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Search for heavy W bosons in 1.8 TeV $p\bar{p}$ collisions

DØ Collaboration

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Abstract

A search for a heavy charged gauge boson, W', using the decay channels $W' \to e\nu$ and $W' \to \tau\nu \to e\nu\nu\bar{\nu}$ is reported. The data used in the analysis were collected by the DØ experiment at the Fermilab Tevatron during the 1992–93 $p\bar{p}$ collider run from an integrated luminosity of 13.9 ± 0.8 pb^{-1} at $\sqrt{s} = 1.8$ TeV. Assuming that the neutrino from W' decay is stable and has a mass significantly less than $m_{W'}$, an upper limit at the 95% confidence level is set on the cross section times branching ratio for $p\bar{p} \to W' \to e\nu$. A W' with the same couplings to quarks and leptons as the standard model W boson is excluded for $m_{W'} < 610$ GeV/c^2.

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1. Introduction

The standard model is the generally accepted theory describing elementary particles and their interactions. Despite its experimental success, the standard model is not considered to be the ultimate theory. Numerous extensions to the standard model have been proposed. Many include an additional charged gauge boson, W' [1].

Additional charged gauge bosons are associated with an extra SU(2) group. In the most general case, the mass eigenstates may be a mixture of the group eigenstates. Hence the mixing angle ξ is a parameter in the model. The fermions coupled to the W' may be new particles. In this case, the fermion-boson coupling g'' is introduced in the model as an additional parameter. Moreover a different Cabbibo-Kobayashi-Maskawa (CKM) matrix U' may be needed. In some extended gauge models, the W' is right-handed, decaying into a right-handed neutrino and a lepton. The mass and decay modes of such a neutrino are unknown. Therefore the mass limits obtained on W' will depend on ξ, g'', U', and the masses of any additional neutrinos. Mass limits in this paper are based on a reference model W' without mixing, with g'' equal to the standard model coupling, U' equal to the standard CKM matrix, and decay to W and Z bosons suppressed.

A number of indirect searches for W' have been carried out in the past. Muon decay has been carefully studied to look for deviations from $V-A$ behavior as an indication of W', valid when $m_\nu < m_\mu$ [2]. Constraints on additional W bosons are also obtained from the mass difference between K_S and K_L [3]. $B_d - \overline{B_d}$ mixing also limits extra charged gauge bosons [4]. The semileptonic branching ratio $b \to Xl\nu$ may be used to set a limit if $m_\nu > m_b$. The above results are combined to exclude W' lighter than 1.3 TeV/c^2 [5]. Cosmological nucleosynthesis studies have established a limit $m_{W'} > \mathcal{O}(1\ \text{TeV/c}^2)$ if $m_\nu < 1$ MeV/c^2 [6]. Analysis from the supernova 1987A, valid for $m_\nu < 10$ MeV/c^2, excludes $m_{W'}$ less than 16 TeV/c^2 [7]. One analysis, however, combines several different experimental results and indicates a W' with a mass ≈ 230 GeV/c^2, given a small mixing angle [8]. Previous direct searches [9] in $p\bar{p}$ collisions have set the limit $m_{W'} > 652$ GeV/c^2.

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2. Experimental procedure

In this paper, a direct search using the DØ detector [10] for a heavy ($m_{W'} > m_W$) charged gauge boson decaying through the channels $W' \to e\nu$ and $W' \to \tau\nu \to e\nu\nu\bar{\nu}$ is reported. Limits are set on the cross section times branching ratio, σB, for $p\bar{p} \to W' \to e\nu$ assuming that the neutrino from W' decay is stable and has a mass significantly less than $m_{W'}$. The branching ratios $W' \to e\nu$ and $W' \to \tau\nu$ are taken to be equal.

Most charged gauge bosons decaying leptonically, $W(W') \to l\nu$, may be identified from the projection of the event onto the plane perpendicular to the beam direction (transverse plane). Candidate events are selected by demanding a lepton with large transverse energy E_T in an event with large missing transverse energy $\not{E}_T$ carried away by the undetected neutrino. In the present study only $W(W')$ decay channels which include an electron in the final state are considered. Transverse mass is defined as the mass of the electron-neutrino system taking into account only the vector components in the transverse plane. In general, the method of search is to look in the transverse mass spectrum for the line shape of a W' superimposed on that expected from the standard model W boson.

The analysis presented here is based on data collected during the Fermilab Tevatron $p\bar{p}$ collider run from August 1992 to May 1993 with an integrated luminosity of 13.9 ± 0.8 pb^{-1} at $\sqrt{s} = 1.8$ TeV. The DØ detector consists of three main subsystems: a central tracking system, a hermetic calorimeter, and a muon spectrometer. The central tracking system is used to identify charged particles within the pseudorapidity range $|\eta| < 3.1$ and to locate the primary event vertex. The calorimeter employs depleted uranium absorber and liquid argon ionization layers. It provides full coverage for $|\eta| < 4.0$ with sufficiently fine transverse and longitudinal segmentation to distinguish electrons and photons from hadronic jets by their electromagnetic shower shape. Energy resolution is $15\%/\sqrt{E(\text{GeV})}$ for electromagnetic particles and $50\%/\sqrt{E(\text{GeV})}$ for single hadrons.

In the primary trigger, events are selected by demanding at least one electromagnetic trigger tower of size 0.2 × 0.2 ($\Delta\eta \times \Delta\phi$) with E_T greater than 10 GeV. In the final trigger where energy clusters are reconstructed, a cluster with $E_T > 20$ GeV fulfilling isolation and electromagnetic shape criteria is required. In addition, $\not\!E_T$ must be greater than 20 GeV.

After off-line event reconstruction, $W(W')$ candidates are required to contain at least one electron with transverse energy $E_T^e > 30$ GeV and to have $\not\!E_T > 30$ GeV. The electron energy is calibrated by using the Z boson mass. The uncertainty in the electron energy scale is 0.5%. $\not\!E_T$ is computed using corrected jet energies. The jet energy correction is determined by requiring energy balance in events with a normal hadronic jet and a predominantly electromagnetic jet or photon. The uncertainty in the corrected jet energy is 6%. The uncertainty in the x or y component of $\not\!E_T$ based on minimum bias data is 1.08 GeV + 0.019 × $\sum|E_T|$, where the sum is over calorimeter cells.

Electrons are required to be isolated and are further identified using shower shape criteria determined from test beam and collider data [11]. There must be a track in the central tracking system connecting the event vertex and the electromagnetic energy cluster in the calorimeter. Additionally, electrons are required to be in the fiducial region of the calorimeter, $|\eta| < 1.1$ in the central barrel and $1.5 < |\eta| < 2.5$ in the end caps. Electrons near module boundaries in the central calorimeter are eliminated, reducing that fiducial region by 10%. Additional cuts are applied to reject events with extra energy due to electronic noise or accelerator background.

The kinematic and geometric acceptance for $W(W')$ events is determined by Monte Carlo simulation. The PYTHIA event generator (version 5.7) [12] is used to generate W and W' ($m_{W'} > m_W$) events. The MRS D−′ parton distribution functions (pdf) [13] are used. They agree well with the W boson asymmetry measurement from $p\bar{p}$ collider data [14]. The uncertainty in this choice is determined by also using MRS D0′ and CTEQ 2M [15] pdf sets. The kinematic and geometric acceptance is (33.9 ± 0.70)% for $W \to e\nu$ and (0.7 ± 0.02)% for $W \to \tau\nu \to e\nu\nu\bar{\nu}$. For a W' with $m_{W'} = 600$ GeV/c^2, the kinematic and geometric acceptance is (72.6 ± 1.6)% for $W' \to e\nu$ and (14.0 ± 0.4)% for $W' \to \tau\nu \to e\nu\nu\bar{\nu}$. The measured trigger efficiency for W events within the acceptance is (98.1 ± 0.7)%.

The component of the reconstruction efficiency for W events due to the selection efficiency for electrons is determined by studying the $Z \to ee$ sample. The contribution of energy resolution effects to reconstruction efficiency is modeled by Monte Carlo. The generated events are passed through a detector simulator which uses parameterized DØ calorimeter energy resolution. The reconstruction efficiency for triggered events within the acceptance is (72.1 ± 1.8)%.

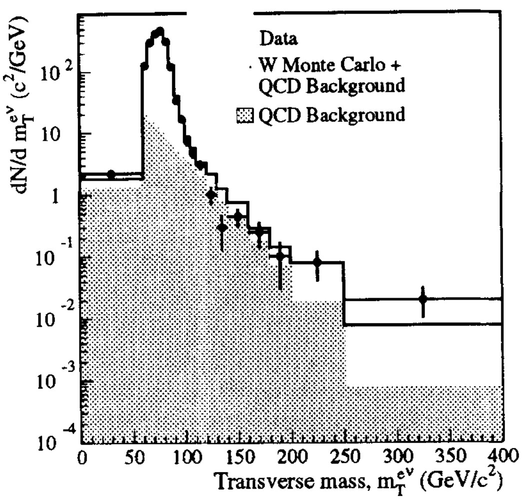

Fig. 1. Electron-neutrino transverse mass distribution for data compared to W Monte Carlo plus QCD background.

There are 9135 events remaining in the final $W(W')$ candidate event sample. The principal background in this sample arises from QCD multijet events in which one of the jets is misidentified as an electron and $\not\!E_T$ occurs in the event due to mismeasurement. The number of QCD background events in the $W(W')$ sample is determined by selecting an event sample with the same electron selection criteria as the W sample but with $\not\!E_T < 20$ GeV. Given the low $\not\!E_T$ requirement, energy clusters identified as electrons in this sample are primarily fake electrons arising from QCD multijet events. The cross section for this process is then extrapolated to the region of $\not\!E_T > 30$ GeV by using the $\not\!E_T$ distribution of similar QCD multijet events. The estimated background is 551 ± 96 events.

Fig. 1 shows the transverse mass $m_T^{e\nu}$ distribution for data and W Monte Carlo plus QCD background modeled from data. The sum of the simulated signal plus background is normalized to the number of observed W candidates. The simulation reproduces the data well. In the region $m_T^{e\nu} > 250$ GeV/c^2 there are three events in the data sample. Monte Carlo plus QCD predict 1.3±0.4 events. In the region $m_T^{e\nu} > 150$ GeV/c^2 there are 16 events in the data sample. Monte Carlo plus QCD predict 19.4 ± 5.7 events.

3. Limits

To gauge the acceptance for W', samples of W' were generated for $m_{W'}$ in the range 100 to 800 GeV/c^2. The W' width $\Gamma_{W'}$ is assumed to scale with the W' mass, $\Gamma_{W'} = (m_{W'}/m_W)\Gamma_W$. For $m_{W'} \geq 200$ GeV/c^2, $\Gamma_{W'}$ is scaled by an additional factor of $\approx 4/3$ since decay channels involving the top quark are assumed to be available. However the impact of the actual value of $\Gamma_{W'}$ on the experimental signature, within the theoretically expected range of $\Gamma_{W'}$, is negligible. This is due to the fact that the W intrinsic width is small compared to the width of the transverse mass distribution.

The W' detection efficiency with respect to the W, $A_{W'}/A_W$, is evaluated as a function of $m_{W'}$. In this calculation, trigger and electron reconstruction efficiencies are assumed to be constant with electron energy. This is substantiated by test beam data up to 150 GeV and by a full detector simulation of high energy electrons. Therefore the ratios obtained reflect the difference in geometrical and kinematic acceptance. The relative W' efficiencies are shown in Table 1. The uncertainties in the ratio are: 2% due to choice of pdf's, 1% due to radiative corrections, 1% from detector simulation, and 1% from Monte Carlo statistical precision giving a total uncertainty in $A_{W'}/A_W$ of 3%. The uncertainty due to radiative corrections is determined by comparing the results from Monte Carlo without radiative corrections and with first order corrections [16].

A binned likelihood approach is applied to the transverse mass distribution in order to obtain an upper limit on the rate for the process $p\bar{p} \to W' \to e\nu$. The probability that n_i events will be observed in the ith bin is given by the Poisson distribution. The predicted number of events f_i is given by:

$$f_i = (1-\alpha) f_i^B + \alpha f_i^{W'},$$

where f_i^B is the W plus QCD background, $f_i^{W'}$ is the W' signal, and α is a free parameter that is varied from 0 to 1. The functions f_i^B and $f_i^{W'}$ are each normalized to the number of events in the sample, N_{obs}, summing over i. The total probability P is the product of the probabilities of all the bins considered. Written as a function of α, P becomes a probability density $P(\alpha)$ that is normalized to 1 by integrating over α. Uncertainty in the probability density is incorporated by assuming a Gaussian distribution and convoluting the functions. The 95% confidence level (C.L.) limit on α, α_{95}, is obtained by:

$$0.95 = \int_0^{\alpha_{95}} P(\alpha) d\alpha.$$

The upper bound on W' production $N_{95}^{W'}$ is obtained from $N_{95}^{W'} = \alpha_{95} \times N_{\text{obs}}$. The limit $N_{95}^{W'}$ may be expressed as a 95% C.L. limit on the ratio $\sigma B(W' \to e\nu)/\sigma B(W \to e\nu)$ using:

$$\left(\frac{\sigma B_{W' \to e\nu}}{\sigma B_{W \to e\nu}}\right)_{95} = \frac{A_W}{A_{W'} A_f N_W} N_{95}^{W'},$$

where N_W is N_{obs} less QCD background and A_f is the fraction of the W' acceptance included in the fit. A_f is typically $\approx 60\%$ since the $m_T^{e\nu}$ region dominated by W background is not included in the fit. Table 1 gives the 95% C.L. limit on this ratio, the limit expressed as expected events, and the lower boundary of the fit region for the different W' masses considered. The uncertainty in the scaling factor, $A_W/(A_{W'} A_f N_W)$, and the uncertainty in the normalization of the background are incorporated into the probability density function as Gaussian distributed errors.

Table 1
For each W' mass: W' acceptance relative to W, minimum $m_T^{e\nu}$ of the fit region, the 95% C.L. expressed as expected events, and the 95% C.L. expressed as $\sigma B(W' \to e\nu)/\sigma B(W \to e\nu)$.

$m_{W'}$ (GeV/c^2)	$A_{W'}/A_W$	$m_T^{e\nu}$ min., fit region	95% C.L., $N_{95}^{W'}$	95% C.L., $\sigma B_{W'}/\sigma B_W$ ($\times 10^{-4}$)
100	1.48	80	36.3	39.4
200	2.19	140	12.4	10.2
300	2.46	210	7.8	6.2
400	2.51	270	6.2	4.7
500	2.54	330	4.4	3.3
600	2.54	380	3.0	2.3
700	2.48	380	3.0	2.3
800	2.41	380	3.0	2.5

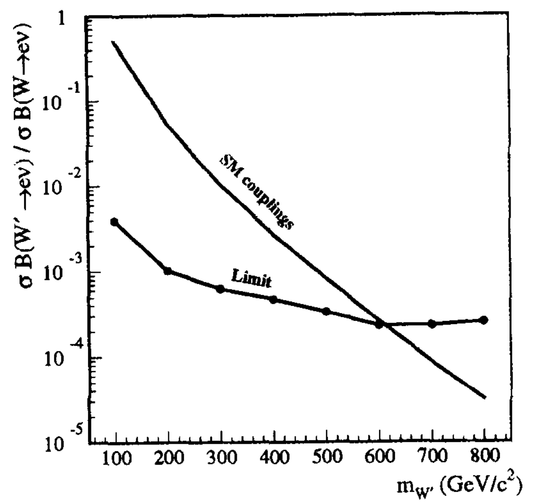

Fig. 2. 95% C.L. upper limit as a function of $m_{W'}$ for $\sigma B(W' \to e\nu)/\sigma B(W \to e\nu)$. The expected value using standard model (SM) couplings is also shown.

4. Conclusions

The 95% C.L. upper limit on $\sigma B(W' \to e\nu)/\sigma B(W \to e\nu)$ is plotted as a function of $m_{W'}$ in Fig. 2 together with the theory curve, the value of this ratio assuming standard model couplings. The theory curve is determined using Born level cross sections including finite width effects [12] corrected with second order scaling factors, $K2$ [17]. $K2$ is determined as a function of the 4-momentum transfer q^2. $K2$ varies from 1.24 to 1.54 for q^2 at the W-pole to $q^2 = 600^2$ GeV^2. There is an uncertainty in the theory of 3% due to choice of pdf's. As determined by the intersection of the two curves, a W' with the same couplings to quarks and leptons as the standard model W boson is excluded at the 95% C.L. for $m_{W'} < 610$ GeV/c^2 with the assumption that neutrinos produced in W' decay are stable and have a mass significantly less than $m_{W'}$.

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