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Relative modification of prompt $\psi(2S)$ and J/ψ yields from pp to PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV

The CMS Collaboration*

Abstract

The relative modification of the prompt ψ(2S) and J/ψ yields from pp to PbPb collisions, at the center of mass energy of 5.02 TeV per nucleon pair, is presented. The analysis is based on pp and PbPb data samples collected by the CMS experiment at the LHC in 2015, corresponding to integrated luminosities of 28.0 pb^{-1} and 464 μb^{-1}, respectively. The double ratio of measured yields of prompt charmonia reconstructed through their decays into muon pairs, $(N_{\psi(2S)}/N_{J/\psi})_{PbPb}/(N_{\psi(2S)}/N_{J/\psi})_{pp}$, is determined as a function of PbPb collision centrality and charmonium transverse momentum p_T, in two kinematic intervals: $|y| < 1.6$ covering $6.5 < p_T < 30$ GeV/c and $1.6 < |y| < 2.4$ covering $3 < p_T < 30$ GeV/c. The centrality-integrated double ratios are 0.36 ± 0.08 (stat) ± 0.05 (syst) in the first interval and 0.24 ± 0.22 (stat) ± 0.09 (syst) in the second. The double ratio is lower than unity in all the measured bins, suggesting that the ψ(2S) yield is more suppressed than the J/ψ yield in the explored phase space.

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*See Appendix B for the list of collaboration members

Quarkonium production is expected to be significantly influenced by the formation of a quark-gluon plasma (QGP) in heavy ion collisions, thereby providing an important probe of the QGP properties. While the early-formed mesons propagate through the medium and probe its space-time evolution, the overall production rates can also reflect later production mechanisms. The suppression of charmonium production due to Debye screening of the color charges in the plasma was proposed 30 years ago [1]. The J/ψ suppression observed in PbPb collisions at the SPS by NA50 [2] and in AuAu collisions at RHIC by PHENIX [3] is compatible with this picture. Another effect, referred to as regeneration, might be at work at sufficiently high energy: uncorrelated charm quarks and antiquarks may coalesce in the medium to form a bound charmonium state, leading to an enhanced production in heavy ion collisions [4, 5]. Hints of the latter were found at the LHC in recent results from ALICE [6, 7], which measured a weaker J/ψ meson suppression than at RHIC, especially at low p_T.

The study of the modification of the excited $\psi(2S)$ state is of particular interest. The strength of medium effects on its production might be significantly different from that of the J/ψ because of the larger size and weaker binding of the $\psi(2S)$ state. The smaller binding energy should make it easier for the $\psi(2S)$ to dissociate in the medium, leading to sequential melting [8]. However, the smaller production cross section and branching fraction to dimuons make the $\psi(2S)$ less accessible experimentally than the J/ψ, especially when a large background is present, such as in heavy ion collisions. At the SPS fixed-target facility, the $\psi(2S)$ production in heavy ion collisions was seen to be more suppressed than the J/ψ by NA38 [9], NA50 [10], and NA60 [11], in sulphur-uranium, lead-lead, and indium-indium collisions, respectively.

A useful variable to compare the strength of medium effects on the J/ψ and $\psi(2S)$ in PbPb collisions is the double ratio $(N_{\psi(2S)}/N_{J/\psi})_{PbPb}/(N_{\psi(2S)}/N_{J/\psi})_{pp}$, which is the ratio of the corresponding nuclear modification factors. While Debye screening in the hot medium should make the double ratio smaller than unity, the presence of regeneration effects could make it exceed unity, especially at low p_T, if uncorrelated quark coalescence produces $\psi(2S)$ mesons more frequently than J/ψ mesons [12]. The double ratio allows for the partial to total cancellation of corrections (including acceptance, efficiency, and integrated luminosity) and their associated uncertainties. The CMS measurement of the prompt charmonium double ratio at a center-of-mass energy per nucleon pair of $\sqrt{s_{NN}} = 2.76\,\text{TeV}$ [13] showed that the $\psi(2S)$ is more suppressed than the J/ψ at midrapidity and high transverse momentum ($|y| < 1.6$, $6.5 < p_T < 30\,\text{GeV}/c$), while at more forward rapidity and intermediate p_T ($1.6 < |y| < 2.4$, $3 < p_T < 30\,\text{GeV}/c$), a smaller suppression of the $\psi(2S)$ than the J/ψ was favored. This behavior could be reproduced by introducing a different time dependence of the J/ψ and $\psi(2S)$ regeneration processes. A similar measurement from the ALICE experiment [14], integrated over p_T and at forward rapidity ($2.5 < y < 4$), favored the $\psi(2S)$ to be more suppressed than the J/ψ, as expected in other models [15, 16].

In this Letter, we report a new study of J/ψ and $\psi(2S)$ relative production in pp and PbPb data collected with the CMS experiment at the CERN LHC in 2015, at $\sqrt{s_{NN}} = 5.02\,\text{TeV}$. The larger integrated luminosities allow for a more precise and differential measurement of the double ratio as a function of centrality and, for the first time, as a function of the charmonium p_T.

The central feature of the CMS apparatus is a superconducting solenoid of 6 m internal diameter, providing a magnetic field of 3.8 T. Within the solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter, each composed of a barrel and two endcap sections. Forward calorimeters extend the coverage provided by the barrel and endcap detectors. Muons are measured in the pseudorapidity range $|\eta| < 2.4$ in gas-ionization detectors embedded in the steel flux-return yoke outside the solenoid, with detection planes made using three technologies: drift tubes, cathode strip chambers, and resistive plate chambers. Matching muons to tracks measured in the silicon tracker leads to a relative transverse momentum resolution between 1 and 2% for a typical muon in this analysis [17]. A more 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. [18].

Hadronic collisions are selected using information from the forward hadron calorimeters (HF), covering $2.9 < |\eta| < 5.2$, in coincidence with a bunch crossing identified by beam pick-up timing detectors. A primary vertex reconstructed with at least two tracks is also required. In addition, a filter is applied on the compatibility of the silicon pixel cluster width distribution and the vertex position. For PbPb collisions only, at least three towers above 3 GeV are requested in the HF on each side of the interaction point. Centrality is defined using fractions of the inelastic hadronic cross section determined from the HF distributions, with 0% denoting the most central collisions [19].

The integrated luminosities are $28.0\,\mathrm{pb}^{-1}$ for pp data and $464\,\mu\mathrm{b}^{-1}$ for PbPb data. The dimuon ratios reported in this paper are unaffected by the small number of extra collisions potentially present in the collected events: the average mean of the Poisson distribution of the number of collisions per bunch crossing (pileup) is approximately 0.9 for the pp data and much smaller for the PbPb data. Dimuon events are selected by the level-1 trigger system, with no explicit muon momentum threshold. The 0–30% most central events have a prescale needed to reduce their high trigger rates, corresponding to an effective luminosity of $351\,\mu\mathrm{b}^{-1}$.

Simulated events are used to tune the muon selection criteria and the signal fitting parameters, as well as for acceptance and efficiency studies. These Monte Carlo (MC) samples, produced using PYTHIA 8.209 [20], are embedded in a realistic PbPb background event generated with HYDJET 1.9 [21] and propagated through the CMS detector with GEANT4 [22]. These events are processed through the trigger emulation and the event reconstruction chain.

The muon reconstruction algorithm starts by finding tracks in the muon detectors, which are then fitted together with tracks reconstructed in the silicon tracker. Kinematic limits are imposed on the single muons so that their reconstruction efficiency stays above 10%. These limits are $p_{\mathrm{T}}^{\mu} > 3.5\,\mathrm{GeV}/c$ for $|\eta^{\mu}| < 1.2$, $p_{\mathrm{T}}^{\mu} > 1.8\,\mathrm{GeV}/c$ for $2.1 < |\eta^{\mu}| < 2.4$, and linearly interpolated in the intermediate $|\eta^{\mu}|$ region. The muons are required to match those used online by the dimuon trigger, to be of opposite charge, and to survive standard quality selection criteria [17]. In order to remove cosmic-ray muons, the transverse and longitudinal distances of closest approach between the muon trajectory and the reconstructed primary vertex are required to be less than 0.3 cm and 20 cm, respectively. The probability that the two muon tracks originate from a common vertex is required to be larger than 1%.

Nonprompt charmonia, originating from the decays of B mesons, are resolved using the pseudo-proper decay length $\ell_{\mathrm{J}/\psi}^{\mathrm{3D}} = c\, L_{xyz}\, m_{\mathrm{J}/\psi}/|p_{\mu\mu}|$, where L_{xyz} is the distance between the primary and dimuon vertices, $m_{\mathrm{J}/\psi}$ the mass of the J/ψ meson (assumed for all dimuon candidates), and $p_{\mu\mu}$ the dimuon momentum. Dimuons are discarded if their $\ell_{\mathrm{J}/\psi}^{\mathrm{3D}}$ is larger than a l_0 threshold, computed using MC simulations to keep 90% of the prompt J/ψ. Since the $\ell_{\mathrm{J}/\psi}^{\mathrm{3D}}$ resolution improves with increasing dimuon p_{T}, from $\approx$100 μm to $\approx$20 μm in this analysis, the l_0 cut values also depend on p_{T}. This selection removes more than 80% of the nonprompt J/ψ. The double ratio of prompt charmonia is deduced from the double ratio of charmonia passing the $\ell_{\mathrm{J}/\psi}^{\mathrm{3D}}$ selection. This is accomplished taking into account the $\ell_{\mathrm{J}/\psi}^{\mathrm{3D}}$ selection efficiencies for prompt (ϵ_P) and nonprompt (ϵ_{NP}) charmonia, both estimated from simulation studies. The contamination from nonprompt charmonia is also accounted for, using dimuons failing the $\ell^{3D}_{J/\psi}$ selection: $f_P = (f_{\text{pass}} - \epsilon_{NP})/(\epsilon_P - \epsilon_{NP})$, with f_P the fraction of prompt charmonia and f_{pass} the fraction of charmonia passing the $\ell^{3D}_{J/\psi}$ selection. This correction changes the double ratio by less than 0.09.

The $\psi(2S)$ to J/ψ yield ratios, $N_{\psi(2S)}/N_{J/\psi}$, are extracted in pp and PbPb collisions from unbinned maximum extended likelihood fits of the $\mu^+\mu^-$ invariant mass distributions in the region $2.2 < m_{\mu^+\mu^-} < 4.5\,\text{GeV}/c^2$. The analysis is carried out differentially in charmonium p_T and event centrality, as well as integrated over these variables, for two kinematic ranges: $|y| < 1.6$, $6.5 < p_T < 30\,\text{GeV}/c$ and $1.6 < |y| < 2.4$, $3 < p_T < 30\,\text{GeV}/c$. The different lower p_T thresholds reflect the detector acceptance.

The sum of two Crystal Ball (CB) functions [23], with different widths but common mean and tail parameters, is used to extract the nominal yield ratios in pp and PbPb data. The J/ψ resonance shape parameters are fixed to the values obtained from simulation. The $\psi(2S)$ and the J/ψ parameters are identical, apart from the mean and width which are both multiplied by the meson mass ratio. The background is described by a polynomial of order N, where N is the lowest value that provides a good description of the data and is determined in each analysis bin by performing a log-likelihood ratio (LLR) test between polynomials of different orders, while keeping the signal parameters fixed; it is never larger than 3.

Integrated over centrality and p_T, the fits yield about 38 000 (293 000) J/ψ and 530 (11 200) $\psi(2S)$ mesons in PbPb (pp) collisions. Examples of such fits for the PbPb data are shown in Fig. 1, for two cases of very different $\psi(2S)$ signal-to-background ratios.

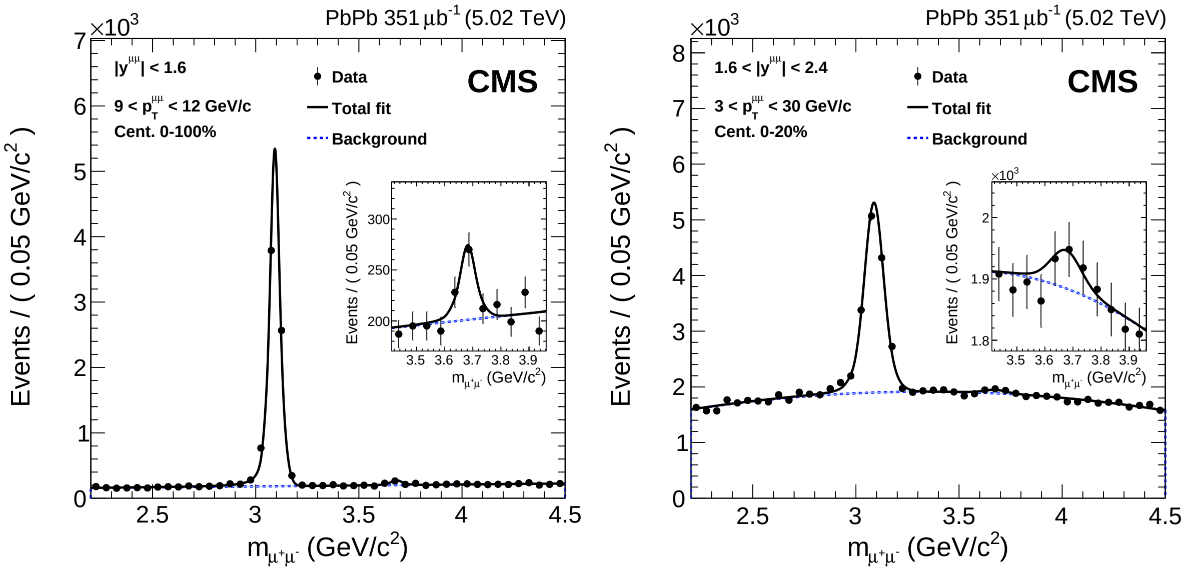

Figure 1: Invariant mass spectrum of $\mu^+\mu^-$ pairs (restricting to the $\psi(2S)$ region in the insets) in PbPb collisions for (left) $|y| < 1.6$, $9 < p_T < 12\,\text{GeV}/c$, all centrality, and (right) $1.6 < |y| < 2.4$, $3 < p_T < 30\,\text{GeV}/c$, 0–20% centrality. The results of the fits described in the text are also shown.

The systematic uncertainties arise from the signal and background fitting model assumptions, the imperfect efficiency cancellation, and the nonprompt residual contamination. These uncertainties are derived separately for pp and PbPb data, and the total systematic uncertainty is computed as the quadratic sum of the partial terms.

In order to determine the uncertainty associated with the fitting procedure, the signal and background models are independently varied in each analysis bin. For the signal, the fixed parameters are released one by one. As a further test, the signal parameters are fixed to the values obtained from a $\psi(2S)$ simulation, instead of the J/ψ simulation. A different signal shape is also tried: a CB function plus a Gaussian function. For the background model, the fitted mass range is varied and an exponential of a polynomial is used, redoing LLR tests to choose the best order for the polynomial in each analysis bin. The maximum difference of the single ratio $N(\psi(2S))/N(J/\psi)$ between the nominal and alternative fits, performed for signal and background separately, is taken as the corresponding systematic uncertainty. These uncertainties depend crucially on the signal-to-background ratio in the $\psi(2S)$ region. In units of the double ratio, the uncertainties remain below 0.02 and 0.11 for the pp and PbPb contributions, respectively.

The nonprompt J/ψ and $\psi(2S)$ fractions in pp collisions, as well as the J/ψ fraction in PbPb collisions, are validated with two-dimensional fits to the dimuon mass and pseudo-proper decay length distributions [24]. The PbPb event sample does not have enough $\psi(2S)$ events to provide a reliable two-dimensional fit. The variation in the double ratio when using nonprompt fractions from the two-dimensional fits is taken as a systematic uncertainty, never exceeding 0.07.

Finally, residual noncancellations of efficiencies in the double ratio are evaluated with MC studies, considering a broad range of p_T spectra compatible with the pp and PbPb data within their uncertainties. The corresponding systematic uncertainty varies between 0.01 and 0.05, with the exception of the lowest p_T bin, where it reaches 0.10. If the quarkonium acceptances were different in pp and PbPb, they would not perfectly cancel in the double ratio. This would be the case if some physics effects (such as polarization or energy loss) would affect quarkonia in PbPb collisions with a strong kinematic dependence within an analysis bin. As in previous analyses [13, 25–27], such possible effects are considered as part of the physics under study and not as systematic uncertainties.

The measured double ratio is shown in Figs. 2 and 3 as a function of p_T and event centrality, respectively. Centrality is commonly represented by the average number of participating nucleons, $\langle N_{part} \rangle$, computed with the Glauber model [28]. In terms of centrality percentiles, the bins correspond to 0–10, 10–20, 20–30, 30–40, 40–50, and 50–100% in the midrapidity region, and 0–20, 20–40, and 40–100% for the forward rapidity region. The most “peripheral” bins are rather wide and, since quarkonium yields scale with the number of nucleon-nucleon collisions, most charmonia are produced close to the most central edge of the bins. The $\langle N_{part} \rangle$ values used in the following are computed for events following a flat centrality distribution. When the measured double ratio is consistent with zero within one standard deviation of its statistical uncertainty, its corresponding 95% confidence level (CL) interval is computed, using the Feldman–Cousins procedure [29]. The numerical values of all measurements, including the 95% CL intervals, are tabulated in Appendix A.

The rightmost panels in Fig. 3 show the double ratio integrated over p_T and centrality: $0.36 \pm 0.08\,(\text{stat}) \pm 0.05\,(\text{syst})$ in the $|y| < 1.6$ and $6.5 < p_T < 30\,\text{GeV}/c$ range, and $0.24 \pm 0.22\,(\text{stat}) \pm 0.09\,(\text{syst})$ in the $1.6 < |y| < 2.4$ and $3 < p_T < 30\,\text{GeV}/c$ range.

The double ratios measured at 5.02 TeV and reported in this paper are below unity in all bins. Assuming that the J/ψ is suppressed in PbPb collisions at $\sqrt{s_{NN}} = 5.02\,\text{TeV}$, as suggested by results at lower energy in the same kinematic range by CMS [24] or at both energies but in a different rapidity range by ALICE [6, 7], the $\psi(2S)$ is more suppressed than the J/ψ in PbPb collisions. This difference in suppression is already present in the most peripheral ranges probed by this analysis, starting at 40 or 50% centrality. No strong dependencies are observed with centrality or transverse momentum.

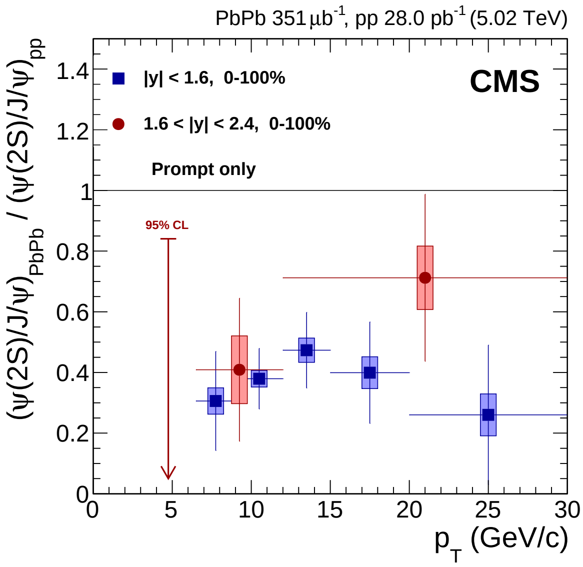

Figure 2: Transverse momentum dependence of $(N_{\psi(2S)}/N_{J/\psi})_{PbPb}/(N_{\psi(2S)}/N_{J/\psi})_{pp}$, for mid (squares) and forward (circles) rapidity, with both muons above the p_T threshold described in the text. The arrow represents the 95% CL interval in the bin where the measurement is consistent with 0. The vertical lines (boxes) represent the statistical (systematic) uncertainties. The horizontal lines represent the width of the p_T bins.

In Fig. 3, a reasonable agreement with the measurement made at $\sqrt{s_{NN}} = 2.76\,\text{TeV}$ can be seen in most of the bins. In the range $1.6 < |y| < 2.4$ and $3 < p_T < 30\,\text{GeV}/c$, the double ratios are consistently lower in the 5.02 TeV data, especially in the most central collisions. The difference is at the level of around 3 standard deviations in the centrality-integrated sample.

In summary, the double ratio $(N_{\psi(2S)}/N_{J/\psi})_{PbPb}/(N_{\psi(2S)}/N_{J/\psi})_{pp}$ was measured to compare the relative production of J/ψ and $\psi(2S)$ mesons in pp and PbPb collisions at $\sqrt{s_{NN}} = 5.02\,\text{TeV}$, as a function of transverse momentum and collision centrality. The double ratio is below unity in all bins, suggesting that the $\psi(2S)$ yield is more suppressed than the J/ψ yield in the kinematic range explored. The 5.02 TeV data do not show the enhancement in the double ratio previously seen for collisions at 2.76 TeV in the $1.6 < |y| < 2.4$ and $3 < p_T < 30\,\text{GeV}/c$ range. No strong variations are observed with charmonium p_T or collision centrality. These results should significantly contribute to a deeper understanding of the medium effects influencing in J/ψ and $\psi(2S)$ production.

We congratulate our colleagues in the CERN accelerator departments for the excellent performance of the LHC and thank the technical and administrative staffs at CERN and at other CMS institutes for their contributions to the success of the CMS effort. In addition, we gratefully acknowledge the computing centers and personnel of the Worldwide LHC Computing Grid for delivering so effectively the computing infrastructure essential to our analyses. Finally, we acknowledge the enduring support for the construction and operation of the LHC and the CMS detector provided by the following funding agencies: BMWFW and FWF (Austria); FNRS and FWO (Belgium); CNPq, CAPES, FAPERJ, and FAPESP (Brazil); MES (Bulgaria); CERN; CAS, MoST, and NSFC (China); COLCIENCIAS (Colombia); MSES and CSF (Croatia); RPF (Cyprus); SENESCYT (Ecuador); MoER, ERC IUT, and ERDF (Estonia); Academy of Finland, MEC, and HIP (Finland); CEA and CNRS/IN2P3 (France); BMBF, DFG, and HGF (Germany); GSRT (Greece); OTKA and NIH (Hungary); DAE and DST (India); IPM (Iran); SFI (Ireland); INFN (Italy); MSIP and NRF (Republic of Korea); LAS (Lithuania); MOE

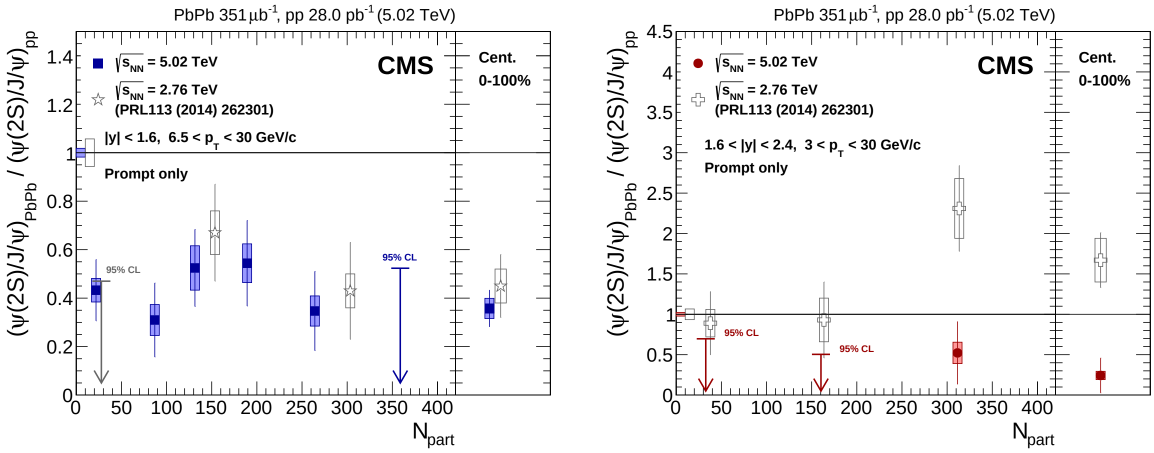

Figure 3: Event centrality dependence of $(N_{\psi(2S)}/N_{J/\psi})_{PbPb}/(N_{\psi(2S)}/N_{J/\psi})_{pp}$, for mid (left) and forward (right) rapidity, with both muons above the p_T threshold described in the text. Values for the centrality-integrated sample are given in the right panels. The arrows represent 95% CL intervals in the bins where the measurement is consistent with 0. The vertical lines (boxes) represent the statistical (systematic) uncertainties. The statistical and systematic uncertainties in the pp measurements, common to all points, are represented as boxes at unity. The measurements from CMS at $\sqrt{s_{NN}} = 2.76$ TeV [13] are also shown.

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A Supplementary information

The numerical values of all measurements, including the 95% CL intervals, are summarized in Tables 1 and 2.

Table 1: Transverse momentum dependence of the double ratio $(N_{\psi(2S)}/N_{J/\psi})_{PbPb}/(N_{\psi(2S)}/N_{J/\psi})_{pp}$, for mid-rapidity ($|y| < 1.6$) and forward rapidity ($1.6 < |y| < 2.4$), with both muons within the CMS acceptance. The 95% CL intervals are also given.

p_T (GeV/c)	$(N_{\psi(2S)}/N_{J/\psi})_{PbPb}/(N_{\psi(2S)}/N_{J/\psi})_{pp}$	95% CL interval
	$\|y\| < 1.6$	
6.5–9	$0.31 \pm 0.16\,(\text{stat}) \pm 0.04\,(\text{syst})$	$[0.01, 0.65]$
9–12	$0.38 \pm 0.10\,(\text{stat}) \pm 0.03\,(\text{syst})$	$[0.18, 0.59]$
12–15	$0.47 \pm 0.13\,(\text{stat}) \pm 0.04\,(\text{syst})$	$[0.23, 0.75]$
15–20	$0.40 \pm 0.17\,(\text{stat}) \pm 0.05\,(\text{syst})$	$[0.08, 0.78]$
20–30	$0.26 \pm 0.23\,(\text{stat}) \pm 0.07\,(\text{syst})$	$[0, 0.81]$
	$1.6 < \|y\| < 2.4$	
3–6.5	$0.15 \pm 0.37\,(\text{stat}) \pm 0.06\,(\text{syst})$	$[0, 0.84]$
6.5–12	$0.41 \pm 0.24\,(\text{stat}) \pm 0.11\,(\text{syst})$	$[0, 0.89]$
12–30	$0.71 \pm 0.28\,(\text{stat}) \pm 0.11\,(\text{syst})$	$[0.17, 1.34]$

Table 2: Event centrality dependence of the double ratio $(N_{\psi(2S)}/N_{J/\psi})_{PbPb}/(N_{\psi(2S)}/N_{J/\psi})_{pp}$, for two kinematic ranges, with both muons within the CMS acceptance. The 95% CL intervals are also given.

Centrality	N_{part}	$(N_{\psi(2S)}/N_{J/\psi})_{PbPb}/(N_{\psi(2S)}/N_{J/\psi})_{pp}$	95% CL interval
		$\lvert y\rvert < 1.6$, $6.5 < p_T < 30\,GeV/c$	
0–100%	114 ± 8	$0.36 \pm 0.08\,(stat) \pm 0.05\,(syst)$	$[0.18, 0.54]$
0–10%	359 ± 2	$0.14 \pm 0.17\,(stat) \pm 0.11\,(syst)$	$[0, 0.55]$
10–20%	264 ± 2	$0.35 \pm 0.16\,(stat) \pm 0.07\,(syst)$	$[0.01, 0.70]$
20–30%	189 ± 4	$0.54 \pm 0.18\,(stat) \pm 0.08\,(syst)$	$[0.17, 0.93]$
30–40%	131 ± 4	$0.53 \pm 0.16\,(stat) \pm 0.09\,(syst)$	$[0.18, 0.89]$
40–50%	87 ± 3	$0.31 \pm 0.15\,(stat) \pm 0.08\,(syst)$	$[0, 0.58]$
50–100%	22 ± 1	$0.43 \pm 0.13\,(stat) \pm 0.06\,(syst)$	$[0.17, 0.72]$
		$1.6 < \lvert y\rvert < 2.4$, $3 < p_T < 30\,GeV/c$	
0–100%	114 ± 8	$0.24 \pm 0.22\,(stat) \pm 0.09\,(syst)$	$[0, 0.67]$
0–20%	312 ± 2	$0.52 \pm 0.39\,(stat) \pm 0.15\,(syst)$	$[0, 1.30]$
20–40%	160 ± 3	$-0.14 \pm 0.34\,(stat) \pm 0.10\,(syst)$	$[0, 0.52]$
40–100%	33 ± 3	$0.22 \pm 0.25\,(stat) \pm 0.10\,(syst)$	$[0, 0.72]$

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