1. Introduction

Whereas $J/\psi$-suppression in relativistic heavy-ion collisions has been investigated in detail for almost 30 years now, the research on the suppression of bottomia in the hot quark-gluon medium that is created in such collisions is a relatively new field. On the experimental side, it started with CMS data from the Large Hadron Collider (LHC) in PbPb collisions at 2.76 TeV c.m. energy per particle pair where the $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ states could be resolved for the first time in a heavy-ion collision ([1] and references therein), followed by the ALICE collaboration [2] – where the $\Upsilon(2S)$ and $\Upsilon(3S)$ states still wait for their resolution –, and STAR measurements from 200 GeV AuAu [3] at RHIC.

There are characteristic differences between $J/\psi$- and $\Upsilon$-suppression which call for a detailed comparative investigation that is beyond the scope of this article. Let me mention, however, the large difference by more than a factor of three in the masses of charm and bottom quarks, and a corresponding difference in the meson masses ($m_{J/\psi} = 3.097 \text{ GeV}/c^2$ vs. $m_{\Upsilon(1S)} = 9.460 \text{ GeV}/c^2$). Accordingly in a PbPb collision at the present energy of 2.76 TeV more than 100 $J/\psi$-mesons are produced in initial hard collisions, but only about 6 – 10 $\Upsilon$-mesons and hence, statistical recombination of heavy quarks following the dissociation of the heavy mesons in the hot quark-gluon plasma (QGP) is an important issue in $J/\psi$-physics, but not in the Upsilon case. Although the statistical recombination of $c$- and $\bar{c}$-quarks is a most interesting process that may even be used as a possible QGP signature together with $J/\psi$-dissociation, its irrelevance in the $bb$-case has the advantage of generating a cleaner environment for heavy-quarkonia dissociation in the QGP.

Another characteristic difference between $J/\psi$- and $\Upsilon$-suppression is the unusual stability of the $\Upsilon(1S)$ ground state, which survives in the QGP up to very high temperatures. In particular, $\Upsilon(1S)$ resists dissociation due to screening of the real part of the quark-antiquark potential up to temperatures of more than four times the critical value, and similarly for other dissociation processes that we shall discuss in this note. This provides a very clean environment...
for investigating the centrality-dependent suppression of this state in the QGP which is quite different from both the excited Upsilon states, and all J/ψ-states.

The heavier the hadron that is produced in the collision, the shorter its formation time. Very heavy mesons such as the J/ψ, or the Υ meson in its 1S spin-triplet ground state are produced in hard collisions at very short times, typically at \( \tau_F \approx 0.1 - 0.5 \text{ fm}/c \). Since the Υ(1S) state is particularly stable, it has a sizeable probability to survive in the hot quark-gluon medium that is produced in the fireball of a heavy-ion collision at LHC energies. We have accordingly devised a model that accounts for the dissociation of the various bottomium states in the hot medium (gluodissociation), the damping of the quark-antiquark binding due to the presence of the medium, which generates an imaginary part of the temperature-dependent potential, and the screening of the real part of the potential. The latter turns out to be unimportant for the Υ(1S) ground state, but it is relevant for the less strongly bound excited states.

Once the bottomia states have survived the quark-gluon plasma environment, the feed-down cascade from the excited states to the ground state has to be considered in detail. Due to the rapid depopulation of the excited states caused by the various mechanisms, the feed-down to the ground state is reduced accordingly, producing additional suppression relative to the situation in pp collisions at the same energy. We then compare the calculated centrality-dependent Υ(nS)-suppression [4, 5] with recent CMS data [1], and predict the suppression at the LHC design energy.

2. Υ suppression in PbPb collisions at LHC energies

The production of heavy mesons and in particular, of bottomia in initial hard partonic interactions in relativistic PbPb collisions at LHC energies is of special interest, because quarkonia in the fireball can act as a probe to test the properties of the hot medium. In our model [4, 5] we investigate the suppression of the Υ(nS) states in PbPb as compared to the expectation from scaled pp collisions at the same energy, and compare with centrality-dependent CMS data [1] for the 1S and 2S states. In the hot medium, the three most important dissociation mechanisms are taken to be gluodissociation, damping, and screening of the real part of the quark-antiquark potential. The calculated gluodissociation cross section for the 1S and 2S states together with the thermal gluon distribution function are shown as functions of the gluon energy at two different temperatures in fig. 1.

Since the matrix elements that characterize gluodissociation (see formulae in [5]) have a finite extent in the gluon energy space, the corresponding cross sections exhibit maxima. Still, when averaged over the temperature-dependent gluon-energy distribution, and considering the momentum-dependent running of the strong-coupling constant [5], the average gluodissociation cross section rises monotonically as function of temperature in the region of interest – that is, for initial temperatures of \( T \approx 550 \) MeV at the Υ formation time \( \tau_F \approx 0.1 - 0.5 \text{ fm}/c \).

In addition to gluodissociation in the hot medium, we have also considered the damping widths due to the imaginary parts of the quark-antiquark potential, and the screening of the real parts. Gluodissociation and damping widths add up incoherently to total bottomia widths for the six states considered in the hot fireball, namely, \( \Upsilon(1S, 2S, 3S) \) and \( \chi_b(1P, 2P, 3P) \); other spin-triplet states are above the \( B\bar{B} \) threshold and hence, are not relevant for a comparison with the measured \( \Upsilon(nS) \) suppression.

The time and centrality dependence of the suppression of these six states in the hot medium is then calculated based on an ideal hydrodynamic time evolution of the medium that includes transverse expansion, as well as the relativistic Doppler effect whenever the mean transverse momenta of the produced bottomia states and the \( p_T \) of the expanding medium are different from each other. The temperature profiles obtained from our hydrodynamic calculation are displayed in fig. 2 for four different values of time in a central PbPb collision along the \( x^1 \)-axis [5]. At the end of the QGP phase – when the temperature has dropped below the critical
temperature – we then calculate the centrality-dependent suppression factors in the QGP-phase of the collision, \( R_{AA}^{QGP} \).

It is very relevant to include at all impact parameters the corona zone where the temperature never rises above the critical value so that none of the QGP dissociation mechanisms play a role there, leading to an occupation of the excited states even in more central collisions where the excited states melt in the high-temperature region due to screening. In the corona, additional hadronic suppression that is mostly due to collisions with pions – which we have investigated separately – may occur.
Once the centrality-dependent suppression in the hot fireball and in the corona is established, the bottomia states de-excite in a feed-down cascade before being detected through the emission of \( \mu^+\mu^- \) pairs, with a branching ratio of approximately 2.48 % for the 1S state, 1.93 % for the 2S state, and 2.18 % for the 3S state. The calculation of the feed-down cascade including the newly detected \( \chi_b(3P) \) state is described in [8]. It yields the final centrality-dependent suppression factors \( R_{AA} \) [5] as shown in fig. 3 in comparison with the CMS data [1] for the \( \Upsilon(1S) \) and \( \Upsilon(2S) \) states for a parameter set indicated in the caption.

The suppression of the spin-triplet ground state and its centrality dependence is in good agreement with the data for all centralities except for the 40 – 50% bin. For the first excited 2S state, however, the calculated centrality dependence is too steep. Although the overall amount of suppression would be enhanced through a shorter formation time \( \tau_F \) with ensuing larger QGP lifetime, such that the central bins are better accounted for, the problem of missing suppression in the three peripheral bins 50 – 100 %, 40 – 50 % and 30 – 40 % remains to be solved. We have checked the influence of hadron-induced dissociation in the corona region, with the result that the centrality-dependence of pion-induced dissociation is probably not strong enough to account for the difference. Another interesting possibility may be the dissociation through the transient magnetic fields, which is expected to be more pronounced for peripheral collisions.

The suppression depends quite strongly on the transverse momentum of the produced bottomia. In our early work [4] we had assumed bottomia production at rest, whereas in [5]
Figure 4. Transverse-momentum dependence of the suppression factors $R_{AA}(1S)$, $R_{AA}(2S)$ and $R_{AA}(3S)$ in central PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV plotted for an $\Upsilon$ formation time of $\tau_F = 0.3$ fm/$c$. From [7].

Figure 5. Predictions for $R_{AA}(1S)$ and $R_{AA}^{QGP}(1S)$ for PbPb collisions at $\sqrt{s_{NN}} = 5.52$ TeV (solid and dotted lines, respectively) and the previous results for $\sqrt{s_{NN}} = 2.76$ TeV (dashed and dash-dotted lines, respectively) as a function of centrality, averaged over $p_T$, plotted for an $\Upsilon$ formation time of $\tau_F = 0.3$ fm/$c$, together with data from CMS [1] and ALICE [2] for $\sqrt{s_{NN}} = 2.76$ TeV. From [5].

we have investigated the more realistic case of finite transverse momenta of the bottomia. The collisions with the light medium particles do not substantially change the transverse momenta of the bottomia and hence, there will be a finite relative velocity between them and the
expanding QGP. The result is a relativistic Doppler shift which causes an angle-dependent effective temperature with a blue shift in the forward, and a red shift in the backward direction relative to the movement of the heavy meson in the medium. With increasing velocity, the red-shifted region is growing, whereas the blue-shifted region is confined to increasingly smaller angles. Averaging over the solid angle, we find that the red shift has more impact on the result, reducing thus the effective temperature that is decisive for the action of the dissociation processes.

The corresponding $p_T$-dependence of the suppression factor for the three $\Upsilon(nS)$-states is displayed in fig. 4. The suppression is most pronounced for $p_T < 6$ GeV/c and is diminished for large values of $p_T$, in qualitative agreement with the expectation from the data. There is, however, no mechanism in our model that could yield a suppression factor above one at large transverse momenta. In the calculation of the suppression shown in the previous factor, we have averaged over the $p_T$-dependence of the suppression factor in the range $4$ GeV/c $\leq p_T \leq 24$ GeV/c. We have omitted lower $p_T$-values because the CMS data cover $p_T > 4$ GeV/c.

Since the results for the ground-state suppression are in agreement with experiment, we have also calculated the $\Upsilon(1S)$ suppression in PbPb at the LHC design energy of 5.52 TeV, solid line in fig. 5. The central initial temperature is increased by 6.6 % to 586 MeV using the scaling relation between the initial entropy density and the charged-particle multiplicity density $s_0 \propto dN_{ch}/d\eta \propto T_0^3$. The ground state is found to be slightly more suppressed in the medium at the higher energy and hence, the total suppression in PbPb as compared to $pp$ is stronger. However, the additional ground state suppression effect is less than 10 % when doubling the c.m. energy.

3. Conclusion
The suppression of the strongly bound $\Upsilon(1S)$ spin-triplet ground state in PbPb collisions at LHC energies as compared to scaled $pp$ collisions at the same energy is a sensitive indicator for the properties of the quark-gluon plasma that causes gluodissociation and damping. The feed-down cascade from the excited bottomia states to the ground state produces additional suppression, since the excited states melt through screening, or depopulate through dissociation processes and hence, there is less feed-down to the 1S ground state as compared to $pp$ at the same energy.

Our model results [5] for the ground state are in good agreement with the CMS data [1]. The transverse-momentum dependence of the modification factor still needs to be compared with forthcoming data and probably requires further investigation, and also the suppression of the first excited state calls for additional centrality-dependent dissociation mechanisms.

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