# Study of the Strong Coupling Constant Using $W+$ Jet Processes

S. Abachi,[12] B. Abbott,[34] M. Abolins,[23] B. S. Acharya,[42] I. Adam,[10] D. L. Adams,[35] M. Adams,[15] S. Ahn,[12] H. Aihara,[20] J. Alitti,[38] G. Álvarez,[16] G. A. Alves,[8] E. Amidi,[27] N. Amos,[22] E. W. Anderson,[17] S. H. Aronson,[3] R. Astur,[40] 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,[37] 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,[37] C. Boswell,[7] A. Brandt,[12] R. Brock,[23] A. Bross,[12] D. Buchholz,[29] V. S. Burtovoi,[33] J. M. Butler,[12] W. Carvalho,[8] D. Casey,[37] H. Castilla-Valdez,[9] D. Chakraborty,[40] S.-M. Chang,[27] S. V. Chekulaev,[33] L.-P. Chen,[20] W. Chen,[40] L. Chevalier,[38] S. Chopra,[32] B. C. Choudhary,[7] J. H. Christenson,[12] M. Chung,[15] D. Claes,[40] A. R. Clark,[20] W. G. Cobau,[21] J. Cochran,[7] W. E. Cooper,[12] C. Cretsinger,[37] D. Cullen-Vidal,[4] M. A. C. Cummings,[14] D. Cutts,[4] O. I. Dahl,[20] K. De,[43] 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,[43] J. Drinkard,[6] Y. Ducros,[38] S. R. Dugad,[42] S. Durston-Johnson,[37] D. Edmunds,[23] J. Ellison,[7] V. D. Elvira,[12,*] R. Engelmann,[40] 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,[37] J. Featherly,[3] S. Feher,[40] D. Fein,[2] T. Ferbel,[37] G. Finocchiaro,[40] H. E. Fisk,[12] Y. Fisyak,[5] E. Flattum,[23] G. E. Forden,[2] M. Fortner,[28] K. C. Frame,[23] P. Franzini,[10] S. Fuess,[12] E. Gallas,[43] A. N. Galyaev,[33] S. G. Gao,[12,†] T. L. Geld,[23] R. J. Genik II,[23] K. Genser,[12] C. E. Gerber,[12,‡] B. Gibbard,[3] V. Glebov,[37] S. Glenn,[5] B. Gobbi,[29] M. Goforth,[13] A. Goldschmidt,[20] B. Gómez,[1] P. I. Goncharov,[33] J. L. González Solís,[9] H. Gordon,[3] L. T. Goss,[44] N. Graf,[3] P. D. Grannis,[40] D. R. Green,[12] J. Green,[28] H. Greenlee,[12] G. Griffin,[6] N. Grossman,[12] P. Grudberg,[20] S. Grünendahl,[37] W. X. Gu,[12,†] G. Guglielmo,[31] J. A. Guida,[40] 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,[37] 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] T. Heuring,[13] R. Hirosky,[13] J. D. Hobbs,[12] B. Hoeneisen,[1,§] J. S. Hoftun,[4] F. Hsieh,[22] Tao Hu,[12,†] Ting Hu,[40] 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,[40] T. Joffe-Minor,[29] H. Johari,[27] K. Johns,[2] M. Johnson,[12] H. Johnstad,[41] A. Jonckheere,[12] M. Jones,[14] H. Jöstlein,[12] S. Y. Jun,[29] C. K. Jung,[40] 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,[39] A. Klatchko,[13] B. Klima,[12] B. I. Klochkov,[33] C. Klopfenstein,[5] 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,[42] S. Krzywdzinski,[12] S. Kunori,[21] S. Lami,[40] G. Landsberg,[12] J-F. Lebrat,[38] A. Leflat,[24] H. Li,[40] J. Li,[43] Y. K. Li,[29] Q. Z. Li-Demarteau,[12] J. G. R. Lima,[36] D. Lincoln,[22] S. L. Linn,[13] J. Linnemann,[23] R. Lipton,[12] Y. C. Liu,[29] F. Lobkowicz,[37] S. C. Loken,[20] S. Lökös,[40] 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,[38] S. Mani,[5] B. Mansoulié,[38] H. S. Mao,[12,†] S. Margulies,[15] R. Markeloff,[28] L. Markosky,[2] T. Marshall,[16] M. I. Martin,[12] M. Marx,[40] B. May,[29] A. A. Mayorov,[33] R. McCarthy,[40] T. McKibben,[15] J. McKinley,[23] T. McMahon,[31] H. L. Melanson,[12] J. R. T. de Mello Neto,[36] 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,[40] N. Mokhov,[12] N. K. Mondal,[42] 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,[42] A. Narayanan,[2] H. A. Neal,[22] J. P. Negret,[1] E. Neis,[22] P. Nemethy,[26] D. Nešić,[4] M. Nicola,[8] D. Norman,[44] L. Oesch,[22] V. Oguri,[36] 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,[42] M. Paterno,[37] J. Perkins,[43] A. Peryshkin,[12] M. Peters,[14] H. Piekarz,[13] Y. Pischalnikov,[34] A. Pluquet,[38] 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,[40] O. Ramirez,[15] M. V. S. Rao,[42] P. A. Rapidis,[12] L. Rasmussen,[40] A. L. Read,[12] S. Reucroft,[27] M. Rijssenbeek,[40] T. Rockwell,[23] N. A. Roe,[20] P. Rubinov,[40] R. Ruchti,[30] S. Rusin,[24] J. Rutherfoord,[2] A. Santoro,[8] L. Sawyer,[43] R. D. Schamberger,[40] H. Schellman,[29] J. Sculli,[26] E. Shabalina,[24] C. Shaffer,[13] H. C. Shankar,[42] Y. Y. Shao,[12,†] 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,[40] J. Solomon,[15] P. M. Sood,[32] M. Sosebee,[43] M. Souza,[8] A. L. Spadafora,[20] R. W. Stephens,[43] M. L. Stevenson,[20] D. Stewart,[22] D. A. Stoianova,[33] D. Stoker,[6] K. Streets,[26] M. Strovink,[20] A. Sznajder,[8] A. Taketani,[12] P. Tamburello,[21] J. Tarazi,[6] M. Tartaglia,[12] T. L. Taylor,[29] J. Teiger,[38] 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]

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A. P. Vorobiev,[33] H. D. Wahl,[13] G. Wang,[13] J. Wang,[12,†] J. Warchol,[30] M. Wayne,[30] H. Weerts,[23] F. Wen,[13] W. A. Wenzel,[20] A. White,[43] J. T. White,[44] J. A. Wightman,[17] J. Wilcox,[27] S. Willis,[28] S. J. Wimpenny,[7] J. V. D. Wirjawan,[44] J. Womersley,[12] E. Won,[37] D. R. Wood,[12] H. Xu,[4] R. Yamada,[12] P. Yamin,[3] C. Yanagisawa,[40] J. Yang,[26] T. Yasuda,[27] C. Yoshikawa,[14] S. Youssef,[13] J. Yu,[37] Y. Yu,[39] D. H. Zhang,[12,†] Y. Zhang,[12,†] Q. Zhu,[26] Z. H. Zhu,[37] D. Zieminska,[16] A. Zieminski,[16] and A. Zylberstejn[38]

(D0 Collaboration)

[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]*Centro de Investigación y de Estudios Avanzados, 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 73109*
[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]*Universidade Estadual do Rio de Janeiro, Rio de Janeiro, Brazil*
[37]*University of Rochester, Rochester, New York 14627*
[38]*Commissariat à l'Energie Atomique, DAPNIA/Service de Physique des Particules, Centre d'Etudes de Saclay, Saclay, France*
[39]*Seoul National University, Seoul, Korea*
[40]*State University of New York, Stony Brook, New York 11794*
[41]*Superconducting Super Collider Laboratory, Dallas, Texas 75237*
[42]*Tata Institute of Fundamental Research, Colaba, Bombay 400005, India*
[43]*University of Texas, Arlington, Texas 76019*
[44]*Texas A&M University, College Station, Texas 77843*

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The ratio of the number of $W + 1$ jet to $W + 0$ jet events is measured with the D0 detector using data from the 1992–93 Tevatron Collider run. For the $W \rightarrow e\nu$ channel with a minimum jet $E_T$ cutoff of 25 GeV, the experimental ratio is $0.065 \pm 0.003(\text{stat}) \pm 0.007(\text{syst})$. Next-to-leading order QCD predictions for various parton distributions agree well with each other and are all over 1 standard deviation below the measurement. Varying the strong coupling constant $\alpha_s$ in both the parton distributions and the partonic cross sections simultaneously does not remove this discrepancy.

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The running coupling constant $\alpha_s$ is a fundamental expansion parameter which sets the strength of all strong interactions. Of particular interest in the current study is the fact that the probability of producing jets in association with a $W$ boson is dependent upon the value of $\alpha_s$. We report here the results of an attempt to extract the value of $\alpha_s$ from an examination of the ratio $\mathcal{R}$ of $W + 1$ jet to $W + 0$ jet cross sections. A similar technique, based on tree-level calculations, has been used by the UA2 [1] and UA1 experiments [2].

In leading-order (LO) QCD, $\mathcal{R}$ is proportional to $\alpha_s$. However, the cross sections computed at LO suffer from relatively large normalization uncertainties due to the lack of higher order corrections. Recent next-to-leading order (NLO) predictions [3] of the $W + 0$ jet and $W + 1$ jet cross sections show significantly reduced $\mu_R$ dependence and differ from LO predictions by about 10% for $\mu_R$ equal to the $W$ mass ($M_W$) [4].

We present an experimental measurement of the ratio, $\mathcal{R}_{\text{meas}}$, using the D0 detector at the Fermilab Tevatron $\bar{p}p$ Collider at $\sqrt{s} = 1.8$ TeV. We utilize 9770 $W \rightarrow e\nu$ candidates collected during the 1992–93 collider run. The experimental result $\mathcal{R}_{\text{meas}}$ is compared with NLO theoretical predictions [5].

The D0 detector is described in detail elsewhere [6]. The detector elements relevant to this analysis are the tracking system and the uranium liquid-argon sampling calorimeter. The tracking system, which has no magnetic field, covers a range of pseudorapidity $\eta$ [7] from $-3.0$ to 3.0. The calorimeter's homogeneous response and hermetic coverage out to $|\eta| \sim 4$ provide excellent measurement of electron and jet energies, as well as missing transverse energy ($\not\!\!E_T$), over the full azimuth ($\phi$). The calorimeter is finely segmented in both the longitudinal and transverse directions, giving enhanced electron identification. The electron energy resolution is $15\%/\sqrt{E(\text{GeV})}$ and the jet transverse energy ($E_T$) resolution is $\sim 80\%/\sqrt{E_T(\text{GeV})}$.

For this analysis, we use a hardware trigger which requires events with a minimum $E_T$ of 10 GeV in an electromagnetic (EM) calorimeter trigger tower of size $0.2 \times 0.2$ in $\eta$-$\phi$ space, covering $|\eta| < 3.2$. Events satisfying the hardware trigger are subjected to a software trigger which requires the event to have $\not\!\!E_T > 20$ GeV and to have an electron candidate which has transverse energy ($E_T^e$) greater than 20 GeV and passes preliminary shower shape and isolation cuts.

The off-line selection of the $W \rightarrow e\nu$ event sample requires $\not\!\!E_T > 25$ GeV and an electron with $E_T^e > 25$ GeV which satisfies three electron quality criteria. The first involves the isolation fraction which is defined as $f_{\text{iso}} = [E(0.4) - E_{\text{EM}}(0.2)]/E_{\text{EM}}(0.2)$, where $E(0.4)$ is the total energy within a cone of radius 0.4 [$\Delta R \equiv \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$] centered around the electron, and $E_{\text{EM}}(0.2)$ is the electromagnetic energy within $\Delta R = 0.2$. A cut of $f_{\text{iso}} < 0.15$ is imposed to require that the electron is isolated from other sources of energy in the event. The second criterion is that the calorimeter energy deposition of the electron has a matching charged track. Finally, a cut is imposed on the $\chi^2$ value of the energy cluster to ensure that its shape is consistent with that of an electron. This value of $\chi^2$ is computed using a 41 dimensional energy covariance matrix [8], which has the mean cell energy depositions of a reference electron shower as its elements, preserving their correlations.

Given the nature of $\mathcal{R}_{\text{meas}}$, it is advantageous, in minimizing systematic uncertainties, to have the electron selection efficiency be the same for events with and without an associated jet. The electron selection criteria applied to the $W \rightarrow e\nu$ candidates preclude the use of this data sample for estimating the selection efficiency because the only electron in the event is already subjected to the selection criteria. Therefore, we use $Z(\rightarrow e^+e^-) + 0$ jet and $Z + 1$ jet candidates from actual data, where only one of the two electrons is required to pass the selection criteria. The electron selection efficiency is then measured by imposing the selection criteria on the other electron. From this study, the electron selection efficiency is found to be the same for these jet multiplicities (0 jet and 1 jet) to within 2%.

Jets in the events are identified with a fixed cone algorithm using a radius $\Delta R = 0.7$. The jet reconstruction efficiency is found to be better than 99% for jets with $E_T > 20$ GeV, based on a Monte Carlo study [9]. The jet $E_T$ is corrected for the calorimeter response, out-of-cone showering, and the underlying event contribution. The jet energy scale correction [10] is obtained by using events with photon + jet final states. In these events, the photon candidate is taken to balance the remaining partons in the event kinematically. The components of the transverse momentum imbalance due to the mismeasurement in hadronic jet energy are then corrected using the $\not\!\!E_T$ projection on the photon candidate axis. The typical size of the correction is $(16 \pm 5)\%$ at 25 GeV and $(24 \pm 5)\%$ at 100 GeV. The jets are required to have a minimum transverse energy ($E_T^{\text{min}}$) of 25 GeV. Before background subtraction, 5736 $W + 0$ jet events have the electron in the central region ($|\eta_e| < 1.2$) and 3083 events have the electron in the forward region ($|\eta_e| > 1.2$). The corresponding numbers of events with one jet are 511 and 284 events, respectively.

The largest background to the $W \rightarrow e\nu$ production comes from multijet processes. A jet from a multijet event may pass all electron selection criteria due to fluctuations in fragmentation. Significant $\not\!\!E_T$ may also be associated with multijet events due to shower fluctuations or calorimeter imperfections. Occasionally a multijet event has both significant $\not\!\!E_T$ and a jet imitating an electron and thereby simulates a $W \rightarrow e\nu$ event.

The fractional background from multijet events is estimated using the $\not\!\!E_T$ distributions from data for events that pass an inclusive electron trigger ($E_T^e > 20$ GeV).

The sample is separated into two subsets. The first subset consists of events failing all three of the electron quality criteria ($f_{\rm iso}$, track matching, and $\chi^2$). Real electrons from $W$ decays contribute negligibly to this subset. The second subset consists of events which pass the three electron quality criteria. This subset includes both backgrounds from multijet events and real $W$ events. The histogram in Fig. 1 represents the $\not\!\!E_T$ distribution of events with electrons satisfying the three electron quality criteria (signal + background) and the solid circles represent the other subset (background). A clear separation between signal and background above $\not\!\!E_T = 20$ GeV is evident because the $\not\!\!E_T$ due to the neutrino in $W$ decay peaks near 40 GeV and far less $\not\!\!E_T$ is expected in true multijet events. The shapes of the two distributions agree well for $\not\!\!E_T < 15$ GeV. The background distribution for $\not\!\!E_T > 25$ GeV is used to estimate the contamination of the $W$ sample from multijet processes.

For events with an electron in the central region, the background is 3.0% ± 0.6%(stat + syst) for $W$ + 0 and (19.3 ± 4.3)% for $W$ + 1 jet events. The background for events with an electron in the forward region is (13.3 ± 1.6)% for $W$ + 0 jet and (52.6 ± 5.2)% for $W$ + 1 jet events. The uncertainties reflect systematic and statistical errors added in quadrature. The statistical uncertainty is the dominant source of error in estimating the background.

Additional sources of background to $W \to e\nu$ production are from electroweak processes which either are improperly identified in the detector or have a signature identical to that of $W \to e\nu$ production. The electroweak processes we considered are $Z \to e^+e^-$ and $q\bar{q} \to \gamma^* \to e^+e^-$ where one of the electrons is lost, and $Z \to \tau^+\tau^-$ where one of the $\tau$'s decays to $e\nu\bar{\nu}$ and the other decays hadronically. We use Monte Carlo event samples to estimate the background contamination from these sources and find the level of contamination to be less than 3% of the signal for both $W$ + 0 jet and $W$ + 1 jet events. The process $W \to \tau\nu$ (where $\tau \to e\nu\bar{\nu}$) is considered as part of the signal because the associated jet production is independent of the $W$ decay mode.

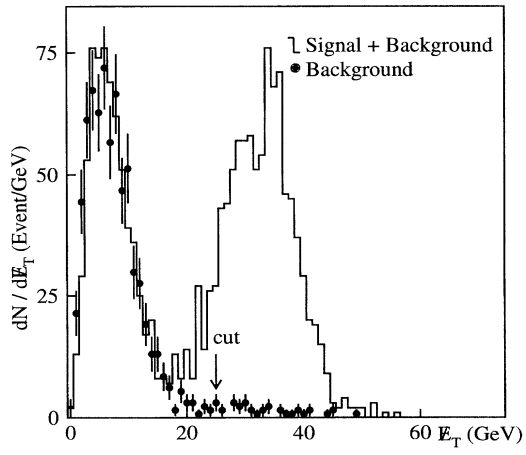


FIG. 1. $\not\!\!E_T$ distributions for $W$ + 0 jet events with the electron in the central region, $|\eta_e| < 1.2$. The histogram represents the signal plus background and solid circles indicate the background. The two distributions are normalized using the number of events in the region $\not\!\!E_T < 15$ GeV. The error bars represent statistical errors only.

The number of $W$ + 0 jet events, after subtracting backgrounds from multijet and electroweak processes, is 8200 ± 94(stat) ± 61(syst), and the number of $W$ + 1 jet events is 532 ± 28(stat) ± 49(syst). The resulting experimental ratio of the number of $W$ + 1 jet events to $W$ + 0 jet events is $\mathcal{R}_{\rm exp} = 0.065 \pm 0.003(\text{stat}) \pm 0.007(\text{syst})$. The dominant systematic error is from the jet energy scale uncertainty. This is due to the rapidly falling shape of the jet $E_T$ spectrum and the resulting sensitivity to the $E_T^{\rm min}$ cutoff. This systematic error is obtained by repeating the complete analysis, varying the jet energy scale correction within errors.

The NLO QCD predictions [3] for $W$ + 0 jet and $W$ + 1 jet cross sections enable parametrizations of each cross section as a power series in $\alpha_s$. The theoretical predictions, using the minimal subtraction ($\overline{\rm MS}$) scheme, take into account the effect of experimental jet energy resolution, as well as the impact of the lepton isolation criteria and other experimental constraints. The cross section for $W$ + $n$ jets is parametrized as $\sigma_{W+n\,\rm jet} = \alpha_s^n(A_n + \alpha_s B_n)$ for $n = 0$ or 1. The coefficients $A_1$ and $B_0$ depend on $E_T^{\rm min}$ of the jet and $B_1$ depends on $E_T^{\rm min}$, the choice of jet cone radius $\Delta R$, and $\mu_R$. The coefficients are computed for a given parton distribution function (PDF) evolved to the scale $M_W$. The evolution is carried out using the value for $\Lambda_{\rm QCD}$ associated with each PDF. This $\Lambda_{\rm QCD}$ value corresponds to a value of $\alpha_s$, calculated at the scale $M_W$ using the second order expression for the running coupling constant and is labeled as $\alpha_s^{\rm PDF}(M_W)$ in Table I. The prediction for the ratio is referred to as $\mathcal{R}_{\rm pred}$.

Figure 2 shows $\mathcal{R}_{\rm meas}$ with its uncertainty given by the shaded area and three open symbols representing $\mathcal{R}_{\rm pred}$ for various PDF's [11–14] at $\alpha_s = \alpha_s^{\rm PDF}(M_W)$. The $\mathcal{R}_{\rm pred}$ for all PDF's considered [11–15] are given in Table I. The error for each prediction reflects only the statistics used in the Monte Carlo calculation. We do not assign an uncertainty due to the choice of $\mu_R$ because the variation in the $W$ + 1 jet cross section is less than 2% for $M_W/2 < \mu_R < 3M_W$ [3,16]. The dependence of $\mathcal{R}_{\rm pred}$ and $\mathcal{R}_{\rm meas}$ on $E_T^{\rm min}$ has been studied in the range $25 < E_T^{\rm min} < 60$ GeV [5] and the relationship between data and theory does not change in this region of $E_T^{\rm min}$. All theory predictions are consistent with each other and are below the data by over 1 standard deviation.

The dashed line in Fig. 2 represents the predicted ratio, as a function of $\alpha_s$, for the CTEQ3M [15] parton distributions if the strong coupling constant is varied only

TABLE I. Values of $\alpha_s$ for various parton distributions [11–15].

| PDF | $\alpha_s^{\mathrm{PDF}}(M_W)$ | $\mathcal{R}_{\mathrm{pred}} \pm \Delta\mathcal{R}_{\mathrm{pred}}$ | $\alpha_s^{\mathrm{ME}}(M_W) \pm \Delta\alpha_s^{\mathrm{ME}}$ |
|---|---|---|---|
| CTEQ2M | 0.112 | 0.053 ± 0.001 | 0.134 ± 0.016 |
| CTEQ2ML | 0.119 | 0.055 ± 0.001 | 0.139 ± 0.017 |
| CTEQ3M | 0.114 | 0.053 ± 0.001 | 0.139 ± 0.017 |
| MRS($D_0'$) | 0.113 | 0.056 ± 0.001 | 0.129 ± 0.015 |
| MRS($D_-'$) | 0.113 | 0.053 ± 0.001 | 0.136 ± 0.016 |
| MRS($A'$) | 0.114 | 0.054 ± 0.001 | 0.134 ± 0.016 |
| GRV94 | 0.111 | 0.055 ± 0.001 | 0.129 ± 0.015 |

in the hard partonic cross section (ME), leaving $\alpha_s$ in the parton distributions fixed at $\alpha_s^{\mathrm{PDF}}$. Lines with practically identical slopes are obtained for the other parton distributions but are not shown. The intercept of $\mathcal{R}_{\mathrm{meas}}$ with this line yields a value of $\alpha_s$ ($\alpha_s^{\mathrm{ME}}$) to NLO for a particular PDF. Table I summarizes the values of $\alpha_s^{\mathrm{ME}}$, at $\mu_R = M_W$, for various PDF's along with the uncertainties. The different sources contributing to the uncertainty are summarized in Table II for the CTEQ2M parton distribution. The error $\Delta\alpha_s^{\mathrm{ME}}$ in Table I is the quadratic sum of all these uncertainties. As expected, because all predictions are below the data, each PDF prefers a value of $\alpha_s^{\mathrm{ME}} > \alpha_s^{\mathrm{PDF}}$ by just over 1 standard deviation.

To determine the running coupling constant in a fully consistent manner, $\alpha_s$ should be varied simultaneously in both the PDF and ME. For each of CTEQ3M [11], MRS($A'$) [12], and GRV94 [13] distributions, we have obtained a family of new PDF's corresponding to a range

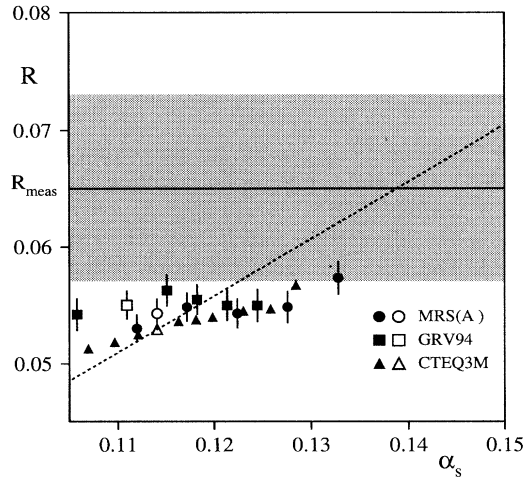


FIG. 2. $\mathcal{R}$ vs $\alpha_s$ for CTEQ3M, MRS($A'$), and GRV94 PDF's fitted with various values of $\alpha_s^{\mathrm{PDF}}$. The symbols represent $\mathcal{R}_{\mathrm{pred}}$ at $\alpha_s^{\mathrm{PDF}}$ for each PDF. The dashed line is the prediction for CTEQ3M PDF when $\alpha_s$ is varied only in the partonic cross section.

of $\alpha_s^{\mathrm{PDF}}$ values, based upon the same data sets as for the standard PDF's. The family of $\mathcal{R}$ vs $\alpha_s$ then calculated is shown for each PDF family as the closed symbols in Fig. 2. Statistical errors from the Monte Carlo calculation are shown for the MRS and GRV families. For the CTEQ family, the individual points are correlated due to the choice of identical random number seeds and thus have negligible relative errors. The variation of $\mathcal{R}_{\mathrm{pred}}$ with $\alpha_s$ for each of these families is quite weak and remains over 1 standard deviation below $\mathcal{R}_{\mathrm{meas}}$ for all reasonable values of $\alpha_s$.

A similar study was made by the UA2 Collaboration [1] at $\sqrt{s} = 630$ GeV using $\mathcal{O}(\alpha_s^2)$ tree-level QCD calculations. Allowing $\alpha_s$ to vary in PDF's and ME resulted in a larger slope in $\mathcal{R}$ vs $\alpha_s$ than we observe at $\sqrt{s} = 1800$ GeV. We have verified that our calculation reproduces the lower energy result and conclude that the major difference derives from the lower parton momentum fraction $x$ values probed at the higher energy. As $\alpha_s$ is increased, the contribution to $\mathcal{R}$ from the ME dependence increases but is compensated by the reduction in $\mathcal{R}$ due to the decrease in the gluon density at the relevant $x$ ($\sim$0.05) and consequent reduction in the $W + 1$ jet cross section. We conclude that the existing QCD calculations cannot be brought into agreement with the measured $\mathcal{R}_{\mathrm{meas}}$ value, though at present the discrepancy [17] is just over 1 standard deviation.

TABLE II. Summary of uncertainties in $\alpha_s^{\mathrm{ME}}$ for the CTEQ2M parton distribution.

| Source | $\alpha_s^{\mathrm{ME}}$ |
|---|---|
| Experimental statistics | 0.005 |
| Jet energy scale correction | 0.013 |
| Jet reconstructuion efficiency | 0.002 |
| Jet energy resolution | 0.005 |
| Monte Carlo statistics | 0.005 |
| Total $\Delta\alpha_s^{\mathrm{ME}}$ | 0.016 |

In summary, we have measured the ratio of $W$ + 1 jet and $W$ + 0 jet cross sections at the Fermilab Tevatron with an accuracy of about 10%. All NLO QCD predictions, using PDF's determined mainly from fits to low energy data, are below our data by over 1 standard deviation. When this measurement is used to extract a value for the strong coupling constant, we find that, after variation of $\alpha_s$ in PDF's is taken into account, the sensitivity to $\alpha_s$ is greatly reduced and an extraction of $\alpha_s$ is not possible.

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

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