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QUARKONIUM PRODUCTION IN $p\bar{p}$ COLLISIONS AT THE TEVATRON

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Charmonium and bottomonium production is studied using $\mu^+\mu^-$ data samples collected by the CDF and D0 experiments during the 1992-96 $p\bar{p}$ collider run at the Fermilab Tevatron. The inclusive cross sections as a function of the transverse momentum of reconstructed quarkonium states are measured. The results are compared with theoretical predictions, which take into account different quarkonium production mechanisms.

1 Introduction

During the 1992-96 $p\bar{p}$ collider Run I, the Tevatron delivered over 150 pb^{-1} of integrated luminosity. The charmonium and bottomonium production rate results presented in this paper were measured by the CDF and D0 collaborations and are based on dimuon subsets of the data. In the quarkonium analyses, differential cross sections for J/ψ, $\psi(2S)$ and three Υ states have been measured using their $\mu^+\mu^-$ decay channels. Two muons in the final state were used as a trigger signature.

In early studies of quarkonium production the dominant contributions were assumed to come from the lowest order Feynman diagrams involving gluon fusion — either directly into quarkonium states and recoiling partons or through a $b\bar{b}$ pair followed by decays $B \rightarrow \Psi X$ — or, in the case of the J/ψ or the Υ, radiative decays of χ_c or χ_b mesons.[b] Various methods are used to disentangle the three sources, providing information about charm and bottom production and fragmentation mechanisms at low transverse momenta.

Previous CDF measurements of J/ψ and $\psi(2S)$ production rates during the 1988-89 collider run[1] showed production cross sections considerably larger than contemporary theory predicted. This drew theoretical interest, but at that time the question of whether or not the excess could be attributed to a large prompt component was not addressed. It has been pointed out that in addition to gluon fusion, the gluon fragmentation processes are also important sources of quarkonium production.[2] We briefly summarize the proposed improvements in the theoretical description of the observed production rates.

[a]Representing the CDF and D0 Collaborations.
[b]Ψ represents both J/ψ and $\psi(2S)$ mesons.

2 Charmonium total cross sections

Muons identified in the central pseudorapidity range, $|\eta| < 0.6$, were used in these analyses. Additionally, the D0 detector provides muon coverage in the forward pseudorapidity region, allowing production rate studies in the range $2.5 < |\eta| < 3.7$.

In the CDF analyses, both muons of the reconstructed Ψ candidate are required to have p_T greater than 2.0 GeV/c, and at least one muon of the pair is required to have $p_T > 2.8$ GeV/c. The reconstructed J/ψ or $\psi(2S)$ candidates must have $p_T > 5.0$ GeV/c. About 22,000 J/ψ events and 800 $\psi(2S)$ events are reconstructed in data samples of 15.4 pb^{-1} and 17.8 pb^{-1}, respectively. In the D0 analysis, muons with transverse momentum greater than 3 GeV/$c$are reconstructed in the central and forward pseudorapidity regions, and dimuon candidates are required to have $p_T > 8$ GeV/c. About 4,000 Ψ events in the central and about 500 events in the forward rapidity ranges are found from a fit to a Gaussian function and physics-motivated background in the samples of 60 pb^{-1} and 9.3 pb^{-1}, respectively. The D0 tracking momentum resolution is such that it does not allow separation of the $\psi(2S)$ and J/ψ states.

CDF measures the product of dimuon branching ratio times integrated cross section to be $17.35 \pm 0.14 \pm 2.79$ nb for J/ψ and $0.57 \pm 0.04 \pm 0.09$ nb for $\psi(2S)$ in the central rapidity region with $p_T > 5.0$ GeV/c, and D0 measures $1.96 \pm 0.16 \pm 0.63$ nb for J/ψ in the central region and $0.40 \pm 0.04 \pm 0.04$ nb in the forward region with $p_T > 8.0$ GeV/c.

3 Charmonium from b Decay

The CDF collaboration, using a silicon vertex detector, separated the J/ψ and $\psi(2S)$ samples into

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their components arising from b decay and from prompt production by analyzing the proper decay-length ($c\tau$) distributions. The $c\tau$ distribution is fitted to three components: an exponential convoluted with a Gaussian resolution function for the b hadron decay component, a Gaussian function centered at 0 for prompt production, and a Gaussian function with positive and negative exponential tails to describe the background, both combinatorial as well as from sequential $b \to \mu^- c \to \mu^+ s$ decays. The samples are subdivided into ranges of $p_T(\mu^+\mu^-)$ and fitted separately for each range. Figure 1 shows the J/ψ and $\psi(2S)$ fractions from b decay as a function of p_T. These fractions are

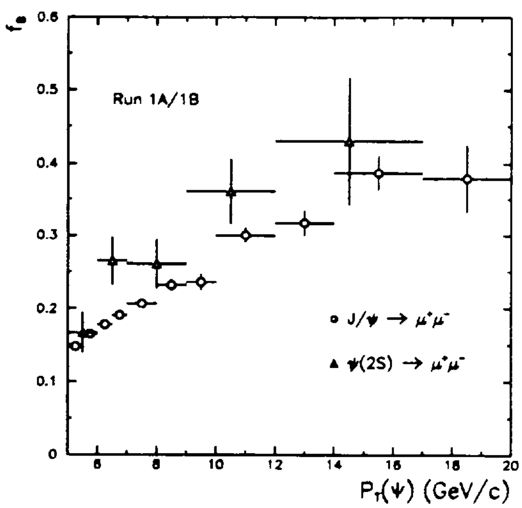

Figure 1: Fraction of J/ψ and $\psi(2S)$ from b decay as a function of p_T.

then convoluted with the charmonium p_T spectra to give the b cross sections, as shown in figure 2. The results are within a factor of 2-3 of the NLO QCD prediction[3] using a central value of the input parameters,[c] and are consistent with other Tevatron b cross section results.[4]

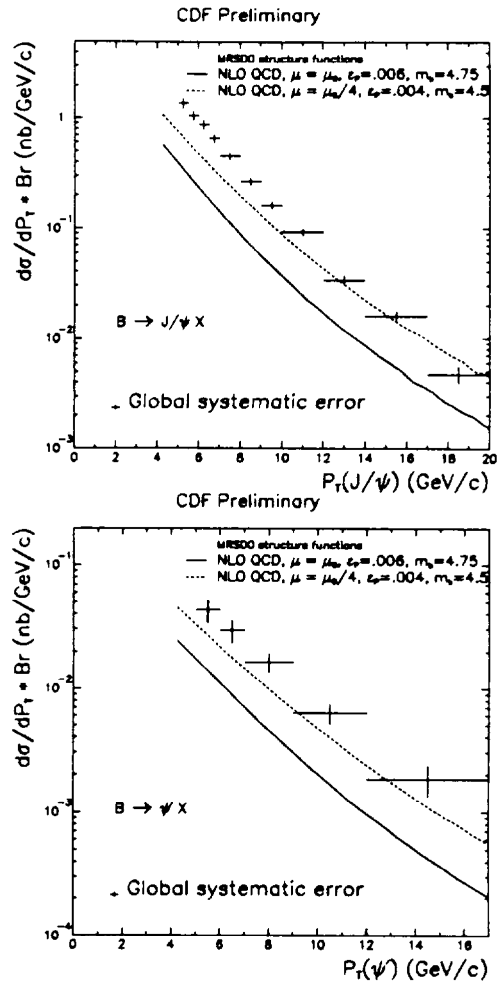

Figure 2: b quark cross section determined from the J/ψ (top) and $\psi(2S)$ (bottom) samples.

4 Prompt Charmonium Production

The cross section for prompt charmonium production is in disagreement with theoretical predictions based on color-singlet production of bound $c\bar{c}$ states.[5] The rate of prompt $\psi(2S)$ production is about a factor of 50 larger than predictions based on such a model. All prompt $\psi(2S)$ are believed to be directly produced since χ_c states with sufficient mass to decay to $\psi(2S)$ lie above the threshold for strong decays to $D\overline{D}$ meson pairs. However, prompt J/ψ are produced not only directly, but also via χ_c radiative decays. CDF has determined the fraction of the prompt J/ψ sample coming from the χ_c decay by fully reconstructing the decay $\chi_c \to J/\psi\gamma$. Photon candidates detected in the central electromagnetic calorimeter with energy greater than 1 GeV and having no charged track pointing to the same calorimeter tower are combined with $\mu^+\mu^-$ pairs consistent with the

[c] The input parameters have the following values: renormalisation and fragmentation scales $\mu_F = \mu_R = \mu_0 = \sqrt{(m_b^2 + p_T^2)}$, the mass of the b quark, m_b=4.75 GeV/c, the Peterson fragmentation parameter, $\epsilon_b = 0.006$.

J/ψ mass. A peak containing 1230 ± 72 χ_c candidates is observed in the mass difference distribution $M(\mu^+\mu^-\gamma) - M(\mu^+\mu^-)$. The background under the peak has been modelled by embedding simulated π^0 and η^0 decay photons in real J/ψ events. The fraction of J/ψ coming from prompt χ_c decay, measured for 4 different p_T bins, ranges from about 32% in the 4-6 GeV/c bin to 28% in the bin $p_T > 10$ GeV/c. The D0 measurement of this fraction is consistent with these results.[6] Multiplying the total prompt J/ψ cross section by the χ_c fraction shows that the rate of J/ψ production from χ_c is within a factor of 2-3 of the theoretical prediction, but, as with the $\psi(2S)$, the remaining direct J/ψ cross section is about a factor of 50 larger than the color-singlet prediction.

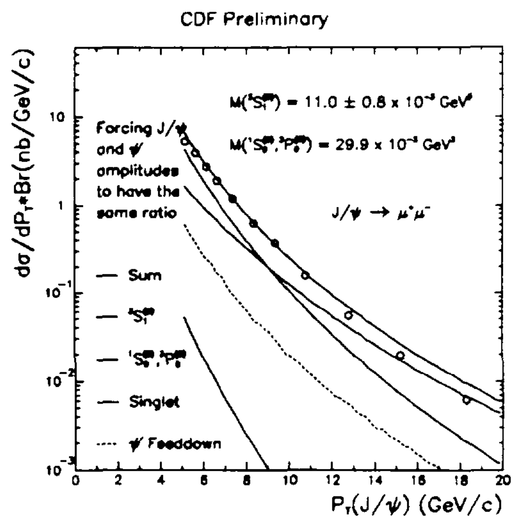

Figure 3: Prompt direct J/ψ sample, compared to the theoretical prediction, with color-octet components fitted simultaneously to the J/ψ and $\psi(2S)$ distributions.

One proposal to explain the observed prompt charmonium production rates is to include $c\bar{c}$ pairs produced in a color-octet state.[7] The initial production can be calculated perturbatively and can be used to predict the p_T dependence of the cross section. The transition to a color-singlet state needed to form a bound $c\bar{c}$ particle proceeds via soft gluon emission. This latter process cannot be calculated perturbatively, so the normalization is found by fitting the theory to the data. Figures 3 and 4 show the prompt J/ψ and $\psi(2S)$ cross sections and the corresponding theoretical predictions when the fitted color-octet contributions are included.[8] The predictions of the model can be

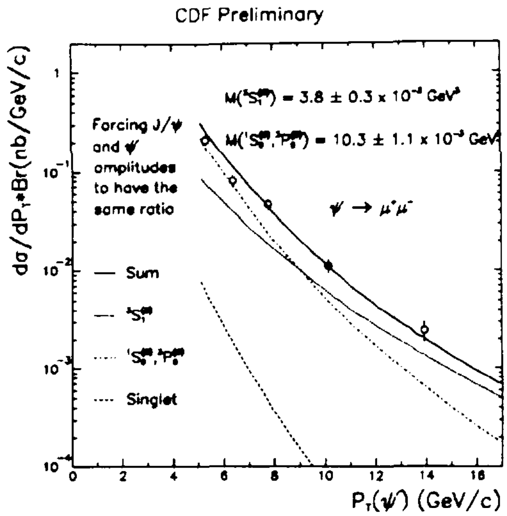

Figure 4: Prompt direct $\psi(2S)$ sample, compared to the theoretical prediction, with color-octet components fitted simultaneously to the J/ψ and $\psi(2S)$ distributions.

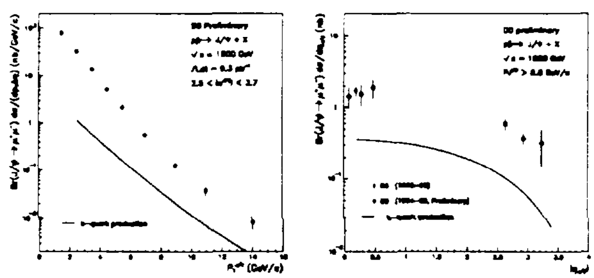

Figure 5: The Ψ cross sections - Br$\cdot d\sigma/dp_T$ for $2.5 < |\eta| < 3.7$ (left), and Br$\cdot d\sigma/d\eta$ for $p_T > 8$ GeV/c(right). The solid curve represents the expected contribution from b quark fragmentation.

further tested by fixed target hadro- and photoproduction experiments and by measurement of the $\psi(2S)$ polarization in $p\bar{p}$ collisions.

5 Forward Charmonium Production

The D0 collaboration determined the differential cross section, $d\sigma/dp_t$, shown in Figure 5, using Ψ candidates reconstructed in the forward region.[9] This is the first measurement of the Ψ cross section at large pseudorapidity. Figure 5 combines data from the central and forward Ψ analyses for transverse momentum greater than 8 GeV/c. The measurements in the central region are consistent with having no η dependence. However in the for-

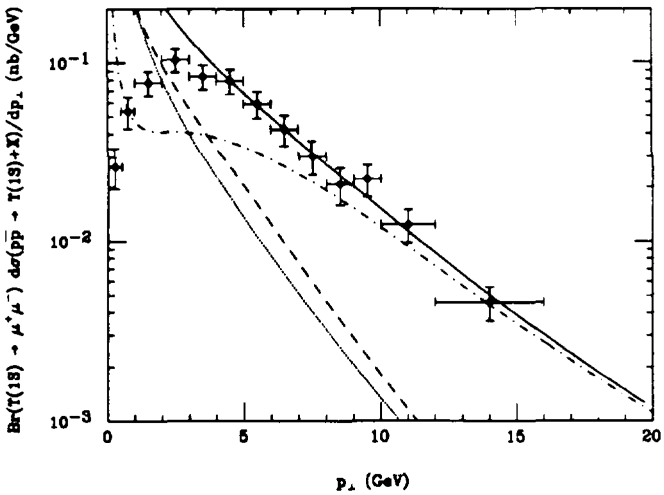

Figure 6: Υ(1S) differential cross section, compared to the theoretical prediction. The dotted line shows the color singlet contribution, while the dashed lines are the color octet components fitted to the data. The solid line is the sum of all contributions.

ward region the measured cross section is approximately a factor of 5 lower than the central region values. The data points are compared in Figure 5 with a preliminary theoretical prediction of the contribution from the b quark decay to Ψ.

6 Bottomonium Production

The CDF collaboration has also published[10] production cross sections for Υ(1S), Υ(2S), and Υ(3S) states based on a data sample of 16 pb^{-1}. All three states combined yield a total of about 1800 candidates reconstructed in the $\mu^+\mu^-$ decay channel. The D0 collaboration has measured combined Υ cross section based on events reconstructed in a 6.6 pb^{-1} data sample.[11]

Recently, a theoretical prediction including color-octet contributions was fitted to the Υ(1S) and Υ(2S) differential distributions.[8] Figure 6 shows Υ(1S) fit results, which describe the shape of the p_T distribution well.

Increased statistics using CDF's full 110 pb^{-1} data sample will allow finer binning in p_T, improving the experimental description of the shape. Reconstruction of the χ_b states via Υγ decay — while difficult due to the small mass difference between χ_b and Υ — would provide an additional probe of the underlying production mechanisms.

7 Conclusion

Measurements of the differential production cross sections for J/ψ, $\psi(2S)$, and three Υ states have been made at the Tevatron Collider. The prompt and b-decay components of both charmonium states have been extracted. The prompt J/ψ cross section has been further subdivided into its direct and χ_c components.

These measurements provided the impetus for new theoretical models, such as the color-octet model, which show potential to explain charmonium production in $p\bar{p}$ collisions. Additional experimental results, such as measurement of the $\psi(2S)$ polarization and reconstruction of χ_b states may provide additional insight into the underlying production mechanisms.

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