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Quarkonia and heavy-flavour production in CMS

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Abstract

The Compact Muon Solenoid (CMS) has measured numerous quarkonium states via their decays into $\mu^+\mu^-$ pairs in pp and PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Quarkonia are especially relevant for studying the quark-gluon plasma since they are produced at early times and propagate through the medium, mapping its evolution. Non-prompt J/ψ from b-hadron decays show a strong suppression in the transverse momentum range ($6.5 < p_T < 30$ GeV/c) when compared to the yield in pp collisions scaled by the number of inelastic nucleon-nucleon collisions. This suppression is related to the in-medium b-quark energy loss. In the same kinematic region, for prompt J/ψ , a strong, centrality-dependent suppression is observed in PbPb collisions. Such strong suppression at high p_T has previously not been observed at RHIC. At midrapidity ($|\eta| < 1.6$) and the same p_T region, inclusive $\psi(2S)$ are even stronger suppressed than J/ψ , whereas $\psi(2S)$ at forward rapidity ($1.6 < |\eta| < 2.4$) and lower p_T ($3 < p_T < 30$ GeV/c) appear to be less suppressed than J/ψ , however, with large uncertainties that prevent a conclusion. Furthermore, low- p_T $\Upsilon(2S)$ and $\Upsilon(3S)$ mesons are strongly suppressed in PbPb collisions. The suppression of the $\Upsilon(1S)$ state is smaller than the suppression of the excited states and consistent with the suppression of the feed-down contribution only.

Keywords: heavy-ion collisions, quarkonium, charmonium, bottomonium, heavy flavour

1. Introduction

The goal of the SPS, RHIC, and LHC heavy-ion programmes is to validate the existence and study the properties of the quark-gluon plasma (QGP), a state of deconfined quarks and gluons. One of its most striking expected signatures is the suppression of quarkonium states [1], both of the charmonium (J/ψ , $\psi(2S)$, χ_c , etc.) and the bottomonium ($\Upsilon(1S, 2S, 3S)$, χ_b , etc.) families. This is thought to be a direct effect of deconfinement, when the binding potential between the constituents of a quarkonium state, a heavy quark and its antiquark, is screened by the colour charges of the surrounding light quarks and gluons. The suppression is predicted to occur above the critical temperature of the medium (T_c) and depends on the Q \bar{Q} binding energy. Since the $\Upsilon(1S)$ is the most tightly bound state among all quarkonia, it is expected to be the one with the highest dissociation temperature. Examples of dissociation temperatures are given in Ref. [2]: $T_{\text{dissoc}} \sim 1 T_c$, $1.2 T_c$, and $2 T_c$ for the $\Upsilon(3S)$, $\Upsilon(2S)$, and $\Upsilon(1S)$, respectively. Similarly, in the charmonium family the dissociation temperatures are $\leq 1 T_c$ and $1.2 T_c$ for the $\psi(2S)$ and J/ψ , respectively. However, there are further possible changes to the quarkonium production in heavy-ion collisions. On the one hand, modifications to the parton distribution functions inside the nucleus (shadowing) and other cold-nuclear-matter effects can reduce the production of quarkonia without the presence of a QGP [3, 4]. On the other hand, the large number of

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heavy quarks produced in heavy-ion collisions, in particular at the energies accessible by the Large Hadron Collider (LHC), could lead to an increased production of quarkonia via statistical recombination [5, 6, 7, 8, 9, 10].

In this proceedings, the CMS measurements of non-prompt and prompt J/ψ , inclusive $\psi(2S)$, and the $\Upsilon(1S, 2S, 3S)$ mesons in PbPb collisions are discussed. The results are presented as nuclear modifications factors (R_{AA}), based on a comparison to the yield measured in a pp reference run at the same $\sqrt{s_{NN}}$, scaled by the number of binary collisions (N_{coll}):

$$R_{AA} = \frac{\mathcal{L}_{pp}}{T_{AA} N_{MB}} \frac{N_{PbPb}(Q\bar{Q})}{N_{pp}(Q\bar{Q})} \cdot \frac{\varepsilon_{pp}}{\varepsilon_{PbPb}}.$$

The measured yields in PbPb ($N_{PbPb}(Q\bar{Q})$) and pp collisions ($N_{pp}(Q\bar{Q})$) are corrected by their respective efficiencies ε_{PbPb} and ε_{pp} . \mathcal{L}_{pp} is the integrated luminosity of the pp dataset, T_{AA} is the nuclear overlap function, which is equal to N_{coll} divided by the elementary nucleon-nucleon cross section, and N_{MB} is the number of minimum bias events in the PbPb sample. While non-prompt and prompt J/ψ results are based on the 2010 dataset corresponding to an integrated luminosity of $\mathcal{L}_{int} = 7.28 \mu\text{b}^{-1}$, the $\psi(2S)$ and Υ results were obtained from the twenty times larger 2011 dataset with an integrated luminosity of $\mathcal{L}_{int} = 150 \mu\text{b}^{-1}$. The pp reference dataset used in all results has an integrated luminosity of $\mathcal{L}_{int} = 231 \text{nb}^{-1}$, which for hard-scattering processes is comparable in size to the 2010 PbPb sample ($7.28 \mu\text{b}^{-1} \cdot 208^2 \approx 315 \text{nb}^{-1}$). A more detailed discussion of the charmonium analyses presented at this conference can be found in [11], whereas details on the bottomonium analyses are discussed in [12].

The central feature of CMS is a superconducting solenoid, of 6 m internal diameter, providing a field of 3.8 T. Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter (ECAL) and the brass/scintillator hadron calorimeter (HCAL). Muons are measured in gas-ionization detectors embedded in the steel return yoke. In addition to the barrel and endcap detectors, CMS has extensive forward calorimetry. The muons are measured in the pseudorapidity window $|\eta| < 2.4$, with detection planes made of three technologies: Drift Tubes, Cathode Strip Chambers, and Resistive Plate Chambers. Matching the muons to the tracks measured in the silicon tracker results in a transverse momentum resolution better than 1.5% for p_T smaller than 100 GeV/c. A much more detailed description of CMS can be found elsewhere [13].

Figure 1 shows the invariant-mass spectrum of $\mu^+\mu^-$ pairs measured in PbPb collisions at $\sqrt{s_{NN}} = 2.76 \text{TeV}$. Both muons of the pair are required to have a transverse momentum of at least 4 GeV/c. The spectrum ranges in mass from 2 GeV/c² to 200 GeV/c² and demonstrates the excellent capabilities of the CMS detector to measure dimuons over a broad kinematic range. Clearly reconstructed are the resonance peaks of the charmonium and bottomonium families, as well as the Z boson.

2. Charmonia

CMS has recently published a measurement of the nuclear modification factor of prompt J/ψ in PbPb collisions at $\sqrt{s_{NN}} = 2.76 \text{TeV}$ as a function of J/ψ p_T and rapidity, and event centrality, based on an integrated luminosity of $\mathcal{L}_{int} = 7.28 \mu\text{b}^{-1}$ [14]. Non-prompt J/ψ from b-hadron decays and prompt J/ψ have been separated in a two dimensional fit to the invariant mass and the transverse distance between the collision vertex and reconstructed secondary vertex of the $\mu^+\mu^-$ pair. The results show a strong, centrality-dependent suppression of prompt J/ψ in PbPb collisions, compared to the yield in pp collisions scaled by the number of inelastic nucleon-nucleon collisions (N_{coll}). The centrality and p_T dependencies of the R_{AA} are shown in the left and right panel of Fig. 2, respectively. In the 10% most central collisions, a nuclear modification factor of $R_{AA} = 0.20 \pm 0.03$ (stat.) ± 0.01 (syst.) has been measured. In peripheral PbPb collisions (50–100%), the suppression is three times smaller than in the most central collisions. The prompt J/ψ R_{AA} does not vary with p_T in the range $6.5 < p_T < 30 \text{GeV}/c$. The results are compared to other inclusive J/ψ measurements at RHIC and the LHC. The preliminary measurement of inclusive high- p_T J/ψ at RHIC by STAR [15] shows a much smaller suppression, even in the most central collisions at RHIC energies ($\sqrt{s_{NN}} = 200 \text{GeV}$). In contrast, the low- p_T J/ψ R_{AA} measured at RHIC by the PHENIX collaboration [16] show a qualitatively similar suppression pattern as the one measured by CMS. The ALICE R_{AA} measurement of low- p_T inclusive J/ψ at forward rapidity ($2.5 < y < 4$) [17] shows almost no centrality dependence of the suppression, which is significantly smaller than the one of high- p_T J/ψ at the LHC. The difference between the strong suppression of high- p_T J/ψ measured by CMS and the R_{AA} of low- p_T J/ψ measured by ALICE at forward rapidity, might be a sign of recombination.

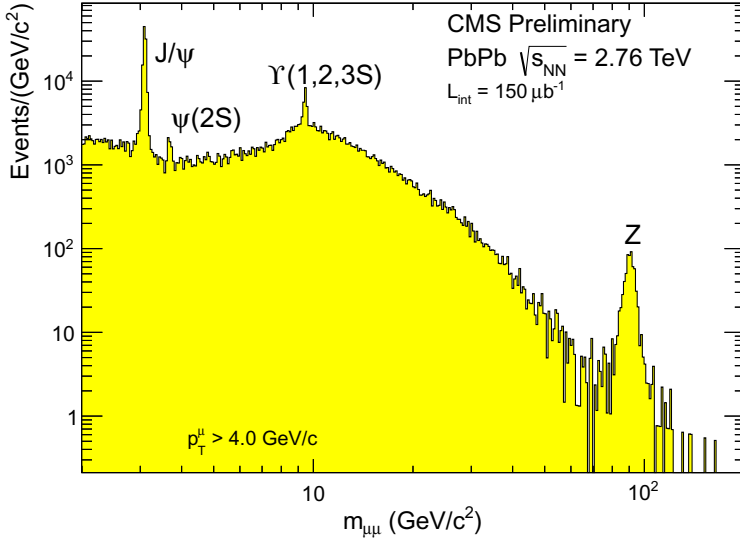


Figure 1: Invariant-mass spectrum of $\mu^+\mu^-$ pairs measured in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. A cut of $p_T > 4$ GeV/c has been applied to both muons. Visible are the resonance peaks of the charmonium and bottomonium families, as well as the Z boson.

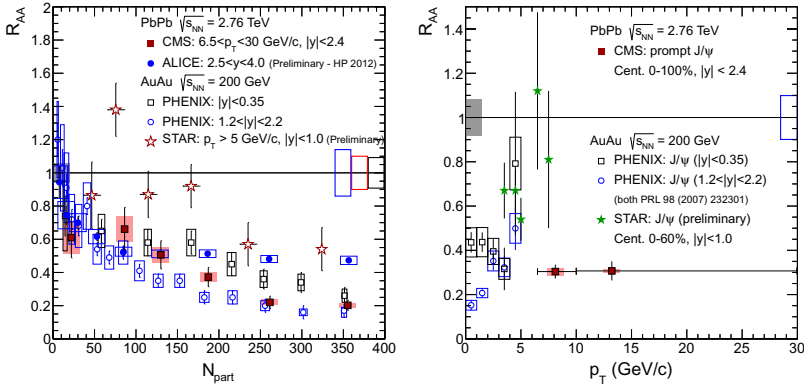


Figure 2: $J/\psi R_{AA}$ as a function of centrality (left) and p_T (right). The prompt J/ψ measurement of CMS (solid red squares) is compared to inclusive J/ψ measurements by ALICE (solid blue circles), STAR (stars), and PHENIX at midrapidity (open black squares) and forward rapidity (open blue circles). Statistical (systematic) uncertainties are shown as bars (boxes). In case of the STAR results, statistical and systematic uncertainties are shown combined as bars. Global uncertainties from the pp luminosity are shown as boxes at unity.

More recently, CMS has also performed a preliminary measurement of the relative suppression of inclusive $\psi(2S)$ mesons with respect to inclusive J/ψ in form of a double ratio $(N_{\psi(2S)}/N_{J/\psi})_{\text{PbPb}}/(N_{\psi(2S)}/N_{J/\psi})_{\text{pp}}$ based on an integrated luminosity of $\mathcal{L}_{\text{int}} = 150 \mu\text{b}^{-1}$ collected in 2011 [18]. This double ratio has been measured as a function of centrality at high p_T ($6.5 < p_T < 30 \text{ GeV}/c$) and midrapidity ($|\eta| < 1.6$), as well as at lower p_T ($3 < p_T < 30 \text{ GeV}/c$) and forward rapidity ($1.6 < |\eta| < 2.4$). For the latter kinematic region a double ratio that increases with centrality has been measured as shown in the left panel of Fig. 3, though with large uncertainties. In the 20% most central collisions, a double ratio of 5.32 ± 1.03 (stat.) ± 0.79 (syst.) ± 2.58 (pp) has been measured, which means that more $\psi(2S)$ are produced compared to J/ψ than in pp collisions, again with large uncertainties mostly originating from the limited size of the pp sample. However, in the right panel of Fig. 3 it can be seen that at high p_T and midrapidity, the double ratio is always less than unity, meaning that, in this kinematic range, $\psi(2S)$ are more suppressed than J/ψ . Within uncertainties, no centrality dependence is observed. For the centrality integrated bins the double ratio can be converted into an inclusive $\psi(2S)$ R_{AA} , by simple multiplication with the published inclusive J/ψ R_{AA} [14]. For $6.5 < p_T < 30 \text{ GeV}/c$ and $|\eta| < 1.6$ the $\psi(2S)$ R_{AA} is:

$$R_{AA}(\psi(2S)) = 0.11 \pm 0.03 \text{ (stat.)} \pm 0.02 \text{ (syst.)} \pm 0.02 \text{ (pp)}.$$

For $3 < p_T < 30 \text{ GeV}/c$ and $1.6 < |\eta| < 2.4$ the $\psi(2S)$ R_{AA} is:

$$R_{AA}(\psi(2S)) = 1.54 \pm 0.32 \text{ (stat.)} \pm 0.22 \text{ (syst.)} \pm 0.76 \text{ (pp)}.$$

These results exhibit a clear $\psi(2S)$ suppression in the midrapidity and higher- p_T region, while the pp uncertainty is too large to draw a firm conclusion in the forward rapidity lower- p_T region.

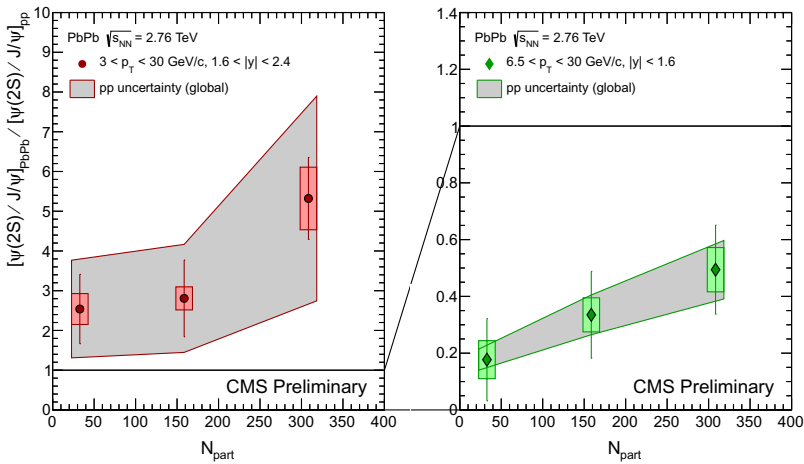


Figure 3: Centrality dependence of the double ratio $(N_{\psi(2S)}/N_{J/\psi})_{\text{PbPb}}/(N_{\psi(2S)}/N_{J/\psi})_{\text{pp}}$ at forward rapidity and low p_T ($1.6 < |\eta| < 2.4$ and $3 < p_T < 30 \text{ GeV}/c$) (left) and at midrapidity and high p_T ($|\eta| < 1.6$ and $6.5 < p_T < 30 \text{ GeV}/c$) (right).

3. Bottomonia

CMS measured the $\Upsilon(1S)$ R_{AA} in PbPb collisions at $\sqrt{s_{NN}} = 2.76 \text{ TeV}$ for the first time in [14] and the suppression of the excited states relative to the $\Upsilon(1S)$ in [19]. Based on an integrated luminosity of $\mathcal{L}_{\text{int}} = 150 \mu\text{b}^{-1}$ recorded in 2011, a more detailed measurement has been made possible [20]. Centrality integrated double ratios have been

measured separately for the $\Upsilon(2S)$ and $\Upsilon(3S)$ states:

$$\begin{aligned} (N_{\Upsilon(2S)}/N_{\Upsilon(1S)})_{\text{PbPb}}/(N_{\Upsilon(2S)}/N_{\Upsilon(1S)})_{\text{pp}} &= 0.21 \pm 0.07 (\text{stat.}) \pm 0.02 (\text{syst.}), \\ (N_{\Upsilon(3S)}/N_{\Upsilon(1S)})_{\text{PbPb}}/(N_{\Upsilon(3S)}/N_{\Upsilon(1S)})_{\text{pp}} &= 0.06 \pm 0.06 (\text{stat.}) \pm 0.06 (\text{syst.}) \quad (< 0.17 \text{ at } 95\% \text{ CL}). \end{aligned}$$

The $\Upsilon(2S)$ double ratio has been measured as a function of centrality, as shown in Fig. 4. Within uncertainties, no pronounced centrality dependence is observed. Furthermore, the nuclear modification factors of all three states have been measured, integrated over centrality:

$$\begin{aligned} R_{AA}(\Upsilon(1S)) &= 0.56 \pm 0.08 (\text{stat.}) \pm 0.07 (\text{syst.}), \\ R_{AA}(\Upsilon(2S)) &= 0.12 \pm 0.04 (\text{stat.}) \pm 0.02 (\text{syst.}), \\ R_{AA}(\Upsilon(3S)) &= 0.03 \pm 0.04 (\text{stat.}) \pm 0.01 (\text{syst.}) \quad (< 0.10 \text{ at } 95\% \text{ CL}). \end{aligned} \quad (1)$$

The centrality dependence of the nuclear modification factors of $\Upsilon(1S)$ and $\Upsilon(2S)$ are shown in the right panel of Fig. 4.

The data show a clear ordering of the suppression with binding energy, the least bound state being the most suppressed. The suppression of the $\Upsilon(1S)$ state is consistent with no suppression of directly produced $\Upsilon(1S)$, but a suppression of feed-down contribution from excited state decays only which is expected to contribute $\approx 50\%$ at high p_T [21]. However, the uncertainties in the measurement of the feed-down contributions preclude quantitative conclusions about the suppression of directly produced $\Upsilon(1S)$.

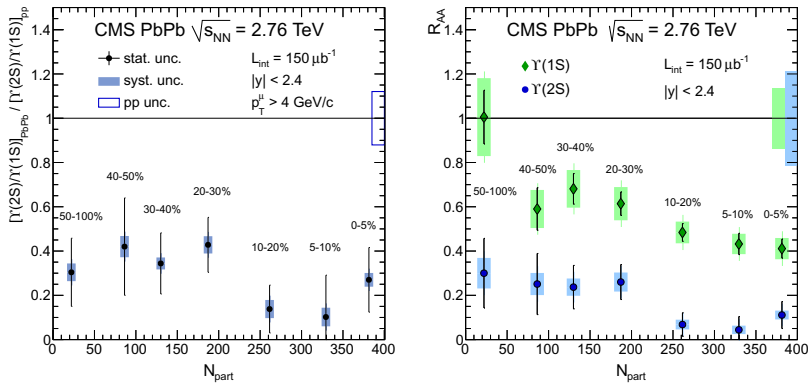


Figure 4: Centrality dependence of the double ratio $(N_{\Upsilon(2S)}/N_{\Upsilon(1S)})_{\text{PbPb}}/(N_{\Upsilon(2S)}/N_{\Upsilon(1S)})_{\text{pp}}$ (left) and the nuclear modification factor of $\Upsilon(1S)$ and $\Upsilon(2S)$ (right). Statistical (systematic) uncertainties are shown as bars (boxes). Global uncertainties from the pp yields and, in case of the R_{AA} , luminosity, are shown as boxes at unity.

4. Open heavy-flavour

As mentioned in section 2, CMS has separated prompt J/ψ and non-prompt J/ψ from b-hadron decays in PbPb collisions [14]. The R_{AA} of non-prompt J/ψ with $6.5 < p_T < 30 \text{ GeV}/c$ and $|y| < 2.4$ is shown in two bins of centrality (0–20% and 20–100%) in the left panel of Fig. 5. A clear suppression of J/ψ from b-hadron decays is observed. While the suppression is the same in the two centrality bins, it is to be noted that the 20–100% bin is very broad and hard probes, such as b hadrons, will be produced predominantly towards the more central edge of the bin. The right panel of Fig. 5 shows a comparison of the non-prompt J/ψ R_{AA} in the 0–20% centrality bin compared to the charged

hadron R_{AA} [22], which reflects the energy loss of light quarks, and the R_{AA} of electroweak bosons [23, 24, 25], which do not interact strongly with the medium. More detailed measurements of the p_T dependence of the non-prompt J/ψ R_{AA} are necessary, before drawing conclusions on a possible mass hierarchy of the in-medium energy loss of light and heavy quarks.

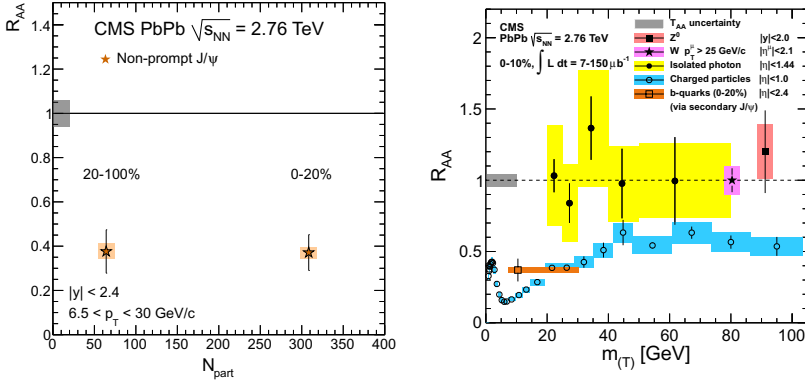


Figure 5: Centrality dependence of the nuclear modification factor of non-prompt J/ψ from b-hadron decays (left) and m_T dependence of the light hadron R_{AA} compared to non-prompt J/ψ and electroweak bosons. Statistical (systematic) uncertainties are shown as bars (boxes). Global uncertainties from the pp luminosity are shown as boxes at unity.

5. Summary

In summary, CMS has measured the nuclear modification factors of all S-wave charmonium and bottomonium vector-meson states below twice the D and B meson masses, respectively. For prompt J/ψ , $\Upsilon(1S)$, and $\Upsilon(2S)$ the centrality dependence of the R_{AA} has been measured. Furthermore, the R_{AA} as a function of p_T and rapidity has been measured for prompt J/ψ and $\Upsilon(1S)$ [14]. A sequential melting of the Υ states is observed. It is interesting to note that also the suppression of prompt J/ψ with $6.5 < p_T < 30$ GeV/c and $|\eta| < 2.4$, as well as inclusive $\psi(2S)$ with $6.5 < p_T < 30$ GeV/c and $|\eta| < 1.6$ follow the same ordering as a function of the binding energy. However, the effect of the p_T and rapidity cuts has to be evaluated. More detailed measurements of the p_T and rapidity measurements are currently limited by the limited size of the pp reference dataset at $\sqrt{s} = 2.76$ TeV. The same is true for the measurement of the possible $\psi(2S)$ enhancement in the kinematic range $3 < p_T < 30$ GeV/c and $1.6 < |\eta| < 2.4$, which is opposite to the expected behaviour in the sequential melting scenario.

The in-medium energy loss of b quarks has been quantified via the nuclear modification factor of non-prompt J/ψ with $p_T > 6.5$ GeV/c, which is comparable in magnitude to the one of light hadrons at high p_T .

6. Acknowledgements

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