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Spectroscopy in the quark-gluon plasma with bottomonia

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The suppression of Υ-mesons in the hot quark-gluon plasma (QGP) versus reduced feed-down is investigated in heavy-ion collisions at energies reached at the Large Hadron Collider (LHC). Our model 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 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, whereas the data for $\Upsilon(2S)$ are more strongly suppressed compared to calculated results in peripheral collisions. Predictions for fixed-target experiments with a 2.76 TeV Pb-beam are shown.

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1. Introduction

The production of quarkonia and, in particular, of bottomonia in relativistic heavy-ion collisions at RHIC and LHC energies provides a sensitive test for the properties of the hot medium. Particles such as the J/ψ or the Υ meson are produced in hard collisions at very short formation times, typically at $\tau_F = 0.3-0.6$ fm/c. Since the spin-triplet $\Upsilon(1S)$-state is particularly stable, it has a sizeable probability to survive in the hot quark-gluon medium of 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], in the hot quark-gluon medium; see [4] 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 $y = 0-2.5$, the $\Upsilon(1S)$-state is found to be suppressed down to 45.3%. The $\Upsilon(2S)$-state has a smaller binding energy and is even more suppressed, to 11.9% [5]. 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 within the uncertainties – experimental results from Ref [6] are 37.8% and 11.4%. For the $3S$ state at 5.02 TeV, only an upper limit of 9.4% at 95% CL is known so far.

2. The model

In [7, 8, 9] 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 $b\bar{b}$ excited states, and also for all $c\bar{c}$ 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% [10], and the total feed-down from excited states to the ground state is estimated to be around 40% [11] 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 $R_{AA} \simeq 0.6$ would thus result, whereas the measured suppression factor of the $\Upsilon(1S)$ state in minimum-bias PbPb collisions at 2.76 TeV is 0.453 [5].

In our model calculation [9], we determine the respective contributions from in-medium suppression, and from reduced feed-down for the $\Upsilon(1S)$ ground state, and the $\Upsilon(2S)$ 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 $\Upsilon(2S)$ state, the QGP effects are expected to be much more important with respect to reduced feed-down. We compare in Ref. [9] with centrality-dependent CMS data [1, 5] for the $\Upsilon(1S)$ and $\Upsilon(2S)$ 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. [9], and is now compared in this note with preliminary CMS data [6].

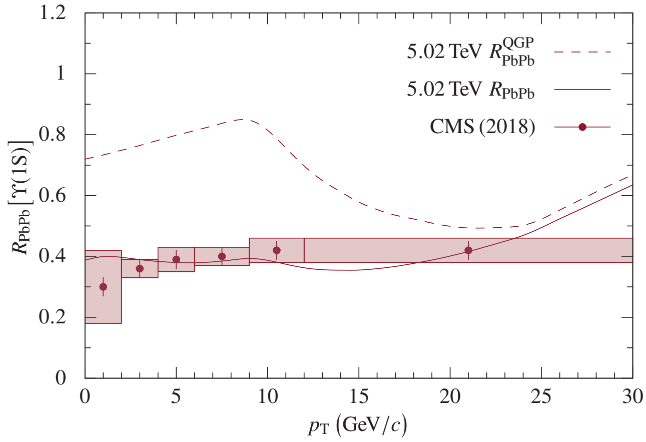

Figure 1: Transverse-momentum dependence of the suppression factor R^{QGP}_{PbPb} in the medium (dashed line), and of the total suppression R_{PbPb} including reduced feed-down (solid line) as calculated previously in Ref. [9] for the $\Upsilon(1S)$ state in minimum-bias PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV ($T_0 = 513$ MeV). The theoretical prediction from Ref. [9] is now compared with recent preliminary CMS data from Ref. [6].

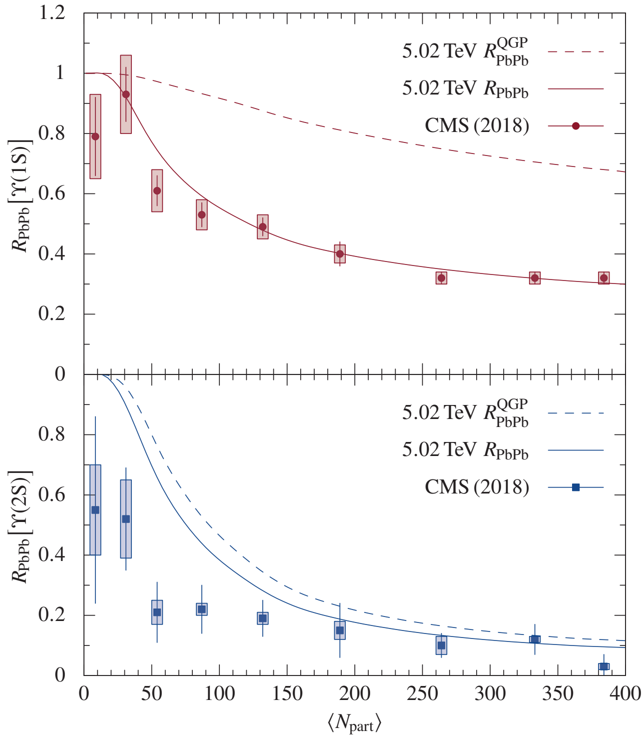

Figure 2: Top: Predicted suppression factor $R_{PbPb}(\Upsilon(1\mathrm{S}))$ in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (solid curve, calculation from [9]) together with centrality-dependent preliminary data from CMS ($|y| < 2.4$, [6]) as function of the number of participants N_{part} (averaged over centrality bins). The suppression factor R^{QGP}_{PbPb} 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 [9]) for the first excited state $R_{PbPb}(\Upsilon(2\mathrm{S}))$ in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV (solid line) together with preliminary data from CMS [6]. The suppression factor R^{QGP}_{PbPb} in the QGP-phase (dashed) accounts for most of the calculated total suppression (solid) of the $\Upsilon(2\mathrm{S})$.

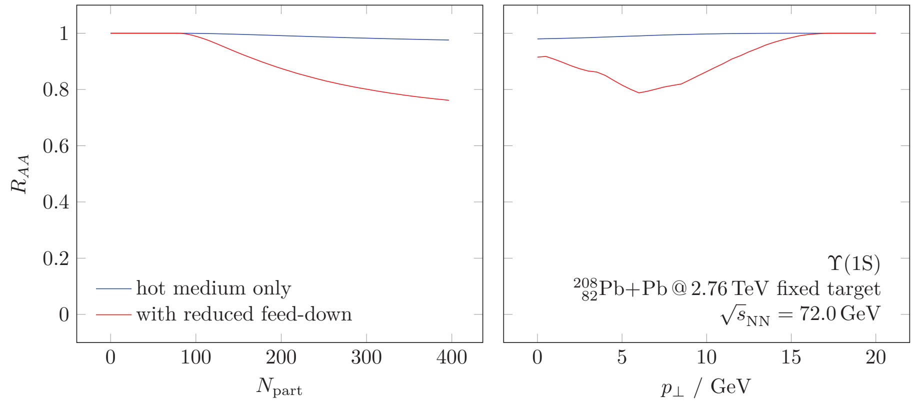

Figure 3: Bottomonia suppression in future fixed-target collisions with a Pb-beam of 2.76 TeV at the LHC: Calculated dependencies of the $\Upsilon(1S)$ suppression factors on centrality (left) and transverse-momentum (right, for minimum-bias collisions). The suppression in the hot quark-gluon medium is R_{AA}^{QGP} (black), whereas R_{AA} includes reduced feed-down (red) as predicted for the $\Upsilon(1S)$ state in PbPb collisions at $\sqrt{s_{NN}} =$ 72 GeV ($T_0 = 322$ MeV). This corresponds to a Pb-beam energy of 2.76 TeV in fixed-target experiments planned for run 3 at the LHC [12].

I do not include an explicit treatment of cold nuclear matter (CNM) effects in the present study. These are certainly very relevant in asymmetric collisions such as pPb where most of the system remains cold during the interaction time. In symmetric systems at RHIC and LHC energies, however, the CNM effects such as shadowing are likely less important and moreover, expected to be very similar for ground and excited states. Statistical recombination of the heavy quarks following bottomonia dissociation is disregarded as well: 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 [8, 9] 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 bottomia 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 $p_\perp$.

3. Results and comparison with 5.02 TeV PbPb data

In Ref. [9] 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 [6] 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 [6] for the $\Upsilon(1S)$ state. Related ALICE data at more forward rapidities $2.5 < y < 4$ are roughly consistent within the error bars [13].

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 forthcoming fixed-target experiments with a 2.76 TeV Pb-beam, corresponding to $\sqrt{s_{NN}} = 72$ GeV in PbPb.

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 [9] the $\Upsilon(1S)$-suppression in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV accurately when compared to recent CMS data [6]. 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 $\Upsilon(2S)$ [6] show more suppression than the model, leaving room for future improvement. Electromagnetic field effects [14] are, however, unlikely to be the origin of the discrepancy. We have also calculated the Υ-suppression for fixed-target experiments with a 2.76 TeV Pb-beam corresponding to $\sqrt{s_{NN}} = 72$ GeV in the forthcoming run 3 at the Large Hadron Collider, where in particular the in-medium suppression is much less pronounced.

Acknowledgments

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