Search for Charged Bosons Heavier than the W Boson in $p\bar{p}$ Collisions at $\sqrt{s} = 1800$ GeV

F. Abe,[13] M. G. Albrow,[7] D. Amidei,[16] J. Antos,[28] C. Anway-Wiese,[4] G. Apollinari,[26] H. Areti,[7] M. Atac,[7] P. Auchincloss,[25] F. Azfar,[21] P. Azzi,[20] N. Bacchetta,[18] W. Badgett,[16] M. W. Bailey,[18] J. Bao,[34] P. de Barbaro,[25] A. Barbaro-Galtieri,[14] V. E. Barnes,[24] B. A. Barnett,[12] P. Bartalini,[23] G. Bauer,[15] T. Baumann,[9] F. Bedeschi,[23] S. Behrends,[3] S. Belforte,[23] G. Bellettini,[23] J. Bellinger,[33] D. Benjamin,[32] J. Benlloch,[15] J. Bensinger,[3] D. Benton,[21] A. Beretvas,[7] J. P. Berge,[7] S. Bertolucci,[8] A. Bhatti,[26] K. Biery,[11] M. Binkley,[7] F. Bird,[29] D. Bisello,[20] R. E. Blair,[1] C. Blocker,[29] A. Bodek,[25] W. Bokhari,[15] V. Bolognesi,[23] D. Bortoletto,[24] C. Boswell,[12] T. Boulos,[14] G. Brandenburg,[9] E. Buckley-Geer,[7] H. S. Budd,[25] K. Burkett,[16] G. Busetto,[20] A. Byon-Wagner,[7] K. L. Byrum,[1] J. Cammerata,[12] C. Campagnari,[7] M. Campbell,[16] A. Caner,[7] W. Carithers,[14] D. Carlsmith,[33] A. Castro,[20] Y. Cen,[21] F. Cervelli,[23] J. Chapman,[16] M.-T. Cheng,[28] G. Chiarelli,[8] T. Chikamatsu,[31] S. Cihangir,[7] A. G. Clark,[23] M. Cobal,[23] M. Contreras,[5] J. Conway,[27] J. Cooper,[7] M. Cordelli,[8] D. Crane,[1] J. D. Cunningham,[3] T. Daniels,[15] F. DeJongh,[7] S. Delchamps,[7] S. Dell'Agnello,[23] M. Dell'Orso,[23] L. Demortier,[26] B. Denby,[23] M. Deninno,[2] P. F. Derwent,[16] T. Devlin,[27] M. Dickson,[25] S. Donati,[23] R. B. Drucker,[14] A. Dunn,[16] K. Einsweiler,[14] J. E. Elias,[7] R. Ely,[14] E. Engels, Jr.,[22] S. Eno,[5] D. Errede,[10] S. Errede,[10] Q. Fan,[25] B. Farhat,[15] I. Fiori,[2] B. Flaugher,[7] G. W. Foster,[7] M. Franklin,[9] M. Frautschi,[18] J. Freeman,[7] J. Friedman,[15] H. Frisch,[5] A. Fry,[29] T. A. Fuess,[1] Y. Fukui,[13] S. Funaki,[31] G. Gagliardi,[23] S. Galeotti,[23] M. Gallinaro,[20] A. F. Garfinkel,[24] S. Geer,[7] D. W. Gerdes,[16] P. Giannetti,[23] N. Giokaris,[26] P. Giromini,[8] L. Gladney,[21] D. Glenzinski,[12] M. Gold,[18] J. Gonzalez,[21] A. Gordon,[9] A. T. Goshaw,[6] K. Goulianos,[26] H. Grassmann,[6] A. Grewal,[21] G. Grieco,[23] L. Groer,[27] C. Grosso-Pilcher,[5] C. Haber,[14] S. R. Hahn,[7] R. Hamilton,[9] R. Handler,[33] R. M. Hans,[34] K. Hara,[31] B. Harral,[21] R. M. Harris,[7] S. A. Hauger,[6] J. Hauser,[4] C. Hawk,[27] J. Heinrich,[21] D. Cronin-Hennessy,[6] R. Hollebeek,[21] L. Holloway,[10] A. Hölscher,[11] S. Hong,[16] G. Houk,[21] P. Hu,[22] B. T. Huffman,[22] R. Hughes,[25] P. Hurst,[9] J. Huston,[17] J. Huth,[9] J. Hylen,[7] M. Incagli,[23] J. Incandela,[7] H. Iso,[31] H. Jensen,[7] C. P. Jessop,[9] U. Joshi,[7] R. W. Kadel,[14] E. Kajfasz,[7,*] T. Kamon,[30] T. Kaneko,[31] D. A. Kardelis,[10] H. Kasha,[34] Y. Kato,[19] L. Keeble,[30] R. D. Kennedy,[27] R. Kephart,[7] P. Kesten,[14] D. Kestenbaum,[9] R. M. Keup,[10] H. Keutelian,[7] F. Keyvan,[4] D. H. Kim,[7] H. S. Kim,[11] S. B. Kim,[16] S. H. Kim,[31] Y. K. Kim,[14] L. Kirsch,[3] P. Koehn,[25] K. Kondo,[31] J. Konigsberg,[9] S. Kopp,[5] K. Kordas,[11] W. Koska,[7] E. Kovacs,[7,*] W. Kowald,[6] M. Krasberg,[16] J. Kroll,[7] M. Kruse,[24] S. E. Kuhlmann,[1] E. Kuns,[27] A. T. Laasanen,[24] N. Labanca,[23] S. Lammel,[4] J. I. Lamoureux,[3] T. LeCompte,[10] S. Leone,[23] J. D. Lewis,[7] P. Limon,[7] M. Lindgren,[4] T. M. Liss,[10] N. Lockyer,[21] C. Loomis,[27] O. Long,[21] M. Loreti,[20] E. H. Low,[21] J. Lu,[30] D. Lucchesi,[23] C. B. Luchini,[10] P. Lukens,[7] P. Maas,[33] K. Maeshima,[7] A. Maghakian,[26] P. Maksimovic,[15] M. Mangano,[23] J. Mansour,[17] M. Mariotti,[23] J. P. Marriner,[7] A. Martin,[10] J. A. J. Matthews,[18] R. Mattingly,[15] P. McIntyre,[30] P. Melese,[26] A. Menzione,[23] E. Meschi,[23] G. Michail,[9] S. Mikamo,[13] M. Miller,[5] R. Miller,[17] T. Mimashi,[31] S. Miscetti,[8] M. Mishina,[13] H. Mitsushio,[31] S. Miyashita,[31] Y. Morita,[13] S. Moulding,[26] J. Mueller,[27] A. Mukherjee,[7] T. Muller,[4] P. Musgrave,[11] L. F. Nakae,[29] I. Nakano,[31] C. Nelson,[7] D. Neuberger,[4] C. Newman-Holmes,[7] L. Nodulman,[1] S. Ogawa,[31] S. H. Oh,[6] K. E. Ohl,[34] R. Oishi,[31] T. Okusawa,[19] C. Pagliarone,[23] R. Paoletti,[23] V. Papadimitriou,[7] S. Park,[7] J. Patrick,[7] G. Pauletta,[23] M. Paulini,[14] L. Pescara,[20] M. D. Peters,[14] T. J. Phillips,[6] G. Piacentino,[2] M. Pillai,[25] R. Plunkett,[7] L. Pondrom,[33] N. Produit,[14] J. Proudfoot,[1] F. Ptohos,[9] G. Punzi,[23] K. Ragan,[11] F. Rimondi,[2] L. Ristori,[23] M. Roach-Bellino,[32] W. J. Robertson,[6] T. Rodrigo,[7] J. Romano,[5] L. Rosenson,[15] W. K. Sakumoto,[25] D. Saltzberg,[5] A. Sansoni,[8] V. Scarpine,[30] A. Schindler,[14] P. Schlabach,[9] E. E. Schmidt,[7] M. P. Schmidt,[34] O. Schneider,[14] G. F. Sciacca,[23] A. Scribano,[23] S. Segler,[7] S. Seidel,[18] Y. Seiya,[31] G. Sganos,[11] A. Sgolacchia,[2] M. Shapiro,[14] N. M. Shaw,[24] Q. Shen,[24] P. F. Shepard,[22] M. Shimojima,[31] M. Shochet,[5] J. Siegrist,[29] A. Sill,[7,*] P. Sinervo,[11] P. Singh,[22] J. Skarha,[12] K. Sliwa,[32] D. A. Smith,[23] F. D. Snider,[12] L. Song,[7] T. Song,[16] J. Spalding,[7] L. Spiegel,[7] P. Sphicas,[15] A. Spies,[12] L. Stanco,[20] J. Steele,[33] A. Stefanini,[23] K. Strahl,[11] J. Strait,[7] D. Stuart,[7] G. Sullivan,[5] K. Sumorok,[15] R. L. Swartz, Jr.,[10] T. Takahashi,[19] K. Takikawa,[31] F. Tartarelli,[23] W. Taylor,[11] Y. Teramoto,[19] S. Tether,[15] D. Theriot,[7] J. Thomas,[29] T. L. Thomas,[18] R. Thun,[16] M. Timko,[32] P. Tipton,[25] A. Titov,[26] S. Tkaczyk,[7] K. Tollefson,[25] A. Tollestrup,[7] J. Tonnison,[24] J. F. de Troconiz,[9] J. Tseng,[12] M. Turcotte,[29] N. Turini,[2] N. Uemura,[31] F. Ukegawa,[21] G. Unal,[21] S. van den Brink,[22] S. Vejcik III,[16] R. Vidal,[7] M. Vondracek,[10] R. G. Wagner,[1] R. L. Wagner,[7] N. Wainer,[7] R. C. Walker,[25] G. Wang,[23] J. Wang,[5] M. J. Wang,[28] Q. F. Wang,[26] A. Warburton,[11] G. Watts,[25] T. Watts,[27] R. Webb,[30] C. Wendt,[33] H. Wenzel,[14] W. C. Wester III,[14] T. Westhusing,[10] A. B. Wicklund,[1] E. Wicklund,[7] R. Wilkinson,[21] H. H. Williams,[21] P. Wilson,[5] B. L. Winer,[25] J. Wolinski,[30] D. Y. Wu,[16] X. Wu,[23] J. Wyss,[20] A. Yagil,[7] W. Yao,[14] K. Yasuoka,[31] Y. Ye,[11] G. P. Yeh,[7] P. Yeh,[28] M. Yin,[6] J. Yoh,[7] T. Yoshida,[19] D. Yovanovitch,[7] I. Yu,[34] J. C. Yun,[7] A. Zanetti,[23] F. Zetti,[23] L. Zhang,[33] S. Zhang,[16] W. Zhang,[21] and S. Zucchelli[2]

(CDF Collaboration)

[1]*Argonne National Laboratory, Argonne, Illinois 60439*
[2]*Istituto Nazionale di Fisica Nucleare, University of Bologna, I-40126 Bologna, Italy*
[3]*Brandeis University, Waltham, Massachusetts 02254*

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[4] *University of California at Los Angeles, Los Angeles, California 90024*
[5] *University of Chicago, Chicago, Illinois 60637*
[6] *Duke University, Durham, North Carolina 27708*
[7] *Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[8] *Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*
[9] *Harvard University, Cambridge, Massachusetts 02138*
[10] *University of Illinois, Urbana, Illinois 61801*
[11] *Institute of Particle Physics, McGill University, Montreal, Canada H3A 2T8 and University of Toronto, Toronto, Canada M5S 1A7*
[12] *The Johns Hopkins University, Baltimore, Maryland 21218*
[13] *National Laboratory for High Energy Physics (KEK), Tsukuba, Ibaraki 305, Japan*
[14] *Lawrence Berkeley Laboratory, Berkeley, California 94720*
[15] *Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*
[16] *University of Michigan, Ann Arbor, Michigan 48109*
[17] *Michigan State University, East Lansing, Michigan 48824*
[18] *University of New Mexico, Albuquerque, New Mexico 87131*
[19] *Osaka City University, Osaka 588, Japan*
[20] *Università di Padova, Istituto Nazionale di Fisica Nucleare, Sezione di Padova, I-35131 Padova, Italy*
[21] *University of Pennsylvania, Philadelphia, Pennsylvania 19104*
[22] *University of Pittsburgh, Pittsburgh, Pennsylvania 15260*
[23] *Istituto Nazionale di Fisica Nucleare, University and Scuola Normale Superiore of Pisa, I-56100 Pisa, Italy*
[24] *Purdue University, West Lafayette, Indiana 47907*
[25] *University of Rochester, Rochester, New York 14627*
[26] *Rockefeller University, New York, New York 10021*
[27] *Rutgers University, Piscataway, New Jersey 08854*
[28] *Academia Sinica, Taiwan 11529, Republic of China*
[29] *Superconducting Super Collider Laboratory, Dallas, Texas 75237*
[30] *Texas A&M University, College Station, Texas 77843*
[31] *University of Tsukuba, Tsukuba, Ibaraki 305, Japan*
[32] *Tufts University, Medford, Massachusetts 02155*
[33] *University of Wisconsin, Madison, Wisconsin 53706*
[34] *Yale University, New Haven, Connecticut 06511*

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We have searched for new, heavy, charged bosons W' through the decay $W' \to e\nu$ in $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV. The data used in the search represent 19.7 pb^{-1} collected by the Collider Detector at Fermilab. Limits are placed on $\sigma B(p\overline{p} \to W' \to e\nu)$ as a function of $M_{W'}$. Assuming standard couplings of the W' to fermions, we establish the limit $M_{W'} > 652$ GeV/c^2 (95% C.L.).

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This Letter presents a search for new, heavy, charged bosons W' through the process $p\overline{p} \to W' \to e\nu$. In its simplest form, the W' appears as a heavier version of the left-handed W, which has a mass $M_W \approx 80$ GeV/c^2. In this case, the primary decay of the W' for very large masses is $W' \to WZ^0$. However, in extended gauge models [1], proposed to restore left-right symmetry to the weak force, the right-handed W' can decay with large probability to right-handed $\ell_R\overline{\nu}_R$ pairs, since it is expected [2] that the coupling at the $W'WZ^0$ vertex is suppressed by a left-right mixing angle $\xi \sim (M_W/M_{W'})^2$. This search assumes that the decay $W' \to WZ^0$ is suppressed and that the ν_R is sufficiently light that the process $W' \to \ell_R\overline{\nu}_R$ can occur.

The coupling of the W' to fermions, which determines the production cross section of the W' in $p\overline{p}$ collisions, is not known. Lorentz invariance and renormalizability restrict the W'-fermion coupling to be of the form $(ig/2\sqrt{2})\overline{\psi}_i(a + b\gamma_5)\gamma_\mu W'^\mu\psi_j U_{ij}$, where a and b are constants and U_{ij} is the Cabibbo-Kobayashi-Maskawa (CKM) matrix element connecting fermions i and j. $SU(2)_L$ gauge invariance in the standard model leads to the $V - A$ character of the weak interaction with $a = 1$, $b = -1$. In the standard model, furthermore, the CKM matrix is approximately diagonal: $U_L \sim 1$. No such constraints exist for a and b or for the right-handed CKM matrix in the context of extended gauge models. With this coupling the partial width to fermions is

$$\Gamma(W' \to f_i f_j) = \left(\frac{a^2 + b^2}{2}\right)\left(\frac{N_c G_F M_W^2 M_{W'}}{6\sqrt{2}\,\pi}\right)|U_{ij}|^2, \tag{1}$$

where N_c is the color factor of 3 for quarks and is 1 for leptons. The case of "standard strength couplings," where $\lambda^2 \equiv \frac{1}{2}(a^2 + b^2) = 1$, holds true in the standard model. It also holds in models in which the left- and right-handed gauge sectors couple to matter with equal strengths, known as left-right symmetry. Manifest left-right symmetry further implies $U_R = U_L$. The cross section limits in this paper assume $U_R = U_L$, and the mass limit further assumes $\lambda^2 = 1$.

Many previous searches have been conducted for the W'. For very light neutrino masses, the most stringent limits are astrophysical or cosmological (all 90% C.L. unless otherwise noted): For $m_\nu < 1$ MeV constraints from the big bang nucleosynthesis [3] imply $M_{W'} >$ 1 TeV, and the energetics of supernova 1987A can in some models imply [4] $M_{W'} > 16$ TeV. Assuming manifest left-right symmetry, a limit of $M_{W'} > 1.3$ TeV has also been derived [5] using experimental data from muon decay [6], the measured difference between the K_L and K_S masses [7], the semileptonic branching ratio $b \to X\ell\nu$ [8], B_d-$\overline{B}_d$ mixing [9], and neutrinoless atomic double beta decay [10]. Finally, direct searches for the decay $W' \to \ell\nu$ at $p\overline{p}$ colliders have established the limit [11] $M_{W'} > 520$ GeV/c^2 (95% C.L.) for the case of manifest left-right symmetry.

We search for the W' in $p\overline{p}$ collisions through the decay $W' \to e\nu$. This search is specific to neither right- nor left-handed bosons, but in the case of the $W_{R'}$ it is assumed that the ν_R is noninteracting and stable. It is not assumed that the ν_R is massless, only that it is much lighter than the W' (for $M_{W'} = 600$ GeV/c^2 and $m_\nu = 60$ GeV/c^2, for example, our cross section limit below is affected by <1%, and the effect on the mass limit is negligible). We search for the signature of a new Jacobian peak in the transverse mass (defined below) spectrum of electron+missing transverse momentum data and set a limit on $\sigma B(p\overline{p} \to W' \to e\nu)$.

This search was conducted using a dataset with an integrated luminosity of 19.7 ± 0.7 pb^{-1} collected with the Collider Detector at Fermilab (CDF) during the 1992–1993 Tevatron collider run. Detailed descriptions of the detector can be found elsewhere [12]. The portions of the detector relevant to this search are (i) electromagnetic and hadronic calorimeters covering the pseudorapidity [13] range $|\eta| < 4.2$ and arranged in a projective tower geometry, (ii) a drift chamber (CTC) immersed in a 1.4 T solenoidal magnetic field for tracking charged particles in the range $|\eta| < 1.4$, (iii) a time-projection chamber (VTX) for vertex finding, and (iv) two arrays of scintillator hodoscopes located on either side of the detector for triggering and luminosity monitoring.

We select events with an electron in the central, barrel region of the detector ($|\eta| < 1.05$) with $E_T >$ 30 GeV [14] and $P_T > 13$ GeV/c, as measured in the CTC. For the high masses considered in this search, excluding the region $|\eta| > 1.05$ decreases the W' acceptance by approximately 20%, and reduces non-W backgrounds considerably. In addition we require $I(\mathrm{trk}) <$ 5 GeV/c, where $I(\mathrm{trk})$ is defined as the scalar sum of the P_T of all tracks in the CTC except the electron track within $\sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.25$. The ratio of energy in the hadron (had) and electromagnetic (EM) calorimeter towers of the electron cluster is required to satisfy $E_{\mathrm{had}}/E_{\mathrm{EM}} < 0.055 + 0.045 \times [E\,(\mathrm{GeV})/100]$. A transverse momentum imbalance is required to signal the presence of the noninteracting neutrino. We require $\not{E}_T > 30$ GeV, where the missing transverse momentum ($\not{E}_T$) is defined as the negative of the vector sum of the E_T in all calorimeter towers with $|\eta| < 3.6$. Finally, the $p\overline{p}$ interaction point, which is distributed by an approximate Gaussian with width $\sigma_Z = 26$ cm about the center of the detector, is required to satisfy $|Z_{\mathrm{int}}| < 60$ cm and the total accidental calorimeter energy not in time with the $p\overline{p}$ collision (measured by the timing in the hadron calorimeters) is required to be <100 GeV. There are 10 845 events passing these cuts. Of these, 82 events with second isolated tracks anywhere in the CTC with $P_T > 10$ GeV/c pointing to electromagnetic clusters are removed from the sample as Z^0 candidates. Also, 229 events with clusters of tracks in the CTC, which point to the $\not{E}_T$ vector in ϕ and to calorimeter cracks at $|\eta| = 0$ or 1.1, are removed from the search sample as mismeasured QCD jet events ("dijets"), leaving 10 534 events.

From a study of electrons from $Z^0 \to e^+e^-$ decays, the efficiency of the isolation, $E_{\mathrm{had}}/E_{\mathrm{EM}}$, out of time energy, and vertex cuts is found to be (95 ± 2)% for $M_{W'} = 80$ GeV/c^2. The $E_{\mathrm{had}}/E_{\mathrm{EM}}$ efficiency, furthermore, agrees well with the efficiency found from an electron test beam and is observed to be flat up to $E \approx 175$ GeV. A Monte Carlo simulation of the detector shows no degradation in the $E_{\mathrm{had}}/E_{\mathrm{EM}}$ efficiency up to $E \approx 500$ GeV. A Monte Carlo calculation [15] indicates that the isolation efficiency will drop by ~1% between $M_{W'} = 80$ and 600 GeV/c^2 due to conversions of photons radiated by W' electrons within the tracking volume. We estimate the efficiency of the Z^0 removal cuts for W' events to be (99.9 ± 0.1)%, and the dijet removal to be (99.5 ± 0.2)%.

The primary background to the W' signal is $W \to e\nu$ decay. Several other processes can also mimic the W' signal. The process $W \to \tau\nu \to e\nu\nu\nu$ has a signature similar to that of the W', but at much lower transverse mass. The process $Z^0 \to e^+e^-$, where one electron is detected and the other is lost because it falls into an uninstrumented region of the detector, can produce the signal of an electron and $\not{E}_T$, as can QCD dijet events, where one jet passes our electron selection criteria and the other is mismeasured or falls into an uninstrumented region of the calorimeter. We estimate the number of $Z^0 \to e^+e^-$ and $W \to \tau\nu$ decays contaminating the search sample using the ISAJET Monte Carlo program [16] and a detector simulation. We normalize to the measured [17] cross sections $\sigma B(p\overline{p} \to Z^0 \to e^+e^-)$ and $\sigma B(p\overline{p} \to W \to e\nu)$. We find that the number of $Z^0 \to e^+e^-$ and $W \to \tau\nu$ events remaining in the sample are 57 ± 17 and 150 ± 45, respectively. The QCD dijet background is estimated [18] by studying a data sample of events with an "electron" $+\not{E}_T$, where the electron has $I(\text{trk}) > 6\ \text{GeV}/c$. These events are predominantly mismeasured dijets. We study the efficiency of our dijet removal cuts on this sample and normalize to the number (229) of events in the sample removed using these cuts. We estimate that the number of dijets left in the sample is 241 ± 40 events. After background subtraction, there are $N_{\text{cand}} = 10\,086$ events which pass the selection criteria. Figure 1 shows the transverse mass distribution of the 10 534 events and the expected contribution of the backgrounds, where $M_T \equiv \sqrt{2E_T^{\text{ele}}\not{E}_T[1 - \cos(\Delta\phi)]}$, E_T^{ele} is the electron E_T, and $\Delta\phi$ is the azimuthal angle between the electron and $\not{E}_T$. We observe 5 events with $M_T > 200\ \text{GeV}/c^2$, while 2.2 events are expected from QCD dijet events and 4.8 events are expected from $W \to e\nu$ decays.

The acceptance $A_{W'}$ is defined as the efficiency for W' events to pass the kinematic cuts on the electron and neutrino and for the electron to be in the fiducial region of the calorimeter. The acceptance is determined using a Monte Carlo program which generates W' events using the leading order diagram $q\overline{q} \to W'$, and decays the W' into an electron and a neutrino. We use the MRS D$-'$ structure functions [19]. The effects of higher order diagrams for W' production are mimicked by giving the bosons P_T according to a previous measurement [20] of the P_T^W spectrum. The dependence of the P_T spectrum with $M_{W'}$ is small [21]. Systematic uncertainties in the acceptance calculation come from the choice of parton distribution functions (1.7%), the modeling of the detector response (1.3%), the effect of higher-order diagrams (0.8%) [22], and the uncertainty in the P_T^W distribution (0.6%). The total relative uncertainty in $A_{W'}$ is found to be 3%. The W' decay width used in the acceptance calculation is calculated from Eq. (1), and includes the decay $W' \to t\overline{b}$ when kinematically allowed [23]. The W' acceptance for $M_{W'} = 80\ \text{GeV}/c^2$ is found to be $A_{W'} = 22\%$ and to increase with $M_{W'}$ to a plateau of 57% for $M_{W'} > 400\ \text{GeV}/c^2$. The difference in acceptances for left- and right-handed W' is negligible.

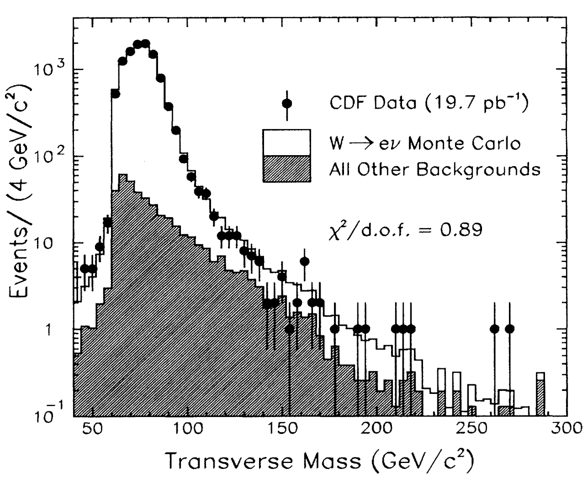

FIG. 1. Transverse mass spectrum of the events in the W' search sample, along with the expected contributions from backgrounds and from $W \to e\nu$ events. The $W \to e\nu$ curve is calculated with the Monte Carlo program used to calculate the W' acceptances.

To determine a limit on $\sigma B(p\overline{p} \to W' \to e\nu)$, a binned log-likelihood fit to the transverse mass spectrum in Fig. 1 is performed. The transverse mass spectrum is fit to the sum of three components: $W' \to e\nu$ decays, $W \to e\nu$ decays, and other backgrounds. The fraction of the data that is from W' decays is determined from the fit. The observed number of events x_i in each bin of the transverse mass spectrum is compared to the expectation μ_i per bin, where $\mu_i \equiv (N_{\text{cand}} - \alpha)W_i + \alpha W_i' + B_i$, W_i, W_i', and B_i are the W, W', and other background predictions for the ith bin, and $N_{\text{cand}} = 10\,086$ is the number of candidates after background subtraction. The background normalization is known bin by bin, and the normalization of the known W shape and the W' shape for a given W' mass is determined from the fit. The parameter α is required to lie in the range $0.0 \le \alpha \le N_{\text{cand}}$ [24].

The probability function $P(\alpha)$ is computed for each W' mass, where $P(\alpha)$ is the probability of obtaining the value α as determined from the likelihood. The systematic uncertainties in the normalization from the acceptance, backgrounds, efficiencies, and luminosity and the systematic uncertainty in the M_T shape from the W P_T are used to "smear" the probability distribution $P(\alpha)$ [25]. The 95% C.L. upper limit on the W' content in the data is obtained from the point α where $\int_0^\alpha \tilde{P}(\alpha')d\alpha' = 0.95$, where $\tilde{P}(\alpha)$ is the smeared probability distribution. For very high W' masses, where there are no events in the data, the fit returns a maximum allowed W' contribution of 3 events, as expected from Poisson statistics. The total systematic uncertainty on σB at high M_T is 5.1%, which includes the 3.6% uncertainty on the luminosity normalization, the 3% uncertainty from the acceptances, and the 2% uncertainty on the electron identification efficiency.

The 95% upper limit on the W' cross section times branching ratio is obtained using the 95% C.L. for α:

$$\sigma B(95\%\ \text{C.L.}) = \frac{\alpha(95\%)}{A_{W'}\varepsilon_{W'}\int \mathcal{L}\,dt}, \qquad (2)$$

where $\int \mathcal{L}\,dt$ is the integrated luminosity, $A_{W'}$ is the W' acceptance, and $\varepsilon_{W'}$ is the efficiency. The 95% C.L. limit on the cross section times branching ratio as a function of the W' mass is shown in Fig. 2. Also shown is the expected σB assuming standard couplings and $U_R = U_L$, as calculated by the same Monte Carlo as used in the acceptances. For $M_{W'} > 600\ \text{GeV}/c^2$ the cross section limit is 0.29 pb. For the case of standard couplings to fermions, we establish the limit $M_{W'} > 652\ \text{GeV}/c^2$ (95% C.L.), the mass at which our cross section upper limit intersects with the theoretical prediction.

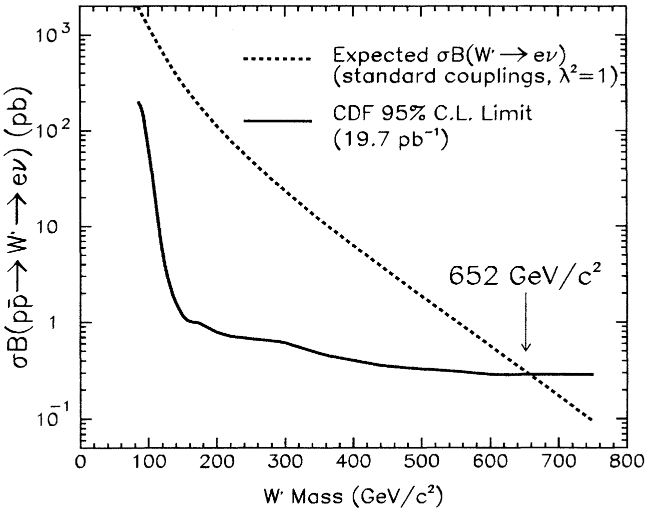

FIG. 2. The 95% C.L. limit on $\sigma B(p\overline{p} \to W' \to e\nu)$ vs the W' mass. Also shown is the expected σB, assuming standard couplings. The point $M_{W'} = 652\ \mathrm{GeV}/c^2$ is our limit, assuming standard couplings.

In conclusion, we have conducted a search for new charged bosons W' through the decay $W' \to e\nu$ in 19.7 pb^{-1} of $p\overline{p}$ collisions at $\sqrt{s} = 1800$ GeV. Assuming that the W' has standard couplings to fermions, assuming that the decay $W' \to WZ^0$ is suppressed, and assuming the right-handed neutrino is light, noninteracting, and stable, the 95% C.L. limit $M_{W'} > 652\ \mathrm{GeV}/c^2$ is obtained.

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*Visitor.

[1] J. Pati and A. Salam, Phys. Rev. D **11**, 566 (1975); **11**, 2558 (1975); R.N. Mohapatra and J.C. Pati, Phys. Rev. D **11**, 566 (1975); **11**, 2558 (1975); G. Senjanovic and R.N. Mohapatra, *ibid.* **12**, 1520 (1975).

[2] P. Ramond, Annu. Rev. Nucl. Part. Sci. **33**, 31 (1983).

[3] G. Stiegman, K.A. Olive, and D. Schramm, Phys. Rev. Lett. **43**, 239 (1979); Nucl. Phys. **B180**, 497 (1981).

[4] R. Barbieri and R.N. Mohapatra, Phys. Rev. D **39**, 1229 (1989); G. Raffelt and D. Seckel, Phys. Rev. Lett. **60**, 1793 (1988).

[5] For an excellent review, see P. Langacker and S. Uma Sankar, Phys. Rev. D **40**, 1569 (1989).

[6] A.E. Jodidio *et al.,* Phys. Rev. D **34**, 1967 (1986); **37**, 237(E) (1988); J. Imazato *et al.,* Phys. Rev. Lett. **69**, 877 (1992).

[7] G. Beal, M. Bander, and A. Soni, Phys. Rev. Lett. **48**, 848 (1982); F.I. Olness and M.E. Ebel, Phys. Rev. D **30**, 1034 (1984).

[8] F.J. Gilman and M.H. Reno, Phys. Rev. D **29**, 937 (1984).

[9] G. Altarelli and P. Franzini, Z. Phys. C **37**, 271 (1988).

[10] R.N. Mohapatra, Phys. Rev. D **34**, 909 (1986).

[11] F. Abe *et al.,* Phys. Rev. Lett. **67**, 2609 (1991).

[12] F. Abe *et al.,* Nucl. Instrum. Methods Phys. Res., Sect. A **271**, 387 (1988).

[13] At CDF, cylindrical coordinates r, ϕ, z are used, where ϕ is the azimuthal angle, and z points in the proton beam direction and is zero at the center of the detector. The pseudorapidity η is defined as $\eta \equiv -\ln[\tan(\theta/2)]$, where θ is the angle with respect to the proton beam direction.

[14] The transverse energy is defined as $E_T = E \sin\theta$, where E is measured in the calorimeter.

[15] R.G. Wagner, Comput. Phys. Commun. **70**, 15 (1992); based on calculations by F. Berends *et al.,* Z. Phys. C **27**, 155 (1985); F. Berends and R. Kleiss, *ibid.* **27**, 365 (1985).

[16] ISAJET Monte Carlo program, in F. Paige and S.D. Protopopescu, BNL Report No. BNL38034, 1986 (unpublished).

[17] F. Abe *et al.,* Phys. Rev. D **44**, 29 (1991). The results of these measurements are scaled up by a factor of 1.109 to account for a correction to the luminosity determination at CDF (see Ref. [23]).

[18] S. Kopp, Ph.D. thesis, The University of Chicago, 1994.

[19] A.D. Martin, R.G. Roberts, and W.J. Stirling, Phys. Lett. B **306**, 145 (1993); **309**, 492(E) (1993).

[20] F. Abe *et al.,* Phys. Rev. Lett. **66**, 2951 (1991).

[21] P. Arnold and R. Kauffman, Nucl. Phys. **B349**, 381 (1991); P. Arnold (private communication).

[22] We have compared our Monte Carlo program with a next-to-leading order Monte Carlo program written by W. Gieli, D. Glover, and D. Kosower, Nucl. Phys. **B403**, 633 (1993).

[23] Evidence for the top quark with mass $m_{\mathrm{top}} = 174 \pm 17\ \mathrm{GeV}/c^2$ has recently appeared in F. Abe *et al.,* Phys. Rev. Lett. **73**, 225 (1994). Including this decay mode leads to a more conservative W' limit.

[24] Particle Data Group, M. Aguilar *et al.,* Phys. Lett. B **204**, 1 (1988).

[25] This procedure is given in detail in F. Abe *et al.,* Phys. Rev. D **43**, 664 (1991).