

## Measurement of Inclusive Differential Cross Sections for $\Upsilon(1S)$ Production in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We present measurements of the inclusive production cross sections of the  $Y(1S)$  bottomonium state in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.96$  TeV. Using the  $Y(1S) \rightarrow \mu^+\mu^-$  decay mode for a data sample of  $159 \pm 10$  pb<sup>-1</sup> collected by the D0 detector at the Fermilab Tevatron collider, we determine the differential cross sections as a function of the  $Y(1S)$  transverse momentum for three ranges of the  $Y(1S)$  rapidity:  $0 < |y^Y| \leq 0.6$ ,  $0.6 < |y^Y| \leq 1.2$ , and  $1.2 < |y^Y| \leq 1.8$ .

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Quarkonium production in hadron-hadron collisions provides insight into the nature of strong interactions. It is a window on the boundary region between perturbative

and nonperturbative QCD. Recent advances in the understanding of quarkonium production have been stimulated by the unexpectedly large cross sections for direct  $J/\psi$  and

$\psi(2S)$  production at large transverse momentum ( $p_T$ ) measured at the Fermilab Tevatron collider [1].

Bottomonium states are produced either promptly or indirectly as a result of the decay of a higher mass state [2], e.g., in a radiative decay such as  $\chi_b \rightarrow Y(1S)\gamma$ . The only detailed studies of  $Y(nS)$  production at the Tevatron have been done by the CDF Collaboration [2,3] in the limited  $Y$  rapidity range of  $|y^Y| < 0.4$  at  $\sqrt{s} = 1.8$  TeV, where  $y = \frac{1}{2} \ln \frac{E+p_z}{E-p_z}$ ,  $E$  is the  $Y$  energy, and  $p_z$  is the  $Y$  momentum parallel to the beam direction.

Three types of models have been used to describe prompt quarkonium formation: the color-singlet model [4], the color-evaporation model [5] (and a follow-up soft color interaction model [6]), and the color-octet model [7]. These models of quarkonium formation lead to different expectations for the production rates and polarization of the quarkonium states, yet many of the model parameters have to be extracted directly from the data. A recent work [8,9] successfully reproduces the shape of the  $p_T$  distribution of  $Y$  states produced at Tevatron energies by combining separate perturbative approaches for the low- and high- $p_T$  regions. The absolute cross section is not predicted by these calculations, which are similar to the color-evaporation model.

Production of heavy quarkonium states at the Tevatron also provides an essential input for the quark gluon plasma searches in relativistic heavy ion collisions and is being used to predict quarkonium production at the CERN LHC [5,10].

In this Letter we concentrate on the production of the  $Y(1S)$  state. A precise measurement of the differential  $Y(1S)$  cross section, using the wide rapidity range accessible by the D0 detector, will provide valuable input to the various quarkonium production models. By reconstructing the  $Y(1S)$  through its decay  $Y(1S) \rightarrow \mu^+ \mu^-$ , we determine production cross sections of the  $Y(1S)$  as a function of its transverse momentum, in three rapidity ranges:  $0 < |y^Y| \leq 0.6$ ,  $0.6 < |y^Y| \leq 1.2$ , and  $1.2 < |y^Y| \leq 1.8$ .

The D0 detector is described in detail elsewhere [11]. Here, we briefly describe only the detector components most relevant to this analysis. The D0 tracking system consists of a high-resolution silicon microstrip tracker (SMT) surrounded by a central scintillating-fiber tracker (CFT) inside a 2 T magnetic field provided by a superconducting solenoid. The tracking volume extends to a radius of approximately 52 cm. Closest to the interaction region is the SMT with a typical strip pitch of 50–80  $\mu\text{m}$ . It has a barrel-disk hybrid structure and provides tracking and vertexing coverage in the pseudorapidity range  $|\eta| < 3.0$ , where  $\eta = -\ln[\tan(\theta/2)]$  and  $\theta$  is the polar angle. The CFT consists of eight concentric cylinders of pairs of scintillating-fiber doublets. On each cylinder, the inner doublet runs parallel to the beam axis and the outer doublet is mounted at a stereo angle of  $\pm 3^\circ$ , alternating with each cylinder. Located outside the superconducting coil is the

uranium-liquid-argon calorimeter. Beyond the calorimeter, the muon system consists of three layers of drift tubes, 10 cm wide in the central region ( $|\eta| < 1$ ) and 1 cm in the forward region ( $1 < |\eta| < 2$ ). Interspersed between the drift tubes are scintillating counters. Located between the innermost and the middle layers of drift tubes are 1.8 T iron toroid magnets. D0 uses up to three levels of triggers to reduce the initial event rate of 1.7 MHz to an output rate of approximately 50 Hz.

The data were collected between June 2002 and September 2003 and correspond to an integrated luminosity of  $159 \pm 10 \text{ pb}^{-1}$  for the chosen two triggers. These triggers are scintillator-based dimuon triggers at the first trigger level and require the confirmation of one or both muons at the second trigger level. The first trigger level is almost fully efficient for muons with a transverse momentum above 5 GeV/ $c$ . For events passing our analysis criteria, the second level trigger requirement kept more than 97% of events which satisfied the first level requirement.

The analysis requires two oppositely charged muons with  $p_T^\mu > 3$  GeV/ $c$  and  $|y^\mu| < 2.2$ . Only muons that are matched to a track found by the central tracking system and which have hits inside and outside the toroidal magnets are used. The track associated with a muon must have at least

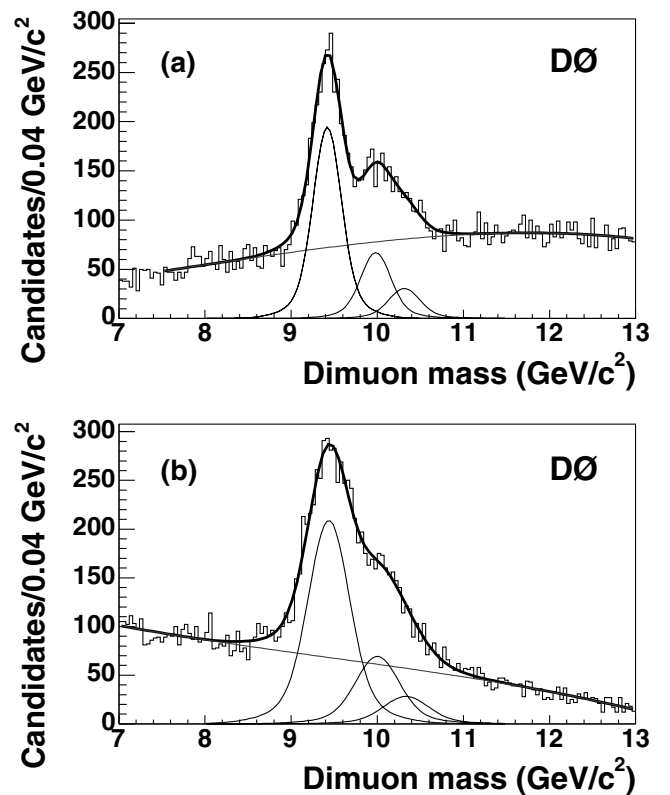


FIG. 1. Example of fits to the dimuon spectra in different bins of rapidity in the  $p_T$  bin of  $4 < p_T^Y < 6$  GeV/ $c$ : (a)  $|y^Y| \leq 0.6$ , (b)  $1.2 < |y^Y| \leq 1.8$ . The heavy line shows the combined fit for signal and background. Also shown are the individual contributions from the three  $Y$  states and the background separately.

TABLE I. Efficiencies used in the cross section calculations.

$ y^Y $	$\varepsilon_{\text{acc}}$	$\varepsilon_{\text{trig}}$	$k_{\text{qual}}$	$k_{\text{trk}}$	$k_{\text{dimu}}$
0.0–0.6	0.15–0.26	0.70	0.85	0.99	0.85
0.6–1.2	0.19–0.28	0.73	0.85	0.99	0.88
1.2–1.8	0.20–0.27	0.82	0.93	0.95	0.95

one hit in the SMT. We reject cosmic ray muons based on timing information from the muon system scintillators. Compared to muons from the dominant  $b\bar{b}$  background, muons from  $Y(nS)$  decays are expected to be relatively isolated, and therefore we require at least one of the muons to satisfy the following criterion: either the sum of the transverse momenta of charged tracks in a cone of radius 0.5 (in  $\eta$ - $\phi$  space) around the muon is less than 1 GeV or the sum of the calorimeter transverse energies in an annular cone of radii 0.1 and 0.5 around the muon is less than 1 GeV. This isolation requirement reduces the background by 35% and the signal by less than 6%.

Two typical examples of dimuon mass distributions in different rapidity bins are shown in Fig. 1. In each plot a strong  $Y(1S)$  signal can be seen, accompanied by a shoulder attributed to unresolved signals due to  $Y(2S)$  and  $Y(3S)$  production. The mass distributions are fit starting from 7.0, 7.5, or 7.8  $\text{GeV}/c^2$ , depending on  $p_T^Y$  and  $y^Y$ , to 13.0  $\text{GeV}/c^2$  using separate mass resolution functions for each of the  $Y(nS)$  states and a third-order polynomial for the background. The mass resolution function is approximated by a sum of two Gaussians with the relative contribution and width of the second Gaussian fixed with respect to the first Gaussian. The values of this contribution were determined from Monte Carlo studies and  $J/\psi$  signal fits to data. This procedure also accounts for small distortions to the  $\mu^+\mu^-$  mass spectrum arising from  $Y(nS) \rightarrow \mu^+\mu^-\gamma$  final states. The mass of the  $Y(1S)$  is a free parameter of the fit and the remaining two masses are shifted by the  $m(Y(nS)) - m(Y(1S))$  differences of 563  $\text{MeV}/c^2$  [ $Y(2S)$ ] and 895  $\text{MeV}/c^2$  [ $Y(3S)$ ], taken from Ref. [12]. In addition, only the width of the  $Y(1S)$  state is allowed to vary. The widths of the other states are assumed to scale with the mass of the resonance. Normalizations of functions representing each resonance are free parameters of the fit. The Monte Carlo samples used in this study were generated with PYTHIA v6.202 [13]. The muon kinematic distributions from data and Monte Carlo simulations agree well within a given  $p_T^Y$  and  $y^Y$  bin.

The cross section for a given kinematic range, multiplied by the branching fraction  $Y(1S) \rightarrow \mu^+\mu^-$ , is given by

$$\frac{d^2\sigma(Y(1S))}{dp_T dy} \times \mathcal{B}[Y(1S) \rightarrow \mu^+\mu^-] = \frac{N(Y(1S))}{\mathcal{L} \Delta p_T \Delta y \varepsilon_{\text{acc}} \varepsilon_{\text{trig}} k_{\text{qual}} k_{\text{trk}} k_{\text{dimu}}}, \quad (1)$$

TABLE II. Fitted number of events and  $d\sigma(Y(1S))/dy \times \mathcal{B}[Y(1S) \rightarrow \mu^+\mu^-]$  per unit of rapidity.

$ y^Y $	Number of $Y(1S)$	$d\sigma(Y(1S))/dy$ (pb)
0.0–0.6	$12\,951 \pm 336$	$732 \pm 19(\text{stat}) \pm 73(\text{syst}) \pm 48(\text{lumin})$
0.6–1.2	$16\,682 \pm 438$	$762 \pm 20(\text{stat}) \pm 76(\text{syst}) \pm 50(\text{lumin})$
1.2–1.8	$17\,884 \pm 566$	$600 \pm 19(\text{stat}) \pm 56(\text{syst}) \pm 39(\text{lumin})$
0.0–1.8	$46\,625 \pm 939$	$695 \pm 14(\text{stat}) \pm 68(\text{syst}) \pm 45(\text{lumin})$

where  $\mathcal{L}$  is the integrated luminosity for the data sample used,  $N(Y(1S))$  is the number of observed  $Y(1S)$ , and  $\varepsilon$  and  $k$  represent the various efficiency, acceptance, and correction factors. The  $Y(1S)$  acceptance and reconstruction efficiency  $\varepsilon_{\text{acc}}$  represents the fraction of generated  $Y(1S)$  events that are successfully reconstructed in the D0 detector, not taking into account any loss in efficiency due to triggering. Its value is based on a Monte Carlo analysis. The dimuon trigger efficiency  $\varepsilon_{\text{trig}}$  for reconstructed  $Y(1S)$  events that satisfy our analysis criteria is estimated using a trigger simulation and verified directly with the data using other triggers. The remaining factors in Eq. (1) account for the differences between the data and Monte Carlo simulations and are referred to as corrections, rather than efficiencies. The correction  $k_{\text{qual}}$  takes into account differences in the track quality requirements, i.e., the isolation and SMT hit requirements and cosmic ray rejection. It is consistent with being independent of  $p_T$ , and its value varies between 0.85 and 0.93 with increasing rapidity. The central tracking correction  $k_{\text{trk}}$  takes into account both differences in the tracking and the track-to-muon matching efficiency. It is derived from the  $J/\psi$  data sample and Monte Carlo simulation and is very close to unity except for the forward rapidity region where  $k_{\text{trk}} \approx 0.95$ . The correction factor  $k_{\text{dimu}}$  accounts for the differences in the local (i.e., muon system only) muon reconstruction, taking into account trigger effects. It was determined using  $J/\psi$  candidates collected with single muon triggers. It does not show a significant  $p_T$  dependence, but it changes with the muon rapidity.

In Table I we summarize the values of efficiencies found in different rapidity regions. The measured cross sections are collected in Table II. These cross sections are normalized per unit of rapidity.

Differential cross sections, normalized to unity, are summarized in Table III. Figure 2 shows these cross sections compared to theoretical predictions from Ref. [9]. There is little variation in the shape of the  $p_T$  distributions with rapidity. This is further illustrated in Fig. 3, which shows the ratio of the differential cross sections of  $\sigma(1.2 < |y^Y| \leq 1.8)$  to  $\sigma(|y^Y| \leq 0.6)$ . In Fig. 4 we show a comparison with results from the CDF Collaboration [3].

The overall systematic uncertainties, excluding luminosity, are approximately 10%. The uncertainty on the luminosity [14] is 6.5%. The main systematic errors are due to

TABLE III. Normalized differential cross sections for  $Y(1S)$  in different rapidity regions. Quoted uncertainties include statistical uncertainties added in quadrature to systematic uncertainties due to the assumed shape of the mass resolution function (cf. stat uncertainties in Table II). The remaining systematic uncertainties are  $p_T$  independent and quoted in Table II.

$p_T^Y$ (GeV/c)	$0.0 <  y^Y  \leq 0.6$	$0.6 <  y^Y  \leq 1.2$	$1.2 <  y^Y  \leq 1.8$	$0.0 <  y^Y  \leq 1.8$
0–1	$0.051 \pm 0.005$	$0.061 \pm 0.006$	$0.050 \pm 0.005$	$0.056 \pm 0.004$
1–2	$0.138 \pm 0.010$	$0.137 \pm 0.010$	$0.136 \pm 0.011$	$0.136 \pm 0.008$
2–3	$0.152 \pm 0.010$	$0.153 \pm 0.010$	$0.175 \pm 0.015$	$0.160 \pm 0.009$
3–4	$0.149 \pm 0.011$	$0.175 \pm 0.012$	$0.160 \pm 0.014$	$0.159 \pm 0.009$
4–6	$0.112 \pm 0.006$	$0.110 \pm 0.007$	$0.115 \pm 0.008$	$0.113 \pm 0.005$
6–8	$0.067 \pm 0.005$	$0.061 \pm 0.004$	$0.056 \pm 0.005$	$0.062 \pm 0.003$
8–10	$0.034 \pm 0.003$	$0.034 \pm 0.003$	$0.034 \pm 0.003$	$0.035 \pm 0.002$
10–15	$0.014 \pm 0.001$	$0.011 \pm 0.001$	$0.011 \pm 0.001$	$0.012 \pm 0.001$
15–20	$0.0032 \pm 0.0005$	$0.0019 \pm 0.0003$	$0.0019 \pm 0.0004$	$0.0023 \pm 0.0002$

the fitting procedure and the determination of  $k_{\text{dimu}}$ . The statistical uncertainty of the fitted number of events in a given kinematic bin and the uncertainty from varying the contribution of the second Gaussian are added in quadrature to give the uncertainties labeled “stat” in Table II. The net effect is an increase in the overall fit uncertainty by less than 40% of its statistical uncertainty alone. An additional uncertainty in the fitting procedure due to varying the fitting range and the background parametrization is at the 4% level. The systematic uncertainty for  $k_{\text{dimu}}$  is 8.7%, 8.2%, and 7.2% for the three rapidity bins. These were derived from uncertainties for the Monte Carlo simulations–data differences for individual muons, determined as a function of muon rapidity and transverse momentum. The other uncertainties considered include momentum

resolution, uncertainties introduced by the track quality and track matching requirements, variations in the input Monte Carlo distributions, and changes in detector performance over time. All these systematic uncertainties contribute less than 2% each.

The current analysis assumes that the  $Y(1S)$  is produced unpolarized, in agreement with the CDF measurement [3]. Although we do not include a contribution to the systematic uncertainty due to this assumption, we estimate the sensitivity of our results to the  $Y(1S)$  polarization by varying  $\alpha$  within  $\pm 0.15$  ( $\pm 0.30$ ). This changes our results by less than 4% (15%) in all  $p_T$  bins.

In conclusion, we present a measurement of the inclusive production cross section of the  $Y(1S)$  bottomonium state using the  $Y(1S) \rightarrow \mu^+ \mu^-$  decay mode. The measured cross section  $\times \mathcal{B}[Y(1S) \rightarrow \mu^+ \mu^-]$  for the  $|y^Y| \leq 0.6$  region is  $732 \pm 19(\text{stat}) \pm 73(\text{syst}) \pm 48(\text{lumin})$  pb. Taking into account a predicted increase in the cross section when the  $p\bar{p}$  center-of-mass energy increases from 1.8 to 1.96 TeV [13], our result is compatible with the CDF Collaboration’s result [3] of  $680 \pm 15(\text{stat}) \pm 18(\text{syst}) \pm 26(\text{lumin})$  pb for  $\sqrt{s} = 1.8$  TeV. We measure the ratios of the cross sections for the  $0.6 < |y^Y| \leq 1.2$  and  $1.2 < |y^Y| \leq 1.8$  ranges to that for the  $|y^Y| \leq 0.6$  range to be

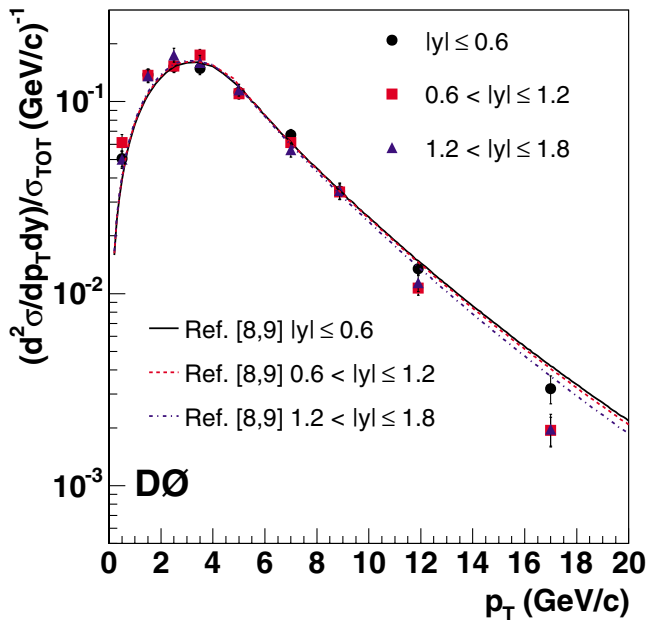


FIG. 2 (color online). Normalized differential cross sections for  $Y(1S)$  production compared with theory predictions [8,9]. The errors shown correspond to the errors in Table III.

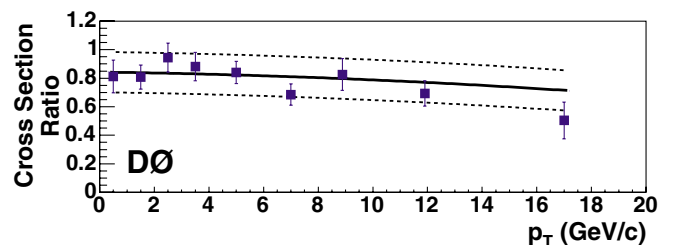


FIG. 3 (color online). The ratio of differential cross sections (squares) for  $\sigma(1.2 < |y^Y| \leq 1.8)$  to  $\sigma(|y^Y| \leq 0.6)$ . The solid line is the Monte Carlo prediction [13] normalized to the measured ratio of the  $p_T$ -integrated cross section. Uncertainties of the relative normalization are indicated by the dashed lines.

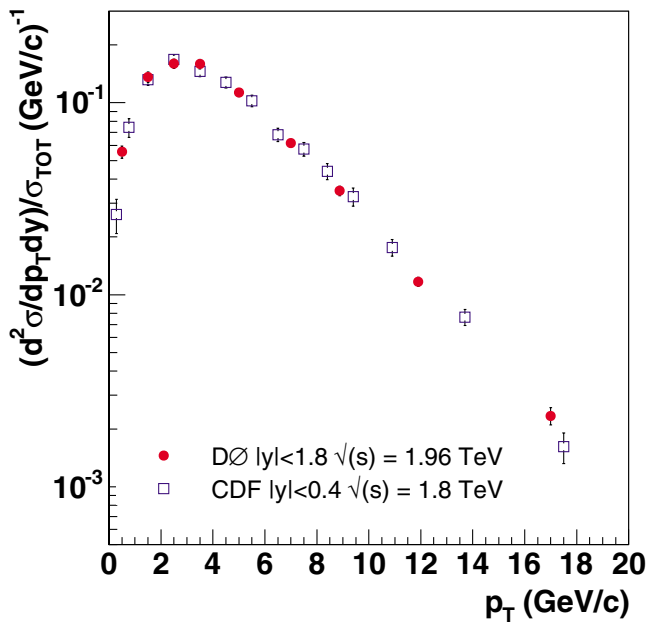


FIG. 4 (color online). Normalized differential cross sections for  $Y(1S)$  production at  $\sqrt{s} = 1.96$  TeV compared with published CDF results [3] at  $\sqrt{s} = 1.8$  TeV. The errors shown are statistical only.

$1.04 \pm 0.14$  and  $0.80 \pm 0.11$ , compared with predictions from Monte Carlo simulations [13] of 0.94 and 0.83. Between the rapidity regions, there is little variation in the shapes of the differential cross sections, and their shapes agree reasonably well with theoretical predictions [9]. The shape of the combined differential cross section for  $|y^Y| \leq 1.8$  is consistent with the CDF measurement in the limited rapidity range of  $|y^Y| < 0.4$  [3]. The results presented in this Letter will allow a more precise determination of parameters of the various bottomonium production models.

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