Evidence for W^+W^- Production in $\overline{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV

F. Abe,[16] H. Akimoto,[35] A. Akopian,[30] M. G. Albrow,[7] S. R. Amendolia,[26] D. Amidei,[19] J. Antos,[32] S. Aota,[35] G. Apollinari,[30] T. Asakawa,[35] W. Ashmanskas,[17] M. Atac,[7] F. Azfar,[25] P. Azzi-Bacchetta,[24] N. Bacchetta,[24] W. Badgett,[19] S. Bagdasarov,[30] M. W. Bailey,[21] J. Bao,[38] P. de Barbaro,[29] A. Barbaro-Galtieri,[17] V. E. Barnes,[28] B. A. Barnett,[15] M. Barone,[9] E. Barzi,[9] G. Bauer,[18] T. Baumann,[11] F. Bedeschi,[26] S. Behrends,[3] S. Belforte,[26] G. Bellettini,[26] J. Bellinger,[37] D. Benjamin,[34] J. Benlloch,[18] J. Bensinger,[3] D. Benton,[25] A. Beretvas,[7] J. P. Berge,[7] J. Berryhill,[5] S. Bertolucci,[9] B. Bevensee,[25] A. Bhatti,[30] K. Biery,[7] M. Binkley,[7] D. Bisello,[24] R. E. Blair,[1] C. Blocker,[3] A. Bodek,[29] W. Bokhari,[18] V. Bolognesi,[2] G. Bolla,[24] D. Bortoletto,[28] J. Boudreau,[27] L. Breccia,[2] C. Bromberg,[20] N. Bruner,[21] E. Buckley-Geer,[7] H. S. Budd,[29] K. Burkett,[19] G. Busetto,[24] A. Byon-Wagner,[7] K. L. Byrum,[1] J. Cammerata,[15] C. Campagnari,[7] M. Campbell,[19] A. Caner,[26] W. Carithers,[17] D. Carlsmith,[37] A. Castro,[24] D. Cauz,[26] Y. Cen,[29] F. Cervelli,[26] P. S. Chang,[32] P. T. Chang,[32] H. Y. Chao,[32] J. Chapman,[19] M.-T. Cheng,[32] G. Chiarelli,[26] T. Chikamatsu,[35] C. N. Chiou,[32] L. Christofek,[13] S. Cihangir,[7] A. G. Clark,[10] M. Cobal,[26] E. Cocca,[26] M. Contreras,[5] J. Conway,[31] J. Cooper,[7] M. Cordelli,[9] C. Couyoumtzelis,[10] D. Crane,[1] D. Cronin-Hennessy,[6] R. Culbertson,[5] T. Daniels,[18] F. DeJongh,[7] S. Delchamps,[7] S. Dell'Agnello,[26] M. Dell'Orso,[26] R. Demina,[7] L. Demortier,[30] M. Deninno,[2] P. F. Derwent,[7] T. Devlin,[31] J. R. Dittmann,[6] S. Donati,[26] J. Done,[33] T. Dorigo,[24] A. Dunn,[19] N. Eddy,[19] K. Einsweiler,[17] J. E. Elias,[7] R. Ely,[17] E. Engels, Jr.,[27] D. Errede,[13] S. Errede,[13] Q. Fan,[29] G. Feild,[38] C. Ferretti,[26] I. Fiori,[2] B. Flaugher,[7] G. W. Foster,[7] M. Franklin,[11] M. Frautschi,[34] J. Freeman,[7] J. Friedman,[18] H. Frisch,[5] Y. Fukui,[16] S. Funaki,[35] S. Galeotti,[26] M. Gallinaro,[24] O. Ganel,[34] M. Garcia-Sciveres,[17] A. F. Garfinkel,[28] C. Gay,[11] S. Geer,[7] D. W. Gerdes,[15] P. Giannetti,[26] N. Giokaris,[30] P. Giromini,[9] G. Giusti,[26] L. Gladney,[25] D. Glenzinski,[15] M. Gold,[21] J. Gonzalez,[25] A. Gordon,[11] A. T. Goshaw,[6] Y. Gotra,[24] K. Goulianos,[30] H. Grassmann,[26] L. Groer,[31] C. Grosso-Pilcher,[5] G. Guillian,[19] R. S. Guo,[32] C. Haber,[17] E. Hafen,[18] S. R. Hahn,[7] R. Hamilton,[11] R. Handler,[37] R. M. Hans,[38] F. Happacher,[9] K. Hara,[35] A. D. Hardman,[28] B. Harral,[25] R. M. Harris,[7] S. A. Hauger,[6] J. Hauser,[4] C. Hawk,[31] E. Hayashi,[35] J. Heinrich,[25] K. D. Hoffman,[28] M. Hohlmann,[5] C. Holck,[25] R. Hollebeek,[25] L. Holloway,[13] A. Hölscher,[14] S. Hong,[19] G. Houk,[25] P. Hu,[27] B. T. Huffman,[27] R. Hughes,[22] J. Huston,[20] J. Huth,[11] J. Hylen,[7] H. Ikeda,[35] M. Incagli,[26] J. Incandela,[7] G. Introzzi,[26] J. Iwai,[35] Y. Iwata,[12] H. Jensen,[7] U. Joshi,[7] R. W. Kadel,[17] E. Kajfasz,[24] H. Kambara,[10] T. Kamon,[33] T. Kaneko,[35] K. Karr,[36] H. Kasha,[38] Y. Kato,[23] T. A. Keaffaber,[28] L. Keeble,[9] K. Kelley,[18] R. D. Kennedy,[7] R. Kephart,[7] P. Kesten,[17] D. Kestenbaum,[11] R. M. Keup,[13] H. Keutelian,[7] F. Keyvan,[4] B. Kharadia,[13] B. J. Kim,[29] D. H. Kim,[7,*] H. S. Kim,[14] S. B. Kim,[19] S. H. Kim,[35] Y. K. Kim,[17] L. Kirsch,[3] P. Koehn,[29] K. Kondo,[35] J. Konigsberg,[8] S. Kopp,[8] K. Kordas,[14] A. Korytov,[8] W. Koska,[7] E. Kovacs,[7,*] W. Kowald,[6] M. Krasberg,[19] J. Kroll,[7] M. Kruse,[29] T. Kuwabara,[35] S. E. Kuhlmann,[1] E. Kuns,[31] A. T. Laasanen,[28] S. Lami,[26] S. Lammel,[7] J. I. Lamoureux,[3] T. LeCompte,[1] S. Leone,[26] J. D. Lewis,[7] P. Limon,[7] M. Lindgren,[4] T. M. Liss,[13] N. Lockyer,[25] O. Long,[25] C. Loomis,[31] M. Loreti,[24] J. Lu,[33] D. Lucchesi,[26] P. Lukens,[7] S. Lusin,[37] J. Lys,[17] K. Maeshima,[7] A. Maghakian,[30] P. Maksimovic,[18] M. Mangano,[26] J. Mansour,[20] M. Mariotti,[24] J. P. Marriner,[7] A. Martin,[38] J. A. J. Matthews,[21] R. Mattingly,[18] P. McIntyre,[33] P. Melese,[30] A. Menzione,[26] E. Meschi,[26] S. Metzler,[25] C. Miao,[19] T. Miao,[7] G. Michail,[11] R. Miller,[20] H. Minato,[35] S. Miscetti,[9] M. Mishina,[16] H. Mitsushio,[35] T. Miyamoto,[35] S. Miyashita,[35] N. Moggi,[26] Y. Morita,[16] J. Mueller,[27] A. Mukherjee,[7] T. Muller,[4] P. Murat,[26] H. Nakada,[35] I. Nakano,[35] C. Nelson,[7] D. Neuberger,[4] C. Newman-Holmes,[7] C.-Y. Ngan,[18] M. Ninomiya,[35] L. Nodulman,[1] S. H. Oh,[6] K. E. Ohl,[38] T. Ohmoto,[12] T. Ohsugi,[12] R. Oishi,[35] M. Okabe,[35] T. Okusawa,[23] R. Oliveira,[25] J. Olsen,[37] C. Pagliarone,[2] R. Paoletti,[26] V. Papadimitriou,[34] S. P. Pappas,[38] N. Parashar,[26] S. Park,[7] A. Parri,[9] J. Patrick,[7] G. Pauletta,[26] M. Paulini,[17] A. Perazzo,[26] L. Pescara,[24] M. D. Peters,[17] T. J. Phillips,[6] G. Piacentino,[2] M. Pillai,[29] K. T. Pitts,[7] R. Plunkett,[7] L. Pondrom,[37] J. Proudfoot,[1] F. Ptohos,[11] G. Punzi,[26] K. Ragan,[14] D. Reher,[17] A. Ribon,[24] F. Rimondi,[2] L. Ristori,[26] W. J. Robertson,[6] T. Rodrigo,[26] S. Rolli,[26] J. Romano,[5] L. Rosenson,[18] R. Roser,[13] W. K. Sakumoto,[29] D. Saltzberg,[5] A. Sansoni,[9] L. Santi,[26] H. Sato,[35] P. Schlabach,[7] E. E. Schmidt,[7] M. P. Schmidt,[38] A. Scribano,[26] S. Segler,[7] S. Seidel,[21] Y. Seiya,[35] G. Sganos,[14] M. D. Shapiro,[17] N. M. Shaw,[28] Q. Shen,[28] P. F. Shepard,[27] M. Shimojima,[35] M. Shochet,[5] J. Siegrist,[17] A. Sill,[34] P. Sinervo,[14] P. Singh,[27] J. Skarha,[15] K. Sliwa,[36] F. D. Snider,[15] T. Song,[19] J. Spalding,[7] T. Speer,[10] P. Sphicas,[18] F. Spinella,[26] M. Spiropulu,[11] L. Spiegel,[7] L. Stanco,[24] J. Steele,[37] A. Stefanini,[26] K. Strahl,[14] J. Strait,[7] R. Ströhmer,[7,*] D. Stuart,[7] G. Sullivan,[5] A. Soumarokov,[32] K. Sumorok,[18] J. Suzuki,[35] T. Takada,[35] T. Takahashi,[23] T. Takano,[35] K. Takikawa,[35] N. Tamura,[12] B. Tannenbaum,[21] F. Tartarelli,[26] W. Taylor,[14] P. K. Teng,[32] Y. Teramoto,[23] S. Tether,[18] D. Theriot,[7] T. L. Thomas,[21]

 0031-9007/97/78(24)/4536(5)$10.00

R. Thun,[19] M. Timko,[36] P. Tipton,[29] A. Titov,[30] S. Tkaczyk,[7] D. Toback,[5] K. Tollefson,[29] A. Tollestrup,[7] H. Toyoda,[23] W. Trischuk,[14] J. F. de Troconiz,[11] S. Truitt,[19] J. Tseng,[18] N. Turini,[26] T. Uchida,[35] N. Uemura,[35] F. Ukegawa,[25] G. Unal,[25] J. Valls,[7,*] S. C. van den Brink,[27] S. Vejcik III,[19] G. Velev,[26] R. Vidal,[7] M. Vondracek,[13] D. Vucinic,[18] R. G. Wagner,[1] R. L. Wagner,[7] J. Wahl,[5] N. B. Wallace,[26] A. M. Walsh,[31] C. Wang,[6] C. H. Wang,[32] J. Wang,[5] M. J. Wang,[32] Q. F. Wang,[30] A. Warburton,[14] T. Watts,[31] R. Webb,[33] C. Wei,[6] C. Wendt,[37] H. Wenzel,[17] W. C. Wester III,[7] A. B. Wicklund,[1] E. Wicklund,[7] R. Wilkinson,[25] H. H. Williams,[25] P. Wilson,[5] B. L. Winer,[22] D. Winn,[19] D. Wolinski,[19] J. Wolinski,[20] S. Worm,[21] X. Wu,[10] J. Wyss,[24] A. Yagil,[7] W. Yao,[17] K. Yasuoka,[35] Y. Ye,[14] G. P. Yeh,[7] P. Yeh,[32] M. Yin,[6] J. Yoh,[7] C. Yosef,[20] T. Yoshida,[23] D. Yovanovitch,[7] I. Yu,[7] L. Yu,[21] J. C. Yun,[7] A. Zanetti,[26] F. Zetti,[26] L. Zhang,[37] W. Zhang,[25] and S. Zucchelli[2]

(CDF Collaboration)

[1]*Argonne National Laboratory, Argonne, Illinois 60439*
[2]*Istituto Nazionale di Fisica Nucleare, University of Bologna, I-40127 Bologna, Italy*
[3]*Brandeis University, Waltham, Massachusetts 02264*
[4]*University of California at Los Angeles, Los Angeles, California 90024*
[5]*University of Chicago, Chicago, Illinois 60638*
[6]*Duke University, Durham, North Carolina 28708*
[7]*Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[8]*University of Florida, Gainesville, Florida 33611*
[9]*Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*
[10]*University of Geneva, CH-1211 Geneva 4, Switzerland*
[11]*Harvard University, Cambridge, Massachusetts 02138*
[12]*Hiroshima University, Higashi-Hiroshima 724, Japan*
[13]*University of Illinois, Urbana, Illinois 61801*
[14]*Institute of Particle Physics, McGill University, Montreal, Canada H3A 2T8, and University of Toronto, Toronto, Canada M5S 1A7*
[15]*The Johns Hopkins University, Baltimore, Maryland 21218*
[16]*National Laboratory for High Energy Physics (KEK), Tsukuba, Ibaraki 315, Japan*
[17]*Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720*
[18]*Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*
[19]*University of Michigan, Ann Arbor, Michigan 48109*
[20]*Michigan State University, East Lansing, Michigan 48824*
[21]*University of New Mexico, Albuquerque, New Mexico 87132*
[22]*The Ohio State University, Columbus, Ohio 43320*
[23]*Osaka City University, Osaka 588, Japan*
[24]*Istituto Nazionale di Fisica Nucleare, Universita di Padova, Sezione di Padova, I-36132 Padova, Italy*
[25]*University of Pennsylvania, Philadelphia, Pennsylvania 19104*
[26]*Istituto Nazionale di Fisica Nucleare, University and Scuola Normale Superiore of Pisa, I-56100 Pisa, Italy*
[27]*University of Pittsburgh, Pittsburgh, Pennsylvania 15270*
[28]*Purdue University, West Lafayette, Indiana 47907*
[29]*University of Rochester, Rochester, New York 14628*
[30]*Rockefeller University, New York, New York 10021*
[31]*Rutgers University, Piscataway, New Jersey 08854*
[32]*Academia Sinica, Taipei, Taiwan 11530, Republic of China*
[33]*Texas A&M University, College Station, Texas 77843*
[34]*Texas Tech University, Lubbock, Texas 79409*
[35]*University of Tsukuba, Tsukuba, Ibaraki 315, Japan*
[36]*Tufts University, Medford, Massachusetts 02155*
[37]*University of Wisconsin, Madison, Wisconsin 53806*
[38]*Yale University, New Haven, Connecticut 06511*
(Received 13 September 1996)

We present results of a search for W^+W^- production through the leptonic decay channel $W^+W^- \to l^+l^-\nu\overline{\nu}$ in $\overline{p}p$ collisions at $\sqrt{s} = 1.8$ TeV. In a 108 pb^{-1} data sample recorded with the Collider Detector at Fermilab, five W^+W^- candidates are found with an expected standard model background of 1.2 ± 0.3 events. The W^+W^- production cross section is measured to be $\sigma(\overline{p}p \to W^+W^-) = 10.2^{+6.3}_{-5.1}(\text{stat}) \pm 1.6(\text{syst})$ pb, in agreement with the standard model prediction. Limits on $WW\gamma$ and WWZ anomalous couplings are presented. [S0031-9007(97)03132-3]

PACS numbers: 13.85.Qk, 13.40.Gp, 14.70.Fm

Observation of W^+W^- production in $\overline{p}p$ collisions provides an opportunity to test the standard model prediction of $WW\gamma$ and WWZ couplings [1]. The gauge structure of the SU(2) $\times$ SU(1) theory of electroweak interactions governs trilinear vector boson couplings, and leads to a cancellation of helicity amplitudes. Anomalous couplings [2], or decays of new particles, such as Higgs bosons, heavy quarks and leptons, and technihadrons, result in enhanced W^+W^- production [3,4].

In this Letter we describe a search for W^+W^- production through the dilepton channel $W^+W^- \rightarrow l^+l^-\nu\overline{\nu}$ ($l = e, \mu$), and compare the results with the standard model prediction. Another similar search has been performed by the D0 collaboration [5]. This analysis is based on a data sample of $\overline{p}p$ collisions at $\sqrt{s} = 1.8$ TeV with an integrated luminosity of 108 pb^{-1}, collected at the Collider Detector at Fermilab (CDF) from 1992 to 1995. Based on our observation of several $W^+W^- \rightarrow l^+l^-\nu\overline{\nu}$ candidates, we measure $\sigma(\overline{p}p \rightarrow W^+W^-)$. Bounds on $WW\gamma$ and WWZ anomalous couplings are also obtained.

The CDF detector is described in detail in Refs. [6,7]. The detailed description of the lepton identification cuts can be found in Ref. [7]. A lepton is identified by either hits in a muon chamber or a cluster of energy in the electromagnetic calorimeter, and an associated track in the central tracking chamber. The jet reconstruction algorithm uses a cone of fixed radius (0.4 in this analysis) in the η-ϕ plane to group clusters of calorimeter energy. Here $\eta = -\ln[\tan(\theta/2)]$ is the pseudorapidity, θ is the polar angle with respect to the proton beam direction, and ϕ is the azimuthal angle. The missing transverse energy $\not{E}_T$ associated with neutrinos is calculated by requiring that the total transverse energy as measured by the calorimeter be balanced. When a muon is present in the event the $\not{E}_T$ is corrected for the muon transverse momentum. In this analysis, electrons are required to have transverse energy $E_T > 20$ GeV, and muons transverse momentum $P_T > 20$ GeV$/c$.

The total $W^+W^- \rightarrow l^+l^- + X$ detection efficiency can be decomposed into several factors:

$$\epsilon_{\rm total} = \epsilon_{{\rm geom}\cdot P_T} \times \epsilon_{\rm ID} \times \epsilon_{\rm Isol} \times \epsilon_{\rm event} \times \epsilon_{0-{\rm jet}} \times \epsilon_{\rm trigger} .$$

The efficiency factors, described below, are computed sequentially and are listed in Table I. In addition to $W^+W^- \rightarrow l^+l^-\nu\overline{\nu}$ ($l = e, \mu$), there is a small contribution from $W^+W^- \rightarrow l\tau\nu\overline{\nu}$ or $\tau\tau\nu\overline{\nu}$, followed by $\tau \rightarrow e$ or μ, which is included in our acceptance.

The acceptance due to geometrical and transverse momentum cuts, denoted by $\epsilon_{{\rm geom}\cdot P_T}$, is the fraction of $W^+W^- \rightarrow l^+l^- + X$ events for which both leptons are inside the detector fiducial region and pass the P_T cut. This efficiency is obtained from W^+W^- Monte Carlo samples. Several Monte Carlo event generators (ISAJET [8], TAOHAN [9], and PYTHIA [10]) are used in conjunction with a detector simulation. While ISAJET and PYTHIA use tree-level matrix element calculations to simulate the W^+W^- + jets process, TAOHAN is based on the full matrix element calculation up to W^+W^- + 2-jets.

TABLE I. Dilepton detection efficiencies. The uncertainties are discussed in the text.

Category	e-e	μ-μ	e-μ
$\epsilon_{{\rm geom}\cdot P_T}$ (%)	30.0	20.0	28.8
$\epsilon_{\rm ID}$ (%)	66.1	86.1	73.6
$\epsilon_{\rm Isol}$ (%)	94.5	88.7	90.1
$\epsilon_{\rm event}$ (%)	54.8	56.3	73.1
$\epsilon_{0-{\rm jet}}$ (%)	68.0	68.0	68.0
$\epsilon_{\rm trigger}$ (%)	98.1	92.8	93.5
$\epsilon_{\rm total}$ (%)	6.9	5.4	8.9

The efficiency of the lepton identification cuts, $\epsilon_{\rm ID}$, is determined from $Z \rightarrow e^+e^-$ $(\mu^+\mu^-)$ data samples.

All leptons are required to pass a calorimeter isolation cut—the total transverse energy in a cone with a radius 0.4 around the lepton in the η-ϕ plane, excluding the lepton transverse energy, divided by the lepton transverse energy must be less than 0.1. A track isolation cut is also applied to both lepton—the sum of the transverse momenta for all tracks in the above cone, excluding the lepton track, divided by the P_T of the lepton must be less than 0.1. The efficiency of these two cuts is denoted by $\epsilon_{\rm Isol}$.

To discriminate against backgrounds from $Z \rightarrow \tau\tau$ and the Drell-Yan process ($\gamma/Z \rightarrow e^+e^-$, $\mu^+\mu^-$), events are required to have a minimum $\not{E}_T$ of 25 GeV. We also reject events where $\not{E}_T$ points along the ϕ direction of one of the leptons [7]. For events with $\not{E}_T < 50$ GeV, we require $\Delta\phi > 20°$, where $\Delta\phi$ is the azimuthal angle between the direction of $\not{E}_T$ and the direction of the nearest lepton. Also we remove events with dilepton invariant mass between 75 and 105 GeV$/c^2$ in the e^+e^- and $\mu^+\mu^-$ channels. The combined efficiency of the $\not{E}_T$ and invariant mass cuts is denoted by $\epsilon_{\rm event}$.

The top quark production background ($\overline{p}p \rightarrow t\overline{t} + X \rightarrow W^+W^-b\overline{b} + X$) is suppressed by removing events with any jet with observed transverse energy exceeding 10 GeV (0-jet requirement). The fraction of $W^+W^- \rightarrow l^+l^- + X$ events with no jets is denoted by $\epsilon_{0-{\rm jet}}$. Simulations of $W^+W^- \rightarrow l^+l^- + X$ production indicate $\epsilon_{0-{\rm jet}} = (68 \pm 7)\%$. Uncertainties are set by the difference between the Monte Carlo generators. When extrapolating the measured fraction of Z events with no jets in the data to the expected fraction in WW events using the above mentioned WW generators together with Z and Drell-Yan (at a mass of 240 GeV$/c^2$, corresponding to the mean WW invariant mass) generators, a consistent number for $\epsilon_{0-{\rm jet}}$ is obtained.

Single lepton (e or μ) hardware triggers were used to collect the data for this analysis. Their efficiencies were measured using data coming from independent triggers. The overall trigger efficiency, $\epsilon_{\rm trigger}$, is the probability that a signal event is collected by any of the single lepton triggers.

Systematic uncertainties in the efficiency calculations come from the lepton identification cuts (3%), lepton isolation cuts (2%), event cuts (4%), choice of parton distribution functions (3%), 0-jet requirement (10%), and Monte Carlo statistics (3%). A 10% uncertainty on the jet energy scale affects the jet multiplicity and the accuracy of the $\not{E}_T$ measurement, and results in a 4% uncertainty in acceptance. The total uncertainty in the efficiency determination (13%) is the sum of these uncertainties in quadrature.

Table II summarizes the expected background from $t\bar{t} \to W^+W^-b\bar{b}$, $Z \to \tau\tau$, the Drell-Yan process, WZ production, and W + jets processes in which jets are misidentified as leptons (fakes). Other backgrounds, such as $b\bar{b}$, ZZ, and $Z \to b\bar{b}$, are found to be negligible. The main backgrounds, Drell-Yan and fakes, are obtained directly from the data, the others from Monte Carlo. When releasing the 0-jet requirement the main background is expected to be $t\bar{t}$. Using the CDF published value for the $t\bar{t}$ production cross section[11] we expect 7 ± 3 events. The expectation from the other backgrounds is 4.6 ± 0.9 events. The expected number of WW events is 5.2 ± 1.8 (using the theoretical cross section from [12]). All together we expect 16.8 ± 3.6 events and find 24 events in the data. The large uncertainty in the $t\bar{t}$ background is significantly reduced when the 0-jet requirement is made.

The number of $W^+W^- \to l^+l^- + X$ events can be written as

$$N_{\text{events}} = \sigma(\bar{p}p \to W^+W^-)B\epsilon_{\text{total}} \int \mathcal{L}\, dt\,,$$

where $\int \mathcal{L}\, dt = 108 \pm 10\ \text{pb}^{-1}$ is the integrated luminosity. A first order-α_s calculation [12] finds the continuum W^+W^- production cross section $\sigma(\bar{p}p \to W^+W^-)$ to be 9.5 pb with 30% theoretical uncertainty. Using 0.011 as the branching ratio, B, for $W^+W^- \to ee\nu\bar{\nu}$ and $\mu\mu\nu\bar{\nu}$, and 0.022 for $W^+W^- \to e\mu\nu\bar{\nu}$, we expect a signal of 3.5 ± 1.2 events.

Five events (two ee and three $e\mu$) survive the selection cuts in our data sample. Given $N_{\text{events}} = 3.8$ after background subtraction, from the above equation we obtain

$$\sigma(\bar{p}p \to W^+W^-) = 10.2^{+6.3}_{-5.1}(\text{stat}) \pm 1.6(\text{syst})\ \text{pb}\,.$$

TABLE II. Predicted background events in the 108 pb^{-1} data sample.

Process	Expected number of events
$t\bar{t}$	0.04 ± 0.01
$Z \to \tau\tau$	0.22 ± 0.06
Drell-Yan	0.40 ± 0.20
WZ	0.12 ± 0.05
Fake	0.40 ± 0.20
Total	1.18 ± 0.29

In Fig. 1, the measured cross section is compared to leading order (LO) [1] and next-to-leading order (NLO) [12,13] calculations. The CDF measurement of $\sigma(\bar{p}p \to W^+W^-)$ is consistent with the standard model prediction.

For WWV anomalous couplings ($V = \gamma, Z$), the most general effective Lagrangian, which is Lorentz, C, and P invariant, may be described in terms of six couplings denoted by g_1^V, κ_V, and λ_V. In the standard model, $g_1^V = 1$, $\kappa_V = 1$, and $\lambda_V = 0$ [2]. To ensure the unitarity of the theory, a dipole form factor of the form $1/(1 + \hat{s}/\Lambda^2)^2$ is introduced, where $\hat{s}$ is the subprocess mass squared and Λ is the energy scale beyond which new resonance particles, multiple boson production, and other new phenomena are expected.

To study WWV anomalous couplings, a tree-level Monte Carlo generator [2] is used to generate $W^+W^- \to l^+l^- + X$ events and the output is fed to the detector simulation. Since there are no QCD corrections in this generator and we are interested only in the relative deviation from the standard model prediction, the number of $W^+W^- \to l^+l^- + X$ events with couplings at their standard model values is normalized to that from the ISAJET calculation. The effect of QCD corrections on anomalous couplings is expected to be small at the Tevatron energy [14,15].

Limits on anomalous couplings are obtained in one scenario that assumes $\kappa_\gamma = \kappa_Z = \kappa$ and $\lambda_\gamma = \lambda_Z = \lambda$. In the "HISZ" scenario [16], on the other hand, λ_γ and κ_γ are chosen as independent parameters. Contour limits at the 95% confidence level (CL) are shown in Fig. 2, with the choices $\Lambda = 1, 2$ TeV. The limit when $\Lambda = 1$ TeV is well within the unitarity bound (not shown in Fig. 2) and consistent with that obtained by the CDF collaboration in searches for WW and WZ in channels containing jets [17]. For a comprehensive review on anomalous couplings, see Refs. [18,19].

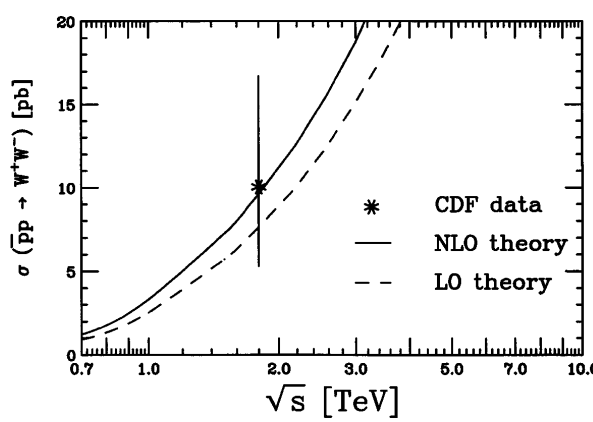

FIG. 1. The W^+W^- production cross section, $\sigma(\bar{p}p \to W^+W^-)$, measured at the CDF, compared to theoretical calculations. The theoretical results are based on the NLO (solid line) and LO (dashed line) calculations.

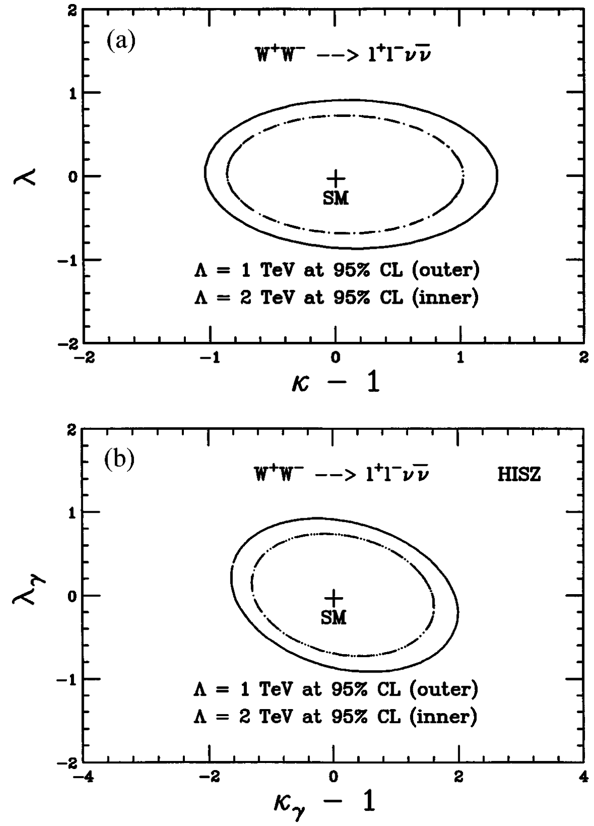

FIG. 2. Limits on anomalous couplings: (a) Assuming $\kappa_\gamma = \kappa_Z = \kappa$ and $\lambda_\gamma = \lambda_Z = \lambda$. (b) The HISZ scenario where κ_γ and λ_γ are used as independent parameters. The standard model value is located at the center. The outer (inner) contour is the 95% CL limits with the energy scale $\Lambda = 1$ TeV (2 TeV).

In conclusion, we observe five dilepton events consistent with W^+W^- production with an expected background of 1.2 ± 0.3. The probability that the observed events correspond to a fluctuation of the background is 1.1%. The W^+W^- production cross section is measured to be $\sigma(\overline{p}p \rightarrow W^+W^-) = 10.2^{+6.3}_{-5.1}(\text{stat}) \pm 1.6(\text{syst})$ pb. This cross section is consistent with the NLO standard model prediction and limits are placed on $WW\gamma$ and WWZ anomalous couplings.

We thank U. Baur, T. Han, J. Ohnemus, and D. Zeppenfeld for Monte Carlo programs and for many stimulating discussions. We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the U.S. Department of Energy and National Science Foundation, the Natural Sciences and Engineering Research Council of Canada, the Italian Istituto Nazionale di Fisica Nucleare, the Ministry of Science, Culture, and Education of Japan, the National Science Council of the Republic of China, the A. P. Sloan Foundation, and the Alexander von Humboldt-Stiftung.

*Visitor.

[1] V. Barger, T. Han, D. Zeppenfeld, and J. Ohnemus, Phys. Rev. D **41**, 2782 (1990), and references therein.
[2] K. Hagiwara, J. Woodside, and D. Zeppenfeld, Phys. Rev. D **41**, 2113 (1990).
[3] V. Barger and R. Phillips, *Collider Physics* (Addison-Wesley, New York, 1987).
[4] E. Eichten, I. Hinchliffe, K. Lane, and C. Quigg, Rev. Mod. Phys. **56**, 579 (1984); **58**, 1065(E) (1986).
[5] A. Abachi *et al.*, Phys. Rev. Lett. **75**, 1023 (1995).
[6] CDF Collaboration, F. Abe *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **271**, 387 (1988).
[7] CDF Collaboration, F. Abe *et al.*, Phys. Rev. D **50**, 2966 (1994), and references therein.
[8] F. Paige and S. D. Protopopescu, BNL Report No. 38034, 1986 (unpublished).
[9] Tao Han (private communication). This Monte Carlo program is based on the matrix element calculation discussed in Ref. [1].
[10] H. Bengtsson and T. Sjostrand, Report No. CERN-TH.6488/92.
[11] CDF Collaboration, F. Abe *et al.*, Phys. Rev. Lett. **74**, 2626 (1995)
[12] J. Ohnemus, Phys. Rev. D **44**, 1403 (1991). We thank him for calculating the NLO cross section for us at several center-of-mass energies.
[13] S. Frixione, Nucl. Phys. **B410**, 280 (1993).
[14] U. Baur (private communication).
[15] U. Baur, T. Han, and J. Ohnemus, Report No. UB-HET-95-03, UCD-95-21, 1995 [Phys. Rev. D (to be published)].
[16] K. Hagiwara, S. Ishihara, R. Szalapski, and D. Zeppenfeld, Phys. Rev. D **48**, 2182 (1993).
[17] F. Abe, *et al.*, Phys. Rev. Lett. **75**, 1017 (1995).
[18] H. Aihara *et al.*, Report No. FERMILAB-Pub-95/031.
[19] S. Errede, in *Proceedings of the XXVII International Conference on High Energy Physics,* edited by P. J. Bussey and I. G. Knowles (Institute of Physics Publishing, London, UK, 1995), Vol. II, p. 433-436.