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Υ-suppression by screening, gluodissociation and collisional damping at the LHC

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We suggest that the combined effect of screening, gluon-induced dissociation, collisional damping, and reduced feed-down explains most of the suppression of Υ states that has been observed by CMS in PbPb relative to pp collisions at $\sqrt{s_{NN}} = 2.76$ TeV at the CERN LHC. The suppression is thus a clear, albeit indirect, indication for the presence of a qgp.

In particular, we calculate the suppression of both the $\Upsilon(1S)$ and $\Upsilon(2S)$ states in the quark-gluon plasma in minimum-bias and centrality-dependent PbPb collisions. In a major extension of our schematic phenomenological approach presented in Brezinski and Wolschin (2012), we explicitly consider the time dependence with transverse and longitudinal expansion, and the effect of collisional damping on the widths of the states, in addition to gluodissociation. The effect of collisional damping of the $\Upsilon(nS)$ and $\chi_b(nP)$ states is computed from a complex potential, and is found to be of the same order of magnitude as the gluon-induced dissociation for the 1S state at the temperatures that are relevant at LHC. The gluodissociation and damping is treated explicitly for all five states considered here ($\Upsilon(1S)$, $\Upsilon(2S)$, $\Upsilon(3S)$, $\chi_b(1P)$ and $\chi_b(2P)$), including the influence of the confining string contribution on the dissociation rates. As compared to pp collisions at the same energy, the feed-down cascade leading to the $\Upsilon(1S)$ ground state is drastically modified due to the substantial suppression of the excited states through screening, damping and gluodissociation. The $\Upsilon(1S)$ ground state remains very stable with respect to screening, its suppression is essentially due to damping, gluodissociation and reduced feed-down. Our results (Nendzig and Wolschin, 2012) are presented for different Υ formation times and qgp lifetimes. For reasonable plasma temperatures at Υ formation time, we compare with the CMS data for the $\Upsilon(1S)$ and $\Upsilon(2S)$ suppression factors as functions of centrality.

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1. The model

Due to the small relative velocity $v \ll c$ of the quarks in the bound state, $Q\bar{Q}$ may be properly described by a Schrödinger equation, with the color-singlet potential V. We use for the short-range part of the potential the complex, coulombic expression which results from pNRQCD and the HTL approximation [1, 2], while the long range part is parameterized as in [3] so that the full potential reads

$$V(r,m_D) = \frac{\sigma}{m_D}\left(1-e^{-m_D r}\right) - \frac{4\alpha_s^s}{3}\left[m_D + \frac{e^{-m_D r}}{r} + iT\int_0^\infty \frac{dz\,2z}{(1+z^2)^2}\left(1-\frac{\sin(m_D rz)}{m_D rz}\right)\right], \quad (1.1)$$

with the Debye mass $m_D = T\sqrt{4\pi\alpha_s^h(N_c/3+N_f/6)}$, number of colors $N_c = 3$, number of flavors in the QGP $N_f = 3$, and the strong coupling constant at the soft scale, $\alpha_s^s = \alpha_s(m_b\alpha_s/2) \simeq 0.48$ and hard scale $\alpha_s^h = \alpha_s(m_b) \simeq 0.24$ ($m_b = 4.89$ GeV), respectively. The imaginary part of the potential accounts for collisional damping by the plasma particles.

The leading-order gluodissociation cross section of the $Q\bar{Q}$ states through E1 absorption of a single gluon had been derived by Bhanot and Peskin [4]. We have modified the approach to approximately include the confining string contribution [5, in preparation]. Next we average the cross sections over the Bose-Einstein distribution function of gluons at temperature T, thus assuming that the medium is thermalized, although the heavy $Q\bar{Q}$ is not, and obtain for the S-states

$$\sigma_{\text{diss}} = \frac{2\pi^2\alpha_s^u E_g}{N_c^2}\int_0^\infty dk\,\delta\left(\frac{k^2}{m}+\varepsilon_n - E_g\right)\left|\langle\psi_n|\hat{\vec{r}}|\chi_k\rangle\right|^2, \quad \Gamma_{\text{diss}} = \frac{g_d}{2\pi^2}\int_0^\infty \frac{dp_g\,p_g^2\,\sigma_{\text{diss}}}{\exp\left[E_g/T\right]-1}, \quad (1.2)$$

with the singlet and octet states $|\psi\rangle$, $|\chi\rangle$ and $\alpha_s^u = \alpha_s(m_b\alpha_s^2) \simeq 0.48$.

The results of the previous first step are inserted in a fireball model. The density distribution of the lead ions is modeled by a Woods-Saxon potential with radius $R = 6.62$ fm and diffuseness $a = 0.546$ fm [6]. The number of produced $b\bar{b}$-pairs at the point (x,y) in the transverse plain and impact parameter b is then proportional to the nuclear overlap T_{AA}, $N_{b\bar{b}}(b,x,y) \propto N_{\text{coll}}(b,x,y) \propto T_{AA}(b,x,y)$. The temperature is parameterized by the number of binary collisions. The dissociation in the fireball then leads to a preliminary suppression factor

$$R_{AA}^{\text{prel}} = \frac{\int d^2b \int dxdy\, T_{AA}(b,x,y)\, e^{-\int_{t_F}^\infty dt\,\Gamma_{\text{tot}}(b,t,x,y)}}{\int d^2b\int dxdy\, T_{AA}(b,x,y)}. \quad (1.3)$$

2. Results

Results for screening and collisional damping are derived from the solutions of the Schrödinger equation with the potential eq. (1.1), while the widths for gluodissociation are derived from eq. (1.2). The total decay widths Γ_{tot} are then inserted into a dynamic calculation for the fireball evolution. Subsequently, the bottomium states pass through a decay cascade so that the higher excited states feed the lower lying states. Our results for the suppression of the Υ(1S,2S) states in PbPb relative to pp, and of the double ratios $(2S,3S/1S)_{\text{PbPb}}/(2S,3S/1S)_{pp}$ at 2.76 TeV as functions of centrality are shown in Fig. 1, and for minimum bias in Table I.

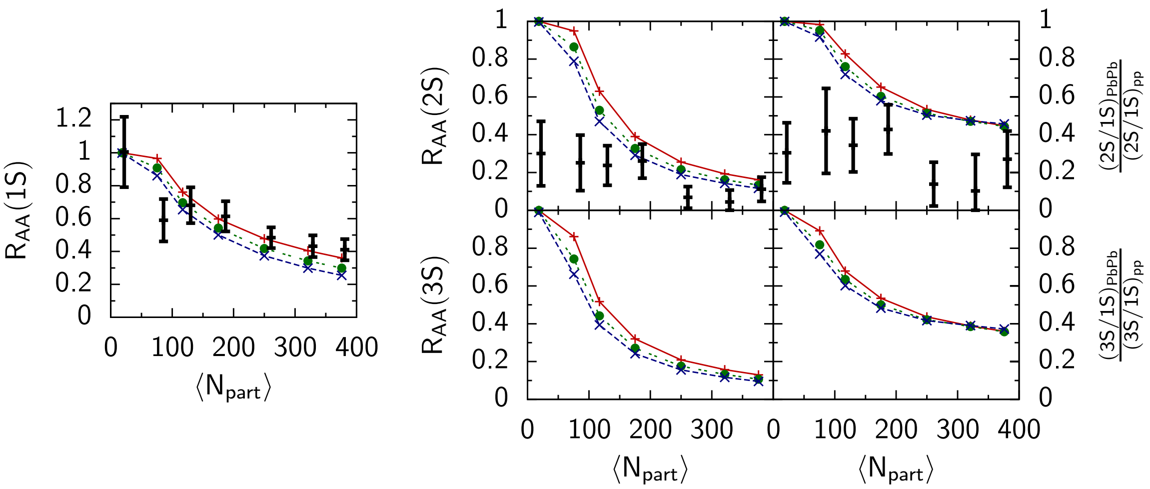

Figure 1: Suppression factors R_{AA} for the Υ(1S) and Υ(2S) states (top left and right) and the double ratios $(nS/1S)_{\mathrm{PbPb}}/(nS/1S)_{pp}$ for $n = 2, 3$ (bottom left and right) calculated for 2.76 TeV PbPb-collisions from screening, collisional damping, gluodissociation and feed-down using three qgp lifetimes $t_{QGP} = 4, 6, 8$ fm/c (red, green and blue lines, respectively) for the centrality bins 0-5%, 5-10%, 10-20%, 20-30%, 30-40%, 40-50%, 50-100%. The corresponding CMS results [7, in black] are in good agreement for the Υ(1S) state, whereas the measured Υ(2S)-populations allow for additional suppression mechanisms.

t_{QGP} (fm/c)	4	6	8	CMS data [7]
$R_{AA}(1S)$	0.51	0.45	0.41	$0.56 \pm 0.08 \pm 0.07$
$R_{AA}(2S)$	0.32	0.27	0.25	$0.12 \pm 0.04 \pm 0.02$
$R_{AA}(3S)$	0.28	0.24	0.22	$0.03 \pm 0.04 \pm 0.01$
$(2S/1S)_{\mathrm{PbPb}}/(2S/1S)_{pp}$	0.62	0.61	0.60	$0.21 \pm 0.07 \pm 0.02$
$(3S/1S)_{\mathrm{PbPb}}/(3S/1S)_{pp}$	0.54	0.53	0.52	$0.06 \pm 0.06 \pm 0.06$

Table 1: Calculated minimum bias results for different t_{QGP} and $t_F = 0.1$ fm/c compared to the CMS results [7] with statistical and systematic error bars, respectively. The $R_{AA}(1S)$ is in good agreement with experiment, but the results for the excited states allow for additional suppression mechanisms.

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