

Measurement of Prompt $\psi(2S)$ to J/ψ Yield Ratios in Pb-Pb and p - p Collisions at $\sqrt{s_{NN}} = 2.76$ TeV

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The ratio between the prompt $\psi(2S)$ and J/ψ yields, reconstructed via their decays into $\mu^+\mu^-$, is measured in Pb-Pb and p - p collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The analysis is based on Pb-Pb and p - p data samples collected by CMS at the Large Hadron Collider, corresponding to integrated luminosities of $150 \mu\text{b}^{-1}$ and 5.4 pb^{-1} , respectively. The double ratio of measured yields $(N_{\psi(2S)}/N_{J/\psi})_{\text{Pb-Pb}}/(N_{\psi(2S)}/N_{J/\psi})_{p-p}$ is computed in three Pb-Pb collision centrality bins and two kinematic ranges: one at midrapidity, $|y| < 1.6$, covering the transverse momentum range $6.5 < p_T < 30 \text{ GeV}/c$, and the other at forward rapidity, $1.6 < |y| < 2.4$, extending to lower p_T values, $3 < p_T < 30 \text{ GeV}/c$. The centrality-integrated double ratio changes from $0.45 \pm 0.13(\text{stat}) \pm 0.07(\text{syst})$ in the first range to $1.67 \pm 0.34(\text{stat}) \pm 0.27(\text{syst})$ in the second. This difference is most pronounced in the most central collisions.

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The goal of the study of ultrarelativistic heavy-ion collisions is to create and characterize the quark-gluon plasma, a medium where quarks and gluons are no longer confined in hadrons [1]. Charmonia should dissociate when the Debye screening radius of this medium, which decreases with increasing quark-gluon plasma temperature, becomes smaller than the binding radius of the charmonium state [2]. Since the $\psi(2S)$ meson is less bound than the J/ψ , it should melt at lower temperatures [3], an idea consistent with charmonium suppression measurements made at the CERN SPS [4,5]. At the CERN LHC, a suppression of J/ψ mesons in Pb-Pb collisions at a center-of-mass energy per nucleon-nucleon pair of $\sqrt{s_{NN}} = 2.76$ TeV was observed by CMS [6] and ALICE [7,8] via the nuclear modification factor R_{AA} , the ratio of nucleus-nucleus and p - p charmonium production yields normalized by the number of inelastic nucleon-nucleon collisions. The suppression increases with transverse momentum (p_T), exhibiting a strong centrality dependence at high p_T , but almost no dependence when integrated over p_T . Related results at the SPS and BNL RHIC are presented in Ref. [9] and references therein.

Given the large number [$\mathcal{O}(100)$] of charm quarks produced per central Pb-Pb collision at $\sqrt{s_{NN}} = 2.76$ TeV [10], charmonia may also be produced at the hadronization stage, through the combination of initially uncorrelated charm and anticharm quarks [11,12]. This mechanism should contribute mostly at low p_T [10]. Charmonium production is also affected by “cold nuclear

matter” effects [10,13,14], such as nuclear modifications of the parton distribution functions. Recently, ALICE [15] and LHCb [16] observed J/ψ suppression in p -Pb collisions, while PHENIX [17] and ALICE [18] reported that the $\psi(2S)$ is more strongly suppressed than the J/ψ in d -Au and p -Pb collisions, complementing analogous observations made by fixed-target experiments [19].

This Letter presents a measurement of the prompt $\psi(2S)$ and J/ψ yields (excluding production from decays of b hadrons) in Pb-Pb and p - p collisions at $\sqrt{s_{NN}} = 2.76$ TeV, using event samples collected by CMS with integrated luminosities of $150 \mu\text{b}^{-1}$ and 5.4 pb^{-1} , respectively. Following related studies of the bottomonium family [20–22], the results are reported as a double ratio $(N_{\psi(2S)}/N_{J/\psi})_{\text{Pb-Pb}}/(N_{\psi(2S)}/N_{J/\psi})_{p-p}$, so that efficiency and acceptance corrections cancel to a large extent, reducing the systematic uncertainties. Using a previous measurement of $R_{AA}(J/\psi)$ [6], a first measurement of $R_{AA}(\psi(2S))$ is derived.

The central feature of CMS is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the field volume are the silicon tracker, the crystal electromagnetic calorimeter, and the brass-scintillator hadron calorimeter. The silicon pixel and strip tracker measures charged-particle trajectories in the pseudorapidity range $|\eta| < 2.5$. Muons are detected in the interval $|\eta| < 2.4$ by gas-ionization detectors made of three technologies: drift tubes, cathode strip chambers, and resistive-plate chambers. The muon p_T is measured with a resolution between 1% and 2% for a typical muon in this analysis. Two steel/quartz-fibre Cherenkov hadron forward (HF) calorimeters cover the range $2.9 < |\eta| < 5.2$ and are used for event selection and Pb-Pb collision centrality determination. Two beam scintillator counters are used for triggering and beam-halo rejection. A more

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detailed description of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in Ref. [23].

The measurements reported here are based on Pb-Pb and p - p events triggered by a hardware-based dimuon trigger without an explicit muon-momentum threshold. Inelastic hadronic Pb-Pb collisions are selected using beam scintillator counter and HF information, in coincidence with a bunch crossing [23]. Events are further filtered off-line by requiring a reconstructed primary vertex and at least three towers in each HF with an energy deposit of more than 3 GeV per tower. Muons are reconstructed off-line using tracks in the muon detectors (“standalone muons”) that are then matched to tracks in the silicon tracker, using an algorithm optimized for the heavy-ion environment [24,25]. In addition, an iterative track reconstruction algorithm [26] is applied to the Pb-Pb data, limited to cone regions defined by the standalone muons. The p - p reconstruction algorithm includes an iterative tracking step in the full silicon tracker. The final parameters of the muon trajectory are obtained from a global fit of the standalone muon with a track in the silicon tracker. The single muon acceptance and identification criteria are the same as in Ref. [6]. Opposite-sign muon pairs are fitted with a common vertex constraint and are kept if the fit χ^2 probability is greater than 1%. Most of the nonprompt J/ψ and $\psi(2S)$ mesons, originating from b -hadron decays, are rejected using the pseudoproper decay length $\ell_\psi = L_{xy} m_\psi / p_T$, where L_{xy} is the transverse distance between the $\mu^+\mu^-$ vertex and the interaction point and m_ψ is the J/ψ or $\psi(2S)$ mass. The ℓ_ψ selection condition is tuned with Monte Carlo (MC) simulation studies, separately for the p - p and Pb-Pb collision systems, such that 90% of the prompt J/ψ and $\psi(2S)$ is kept, typically rejecting 80% of the nonprompt ones. For these studies, unpolarized prompt and nonprompt J/ψ and $\psi(2S)$ mesons are generated with PYTHIA 6.424 [27] and decayed with EVTGEN [28], while the final-state bremsstrahlung is simulated with PHOTOS [29]. The signal events are embedded in underlying heavy-ion events, generated with HYDJET 1.8 [30], at the level of detector hits and with matching vertices. The detector response is simulated with GEANT4 [31] and the resulting information is processed through the full event reconstruction chain, including trigger emulation. The selection efficiency cancels in the double ratio and the remaining nonprompt contamination is accounted for as a systematic uncertainty.

The analysis is performed in two dimuon kinematic domains: the “midrapidity” domain covers the range $|y| < 1.6$, where the J/ψ and $\psi(2S)$ mesons are only reconstructed for $p_T > 6.5$ GeV/ c , while the “forward rapidity” domain covers the range $1.6 < |y| < 2.4$, where the acceptance extends down to $p_T = 3$ GeV/ c . Dimuons are restricted to $p_T < 30$ GeV/ c in order to have a well defined kinematic interval. The available Pb-Pb data at forward rapidity could not be fitted reliably when split

into the intervals $3 < p_T < 6.5$ GeV/ c and $6.5 < p_T < 30$ GeV/ c . Therefore, this analysis cannot differentiate between p_T and rapidity dependent effects on the measured double ratios. The Pb-Pb sample is split in three bins of collision centrality, defined using fractions of the inelastic hadronic cross section where 0% denotes the most central collisions: 40%–100%, 20%–40%, and 0%–20%. This fraction is determined from the HF energy distribution [32]. Related variables, such as the number of nucleons participating in the collision (N_{part}), are evaluated using a Glauber-model calculation [33] and are only used to display the centrality dependence of the measurements. The average N_{part} values corresponding to the three centrality bins above are $\langle N_{\text{part}} \rangle = 32.8, 158.7$, and 308.4, respectively.

Figure 1 shows the dimuon invariant-mass ($m_{\mu^+\mu^-}$) distributions measured in central (0%–20%) Pb-Pb and p - p collisions, for the midrapidity and forward rapidity bins. The results of unbinned maximum likelihood fits are also shown. Each charmonium resonance is described by the sum of a Gaussian function and a Crystal Ball (CB) function [34], with common mean m_0 , independent widths σ_G and σ_{CB} , and relative contribution of the Gaussian to the signal yield f_G . In all cases, the fitted J/ψ mean agrees within 0.3% with the world average [35]. The resolution, after averaging the Gaussian and CB widths, is about 30 MeV/ c^2 at midrapidity and 50 MeV/ c^2 at forward rapidity, both for p - p and Pb-Pb data. The CB radiative tail parameters α and n , common to both charmonia, are fixed to the values obtained in fits to simulated distributions. The m_0 , σ_G , and σ_{CB} parameters of the $\psi(2S)$ resonance shape match the J/ψ parameters, scaled by the ratio of their masses, $m_{\psi(2S)}/m_{J/\psi}$ [35]. This scaling assumption has been validated in analyses of larger event samples [21,36]. The same value for f_G is used in the definition of the $\psi(2S)$ and J/ψ signal shapes. Six parameters are left free in the p - p fit: m_0 , σ_G , σ_{CB} , f_G , the J/ψ yield, and the $\psi(2S)$ to J/ψ yield ratio. In the Pb-Pb fits, instead, the double ratio replaces the $\psi(2S)$ to J/ψ ratio as one of the free parameters. In addition, given their smaller signal-to-background ratio, the Pb-Pb data are fitted fixing the $\sigma_G/\sigma_{\text{CB}}$ ratio to the value obtained in fits to MC distributions.

The background is described by Chebyshev polynomials, of order ($0 \leq N \leq 3$) determined for each analysis bin with log-likelihood ratio tests. The background shape is mostly determined by the kinematic distributions of the muons produced in meson decays, which are expected to change with collision centrality [6,37,38]. Once the background functions are selected, the p - p and three Pb-Pb centrality samples are fitted simultaneously. Since the signal shape does not depend on the collision centrality [6], the three Pb-Pb centrality bins are fitted with common signal shape parameters, which are independent of the p - p values; the four background shapes are independent. The simultaneous fit directly provides the three double ratios (one per centrality class) for each rapidity interval.

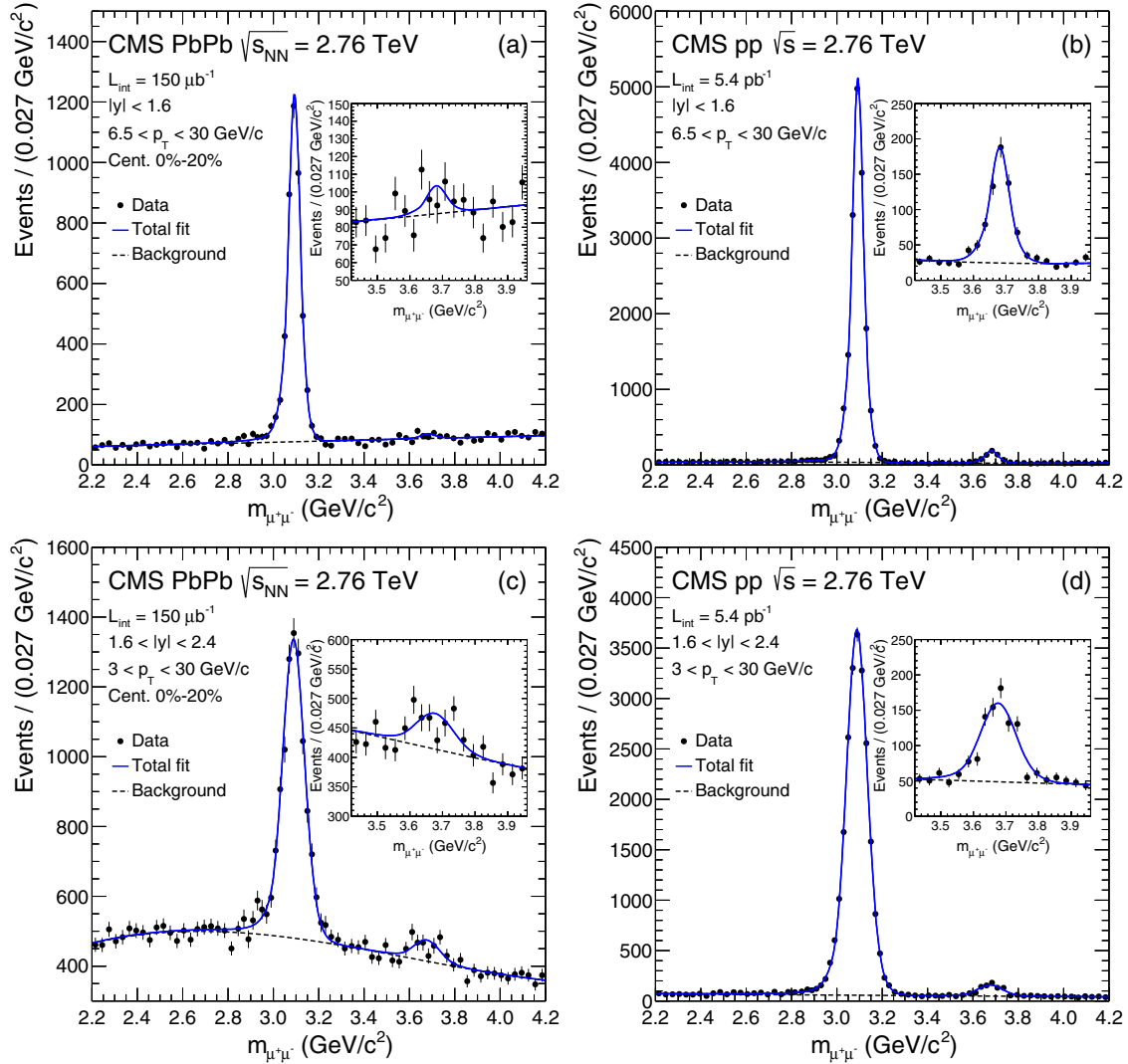


FIG. 1 (color online). Dimuon invariant-mass distributions measured in central Pb-Pb (left) and p - p (right) collisions, for $|y| < 1.6$ and $6.5 < p_T < 30$ GeV/c (top) as well as $1.6 < |y| < 2.4$ and $3 < p_T < 30$ GeV/c (bottom). The results of unbinned maximum likelihood fits are also shown. The $\psi(2S)$ region is magnified in the insets.

The systematic uncertainties from the fitting method are studied by varying the signal and background shapes as well as the fitted invariant-mass range. As an alternative signal shape, the sum of two CB functions with common mean and tail parameters is used, leaving all parameters free in the fit except for the mass scaling between the J/ψ and $\psi(2S)$ means and widths. The uncertainty on the background is evaluated by considering three fit variations: (i) use as background shape an exponential function with a Chebyshev polynomial of order $1 \leq N \leq 3$ (determined with a log-likelihood ratio test) as an argument; (ii) extend the fitted mass region to $1.8 < m_{\mu^+\mu^-} < 5$ GeV/c²; (iii) fit the J/ψ and $\psi(2S)$ regions (below 3.5 GeV/c² and above 3.3 GeV/c², respectively) with independent background functions. The maximum deviation from the nominal fit is added in quadrature with the signal shape uncertainty to obtain the fit systematic uncertainty in the double ratio,

which varies between 8% at midrapidity and 28% at forward rapidity. The dominant contribution to this uncertainty changes from bin to bin because of the strongly varying signal-to-background ratio. A cross-check made on the centrality-integrated sample shows that counting the signal yields above a polynomial exclusively fitted to the sidebands gives a result consistent with the nominal values.

Assuming no change in their polarizations, the J/ψ and $\psi(2S)$ acceptances are independent of the collision system and cancel in the double ratio. Residual effects from imperfect double-ratio cancellations of the muon reconstruction and trigger efficiency corrections have been evaluated with MC simulation studies. The MC double ratio of the signal efficiencies is compatible with unity. The MC statistical uncertainties, 1% at midrapidity and 5% at forward rapidity, are assigned as the systematic uncertainties on the assumption that the efficiency corrections

cancel. Differences between the MC and data distributions [6] have a negligible impact on the efficiency double ratio. The same charmonium p_T and rapidity distributions have been used in the generation of p - p and Pb-Pb events. The efficiency double ratio varies by less than 1% when changing the kinematic distributions in Pb-Pb events within a reasonable range, evaluated using R_{AA} measurements as a function of p_T and rapidity [6].

The prompt charmonia are simulated unpolarized, a scenario in good agreement with p - p measurements [39–41]. Alternative scenarios have been considered, where the polarizations change significantly from the J/ψ to the $\psi(2S)$ and/or from p - p to Pb-Pb collisions. The impact is completely negligible on the double ratio of the measurement efficiencies, while the double ratio of the acceptances can change by $\approx 20\%$. As in previous analyses [20–22], such possible physics effects are not considered as systematic uncertainties.

In p - p collisions, around 20%–25% of the charmonium yields are due to b -hadron decays [36]; no evidence for different values has been seen in Pb-Pb collisions [6]. Considering a b -hadron rejection inefficiency of about 20%, the prompt J/ψ and $\psi(2S)$ yields include a residual contamination from b -hadron decays of up to 5%. These b -hadron contaminations are conservatively assumed to be independent in the four yields entering the double ratio.

Adding in quadrature the uncertainties mentioned above leads to total systematic uncertainties of 13%–30%, values smaller than the corresponding statistical uncertainties.

The double ratio of measured yields $(N_{\psi(2S)}/N_{J/\psi})_{\text{Pb-Pb}}/(N_{\psi(2S)}/N_{J/\psi})_{p-p}$ is shown in Fig. 2 as a function of centrality, for both kinematic bins. The quadratic sum of the p - p statistical and systematic uncertainties ($\approx 6\%$) is common to all centralities. The centrality-integrated results are also displayed, in the right panel of Fig. 2. In the most peripheral Pb-Pb collisions, no significant $\psi(2S)$ signal has been observed in the midrapidity bin and an upper limit of 0.47 at 95% confidence level (C.L.) is set on the double ratio, using the Feldman-Cousins method [42].

In the midrapidity bin, restricted to $p_T > 6.5$ GeV/ c , the double ratio is below unity in all centrality bins, with a centrality-integrated value of $0.45 \pm 0.13(\text{stat}) \pm 0.07(\text{syst})$, including the global p - p uncertainties. In the forward rapidity bin, which extends down to $p_T = 3$ GeV/ c , the centrality-integrated double ratio increases to $1.67 \pm 0.34(\text{stat}) \pm 0.27(\text{syst})$. While the forward-rapidity double ratio is consistent with unity in peripheral Pb-Pb collisions, it becomes $2.31 \pm 0.53(\text{stat}) \pm 0.37(\text{syst}) \pm 0.15(\text{pp})$ in the 20% most central collisions, indicating that the $\psi(2S)$ to J/ψ yield ratio is enhanced in central Pb-Pb collisions with respect to p - p collisions (the hypothesis of being compatible with unity has a p value of only 0.011).

Nuclear modification factors for prompt $\psi(2S)$ production, $R_{AA}(\psi(2S))$, can be derived by multiplying the

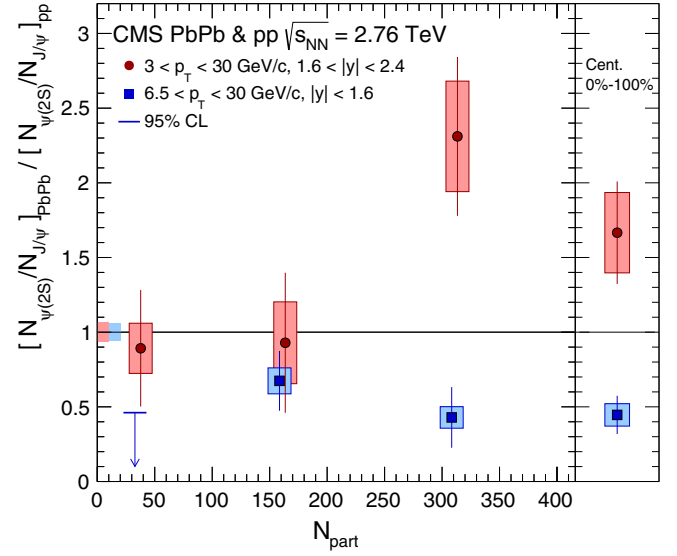


FIG. 2 (color online). Double ratio of measured yields $(N_{\psi(2S)}/N_{J/\psi})_{\text{Pb-Pb}}/(N_{\psi(2S)}/N_{J/\psi})_{p-p}$ as a function of centrality, for the midrapidity (blue squares) and forward rapidity (red circles, slightly shifted) analysis bins. The centrality-integrated results are displayed in the right panel. Statistical (systematic) uncertainties are shown as bars (boxes). The boxes at unity indicate the (global) p - p uncertainties.

centrality-integrated double ratios by the corresponding prompt J/ψ R_{AA} , which can be found in Ref. [6]. The resulting centrality-integrated R_{AA} values for $\psi(2S)$ are $0.13 \pm 0.04(\text{stat}) \pm 0.02(\text{syst}) \pm 0.01(p-p)$ at midrapidity and $0.67 \pm 0.16(\text{stat}) \pm 0.11(\text{syst}) \pm 0.07(p-p)$ at forward rapidity. While the $\psi(2S)/(J/\psi)$ ratio at low p_T (forward rapidity) is enhanced in central Pb-Pb collisions, as compared to p - p collisions, the yield of $\psi(2S)$ itself in Pb-Pb collisions is still suppressed in comparison to the yield in p - p collisions scaled by the number of inelastic nucleon-nucleon collisions.

In summary, the CMS measurements reported in this Letter show two interesting observations. First, $\psi(2S)$ production is suppressed in Pb-Pb collisions with respect to p - p collisions, in both kinematic regions investigated. Second, in comparison to J/ψ production and in the most central Pb-Pb collisions, $\psi(2S)$ production is suppressed in the range $|y| < 1.6$ and $6.5 < p_T < 30$ GeV/ c , as expected in the sequential melting scenario and matching the corresponding bottomonia pattern [21], while it is enhanced in the range $1.6 < |y| < 2.4$ and $3 < p_T < 30$ GeV/ c . Such behavior implies the presence of physics processes that either cause the p_T dependence of $R_{AA}(\psi(2S))$ to be weaker than for the $R_{AA}(J/\psi)$ or cause the $R_{AA}(\psi(2S))$ to start decreasing at higher p_T . Alternatively, these processes would have to have the opposite dependence with increasing rapidity. Larger event samples are needed to evaluate in more detail how these observations depend separately on the p_T and rapidity of the charmonium states.

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