Search for Right-Handed W Bosons and Heavy W' in p\bar{p} Collisions at $\sqrt{s} = 1.8$ TeV

We report on a search for right-handed $W$ bosons ($W_R$) with mass greater than 200 GeV/$c^2$. We used data collected with the D0 detector at the Fermilab Tevatron $p \bar{p}$ collider at $\sqrt{s} = 1.8$ TeV to search for $W_R$ decays into an electron and a massive right-handed neutrino $W_R \to e^\nu N_R$. Using the inclusive electron data, we set mass limits independent of the $N_R$ decay: $m_{W_R} > 650$ GeV/$c^2$ and $m_{W_R} > 720$ GeV/$c^2$ at the 95% confidence level, valid for $m_{N_R} < \frac{1}{2} m_{W_R}$ and $m_{N_R} \ll m_{W_R}$, respectively. The latter also represents a new lower limit on the mass of a heavy left-handed $W$ boson ($W^0$) decaying into $e\nu$. In addition, limits on $m_{W_R}$ valid for larger values of the $N_R$ mass are obtained assuming that $N_R$ decays to an electron and two jets. [S0031-9007(96)00094-4]
Right-handed W gauge bosons ($W_R$) are additional intermediate vector particles that arise in extensions of the standard model (SM) such as the left-right symmetric model (LRM) [1]. In the LRM, an enlarged $SU(2)_R \times SU(2)_L \times U(1)$ symmetry group replaces the $SU(2)_L \times U(1)$ group of the SM. As a result of the additional symmetry, three new gauge bosons, two charged $W_R^\pm$ and one neutral $Z'$, appear along with massive right-handed neutrinos ($N_R$).

In this Letter, we report a direct search for $W_R$ bosons with mass greater than 200 GeV/c$^2$ which decay into an electron (or positron) and a massive right-handed neutrino, $W_R \rightarrow eN_R$ [2]. We assume the $N_R$ decays promptly through the right-handed charged current into a mode that depends on the mixing angle $\xi$ between $W_L$ and $W_R$. If the mixing is negligible (no mixing case), the $N_R$ will decay into an electron and an off-shell $W_R$, $N_R \rightarrow eW_R$. The right-handed neutrinos from other lepton families are assumed to be at least as massive as the electron $N_R$. Therefore, the off-shell $W_R$ can decay only into quarks, $W_R^* \rightarrow q\bar{q}'$. However, if the mixing is large, the $N_R$ decays into an electron and a $W$ boson, which decays into quarks two-thirds of the time. In both cases, the decay chain leads predominantly to a final state with $eeqq$.

Previous direct searches at hadron colliders ruled out the existence of $W_R$ bosons with $101 < m_{W_R} < 261$ GeV/c$^2$ [3], for any value of the mass of the right-handed neutrino, and $m_{W_R} < 652$ GeV/c$^2$ [4], if the right-handed neutrino is light ($m_{N_R} \ll m_{W_R}$) and does not decay or interact within the detector. Indirect searches based on low energy phenomena such as $\mu$ decay, the $K_L - K_S$ mass difference, and neutrinoless double beta decay provide additional stringent lower limits [5]. Limits from direct and indirect searches depend, however, on the assumed values of the elements of the mixing matrix $V^R$ for the right-handed quarks, the coupling constant $g_R$, the mass and type (Dirac or Majorana) of the right-handed neutrinos, and the mixing angle $\xi$. The most general limit (obtained assuming that $V^R$ is not exactly diagonal or fine-tuned) is $m_{W_R}(g_R^L/g_R) > 300$ GeV/c$^2$ [5]. It has been shown [6] that internal consistency within the LRM requires that $g_R \geq 0.55 g_L$. In addition, an upper limit on the $W_R$ boson mass has been derived in the context of left-right supersymmetric models [7].

Two different methods, corresponding to different values of the ratio $R_m = m_{N_R}/m_{W_R}$, are used for this search. For $R_m \approx 1/2$, the products of the $N_R$ decay are not likely to be well separated due to the large momentum of the $N_R$ relative to its mass, making their individual identification difficult. Therefore, the transverse momentum spectrum of the $W_R$ decay electron, which is expected to be hard and to have a distinctive Jacobian peak at $(m_{W_R}^2 - m_{N_R}^2)/2m_{W_R}$, is used as a signature. A search for such a peak, henceforth referred to as the peak search, is carried out using the high-$p_T$ inclusive electron data. This method does not discriminate between helicities of the $W$ boson. Therefore, the peak search is also sensitive to heavy left-handed $W$ bosons ($W'$) which decay via $W' \rightarrow ev$. For $R_m \geq 1/2$, the $N_R$ momentum and its mass are comparable. Therefore, the products of the $N_R$ decay are likely to be well separated, enabling the detection of the exclusive final state with two electrons and two jets. After requiring the two electrons to be inconsistent with $Z \rightarrow ee$ decay, the background due to other known physics processes is small. Therefore, a simple counting experiment, referred to here as the $eejj$ search, is performed. The peak and $eejj$ searches overlap in sensitivity for intermediate values of $R_m$. The analysis presented here is based on $=79$ pb$^{-1}$ of data collected during two Fermilab Tevatron $p\bar{p}$ collider runs at $\sqrt{s} = 1.8$ TeV.

The D0 detector [8] consists of three major subsystems: a nonmagnetic central tracking system, a hermetic uranium-liquid argon sampling calorimeter, and a muon magnetic spectrometer. The calorimeter has fine longitudinal and transverse segmentation in pseudorapidity ($\eta$) and azimuth ($\phi$) that allows electromagnetic (EM) showers to be distinguished from jets. It provides full coverage for $|\eta| \leq 4$ with energy resolution $15\% / \sqrt{E(\text{GeV})}$ for EM showers and $80\% / \sqrt{E(\text{GeV})}$ for hadronic jets. The drift chambers are used to identify charged tracks for $|\eta| \leq 3.1$ and to locate the primary vertex.

To identify electrons [9], the presence of an isolated EM energy cluster with shape consistent with that of an electron in test beam measurements is required. We also require an associated charged track matching the calorimeter cluster in $\eta$ and $\phi$, whose ionization in the drift chambers is consistent with that of a single minimum ionizing particle. Jets are reconstructed using a cone algorithm with a radius of 0.5 in $\eta$-$\phi$ space.

For the peak search, events were collected using a single EM cluster trigger. Off-line, 100 inclusive high-$p_T$ electron events were selected by requiring an electron candidate with $p_T^e > 55$ GeV/c and $|\eta_e| < 1.1$. For this selection, strict electron identification criteria were imposed to reduce the multijet background (QCD) from events with a jet misidentified as an electron. These strict criteria reduced the electron identification efficiency by 30% with respect to other D0 analyses [9].

The primary background in the peak search is due to highly off-shell and large-$p_T$ W and Z boson production. These processes were simulated using a Monte Carlo (MC) program based on a theoretical calculation of the bosons’ $p_T$ [10] and on the bosons’ line shape, obtained using the PYTHIA [11] program, with a simple detector simulation. The QCD background was modeled using the collider data.
A simultaneous fit to the transverse mass \((m_T)\) distribution, formed by the electron and the missing transverse energy \(E_T\), and to the electron transverse momentum \((p_T^e)\) distribution was performed. A binned maximum likelihood fit was used to find the contributions of the combined \(W\) and \(Z\) boson backgrounds and the QCD background \([12]\). Figure 1 shows the \(p_T^e\) and \(m_T\) distributions with their corresponding fits. The confidence level (CL) is 71% for the \(p_T^e\) fit and 90% for the \(m_T\) fit. The presence of \(W_R \rightarrow e N_R\) decays would appear as an excess in a few consecutive bins in the \(p_T^e\) distribution. No evidence for such an excess is observed.

The acceptance and \(p_T^e\) distribution of the signal were obtained for a grid of points in the \((m_{W_R}, m_{N_R})\) plane using PYTHIA samples with a detector simulation based on the GEANT program \([13]\). The 95% CL upper limit on the number of \(W_R\) events was obtained by integrating the probability of the presence of a \(W_R\) component in the measured \(p_T^e\) distribution for every point in the grid. This was converted into an upper limit on the cross section times branching fraction \((\sigma B)\) by normalizing to the measured \(W\) and \(Z\) boson production cross sections \([14]\) using the observed \(W/Z\) component in the initial simultaneous \(p_T^e\) and \(m_T\) fit and the acceptances as calculated from MC simulation.

The resulting background subtracted upper limit, including the effect of systematic uncertainties (dominated by a 7.6% uncertainty in the \(W/Z\) background normalization), is shown in Fig. 2. Also shown is a second order \((\alpha_s^2)\) theoretical calculation \([15]\) of \(\sigma B\), assuming \(g_R = g_L\) and \(V^R = V^L\). The next-to-leading order MRS(H) \([16]\) parton distributions were used for the calculation. The branching fraction \(B(W_R \rightarrow e N_R)\) was calculated taking into account the \(N_R\) and \(t\)-quark masses and assuming \(m_{N_R} = m_{N_R}^e = m_{N_R}^L\). For small \(N_R\) mass, this fraction approaches the naive \(1/4\) value. Figure 3 shows the corresponding excluded mass region. The contours are shown for different values of the LRM parameters \(g_R\) and \(V^R\) \([17]\). The extreme effect of varying \(V^R\) is illustrated by displaying the contour for a mixing matrix with \(V^R_{ud} = 1\) (thus \(V^R_{us} = 0\) for \(V^R\) unitary), suppressing the primary \(ud \rightarrow W_R\) production mechanism. Because the limit from this part of the search was extracted from the inclusive \(p_T^e\) distribution, without additional topological requirements, it is valid irrespective of the specific decay mechanism for the \(N_R\) or the \(W\) helicity.

For the \(eejj\) search, events were selected using a trigger that required two EM energy clusters, each with \(E_T > 20\) GeV. After event reconstruction, 22 events had two good isolated electrons with \(E_T > 25\) GeV and two or more jets with \(E_T > 25\) GeV with \(|\eta_{ee}| < 2.5\). Events consistent with \(Z + \text{jets}\) production were rejected by demanding that the invariant mass of the two electrons \(m_{ee}\) be outside the range \(70 \leq m_{ee} \leq 110\) GeV/c\(^2\). Two events remained in the sample and were therefore considered \(W_R\) candidates.

The largest background to the \(eejj\) signal is multijet production (QCD) with two jets misidentified as electrons. To calculate this background, a combination of MC and collider data were used \([12]\). The background from \(Z, \gamma^* \rightarrow \text{jets}\) production was estimated by scaling the number of observed events in the \(Z\) peak of the \(m_{ee}\) distribution, in events with two or more additional jets, by the tail-to-peak ratios obtained from MC. Additional background is due to \(t\bar{t}\) and \(WW\) production. The yield from \(t\bar{t}\) was obtained using a Monte Carlo sample with a detailed detector simulation and the measured 6.4 \pm 2.2 pb \([18]\) cross section. For the \(WW\) background, a sample of MC events and the theoretical cross section were used. To verify the background estimation,
the yield of the above processes to a final state with two electrons and one or more jets was also calculated. The background estimates and event yields are summarized in Table I for the eej and eejj final states.

As for the peak search, the signal acceptance for the eejj search was calculated for a grid of points in the \(s_{m_{W_R}}-m_{N_R}d\) plane using MC simulation. The electron identification efficiency was determined from \(Z \rightarrow ee\) data. Example signal efficiencies for the no mixing case are (15.0 \(\pm\) 1.7)\%, (10.1 \(\pm\) 1.4)\%, and (1.0 \(\pm\) 0.4)\% for \((m_{W_R},m_{N_R}) = (650,200), (400,350), \) and (400,50) GeV/c\(^2\), respectively. For the large mixing case the efficiencies are lower due to the smaller \(N_R \rightarrow eqq\) branching fraction. For the large mixing case the search was restricted to \(m_{N_R} \geq 90\) GeV/c\(^2\) since the efficiencies vanish when \(m_{N_R} = m_W\) due to a threshold effect.

Given no observed excess of events beyond the expected background, we set a 95% CL upper limit on \(\sigma B\) using a Bayesian approach [19] with a flat prior distribution for the signal cross section. The uncertainties on the overall efficiency (10\%–20\%), the integrated luminosity (5.5\%), and the background estimation (25\%) were included in the limit calculation with Gaussian prior distributions. The resulting background subtracted upper limits for no mixing and large mixing are plotted in Fig. 2, while

![FIG. 3. 95% CL excluded \(W_R\) mass region from the peak search. The lines represent the contours for different values of the LRM parameters. The diagonal line is the kinematic limit for the \(W_R \rightarrow e N_R\) decay.](image1)

![FIG. 4. 95% CL excluded region of \(W_R\) mass from the eejj search for the no mixing case.](image2)

![TABLE I. Background estimates and event yields for the eej and eejj samples.](image3)

<table>
<thead>
<tr>
<th>Background process</th>
<th>Event yield for 79.0 (\pm) 4.3 pb(^{-1}) eej</th>
<th>eejj</th>
</tr>
</thead>
<tbody>
<tr>
<td>(Z, \gamma)</td>
<td>12.84 (\pm) 2.31</td>
<td>1.26 (\pm) 0.34</td>
</tr>
<tr>
<td>(t\bar{t})</td>
<td>0.61 (\pm) 0.35</td>
<td>0.43 (\pm) 0.16</td>
</tr>
<tr>
<td>(WW)</td>
<td>0.13 (\pm) 0.02</td>
<td>0.01 (\pm) 0.01</td>
</tr>
<tr>
<td>QCD</td>
<td>9.90 (\pm) 4.01</td>
<td>1.38 (\pm) 0.68</td>
</tr>
<tr>
<td>Total</td>
<td>23.48 (\pm) 4.64</td>
<td>3.08 (\pm) 0.78</td>
</tr>
<tr>
<td>Observed</td>
<td>23</td>
<td>2</td>
</tr>
</tbody>
</table>

![FIG. 5. Excluded regions of \(W_R\) mass at the 95% CL assuming \(g_R = g_L\) and \(V_R = V_L\).](image4)
Fig. 4 shows the excluded region of the \((m_{W_R}, m_{N_R})\) plane for the no mixing case.

In conclusion, no evidence for the production of right-handed \(W\) bosons with mass greater than 200 GeV/c\(^2\) was found. From a peak search we set mass limits independent of the \(N_R\) decay: \(m_{W_R} > 650\) GeV/c\(^2\) and \(m_{W_L} > 720\) GeV/c\(^2\) at the 95% CL, valid for \(m_{N_R} \ll m_{W_R}\). Also, from the peak search, we set a mass limit of \(m_{W_R} > 650\) GeV/c\(^2\) at the 95% CL, extending the previous limit for heavy left-handed \(W\) bosons [4] which decay into \(e\nu\). Limits on \(m_{W_R}\) valid for larger values of the \(N_R\) mass were obtained assuming that the \(N_R\) decays to an electron and two jets.

Figure 5 summarizes the results of the two methods used for the search as an exclusion region in the \((m_{W_R}, m_{N_R})\) plane. These limits on \(m_{W_R}\) place stringent, though model dependent, limits on possible \(V_1A\) components in low energy weak decays. Such components, which scale as \((m_{W_L}/m_{W_R})^4\), are therefore constrained to be smaller than 0.015% if the \(N_R\) is light and \(g_R = g_L\).

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[6] T. Sjöstrand, Comp. Phys. Commun. **82**, 74 (1994). The boson width is assumed to be \(\Gamma_{W_R} = \Gamma_{W_L}(m_{W_R}/m_W)^4\), with corrections applied for the number of open channels.


[11] T. Sjöstrand, Comp. Phys. Commun. **82**, 74 (1994). The boson width is assumed to be \(\Gamma_{W_R} = \Gamma_{W_L}(m_{W_R}/m_W)^4\), with corrections applied for the number of open channels.


