Production of $\psi(2S)$ Mesons in $p\bar{p}$ Collisions at 1.96 TeV

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We have measured the differential cross section for the inclusive production of $\psi(2S)$ mesons decaying to $\mu^+\mu^-$ that were produced in prompt or $B$-decay processes from $p\bar{p}$ collisions at 1.96 TeV. These measurements have been made using a data set from an integrated luminosity of 1.1 fb$^{-1}$ collected by the CDF II detector at Fermilab. For events with transverse momentum $p_T(\psi(2S)) > 2$ GeV/$c$ and rapidity $|y(\psi(2S))| < 0.6$ we measure the integrated inclusive cross section $\sigma(p\bar{p} \to \psi(2S)X) \cdot \text{Br}(\psi(2S) \to \mu^+\mu^-)$ to be $3.29 \pm 0.04(\text{stat.}) \pm 0.32(\text{syst.})$ nb.

The mechanism for producing heavy vector mesons in $p\bar{p}$ collisions is not well understood. The experimental measurement of prompt $J/\psi$ and $\psi(2S)$ production cross sections by CDF in Tevatron Run I [1] showed that the measured cross sections were one to two orders of magnitude larger than expected from the leading order (LO) color-singlet models. Theoretical efforts to improve the calculations added color octet contributions that increased the predicted cross sections, e.g., in the non-relativistic QCD model (NRQCD) [2]. Recently there have been other...
approaches that do not directly introduce a color octet amplitude; rather, they incorporate the effects of multiple gluon processes during the production process, e.g., the $k_T$-factorization formalism \cite{3} and the gluon tower model \cite{4}.

The NRQCD model with parametrized production matrix elements adjusted to data can successfully account for the Tevatron prompt $\psi(2S)$ cross section measurements, but it makes an unequivocal prediction of increasing transverse polarization of vector mesons as their transverse momentum $p_T$ from production increases \cite{2}. A recent polarization measurement at CDF \cite{3} contradicts the NRQCD model prediction.

Experimentally, the extraction of direct $J/\psi$ production information is complicated by significant feed-down from decays of promptly-produced higher-mass charmonium states ($\chi_{c}, \psi(2S)$) to $J/\psi$ mesons. This is not a problem for direct $\psi(2S)$ production because there are no reported charmonium states with significant hadronic production cross sections that decay to the $\psi(2S)$. Consequently the $\psi(2S)$ provides an ideal testing ground for studying charmonium hadroproduction mechanisms. In this paper we present a measurement of the $p_T$ dependence of the $\psi(2S)$ production cross section over the $\psi(2S)$ transverse momentum range $2 < p_T(\psi(2S)) < 30$ GeV/c with rapidity $|y(\psi(2S))| < 0.6$. This measurement greatly increases the statistical power of the data in the perturbative regime ($m_T \gg \lambda_{QCD}$), facilitating comparison with theory.

We use data taken using the CDF II detector at the Fermilab Tevatron at 1.96 TeV \cite{6}. The integrated luminosity of the data sample is 1.1 fb$^{-1}$. The CDF II detector, described in detail elsewhere \cite{5}, includes a tracking system in a solenoidal 1.4 T magnetic field. Electromagnetic and hadronic calorimeters backed by muon detectors surround the tracker. The essential detector elements for this analysis are the silicon strip tracking detector (SVX II), the central drift chamber (COT) and the central muon system (CMU and CMP). The CMU is a four-layer planar drift chamber system outside the CDF magnet coil and calorimeter steel (5 interaction lengths). The CMP is another muon chamber system behind the CMU, shielded by an additional 0.6 m of iron in the flux return yoke. In this analysis, we use only information provided by the central sector of the detector, with pseudorapidity $|\eta| < 0.6$.

Muon candidates are identified by a first-level hardware-based trigger that reconstructs a charged track in four axial layers of the COT \cite{8}. The trigger then projects the track into the CMU/CMP system and matches the projected trajectory to a collection of three or four hits in the CMU muon system within a search window around the extrapolated track \cite{9}. The dimuon trigger requires two opposite-sign muon candidates each having $p_T > 1.5$ GeV/c.

The $\psi(2S) \rightarrow \mu^+\mu^-$ candidates were reconstructed from muon pairs. The $\psi(2S)$ events may originate from the primary interaction (prompt) or from decays of $B$-hadrons ($B$-decay). In offline reconstruction, each muon had to have at least three hits in the $r$-$\phi$ strips of SVX II in order to guarantee good vertex information to separate prompt and $B$-decay candidates. The minimum muon $p_T$ is 2 GeV/c. If the CMU candidate has matching hits in the CMP chambers \cite{3}, the track $p_T$ requirement is raised to 3 GeV/c to account for the extra iron traversed.

The $\psi(2S)$ mass and proper time distributions are used in a joint unbinned maximum likelihood fit to extract the prompt and $B$-decay signals in bins of $p_T$ for $\psi(2S)$ candidates. The mass component separates signal from background, while the proper time component separates prompt $\psi(2S)$ events from those produced by $B$-decays. The mass distribution including the radiative tail is described by a combination of a Gaussian plus an asymmetric function (CBF) \cite{10} given by

\[
CBF = \begin{cases} 
A \cdot e^{-\frac{(M-m_0)^2}{2\sigma^2}} & \frac{M-m_0}{\sigma} > -\beta \\
A \cdot \left(\frac{n}{\beta}\right)^{n} \frac{M-m_0}{\sigma} & \frac{M-m_0}{\sigma} \leq -\beta
\end{cases}
\]

where $m_0$ is a fit parameter for the invariant mass peak, $M$ is the dimuon invariant mass of each event, $A$ is the normalization constant, and empirical parameters $\beta$ and $n$ describe the tails of the function.

The parameters $n$ and $\beta$ of the tail function, and the relative fraction of the Gaussian and CBF are fixed by a fit to the entire $p_T$ range. The Gaussian and the Gaussian part of CBF have the same width $\sigma$. This width is $p_T$-dependent due to experimental effects. We use simulation results to describe the relative $p_T$ dependence in the different bins, leaving one width parameter to be fit in the mass probability density function (PDF). The background mass function
is linear \(P_{\text{mass}}^{\text{mass}} \propto M\).

The proper decay length \(ct\) is used to identify prompt and \(B\)-decay contributions to the mass signal. Here \(ct = \frac{L_{xy}}{p_T/M}\), where \(L_{xy}\) is the transverse decay length projected onto the \(\psi(2S)\) momentum. The prompt component is described by a double Gaussian function centered at zero \((P_{ct}^p)\). The long-lived component is an exponential \((P_{ct}^{\text{long}})\). Because the \(\psi(2S)\) events from \(B\)-decay come from \(B_h \rightarrow \psi(2S)X\), they do not have a \(B\)-hadron lifetime distribution. We use the effective lifetime of the \(B\)-decay signal as a fit parameter. Because it is defined in the \(\psi(2S)\) rest frame, it is the same in all \(p_T\) bins. Finally, the background in the \(ct\) distribution is described by the sum of a prompt double Gaussian \((P_{ct}^p)\) plus three exponentials, each convolved with a Gaussian resolution function: one symmetric about zero \((P_{ct}^{\text{sym}})\), one for positive \(ct\) only \((P_{ct}^+)^{\text{sym}}\), and one for negative \(ct\) only \((P_{ct}^-)\). The likelihood function is

\[
L = f_s P_{\text{mass}}^s [fp P_{ct}^p + (1-f_p) P_{ct}^{\text{long}}] + (1-f_s) P_{\text{mass}}^{\text{bkg}} \times \\
[f_{\text{sym}} P_{\text{sym}}^c + f_+ P_{ct}^+ + f_- P_{ct}^- + (1-f_{\text{sym}} - f_+ - f_-) P_{ct}^0] .
\]

(1)

The population fractions include \(f_s\), the \(\psi(2S)\) signal fraction from the total number of candidates in the fit, \(f_p\), the fraction of prompt \(\psi(2S)\), \(f_{\text{sym}}\), the fraction of symmetric long-lived background, \(f_+\), the fraction of positive-\(ct\) long-lived background, and \(f_-\), the fraction of negative-\(ct\) long-lived background. The PDFs for the mass fit include \(P_{\text{mass}}^s\), a (CBF + Gaussian) distribution for signal, and \(P_{\text{mass}}^{\text{bkg}}\).

The fit parameters are the width of the overall Gaussian in \(P_{\text{mass}}^{\text{mass}}\), the parameters of the double Gaussians for the prompt signal and background \(ct\) density distributions, the lifetime of the overall long-lived signal, the five data fractions \(f_i\) from Eq.(1), and the parameters of the long-lived background functions in each \(p_T\) bin. The fit projections in mass and proper time for \(5.5 < p_T < 6.0 \text{ GeV/c}\) are shown in Fig. 1. Projecting the likelihood fits onto the mass distribution in each \(p_T\) bin gives \(\chi^2\) probabilities in the range [0.4 - 100]%.

The fitted yields in each \(p_T\) bin are summarized in Table I. Signal events are classified as prompt or long-lived by the fit parameter \(f_p\). For each \(\psi(2S)\) \(p_T\) bin we know the total number of events \(N\). The fit returns the signal fraction \(f_s\) and its uncertainty \(\sigma_{f_s}\). The signal yield is \(S = f_s \cdot N\); \(\sigma_{S} = (\sigma_{f_s} \cdot N)^2 + N \cdot f_s^2\). Analogous equations hold for the prompt yield \(P = f_p \cdot S\) and the \(B\)-decay yield \(B = (1 - f_s) \cdot S\). The correlation between the signal fraction and the prompt fraction is considered in the uncertainty of the prompt and \(B\)-decay yield. The number of prompt and \(B\)-decay events are also listed in Table I.

![FIG. 1: The projections on the invariant mass (a) and the proper decay length (b) for \(5.5 < p_T < 6.0 \text{ GeV/c}\). The fitted curve for total signal plus background is overlaid on the data points. The prompt (solid) and long-lived (dashed) proper time signal curves are shown separately.](image)

We have checked the \(p_T\) dependence of all the fit parameters. The variation is smooth and shows no indications of rapid changes of the background functions at any \(p_T\). The prompt fraction decreases approximately linearly in the interval \(2 < p_T < 30 \text{ GeV/c}\).
The differential cross section is evaluated using the expression
\[
\frac{d\sigma(\psi(2S))}{dp_T} = \frac{N(\psi(2S))}{A \cdot \varepsilon_{\text{reco}} \cdot \int \mathcal{L} dt \cdot \Delta p_T}.
\]

Here \( \frac{d\sigma(\psi(2S))}{dp_T} \) is the average cross section for \( \psi(2S) \) production in the given \( p_T \) bin integrated over rapidity in the range \( |y| \leq 0.6 \), \( N(\psi(2S)) \) is the number of \( \psi(2S) \) events determined by the fit, \( A \) is the geometric acceptance combined with the CDF dimuon trigger efficiency, \( \varepsilon_{\text{reco}} \) is the reconstruction efficiency. \( \int \mathcal{L} dt \) is the integrated luminosity of the data set, and \( \Delta p_T \) is the width of the \( p_T \) bin. The acceptance and reconstruction efficiency are determined as follows.

The geometric acceptance is calculated by a Monte Carlo simulation (MC) method, using \( \psi(2S) \to \mu^+\mu^- \) decays generated uniformly for \( 1 < p_T < 40 \text{ GeV}/c \), \( |y| < 1 \), and \( 0 \leq \phi \leq 2\pi \). The \( \psi(2S) \) decays are handled by \textsc{evtgen} [11], allowing us to specify the decay polarization as transverse, longitudinal or unpolarized. We generate independent MC sets of these three options. Because the tracking proceeds from the large-radius detectors inward, the geometric acceptance calculated for the prompt events is insensitive to small displacements of the \( \psi(2S) \) decay point. Therefore we use the same MC samples for calculating the geometric acceptance for both prompt and \( B \)-decay events. The systematic uncertainty for this assumption is negligible.

The MC events are passed through the CDF II \textsc{geant}-based simulation [12] and the standard CDF reconstruction. Events that pass the geometric selection are accepted based on each event’s dimuon trigger efficiency, derived from CDF data for muon pairs having \( |y| \leq 0.6 \) with each muon having \( p_T \geq 2 \text{ GeV}/c \) [13]. Variations with run and luminosity are included in the measurements. The prompt MC sample was analyzed with the likelihood fitter to check for \( p_T \) variations in prompt selection efficiency. None were seen.

Determining \( A \) is sensitive to the \( \psi(2S) \) polarization parameter \( \alpha \), which defines the muon decay angular distribution in the vector meson rest frame: \( dN/d\cos\theta = 1 + \alpha \cos^2 \theta \). The polar angle \( \theta \) is measured from the vector meson’s direction in the laboratory frame.

We have previously measured the \( \psi(2S) \) polarization in three \( p_T \) bins for prompt events and the average polarization in \( B \)-decay events [3]. By symmetry prompt events have \( \alpha = 0 \) at \( p_T = 0 \). With 15% probability a \( \chi^2 \) fit shows...
The data are plotted versus resulting inclusive cross sections for prompt and $\varepsilon$. Statistical or systematic uncertainty. The 1.1 fb dimuon trigger prescale factor to calculate the cross section. This is done on a run-by-run basis and has negligible $\varepsilon$.

Because the instantaneous CDF trigger rate might exceed our data handling capacity, the dimuon trigger, like many others, is prescaled. The integrated luminosity for the data sample has to be reduced by the luminosity-dependent dimuon trigger prescale factor to calculate the cross section. This is done on a run-by-run basis and has negligible statistical or systematic uncertainty. The 1.1 fb$^{-1}$ sample luminosity is reduced to 0.95 fb$^{-1}$ for this trigger. The resulting inclusive cross sections for prompt and $B$-decay production are listed in Table II. The prompt and $B$-decay data are plotted versus $p_T$ in Fig. 2(a). Data from the Run I CDF measurement [1] are also included in Fig. 2(b).

The major systematic uncertainties on these results are due to the systematic uncertainty in the luminosity deter-

\begin{table}
\centering
\begin{tabular}{|c|c|c|c|}
\hline
$p_T$ (GeV/c) & Inclusive $\frac{d\sigma}{dp_T}$ Br (pb/GeV/c) & Prompt $\frac{d\sigma}{dp_T}$ Br (pb/GeV/c) & $B$-decay $\frac{d\sigma}{dp_T}$ Br (pb/GeV/c) \\
\hline
2.0 - 2.5 & 1144 ± 58 ± 132 & 953 ± 54 ± 113 & 191 ± 28 ± 45 \\
2.5 - 3.0 & 1153 ± 36 ± 112 & 946 ± 34 ± 95 & 207 ± 15 ± 32 \\
3.0 - 3.5 & 1037 ± 26 ± 102 & 856 ± 24 ± 87 & 181 ± 11 ± 30 \\
3.5 - 4.0 & 779 ± 19 ± 73 & 630 ± 18 ± 61 & 149 ± 8 ± 23 \\
4.0 - 4.5 & 611 ± 14 ± 60 & 483 ± 13 ± 49 & 128 ± 6 ± 21 \\
4.5 - 5.0 & 490 ± 11 ± 48 & 383 ± 10 ± 39 & 107 ± 5 ± 18 \\
5.0 - 5.5 & 316 ± 8 ± 29 & 248 ± 7 ± 23 & 68 ± 3 ± 10 \\
5.5 - 6.0 & 262 ± 6 ± 24 & 204 ± 6 ± 19 & 58 ± 3 ± 8 \\
6.0 - 6.5 & 189 ± 5 ± 17 & 143 ± 4 ± 13 & 46 ± 2 ± 6 \\
6.5 - 7.0 & 146 ± 4 ± 13 & 111 ± 3 ± 10 & 35 ± 2 ± 5 \\
7.0 - 7.5 & 105.4 ± 2.9 ± 9.5 & 77.1 ± 2.6 ± 7.1 & 28.3 ± 1.5 ± 3.8 \\
7.5 - 8.0 & 81.9 ± 2.3 ± 7.4 & 59.8 ± 2.1 ± 5.5 & 22.1 ± 1.2 ± 2.9 \\
8.0 - 8.5 & 60.9 ± 1.9 ± 5.5 & 42.1 ± 1.7 ± 3.9 & 18.8 ± 1.1 ± 2.5 \\
8.5 - 9.0 & 45.4 ± 1.6 ± 4.0 & 30.5 ± 1.3 ± 2.7 & 14.9 ± 0.9 ± 1.8 \\
9.0 - 9.5 & 32.3 ± 1.3 ± 2.8 & 21.8 ± 1.1 ± 1.9 & 10.5 ± 0.7 ± 1.2 \\
9.5 - 10 & 25.9 ± 1.1 ± 2.2 & 17.2 ± 1.0 ± 1.5 & 8.7 ± 0.6 ± 0.9 \\
10 - 11 & 17.7 ± 0.6 ± 1.5 & 11.4 ± 0.54 ± 1.0 & 6.3 ± 0.4 ± 0.7 \\
11 - 12 & 11.96 ± 0.5 ± 1.1 & 7.72 ± 0.43 ± 0.69 & 4.24 ± 0.30 ± 0.51 \\
12 - 13 & 7.33 ± 0.39 ± 0.64 & 4.56 ± 0.33 ± 0.40 & 2.77 ± 0.23 ± 0.31 \\
13 - 14 & 5.03 ± 0.32 ± 0.44 & 2.85 ± 0.26 ± 0.24 & 1.88 ± 0.20 ± 0.24 \\
14 - 15 & 3.42 ± 0.25 ± 0.29 & 1.93 ± 0.20 ± 0.16 & 1.49 ± 0.15 ± 0.15 \\
15 - 17.5 & 1.61 ± 0.11 ± 0.14 & 0.85 ± 0.09 ± 0.07 & 0.76 ± 0.07 ± 0.08 \\
17.5 - 20 & 0.68 ± 0.07 ± 0.06 & 0.35 ± 0.06 ± 0.03 & 0.33 ± 0.05 ± 0.03 \\
20 - 25 & 0.27 ± 0.03 ± 0.02 & 0.15 ± 0.03 ± 0.01 & 0.12 ± 0.02 ± 0.01 \\
25 - 30 & 0.089 ± 0.020 ± 0.007 & 0.053 ± 0.017 ± 0.004 & 0.036 ± 0.011 ± 0.003 \\
\hline
\end{tabular}
\caption{The differential cross section (pb/GeV/c) times the dimuon branching fraction as a function of $p_T$ for $|y| \leq 0.6$. For the $B$-decay measurement the symbol Br includes the branching fraction for b quark inclusive decay to $\psi(2S)X$ as well as the dimuon branching fraction of $\psi(2S)$.}
\end{table}
minimization (6%) [14] and the polarization uncertainty in the acceptance calculation (9% at low $p_T$, 2% at high $p_T$). Other systematic uncertainties arise from $p_T$ variations in the trigger (< 3%) and reconstruction efficiencies (4.7%). Systematic uncertainties due to the mass shape parametrization, fitting function parametrization, and prompt fraction determination are all less than 1%. The data in Fig. 2 have both statistical and systematic uncertainties included.

The integrated cross sections are calculated by summing the differential cross sections across $p_T$ bins. The systematic uncertainty on the integrated cross section is calculated by assuming that all sources of uncertainty are fully correlated among $p_T$ bins, with the exception of the trigger efficiency uncertainty, which is uncorrelated among $p_T$ bins. After calculating the uncertainty on the integrated cross section from each source, the total uncertainty is calculated by summing the individual contributions in quadrature.

The integrated inclusive differential cross section for $p_T > 2$ GeV/c and $|y| < 0.6$ is measured to be:

$$p_T(\psi(2S)) > 2 \text{ GeV/c} \quad \sigma(p\bar{p} \rightarrow \psi(2S)X) \cdot \text{Br}(\psi(2S) \rightarrow \mu^+\mu^-) = 3.29 \pm 0.04(\text{stat.}) \pm 0.32(\text{syst.}) \text{ nb.}$$

For comparison to the Run I measurement, we limit the $p_T$ range to $p_T > 5$ GeV/c. Then the measured integrated inclusive cross section is:

$$p_T(\psi(2S)) > 5 \text{ GeV/c} \quad \sigma(p\bar{p} \rightarrow \psi(2S)X) \cdot \text{Br}(\psi(2S) \rightarrow \mu^+\mu^-) = 0.69 \pm 0.01(\text{stat.}) \pm 0.06(\text{syst.}) \text{ nb.}$$

At 1.8 TeV the integrated inclusive cross section for $p_T > 5$ GeV/c and pseudorapidity < 0.6 was $0.57 \pm 0.04^{+0.08}_{-0.09} \text{ nb}$ [1]. The increase is (21 ± 19) %, compared to a theoretical prediction of (14 ± 8) % based on changes in the parton energy distribution at the higher collision energy [15]. The uncertainty on the experimental ratio is dominated by the Run I measurement due to its much lower statistics.

Prompt $\psi(2S)$ production has a harder $p_T$ spectrum than that for $J/\psi$ production [7]. We plot the ratio of these two cross sections as a function of vector meson $p_T$ in Fig. 3(a). The increase in the ratio at larger $p_T$ reflects the slope difference. Even though it neglects any feed-down contributions to $J/\psi$ prompt production, the model of Ref. [4] predicts the $p_T$ dependence of this behavior, as shown by the dashed line in Fig. 3(a). The model prediction is normalized to these data in the $p_T$ bin covering 8-9 GeV/c. This same behavior is seen in the ratio of cross sections for production from $B$-decay, also shown in Fig. 3(a). The ratio of these two ratios is independent of $p_T$, as shown in Fig. 3(b). There is no theoretical motivation for this relation.
FIG. 3: (a) The differential cross section ratio of $\psi(2S)$ to $J/\psi$ as a function of vector meson $p_T$ for prompt events ($R_p$) and $B$-decay events ($R_b$). The main error bar on each point is the quadrature sum of the statistical and uncorrelated systematic uncertainties for that $p_T$ bin. The extensions to the error bars show the correlated uncertainty from the luminosity. The dashed line is calculated using the prompt ratio predicted from Ref. [4] normalized to data for the $p_T$ bin covering 8-9 GeV/c. (b) The ratio of $B$-decay to prompt ratios $R_b/R_p$ as a function of vector meson $p_T$. The fit to a constant gives a $\chi^2$ of 13 for 14 degrees of freedom.

In conclusion, we have measured the $p_T$ dependence of the cross section for $\psi(2S)$ production in $p\bar{p}$ production at 1.96 TeV. These data have at least an order of magnitude more events than the Run I measurements and show more precisely the trends seen in those data. The increase in the inclusive cross section at the higher energy of Run II (1.96 TeV) compared to Run I (1.8 TeV) agrees with expectations based on the increase in parton energy distribution.

These data extend the $\psi(2S)$ differential cross section measurement up to 30 GeV/c. They are an important input for an update of the matrix elements in the NRQCD factorization approach [2]. In the gluon tower model [4], the prompt hadroproduction of $J/\psi$, $\psi(2S)$, and $\Upsilon$ states have been calculated. The uncertainties of their calculation are rather large but their cross section prediction with adjusted parameters describes the published Tevatron data. In addition, their mechanism predicts a longitudinal polarization of $J/\psi$ at large transverse momentum which agrees qualitatively with the recent Tevatron measurement [5]. We hope that in future calculations with this and other models the uncertainties can be reduced in order to make a meaningful comparison to these new cross section data. A successful description of both the cross section data and polarization measurements in the perturbative $p_T$ region would demonstrate a good understanding of the charmonium hadroproduction mechanisms.

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The CDF coordinate system has $\hat{z}$ along the proton direction, $\hat{x}$ horizontal pointing outward from the Tevatron ring, and $\hat{y}$ vertical. $\theta$ ($\phi$) is the polar (azimuthal) angle measured with respect to $\hat{z}$ and $\eta$ is the pseudorapidity defined as $-\ln (\tan (\theta/2))$. The transverse momentum of a particle is denoted as $p_T = p \sin \theta$. 

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