Search for a new heavy gauge boson W' with event signature electron $+$ missing transverse energy in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

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We present a search for a new heavy charged vector boson W' decaying to an electron-neutrino pair in $p\bar{p}$ collisions at a center-of-mass energy of 1.96 TeV. The data were collected with the CDF II detector and correspond to an integrated luminosity of 5.3 fb^{-1}. No significant excess above the standard model expectation is observed and we set upper limits on $\sigma \cdot \mathcal{B}(W' \to e\nu)$. Assuming standard model couplings to fermions and the neutrino from the W' boson decay to be light, we exclude a W' boson with mass less than 1.12 TeV/c^2 at the 95% confidence level.

The W' [1] is a postulated charged heavy vector boson which is predicted in models that extend the gauge structure of the standard model. In the left-right (LR) symmetric model [2] considered here, the right-handed W' boson mass is obtained by the symmetry breaking of the right-handed electroweak gauge group of $SU(2)_R \times SU(2)_L \times U(1)_{B,L}$. This provides a natural explanation for the observed suppression of $V + A$ currents in low-energy weak processes. The LR symmetric model can also be motivated by the manifestation of a higher symmetry predicted at intermediate energies in grand unified theories [3].

The manifest LR symmetric model assumes that the right-handed Cabibbo-Kobayashi-Maskawa matrix and the gauge coupling constants are identical to those of the standard model [4]. The W' can decay in the same way as the standard model W, with the exception that the tb [5] decay channel is accessible if the W' is heavy enough and that the diboson decay channel ($W' \to WZ$) is suppressed in the extended gauge model [1].

The W' boson has been previously searched for in high-energy physics experiments using final state signatures such as leptons, jets, and/or missing energy. The most recent direct searches for a charged heavy vector boson have been performed at the Tevatron collider at Fermilab. The CDF experiment previously set limits on the cross section times branching fraction in the decay mode $W' \to tb$ and excluded a W' boson mass below 800 GeV/c^2 at the 95% confidence level (C.L.) using 1.9 fb^{-1} data of $p\bar{p}$ collisions [6]. The D0 experiment set limits on the product of the cross section and branching fraction in the decay mode $W' \to e\nu$ and excluded a W' boson mass below 1.00 TeV/c^2 at the 95% C.L. using 1.0 fb^{-1} of data [7]. Both of these recent mass limits assume that the couplings between the new vector boson and the fermionic final states are the same as in the standard model.

In this paper, we present the results of a search for a W' boson in the $e\nu$ decay mode, assuming the manifest LR symmetric model and the right-handed neutrino from the boson decay to be light ($m_\nu \ll m_{W'}$) and stable. Under these assumptions, the results in this paper can be useful in the generic model [1] since the kinematics of the left- and right-handed W' bosons is not different. We use a data sample corresponding to 5.3 fb^{-1} integrated luminosity of $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV recorded by the upgraded Collider Detector at Fermilab (CDF II). We select events that are consistent with the production of the standard

model W and the heavier W' boson that decay to an electron and neutrino in the final state. The analysis technique applied is the same as in a previous search [8].

The CDF II detector is described in detail elsewhere [9]. CDF II is a general purpose solenoidal detector which combines precision charged-particle tracking with fast projective calorimetry and fine-grained muon detection. Tracking systems are contained inside a superconducting solenoid, 1.5 m in radius and 4.8 m in length, which generates a 1.4 T magnetic field parallel to the beam axis. Calorimeters and muon systems surround the solenoid and the tracking system. Electron candidates are identified by an energy deposit in the electromagnetic calorimeter with a track pointing to it. A set of charged-particle detectors surrounding the calorimeters identify muon candidates. The energy of the electron candidate is measured by the calorimeter and its direction is determined from the tracking system. The component of the neutrino momentum transverse to the beam line is inferred to be equal to the missing transverse energy E_T [10], which is derived from the transverse energy imbalance of all the deposited energy in the calorimeters.

The on-line selection requires either one electron candidate in the electromagnetic calorimeter with transverse energy $E_T > 18$ GeV that has a matching track with transverse momentum $p_T > 9$ GeV/c or an electron candidate in the electromagnetic calorimeter with transverse energy $E_T > 70$ GeV. No restrictions on the amount of energy leakage into the hadronic calorimeter were imposed, in order to ensure high efficiency for high-E_T electrons. We select the candidate event sample off-line by requiring an isolated electron candidate with $E_T > 25$ GeV and the existence of an associated track with $p_T > 15$ GeV/c that is contained in the fiducial region of the tracking system of $|\eta| < 1.0$ [11]. Electron candidates are selected based on an E_T-dependent isolation cut [12] in order to maximize the efficiency in the high-E_T region. The electron shower profile is required to be consistent with that of test-beam electrons in order to match with the expected electromagnetic shower [13]. In events with high-energy muons, the E_T is adjusted by adding the muon momentum and removing the expected ionization energy deposition in the calorimeter. The E_T is corrected further for η- and energy-dependent nonuniformities of the calorimeter response. In the final selection, the corrected E_T is required to be greater than 25 GeV. Dilepton events coming from

Drell-Yan, $t\bar{t}$, and diboson backgrounds are vetoed by rejecting events with a second isolated lepton, either an electron or a muon, with $p_T > 15$ GeV/c. QCD multijet events are a background to $W/W' \rightarrow e\nu$ when a jet is misidentified as an electron and mismeasured jets lead to significant E_T. The electron candidate E_T and the event E_T are likely to significantly differ in magnitude in this case. In contrast, a $W/W' \rightarrow e\nu$ event will have an electron and neutrino emitted in opposite directions which results in the electron E_T and E_T being of comparable magnitude, respectively, assuming the p_T of the boson is much smaller than its mass. Thus, in order to reduce the QCD multijet background, we require the candidate events to satisfy $0.4 < E_T/E_T < 2.5$. The efficiency of this requirement is larger than 99% for W/W' events whereas the rejection fraction is $\sim 40\%$ for QCD multijet events with $E_T > 100$ GeV. After all selection requirements, the transverse mass of a candidate event is calculated as

$$m_T \equiv \sqrt{2E_T E_T (1 - \cos\phi_{e\nu})}, \qquad (1)$$

where $\phi_{e\nu}$ is the azimuthal opening angle between the electron candidate and the E_T direction.

The $W' \rightarrow e\nu$ signal events are generated with PYTHIA [14] using the CTEQ5L [15] parton distribution functions (PDFs) and a simulation of the CDF II detector [16]. Since the cross sections calculated by PYTHIA are at leading order, next-to-next-to-leading-order K factors are applied to the leading order cross sections. Mass-dependent next-to-next-to-leading-order K factors from Ref. [17] are obtained with an approximate magnitude around 1.3. The total acceptance times efficiency of the event selection cuts ranges from 45% to 35% and decreases above a W' boson mass of 800 GeV/c^2. Figure 1 shows the expected W' boson transverse mass distributions for various input masses with the background predictions. The on-shell production of heavy bosons near the kinematic limit is suppressed due to the smallness of the PDFs at large momentum fraction, which results in the low acceptance rate of W' events at high mass above 800 GeV/c^2 after applying the kinematic selection requirements.

The background sources to $W' \rightarrow e\nu$ are primarily processes with an electron and missing energy in the final state. These sources of background are $W \rightarrow e\nu$, $W \rightarrow \tau\nu \rightarrow e\nu\nu\nu$, $Z/\gamma^* \rightarrow \tau\tau \rightarrow eX$, tt, and diboson (WW, WZ) production. The $Z/\gamma^* \rightarrow ee$ process can also produce missing energy when one of the electrons escapes detection. The m_T distributions and acceptance times efficiency of the nonmultijet backgrounds are obtained using PYTHIA and a simulation of the CDF II detector. Theoretical cross section predictions are used to estimate the expected background yields [17–19]. For the QCD multijet background estimation, a data-driven method is applied that uses the distribution of the azimuthal angle between the primary electron candidate and the vector sum of the jet energy. For
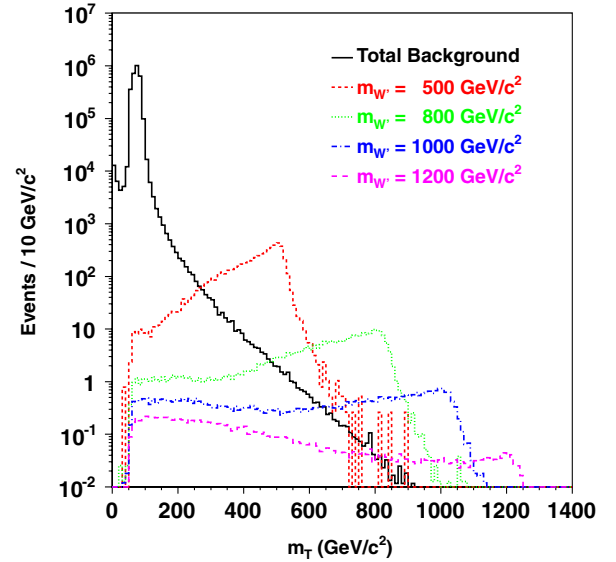

FIG. 1 (color online). The transverse mass distributions for $W' \rightarrow e\nu$ signal events generated using PYTHIA with total background expectation.

the multijet case, a jet misidentified as an electron candidate will appear to recoil against the rest of the jet in the event. Therefore, a back-to-back distribution is expected in the azimuthal opening angle. The $W/W' \rightarrow e\nu$ process, however, does not have a strong correlation in this angle. The QCD multijet contribution is estimated by a likelihood fit to the data using the different angular shapes. The multijet m_T distribution is obtained using a QCD enriched sideband sample with the isolation cut inverted. The data and the total background m_T distributions are compared in Fig. 2. The contributions from $W \rightarrow e\nu$, QCD multijet, and
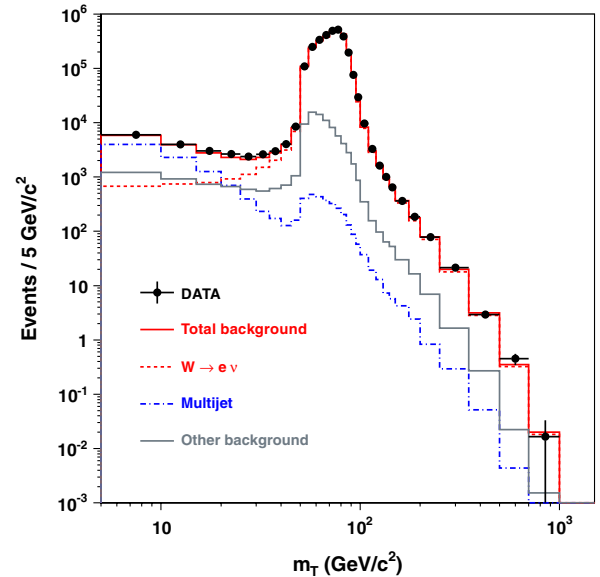

FIG. 2 (color online). The transverse mass distributions of $e\nu$ candidate events compared to the total backgrounds.

TABLE I.   The event yields for the background sources in m_T above 200 GeV/c^2 compared to the observed data.

	Events in m_T bins (GeV/c^2)				
	200–250	250–350	350–500	500–700	700–1000
$W \to e\nu$	711^{+50}_{-50}	359^{+25}_{-25}	85^{+6}_{-6}	13^{+1}_{-1}	$1.1^{+0.1}_{-0.1}$
Multijet	9^{+2}_{-2}	6^{+1}_{-1}	2^{+2}_{-2}	$0.2^{+1.6}_{-0.2}$	$0.01^{+1.10}_{-0.01}$
Other background	70^{+9}_{-6}	33^{+4}_{-3}	8^{+1}_{-1}	$1^{+0.1}_{-0.1}$	$0.09^{+0.01}_{-0.01}$
Total background	790^{+61}_{-58}	398^{+31}_{-30}	94^{+9}_{-8}	14^{+3}_{-1}	$1.2^{+1.2}_{-0.1}$
Data	784	426	88	18	1

the other backgrounds in the mass region above $m_T = 200$ GeV/c^2 are listed in Table I. This comparison shows good agreement between the data and the total backgrounds.

In order to quantify the size of the potential signal contributions in the data sample, a binned maximum likelihood fit was performed on the observed m_T distribution between 0 and 1500 GeV/c^2, using the background predictions and the expected W' boson contribution for

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

$m_{W'}$	$N_{\rm exp}$	$\beta(= \frac{\sigma \cdot \mathcal{B}(W' \to e\nu)}{\sigma \cdot \mathcal{B}(W' \to e\nu)_{\rm LR}})$	
(GeV/c^2)	(events)	Fit ($\times 10^{-2}$)	Upper limit
500	5828	$0.08^{+0.21}_{-0.08}$	5.38×10^{-3}
550	3407	$0.18^{+0.26}_{-0.18}$	7.16×10^{-3}
600	2037	$0.28^{+0.36}_{-0.28}$	1.01×10^{-2}
650	1218	$0.43^{+0.54}_{-0.43}$	1.52×10^{-2}
700	731	$0.36^{+0.83}_{-0.36}$	2.22×10^{-2}
750	433	$0.15^{+1.07}_{-0.15}$	2.80×10^{-2}
800	263	$0.03^{+1.36}_{-0.03}$	3.82×10^{-2}
850	160	$0.00^{+1.89}_{-0.00}$	5.68×10^{-2}
900	100	$0.00^{+2.80}_{-0.00}$	8.79×10^{-2}
950	62	$0.00^{+4.53}_{-0.00}$	1.49×10^{-1}
1000	41	$0.00^{+6.64}_{-0.00}$	2.48×10^{-1}
1050	27	$0.00^{+10.8}_{-0.00}$	4.36×10^{-1}
1100	19	$0.00^{+17.7}_{-0.00}$	7.62×10^{-1}
1150	14	$0.00^{+32.5}_{-0.00}$	1.39
1200	10	$0.00^{+62.7}_{-0.00}$	2.47
1250	8.1	$0.00^{+114}_{-0.00}$	3.96
1300	6.7	$0.00^{+224}_{-0.00}$	6.24

different mass values ranging from 500 to 1300 GeV/c^2. The fit results are shown in Table II, normalized to

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

where the numerator is the observed cross section times the branching fraction and the denominator is that expected from the manifest LR symmetric model. The expected signal yield was normalized to the observed W boson yield obtained from the fit. This removes several sources of systematic uncertainty such as the integrated luminosity,
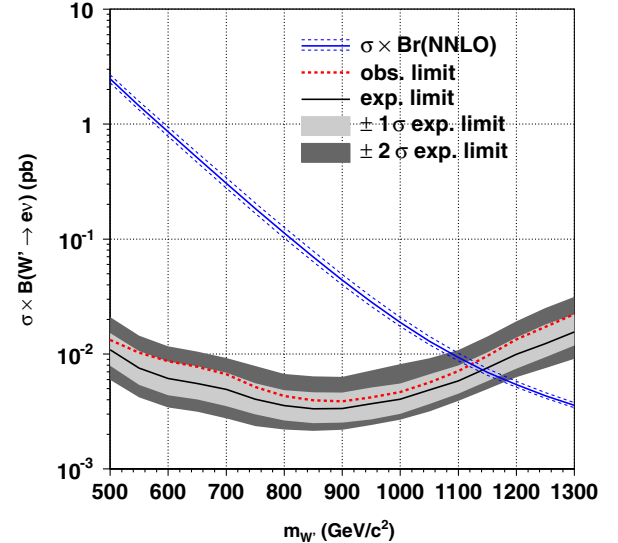

FIG. 3 (color online).   The 95% C.L. limits on the cross section times the branching fraction as a function of W' boson mass and the expected limits from the simulated experiments with background only. The black solid lines represent the median expected; the shaded bands indicate the $\pm 1\sigma$ and $\pm 2\sigma$ invervals on the expected limits. The region above the red dashed line (observed limit) is excluded at the 95% C.L. The cross section times the branching fraction assuming the manifest LR symmetric model, $\sigma \cdot \mathcal{B}(W' \to e\nu)_{\rm LR}$, is shown along with its uncertainty. The intercept of the cross section limit curve and the lower bound of the theoretical cross section yields $m_{W'} > 1.12$ TeV/c^2 at the 95% C.L.

the trigger, and the identification efficiencies, all of which cancel in the ratio.

Systematic uncertainties on the signal and the background rates were considered for the PDFs, the jet energy scale, the theoretical cross sections, the multijet background, the initial and final state radiation of the signal, and the energy scale of the electromagnetic calorimeter. The dominant contribution to the systematic uncertainty comes from the PDFs. The total systematic uncertainty varies from $\pm 5\%$ to $\pm 10\%$ for W' boson masses ranging from $m_{W'} = 500$ to 1300 GeV/c^2.

To determine the limit on β, we use a Bayesian approach [20] by constructing a marginalized posterior probability distribution $[p(\beta)]$ from the likelihood function. Sources of systematic uncertainty are included as nuisance parameters in the definition of the likelihood function. The 95% C.L. upper limits on the ratio of the observed to the expected cross section are obtained from the fit. We use the resulting likelihood function, and the obtained upper limits are summarized in Table II and plotted in Fig. 3 as a function $m_{W'}$ together with the expected limits obtained from simulated experiments with background only. Using theoretical predictions that assume the manifest LR symmetric model [4], the limits on the cross section times the branching fraction are converted into limits on the mass of the W' boson. The lower mass limit can be set at the mass value for which $\beta_{95} = 1$, where $\int_0^{\beta_{95}} p(\beta)d\beta = 0.95$. We take the lower bound of the theoretical cross section to obtain the mass limit. Hence, the 95% C.L. is found to be $m_{W'} > 1.12$ TeV/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 $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV. We do not observe any statistically significant excess over the background expectations. We use a fit to the m_T distribution to set upper limits on the production and decay rate of a W' boson as a function of $m_{W'}$ and exclude a W' boson with $m_{W'} < 1.12$ TeV/c^2 at the 95% C.L., assuming the manifest LR symmetric model.

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[11] We use a coordinate system where θ is the polar angle to the proton beam, ϕ is the azimuthal angle about the beam axis, and η is the pseudorapidity defined as $-\ln(\tan(\theta/2))$. Energy (track momentum) measured transverse to the beam line is denoted as E_T (p_T).

[12] The additional energy ($\equiv E_T^{0.4} - E_T^{\text{ele}}$) must be less than $3 + 0.02 \times E_T^{\text{ele}}$, where $E_T^{0.4}$ is the transverse energy in the cone of $\Delta R (\equiv \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}) < 0.4$ centered on the electron track and E_T^{ele} is the transverse energy of the electron candidate. Both energies are in units of GeV.

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