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QUARKONIA PRODUCTION AT DØ

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We present results on inclusive J/ψ production in the central and forward regions and Υ production in the central region using dimuon data collected with the DØ detector during the 1992-1995 Tevatron collider run. Results on inclusive single muon production in the forward region are also given.

1 Introduction

The production of bound $c\bar{c}$ and $b\bar{b}$ states at the Tevatron provides an important test of perturbative QCD. One current picture [1] of charmonium production is thought to contain the following elements: B hadron decays into J/ψ and χ_c, direct production (gluon fusion) into J/ψ and χ_c, and gluon and charm fragmentation into color singlet J/ψ and χ_c via color singlet and color octet $q\bar{q}$ pairs. Other descriptions of charmonium production exist as well. [2]

The B hadron fragmentation and gluon fusion components are understood theoretically. Gluon and charm fragmentation contributions (proportional to P_T^2/m_q^2) were added to explain why the measured J/ψ cross section at the Tevatron lay above the sum of contributions from B hadron decay and direct production. However even after charm and gluon fragmentation contributions were added to direct production, the inclusive prompt ψ' data from CDF remained a factor of 30 above the theoretical predictions. More recent efforts to explain this discrepancy by a number of theorists have introduced charmonium production through fragmentation into color octet components of its wave function. [3] The absolute normalization of the color octet contribution must be fixed by data however.

Similar motivation can be given for studying Υ production. In this case there is no contribution from B hadron decay, gluon fragmentation is suppressed, and color octet effects are expected to be smaller. In this paper, DØ results on J/ψ production in the central and forward regions, Υ production in the central region, and inclusive single muons in the forward region are summarized. All results are preliminary unless stated otherwise.

The DØ detector and trigger system are described in detail elsewhere. [4] Both the wide angle muon system (WAMUS) and small angle muon system (SAMUS) consist of three layers of proportional drift tubes and a magnetized iron toroid located between the first two layers. In WAMUS each layer consists of three or four planes of 10 cm wide drift cells with cathode pad readout for the orthogonal coordinate. In SAMUS each layer consists of six planes of 3 cm drift tubes in an x-y-u configuration. The muon momentum resolution at low momentum is dominated by multiple scattering in the iron toroids. The minimum thickness of the calorimeter plus toroid is 13 λ which reduces the hadronic punchthrough in the muon system to less than 0.5% of all sources of low transverse momentum muons.

2 Central J/ψ Production

J/ψ's in the central region ($|\eta^{J/\psi}| < 0.6$) were collected by DØ during the 1992-93 Tevatron collider run. A total of 1146 dimuons remains after all cuts and corresponds to an integrated luminosity of 6.6 pb^{-1}. The cuts include a trigger filter and muon selection cuts. At least two muons are required at the hardware and software trigger levels. Muons are required to have good fits to the vertex in the bend and non-bend views and matching energy in the calorimeter cell hit plus two nearest neighbors of > 1 GeV. Also the following kinematic cuts are applied: $|\eta^{\mu}| < 1.0$, $|\eta^{\mu\mu}| < 0.6$, and $M^{\mu\mu} < 6$ GeV/c^2.

The fraction of J/ψ's from B decays is determined by an impact parameter analysis using muons which have matching tracks in the central drift chamber (CDC) and vertex detector (VTX). The VTX impact parameter resolution in the r-ϕ plane is approximately 200 μm and the CDC-VTX muon track matching efficiency is approximately 50%. The fraction of the J/ψ's from $B \to J/\psi$X is found using a maximum likelihood analysis. The variables used are $M^{\mu\mu}$ and the impact parameter in the r-ϕ plane. The processes fit include $B \to J/\psi$X, $b\bar{b}$ and $c\bar{c}$ production, direct production of χ_c, and Drell-Yan. From the results of the fit and with $< P_T^{J/\psi} >= 11.8$ GeV/c, the fraction of J/ψ from B decays, f_b, is found to be $f_b = 0.35 \pm 0.09$ (stat) $\pm$ 0.10 (sys). The fraction f_b was subsequently used to extract the b quark cross section as shown in another talk at this workshop. [5]

To determine the fraction of J/ψ from χ_c a search is made for photons with energy > 1 GeV in a cone of $\Delta R = 2.0$ about the dimuon direction using a sample of J/ψ with $P_T^{J/\psi} > 8$ GeV/c. Restrictions on calorimeter cluster shape are used for maximum discrimination against hadrons. The distribution of $\Delta M = M^{\mu\mu\gamma}$ - $M^{\mu\mu}$ is fit to a Gaussian plus a background shape determined from the data. A total of 74 ± 13 χ_c events is found from the fit. Correcting for photon efficiency and acceptance, we find the fraction of J/ψ from χ_c decays to be $f_\chi = 0.32 \pm 0.07$ (stat) $\pm$ 0.07 (sys). Correcting for the fraction of χ_c coming from B decays (0.08 ± 0.03) we infer there is a fraction $f = (1$ - f_b - f_χ

$+ f_{B\to\chi}) = 0.41 \pm 0.17$ of J/ψ that do not come from either B or χ_c decays for $< P_T^{J/\psi} >= 11.8$ GeV/c. Prompt J/ψ production is not dominated by χ_c decay as expected from gluon fragmentation models. All of the preceeding results are published. [6]

3 Forward J/ψ Production

The η dependence of J/ψ production was measured using dimuons collected during the 1994-95 Tevatron run. This is interesting because the relative contributions of J/ψ production mechanisms may vary with J/ψ rapidity. In addition, forward production $(2.5 < |\eta^{J/\psi}| < 3.7)$ of J/ψ's probes smaller Feynman x values of the gluon structure function compared to production in the central region $(|\eta^{J/\psi}| < 0.6)$.

Offline cuts to select quality dimuons in the central region are identical to those described above. Good muon tracks in the forward region are required to have five hits from six planes in the SAMUS A layer and sixteen hits from eighteen planes in all three layers. Additionally, the energy deposited in the hit calorimeter cell plus nearest neighbors has to exceed 1.5 GeV and the field integral seen by each track has to be greater than 1.2 T·m. For good sign determination, each muon is required to have $p^{\mu} < 150$ GeV/c. Combinatoric background is estimated at less than 2%.

Dimuons in the central and forward regions are selected from dimuon triggers corresponding to integrated luminosities of 57 pb^{-1} and 9.3 pb^{-1} respectively. After all cuts, a total of 9735 dimuons with $M^{\mu\mu} < 6$ GeV/c^2 is used to determine the differential cross section in the central region while a sample of 1234 dimuons is used for the forward cross section. The data are divided into six different $\eta^{J/\psi}$ regions and a clear J/ψ signal is observed in all regions with a mass resolution consistent with Monte Carlo simulation of the muon detector.

The number of J/ψ in each $P_T^{J/\psi}$ bin is determined by fitting the dimuon invariant mass to the sum of a Gaussian function plus physics motivated background in the mass range $2 < M^{\mu\mu} < 6$ GeV/c^2. The $P_T^{J/\psi}$ distribution is subsequently corrected for muon momentum resolution, acceptance, and efficiency. The resulting cross section, $Br \cdot d\sigma/dp_T^{J/\psi}/\Delta\eta$, for central muons is in excellent agreement with our previously published result using 1992-93 data. [6] The differential cross section for the forward region is shown in Figure 1. This is the first measurement at a hadron collider of the inclusive J/ψ cross section at large $\eta^{J/\psi}$. The curve shown in the figure is the predicted contribution from B decays only.[7]

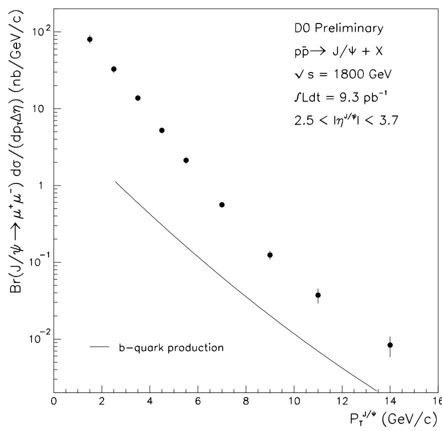

Figure 1: $Br \cdot d\sigma/dp_T^{J/\psi}/\Delta\eta$ for J/ψ production for $2.5 < |\eta^{J/\psi}| < 3.7$.

Combining both central and forward J/ψ data, the differential cross section, $Br \cdot d\sigma/d\eta^{J/\psi}$, for $P_T^{J/\psi} > 8$ GeV/c is given in Figure 2. The production cross section in the forward region ($\eta^{J/\psi} \approx 2.9$) is smaller than that in the central region by a factor of about five. A similar dependence is seen in the B decay contribution to J/ψ production [7] which is also shown in Figure 2. Calculation of the contributions from other production mechanisms is in progress.

4 Forward Inclusive Single Muon Production

We have also measured the inclusive single muon cross section in the forward region, $2.4 < |y^\mu| < 3.2$. The motivation for this measurement is similar to that for the forward J/ψ cross section. Different b-quark production mechanisms can contribute differently as a function of rapidity. Also, the b-quark cross section in the small angle region probes more of the low Feynman x region of the gluon structure function.

Muons in the forward region are selected with the cuts described above. Only single interaction events are used. A total of 3224 events corresponding to an integrated luminosity L of 59.8 nb^{-1} remains after all cuts from events taken with a single muon trigger during the 1994-95 collider run.

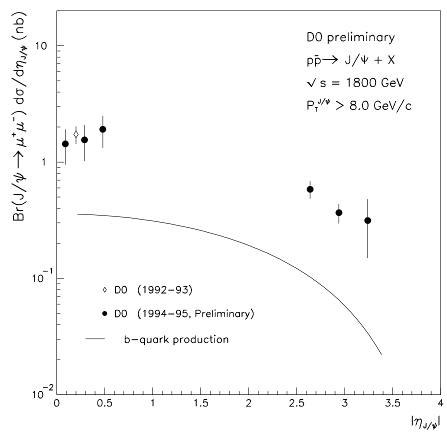

Figure 2: $Br \cdot d\sigma/d\eta^{J/\psi}$ for J/ψ production with $P_T^{J/\psi} > 8$ GeV/c.

The inclusive muon cross section is determined as follows:

$$\frac{d\sigma^\mu}{dp_T^\mu dy} = \frac{1}{L\Delta y \Delta p_T}\frac{N^\mu f_p}{\epsilon}, \tag{1}$$

where f_p is a correction factor that accounts for momentum resolution and N^μ is the number of muons per Δp_T and Δy bin. Because of high correlations between variables and cuts, this correction and that of the detection efficiency (ϵ) are determined by:

$$\frac{N^\mu f_p}{\epsilon} = \frac{H(data)H(MCgen)}{H(MCreco)}, \tag{2}$$

where the H's are elements of 2-dimensional histograms in the (p_T, y) plane. $H(data)$ is the data distribution with all offline cuts, $H(MCgen)$ is the generated Monte Carlo distribution, and $H(MCreco)$ is the reconstructed Monte Carlo distribution with full detector simulation and the same cuts as the data. The Monte Carlo events are weighted in an iterative procedure to match the p_T and y spectra of the data.

The contribution to the cross section from π/K decays is determined by ISAJET and subtracted. In the lowest P_T^μ bin (2-3 GeV/c) there is good agreement between data and the ISAJET π/K decay prediction. The fraction of muons from b-quark decay to those from b and c-quark decays is also determined by ISAJET. We have shown previously that ISAJET gives a good

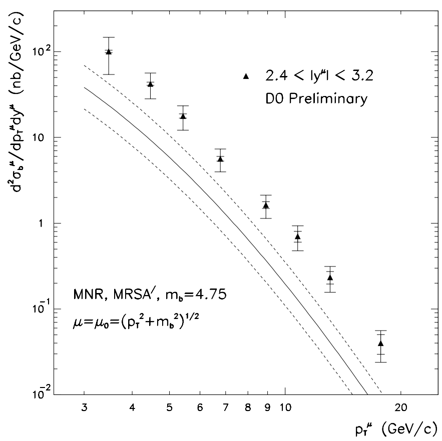

Figure 3: $d^2\sigma_b^\mu/dp_T^\mu dy^\mu$ for $2.4 < |y^\mu| < 3.2$.

description of this fraction in the central region. [8] Using this fraction we find the inclusive muon cross section from b-quark decays shown in Figure 3. Also shown is the NLO QCD prediction. [9] In both the central and forward regions the shape of the predictions match the data well. In the forward region the data are a factor of four above the central values of the theory while only a factor of two above the central values in the central region.

By combining the inclusive cross section measurements in the central and forward regions we obtain the differential cross section as a function of muon rapidity $d\sigma_b^\mu/dy^\mu$ as shown in Figure 4 along with the NLO QCD predictions. The predictions are not a good representation of the data in the forward region.

5 Υ Production

In $p\bar{p}$ collisions, Υ's are understood to be produced via gluon-gluon fusion into χ_b states $(\mathcal{O}(\alpha_s^2))$ which radiatively decay into Υ or through parton-parton scattering into Υ or χ_b states $(\mathcal{O}(\alpha_s^3))$. There is no contribution from b-quark decay and gluon fragmentation contributions are expected to be much smaller compared with charmonium production.

The Υ cross section was measured using data collected with a dimuon trigger during the 1992-93 collider run. Offline cuts similar to those described above are applied to select events with two central muons. Υ candidates are

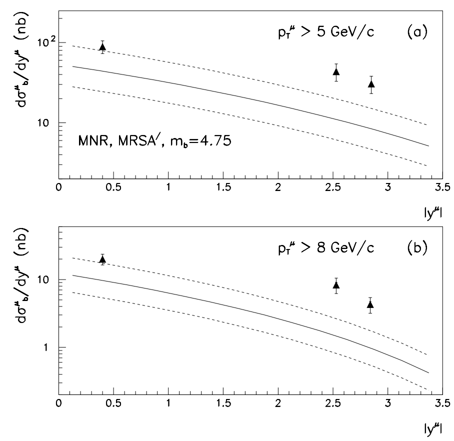

Figure 4: $d\sigma_b^\mu/dy^\mu$ for a) $P_T^\mu > 5$ GeV/c and b) $P_T^\mu > 8$ GeV/c.

then selected by further cuts: $|y^{\mu\mu}| < 0.7$, $6 < M^{\mu\mu} < 35$ GeV/c^2, and the requirement of opposite sign dimuons. In order to reduce cosmic ray background, an opening angle cut between the two muons of less than 165° is imposed. Finally, both muons are required to be isolated. A total of 249 events corresponding to an integrated luminosity of 6.3 pb^{-1}remains after all cuts.

The signal and background contributions are resolved using a maximum likelihood fit to the data. A simultaneous fit is made to the dimuon invariant mass, energy in a halo about each muon ($E_{\rm cal}^{\Delta R=0.6} - E_{\rm cal}^{\Delta R=0.2}$), and reconstructed time offset from beam crossing (called t_0) distributions. The contributing processes to the data distributions in addition to the Υ signal are backgrounds of QCD ($b\bar{b}$, $c\bar{c}$, and π/K) production, Drell-Yan production, and cosmic rays. The mass distributions for signal and background processes are taken from Monte Carlo while the energy halo and t_0 distributions are taken from appropriate data samples.

The differential cross section $Br \cdot d\sigma/dp_T^\Upsilon$ is obtained using the results of the fit. The results are shown in Figure 5. Note the cross section is a sum over all Υ S-states since the DØ detector cannot resolve the different states. The theoretical curve shown in Figure 5 is given using a program written by M. Mangano [10] which gives similar results to calculations by Baier and Rückl [11]. The $\mathcal{O}(\alpha_s^3)$ prediction is roughly a factor of five lower than the data for P_T^Υ

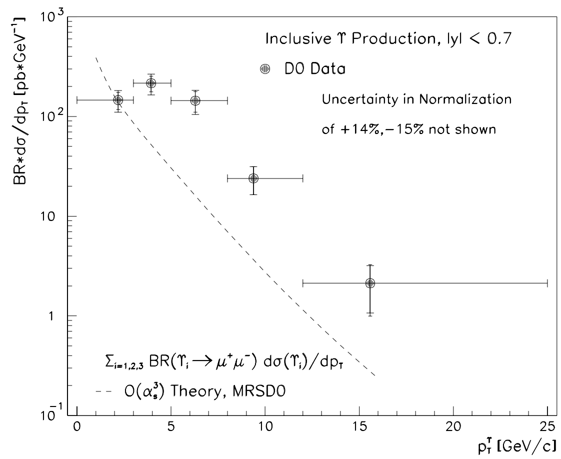

Figure 5: $Br \cdot d\sigma/dp_T^\Upsilon$ for $|y^{\mu\mu}| < 0.7$.

$>$ 5 GeV/c and diverges as $P_T^\Upsilon \to 0$.

Integrating the differential cross section and dividing by the rapidity bin width gives the total cross section $Br \cdot d\sigma/dy\ |_{y=0}$. This result is plotted in Figure 6 along with lower energy data. The theoretical curves in this case are phenomenological predictions using the color evaporation model. [12]

6 Conclusions

We have presented results on charmonium and bottomonium production using dimuons collected with the DØ detector during the 1992-1995 collider run. In general, the QCD predictions for charmonium and bottomonium are incomplete. In charmonium production, prompt J/ψ production appears not to be dominated by χ_c decay. In bottomonium production, the predicted Υ cross section is underestimated by a factor of five indicating the presence perhaps of yet unseen χ_b 3P- or D-wave states. Finally, the inclusive single muon cross section in the forward region is a factor of four above the NLO QCD prediction. This difference is larger than that found in the central region by a factor of two.

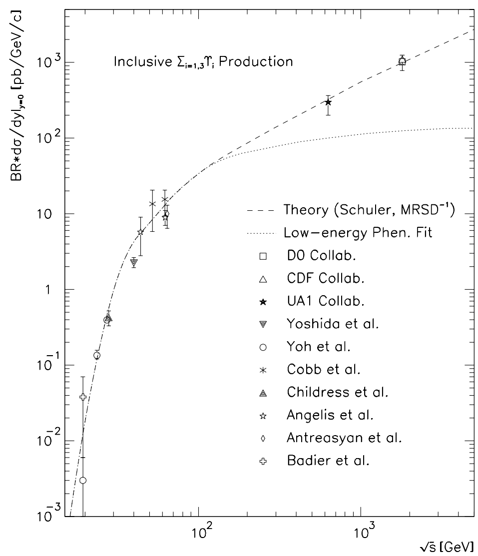

Figure 6: $Br \cdot d\sigma/dy\ |_{y=0}$ as a function of center-of-mass energy.

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