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Measurement of the $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ cross sections in pp collisions at $\sqrt{s} = 7$ TeV ☆

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ABSTRACT

The $\Upsilon(1S)$, $\Upsilon(2S)$, and $\Upsilon(3S)$ production cross sections are measured using a data sample corresponding to an integrated luminosity of $35.8 \pm 1.4\ \text{pb}^{-1}$ of proton–proton collisions at $\sqrt{s} = 7$ TeV, collected with the CMS detector at the LHC. The Υ resonances are identified through their decays to dimuons. Integrated over the Υ transverse momentum range $p_T^{\Upsilon} < 50\ \text{GeV}/c$ and rapidity range $|y^{\Upsilon}| < 2.4$, and assuming unpolarized Υ production, the products of the Υ production cross sections and dimuon branching fractions are

$$\sigma(\text{pp} \to \Upsilon(1S)X) \cdot \mathcal{B}(\Upsilon(1S) \to \mu^+\mu^-) = (8.55 \pm 0.05^{+0.56}_{-0.50} \pm 0.34)\ \text{nb},$$
$$\sigma(\text{pp} \to \Upsilon(2S)X) \cdot \mathcal{B}(\Upsilon(2S) \to \mu^+\mu^-) = (2.21 \pm 0.03^{+0.16}_{-0.14} \pm 0.09)\ \text{nb},$$
$$\sigma(\text{pp} \to \Upsilon(3S)X) \cdot \mathcal{B}(\Upsilon(3S) \to \mu^+\mu^-) = (1.11 \pm 0.02^{+0.10}_{-0.08} \pm 0.04)\ \text{nb},$$

where the first uncertainty is statistical, the second is systematic, and the third is from the uncertainty in the integrated luminosity. The differential cross sections in bins of transverse momentum and rapidity, and the cross section ratios are presented. Cross section measurements performed within a restricted muon kinematic range and not corrected for acceptance are also provided. These latter measurements are independent of Υ polarization assumptions. The results are compared to theoretical predictions and previous measurements.

1. Introduction

No existing theoretical approach successfully reproduces both the differential cross section and the polarization measurements of the J/ψ or Υ states [1] in hadron collisions. Studying quarkonium hadroproduction at high center-of-mass energies and over a wide rapidity and transverse momentum range will facilitate significant improvements in our understanding of the processes involved.

Measurements of Υ production have been performed by several experiments [1–5]. The first measurement at $\sqrt{s} = 7$ TeV at the Large Hadron Collider (LHC) was reported by the Compact Muon Solenoid (CMS) Collaboration [6], using a data sample corresponding to an integrated luminosity of 3 pb^{-1}. This Letter constitutes an extension of that first cross section measurement, using a larger, independent sample, corresponding to an integrated luminosity of $35.8 \pm 1.4\ \text{pb}^{-1}$ collected in 2010.

Two different approaches to the measurement of the $\Upsilon(nS)$ production cross sections, where $n = 1$–3, are pursued in this Letter. In each approach, the Υ is reconstructed in the decay $\Upsilon \to \mu^+\mu^-$. In the first approach, a cross section measurement corrected for detector acceptance and efficiencies is presented, as in Ref. [6]. This cross section measurement depends on the spin alignment of the Υ. No net polarization is assumed for the main results. To show the sensitivity of the results to the polarization and to allow for interpolation, we provide measurements for other polarization assumptions. Recently, the CMS Collaboration has measured the polarizations of the $\Upsilon(nS)$ in pp collisions at $\sqrt{s} = 7$ TeV, which are found to be small [7]. Cross section measurements are also provided in the Υ transverse momentum (p_T^{Υ}) and rapidity (y^{Υ}) ranges matching those of the polarization measurement, and these polarization results are used to estimate the associated systematic uncertainty. The motivation for the second approach, also used by the ATLAS Collaboration [5], is to eliminate the dependence of the measured cross sections on the spin alignment of the Υ. In this second approach, a fiducial cross section measurement, corrected for detector efficiencies but not for acceptance, is presented. This cross section is defined within a muon kinematic range.

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The Letter is organized as follows. Section 2 contains a short description of the CMS detector. Section 3 presents the data collection, the trigger and offline event selections, and the reconstruction of the Υ resonances. Section 4 describes the measurement technique. The detector acceptance and efficiencies to reconstruct Υ resonances that decay to two muons are discussed in Sections 5 and 6. The evaluation of systematic uncertainties in the measurements is described in Section 7. In Sections 8 and 9, the $\Upsilon(n\mathrm{S})$ fiducial and acceptance-corrected cross section results and comparisons to other experiments and to theoretical predictions are presented.

2. CMS detector

The central feature of the CMS apparatus is a superconducting solenoid, of 6 m inner diameter, producing a magnetic field of 3.8 T. Within the superconducting solenoid volume are a silicon pixel and strip tracker, a lead tungstate crystal electromagnetic calorimeter, and a brass/scintillator hadron calorimeter. Muons are detected by three types of gas-ionization detectors embedded in the magnet steel return yoke surrounding the solenoid: drift tubes, cathode strip chambers, and resistive-plate chambers. The muon measurement covers the pseudorapidity range $|\eta^{\mu}| < 2.4$, where $\eta = -\ln[\tan(\theta/2)]$ and the polar angle θ is measured from the axis pointing along the counterclockwise-beam direction. The muon transverse momentum measurement, p_{T}^{μ}, based on information from the silicon tracker alone, has a resolution of about 1% for a typical muon in this analysis. The two-level CMS trigger system selects events of interest for permanent storage. The first trigger level, composed of custom hardware processors, uses information from the calorimeter and muon detectors to select events in less than 3.2 µs. The high-level trigger software algorithms, executed on a farm of commercial processors, further reduce the event rate using information from all detector subsystems. A detailed description of the CMS detector can be found in Ref. [8].

3. Data selection and event reconstruction

The data sample was collected in 2010, in low instantaneous luminosity conditions, allowing a less restrictive selection at the trigger level in comparison to subsequent data taking periods. Data are included in the analysis for all periods where the silicon tracker, the muon detectors, and the trigger were performing well and the luminosity information was available. In the first data-taking period, the trigger requires the detection of two muons without an explicit p_{T}^{μ} requirement. The minimum distance between each reconstructed muon trajectory and the average proton–proton interaction point in the transverse plane must be less than 2 cm. In the second data-taking period, characterized by higher LHC instantaneous luminosities, additional requirements are imposed at trigger level: the two muons must have opposite charge and an invariant mass in the mass range $1.5 < M_{\mu\mu} < 14.5\ \mathrm{GeV}/c^2$. All three muon systems take part in the trigger decision. In the first (second) data-taking period the trigger selected about 2 (5) million events.

Simulation is employed to design the offline selection, assess the detector acceptance, and study systematic effects. The $\Upsilon(n\mathrm{S})$ events are simulated using PYTHIA 6.412 [9], which generates events based on the leading-order color-singlet and color-octet mechanisms, with nonrelativistic quantum chromodynamics (QCD) matrix elements, tuned by comparing calculations with CDF data [10], and applying the normalization and wave functions recommended in Ref. [11]. The underlying-event simulation uses the CTEQ6L1 parton distribution functions [12]. Since PYTHIA does not provide a simulation of $\Upsilon(2\mathrm{S})$ and $\Upsilon(3\mathrm{S})$, the predictions for these states are obtained by replacing the $\Upsilon(1\mathrm{S})$ mass in the simulation with the $\Upsilon(2\mathrm{S})$ and $\Upsilon(3\mathrm{S})$ masses, respectively. Contributions from the decays of higher-mass bottomonium states (feed-down) are included in the simulation. For simulating the $\Upsilon(2\mathrm{S})$ feed-down component, the masses of the 2P states replace the corresponding 1P states. For the $\Upsilon(3\mathrm{S})$ the feed-down is assumed to be small and is not simulated. Final-state radiation (FSR) is implemented using PHOTOS [13,14]. The response of the CMS detector is simulated with a GEANT4-based [15] Monte Carlo (MC) simulation program. Simulated events are processed with the same reconstruction and trigger algorithms used for data.

The offline selection starts from Υ candidates reconstructed from pairs of oppositely charged muons with invariant mass between 7 and 14 GeV/c^2. The muons are required to have one or more reconstructed track segments in the muon systems that are well matched to the extrapolated position of a track reconstructed in the silicon tracker. Quality criteria are applied to the tracks to reject muons from kaon and pion decays. Tracks are required to have at least 11 hits in the silicon tracker, at least one of which must be in the pixel detector, and a track-fit χ^2 per degree of freedom smaller than 5. In addition, tracks are required to extrapolate back to a cylindrical volume of radius 2 mm and length 25 cm, centered on the pp interaction region and parallel to the beam line. After offline confirmation of the trigger selection, muons are required to satisfy a kinematic threshold that depends on pseudorapidity

$$\begin{aligned} p_{\mathrm{T}}^{\mu} &> 3.75\ \mathrm{GeV}/c \quad \text{if } |\eta^{\mu}| < 0.8, \\ p_{\mathrm{T}}^{\mu} &> 3.5\ \mathrm{GeV}/c \quad \text{if } 0.8 < |\eta^{\mu}| < 1.6, \\ p_{\mathrm{T}}^{\mu} &> 3.0\ \mathrm{GeV}/c \quad \text{if } 1.6 < |\eta^{\mu}| < 2.4. \end{aligned} \tag{1}$$

These kinematic acceptance criteria are chosen to ensure that the trigger and muon reconstruction efficiencies are high and not rapidly changing within the phase space of the analysis. The longitudinal separation between the two muons along the beam axis is required to be less than 2 cm. The two muon helices are fit with a common vertex constraint, and events are retained if the fit χ^2 probability is larger than 0.1%. If multiple dimuon candidates are found in the same event, the candidate with the smallest vertex-fit χ^2 probability is retained; the fraction of Υ candidates rejected by this requirement is about 0.6%.

4. Measurement of the inclusive differential cross section

The product of the $\Upsilon(n\mathrm{S})$ differential cross section, σ, and the dimuon branching fraction, $\mathcal{B}$, is determined from the signal yield $N^{\mathrm{cor}}_{\Upsilon(n\mathrm{S})}$, corrected by the acceptance $\mathcal{A}$ and the efficiency ϵ, using

$$\begin{aligned} &\frac{\mathrm{d}\sigma(\mathrm{pp} \to \Upsilon(n\mathrm{S})X)}{\mathrm{d}p_{\mathrm{T}}^{\Upsilon}\,\mathrm{d}y^{\Upsilon}} \cdot \mathcal{B}\big(\Upsilon(n\mathrm{S}) \to \mu^+\mu^-\big) \\ &\quad = \frac{N^{\mathrm{cor}}_{\Upsilon(n\mathrm{S})}(p_{\mathrm{T}}^{\Upsilon}, y^{\Upsilon}; \mathcal{A}, \epsilon)}{\mathcal{L} \cdot \Delta p_{\mathrm{T}}^{\Upsilon} \cdot \Delta y^{\Upsilon}}, \end{aligned} \tag{2}$$

where $\mathcal{L}$ is the integrated luminosity of the data set, and $\Delta p_{\mathrm{T}}^{\Upsilon}$ and Δy^{Υ} are the bin widths of the Υ transverse momentum and rapidity, respectively. The rapidity is defined as $y = \frac{1}{2}\ln(\frac{E+p_z c}{E-p_z c})$, where E is the energy and p_z is the momentum component parallel to the beam axis of the muon pair.

The $\Upsilon(n\mathrm{S})$ yields are extracted via an extended unbinned maximum-likelihood fit to the dimuon invariant-mass spectrum. The measured mass line shape of each Υ state is parametrized by a "Crystal Ball" (CB) [16] function, which consists of a Gaussian core portion and a power-law low-side tail to allow for FSR,

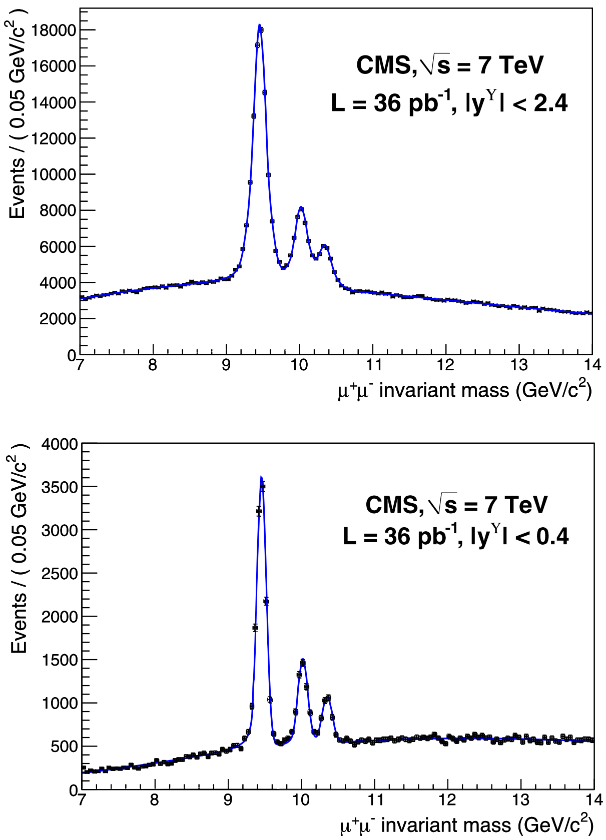

Fig. 1. The dimuon invariant-mass distribution in the vicinity of the $\Upsilon(nS)$ resonances for $|y^{\Upsilon}| < 2.4$ (top) and for the subset of events where the rapidity of the $\Upsilon(nS)$ satisfies $|y^{\Upsilon}| < 0.4$ (bottom). The solid lines represent the results of the fits to the signal-plus-background functions described in the text.

with the low-mass tail parameters fixed from MC simulation [6]. The three $\Upsilon(nS)$ states are fitted simultaneously since the three resonances overlap in the measured dimuon mass range. The resolution, given by the standard deviation of the Gaussian component of the CB, is a free parameter in the fit, but is constrained to scale with the ratios of the resonance masses. However, the mass resolution varies with Υ rapidity. Consequently, a single resolution term in the Gaussian component of the CB is not sufficient to describe the data. For this reason, in the p_T^{Υ} intervals with sufficient statistical precision, the sum of two CBs with the same mean and FSR tail parameters, but different resolutions, is used for each Υ state. The fitted resolution is consistent with expectation from MC at the few percent level. The $\Upsilon(nS)$ mass ratios are fixed to their world-average values [17]. The background in the 7–14 GeV/c^2 mass-fit range is nonpeaking and in some kinematic bins has a turn-on caused by the trigger and offline requirements. In general, the product of an error function and an exponential is chosen to describe the background [18], except when, for bins with poor statistical precision, a single exponential function is used. The dimuon invariant-mass spectra in the $\Upsilon(nS)$ region, before accounting for acceptance and efficiencies, are shown in Fig. 1 and in the supplemental material.

Following Ref. [6], given the significant p_T^{μ} and η^{μ} dependencies of the acceptances and efficiencies of the muons from $\Upsilon(nS)$ decays, we correct for them on a candidate-by-candidate basis before performing the mass fit to obtain $N^{\mathrm{cor}}_{\Upsilon(nS)}$ used in Eq. (2). The fiducial differential cross section is determined from the efficiency-corrected signal yield within the kinematic region defined in Eq. (1).

5. Acceptance

The $\Upsilon \to \mu^+\mu^-$ acceptance of the CMS detector is the product of two terms. The first is, for a given p_T^{Υ} and y^{Υ}, the fraction of dimuon decays in which both muons are within the phase space specified in Eq. (1). The second is the probability that when there are only two muons in the event both can be reconstructed in the tracker without requiring the quality criteria. Both components are evaluated by simulation and parametrized as a function of p_T^{Υ} and y^{Υ}. The second component is close to unity, as verified in simulation and data.

Following Ref. [6], the acceptance is defined by the ratio

$$\mathcal{A}(p_T^{\Upsilon}, y^{\Upsilon}) = \frac{N^{\mathrm{reco}}(p_T^{\Upsilon}, y^{\Upsilon} \mid \text{Si tracks satisfying Eq. (1)})}{N^{\mathrm{gen}}(p_T^{\Upsilon}, y^{\Upsilon})}, \qquad (3)$$

and is computed in small bins in $(p_T^{\Upsilon}, y^{\Upsilon})$. The parameter N^{gen} is the number of Υ particles generated within a given $(p_T^{\Upsilon}, y^{\Upsilon})$ bin, while N^{reco} is the number of Υ particles with reconstructed $(p_T^{\Upsilon}, y^{\Upsilon})$ values within that bin, and having the silicon tracks satisfying Eq. (1). The $(p_T^{\Upsilon}, y^{\Upsilon})$ values represent the generated and reconstructed values, respectively in the denominator and the numerator, thus accounting also for the effect of detector resolution in the definition of $\mathcal{A}$. In addition the numerator requires the two tracks to be reconstructed with opposite charges and have an invariant mass within the Υ mass-fit range of 7–14 GeV/c^2.

The acceptance is evaluated with a signal MC simulation sample in which the Υ decay to two muons is generated with the EVTGEN [19] package, including FSR. There are no particles in the event besides the Υ, its daughter muons, and the FSR photons. The Υ mesons are generated uniformly in p_T^{Υ} and y^{Υ}. This sample is then simulated and reconstructed with the CMS detector simulation software to assess the effects of multiple scattering and finite resolution of the detector. An acceptance map with the assumption of zero Υ polarization can be found in Ref. [6]. Systematic uncertainties arising from the dependence of the cross section measurement on the MC simulation description of the p_T spectrum and resolution are evaluated in Section 7. The acceptance is calculated as a two-dimensional grid in p_T^{Υ} and $|y^{\Upsilon}|$ using bin sizes of 0.1 in rapidity and 0.5 GeV/c in p_T^{Υ} for $0 < p_T^{\Upsilon} < 2$ GeV/c and 1 GeV/c for $2 < p_T^{\Upsilon} < 50$ GeV/c. The corresponding correction is then performed on a candidate-by-candidate basis. The acceptance depends on the resonance mass; the $\Upsilon(3S)$ gives rise to higher-momenta muons which results in a roughly 10% larger acceptance for the $\Upsilon(3S)$ than for the $\Upsilon(1S)$. Consequently, the corrected yield for each of the $\Upsilon(nS)$ resonances is obtained from a fit in which the corresponding $\Upsilon(nS)$ acceptance is employed. The acceptance decreases with rapidity, and there are no accepted events beyond $|y^{\Upsilon}| = 2.4$. The acceptance has a minimum near $p_T^{\Upsilon} = 5$ GeV/c, as a result of the softer muon failing the p_T^{μ} cut. The polarization of the Υ strongly influences the muon angular distributions and could be a function of p_T^{Υ}. In order to show the sensitivity of the result to the $\Upsilon(nS)$ polarization and to allow for interpolation, we provide cross section measurements for unpolarized (default) and 6 polarization scenarios in which the polar anisotropy parameter λ_θ [7] is changed from fully longitudinal to fully transverse polarization, corresponding to $\lambda_\theta = -1, -0.5, -0.25, 0.25, 0.5, 1$, in both the center-of-mass helicity and Collins–Soper [20] reference frames. Cross section measurements for the p_T^{Υ} and y^{Υ} ranges used in Ref. [7] are also provided in Fig. 4. In that case, the polarization results from Ref. [7] are used to estimate the corresponding systematic uncertainty.

6. Efficiency

The total muon efficiency is factorized into the three conditional terms,

$$\begin{aligned}\varepsilon &= \varepsilon(\text{trig}|\text{id}) \times \varepsilon(\text{id}|\text{track}) \times \varepsilon(\text{track}|\text{accepted}) \\ &\equiv \varepsilon_{\text{trig}} \times \varepsilon_{\text{id}} \times \varepsilon_{\text{track}}.\end{aligned} \tag{4}$$

The tracking efficiency, $\varepsilon_{\text{track}}$, combines the efficiency that the accepted track of a muon from a $\Upsilon(n\mathrm{S})$ decay is reconstructed in the presence of additional particles in the silicon tracker, as determined with a track-embedding technique [21], and the efficiency for the track to satisfy the track-quality criteria. The efficiency of the track-quality criteria [21] is nearly uniform in p_{T} and η and has an average value of $(98.66 \pm 0.05)\%$, as measured in Ref. [6], with negligible dependence on instantaneous luminosity. The muon identification efficiency, ε_{id}, is the probability that the silicon track caused by a muon is correctly identified as a muon. The efficiency that an identified muon satisfies the trigger is denoted by $\varepsilon_{\text{trig}}$. The track quality, muon trigger, and muon identification efficiencies are determined using the tag-and-probe (T&P) technique. The T&P implementation follows Ref. [6], and utilizes a J/ψ data sample as it provides a statistically independent, large-yield dimuon sample.

The Υ efficiency is estimated from the product of the single-muon efficiencies. A factor, ρ, is used as a correction to this factorization hypothesis, and to account for possible biases introduced by the T&P efficiency measurement with the J/ψ sample. We define ρ as

$$\rho\left(p_{\mathrm{T}}^{\Upsilon}, |y^{\Upsilon}|\right) = \frac{\epsilon(\Upsilon)}{\epsilon(\mu^{+}_{\mathrm{J}/\psi}) \cdot \epsilon(\mu^{-}_{\mathrm{J}/\psi})}, \tag{5}$$

where $\epsilon(\Upsilon)$ is the efficiency for a Υ to pass the trigger and muon identification selections, and $\epsilon(\mu^{+}_{\mathrm{J}/\psi})$ and $\epsilon(\mu^{-}_{\mathrm{J}/\psi})$ are the corresponding efficiencies for positively and negatively charged muons from a J/ψ decay with the same p_{T} and η as a muon in the Υ decay. The Υ efficiency is taken from MC simulation generator-level matching, which is performed by associating the two generated muons from the Υ with the reconstructed muons or trigger objects. The single-muon efficiencies are from the T&P method utilizing a J/ψ MC simulation sample. Finally, the efficiency of the vertex-fit χ^2 probability requirement is determined from data to be $(99.16 \pm 0.09)\%$ and constant over the entire kinematic range.

7. Systematic uncertainties

Systematic uncertainties in the cross section measurement stem from variations in the acceptance determination, potential residual inaccuracies in the efficiency measurement, the method of yield extraction, and the integrated luminosity. For each uncertainty, we give below in parentheses a representative range of values corresponding to the variation with $p_{\mathrm{T}}^{\Upsilon}$. The acceptance is varied in the dimuon invariant-mass fit coherently by ± 1 standard deviation, reflecting the uncertainty from the finite MC simulation statistics (0.3–1%). The acceptance is sensitive to biases in track momentum and differences in resolution between simulation and data. To determine the effect on the Υ acceptance, we introduce a track p_{T} bias of 0.2%, chosen based on the momentum scale biases seen in simulation and data [22]. We also vary the transverse momentum resolution by $\pm 10\%$, corresponding to the uncertainty in the resolution measurement using J/ψ in data. This reflects a conservative estimation of resolution effects. The acceptance map as a function of $p_{\mathrm{T}}^{\Upsilon}$ and $|y^{\Upsilon}|$ is then recalculated, and the systematic uncertainty is the difference in the resulting cross sections when using the perturbed acceptance map rather than the nominal one (0.0–0.7%). Imperfect knowledge of the production p_{T} spectrum of the Υ resonances at $\sqrt{s} = 7$ TeV contributes a systematic uncertainty. Using either a flat p_{T} distribution or the p_{T} distribution from PYTHIA, which is found to be consistent with the previously measured p_{T} distribution [6], gives rise to a systematic uncertainty (0.2%). FSR is incorporated into the simulation using the PHOTOS algorithm. To estimate the systematic uncertainty associated with this procedure, the acceptance is calculated without FSR, and 20% of the difference is taken as the uncertainty (0.1–0.8%), based on a study in Ref. [14].

Variation of the measured factorized efficiencies within their uncertainties also gives rise to a systematic uncertainty. The systematic uncertainties for the tracking efficiency (0.3–0.4%), muon identification efficiency (2–4%), and trigger efficiency (1–5%) are evaluated conservatively by coherently varying all bins by ± 1 standard deviation. The systematic uncertainty arising from the choice of bin size for the efficiencies is determined by fitting the efficiency turn-on curves as a function of muon p_{T}^{μ} in different $|\eta^{\mu}|$ regions using a hyperbolic tangent function and taking the muon efficiencies from the function instead of the binned value to compute the cross section (1–4%). The intrinsic bias from the T&P method, including possible bias in the T&P technique and differences in the J/ψ and Υ kinematics, as well as the possible misestimation of the double-muon Υ efficiency as the product of the single-muon efficiencies, are all included in the correction factor ρ. The average rho factor value is 1.07 and the full range of variation is from 0.92 to 1.20. As a conservative estimate of the systematic uncertainty associated with ρ, the measurements are repeated with a correction factor of unity and half of the variation is taken as the systematic uncertainty (2–5%).

In addition, systematic uncertainties may arise from differences between the dimuon invariant-mass distribution in the data and the probability density functions (PDF) chosen for the signal and background components in the fit. Since the CB parameters, which describe the radiative tail of each signal resonance, are fixed from MC simulation in the fit to the data, we fit the full data set with free tail parameters and use the values obtained to fix the tail parameters for the yield extraction in the $(\Delta p_{\mathrm{T}}^{\Upsilon}, \Delta y^{\Upsilon})$ bins. The difference in the fit yield is taken as a systematic uncertainty (1–4%). We vary the background PDF by replacing the product of the exponential and error function by a polynomial function, while restricting the fit to the mass range 8–12 GeV/c^2 (1–5%). The determination of the integrated luminosity is made with an uncertainty of 4% [23]. A summary of systematic uncertainties for the $\Upsilon(n\mathrm{S})$ production cross section, integrated over the full transverse momentum ($p_{\mathrm{T}}^{\Upsilon}$) and rapidity ($y^{\Upsilon}$) ranges, is shown in Table 1. The largest sources of systematic uncertainty arise from the statistical precision of the efficiency measurements determined from data, the efficiency correction factor ρ, and from the measurement of the integrated luminosity.

The cross section measurement uses acceptance maps corresponding to different Υ polarization scenarios. The values of the resulting cross sections vary approximately linearly by about $\pm 5\%$, $\pm 10\%$, and $\pm 20\%$, respectively, assuming $\lambda_\theta = \pm 0.25$, ± 0.5, and ± 1, as shown in Table 2. The cross sections are also measured for $10 < p_{\mathrm{T}}^{\Upsilon} < 50$ GeV/c and $|y^{\Upsilon}| < 1.2$ using the measured $\Upsilon(n\mathrm{S})$ polarizations [7] to compute the acceptance corrections. The three anisotropy parameters in the center-of-mass helicity and Collins–Soper frames are varied coherently by ± 1 standard deviation, and the largest positive and negative variations with respect to the nominal (no polarization) case are taken as systematic uncertainties. These are listed in Table 4. They are comparable to, or smaller than, the result of varying the longitudinal or transverse polarizations by setting λ_θ to ± 0.25 for the $\Upsilon(1\mathrm{S})$ case, while they are

Table 1
Relative systematic uncertainties in the $\Upsilon(n\text{S})$ production cross section, integrated over the rapidity range $|y^{\Upsilon}| < 2.4$, times the dimuon branching fraction, in percent. The symbols $\mathcal{A}$, $\epsilon_{\text{T\&P}}$, ϵ_ρ, and PDF refer to the systematic uncertainties arising from the acceptance, tag-and-probe efficiencies, correction factor ρ, and signal-and-background PDF. The remaining systematic uncertainties are summed in the "other" category. The integrated luminosity uncertainty of 4% is not shown. The numbers in parentheses are negative variations.

	p_{T} (GeV/c)	$\mathcal{A}$	$\epsilon_{\text{T\&P}}$	ϵ_ρ	PDF	Other
$\Upsilon(1\text{S})$	0–50	1.0 (1.0)	5.2 (4.3)	3.4	1.8	0.4 (0.3)
$\Upsilon(2\text{S})$	0–42	1.1 (1.1)	5.5 (4.1)	3.7	2.6	0.4 (0.4)
$\Upsilon(3\text{S})$	0–38	1.2 (1.1)	6.7 (4.9)	4.0	3.8	0.6 (0.5)

Table 2
The fractional change in percent to the central value of the $\Upsilon(n\text{S})$ cross section integrated over the rapidity range $|y^{\Upsilon}| < 2.4$, relative to the unpolarized value, for six polarization scenarios in the center-of-mass helicity and Collins–Soper frames. The polarization assumption changes from fully longitudinal to fully transverse polarization as λ_θ changes from -1 to 1.

	p_{T} (GeV/c)	Helicity frame λ_θ						Collins–Soper frame λ_θ					
		1	0.5	0.25	−0.25	−0.5	−1	1	0.5	0.25	−0.25	−0.5	−1
$\Upsilon(1\text{S})$	0–50	+19	+10	+5	−5	−11	−24	+16	+8	+4	−5	−9	−19
$\Upsilon(2\text{S})$	0–42	+14	+5	+3	−7	−12	−24	+13	+6	+2	−6	−10	−20
$\Upsilon(3\text{S})$	0–38	+16	+9	+5	−4	−9	−21	+14	+8	+5	−3	−7	−17

between the results obtained by setting λ_θ to ± 0.25 and ± 0.5 for the $\Upsilon(2\text{S})$ and $\Upsilon(3\text{S})$. The fiducial cross sections do not depend on the acceptance, the assumed Υ polarization, or the associated uncertainties. The definition of the acceptance in Eq. (3) includes reconstructed quantities. The variation in the cross section using only generator-level quantities is less than 1%.

8. Differential fiducial cross section measurement and comparison to theory

The fiducial $\Upsilon(n\text{S})$ cross sections are determined from the efficiency-corrected signal yields within the muon kinematic range specified by Eq. (1), using Eq. (2) with the acceptance term set to unity. The resulting total fiducial $\Upsilon(n\text{S})$ cross sections times dimuon branching fractions at $\sqrt{s} = 7$ TeV for $|y^{\Upsilon}| < 2.4$ are

$$\sigma(\text{pp} \to \Upsilon(1\text{S})X) \cdot \mathcal{B}(\Upsilon(1\text{S}) \to \mu^+\mu^-) = (3.06 \pm 0.02\,^{+0.20}_{-0.18} \pm 0.12)\ \text{nb},$$
$$\sigma(\text{pp} \to \Upsilon(2\text{S})X) \cdot \mathcal{B}(\Upsilon(2\text{S}) \to \mu^+\mu^-) = (0.910 \pm 0.011\,^{+0.055}_{-0.046} \pm 0.036)\ \text{nb},$$
$$\sigma(\text{pp} \to \Upsilon(3\text{S})X) \cdot \mathcal{B}(\Upsilon(3\text{S}) \to \mu^+\mu^-) = (0.490 \pm 0.010\,^{+0.029}_{-0.029} \pm 0.020)\ \text{nb},$$

where the first uncertainty is statistical, the second is systematic, and the third is associated with the estimation of the integrated luminosity of the data sample. The integrated results are obtained from the sum of the differential p_{T}^{Υ} results. The measured cross sections include feed-down from higher-mass bottomonium states.

The $\Upsilon(n\text{S})$ differential p_{T} fiducial cross sections are summarized in Table 3 and plotted in Fig. 2(a), (b), (c) and the supplemental material. In the figures, $\mathcal{B}(\Upsilon(n\text{S}) \to \mu^+\mu^-)$ is denoted as $B(\mu\mu)$. The results are also given for six rapidity intervals in the supplemental material. Here, and throughout the Letter, in figures illustrating differential cross sections, the data points are plotted at the average p_{T} (or rapidity) of the data in each bin. The p_{T}^{Υ} dependence of the cross sections has the same trend for all six rapidity intervals. The $\Upsilon(n\text{S})$ p_{T}-integrated, differential rapidity fiducial cross sections, plotted in Fig. 2(d) and the supplemental material, are all roughly constant from $|y^{\Upsilon}| = 0$ to about 1.6, where they then fall quickly. The ratios of the $\Upsilon(n\text{S})$ differential p_{T} fiducial cross sections, also shown in the supplemental material, increase with p_{T}^{Υ}.

A comparison between the fiducial cross section measurement and theoretical predictions is shown in Fig. 2. Each of the predictions is made with the assumption of unpolarized $\Upsilon(n\text{S})$ production. The comparison is made to the CASCADE [24] MC generator in the fixed-order-plus-next-to-leading-log (FONLL) framework, including feed-down from $\chi_b(1\text{P})$, $\chi_b(2\text{P})$, $\chi_b(3\text{P})$ [25], and other higher-mass Υ states, and to PYTHIA [11] including feed-down for the $\Upsilon(1\text{S})$ and $\Upsilon(2\text{S})$ from the P-wave states with the same principal quantum number. The p_{T} dependence of the cross section predicted by CASCADE agrees with the data for the $\Upsilon(1\text{S})$, is marginally consistent for the $\Upsilon(2\text{S})$ but does not describe the $\Upsilon(3\text{S})$ spectrum, where it predicts a softer p_{T} spectrum. For each resonance, the total cross section predicted by PYTHIA is higher, by factors of about 2, than the measured cross section. In Fig. 2, for each resonance the PYTHIA prediction is normalized to the measured total cross section, in order to facilitate the comparison of the cross section dependences with the predictions. The PYTHIA prediction of the p_{T} dependence agrees with data for the $\Upsilon(1\text{S})$ and $\Upsilon(3\text{S})$, but not for the $\Upsilon(2\text{S})$. Both CASCADE and PYTHIA provide a good description of the shape of the rapidity dependence for the three states. Complete tables of results for the differential fiducial cross sections for the three Υ states are available in the supplemental material.

9. Acceptance-corrected differential cross section measurement and comparison to theory

The acceptance-corrected $\Upsilon(n\text{S})$ production cross sections times the dimuon branching fractions at $\sqrt{s} = 7$ TeV for $|y^{\Upsilon}| < 2.4$ are measured to be

$$\sigma(\text{pp} \to \Upsilon(1\text{S})X) \cdot \mathcal{B}(\Upsilon(1\text{S}) \to \mu^+\mu^-) = (8.55 \pm 0.05\,^{+0.56}_{-0.50} \pm 0.34)\ \text{nb},$$
$$\sigma(\text{pp} \to \Upsilon(2\text{S})X) \cdot \mathcal{B}(\Upsilon(2\text{S}) \to \mu^+\mu^-) = (2.21 \pm 0.03\,^{+0.16}_{-0.14} \pm 0.09)\ \text{nb},$$
$$\sigma(\text{pp} \to \Upsilon(3\text{S})X) \cdot \mathcal{B}(\Upsilon(3\text{S}) \to \mu^+\mu^-) = (1.11 \pm 0.02\,^{+0.10}_{-0.08} \pm 0.04)\ \text{nb},$$

where the first uncertainty is statistical, the second is systematic, and the third is from the estimation of the integrated luminosity. These results assume unpolarized $\Upsilon(n\text{S})$ production. The $\Upsilon(1\text{S})$ integrated production cross section in the restricted rapidity range $|y^{\Upsilon}| < 2.0$ is 7.496 ± 0.052(stat.) nb, which is consistent with the previous CMS result of 7.37 ± 0.13(stat.) nb [6], measured in the

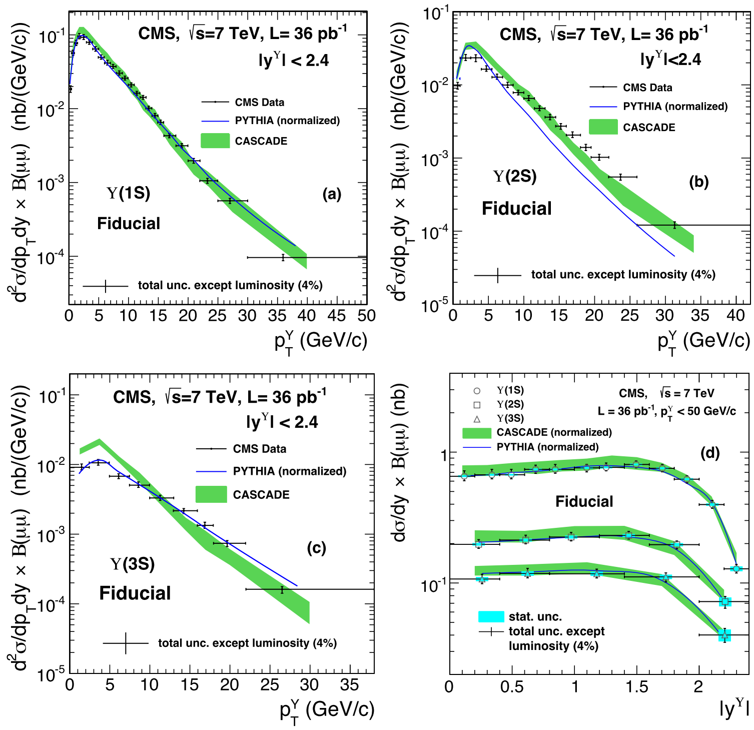

Fig. 2. Differential fiducial cross section of (a) $\Upsilon(1S)$, (b) $\Upsilon(2S)$, and (c) $\Upsilon(3S)$ as a function of p_T^Υ in the rapidity range $|y^\Upsilon| < 2.4$, and comparison to the predictions from CASCADE and PYTHIA. (d) Differential fiducial cross section of the $\Upsilon(nS)$ as a function of rapidity and comparison to the predictions from CASCADE and PYTHIA. The PYTHIA prediction is normalized to the measured total cross section, in order to facilitate the comparison of the shape of the dependences. The full CASCADE prediction is shown in (a), (b), and (c); the normalized CASCADE prediction is shown in (d). The bands indicate the estimated uncertainties in the CASCADE prediction.

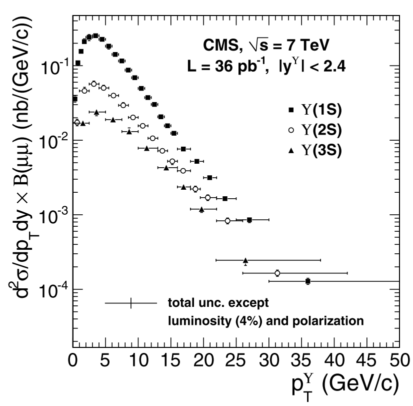

Fig. 3. Acceptance-corrected differential cross sections as a function of p_T^Υ in the rapidity range $|y^\Upsilon| < 2.4$.

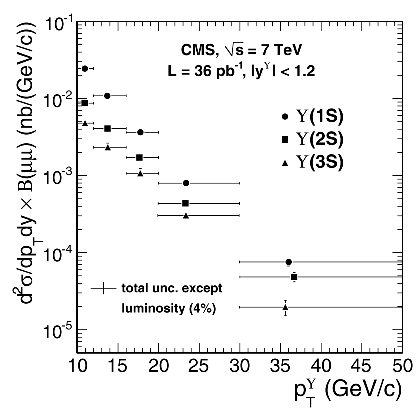

Fig. 4. Acceptance-corrected differential cross sections as a function of p_T^Υ for $|y^\Upsilon| < 1.2$. The error bars represent the total uncertainties, including the systematic uncertainties from the measurement of the $\Upsilon(nS)$ polarization [7], but not the uncertainty (4%) in the integrated luminosity.

same rapidity range. The results of the $\Upsilon(nS)$ production cross sections for the same p_T^Υ and y^Υ ranges used for the measurement of the $\Upsilon(nS)$ polarizations in Ref. [7] are shown in Table 4.

The acceptance-corrected $\Upsilon(nS)$ differential p_T cross sections for the rapidity range $|y^\Upsilon| < 2.4$ are plotted in Fig. 3 and summarized in Table 3. Fig. 4 shows the same for the ranges $10 < p_T^\Upsilon < 50$ GeV/c, $|y^\Upsilon| < 1.2$ used in Ref. [7] and includes the systematic uncertainties from the polarization measurement of Ref. [7], as explained in Section 7. The $\Upsilon(nS)$ differential p_T cross sections for six different rapidity bins are given in the supplemental material. The p_T^Υ dependence of the cross section in the six exclusive rapidity intervals shows a similar trend within the uncertainties. The $\Upsilon(nS)$ p_T-integrated, differential rapidity cross section results are shown in Fig. 5. Similar to the fiducial differential rapidity cross sections, the acceptance-corrected cross sections are approximately flat from $|y^\Upsilon| = 0$ to about 2.0, where they then begin to fall. In Fig. 5, a comparison with similar results from the LHCb Collaboration [4] is also shown. The two sets of measurements are complementary in their rapidity coverage and consistent within the uncertainties in the region of overlap. The fiducial cross sections and the acceptance-corrected cross sections exhibit similar p_T^Υ and $|y^\Upsilon|$ dependencies. However, the decrease in the cross section at large values of the rapidity is greater for the fiducial cross section than for the acceptance-corrected cross section because the acceptance also decreases with rapidity. A comparison to the normalized differential p_T cross section results from CDF [2] and D0 [3], provided in the supplemental material, indicates a harder spectrum at the LHC. Comparisons to results from ATLAS [5], shown also in the supplemental material, show good agreement. The ratios of the $\Upsilon(nS)$ differential p_T cross sections are plotted in Fig. 6,

Table 3
The product of the fiducial or acceptance-corrected $\Upsilon(n\mathrm{S})$ production cross sections, σ, integrated and differential in $p_{\mathrm{T}}^{\Upsilon}$, and the respective dimuon branching fraction, $\mathcal{B}$, integrated over the rapidity range $|y^{\Upsilon}| < 2.4$. The cross sections assume the $\Upsilon(n\mathrm{S})$ are unpolarized. The fiducial $\Upsilon(n\mathrm{S})$ cross sections are independent of the $\Upsilon(n\mathrm{S})$ polarization. The statistical uncertainty (stat.), the sum of the systematic uncertainties in quadrature ($\sum_{\mathrm{syst.}}$), and the total uncertainty ($\Delta\sigma$; including stat., $\sum_{\mathrm{syst.}}$, and the uncertainty in the integrated luminosity) are in percent. The numbers in parentheses are negative variations.

	p_{T} (GeV/c)	Mean	Fiducial cross section				Cross section			
			$\sigma \cdot \mathcal{B}$ (nb)	$\frac{\text{stat.}}{\sigma}$	$\frac{\sum_{\text{syst.}}}{\sigma}$	$\frac{\Delta\sigma}{\sigma}$	$\sigma \cdot \mathcal{B}$ (nb)	$\frac{\text{stat.}}{\sigma}$	$\frac{\sum_{\text{syst.}}}{\sigma}$	$\frac{\Delta\sigma}{\sigma}$
$\Upsilon(1\mathrm{S})$	0–0.5	0.33	0.0440	5.4	8 (8)	11 (11)	0.0859	5.4	8 (7)	11 (10)
	0.5–1	0.77	0.133	3.1	8 (8)	10 (10)	0.263	3.3	8 (7)	9 (9)
	1–1.5	1.26	0.182	2.5	8 (8)	9 (9)	0.374	2.6	8 (8)	9 (9)
	1.5–2	1.75	0.228	2.4	8 (8)	10 (9)	0.505	2.4	9 (8)	10 (9)
	2–3	2.49	0.442	1.6	8 (7)	9 (8)	1.16	1.6	8 (10)	9 (11)
	3–4	3.48	0.374	1.8	6 (6)	8 (7)	1.21	2.1	7 (6)	9 (8)
	4–5	4.48	0.302	1.8	7 (7)	8 (8)	1.084	2.1	7 (6)	8 (8)
	5–6	5.49	0.236	2.0	7 (6)	8 (7)	0.879	1.9	7 (9)	8 (10)
	6–7	6.49	0.195	2.0	8 (7)	9 (9)	0.680	2.6	6 (6)	8 (7)
	7–8	7.49	0.174	2.1	5 (5)	7 (6)	0.556	2.0	6 (5)	7 (7)
	8–9	8.48	0.144	2.3	6 (5)	7 (7)	0.419	2.2	5 (5)	7 (7)
	9–10	9.48	0.1235	2.4	5 (4)	7 (6)	0.331	2.3	5 (4)	7 (6)
	10–11	10.48	0.0988	2.5	6 (5)	8 (7)	0.238	2.5	5 (4)	7 (6)
	11–12	11.49	0.0759	2.8	4 (4)	7 (6)	0.179	2.9	5 (4)	7 (6)
	12–13	12.49	0.0670	2.9	4 (4)	7 (6)	0.145	2.9	5 (4)	7 (7)
	13–14	13.47	0.0477	3.3	5 (4)	7 (7)	0.0990	3.2	4 (5)	7 (7)
	14–15	14.49	0.0381	3.6	5 (5)	7 (7)	0.0750	3.6	5 (5)	8 (7)
	15–16	15.48	0.0312	4.0	5 (4)	8 (7)	0.0595	3.8	5 (5)	7 (7)
	16–18	16.91	0.0412	3.5	5 (5)	7 (7)	0.0732	3.4	5 (5)	7 (7)
	18–20	18.98	0.0296	4.0	5 (4)	7 (7)	0.0500	3.8	5 (4)	7 (7)
	20–22	20.94	0.0187	5.1	4 (4)	8 (8)	0.0302	5.1	5 (4)	8 (8)
	22–25	23.30	0.0148	5.8	4 (4)	8 (8)	0.0237	5.6	5 (4)	8 (8)
	25–30	27.03	0.0133	6.1	4 (4)	8 (8)	0.0205	6.0	5 (4)	9 (8)
	30–50	35.97	0.00923	7.8	6 (6)	11 (10)	0.0123	7.4	6 (6)	10 (10)
	0–50	5.34	3.06	0.6	6 (6)	8 (7)	8.55	0.6	7 (6)	8 (7)
$\Upsilon(2\mathrm{S})$	0–1	0.66	0.0467	6.3	7 (8)	10 (11)	0.0829	5.9	9 (8)	11 (11)
	1–2.5	1.79	0.168	3.4	8 (8)	10 (10)	0.331	3.3	11 (10)	12 (12)
	2.5–4	3.21	0.169	3.1	8 (11)	9 (12)	0.409	3.1	9 (8)	10 (9)
	4–5.5	4.71	0.118	3.3	8 (7)	10 (9)	0.362	3.3	8 (7)	9 (9)
	5.5–7	6.22	0.0917	3.6	6 (5)	8 (8)	0.286	3.6	7 (6)	9 (8)
	7–8.5	7.71	0.0716	3.4	7 (7)	9 (9)	0.212	3.9	7 (7)	9 (9)
	8.5–10	9.21	0.0564	4.0	5 (5)	8 (8)	0.146	4.0	6 (6)	9 (8)
	10–11.5	10.69	0.0470	4.1	6 (5)	8 (8)	0.1123	4.1	6 (6)	9 (8)
	11.5–13	12.21	0.0343	4.6	4 (4)	7 (8)	0.0765	4.6	5 (5)	8 (8)
	13–14.5	13.70	0.0260	5.2	5 (5)	8 (8)	0.0519	5.1	5 (5)	8 (8)
	14.5–16	15.22	0.0196	5.7	4 (6)	8 (9)	0.0376	5.7	5 (7)	9 (10)
	16–18	16.88	0.0198	5.5	6 (5)	9 (8)	0.0373	5.3	6 (5)	9 (8)
	18–19.5	18.76	0.01005	7.5	4 (5)	9 (10)	0.0159	7.4	5 (4)	10 (9)
	19.5–22	20.65	0.0123	6.8	5 (5)	9 (9)	0.0204	6.6	5 (5)	9 (9)
	22–26	23.69	0.0104	7.4	4 (5)	9 (10)	0.0158	7.2	5 (4)	10 (9)
	26–42	31.30	0.00930	8.0	5 (5)	10 (10)	0.0126	7.7	6 (5)	10 (10)
	0–42	5.32	0.910	1.2	6 (5)	7 (7)	2.21	1.2	7 (6)	8 (7)
$\Upsilon(3\mathrm{S})$	0–2.5	1.54	0.107	5.3	7 (7)	10 (10)	0.203	5.3	8 (8)	11 (10)
	2.5–5	3.62	0.125	4.5	8 (8)	10 (10)	0.287	4.5	10 (11)	12 (12)
	5–7.5	6.15	0.0801	4.7	6 (6)	9 (8)	0.227	4.6	9 (8)	11 (10)
	7.5–10	8.62	0.0604	4.8	9 (8)	11 (10)	0.157	4.8	11 (10)	12 (12)
	10–13	11.31	0.0476	4.5	6 (7)	8 (9)	0.113	4.3	7 (5)	9 (8)
	13–16	14.30	0.0308	5.1	5 (6)	8 (9)	0.0617	5.0	5 (5)	8 (8)
	16–18	16.94	0.0127	7.5	6 (5)	10 (10)	0.0227	7.4	6 (5)	10 (10)
	18–22	19.72	0.0140	6.9	7 (7)	11 (11)	0.0229	7.0	7 (6)	10 (10)
	22–38	26.51	0.0124	7.4	9 (9)	12 (12)	0.0185	7.6	13 (13)	15 (15)
	0–38	5.31	0.490	2.0	6 (6)	8 (7)	1.11	2.0	9 (8)	10 (9)

along with comparisons to the CASCADE and PYTHIA predictions. The ratios increase with $p_{\mathrm{T}}^{\Upsilon}$, as they do for the fiducial cross sections. The predictions for the ratios from CASCADE have relatively large uncertainty bands; this arises as a consequence of the asymmetric variation of the uncertainty of the predictions in Fig. 2 as a function of $p_{\mathrm{T}}^{\Upsilon}$. The CASCADE prediction is consistent with the $\Upsilon(2\mathrm{S})/\Upsilon(1\mathrm{S})$ and $\Upsilon(3\mathrm{S})/\Upsilon(2\mathrm{S})$ measurements, while it disagrees with the $\Upsilon(3\mathrm{S})/\Upsilon(1\mathrm{S})$ results at low p_{T}. The PYTHIA prediction agrees with the measured $\Upsilon(3\mathrm{S})/\Upsilon(1\mathrm{S})$ values, but is inconsistent with the $\Upsilon(2\mathrm{S})/\Upsilon(1\mathrm{S})$ and $\Upsilon(3\mathrm{S})/\Upsilon(2\mathrm{S})$ results.

The acceptance-corrected differential p_{T} and rapidity $\Upsilon(n\mathrm{S})$ cross sections and the theoretical predictions are shown in Fig. 7. The measurements and predictions in Figs. 7(a), (b), (c) are for $|y^{\Upsilon}| < 2.0$ and assume unpolarized $\Upsilon(n\mathrm{S})$ production. Comparisons are made to the CASCADE MC generator; the normalized PYTHIA (as explained in Section 8); the color-evaporation model (CEM) [26] with feed-down not included; nonrelativistic QCD (NRQCD) at next-to-leading order (NLO) including feed-down, as described in Ref. [27]; the color-singlet model (CSM) to NLO and NNLO* [28], with feed-down accounted for by scaling the $\Upsilon(1\mathrm{S})$ and $\Upsilon(2\mathrm{S})$ direct-production cross sections by factors 2 and 1.43, respectively [28], and no feed-down for the $\Upsilon(3\mathrm{S})$. The theoretical predictions are based on published models for $\Upsilon(n\mathrm{S})$ production, and, except for NRQCD [27], are made for lower $\sqrt{s}$ [24,26,28].

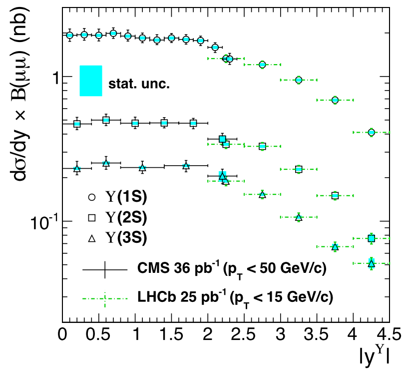

Fig. 5. Acceptance-corrected differential production cross sections as a function of rapidity, and comparison with LHCb results [4]. The bands represent the statistical uncertainty and the error bars represent the total uncertainty, except for those from the $\Upsilon(n\mathrm{S})$ polarization.

Table 4
The product of the acceptance-corrected $\Upsilon(n\mathrm{S})$ production cross sections, σ, and the dimuon branching fraction, $\mathcal{B}$, integrated over the rapidity range $|y^{\Upsilon}| < 1.2$, and the p_T^{Υ} range from 10 to 50 GeV/c, as used in Ref. [7] for the measurement of the Υ polarizations. The cross sections assume the $\Upsilon(n\mathrm{S})$ are unpolarized. The statistical uncertainty (stat.), the sum in quadrature of the systematic uncertainties ($\sum_{\text{syst.}}$), excluding the contribution from the polarization uncertainty, the systematic uncertainties from the polarization (pol.), and the total uncertainty ($\Delta\sigma$; including stat., $\sum_{\text{syst.}}$, pol., and the uncertainty in the integrated luminosity) are in percent. The numbers in parentheses are negative variations.

	$\sigma \cdot \mathcal{B}$ (nb)	$\frac{\text{stat.}}{\sigma}$	$\frac{\sum_{\text{syst.}}}{\sigma}$	$\frac{\text{pol.}}{\sigma}$	$\frac{\Delta\sigma}{\sigma}$
$\Upsilon(1\mathrm{S})$	0.558	1.3	6 (5)	4 (2)	8 (7)
$\Upsilon(2\mathrm{S})$	0.213	2.4	5 (5)	7 (3)	10 (8)
$\Upsilon(3\mathrm{S})$	0.127	3.2	7 (5)	7 (3)	11 (8)

These models have been updated by their respective authors to $\sqrt{s} = 7$ TeV when relevant. The updates are unpublished and are in the form of private communications. Our measured $\Upsilon(1\mathrm{S})$ cross section is in good agreement with NRQCD, for the prediction provided for p_T in 8–30 GeV/c. The CEM predictions for the three states are, within their uncertainties, also compatible with the data. The data agree with CASCADE for the $\Upsilon(1\mathrm{S})$ and $\Upsilon(2\mathrm{S})$, but the agreement is not as satisfactory for the $\Upsilon(3\mathrm{S})$ when judged on the basis of the smaller uncertainties quoted by this prediction. The NLO CSM does not describe the data, while the NNLO* CSM shows improved agreement within the large uncertainties. The total cross section predicted by PYTHIA is higher than the measured cross section by about a factor 2; in Fig. 7, the PYTHIA predictions are for this reason normalized to the measured $\Upsilon(n\mathrm{S})$ cross sections. The p_T dependence of the cross section predicted by PYTHIA agrees with the data for the $\Upsilon(1\mathrm{S})$ and $\Upsilon(3\mathrm{S})$ but not for the $\Upsilon(2\mathrm{S})$. CASCADE and PYTHIA also describe the rapidity dependence over the range of the measurement, as shown in Fig. 7(d). Complete tables of results for the differential cross sections for the three Υ states are available in the supplemental material, including variations for extreme polarization scenarios.

10. Summary

Measurements of the $\Upsilon(n\mathrm{S})$ differential and total production cross sections from proton–proton collisions at $\sqrt{s} = 7$ TeV with the CMS detector have been presented. The results have been shown in two ways: as acceptance-corrected cross sections, and fiducial cross sections in which both muons from the $\Upsilon(n\mathrm{S})$ decay are within the detector acceptance. The latter cross sections are independent of the assumed $\Upsilon(n\mathrm{S})$ polarizations. The differential cross sections have been given as a function of p_T^{Υ} and $|y^{\Upsilon}|$, and compared to theoretical predictions. The differential cross sections as a function of p_T^{Υ} and y^{Υ} for each $\Upsilon(n\mathrm{S})$ state have also been measured and compared to theoretical predictions. Finally, the Υ cross section ratios have been given. The dominant sources of systematic uncertainty in the cross section measurements arise from the determination of the muon identification and trigger efficiencies, and the integrated luminosity.

The measurements are consistent with previous CMS results based on less than 10% of the integrated luminosity analyzed here. These earlier measurements have been extended in terms of both the precision attained and the kinematic reach. In addition, this Letter expands upon the previous result by the inclusion of fiducial cross section measurements and the polarization systematics, utilizing the recent Υ polarization results from CMS. The results are compared to the ATLAS and LHCb Collaborations' measurements, and are found to be consistent in the regions of overlap. Comparisons to measurements by the CDF, D0, and LHCb Collaborations also illustrate the achieved extension in kinematic coverage. The results presented here will allow for a more precise determination of the parameters of the various bottomonium production models.

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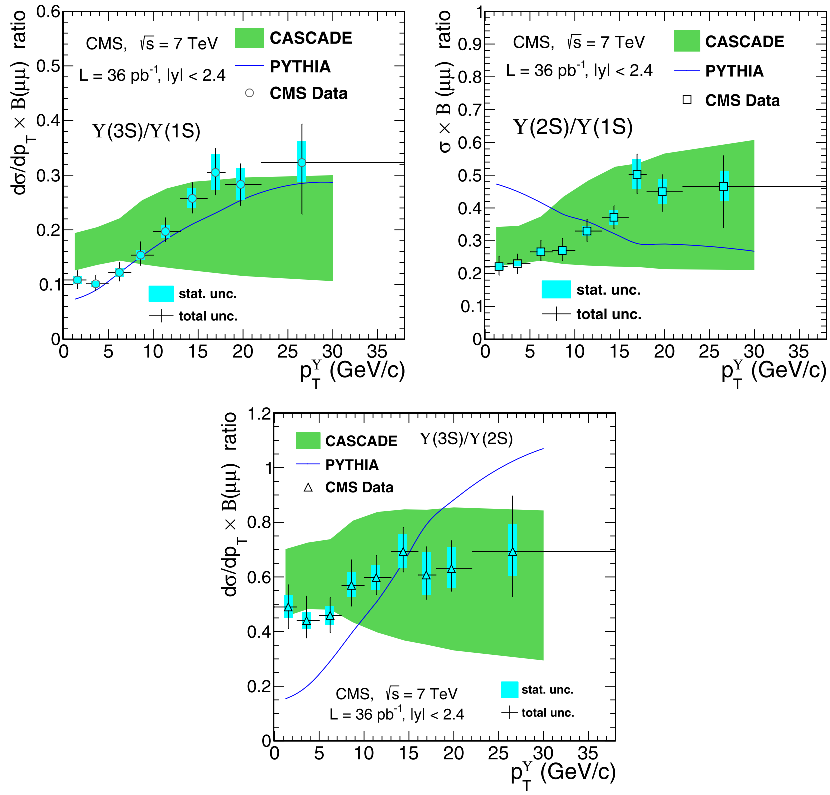

Fig. 6. Ratios of acceptance-corrected differential cross sections as a function of p_T^{Υ} in the rapidity range $|y^{\Upsilon}| < 2.4$, along with predictions from CASCADE (bands) and PYTHIA (lines), for the $\Upsilon(3S)/\Upsilon(1S)$, $\Upsilon(2S)/\Upsilon(1S)$ and $\Upsilon(3S)/\Upsilon(2S)$. The width of a band indicates an estimate of the uncertainty in the prediction.

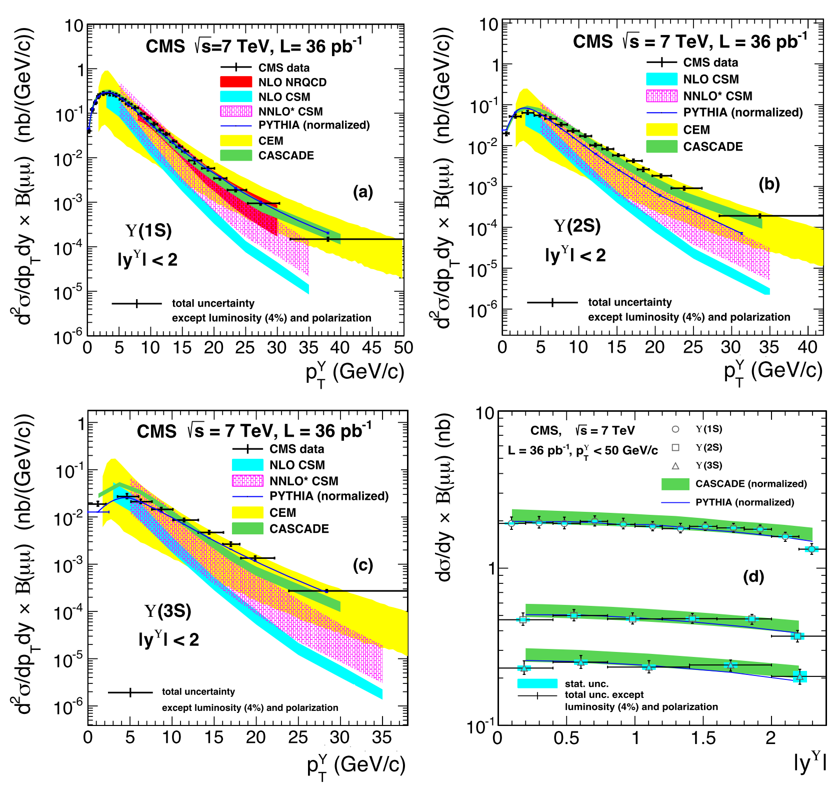

Fig. 7. Acceptance-corrected differential cross sections of (a) $\Upsilon(1S)$, (b) $\Upsilon(2S)$, and (c) $\Upsilon(3S)$ as a function of p_T^{Υ} in the rapidity range $|y^{\Upsilon}| < 2$, and comparison to various theoretical predictions. (d) Acceptance-corrected differential cross section of the $\Upsilon(nS)$ as a function of rapidity and comparison to CASCADE and PYTHIA. The PYTHIA prediction is normalized to the measured total cross section, in order to facilitate the comparison of the shape of the dependences; for the rapidity differential results (d), the normalized CASCADE prediction is also shown. The width of a band indicates an estimate of the uncertainty in the prediction by the author of the prediction.

Open access

Appendix A. Supplemental material

Supplemental material related to this article can be found online at http://dx.doi.org/10.1016/j.physletb.2013.10.033.

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