Latest Results on Quarkonium Production from CMS

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Abstract. The understanding of quarkonium production in heavy-ion collisions requires the inclusion of many phenomena such as dissociation in the QGP, partonic energy loss, statistical recombination, on top of cold nuclear matter effects (modifications of nPDFs, initial-state energy loss, nuclear break-up). The Compact Muon Solenoid (CMS) collaboration has measured various quarkonium states via their decay into muon pairs in pp, pPb and PbPb collisions at 5.02 TeV, and can address some of these phenomena. In this talk, the most recent CMS results on quarkonium production will be presented.

1. Introduction
The measurement of quarkonium production in heavy ion collisions constitutes a powerful probe for studying properties of matter at high energy densities and temperatures. A strongly interacting medium of deconfined quarks and gluons, the quark-gluon-plasma (QGP), has been predicted in such an environment. Recent measurements of quarkonium production performed by the CMS Collaboration have been found to support theoretical models of sequential melting of quarkonia in QGP [1, 2, 3]. However, quarkonium production in heavy-ion collisions is affected also by initial state effects, such as modification of the nuclear parton distribution functions (nPDFs) [4], initial state parton energy loss [6], and Cronin effect [5, 6]. These are in addition to final state effects such as Debye color screening and statistical recombination.

In this talk, a report was made on the measurements of the nuclear modification factors, $R_{AA}$, of prompt $J/\psi$, $\psi(2S)$, $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ mesons, measured in their dimuon decay channel. The results use pp and PbPb data collected at the end of 2015 by the CMS Collaboration at $\sqrt{s_{NN}} = 5.02$ TeV, corresponding to an integrated luminosities of 28 $pb^{-1}$ and 351-368 $\mu$b$^{-1}$, respectively.The results are compared to those obtained at 2.76 TeV. The larger integrated luminosities allow for more precise and more differential measurements of $R_{AA}$, as functions of event centrality, rapidity ($y$), and transverse momentum ($p_T$).

2. Environmental setup and analysis procedure
The central feature of the CMS apparatus is a superconducting solenoid, providing an axial magnetic field of 3.8 T. Immersed in the magnetic field are the silicon pixel and strip tracker, the lead-tungstate crystal electromagnetic calorimeter, and the brass/scintillator hadron calorimeter. Muons are measured in gas ionization detectors embedded in the steel return yoke and 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
Figure 1. **Top:** Dimuon invariant-mass (left) and pseudo-proper decay length (right) distributions, for the $J/\psi$ analysis [8]. The spectra are integrated over centrality, rapidity range $1.8 < |y| < 2.4$, and $p_T$ range $4.5 < p_T < 5.5$ GeV/c. The projections of the two-dimensional fit onto the respective axes are overlaid as solid black lines. The dashed red lines show the fitted contribution of non-prompt $J/\psi$. The fitted background contributions are shown as dotted blue lines. **Bottom:** Dimuon invariant-mass distributions used in the $\psi(2S)$ analysis [9], for $9 < p_T < 12$ GeV/c, $|y| < 1.6$, and 0–100% centrality (left), and $3 < p_T < 30$ GeV/c, the 1.6 < |y| < 2.4 and 0–20% centrality (right).

Figure 2. Dimuon invariant mass distributions in pp (left) and PbPb (right) collisions for the $\Upsilon$ analysis [12]. In both figures, the results of the fits to the data are shown as solid blue lines. The dashed red lines in the right panel are the result of the fits in PbPb (blue solid line) but with the fitted $\Upsilon$ yield for each state scaled by the inverse of its measured $R_{AA}$.

than 1.5% for $p_T$ smaller than 100 GeV/c. A more detailed description of the CMS detector can be found in Ref. [7].

The invariant mass spectrum of all $\mu^+\mu^-$ pairs used in the $J/\psi$ PbPb analysis [8] is shown in
the upper-left of Figure 1. The black curve is an extended unbinned maximum likelihood fit to the spectrum, using the sum of two Crystal Ball (CB) functions for signal, and an exponential for the background. To measure the fraction of non-prompt $J/\psi$ (the so called b-fraction), the pseudo-proper decay length $r^{3D}_{J/\psi}$, shown in the uppwer-right of Figure 1, is computed as $L_{xyz}m_{J/\psi}/p_T$. Here, the $L_{xyz}$ is defined as,

$$L_{xyz} = \frac{\hat{u}^T S^{-1} \hat{r}}{\hat{u}^T S^{-1} \hat{u}},$$

where $\hat{u}$ is the unit vector in the direction of the $J/\psi$ $p_T$ and $S$ is the sum of the primary and secondary vertex covariance matrices. In the $\psi(2S)$ analysis [9], the nonprompt component is removed by requesting the dimuon $l^{3D}_{\psi}$ be smaller than a $l_0$ threshold. The threshold was chosen using MC simulations, such that it keeps 90% of the prompt $\psi$s. Since the $r^{3D}_{\psi}$ resolution improves with increasing dimuon $p_T$, from $\approx 100$ $\mu$m to $\approx 20$ $\mu$m, the $l_0$ cut is $p_T$ dependent [9].

Figure 2 shows the invariant mass distribution for pp and PbPb data, in the mass range used in the $\Upsilon(nS)$ analysis [12]. The yields are extracted from an unbinned maximum likelihood fit. The signal shape of each $\Upsilon(nS)$ state is modeled by a CB function. The $\Upsilon(nS)$ mass ratios are fixed to their world average values [11]. The background shape is modeled by an exponential function multiplied by an error function, and all its parameters are left free in the fit, as explained in Ref. [12].

3. Results

The hot and dense nuclear matter effects can be quantified by the nuclear modification factors $R_{AA}$ computed as:

$$R_{AA} = \frac{L_{pp} N_{PbPb}}{T_{AA} N_{MB}} \frac{N_{PbPb}}{N_{pp}} \frac{\varepsilon_{pp}}{\varepsilon_{PbPb}},$$

where $T_{AA} = <N_{coll}> / \sigma^{NN}_{inel}$ is calculated from a Glauber model, to account for the nuclear collision geometry [13], $L_{pp}$ is the integrated luminosity of pp collisions, and $N_{pp/PbPb}$ are the raw yields measured in pp and PbPb collisions, $N_{MB}$ is the count of minimum bias events in PbPb, and $\varepsilon_{pp}/\varepsilon_{PbPb}$ is the multiplicity dependent ratio of the efficiencies in pp and PbPb collisions for trigger and reconstruction, which is determined by a Monte-Carlo simulation based on embedding PYTHIA signal event [14] to a HYDJET background event [15].

3.1. Charmonia in pp and PbPb collisions

In Figure 3, the $R_{AA}$ of prompt $J/\psi$ mesons as function of $N_{part}$, $p_T$, and rapidity are shown, integrated in each case over the other two non-plotted variables. The results are compared to those obtained at $\sqrt{s_{NN}} = 2.76$ TeV [16], and found to be in good overall agreement: no strong dependence of the suppression is observed even for the most peripheral bin (70-100%), with the suppression slowly increasing with $N_{part}$. Although no clear dependence is observed in the $R_{AA}$ as a function of $p_T$ in the range of 5-20 GeV/c, an indication of less suppression at higher $p_T$ is seen for the first time [8]. No significant rapidity dependence between the two energies is observed.

Figure 4 shows the double ratio as functions of $p_T$ (left) and $N_{part}$ (middle and right). The double ratios, $(N_{\psi(2S)}/N_{J/\psi})_{ppPb}/(N_{\psi(2S)}/N_{J/\psi})_{pp}$, measured at 5.02 TeV are below unity in all bins. Since $J/\psi$ is suppressed [8], the results show that $\psi(2S)$ is more suppressed than the $J/\psi$ in PbPb collisions. No strong dependences are observed with centrality or transverse momentum. A reasonable agreement with the measurement made at $\sqrt{s_{NN}} = 2.76$ TeV can be seen in most of the bins. Systematic uncertainties are uncorrelated between the two datasets. In the range $1.6 < |y| < 2.4$ and $3 < p_T < 30$ GeV/c, the double ratios are consistently lower in the 5.02 TeV data, especially in the most central collisions. The difference is at the level of around 3 standard deviations in the centrality-integrated sample [9].
Figure 3. The nuclear modification factor of prompt $J/\psi$ as a function of $N_{\text{part}}$ (left), $p_T$ (middle) and rapidity (right) at $\sqrt{s_{NN}} = 5.02$ TeV [8] and 2.76 TeV [16]. For the results as a function of $N_{\text{part}}$, the most central bin corresponds to 0-5%, and the most peripheral one to 70-100% centrality. The bars (boxes) represent statistical (systematic) point-by-point uncertainties. The boxes plotted at $R_{AA} = 1$ indicate the size of the global relative uncertainties.

Figure 4. The double ratio $(N_{\psi(2S)}/N_{{J/\psi}})_{\text{PbPb}}/(N_{\psi(2S)}/N_{{J/\psi}})_{\text{pp}}$ versus $p_T$ (left) and $N_{\text{part}}$ at mid- (middle) and forward- (right) rapidity [9]. The closed blue squares and red circles are 5.02 TeV and, the open stars and crosses are 2.76 TeV. The arrow represents the 95% CL interval in the bin where the measurement is consistent with 0. Vertical lines (boxes) represent the statistical (systematic) uncertainties.

Figure 5. Nuclear modification factor of $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ mesons as a function of $<N_{\text{part}}>$ (left), $p_T$ (middle), and integrated over $p_T$, $<N_{\text{part}}>$ and $y$ (right) [12]. For the $\Upsilon(3S)$ meson, the upper limits at 68% (green box) and 95% (green arrow) C.L are shown. The lines in the left panel represent calculations from Ref. [19].

3.2. Bottomonia in pp and PbPb collisions

Figure 5 shows the nuclear modification factor for the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ mesons as functions of $N_{\text{part}}$ (right) and $p_T$ (middle) [12]. Within the systematic uncertainties, the $R_{AA}$
values show no dependence on $p_T$. The excited $\Upsilon$ states are found to have larger suppression than the ground state, with $R_{AA} < 0.2$ over the full kinematic range examined here. The kinematic dependence of $R_{AA}$ is useful to constrain models of $\Upsilon$ meson suppression in a deconfined medium [19]. The strong suppression of the $\Upsilon(3S)$ meson is observed in both centrality bins studied, 0-30% and 30-100%. The $R_{AA}$ decreases with increasing centrality in the case of the $\Upsilon(1S)$ and $\Upsilon(2S)$ mesons. The theoretical calculations of Krouppa and Strickland, shown in the left panel of figure 5, are in agreement with the results. The model incorporates color-screening effects on the bottomonium family and feed-down contributions from decays of heavier quarkonia. In the right panel of Fig. 5 the centrality-integrated $R_{AA}$ values at $\sqrt{s_{NN}} = 2.76$ TeV and 5.02 TeV are compared. The suppression at 5.02 TeV is larger by a factor of $1.2 \pm 0.15$, although the two $R_{AA}$ values are compatible within the uncertainties.

4. Summary
Prompt $J/\psi$ and $\psi(2S)$ meson productions have been studied in pp and PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, as functions of rapidity, transverse momentum, and collision centrality. The $R_{AA}$ results of prompt $J/\psi$ show a strong centrality dependence, with an increasing suppression for increasing centrality. The double ratio, $(N_{\psi(2S)}/N_{J/\psi})_{PbPb}/(N_{\psi(2S)}/N_{J/\psi})_{pp}$, is below unity in all bins, suggesting that the $\psi(2S)$ yield is more suppressed than the $J/\psi$ yield in the kinematic range explored. A gradual decrease in $R_{AA}$ with centrality for the $\Upsilon(1S)$ and $\Upsilon(2S)$ states is observed, while no significant dependence on $p_T$ or $y$ is found in the measured region. The $R_{AA}$ of the $\Upsilon(3S)$ state is measured to be below 0.094 at 95\% confidence level, making this the smallest $R_{AA}$ value found for any hadron species in heavy ion collisions.

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