung Dinh contributed in his MSc. thesis CNM results for modifications of Υ-yields in pPb collisions at LHC energies. I am grateful to my colleagues from the Corfu Summer Institute and the CPOD conference for setting up this meeting, and for sponsoring part of the participation.

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