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Measurement of the Υ(1S), Υ(2S), and Υ(3S) differential cross sections in pp collisions at $\sqrt{s} = 13.6$ TeV

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Abstract: The production cross sections of the Υ(1S), Υ(2S), and Υ(3S) mesons are measured in proton-proton collisions at $\sqrt{s} = 13.6$ TeV, using a data sample collected in 2022 by the CMS experiment and corresponding to an integrated luminosity of 37.4 fb^{-1}. The measurement is performed in the $\mu^+\mu^-$ decay channels, differentially as a function of transverse momentum in the 20–200 GeV range, in the $|y| < 0.6$ and $0.6 < |y| < 1.2$ rapidity intervals.

Keywords: Hadron-Hadron Scattering, Quarkonium

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Contents

1 Introduction

The production of charmonium and bottomonium states (bound states of, respectively, charm and beauty quark-antiquark pairs) provides crucial insights for the understanding of hadron formation in the scope of quantum chromodynamics (QCD), the theory of strong interactions [1, 2]. Several theoretical models have been developed to describe quarkonium production, including the "colour singlet model" and the "colour evaporation model" (refs. [3, 4] and references therein). Currently, the most widely accepted theoretical description of quarkonium production is based on the assumption that the charm and beauty quarks are sufficiently heavy to allow the factorization of short- and long-distance effects, a conjecture at the basis of the non-relativistic QCD (NRQCD) framework [5]. Within this theoretical approach, quarkonium production is described as a superposition of several contributions, each corresponding to a possible configuration of the intermediate $\mathrm{Q\overline{Q}}(^{2S+1}L_J^{[c]})$ state, characterized by its spin (S), orbital angular momentum (L), total angular momentum (J), and colour ($c = 1$ or 8). These contributions are organized in an expansion in powers of the relative $\mathrm{Q\overline{Q}}$ velocity so that only a small number of leading and subleading terms remain quantitatively relevant. In the case of S-wave quarkonia, the leading contributions are the $^1S_0^{[8]}$, $^3S_1^{[8]}$, and $^3P_J^{[8]}$ colour octets [1, 2, 5], the first of them being unpolarized. Each term contributes to the quarkonium production cross section as the product of two factors. The first factor is the production cross section of the $\mathrm{Q\overline{Q}}$ "pre-resonance", a function of its transverse momentum (p_{T}) and rapidity (y) evaluated through perturbative QCD computations and denoted as the "short-distance coefficient" (SDC). The second, known as the "long-distance matrix element" (LDME), is a phenomenological parameter (supposedly constant and universal) reflecting the probability of the (non-perturbative) evolution of that specific $\mathrm{Q\overline{Q}}$ state to the observed meson. For S-wave charmonium and bottomonium production, the dominant octet terms have been computed up to next-to-leading order (NLO) accuracy in the strong coupling parameter [6–9]. The LDMEs are not calculable by the currently existing theory methods and are, instead, determined from global fits to experimental data. Different sets of LDMEs have been extracted in the past, depending on which sets of measurements are included in the fit, on the minimum p_{T} threshold used in the data selection, and, most significantly, on whether the fit analyses are restricted to differential cross sections or also include polarization measurements. More details can be found in refs. [6–17] and references therein.

Production cross sections of S-wave quarkonia have been measured in proton-proton (pp) collisions at the LHC, as functions of p_{T} and in several y ranges, by the ALICE, ATLAS, CMS, and LHCb Collaborations [18–32]. Quarkonium polarization measurements have also been performed, providing complementary information regarding the production mechanisms [33–39]. More details on these measurements can be found in ref. [40] and references therein. This article reports a measurement of the Υ(1S), Υ(2S), and Υ(3S) (denoted by $\Upsilon(n\mathrm{S})$) differential cross sections in pp collisions at $\sqrt{s} = 13.6\,\mathrm{TeV}$, on the basis of a data sample collected in 2022 by the CMS experiment, corresponding to an integrated luminosity of $37.4\,\mathrm{fb}^{-1}$. The measurements are performed in the dimuon decay channels and cover the broad 20–200 GeV p_{T} range, in the $|y| < 0.6$ and $0.6 < |y| < 1.2$ regions. The reported cross sections include feed-down contributions from heavier bottomonia.

With respect to the results obtained with a $\sqrt{s} = 13\,\mathrm{TeV}$ pp data sample reported in a previous CMS publication [32], this analysis extends the p_{T} reach from 100 to 200 GeV. The $\Upsilon(n\mathrm{S})$ signal yields, $N(p_{\mathrm{T}}, |y|)$, are extracted, in each $(p_{\mathrm{T}}, |y|)$ two-dimensional bin, from an extended binned maximum likelihood fit to the dimuon invariant mass spectrum. The two-dimensional acceptance, $\mathcal{A}(p_{\mathrm{T}}, |y|)$, is computed through detector simulation, while the corresponding detection efficiencies, $\epsilon(p_{\mathrm{T}}, |y|)$, are evaluated from measured data using the tag-and-probe method [18, 27, 32] for the single muon terms and from the simulated event samples for the terms that depend on the muon-pair correlations. All measurements are reported in terms of the product between the $\Upsilon(n\mathrm{S})$ production cross section, σ, and the branching fraction of the corresponding dimuon decay channel, $\mathcal{B}(\Upsilon \to \mu^+\mu^-)$, abbreviated as $\mathcal{B}$ in the following. In summary, we compute the p_{T}-differential cross section times branching fraction, per unit of rapidity and in two rapidity ranges, as

$$\mathcal{B}\,\frac{\mathrm{d}^2\sigma}{\mathrm{d}y\mathrm{d}p_{\mathrm{T}}} = \frac{N(p_{\mathrm{T}}, |y|)}{\mathcal{L}\,\Delta y\,\Delta p_{\mathrm{T}}}\,\frac{1}{\epsilon(p_{\mathrm{T}}, |y|)}\,\frac{1}{\mathcal{A}(p_{\mathrm{T}}, |y|)}\,, \tag{1.1}$$

where $\mathcal{L}$ is the integrated luminosity, Δp_{T} is the width of the p_{T} bin under consideration, and $\Delta y = 1.2$ for both $|y|$ bins. The numerical values are reported in the HEPData record of this analysis [41].

2 The CMS apparatus, event samples, and selection criteria

The CMS apparatus is a multipurpose detector [42] designed to trigger on and identify electrons, muons, photons, and (charged and neutral) hadrons [43–45]. A superconducting solenoid of 6 m internal diameter provides a magnetic field of 3.8 T. Within the solenoid volume are the silicon pixel and strip tracker, a crystal electromagnetic calorimeter, and a brass and scintillator hadron calorimeter. Forward calorimeters extend the pseudorapidity (η)

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coverage provided by the barrel and endcap detectors. Muons are measured in the $|\eta| < 2.4$ range, with gas-ionization detectors (drift tubes, cathode strip chambers, and resistive plate chambers) embedded in the steel flux-return yoke outside the solenoid. Muons are identified as tracks in the silicon tracker consistent with either a track or several hits in the muon system, and associated with calorimeter deposits compatible with the muon hypothesis. The relative p_{T} resolution is 1% in the barrel and 3% in the endcaps, for muons with p_{T} up to 100 GeV. More detailed descriptions of the CMS detector, together with a definition of the coordinate system used and the relevant kinematic variables, can be found in refs. [42, 46].

The events of interest are selected using a two-tiered trigger system. The first level (L1), composed of custom hardware processors, uses information from the calorimeters and muon detectors to select events at a rate of 100 kHz within a fixed latency of $4\,\mu$s [47]. The L1 trigger used in this analysis selects events with at least two opposite-sign muons with $p_{\mathrm{T}} > 4.5$ GeV and $|\eta| < 2$, having a dimuon mass, $m_{\mu\mu}$, larger than 7 GeV. The second level, consisting of a farm of processors running a faster version of the full event reconstruction software, reduces the rate to around 1 kHz before data storage [48, 49]. The trigger used in this analysis only retains dimuons with $8.5 < m_{\mu\mu} < 11.5$ GeV, $p_{\mathrm{T}} > 9.9$ GeV, and $|y| < 1.4$. The two muon tracks are fitted together, imposing a common vertex, and the χ^2 fit probability is required to be larger than 0.5%. The events selected for the final analysis also need to pass data-quality certification criteria.

At the offline analysis level, where the kinematical properties of the muons are known with a higher precision than at the trigger level, further selection criteria are applied. To start with, the selected muons must match the trigger requirements and pass certain ("soft muon") quality requirements [44]. Furthermore, only muons that have $p_{\mathrm{T}} > 10$ GeV and $|\eta| < 1.4$ are kept. In addition, the dimuon vertex fit is redone and the resulting χ^2 probability is required to be larger than 1%. If an event has more than one muon pair passing the requirements (happening in less than 0.05% of the selected events), only the pair with the largest vertex χ^2 probability is kept.

For several steps of the analysis procedure, described below, detailed Monte Carlo (MC) simulations are performed, covering the full data collection and reconstruction chain, from the trigger step to the offline event selection. The event samples are generated with the PYTHIA 8.306 event generator [50, 51], configured with the CP5 tune [52] and the NNPDF3.1 NNLO set of parton distribution functions [53]. The emitted muons undergo final-state radiation, generated through the PHOTOS 3.61 package [54]. The simulation includes effects from multiple pp interactions in the same or nearby bunch crossings, with a multiplicity distribution matching the data. The events are then processed through a simulation of the CMS detector, based on the GEANT4 package [55], using the same trigger, reconstruction algorithms, and selection criteria as used to collect and process the data.

3 Acceptance and efficiencies

The acceptances, $\mathcal{A}(p_{\mathrm{T}}, |y|)$, are calculated using a large sample of simulated Υ(1S) events, covering a broader phase space window than that used in the analysis. The Υ(1S) p_{T} and $|y|$ distributions used in the event generation are reweighted by the ratios between the background-subtracted measured spectra [56] and the simulated spectra. For each $(p_{\mathrm{T}}, |y|)$

bin of the $\Upsilon(1S)$, the acceptance is computed as the fraction of generated events where both decay muons have $p_T > 10\,\text{GeV}$ and $|\eta| < 1.4$. The differences between the acceptance values evaluated for the three bottomonium states are negligible (less than 1%), given the high granularity of the acceptance tables, as well as their similar masses and decay kinematics, so that the $\Upsilon(1S)$ values are also used to obtain the $\Upsilon(2S)$ and $\Upsilon(3S)$ cross sections.

The default acceptances are computed assuming that the $\Upsilon(nS)$ mesons are produced unpolarized, an assumption compatible with the currently available measurements [35]. The reported cross sections can be converted to those that would have been obtained if other polarization scenarios had been assumed, by using the correction factors presented in table 1 of appendix A, corresponding to full transverse or full longitudinal production (i.e., assuming that the polar asymmetry parameter in the centre-of-mass helicity frame takes the extreme values $\lambda_\vartheta = \pm 1$).

The detection efficiencies of the muons used in the analysis are factorized into three terms: trigger, muon identification, and muon reconstruction. They have been measured, as functions of the muon p_T and in several $|\eta|$ bins, with a tag-and-probe technique [18, 27, 32] applied to a sample of $\Upsilon(1S)$ events collected with single muon triggers. The dimuon efficiency that enters in eq. (1.1) is computed as the product of the two single-muon efficiencies, times a scaling factor that corrects for the detection inefficiency that occurs when the two muons are emitted close to each other in angular and momentum space, so that they might be considered as a single track at L1 and, hence, fail to trigger the data acquisition system [19, 23, 34, 39]. This correction factor, which also accounts for the dimuon vertex inefficiency, is evaluated using the detailed simulation of the full detection chain.

4 Yield extraction

The $\Upsilon(nS)$ signal yields are evaluated, in each $(p_T, |y|)$ bin, by performing a binned extended maximum likelihood fit (using RooFit [57]) to the measured dimuon invariant mass distribution. The measured distributions are fitted with a model composed of three signal terms, each of them parametrized by the sum of two Crystal Ball (CB) functions [58], plus a second-order polynomial function to describe the underlying continuum background. The two CB functions that describe each of the three Υ resonances have shapes determined by their means (μ_1 and μ_2), widths (σ_1 and σ_2), and non-Gaussian tail parameters (n_1, n_2, α_1, and α_2). This fit model (and the fixed shape parameters mentioned below) has been defined from studies of simulated event distributions, validated with data distributions integrated over p_T.

A good description of the mass spectra is obtained with a relatively small number of free parameters. Specifically, the fit model imposes $\mu_2 = \mu_1$, $\sigma_2/\sigma_1 = 1.55$, $n_1 = 1$, $n_2 = 2$, $\alpha_1 = \alpha_2 = 2$. The two CB functions contribute to the total signal function as $f\,CB_1 + (1-f)\,CB_2$, where $f = 0.4$ is the weight of the narrowest term. The shapes of the three signal peaks are jointly determined, imposing that the differences between the three μ parameters are identical to the differences between the world-average values of the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ masses [59] and that the three σ_1 values scale in the same proportions as those masses. In short, the free parameters in the fits, for each $(p_T, |y|)$ bin, are the amplitudes of the three signal terms, the μ_1 and σ_1 shape parameters of the $\Upsilon(1S)$ peak, and the three parameters specifying the background term. All the independently-fitted dimuon

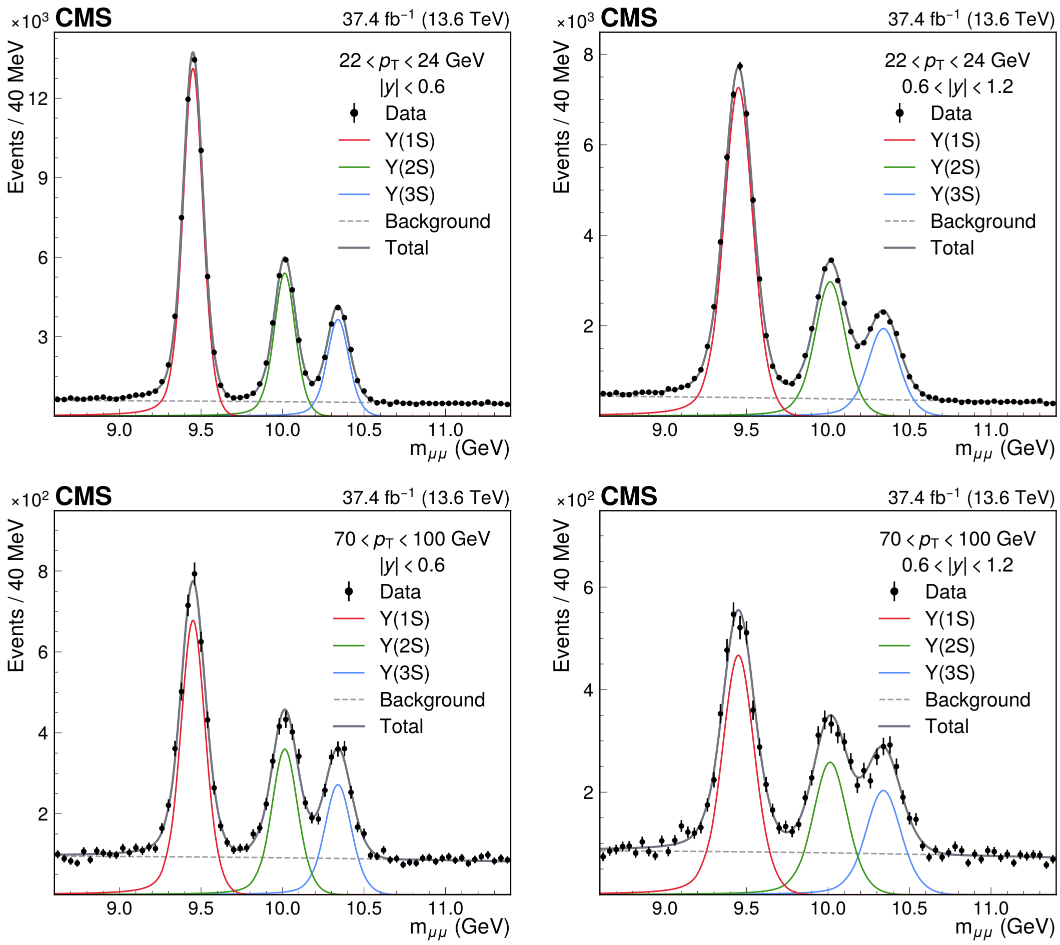

Figure 1. Invariant dimuon mass distributions for dimuon p_T of $22 < p_T < 24$ GeV (upper) and $70 < p_T < 100$ GeV (lower) with dimuon rapidity of $|y| < 0.6$ (left) and $0.6 < |y| < 1.2$ (right). The results of the fits are represented by the solid coloured lines (signal peaks), the dashed gray lines (background), and the solid black lines (total).

mass distributions are well described by this model, with the μ_1 parameter being close to 9.45 GeV, independently of p_T and y, while σ_1 increases approximately linearly with p_T, in the 20–200 GeV range, from 50 to 65 MeV (from 65 to 90 MeV) for $|y| < 0.6$ ($0.6 < |y| < 1.2$). Figure 1 shows the $m_{\mu\mu}$ distributions measured for two illustrative p_T bins, in both $|y|$ bins, together with the result of the corresponding fits.

5 Systematic uncertainties

Several sources of systematic uncertainty are considered. The integrated luminosity is measured with an uncertainty of 1.4% [60]. This is a global uncertainty, commonly affecting all (p_T, y) bins.

The uncertainties in the signal yields are evaluated by refitting the $m_{\mu\mu}$ distributions with alternative fit models for the signal and background terms that still provide a reasonably good description the data. Specifically, the fits were redone in the following alternate conditions:

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leaving the three μ parameters free; leaving the three σ_1 parameters free; changing the n_1 and n_2 fixed CB tail parameters by ± 0.5, independently of each other or simultaneously; and varying the fixed σ_2/σ_1 ratio by 0.05. To evaluate the systematic uncertainty in the signal yields reflecting the function assumed for the combinatorial background term, the fits were redone replacing the second-order polynomial by an exponential function, a linear function or a third-order polynomial. For all variations, the maximal difference between the baseline and the alternate options (in each $(p_{\mathrm{T}}, |y|)$ bin) is taken as the uncertainty. The systematic uncertainty in the measured cross sections resulting from the evaluation of the signal yields is uncorrelated in p_{T} and $|y|$, with values in the ranges $\approx$2–3% for the Υ(1S), $\approx$3–5% for the Υ(2S), and $\approx$3–7% for the Υ(3S).

The uncertainty in the acceptance is evaluated from the differences between the baseline values and those obtained with a simulation where the Υ(1S) p_{T} and $|y|$ distributions are generated without any reweighting to match the simulated and measured spectra. The corresponding uncertainty in the measured cross sections decreases as the dimuon p_{T} increases, from $\approx$10% at low p_{T} to less than 1% for $p_{\mathrm{T}} > 50\,\mathrm{GeV}$. This systematic uncertainty is strongly correlated between p_{T} and $|y|$ bins. We also verified that the differences between the three $\Upsilon(n\mathrm{S})$ acceptances are negligible.

The uncertainty in the dimuon detection efficiency includes two sources: the single muon efficiencies of each of the two muons and the muon-pair detection inefficiency occurring when the two muons have trajectories that are too close to each other. The uncertainties in the single muon efficiencies are evaluated by propagating the uncertainties of the tag-and-probe measurements. The corresponding uncertainties in the measured cross sections vary between $\approx$4% at low p_{T} and $\approx$6% for the highest p_{T} bins. The uncertainty in the factor that corrects for the muon-pair trigger inefficiency reflects potential residual differences between the effect induced by the detector and its emulation in the detailed MC simulation. To evaluate the magnitude of such potential variations, we start by comparing the MC event distributions (at the level of reconstructed variables) before and after applying the dimuon trigger criteria, to quantify how the dimuon trigger efficiency decreases as the two muon trajectories approach each other [19, 23, 34, 39]. Such studies allow us to identify events with low dimuon trigger efficiency, those for which the inefficiency correction is the largest and, hence, make the analysis the most sensitive to the accuracy of the MC simulation. The cross section measurement is then redone after rejecting that subsample of events, removing this source of a potential bias at the cost of increasing the statistical uncertainty. The differences between the baseline cross sections and the values obtained after rejecting events with low dimuon detection efficiency are within the fluctuations expected from the reduction in the size of the event sample. Nevertheless, to ensure that the results account for potential inaccuracies in the MC dimuon trigger emulation, we evaluated a corresponding uncertainty, increasing from $\approx$1% (2.5%) in the lowest p_{T} bin to $\approx$6% (9%) for $p_{\mathrm{T}} \approx 50\,\mathrm{GeV}$, in the $|y| < 0.6$ ($0.6 < |y| < 1.2$) range, remaining flat at higher p_{T}. This systematic uncertainty is strongly correlated between p_{T} and $|y|$ bins.

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6 Results

Figure 2 (top) shows the measured p_T-differential $\Upsilon(nS)$ cross sections times the branching fractions of their $\mu^+\mu^-$ decays for $|y| < 0.6$ and $0.6 < |y| < 1.2$. The data points are shown at the mean values of the p_T distributions of the measured events inside each p_T bin; the numerical values, for the three $\Upsilon(nS)$ states, are listed in tables 2–4, in appendix A. The measured cross sections include feed-down decays from heavier bottomonium states and are based on the assumption that the mesons are produced unpolarized. Table 1 can be used to adjust the data to other polarization scenarios. The two rapidity ranges (both close to midrapidity) lead to almost identical cross sections. No $\Upsilon(2S)$ and $\Upsilon(3S)$ values are provided for the highest p_T bin because the collected number of events is too small to provide a robust extraction of those two yields.

In order to better appreciate how the shapes of the p_T-differential cross sections vary among the three $\Upsilon(nS)$ states, figure 2 (bottom) shows the cross section ratios with respect to the ground state. For $p_T \gtrsim 55\,\text{GeV}$, the ratios seem to reach a plateau.

Both panels of figure 2 include NRQCD predictions [61] for the collision energy and kinematical phase space of our measurement. Contributions from feed-down decays of heavier S- and P-wave bottomonia are included. The NRQCD predictions describe the general trends of the measured cross sections reasonably well. Different curves would be obtained if computed with alternative LDME values, with other feed-down fractions and polarization scenarios, including higher-order terms in the perturbative expansion, etc., so that this specific comparison is only meant to illustrate that the new measurements reported in this article provide important constraints for improved phenomenological global-fit data analyses.

Figure 3 shows the ratios between the new $\Upsilon(nS)$ measurements, made at $\sqrt{s} = 13.6\,\text{TeV}$, and the corresponding cross sections measured at 7 and 13 TeV, using event samples corresponding to integrated luminosities of 4.9 and $2.7\,\text{fb}^{-1}$, respectively [31, 32].

7 Summary

The cross sections of the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ bottomonium states, times the branching fractions of their dimuon decays, were measured as a function of their transverse momentum in a broad p_T range, from 20 to 200 GeV, in two rapidity regions, $|y| < 0.6$ and $0.6 < |y| < 1.2$. The analysis was based on an event sample of pp collisions at $\sqrt{s} = 13.6\,\text{TeV}$, collected by CMS in 2022 and corresponding to an integrated luminosity of $37.4\,\text{fb}^{-1}$. The reported cross sections include feed-down contributions from heavier bottomonia. These results are an important input to global fits of quarkonium cross sections and polarizations, made in the context of the NRQCD framework or of other models of quarkonium production.

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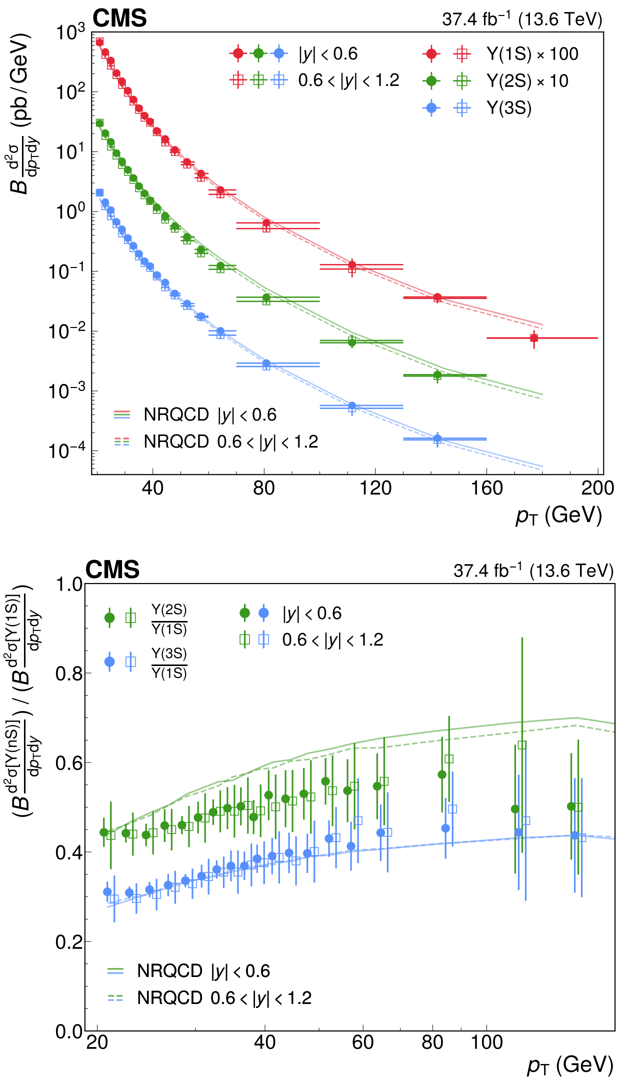

Figure 2. Top: Measured p_T-differential Υ(1S) (red), Υ(2S) (green), and Υ(3S) (blue) cross sections times the $\mu^+\mu^-$ decay branching fractions, per rapidity unit, in the 0–0.6 (filled circles) and 0.6–1.2 (open squares) $|y|$ ranges. For visibility, the Υ(1S) and Υ(2S) values are scaled by factors of 100 and 10, respectively. Bottom: Corresponding Υ(2S) over Υ(1S) (green) and Υ(3S) over Υ(1S) (blue) ratios, in the 0–0.6 (filled circles) and 0.6–1.2 (open squares) $|y|$ ranges. For visibility purposes, the data points are slightly displaced in the x axis. In both panels, the error bars represent the total uncertainties. The NRQCD curves are shown for illustration.

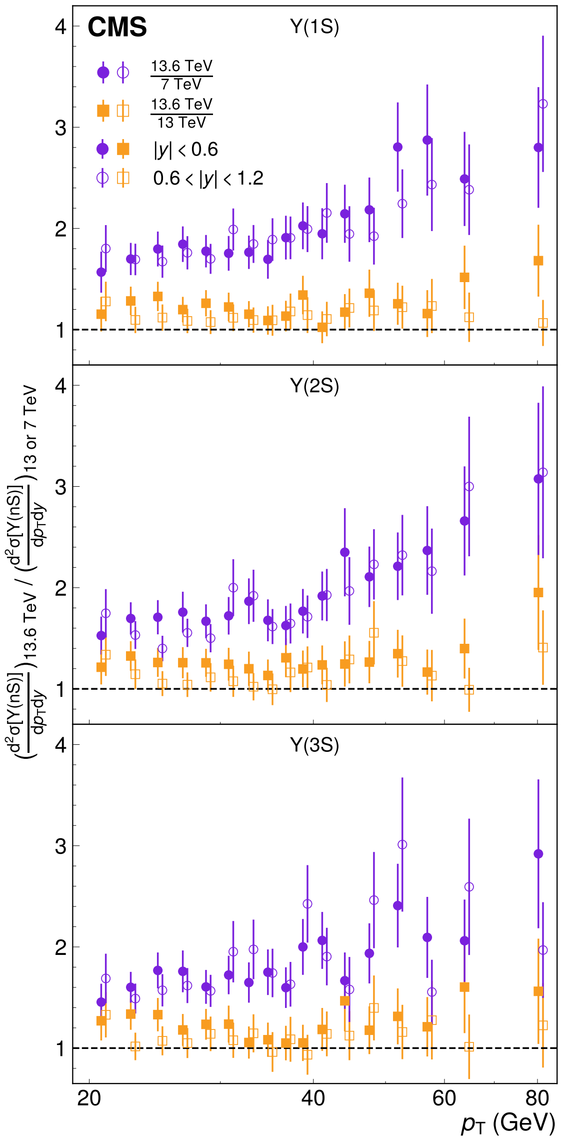

Figure 3. Ratios of $\Upsilon(nS)$ cross sections between this measurement, made at $\sqrt{s} = 13.6\,\text{TeV}$, and previous measurements, made at 7 and 13 TeV [31, 32], treating all uncertainties as uncorrelated. For visibility purposes, the data points are slightly displaced in the x axis.

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A Tables of cross sections and correction factors

This appendix collects a table 1 listing the scaling factors needed to derive, from the "unpolarized values", the cross sections corresponding to any other polarization scenario, by interpolating between the two most extreme polarization cases, in the helicity frame. It also includes three tables 2–4 with the numerical values of the p_{T}-differential Υ(1S), Υ(2S), and Υ(3S) cross section measurements, in two rapidity ranges, under the assumption of unpolarized production. The $\langle p_{\mathrm{T}} \rangle$ values are the mean values of the background-subtracted and efficiency-corrected p_{T} distributions, in each p_{T} bin.

Δp_{T} (GeV)	$\lvert y\rvert < 0.6$		$0.6 < \lvert y\rvert < 1.2$	
	$\lambda_\theta = +1$	$\lambda_\theta = -1$	$\lambda_\theta = +1$	$\lambda_\theta = -1$
20–22	1.32	0.67	1.30	0.68
22–24	1.31	0.68	1.28	0.70
24–26	1.30	0.68	1.27	0.70
26–28	1.29	0.69	1.27	0.70
28–30	1.28	0.69	1.25	0.71
30–32	1.26	0.70	1.25	0.71
32–34	1.26	0.71	1.25	0.72
34–36	1.25	0.72	1.23	0.73
36–38	1.24	0.72	1.23	0.73
38–40	1.23	0.73	1.22	0.74
40–43	1.22	0.73	1.21	0.74
43–46	1.21	0.75	1.20	0.75
46–50	1.20	0.75	1.19	0.76
50–55	1.18	0.77	1.18	0.77
55–60	1.17	0.78	1.16	0.78
60–70	1.15	0.79	1.15	0.80
70–100	1.12	0.83	1.12	0.83
100–130	1.09	0.86	1.09	0.86
130–160	1.07	0.88	1.07	0.88
160–200	1.06	0.90		

Table 1. Scaling factors needed to obtain the $\Upsilon(n\mathrm{S})$ differential cross sections corresponding to two extreme polarization scenarios in the helicity frame, $\lambda_\theta^{\mathrm{HX}} = +1$ or -1, from the values reported in tables 2–4.

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Δp_T (GeV)	$\langle p_T \rangle$ (GeV)	$\mathcal{B}\, d^2\sigma/dp_T dy$: $\lvert y\rvert < 0.6$ (pb/GeV)	δ_{stat} (%)	δ_{syst} (%)	$0.6 < \lvert y\rvert < 1.2$ (pb/GeV)	δ_{stat} (%)	δ_{syst} (%)
20–22	20.9	6.64	0.50	11	6.98	0.58	12
22–24	22.9	4.62	0.47	7.4	4.13	0.54	8.0
24–26	24.9	3.32	0.50	7.6	2.73	0.56	8.2
26–28	26.9	2.06	0.54	8.5	1.90	0.61	7.9
28–30	28.9	1.50	0.61	6.7	1.30	0.67	7.1
30–32	31.0	1.04	0.69	7.8	9.63×10^{-1}	0.75	8.0
32–34	33.0	7.41×10^{-1}	0.77	7.3	6.85×10^{-1}	0.84	6.9
34–36	35.0	5.32×10^{-1}	0.88	8.5	4.97×10^{-1}	0.95	9.3
36–38	37.0	3.99×10^{-1}	0.99	8.6	3.68×10^{-1}	1.1	8.9
38–40	39.0	3.18×10^{-1}	1.1	8.4	3.03×10^{-1}	1.2	8.8
40–43	41.4	2.22×10^{-1}	1.1	8.3	2.11×10^{-1}	1.1	11
43–46	44.4	1.63×10^{-1}	1.2	11	1.42×10^{-1}	1.3	10
46–50	47.9	1.07×10^{-1}	1.3	8.9	9.81×10^{-2}	1.4	12
50–55	52.3	6.73×10^{-2}	1.5	9.1	6.06×10^{-2}	1.6	11
55–60	57.3	4.31×10^{-2}	1.8	9.5	3.65×10^{-2}	2.0	14
60–70	64.3	2.29×10^{-2}	1.8	11	1.93×10^{-2}	2.0	14
70–100	80.8	6.44×10^{-3}	2.1	14	5.17×10^{-3}	2.3	12
100–130	111.6	1.29×10^{-3}	5.1	12	1.09×10^{-3}	5.8	27
130–160	142.3	3.72×10^{-4}	11	13	3.53×10^{-4}	11	13
160–200	177.0	7.61×10^{-5}	26	9.8	7.71×10^{-5}	29	19

Table 2. The Υ(1S) differential cross section times dimuon branching fraction, $\mathcal{B}\, d^2\sigma/dp_T dy$, in two rapidity ranges, for the unpolarized scenario. The relative uncertainties (statistical and systematic) are given in percent. The systematic uncertainties are partially correlated across all the $(p_T, |y|)$ bins.

Δp_{T}	$\langle p_{\mathrm{T}} \rangle$	$\mathcal{B}\,\mathrm{d}^2\sigma/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y$					
		$\lvert y \rvert < 0.6$			$0.6 < \lvert y \rvert < 1.2$		
(GeV)	(GeV)	(pb/GeV)	δ_{stat} (%)	δ_{syst} (%)	(pb/GeV)	δ_{stat} (%)	δ_{syst} (%)
20–22	20.9	2.95	0.80	11	3.05	0.95	13
22–24	22.9	2.04	0.75	7.6	1.82	0.88	8.5
24–26	24.9	1.45	0.79	8.0	1.21	0.91	8.2
26–28	26.9	9.44×10^{-1}	0.84	9.0	8.56×10^{-1}	1.0	8.6
28–30	28.9	6.89×10^{-1}	0.94	6.7	5.96×10^{-1}	1.1	7.5
30–32	31.0	4.96×10^{-1}	1.0	8.1	4.58×10^{-1}	1.2	8.4
32–34	33.0	3.62×10^{-1}	1.2	7.7	3.36×10^{-1}	1.3	6.9
34–36	35.0	2.65×10^{-1}	1.3	8.8	2.44×10^{-1}	1.5	10
36–38	37.0	2.00×10^{-1}	1.5	8.4	1.86×10^{-1}	1.6	9.3
38–40	39.0	1.52×10^{-1}	1.7	8.2	1.49×10^{-1}	1.9	9.1
40–43	41.4	1.17×10^{-1}	1.5	8.7	1.06×10^{-1}	1.7	10
43–46	44.4	8.46×10^{-2}	1.8	12	7.28×10^{-2}	2.0	10
46–50	47.9	5.69×10^{-2}	1.9	8.8	5.13×10^{-2}	2.1	13
50–55	52.3	3.76×10^{-2}	2.1	8.8	3.25×10^{-2}	2.3	11
55–60	57.3	2.32×10^{-2}	2.7	9.3	1.99×10^{-2}	3.0	15
60–70	64.3	1.25×10^{-2}	2.6	10	1.08×10^{-2}	2.9	14
70–100	80.5	3.69×10^{-3}	3.0	14	3.14×10^{-3}	3.3	11
100–130	111.6	6.39×10^{-4}	8.3	13	6.97×10^{-4}	8.2	21
130–160	142.3	1.87×10^{-4}	19	9.4	1.77×10^{-4}	19	14

Table 3. The Υ(2S) differential cross section times dimuon branching fraction, $\mathcal{B}\,\mathrm{d}^2\sigma/\mathrm{d}p_{\mathrm{T}}\mathrm{d}y$, in two rapidity ranges, for the unpolarized scenario. The relative uncertainties (statistical and systematic) are given in percent. The systematic uncertainties are partially correlated across all the $(p_{\mathrm{T}}, \lvert y \rvert)$ bins.

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		$\mathcal{B}\,\mathrm{d}^2\sigma/\mathrm{d}p_\mathrm{T}\mathrm{d}y$					
Δp_T	$\langle p_\mathrm{T}\rangle$	$\|y\| < 0.6$			$0.6 < \|y\| < 1.2$		
(GeV)	(GeV)	(pb/GeV)	δ_stat (%)	δ_syst (%)	(pb/GeV)	δ_stat (%)	δ_syst (%)
20–22	20.9	2.07	0.50	11	2.06	1.2	13
22–24	22.9	1.43	0.58	7.5	1.22	1.1	8.2
24–26	24.9	1.05	0.69	7.8	8.33×10^{-1}	1.1	8.2
26–28	26.9	6.70×10^{-1}	0.86	8.7	6.10×10^{-1}	1.2	8.2
28–30	28.9	5.04×10^{-1}	0.94	6.7	4.29×10^{-1}	1.3	7.3
30–32	31.0	3.60×10^{-1}	1.1	8.0	3.32×10^{-1}	1.4	8.2
32–34	33.0	2.67×10^{-1}	1.3	7.5	2.43×10^{-1}	1.6	6.9
34–36	35.0	1.96×10^{-1}	1.4	8.7	1.76×10^{-1}	1.8	9.8
36–38	37.0	1.47×10^{-1}	1.8	8.5	1.37×10^{-1}	2.0	9.1
38–40	39.0	1.22×10^{-1}	1.8	8.4	1.14×10^{-1}	2.2	8.9
40–43	41.4	8.67×10^{-2}	1.7	8.5	8.19×10^{-2}	2.0	10
43–46	44.4	6.50×10^{-2}	2.1	11	5.37×10^{-2}	2.5	10
46–50	47.9	4.26×10^{-2}	2.5	8.9	3.94×10^{-2}	2.5	12
50–55	52.3	2.89×10^{-2}	2.4	8.9	2.62×10^{-2}	2.7	11
55–60	57.3	1.78×10^{-2}	3.2	9.4	1.71×10^{-2}	3.3	14
60–70	64.3	1.01×10^{-2}	3.0	11	8.56×10^{-3}	3.4	14
70–100	80.6	2.92×10^{-3}	3.8	14	2.56×10^{-3}	3.8	11
100–130	111.6	5.72×10^{-4}	9.7	12	5.13×10^{-4}	10	24
130–160	142.3	1.62×10^{-4}	25	11	1.52×10^{-4}	22	13

Table 4. The $\Upsilon(3\mathrm{S})$ differential cross section times dimuon branching fraction, $\mathcal{B}\,\mathrm{d}^2\sigma/\mathrm{d}p_\mathrm{T}\mathrm{d}y$, in two rapidity ranges, for the unpolarized scenario. The relative uncertainties (statistical and systematic) are given in percent. The systematic uncertainties are partially correlated across all the $(p_\mathrm{T}, |y|)$ bins.

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Data Availability Statement. Release and preservation of data used by the CMS Collaboration as the basis for publications is guided by the CMS data preservation, re-use and open access policy.

Code Availability Statement. The CMS core software is publicly available on GitHub.

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The CMS collaboration

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