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

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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 $W_R^{\pm} \rightarrow e^{\pm} N_R$. 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 $e\nu$. 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]

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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 $\mathrm{SU}(2)_R \times \mathrm{SU}(2)_L \times \mathrm{U}(1)$ symmetry group replaces the $\mathrm{SU}(2)_L \times \mathrm{U}(1)$ 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, $W_R \to eN_R$ [2]. We assume the N_R decays promptly through the right-handed charged current into a mode that depends on the mixing angle ξ 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, $N_R \to eW_R^*$. 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, $W_R^* \to q\bar{q}'$. 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 μ 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 ξ. The most general limit (obtained assuming that V^R is not exactly diagonal or fine-tuned) is $m_{W_R}(g_L/g_R) > 300$ 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 $R_m \lesssim \frac{1}{2}$, 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 $W' \to e\nu$. For $R_m \gtrsim \frac{1}{2}$, 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 $Z \to ee$ 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 $\approx$79 pb^{-1} of data collected during two Fermilab Tevatron $p\overline{p}$ 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 (η) and azimuth (ϕ) that allows electromagnetic (EM) showers to be distinguished from jets. It provides full coverage for $|\eta| \leq 4$ with energy resolution $15\%/\sqrt{E(\mathrm{GeV})}$ for EM showers and $80\%/\sqrt{E(\mathrm{GeV})}$ 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 η and ϕ, 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 η-ϕ 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 $\not{E}_T$, 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 $W_R \to eN_R$ 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 (σB) 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 (α_S^2) theoretical calculation [15] of σB, 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 $B(W_R \to eN_R)$ was calculated taking into account the N_R and t-quark masses and assuming $m_{N_R^e} = m_{N_R^\mu} = m_{N_R^\tau}$. For small N_R mass, this fraction approaches the naive $\frac{1}{12}$ 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 $V_{us}^R = 1$ (thus $V_{ud}^R = 0$ for V^R unitary), suppressing the primary $ud \to W_R$ 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 $|\eta_{e,j}| < 2.5$. Events consistent with Z + jets production were rejected by demanding that the invariant mass of the two electrons m_{ee} be outside the range $70 \le m_{ee} \le 110$ 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, γ^* + 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 ± 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,

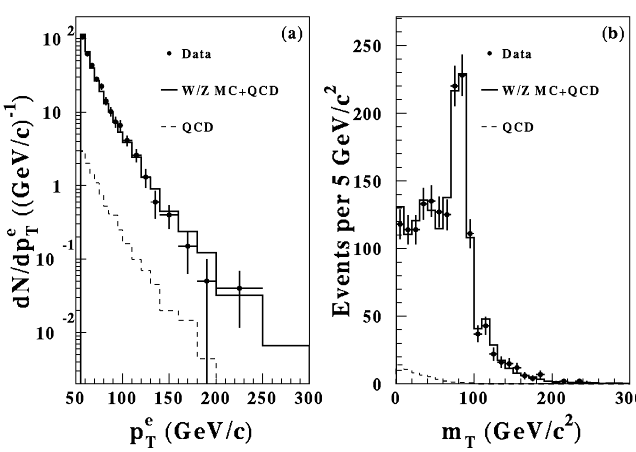

FIG. 1. (a) Electron transverse momentum and (b) transverse mass (formed by the electron and $\not{E}_T$) distributions of the inclusive high-p_T electron sample.

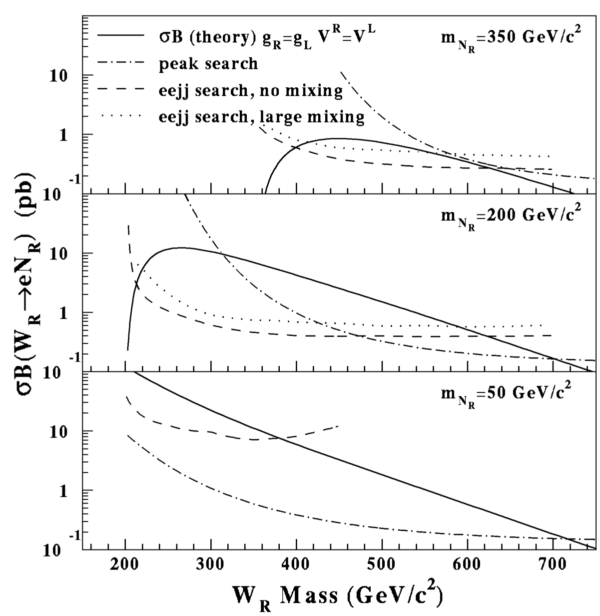

FIG. 2. 95% CL upper limit on σB as a function of the W_R boson mass. Limits are shown for three values of the N_R mass.

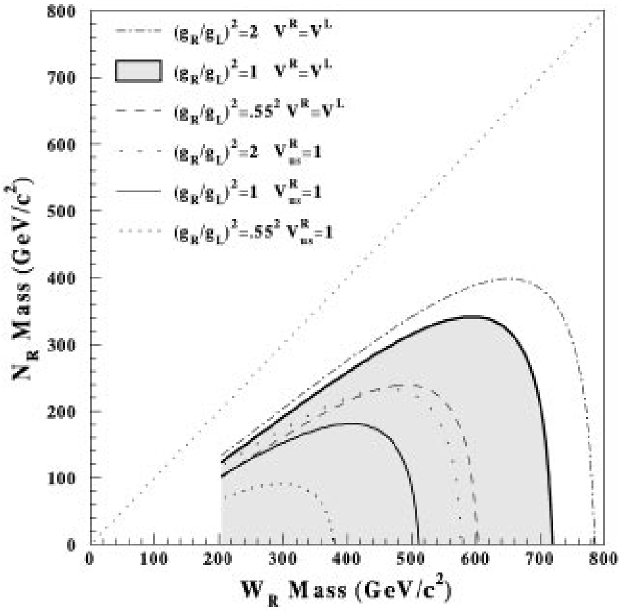

FIG. 3. 95% CL excluded W_R mass region from the *peak search*. The lines represent the contours for different values of the LRM parameters. The diagonal line is the kinematic limit for the $W_R \to eN_R$ decay.

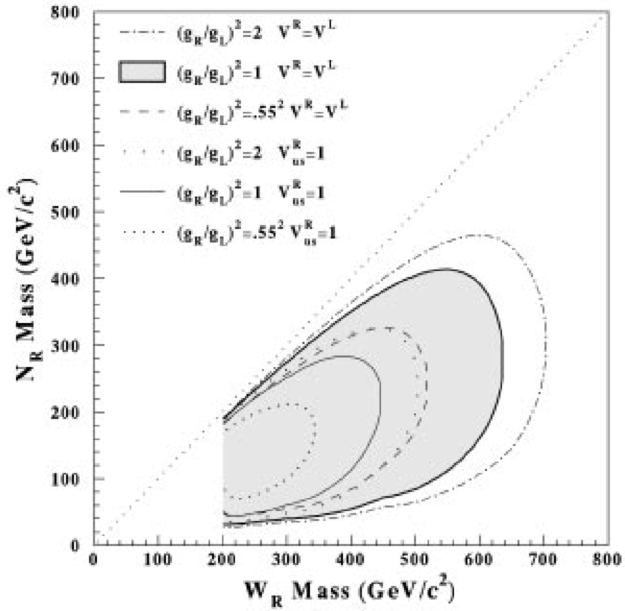

FIG. 4. 95% CL excluded region of W_R mass from the *eejj* search for the no mixing case.

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 (m_{W_R}, m_{N_R}) plane using MC simulation. The electron identification efficiency was determined from $Z \to ee$ 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 $N_R \to eqq$ 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 $m_{N_R} \approx m_W$ due to a threshold effect.

TABLE I. Background estimates and event yields for the *eej* and *eejj* samples.

Background process	Event yield for 79.0 ± 4.3 pb^{-1} *eej*	*eejj*
Z, γ^*	12.84 ± 2.31	1.26 ± 0.34
$t\bar{t}$	0.61 ± 0.35	0.43 ± 0.16
WW	0.13 ± 0.02	0.01 ± 0.01
QCD	9.90 ± 4.01	1.38 ± 0.68
Total	23.48 ± 4.64	3.08 ± 0.78
Observed	23	2

Given no observed excess of events beyond the expected background, we set a 95% CL upper limit on σB 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

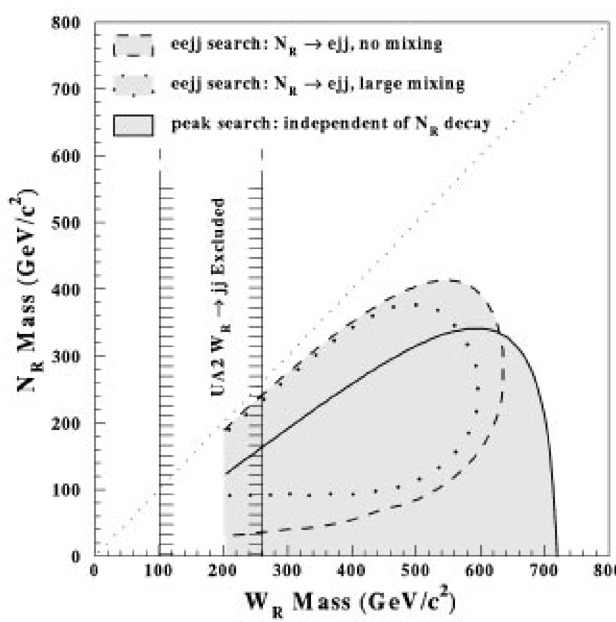

FIG. 5. Excluded regions of W_R mass at the 95% CL assuming $g_R = g_L$ and $V^R = V^L$.

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 $m_{W_R} > 720$ 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 $m_{W'} > 720$ 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 $V + A$ 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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