Measurement of the $\Upsilon(1S)$ Production Cross-Section in $pp$ Collisions at $\sqrt{s} = 7$ TeV in ATLAS

The ATLAS Collaboration

Abstract

A measurement of the cross-section for $\Upsilon(1S) \rightarrow \mu^+ \mu^-$ production in proton-proton collisions at centre of mass energy of 7 TeV is presented. The cross-section is measured as a function of the $\Upsilon(1S)$ transverse momentum in two bins of rapidity, $|y^{\Upsilon(1S)}| < 1.2$ and $1.2 < |y^{\Upsilon(1S)}| < 2.4$. The measurement requires that both muons have transverse momentum $p_T^{\mu} > 4$ GeV and pseudorapidity $|\eta^{\mu}| < 2.5$ in order to reduce theoretical uncertainties on the acceptance, which depend on the poorly known polarization. The results are based on an integrated luminosity of 1.13 pb$^{-1}$, collected with the ATLAS detector at the Large Hadron Collider. The cross-section measurement is compared to theoretical predictions: it agrees to within a factor of two with a prediction based on the NRQCD model including colour-singlet and colour-octet matrix elements as implemented in PYTHIA while it disagrees by up to a factor of ten with the next-to-leading order prediction based on the colour-singlet-model.

1. Introduction

The production of $J/\psi$ and $\Upsilon$ mesons has been studied since their discovery in the 1970s \cite{1,2}, and even today there is no conclusive coherent theoretical picture of $J/\psi$ and $\Upsilon$ hadroproduction. There are major questions associated with the consistency of measurements made at the Tevatron, HERA and fixed target experiments \cite{3}. In particular it is difficult to reconcile the cross-section measurements with those of the spin alignment \cite{4}, and there are significant disagreements between the two Tevatron experiments on the measurement of the spin alignment in the case of $\Upsilon$ production \cite{5,6}. It is thus important for the LHC experiments to measure the production of these mesons in order to shed further light on the puzzle.

The CMS collaboration has recently presented a measurement of $\Upsilon$ production \cite{7}, correcting for the detector acceptance of the two daughter muons in both angular and momentum range. This approach was also adopted in the ATLAS $J/\psi$ cross-section publication \cite{8}. Correction of the data in this way introduces uncertainties due to the poorly known spin alignment of the $\Upsilon$ (or $J/\psi$). Note, that CMS quote the measurement for a wide variety of assumptions on the spin alignment, and the ATLAS $J/\psi$ measurement takes the differences between the corrections obtained with different spin alignments as an additional systematic uncertainty.

With that in mind, a somewhat different approach to the measurement of the $\Upsilon(1S)$ production cross-section is adopted in this analysis. The result is presented as a function of transverse momentum, $p_T$, and rapidity, $y$, of the $\Upsilon(1S)$, corrected for detector response and efficiencies but defined within a restricted range of muon kinematics where both muons have $p_T^{\mu}$ greater than 4 GeV and absolute pseudorapidity $|\eta^{\mu}|$, less than 2.5. The relative fraction of $\Upsilon(1S)$ mesons where both muons fulfill the kinematic requirements compared to all $\Upsilon(1S)$ mesons depends strongly on the spin alignment of the $\Upsilon(1S)$. For instance, assuming full transverse or longitudinal spin alignment versus unpolarised production changes this fraction by typically 30%.

By quoting the measurement in a restricted region of phase space where muons are detected, uncertainties due to the $\Upsilon$ spin alignment on the measurement are almost eliminated so that the quoted cross-section is free of any assumptions about this property.

A single muon trigger with a threshold of $p_T^{\mu} >$...
4 GeV is used. This limits the dataset used for this measurement to the low luminosity periods of 2010 corresponding to an integrated luminosity of 1.13 ± 0.04 pb\(^{-1}\).

In the following sections, a brief description of the ATLAS detector is given with emphasis on the aspects most relevant to this analysis. Next the measurement strategy is outlined, followed by a description of the Monte Carlo simulation used. The event selection and the determination of the number of \(\Upsilon(1S)\) events are then described before the results are presented, and a conclusion is given.

2. The ATLAS Detector

The ATLAS detector \([8]\) consists of an inner tracker, a calorimeter and a muon system. The inner detector (ID) directly surrounds the interaction point; it includes a silicon pixel detector (Pixel), a silicon strip detector (SCT) and a transition radiation tracker (TRT), and is embedded in an solenoidal 2 T magnetic field. The ID covers the range \(|\eta| < 2.5\) and is enclosed by a calorimeter system containing electromagnetic and hadronic sections. The calorimeter is surrounded by a large muon spectrometer (MS) inside an air-core toroid magnet system which contains a combination of monitored drift tubes (MDT) and cathode strip chambers (CSC), designed to provide precise position measurements in the bending plane and covering the range \(|\eta| < 2.0\) and \(2.0 < |\eta| < 2.7\), respectively. In addition, resistive plate chambers (RPC) and thin gap chambers (TGC) with a coarse position resolution but a fast response time are used primarily to trigger muons in the rapidity ranges \(|\eta| < 1.05\) and \(1.05 < |\eta| < 2.4\), respectively. Momentum measurements in the MS are based on track segments formed separately in at least two of the three station layers of the MDT and the CSC. The RPC and TGC are used to improve the pattern recognition and track reconstruction in the non-bending plane. They do not improve the position measurement in the bending plane.

The first level muon trigger looks for hit coincidences within different RPC or TGC detector layers inside programmed geometrical windows that define the muon \(p_T\) and provide a rough estimate of their positions \([9]\). The lowest available \(p_T\) threshold is used for this analysis. In addition, muons are required to pass a high-level trigger selection similar to that of the offline reconstruction and a transverse momentum threshold of \(p^*_{T} > 4\, \text{GeV}\).

3. Outline of the Measurement

The differential \(\Upsilon(1S)\) cross-section is given as

\[
\frac{d^2\sigma}{dp_Td\eta} \times \text{BR}(\Upsilon(1S) \to \mu^+\mu^-) = \frac{N_{\Upsilon(1S)}}{\int \mathcal{L} dt \times \Delta p_T \times \Delta \eta},
\]

where \(\int \mathcal{L} dt\) is the integrated luminosity, and \(\Delta p_T\) and \(\Delta \eta\) are the bin sizes in \(p^*_{T}\) and \(\eta\), respectively. \(N_{\Upsilon(1S)}\) is the corrected number of \(\Upsilon(1S)\) mesons. It is determined with an unbinned maximum likelihood fit to the dimuon mass distribution after applying a weight to each candidate that is the inverse of its selection efficiency as described in Section 5. The cross-section is defined within the fiducial cuts \(p^*_{T} > 4\, \text{GeV}\) and \(|\eta| < 2.5\) on both muons, where the \(\mu\) kinematics are those before any final state QED radiation.

The key aspects of this measurement are the efficiency determination and the fit to extract \(N_{\Upsilon(1S)}\). These are described in detail in Sections 5 and 6, respectively.

The effect of bin migrations due to finite detector resolution and final state photon radiation has been studied. Given the good muon momentum resolution of \(\sigma(p_T)/p_T < 0.5\%\) in the momentum range relevant for this analysis \([10]\) and the relatively coarse binning used for this measurement, the bin migrations due to detector resolution and final state radiation are smaller than 2% in all bins. This 2% also accounts for the migrations across the \(p^*_{T}\) and \(\eta\) cuts. This small effect is not corrected for and therefore considered as part of the systematic uncertainty, which is discussed in Section 7. Any residual impacts of the assumption on the \(\Upsilon\) polarization have also been assessed and are within this 2% uncertainty.

4. Monte Carlo Simulation

In this analysis, all efficiency factors are determined directly from the data. The differential cross-section expressed in Eq. 1 does not need any large acceptance corrections which would require a detailed modelling of the kinematic properties of the events. Monte Carlo (MC) simulation is only used to construct templates for the likelihood fits to the dimuon mass distribution, and to assess the corrections due to migrations between \(p^*_{T}\) and \(\eta\) bins.

MC events are generated using PYTHIA6 \([11]\) with the ATLAS MC09 tune \([12]\) and MRST
LO\(^\text{[13]}\) parton distribution functions. They are simulated with the ATLAS simulation framework \([14]\) using GEANT4 \([15]\) and fully reconstructed with the same software that is used to process the data from the detector.

For the \(\Upsilon\) MC samples, PYTHIA6’s implementation of \(\Upsilon\) production subprocesses using the non-relativistic QCD (NRQCD) \([16]\) framework and the parameters recommended in Ref. \([17]\) are used. In this model, quarkonium is produced in both a colour-singlet and a colour-octet state, and evolves non-perturbatively into physical quarkonium. Each \(\Upsilon(nS)\) state is generated separately and includes direct production from the hard interaction, as well as production through radiative feed-down from \(\Upsilon_b(nP) \rightarrow \Upsilon(nS)/\Upsilon\) decays. The samples are generated without polar or azimuthal anisotropy in the decay of the \(\Upsilon\) (the default in PYTHIA).

Background contributions come mainly from open production of charm and bottom quarks with subsequent decay of the \(c\) - or \(b\) -hadron to a muon. A further, much smaller contribution comes from Drell-Yan production. These continuum backgrounds are described using the minimum-bias processes in PYTHIA. In order to avoid double-counting, any generated minimum bias events containing \(\Upsilon\)-mesons are explicitly removed from the sample. This background sample is only used to estimate a systematic uncertainty on the background modelling.

In all samples final state QED radiation is considered using PHOTOS \([18]\) interfaced to PYTHIA.

5. Event Selection and Efficiency Determination

Selected events are first requested to satisfy a single muon trigger with a threshold of \(p_T^\mu > 4\) GeV. Then two offline muons are required with \(p_T^\mu > 4\) GeV and \(|\eta^\mu| < 2.5\).

Reconstructed muons that combine a track reconstructed in the MS with a track reconstructed in the ID are referred to as combined muons \([8]\). In order to recover efficiency for muons with low momenta, tagged muons extrapolate an ID track to the muon system and attach MS track segments that are not associated to any MS track. For both categories of muons in this analysis, the kinematic properties of the muons are solely determined from the parameters of the ID tracks associated with the muons. At least one of the two offline muons must be a combined muon, and at least one of them must match geometrically to a trigger muon. At low dimuon \(p_T\) about 60% of the events have two combined muons, and at high \(p_T\) this fraction increases to about 90%. Since the measurement is restricted to \(|y^{(15)}| < 2.4\) and \(p_T^\mu > 4\) GeV at least one of the two decay muons is within the trigger pseudorapidity acceptance.

Both muon tracks are required to have at least one pixel hit and six SCT hits. Since the \(\Upsilon\) is produced promptly, background from heavy flavour decays is suppressed by requiring the muons to originate from the primary vertex. Cuts requiring \(|d_0| < 150\) \(\mu m\) and \(|z_0| \sin \theta < 1.5\) mm are applied where \(d_0\) (\(z_0\)) is the impact parameter with respect to the event vertex in the transverse (longitudinal) direction. The event vertex is required to have at least three associated tracks to reject background due to cosmic ray muons. The two selected muons are further required to have opposite electric charge.

The muon trigger and reconstruction efficiencies are determined using the high statistics \(J/\psi\) data sample \([19]\) as a function of \(p_T^\mu\) and \(\eta^\mu\). For a single muon, the trigger efficiency varies between 40% and 90% over the relevant \(p_T^\mu\) and \(\eta^\mu\) range \([19, 6]\). Using the single muon trigger, this results in an average trigger efficiency for the selected dimuon events between 80% and 95% in any measurement bin. Within the kinematic range considered in this measurement, the offline muon reconstruction efficiency varies with \(p_T^\mu\) and \(\eta^\mu\) between 80% and 100%. The small gaps in the muon acceptance at certain \(\eta\) regions (mostly at \(|\eta| \approx 0\) and \(|\eta| \approx 1.3\) are corrected for as part of the efficiency correction assuming the nearly flat \(\eta\) dependence predicted by the simulation, and represent a small fraction of the total angular range. The efficiency of the pixel and SCT hit requirements has been measured using \(J/\psi\) mesons as 99.5 ± 0.5% per track, and the efficiency of the primary vertex requirement is > 99.9%. The \(z_0 \sin \theta\) cut efficiency is nearly 100% in both data and MC.

The efficiencies of the transverse impact parameter cut are determined using two independent methods. The impact parameter resolution is sensitive to the alignment of the ID and to the multiple scattering in the ID volume. The former dominates the resolution at high \(p_T^\mu\) while the latter dominates at low \(p_T^\mu\). The primary method to determine the resolution uses muons from \(J/\psi\) decays and fits the impact parameter distribution using templates constructed from prompt and non-prompt \(J/\psi\) MC. In order to allow for small deviations of the observed resolution with respect to the MC, an additional \(d_0\) resolution smearing parameter is introduced. This smearing parameter is of order 10\(\mu m\) due to imperfections in the material description and tracker alignment. The efficiency determined with
the method agrees well with the simulation and is about 99.5% in the central region, decreasing to 96.5% at the highest $\eta^\mu$ and lowest $p_T^\mu$. The second method uses Z-bosons to determine the impact parameter resolution at high $p_T^\mu$, and translates it to the low $p_T^\mu$ region using the known dependence of the resolution on $p_T^\mu$ also taking into account the uncertainty on the material distribution within the ID [20]. The efficiencies measured using the $J/\psi \to \mu^+\mu^-$ decays are used for the central value, and the difference between the two methods is considered as a systematic uncertainty on the muon impact parameter cut efficiency. It is less than 1% for $|\eta^\mu| < 2$, and 1.5 - 2.5% for $|\eta^\mu| > 2$ depending on $p_T^\mu$.

The efficiencies are accounted for in the cross-section measurement by applying a weight to each candidate. The weight is given by the inverse of the event selection efficiency, $w = 1/\epsilon_{\text{trig}}$, which is evaluated from the single-muon trigger and reconstruction efficiencies as

$$
\epsilon_{\mu\mu} = \epsilon_{\text{trig}} \epsilon_{\text{reco}}
$$

where the individual terms are given by

$$
\epsilon_{\text{trig}} = 1 - (1 - \epsilon_{\text{ch}}^+)(1 - \epsilon_{\text{ch}}^-)
$$

$$
\epsilon_{\text{reco}} = \epsilon_{\text{cb}}^+ \epsilon_{\text{cb}}^-/\epsilon_{\text{tag}}^+ \epsilon_{\text{tag}}^- - \epsilon_{\text{tag}}^+ \epsilon_{\text{tag}}^-
$$

Here $\epsilon_{\text{ch}}^+$ and $\epsilon_{\text{ch}}^-$ are the trigger efficiencies for a positively and negatively charged muon, respectively. $\epsilon_{\text{cb}}^+ \epsilon_{\text{cb}}^- / \epsilon_{\text{tag}}^+ \epsilon_{\text{tag}}^-$ give the single muon reconstruction efficiencies for a combined or tagged or just a tagged muon, respectively, for positively (negatively) charged muons. For each muon the efficiency is determined as a function of $p_T$, $\eta$ and the electric charge. The final weights span the range from about 1.4 at low $p_T$ to 1.1 at high $p_T$.

### 6. Determination of the Number of $\Upsilon(1S)$ Events

The number of $\Upsilon(1S)$ events is determined from an unbinned maximum likelihood fit to the dimuon mass distributions in each bin in $p_T^{\mu\mu}$ and $\gamma^{\mu\mu}$ where $p_T^{\mu\mu}$ ($\gamma^{\mu\mu}$) is the $p_T$ ($\gamma$) of the dimuon system. The distributions and corresponding fit results are shown for four representative kinematic bins in Fig. 1.

The shape of these distributions is rather complex. The background varies substantially over the considered mass range and its shape changes significantly depending on the kinematic bin. At low $p_T^{\mu\mu}$, the background increases sharply with $m^{\mu\mu}$ and is significant in the $\Upsilon(1S)$ mass range. At high $p_T^{\mu\mu}$, the background is nearly independent of the dimuon mass and also relatively low compared to the signal. Additionally, the $\Upsilon(1S)$ signal is not well separated from the $\Upsilon(2S)$ and $\Upsilon(3S)$, particularly in the forward region ($1.2 < |\gamma^{\mu\mu}| < 2.4$), due to the limited track momentum resolution [21]. Resolving the $\Upsilon(2S)$ and $\Upsilon(3S)$ is even more difficult, and thus measurements of $\Upsilon(2S)$ and $\Upsilon(3S)$ production are not presented in this letter.

A template based likelihood fit method is employed where four parameters are fitted independently in each kinematic bin: the numbers of $\Upsilon(1S)$, $\Upsilon(2S)$ and $\Upsilon(3S)$ mesons, and a background normalisation parameter. The three $\Upsilon$ signal templates are taken from the corresponding $\Upsilon$ MC samples. The background templates are constructed from data by pairing a muon with a track reconstructed in the ID of opposite electric charge (OS) that passes the ID track selection requirements described in Section 5 and the kinematic requirements of $p_T > 4$ GeV and $|\eta| < 2.5$. This template (denoted as “OS $\mu$+track”) gives an adequate description of the background since its shape is primarily determined by the kinematic selection requirements. The $\Upsilon$ signal contamination in this sample is expected to be negligible.

The fit results for $N_{\Upsilon(1S)}$ are given in Fig. 1 for four kinematic bins. The goodness of fit is assessed by a $\chi^2$ test comparing the data to the template distributions using the normalisations determined by the likelihood fit to the data. In all bins the $\chi^2$ probability is > 5%.

Alternative templates for the shape of the background are constructed using dimuon events in $b\bar{b}$ and $c\bar{c}$ MC or $\mu$+track events with the same electric charge (SS $\mu$+track). A comparison of these alternative background templates shapes is shown in Fig. 2 for two representative bins. The shapes of the alternative templates are similar to the default template at both low and high $p_T$, and any differences are considered as part of the systematic uncertainty, as discussed in Section 7.

The momentum resolution is determined from cosmic rays, $J/\psi$ and $Z$ mass distributions [22] and the central mass value for the $\Upsilon(1S)$ is fixed to the expected value [22]. The validity of fixing the mass resolution and the overall mass scale is considered as part of the systematic uncertainty, as described in Section 7.

### 7. Systematic Uncertainties

The following systematic uncertainties are considered:
Figure 1: Dimuon mass distributions for four representative bins in $|y_{\mu\mu}|$ and $p_{T,\mu\mu}$. The data (filled circles) are shown together with the result of the unbinned maximum likelihood fit (histogram) as explained in the text. The shaded histogram shows the background contribution, and the three other histograms show the contributions from the three $\Upsilon$ states. All histograms are normalised by the factor determined in the fit. In the individual plots, the fitted $N_{\Upsilon(1S)}$ yield with its statistical uncertainty, the $\chi^2$ and the number of degrees of freedom are also given. It should be noted that this is simply a binned graphical representation of the fit; the actual fit is unbinned and interpolates the template histograms to obtain the input probability density function.
Figure 2: Two examples of the templates used for the description of the dimuon mass dependence of the background are shown. The solid histogram shows the opposite-sign (OS) $\mu+\text{track}$, the dashed histogram shows the same-sign (SS) $\mu+\text{track}$ and the filled circles show the histogram derived from dimuon events in open $b\bar{b}$ and $c\bar{c}$ MC (heavy flavour MC). The error bars reflect the statistical uncertainty on the MC-based template. All histograms are normalised to the same absolute amount of background as determined in the fit for each kinematic bin (see also Fig. 1 and Section 6).

The luminosity calibration has been determined using the van der Meer scan technique [23] with a precision of 3.4% [24, 25]. It directly translates into a cross-section uncertainty of 3.4%.

The uncertainties on the single muon reconstruction efficiency, trigger efficiency [19] and impact parameter resolution (described in Section 5) result in 1%, <1% and 1-3.5% uncertainties on the cross-section measurement, respectively.

The impact of bin migrations is studied using MC, considering different shapes of the $p_T^{\Upsilon(1S)}$ distribution. A systematic uncertainty of 2% is associated with this.

The uncertainties on the fit model are evaluated using pseudo-experiments: 1000 sets of pseudo-data are created assuming a Poisson distribution corresponding to the prediction of the default template used for the data fits, and these are then fit with an alternative model as described below. The difference between the mean value of the 1000 pseudo-experiments and the value from the default template is used to assess the systematic effect. This method is used in order to avoid the propagation of statistical uncertainties in the data as part of the systematic uncertainty. However, fitting the data directly with any of the alternative choices gives consistent results. The systematic uncertainties related to the fit arise from the following contributions.

- The uncertainty on the template for the background model is assessed by constructing alternative templates based on the SS $\mu+\text{track}$ templates and on dimuon events in open $b\bar{b}$ and $c\bar{c}$ MC, as described in Section 6. The larger of the two differences, as determined using the pseudo-experiment technique described above, is taken as the uncertainty. The resulting uncertainty on the cross-section is typically about 4% but in some bins can be as high as 8%. Same-sign dimuon templates were also considered but are statistically too limited.

- The uncertainty on the signal model is assessed by changing from the signal templates to Crystal-Ball functions [26]. Here the three $\Upsilon$ states are considered and the differences between their mass values is fixed to the PDG value [22]. Their relative normalisations are allowed to float as in the default fit. In addition a common scale parameter and the parameters that describe the low-mass tail of the Crystal-Ball function float freely in the fit. The width is constrained to the value predicted by smeared MC to match resolutions measured in data. In the central region ($|y^{\Upsilon(1S)}| < 1.2$) the resulting difference is typically 1% while in the forward region ($1.2 < |y^{\Upsilon(1S)}| < 2.4$) it is about 5-10%, and these values are included in the systematic uncertainty. The data were also directly fit-
ted with this alternative model and the result was found to be consistent with respect to the default fit.

- Both the overall mass scale and the separation between the three \( \Upsilon \) states are fixed in the fit. The position of the reconstructed \( \Upsilon(1S) \) mass peak is influenced by the overall momentum scale and the energy loss. The momentum scale has been determined using \( J/\psi \) mesons and \( Z \) bosons to better than 0.2\% [21]. The energy loss has been evaluated from the variations of the \( J/\psi \) and \( K_S^0 \) masses [20] in different regions of the detector. Evaluated at the world average \( \Upsilon(1S) \) mass, both effects together allow for a mass position uncertainty of 25 MeV. To assess the corresponding systematic uncertainty, pseudo-experiments are used to evaluate the impact of a possible shift in the mass scale by 25 MeV on \( N_{\Upsilon(1S)} \). The difference to the default fit is found to be less than 1\% in most bins but up to 5\% in the highest-\( p_T \) forward bin. The mass separation is only influenced by the momentum scale: considering an uncertainty of 0.2\% on the mass scale results in an uncertainty on the cross-section of at most 2\% in any bin.

- The mass resolution is fixed to the value determined from detailed studies based on \( J/\psi \)s, \( Z \)s and cosmic rays [10]. A systematic uncertainty is assessed by changing the momentum resolution by 1\( \sigma \). The resulting systematic uncertainty on the cross-section measurement is below 3\% in all bins.

All these systematic uncertainties are uncorrelated and added in quadrature to give the total systematic uncertainty. It is typically 5\% in the central and 10\% in the forward region. This can be compared to the statistical uncertainty of about 10\% (15\%) at low \( p_T^{\Upsilon(1S)} \) for the central (forward) region and 30\% at the highest \( p_T^{\Upsilon(1S)} \).

The number of \( \Upsilon(1S) \) events and the statistical and systematic uncertainties for each bin are listed in Table I.

8. Differential \( \Upsilon(1S) \) Cross-Section Measurement and Comparison to Theoretical Predictions

Figure 3 shows the differential \( \Upsilon(1S) \) cross-section measurement for the central and forward regions in 8 bins in \( p_T^{\Upsilon(1S)} \) covering 0 to 26 GeV for \( p_T^\mu > 4 \text{ GeV and } |\eta^\mu| < 2.5 \) on both muons. The results are also listed in Table I. The cross-section falls by about a factor of 50 over this \( p_T \)-range in both the central and the forward region.

Two theoretical predictions for quarkonium production are compared to the experimental data in Fig. [3] [27]. The first is the result of predictions from PYTHIA 8.135 [27] using the NRQCD [16] framework. This prediction uses the NRQCD matrix elements as recommended in Ref. [17] and determined from Tevatron data, and a \( p_T \) and \( Q^2 \)-dependent reweighting of the differential cross-section as described in Ref. [28] to prevent a divergence of the cross-section at low \( p_T \). The CTEQ5L parton distribution functions are used [29]. The second prediction is a next-to-leading-order QCD calculation of the \( \Upsilon(1S) \) production cross-section in a colour-singlet state [30] as implemented in MCFM [31] which corresponds to the leading contribution in the NRQCD expansion (CSM NLO). This prediction is not available for \( p_T^{\Upsilon(1S)} < 4 \text{ GeV (} p_T^{\Upsilon(1S)} < 6 \text{ GeV) in the central (forward) region since the perturbative expansion is not under proper control and this fixed-order calculation fails to provide a reliable estimate [30]. Note that this prediction does not reproduce the differential cross-section measurements at the Tevatron unless additional higher-order terms of \( \mathcal{O}(a_s^5) \) are considered and the data are corrected for feed-down from \( \chi_b \rightarrow \Upsilon \gamma \) production [32] and other excited \( \Upsilon \) states. The renormalisation and factorisation scales for this prediction are set to \( m_b = \sqrt{4m_b^2 + p_T^2} \) where \( m_b = 4.75 \text{ GeV and } p_T \) is the transverse momentum of the \( \Upsilon(1S) \). These scales are varied by a factor of two to assess the sensitivity of the calculation to these parameters. The CTEQ6M parton distribution functions are used for this prediction [33].

The measured differential cross-section has a different \( p_T \) dependence, but its normalisation is in reasonable overall agreement with the NRQCD prediction. In particular, at high (low) \( p_T^{\Upsilon(1S)} \) the prediction is systematically higher (lower) than the data. The cross-section from data is higher than the NLO colour-singlet prediction over the entire \( p_T \) range. Part of the discrepancy can likely be accounted for by the fact that this prediction does not include any feed-down from higher mass states.

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2 The following five parameters have been changed from the default PYTHIA 8.135 implementation as recommended by the PYTHIA authors: PhaseSpace:PHatMin=1 GeV, PhaseSpace:PHatMinDiverge=0.5, SuppressSmallPFT(1, 3, false); Bottomonium:0Pseudo3P08 = 0.02; Bottomonium:CHiB03P01=0.085.
Table 1: Measured differential cross-sections for $\Upsilon(1S)$ production in the fiducial acceptance ($p_T^{\Upsilon} > 4 \text{ GeV}, |\eta^{\mu}| < 2.5$ on both muons). Also listed are the corrected yields of $\Upsilon(1S)$ mesons, $N_{\Upsilon(1S)}$, and the fractional statistical ($\delta_{\text{stat}}$), systematic ($\delta_{\text{syst}}$) and total ($\delta_{\text{tot}}$) uncertainties.

| $p_T^{\Upsilon(1S)}$ (GeV) | $N_{\Upsilon(1S)}$ | $d^2\sigma/dp_Tdy$ (pb/GeV) | $\delta_{\text{stat}}$ (%) | $\delta_{\text{syst}}$ (%) | $\delta_{\text{tot}}$ (%) |
|-----------------------------|---------------------|-------------------------------|-----------------------------|-----------------------------|-----------------------------|
| $|y^{\Upsilon(1S)}| < 1.2$ |                     |                               |                             |                             |                             |
| 0 - 2                       | 213                 | 39.3                          | 12                          | 6                           | 13                          |
| 2 - 4                       | 246                 | 45.4                          | 10                          | 5                           | 11                          |
| 4 - 6                       | 190                 | 35.0                          | 12                          | 5                           | 13                          |
| 6 - 8                       | 175                 | 32.2                          | 12                          | 6                           | 13                          |
| 8 - 11                      | 203                 | 24.9                          | 10                          | 4                           | 11                          |
| 11 - 14                     | 110                 | 13.6                          | 13                          | 7                           | 15                          |
| 14 - 18                     | 70                  | 6.5                           | 15                          | 7                           | 17                          |
| 18 - 26                     | 17                  | 0.8                           | 33                          | 9                           | 34                          |
| $1.2 < |y^{\Upsilon(1S)}| < 2.4$ |                     |                               |                             |                             |                             |
| 0 - 2                       | 163                 | 30.0                          | 17                          | 13                          | 22                          |
| 2 - 4                       | 238                 | 43.8                          | 13                          | 13                          | 18                          |
| 4 - 6                       | 124                 | 22.9                          | 18                          | 9                           | 20                          |
| 6 - 8                       | 129                 | 23.7                          | 15                          | 9                           | 17                          |
| 8 - 11                      | 132                 | 16.2                          | 14                          | 7                           | 16                          |
| 11 - 14                     | 75                  | 9.3                           | 18                          | 9                           | 20                          |
| 14 - 18                     | 71                  | 6.5                           | 17                          | 10                          | 20                          |
| 18 - 26                     | 28                  | 1.3                           | 29                          | 15                          | 33                          |

Figure 3: The differential $\Upsilon(1S)$ cross-section for $|y^{\Upsilon(1S)}| < 1.2$ (left) and $1.2 < |y^{\Upsilon(1S)}| < 2.4$ (right) as function of $p_T^{\Upsilon(1S)}$ for $p_T^{\mu} > 4 \text{ GeV}$ and $|\eta^{\mu}| < 2.5$ on both muons. Also shown is the colour-singlet NLO (CSM) prediction using $m_T$ for the renormalisation and factorisation scales. The shaded area shows the change in the theoretical prediction when varying the renormalisation and factorisation scales by a factor of two. The CSM NLO calculation accounts only for direct production of $\Upsilon(1S)$ mesons and not for any feed-down from excited states. The NRQCD prediction as implemented in PYTHIA8 is also shown for a particular choice of parameters as discussed in the text.
which was estimated to contribute about a factor of 2 at the Tevatron [3,4]. In Ref. [3], it was shown that additional higher order corrections increase with increasing \( p_T \) (they contribute about a factor of 10 at high \( p_T \)), and are required to describe the Tevatron data. This is qualitatively consistent with the discrepancies observed between the data presented here and the NLO prediction. Whether or not these data can be consistently understood together with the data from previous collider experiments within a consistent theoretical framework remains to be seen.

The data are not compared directly to previous measurements [4,5,6] since in the present analysis no correction is made for the \( p_T^\mu \) and \( \eta^\mu \) cuts in order to avoid the need for any assumption on the spin alignment of the \( \Upsilon(1S) \).

9. Conclusions

A measurement of the differential production cross-section of \( \Upsilon(1S) \) mesons decaying into two muons measured in the fiducial region with \( p_T^\mu > 4 \) GeV and \( |\eta^\mu| < 2.5 \) has been presented as function of \( p_T^\Upsilon(1S) \) and \( y^\Upsilon(1S) \). The typical uncertainty of the measurement is about 10-15% at low \( p_T^\Upsilon(1S) \) and 35% at high \( p_T^\Upsilon(1S) \) and is dominated by the statistical precision of the data. Due to the restriction to \( p_T^\mu > 4 \) GeV and \( |\eta^\mu| < 2.5 \), the measurement is almost independent of any assumption on the spin alignment of the \( \Upsilon(1S) \).

The data significantly exceed the NLO prediction but this may well be explained due to contributions from higher mass bound states and by the need for additional higher order corrections to \( \Upsilon(1S) \) production. In contrast, the data are in reasonable agreement with the NRQCD prediction as implemented in PYTHIA8 but differences in the shape of the \( p_T \) spectrum of about a factor of two are observed. The data presented here will be useful to further understand the complex mechanisms that govern quarkonium production.

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6 Department of Physics, University of Arizona, Tucson AZ, United States of America
7 Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America
8 Physics Department, University of Athens, Athens, Greece
9 Physics Department, National Technical University of Athens, Zografou, Greece
10 Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
11 Institut de Física d’Altes Energies and Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain
12 (a) Institute of Physics, University of Belgrade, Belgrade; (b) Vinca Institute of Nuclear Sciences, Belgrade, Serbia
13 Department for Physics and Technology, University of Bergen, Bergen, Norway
14 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America
15 Department of Physics, Humboldt University, Berlin, Germany
16 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
17 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
18 (a) Department of Physics, Bogazici University, Istanbul; (b) Division of Physics, Dogus University, Istanbul; (c) Department of Physics Engineering, Gaziantep University, Gaziantep; (d) Department of Physics, Istanbul Technical University, Istanbul, Turkey
19 (a) INFN Sezione di Bologna; (b) Dipartimento di Fisica, Università di Bologna, Bologna, Italy
20 Physikalisches Institut, University of Bonn, Bonn, Germany
21 Department of Physics, Boston University, Boston MA, United States of America
22 Department of Physics, Brandeis University, Waltham MA, United States of America
23 (a) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (b) Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
24 Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
25 (a) National Institute of Physics and Nuclear Engineering, Bucharest; (b) University Politehnica Bucharest, Bucharest; (c) West University in Timisoara, Timisoara, Romania
26 Departamento de Fisica, Universidad de Buenos Aires, Buenos Aires, Argentina
27 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
28 Department of Physics, Carleton University, Ottawa ON, Canada
29 CERN, Geneva, Switzerland
30 Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
31 (a) Departamento de Fisica, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Fisica, Universidad Técnica Federico Santa María, Valparaíso, Chile
32 (a) Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b) Department of Modern Physics, University of Science and Technology of China, Anhui; (c) Department of Physics, Nanjing University, Jiangsu; (d) High Energy Physics Group, Shandong University, Shandong, China
33 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Aubiere Cedex, France
34 Nevis Laboratory, Columbia University, Irvington NY, United States of America
35 Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
36 (a) INFN Gruppo Collegato di Cosenza; (b) Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy
37 Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Krakow, Poland
38 The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
39 Physics Department, Southern Methodist University, Dallas TX, United States of America
40 Physics Department, University of Texas at Dallas, Richardson TX, United States of America
41 DESY, Hamburg and Zeuthen, Germany
42 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
43 Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany
44 Department of Physics, Duke University, Durham NC, United States of America
National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America
Group of Particle Physics, University of Montreal, Montreal QC, Canada
P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
Nagasaki Institute of Applied Science, Nagasaki, Japan
Graduate School of Science, Nagoya University, Nagoya, Japan
(a) INFN Sezione di Napoli; (b) Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America
Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
(a) INFN Sezione di Napoli; (b) Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
(a) INFN Sezione di Roma; (b) Dipartimento di Fisica, Università La Sapienza, Roma, Italy
(a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
(a) INFN Sezione di Roma Tre; (b) Dipartimento di Fisica, Università Roma Tre, Roma, Italy
135 (a) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; (b) Centre National de l’Energie des Sciences Techniques Nucléaires, Rabat; (c) Université Cadi Ayad, Faculté des sciences Semlalia Département de Physique, B.P. 2390 Marrakech 40000; (d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; (e) Faculté des Sciences, Université Mohammed V, Rabat, Morocco

136 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat a l’Energie Atomique), Gif-sur-Yvette, France

137 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America

138 Department of Physics, University of Washington, Seattle WA, United States of America

139 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom

140 Department of Physics, Shinshu University, Nagano, Japan

141 Fachbereich Physik, Universität Siegen, Siegen, Germany

142 Department of Physics, Simon Fraser University, Burnaby BC, Canada

143 SLAC National Accelerator Laboratory, Stanford CA, United States of America

144 (a) Department of Physics, University of Johannesburg, Johannesburg; (b) School of Physics, University of the Witwatersrand, Johannesburg, South Africa

145 (a) Department of Physics, Stockholm University; (b) The Oskar Klein Centre, Stockholm, Sweden

146 Physics Department, Royal Institute of Technology, Stockholm, Sweden

147 Department of Physics and Astronomy, Stony Brook University, Stony Brook NY, United States of America

148 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom

149 School of Physics, University of Sydney, Sydney, Australia

150 Institute of Physics, Academia Sinica, Taipei, Taiwan

151 Department of Physics, Technion; Israel Inst. of Technology, Haifa, Israel

152 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel

153 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece

154 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan

155 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan

156 Department of Physics, Tokyo Institute of Technology, Tokyo, Japan

157 Department of Physics, University of Toronto, Toronto ON, Canada

158 (a) TRIUMF, Vancouver BC; (b) Department of Physics and Astronomy, York University, Toronto ON, Canada

159 Institute of Pure and Applied Sciences, University of Tsukuba, Ibaraki, Japan

160 Science and Technology Center, Tufts University, Medford MA, United States of America

161 Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia

162 Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of America

163 (a) INFN Gruppo Collegato di Udine; (b) ICTP, Trieste; (c) Dipartimento di Fisica, Università di Udine, Udine, Italy

164 Department of Physics, University of Illinois, Urbana IL, United States of America

165 Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden

166 Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain

167 Department of Physics, University of British Columbia, Vancouver BC, Canada

168 Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada

169 Waseda University, Tokyo, Japan

170 Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel

171 Department of Physics, University of Wisconsin, Madison WI, United States of America
Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
Department of Physics, Yale University, New Haven CT, United States of America
Yerevan Physics Institute, Yerevan, Armenia
Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France
Also at Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal
Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal
Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom
Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
Also at TRIUMF, Vancouver BC, Canada
Also at Department of Physics, California State University, Fresno CA, United States of America
Also at Faculty of Physics and Applied Computer Science, AGH-University of Science and Technology, Krakow, Poland
Also at Department of Physics, University of Coimbra, Coimbra, Portugal
Also at Università di Napoli Parthenope, Napoli, Italy
Also at Institute of Particle Physics (IPF), Canada
Also at Department of Physics, Middle East Technical University, Ankara, Turkey
Also at Louisiana Tech University, Ruston LA, United States of America
Also at Group of Particle Physics, University of Montreal, Montreal QC, Canada
Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
Also at Department of Physics, Colorado State University, Fort Collins CO, United States of America
Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China
Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
Also at High Energy Physics Group, Shandong University, Shandong, China
Also at California Institute of Technology, Pasadena CA, United States of America
Also at Section de Physique, Université de Genève, Geneva, Switzerland
Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal
Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America
Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary
Also at Institute of Physics, Jagiellonian University, Krakow, Poland
Also at Department of Physics, Oxford University, Oxford, United Kingdom
Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l’Univers), CEA Saclay (Commissariat à l’Energie Atomique), Gif-sur-Yvette, France
Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
Also at Department of Physics, Nanjing University, Jiangsu, China
Deceased