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Measurement of quarkonium production cross sections in pp collisions at $\sqrt{s} = 13$ TeV

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ABSTRACT

Differential production cross sections of prompt J/ψ and ψ(2S) charmonium and Υ(nS) (n = 1, 2, 3) bottomonium states are measured in proton–proton collisions at $\sqrt{s} = 13$ TeV, with data collected by the CMS detector at the LHC, corresponding to an integrated luminosity of 2.3 fb^{-1} for the J/ψ and 2.7 fb^{-1} for the other mesons. The five quarkonium states are reconstructed in the dimuon decay channel, for dimuon rapidity $|y| < 1.2$. The double-differential cross sections for each state are measured as a function of y and transverse momentum, and compared to theoretical expectations. In addition, ratios are presented of cross sections for prompt ψ(2S) to J/ψ, Υ(2S) to Υ(1S), and Υ(3S) to Υ(1S) production.

1. Introduction

Since the discovery of heavy-quark bound states, quarkonium production in hadronic collisions has been the subject of many theoretical and experimental studies. A well established theoretical framework to describe quarkonium production is nonrelativistic quantum chromodynamics (NRQCD) [1–3], an effective theory that assumes that the mechanism can be factorized in two steps. In the first step, a heavy quark–antiquark pair is produced in a given spin and orbital angular momentum state, either in a color-singlet or color-octet configuration. The corresponding parton-level cross sections, usually called short-distance coefficients (SDCs), are functions of the kinematics of the state and can be calculated perturbatively, presently up to next-to-leading order (NLO) [4–7]. In the second step, the quark–antiquark pairs bind into the final quarkonium states through a nonperturbative hadronization process, with transition probabilities determined by process-independent long-distance matrix elements (LDMEs). Unlike the SDCs, the LDMEs are presently not calculable and must be obtained through fits to experimental data [4–9]. Until recently, for directly produced S-wave quarkonia, the color-octet $^3S_1$ term was thought to dominate, which would result in a strong transverse polarization of the mesons relative to their direction of motion (helicity frame) at large transverse momentum, p_T.

Experiments at the CERN LHC have provided measurements of the production of the S-wave quarkonium states η_c(1S), J/ψ, ψ(2S), and Υ(nS) (n = 1, 2, 3), and of the P-wave states, $\chi_{c1,2}$ and $\chi_{b1,2}$(1P) [10–14], at center-of-mass energies of 2.76, 7 and 8 TeV. These measurements of the S-wave states include both the differential cross sections [15–29] and polarizations [30–34], and offer strong indication that, contrary to previous expectations, these mesons are produced unpolarized. Further theoretical and experimental work can provide deeper insights on how to interpret these observations. In particular, additional data can help in improving the fits and determine more precisely the relative weights of the LDMEs.

We report the measurement of double-differential cross sections of five S-wave quarkonium states J/ψ, ψ(2S), and Υ(nS) in pp collisions at $\sqrt{s} = 13$ TeV by the CMS detector at the LHC. The increased center-of-mass energy and production cross sections provide an extended reach in p_T and improved statistical precision relative to similar measurements at 7 TeV [24–27,35]. The measurements performed at 13 TeV also provide the opportunity to test the $\sqrt{s}$ dependence of the cross sections and to check the validity of the factorization hypothesis and LDME universality implied in NRQCD.

The product of the branching fraction of quarkonia to muon pairs, $\mathcal{B}(\mathcal{Q} \to \mu^-\mu^+)$, and the double-differential production cross section, $d^2\sigma/(dp_T\,dy)$, in bins of p_T and rapidity, y, is given by

$$\mathcal{B}(\mathcal{Q} \to \mu^-\mu^+)\,\frac{d^2\sigma}{dp_T\,dy} = \frac{N(p_T, y)}{\mathcal{L}\Delta y \Delta p_T}\left\langle \frac{1}{\epsilon(p_T, y)\mathcal{A}(p_T, y)} \right\rangle, \qquad (1)$$

where $N(p_T, y)$ is the number of prompt signal events in the bin, $\mathcal{L}$ is the integrated luminosity, Δy and Δp_T are the bin widths,

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and $\langle 1/(\epsilon(p_T, y)\mathcal{A}(p_T, y))\rangle$ represents the average of the product of the inverse acceptance and efficiency for all the events in the bin. Only prompt signal events are considered. The nonprompt components of the J/ψ and ψ(2S) mesons, i.e. originating from decays of b hadrons, are separated using the decay length defined as $\ell = L_{xy} \cdot m/p_T$, where L_{xy} is the distance measured in the transverse plane between the average location of the luminous region and the fitted position of the dimuon vertex, m is the mass of the J/ψ (ψ(2S)) from Ref. [36], and p_T the transverse momentum of the dimuon candidate. For the prompt signal events, we do not distinguish between feed-down decays of heavier quarkonium states and directly produced quarkonia.

2. The CMS detector, data set, and event selection

The analysis uses dimuon events collected in pp collisions at $\sqrt{s} = 13$ TeV with 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 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. Muons are detected in gas-ionization chambers embedded in the steel flux-return yoke outside the solenoid [37]. 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. [38].

The data were collected using a multilevel trigger system [39]. The first level (L1), made of custom hardware processors providing coarse momentum information, requires two muons within the range $|\eta| < 1.6$ without requesting an explicit p_T threshold on the individual muons. Second (L2) and third (L3) levels, collectively known as the HLT (High-Level Trigger), are implemented in software. At these levels, the muon selection is refined, then opposite-charge muon candidates are paired and required to have an invariant mass in the regions 2.9–3.3, 3.35–4.05, or 8.5–11 GeV for the J/ψ, ψ(2S), and Υ(nS), respectively. The dimuon p_T is required to be above 9.9 GeV for the J/ψ and above 7.9 GeV for the remaining states. For all five states, the dimuon rapidity is restricted to $|y| < 1.25$. A fit of the positions and momenta of the two muon candidates to a common vertex is performed, and the fit χ^2 probability is required to be above 0.5%. The sample collected with these triggers has a total integrated luminosity of 2.3 fb^{-1} for the J/ψ and 2.7 fb^{-1} for the other mesons. The lower value for the J/ψ is the consequence of the trigger prescaling that was applied to limit the rate during part of the data taking, when the instantaneous luminosity increased.

When reconstructing the five states offline, further requirements are applied: only muons with $p_T^\mu > 4.5$ GeV in the range $|\eta^\mu| < 0.3$, or $p_T^\mu > 4.0$ GeV in the range $0.3 < |\eta^\mu| < 1.4$ are selected. The muons have to match the triggered pair and be identified as reconstructed tracks with at least five measurements in the silicon tracker and at least one in the pixel detector. The track is required to match at least one muon segment identified by a muon detector plane. Loose criteria are applied on the longitudinal and transverse impact parameters to reject cosmic rays and in-flight hadron decays. The dimuon vertex χ^2 probability is required to be greater than 1%. In the CMS magnetic field, the two muons can bend towards or away from each other; only the second type of event is considered in this analysis since the first type exhibits high trigger inefficiencies. It was verified that this requirement does not introduce any bias in the determination of the prompt component for the J/ψ and ψ(2S) mesons. The dimuon rapidity is restricted to $|y| < 1.2$. Trigger bandwidth limitations prevented the extension of the measurement to the full CMS acceptance.

The double-differential cross sections are presented in four (two) rapidity bins for the prompt J/ψ and ψ(2S) (Υ(nS)), and in several bins of p_T, covering a p_T range between 20 and 120 (100) GeV for J/ψ (ψ(2S), Υ(nS)), extending up to 150 (130) GeV for measurements integrated in rapidity.

3. Acceptance and efficiencies

The acceptance is calculated using simulated events produced with a single-particle event generator. The quarkonium states are generated with a flat y distribution and a realistic p_T distribution derived from data [25,26], covering the analysis phase space. The PYTHIA 8.205 [40] Monte Carlo event generator is used to produce an unpolarized dimuon decay (corresponding to a flat dimuon angular distribution), also accounting for final-state photon radiation. The simulated events include multiple proton–proton interactions in the same or nearby beam crossings (pileup), with the distribution matching that observed in data, with an average of about 11 collisions per bunch crossing. The acceptance for events in a given $(p_T, |y|)$ range is defined as the ratio of the number of generated events that pass the kinematic selection criteria described above to the total number of simulated events in that p_T and $|y|$ range. The acceptance depends on the quarkonium polarization. It is derived for the unpolarized scenario, which is compatible with experimental measurements within uncertainties. We also calculate multiplicative correction factors that allow, from the unpolarized case, to infer the acceptance that corresponds to three different values of the polar anisotropy parameter, λ_θ^{HX}, in the helicity frame: -1 (fully longitudinal), $+1$ (fully transverse), and k, with k reflecting the CMS measured value of λ_θ^{HX} for each quarkonium state [31,32], also used in Refs. [26,27]. The multiplicative factors to convert the cross sections calculated using the unpolarized scenario to the ones calculated employing one of the polarization scenarios described above are provided. It was verified that the use of only events with two muons bending away from each other does not introduce any bias in the determination of the acceptance.

The single-muon trigger, reconstruction, and identification efficiencies are measured individually from data as a function of muon p_T and $|\eta|$, applying a tag-and-probe [24,35] technique on J/ψ and Υ(1S) candidates acquired with triggers that are independent from those used for the measurements of the yields. The individual efficiencies are multiplied and then parameterized using a sigmoid function. The dimuon efficiency is obtained as the product of the efficiencies of the two muons, multiplied by a correction factor, ρ, that takes into account the correlation between the two muons. The ρ factor is derived from data, using a trigger, independent from the ones used for the measurement of the yield, requiring a single muon at L1. ρ becomes increasingly important with higher dimuon p_T, when the two muons are close to each other in space, causing the efficiency to decrease. Dimuon efficiencies are around 85% for the J/ψ and ψ(2S) up to a dimuon p_T of 50 GeV and decrease slowly for higher p_T due to the ρ factor. In the case of the Υ(nS) states, the dimuon efficiencies are nearly constant around 90%. The acceptance and efficiency term in Eq. (1) is obtained by averaging the values of the inverse of the acceptance times efficiency for all the individual dimuon candidates in each p_T and $|y|$ range.

4. Determination of the yields

The signal and background yields are obtained through an extended unbinned maximum-likelihood fit to the dimuon invariant mass distribution in the case of the Υ(nS) states, and to the