Search for $W' \to e\nu$ and $W' \to \mu\nu$ in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV

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The W' is a charged, heavy, vector boson predicted to exist by some extensions of the standard model. We have searched for the processes $W' \to e\nu$ and $W' \to \mu\nu$ for $M_{W'} > 100$ GeV/c^2, in $\bar{p}p$ collisions at $\sqrt{s} = 1.8$ TeV, using data taken with the Collider Detector at Fermilab. The nonobservation of these processes leads to a lower limit of 520 GeV/c^2 (95% confidence level) on the mass of the W', assuming standard-strength couplings to three fermion generations.

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The W' is a charged, heavy ($M_{W'} > M_W$), vector boson that appears in certain attempts to enlarge the $SU(2)_L \times U(1)_Y$ gauge group of the standard model. Left-right symmetric models [1], for example, feature a right-handed SU(2) and corresponding new gauge bosons, including a heavy, right-handed W', denoted W_R. Previous direct searches [2] for the process $W' \to e\nu$ in $\bar{p}p$ collisions have set a lower limit of 220 GeV/c^2 (90% confidence level) on the W' mass, assuming standard couplings to fermions. A variety of experiments [3] have searched for a right-handed charged-current interaction by looking for departures from the expected $V-A$ angular distribution in polarized muon decay. In this way a lower limit of 450 GeV/c^2 (90% confidence level) was obtained for the mass of the W_R, assuming a light right-handed neutrino ($m_{\nu_R} \lesssim 10$ MeV/c^2). We have searched for the processes $W' \to e\nu$ and $W' \to \mu\nu$ for $M_{W'} > 100$ GeV/c^2, in $\bar{p}p$ collisions at a center-of-mass energy $\sqrt{s} = 1.8$ TeV, using data taken with the Collider Detector at Fermilab (CDF) during the 1988–1989 Tevatron Collider run. The signature of these processes is a high-P_T lepton together with missing energy from the neutrino. The analysis presented below applies to both left- and right-handed W''s provided that the associated neutrino is not too heavy ($m_{\nu_R} \lesssim 15$ GeV/c^2) and does not decay to observable particles before exiting the detector.

The CDF has been described in detail elsewhere [4]. Here we give a brief description of the components relevant to this analysis. The location of the event vertex is determined to within 1 mm along the beam direction using a vertex time projection chamber. The momenta of charged particles are measured in the central tracking chamber (CTC), which is immersed in a 1.4-T axial magnetic field and has a resolution of $\delta P_T/P_T = 0.0011 P_T$, where the transverse momentum P_T is expressed in GeV/c and the track is constrained to pass through the event vertex. Outside the CTC, electromagnetic and hadronic calorimeters, arranged in a projective tower geometry, cover the pseudorapidity region $|\eta| < 4.2$ [where $\eta = -\ln\tan(\theta/2)$ and θ is the polar angle with respect to the direction of the proton beam], allowing reliable measurements of the imbalance in transverse energy ($E_T = E\sin\theta$) due to the undetected neutrino in W or W' boson decay. In the central region ($|\eta| < 1.1$), the electromagnetic and hadronic calorimeters are organized in projective towers of size $\delta\eta \times \delta\phi = 0.1 \times 15°$. The central electromagnetic calorimeter, on which the electron portion of this analysis is based, provides an energy resolution σ_{E_T}/E_T of $(13.5\%/E_T^{1/2}) \pm 2\%$. Outside the calorimeters, at a radius of 3.5 m, drift chambers in the region $|\eta| < 0.61$ provide muon identification.

Events for this measurement were collected using inclusive electron and muon triggers. The electron trigger required an energy cluster in the central electromagnetic calorimeter with $E_T > 12$ GeV, together with an associated CTC track with transverse momentum $P_T > 6$ GeV/c. The ratio of hadronic to electromagnetic energy in the cluster (HAD/EM) was required to be less than 12.5%. This trigger was measured to be $(97.3 \pm 0.5)\%$ efficient for electrons with $15 < E_T \lesssim 150$ GeV [5]. Very-high-E_T electrons ($E_T \gtrsim 150$ GeV) may exceed the single-tower dynamic range and lead to trigger inefficiency. For such events, a trigger requiring only a calorimeter energy cluster with $E_T > 60$ GeV was available, ensuring nearly full trigger efficiency at high E_T. The muon trigger required a match between a CTC track with $P_T > 9$ GeV/c and a track segment in the muon chambers. This trigger was measured to be $(91 \pm 2)\%$ efficient for muons with $P_T > 20$ GeV/c.

From events passing the above triggers, we have selected electron and muon events with cuts designed to remain very efficient for high-P_T leptons. Electron candidates were required to be in a fiducial region of the central electromagnetic calorimeter and to have HAD/EM $< 10\%$. In addition, the ratio of the calorimeter energy E to the track momentum P was required to be less than

2. An algorithm was applied to reject electrons coming from photon conversions [6]. Muon candidates were required to have an energy deposition in the calorimeters characteristic of a minimum-ionizing particle. A cut on the impact parameter of the track relative to the beam position was used to reject muons coming from the decay in flight of pions and kaons. Muon tracks were also required to pass quality cuts and to extrapolate to a fiducial region of the muon chambers. Cosmic rays were rejected with a filter determined to be over 99% efficient for real, primary muons with $P_T > 20$ GeV/c. Both electron and muon candidates were required to have less than 5 GeV of E_T in the neighboring calorimeter towers. This cut reduces background from nonisolated particles in jets that may fake a high-P_T lepton. Events were also rejected if there existed a second electromagnetic cluster (for electron events) or track (for muon events) whose invariant mass with the first lepton was within 25 GeV/c^2 of the Z^0 mass. The combined efficiency of the electron identification cuts is 0.88 ± 0.04 for electrons typical of W decay, and falls to 0.75 ± 0.04 for 250-GeV electrons due to increased bremsstrahlung (which lowers the E/P and isolation efficiencies) and greater leakage of the electromagnetic shower into the hadronic calorimeter (which lowers the HAD/EM efficiency). The combined efficiency of the muon identification cuts is 0.75 ± 0.06, and is independent of P_T for $P_T > 20$ GeV/c.

In addition to the above identification cuts, electrons were required to have cluster $E_T > 30$ GeV, and muons were required to have track $P_T > 30$ GeV/c. The missing transverse energy ($\not\!E_T$), defined as the magnitude of the vector sum of transverse energy over all calorimeter towers in the region $|\eta| < 3.6$, was required to be greater than 30 GeV. In muon events, the calorimeter energy of the muon was removed and the $\not\!E_T$ was recalculated to account for the muon P_T. The electron sample contains 1796 events in an integrated luminosity of 4.15 ± 0.28 pb^{-1}, and the muon sample contains 783 events in 3.54 ± 0.24 pb^{-1}. The acceptance, including all fiducial and kinematic cuts, was determined from Monte Carlo studies to be 23% for electrons and 13% for muons from W decay. The acceptance rises quickly to 55% for electrons and 34% for muons from higher-mass W''s ($M_{W'} \gtrsim 200$ GeV/c^2), whose decay leptons are more likely to be in the central rapidity region and less likely to fail the E_T and $\not\!E_T$ cuts. The acceptance uncertainty was determined to be $\pm 1\%$ in all cases.

For each event, we form the transverse mass, $M_T = [2E_T\not\!E_T(1-\cos\phi^{l\nu})]^{1/2}$, where $\phi^{l\nu}$ is the angle in the azimuthal plane between the lepton vector and the missing energy vector. The transverse mass resolution σ_{M_T} is $\sim 3\times 10^{-4} M_{W'}^2$ in the muon channel, with $M_{W'}$ in GeV/c^2. In the electron channel, σ_{M_T} is 3–5 GeV/c^2 and is independent of $M_{W'}$ over the mass range of this search. The M_T distribution should show a Jacobian peak near the mass of any heavy object that decays to an electron or muon plus a neutrino. Backgrounds at high M_T from other electroweak processes, such as $W \to \tau\nu$ and Z^0 decay in which one lepton was lost, were determined to be less than 0.1 event. Two-jet events in which one jet fakes a lepton, while the balancing jet is poorly measured resulting in substantial $\not\!E_T$, contribute less than 3 events to each sample. Residual cosmic rays contribute 3 ± 2 events by the muon sample. The M_T distributions for the electron and muon samples are shown in Fig. 1, together with a Monte Carlo prediction for W boson decay (see below). The data are well described by W production and decay alone. The highest transverse mass events are at 185 GeV/c^2 in the electron channel and 205 GeV/c^2 in the muon channel.

To search for a W' signal, we have generated Monte Carlo transverse mass distributions $W'(M_T)$ for a variety of W' masses, and have performed a binned likelihood fit of the observed transverse mass spectrum by the superposition

$$\frac{dN}{dM_T^{\rm obs}} = \alpha W'(M_T) + \beta W(M_T)\,,$$

where $W(M_T)$ is the Monte Carlo M_T distribution for W decay. Throughout the fit, the W' fraction α was constrained to be non-negative. The Monte Carlo distribution generated W and W' bosons from the leading-order diagram $q\bar{q} \to W(W')$ using the HMRS(B) structure functions [7]. The leading-order cross section was multiplied by a K factor of $1+(8\pi/9)\alpha_s(M_{W'}^2)$ to account for higher-order QCD effects. The P_T distributions for the W and W' were taken from a next-to-leading-order QCD calculation [8]. The width of the W' was taken to have the form $\Gamma_{W'} = (2.76\ \text{GeV}) M_{W'}/M_W$, where 2.76 GeV is

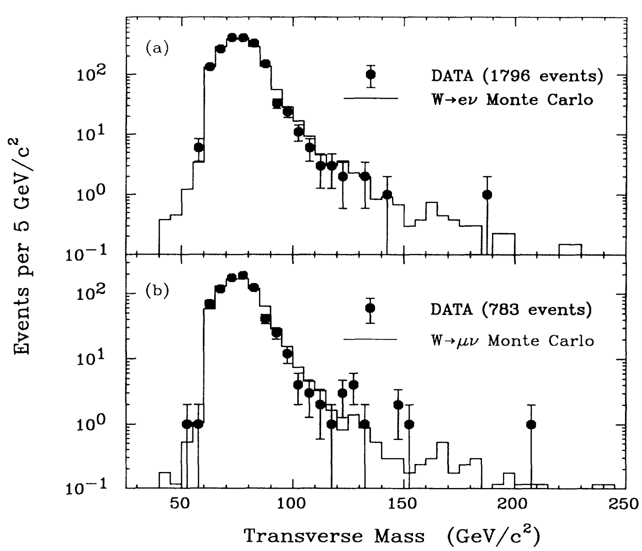

FIG. 1. Observed transverse mass distributions for the (a) electron and (b) muon samples. Error bars are statistical. Superimposed is the Monte Carlo prediction for W boson decay, normalized to the W fraction β obtained from the fit.

TABLE I. The fitted W' fraction α for the electron and muon samples, the predicted cross section times branching ratio (σB) for standard couplings, and the 95%-confidence-level limits on the cross section times branching ratio for the electron, muon, and combined channels.

$M_{W'}$ (GeV/c^2)	$\alpha \pm$ (stat) $\pm$ (syst) (electron)	$\alpha \pm$ (stat) $\pm$ (syst) (muon)	σB (pb) (standard strength)	σB (pb) (electron)	σB (pb) (muon)	σB (pb) (combined)
100	$0^{+0.004}_{-0.000} \pm 0.004$	$0^{+0.008}_{-0.000} \pm 0.024$	920	< 20	< 57	< 20
125	$0^{+0.003}_{-0.000} \pm 0.001$	$0.017^{+0.021}_{-0.017} \pm 0.022$	460	< 6.5	< 36	< 7.4
150	$0^{+0.003}_{-0.000} \pm 0.001$	$0.028^{+0.025}_{-0.020} \pm 0.022$	260	< 3.6	< 25	< 4.4
200	$0^{+0.010}_{-0.000} \pm 0.003$	$0^{+0.060}_{-0.000} \pm 0.016$	98	< 3.0	< 10	< 3.0
300	$0^{+0.018}_{-0.000} \pm 0.002$	$0^{+0.037}_{-0.000} \pm 0.002$	21	< 2.0	< 4.2	< 1.5
400	$0^{+0.056}_{-0.000} \pm 0.002$	$0^{+0.105}_{-0.000} \pm 0.002$	5.6	< 1.9	< 3.4	< 1.3
500	$0^{+0.188}_{-0.000} \pm 0.001$	$0^{+0.389}_{-0.000} \pm 0.002$	1.6	< 1.9	< 3.8	< 1.3

the standard model width of the W with decays available to three generations of light fermions. For lighter W''s the top-quark decay channel may be fully or partially closed, but the limits presented below are insensitive to the W''s intrinsic width, which is smeared out by detector effects. The Monte Carlo distributions $W(M_T)$ and $W'(M_T)$ were then obtained using a simple detector model, with nominal energy and momentum resolutions and a $\not{E}_T$ resolution determined from a full detector simulation. The distributions were normalized to the number of events expected in the data, assuming standard-strength couplings and the nominal branching ratios to each lepton family of $\frac{1}{9}$ for W's and $\frac{1}{12}$ for W''s. The result of the fit was a likelihood function for the W' fraction α as a function of $M_{W'}$. The value of α is statistically consistent with zero for all values of $M_{W'}$. Fitted values of α are shown in Table I. For all W' masses, the data are well fitted by $\beta = 0.92$–0.94.

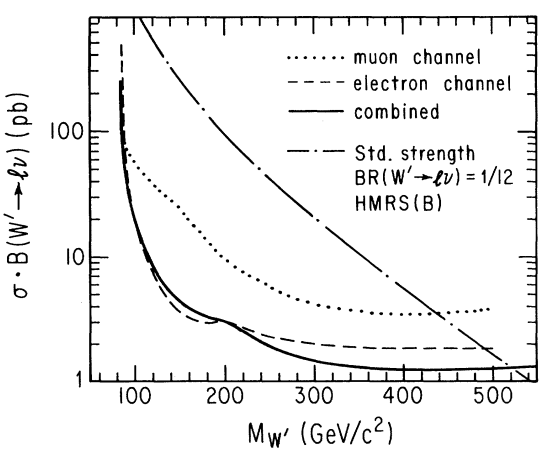

FIG. 2. The 95%-confidence-level limits on the cross section times branching ratio, σB, for $W' \rightarrow \mu\nu$ (dotted line), $W' \rightarrow e\nu$ (dashed line), and combined (solid line). Also shown (dot-dashed line) is the predicted value, assuming standard-strength couplings to quarks and a branching ratio of $\frac{1}{12}$ to each lepton family.

Systematic uncertainties in this analysis are of two types: those that affect the shape of the Monte Carlo transverse mass distributions, and hence change the relative values of α and β, and those that affect only the overall event rates. Uncertainties of the first type are dominated by the uncertainties in the W and W' P_T distributions. We have varied the P_T of the W and W' by an overall scale of $\pm 25\%$, based on the theoretical error in the calculation, to assign these uncertainties, which are shown in Table I. Uncertainties of the second type include uncertainties in the lepton identification efficiencies and the overall 6.8% uncertainty in the luminosity normalization [5]. These uncertainties were incorporated into the likelihood function using a Monte Carlo procedure that has been used previously [6]. The resulting likelihood function was integrated to obtain the 95%-confidence-level limit on the W' fraction in the data, as a function of $M_{W'}$.

These results, expressed as a limit on $\sigma B(W' \rightarrow l\nu)$, are shown in Table I and Fig. 2 for the electron, muon, and combined channels. If one assumes that the W' has standard-strength couplings, these limits can be converted into a limit on the W' mass itself. We emphasize that the limits on the cross section times branching ratio are independent of such assumptions. To calculate the standard-strength production cross section as a function of $M_{W'}$, we have used the HMRS(B) structure functions. Other recent structure function sets [9,10] bracket the HMRS(B) prediction and lead to similar mass limits to those given below (within ± 15 GeV/c^2). For standard-strength couplings and a branching ratio of $\frac{1}{12}$ to each lepton family, the limit is $M_{W'} > 490$ GeV/c^2 in the electron channel, and $M_{W'} > 435$ GeV/c^2 in the muon channel, both at 95% confidence level. Combining the two channels we find $M_{W'} > 520$ GeV/c^2 at 95% confidence level.

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