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D0

**Rapidity Dependence of the Inclusive  $J/\psi$  Production in  $p\bar{p}$   
Collisions at  $\sqrt{s} = 1.8$  TeV**

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The D0 Collaboration

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# Rapidity Dependence of the Inclusive $J/\psi$ Production in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

The DØ Collaboration<sup>1</sup>  
(July 1996)

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We have studied the  $J/\psi$  production in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.8$  TeV with the DØ detector at the Fermilab Tevatron, using a  $\mu^+\mu^-$  data sample collected during the 1994-95 running period. We have measured the inclusive  $J/\psi$  production cross section as a function of the  $J/\psi$  transverse momentum,  $p_T^{J/\psi}$ , in the central and forward rapidity regions. The new measurement of the cross section  $d\sigma/dp_T^{J/\psi}$  for  $|\eta^{J/\psi}| < 0.6$  is in a good agreement with the CDF and earlier DØ results. The cross section measurement  $d\sigma/dp_T^{J/\psi}$  for  $2.5 < |\eta^{J/\psi}| < 3.7$  covers the  $p_T^{J/\psi}$  range from 1 to 16 GeV/c. We combine the measurements in several  $|\eta^{J/\psi}|$  regions to discuss  $d\sigma/d\eta^{J/\psi}$  for  $p_T^{J/\psi} > 8$  GeV/c. The data are compared with the next-to-leading (NLO) QCD calculations, which take into account different  $J/\psi$  production mechanisms.

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## INTRODUCTION

In early studies of heavy quarkonium hadroproduction the dominant contributions to  $J/\psi$  production were assumed to come from the lowest order Feynman diagrams involving gluon fusion, either directly into charmonium and a recoiling gluon (1), or through a  $b\bar{b}$  pair followed by a decay  $B \rightarrow J/\psi X$  (2,3). More recently (4) it has been pointed out that, in addition to gluon-gluon fusion, the process of gluon fragmentation, i.e. splitting of a virtual gluon into a charmonium state and other partons, is an important source of  $J/\psi$ . While this process is of higher order in the QCD coupling constant  $\alpha_s$ , it is enhanced by a factor of  $p_T^2/m_c^2$  with respect to fusion and thus may play a significant role at sufficiently high transverse momentum. Furthermore, it has been argued that the color octet terms in the gluon fragmentation function into charmonium play an important role (5). The new production mechanisms are necessary to explain the large  $J/\psi$  production cross section measured at the Tevatron (6,7).

$J/\psi$  production at hadron colliders has been studied so far in the central region (6–8) only.

One expects the relative contributions from different production mechanisms to depend on the  $J/\psi$  rapidity.

In this paper we present results on the  $J/\psi$  production in  $p\bar{p}$  collisions at  $\sqrt{s}=1.8$  TeV with the DØ detector at Fermilab, using a  $\mu^+\mu^-$  data sample collected during the 1994-95 collider run. We observe a  $J/\psi$  signal over a wide range of pseudorapidity. The cross section measurement  $d\sigma/dp_T^{J/\psi}$  for  $|\eta^{J/\psi}| < 0.6$  ( $\eta = -\ln[\tan(\theta/2)]$  where  $\theta$  is the polar angle with respect to the beam axis) covers the  $p_T^{J/\psi}$  range from 8 to 20 GeV/c. The new measurements are in a good agreement with the earlier CDF (6) and DØ (7) results. The cross section measurement  $d\sigma/dp_T^{J/\psi}$  for  $2.5 < |\eta^{J/\psi}| < 3.7$  covers the  $p_T^{J/\psi}$  range from 1 to 16 GeV/c. The data are compared with the recent NLO QCD calculations (3,9), which take into account different  $J/\psi$  production mechanisms. The cross section measurement in the pseudorapidity region  $0.6 < |\eta^{J/\psi}| < 1.5$  is in progress. All results presented in this paper are preliminary.

## DØ DETECTOR AND DATA SELECTION

The DØ detector (10) has three major subsystems: a central tracking detector (with no central magnetic field), a highly segmented liquid-argon uranium calorimeter with good energy resolution and a muon spectrometer. The muon system consists of 5 iron toroids plus 3 layers of proportional drift tubes. The combined calorimeter plus the toroid thickness varies from about 14 interaction lengths in the central region to 19 interaction lengths in the end regions. This thickness reduces the hadron punchthrough to a negligible level. The central tracking system helps in identifying muons associated with the interaction vertex.

Three layers of drift chambers, one between the calorimeter and toroid and two outside the toroid, are used to measure muon trajectories. The wide-angle system consists of 164 chambers, using 10 cm cells, which cover the angles greater than about 10 degrees. These chambers combine the drift time measurement with time division and vernier pads to obtain three-dimensional points. The innermost layer has four measurement planes while the outer two have three each so that most muon trajectories are measured with ten three-dimensional points. In the forward region, between 5 and 20 degrees in  $\theta$ , six modules of 3.0 cm diameter drift cells are used with each module having six planes in a horizontal (XX), vertical (YY), and stereo (UU) configuration. The muon system provides a momentum resolution of  $\delta p/p = [(\frac{0.18(p-2)}{p})^2 + (0.008p)^2]^{1/2}$ , ( $p$  in GeV/c).

The dimuon data selection used a multi-level trigger system (11). The Level 0 trigger employed scintillating counters. It determined the number of interactions and the vertex position of an event, rejected beam-gas events and provided luminosity measurements. The Level 1 muon hardware trigger in the central region used 60 cm wide hodoscopic elements formed from hits in the muon drift chambers to find muon candidate tracks coming from the interaction region. Smaller size hodoscopic elements were used in the forward region. The forward trigger faces a large combinatoric problem due to the large flux of particles near the beam axis. Therefore, a single interaction flag was required for forward dimuon triggers. Also a cut on the total hit multiplicity in the forward muon chambers was imposed. This cut rejected 46% of the events. The software-based muon event filter (Level 2) required two reconstructed muons with transverse momentum  $p_T^\mu > 3$  GeV/c (1 GeV/c in the forward region). All muons were required to deposit at least 1 GeV of energy along their trajectory in the hadronic part of the calorimeter.

The trigger efficiency (including the effect of muon chamber efficiencies) was determined by a complete Monte Carlo simulation of the detector and trigger. In addition, for the

forward dimuon analysis, Monte Carlo events were mixed with real minimum bias single interaction events to better simulate background conditions. Efficiency uncertainties were taken as the difference between Monte Carlo efficiencies and those found using data collected with a single muon plus jet(s) trigger.

Offline cuts were applied to select two high quality muons. Each central muon ( $|\eta^\mu| < 1.0$ ) was required to have a good track fit and impact parameter in the bend and non-bend views. Additionally, each track needed to have a good match to a track in the central tracking chamber and a reconstructed vertex. At least 1 GeV of energy deposited in the hit calorimeter cells plus their nearest neighbors was required for each muon as well; the mean energy loss for a single muon is about 2.5 GeV. A kinematic cut  $p_T^\mu > 3$  GeV/c was also applied. A fiducial cut removing muons in the region  $80^\circ < \phi_\mu < 110^\circ$  was employed since the chamber efficiencies in that region were very low due to radiation damage effects from the main ring accelerator.

A good forward muon ( $2.2 < |\eta^\mu| < 3.3$ ) was required to have at least 5 hits in six planes of the first layer and 16 hits in 18 planes in total. The energy deposited in the calorimeter along the muon trajectory had to exceed 1.5 GeV and the integral of the magnetic field traversed by a muon had to be greater than 1.2 T·m. A kinematic cut on a muon momentum of  $p^\mu < 150$  GeV/c was imposed to ensure a reliable muon charge determination.

The total number of opposite charge dimuons satisfying the above criteria, in the mass range  $M^{\mu\mu} < 6$  GeV/c<sup>2</sup>, is 9735 and 1234 in the central ( $|\eta^{J/\psi}| < 0.6$ ) and forward ( $2.5 < |\eta^{J/\psi}| < 3.7$ ) regions, respectively. The corresponding integrated luminosities are 57 pb<sup>-1</sup> and 9.3 pb<sup>-1</sup>.

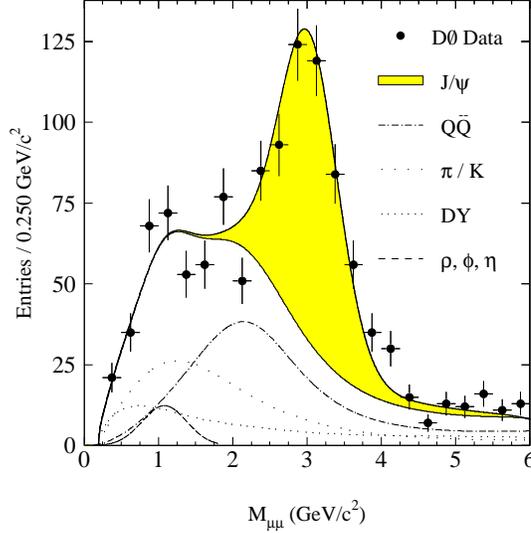
## DIMUON MASS SPECTRA

The invariant mass spectrum for opposite sign dimuons from the 1992-93 run, at  $|\eta^{J/\psi}| < 0.6$ , is shown in Fig. 1. In Ref. (7) a maximum likelihood fit was performed to extract contribution of various processes to this sample. It was demonstrated that the dominant contribution to the continuum in the central region is due to processes involving heavy quarks:  $b\bar{b}$  and  $c\bar{c}$  events (jointly denoted  $Q\bar{Q}$ ) with both heavy quarks decaying semileptonically, sequential semileptonic decays  $b \rightarrow c + \mu$ ,  $c \rightarrow \mu$  as well as cases where one muon comes from a  $b$  or  $c$  decay and the other from a decay of a  $\pi$  or  $K$  meson. Other mechanisms that yield opposite sign dimuons are virtual photon decays (12), referred to as the Drell-Yan process, and decays of light quark mesons, such as  $\rho$ ,  $\phi$  and  $\eta$ . Similar processes, however with different relative rates, are expected to contribute over the entire rapidity range.

Figure 2 shows the dimuon mass distributions from the 1994-95 running period, for six different  $|\eta^{J/\psi}|$  regions. A clear  $J/\psi$  signal is observed in all cases, with a mass resolution well represented by a function obtained from a Monte Carlo simulation of the DØ muon spectrometer. A fit to a sum of a Gaussian function and a physics motivated background, in the mass range  $2$  GeV/c<sup>2</sup>  $< M^{\mu\mu} < 6$  GeV/c<sup>2</sup>, yields a total number of  $1156 \pm 75$ ,  $915 \pm 99$ ,  $152 \pm 19$ ,  $115 \pm 12$ ,  $255 \pm 21$  and  $159 \pm 16$   $J/\psi$  events for  $|\eta^{J/\psi}| < 0.3$ ,  $0.3 < |\eta^{J/\psi}| < 0.6$ ,  $0.6 < |\eta^{J/\psi}| < 0.9$ ,  $2.5 < |\eta^{J/\psi}| < 2.8$ ,  $2.8 < |\eta^{J/\psi}| < 3.1$ , and  $3.1 < |\eta^{J/\psi}| < 3.4$ , respectively.

## DIFFERENTIAL CROSS SECTIONS $d\sigma/dp_T^{J/\psi}$

The  $J/\psi$  transverse momentum distribution resulting from mass fits in  $p_T^{J/\psi}$  bins was corrected for a finite detector momentum resolution (16), acceptance and efficiency. The differential  $J/\psi$  production cross section as a function of  $p_T^{J/\psi}$  for the central dimuons is



**FIG. 1.** The invariant mass spectrum of opposite sign muon pairs at  $|\eta^{\mu\mu}| < 0.6$  for the the 1992-93 data. The hatched area indicates the  $J/\psi$  signal on top of the sum of the background contributions. The background contributions are also shown separately. This data sample corresponds to an integrated luminosity of  $6.6 \text{ pb}^{-1}$  (7).

shown in Fig. 3. The data points are shown with the statistical and systematic errors added in quadrature <sup>2</sup>. The total systematic uncertainty of  $\sim 31\%$  includes contributions from trigger efficiency (20%), background subtraction (20%), offline dimuon selection cuts (5%), Monte Carlo statistics (10%) and the integrated luminosity (5%). The 1994-95 results are in an excellent agreement with the 1992-93 data (7), also shown in Fig. 3. By integrating over all bins we obtain a total cross section of:

$$\sigma(p\bar{p} \rightarrow J/\psi + X) \cdot B(J/\psi \rightarrow \mu^+ \mu^-) = 1.96 \pm 0.16(\text{stat}) \pm 0.63(\text{syst}) \text{ nb},$$

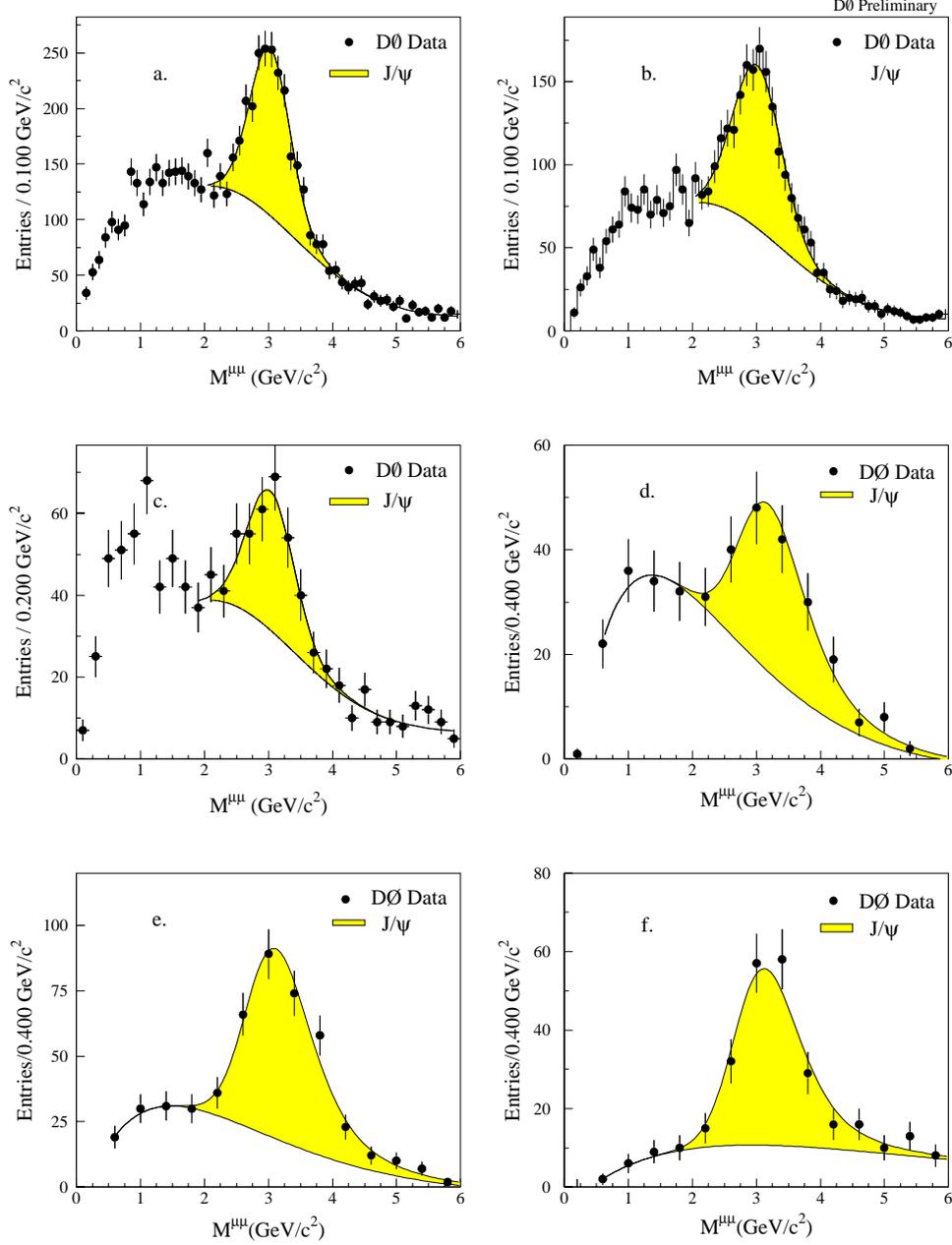
$$p_T^{J/\psi} > 8.0 \text{ GeV}/c \quad \text{and} \quad |\eta^{J/\psi}| < 0.6$$

The same cross section determined for the 1992-93 sample is  $2.08 \pm 0.17(\text{stat}) \pm 0.46(\text{syst}) \text{ nb}$  (7).

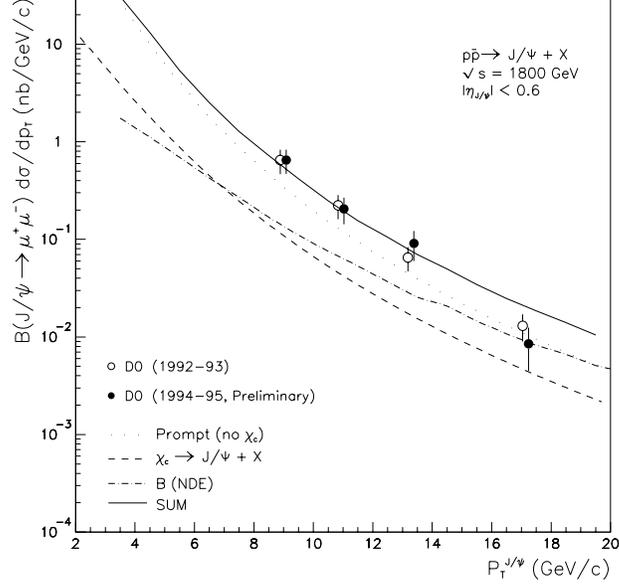
After accounting for the contribution due to fragmentation, the theoretical NLO QCD curve, with the color octet term adjusted to fit the CDF prompt  $J/\psi$  production cross section (9), describes our spectrum well. This prediction, shown in Fig.3, is based on the use of MRSDO structure functions with  $\Lambda_{\overline{MS}}^5 = 140 \text{ MeV}$ , the factorization-renormalization scale  $\mu = \mu_0$ , where  $\mu_0 = \sqrt{m_b^2 + \langle p_T^b \rangle^2}$ , and  $m_b = 4.75 \text{ GeV}/c^2$ . The same values of theoretical parameters are used throughout the paper.

The differential  $J/\psi$  production cross section as a function of  $p_T^{J/\psi}$  in the forward region is shown in Fig. 4. By integrating over bins with  $p_T^{J/\psi} > 8 \text{ GeV}/c$  we obtain a total cross

<sup>2</sup>only a subsample of the 1994-1995 data, corresponding to the integrated luminosity of  $8.6 \text{ pb}^{-1}$ , was used for the cross section determination



**FIG. 2.** The invariant mass spectra for opposite sign muon pairs. The hatched area corresponds to the fitted  $J/\psi$  signal. (a)  $|\eta^{\mu\mu}| < 0.3$ ; (b)  $0.3 < |\eta^{\mu\mu}| < 0.6$ ; (c)  $0.9 < |\eta^{\mu\mu}| < 1.2$ ; (d)  $2.5 < |\eta^{\mu\mu}| < 2.8$ ; (e)  $2.8 < |\eta^{\mu\mu}| < 3.1$ ; (f)  $3.1 < |\eta^{\mu\mu}| < 3.4$ .



**FIG. 3.** The  $J/\psi$  production cross section  $d\sigma/dp_T \cdot B$  for  $|\eta^{J/\psi}| < 0.6$  as a function of the  $J/\psi$   $p_T$ . The error bars are statistical and systematic added in quadrature. Both 1992-93 and 1994-95 results are shown. The curves represent expected contributions from various production mechanisms (3,9) calculated with the factorization-renormalization scale  $\mu=\mu_0$  (see text).

section of:

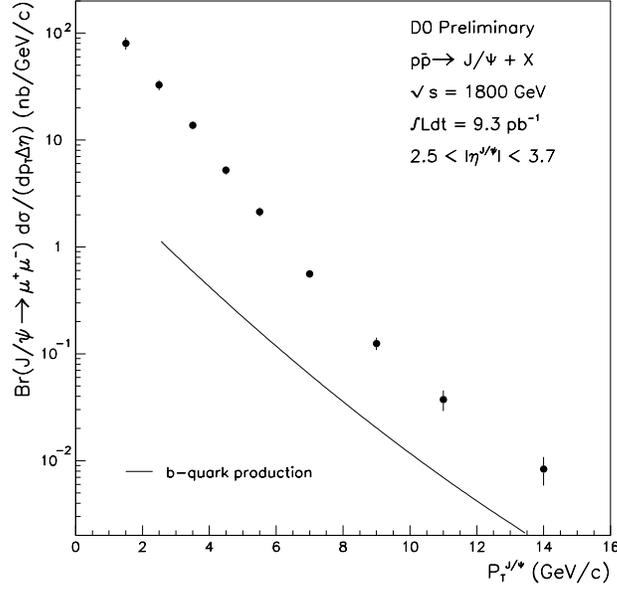
$$\sigma(p\bar{p} \rightarrow J/\psi + X) \cdot B(J/\psi \rightarrow \mu^+ \mu^-) = 0.40 \pm 0.04(\text{stat}) \pm 0.04(\text{syst}) \text{ nb},$$

$$p_T^{J/\psi} > 8.0 \text{ GeV}/c \quad \text{and} \quad 2.5 < |\eta^{J/\psi}| < 3.4$$

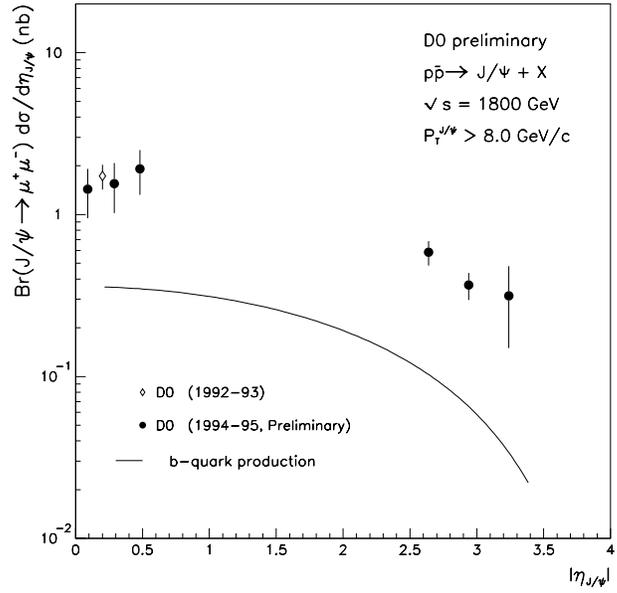
This is the first measurement of the  $J/\psi$  cross section at large  $|\eta^{J/\psi}|$ . The data are compared with the expected contribution from the  $b$  quark decay (3). Our measurement implies that the fraction of  $J/\psi$  from  $b$  decays increases with  $p_T^{J/\psi}$ .

### DIFFERENTIAL CROSS SECTIONS $d\sigma/d\eta^{J/\psi}$

The  $d\sigma/d\eta^{J/\psi}$  plot, Fig.5, combines data from the central and forward dimuon analyses for  $p_T^{J/\psi} > 8 \text{ GeV}/c$ . There are three entries for  $|\eta^{J/\psi}| < 0.6$ , consistent with no  $\eta$  dependence in that region. On the other hand, the cross section for  $|\eta^{J/\psi}| \sim 2.9$  is lower by a factor  $\sim 5$ . The predicted  $b$  quark contribution to the  $J/\psi$  production, calculated with the MRSD0 structure functions, exhibits a similar  $|\eta^{J/\psi}|$  dependence.



**FIG. 4.** The  $J/\psi$  production cross section  $d\sigma/dp_T \cdot B$  for  $2.5 < |\eta^{J/\psi}| < 3.7$  as a function of  $p_T^{J/\psi}$ . The error bars are statistical only. The solid curve represents the expected contribution from the  $b$  quark fragmentation.



**FIG. 5.** The  $J/\psi$  production cross section  $d\sigma/d\eta \cdot B$  as a function of  $|\eta^{J/\psi}|$  for  $p_T^{J/\psi} > 8 \text{ GeV}/c$ . The error bars are statistical and systematic added in quadrature.

## CONCLUSIONS

We have measured the inclusive  $J/\psi$  production cross section as a function of  $J/\psi$  transverse momentum  $p_T^{J/\psi}$  in the central and forward rapidity regions. The cross section measurement  $d\sigma/dp_T^{J/\psi}$  for  $|\eta^{J/\psi}| < 0.6$  covers the  $p_T^{J/\psi}$  range from 8 to 20 GeV/c. The new measurements are in good agreement with the earlier CDF (6) and DØ (7) results. They also agree with the recent QCD calculations which include contributions from several  $J/\psi$  production mechanisms:  $b$  quark decays, direct charmonium production and gluon fragmentation processes that involve color octet terms.

The measured cross section  $d\sigma/dp_T^{J/\psi}$  for  $2.5 < |\eta^{J/\psi}| < 3.7$  covers the  $p_T^{J/\psi}$  range from 1 to 16 GeV/c. A strong dependence of the  $J/\psi$  production cross section on rapidity is observed at large  $|\eta^{J/\psi}|$ . Theoretical predictions for the  $b$  quark contribution exhibit a similar  $|\eta^{J/\psi}|$  dependence. It will be interesting to verify whether theoretical calculations, adjusted to reproduce experimental data in the central region, can be successfully extended to the forward rapidity region.

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