Inclusive J/ψ, $\psi(2S)$, and b-Quark Production in $\bar{p}p$ Collisions at $\sqrt{s}=1.8$ TeV

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Inclusive J/ψ and $\psi(2S)$ production has been studied in $\bar{p}p$ collisions at $\sqrt{s}=1.8$ TeV using 2.6 ± 0.2 pb^{-1} of data taken with the Collider Detector at Fermilab. The products of production cross section times branching fraction were measured as functions of P_T for $J/\psi\rightarrow\mu^+\mu^-$ and $\psi(2S)\rightarrow\mu^+\mu^-$. In the kinematic range $P_T>6$ GeV/c and $|\eta|\leq0.5$ we get $\sigma(\bar{p}p\rightarrow J/\psi X)B(J/\psi\rightarrow\mu^+\mu^-)=6.88\pm0.23(\text{stat})^{+0.93}_{-1.08}(\text{syst})$ nb, and $\sigma(\bar{p}p\rightarrow\psi(2S)X)B(\psi(2S)\rightarrow\mu^+\mu^-)=0.232\pm0.051(\text{stat})^{+0.029}_{-0.032}(\text{syst})$ nb. From these values we calculate the inclusive b-quark production cross section.

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We report a study of the reactions $\bar{p}p\rightarrow J/\psi[\psi(2S)]X\rightarrow\mu^+\mu^-X$ at $\sqrt{s}=1.8$ TeV. This study yields the P_T dependence of the products of production cross section times branching fraction over the kinematic range $P_T>6$ GeV/c and $|\eta|\leq0.5$. The products of integrated cross section times branching fraction are also presented. These measurements are important for the investigation of charmonium production mechanisms in $\bar{p}p$ collisions [1]. Both J/ψ's and $\psi(2S)$'s can be produced either by direct gluon fusion or in the decay of B mesons. J/ψ's also occur as daughters of directly produced χ's. The resulting differences in P_T distributions for J/ψ and $\psi(2S)$ can help to understand these mechanisms. We also emphasize the importance of the J/ψ and $\psi(2S)$ signals to study the production of b quarks at low P_T [2,3]. We have compared J/ψ and $\psi(2S)$ production with a Monte Carlo model for b-quark production and B-meson decay in order to obtain the inclusive cross section for production of b quarks. This technique was first used by the UA1 Collaboration [2].

This is the first measurement of J/ψ and $\psi(2S)$ cross sections at Tevatron energies. The data were taken with the Collider Detector at Fermilab (CDF), which has been described in detail elsewhere [4]. Here we give a brief description of the components relevant to this analysis. The central tracking chamber (CTC) is in a 1.4116 T axial magnetic field and has a resolution of $\delta P_T/P_T=[(0.0011P_T)^2+0.0066)^2]^{1/2}$ for beam constrained tracks, where P_T is the momentum transverse to the beam direction. The central muon chambers, at a radius of 3.5 m from the beam axis, provide muon identification in the region of pseudorapidity $|\eta^\mu|<0.61$, where $\eta^\mu=-\ln[\tan(\theta/2)]$ and θ is the polar angle with respect to the beam axis. The measurements reported here are based on a data sample with a total integrated luminosity of 2.6 ± 0.2 pb^{-1}, collected with a multilevel central dimuon trigger. The level 1 trigger required a track segment in the central muon chambers with a threshold set at a nominal transverse momentum, $P_T^\mu>3.0$ GeV/c. The level 2 trigger required two muon chamber track segments that each satisfied the level 1 trigger, that were separated from each other by at least one full muon module (15° wide in ϕ), and that each matched, within a muon module, to a track in the CTC. From events passing this trigger, a sample of opposite sign dimuons was selected with the following cuts: $P_T^\mu>3.0$ GeV/c for each muon; less than a 3σ difference in position between each muon chamber track and its associated, extrapolated

CTC track, where σ is the calculated uncertainty due to multiple scattering, energy loss, and measurement uncertainties; a common vertex along the beam axis for the two muons; $|\eta| \leq 0.5$ and $6.0 < P_T < 14.0$ GeV/c for the muon pair. The resulting mass distributions after all cuts are shown in Fig. 1. The J/ψ and $\psi(2S)$ peaks were each fitted by a Gaussian line shape plus a linear background. The number of J/ψ candidates above background within a $\pm 2.5\sigma$ mass signal region, $3.05 < m_{\mu^+\mu^-} < 3.15$ GeV/c^2, is 889 ± 30 and the resulting J/ψ mass is 3.0965 ± 0.0007 GeV/c^2 with $\sigma = 18.5 \pm 0.6$ MeV/c^2. The number of $\psi(2S)$ candidates above background within a $\pm 2.5\sigma$ mass signal region, $3.63 < m_{\mu^+\mu^-} < 3.73$ GeV/c^2, is 35 ± 8 and the $\psi(2S)$ mass is 3.683 ± 0.005 GeV/c^2 with $\sigma = 20 \pm 4$ MeV/c^2.

The geometric and kinematic acceptances for $J/\psi \to \mu^+\mu^-$ and $\psi(2S) \to \mu^+\mu^-$ were evaluated by a dimuon event generator that produces J/ψ's and $\psi(2S)$'s with flat P_T, η, and ϕ distributions and with a tunable polarization distribution. The generated events were processed with the full detector simulation and the same reconstruction used for the data. The acceptance is P_T dependent, increasing from 3% at 6 GeV/c to plateaus of 15.5% for J/ψ and 19% for $\psi(2S)$. To verify that this is independent of the kinematic distribution of generated events, the acceptance calculation was repeated for J/ψ using the ISAJET generator [5]. This yielded good agreement between the two acceptance calculations.

Efficiency corrections required for the J/ψ and $\psi(2S)$ cross-section calculations are the following: The level 1 trigger efficiency for each muon is an increasing function of P_T, rising from (68 ± 5)% at 3 GeV/c to (91 ± 3)% for $P_T > 6$ GeV/c. The CTC track finding efficiency in the level 2 trigger is (99 ± 1)% for each muon. The total trigger efficiency for each dimuon event is taken to be the product of the level 1 and level 2 efficiencies for each muon. The off-line CTC track reconstruction efficiency is (97 ± 2)%. The muon reconstruction efficiency is (98 ± 1)%. The matching cut on the difference between the muon chamber track and the extrapolated CTC track is (97 ± 1)% efficient. The cuts on the J/ψ and $\psi(2S)$ mass window are (97 ± 2)% efficient.

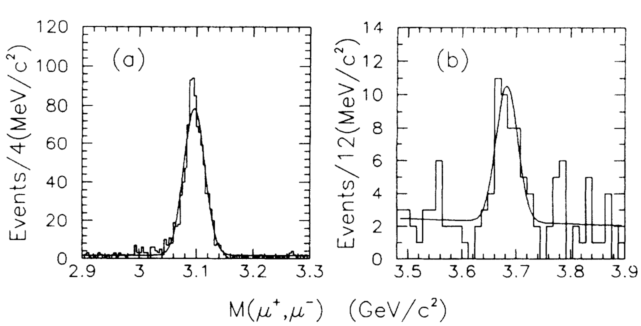

FIG. 1. The mass distribution of $\mu^+\mu^-$ for (a) J/ψ and (b) $\psi(2S)$. The histogram corresponds to the data and the solid curve is a fit by a Gaussian plus a linear background.

Polarized J/ψ's [$\psi(2S)$'s] from B meson decay would produce muons with an angular distribution of $d\sigma/d\Omega \sim 1 + \alpha\cos^2\theta$, where α is a parameter that depends on the J/ψ [$\psi(2S)$] polarization and θ is the angle in the J/ψ [$\psi(2S)$] rest frame between one of the emerging muons and the J/ψ [$\psi(2S)$] direction in its parent's rest frame. The uncertainty introduced in the quarkonium cross sections by the unknown polarization was evaluated by calculating the acceptance with the two extreme values $\alpha = +1$ and $\alpha = -1$ with the conservative assumption that all J/ψ's [$\psi(2S)$'s] originate from B mesons. Two sets of J/ψ's [$\psi(2S)$'s], one of each polarization, were generated in the B meson rest frame with a momentum spectrum given by ARGUS [6] for J/ψ and by CLEO [7] for $\psi(2S)$. The B mesons were produced from b quarks with the transverse momentum spectrum given by Nason, Dawson, and Ellis (NDE) [8] and with the Peterson fragmentation function [9], using $\epsilon_P = 0.006 \pm 0.002$ [10]. The central values of the J/ψ [$\psi(2S)$] production cross sections are given for zero polarization, and the systematic uncertainties due to unknown polarizations are $^{+6.5(4.4)}_{-11.2(7.3)}$%.

The other major systematic uncertainty in both the J/ψ and $\psi(2S)$ production cross sections is due to the trigger efficiency and was estimated to be ± 9%.

The acceptance and efficiency corrected J/ψ and $\psi(2S)$ differential cross sections for $P_T > 6$ GeV/c and $|\eta| \leq 0.5$ are displayed in Fig. 2 as functions of P_T. The vertical error bars are from statistical fluctuations in the number of counts (background fluctuations included) and the P_T-dependent systematic uncertainties added in quadrature. Theoretical predictions for the two types of processes expected to dominate J/ψ and $\psi(2S)$ production are also plotted.

The solid curve in Fig. 2(a) [2(b)] is a next-to-leading-order calculation by NDE of the production of b quarks [8] leading to B mesons and subsequent decay to J/ψ [$\psi(2S)$] as discussed above. We refer to this overall calculation as the B-production model (BPM). Uncertainties in this prediction arise because the b mass is comparable to the P_T of this experiment and in a range where neglected higher-order terms may be significant. Further, the strongest leading-order processes for b production are gluon fusion at low x where the structure functions are not well known. For these reasons, "the prediction of bottom production at collider energies is subject to considerable uncertainty" [11].

The dashed curve in Fig. 2(a) [2(b)] corresponds to J/ψ's [$\psi(2S)$'s] from direct charmonium production [1, 12]. We refer to this overall calculation as the charmonium production model (CPM). The direct $\psi(2S)$ production was estimated [12] with the same parameters and structure functions as used for J/ψ direct charmonium production and is found to be very small, ~ 25 times smaller in magnitude than the data.

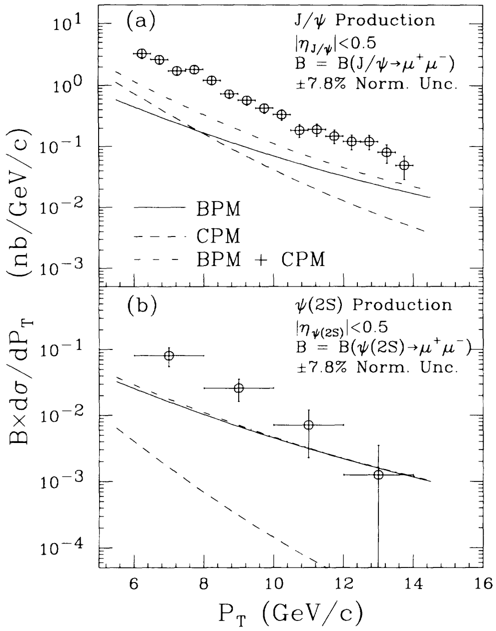

FIG. 2. The product $B(d\sigma/dP_T)$ vs P_T for (a) $J/\psi \rightarrow \mu^+\mu^-$ and (b) $\psi(2S) \rightarrow \mu^+\mu^-$. The circles correspond to the data. The solid curve corresponds to J/ψ's [$\psi(2S)$'s] produced from B meson decays by using Refs. [6-9]. The dashed curve corresponds to J/ψ's [$\psi(2S)$'s] from direct charmonium production from the model of Ref. [1]. The dot-dashed curve is their sum. Uncertainties in the theoretical curves are discussed in the text.

The sum of these two contributions (BPM and CPM) to J/ψ production is plotted in Fig. 2(a). We also fit these theoretical shapes to the data by summing the two theoretical contributions with independent normalization factors. This assumes that there are no other significant contributions to J/ψ production. Systematic uncertainties in the theoretical shapes were neglected. With no normalization constraints a good fit ($\chi^2/N_{\rm DF}=9.1/14$) was obtained with the CPM factor at ~ 4.4 ($\sim 69\%$ of J/ψ production) and the BPM factor at ~ 2.2 ($\sim 31\%$). The fit suppresses the BPM contribution because of the difference in slope between the BPM curve and the data. However, a previous CDF study [3] of $B^{\pm} \rightarrow J/\psi K^{\pm}$ showed that the BPM calculation underestimates the b-quark cross section by a factor of 5.5 ± 2.8, which indicates that $(75^{+25}_{-40})\%$ of our J/ψ's come from B decays. This datum was added to the fit with a Poisson probability distribution yielding $\chi^2/N_{\rm DF}=14.9/15$ and a BPM factor of 2.9 ± 0.5 corresponding to $\sim 42\%$ J/ψ's from B production. The 90% C.L. upper limit on the BPM contribution is $\sim 60\%$. If future measurements exceed this value, then one must conclude that not only the normalization of BPM, but also the P_T dependence of at least one of the models, is wrong.

Figure 2(b) shows a similar set of curves for $\psi(2S)$ production. While the normalization and slope of the BPM contribution seem to differ from those of the data in the same way as those for J/ψ, the statistical significance here does not allow any conclusion.

The products of the inclusive production cross section times branching fraction in the kinematic range $P_T > 6$ GeV/c and $|\eta| \le 0.5$ are

$$\sigma(\bar{p}p \rightarrow J/\psi X) B(J/\psi \rightarrow \mu^+\mu^-) = 6.88 \pm 0.23(\text{stat})^{+0.93}_{-1.08}(\text{syst}) \text{ nb},$$

$$\sigma(\bar{p}p \rightarrow \psi(2S) X) B(\psi(2S) \rightarrow \mu^+\mu^-) = 0.232 \pm 0.051(\text{stat})^{+0.029}_{-0.032}(\text{syst}) \text{ nb},$$

where an extrapolation of the cross sections for values of $P_T > 14$ GeV/c was carried out. We assign a 2% uncertainty in the above values due to this extrapolation. Using the tabulated [13] branching fractions, $B(J/\psi \rightarrow \mu^+\mu^-)=0.0597 \pm 0.0025$ and $B(\psi(2S) \rightarrow \mu^+\mu^-)=0.0077 \pm 0.0017$ we obtain

$$\sigma(\bar{p}p \rightarrow J/\psi X) = 115.2 \pm 3.9(\text{stat})^{+15.6}_{-18.1}(\text{syst}) \pm 4.8(\text{frac}) \text{ nb},$$

$$\sigma(\bar{p}p \rightarrow \psi(2S) X) = 30.1 \pm 6.6(\text{stat})^{+3.8}_{-4.2}(\text{syst}) \pm 6.6(\text{frac}) \text{ nb},$$

where (frac) is the uncertainty due to the branching fraction error.

In order to determine the b-quark cross section, we use the measurement of the J/ψ [$\psi(2S)$] inclusive production cross sections, the ratio R of J/ψ [$\psi(2S)$] to b-quark cross sections as determined by a Monte Carlo technique [6-9,14], the combined branching ratios $B(B \rightarrow J/\psi[\psi(2S)]X)B(J/\psi[\psi(2S)] \rightarrow \mu^+\mu^-)$, and the fraction f_B of J/ψ's [$\psi(2S)$'s] from B meson decays:

$$\sigma^b_{\rm exp}(P^b_T > P^{\rm min}_T, |y^b| < 1) = \frac{B(J/\psi[\psi(2S)] \rightarrow \mu^+\mu^-)\sigma^c_{\rm exp}(P^c_T > 6 \text{ GeV}/c, |\eta^c| < 0.5) R f_B}{2B(B \rightarrow J/\psi[\psi(2S)]X) B(J/\psi[\psi(2S)] \rightarrow \mu^+\mu^-)}, \tag{1}$$

where

$$R = \frac{\sigma^b_{\rm BPM}(P^b_T > P^{\rm min}_T, |y^b| < 1.0)}{\sigma^c_{\rm BPM}(P^c_T > 6 \text{ GeV}/c, |\eta^c| < 0.5)}$$

and the index c stands for J/ψ [$\psi(2S)$]. The rapidity of the b quark is

$$y^b = \frac{1}{2} \ln \left(\frac{E^b + P^b_{\parallel}}{E^b - P^b_{\parallel}} \right).$$

The Monte Carlo program is used to determine $P^{\rm min}_T$ which is chosen such that approximately 90% of the produced J/ψ [$\psi(2S)$] have $P^b_T > P^{\rm min}_T$; we have set $P^{\rm min}_T = 8.5$ GeV/c for this analysis. The branching ratios are taken as unity for the calculation of $\sigma^c_{\rm BPM}$ in the Monte Carlo program. The combined branching ratios we use are $B(B \rightarrow J/\psi X)B(J/\psi \rightarrow \mu^+\mu^-) = (7.7 \pm 1.3) \times 10^{-4}$ [15,16] and $B(B \rightarrow \psi(2S)X)B(\psi(2S)$

$\rightarrow \mu^+\mu^-) = (3.6 \pm 1.4) \times 10^{-5}$ [15,17]. The 2 in the denominator of Eq. (1) arises since J/ψ's [$\psi(2S)$'s] can be produced by either b or $\bar{b}$ quarks and we are interested only in the b-quark cross section. We assign an 8% systematic error to the b-quark cross section due to the uncertainty in the shape of the ARGUS (CLEO) momentum spectra for J/ψ's [$\psi(2S)$'s]. Although we are sensitive to b quarks with $|y^b| < 0.6$, we are quoting the b-quark cross section in the rapidity range $|y^b| < 1.0$ for comparison with theory [8]. We assign a 4% systematic error to the b-quark cross section due to the uncertainty in the rapidity spectrum in the range $0.6 < |y^b| < 1.0$. We also assign a 5% systematic error to the b-quark cross section due to variations in the shape of the b-quark P_T spectrum and a 6% systematic error due to the uncertainty in ϵ_P. Assuming the fraction f_B to be unity, we get

$$\sigma^b(P_T^b > 8.5 \text{ GeV}/c, |y^b| < 1) = 18.9^{+4.7}_{-5.0}\,\mu\text{b} \quad \text{using } J/\psi\text{'s},$$

$$\sigma^b(P_T^b > 8.5 \text{ GeV}/c, |y^b| < 1) = 10.5^{+5.0}_{-5.1}\,\mu\text{b} \quad \text{using } \psi(2S)\text{'s}.$$

The fraction is believed to be close to 1 for $\psi(2S)$'s [1,12,18] but not for J/ψ's. The b-quark cross section we get using $\psi(2S)$'s is approximately 1.5 standard deviations higher than the theoretical calculation [8], in reasonable agreement with Ref. [3].

We have measured the differential and integrated ($P_T > 6$ GeV/c) inclusive production cross sections for J/ψ and $\psi(2S)$ and we have compared them with theoretical predictions. From the integrated cross sections we have also determined the cross section for b-quark production.

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