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

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Search for Right-Handed W Bosons and Heavy W' in pp Collisions at √s = 1.8 TeV

We report on a search for right-handed W bosons ($W_R$). We used data collected with the DØ 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 $W_R^\pm \rightarrow e^\pm N_R$. 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 ($W'$) decaying into $ee$. 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.
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, 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] is reported. The $N_R$ is assumed to decay 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 $W_R$, $N_R \rightarrow eW_R^\pm$. 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, $W_R^\pm \rightarrow q\bar{q}$. On the other hand, 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 yielded the lower limits $m_{W_R} > 261$ GeV/c$^2$ [3], valid for any value of the mass of the right-handed neutrino, and $m_{W_R} > 652$ GeV/c$^2$ [4], valid only for a light right-handed neutrino ($m_{N_R} \ll m_{W_R}$) that 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 is $m_{W_R} > 300$ GeV/c$^2$.

Two different methods, corresponding to different values of the ratio $R_m = m_{N_R}/m_{W_R}$, are used for this search. For $R_m \lesssim 1$, the products of the $N_R$ decay are not likely to be well separated, 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 ($W^L$) which decay into an electron and an electron neutrino $W^L \rightarrow eeN_R$. For $R_m \gtrsim 1/2$, the products of the $N_R$ decay are likely to be well separated, making possible the detection of the exclusive final state with two electrons and two jets.

The DØ detector consists of three major subsystems: a central tracking system with no magnetic field, 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 showers to be distinguished from jets. It provides full coverage for $|\eta| \leq 4$ with energy resolution $15\%/\sqrt{E(\text{GeV})}$ for electromagnetic showers and $60\%/\sqrt{E(\text{GeV})}$ for hadronic jets. The central and forward drift chambers are used to identify charged tracks for $|\eta| \leq 3.1$ and to locate the primary vertex. A more detailed description of the DØ detector can be found elsewhere [6].

To identify electrons [7], the presence of an isolated electromagnetic energy cluster with shape consistent with that of an electron (as determined from test beam measurements) is required. In addition, an associated charged track that matches the calorimeter cluster in $\eta$ and $\phi$ and with an ionization in the drift chambers consistent with that of a minimum ionizing particle must be found. Jets are reconstructed using a cone algorithm with a cone radius of 0.5 in $\eta$-$\phi$ space.

For the peak search, events were collected using a single electromagnetic cluster trigger. Offline, the inclusive high-$p_T$ electron events were selected by requiring an electron candidate with $p_T > 55$ GeV/c and $|\eta| < 1.1$. To reduce the multijet background (QCD) from events with a jet misidentified as an electron, strict electron identification criteria were imposed. The 101 events with $p_T > 100$ GeV/c were scanned to search for anomalies; we discarded one event which was consistent with being a high energy cosmic ray muon that showered in the electromagnetic part of the calorimeter, mimicking an electron.

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’ $p_T$ [8] and on the bosons’ line shape obtained using the PYTHIA [9] MC 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

\[ m_T = \sqrt{(E_T + m_T)^2 - p_T^2} \]
the inclusive high-\(p_T\) electron sample.

\(p_T\) 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 [10]. Figure 1 shows the \(p_T\) and \(m_T\) distributions with their corresponding fits. The confidence level (CL) is 71\% for the \(p_T\) 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 \(p_T\) distribution. No evidence for such an excess is observed.

The acceptance and \(p_T\) fit distribution of the signal were obtained for a grid of points in the \((m_{W_R}, m_{N_R})\) plane using PYTHIA MC samples with a detector simulation based on the GEANT program [11]. 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 \(p_T\) 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 [12] using the observed W/Z component in the initial simultaneous \(p_T\) and \(m_T\) fit and the acceptance 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 [13] of \([\sigma B]\) assuming \(g_R = g_L\) and \(V^R = V^L\). The next to leading order MRS(H) [14] 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 \(m_{N_R} = m_{N_R^a} = m_{N_R^c}\). For small \(N_R\) mass, this fraction approaches the naive \(1/17\) value. Figure 3 shows the corresponding excluded mass region. The contours are shown for different values of the LRM parameters \(g_R\) and \(V^R\) [15]. The extreme effect of varying \(V^R\) is illustrated by displaying the contour for a mixing matrix with \(V^R_{ud} = 1\) (thus \(V^R_{un} = 0\) 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 \(p_T\) 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 electromagnetic energy clusters, each with \(E_T > 20\) GeV. After event reconstruction, 22 events...
had two good isolated electrons with \( E_T > 25 \text{ GeV} \) and two or more jets with \( E_T > 25 \text{ GeV} \) within a pseudorapidity range \( |\eta_{e,j}| < 2.5 \). 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 \( 70 < m_{ee} < 110 \text{ GeV}/c^2 \). 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, the invariant mass spectrum of the jet pair with the largest electromagnetic fraction in events with four or more jets was found. This distribution was then scaled by a factor determined from a two-component fit to the inclusive dielectron data using the dielectron invariant mass spectrum from \( Z, \gamma' \) MC and the measured inclusive dijet invariant mass spectrum. The background from \( Z, \gamma' + \text{jets} \) production was estimated by scaling the number of observed events in the 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 \( 6.4 \pm 2.2 \text{ pb} \) [16] 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 \( eejj \) final states.

As for the peak search, the signal acceptance for the \( eejj \) search was calculated for a grid of points in the \( (m_{W_R}, m_{N_R}) \) 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 corresponding efficiencies are lower due to the smaller \( N_R \rightarrow eqq \) branching fraction. Also, for the large mixing case the search was restricted to \( m_{N_R} \geq 90 \text{ GeV}/c^2 \) since the efficiencies vanish when \( m_{N_R} \approx m_W \) 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 [17] 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
limit is plotted in Fig. 2, while 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 was found. From a peak search we set mass limits independent of the \(N_R\) decay: \(m_{W_R} > 650\) GeV/c\(^2\) and \(m_{W_R} > 720\) GeV/c\(^2\) at the 95\% CL, valid for \(m_{N_R} < \frac{1}{2} m_{W_R}\) and \(m_{N_R} \ll m_{W_R}\) respectively, assuming SM coupling \((g_R = g_L\) and \(V^R = V^L\)). Also from the peak search, we set a mass limit of \(m_{W_R} > 720\) GeV/c\(^2\) at the 95\% CL, extending the previous most stringent limit for heavy left-handed \(W\) bosons [4] which decay into \(e\nu\). In addition, 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 \(V + A\) couplings.

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