# Search for $W'$ Boson Decaying to Electron-Neutrino Pairs in $p\bar{p}$ Collisions at $\sqrt{s} = 1.96$ TeV

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We present the results of a search for $W'$ boson decaying to electron-neutrino pairs in $p\bar{p}$ collisions at a center-of-mass energy of 1.96 TeV, using a data sample corresponding to 205 pb$^{-1}$ of integrated luminosity collected by the CDF II detector at Fermilab. We observe no evidence for this decay mode and set limits on the production cross section times branching fraction, assuming the neutrinos from $W'$ boson decays to be light. If we assume the manifest left-right symmetric model, we exclude a $W'$ boson with mass less than 788 GeV/$c^2$ at the 95% confidence level.

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Although to date all data are consistent with the standard model of particle physics, the model is not a complete theory. For example, it does not explain the number of lepton and quark generations nor their mass hierarchy. Many theories have been proposed to address these deficiencies of the standard model. Some of these theories contain gauge symmetries that can be spontaneously broken down to the left-right symmetry [1] featuring a right-handed SU(2) symmetry and corresponding additional gauge bosons, including a right-handed charged heavy vector boson, generically known as a $W'$ boson [2, 3].

Previous direct searches for a new charged heavy vector boson have set model-dependent limits on the cross section times branching fraction. Searches considering the decay mode $W' \to e\nu_e$ and $W' \to \mu\nu_\mu$ have excluded a $W'$ boson with a mass below 754 and 660 GeV/$c^2$, respectively, at the 95% confidence level (CL) [4, 5]. Assuming the universality of lepton-$W'$ boson couplings, a $W'$ boson with a mass below 786 GeV/$c^2$ has been excluded at the 95% CL by combining the limits of both leptonic decay modes [4]. Also, a search considering a decay mode $W' \to t\bar{b}$ has excluded at the 95% CL a $W'$ boson with a mass below 670 GeV/$c^2$ for models with a right-handed neutrino that is heavier than a $W'$ boson [6]. These mass limits all assume the manifest left-right symmetry, where the right-handed CKM matrix and the gauge coupling constant are identical to those of the standard model [7]. Indirect searches have set model independent mass limits with less sensitivity studying, for example, the Michel spectrum in polarized muon decay [8].

In this report, we present the results of a search for a $W'$ boson in the $e\nu_e$ decay mode [9]. We use a data sample with an integrated luminosity of 205 pb$^{-1}$ of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV recorded by the upgraded Collider Detector at Fermilab (CDF II) during 2002–2003. This search is based on an analysis of high mass $e\nu_e$ final state candidates and assumes the neutrino from a $W'$ boson decay to be light and stable.

In this search, we select events that are consistent with the production of the standard model $W$ boson followed by its decay to an $e\nu_e$ final state and any heavier object that decays in the same manner. We set a limit on the production and decay of the heavier objects normalized by the observed rate of W bosons to this final state. This technique allows us to avoid uncertainties associated with the measurement of the absolute cross section or limit. This limit on the rate can be applied to any process that yields an $e\nu_e$ final state and has similar kinematic properties. We then use the limits on the rates to set a limit on the mass of the $W'$ boson, assuming the manifest left-right symmetric model and a suppression of diboson decay channels. The CDF II detector is described in detail elsewhere [10]. We use a coordinate system where $\theta$ is the polar angle to the proton beam, $\phi$ is the azimuthal angle about the beam axis, and $\eta$ is the pseudorapidity defined as $-\ln(\tan(\theta/2))$. The detector has a charged particle tracking system immersed in a 1.4-T solenoidal magnetic field coaxial with the proton and antiproton beams. The tracking system consists of an open-cell drift chamber surrounding a silicon tracking system that measures particle momentum. The electromagnetic and hadronic calorimeters surrounding the tracking system measure the energy of particles that interact electromagnetically or hadronically. These calorimeters are segmented in a projective tower geometry and divided into central calorimeters covering $|\eta| < 1.1$ and forward calorimeters covering $1.2 < |\eta| < 3.6$. An electron candidate is identified by an energy deposit with a track pointing to it in the electromagnetic calorimeter. A set of charged particle detectors surrounding the calorimeters is used to identify muon candidates with $|\eta| < 1.0$.

Candidate events are identified by the CDF trigger system requiring at least one electron candidate in the central electromagnetic calorimeter with transverse energy $E_T > 18$ GeV and a matching track with transverse momentum $p_T > 9$ GeV/$c$, where $E_T$ and $p_T$ are energy and momentum measured transverse to the beam line, respectively. An additional trigger with $E_T > 70$ GeV and no restriction on the amount of energy leakage into the hadronic calorimeter is used to ensure high efficiency for high $E_T$ electrons. Subsequently, we refine the candidate sample after full event reconstruction by requiring an electron candidate with $E_T > 25$ GeV and its track $p_T$ greater than 15 GeV/$c$ in the fiducial region of the detector within $|\eta| < 1.0$. We also require the electron candidates to be well isolated from energy flow in the event and to have shower profiles consistent with that of electron initiated showers [11]. The presence of a neutrino is inferred from a sizable missing transverse energy, $\not\!\!E_T$ [12]. We require the missing transverse energy in the event, $\not\!\!E_T$, to be greater than 25 GeV.

Additional requirements are imposed to reject specific sources of background. Dilepton events from Drell-Yan, $t\bar{t}$, and diboson backgrounds are removed by vetoing events with a second isolated lepton candidate, either an electron or a muon, with $p_T > 15$ GeV/$c$. QCD multijet events get misclassified into the $W/W' \to e\nu_e$ sample when one of the jets is misidentified as an electron candidate and the $\not\!\!E_T$ requirement is satisfied due to energy mismeasurement. In these QCD multijet events, the $\not\!\!E_T$ due to jet energy mismeasurement is generally much smaller than the $E_T$ of the jet misidentified as an electron candidate when the $E_T$ is large. However, $W/W' \to e\nu_e$ events will produce $E_T$ and $\not\!\!E_T$ comparable in magnitude, if the $p_T$ of the boson is much smaller than the mass of the boson. We require the ratio of the electron candidate $E_T$ to $\not\!\!E_T$ to be between 0.4 and 2.5. Any $W/W' \to e\nu_e$ events that lie outside the allowed region mostly have a high $p_T$ boson. This requirement has an efficiency above 99% for $W/W' \to e\nu_e$ events and an estimated rejection rate of $\sim 40\%$ for the misclassified QCD multijet events with high $E_T$. Additional details of the event selection requirements are presented in Ref. [13].

The resulting sample contains 120 484 events. The transverse mass of a candidate event is calculated as

$$M_T \equiv \sqrt{2E_T \not\!\!E_T \,(1 - \cos\phi_{e\nu})}, \qquad (1)$$

where $\phi_{e\nu}$ is the azimuthal opening angle between the electron candidate and the $\not\!\!E_T$ direction. This $M_T$ distribution has a clear Jacobian peak associated with the production and decay of the $W$ boson as shown in Fig. 1.

The shapes of $M_T$ distributions and the acceptance times efficiency for the $W'$ boson signal are estimated using PYTHIA Monte Carlo calculation [14] with CTEQ5L parton distribution functions (PDFs) [15], together with the GEANT [16]–based CDF II detector simulation. We require the $W'$ boson to have right-handed couplings to the fermions when generating signal Monte Carlo samples. The acceptance times efficiency rises from 41% for $M_{W'} = 200$ GeV/$c^2$, plateaus at 48% for 350 GeV/$c^2$, remains roughly flat up to 800 GeV/$c^2$, and then falls to 45% for $M_{W'} = 950$ GeV/$c^2$. The initial increase in the acceptance times efficiency is due to a heavier $W'$ boson produced more centrally. The subsequent fall is due to event selection requirements becoming less efficient for the high-energy electrons. We use a next-to-next-

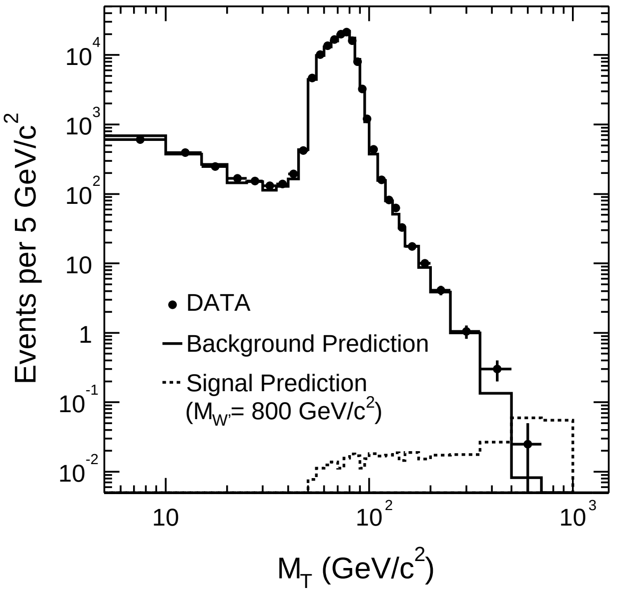

FIG. 1: The transverse mass distributions of $e\nu_e$ candidate events. The background rates are obtained from the fit described in the text. The distribution expected from the production of a $W'$ boson of $M_{W'} = 800$ GeV/$c^2$ is shown by the dashed line.

to-leading order (NNLO) cross section prediction [17] for the $W'$ boson production using MRST1 PDFs [18].

The largest background sources are $W$ or $Z$ boson production with the boson decaying to final states that contain electrons. These include $W \to e\nu_e$ which is the dominant background, $W \to \tau\nu_\tau \to e\nu_e\nu_\tau\nu_\tau$, $Z/\gamma^* \to ee$, and $Z/\gamma^* \to \tau\tau \to eX$. The other background sources are electrons coming from diboson production and $t\bar{t}$ production, and jets misidentified as electron candidates from QCD multijet production. The shapes of the $M_T$ distributions and acceptance times efficiency of the non-multijet backgrounds are calculated using samples generated with PYTHIA, except for $WW$ and $WZ$ backgrounds, which are calculated with ALPGEN [19], interfaced with HERWIG [20]. All Monte Carlo samples are subjected to the CDF II detector simulation. We use theoretical cross section predictions to estimate the expected background yields [17, 21, 22].

For the QCD multijet background, the predicted number of events is estimated from the data sample using the azimuthal opening angle between the direction of the electron candidate and the vector sum of the jet energy flow. Since a jet misidentified as an electron candidate will be seen as recoiling against the rest of the jets in the event, we expect to see back-to-back behavior in the azimuthal opening angle, whereas $W/W' \to e\nu_e$ events do not have a strong angular correlation [13]. The data and estimated background $M_T$ distributions are compared in Fig. 1. A small excess of events with a significance of about 1.8 standard deviations above the background expectation is observed in the 350–500 GeV/$c^2$ $M_T$ bin. The contributions from $W \to e\nu_e$, QCD multijet, and the rest of the backgrounds above $M_T = 200$ GeV/$c^2$ are listed in Table I.

In order to estimate the size of the potential signal contribution in the sample, a binned maximum likelihood fit is performed on the observed $M_T$ distribution between 0 and 1 500 GeV/$c^2$, using the background predictions and the expected $W'$ boson contribution with different mass values ranging from 200 to 950 GeV/$c^2$. The fit results are shown in Table II, expressed as

$$\beta \equiv \frac{\sigma \cdot \mathcal{B}(W' \to e\nu_e)}{\sigma \cdot \mathcal{B}(W' \to e\nu_e)_{LR}}, \tag{2}$$

where the numerator is the observed cross section times branching fraction and the denominator is the expected value from the manifest left-right symmetric model. The expected signal yield is normalized by the observed $W$ boson yield obtained from the fit. This normalization reduces the effects of uncertainties common to both the $W$ boson and W' boson yields, such as the uncertainties of an integrated luminosity and of theoretical cross sections.

We set upper limits on the rate of a $W'$ boson by constructing the posterior distribution for $\beta$ for each fixed value of $M_{W'}$. The likelihood is maximized for a fixed value of $\beta$ with respect to the background contributions. We use the resulting likelihood distribution to set the 95% CL upper limit on the ratio $\beta$ by numerically integrating over $\beta$. We consider the likelihood function only in the physical region where $\beta$ is greater than or equal to zero. Systematic uncertainties in the signal and background rates are incorporated in the upper limit using the Bayesian prescription of convoluting the likelihood function with a truncated Gaussian prior distribution for each nuisance parameter [23]. The upper limits in the cross section times branching fraction are obtained by multiplying the upper limits in $\beta$ by the theoretical cross section times branching fraction.

We consider systematic uncertainties due to uncertainties in PDFs, electron energy measurement, initial state radiation, and jet energy measurement. Since the uncertainty in the theoretical cross section of the $W'$ boson production does not affect the limit on the cross section, this uncertainty is not included when calculating the limit. The systematic uncertainty in the PDFs is decomposed into a component affecting the theoretical $W'$ production cross section and one affecting the expected acceptance of the $W'$ boson. The component affecting the theoretical cross section is thus removed from the cross section limit calculation but contributes to the mass limit calculation. The cross section uncertainties of backgrounds are also taken into account. The largest contribution to the systematic uncertainty below $M_{W'} = 700$ GeV/$c^2$ comes from the uncertainty in the jet energy measurement. The uncertainty in the signal acceptance due to the uncertainty in the PDFs is the dominant contribution above 700 GeV/$c^2$. The resulting

TABLE I: The event yields for the background sources in $M_T$ above 200 GeV/$c^2$ compared to the observed data. The uncertainties are correlated. The correlations are properly taken care of in the systematic uncertainty estimation.

| Background | Events in each $M_T$ bin (GeV/$c^2$) | | | | |
|---|---|---|---|---|---|
| | 200 - 250 | 250 - 350 | 350 - 500 | 500 - 700 | 700 - 1000 |
| $W \to e\nu$ | $30.8 \pm 5.7$ | $17.0 \pm 4.0$ | $3.52 \pm 1.70$ | $0.27 \pm 0.45$ | $< 0.01$ |
| QCD Multijet | $2.7 \pm 6.1$ | $0.0 \pm 3.3$ | $0.00 \pm 0.29$ | $0.00 \pm 0.01$ | $< 0.01$ |
| Other Backgrounds | $5.2 \pm 1.0$ | $3.0 \pm 0.9$ | $0.51 \pm 0.22$ | $0.06 \pm 0.08$ | $0.00 \pm 0.03$ |
| Total Background | $38.7 \pm 8.9$ | $20.0 \pm 5.9$ | $4.03 \pm 1.97$ | $0.33 \pm 0.53$ | $0.00 \pm 0.03$ |
| Data | 41 | 21 | 9 | 1 | 0 |

TABLE II: The expected numbers of the events from the $W' \to e\nu_e$ process, $N_{\rm exp}$, assuming the manifest left-right symmetric model and normalized by the observed $W$ boson yield. We also show observed rate of $W'$ boson production from the fit described in the text, and the 95% CL upper limit on this rate. The uncertainties are statistical only and do not include systematic uncertainties. The 95% upper limits include both statistical and systematic uncertainties.

| $M_{W'}$ | $N_{\rm exp}$ | $\beta\left(= \frac{\sigma\cdot\mathcal{B}(W'\to e\nu_e)}{\sigma\cdot\mathcal{B}(W'\to e\nu_e)_{LR}}\right)$ | |
|---|---|---|---|
| (GeV/$c^2$) | (events) | Fit | Upper Limit |
| 200 | 12000 | $0.002^{+0.002}_{-0.001}$ | 0.01 |
| 250 | 5390 | $0.002^{+0.002}_{-0.002}$ | 0.01 |
| 300 | 2630 | $0.001^{+0.003}_{-0.001}$ | 0.01 |
| 350 | 1380 | $0.008^{+0.006}_{-0.005}$ | 0.02 |
| 400 | 753 | $0.012^{+0.008}_{-0.006}$ | 0.03 |
| 450 | 417 | $0.019^{+0.012}_{-0.010}$ | 0.03 |
| 500 | 236 | $0.028^{+0.019}_{-0.015}$ | 0.08 |
| 550 | 135 | $0.030^{+0.030}_{-0.021}$ | 0.11 |
| 600 | 77.0 | $0.034^{+0.026}_{-0.026}$ | 0.16 |
| 650 | 43.7 | $0.040^{+0.064}_{-0.036}$ | 0.23 |
| 700 | 25.1 | $0.050^{+0.099}_{-0.050}$ | 0.36 |
| 750 | 14.2 | $0.060^{+0.162}_{-0.060}$ | 0.57 |
| 800 | 7.89 | $0.075^{+0.279}_{-0.075}$ | 1.00 |
| 850 | 4.35 | $0.081^{+0.512}_{-0.081}$ | 1.84 |
| 900 | 2.35 | $0.06^{+1.00}_{-0.06}$ | 3.70 |
| 950 | 1.24 | $0.00^{+2.15}_{-0.00}$ | 8.26 |

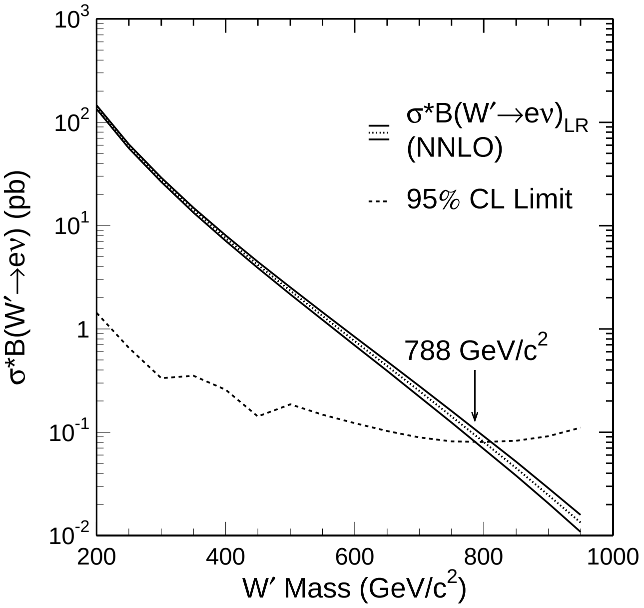

FIG. 2: The 95% CL limits on cross section times branching fraction as a function of $W'$ boson mass. The region above the dashed line is excluded at the 95% CL. Also, the cross section times branching fraction assuming the manifest left-right symmetric model, $\sigma \cdot \mathcal{B}(W' \to e\nu_e)_{LR}$, is shown along with its uncertainty. The intercept of the cross section limit curve and the lower bound of the theoretical cross section yields $M_{W'} > 788$ GeV/$c^2$ at the 95% CL.

upper limits in $\beta$ are summarized in Table II and the upper limits in the production cross section times branching fraction are plotted as a function of $M_{W'}$ in Fig. 2.

Using theoretical predictions assuming the manifest left-right symmetric model, which has the right-handed CKM matrix and the gauge coupling constant identical to those of the standard model, these limits on the cross section times branching fraction are converted into limits on the mass of a $W'$ boson. The uncertainty on the theoretical cross section is calculated by varying the momentum transfer scale and by using the uncertainties in the PDF parametrization. The uncertainty is shown as the band in Fig. 2. We take the lower bound of the theoretical cross section to obtain the mass limit. This allows us to exclude a $W'$ boson with mass below 788 GeV/$c^2$ at the 95% CL.

We estimate the sensitivity of our search to be 835 GeV/$c^2$ by calculating the median expected mass limit in a large ensemble of background-only pseudo-experiments. The discrepancy between the measured limit and the expected limit is largely due to the excess, though not statistically significant, observed in the $M_T$ region of 350–500 GeV/$c^2$.

In summary, we have performed a search for a new heavy charged vector boson decaying to an electron-neutrino pair with a light and stable neutrino in 1.96 TeV

$p\bar{p}$ collisions. We do not observe any statistically significant excess over background expectations. We use a fit of the $M_T$ distribution to set upper limits on the production and decay rate of a $W'$ boson and exclude a $W'$ boson with $M_{W'} < 788$ GeV/$c^2$ at the 95% CL, assuming the manifest left-right symmetric model.

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