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

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Collider Detector at Fermilab Collaboration

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

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We present the first general search for new heavy particles,  $X$ , which decay via  $X \rightarrow WZ^0 \rightarrow e\nu + jj$  as a function of  $M_X$  and  $\Gamma(X)$  in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.8$  TeV. No evidence is found for production of  $X$  in  $110 \text{ pb}^{-1}$  of data collected by the Collider Detector at Fermilab. General cross section limits are set at the 95% C.L. as a function of mass and width of the new particle. The results are further interpreted as mass limits on the production of new heavy charged vector bosons which decay via  $W' \rightarrow WZ^0$  in an extended gauge model as a function of the width,  $\Gamma(W')$ , and mixing factor between the  $W'$  and the standard model  $W$  bosons.

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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].

A number of theories, including extended gauge models, nonlinear realizations of electroweak theory, a strongly interacting Higgs, and Technicolor, all predict new high mass particles  $X$  which decay via  $X \rightarrow WZ^0$  [2–4]. A general  $X \rightarrow WZ^0$  search can address all of these models, as well as new theories that may be proposed in the future. While typical searches in  $p\bar{p}$  collisions, such as for a Technicolor  $\rho_T \rightarrow WZ^0$  [4], consider the narrow resonance case,  $\Gamma(X) \ll M_X$ , there are good reasons to consider a general search which looks for  $X$  as a function of both mass and width, even for large widths. For instance, a new heavy charged vector boson,  $W'$ , has a width which can vary greatly because it depends on a mixing factor,  $\xi$ , between the  $W'$  and the  $W$  [5].

In this Letter, we present the first general search for  $X \rightarrow WZ^0$  production as a function of  $M_X$  and  $\Gamma(X)$  using  $p\bar{p}$  collisions at  $\sqrt{s} = 1.8$  TeV using the Collider Detector at Fermilab (CDF). We use the final state  $WZ^0 \rightarrow e\nu jj$  since it has the experimental advantages of a large branching ratio for  $Z^0 \rightarrow jj$  and a striking signature of  $W \rightarrow e\nu$ . The data, taken during the 1992–1995 Tevatron Collider run, correspond to an integrated luminosity of  $110 \text{ pb}^{-1}$ . Detailed descriptions of the detector can be found elsewhere [6]. 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  $|\eta| < 1.1$  [7], and (iii) electromagnetic and hadronic calorimeters covering the pseudorapidity range  $|\eta| < 4.2$ . An electron is 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 clusters 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,  $\cancel{E}_T$ , in the transverse plane as measured in the calorimeters.

Candidate events are selected on-line by using a three-level trigger system [6] to identify  $W \rightarrow e\nu$  decays based on the requirement of an electron candidate with  $E_T > 22$  GeV,  $|\eta| < 1.1$  and a matching drift chamber track, and  $\cancel{E}_T > 22$  GeV. Several backup trigger paths, imposing, for example, electron  $E_T > 25$  GeV with no track requirement and  $\cancel{E}_T > 25$  GeV, combine to make the trigger inefficiency for  $X \rightarrow WZ^0$  production negligible in the final  $W \rightarrow e\nu$  sample. To search for resonant  $WZ^0$  production, and to reduce standard model backgrounds, we raise the  $E_T$  and  $\cancel{E}_T$  thresholds and require two jets to be present. The final event selection requires an isolated electron [8] with  $E_T > 30$  GeV and  $\cancel{E}_T > 30$  GeV, and two jets with  $E_T > 50$  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 [9], 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  $X \rightarrow WZ^0 \rightarrow e\nu jj$  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  $X \rightarrow WZ^0$  and  $W \rightarrow e\nu$ ; the  $Z^0$  is allowed to have all decays. This definition allows nonquark decays of  $Z^0$ , such as  $Z^0 \rightarrow \tau^+\tau^- \rightarrow jj$ , to contribute to the acceptance. To compute  $A_X$ , we use the process  $W' \rightarrow WZ^0$  in the PYTHIA Monte Carlo (MC) [10], followed by a parametric simulation of the CDF detector. We simulate  $W' \rightarrow WZ^0$  production for a variety of masses and widths,  $\Gamma(W')$ . For narrow resonances,  $\Gamma(W') \ll M_{W'}$ , the acceptance rises from 7% at  $M_{W'} = 200 \text{ GeV}/c^2$  to 31% at  $M_{W'} = 600 \text{ GeV}/c^2$ . For a given mass, the acceptance falls with increasing particle width.

New production would show up as a resonance (peak) in both the dijet mass ( $M_{\text{dijet}} = M_{Z^0}$ ) and the  $W + \text{dijet}$  mass ( $M_{W+\text{dijet}} = M_X$ ). 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 the  $W + \text{dijet}$  mass plane. Invariant masses are calculated using the measured energies and directions of the electron,  $\cancel{E}_T$ , and the two jets. To form the  $W + \text{dijet}$  mass we fix the mass of the electron +  $\cancel{E}_T$  system to be equal to the  $W$  boson mass, which restricts the neutrino's unmeasured longitudinal momentum,  $p_z^\nu$ , to at most two possible values. When there are two solutions, we choose the one that yields a lower  $W + \text{dijet}$  invariant mass. When there is no solution, we fix  $p_z^\nu$  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  $W + \text{dijet}$  mass distribution is given by this mass resolution and the intrinsic particle width.

The primary background to this search is SM  $W + \text{jets}$  production with  $W \rightarrow e\nu$ . To estimate this background, we use the VECBOS MC [11] with  $Q^2 = \langle p_T^{\text{partons}} \rangle^2 + M_W^2$ , MRSDO' structure functions [12], HERWIG parton fragmentation [13], and the detector simulation. The  $W \rightarrow \tau\nu \rightarrow e\nu\nu\nu$  background is similarly estimated but with TAUOLA MC [14] 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  $t\bar{t}$ ,  $W^+W^-$ ,  $t\bar{b}$ ,  $WZ^0$ ,  $Z^0(\rightarrow e^+e^-) + \text{jets}$ ,  $Z^0(\rightarrow \tau^+\tau^-) + \text{jets}$ , 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 [15]. 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  $Z^0(\rightarrow e^+e^-) + \text{jets}$  and  $Z^0(\rightarrow \tau^+\tau^-) + \text{jets}$  events can fake the  $e\cancel{E}_T jj$  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  $\cancel{E}_T$  and an electron or tau is misidentified as a jet. We estimate the  $Z^0 + \text{jets}$  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  $36 \pm 5$   $Z^0(\rightarrow e^+e^-) + \text{jets}$  events and  $1.6 \pm 0.6$   $Z^0(\rightarrow \tau^+\tau^-) + \text{jets}$  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  $\cancel{E}_T$ . We estimate this background from the data in a manner similar to that used in Ref. [16], and predict that  $27 \pm 3$  QCD multijet events remain in the final sample. The contribution from all processes other than  $W + \text{jets}$  is  $123 \pm 16$  events.

We use a binned likelihood fit in the dijet vs  $W + \text{dijet}$  mass plane ( $20 \text{ GeV}/c^2 \times 20 \text{ GeV}/c^2$  bins) to search for resonant  $WZ^0$  production. All backgrounds, except  $W + \text{jets}$ , are normalized absolutely. The normalization of the

$W + \text{jets}$  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  $W + \text{jets}$  background is the only free parameter in the fit [17]. The  $W + \text{dijet}$  mass spectrum for the data and background is shown in Fig. 1 for events with the dijet mass around  $M_{Z^0}$  and in the regions outside a  $25 \text{ GeV}/c^2$  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.

To set general limits on the process  $p\bar{p} \rightarrow X \rightarrow WZ^0$ , we take  $X$  to be a  $W'$  in an extended gauge model as it spans both the  $M_X$  and  $\Gamma(X)$  parameter space. Following the prescription of Ref. [5] (no additional fermions and the  $W$  and  $W'$  vertex couplings,  $Wq\bar{q}'$ ,  $W\ell\nu$ , and  $WWZ^0$ , are identical), the production cross sections are uniquely determined as a function of mass, and the partial width of the  $W'$ ,  $\Gamma(W' \rightarrow WZ^0)$ , is determined by a mixing factor, labeled  $\xi$ , which describes the amount of mixing between the  $W$  and the  $W'$ . While this makes  $\Gamma$  a free parameter in the theory, we quote results in two specific cases. The full mixing case, or reference model [5], is where the new particle  $X$  couples in the same way as the SM  $W$  ( $\xi = 1$ )

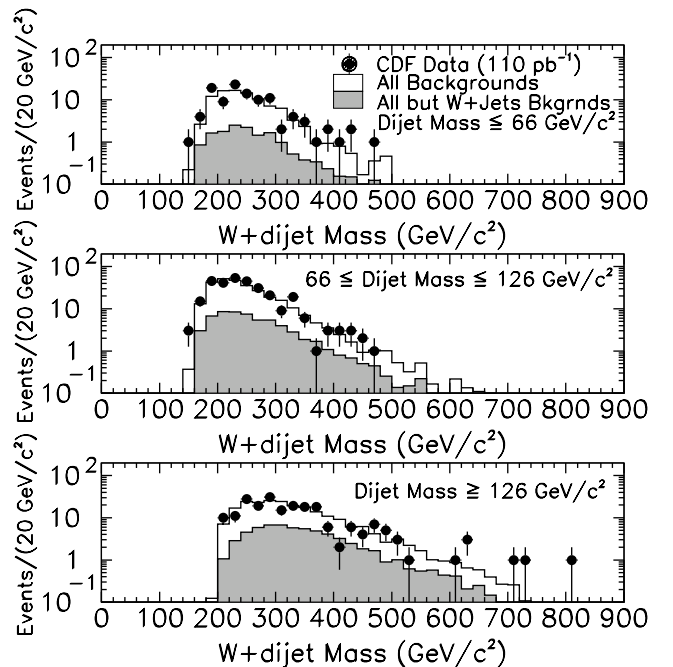


FIG. 1. The  $W + \text{dijet}$  mass spectra for the data and background with three different dijet mass requirements:  $M_{\text{dijet}} \leq 66 \text{ GeV}/c^2$ ,  $66 \leq M_{\text{dijet}} \leq 126 \text{ GeV}/c^2$ , and  $M_{\text{dijet}} \geq 126 \text{ GeV}/c^2$ . A signal would appear as a resonance in the middle plot. The  $W + \text{jets}$  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.

and gives  $\Gamma(W' \rightarrow WZ^0) \propto M_{W'}^5$ , yielding a large branching fraction into  $WZ^0$ , and widths comparable to the mass for  $M_{W'} \approx 425 \text{ GeV}/c^2$ . A second special case is  $\xi = (\frac{M_W}{M_{W'}})^2$  as in extended gauge models which restore left-right symmetry to the weak force and predict an effective  $W'WZ^0$  vertex term [2]. In this case,  $\Gamma(W') \ll M_{W'}$  for all masses.

We set limits on  $\sigma(p\bar{p} \rightarrow X) \cdot \mathcal{B}$ , where  $\mathcal{B} \equiv \mathcal{B}(X \rightarrow WZ^0) \cdot \mathcal{B}(W \rightarrow e\nu)$ , 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. [18]. The dominant source of uncertainty is the jet energy scale which would bias the measurement of the dijet and  $W + \text{dijet}$  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  $\xi = (\frac{M_W}{M_{W'}})^2$ . Other notable sources of uncertainty are uncertainty in the jet resolution (between 15% and 30%), effect of the  $Q^2$  scale on the  $W + \text{jets}$  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  $\xi = (\frac{M_W}{M_{W'}})^2$ .

The 95% C.L. upper limits on  $\sigma \cdot \mathcal{B}$  for  $M_X = 200, 300, 400,$  and  $500 \text{ GeV}/c^2$  are shown in Fig. 2 as a func-

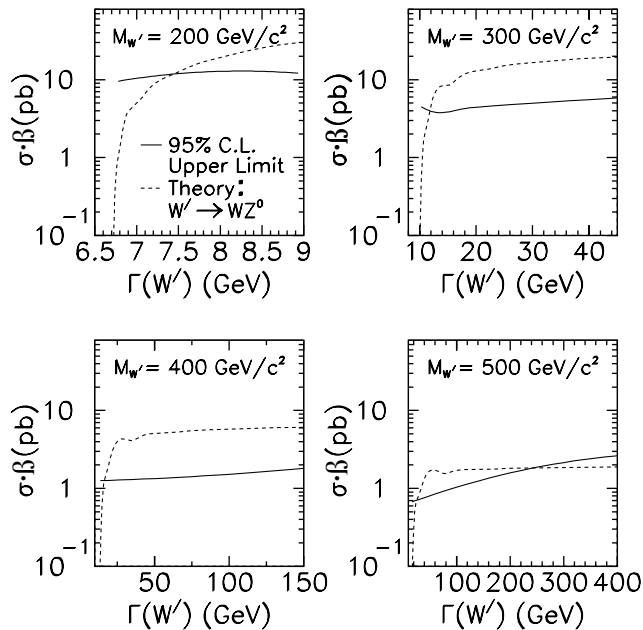


FIG. 2. The 95% C.L. upper limits on  $\sigma \cdot \mathcal{B}$  as a function of the width. We use  $\Gamma(W')$  because it uniquely determines the  $W' \rightarrow WZ^0$  branching ratio. Our results include the  $W' \rightarrow WZ^0$  and  $W \rightarrow e\nu$  branching ratios.

TABLE I. Final results from the  $X \rightarrow WZ^0$  search using  $110 \text{ pb}^{-1}$  of data for  $\Gamma(X) \ll M_X$ . Here we have modeled the new particle production with  $W' \rightarrow WZ^0$  in an extended gauge model for the special case of  $\xi = (\frac{M_W}{M_{W'}})^2$ , where  $\xi$  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  $X \rightarrow WZ^0$  with  $W \rightarrow e\nu$ . 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

tion of the width. While these limits are not sensitive enough to set mass limits on  $\rho_T \rightarrow WZ^0$  production [4], they exclude a large region of  $W'$  parameter space. Table I gives a summary of results for the  $\Gamma(W') \ll M_{W'}$  approximation using  $\xi = (\frac{M_W}{M_{W'}})^2$ . The results in Fig. 2 can be interpreted as the first cross section limits as a function of  $W'$  width, and Fig. 3 shows the first  $W'$  exclusion region for  $\xi$  vs  $M_{W'}$ , where the theoretical cross section exceeds the calculated 95% C.L. upper limit. Other direct searches for  $W'$  at the Tevatron in the  $W' \rightarrow \ell\nu$  and  $W' \rightarrow jj$  channels have established a limit of  $M_{W'} > 786 \text{ GeV}/c^2$  [16,18,19], but only in the region of  $\xi = 0$ , which is

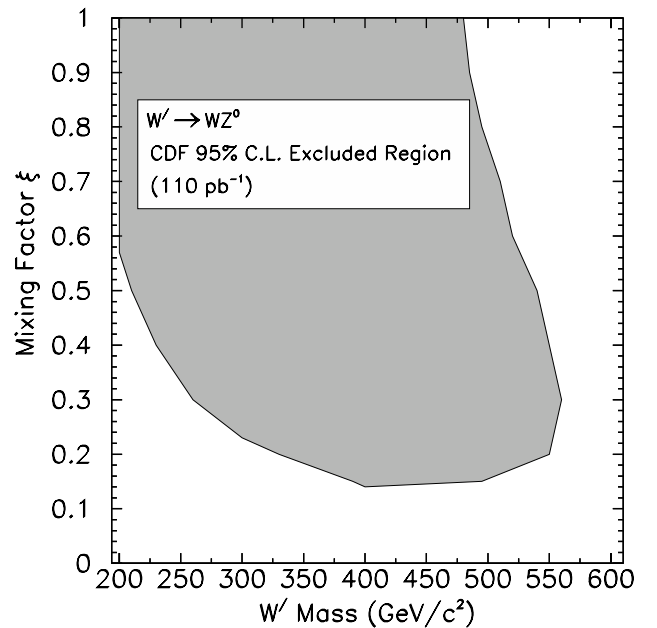


FIG. 3. The 95% C.L. excluded region in the  $\xi$  vs  $M_{W'}$  plane, where  $\xi$  is the mixing factor between the  $W'$  and the SM  $W$  boson. While the branching fraction goes up with increasing values of  $\xi$  and mass, the acceptance goes down as  $\xi$  and the width increase. This causes the “nose” effect in the exclusion region. The largest mass exclusion occurs for  $\xi = 0.3$ , where we exclude  $M_{W'} < 560 \text{ GeV}/c^2$ .

complementary to the region excluded in Fig. 3, and is only valid for  $\Gamma(W') \ll M_{W'}$ . A previous search for  $W' \rightarrow WZ^0$  [20] sets cross section limits for  $M_{W'} = 200, 350,$  and  $500 \text{ GeV}/c^2$ , but only for  $\Gamma(W') \ll M_{W'}$ .

For a  $W'$  in the reference model ( $\xi = 1$ ), we exclude the region  $200 \leq M_{W'} \leq 480 \text{ GeV}/c^2$ . For masses below  $200 \text{ GeV}/c^2$ , the widths are small and the reference model is excluded at the 95% C.L. by the  $W' \rightarrow \ell\nu$  results [5,16]. Since the reference model is no longer valid for masses above  $425 \text{ GeV}/c^2$  [ $\Gamma(W')$  becomes so large that perturbation theory is no longer valid [21]], the entire model is now excluded. These results are generally applicable to other new particles  $X$  with wide widths [3].

In conclusion, we have conducted a general search for new particles which decay via  $X \rightarrow WZ^0$  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. The results are further interpreted as mass limits on the production of new heavy charged vector bosons which decay via  $W' \rightarrow WZ^0$  in extended gauge models as a function of the width,  $\Gamma(W')$ , and mixing factor between the  $W'$  and the  $W$  bosons. These are the first limits on  $X \rightarrow WZ^0$  as a function of both mass and width, and are the only direct mass limits on  $W' \rightarrow WZ^0$  to date.

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- [8] 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 must be less than  $5 \text{ GeV}/c$ , and that the  $E_T$  in a cone of  $\Delta R = 0.4$  around, but not including, the electron candidate must be less than 10% of the electron  $E_T$ .
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