Quarkonium production in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

The CMS Collaboration

Abstract

This physics analysis summary describes the $J/\psi \rightarrow \mu^+\mu^-$ and the $\Upsilon \rightarrow \mu^+\mu^-$ analyses performed on PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV data, recorded in 2010 with the CMS detector. The inclusive $J/\psi$ yield is measured, separated also in prompt and non-prompt contributions, and compared to $pp$ at 2.76 TeV, recorded in March 2011, scaled by the number of binary collisions. Prompt $J/\psi$ are suppressed in central collisions compared to peripheral collisions, and the most peripheral bin shows also suppression with respect to the $pp$ reference. Non-prompt $J/\psi$ are also suppressed but less than the prompt $J/\psi$, and show no centrality dependence. The $\Upsilon(1S)$ production is measured and observed also suppressed. Finally, the suppression of the $\Upsilon(2S+3S)/\Upsilon(1S)$ ratio in PbPb with respect to $pp$ is quantified.
1 Introduction

At large energy densities and/or high temperatures, a new form of matter exists, in which the relevant degrees of freedom are quarks and gluons. This matter, called ‘quark-gluon plasma’ (QGP), constitutes the main object of the studies performed with the relativistic heavy-ion collisions. The final goal of such studies is to characterize and quantify the properties of this matter.

The QGP can manifest itself in a large variety of ways. One of its most striking expected characteristics is the suppression of quarkonium states [1], both from the charmonium ($J/\psi, \psi', \chi_c$, etc.) and bottomonium families ($\Upsilon(1S, 2S, 3S), \chi_b$, etc.). This is thought to be a direct effect of deconfinement, when the force between the constituents of a quarkonium state, a heavy quark and its antiquark, is weakened by the color screening produced by the surrounding light quarks and gluons. The suppression is predicted to occur (1) above a critical temperature of the medium ($T_c$), and (2) sequentially, in order of the binding energy. Since the $\Upsilon(1S)$ is the strongest bound state among all quarkonia, it is expected to be the last to melt in the QGP. Examples of dissociation temperatures are given in reference [2]: $< T_c$, $1.2 T_c$, and more than $2 T_c$ for the $\Upsilon(3S)$, $\Upsilon(2S)$ and $\Upsilon(1S)$ respectively, in units of the critical temperature.

On the charmonia side, studies in heavy-ion collisions have been carried out for more than 20 years first at the Super Proton Synchrotron (SPS) by the NA50 [3] and NA60 [4] experiments, and then at the Relativistic Heavy Ion Collider (RHIC) by PHENIX [5] and STAR [6] at 17.3 and 200 GeV centre-of-mass energy per nucleon pair ($\sqrt{s_{NN}}$) respectively. In all cases, $J/\psi$ meson suppression was observed in most central collisions. Furthermore, at the SPS [7], the suppression of the $\psi'$ meson was also observed. For bottomonia, the production cross section is too small at RHIC to make definitive measurements. The PHENIX experiment has reported a preliminary result of an overall suppression in the $\Upsilon$-states mass region of less than 0.64 at the 90% confidence level, in minimum bias AuAu collisions at $\sqrt{s_{NN}} = 200$ GeV [8]. The STAR experiment also reported a preliminary modification factor of the yield in the $\Upsilon$ mass region of $0.78 \pm 0.28 \pm 0.20$, thus compatible with unity, in $d$Au collisions [9]. With the higher energy and luminosity available at the Large Hadron Collider (LHC) in heavy-ion collisions, new studies for charmonia become possible in a different energy regime than at RHIC or the SPS, and the bottomonium family can be measured significantly.

This paper presents the first measurements of the prompt and non-prompt $J/\psi$, as well as of the $\Upsilon(1S)$ and $\Upsilon(2S+3S)$ mesons via their decay into $\mu^+\mu^-$ pairs in PbPb and $pp$ collisions at $\sqrt{s_{NN}} = 2.76$ TeV. Inclusive $J/\psi$ results are also presented. The measurements are based on data recorded with the CMS detector from the first LHC PbPb run at the end of 2010, and from the $pp$ run during March 2011 at $\sqrt{s} = 2.76$ TeV.

Differential cross sections and nuclear modification factors for prompt $J/\psi$, non-prompt $J/\psi$, and $\Upsilon(1S)$ are reported in multiple bins of rapidity, $p_T$ and centrality of the collision. The results are fully corrected for efficiency loss and the limitations of the detector acceptance. The fraction of non-prompt $J/\psi$ is presented as a function of $p_T$. Finally we quantify the $Y(2S+3S)/Y(1S)$ ratio of PbPb relative to $pp$.

The paper is organized as follows. Section 2 gives a brief presentation of the CMS detector. Section 3 presents the data collections, the event selection, the muon reconstruction and selection, and the Monte Carlo simulations. The methods employed for signal extraction are detailed in Section 4. In Sections 5 the acceptance correction factors and the estimation of the reconstruction efficiencies are described. The $pp$ reference studies are summarized in Section 6. The
results are presented in Section 7 followed by conclusions in Section 8.

2 The CMS Detector

A detailed description of the Compact Muon Solenoid (CMS) experiment can be found elsewhere [10]. The central feature of the CMS apparatus is a superconducting solenoid, of 6 m internal diameter. Within the field volume are the silicon tracker, the crystal electromagnetic calorimeter (ECAL) and the brass/scintillator hadron calorimeter (HCAL). Muons are detected in the pseudorapidity window $|\eta| < 2.4$, by gaseous detectors made of three technologies: Drift Tubes (DT), Cathode Strip Chambers (CSC), and Resistive Plate Chambers (RPC), embedded in the iron return yoke. The silicon tracker is composed of pixel detectors (three barrel layers and two forward disks in either side of the detector, made of 66 million $100 \times 150 \, \mu m^2$ pixels) followed by microstrip detectors (ten barrel layers plus three inner disks and nine forward disks in either side of the detector, with strips of pitch between 80 and 180 $\mu m$).

The transverse momentum, $p_T$, of the muons matched to reconstructed tracks is measured with a resolution better than $\sim 1.5\%$ for $p_T$ smaller than 100 GeV/$c$ [11]. This is the result of the strong magnetic field, 3.8 T, and of the high granularity of the silicon tracker. The silicon tracker also provides the vertex position, with $\sim 15 \, \mu m$ accuracy. In addition, CMS has extensive forward calorimetry, in particular two steel/quartz-fiber Čerenkov, hadron forward (HF) calorimeters, which cover the pseudorapidity, $\eta$ range $2.9 < |\eta| < 5.2$. These detectors were used in the present analysis for the event selection and collision centrality determination as described next section.

3 Data Selection

3.1 Event Selection

The analysis is based on a data sample recorded by the CMS detector in PbPb collisions at $\sqrt{s_{NN}} = 2.76$ TeV.

Hadronic PbPb collisions were selected using information from the two Beam Scintillator Counters and Forward Hadronic calorimeters (HF), in coincidence with a bunch crossing identified by the Beam Pick-up Timing Experiment detectors. Events were further filtered offline, by requiring a reconstructed primary vertex made of at least two tracks, and a coincidence of hits in 3 towers of both HFs with a total deposited energy of at least 3 GeV per tower. These criteria reduce contributions from single-beam interactions with the environment (e.g. beam-gas and beam halo collisions with the beam pipe), ultra-peripheral electromagnetic collisions, and cosmic-ray muons. The acceptance of this selection is 97% of the hadronic inelastic cross section. A sample of 55 million minimum bias (MB) event sample passed all these filters. Assuming an inelastic PbPb cross section of $\sigma_{\text{PbPb}} = 7.65$ b, this sample corresponds to an integrated luminosity of $L_{\text{int}} = 7.28 \, \mu b^{-1}$.

The measurements reported here are based on (di)muon events triggered by the Level-1 (L1) and High Level Trigger (HLT) processor farm. The first is a hardware trigger that uses information from the calorimeters and the muon detectors. At the HLT, the L1 muon objects are no further processed for this analysis, apart from adding a quality requirement on the two muons to decrease the event rate before data storage.

Figure 1 shows the centrality distribution of minimum bias events (in black) and events scaled by the double muon trigger (in red). The most central the collisions are, the smaller the central-
ity variable is. Using a Glauber calculation as described in [12], one can then estimate variables related to centrality, like the number of nucleon participating in the collisions, $N_{\text{part}}$, or the number of binary collisions, $N_{\text{coll}}$. The minimum bias trigger efficiency is very high, with a 3% loss arising only in the peripheral bin. The number of muon triggered events is also biased towards central events as the main physics processes that generate dimuons scale with the number of hard collisions.

Simulated events were used to tune the muon selection criteria, to check the agreement with data, and to compute the acceptance and efficiencies corrections. For the acceptance corrections described in Sec. 5.1, four separate Monte Carlo samples were generated: prompt $J/\psi$, non-prompt $J/\psi$, $Y(1S)$ and $Y(2S)$. They were produced using PYTHIA 6.424 [13] at $\sqrt{s} = 2.76$ TeV which generates events based on the leading-order color-singlet and color-octet mechanisms, with non-relativistic QCD (NRQCD) matrix elements tuned [14] by comparison with CDF data [15]. Color octet states undergo a shower evolution. Final state bremsstrahlung was implemented using PHOTOS [16, 17]. For the non-prompt $J/\psi$ studies, the B-hadron events were produced with PYTHIA in generic QCD 2→2 processes (MSEL=1). In all four samples, the decay part was done using the EVTGEN [18] package, with the default polarization values for the three signals. For the rest of the Monte Carlo studies, and in particular the efficiency corrections described in Sec. 5.2, the PYTHIA signal was embedded in a realistic heavy-ion background event, generated with the HYDJET [19] event generator, and then simulated with GEANT4 [20] and processed through the trigger emulation and the full event reconstruction chain. The embedding was done at the level of detector hits, taking care to match the signal and background production vertices to the real-data vertex.

3.2 Muon Selection

Muon offline reconstruction starts with $\sim 99\%$ efficiency by tracks from the muon detectors, called stand-alone muons. These tracks are then matched to tracks reconstructed in the silicon tracker by means of an algorithm optimized for the heavy-ion environment [12]. The final muon objects called global muons result from a global fit of the muon and tracker tracks. Those will be used to obtain the results presented from Sec. 7.1 on.
In order to have a clear separation between acceptance and efficiency corrections a single muon acceptance is defined in $p_T^\mu - \eta^\mu$ space along the contour which roughly matches a global muon reconstruction efficiency of 10%. A muon is declared to be detectable if its reconstruction efficiency\(^1\) is higher than 10%. Fig. 2 presents the result of this efficiency in single muon coordinates $p_T^\mu$ as a function of $\eta^\mu$. The superimposed white lines highlight the contour of the kinematical limits that will be used for the prompt and non-prompt $J/\psi$, also given by Eq. 1:

\[
\begin{align*}
|\eta^\mu| &< 1.0 \quad \to \quad p_T^\mu > 3.4 \text{ GeV}/c, \\
1.0 &\leq |\eta^\mu| < 1.6 \quad \to \quad p_T^\mu > 5.8 - 2.4 \times |\eta^\mu| \text{ GeV}/c, \\
1.6 &\leq |\eta^\mu| < 2.4 \quad \to \quad p_T^\mu > 3.4 - 0.78 \times |\eta^\mu| \text{ GeV}/c.
\end{align*}
\] (1)

Only muons fulfilling this condition are considered in this analysis to avoid too large efficiency corrections and kinematic regions in which the single muon acceptance is zero. Efficiency corrections discussed in Section 5.2 will account for all the muons lost above this cut from the trigger, reconstruction or muon selection inefficiencies. Muons lost because of this cut will be accounted for in the acceptance corrections discussed in Section 5.1.

\[p_T^\mu > 4 \text{ GeV}/c\] (2)

In addition to lowering the PbPb background, this selection of high transverse momentum muons raises the acceptance for the excited states relative to the ground state.

\(^1\)The reconstruction efficiency here is defined as all reconstructed single muons over all generated muons.
Different variables to select good quality global muons have been studied in Monte-Carlo generated PbPb events. Prior to these studies, checks were made to ensure that the MC distributions of the J/ψ decay muons are in good agreement with those from data. The agreement was found to be better than 2%, which is within the systematic uncertainty that was estimated on the data/MC efficiency comparison (see Sec. 5.2). In order to resolve ambiguities when two muons share the same segment in the muon stations, a requirement on the arbitration of each muon is made. The transverse (longitudinal) impact parameter from the measured vertex is required to be less than 3 (15) cm. Tracks are only kept if they have 11 hits or more in the silicon tracker and the $\chi^2$ per degree of freedom of the global (tracker) track fit is required to be lower than 20 (4). The probability of the two tracks to belong to a common vertex is requested to be better than 1%, removing background arising from B-meson semileptonic decays. These selection criteria result in a 6.6%, 5.1% 3.9% loss of the prompt J/ψ, non-prompt J/ψ and Υ(1S) MC signals respectively.

Fig. 3 shows the dimuon spectrum in PbPb collisions at 2.76 TeV, between 2 and 200 GeV/$c^2$ with a single muon $p_T$ cut at 4 GeV/$c$, after applying all of the above mentioned event filters and single-muon selection criteria.

![Figure 3: Invariant mass spectrum of $\mu^+\mu^-$ pairs over the mass range $2.0 \leq m_{\mu\mu} < 200$ GeV/$c^2$ for single muons with $p_T > 4.0$ GeV/$c$. Visible are the J/ψ, Y and Z peaks.](image)

4 Signal Extraction

4.1 J/ψ Analysis

4.1.1 Inclusive J/ψ

The J/ψ analysis follows closely the $pp$ analysis published in Ref. [21]. The invariant mass spectrum of $\mu^+\mu^-$ pairs with $p_T < 30$ GeV/$c$, in the region $2 \leq m_{\mu\mu} < 4$ GeV/$c$, after applying the single muon quality cuts, is shown in Fig. 4 as black circles for all $\mu^+\mu^-$ pairs in $|y| < 2.4$. The same sign muon pair spectrum ($\mu^+\mu^- - \mu^-\mu^-$) is overlaid as red squares for the same selection. The curve is an unbinned maximum log-likelihood fit with a “Crystal Ball” function [22].
(C.B.) and a Gaussian, with common mean and width for the signal, and an exponential for the background. The number of inclusive J/\(\psi\) obtained is 734 ± 54.

![Figure 4: Invariant mass spectrum of \(\mu^+\mu^-\) pairs (solid black circles) with 0 < \(p_T\) < 30 GeV/c and \(|y|\) < 2.4 in minimum bias collisions and same sign muon pair (red square) with the same selection criteria.](image)

In the analysis, the data has been binned in \(p_T\) and rapidity of the \(\mu^+\mu^-\) pairs as well as in bins of the event centrality: 0–10%, 10–20%, 20–30%, 30–40%, 40–50%, and 50–100%. The bins in rapidity are: 0.0 ≤ |\(y\)| < 1.2, 1.2 ≤ |\(y\)| < 1.6, and 1.6 ≤ |\(y\)| < 2.4. The \(p_T\) ranges in the three rapidity bins are constrained by the detector acceptance, i.e. for |\(y\)| < 1.2 there is no acceptance for J/\(\psi\) with \(p_T\) < 6.5 GeV/c. In 1.2 ≤ |\(y\)| < 1.6, the \(p_T\) reach of the J/\(\psi\) is \(p_T\) = 5.5 GeV/c, and in 1.6 ≤ |\(y\)| < 2.4, J/\(\psi\) with an even lower \(p_T\) are measured, down to \(p_T\) = 3.0 GeV/c. This leads to the following J/\(\psi\) bin for the analysis: \(p_T\) > 6.5 in |\(y\)| ∈ [0, 2.4].

The unbinned maximum log-likelihood fit with the C.B. and the Gaussian is performed in each bin. This is the default line shape used in the \(pp\) at 7 TeV analysis, but due to the limited statistics in the heavy ion data sample, the parameters of the signal shape are fitted in the \(p_T\) and centrality integrated bin for each rapidity bin. The values are then fixed for the finer bins in \(p_T\) and centrality. The background shape is left free in each bin. These systematics checks lead to an estimation of systematic uncertainties between 0.5 and 5% for the result of the total (signal, prompt and non-prompt J/\(\psi\), plus background) fit is illustrated with a black line in Fig. 8 for \(\mu^+\mu^-\) pair with 6.5 < \(p_T\) < 30.0 GeV/c and |\(y\)| < 2.4 for minimum bias collisions.

### 4.1.2 Prompt and Non-prompt J/\(\psi\)

The identification of J/\(\psi\) coming from B-hadron decays relies on the measurement of a secondary \(\mu^+\mu^-\) vertex displaced from the primary collision vertex. The distance between the \(\mu^+\mu^-\) vertex and the primary vertex is measured in the plane transverse to the beam direction.
Figure 5: The figures show invariant mass spectra of $\mu^+\mu^-$ pairs for four choices of centrality and rapidity bins. The left column shows events with $\mu^+\mu^-$ pairs in $|y| < 2.4$ and 0–10%, 10–20%, and 50–100% centrality, respectively. The right column is for 0–100% centrality, with rapidity ranges being $|y| < 1.2$, $1.2 \leq |y| < 1.6$, and $1.6 \leq |y| < 2.4$, respectively. The data are overlaid with the projection of the 2-dimensional fit onto the invariant mass axis of $\mu^+\mu^-$ pairs with $6.5 < p_T < 30\text{ GeV}/c$ as a black line. The red line shows the fitted contribution of non-prompt $J/\psi$ discussed in Section 4.1.2. The fitted background is shown as a blue line.
The estimate of the B-hadron decay length follows the prescription of the \( pp \) analysis [21]:

From the measured distance \( \vec{x} \) between the \( \mu^+\mu^- \) vertex and the primary vertex the most probable transverse decay length is calculated as

\[
L_{xy} = \frac{\hat{u}^T \sigma^{-1} \vec{x}}{\hat{u}^T \sigma^{-1} \hat{u}}
\]

where \( \hat{u} \) is the unit vector of the \( J/\psi \) \( p_T \) and \( \sigma \) is the sum of the primary and secondary vertex covariance matrices. From this quantity, the pseudo-proper decay length \( \ell_{J/\psi} = L_{xy} m_{J/\psi} / p_T \) is computed as an estimate of the B-hadron decay length.

To measure the fraction of non-prompt \( J/\psi \) the invariant mass spectrum of \( \mu^+\mu^- \) pairs and their \( \ell_{J/\psi} \) distribution are fitted simultaneously in a 2-dimensional unbinned maximum-likelihood fit in bins of \( p_T \), rapidity, and centrality. The fitting procedure is explained in Ref. [21]. The only difference is the Monte Carlo template used for the true \( \ell_{J/\psi} \) distribution of generated \( J/\psi \) for which both muons were reconstructed. The distribution of this quantity differs due to the different heavy ion tracking algorithm: in contrast to \( pp \), in order to cope with much higher detector occupancy, the PbPb tracking algorithm is done in one iteration, requires a pixel triplet seed to point to the reconstructed primary vertex within 2 mm and finally, at the last step of the tracking, a filter which requires the track to point back to the primary vertex within 6 \( \sigma \) of the primary vertex resolution. The effect of this setting is presented in Fig. 6, where the true generated pseudo-proper decay length, \( \ell_{J/\psi} = L_{xy} m_{J/\psi} / p_T \), of reconstructed \( J/\psi \) is shown for the \( pp \) tracking case and the PbPb tracking: the departure from the exponential trend shows a lower efficiency to reconstruct non-prompt \( J/\psi \) with a large \( \ell_{J/\psi} \) in the PbPb case.

The prompt \( J/\psi \) result is presented in centrality bins of: 0–10%, 10–20%, 20–30%, 30–40%, 40–50%, and 50–100%. Due to the smaller statistics of the non-prompt \( J/\psi \) sample, the result is presented only for the centrality bins 0–20% and 20-100%. The projections of the 2-dimensional fits onto the mass and the \( \ell_{J/\psi} \) axes are shown in Fig. 8 and Fig. 7, respectively. Fig. 8 shows the projections onto the mass and the \( \ell_{J/\psi} \) axes for \( \mu^+\mu^- \) pairs in \(|y| < 2.4\) with 6.5 < \( p_T \) < 30 GeV/c.
and 0–100% centrality.

In order to determine the systematic uncertainty on the yield extraction, the signal and background shapes have been varied. For the signal mass shape, in addition to the default C.B. and Gaussian functions, a single Gaussian and a single Crystal Ball are tried. In addition, a variation of $\alpha$ and $\eta$ parameters of the C.B. and Gaussian is tried, fixing them individually for each $p_T$ and rapidity bin to the values found in the 0–100% centrality bin. This is in contrast to the default procedure in which the values for each rapidity bin are fixed to the values found in the 0–100% bin integrated over all $p_T$. For the background mass shape, a first order polynomial is tried as an alternative.

The systematic uncertainty was determined in each bin varying the fit parameters as the root-mean-square (RMS) of the variation of the yields and its parameters. The systematic uncertainties vary between 0.5% and 5% for the prompt $J/\psi$ yield, while the non-prompt $J/\psi$ yield has uncertainties up to 14% in the most forward ($|y| \in [1.6, 2.4]$) and lowest $p_T (> 3.0 \text{ GeV/c})$ bin.

### 4.2 Y Analysis

The Y yield extraction follows the $pp$ analysis published in Ref [23]. As mentioned in Sec. 3.2, quality cuts are imposed on the single muons in addition to the acceptance/kinematical cuts chosen to suppress the background.

The Y(1S) yield is extracted via an extended unbinned maximum likelihood fit to the $\mu^+\mu^-$ invariant-mass spectrum. The measured mass-lineshape of the Y(1S) state is parameterized by a C.B. function. The parameters describing the radiative tail are fixed to the MC PbPb Y(1S) shape. As the resonances overlap, the three Y(1S), Y(2S) and Y(3S) states are fitted simultaneously with three C.B. functions. In addition, as the signal is limited in data, the Y(1S) resolution is fixed to the MC value 92 MeV/$c^2$, consistent with what is measured when leaving this parameter free when fitting the data over $|\eta^\mu| < 2.4$ where $\sigma = 122 \pm 30 \text{ MeV}/c^2$. The width of the Y(2S) and Y(3S) states is fixed to the Y(1S) width scaled by their respective mass ratios.

The mass of the Y(1S) is a free parameter in the fit, to accommodate the uncertainties in the momentum scale calibration. The number of free parameters is reduced by fixing the mass difference between Y(3S), Y(2S) and Y(1S) to the world average value. In the nominal configuration, a second-order polynomial is chosen to describe the background in the mass range 7–14 GeV/$c^2$. The fit to the dimuon invariant-mass spectrum in PbPb in the Y region is shown in Fig. 9. The mean value is $m_{0} = 9.441 \pm 0.024 \text{ GeV}/c^2$. From this fit, before accounting for acceptance and efficiencies, the Y(1S) raw yield measured is $86 \pm 12$.

Furthermore, data has been binned in $p_T$ and rapidity of the $\mu^+\mu^-$ pairs, as well as in bins of the event centrality (0–10%, 10–20%, and 20–100%). Fig. 10 illustrates the centrality bins of the Y invariant mass distribution. The bins in rapidity are: $0.0 \leq |y| < 1.2$ and $1.2 \leq |y| < 2.4$. The sum of the yields in each $p_T$ or rapidity interval is consistent with the yield determined from a fit to the entire rapidity and $p_T$ range of this analysis within uncertainty. In contrast to the $J/\psi$ case, CMS has acceptance for Y with $p_T = 0 \text{ GeV/c}$ over the full rapidity range. The $p_T$ bins in this analysis are $0 \leq p_T < 6.5 \text{ GeV/c}$, $6.5 \leq p_T < 10 \text{ GeV/c}$, and $10.0 \leq p_T < 20 \text{ GeV/c}$.

In order to estimate the combined systematic uncertainty on the Y(1S) yield from the different sources, the following parameters are varied: C.B. parameters for which three times the RMS over mean of the fit result is taken as a systematic uncertainty, the fixed mass resolution to 92 MeV/$c^2$ by 5 MeV/$c^2$, the mass mean, the fitting range of two different background probability density functions (PDFs) by 1 GeV/$c^2$. The RMS of the fitted values is taken as the total systematic. The systematic uncertainty of the fitting procedure is dominated by the variation.
Figure 7: Projection of the 2-dimensional fit onto the $\ell/\psi$ axis of $\mu^+\mu^-$ pair with $6.5 \leq p_T < 30$ GeV/c. The left column shows events with $\mu^+\mu^-$ pairs in $|y| < 2.4$ in 0–10%, 10–20%, and 50–100% centrality, respectively. The right column are for 0–100% centrality, with rapidity ranges being $|y| < 1.2$, $1.2 \leq |y| < 1.6$, and $1.6 \leq |y| < 2.4$, respectively.
4.2 Y Analysis

Figure 8: Projection of the 2-dimensional fit onto the mass axis (left) and $J/\psi$ axis (right) of $\mu^+\mu^-$ pair with $|y| < 2.4$ with $6.5 < p_T < 30$ GeV/c and 0–100% centrality.

Figure 9: Invariant mass spectrum of $\mu^+\mu^-$ pairs (solid black circles) with $p_T < 20$ GeV/c and $|y| < 2.4$ in minimum bias collisions, for muons above 4 GeV/c.
of the resolution of the mass fit, and is of the order of approximately 10%, reaching 13% for the 0–10% centrality bin.

5 Acceptance and Efficiency

5.1 Acceptance

The dimuon signal acceptance, \( \alpha \), is defined as the fraction of dimuon signal produced within a restricted mass interval \( M \), for which the muons are declared detectable and reconstructible in the CMS detector.

\[
\alpha(p_T, y; \lambda_\theta) = \frac{N_{\mu^+\mu^- \text{detectable},M}^J(p_T, y; \lambda_\theta)}{N_{|y^\mu^+\mu^-| < 2.4}^J(p_T, y; \lambda_\theta)}
\]  

(4)

where

- \( N_{\mu^+\mu^- \text{detectable},M}^J \) is the number of generated events in the Monte Carlo simulation, declared detectable in a given \( (p_T, y) \) bin according to the cuts defined in Sec. 3.2, within a mass interval \( M \) ([2.5, 3.1] GeV/\( c^2 \) for \( J/\psi \) and [8.0, 12.0] GeV/\( c^2 \) for \( \Upsilon \)).

- \( N_{|y^\mu^+\mu^-| < 2.4}^J \) is the number of all dimuons generated within the muon stations coverage of the CMS detector.

\( \alpha \) depends on the transverse momentum \( p_T \), the pseudo-rapidity \( \eta \), and the polarization scenario chosen \( \lambda_\theta \).

Different polarizations of the \( J/\psi \) and \( \Upsilon \) will cause different single muon angular distributions in the laboratory frame, and hence, different probability for the muons to fall outside the CMS detector acceptance. Given the fact that polarization has not been well measured so far by experiments, final results are quoted for the no-polarization scenario only. The impact of the polarization on the acceptance is estimated to be of the order of 20% [21]. The acceptance values obtained in this way are used to calculate the integrated invariant yield.

The acceptance is estimated using the MC sample described in Sec. 3.1. Figure 11 top shows the acceptance \( (p_T \text{ vs. } y) \) for prompt \( J/\psi \) on the left and for \( \Upsilon(1S) \) on the right at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \). Figure 11 bottom illustrates the \( p_T \) (left) and rapidity (right) projections for the prompt \( J/\psi \) and \( \Upsilon(1S) \) acceptance.
Figure 11: Top: acceptance $p_T$ vs. rapidity distribution for the prompt $J/\psi$ on the left and the $\Upsilon$(1S) on the right. Bottom: Acceptance $p_T$ (left) and rapidity (right) of the quarkonium signals at 2.76 TeV, for prompt $J/\psi$ in red square symbol and $\Upsilon$(1S) in green diamond symbol.

The statistical uncertainty at high-$p_T$ for the $J/\psi$ case (Fig. 11 top left) does not play any role in the final result, given the fact that the acceptance is calculated in the bin $10 - 30$ GeV/c, corresponding to the highest analysis bin. The systematic uncertainty on the acceptance corrections were estimated varying by 30% up and down the baseline MC-generated rapidity and $p_T$ shape. The variations were done between $y = -2.0$ and $y = 2.0$ for the rapidity shape and $p_T = 0$ and $p_T = 30$ (20 for $\Upsilon$) GeV/c. The RMS of the variations are summed quadratically to compute the final relative uncertainty. The biggest systematic relative uncertainty obtained is 4.2%, 3.2%, 2.8% respectively for the prompt $J/\psi$, non-prompt $J/\psi$, and $\Upsilon$(1S).

5.2 Efficiency

Trigger, reconstruction and selection efficiencies of $\mu^+\mu^-$ pairs are estimated using the MC signal embedded in PbPb events as described in Sec. 3.1. These events were processed through the trigger emulation and event reconstruction chain. The final efficiency corrections correspond to the fraction of reconstructed signal passing all the analysis selections with respect to the generated signal, in each analysis bin. On the embedded sample, the ratio of signal over background is increased compared to data, so a simple counting is used to extract the signal
instead of using a fit. Only muons in the kinematic region defined in Sec. 3.2 are considered. The efficiency uncertainties are cross-checked with two different methods based on MC truth information and using exactly the same fits as if it were real data, giving further confidence in the final corrections.

Figures 12 illustrates the efficiency corrections as a function of the dimuon $p_T$, rapidity and centrality, for each signal: in red filled squares for prompt $J/\psi$, orange stars for non prompt $J/\psi$, and green diamonds for $\Upsilon(1S)$. The efficiency of non-prompt $J/\psi$ is lower than of the prompt $J/\psi$, reaching about 35% above 10 GeV/c. This is the effect of a filter present in the heavy ion tracking algorithm, that restricts the reconstruction to tracks that point within certain limits of the primary vertex, as described in Sec. 4.1.2. The prompt $J/\psi$ efficiency increases until about 10 GeV/c stabilizing a little above 50%, while the $\Upsilon(1S)$ efficiency stays more or less flat above 50%. The rapidity distributions decreases at the very forward and very backward rapidities as well as around $|y| = 0$. Versus centrality, the efficiencies are decreasing slowly, the difference between peripheral and central collisions being 17.2%.

Figure 12: Efficiency corrections as a function of $p_T$, rapidity and centrality for each signal: in red squares and orange stars for prompt and non prompt $J/\psi$ respectively, and in green diamonds for $\Upsilon(1S)$.

The systematic uncertainty on the final corrections takes into account the statistical precision of
the Monte-Carlo sample, which dominates, and a 30\% variation of the input generated \( p_T \) and rapidity shape used to estimate the efficiencies, similar to the acceptance variation described in the previous section. The final systematic uncertainties on efficiencies are on the order of 1-1.5\%, 2-4\% and 1.5-3\% for prompt J/\( \psi \), non-prompt J/\( \psi \) and \( \Upsilon \) respectively.

The individual components of the MC efficiency are cross checked using real data and muons from J/\( \psi \), with a technique called tag-and-probe, similar to the one used for the corresponding pp measurement [21]. The method consists in fitting the J/\( \psi \) candidates with a \( p_T \) above 6.5 GeV/c as it is the region measured over all the acceptance, with and without applying the probed selection on one of the muons:

1. The trigger efficiency is probed by testing the trigger response to global muons from a sample triggered by a single-muon requirement. A Crystal Ball function was used to describe the J/\( \psi \) peak. The \( p_T^\mu \) and \( \eta^\mu \) dependence of the trigger efficiency compares rather well between data and MC as shown in Fig. 13 left column for J/\( \psi \) with \( p_T > 6.5 \) GeV/c. The \( p_T^\mu \) and \( \eta^\mu \) integrated trigger efficiency is 95.9\% in MC and (95.1 \pm 0.9)\% in data. As the difference is less than the statistical precision with which the data efficiency is measured, twice the relative statistical uncertainty is used as a systematic on the dimuon trigger efficiency : 1.8\%. This value covers the uncertainties of this measurement even when going to lower J/\( \psi \) \( p_T \), at forward rapidity, where the trigger efficiency is slightly different. Also shown, in Fig. 13 left column bottom plot, is the trigger efficiency as function of centrality which, as expected, shows no significant centrality dependence in data or MC.

2. The silicon tracker reconstruction efficiency, including matching between the tracker track and the muon stations track, and the quality selection criteria, are probed with stand-alone muons passing quality selections of the analysis. For this efficiency estimation, in data, the signal is fitted with a Gaussian function and the background with a polynomial of order 2. Fig. 13 right column shows this efficiency as function of \( p_T^\mu \), \( \eta^\mu \) and centrality for all J/\( \psi \). No cut \( p_T > 6.5 \) GeV/c cut was used here, as the poor \( p_T^\mu \) resolution of stand-alone muons would have biased the measurement. MC and data show a very good agreement, respectively with 84.9\% and (83.7 \pm 0.57 \pm 0.53)\% for single muon efficiency. Similarly to the trigger efficiency measurement, as agreement between MC and data is better than twice the relative statistical uncertainty is used as a systematic on the tracking efficiency which amounts to 13.6\%. Within uncertainties, no difference in the centrality dependence of the tracking efficiency between data and MC is observed. The bin 30-100\% is not peripheral enough to observe a higher efficiency when compared to the most central bin 0-10\%.

The stand-alone muon reconstruction efficiency could not be probed with tracker tracks as the lower \( p_T \) resolution measured by the stations does not allow for an adequate constraint of the background. As this part of the reconstruction is identical to the pp algorithm, an additional 1\% systematics on the dimuon measurement is added, to account for the stand-alone muon uncertainty, following [24].

6 The pp Reference Sample

A pp run at \( \sqrt{s} = 2.76 \) TeV was delivered by the LHC in March 2011. The luminosity CMS recorded was 225 nb\(^{-1}\) with an associated uncertainty of 7\% based on the analysis of the Van der Meer scans. For probes that follow binary scaling, the integrated luminosity of the pp sample is comparable to the one of the PbPb sample.
A trigger requiring slightly higher quality muons and single muons $p_T > 0$ was used during the $pp$ run in order to reduce the higher rate compared to PbPb. The quality of the muon continued to be defined just by the L1 trigger. This differences between the PbPb and $pp$ triggers were studied in two ways:

1. From data, using the tag and probe technique described in Sec. 5.2, for the $pp$ trigger and for the PbPb trigger. The single muon efficiency as a function of $p_T^\mu > 5$ GeV/c, for all muons from $J/\psi$ with $p_T > 6.5$ GeV/c, the $pp$ trigger efficiency is $(92.5 \pm 0.6)$%, and the PbPb one is $(95.1 \pm 0.9)$%. Restricting this measurement to muons with $p_T > 4$ GeV/c as is done in the $\Upsilon$ analysis, the $pp$ trigger efficiency is $(95.5 \pm 0.6)$% and the PbPb one is $(96.1 \pm 1.0)$%. Hence, the two triggers in PbPb and $pp$ have a very close efficiency where the $\Upsilon$ is measured. The systematics that will be used when making the ratios of PbPb and $pp$ is twice this difference, 1% on the dimuon.

2. From MC simulations using the technique described in Sec. 5.2, the trigger efficiency in $pp$ and PbPb was estimated for $J/\psi$ and $\Upsilon$. The trigger efficiency in $pp$ for dimuons is $(91.7 \pm 0.03)$% and $(92.5 \pm 0.06)$% in PbPb. For the $\Upsilon$(1S) it is $(93.9 \pm 0.01)$% in $pp$ while $(95.9 \pm 0.07)$% for the PbPb trigger. For the $\Upsilon$(2S) it is $(94.0 \pm 0.01)$% in $pp$ while $(95.9 \pm 0.04)$% in PbPb. These efficiency differences are within the systematic uncertainties quoted.

The offline selection is the same as in the PbPb analysis, only slightly relaxed for the HF coincidence requirement: one tower with at least 3 GeV deposited is required for $pp$ case, instead of three. The same reconstruction algorithm, the heavy-ion one, was used for both $pp$ and PbPb. Since the $pp$ data is used exclusively in ratios to the PbPb data in this analysis, having the same algorithm allows most of the reconstruction systematic uncertainties to cancel, leaving only the following factors to be accounted for: the luminosity uncertainty, the trigger difference, and the multiplicity dependence of the reconstruction. The first is a global systematic uncertainty, that makes the points of the ratios move globally. The trigger efficiency systematic uncertainty is estimated to be 2% for dimuon by comparing MC and data and PbPb with $pp$ using the tag-and-probe method. The same approach, using tag-and-probe, was also used for calculating the tracking systematic uncertainty due to different multiplicity in $pp$ and central PbPb. First, since the $pp$ multiplicity is similar to the multiplicity in the peripheral PbPb bins, the calculations were done using these peripheral bins. Then, the ratio of the efficiencies in peripheral (low multiplicity) and central (high multiplicity) bins was compared in MC and in PbPb data using tag-and-probe (Sec. 5.2). Data and MC results agree within the statistical uncertainties of the method 13.6%, and this value was propagated as the final tracking systematic uncertainty in all the ratios of PbPb to $pp$ data. The overall trigger, reconstruction and selection efficiency measured in $pp$ MC is $(42.5 \pm 0.3)$%, $(55.1 \pm 0.1)$% and $(55.4 \pm 0.1)$% respectively for the prompt $J/\psi$, $\Upsilon$(1S) and $\Upsilon$(2S).

The quarkonium signals in $pp$ are extracted following the same methods as in PbPb described in 4.1 and 4.2, apart from the fact that for the non-prompt $J/\psi$ signal extraction, the four Gaussians of the lifetime resolution are fixed to the MC values due to lack of statistics in the sidebands. The systematic uncertainty of the signal extraction in $pp$ is estimated to be about 0.5-6% for the prompt $J/\psi$, 5-20% for the non-prompt $J/\psi$, and 10% for the $\Upsilon$(1S), with the highest values in the most forward and lowest $p_T$ bins. Figure 15 illustrates the $J/\psi$ prompt and non-prompt extraction in $0.0 \leq |y| < 2.4$ and for $6.5 \leq p_T < 30.0$ GeV/c.
Figure 16 shows on the left the Y uncorrected invariant yield in \( pp \) with the heavy ion reconstruction. The exact same procedure as the one described for PbPb is used. The excited states over ground state ratio in this 2.76 TeV ratio is noted to be slightly different than the one published by CMS for the 7 TeV data sample [23]. This difference is due to (1) the restriction of using global muons and thus to a slightly different phase-space mapping, (2) different triggers, (3) different analysis selection criteria, including the single muon \( p_T \) cut of > 4 GeV/c, and (4) an overall dimuon rapidity cut of \( |y| < 2.4 \) instead of \( |y| < 2.0 \). As a comparison, the 2.76 TeV sample was analyzed again following the 7 TeV analysis tighter selection criteria, including the \( pp \) reconstruction algorithm, using tracker muons, with muon selection cuts of the 7 TeV analysis, and looking only within \( |y| < 2.0 \). Figure 17 illustrates the agreement of the measurement at the two energies under such conditions, with a fit to the background using a third order polynomial function to describe better the lowest mass range. The only difference still remaining is the trigger that was different (more restrictive) during data taking at \( \sqrt{s} = 7 \text{TeV} \). Furthermore, this comparison leads to a ratio of \( Y(2S)+Y(3S)/Y(1S) \) of 0.49 ± 0.08 at 2.76 TeV and 0.42 ± 0.02 at 7 TeV, showing consistency within statistical uncertainties.

In the following result section, the \( pp \) quarkonia measurement at 2.76 TeV will serve as a reference to quantify the quarkonium production in the hot medium created in PbPb collisions.
Figure 13: Comparison of the trigger efficiency (left column) and tracking efficiency (right column) measured with Tag and Probe in PbPb data (red circles) and Monte Carlo (blue squares) as function of $p_T$ (top), $\eta$ (middle) and centrality, $N_{\text{part}}$ (bottom).
Figure 14: Comparison of the trigger efficiency measured with Tag and Probe in pp (red circles) for MC and (blue squares) for data, and PbPb (orange open circles) as function of $p_T$ (left), $\eta$ (right) and centrality (bottom).

Figure 15: Non-prompt $J/\psi$ signal extraction: left dimuon invariant mass fit and right life time fit, for pp at 2.76 TeV reconstructed with the heavy ion algorithm.
Figure 16: Fit to the $pp$ 2.76 TeV dimuon invariant-mass distribution in the range $p_T < 20 \text{ GeV/c}$ for $|y| < 2.4$, showing the Y peaks, with the heavy ion algorithm.

Figure 17: Invariant mass distributions of 7 TeV and 2.76 TeV data, reconstructed with the $pp$ algorithms, using tracker muons and applying the acceptance and the muon quality cuts used for $pp$ analysis.
7 Results

7.1 Invariant Yields

The differential cross sections are reported in the form of:

\[
\frac{1}{T_{AA}} \cdot \frac{d^2N}{dp_Tdy} = \frac{1}{T_{AA}} \cdot \frac{1}{\Delta y \Delta p_T} \cdot \frac{N_{QQ}}{\alpha \epsilon N_{MB}} \tag{5}
\]

where

- \(N_{QQ}\) is the number of measured prompt J/\(\psi\), non-prompt J/\(\psi\), or Y in the \(\mu^+\mu^-\) decay channel.
- \(N_{MB}\) is the number of minimum bias events sampled by the event selection. It is multiplied by the centrality bin width for distributions as a function of \(N_{\text{part}}\).
- \(\alpha\) is the geometric acceptance which depends on the \(p_T\) and rapidity of the quarkonium state;
- \(\epsilon\) is the combined trigger and reconstruction efficiency which depends on the \(p_T\) and rapidity of the quarkonium state and the centrality of the collision;
- \(\Delta y\) and \(\Delta p_T\) are the bin width in rapidity and \(p_T\);
- \(T_{AA}\) is the nuclear overlap function which varies with the centrality of the collision and has units of \(\text{mb}^{-1}\). It is defined as: \(T_{AA} = N_{\text{coll}}/\sigma_{pp}\), with \(\sigma_{pp}\) the inelastic pp cross section.

Following Eq. (5), the raw yields of inclusive, prompt, and non-prompt J/\(\psi\) and Y(1S), presented in Section 4.1 and Section 4.2, are corrected for acceptance and efficiency and converted into an invariant yield divided by the geometric overlap function \(T_{AA}\). This quantity can be directly compared to cross sections measured in \(pp\) collisions. All results are for the unpolarized scenario only and they are listed in Tab. 1–4 in Appendix A.

The systematic uncertainties detailed in the previous sections for all the terms appearing in Eq. 5 (\(N_{MB}\), \(\alpha\), and \(\epsilon\)) are summed in quadrature, leading to a total of 15-20% on the corrected yields. The uncertainties on the \(T_{AA}\) range between 4.3% in the most peripheral bins to 15% in the most central bins [12].

In all this section, statistical uncertainties will be represented by error bars and systematic uncertainties by boxes on the points. Results as function of rapidity are averaged over positive and negative rapidity and plotted on the positive rapidity as solid symbols and are reflected as open symbols onto the negative side for symmetry. The minimum bias measurements appear on distributions as a function of \(N_{\text{part}}\) with open symbols.

Results are tabulated in App. A.

7.1.1 Transverse momentum and rapidity dependence

Fig. 18 shows the invariant yield normalized by \(T_{AA}\) of inclusive and prompt J/\(\psi\) as function of \(p_T\) and rapidity.

The B-fraction in minimum bias collisions as function of \(p_T\) in bins of rapidity is shown in Fig. 19. It is compared to data from CDF [15] and CMS [21]. No deviation from the \(pp\) (\(p\bar{p}\)) results is observed within uncertainties.

Fig. 20 shows the invariant yield of Y(1S) as function of \(p_T\) and rapidity.
Figure 18: Invariant yield divided by $T_{AA}$ as function of $p_T$ (left) and rapidity (right) for inclusive J/$\psi$ (blue circles) compared to prompt J/$\psi$ (red squares). The negative rapidity points (open symbols) are reflections of the positive rapidity points.

Figure 19: B-fraction of J/$\psi$ production in PbPb at 2.76 TeV as function of $p_T$ for the rapidity bin $|y| < 2.4$ (red circles) and $1.6 \leq |y| < 2.4$ (blue square). The data are compared to B-fractions measured by CDF in $p\bar{p}$ at $\sqrt{s} = 1.96$ TeV [15] and CMS in $pp$ at $\sqrt{s} = 7$ TeV [21].
7.2 Nuclear Modification Factor

Using data from the $pp$ run at $\sqrt{s} = 2.76$ TeV, the nuclear modification factor can be calculated using the following equation:

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

(6)

based on raw yields, correcting only for the multiplicity dependent fraction of the efficiency ($\epsilon_{PbPb} \sim 1.17$ for the most central bin).
Figure 21: Invariant yield divided by $T_{AA}$ for inclusive $J/\psi$ (blue circles) and prompt $J/\psi$ (red squares) as function of $N_{\text{part}}$. Also shown as gray shaded area is an interpolation of the expected $pp$ yield at $\sqrt{s} = 2.76$ TeV [25].

Figure 22: Invariant yield divided by $T_{AA}$ as function of $N_{\text{part}}$ for non-prompt $J/\psi$ (orange stars).
The results are tabulated in App. A.

### 7.2.1 Transverse Momentum and Rapidity dependence

Fig. 23 presents the $R_{AA}$ of prompt $J/\psi$ as function of $p_T$ and rapidity. A suppression of $J/\psi$ by a factor of $\sim 3$ with respect to $pp$ is observed and does not exhibit a $p_T$ dependence in the measured $p_T$ range, while there is an indication of less suppression in the most forward bin $(1.6 \leq |y| < 2.4)$. Figure 24 shows the $R_{AA}$ of $Y(1S)$ as function of $p_T$ and rapidity. The $p_T$ dependence shows a suppression by a factor $\sim 2.3$ at low $p_T$ which disappears for $p_T > 6.5 \text{GeV/cm}$ and the rapidity dependence indicates a slightly smaller suppression at forward rapidity, however the statistical uncertainties are too large for any strong conclusions.

### 7.2.2 Centrality Dependence

The results in the $p_T$ range $6.5 \leq p_T < 30.0 \text{GeV/cm}$ and integrated over all rapidity are shown for prompt, and non-prompt $J/\psi$ as well as $Y(1S)$ (with $0.0 \leq p_T < 20 \text{ GeV/cm}$) in Fig. 25, as red squares, orange stars, and green diamonds, respectively. A centrality dependent suppression of prompt $J/\psi$ is observed. The non-prompt $J/\psi$ are suppressed with respect to $pp$ but do not exhibit a centrality dependence which may just be due to the large width of the “peripheral” bin (20–100%)$^2$.

Comparing the $R_{AA}$ values for most central collisions, Fig. 25 left, one sees an ordering of the suppression: prompt $J/\psi$ are the most suppressed, followed by the non-prompt $J/\psi$ and then the $Y(1S)$. When integrated over all centrality bins (minimum bias), the prompt and non-prompt $J/\psi$ are compatible with each other, while the $Y(1S)$ continues to be the least suppressed.

In Fig. 26, the prompt $J/\psi R_{AA}$ results of CMS, from PbPb at 2.76 TeV, in the $p_T$ range $6.5 \leq p_T < 30.0 \text{GeV/cm}$ and $|y| < 2.4$, are compared to inclusive PHENIX results [26] from AuAu at 0.2 TeV, measured in the $p_T$ range $0.0 \leq p_T < 5.0 \text{GeV/cm}$ and in two rapidity regions: with electrons in $|y| < 0.35$ and with muons in the forward region, $1.2 < |y| < 2.2$. The suppression pattern is similar, despite the difference in the colliding energy and very different $J/\psi$ kinematics: high-$p_T$ in the CMS case, low-$p_T$ in the PHENIX case.

At forward rapidity, CMS is able to reach lower $p_T$. The $R_{AA}$ values are tabulated in App. A.

### 7.3 Y Double Ratio

The results of the double ratio analysis are discussed in Ref. [27]. We briefly summarize the results here for completeness.

While all charmonium states as well as excited bottomonium states are expected to be suppressed in the hot and dense medium, the strongly-bound $Y(1S)$ state is expected to be the last to melt-down in the QGP. The suppression of $Y(nS)$ states is studied by comparing their production rates in PbPb and $pp$ collision data, taken at the same collision energy of $\sqrt{s} = 2.76 \text{TeV}$. In addition, the suppression of the higher-mass states is measured relative to the ground state. In this way, one explores the double ratio — $Y(2S+3S)$ vs. $Y(1S)$ and PbPb vs. $pp$— which allows a self-calibrated measurement, where possible effects associated to selection, acceptance, and reconstruction cancel.

The ratio of the excited states $Y(2S+3S)$ to the ground state $Y(1S)$ in the $pp$ and PbPb data is

$^2$Hard probes are produced following a binary collision scaling, thus such a large bin, 20-100%, is mostly driven by the most central events.
Figure 23: The nuclear modification factor as function of $p_T$ (left) and rapidity (right) for prompt $J/\psi$. An uncertainty of 7% on the measured integrated luminosity of the $pp$ data sample is shown as gray box as a global scale uncertainty at $R_{AA}=1$. The negative rapidity points (open symbols) are reflections of the positive rapidity points.

Figure 24: The nuclear modification factor as function of $p_T$ (left) and rapidity (right) for $\Upsilon(1S)$. An uncertainty of 7% on the measured integrated luminosity of the $pp$ data sample is shown as gray box as a global scale uncertainty at $R_{AA}=1$. The negative rapidity points (open symbols) are reflections of the positive rapidity points.
measured to be:

\[ \frac{\Upsilon(2S+3S)}{\Upsilon(1S)}_{pp} = 0.78^{+0.16}_{-0.14}(\text{stat}) \pm 0.02(\text{syst}), \]

(7)

\[ \frac{\Upsilon(2S+3S)}{\Upsilon(1S)}_{PbPb} = 0.24^{+0.13}_{-0.12}(\text{stat}) \pm 0.02(\text{syst}). \]

(8)

The suppression of the excited states relative to the ground state is quantified by the double ratio observable

\[ \frac{\left[ \frac{\Upsilon(2S+3S)}{\Upsilon(1S)} \right]_{PbPb}}{\left[ \frac{\Upsilon(2S+3S)}{\Upsilon(1S)} \right]_{pp}} = 0.31^{+0.19}_{-0.15}(\text{stat}) \pm 0.03(\text{syst}). \]

(9)

The probability to obtain this measured value, or lower, if the true double ratio is unity, has been calculated to be less than 1%.

8 Conclusions

This paper presented the first measurements of the prompt and non-prompt J/ψ, as well as of the Y(1S) and Y(2S+3S) mesons via their decay into μ⁺μ⁻ pairs in PbPb and pp collisions at \( \sqrt{s_{NN}} = 2.76 \) TeV. The measurements are based on data recorded with the CMS detector from the first LHC PbPb run at the end of 2010, and from the pp run during March 2011 at \( \sqrt{s} = 2.76 \) TeV.

Differential cross sections and nuclear modification factors for prompt J/ψ, non-prompt J/ψ, and Y(1S) are reported in multiple bins of rapidity, \( p_T \) and centrality of the collision. The results are fully corrected for efficiency loss and the limitations of the detector acceptance. Detailed systematic studies were carried out with Monte-Carlo generated data and real collisions data, in order to check the level of agreement between the two samples and take into account any potential discrepancy. Data-driven methods were used to cross-check the efficiency corrections, and the differences were propagated in the final systematic uncertainties. In addition, the \( \frac{\Upsilon(2S+3S)}{\Upsilon(1S)} \) ratio of PbPb over pp integrated over the full measured phase-space was quantified.

The prompt J/ψ has been separated from the non prompt J/ψ for the first time in heavy-ion collisions. The cross section results presented as a function of centrality show a factor of two suppression in central collisions with respect to peripheral collisions. With respect to pp, a nuclear modification factor of \( R_{AA} = 0.20 \pm 0.03(\text{stat}) \pm 0.01(\text{syst}) \) has been measured in the 10% most central collisions. Already the prompt J/ψ produced in peripheral collisions are suppressed with respect to pp: \( R_{AA} = 0.59 \pm 0.12(\text{stat}) \pm 0.10(\text{syst}) \) in the 50–100% centrality bin.

The non-prompt J/ψ, though strongly suppressed (\( R_{AA} = 0.36 \pm 0.08(\text{stat}) \pm 0.03(\text{syst}) \) in the 20% most central collisions), shows no strong centrality dependence within uncertainties. Calculations of unmodified prompt and non-prompt J/ψ production, based on existing measurements in pp collisions at lower and higher collision energies, have large uncertainties for the kinematic region where the present CMS measurements are done. The LHC pp run at the same center of mass energy as the PbPb data was therefore instrumental for the final result presented here that addresses suppression of the quarkonium states in the medium produced in heavy-ion collisions.

The Y(1S) yield as a function of \( p_T, \) rapidity, and centrality has been measured. No strong centrality dependence is observed within errors. The nuclear modification factor for the 20% most central collisions is \( R_{AA} = 0.60 \pm 0.12(\text{stat}) \pm 0.10(\text{syst}) \).

In most central collision bin, a clear ordering of the degree of suppression is observed, with the prompt J/ψ being the most suppressed, followed by the non-prompt J/ψ and with the Y(1S) be-
ing the least suppressed. When integrated over all centrality bins (minimum bias), the prompt and non-prompt J/ψ are compatible with each other, while the Y(1S) continues to be the least suppressed. At this point, it is to be noted that the observed ordering does not necessarily implies the same cause/mechanism to be responsible for a particular level of suppression reached by the pure quarkonium states or by the non-prompt J/ψ.

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 partial disappearance of the higher states with respect to the ground state Υ(1S) in the PbPb collisions. The details of this measurement are presented in Ref. [27].

References


Figure 25: $R_{AA}$ for prompt $J/\psi$ (red squares) in coarser centrality binning, overlaid with the non-prompt $J/\psi$ (orange stars) and the $\Upsilon(1S)$ (green diamonds), the open symbols indicate the minimum bias result. An uncertainty of 7% on the measured integrated luminosity of the $pp$ data sample is shown as gray box as a global scale uncertainty at $R_{AA} = 1$. 
Figure 26: Nuclear modification factor for prompt $J/\psi$ (red squares) as function of $N_{\text{part}}$. Below, PHENIX results are overlaid with CMS points for comparison, at forward (open blue circles) and midrapidity (open black squares).
Figure 27: $\mu^+\mu^-$ invariant mass spectrum in the $\Upsilon$ region measured in PbPb overlaid with two fits. The red continuous line is a free fit to the PbPb data. The dashed blue line is a fit with a free background shape but with the signal fixed to the $\sqrt{s} = 2.76$ TeV $pp$ fit results, normalized to the $\Upsilon(1S)$ yield measured in PbPb.
### A Data Tables

Table 1: Invariant Yield divided by $T_{AA}$ of inclusive $J/\psi$ as function of rapidity, $p_T$, and centrality. Quoted uncertainties are statistical and systematic.

| $|y(J/\psi)|$ | $p_T(J/\psi)$ [GeV/c] | centrality  | $\langle p_T(J/\psi) \rangle$ [GeV/c] | $\frac{1}{T_{AA}} \cdot \frac{dN}{dy}$ [nb] | $R_{AA}$ |
|-------------|-------------------------|-------------|-------------------------------------|----------------------------------------|---------|
| 0.0–2.4     | 6.5–30.0                | 0–100%      | 9.87                                | 2.41±0.15±0.37                        | 0.31±0.02±0.02 |
|             | 6.5–10.0                | 0–100%      | 8.11                                | 2.05±0.15±0.32                        | 0.31±0.03±0.03 |
|             | 10.0–30.0               | 0–100%      | 13.22                               | 0.40±0.04±0.06                        | 0.30±0.03±0.02 |
| 0.0–1.2     | 6.5–30.0                | 0–100%      | 10.92                               | 2.76±0.26±0.44                        | 0.29±0.04±0.02 |
| 1.2–1.6     | 5.5–30.0                | 0–100%      | 9.21                                | 3.57±0.45±0.58                        | 0.23±0.03±0.02 |
|             | 6.5–30.0                | 0–100%      | 9.65                                | 2.29±0.28±0.35                        | 0.26±0.04±0.02 |
| 1.6–2.4     | 3.0–30.0                | 0–100%      | 6.27                                | 21.23±3.00±3.33                       | 0.40±0.06±0.03 |
|             | 6.5–30.0                | 0–100%      | 8.92                                | 2.22±0.21±0.34                        | 0.39±0.04±0.03 |
| 0.0–2.4     | 6.5–30.0                | 0–10%       | 10.39                               | 1.78±0.20±0.28                        | 0.22±0.03±0.02 |
|             |                        | 10–20%      | 9.70                                | 1.93±0.24±0.30                        | 0.24±0.03±0.02 |
|             |                        | 20–30%      | 10.23                               | 2.37±0.33±0.37                        | 0.31±0.04±0.03 |
|             |                        | 30–40%      | 9.27                                | 3.73±0.53±0.62                        | 0.48±0.07±0.05 |
|             |                        | 40–50%      | 9.29                                | 5.23±0.81±0.93                        | 0.67±0.11±0.08 |
|             |                        | 50–100%     | 9.64                                | 4.67±0.80±0.97                        | 0.59±0.10±0.10 |
|             |                        | 0–20%       | 9.27                                | 1.84±0.15±0.28                        | 0.23±0.02±0.02 |
|             |                        | 20–100%     | 9.29                                | 3.46±0.26±0.57                        | 0.45±0.04±0.04 |
Table 2: Invariant Yield divided by $T_{AA}$ of prompt J/ψ as function of rapidity, $p_T$, and centrality. Quoted uncertainties are statistical and systematic.

| $|y(J/\psi)|$ | $p_T(J/\psi)$ [GeV/c] | centrality | $\langle p_T(J/\psi) \rangle$ [GeV/c] | $T_{AA} \cdot \frac{dN}{dy}$ [nb] | $R_{AA}$ |
|---|---|---|---|---|---|
| 0.0–2.4 | 6.5–30.0 | 0–100% | 9.87 | $1.79 \pm 0.13 \pm 0.28$ | $0.30 \pm 0.02 \pm 0.02$ |
| 0.0–2.4 | 6.5–30.0 | 0–10% | 10.92 | $2.12 \pm 0.23 \pm 0.34$ | $0.28 \pm 0.04 \pm 0.02$ |
| 0.0–1.2 | 6.5–30.0 | 0–100% | 9.21 | $2.95 \pm 0.44 \pm 0.47$ | $0.23 \pm 0.04 \pm 0.02$ |
| 1.2–1.6 | 5.5–30.0 | 0–100% | 9.65 | $1.71 \pm 0.26 \pm 0.26$ | $0.25 \pm 0.04 \pm 0.02$ |
| 1.6–2.4 | 3.0–30.0 | 0–100% | 6.27 | $17.82 \pm 2.63 \pm 2.80$ | $0.39 \pm 0.06 \pm 0.03$ |
| 0.0–2.4 | 6.5–30.0 | 0–10% | 10.39 | $1.18 \pm 0.17 \pm 0.18$ | $0.20 \pm 0.03 \pm 0.01$ |
| 0.0–2.4 | 6.5–30.0 | 10–20% | 9.70 | $1.29 \pm 0.21 \pm 0.20$ | $0.21 \pm 0.04 \pm 0.02$ |
| 0.0–2.4 | 6.5–30.0 | 20–30% | 10.23 | $2.18 \pm 0.33 \pm 0.34$ | $0.36 \pm 0.06 \pm 0.03$ |
| 0.0–2.4 | 6.5–30.0 | 30–40% | 9.27 | $2.97 \pm 0.49 \pm 0.50$ | $0.49 \pm 0.08 \pm 0.05$ |
| 0.0–2.4 | 6.5–30.0 | 40–50% | 9.29 | $3.88 \pm 0.75 \pm 0.69$ | $0.64 \pm 0.13 \pm 0.08$ |
| 0.0–2.4 | 6.5–30.0 | 50–100% | 9.64 | $3.58 \pm 0.70 \pm 0.74$ | $0.59 \pm 0.12 \pm 0.10$ |
| 0.0–2.4 | 6.5–30.0 | 0–20% | 9.27 | $1.23 \pm 0.14 \pm 0.18$ | $0.20 \pm 0.02 \pm 0.01$ |
| 0.0–2.4 | 6.5–30.0 | 20–100% | 9.29 | $2.85 \pm 0.25 \pm 0.47$ | $0.47 \pm 0.05 \pm 0.05$ |

Table 3: Invariant yield divided by $T_{AA}$ of non-prompt J/ψ as function of rapidity, $p_T$, and centrality. Quoted uncertainties are statistical and systematic.

| $|y(J/\psi)|$ | $p_T(J/\psi)$ [GeV/c] | centrality | $\langle p_T(J/\psi) \rangle$ [GeV/c] | $T_{AA} \cdot \frac{dN}{dy}$ [nb] | $R_{AA}$ |
|---|---|---|---|---|---|
| 0.0–2.4 | 6.5–30.0 | 0–100% | 9.87 | $0.60 \pm 0.09 \pm 0.09$ | $0.37 \pm 0.07 \pm 0.03$ |
| 1.6–2.4 | 3.0–30.0 | 0–100% | 6.27 | $3.30 \pm 0.85 \pm 0.69$ | $0.49 \pm 0.14 \pm 0.04$ |
| 0.0–2.4 | 6.5–30.0 | 0–20% | 9.27 | $0.59 \pm 0.12 \pm 0.10$ | $0.36 \pm 0.08 \pm 0.03$ |
| 0.0–2.4 | 6.5–30.0 | 20-100% | 9.29 | $0.60 \pm 0.14 \pm 0.10$ | $0.37 \pm 0.10 \pm 0.04$ |
Table 4: Invariant yield divided by $T_{AA}$ of $\Upsilon(1S)$ as function of rapidity, $p_T$, and centrality. Quoted uncertainties are statistical and systematic.

| $|y(\Upsilon)|$ | $p_T(\Upsilon)$ [GeV/c] | centrality | $\langle p_T(\Upsilon) \rangle$ [GeV/c] | $\frac{1}{T_{AA}} \cdot \frac{d^3N}{dp_Tdy}$ [nb/(GeV/c)] | $R_{AA}$ |
|---------------|--------------------------|------------|---------------------------------|---------------------------------|---------|
| 0.0–2.4       | 0.0–6.5                  | 0–100%     | 3.06                            | 0.293±0.057±0.053               | 0.43±0.10±0.07 |
|               | 6.5–10.0                | 0–100%     | 7.91                            | 0.093±0.028±0.017               | 0.88±0.37±0.14 |
|               | 10.0–20.0               | 0–100%     | 13.21                           | 0.066±0.016±0.012               | 1.72±0.74±0.25 |
|               | 0.0–20.0                | 0–100%     | 6.45                            | 0.485±0.066±0.089               | 0.62±0.11±0.10 |
| 0.0–1.2       | 0.0–20.0                | 0–100%     | 6.57                            | 0.495±0.091±0.091               | 0.52±0.12±0.08 |
| 1.2–2.4       | 0.0–20.0                | 0–100%     | 6.30                            | 0.498±0.097±0.092               | 0.83±0.24±0.13 |
| 0.0–10%       | 6.22                    | 0.347±0.096±0.069 | 0.44±0.13±0.08 |
| 10–20%        | 6.93                    | 0.643±0.144±0.118 | 0.82±0.21±0.13 |
| 20–100%       | 6.19                    | 0.517±0.101±0.101 | 0.66±0.15±0.11 |
| 0–20%         | 6.59                    | 0.468±0.081±0.094 | 0.60±0.12±0.10 |