Quarkonium production in 2.76 TeV PbPb collisions in CMS

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Abstract. The Compact Muon Solenoid (CMS) is fully equipped to measure hard probes in the di-muon decay channel in the high multiplicity environment of nucleus-nucleus collisions. Such probes are especially relevant for studying the quark-gluon plasma since they are produced at early times and propagate through the medium, mapping its evolution. CMS has measured the nuclear modification factors of non-prompt J/Ψ (from b-hadron decays), prompt J/Ψ and Y(1S) in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Suppression of the excited Y-states has also been measured with respect to the Y(1S). Results from the 2010 data taking period are reported and an outlook on the 2011 data analysis will be given.

1. Introduction
Quarkonia have been singled out as a key signature for the study of the quark gluon plasma (QGP) since not only are they produced early and propagate through the medium mapping its evolution but their higher masses allow a non relativistic quantum treatment of their properties. Due to the small relative velocity of the quarks in the quarkonium states a hierarchy of scales is set in the order of $m$, $mv$ and $mv^2$ where potential Effective Field Theories can be applied. In other words, the behavior of quarkonia is characterized by different energy and momentum scales related to non-relativistic bound states with heavy quark velocity $v$ and mass $m$. The scale related to the inverse distance between the $Q$ and $\bar{Q}$ is $mv$ while $mv^2$ is the scale related to the binding energy of the state. It’s worth noting that this scale hierarchy feature is only found in heavy Quarkonia making their study of prime importance. In particular, the J/Ψ in heavy-ion collisions was suggested to be a promising probe of the QGP video as the deconfined medium should screen the two quarks leading to a suppression of their production[1]. The suppression is predicted to occur above a critical temperature of the medium, and sequentially, in the order of the $Q\bar{Q}$ binding energy, making Quarkonia a perfect thermometer due to their different radii. The full spectroscopy of quarkonium states as a possible thermometer for the QGP has been suggested since the early 1990’s [7]. For the J/Ψ, studies have been performed at different energies and with different collision systems without yet giving a fully understood complete description [2, 3, 4, 5]. Measuring the charmonium production at the LHC energies in PbPb collisions will help constrain predictions, in particular those with a large recombination probability for prompt J/Ψs. Indeed, the abundance of charm quarks in the medium could lead to a strong production enhancement at LHC energies [6]. In addition to charmonium precision
studies, the LHC center-of-mass energy allows copious $\Upsilon$ production in PbPb collisions. Detailed measurements of bottomonia will help characterize the dense matter produced in heavy-ion collisions complementing the measurements accessible at RHIC energies. Also, since bottom $Q\bar{Q}$ quarks and anti-quarks are relatively rare within the plasma, the probability for regeneration of bottomonium states through recombination is much smaller than for charm quarks. As well as the fact that the effects of initial state nuclear suppression are expected to be reduced.

This paper reviews CMS prompt and non-prompt $J/\Psi$ as well as $\Upsilon$ measurements in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, as well as in pp collisions at the same energy which serves as a reference for the observation of hot nuclear effects in PbPb. Due to the high granularity of the tracker which translates into excellent momentum resolution and precise extrapolation of charged particle trajectories, CMS is able to differentiate between the primary and secondary (displaced) vertices making it feasible to distinguish non-prompt $J/\Psi$ from prompt $J/\Psi$ in both pp and PbPb collisions. The nuclear modification factor ($R_{AA}$) of prompt, non-prompt $J/\Psi$, and $\Upsilon(1S)$ in PbPb is measured as a function of transverse momentum ($p_T$), rapidity ($y$) and number of nucleons participating ($N_{part}$) in the collision [8]. Finally, the relative suppression of the excited states compared to the ground state is quantified in the form of a double ratio [9].

2. CMS Detector, Muon reconstruction, and Datasets

A detailed description of the CMS detector can be found elsewhere [10]. Its central feature is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the field volume are the silicon pixel and strip tracker, the crystal electromagnetic calorimeter, and the brass/scintillator hadron calorimeter. Muons are measured in gas-ionisation detectors embedded in the steel return yoke. In addition, CMS has extensive forward calorimetry, in particular two steel/quartz-fiber Čerenkov hadron forward (HF) calorimeters, which cover the pseudorapidity range $2.9 < |\eta| < 5.2$.

In this paper, quarkonia are identified through their dimuon decay. The silicon pixel and strip tracker measures charged-particle trajectories for the range $|\eta| < 2.5$. The tracker consists of 66M pixel and 10M strip detector channels, providing a vertex resolution of $\sim 15 \mu m$ in the transverse plane. Muons are detected for the $|\eta| < 2.4$ range, with detection planes based on three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. Due to the strong magnetic field and the fine granularity of the silicon tracker, the muon transverse momentum measurement based on information from the silicon tracker alone has a resolution between 1 and 2% for a typical muon in this analysis. CMS is therefore very well suited to measure dimuons. In pp, the mass resolution obtained measuring $J/\Psi$ in $|y| < 0.5$ is 20 MeV/$c^2$, and 67 MeV/$c^2$ for the $\Upsilon(1S)$ in $|\eta| < 1$.

In March 2011, CMS recorded a little more than $L_{int} = 220$ nb$^{-1}$ pp events at $\sqrt{s} = 2.76$ TeV. These data is used as a reference for the PbPb measurement. In November 2010, CMS recorded $L_{int} = 7.28$ $\mu$b$^{-1}$ of PbPb events, leading to about the same amount of quarkonia statistics as the reference pp run at 2.76 TeV. Both data sets have been analyzed following similar conditions [8, 9]: (1) events are selected by the CMS two-level trigger keeping any dimuon activity in the muon chambers, (2) offline muon reconstruction is seeded with $\approx 99\%$ efficient tracks in the muon detectors, which are then matched to tracks reconstructed in the silicon tracker by means of an algorithm optimized for the heavy-ion environment [13, 14], (3) the same analysis procedure is followed for the offline selection with very loose criteria. Signal extraction is based on the procedures in CMS 7 TeV publications for the signal extraction [11, 12].

Using both data sets, the production measured in PbPb collisions is compared to expectations from an independent superposition of nucleon-nucleon collisions typically expressed in terms of the nuclear modification factor:

$$R_{AA} = \frac{L_{pp}}{N_{MB}} \frac{N_{PbPb}(Q\bar{Q})}{N_{pp}(Q\bar{Q})} \frac{\varepsilon_{pp}}{\varepsilon_{PbPb}}.$$  (1)
Here is the nuclear overlap function, \( \mathcal{L}_{pp} \) is the pp luminosity, \( N_{MB} \) is the measured number of equivalent minimum bias events in PbPb, \( \frac{N_{PbPb}(Q\bar{Q})}{N_{pp}(Q\bar{Q})} \) is the raw yield ratio, and \( \varepsilon_{PbPb}^{Q\bar{Q}} \) the multiplicity dependent fraction of the efficiency (\( \varepsilon_{PbPb}^{Q\bar{Q}} \sim 1.17 \) for the most central bin). This paper explores the \( R_{AA} \) for three different Quarkonium states.

3. Lower Mass Quarkonia

For the lower mass Quarkonia (J/Ψs) we can further subdivide them into two types depending on whether they come from the primary vertex (prompt J/Ψs) or are produced from decays of B mesons (non-prompt J/Ψs), in other words from the secondary vertex. Prompt J/Ψs contain both direct J/Ψ production and J/Ψs coming from the feed-down of higher excited states such as ψ(3S) and χc. Due to the long lifetime of the B meson, non-prompt J/Ψs are produced at a distance \( L_{xy} \) from the primary vertex and can therefore be separated from the prompt contribution given the good secondary vertex resolution. This disentanglement is done in CMS by reconstructing the \( \mu^+\mu^- \) vertices and performing a 2-dimensional unbinned simultaneous fit of the invariant mass distribution and the pseudo-proper decay length, \( l = L_{xy} \mu_T \), leaving the B fraction as a free parameter (see [11] for details). Note that we need to use the pseudo-proper decay length, as we do not exactly know the kinematics of the B meson but only the kinematics of the J/Ψ instead (after we reconstruct the dimuon candidate).

Despite the busier heavy-ion environment the CMS detector performs extremely well, such that the good momentum resolution can be used to separate non-prompt from prompt J/Ψ just as in the pp case, making use of the distance between the non-prompt vertex and the primary vertex. An example of the 2-dimensional fit in PbPb collisions is shown on Fig. 1 for J/Ψ with \( p_T > 6.5 \text{ GeV/c} \). For more details see [8, 20, 21].

![Figure 1.](image)

**Figure 1.** Pseudo-proper decay length (left) and invariant mass distribution (right) for J/Ψ with \( p_T > 6.5 \text{ GeV/c} \) in PbPb collisions. The black dots are the data, the dotted line filled in blue the background, the dashed line filled in red the background and non-prompt contribution, and the black straight line the total fit.

For the first time, the secondary J/Ψ \( R_{AA} \) is measured in heavy-ion collisions. Fig. 2 (left) illustrates B-meson suppression via their J/Ψ decays through the \( R_{AA} \) as a function of \( N_{part} \). \( R_{AA} = 0.36 \pm 0.08 \text{(stat)} \pm 0.03 \text{(syst)} \) in the 20% most central collisions. This suppression could

\(^1\) Ratio of the number of binary nucleon-nucleon collisions \( N_{coll} \) calculated from a Glauber model of the nuclear collision geometry [15, 16] and the inelastic nucleon-nucleon cross section \( \sigma_{inel}^{NN} = (64 \pm 5) \text{ mb} \) at \( \sqrt{s} = 2.76 \text{ TeV} \) [17]
be a hint of b-quark energy loss. The level of suppression is of the same order of magnitude as charged hadrons as observed on Fig. 2 (right) where the non-prompt J/Ψ \( R_{AA} \) is plotted as a function of \( p_T \) for 0–20% while the bosons and charged hadrons are presented as a function of the transverse mass for 0–10% [19].

**Figure 2.** Left: Non-prompt J/Ψ \( R_{AA} \) in two centrality bins 0–20% and 20–100% in closed symbols. Right: \( R_{AA} \) vs. \( m_T \) for Z (squares), isolated photons (closed circles) and charged hadrons (open circles) compared to the secondary J/Ψ measurement as a function of \( p_T \) (open squares).

Fig. 3 shows the prompt J/ψ \( R_{AA} \) (filled squares) as a function of \( p_T \), \( y \) and \( N_{\text{part}} \). A factor three suppression is observed for the two \( p_T \) bins. CMS points are compared to measurements at \( \sqrt{s_{NN}} = 200 \) GeV from PHENIX [22] at mid- (open squares) and forward (open circles) rapidity for lower \( p_T \), and from STAR [23] up to \( p_T = 8 \) GeV/c\(^2\). The tendency of high-\( p_T \) J/Ψ’s to survive at RHIC is not seen at the LHC. Furthermore, CMS measures less suppression at forward rapidity for high-\( p_T \) J/Ψ. One should remember that the \( x \) probed with \( \langle p_T^{J/Ψ} \rangle = 10 \) GeV/c by CMS over \( |y| < 2.4 \) are \( x_1 \sim 0.02 \) and \( x_2 \sim 5 \cdot 10^{-4} \). Therefore, anti-shadowing could play a role in the suppression observed and could contribute to seeing an opposite trend than PHENIX as a function of \( y \), or an increase of the \( R_{AA} \) when going to low \( p_T \) and more forward regions as for ALICE measurements [24]. For \( p_T > 3 \) GeV/c and 1.6 < \( y < 2.4 \), CMS measures \( R_{AA} = 0.39 \pm 0.06(\text{stat.}) \pm 0.03(\text{syst.}) \). Finally, in the 10% most central collisions, CMS observes a factor five suppression, much greater than measured by STAR.

4. \( \Upsilon \) Family

CMS is able to disentangle the \( \Upsilon(1S) \) contribution from the higher states in PbPb as in pp collisions. Fig. 4 compares the \( \Upsilon \) invariant mass distribution at \( \sqrt{s} = 2.76 \) TeV in pp (left) and PbPb (right) collisions, for \( p_T^\text{min} > 4 \) GeV/c. The higher state contribution relative to the ground state is strikingly smaller in PbPb collisions. In order to quantify this suppression, an extended unbinned maximum likelihood simultaneous fit to the pp and PbPb mass spectra is performed, following the method described in [9], using the parameters detailed in [25]. The ratio of \( \Upsilon(2S + 3S)/\Upsilon(1S) \) in PbPb over the same ratio in pp benefits from an almost complete cancellation of possible acceptance and/or efficiency differences among the \( \Upsilon \) levels.

\(^2\) PHENIX and STAR measurements are inclusive measurements but the contamination from secondary J/Ψ is expected to be small at RHIC energies.
states in pp and PbPb collisions, taken at the same center-of-mass energy, is consistent with the measurement is compared to STAR Υ(1S+2S+3S) preliminary result in AuAu collisions at In addition, Υ(1S) are suppressed by a factor two in 0–10% central collisions. The CMS In both cases however, the statistical uncertainties are too large for any strong conclusions.

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Conclusions

In summary, this paper presented highlights of CMS quarkonia measurements in pp and PbPb collisions at √s = 2.76 GeV recorded in 2010 and 2011 (for the pp case). The high statistics accumulated at the LHC allows the performance of detailed studies that further constrain production mechanisms. CMS has performed the measurements of the prompt and non-prompt , as well as of the Υ(1S) and Υ(2S+3S) mesons via their decay into pairs in PbPb and pp collisions at 2.76 TeV. Prompt has been separated from non-prompt for the first time in heavy-ion collisions. A strong suppression of prompt J/Ψ with pT > 6.5 GeV/c is measured in central collisions, and already in peripheral collisions, showing a clear dependence with centrality. Non-prompt , though strongly suppressed, show no strong centrality dependence within uncertainties. This is the first hint of b-quark energy loss in the hot medium. Furthermore, Υ(1S) are suppressed by 40% in the 20% most central collisions. The comparison of the ratios of Υ(nS)-states in pp and PbPb collisions, taken at the same center-of-mass energy, is consistent with the

Figure 3. CMS prompt J/Ψ RAA measurement (filled squares) compared to PHENIX mid (open squares) and forward (open circles) rapidity measurement and STAR higher pT measurement (stars) as a function of pT (left), y (center), and Npart (right).

The Υ(1S) suppression has a been studied as a function of pT, y and centrality as shown on Fig. 5. A suppression by a factor ~ 2.3 is observed for low pT. This seems to disappear for pT > 6.5. The rapidity dependence indicates a slightly smaller suppression at forward rapidity. In both cases however, the statistical uncertainties are too large for any strong conclusions. In addition, Υ(1S) are suppressed by a factor two in 0–10% central collisions. The CMS measurement is compared to STAR Υ(1S+2S+3S) preliminary result in AuAu collisions at √sNN = 200 GeV [26] showing a suppression of the same order of magnitude but with large uncertainty.

reconstructed resonances. The double ratio obtained is

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\frac{\text{Υ}(2S + 3S)/\text{Υ}(1S)|_{\text{PbPb}}}{\text{Υ}(2S + 3S)/\text{Υ}(1S)|_{\text{pp}}} = 0.31^{+0.19}_{-0.15} \text{ (stat.)} \pm 0.03 \text{ (syst.)},
\]

where the systematic uncertainty (10%) arises from varying the lineshape in the simultaneous fit, thus taking into account partial cancellations of systematic effects. Finally, using an ensemble of one million pseudo-experiments generated with the signal lineshape obtained from the pp data, Fig. 4 (left), the background lineshapes from both data sets, and a double ratio (Eq. 2) equal to unity within statistical and systematic uncertainties (absence of a suppression), the probability of finding the measured value of 0.31 or a downward fluctuation is estimated to be 0.9%, corresponding to 2.4 sigma in a one-tailed integral of a Gaussian distribution.

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Figure 5. $\Upsilon(1S)$ $R_{AA}$ as a function of $p_T$ (left), $y$ (middle), and $N_{part}$ (right), compared to STAR inclusive preliminary measurement (stars) for the latter.

partial disappearance of the higher states with respect to the ground state in the PbPb collisions. Those two observations could indicate that the $\Upsilon(1S)$ suppression is due to the melting of the excited states only in PbPb collisions. Measuring the amount of suppression caused by shadowing through pA collisions together with more precise measurements will be crucial for interpreting what the melting is due to. As an outlook, in 2011 CMS recorded around 15 times more statistics, based on a PbPb dataset of 150 $\mu$b$^{-1}$, we measured the double ratio $Y(2S)/Y(1S)$ in PbPb relative to pp collisions to be $0.21 \pm 0.07$ (stat.) $\pm 0.02$ (syst.). No noticeable dependencies are observed on the dimuon rapidity or transverse momentum, within the current statistical precision. No clear centrality dependence of the double ratios can be inferred from the data, while such a dependence is observed when inspecting the individual $Y(1S)$ and $Y(2S)$ nuclear
modification factors, $R_{AA}$. The centrality-integrated $R_{AA}$ values for the $\Upsilon(1S)$ and $\Upsilon(2S)$ states are $0.56 \pm 0.08$ (stat.) $\pm 0.07$ (syst.) and $0.12 \pm 0.04$ (stat.) $\pm 0.02$ (syst.), respectively. The $3S$ state is not observed prominently in the data, and upper limits on its suppression ratios are set.

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