Fermi National Accelerator Laboratory

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Search for W' and Z' at CDF

The CDF Collaboration

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ABSTRACT

We have searched for heavy charged and neutral vector bosons via the decays $W' \to e\nu$, $W' \to \mu\nu$, $Z' \to ee$, and $Z' \to \mu\mu$ 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 (95% confidence level) of 520 GeV/c^2 on the mass of the W' and of 412 GeV/c^2 on the mass of the Z' , assuming standard model couplings to fermions.

1. Introduction

The W' and Z' are charged and neutral vector bosons that appear in some extensions of the standard model such as grand unified theories and left-right symmetric models.[1] These particles may be produced in $\bar{p}p$ collisions and observed via their decay to very high transverse momentum (P_T) electrons and muons. Observation of such events would provide evidence for physics beyond the standard model. Previous direct searches in $\bar{p}p$ collisions for W' and Z' bosons have produced lower limits (90% confidence level) for the W' mass of 220 GeV/c^2 from UA1[2] and 209 GeV/c^2 from UA2[3] and for the Z' mass of 173 GeV/c^2 from UA1[2] and 180 GeV/c^2 from UA2.[3] There are also limits from indirect searches.[4] Reported here is a search for the processes $W' \to \mu\nu$,[5] $W' \to e\nu$,[5] $Z' \to ee$,[6] and $Z' \to \mu\mu$, for $M_{W'} > 100$ GeV/c^2 and $M_{Z'} > 100$ 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 1988-89 Tevatron Collider run.

2. Data Selection

CDF is a general purpose solenoidal detector system at the Tevatron Collider. Detailed descriptions of it can be found in the references.[7]

The W' and Z' searches are based on events that satisfy the inclusive central electron and muon triggers. The electron trigger was measured to be $97.3 \pm 0.5\%$ efficient for electrons with transverse energy in the range $15 < E_T \lesssim 150$ GeV[8] and nearly fully efficient for higher-E_T electrons. The muon trigger was measured to be $91 \pm 2\%$ efficient for muons with $P_T > 20$ GeV/c.

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Data Sample	Number of Events	Integrated Luminosity (pb^{-1})	Efficiency (including acceptance)
$W' \to e\nu$	1796	4.15	20% at M_W rising to 41% at higher masses
$W' \to \mu\nu$	783	3.54	10% at M_W rising to 26% at higher masses
$Z' \to ee$	406	4.05	36% at M_Z rising to 51% at higher masses
$Z' \to \mu\mu$	148	3.54	16% at M_Z rising to 30% at higher masses

Table 1: Summary of data samples used in the heavy vector boson search.

From events passing these triggers, we have selected electron and muon events with cuts optimized for high-P_T leptons. Each of the four data sets, ee, $e\nu$, $\mu\mu$, and $\mu\nu$, consists of events selected by making definitive cuts on one charged lepton and either less restrictive cuts on a second charged lepton or a missing transverse energy ($\not{E}_T$) requirement for the ν. The electron selection requires an energy cluster in the central calorimeter, with $E_T > 30$ GeV for the $W' \to e\nu$ data sample and $E_T > 15$ GeV for the $Z' \to ee$ data sample, together with a track in the central tracking chamber (CTC) that matches the cluster in both energy and position. Both of these samples require the electron to have a high ratio of electromagnetic to hadronic energy and to satisfy isolation requirements. The muon selection requires a CTC track, $P_T > 30$ GeV/c for the $W' \to \mu\nu$ data sample and $P_T > 20$ GeV/c for the $Z' \to \mu\mu$ data sample, that extrapolates to a track segment in the fiducial volume of the muon chambers. Each of these samples requires the muon track to have energy deposition in the calorimeter that is consistent with that of a minimum ionizing particle, to not be a cosmic ray, and to satisfy isolation requirements. The $W' \to \mu\nu$ and $W' \to e\nu$ data samples require, in addition to the charged lepton, that the event not be a Z^0 and that the $\not{E}_T$ is greater than 30 GeV. The $Z' \to ee$ sample requires, in addition to one electron with the above cuts, either a second isolated electromagnetic cluster with $E_T > 7$ GeV and a matching CTC track, or simply a CTC track with $P_T > 20$ GeV/c that is outside the calorimeter fiducial region. The $Z' \to \mu\mu$ data sample requires, in addition to one muon with the above cuts, a CTC track with $P_T > 20$ GeV/c and charge opposite that of the first muon. These data sets are summarized in Table 1.

3. $e\nu, \mu\nu, ee$, and $\mu\mu$ Mass Distributions

For the $e\nu$ and $\mu\nu$ events, we form the transverse mass, $M_T = \sqrt{2E_T \not{E}_T(1 - \cos\phi^{l\nu})}$, where $\phi^{l\nu}$ is the angle in the azimuthal plane between the lepton vector and the missing energy vector. 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. The M_T distributions for the $e\nu$ and $\mu\nu$ samples are shown in Figures 1 and 2 together with a Monte Carlo prediction for W boson decay. The highest transverse mass events are at 185 GeV/c^2 in the electron channel and 205 GeV/c^2 in the muon channel. For the ee and $\mu\mu$ events we plot invariant mass distributions. These are shown in Figures 3 and 4 with the Monte Carlo prediction for dileptons from Z^0 decay and from virtual photon γ^* decay. There are no events with mass above 190 GeV/c^2 in the electron channel and 155 GeV/c^2 in the muon channel. In all four cases the data are well described by the standard model predictions.

4. Background

As shown in Figures 3 and 4, there are very few events in the high transverse and invariant mass ranges. Therefore, any backgrounds to these data samples in the regions of interest, $M_T > 100$ GeV/c^2 and $M > 100$ GeV/c^2, are also small. However, as a check, the expected background contributions were studied.

Backgrounds to the $W' \to e\nu$ and $W' \to \mu\nu$ data samples at high M_T from electroweak processes, such as $W \to \tau\nu$ and Z^0 decay, are determined to be less than 0.1 event. Two-jet events, in which one jet fakes a lepton, contribute less than 3 events to each W' sample at $M_T > 120$ GeV/c^2. Residual cosmic rays contribute 3 ± 2 events to the lower M_T range of the muon sample. The presence of small background results in a slightly more conservative limit. No correction for background was made to the $W' \to e\nu$ and $W' \to \mu\nu$ data samples.

Primary backgrounds to the $Z' \to ee$ sample are dijet and W-jet events. While this background is estimated to be 33 ± 5 events in the data sample as a whole, only two of these events are expected in the range $M > 100$ GeV/c^2. A background of 4 ± 1 events in the low mass range, $M < 100$ GeV/c^2, is expected from $Z^0 \to \tau\tau \to ee$ events. The fitted background was subtracted from the $Z' \to ee$ data sample.

The main background in the $Z' \to \mu\mu$ data sample comes from W+jet events. The presence of this type of background is indicated by the presence of same sign muon pairs. If the opposite sign requirement is relaxed, only two same sign dimuon events pass the selection criteria, one at 40 GeV/c^2 and one in the Z^0 mass range. The efficiency of the cosmic ray removal procedure is measured to be over 99% and the residual cosmic ray contamination is expected to be small. Because the background is found to be small, no background subtraction is made in the $Z' \to \mu\mu$ data sample.

5. Limits on the W' and Z' Signals

5.1. Method

To search for W' and Z' signals the observed lepton-neutrino $l\nu$ and di-lepton ll mass distributions are compared with those of standard model $l\nu$ or ll events plus W' or Z' events generated by Monte Carlo. A binned maximum likelihood fit using Poisson statistics is made of the observed mass spectra to the Monte Carlo superpostions

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

$$\frac{dN(ll)}{dM^{obs}} = \alpha M(Z') + \beta M(Z^0 + \gamma^*),$$

where $M_T(W')$, $M_T(W)$, $M(Z')$, and $M(Z^0 + \gamma^*)$ are Monte Carlo mass distributions generated with standard model couplings and branching ratios and corrected for acceptance and efficiency. A minimization of the likelihood function determines the parameters α and β. The Monte Carlo distributions were normalized so that these parameters represent the fraction of W' (Z') and W ($Z+\gamma^*$) relative to the prediction from standard-strength couplings and branching ratios.

5.2. Monte Carlo

In the Monte Carlo the width of the W' was taken to have the form $\Gamma_{W'} = (2.76\ \mathrm{GeV/c^2}) M_{W'}/M_W$, where 2.76 GeV/$c^2$ is the standard model width of the W with decays available to 3 generations of light fermions. The Z' width is taken to be that of the Z^0 scaled by a factor $M_{Z'}/M_{Z^0}$, as is expected for standard model couplings. The Monte Carlo distributions $M_T(W)$, $M_T(W')$, $M(Z^0 + \gamma^*)$, and $M(Z')$ 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.

5.3. Systematic Uncertainties

Systematic uncertainties in these analyses 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 in the W' search 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 ± 25 % to assign these uncertainties. In the Z' analysis there is a mass-dependent uncertainty that ranges from 5% at $M_{Z'} = 92$ GeV/c^2 to 10% at $M_{Z'} = 400$ GeV/c^2 due to higher-order QCD corrections. Uncertainties of the second type, in both the W' and the Z' searches, include uncertainties the lepton identification efficiencies and the overall 6.8% uncertainty in the luminosity normalization.[8] These uncertainties are incorporated into the results of the fit using a Monte Carlo procedure that has been described previously.[10]

5.4. Limits on $\sigma(W') \cdot$ B , $\sigma(Z') \cdot$ B , $M_{Z'}$, and $M_{W'}$

The results of the fit of the observed mass spectra to the Monte Carlo distributions are likelihood functions for the W' (Z') fraction α as a function of $M_{W'}$ ($M_{Z'}$). The best fit value of α is statistically consistent with zero for all values of $M_{W'}(M_{Z'})$. The results, expressed as a limit on $\sigma \cdot B(W' \to l\nu)$ and $\sigma \cdot B(Z' \to ll)$, are shown in Figures 5 and 6 for the electron, muon, and combined channels. Also shown are the predictions for $\sigma(W') \cdot$ B and $\sigma(Z') \cdot$ B with standard model production cross sections. These are calculated as a function of $M_{W'}$ and $M_{Z'}$ using the HMRS(B)[9] structure functions.*

*Other recent structure function sets[11,12] bracket the HMRS(B) W' prediction and lead to mass limits within ± 15 GeV/c^2 of those reported here. The Z' production cross section predicted by these

The W' and Z' mass limits can be obtained from the intersection of the experimental and predicted curves. For standard model couplings and a branching ratio of 1/12 to each lepton family, the W' 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. Similarly the Z' limit, for standard model couplings and branching ratios, is $M_{Z'} > 380$ GeV/c^2 in the electron channel, and $M_{Z'} > 320$ GeV/c^2 in the muon channel, both also at 95% confidence level. Combining the two channels we find $M_{Z'} > 412$ GeV/c^2.

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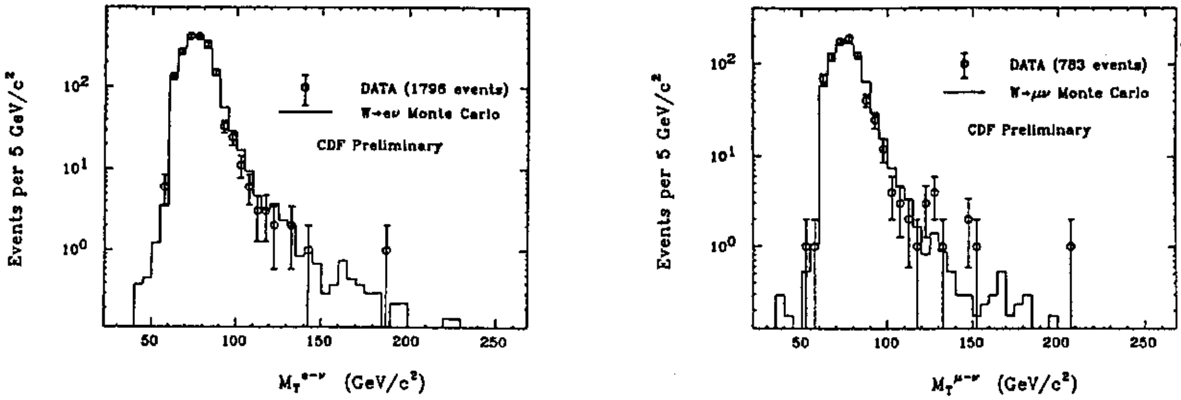
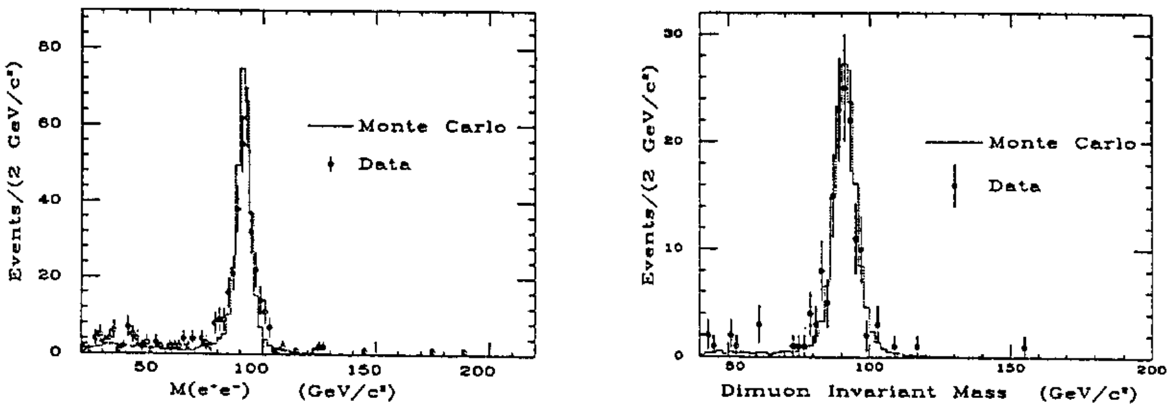
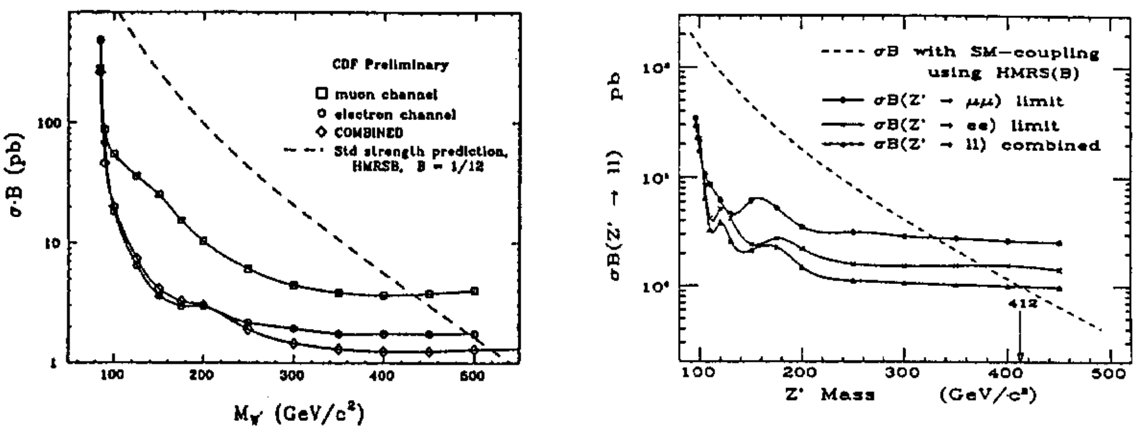
structure functions[11,12] is in progress.



Figures 1 and 2: The transverse mass distributions for the electron and muon W' data samples. Superimposed is the Monte Carlo prediction for W boson decay.



Figures 3 and 4: The invariant mass distribution for the electron and muon Z' data samples. Superimposed is the Monte Carlo prediction for Z^0 and γ^* decay.



Figures 5 and 6: The 95 % C.L. limit on $\sigma(W')\cdot$B and $\sigma(Z')\cdot$B for Z' and W' production measured in the electron channel, the muon channel, and the combined channels. The dashed line is the predicted value of $\sigma\cdot$B, assuming standard model couplings.