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Measurement of prompt ψ(2S) production cross sections in proton–lead and proton–proton collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$

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ABSTRACT

Measurements of prompt ψ(2S) meson production cross sections in proton–lead (pPb) and proton–proton (pp) collisions at a nucleon–nucleon center-of-mass energy of $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ are reported. The results are based on pPb and pp data collected by the CMS experiment at the LHC, corresponding to integrated luminosities of $34.6\,\mathrm{nb}^{-1}$ and $28.0\,\mathrm{pb}^{-1}$, respectively. The nuclear modification factor R_{pPb} is measured for prompt ψ(2S) in the transverse momentum range $4 < p_{\mathrm{T}} < 30\,\mathrm{GeV}/c$ and the center-of-mass rapidity range $-2.4 < y_{\mathrm{CM}} < 1.93$. The results on ψ(2S) R_{pPb} are compared to the corresponding modification factor for prompt J/ψ mesons. The results point to different nuclear effects at play in the production of the excited charmonium state compared to the ground state, in the region of backward rapidity and for $p_{\mathrm{T}} < 10\,\mathrm{GeV}/c$.

1. Introduction

The study of quarkonium production in nuclear collisions has a long and rich history, dating back to the original proposal by Matsui and Satz predicting J/ψ suppression in heavy ion collisions due to Debye screening in the quark–gluon plasma (QGP) [1]. After this proposal, the first J/ψ measurements in heavy ion collisions were performed in fixed target experiments at the CERN SPS, at a nucleon–nucleon center-of-mass energy of $\sqrt{s_{\mathrm{NN}}} \approx 20\,\mathrm{GeV}$ [2,3]. A similar level of suppression was later observed in gold–gold collisions at the BNL RHIC, at $\sqrt{s_{\mathrm{NN}}} = 200\,\mathrm{GeV}$ [4,5]. At the CERN LHC, the production of charmonium (J/ψ, ψ(2S)) and bottomonium (Υ(1S), Υ(2S), Υ(3S)) states has been studied in lead–lead (PbPb) collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ and $5.02\,\mathrm{TeV}$ [6–12], bringing new elements for the understanding of the medium produced in high-energy heavy ion collisions.

The quarkonium yields can be modified in heavy ion collisions because of several effects [13], including suppression [1] and recombination of charm quark pairs [14] inside the hot matter (QGP), and cold nuclear matter effects. An unambiguous interpretation of the nucleus–nucleus LHC results requires a quantitative understanding of cold nuclear matter effects. The nuclear parton distribution functions (nPDFs) are known to be different from those in a free proton [15,16]. In addition, gluon radiation induced by multiple parton scattering in the nucleus leads to transverse momentum (p_{T}) broadening and coherent energy loss, resulting in a significant quarkonium suppression in nuclear collisions at all available energies [17,18]. These phenomena are best studied in proton-nucleus collisions, in which hot medium effects, such as those due to the QGP, are likely to be limited.

Many charmonium production measurements have been performed in proton-induced collisions, on several nuclei, at the SPS [19–22], HERA [23], and Tevatron [24]. A global analysis of the fixed-target measurements can be found in Ref. [25]. At RHIC, J/ψ and ψ(2S) data in deuteron-gold collisions have been reported by the PHENIX [26] and STAR [27] Collaborations. At the LHC, the cross section of J/ψ in proton–lead (pPb) collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ has been measured by the ALICE [28,29], ATLAS [30], CMS [31], and LHCb [32] Collaborations. A significant suppression of the prompt J/ψ yield in pPb collisions has been observed at forward rapidity (y) and low p_{T}, while no strong nuclear effects are reported at backward rapidity, where forward and backward indicate, respectively, the directions of the proton and Pb beams. Measurements of the Υ(1S) in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$ have also been performed by the ALICE [33], ATLAS [34], and LHCb [35] experiments, indicating that the Υ(1S) state is less suppressed than the J/ψ.

Additional information can be obtained by studying the behavior of the excited states, which are less tightly bound compared to

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the ground states and might suffer stronger suppression in heavy ion collisions. At the LHC, the ALICE [36] and CMS [11] Collaborations have reported a stronger suppression of the $\psi(2S)$ state compared to the J/ψ in PbPb collisions. In pPb collisions, ALICE [37], ATLAS [34], and LHCb [38] data show that $\psi(2S)$ suppression, integrated over transverse momentum, is more pronounced than that of the J/ψ. This observation suggests final-state effects for the excited states, possibly due to inelastic interactions with the medium produced in pPb collisions [39]. In the bottomonium sector, the double yield ratios $\Upsilon(3S)/\Upsilon(1S)$ and $\Upsilon(2S)/\Upsilon(1S)$ in pPb relative to pp collisions have been measured by CMS [40] and found to be less than unity, again indicating stronger final-state effects in the production of excited quarkonium states.

This Letter reports measurements of the cross sections for prompt $\psi(2S)$ production in pp and pPb collisions at $\sqrt{s_{NN}} = 5.02\,\text{TeV}$, with the $\psi(2S)$ decaying to $\mu^+\mu^-$, over the p_T range 4–30 GeV/c and center-of-mass rapidity range $-2.4 < y_{CM} < 1.93$. The data were collected with the CMS detector at the LHC, in 2013 for the pPb sample and in 2015 for the pp sample, corresponding to integrated luminosities of $34.6 \pm 1.2\,\text{nb}^{-1}$ [41] and $28.0 \pm 0.6\,\text{pb}^{-1}$ [42], respectively. In addition, the modification of quarkonium production in pPb collisions is quantified by the nuclear modification factor, R_{pPb}, which is defined as the ratio of the cross sections in pPb and pp collisions divided by the Pb mass number, $A = 208$. The $\psi(2S)$ R_{pPb} is determined as a function of y_{CM} and p_T, and is compared to that of the J/ψ mesons measured at the same center-of-mass energy [31]. This is the first measurement of $\psi(2S)$ R_{pPb} at $\sqrt{s_{NN}} = 5.02\,\text{TeV}$ in differential bins of p_T and y_{CM} that uses the pp data measured at the same center-of-mass energy.

2. The CMS detector

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 there 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 pseudorapidity (η) coverage provided by the barrel and endcap detectors. The forward hadron (HF) calorimeter uses steel as absorber and quartz fibers as the sensitive material. The two halves of the HF are located at ±11.2 m from the nominal interaction point. Together they provide coverage in the range $3.0 < |\eta| < 5.2$ and also serve as luminosity monitors. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid, in the range $|\eta| < 2.4$, 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 results in a relative p_T resolution for typical muons in this analysis of 1.3–2.0% in the barrel and better than 6% in the endcaps [43]. 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. [44].

3. Event selection

The pPb collisions at $\sqrt{s_{NN}} = 5.02\,\text{TeV}$ correspond to a proton beam energy of 4 TeV and a lead beam energy of 1.58 TeV per nucleon. The proton beam traveled in the $-\eta$ direction (in the detector coordinate system) in the first part of the run, corresponding to an integrated luminosity $\mathcal{L}_{int} = 20.7\,\text{nb}^{-1}$, and in the opposite direction in the second part of the run, corresponding to $\mathcal{L}_{int} = 13.9\,\text{nb}^{-1}$. Particles emitted at $|\eta_{CM}| = 0$ in the nucleon–nucleon center-of-mass frame are detected in the laboratory frame at $\eta_{lab} = \pm 0.465$ depending on the proton beam direction. In this paper, data for half of the run were reflected so that positive η always corresponds to the direction of the proton beam. The pp data set, collected at the same collision energy as the pPb sample, corresponds to $\mathcal{L}_{int} = 28.0\,\text{pb}^{-1}$. In the pp sample, the dimuons from $\psi(2S)$ decays are reconstructed within $|y_{CM}| < 2.4$ and in the same p_T range as the pPb data, $4 < p_T < 30\,\text{GeV}/c$.

Inelastic hadronic collisions are selected by requiring at least one HF tower with more than 3 GeV of total energy in each of the two HF calorimeters. This is not required in pp collisions, which suffer less from photon-induced interactions compared to pPb collisions. The pp and pPb events are further selected to have at least one reconstructed primary vertex composed of two or more associated tracks, excluding the two muons, within 25 cm from the nominal interaction point along the beam axis and within 2 cm in the transverse plane. To reject the beam-gas background events, the fraction of good-quality tracks associated with the primary vertex is required to be larger than 25% when there are more than 10 tracks per event.

The dimuon events are selected by the level-1 trigger, a hardware-based trigger system requiring two muon candidates in the muon detectors with no explicit limitations on their p_T or η. In the offline analysis, muons are required to be within the following kinematic regions, which ensure single-muon reconstruction efficiencies above 10%:

$$\begin{aligned}
&p_T^{\mu} > 3.3\,\text{GeV}/c && \text{for } |\eta_{lab}^{\mu}| < 1.2, \\
&p_T^{\mu} > (4 - [1.1\,|\eta_{lab}^{\mu}|])\,\text{GeV}/c && \text{for } 1.2 < |\eta_{lab}^{\mu}| < 2.1, \\
&p_T^{\mu} > 1.3\,\text{GeV}/c && \text{for } 2.1 < |\eta_{lab}^{\mu}| < 2.4.
\end{aligned} \tag{1}$$

The oppositely charged muon pairs are further selected to originate from a common vertex with a χ^2 probability greater than 1%, and to survive standard identification criteria [43]. 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. All of these selections are common to both the pp and the pPb data sets.

4. Yield extraction

The prompt $\psi(2S)$ signal extraction procedure is similar to that in previous CMS analyses [8,11], and is the same for the pp and pPb data sets. The dimuon mass distribution is fitted with signal (including both the J/ψ and $\psi(2S)$ resonances) and background contributions using an extended unbinned maximum likelihood procedure [45]. While the scope of the present Letter is the measurement of the prompt $\psi(2S)$ production, the J/ψ resonance was included in the $\psi(2S)$ fit to increase the peak fitting stability. It has been checked that the prompt J/ψ results obtained in this analysis agree with the ones in Ref. [31], which used a different method for separating prompt from nonprompt charmonia. The prompt J/ψ results of Ref. [31] are the ones used in this Letter for comparison with the new analysis of $\psi(2S)$ production. Both resonance shapes are modeled by the weighted sum of a Crystal Ball (CB) [46] and a Gaussian function. The CB function, $g_{CB}(m)$, combines a Gaussian core and a power law tail with exponent n, accounting for energy loss due to final-state photon radiation, with a parameter α defining the transition between the Gaussian and the power law functions:

$$g_{\mathrm{CB}}(m) = \begin{cases} \dfrac{N}{\sqrt{2\pi}\,\sigma_{\mathrm{CB}}} \exp\left(-\dfrac{(m-m_0)^2}{2\,\sigma_{\mathrm{CB}}^2}\right), & \text{for } \dfrac{m-m_0}{\sigma_{\mathrm{CB}}} > -\alpha; \\ \dfrac{N}{\sqrt{2\pi}\,\sigma_{\mathrm{CB}}} \left(\dfrac{n}{|\alpha|}\right)^n \exp\left(-\dfrac{|\alpha|^2}{2}\right) & \\ \quad \times \left(\dfrac{n}{|\alpha|} - |\alpha| - \dfrac{m-m_0}{\sigma_{\mathrm{CB}}}\right)^{-n}, & \text{for } \dfrac{m-m_0}{\sigma_{\mathrm{CB}}} < -\alpha. \end{cases} \quad (2)$$

The CB and Gaussian functions have independent widths, σ_{CB} and σ_{G}, to accommodate the dependence of the dimuon invariant mass resolution on the dimuon rapidity and p_{T}, but share a common mean m_0 representing the J/ψ mass. The signal models used for the ψ(2S) and J/ψ share the same α and n parameters. The mean and the width of the Gaussian model for the ψ(2S) are obtained from those of the J/ψ, scaled by their mass ratio ($m_{\psi(2\mathrm{S})}/m_{\mathrm{J}/\psi} = 1.1903$ [47]). The following parameters are left free in the fit: m_0, σ_{CB}, σ_{G}, $N_{\mathrm{J}/\psi}$ (the J/ψ yield), $N_{\psi(2\mathrm{S})}$ (the ψ(2S) yield), f (the relative contribution of the Gaussian and CB functions), and α. Based on simulation studies, the value of the parameter n is fixed to 2.1. The parameter α is left free, covering the variation of signal shapes in each of the p_{T} and rapidity bins. The same value for f is used in the definition of the ψ(2S) and J/ψ signal shapes. The underlying background is described by a Chebyshev polynomial of degree N ($1 \leq N \leq 3$). The degree of the Chebyshev polynomial is obtained in each (p_{T}, y_{CM}) bin of the analysis using a log-likelihood ratio test. Several alternative fitting procedures have been tested, and the yield variations with respect to the nominal result are included as a systematic uncertainty, as explained in Section 6. The two pPb data sets, corresponding to each proton beam direction, are merged and analyzed together after having verified that the independent results are compatible with each other.

The J/ψ and ψ(2S) coming from b hadron decays (nonprompt charmonia) are evaluated using the displacement of the $\mu^+\mu^-$ vertex from the primary collision vertex. This secondary $\mu^+\mu^-$ vertex is characterized by the pseudo-proper decay length,

$$\ell_{\mathrm{J}/\psi} = L_{xy}\,\frac{m_{\mathrm{J}/\psi}}{p_{\mathrm{T}}}, \quad (3)$$

where L_{xy} is the transverse distance between the primary and dimuon vertices, $m_{\mathrm{J}/\psi}$ is the mass of the J/ψ [47] (assumed for all muon pairs), and p_{T} is the transverse momentum of the dimuon. Prompt charmonia are selected by requiring $\ell_{\mathrm{J}/\psi}$ to be smaller than a threshold value l_0, which is tuned using simulation separately for the pp and pPb collisions systems, in order to keep 90% of the total prompt charmonia [11]. Since the $\ell_{\mathrm{J}/\psi}$ resolution improves with increasing dimuon p_{T}, the l_0 values also depend on p_{T}. The l_0 values used remove between 70% and 90% (80% and 90%) of the nonprompt ψ(2S) in pPb (pp) collisions, from low- to high-p_{T}.

The yields so obtained have a small nonprompt contamination, which is corrected using the number of simulated events passing and failing the $\ell_{\mathrm{J}/\psi}$ threshold criteria [11]. The full value of this correction is also propagated as a source of systematic uncertainty.

Fig. 1 shows the dimuon invariant mass distributions with the J/ψ and ψ(2S) peaks in pPb and pp data, for one of the bins with the smallest signal-to-background ratio (lowest p_{T} and most backward y), after applying the $\ell_{\mathrm{J}/\psi}$ selection, together with the curves resulting from the fits. The raw prompt ψ(2S) yield extracted in these bins is ~300 for the pPb, and twice as much for the pp samples.

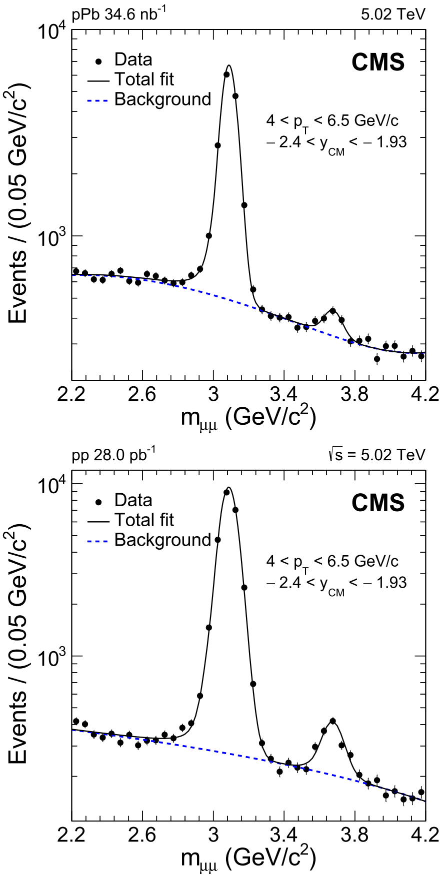

Fig. 1. Dimuon invariant mass distribution showing the J/ψ and ψ(2S) peaks in pPb (top panel) and pp (bottom panel) data, after applying the $\ell_{\mathrm{J}/\psi}$ selection, for $-2.4 < y_{\mathrm{CM}} < -1.93$ and $4 < p_{\mathrm{T}} < 6.5\,\mathrm{GeV}/c$. The fits to the distributions are also shown.

5. Acceptance and efficiency corrections

Simulated events are used to obtain the acceptance and efficiency correction factors for the measured ψ(2S) yields. The events are generated using PYTHIA 6.424 [48] for pPb collisions and PYTHIA 8.209 [49] for pp collisions. The generated particles in the pPb Monte Carlo (MC) are boosted by the β of the center-of-mass system in the laboratory frame, resulting in $\Delta y = \pm 0.465$. The prompt J/ψ and ψ(2S) are assumed to be produced unpolarized in both pp and pPb collisions, which is supported by measurements in pp collisions at $\sqrt{s} = 7\,\mathrm{TeV}$ [50,51]. The final-state QED radiation of the decay muons is simulated using PHOTOS 215.5 [52]. Finally, the CMS detector response is simulated using GEANT4 [53].

The acceptance in a given (p_{T}, y_{CM}) bin is defined as the fraction of generated ψ(2S) mesons resulting in a detectable muon pair, i.e., passing the single muon selection criteria defined in Eq. (1). The efficiency is given by the fraction of generated and detectable muon pairs that result in a reconstructed muon pair, also passing the trigger and offline selections. The combined ψ(2S) acceptance and efficiency for pPb (pp) results ranges between 13% (14%) in the lowest p_{T} region ($4.0 < p_{\mathrm{T}} < 6.5\,\mathrm{GeV}/c$) and 66% (67%) in the highest p_{T} region ($10.0 < p_{\mathrm{T}} < 30.0\,\mathrm{GeV}/c$). It is maximum in the overlap region between barrel and endcap detectors, and decreases to minimum values for $|y_{\mathrm{CM}}| > 2$.

The individual components of the simulation-based dimuon efficiency (track reconstruction, muon identification and selection, and triggering) are probed using single muons from J/ψ meson decays in both simulated and collision data, with the *tag-and-probe*

(T&P) method [31,54]. The data-to-simulation ratios of single muon efficiencies obtained from T&P, calculated as a function of muon η and p_{T}, are used as weights (*scale factors*) to correct event-by-event the dimuon efficiency. The effect of this correction on the dimuon efficiency is similar for pp and pPb events and ranges from 0.99 to 1.33, with larger corrections at lower p_{T} and more forward/backward rapidities.

6. Systematic uncertainties

The following sources of point-to-point systematic uncertainties are considered for both pp and pPb data: the yield extraction method, given the choice of signal and background models; acceptance and efficiency corrections, including T&P scale factors and the possible difference in the dimuon p_{T} spectrum between data and simulation; and the nonprompt charmonia contamination. The evaluation of these systematic uncertainties is described below.

- **Signal shape variation.** This systematic uncertainty is obtained by changing the fitting constraints on the CB shape parameters. In the nominal fits, the CB parameter n is fixed from simulation, $n = 2.1$, and the parameter α is left free. In a first variation, the parameter α is fixed to the MC-based value 1.7, and n is left free. A second variation consists in fixing both parameters to the values extracted from MC, $n = 2.1$ and $\alpha = 1.7$. The maximum difference, in each analysis bin, between the yields extracted with the nominal fit and either of these variations, is taken as a systematic uncertainty.
- **Background shape variation.** The degree N of the Chebyshev polynomial is changed to $N+1$ if $N < 3$, and to $N-1$ if $N = 3$. The systematic uncertainty is estimated as the absolute difference in the yields with respect to the nominal case.
- **Simulated dimuon p_{T} spectrum.** The acceptance and efficiency correction factors depend on the shape of the simulated $\psi(2S)$ p_{T} distribution; the difference between data and simulation is a source of systematic uncertainty. The ratio of the corrected yields in data and simulation is evaluated as a function of p_{T}, for each rapidity bin. Continuous weighting factors are obtained by fitting these data-to-simulation ratios with a linear function in p_{T}. The acceptance and efficiency values are evaluated again after weighting the p_{T} distribution of the generated $\psi(2S)$ mesons in the simulation by the function obtained. The difference between the reweighed simulation and the nominal yields is taken as a systematic uncertainty.
- **T&P scale factors.** The statistical uncertainty on the T&P scale factors, as well as systematic uncertainties in their derivation, are accounted for as a systematic uncertainty. These uncertainties are further described in Ref. [31].
- **Nonprompt contamination.** The difference between the prompt meson yields with and without the correction for the residual nonprompt contamination is propagated as a systematic uncertainty.

The systematic uncertainty in the yield extraction, determined by summing the uncertainties from the signal and background shape variations in quadrature, is in the range 1.0–22% and 0.4–6.5% for the pPb and pp results, respectively. This large range is mostly driven by the variation of the signal over background ratio across the analysis bins. The dominant part in this uncertainty is from background modeling, with an average over all the p_{T} and y_{CM} bins of 3.9 (2.4)% and a maximum of 22 (4.9)% for the pPb (pp) results. The average signal modeling contribution is 1.9% and 1.4%, for the pPb and pp results, respectively.

The systematic uncertainty in the acceptance and efficiency correction factors, combining the dimuon p_{T} spectrum reweighting and T&P uncertainties, lies within 2.0–7.4% and 1.9–8.1% for the pPb and pp results, respectively. The prompt selection method induces an uncertainty of 4.5–15% (0.2–8.0%) for the pPb (pp) results, with the maximum value in the lowest p_{T} bin in the backward y region. The total systematic uncertainty, calculated as the sum in quadrature of the individual uncertainties, is in the range 5–26% (4–11%) for the pPb (pp) cross section measurements. In general, the uncertainty is minimum in the highest p_{T} bins in the central y region, and increases when going to lower p_{T} and forward/backward y regions. For the R_{pPb} measurement, the pp and pPb uncertainties are considered independent and added in quadrature point-by-point. The total systematic uncertainty in this case is in the range 5.0–22.6%.

The global (common to all points) systematic uncertainty due to the uncertainty in the integrated luminosity of the pPb and pp data sets is 3.5% [41] and 2.3% [42], respectively. For the cross section results, this uncertainty is not included to the point-to-point uncertainties, while for the R_{pPb} results the two numbers are added in quadrature and displayed as a box around $R_{\mathrm{pPb}} = 1$. The dominant source of uncertainty for the R_{pPb} measurement is the statistical uncertainty in the pPb data.

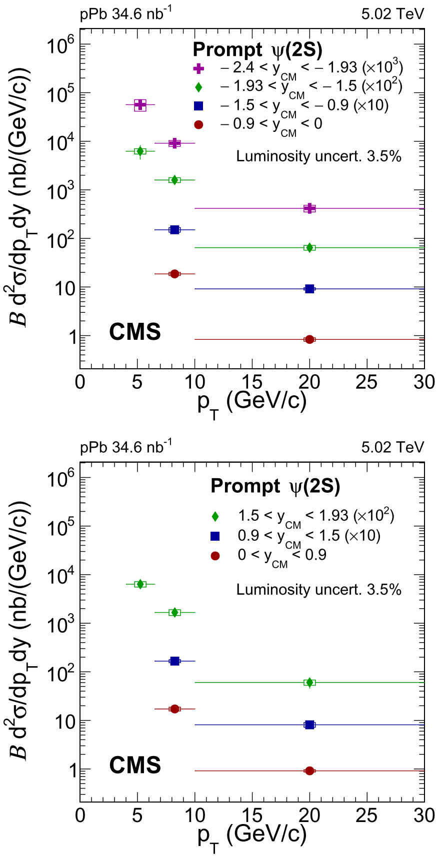

Fig. 2. Differential cross section (multiplied by the dimuon branching fraction) of prompt $\psi(2S)$ production in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02\,\mathrm{TeV}$, as a function of p_{T}, in several rapidity bins and separately for backward (top panel) and forward (bottom panel) rapidity regions. Statistical and systematic uncertainties are represented with error bars and boxes, respectively. The fully correlated luminosity uncertainty of 3.5% is not included in the point-by-point uncertainties.

7. Results

The prompt $\psi(2S)$ production cross section (multiplied by the $\psi(2S)$ branching fraction to $\mu^+\mu^-$, $\mathcal{B}(\psi(2S) \to \mu^+\mu^-)$) in the dimuon decay channel is determined as

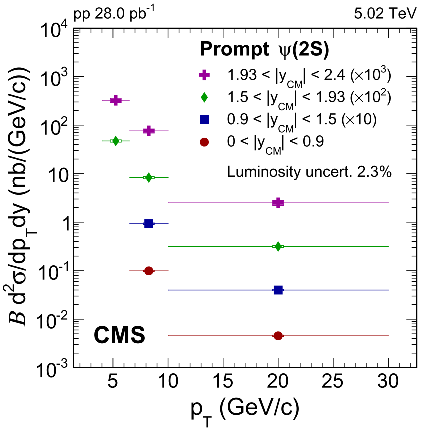

Fig. 3. Differential cross section (multiplied by the dimuon branching fraction) of prompt $\psi(2S)$ production in pp collisions at $\sqrt{s} = 5.02\,\text{TeV}$ as a function of p_T, in four y_{CM} bins. Statistical and systematic uncertainties are represented with error bars and boxes, respectively. The fully correlated luminosity uncertainty of 2.3% is not included in the point-by-point uncertainties.

$$\mathcal{B}(\psi(2S) \to \mu^+\mu^-)\frac{d^2\sigma}{dp_T\,dy_{CM}} = \frac{N_{\text{fit}}^{\psi(2S)}/(\text{acc}\,\varepsilon)}{\mathcal{L}_{\text{int}}\,\Delta p_T\,\Delta y_{CM}}, \tag{4}$$

where $N_{\text{fit}}^{\psi(2S)}$ is the extracted raw yield of prompt $\psi(2S)$ mesons in a given (p_T, y_{CM}) bin, $(\text{acc}\,\varepsilon)$ is the product of the dimuon acceptance and efficiency described in Section 5, and Δp_T and Δy_{CM} are the widths of the kinematic bin considered.

Figs. 2 and 3 show the production cross sections of prompt $\psi(2S)$ mesons in pPb and pp collisions at $\sqrt{s_{NN}} = 5.02\,\text{TeV}$, respectively. The results are given as a function of p_T and in four rapidity bins, separately for forward (the direction of the proton beam) and backward (the direction of the Pb beam) rapidities in the case of the pPb measurements.

The second observable considered is the nuclear modification factor, defined as

$$R_{pPb}(p_T, y_{CM}) \equiv \frac{(d^2\sigma/dp_T\,dy_{CM})_{pPb}}{A(d^2\sigma/dp_T\,dy_{CM})_{pp}}. \tag{5}$$

In the absence of any nuclear effects the measured yield in pPb collisions would be just a superposition of $A = 208$ (the number of nucleons in the Pb nucleus) pp collisions, and the R_{pPb} would be one.

Fig. 4 shows the rapidity dependence of the prompt $\psi(2S)$ R_{pPb} in three p_T ranges: 4–6.5, 6.5–10, and 10–30 GeV/c. In the backward rapidity region, the prompt $\psi(2S)$ mesons are suppressed in the intermediate p_T region, and compatible with unity in the rest. In the forward rapidity region, the R_{pPb} is consistent with unity for all p_T bins (although systematically smaller). For comparison, the prompt J/ψ nuclear modification factor [31] is also shown in Fig. 4. The measured value of R_{pPb} for prompt $\psi(2S)$ mesons, when integrated over p_T and rapidity ($6.5 < p_T < 30\,\text{GeV}/c$, $|y| < 1.6$), is $0.852 \pm 0.037\text{stat} \pm 0.062\text{syst}$. The prompt J/$\psi$ R_{pPb} in the same kinematic range is $1.108 \pm 0.021\text{stat} \pm 0.055\text{syst}$. The R_{pPb} for prompt J/ψ mesons lies systematically above that of the $\psi(2S)$ state. The difference between the two sets of results was quan-

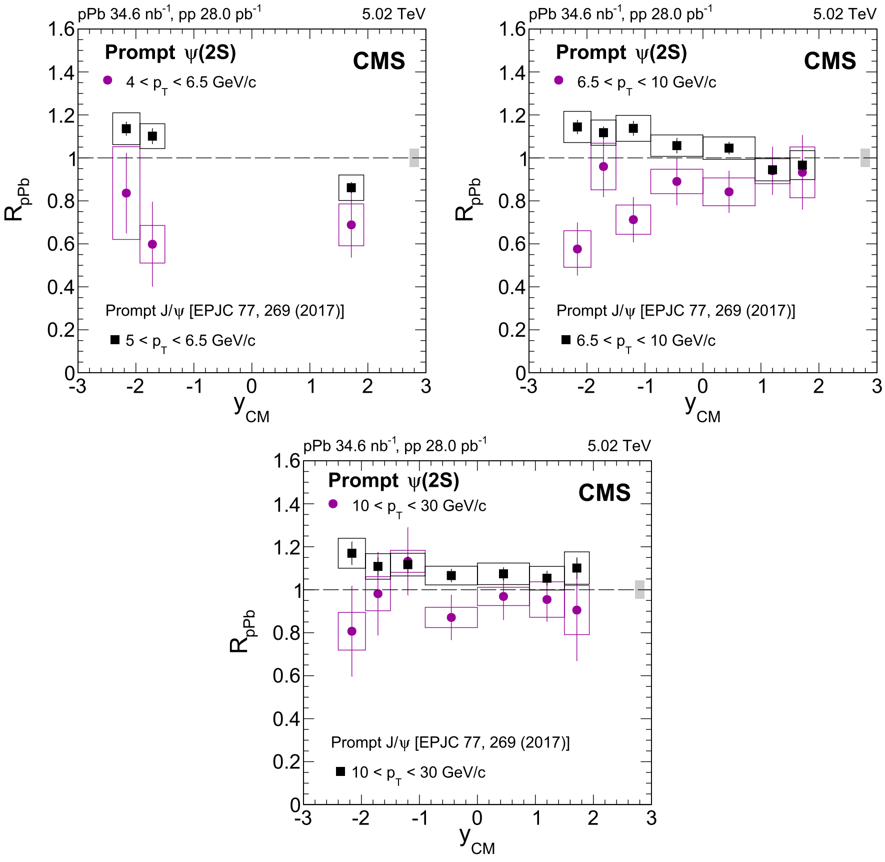

Fig. 4. Rapidity dependence of the prompt $\psi(2S)$ R_{pPb} in three p_T ranges. For comparison, the prompt J/ψ nuclear modification factor [31] is also shown. Statistical and systematic uncertainties are represented with error bars and boxes, respectively. The fully correlated global uncertainty of 4.2% (that affects both charmonia) is displayed as a box around $R_{pPb} = 1$.

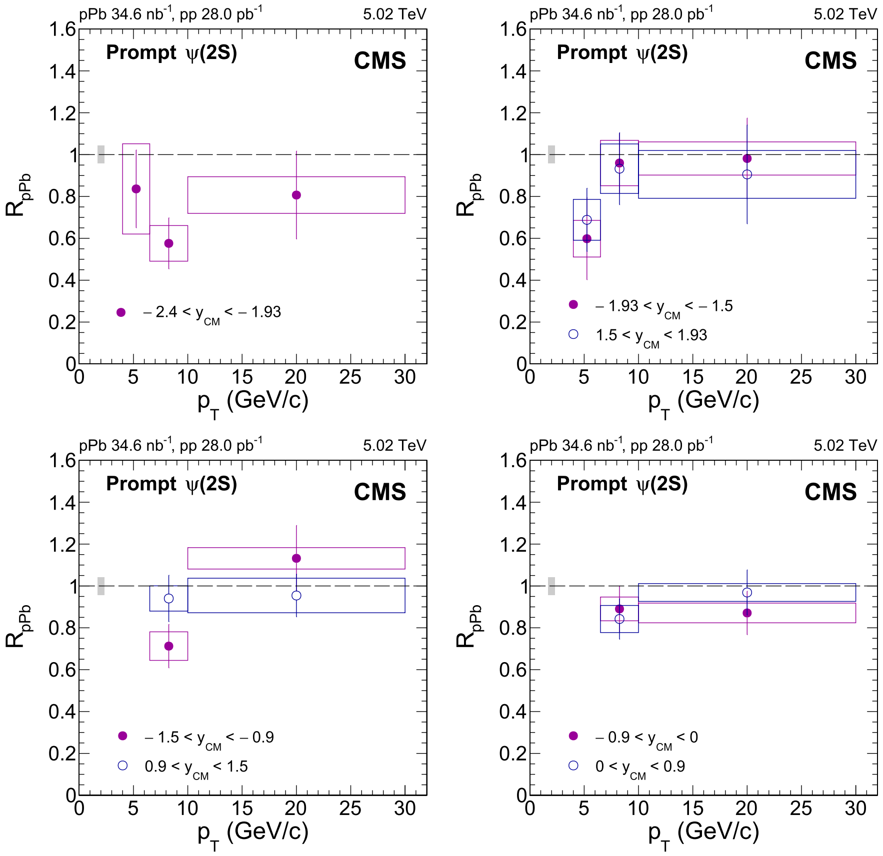

Fig. 5. Transverse momentum dependence of the prompt $\psi(2S)$ R_{pPb} in four rapidity ranges. Statistical and systematic uncertainties are represented with error bars and boxes, respectively. The fully correlated global uncertainty of 4.2% is displayed as a box around $R_{pPb} = 1$.

tified, separately for the backward and forward regions, by comparing the two distributions with a χ^2-test, removing the correlated uncertainties from the integrated luminosity. The p-values are < 0.05 for the lowest two p_T ranges in the backward rapidity region, and > 0.37 in all the other rapidity and p_T intervals. This shows that, with a p-value cutoff of 0.05, the two sets of results are incompatible with each other in the backward rapidity region for $p_T < 10\,\text{GeV}/c$, but are compatible in the rest. This suggests the presence of different nuclear effects at play in the production of the excited charmonium state compared to the ground state, in the region of backward rapidity and for $p_T < 10\,\text{GeV}/c$.

Fig. 5 shows the p_T dependence of the prompt $\psi(2S)$ R_{pPb} in seven rapidity bins, from the most backward $-2.4 < y_{CM} < -1.93$ to the most forward $1.5 < y_{CM} < 1.93$ accessible regions. Also in this case, a χ^2-test was used to quantify the significance of the difference of the results from unity, in which the fully correlated global uncertainty, displayed as a box around $R_{pPb} = 1$, was not included. The p-values are below 0.05 only in the most backward region. This points to the presence of nuclear effects affecting the $\psi(2S)$ production in the most backward region that persists at large transverse momentum.

The suppression of prompt $\psi(2S)$ mesons as compared to prompt J/ψ mesons, seen in Fig. 4, is compatible with what was measured by the ALICE [37], ATLAS [34], and LHCb [38] Collaborations for p_T integrated charmonium production in pPb collisions at the same collision energy. While nPDFs [15,16] and coherent energy loss [17,18] are the most discussed effects to explain prompt J/ψ meson suppression, these two phenomena are expected to affect the R_{pPb} of prompt J/ψ and $\psi(2S)$ mesons by a similar amount. On the contrary, the final-state interaction with hadrons moving along with the produced charmonium might lead to a stronger suppression of the $\psi(2S)$ meson, due to its larger size [39,55]. The present measurements, covering wide transverse momentum ($4 < p_T < 30\,\text{GeV}/c$) and rapidity ($-2.4 < y_{CM} < 1.93$) ranges, will help understand the origin of the suppression of excited quarkonium states in pPb collisions at the LHC.

8. Summary

The data collected by CMS in pp and pPb collisions at $\sqrt{s_{NN}} = 5.02\,\text{TeV}$ are used to investigate prompt $\psi(2S)$ meson production. The results are based on data samples corresponding to integrated luminosities of $28.0\,\text{pb}^{-1}$ for pp collisions and $34.6\,\text{nb}^{-1}$ for pPb collisions. The nuclear modification factor (R_{pPb}) of prompt $\psi(2S)$, in the kinematic range $4 < p_T < 30\,\text{GeV}/c$ and $-2.4 < y_{CM} < 1.93$, is determined and compared to that of prompt J/ψ mesons, reported in Ref. [31]. The prompt $\psi(2S)$ production is suppressed in the intermediate 6.5–10 GeV/c p_T interval in the region of backward rapidity. The R_{pPb} is consistent with unity everywhere else (although systematically smaller). The R_{pPb} values of prompt J/ψ when compared to those of prompt $\psi(2S)$ mesons, point to different nuclear effects at play in the production of the excited charmonium state compared to the ground state, in the region of backward rapidity and for $p_T < 10\,\text{GeV}/c$. The effects of nuclear parton distribution functions or coherent energy loss are expected to affect the R_{pPb} of prompt J/ψ and $\psi(2S)$ by a similar amount, thus the results hint the presence of final-state interactions with the medium (partonic or hadronic) produced in pPb collisions.

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