

Hot-medium effects on Υ yields in p-Pb and Pb-Pb collisions

Georg Wolschin^{1,a}

¹*Institut für Theoretische Physik der Universität Heidelberg, Philosophenweg 16, D-69120 Heidelberg, Germany, EU*

Abstract. The modification of bottomonia yields in Pb-Pb and p-Pb collisions at LHC energies with respect to the expectation from p-p is investigated in a theoretical approach. Dissociation of the $\Upsilon(nS)$ and $\Upsilon(nP)$ states in the hot quark-gluon plasma (QGP) occurs due to screening of the real quark-antiquark potential, collisional damping through the imaginary part of the potential, and gluon-induced dissociation. Reduced feed-down plays a decisive role. Transverse-momentum and centrality-dependent data are well reproduced. In the asymmetric p-Pb system, alterations of the parton density functions in the lead nucleus account for the leading fraction of the modifications in cold nuclear matter (CNM), but the hot-medium effects turn out to be relevant in spite of the small initial spatial extent of the fireball.

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 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 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 [1–4], in the hot quark-gluon medium; see [5] and references therein for a review. In minimum-bias PbPb-collisions at LHC energies of $\sqrt{s_{NN}} = 5.02$ TeV in the midrapidity range, the strongly bound $\Upsilon(1S)$ -state is found to be suppressed down to about 38% as compared to the expectation from scaled pp collisions at the same energy. The $\Upsilon(2S)$ -state has a smaller binding energy and is even more suppressed, down to 12% [6]. 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 of 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.

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. I report

^ae-mail: wolschin@uni-hd.de

Work done in collaboration with V.H. Dinh, now PhD student at Orsay, and J. Hölck, PhD student at Heidelberg.

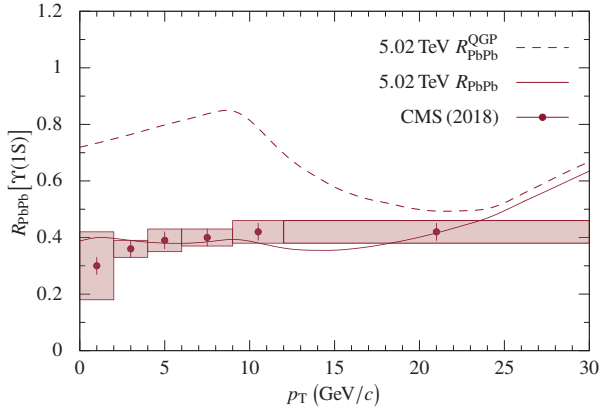


Figure 1: Transverse-momentum dependence of the modification factor $R_{\text{PbPb}}^{\text{QGP}}[\Upsilon(1S)]$ in the hot medium (dashed curve), and of the total suppression including reduced feed-down (solid curve) for the $\Upsilon(1S)$ state in minimum-bias PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV ($T_0 = 513$ MeV). Recent CMS data from Ref. [6] are compared with our theoretical prediction from Ref. [11].

some of the results of our multiparticle dynamics group from Ref. [8], and compare with recent LHCb and ALICE data in this conference contribution. It turns out that in pPb, the bottomonia dissociation in the hot medium is relevant in spite of the small spatial extent of the fireball.

2 The model

In Refs. [9–11] 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 $b\bar{b}$ 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% [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 modification factor $R_{AA}(\Upsilon(1S)) \approx 0.6$ would thus result, whereas the measured modification factor of the $\Upsilon(1S)$ state in minimum-bias PbPb collisions at 2.76 TeV is 0.453 ± 0.014 (stat) ± 0.046 (syst) [14], and 0.378 ± 0.013 (stat) ± 0.035 (syst) at 5.02 TeV [6]. Hence, there clearly exist in-medium suppression mechanisms for the strongly bound $\Upsilon(1S)$ state which we aim to account for in detail, together with the suppression of the excited states, and the reduced feed-down.

In our model calculation [11], we thus 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 considered. For the

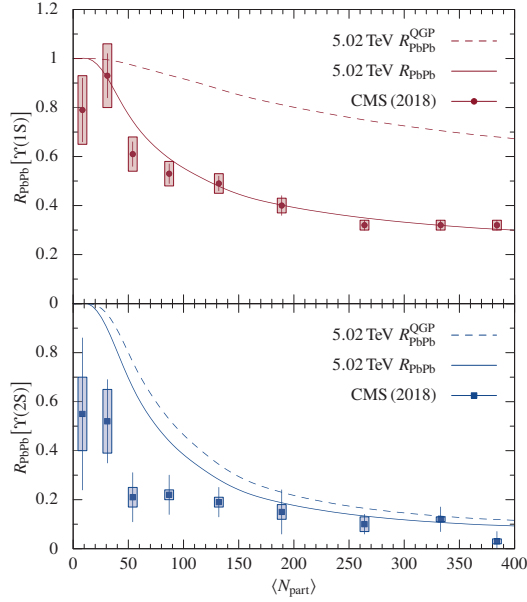


Figure 2: Top: Predicted modification factor $R_{\text{PbPb}}[\Upsilon(1S)]$ in PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV (solid curve) with centrality-dependent data from CMS ($|y| < 2.4$, [6]) as function of the number of participants $\langle N_{\text{part}} \rangle$ (averaged over centrality bins). The modification factor 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 modification factor for the first excited state $R_{\text{PbPb}}[\Upsilon(2S)]$ in PbPb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV (solid curve) with data from CMS [6]. The modification factor in the QGP-phase (dashed) accounts for most of the calculated total suppression (solid) of the $\Upsilon(2S)$ state. Predictions are from Ref. [11].

$\Upsilon(2S)$ state, the QGP effects are expected to be much more important than reduced feed-down. We compare in Ref. [11] with centrality-dependent CMS data [1, 14] 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 $\sqrt{s_{\text{NN}}} = 5.02$ 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]. Statistical recombination of the heavy quarks following bottomonia dissociation is disregarded: Although this is certainly a relevant process in the J/ψ case, the cross section for Υ production is significantly smaller.

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} .

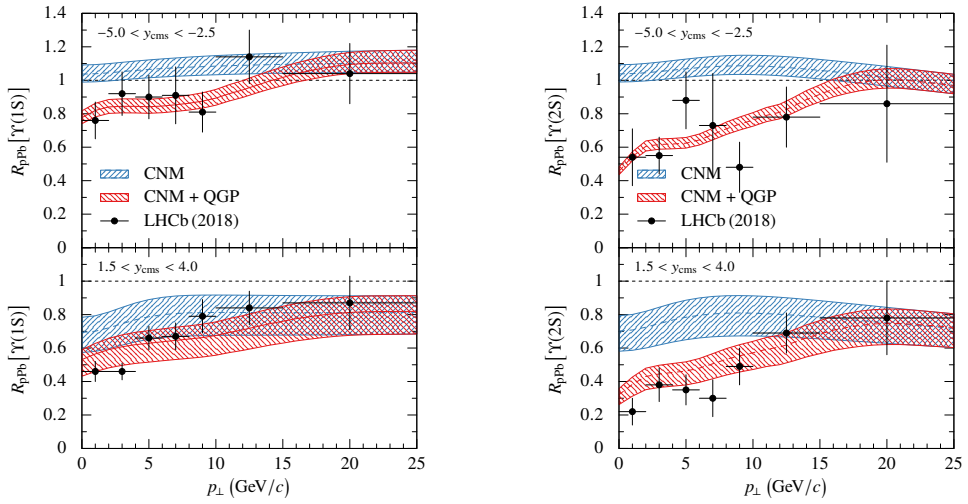


Figure 3: Calculated p_{\perp} -dependent nuclear modification factors R_{pPb} for the $\Upsilon(1S)$ spin-triplet ground state (left) and the excited $\Upsilon(2S)$ state (right) in pPb collisions at = 8.16 TeV are compared with LHCb data [15] in the backward (Pb-going, top) and forward (p-going, bottom) region, for minimum-bias centrality. Results for 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. From Dinh, Hoelck and Wolschin [8].

3 Results and comparison with data

In Ref. [11] we have 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 [16].

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.

For bottomonia in asymmetric collisions, pPb at $\sqrt{s_{\text{NN}}} = 8.16$ TeV has been investigated experimentally by the LHCb [15] and ALICE [16] 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 in regions where the temperature remains above the critical value. We have investigated the respective cold-matter and hot-medium effects on Υ -dissociation in 8.16 pPb collisions [8].

Representative results from this work are shown in Fig. 3 for the transverse-momentum dependence, and Fig. 4 for the rapidity dependence. The plots show CNM (blue, upper bands) and CNM plus QGP (red, lower bands) effects on the $\Upsilon(1S)$ and $\Upsilon(2S)$ yields in 8.16 TeV pPb collisions at the LHC. The transverse-momentum dependence in the backward direction (top) shows enhancement due

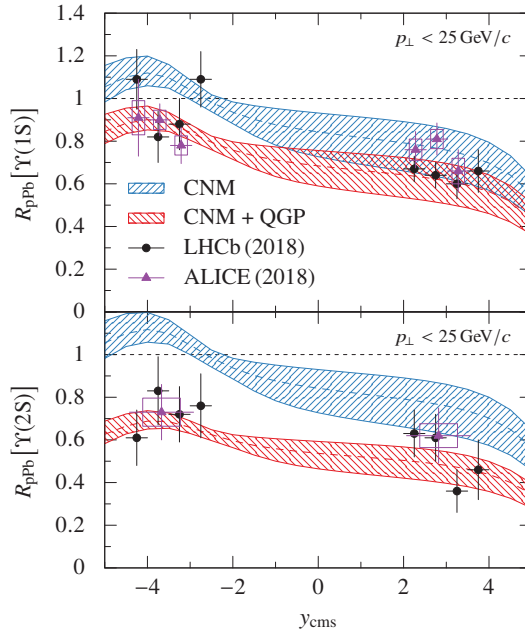


Figure 4: Calculated rapidity-dependent nuclear modification factors R_{pPb} for the $\Upsilon(1S)$ (top) and $\Upsilon(2S)$ state (bottom) in pPb collisions at $\sqrt{s_{NN}} = 8.16$ TeV with preliminary ALICE data, triangles [16], and with LHCb data, circles [15]. Results for cold nuclear matter (CNM) 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 $T_0 \approx 460$ MeV. From Dinh, Hoelck and Wolschin [8], with added $\Upsilon(2S)$ LHCb data.

to antishadowing when only the CNM effects are considered, whereas the data for $\Upsilon(1S)$ are clearly suppressed at $p_{\perp} < 10$ GeV/c, and for $\Upsilon(2S)$ at all measured p_{\perp} values. This discrepancy is cured through the consideration of dissociation in the QGP, as shown in our cold-matter plus hot-medium calculation (red).

The forward/backward asymmetric shape of the nuclear modification factors as functions of rapidity (Fig. 4) 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 again shown in the lower (red) curves, which are in better agreement with the data for the $\Upsilon(1S)$ ground state not only in the backward, but also in the forward direction. 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 LHCb data [15], and the ALICE data point from Refs. [16, 17].

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 [6]. Screening is unimportant for the $\Upsilon(1S)$ state, whereas reduced feed-down is responsible for a considerable fraction 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 [18] are unlikely to be the origin of the discrepancy.

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, rapidly expanding fireball. This is consistent with the presence of a quark-gluon droplet in asymmetric systems at LHC energies.

Acknowledgments

This work was performed in collaboration with Johannes Hölck (ITP Heidelberg), and Viet Hung Dinh (now IJC Paris-Saclay) who 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 New Mexico and Texas – in particular, Ivan Vitev – for setting up the ISMD at Santa Fe.

References

- [1] S. Chatrchyan et al. (CMS Collaboration), Phys. Rev. Lett. **109**, 222301 (2012)
- [2] B. Abelev et al. (ALICE Collaboration), Phys. Lett. B **738**, 361 (2014)
- [3] L. Adamczyk et al. (STAR Collaboration), Phys. Lett. B **735**, 127 (2014)
- [4] Z. Liu et al. (STAR Collaboration), PoS (HardProbes 2018) p. 161 (2018)
- [5] A. Andronic, F. Arleo, R. Arnaldi, A. Beraudo et al., Eur. Phys. J. C **76**, 107 (2016)
- [6] A.M. Sirunyan et al. (CMS Collaboration), Phys. Lett. B **790**, 270 (2019)
- [7] J.L. Albacete et al., Nucl. Phys. A **972**, 18 (2018)
- [8] V.H. Dinh, J. Hoelck, G. Wolschin, Phys. Rev. C **100**, 024096 (2019)
- [9] F. Nendzig, G. Wolschin, Phys. Rev. C **87**, 024911 (2013)
- [10] F. Nendzig, G. Wolschin, J. Phys. G: Nuclear and Particle Physics **41**, 095003 (2014)
- [11] J. Hoelck, F. Nendzig, G. Wolschin, Phys. Rev. C **95**, 024905 (2017)
- [12] R. Aaij et al. (LHCb Collaboration), JHEP **11**, 031 (2012)
- [13] G. Manca (LHCb Collaboration), private communication (2018)
- [14] V. Khachatryan et al. (CMS Collaboration), Phys. Lett. B **770**, 357 (2017)
- [15] R. Aaij et al. (LHCb Collaboration), JHEP **11**, 194 (2018)
- [16] D. Adamová et al. (ALICE Collaboration), ALICE-PUBLIC-2018-008 (2018)
- [17] S. Acharya et al. (ALICE Collaboration), Phys. Lett. B, submitted; 1910.14405 (2019)
- [18] J. Hoelck, G. Wolschin, Eur. Phys. J. A **53**, 241 (2017)