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## Search for Quark-Lepton Compositeness and a Heavy $W$ Boson Using the $e\nu$ Channel in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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# Search for Quark-Lepton Compositeness and a Heavy $W'$ Boson Using the $e\nu$ Channel in $p\bar{p}$ Collisions at $\sqrt{s} = 1.8$ TeV

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We present searches for quark-lepton compositeness and a heavy  $W'$  boson at high electron-neutrino transverse mass. We use  $\sim 110 \text{ pb}^{-1}$  of data collected in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.8 \text{ TeV}$  by the CDF Collaboration during 1992–1995. The data are consistent with standard model expectations. Limits are set on the quark-lepton compositeness scale  $\Lambda$ , the ratio of partial cross sections  $\sigma(W' \rightarrow e\nu)/\sigma(W \rightarrow e\nu)$ , and the mass of a  $W'$  boson with standard model couplings. We exclude  $\Lambda < 2.81 \text{ TeV}$  and a  $W'$  boson with mass below  $754 \text{ GeV}/c^2$  at the 95% confidence level. Combining with our previously published limit obtained using the muon channel, we exclude a  $W'$  boson with mass below  $786 \text{ GeV}/c^2$  at the 95% confidence level.

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The standard model (SM) gives a good description of nature in terms of the fundamental fermions and their interactions via gauge bosons. However, the SM is not expected to be a complete theory. For example, it does not explain the number of fermion families or their mass hierarchy. It also does not provide a unified description of all gauge symmetries. Compositeness models postulate constituents of the SM fermions and new strong dynamics that bind these constituents [1]. Other extensions of the SM postulate larger gauge groups and therefore new forces associated with additional charged gauge bosons, which we generically call  $W'$ . For instance, the left-right symmetric model [2] expands the  $SU(2)_L \times U(1)$  electroweak group to  $SU(2)_L \times SU(2)_R \times U(1)$ , predicting an additional right-handed charged gauge boson.

At center-of-mass energies much smaller than the compositeness energy scale  $\Lambda$ , interactions between composite quarks and/or leptons have been parametrized by effective four-fermion contact interactions [1]. Atomic parity violation experiments have set stringent, though model-dependent limits on quark-lepton compositeness in the neutral current channel [3]. Direct searches have set limits on  $\Lambda$  in the range 2.5–7.9 TeV [4–11] in a broad class of neutral current models. In this Letter, we present the first results of a search for compositeness in the charged current channel ( $q\bar{q}'e\nu$ ) using the  $e\nu$  final state.

The  $e\nu$  final state is also sensitive to the direct production and decay of a  $W'$  boson. Previous indirect searches based on  $\mu$  decay, the  $K_L - K_S$  mass difference, neutrinoless double beta decay, and studies of  $b$  particles have resulted in stringent model-dependent limits on possible  $W'$  bosons [12]. Direct searches in various decay modes have produced lower limits on the  $W'$  mass,  $m_{W'}$ . The best limit of  $m_{W'} > 720 \text{ GeV}/c^2$  in the  $W' \rightarrow e\nu$  channel [13] assumes a light and stable neutrino, standard model couplings for the  $W'$  to fermions, and suppressed  $W' \rightarrow WZ$  decays, as in extended gauge models [14]. In this Letter, we set upper limits on the ratio of partial cross sections  $\sigma(W' \rightarrow e\nu)/\sigma(W \rightarrow e\nu)$  under the same assumptions. We use the latter to obtain the most stringent lower limit on  $m_{W'}$ . We also present the combined  $W'$  mass limit with our previously published limit obtained using the muon channel [15].

We use  $\sim 110 \text{ pb}^{-1}$  of data collected in  $p\bar{p}$  collisions at  $\sqrt{s} = 1.8 \text{ TeV}$  by the Collider Detector at Fermilab [16] during 1992–1995. The detector includes a tracking system immersed in a 1.4 T magnetic field, scintillator-based sampling electromagnetic and hadronic calorimeters, and a muon detector. For this analysis, electron candidates are accepted in the pseudorapidity range  $0.05 < |\eta| < 1.0$ , where  $\eta = -\log[\tan(\theta/2)]$ , and  $\theta$  is the polar angle with respect to the beam axis. Electrons detected near the fiducial edges of the calorimeter are removed to ensure uniform calorimeter response. We use a combination of electron and neutrino triggers to obtain an efficiency exceeding 99% for the high transverse mass  $e\nu$  final states that pass our off-line selection criteria.

After off-line reconstruction, the electromagnetic calorimeter cluster with the highest transverse energy ( $E_T \equiv E \sin\theta$ ) in the event must satisfy the following requirements: (i) the electron must deposit most [17] of its energy in the electromagnetic calorimeter, (ii) a track in the central drift chamber must match the calorimeter cluster in position, and (iii) the electron must be isolated in a cone of radius  $R \equiv \sqrt{\Delta\eta^2 + \Delta\phi^2} = 0.4$ , such that the fractional excess transverse energy in the cone,  $[E_T^{\text{tot}}(R=0.4) - E_T^e]/E_T^e < 0.1$ , where  $E_T^{\text{tot}}$  and  $E_T^e$  are the total and electron transverse energies, respectively. The kinematic cuts used to define the data sample are  $E_T^e > 30 \text{ GeV}$ , the transverse momentum ( $p_T$ ) of the associated track  $p_T^e > 13 \text{ GeV}/c$ , the missing transverse energy  $\cancel{E}_T > 30 \text{ GeV}$ , and the electron-neutrino transverse mass  $m_T(e\nu) > 50 \text{ GeV}/c^2$ , where  $m_T(e\nu) = \sqrt{2E_T^e \cancel{E}_T(1 - \cos\phi_{e\nu})}$ , and  $\phi_{e\nu}$  is the azimuthal angle between the electron and the  $\cancel{E}_T$  direction. The neutrino transverse momentum is identified with  $\cancel{E}_T$  by requiring transverse momentum balance in the event. Electron identification cuts based on  $E/p$  (ratio of calorimeter energy to matched track momentum) and calorimeter energy profiles, which are imposed for  $E_T^e < 50 \text{ GeV}$  to suppress jet misidentification backgrounds, are released for  $E_T^e > 50 \text{ GeV}$  to ensure maximum signal efficiency. A total of 31 436 events pass our selection criteria.

We use the PYTHIA [18] program to compute the compositeness and  $W'$  signal processes. The contact

interaction Lagrangian is weak-isoscalar and helicity-non-conserving. It is universal with respect to quark and lepton flavor, and conserves lepton flavor and lepton number. The contact interaction couplings are all set to  $g = \sqrt{4\pi}$ .

The detector response is simulated using a parametrized Monte Carlo program. The electromagnetic calorimeter sampling term is derived from test beam data. The underlying event contribution to the electron energy resolution is derived from  $W \rightarrow e\nu$  collider data. The constant term in the electromagnetic resolution is tuned to reproduce the observed width of the  $Z \rightarrow ee$  mass peak. The electromagnetic energy scale is set so that the reconstructed  $Z$  boson mass agrees with the world-average  $Z$  mass [19]. The hadronic response and resolution are tuned by studying the  $p_T$  balance in  $Z \rightarrow ee$  events.

In this analysis we normalize the number of SM background Monte Carlo events after detector simulation to the large inclusive  $W$  boson sample in the data. Thus we are analyzing the shape of the  $e\nu$  transverse mass distribution, and are insensitive to the uncertainty in the integrated luminosity of the data and to the overall efficiency. The efficiency of the additional electron identification cuts applied for  $E_T^e < 50$  GeV is determined using  $Z \rightarrow ee$  data where one of the electrons is tagged. The second electron then provides an unbiased sample with which to measure the efficiencies. Background subtraction is performed using the sidebands of the  $Z$  boson mass distribution. The combined efficiency of these additional cuts is  $(95.8 \pm 0.3)\%$ , relative to the full efficiency at high  $E_T^e$ .

The most important sources of misidentification background to  $p\bar{p} \rightarrow e\nu + X$  are (i) QCD multijet events, where a jet is misidentified as an electron and there is sufficient energy mismeasurement to create significant  $\cancel{E}_T$ , and (ii)  $Z \rightarrow ee$  events where one electron is lost or misreconstructed. The electromagnetic energy in a jet which has been misidentified as an electron is likely to be nonisolated. We select a representative sample of misidentified electrons by making the electron identification cuts on the base sample without the isolation cut, and then selecting nonisolated candidates. The relative normalization of this sample to the jet background in the signal sample is obtained from a “pure-jet” sample. The pure-jet sample is obtained in the same way as the signal sample except  $\cancel{E}_T < 10$  GeV, which excludes almost all  $W$  events. We make the non-isolation and isolation cuts on the pure-jet sample, and the ratio of the respective number of events accepted provides the normalization factor for the background. This technique assumes that the isolation for a jet is independent of  $\cancel{E}_T$ . The systematic uncertainty of 30% on the jet misidentification background is estimated by studying the correlation between isolation and  $\cancel{E}_T$ . The  $Z \rightarrow ee$  background is estimated using a Monte Carlo sample of  $Z \rightarrow ee$  events, passed through a full detector simulation and reconstructed like the data. The systematic uncertainty of 23% on the  $Z \rightarrow ee$  background is estimated by varying the detector response to electrons near the fiducial edges of the calorimeter. Other systematic uncertainties, indi-

TABLE I. Systematic uncertainties on the SM background and the signal due to the parton distribution functions (PDFs), the  $K$  factor, and the detector model.

	SM background (%)	Signal (%)
PDFs	10	10
$K$ factor	4	4
Hadronic resolution	0.1	2
Vertex $z$ width	0.5	1.8
Hadronic scale	0.2	1.6
EM resolution	0.1	1.5
Electron efficiency	1.0	1.0
EM scale	0.2	0.9
Total	11	12

cated in Table I, are derived by varying the parameters in the Monte Carlo simulation. In our published  $W' \rightarrow \mu\nu$  analysis [15], the maximum parton-distribution-function (PDF) uncertainty was found to be 10% at high  $m_T(e\nu)$ . This estimate is consistent with the PDF analysis discussed in [20]. We conservatively take the PDF uncertainty to be 10% in all our high  $m_T(e\nu)$  search bins.

Other high  $p_T$  processes also contribute to  $e\nu$  final states. Using PYTHIA, we evaluate the following background processes:  $W \rightarrow e\nu$  (dominant),  $W \rightarrow \tau\nu \rightarrow e\nu X$ ,  $t\bar{t} \rightarrow e\nu X$ ,  $WW \rightarrow e\nu X$ ,  $WZ \rightarrow e\nu X$ ,  $ZZ \rightarrow e\nu X$ , and  $\gamma^*/Z \rightarrow \tau\tau \rightarrow e\nu X$ . We pass these Monte Carlo events through the parametrized detector simulation to estimate their contribution. These physics backgrounds dominate over the misidentification backgrounds at high  $e\nu$  transverse mass, due to the presence of real neutrino(s) producing large  $\cancel{E}_T$ . For example, the jet and  $Z \rightarrow ee$  misidentification background fractions amount to 25% and 3%, respectively, for  $m_T(e\nu) > 150$  GeV/ $c^2$ .

Figure 1 shows the transverse mass distribution of the data events normalized to the bin width. Also shown is the expectation based on SM processes and detector backgrounds. We apply a mass-dependent  $K$  factor [defined as the ratio of the next-to-next-to leading order (NNLO) and the leading-order (LO) Drell-Yan cross section calculations from Ref. [21]] to the LO PYTHIA calculation. The  $K$  factor varies between 1.24 at 80 GeV/ $c^2$  and 1.65 at 800 GeV/ $c^2$ . The effects of the detector acceptance and response have been folded into the theoretical prediction. Table II shows the expected and the observed number of events in the high transverse mass bins. There is good agreement between the data and the expectation. Also shown are all backgrounds excluding the dominant SM  $W \rightarrow e\nu$  process, and the expectation of the compositeness model with  $\Lambda = 2$  TeV.

To set a limit on the compositeness scale  $\Lambda$ , we generate Monte Carlo events for the compositeness process using PYTHIA, corrected with the  $K$  factor. We perform a Bayesian analysis [19] of the shape of the  $m_T$  distribution of events. The expected number of events in the  $k$ th transverse mass bin is denoted by  $N_\Lambda^k = b^k + \mathcal{L} \epsilon^k \sigma_\Lambda^k$ , where  $\sigma_\Lambda^k$  is the predicted cross section for a given scale  $\Lambda$ ,

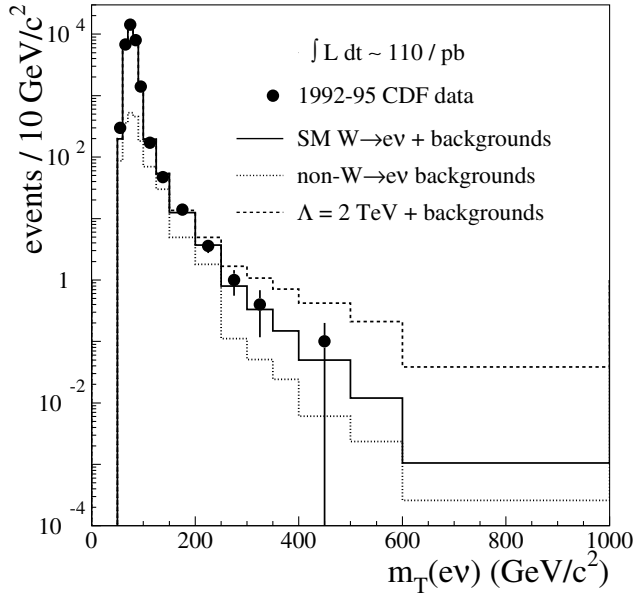


FIG. 1. The event yield from the data as a function of the  $e\nu$  transverse mass, normalized to the bin width. Also shown are the SM prediction including backgrounds, all backgrounds excluding the dominant SM  $W \rightarrow e\nu$  process, and the prediction of the compositeness process with energy scale  $\Lambda = 2$  TeV. The simulation of the physics processes includes the effects of detector acceptance and response.

and  $\epsilon^k$  and  $b^k$  denote the total acceptance and remaining backgrounds in the  $k$ th bin. The prediction for the number of events, including all backgrounds, is normalized to the observed number of events for  $m_T(e\nu) < 150$  GeV/ $c^2$ . Given the data ( $D$ ), we compute the posterior probability distribution for  $\Lambda$  according to

$$P(\Lambda | D) = \frac{1}{A} \int db d\epsilon \prod_{k=1}^n \left[ \frac{e^{-N_o^k} N_o^{k N_o^k}}{N_o^k!} P(b^k, \epsilon^k) \right] P(\Lambda).$$

$N_o^k$  denotes the observed number of events. We take the prior distribution  $P(b^k, \epsilon^k)$  of the nuisance parameters  $b$  and  $\epsilon$  to be Gaussian with the rms given by their total uncertainties. The bin-to-bin correlations in the uncertainty on the acceptance and background are taken into account. We make the conventional choice for the prior distribution

TABLE II. The observed number of events and the total expected number of events from SM and detector background sources, in transverse mass bins.

$m_T$ bin (GeV/ $c^2$ )	$N_{\text{observed}}$	$N_{\text{expected}}$
150–200	70	$62.2 \pm 8.5$
200–250	18	$18.3 \pm 3.4$
250–300	5	$4.01 \pm 0.44$
300–350	2	$1.61 \pm 0.18$
350–400	0	$0.72 \pm 0.08$
400–500	1	$0.49 \pm 0.06$
500–600	0	$0.11 \pm 0.02$
600–1000	0	$0.05 \pm 0.01$

$P(\Lambda)$  to be uniform in  $1/\Lambda^2$ . The 95% confidence level (C.L.) lower limit is defined by  $\int_{\Lambda}^{\infty} P(\Lambda' | D) d\Lambda' = 0.95$ , yielding  $\Lambda > 2.81$  TeV. The expected limit, obtained when the observed number of events is set equal to the expected number, is  $\Lambda > 2.70$  TeV. Varying the choice of the prior distribution  $P(\Lambda)$  changes the limit by 10%.

To set a limit on the mass of a  $W'$  boson, we compute the Poisson probability for the observed number of events given  $N_{\text{expected}} = N_{\text{background}} + N_{W'}$ . The Poisson probability is computed separately in three search windows:  $0.5M_{W'} < m_T < 0.65M_{W'}$ ,  $0.65M_{W'} < m_T < 0.8M_{W'}$ , and  $0.8M_{W'} < m_T < 1.1M_{W'}$ , and then the probabilities are combined. The use of three windows allows us to exploit the difference in the shape of the  $W'$  signal and background  $m_T$  distributions. Uncertainties in the backgrounds and signal acceptance are incorporated by convoluting the probability  $P(N_{W'})$  over Gaussian fluctuations in these parameters, taking correlations across bins into account. The 95% C.L. upper limit on the number of  $W'$  signal events,  $N_{W'}^{95}$ , is defined by  $\int_0^{N_{W'}^{95}} P(N_{W'}) d(N_{W'}) = 0.95$ . The limit  $N_{W'}^{95}$  may be expressed as a 95% C.L. limit on the ratio  $\sigma B(W' \rightarrow e\nu)/\sigma B(W \rightarrow e\nu)$  using

$$\left( \frac{\sigma B(W' \rightarrow e\nu)}{\sigma B(W \rightarrow e\nu)} \right)_{95} = \frac{N_{W'}^{95} A_W}{A_{W'} N_W},$$

where  $N_W$  is the observed number of SM  $W$  events and  $A_{W'}$  ( $A_W$ ) is the total acceptance for  $W' \rightarrow e\nu$  ( $W \rightarrow e\nu$ ) decays. The 95% C.L. upper limit on  $\sigma B(W' \rightarrow e\nu)/\sigma B(W \rightarrow e\nu)$  is plotted as a function of  $M_{W'}$  in Fig. 2 together with the theory curve from PYTHIA 6.129, assuming standard model couplings and including the  $K$  factor. From the intersection of the two curves, a  $W'$  boson with mass  $m_{W'} < 754$  GeV/ $c^2$  is excluded at 95% C.L. The expected limit in this case is 748 GeV/ $c^2$ . We combine this result with our previously published result on a  $W'$  boson using the  $\mu\nu$  final state [15]. Taking the PDF uncertainty to be fully correlated between the two analyses and with the same model assumptions, we obtain the combined limit excluding  $m_{W'} < 786$  GeV/ $c^2$  at the 95% C.L.

In conclusion, we find no significant deviation between the measured  $e\nu$  transverse mass distribution at high transverse mass and the SM prediction. We have used the data to exclude the quark-lepton compositeness scale  $\Lambda < 2.81$  TeV, in the context of an effective contact interaction. We set limits on the ratio of the cross section times branching ratio to  $e\nu$  of a  $W'$  boson to a standard model  $W$  boson. We use the latter to exclude a  $W'$  boson with SM couplings and mass  $m_{W'} < 754$  GeV/ $c^2$ . Combining with our muon channel result, we exclude  $m_{W'} < 786$  GeV/ $c^2$  at the 95% C.L.

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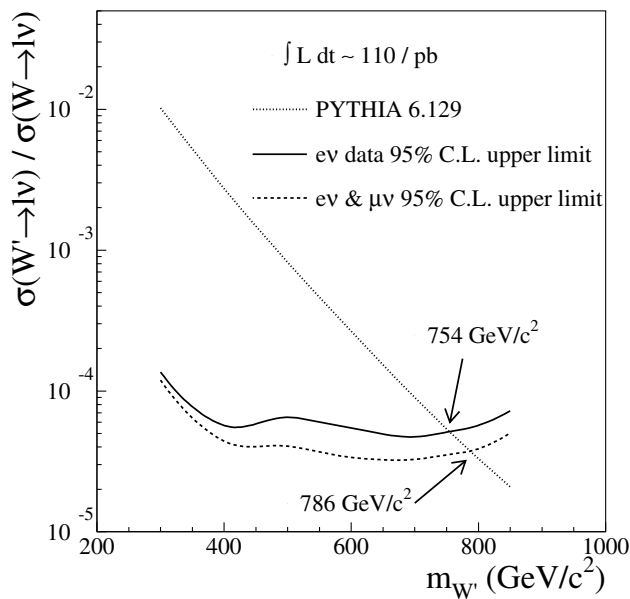


FIG. 2. The 95% C.L. upper limit on the ratio of partial cross sections  $\sigma(W' \rightarrow \ell\nu)/\sigma(W \rightarrow \ell\nu)$ , for the  $e$  data and the combined  $e + \mu$  data. Also shown is the SM prediction for this ratio, and the  $m_{W'}$  limits obtained from the intersection of the experimental and theory curves.

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