Fermi National Accelerator Laboratory

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Rapidity Dependence of the Inclusive J/ψ Production in p$\overline{\text{p}}$ Collisions at $\sqrt{s}$ = 1.8 TeV

S. Abachi et al.
The D0 Collaboration

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

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

The DØ Collaboration[1]

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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 collected during the 1994-95 collider run. We have measured the inclusive J/ψ production cross section as a function of the J/ψ transverse momentum, $p_T^{J/\psi}$, in the central and forward rapidity regions. The cross section $d\sigma/dp_T^{J/\psi}$ for $\left|\eta^{J/\psi}\right| < 0.6$ covers the $p_T^{J/\psi}$ range from 8 to 20 GeV/c. The new measurements are in a good agreement with the CDF and earlier DØ results. The cross section $d\sigma/dp_T^{J/\psi}$ for $2.6 < \left|\eta^{J/\psi}\right| < 3.4$ covers the $p_T^{J/\psi}$ range from 3 to 12 GeV/c. We combine the measurements in the two $\left|\eta^{J/\psi}\right|$ regions to calculate $d\sigma/d\eta^{J/\psi}$ 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/ψ production mechanisms.

S. Abachi,[12] B. Abbott,[34] M. Abolins,[23] B.S. Acharya,[41] I. Adam,[10] D.L. Adams,[35] M. Adams,[15] S. Ahn,[12] H. Aihara,[20] J. Alitti,[37] G. Álvarez,[16] G.A. Alves,[8] E. Amidi,[27] N. Amos,[22] E.W. Anderson,[17] S.H. Aronson,[3] R. Astur,[39] R.E. Avery,[29] A. Baden,[21] V. Balamurali,[30] J. Balderston,[14] B. Baldin,[12] J. Bantly,[4] J.F. Bartlett,[12] K. Bazizi,[7] J. Bendich,[20] S.B. Beri,[32] I. Bertram,[35] V.A. Bezzubov,[33] P.C. Bhat,[12] V. Bhatnagar,[32] M. Bhattacharjee,[11] A. Bischoff,[7] N. Biswas,[30] G. Blazey,[12] S. Blessing,[13] P. Bloom,[5] A. Boehnlein,[12] N.I. Bojko,[33] F. Borcherding,[12] J. Borders,[36] C. Boswell,[7] A. Brandt,[12] R. Brock,[23] A. Bross,[12] D. Buchholz,[29] V.S. Burtovoi,[33] J.M. Butler,[12] D. Casey,[36] H. Castilla-Valdez,[9] D. Chakraborty,[39] S.-M. Chang,[27] S.V. Chekulaev,[33] L.-P. Chen,[20] W. Chen,[39] L. Chevalier,[37] S. Chopra,[32] B.C. Choudhary,[7] J.H. Christenson,[12] M. Chung,[15] D. Claes,[39] A.R. Clark,[20] W.G. Cobau,[21] J. Cochran,[7] W.E. Cooper,[12] C. Cretsinger,[36] D. Cullen-Vidal,[4] M.A.C. Cummings,[14] D. Cutts,[4] O.I. Dahl,[20] K. De,[42] M. Demarteau,[12] R. Demina,[27] K. Denisenko,[12] N. Denisenko,[12] D. Denisov,[12] S.P. Denisov,[33] W. Dharmaratna,[13] H.T. Diehl,[12] M. Diesburg,[12] G. Di Loreto,[23] R. Dixon,[12] P. Draper,[42] J. Drinkard,[6] Y. Ducros,[37] S.R. Dugad,[41] S. Durston-Johnson,[36] D. Edmunds,[23] J. Ellison,[7] V.D. Elvira,[12,‡] R. Engelmann,[39] S. Eno,[21] G. Eppley,[35] P. Ermolov,[24] O.V. Eroshin,[33] V.N. Evdokimov,[33] S. Fahey,[23] T. Fahland,[4] M. Fatyga,[3] M.K. Fatyga,[36] J. Featherly,[3] S. Feher,[39] D. Fein,[2] T. Ferbel,[36] G. Finocchiaro,[39] H.E. Fisk,[12] Yu. Fisyak,[24] E. Flattum,[23] G.E. Forden,[2] M. Fortner,[28] K.C. Frame,[23] P. Franzini,[10] S. Fuess,[12] A.N. Galjaev,[33] E. Gallas,[42] C.S. Gao,[12,*] S. Gao,[12,*] T.L. Geld,[23] R.J. Genik II,[23] K. Genser,[12] C.E. Gerber,[12,§] B. Gibbard,[3] V. Glebov,[36] S. Glenn,[5] B. Gobbi,[29] M. Goforth,[13] A. Goldschmidt,[20] B. Gómez,[1] P.I. Goncharov,[33] H. Gordon,[3] L.T. Goss,[43] N. Graf,[3] P.D. Grannis,[39] D.R. Green,[12] J. Green,[28] H. Greenlee,[12] G. Griffin,[6] N. Grossman,[12] P. Grudberg,[20] S. Grünendahl,[36] W. Gu,[12,*] G. Guglielmo,[31] J.A. Guida,[39] J.M. Guida,[3] W. Guryn,[3] S.N. Gurzhiev,[33] P. Gutierrez,[31] Y.E. Gutnikov,[33] N.J. Hadley,[21] H. Haggerty,[12] S. Hagopian,[13] V. Hagopian,[13] K.S. Hahn,[36] R.E. Hall,[6] S. Hansen,[12] R. Hatcher,[23] J.M. Hauptman,[17] D. Hedin,[28] A.P. Heinson,[7] U. Heintz,[12] R. Hernández-Montoya,[9]

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T. Heuring,[13] R. Hirosky,[13] J.D. Hobbs,[12] B. Hoeneisen,[1,¶] J.S. Hoftun,[4] F. Hsieh,[22] Ting Hu,[39] Tong Hu,[16] T. Huehn,[7] S. Igarashi,[12] A.S. Ito,[12] E. James,[2] J. Jaques,[30] S.A. Jerger,[23] J.Z.-Y. Jiang,[39] T. Joffe-Minor,[29] H. Johari,[27] K. Johns,[2] M. Johnson,[12] H. Johnstad,[40] A. Jonckheere,[12] M. Jones,[14] H. Jöstlein,[12] S.Y. Jun,[29] C.K. Jung,[39] S. Kahn,[3] G. Kalbfleisch,[31] J.S. Kang,[18] R. Kehoe,[30] M.L. Kelly,[30] A. Kernan,[7] L. Kerth,[20] C.L. Kim,[18] S.K. Kim,[38] A. Klatchko,[13] B. Klima,[12] B.I. Klochkov,[33] C. Klopfenstein,[39] V.I. Klyukhin,[33] V.I. Kochetkov,[33] J.M. Kohli,[32] D. Koltick,[34] A.V. Kostritskiy,[33] J. Kotcher,[3] J. Kourlas,[26] A.V. Kozelov,[33] E.A. Kozlovski,[33] M.R. Krishnaswamy,[41] S. Krzywdzinski,[12] S. Kunori,[21] S. Lami,[39] G. Landsberg,[12] R.E. Lanou,[4] J-F. Lebrat,[37] A. Leflat,[24] H. Li,[39] J. Li,[42] Y.K. Li,[29] Q.Z. Li-Demarteau,[12] J.G.R. Lima,[8] D. Lincoln,[22] S.L. Linn,[13] J. Linnemann,[23] R. Lipton,[12] Y.C. Liu,[29] F. Lobkowicz,[36] S.C. Loken,[20] S. Lökös,[39] L. Lueking,[12] A.L. Lyon,[21] A.K.A. Maciel,[8] R.J. Madaras,[20] R. Madden,[13] I.V. Mandrichenko,[33] Ph. Mangeot,[37] S. Mani,[5] B. Mansoulié,[37] H.S. Mao,[12,*] S. Margulies,[15] R. Markeloff,[28] L. Markosky,[2] T. Marshall,[16] M.I. Martin,[12] M. Marx,[39] B. May,[29] A.A. Mayorov,[33] R. McCarthy,[39] T. McKibben,[15] J. McKinley,[23] T. McMahon,[31] H.L. Melanson,[12] J.R.T. de Mello Neto,[8] K.W. Merritt,[12] H. Miettinen,[35] A. Milder,[2] A. Mincer,[26] J.M. de Miranda,[8] C.S. Mishra,[12] M. Mohammadi-Baarmand,[39] N. Mokhov,[12] N.K. Mondal,[41] H.E. Montgomery,[12] P. Mooney,[1] M. Mudan,[26] C. Murphy,[16] C.T. Murphy,[12] F. Nang,[4] M. Narain,[12] V.S. Narasimham,[41] A. Narayanan,[2] H.A. Neal,[22] J.P. Negret,[1] E. Neis,[22] P. Nemethy,[26] D. Nešić,[4] D. Norman,[43] L. Oesch,[22] V. Oguri,[8] E. Oltman,[20] N. Oshima,[12] D. Owen,[23] P. Padley,[35] M. Pang,[17] A. Para,[12] C.H. Park,[12] Y.M. Park,[19] R. Partridge,[4] N. Parua,[41] M. Paterno,[36] J. Perkins,[42] A. Peryshkin,[12] M. Peters,[14] H. Piekarz,[13] Y. Pischalnikov,[34] A. Pluquet,[37] V.M. Podstavkov,[33] B.G. Pope,[23] H.B. Prosper,[13] S. Protopopescu,[3] D. Pušeljić,[20] J. Qian,[22] P.Z. Quintas,[12] R. Raja,[12] S. Rajagopalan,[39] O. Ramirez,[15] M.V.S. Rao,[41] P.A. Rapidis,[12] L. Rasmussen,[39] A.L. Read,[12] S. Reucroft,[27] M. Rijssenbeek,[39] T. Rockwell,[23] N.A. Roe,[20] P. Rubinov,[39] R. Ruchti,[30] S. Rusin,[24] J. Rutherfoord,[2] A. Santoro,[8] L. Sawyer,[42] R.D. Schamberger,[39] H. Schellman,[29] J. Sculli,[26] E. Shabalina,[24] C. Shaffer,[13] H.C. Shankar,[41] R.K. Shivpuri,[11] M. Shupe,[2] J.B. Singh,[32] V. Sirotenko,[28] W. Smart,[12] A. Smith,[2] R.P. Smith,[12] R. Snihur,[29] G.R. Snow,[25] S. Snyder,[39] J. Solomon,[15] P.M. Sood,[32] M. Sosebee,[42] M. Souza,[8] A.L. Spadafora,[20] R.W. Stephens,[42] M.L. Stevenson,[20] D. Stewart,[22] D.A. Stoianova,[33] D. Stoker,[6] K. Streets,[26] M. Strovink,[20] A. Taketani,[12] P. Tamburello,[21] J. Tarazi,[6] M. Tartaglia,[12] T.L. Taylor,[29] J. Teiger,[37] J. Thompson,[21] T.G. Trippe,[20] P.M. Tuts,[10] N. Varelas,[23] E.W. Varnes,[20] P.R.G. Virador,[20] D. Vititoe,[2] A.A. Volkov,[33] A.P. Vorobiev,[33] H.D. Wahl,[13] G. Wang,[13] J. Wang,[12,*] L.Z. Wang,[12,*] J. Warchol,[30] M. Wayne,[30] H. Weerts,[23] F. Wen,[13] W.A. Wenzel,[20] A. White,[42] J.T. White,[43] J.A. Wightman,[17] J. Wilcox,[27] S. Willis,[28] S.J. Wimpenny,[7] J.V.D. Wirjawan,[43] J. Womersley,[12] E. Won,[36] D.R. Wood,[12] H. Xu,[4] R. Yamada,[12] P. Yamin,[3] C. Yanagisawa,[39] J. Yang,[26] T. Yasuda,[27] C. Yoshikawa,[14] S. Youssef,[13] J. Yu,[36] Y. Yu,[38] Y. Zhang,[12,*] Y.H. Zhou,[12,*] Q. Zhu,[26] Y.S. Zhu,[12,*] Z.H. Zhu,[36] D. Zieminska,[16] A. Zieminski,[16] and A. Zylberstejn[37]

[1]Universidad de los Andes, Bogotá, Colombia
[2]University of Arizona, Tucson, Arizona 85721
[3]Brookhaven National Laboratory, Upton, New York 11973
[4]Brown University, Providence, Rhode Island 02912
[5]University of California, Davis, California 95616
[6]University of California, Irvine, California 92717
[7]University of California, Riverside, California 92521
[8]LAFEX, Centro Brasileiro de Pesquisas Físicas, Rio de Janeiro, Brazil
[9]CINVESTAV, Mexico City, Mexico
[10]Columbia University, New York, New York 10027
[11]Delhi University, Delhi, India 110007

[12]Fermi National Accelerator Laboratory, Batavia, Illinois 60510
[13]Florida State University, Tallahassee, Florida 32306
[14]University of Hawaii, Honolulu, Hawaii 96822
[15]University of Illinois at Chicago, Chicago, Illinois 60607
[16]Indiana University, Bloomington, Indiana 47405
[17]Iowa State University, Ames, Iowa 50011
[18]Korea University, Seoul, Korea
[19]Kyungsung University, Pusan, Korea
[20]Lawrence Berkeley Laboratory and University of California, Berkeley, California 94720
[21]University of Maryland, College Park, Maryland 20742
[22]University of Michigan, Ann Arbor, Michigan 48109
[23]Michigan State University, East Lansing, Michigan 48824
[24]Moscow State University, Moscow, Russia
[25]University of Nebraska, Lincoln, Nebraska 68588
[26]New York University, New York, New York 10003
[27]Northeastern University, Boston, Massachusetts 02115
[28]Northern Illinois University, DeKalb, Illinois 60115
[29]Northwestern University, Evanston, Illinois 60208
[30]University of Notre Dame, Notre Dame, Indiana 46556
[31]University of Oklahoma, Norman, Oklahoma 73019
[32]University of Panjab, Chandigarh 16-00-14, India
[33]Institute for High Energy Physics, 142-284 Protvino, Russia
[34]Purdue University, West Lafayette, Indiana 47907
[35]Rice University, Houston, Texas 77251
[36]University of Rochester, Rochester, New York 14627
[37]CEA, DAPNIA/Service de Physique des Particules, CE-SACLAY, France
[38]Seoul National University, Seoul, Korea
[39]State University of New York, Stony Brook, New York 11794
[40]SSC Laboratory, Dallas, Texas 75237
[41]Tata Institute of Fundamental Research, Colaba, Bombay 400005, India
[42]University of Texas, Arlington, Texas 76019
[43]Texas A&M University, College Station, Texas 77843

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 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). 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's. 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.

The J/ψ production at hadron colliders has been so far studied in the central region (5–7) only. One expects the ratios of contributions from different production mechanisms to depend on the J/ψ rapidity. Further, predictions for the forward production of J/ψs are expected to be particularly sensitive to the gluon structure functions of the colliding particles.

In this paper we present results on the J/ψ production in $p\bar{p}$ collisions at $\sqrt{s}$ =1.8 TeV with the DØ detector at Fermilab, using $\mu^+\mu^-$ data sample, collected during the 1994-95 collider run. We have measured the inclusive J/ψ production cross section as a function of J/ψ transverse momentum $p_T^{J/\psi}$ in the central and forward rapidity regions. The cross section $d\sigma/dp_T^{J/\psi}$ for $|\eta^{J/\psi}| < 0.6$ ($\eta = -\ln[\tan(\theta/2)]$ where θ 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 an excellent agreement with the earlier CDF (6) and DØ (7) results. The cross section $d\sigma/dp_T^{J/\psi}$ for $2.6 < |\eta^{J/\psi}| < 3.4$ covers the $p_T^{J/\psi}$ range from 3 to 12 GeV/c. We combine the measurements in the two $|\eta^{J/\psi}|$ regions to calculate $d\sigma/d\eta^{J/\psi}$ for $p_T^{J/\psi} > 8$ GeV/c. The data are compared with the recent NLO QCD calculations by Mangano et al. (3), which take into account different J/ψ production mechanisms. At the time of the writing, predictions for the forward region include the b quark contribution only. All results presented in this paper are preliminary.

DØ DETECTOR AND DATA SELECTION

The DØ detector (8), shown in Fig.1, 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 θ, 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 (9). The Level Ø 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 beam jet related 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 chambers was imposed. This cut rejected 50% of 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 complete Monte Carlo simulation of the detector and trigger. In addition, for the forward analysis, Monte Carlo dimuon events were mixed with the real minimum bias single interactions events to better simulate background conditions. Efficiency uncertainties were taken

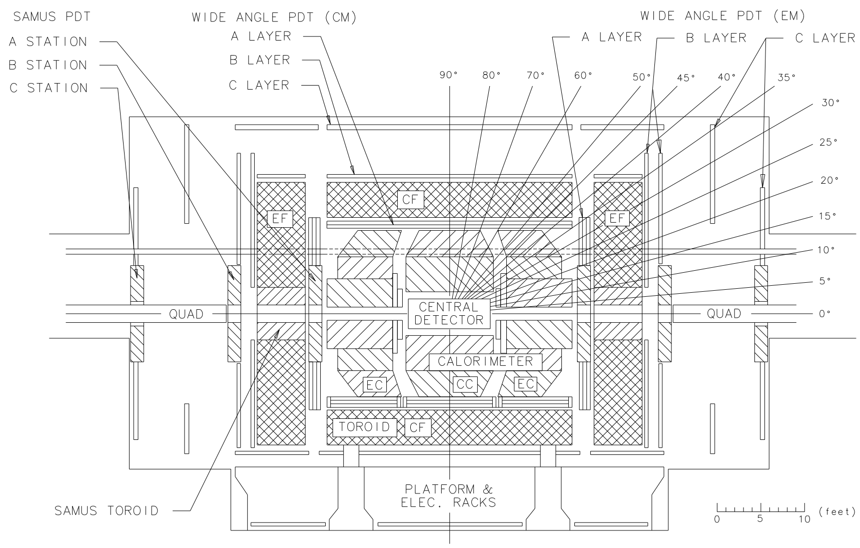

FIG. 1. The layout of the DØ detector

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 reconstructed vertex. At least 1 GeV of energy in the hit calorimeter cells plus their first 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 (out of 6 maximum) in the first layer and 16 hits out of 18 maximum 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 10 GeV/c $< p^\mu <$ 100 GeV/c was imposed to ensure a reliable muon charge determination.

Only a fraction of the total 1994-95 data was used for this analysis. The total number of opposite charge dimuons satisfying the above criteria, in the mass range $0.2 < M^{\mu\mu} < 6$

GeV/c^2, is 1732 and 285 in the central and forward regions, respectively. The corresponding integrated luminosities are 8.6 pb^{-1} and 4.6 pb^{-1}, respectively. An additional dimuon event sample, not discussed before, with one central muon and another muon within the $1.0<\eta^{\mu}<1.7$ pseudorapidity range, has been collected. There are 57 such events corresponding to 4.0 pb^{-1} of the integrated luminosity.

DIMUON MASS SPECTRA

The invariant mass, $M^{\mu\mu}$, distributions for opposite charge dimuons are shown in Figs. 2 and 3 for three different $|\eta^{J/\psi}|$ regions. The mass plots for the central dimuon samples are shown for the $|\eta^{J/\psi}|<0.6$ 1992-93 data (Fig. 2a), the $|\eta^{J/\psi}|<0.6$ 1994-95 data (Fig. 2b) and the recently available $0.7<|\eta^{J/\psi}|<1.2$ 1994-95 data (Fig. 3a). The forward results are shown in Fig. 3b. A clear J/ψ signal is observed in all cases with a mass resolution well represented by a Gaussian function. A fit to a sum of a Monte Carlo-determined mass-resolution function and a linear background, in the mass range 1.6 GeV/c^2 $< M^{\mu\mu} <$ 5 GeV/c^2, yields a total number of 542$\pm$33, 37$\pm$7 and 162$\pm$14 J/ψ events for the WAMUS ($|\eta^{J/\psi}|<0.6$), ($0.7<|\eta^{J/\psi}|<1.2$), and ($2.6<|\eta^{J/\psi}|<3.4$) 1994-95 data samples, respectively. The fits were repeated for the individual dimuon mass spectra corresponding to different kinematic regions ($p_T^{J/\Psi}$ and $\eta^{J/\Psi}$ bins). In Ref. (7) a maximum likelihood fit was performed to extract contribution of various processes to the dimuon mass spectrum for the 1992-93 data sample. A simple fit to the mass distribution, similar to the one described here, gave identical results within 10%.

It was demonstrated in Ref. (7) 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 π or K meson. Other mechanisms that yield opposite sign dimuons are virtual photon decays (10), referred to as the Drell-Yan process, and decays of light quark mesons, such as ρ, ϕ and η. Similar processes, however with different relative rates, are expected to contribute to the forward dimuon spectrum.

We generated two samples of J/ψ Monte Carlo events using the ISAJET program (11). 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. To simulate the direct charmonium production we used a modified version of ISAJET, with the standard hard scattering matrix elements replaced by those of Humpert (12).

Each ISAJET Monte Carlo sample was run through a chain of programs simulating the effects of the detector (13) and trigger response and then processed with the standard offline reconstruction program. The two J/ψ Monte Carlo samples gave consistent results for the J/ψ trigger and reconstruction efficiency as a function of $p_T^{J/\psi}$.

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

The J/ψ transverse momentum distribution resulting from the mass fits in a given $p_T^{J/\Psi}$ bin was then corrected for detector p_T smearing (14) and corrected for acceptance and efficiency. The differential J/ψ production cross section as a function of the J/ψ p_T for the central dimuons is shown in Fig. 4. The data points are shown with the statistical and

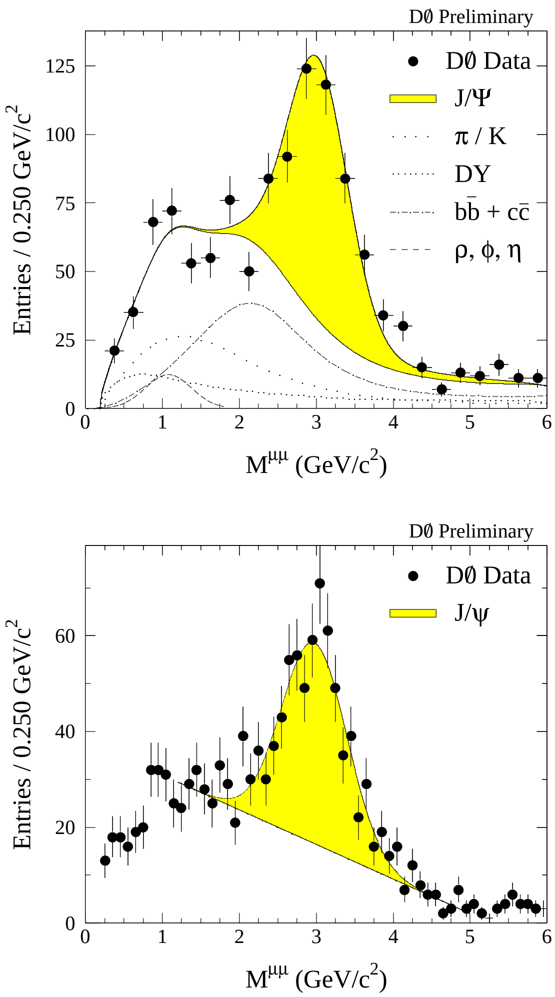

FIG. 2. The dimuon mass distribution in the range $0.2 < M^{\mu\mu} < 6$ GeV/c^2. The hatched area indicates the J/ψ signal on the top of the sum of the background contributions: (a) the 1992-93 data for which a maximum likelihood fit was performed. The background contributions are also shown separately. This data sample corresponds to an integrated luminosity of 6.6 pb^{-1} (7) ; (b) the 1994-95 data for which only a simple fit with a linear background was performed. This data sample corresponds to an integrated luminosity of 8.6 pb^{-1}.

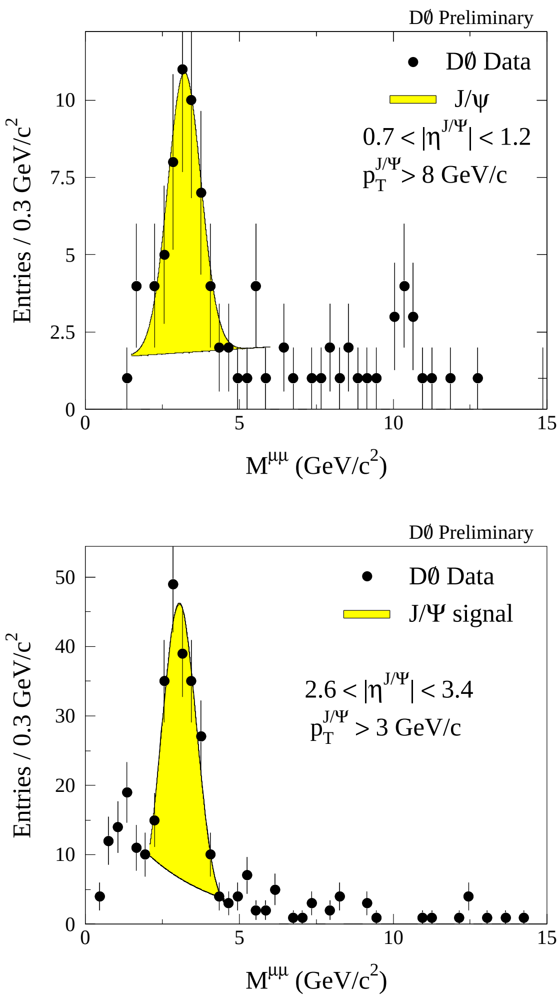

FIG. 3. The invariant mass distribution for opposite sign muon pairs in: (a) the part of the DØ central muon detector corresponding to the $0.7 < |\eta^{\mu\mu}| < 1.2$ range. The solid curve is the fitted sum of the J/ψ signal (hatched area) and background contribution in the mass range $1.6 < M^{\mu\mu} < 5.0$ GeV/c^2. (b) the DØ forward muon detector $2.6 < |\eta^{\mu\mu}| < 3.4$. The solid curve is the fitted sum of the J/ψ signal (hatched area) and background contribution in the mass range $2.1 < M^{\mu\mu} < 4.5$ GeV/c^2.

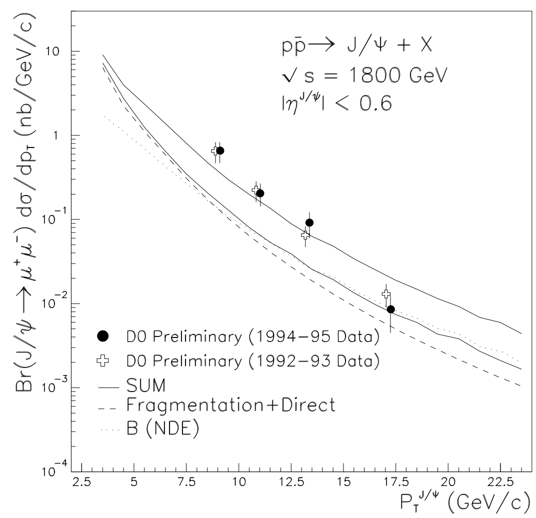

FIG. 4. The J/ψ production cross section $Br \cdot d\sigma/dp_T$ as a function of the J/ψ p_T. The error bars are statistical and systematic added in quadrature. Both 1992-93 and 1994-95 results are shown. The solid curves represent the error band on the sum of the expected contributions.

systematic errors added in quadrature. 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.4. By integrating over all bins we obtain a total cross section of:

$$Br(J/\psi \to \mu^+\mu^-) \cdot \sigma(p\bar{p} \to J/\psi + X) = 1.96 \pm 0.16(\text{stat}) \pm 0.63(\text{syst})\ \text{nb},$$
$$p_T^{J/\psi} > 8.0\ \text{GeV/c} \quad \text{and} \quad |\eta^{J/\psi}| < 0.6$$

The same cross section determined for the 1992-93 sample yielded $1.93 \pm 0.16(\text{stat}) \pm 0.43(\text{syst})$ nb (7). The average of the two measurements gives $1.94 \pm 0.11(\text{stat}) \pm 0.39(\text{syst})$ nb.

After accounting for the contribution due to fragmentation, the theoretical NLO QCD predictions describe our spectrum moderately well, but the data have a steeper slope. This prediction, shown in Fig.4, is based on use of MRSDO structure functions with $\Lambda_5^{\overline{MS}} = 140\ MeV$, and $m_b = 4.75\ GeV/c^2$. The theoretical uncertainty results from choosing $100 < \Lambda_5^{\overline{MS}} < 187\ MeV$, and the factorization-renormalization scale μ in the range $\mu_0/4 < \mu < \mu_0$, where $\mu_0 = \sqrt{m_b^2 + \langle p_T^b \rangle^2}$. The same values of theoretical parameters are used throughout the paper.

It should also be noted that our spectrum agrees closely in normalization and shape with the J/ψ inclusive cross section measured by the CDF collaboration (6).

The differential J/ψ production cross section as a function of $p_T^{J/\psi}$ in the forward region is shown in Fig. 5. By integrating over bins with $p_T^{J/\psi} >$ 8GeV/c we obtain a total cross section of:

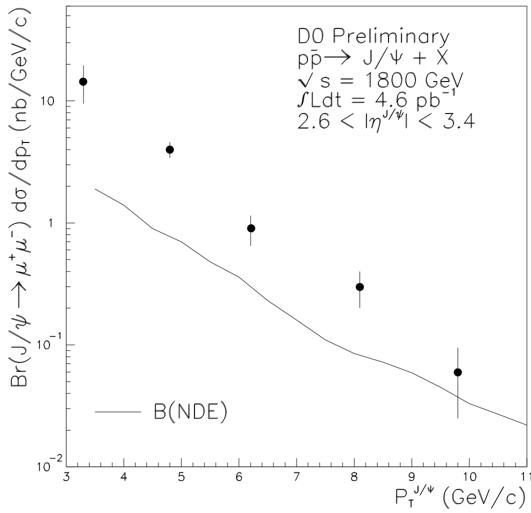

FIG. 5. The J/ψ production cross section $Br \cdot d\sigma/dp_T$ as a function of $p_T^{J/\psi}$. The error bars are statistical only. The solid curve represents the expected contribution from the b quark fragmentation

$$Br(J/\psi \to \mu^+\mu^-) \cdot \sigma(p\bar{p} \to J/\psi + X) = 0.51 \pm 0.08(\mathrm{stat}) \pm 0.10(\mathrm{syst})\ \mathrm{nb},$$
$$p_T^{J/\psi} > 8.0\ \mathrm{GeV/c} \quad \mathrm{and} \quad 2.6 < |\eta^{J/\psi}| < 3.4$$

This is the first measurement of the J/ψ cross section at large $|\eta^{J/\psi}|$. The data are compared with the expected contribution from the b quark fragmentation (3). A less steep dependence of $d\sigma/dp_T^{J/\psi}$ then predicted by the theory might imply that the fraction of J/ψs 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.6, combines data from the central and forward dimuon analyses for $p_T^{J/\psi} > 8$ GeV/c. There are three entries for $|\eta^{J/\psi}| < 0.6$ consistent with no η dependence in that region. On the other hand, the cross section for $2.6 < |\eta^{J/\psi}| < 3.4$ is lower by a factor ~ 5. The predicted b quark contribution to the J/ψ production exhibits similar $|\eta^{J/\psi}|$ dependence. Theoretical predictions for other processes are being calculated.

CONCLUSIONS

We have measured the inclusive J/ψ production cross section as a function of J/ψ transverse momentum $p_T^{J/\psi}$ in the central and forward rapidity regions. The cross section $d\sigma/dp_T^{J/\psi}$ for $|\eta^{J/\psi}| < 0.6$ covers the $p_T^{J/\psi}$ range from 8 to 20 GeV/c. The new measurements are in an excellent agreement with the earlier CDF (6) and DØ (7) results. The cross section $d\sigma/dp_T^{J/\psi}$ for $2.6 < |\eta^{J/\psi}| < 3.4$ covers the $p_T^{J/\psi}$ range from 3 to 12 GeV/c.

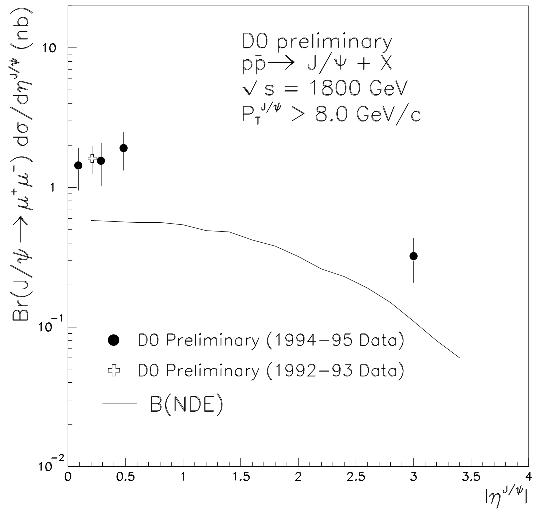

FIG. 6. The J/ψ production cross section $Br \cdot d\sigma/d\eta$ as a function of $\left|\eta^{J/\psi}\right|$ for $p_T^{J/\psi} > 8$ GeV/c. The error bars are statistical and systematic added in quadrature.

We combine the measurements in the two $\left|\eta^{J/\psi}\right|$ regions to calculate $d\sigma/d\eta^{J/\psi}$ for $p_T^{J/\psi} >$ 8 GeV/c.

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[*] Visitor from IHEP, Beijing, China.
[‡] Visitor from CONICET, Argentina.
[§] Visitor from Universidad de Buenos Aires, Argentina.
[¶] Visitor from Univ. San Francisco de Quito, Ecuador.

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