Fermilab

FERMILAB-Pub-01/219-E CDF September 2001

Search for New Heavy Particles in the WZ^0 Final State in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

T. Affolder,[23] H. Akimoto,[45] A. Akopian,[37] M. G. Albrow,[11] P. Amaral,[8] D. Amidei,[25] K. Anikeev,[24] J. Antos,[1] G. Apollinari,[11] T. Arisawa,[45] A. Artikov,[9] T. Asakawa,[43] W. Ashmanskas,[8] F. Azfar,[30] P. Azzi-Bacchetta,[31] N. Bacchetta,[31] H. Bachacou,[23] S. Bailey,[16] P. de Barbaro,[36] A. Barbaro-Galtieri,[23] V. E. Barnes,[35] B. A. Barnett,[19] S. Baroiant,[5] M. Barone,[13] C. Battle,[39] G. Bauer,[24] F. Bedeschi,[33] S. Belforte,[42] W. H. Bell,[15] G. Bellettini,[33] J. Bellinger,[46] D. Benjamin,[10] J. Bensinger,[4] A. Beretvas,[11] J. P. Berge,[11] J. Berryhill,[8] A. Bhatti,[37] M. Binkley,[11] D. Bisello,[31] M. Bishai,[11] R. E. Blair,[2] C. Blocker,[4] K. Bloom,[25] B. Blumenfeld,[19] S. R. Blusk,[36] A. Bocci,[37] A. Bodek,[36] W. Bokhari,[32] G. Bolla,[35] Y. Bonushkin,[6] D. Bortoletto,[35] J. Boudreau,[34] A. Brandl,[27] S. van den Brink,[19] C. Bromberg,[26] M. Brozovic,[10] E. Brubaker,[23] N. Bruner,[27] E. Buckley-Geer,[11] J. Budagov,[9] H. S. Budd,[36] K. Burkett,[16] G. Busetto,[31] A. Byon-Wagner,[11] K. L. Byrum,[2] S. Cabrera,[10] P. Calafiura,[23] M. Campbell,[25] W. Carithers,[23] J. Carlson,[25] D. Carlsmith,[46] W. Caskey,[5] A. Castro,[3] D. Cauz,[42] A. Cerri,[33] A. W. Chan,[1] P. S. Chang,[1] P. T. Chang,[1] J. Chapman,[25] C. Chen,[32] Y. C. Chen,[1] M. -T. Cheng,[1] M. Chertok,[5] G. Chiarelli,[33] I. Chirikov-Zorin,[9] G. Chlachidze,[9] F. Chlebana,[11] L. Christofek,[18] M. L. Chu,[1] Y. S. Chung,[36] C. I. Ciobanu,[28] A. G. Clark,[14] A. Connolly,[23] J. Conway,[38] M. Cordelli,[13] J. Cranshaw,[40] R. Cropp,[41] R. Culbertson,[11] D. Dagenhart,[44] S. D'Auria,[15] F. DeJongh,[11] S. Dell'Agnello,[13] M. Dell'Orso,[33] L. Demortier,[37] M. Deninno,[3] P. F. Derwent,[11] T. Devlin,[38] J. R. Dittmann,[11] A. Dominguez,[23] S. Donati,[33] J. Done,[39] M. D'Onofrio,[33] T. Dorigo,[16] N. Eddy,[18] K. Einsweiler,[23] J. E. Elias,[11] E. Engels, Jr.,[34] R. Erbacher,[11] D. Errede,[18] S. Errede,[18] Q. Fan,[36] H.-C. Fang,[23] R. G. Feild,[47] J. P. Fernandez,[11] C. Ferretti,[33] R. D. Field,[12] I. Fiori,[3] B. Flaugher,[11] G. W. Foster,[11] M. Franklin,[16] J. Freeman,[11] J. Friedman,[24] Y. Fukui,[22] I. Furic,[24] S. Galeotti,[33] A. Gallas,[(**) 16] M. Gallinaro,[37] T. Gao,[32] M. Garcia-Sciveres,[23] A. F. Garfinkel,[35] P. Gatti,[31] C. Gay,[47] D. W. Gerdes,[25] P. Giannetti,[33] P. Giromini,[13] V. Glagolev,[9] D. Glenzinski,[11] M. Gold,[27] J. Goldstein,[11] I. Gorelov,[27] A. T. Goshaw,[10] Y. Gotra,[34] K. Goulianos,[37] C. Green,[35] G. Grim,[5] P. Gris,[11] L. Groer,[38] C. Grosso-Pilcher,[8] M. Guenther,[35] G. Guillian,[25] J. Guimaraes da Costa,[16] R. M. Haas,[12] C. Haber,[23] S. R. Hahn,[11] C. Hall,[16] T. Handa,[17] R. Handler,[46] W. Hao,[40] F. Happacher,[13] K. Hara,[43] A. D. Hardman,[35] R. M. Harris,[11] F. Hartmann,[20] K. Hatakeyama,[37] J. Hauser,[6] J. Heinrich,[32] A. Heiss,[20] M. Herndon,[19] C. Hill,[5] K. D. Hoffman,[35] C. Holck,[32] R. Hollebeek,[32] L. Holloway,[18] B. T. Huffman,[30] R. Hughes,[28] J. Huston,[26] J. Huth,[16] H. Ikeda,[43] J. Incandela,[11] G. Introzzi,[33] J. Iwai,[45] Y. Iwata,[17] E. James,[25] M. Jones,[32] U. Joshi,[11] H. Kambara,[14] T. Kamon,[39] T. Kaneko,[43] K. Karr,[44] H. Kasha,[47] Y. Kato,[29] T. A. Keaffaber,[35] K. Kelley,[24] M. Kelly,[25] R. D. Kennedy,[11] R. Kephart,[11] D. Khazins,[10] T. Kikuchi,[43] B. Kilminster,[36] B. J. Kim,[21] D. H. Kim,[21] H. S. Kim,[18] M. J. Kim,[21] S. B. Kim,[21] S. H. Kim,[43] Y. K. Kim,[23] M. Kirby,[10] M. Kirk,[4] L. Kirsch,[4] S. Klimenko,[12] P. Koehn,[28] K. Kondo,[45] J. Konigsberg,[12] A. Korn,[24] A. Korytov,[12] E. Kovacs,[2] J. Kroll,[32] M. Kruse,[10] S. E. Kuhlmann,[2] K. Kurino,[17] T. Kuwabara,[43] A. T. Laasanen,[35] N. Lai,[8] S. Lami,[37] S. Lammel,[11] J. Lancaster,[10] M. Lancaster,[23] R. Lander,[5] A. Lath,[38] G. Latino,[33] T. LeCompte,[2] A. M. Lee IV,[10] K. Lee,[40] S. Leone,[33] J. D. Lewis,[11] M. Lindgren,[6] T. M. Liss,[18] J. B. Liu,[36] Y. C. Liu,[1] D. O. Litvintsev,[11] O. Lobban,[40] N. Lockyer,[32] J. Loken,[30] M. Loreti,[31] D. Lucchesi,[31] P. Lukens,[11] S. Lusin,[46] L. Lyons,[30] J. Lys,[23] R. Madrak,[16] K. Maeshima,[11] P. Maksimovic,[16] L. Malferrari,[3] M. Mangano,[33] M. Mariotti,[31] G. Martignon,[31] A. Martin,[47] J. A. J. Matthews,[27] J. Mayer,[41] P. Mazzanti,[3] K. S. McFarland,[36] P. McIntyre,[39] E. McKigney,[32] M. Menguzzato,[31] A. Menzione,[33] C. Mesropian,[37] A. Meyer,[11] T. Miao,[11] R. Miller,[26] J. S. Miller,[25] H. Minato,[43] S. Miscetti,[13] M. Mishina,[22] G. Mitselmakher,[12] N. Moggi,[3] E. Moore,[27] R. Moore,[25] Y. Morita,[22] T. Moulik,[35] M. Mulhearn,[24] A. Mukherjee,[11] T. Muller,[20] A. Munar,[33] P. Murat,[11] S. Murgia,[26] J. Nachtman,[6] V. Nagaslaev,[40] S. Nahn,[47] H. Nakada,[43] I. Nakano,[17] C. Nelson,[11] T. Nelson,[11] C. Neu,[28] D. Neuberger,[20] C. Newman-Holmes,[11] C.-Y. P. Ngan,[24] H. Niu,[4] L. Nodulman,[2] A. Nomerotski,[12] S. H. Oh,[10] Y. D. Oh,[21] T. Ohmoto,[17] T. Ohsugi,[17] R. Oishi,[43] T. Okusawa,[29] J. Olsen,[46] W. Orejudos,[23] C. Pagliarone,[33] F. Palmonari,[33] R. Paoletti,[33] V. Papadimitriou,[40] D. Partos,[4] J. Patrick,[11] G. Pauletta,[42] M. Paulini,[(*) 23] C. Paus,[24] D. Pellett,[5] L. Pescara,[31] T. J. Phillips,[10] G. Piacentino,[33] K. T. Pitts,[18] A. Pompos,[35] L. Pondrom,[46] G. Pope,[34] M. Popovic,[41] F. Prokoshin,[9] J. Proudfoot,[2] F. Ptohos,[13] O. Pukhov,[9] G. Punzi,[33] A. Rakitine,[24] F. Ratnikov,[38] D. Reher,[23] A. Reichold,[30] A. Ribon,[31] W. Riegler,[16] F. Rimondi,[3] L. Ristori,[33] M. Riveline,[41] W. J. Robertson,[10] A. Robinson,[41] T. Rodrigo,[7] S. Rolli,[44] L. Rosenson,[24] R. Roser,[11] R. Rossin,[31] C. Rott,[35] A. Roy,[35] A. Ruiz,[7] A. Safonov,[5] R. St. Denis,[15] W. K. Sakumoto,[36] D. Saltzberg,[6] C. Sanchez,[28] A. Sansoni,[13] L. Santi,[42] H. Sato,[43] P. Savard,[41] P. Schlabach,[11] E. E. Schmidt,[11] M. P. Schmidt,[47] M. Schmitt,[(**) 16] L. Scodellaro,[31] A. Scott,[6] A. Scribano,[33] S. Segler,[11] S. Seidel,[27] Y. Seiya,[43] A. Semenov,[9] F. Semeria,[3] T. Shah,[24] M. D. Shapiro,[23] P. F. Shepard,[34] T. Shibayama,[43] M. Shimojima,[43] M. Shochet,[8] A. Sidoti,[31] J. Siegrist,[23] A. Sill,[40] P. Sinervo,[41] P. Singh,[18] A. J. Slaughter,[47] K. Sliwa,[44] C. Smith,[19] F. D. Snider,[11] A. Solodsky,[37] J. Spalding,[11] T. Speer,[14] P. Sphicas,[24] F. Spinella,[33] M. Spiropulu,[16] L. Spiegel,[11] J. Steele,[46] A. Stefanini,[33] J. Strologas,[18] F. Strumia, [14] D. Stuart,[11] K. Sumorok,[24] T. Suzuki,[43] T. Takano,[29] R. Takashima,[17] K. Takikawa,[43] P. Tamburello,[10] M. Tanaka,[43] B. Tannenbaum,[6] M. Tecchio,[25] R. Tesarek,[11] P. K. Teng,[1] K. Terashi,[37] S. Tether,[24] A. S. Thompson,[15] R. Thurman-Keup,[2] P. Tipton,[36] S. Tkaczyk,[11] D. Toback,[39] K. Tollefson,[36] A. Tollestrup,[11] D. Tonelli,[33] H. Toyoda,[29] W. Trischuk,[41] J. F. de Troconiz,[16] J. Tseng,[24] N. Turini,[33] F. Ukegawa,[43] T. Vaiciulis,[36] J. Valls,[38] S. Vejcik III,[11] G. Velev,[11] G. Veramendi,[23] R. Vidal,[11] I. Vila,[7] R. Vilar,[7] I. Volobouev,[23] M. von der Mey,[6] D. Vucinic,[24] R. G. Wagner,[2] R. L. Wagner,[11] N. B. Wallace,[38] Z. Wan,[38] C. Wang,[10] M. J. Wang,[1] B. Ward,[15] S. Waschke,[15] T. Watanabe,[43] D. Waters,[30] T. Watts,[38] R. Webb,[39] H. Wenzel,[20] W. C. Wester III,[11] A. B. Wicklund,[2] E. Wicklund,[11] T. Wilkes,[5] H. H. Williams,[32] P. Wilson,[11] B. L. Winer,[28] D. Winn,[25] S. Wolbers,[11] D. Wolinski,[25] J. Wolinski,[26] S. Wolinski,[25] S. Worm,[27] X. Wu,[14] J. Wyss,[33] W. Yao,[23] G. P. Yeh,[11] P. Yeh,[1] J. Yoh,[11] C. Yosef,[26] T. Yoshida,[29] I. Yu,[21] S. Yu,[32] Z. Yu,[47] A. Zanetti,[42] F. Zetti,[23] and S. Zucchelli[3]

(CDF Collaboration)

[1] *Institute of Physics, Academia Sinica, Taipei, Taiwan 11529, Republic of China*
[2] *Argonne National Laboratory, Argonne, Illinois 60439*
[3] *Istituto Nazionale di Fisica Nucleare, University of Bologna, I-40127 Bologna, Italy*
[4] *Brandeis University, Waltham, Massachusetts 02254*
[5] *University of California at Davis, Davis, California 95616*
[6] *University of California at Los Angeles, Los Angeles, California 90024*
[7] *Instituto de Fisica de Cantabria, CSIC-University of Cantabria, 39005 Santander, Spain*
[8] *Enrico Fermi Institute, University of Chicago, Chicago, Illinois 60637*
[9] *Joint Institute for Nuclear Research, RU-141980 Dubna, Russia*
[10] *Duke University, Durham, North Carolina 27708*
[11] *Fermi National Accelerator Laboratory, Batavia, Illinois 60510*
[12] *University of Florida, Gainesville, Florida 32611*
[13] *Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, I-00044 Frascati, Italy*
[14] *University of Geneva, CH-1211 Geneva 4, Switzerland*
[15] *Glasgow University, Glasgow G12 8QQ, United Kingdom*
[16] *Harvard University, Cambridge, Massachusetts 02138*
[17] *Hiroshima University, Higashi-Hiroshima 724, Japan*
[18] *University of Illinois, Urbana, Illinois 61801*
[19] *The Johns Hopkins University, Baltimore, Maryland 21218*
[20] *Institut für Experimentelle Kernphysik, Universität Karlsruhe, 76128 Karlsruhe, Germany*
[21] *Center for High Energy Physics: Kyungpook National University, Taegu 702-701; Seoul National University, Seoul 151-742; and SungKyunKwan University, Suwon 440-746; Korea*
[22] *High Energy Accelerator Research Organization (KEK), Tsukuba, Ibaraki 305, Japan*
[23] *Ernest Orlando Lawrence Berkeley National Laboratory, Berkeley, California 94720*
[24] *Massachusetts Institute of Technology, Cambridge, Massachusetts 02139*
[25] *University of Michigan, Ann Arbor, Michigan 48109*
[26] *Michigan State University, East Lansing, Michigan 48824*
[27] *University of New Mexico, Albuquerque, New Mexico 87131*
[28] *The Ohio State University, Columbus, Ohio 43210*
[29] *Osaka City University, Osaka 588, Japan*
[30] *University of Oxford, Oxford OX1 3RH, United Kingdom*
[31] *Universita di Padova, Istituto Nazionale di Fisica Nucleare, Sezione di Padova, I-35131 Padova, Italy*
[32] *University of Pennsylvania, Philadelphia, Pennsylvania 19104*
[33] *Istituto Nazionale di Fisica Nucleare, University and Scuola Normale Superiore of Pisa, I-56100 Pisa, Italy*
[34] *University of Pittsburgh, Pittsburgh, Pennsylvania 15260*
[35] *Purdue University, West Lafayette, Indiana 47907*
[36] *University of Rochester, Rochester, New York 14627*
[37] *Rockefeller University, New York, New York 10021*
[38] *Rutgers University, Piscataway, New Jersey 08855*
[39] *Texas A&M University, College Station, Texas 77843*
[40] *Texas Tech University, Lubbock, Texas 79409*
[41] *Institute of Particle Physics, University of Toronto, Toronto M5S 1A7, Canada*
[42] *Istituto Nazionale di Fisica Nucleare, University of Trieste/ Udine, Italy*
[43] *University of Tsukuba, Tsukuba, Ibaraki 305, Japan*
[44] *Tufts University, Medford, Massachusetts 02155*
[45] *Waseda University, Tokyo 169, Japan*
[46] *University of Wisconsin, Madison, Wisconsin 53706*
[47] *Yale University, New Haven, Connecticut 06520*
[*] *Now at Carnegie Mellon University, Pittsburgh, Pennsylvania 15213*
[**] *Now at Northwestern University, Evanston, Illinois 60208*

We present a search for new heavy particles, X, which decay via $X \rightarrow WZ^0 \rightarrow e\nu + jj$ in $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV. No evidence is found for production of X in 110 pb^{-1} of data collected by the Collider Detector at Fermilab. Limits are set at the 95% C.L. on the mass and the production of new heavy charged vector bosons which decay via $W' \to WZ^0$ in extended gauge models as a function of the width, $\Gamma(W')$, and mixing factor between the W' and the Standard Model W bosons.

PACS numbers: XXX

The Standard Model (SM) of particle physics is widely believed to be incomplete. Because alternative models are numerous and varied, it is advantageous to search for new physics using methods that are not specific to a single model, but which retain the most compelling aspects of currently favored scenarios [1]. Searching for new high mass particles, X, which decay via $X \to WZ^0 \to \ell\nu jj$ has the theoretical advantage that many models predict new particles with large couplings to gauge bosons, and the experimental advantages of a large branching ratio for $Z^0 \to jj$ and a striking signature of $W \to \ell\nu$. One example of $X \to WZ^0$, common in extended gauge models [2], is the production of a new heavy charged vector boson W', where $W' \to WZ^0$. In this case the width, $\Gamma(W')$, can vary greatly and is a function of the mixing factor, ξ, between the W' and the W. Other models such as Technicolor with $\rho_T \to WZ^0$ [3] also exist.

In this Letter, we present a search for $X \to WZ^0 \to e\nu jj$ production as a function of $\Gamma(X)$ using $p\bar{p}$ collisions at $\sqrt{s} = 1.8$ TeV using the Collider Detector at Fermilab (CDF). The data, taken during the 1992–1995 Tevatron collider run, correspond to an integrated luminosity of 110 pb^{-1}. Detailed descriptions of the detector can be found elsewhere [4]. The portions of the detector relevant to this search are: (i) a time projection chamber for vertex finding, (ii) a drift chamber immersed in a 1.4 T solenoidal magnetic field for tracking charged particles in the range $|\eta| < 1.1$ [5], and (iii) electromagnetic and hadronic calorimeters covering the pseudorapidity range $|\eta| < 4.2$. Electrons are identified as a narrow shower in the electromagnetic calorimeter that is matched in position with a track in the drift chamber. Jets are reconstructed as a cluster of energy in the calorimeter using a fixed-cone algorithm with cone size $\Delta R \equiv \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2} = 0.4$. The presence of neutrinos is inferred from the momentum imbalance, $\not\!\!E_T$, in the transverse plane as measured in the calorimeters.

Candidate events are selected online using a three-level trigger system [4] to identify $W \to e\nu$ decays based on the requirement of an electron candidate with $E_T > 22$ GeV, $|\eta| < 1.1$ and a matching drift chamber track, and $\not\!\!E_T > 22$ GeV. Several backup trigger paths, imposing for example electron $E_T > 25$ GeV with no track requirement and $\not\!\!E_T > 25$ GeV, combine to make the trigger inefficiency for $X \to WZ^0$ production negligible in the final $W \to e\nu$ sample. To search for resonant WZ^0 production, and to reduce standard model backgrounds, we raise the E_T and $\not\!\!E_T$ thresholds and require two jets to be present. The final event selection requires an isolated electron [6] with $E_T > 30$ GeV, $\not\!\!E_T > 30$ GeV, and two jets with $E_T > 50$ GeV and 20 GeV respectively, each with $|\eta| < 2.0$. To reduce instrumental backgrounds, we restrict electrons to be in the fiducial region of the detector [7], and reject events in which significant hadron calorimeter energy is deposited out of time with the $p\bar{p}$ collision. A total of 512 events pass these requirements.

The acceptance, A_X, for the process $X \to WZ^0 \to e\nu jj$, is defined as the number of events originating from X production and passing the final event selection, divided by the number of events in which $X \to WZ^0$, $W \to e\nu$; the Z^0 is allowed to have all decays. This definition allows non-quark decays of Z^0, such as $Z^0 \to \tau^+\tau^- \to jj$, to contribute to the acceptance. To compute A_X, we use the process $W' \to WZ^0$ in the PYTHIA Monte Carlo (MC) [8], followed by a parametric simulation of the CDF detector. We simulate $W' \to WZ^0$ production for a variety of widths, $\Gamma(W')$. For narrow resonances, $\Gamma(W') \ll M_{W'}$, the acceptance rises from 7% at $M_{W'} = 200$ GeV/c^2 to 31% at $M_{W'} = 600$ GeV/c^2, as shown in Table I.

TABLE I. Final results from the $X \to WZ^0$ search using 110 pb^{-1} of data for $\Gamma(X) \ll M_X$. Here we have modeled the new particle production with $W' \to WZ^0$ in an extended gauge model with $\xi = (\frac{M_W}{M_{W'}})^2$, where ξ is the mixing factor between the W' and the SM W boson. Note that the 95% C.L. cross section upper limit from the fit is on $X \to WZ^0$ with $W \to e\nu$. In the denominator of the acceptance, A_X, we have allowed Z^0 to have all decays.

M_X (GeV/c^2)	A_X	95% C.L. $\sigma \cdot \mathcal{B}$ Limit (pb)
200	0.07	9.5
300	0.17	4.5
400	0.24	1.3
500	0.29	0.7
600	0.31	0.5

New production would show up as a resonance (peak) in both the dijet mass ($M_{\rm dijet} = M_{Z^0}$) and the W+dijet mass ($M_{W+\rm dijet} = M_X$). Since a signal would appear as a clustered excess of events above the background spectrum, we search by analyzing the shape of the data in the dijet vs. W+dijet mass plane. Invariant masses are calculated using the measured energies and directions of the electron, $\not\!\!E_T$, and the two jets. To form the W+dijet mass we fix the mass of the electron+$\not\!\!E_T$ system to be equal to the W boson mass, which restricts the neutrino's unmeasured longitudinal momentum to at most two possible values. When there are two solutions, we choose the one that yields a lower W+dijet invariant mass. When there is no solution, we fix p_z^ν such that the reconstructed W mass equals the transverse mass: $M_W = M_T \equiv 2p_T^e p_T^\nu[1-\cos(\phi^e - \phi^\nu)]^{1/2}$. For $\Gamma(X) \ll M_X$, MC studies show that on average these choices correctly reproduce the Z^0 and X masses with 15% resolution and no significant bias. For a given $\Gamma(X)$ the W+dijet mass distribution is given by this mass resolution and the intrinsic particle width.

The primary background to this search is SM W+jets production with $W \to e\nu$. To estimate this background, we use the VECBOS MC [9] with $Q^2 = \langle P_T^{\rm partons}\rangle^2 + M_W^2$, MRSDO$'$ structure functions [10], HERWIG parton fragmentation [11], and the detector simulation. The $W \to$

$\tau\nu \rightarrow e\nu\nu\nu$ background is similarly estimated but with TAUOLA MC [12] used to model the decay $\tau \rightarrow e\nu\nu$. We use VECBOS to model the kinematics of the events, but use the data for an overall normalization. Other backgrounds which produce the $e\nu jj$ final state include SM production of $t\bar{t}$, W^+W^-, $t\bar{b}$, WZ^0, $Z^0(\rightarrow e^+e^-)$ + jets, $Z^0(\rightarrow \tau^+\tau^-)$ + jets, and multijet fakes. The $t\bar{t}$, W^+W^-, $t\bar{b}$, and WZ^0 backgrounds directly produce $e\nu jj$ events. Each is estimated using PYTHIA and the detector simulation, and is normalized to the measured or theoretical cross sections [13]. We estimate that there are 45 $\pm$ 14 $t\bar{t}$ events, 9 $\pm$ 3 W^+W^- events, 3.0 $\pm$ 0.9 $t\bar{b}$ events and 1.6 $\pm$ 0.5 WZ^0 events in the data. The $Z^0(\rightarrow e^+e^-)$ + jets and $Z^0(\rightarrow \tau^+\tau^-)$ + jets events can fake the $e\not{E}_T jj$ signature if an electron from a $Z^0(\rightarrow e^+e^-)+ \geq 2$ jet event is lost, faking the neutrino signature, or if in a Z^0 + 1 jet event an energy mismeasurement gives fake $\not{E}_T$ and an electron or tau is misidentified as a jet. We estimate the Z^0+jets backgrounds using a combination of the PYTHIA and VECBOS MC programs and the detector simulation, and normalize to the measured number of Z^0 + 1 jet data events in the $Z^0 \rightarrow e^+e^-$ channel. We estimate that there are 36 $\pm$ 5 $Z^0(\rightarrow e^+e^-)$ + jets events and 1.6 $\pm$ 0.6 $Z^0(\rightarrow \tau^+\tau^-)$ + jets events in the data. QCD multijet events can fake the $e\nu jj$ signature if a jet is misidentified as an electron and an energy mismeasurement in the calorimeter causes $\not{E}_T$. We estimate this background from the data in a manner similar to that used in Ref. [14], and predict that 27 $\pm$ 3 QCD multijet events remain in the final sample. The contribution from all processes other than W+jets is 123 $\pm$ 16 events.

We use a binned likelihood fit in the dijet vs. W+dijet mass plane (20 GeV/c^2 $\times$ 20 GeV/c^2 bins) to search for resonant WZ^0 production. All backgrounds except W+jets are normalized absolutely. The normalization of the W+jets background in the fit is fixed such that the sum of the signal and all backgrounds equals the number of events observed in the data. The relative magnitude of the signal and the W+jets background is the only free parameter in the fit [15]. The W+dijet mass spectrum for the data and background is shown in Figure 1 for events with the dijet mass around M_{Z^0} and in the regions outside a 25 GeV/c^2 mass window, with the expected distributions plotted assuming no signal contribution. The results of the fit require no significant signal contribution and there is no evidence of resonant WZ^0 production for any mass or width for the acceptance model.

In order to examine the sensitivity to new particle production, we consider a class of models which extend the SM and contain heavier versions of the ordinary W and Z^0 vector bosons, labeled W' and Z' [16]. In the simplest model there are no additional fermions, the W' is a heavier version of the SM W, and the W and W' vertex couplings ($Wq\bar{q}'$, $W\ell\nu$ and WWZ^0) are identical. The dominant features of this reference model are the high production cross sections, and the increase in the partial width of the W', $\Gamma(W' \rightarrow WZ^0) \propto M^5_{W'}$, which yields a large branching fraction into WZ^0. However,

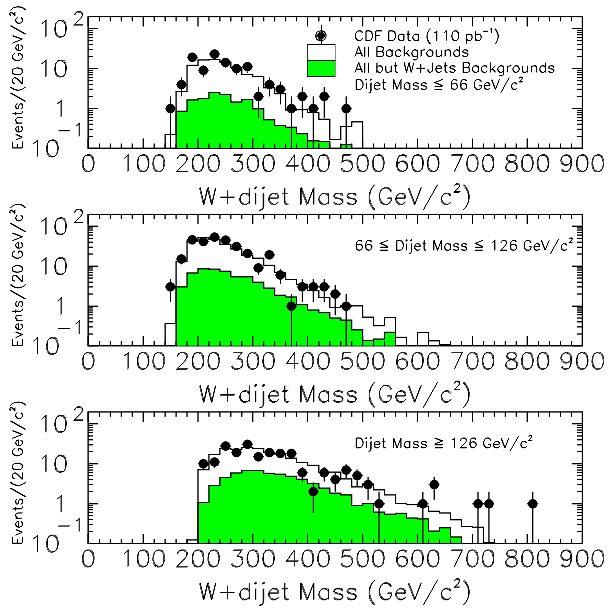

FIG. 1. The W+dijet mass spectra for the data and background with three different dijet mass requirements: $M_{\rm dijet} \leq 66$ GeV/c^2, $66 \leq M_{\rm dijet} \leq 126$ GeV/c^2 and $M_{\rm dijet} \geq 126$ GeV/c^2. A signal would appear as a resonance in the middle plot. The W+jets background spectrum is normalized as described in the text so that there are the same number of events in the data as in the backgrounds. The upper and lower plots show that the region outside the signal region is well modeled.

at large masses, $M_{W'} \approx 425$ GeV/c^2, $\Gamma(W')$ becomes so large that perturbation theory is no longer valid [17]. While the presence of a direct $W'WZ^0$ vertex makes the reference model itself implausible, similar results can be obtained with a strongly interacting Higgs or non-linear realization of electroweak theory [18].

Extended gauge models [19], which restore left-right symmetry to the weak force, predict an effective $W'WZ^0$ vertex term due to W' and W mixing. These models give the same $W'WZ^0$ vertex as in the reference model, but multiplied by a mixing factor, ξ, which is estimated to be of the order $(\frac{M_W}{M_{W'}})^2$ [2]. Using $\xi = 1$ reproduces the reference model. In this case the width only increases linearly with $M_{W'}$ and is small compared to both the mass and the detector resolution for all masses. Most previous searches for direct production and decay of W' have assumed this type of result with small ξ and searched in the $W' \rightarrow \ell\nu$ and $W' \rightarrow jj$ channels, establishing a limit of $M_{W'} > 786$ GeV/c^2 [14,20,21]. However, if the ν is heavy, unstable, or highly interacting (as might be the case with right-handed neutrinos), or the $W' \rightarrow \ell\nu$ and $W' \rightarrow jj$ decays are otherwise forbidden, the branching fraction of $W' \rightarrow WZ^0$ can be large. Although other models also predict new particles which have large branching fractions into WZ^0, we set limits in the extended gauge model to allow quantitative comparisons.

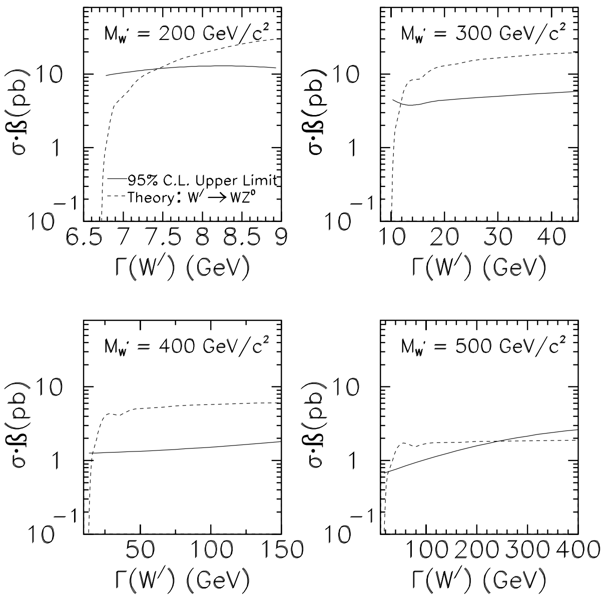

FIG. 2. The 95% C.L. upper limits on $\sigma \cdot \mathcal{B}$ as a function of the width, $\Gamma(W')$. Here the branching ratio includes $W' \to WZ^0$ and $W \to e\nu$.

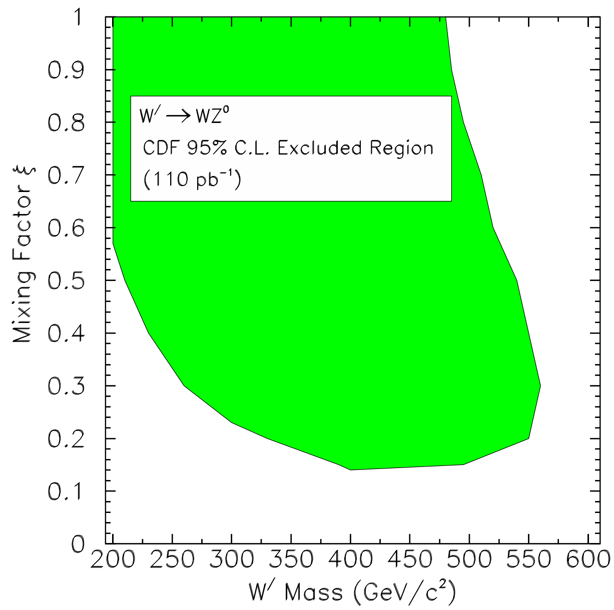

FIG. 3. The 95% C.L. excluded region in the ξ vs. $M_{W'}$ plane, where ξ is the mixing factor between the W' and the SM W boson. The largest mass exclusion occurs for $\xi = 0.3$, where we exclude $M_{W'} < 560$ GeV/c^2.

Since ξ directly affects the total width, resonant production can be modeled as a function of either ξ or $\Gamma(W')$. A previous search for $W' \to WZ^0$ for $\Gamma(W') \ll M_{W'}$ can be found in [22].

We set cross section limits on $\sigma \cdot \mathcal{B}(p\bar{p} \to X \to WZ^0) \cdot \mathcal{B}(W \to e\nu)$ using the fit technique described above and convoluting in systematic uncertainties, which depend on both mass and width, using the same methods as in Ref. [20]. The dominant source of uncertainty is the jet energy scale which would bias the measurement of the dijet and W+dijet masses from the new particle X. The effect of such a bias is largest at lower mass, where increased background in the signal region can cause a large variation in the cross section limit. For example, the effect is between 50% and 100% for the reference model and between 30% and 60% for the extended gauge model with $\xi = (\frac{M_W}{M_{W'}})^2$. Other notable sources of uncertainty are: uncertainty in the jet resolution (between 15% and 30%), effect of the Q^2 scale on the W+jets background shape (between 5% and 25%), choice of parton distribution functions (between 10% and 30%), uncertainty in W' acceptance (between 5% and 30%), and MC modeling of initial and final state radiation (between 5% and 15%). The total systematic uncertainty is found by adding the above sources in quadrature, and varies between 50-100% for the reference model and 40-75% for the extended gauge model with $\xi = (\frac{M_W}{M_{W'}})^2$.

The 95% C.L. upper limits on $\sigma \cdot \mathcal{B}$ are shown in Figure 2 as a function of $\Gamma(W')$ along with the predictions of the extended gauge model. Table I gives a summary of results for the $\Gamma(W') \ll M_{W'}$ approximation using $\xi = (\frac{M_W}{M_{W'}})^2$. Figure 3 shows the W' exclusion region for ξ vs. $M_{W'}$ where the theoretical cross section exceeds the calculated 95% C.L. upper limit. For the reference model ($\xi = 1$), we exclude the region $200 \leq M_{W'} \leq 480$ GeV/c^2. Since the reference model is no longer valid for masses above 425 GeV/c^2, and $W' \to \ell\nu$ searches have excluded it for masses less than 200 GeV/c^2, the entire model is excluded.

In conclusion, we have conducted a search for new particles which decay via $X \to WZ^0$ in the $e\nu jj$ channel. We observe no evidence of resonant production and estimate production cross section limits as a function of mass and width. We exclude at the 95% C.L. direct $W' \to WZ^0$ decay in a reference model with a W' having the same couplings as a SM W boson. We further exclude regions in the ξ vs. $M_{W'}$ space for an extended gauge model. These are the most comprehensive exclusions for direct $W' \to WZ^0$.

We thank JoAnne Hewett, Tom Rizzo, and Jon Rosner for useful discussions and Jose Benlloch, Dan Hennessy, Marcus Hohlmann, Sacha Kopp, 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 Italian Istituto Nazionale di Fisica Nucleare; the Ministry of Education, Science, Sports and Culture of Japan; the Natural Sciences and Engineering Research Council of Canada; the National Science Council of the Republic of China; the Swiss National Science Foundation; the A. P. Sloan Foundation; the Bundesministerium fuer Bildung und Forschung, Germany; the Korea Science and Engineering Foundation (KoSEF); the Korea

Research Foundation; and the Comision Interministerial de Ciencia y Tecnologia, Spain.

---

[1] Examples of such analyses include CDF Collaboration, F. Abe *et al.,* Phys. Rev. Lett. **81**, 1791 (1998); DØ Collaboration, B. Abbott *et al.,* Phys. Rev. Lett. **86**, 3712 (2001).
[2] P. Ramond, Ann. Rev. Nucl. Part. Sci. **33**, 31 (1983).
[3] K. Lane and E. Eichten, Phys. Lett. B **222**, 274 (1989); K. Lane, Phys. Rev. D **60**, 075007 (1999); also see K. Lane, hep-ph/0007304 (2000).
[4] CDF Collaboration, F. Abe *et al.,* Nucl. Instrum. Methods **271**, 387 (1988).
[5] We use cylindrical coordinates where positive z points along the proton beam 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 polar angle with respect to the proton beam direction and ϕ is the azimuthal angle. The transverse energy is defined as $E_T = E\sin\theta$, where E is measured in the calorimeter.
[6] We require that the electron candidate pass identification and isolation requirements. The scalar sum of the p_T of all tracks in the tracking chamber within a cone of $\Delta R = 0.25$ surrounding, but not including, the electron be less than 5 GeV/c, and that the E_T in a cone of $\Delta R = 0.4$ around, but not including, the electron candidate be less than 10% of the electron E_T.
[7] The fiducial region is $0.05 \leq |\eta| < 1.05$ and away from the edges of the calorimeter; for a more complete discussion of the fiducial region, see section 2.c. of F. Abe *et al.,* Phys. Rev. D **52**, 2624 (1995).
[8] H. Bengtsson and T. Sjöstrand, Comput. Phys. Commun. **46**, 43 (1987).
[9] F.A. Berends, W.T. Giele, H. Kuijf, and B. Tausk, Nucl. Phys. B **357**, 32 (1991).
[10] A.D. Martin, R.G. Roberts, and W.J. Stirling, Phys. Rev. D **50**, 6734 (1994).
[11] We have interfaced the subsequent parton shower evolution and hadronization by the interface using the routines of G. Marchesini and B.R. Webber, Nucl. Phys. B **310**, 461 (1988); G. Marchesini *et al.,* Comput. Phys. Commun. **67**, 465 (1992).
[12] S. Jadach, Z. Was, R. Decker, and J.H. Kuhn, TAUOLA version 2.4, Comput. Phys. Commun. **76**, 361 (1993).
[13] CDF Collaboration, F. Abe *et al.,* Phys. Rev. Lett. **73**, 2667 (1994); S. Willenbrock and D.A. Dicus, Phys. Rev. D **34**, 155 (1986); J. Ohnemus, Phys. Rev. D **44**, 1403 (1991); **44**, 3477 (1991).
[14] CDF Collaboration, F. Abe *et al.,* Phys. Rev. Lett. **74**, 2900 (1995).
[15] We note that the assumption of fixing the normalization of the non-W backgrounds has between a 1%-5% effect on the limit. This variation has been incorporated into the overall systematic uncertainty.
[16] G. Altarelli, B. Mele, and M. Ruiz-Altaba, Z. Phys. C **45**, 109 (1989).
[17] J. Gunion, H. Haber, G. Kane, and S. Dawson, *The Higgs Hunter's Guide*, Frontiers in Physics series (1989).
[18] P. Chiappetta and S. Narison, Phys. Lett. B **198**, 421 (1987); R. Casalbuoni *et al.,* Nucl. Phys. B **310**, 181 (1988).
[19] J. Pati and A. Salam, Phys. Rev. D **10**, 275 (1974); R.N. Mohapatra and J. Pati, Phys. Rev. D **11**, 566 (1975); **11**, 2558 (1975); G. Senjanovic and R.N. Mohapatra, Phys. Rev. D **12**, 1502 (1975).
[20] CDF Collaboration, F. Abe *et al.,* Phys. Rev. Lett. **74**, 3538 (1995).
[21] CDF Collaboration, T. Affolder *et al.,* submitted to Phys. Rev. Lett., hep-ex/0107008; DØ Collaboration, S. Abachi *et al.,* Phys. Lett. B **358**, 405 (1995); Phys. Rev. Lett. **76**, 3271 (1996).
[22] DØ Collaboration, V. M. Abazov *et al.,* hep-ex/0106039.