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D0

J/ψ Production in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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The D0 Collaboration

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J/ψ Production in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

The DØ Collaboration¹
(July 1995)

We have studied J/ψ production in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV with the DØ detector at Fermilab, using a $\mu^+\mu^-$ data sample corresponding to an integrated luminosity of 13 pb^{-1} . We have measured the inclusive J/ψ production cross section as a function of J/ψ transverse momentum p_T . For the kinematic range $p_T > 8 \text{ GeV}/c$ and $|\eta| < 0.6$ we obtain $B\mathcal{R}(J/\psi \rightarrow \mu^+\mu^-) \cdot \sigma(p\bar{p} \rightarrow J/\psi + X) = 1.93 \pm 0.16(\text{stat}) \pm 0.43(\text{syst}) \text{ nb}$. Using the muon impact parameter we have estimated the fraction of J/ψ mesons coming from B meson decays to be $f_b = 0.35 \pm 0.09(\text{stat}) \pm 0.10(\text{syst})$ and inferred the inclusive b production cross section. From the information on the event topology a fraction of non-isolated J/ψ events has been measured to be $f_{\text{non-isol}} = 0.64 \pm 0.09(\text{stat}) \pm 0.06(\text{syst})$. We have also obtained the fraction of events resulting from radiative decays of χ_c states as $f_\chi = 0.30 \pm 0.07(\text{stat}) \pm 0.07(\text{syst})$. We discuss the implications of our measurements for charmonium production processes.

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INTRODUCTION

In high energy $p\bar{p}$ collisions the dominant contributions to J/ψ production are expected to come from the lowest order Feynman diagrams with gluon-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). It has been argued recently (4) 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/ψ . While this process is of higher order in the QCD coupling constant α_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. Table 1 lists the salient characteristics to be expected for each mechanism of J/ψ production.

Existing data from $p\bar{p}$ collider experiments UA1 (5) and CDF (6) indicate that gluon-gluon fusion processes alone fail to reproduce the observed J/ψ production rate. Our measurement of the inclusive J/ψ production cross section presented in this paper confirms these earlier results. In addition, a detailed study of the J/ψ data, including the event topology, muon impact parameter and the rate of χ_c radiative decays, allows us to estimate the role of various charmonium production mechanisms in $p\bar{p}$ collisions and to infer the

Production Mechanism	Expected Characteristics
B decay	Non isolated Non prompt (displaced vertex)
Direct Charmonium Production	Isolated Prompt
g or c fragmentation	Non isolated Prompt

TABLE 1. Characteristics expected in J/ψ events from various production mechanisms

inclusive b production cross section.

EXPERIMENT AND ANALYSIS

The DØ detector (7) 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 with a resolution of

$\delta p/p = [(\frac{0.18(p-2)}{p})^2 + (0.008p)^2]^{1/2}$, (p in GeV/ c). The total thickness for the calorimeter plus the toroid varies from 13 to 15 interaction lengths and reduces the hadron punchthrough to a negligible level. The central tracking system helps in identifying muons associated with the interaction vertex.

Dimuon data were collected with a multilevel trigger, with a total integrated luminosity of 13 pb^{-1} . The Level 1 hardware muon trigger and Level 2 software trigger are described elsewhere (8).

In the offline analysis two good quality muons were required in the pseudorapidity range $|\eta^\mu| < 1.0$ ($\eta^\mu = -\ln[\tan(\theta/2)]$ where θ is the polar angle with respect to the beam axis). In addition, both muon trajectories were required to be consistent with the reconstructed vertex position and to match with a track in the central detector and with a calorimeter energy deposition. The total number of opposite charge dimuons satisfying the above criteria, in the mass range $M_{\mu\mu} < 6 \text{ GeV}/c^2$, is 4726.

The inclusive J/ψ cross section determination and the inferred integrated b quark cross section were based on a restricted data sample of 1221 events, corresponding to a total integrated luminosity of 6.6 pb^{-1} . For this sample it was required that the events had two muons at both trigger Level 1 and Level 2 and the pseudorapidity range for the dimuon was restricted to $|\eta| < 0.6$.

INCLUSIVE J/ψ PRODUCTION CROSS SECTION

The invariant mass, $M_{\mu\mu}$, distribution for opposite charge dimuons is shown in Fig. 1. A clear J/ψ signal is observed with a mass resolution well represented by a Gaussian function. The dominant contribution to the continuum is expected to come from 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 π or K meson. Other

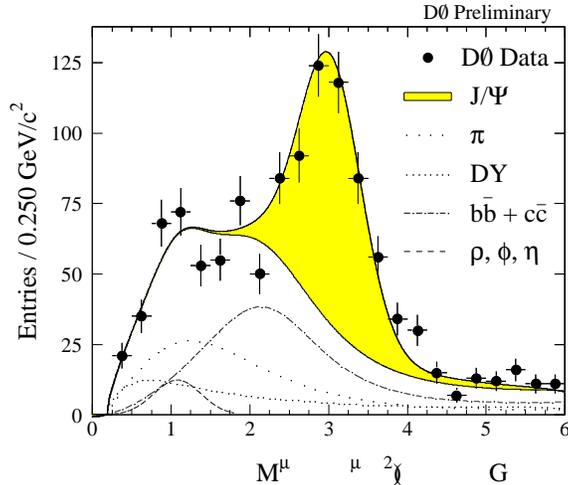


FIG. 1. The mass spectrum for opposite sign muon pairs. The solid curve is the fitted sum of the J/ψ signal and background contributions, which are also shown separately.

mechanisms that yield opposite sign dimuons are virtual photon decays (9), referred to as the Drell-Yan process, and decays of light quark mesons, such as ρ , ϕ and η .

Muons originating from b or c decays are accompanied by a collimated jet of hadrons that can be detected in the calorimeter. Gluon fragmentation into charmonium is also expected to produce muons embedded in jets. By contrast, muons from Drell-Yan events and those coming from the direct charmonium production are expected to be isolated.

We measure the isolation parameter for a muon, I_μ , by summing the energy in the calorimeter cells traversed by the muon and their two nearest neighbors and subtracting the expected energy deposition for a minimum ionizing particle of that momentum. If the other muon of the pair lies within an $\eta - \phi$ cone of radius $\Delta R = 0.6$ about the direction of the first muon, the energy loss of that muon is subtracted as well. The dimuon isolation $I_{\mu\mu}$ is defined as the isolation of the more energetic muon. The dimuon momentum transverse to the jet axis, $p_{T,rel}^{\mu\mu}$, is defined as follows. The dimuon has an associated jet if there is a reconstructed jet within a cone of radius $\Delta R = 0.7$ about the direction of the dimuon momentum. If the dimuon has no associated jet, $p_{T,rel}^{\mu\mu}$ is set to 0. We used the information on $M_{\mu\mu}$, $I_{\mu\mu}$, and $p_{T,rel}^{\mu\mu}$ to separate various sources of dimuon events.

For each of the dimuon production processes mentioned above we generated a sample of Monte Carlo events using the ISAJET program (10). We also generated two samples of J/ψ events. The process $B \rightarrow J/\psi X$ served as a paradigm for the 'non-isolated' J/ψ production, including the possible gluon fragmentation process, for which no simulation program is currently available. Similarly, the direct charmonium production was used as a template for all possible sources of isolated J/ψ . To simulate the direct charmonium production we used the explicit formulae for parton cross sections for gluonic production of $c\bar{c}$ P wave states given by Humpert (11).

Each ISAJET Monte Carlo sample was run through a chain of programs simulating the effects of the detector (12) and trigger response and then processed with the standard offline reconstruction program. For each process we parametrized the distributions of the three selected physics variables, $M_{\mu\mu}$, $p_{T,rel}^{\mu\mu}$, and $I_{\mu\mu}$. We applied the maximum likelihood

method to determine the relative contribution of each process. The results are shown in Fig. 1. The total estimated number of J/ψ events is 407 ± 28 , of which 147 ± 33 are isolated.

As a result of the fit each event was assigned a probability of originating from a given process. The inclusive J/ψ transverse momentum spectrum obtained by this procedure was then unfolded using the technique of Ref. (13). The unfolded spectrum, corrected for the acceptance and efficiency determined with simulated events, was used to calculate the differential J/ψ cross section $d\sigma/dp_T$.

The overall acceptance and efficiency as a function of $p_T^{\mu\mu}$ increases from 1% at 8 GeV/c to a plateau of 10% at 15 GeV/c. The total systematic uncertainty is estimated to be 22%. It includes contributions from trigger efficiency (15%), background subtraction (14%), offline dimuon selection cuts (6%) and the integrated luminosity (6%).

Finally, the acceptance of the two muons depends on the unknown polarization of the parent J/ψ meson. Our results are presented for the case of zero polarization. For the extreme cases of 100% longitudinal and transverse polarisation, the estimated cross section is changed by +20% and -25%, respectively.

For the integrated cross section we obtain

$$Br(J/\psi \rightarrow \mu^+ \mu^-) \cdot \sigma(p\bar{p} \rightarrow J/\psi + X) = 1.93 \pm 0.16(stat) \pm 0.43(syst) \text{ nb},$$

$$p_T > 8.0 \text{ GeV}/c, |\eta| < 0.6.$$

The inclusive J/ψ production cross section as a function of transverse momentum is shown in Fig. 2. The data points are shown with statistical and p_T dependent systematic errors added in quadrature. The spectrum agrees closely in size and shape with the J/ψ inclusive cross section measured by the CDF collaboration (6). Also plotted in Fig. 2 are theoretical predictions for the J/ψ production cross section. They agree with our measurement within the total experimental and theoretical uncertainty but tend to be less steeply falling with p_T .

J/ψ PRODUCTION FROM B MESON DECAYS

To determine the fraction f_b of J/ψ from B meson decays we have examined the distribution of the impact parameter of the muons relative to the event vertex, in the $r - \phi$ plane. Each muon was required to have a matching track in the central drift chamber and in the vertex drift chamber. We have performed a simultaneous mass and impact parameter maximum likelihood fit to the opposite sign dimuon data in the mass range 2 - 4.4 GeV/c² and the impact parameter range -0.08 cm to 0.16 cm. Fig. 3 shows muon impact parameter distribution together with the results of the fit.

The total number of fitted J/ψ events is 143 ± 17 events, over a background of $120 \pm 15 Q\bar{Q}$ and 8 ± 4 Drell-Yan events. The fitted value of the J/ψ b fraction is $f_b = 0.35 \pm 0.09$ (stat) ± 0.10 (syst). For this sample the mean value of the J/ψ transverse momentum is 11.8 GeV/c. The CDF collaboration has determined the f_b fraction as a function of the J/ψ transverse momentum by measuring the decay distance of the dimuon in the transverse plane (14). There is a good agreement of our result with the the CDF values in the overlapping region, $p_T > 8$ GeV/c.

To determine the b quark cross section (the average of the b and \bar{b} quark inclusive cross sections) we used a technique first used by the UA1 collaboration (15). We scaled the measured J/ψ inclusive production cross section by the following factors:

- the predicted Monte Carlo acceptance for b quarks with transverse momentum greater than $p_T^{min}(b)$ that give rise to J/ψ 's satisfying the kinematic cut $p_T > p_T^{min}(J/\psi)$,

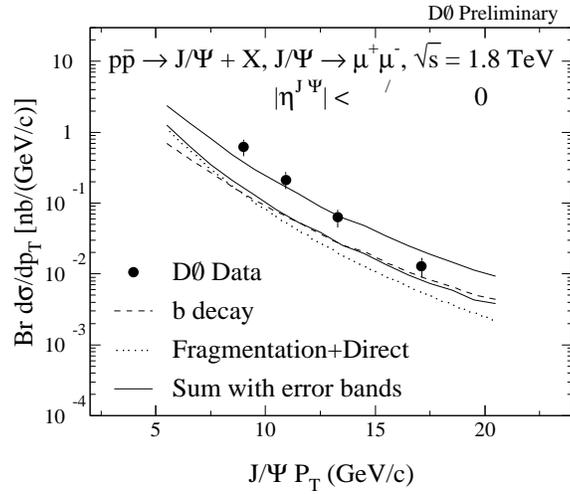


FIG. 2. The product $B(d\sigma/dp_T)$ vs p_T for $J/\psi \rightarrow \mu^+ \mu^-$. The dotted line corresponds to J/ψ production through B meson decays. The dashed line corresponds to the prompt J/ψ production. The sum, with theoretical uncertainties, is indicated by the shaded band, Ref. [3].

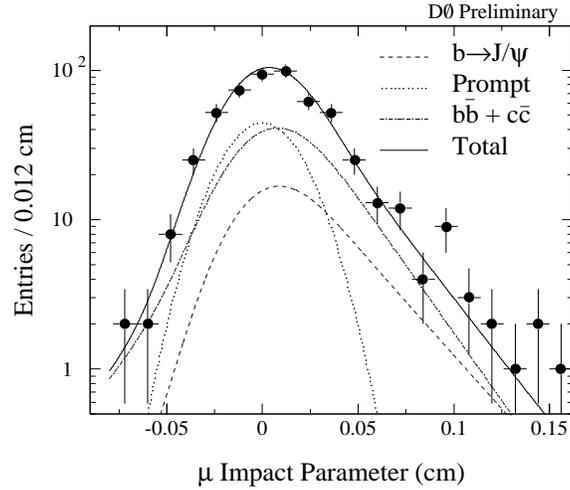


FIG. 3. Impact parameter distribution with respect to the event vertex in the transverse plane, for muons in the J/ψ region. Also shown are the fitted contributions from prompt J/ψ (dotted line), B produced J/ψ (dashed line) and $Q\bar{Q}$ continuum (dashed-dotted line).

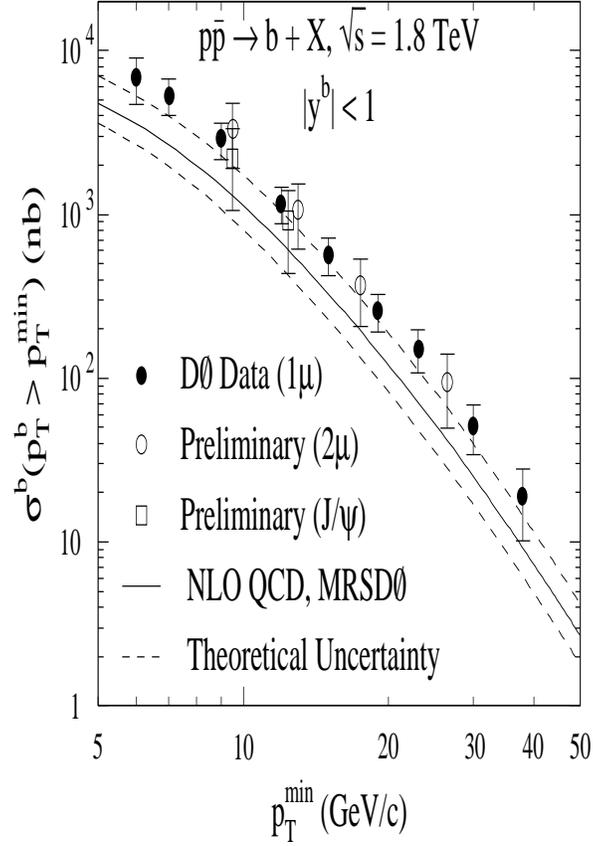


FIG. 4. Integrated b quark production cross section vs $p_T^b \min$. The squares correspond to D0 J/ψ data (this work); the full circles correspond to D0 single muon data, Ref. [16] and open circles correspond to the D0 dimuon data Ref. [17]. The curve represents the QCD NLO prediction, Ref. [18]. This prediction is based on use of MRSD0 structure functions with $\Lambda_5^{\overline{MS}} = 140 \text{ MeV}$, and $m_b = 4.75 \text{ GeV}/c^2$. The theoretical uncertainty results from choosing $100 < \Lambda_5^{\overline{MS}} < 187 \text{ MeV}$, and the factorization-renormalization scale μ in the range $\mu_0/2 < \mu < 2\mu_0$, where $\mu_0 = \sqrt{m_b^2 + \langle p_T^b \rangle^2}$.

- the combined branching ratios $Br(B \rightarrow J/\psi + X) \cdot Br(J/\psi \rightarrow \mu^+ \mu^-)$,
- the fraction f_b of J/ψ from B meson decays.

$p_T^{min}(b)$ is defined such that 90 % of the b quarks remaining after application of the cut on the J/ψ transverse momentum $p_T > p_T^{min}(J/\psi)$ have $p_T^b > p_T^{min}(b)$. Fig. 4 shows the b quark integrated cross section for $p_T^{min}(b) = 9.9$ and 12.4 GeV/ c , corresponding to $p_T^{min}(J/\psi) = 8$ and 10 GeV/ c . Also shown are DØ results obtained from single muons (16) and dimuons (17). The agreement is excellent. The curves show next to leading order (NLO) QCD predictions (18) with theoretical uncertainties.

DIRECT CHARMONIUM PRODUCTION

J/ψ production in the direct charmonium production model proceeds predominantly via P wave states χ_c , followed by their radiative decays: $gg \rightarrow \chi_c X \rightarrow J/\psi + \gamma$. By contrast, in decays of B mesons, the fraction of J/ψ mesons coming from χ_c decays is only $(23 \pm 8)\%$ (19). We have found a χ_c signal by performing a full reconstruction of the decay chain $\chi_c \rightarrow J/\psi + \gamma, J/\psi \rightarrow \mu\mu$. For events with a pair of opposite charge muons in the J/ψ mass region, defined as $2 < M_{\mu\mu} < 4$ GeV/ c^2 , we searched for photons with energy greater than 0.8 GeV, in the cone about the dimuon $\Delta R=2$.

The difference between the invariant mass of the $\mu\mu\gamma$ and $\mu\mu$ systems, ΔM , is plotted in Fig. 5. To estimate the background shape we have combined dimuons with electromagnetic clusters from different events. The number of χ_c events was obtained by fitting the ΔM distribution to a Gaussian signal plus background. The fit gives $66 \pm 15(\text{stat}) \pm 5(\text{syst})$ χ_c events. The combined correction factor for the acceptance and efficiency was obtained by the Monte Carlo method. With the efficiency of $30 \pm 4\%$, the measured fraction of J/ψ events coming from χ_c decay is $f_\chi = 0.30 \pm 0.07(\text{stat}) \pm 0.07(\text{syst})$. Of all χ_c events $0.73 \pm 0.24(\text{stat}) \pm 0.08(\text{syst})$ are found to have isolated dimuons. Using a similar technique, the CDF collaboration obtained (20) $f_\chi = 0.45 \pm 0.05(\text{stat}) \pm 0.15(\text{syst})$ for $p_T > 6$ GeV/ c .

SUMMARY

From the simultaneous fit to $M_{\mu\mu}$, $p_{T,rel}^{\mu\mu}$ and $I_{\mu\mu}$ discussed earlier, the fraction of J/ψ events with an isolated dimuon, averaged over $p_{T,rel}^{\mu\mu}$ is $f_{isol} = 0.36 \pm 0.11$. Independently, we find the fraction of J/ψ events due to isolated χ_c states to be 0.22 ± 0.09 . This leaves a fraction of 0.14 ± 0.14 isolated J/ψ events that are not coming from decays of P wave states.

The fraction of J/ψ events with a nonisolated dimuon is 0.64 ± 0.11 . With $f_b = 0.35 \pm 0.14$ and the known branching ratios (19) for decays $B \rightarrow \chi_c$ and $\chi_c \rightarrow J/\psi$ we expect a fraction 0.08 ± 0.03 of all J/ψ events to come from the decay chain $B \rightarrow \chi_c \rightarrow J/\psi$. It is consistent with our measured value, 0.08 ± 0.04 . There is a balance of 0.29 ± 0.17 of all J/ψ events with nonisolated prompt dimuons. They do not appear to be produced via χ_c decays. The results are summarized in Table 2.

In conclusion, we have measured the inclusive J/ψ production cross-section at $p_T > 8$ GeV/ c and $|\eta| < 0.6$ and inferred the b cross section, using our measured fraction of J/ψ events due to b decays. We have also measured the fraction of J/ψ events due to P wave charmonium decays. We have discussed the results in terms of current charmonium production models.

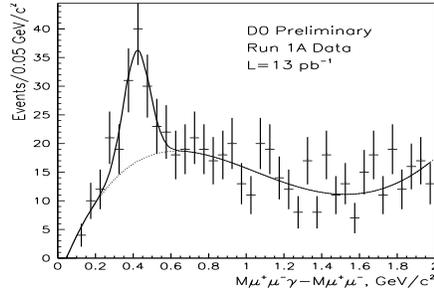


FIG. 5. Distribution in $\Delta M = M_{\mu\mu\gamma} - M_{\mu\mu}$ for dimuon events in the J/ψ region.

	Isolated	Non isolated
Prompt		
from χ_c	0.22 ± 0.09	
not from χ_c	0.14 ± 0.14	
Total	0.36 ± 0.11	0.29 ± 0.17
Non prompt		
$B \rightarrow J/\psi$		0.20 ± 0.14
$B \rightarrow \chi_c$		0.08 ± 0.03
$B \rightarrow \psi(2S)$		0.07 ± 0.03
Total		0.35 ± 0.14

TABLE 2. Relative contributions of various J/ψ production processes.

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