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Searches for New Gauge Bosons Using the D0 Detector

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SEARCHES FOR NEW GAUGE BOSONS USING THE D0 DETECTOR

The D0 Collaboration[1]
(July 1995)

We present the results of searches for additional gauge bosons beyond the W and Z bosons using the 1992-1993 Tevatron data set collected with the D0 detector. The signatures studied are $W' \rightarrow e\nu$, $W' \rightarrow \tau\nu$ with $\tau \rightarrow e\nu\overline{\nu}$, assuming stable neutrinos; $W_R \rightarrow e + X$ and $W_R \rightarrow eejj$, assuming massive neutrinos; and $Z' \rightarrow ee$. Lower limits on the W' mass and Z' mass at the 95% confidence level, and the mass exclusion contour in the W_R mass *vs.* neutrino mass plane are presented.

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I. INTRODUCTION

Additional gauge bosons, generically called W' and Z', appear in many extensions of the Standard Model (1). In left-right symmetric extensions of the Standard Model with an additional group, $\mathrm{SU}(2)_R$, the new charged gauge bosons decay into a right-handed neutrino and charged lepton. In this case, the mass and nature of the right-handed neutrino are parameters of the model. The W' in this model is commonly referred to as W_R. Limits on the mass of additional charged gauge bosons have been set by indirect searches at low energy by testing μ decay for deviations from the Standard Model predictions for right-handed currents (2), the mass difference between K_S and K_L (3), B_d mixing (4), semileptonic decay of the b quark, double beta decay (5), and cosmology (6) (7). Previous direct searches in $p\bar{p}$ collisions for decays into a charged lepton and a light stable neutrino have excluded additional charged gauge bosons for $M_{W'} < 652$ GeV/c^2 (8). Direct searches for $p\bar{p} \rightarrow Z' \rightarrow ee$ have excluded $M_{Z'} < 505$ GeV/c^2 (9).

II. THE DØ DETECTOR AND ELECTRON IDENTIFICATION

The data were collected during the 1992-1993 Tevatron run using the DØ detector. The DØ detector is composed of a central non-magnetic tracking system, a nearly hermetic uranium-liquid argon calorimeter, and a muon spectrometer. These detectors are described in detail elsewhere (10). The calorimeter is divided into a central barrel and two end cap calorimeters. The electromagnetic portion of the calorimeter consists of four radial layers with segmentation 0.1 × 0.1 in pseudorapidity (η) × azimuthal angle (ϕ) space in layers 1, 2 and 4, and 0.05 × 0.05 in $\eta \times \phi$ at the shower maximum in layer 3. The hadronic portion of the calorimeter consists of five layers with 0.1 × 0.1 $\eta \times \phi$ segmentation.

Electrons are identified using the central tracking system to detect the presence of a charged track and the calorimeter to detect a clustered deposit of electromagnetic energy. Electron identification is refined by additional criteria. These include using additional information from the tracking system such as the significance of the position match between the electromagnetic cluster, and the corresponding track, and requiring that the track be consistent with a single minimum ionizing particle, and that the transition radiation be consistent with an electron. Other calorimeter based information used for electron identification includes the longitudinal and transverse development of the electromagnetic shower determined from test beam data and the isolation of the electromagnetic cluster with respect to other deposits of energy in the calorimeter (11).

The efficiency of the electron identification cuts is determined by using a sample of $Z \rightarrow ee$ events in which electron identification cuts are applied to one of the electrons and the invariant mass of the dielectron pair is restricted to fall within 10 GeV/c^2 of the central value of the Z boson mass. The cuts are then applied to the unbiased electron to determine the efficiency of the electron identification criteria. The rate of misidentifying a jet as an electron is studied using samples of events in which an electron has been identified, but which are not consistent with W or Z boson production.

III. SEARCH FOR W' DECAYING TO STABLE NEUTRINOS

In the search for an additional W boson decaying into an electron and a light (M_ν significantly less than $M_{W'}$), stable neutrino, we examine the transverse mass distribution $M_T^{e\nu}$ for structure not explained by standard W boson production or by QCD events with a jet misidentified as an electron (12). The event selection is: one electron with $E_T > 30$ GeV, $|\eta| < 2.5$, and $\not\!\!E_T > 30$ GeV. Loose criteria on the shape of the electromagnetic shower, the isolation and the significance of the match between the calorimeter cluster and the track are used to identify the electrons. Additionally any jets with $E_T > 20$ GeV must pass cuts which reject events with $\not\!\!E_T$ arising from electronic or accelerator background sources. The trigger conditions for this sample require a single electron with $E_T > 20$ GeV and $\not\!\!E_T > 20$ GeV. These trigger conditions are $98.1 \pm 0.7\%$ efficient for W bosons within the acceptance of the selection cuts. There are 9135 events in $\int \mathcal{L}dt = 13.5 \pm 1.6$ pb^{-1} which meet this selection.

The resulting $M_T^{e\nu}$ distribution for these events is shown in Fig. 1(a). The solid portion indicates the estimated amount of QCD background events in which a jet has been misidentified as an electron and $\not\!\!E_T$ results from mismeasured energy. The rate of this type of background is determined by examining events with an electromagnetic cluster $E_T > 30$ GeV. This sample is divided into two samples, one with $\not\!\!E_T < 20$ GeV, the other with $\not\!\!E_T > 30$ GeV. For those two samples the number of events containing electromagnetic clusters that pass electron identification cuts as well as the number of events passing "anti"-electron identification cuts are determined and used to estimate the background fraction. The contribution of W boson production is estimated from PYTHIA Monte Carlo (13) and simulation of the DØ detector. The sum of W boson production and misidentified QCD events, which together reproduces the data spectrum well, is shown in the solid histogram on Fig. 1(a).

The acceptance for W' boson production as a function of $M_{W'}$ is also calculated using PYTHIA Monte Carlo with MRS D−′ parton distribution functions (pdf's) (14) and a fast

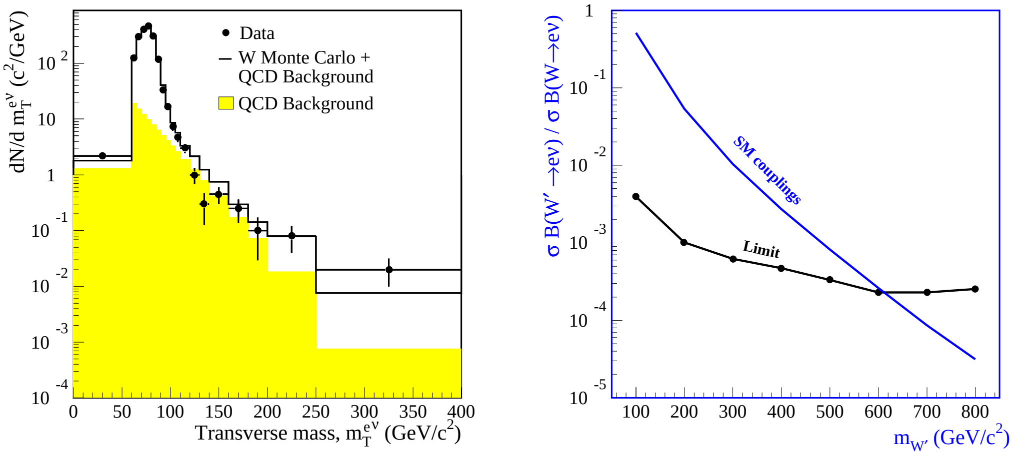

FIG. 1. a)$M_T^{e\nu}$ distribution. Data are shown in points, QCD contribution to background in the solid. The sum of W Monte Carlo and the QCD background is shown in histogram. b)The upper limit on the ratio of the cross section × branching fraction for W'/W boson production at the 95% confidence level. The theoretical prediction for the ratio assuming Standard Model couplings is also shown.

detector simulation. The W' acceptance relative to the W boson acceptance, shown for two values of the W' mass, is:

$$M_{W'} = 100 \text{ GeV/c}^2 : A(W')/A(W) = 1.48 \pm 0.05$$

$$M_{W'} = 600 \text{ GeV/c}^2 : A(W')/A(W) = 2.54 \pm 0.08$$

The upper limit on the cross section for W' boson production is calculated using a binned likelihood method with Poisson statistics to estimate the contribution of W' boson production. Fig. 1(b) shows the resulting upper limit on the cross section times branching fraction at the 95% confidence level and the theoretical cross section, assuming Standard Model couplings, as a function of W' mass. There is a 3% uncertainty in the theoretical prediction due to the choice of pdf's. A W' with the same couplings to quarks and leptons as the Standard Model W boson is excluded at the 95% confidence level for $M_{W'} < 610$ GeV/c^2 assuming that the neutrinos produced in W' decay are stable and have a mass significantly less than $M_{W'}$.

IV. SEARCH FOR W_R DECAYING TO MASSIVE NEUTRINOS

This analysis examines final states that could be attributed to the decay of a right-handed W boson (W_R) into a charged lepton and a massive neutrino (N). The neutrino decays into a charged lepton and a virtual W_R when there is no mixing between the gauge eigenstates, or into a charged lepton and W boson (virtual or on-shell depending on the mass of the neutrino) in the case of maximum mixing. This analysis examines decays in which the charged lepton is an electron and the gauge boson which results from the decay of the massive neutrino decays into a quark-anti-quark pair. The topology of the final state will depend on the mass of the neutrino. When the neutrino is relatively heavy, the decay products of the W_R boson and N are relatively well separated, resulting in final states with two electrons and two jets. This case is addressed with an event counting analysis. When the neutrino is lighter, the electron from the neutrino decay is not well separated from the jets. In this case, the Jacobian shape of the electron E_T from the two body decay of the W_R boson and the lack of $\not\!\!E_T$ in the W_R signature are used in a fitting analysis. The results in this section are preliminary.

A. The Shape Fitting Analysis

The selection criteria for the sample used in the shape fitting analysis required

$$\text{one electron with } E_T > 55 \text{ GeV}$$
$$|\eta| < 1.1$$

The electron identification cuts applied include very restrictive criteria on the shape and isolation of the electromagnetic shower, and the significance of the spatial match between the calorimeter cluster and the track. Additionally the dE/dx for the electron was required to be consistent with a single minimum ionizing track and the transition radiation consistent with an electron. These electron identification cuts are relatively severe since the high E_T electron is the only feature of the signal used to select the events. The trigger used to collect this data required a single electron object with $E_T > 20$ GeV and is fully efficient for this search. There are 256 such events in $\int \mathcal{L} dt = 13.5 \pm 1.6$ pb^{-1}. The distributions of the electron E_T and $M_T^{e\nu}$ for these events are shown in Fig. 2. The distributions in E_T and $M_T^{e\nu}$ for a W_R boson with mass 500 GeV/c^2 and neutrino mass 100 GeV/c^2, as calculated from PYTHIA version 5.6 modified to include W_R boson production and a DØ detector simulation, are shown in Fig. 2 in the plots labelled W_R MC. The electron E_T distribution has the characteristic Jacobian shape and the electron E_T cut is efficient for heavy W_R mass and relatively lighter N mass. There are no distinguishing features of the $M_T^{e\nu}$ distribution for the W_R boson as there is no $\not\!\!E_T$ expected in the signal. The known physics processes which contribute to the data sample are W and Z boson production and QCD jet events in which a jet is misidentified as an electron. The shape of the W boson distributions in electron E_T and $M_T^{e\nu}$ are calculated from PYTHIA Monte Carlo and a fast simulation of the DØ detector. The combined distributions for Z boson and QCD events are calculated from data and are shown in Fig. 2.

The fitting technique is a binned log likelihood method in which the relative amounts of W and Z boson production and QCD processes, and W_R boson production are allowed to vary. The fits to both electron E_T and $M_T^{e\nu}$ are performed over a range of W_R masses and neutrino masses. The results of one such fit are shown in Fig. 3. The data are shown by the points and the sum of all contributions is shown by the dashed line. The contribution of W_R is negligible for this fit. Using the fitted amount of W_R boson production contributing to the data, upper limits on the production cross section times the branching fraction at 95% confidence level assuming Standard Model couplings are established as a function of the W_R and neutrino masses. Fig. 4(a) shows these cross section upper limits for three different masses of the neutrino.

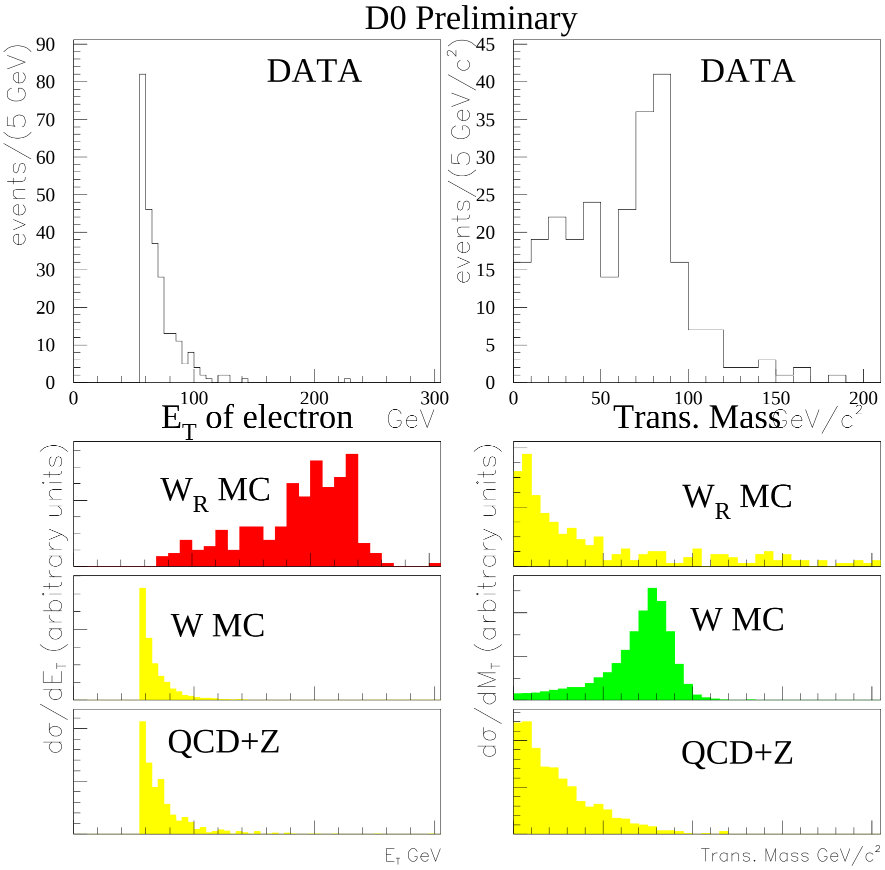

FIG. 2. Preliminary E_T and $M_T^{e\nu}$ distributions for data sample, W_R boson production, Z and QCD production and W boson production. In the left column, the electron E_T distribution is shown (from top to bottom) for data, W_R Monte Carlo ($M_{W_R} = 500$ GeV/c^2, $M_N = 100$ GeV/c^2), W Monte Carlo, and QCD + Z production calculated from the data. The $M_T^{e\nu}$ distributions are shown on the right. The W_R electron E_T distribution shows the Jacobian shape while the W_R $M_T^{e\nu}$ distribution shows no features.

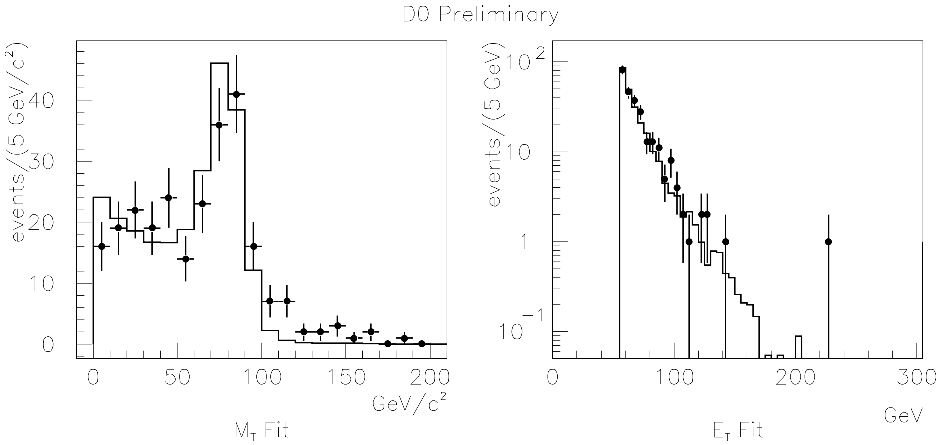

FIG. 3. Example of a fit using $M_T^{e\nu}$ and E_T distributions. The points shown in the plots are the data. The dashed lines indicate the sum of all contributions to the fit.

B. The Counting Analysis

Complementary to the shape analysis search for W_R boson production is the analysis in which it is assumed that all of the decay products of the W_R boson and massive neutrino are well separated. The signature is two electrons and two jets. The selection criteria used for this analysis are

$$\begin{aligned} \text{two electrons with } E_T &> 25 \text{ GeV} \\ |\eta| &< 2.5 \\ \text{two jets with } E_T &> 25 \text{ GeV} \\ M(ee) &< 70 \text{ GeV/c}^2 \text{ or} \\ M(ee) &> 110 \text{ GeV/c}^2 \end{aligned}$$

The electron identification criteria include the shape of the electromagnetic shower, the isolation, and the significance of the match between the calorimeter cluster and the track. Additionally, one of the electrons must be consistent with a single minimum ionizing particle. The 1992/3 data set yields one event passing these cuts in $\int \mathcal{L}dt = 13.5\pm\ 1.6$ pb^{-1}. The estimate of the number of events passing these cuts for the dominant sources of background (Z boson production with associated jets, $t\bar{t}$ production with both W bosons decaying into electrons and QCD multijet production in which two jets are misidentified as electrons) is 0.48 $\pm$0.08 events. The upper limit on the cross section times branching fraction at the 95% confidence level is established by taking the observed event as signal. The upper limit on the cross section is shown in Fig. 4(b) as a function of the W_R boson mass and is shown for three different neutrino masses. At lighter values of neutrino mass, this analysis is not as powerful as the method described above, but it is more powerful for the region in which the difference between the mass of the W_R boson and that of the neutrino is relatively small. The upper limits on the cross section times branching fraction can be used to form a mass

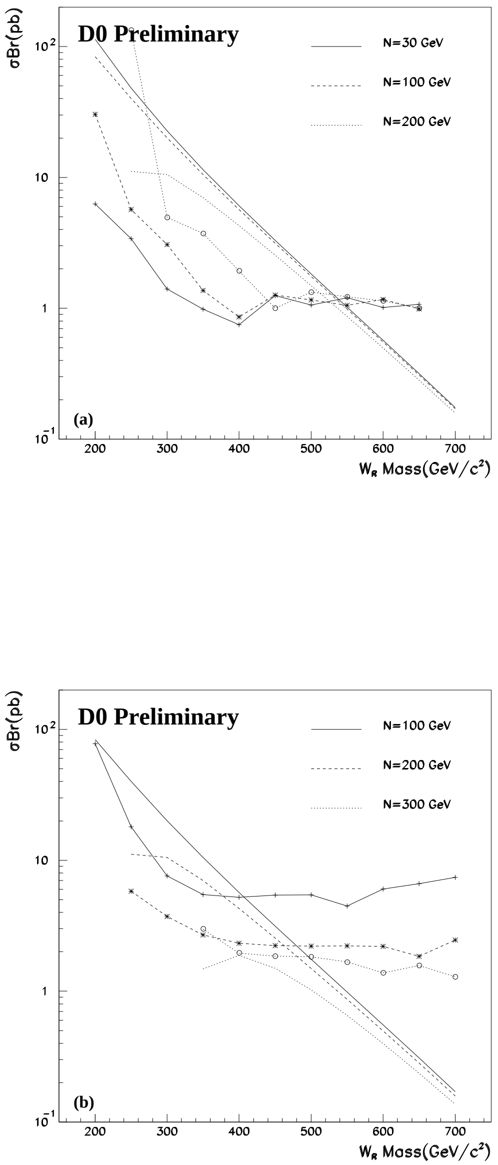

FIG. 4. Upper limit on cross section times branching ratio for W_R boson production for (a) the shape analysis and (b) the event counting analysis with the mixing parameter $\xi = 0$. The theoretical prediction and experimental upper limit curves are shown for three masses of N, the massive neutrino.

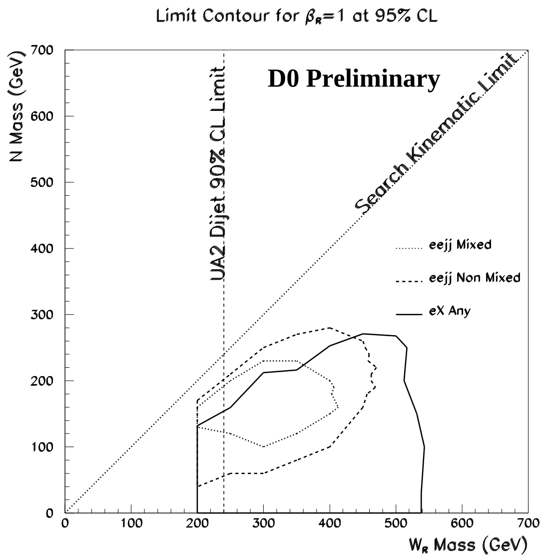

FIG. 5. Preliminary exclusion contour in the plane of W_R boson mass *vs.* neutrino mass for combined shape and counting analysis and for minimum and maximum values of the mixing parameter ξ.

exclusion contour in the plane of the neutrino mass *vs.* the mass of the W_R boson (Fig. 5). The kinematic limit of the search shown is the constraint that the neutrino must be less massive than the W_R boson. The W_R mass limit independent of the mass of the neutrino from a previous search with the W_R boson decaying into jets is also shown. The solid line shows the mass exclusion contour for the shape analysis, and the two dotted contours show the mass exclusion contour for the counting analysis for the cases of maximum and minimum mixing. The complementary nature of the two approaches is seen in this set of contours. The shape analysis excludes low mass neutrino regions in which the decay products of the neutrino are not well separated or are not sufficiently energetic to pass the cuts. The counting experiment analysis (especially in the no mixing case) extends the excluded region for high mass neutrinos.

V. SEARCH FOR Z' DECAYING INTO TWO ELECTRONS

We have also searched for Z' bosons in the decay channel: $Z' \rightarrow ee$. The method of search is similar to that for the W'. We look in the ee invariant mass spectrum for the Breit-Wigner peak of a Z' superimposed on the invariant mass spectrum expected in the Standard Model arising from Z and Drell-Yan production. The event selection is: two electrons with $E_T > 30$ GeV and $|\eta| < 2.5$ with $|\eta| < 1.1$ for at least one of the electrons. The trigger requires two electrons with $E_T > 20$ GeV. There are 886 events in the $Z(Z')$

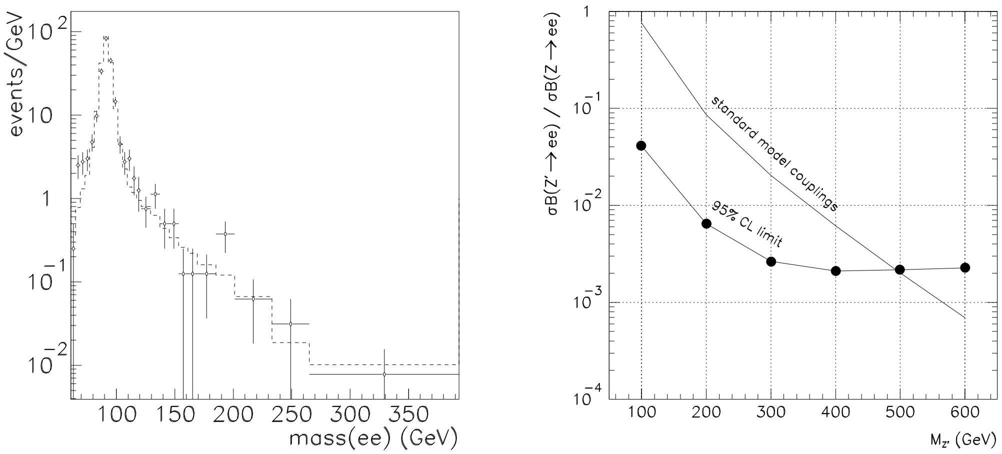

FIG. 6. a)Invariant mass(ee) distribution. Observed dielectron events (discrete points) are compared to the combined Z/Drell-Yan Monte Carlo and dijet background. b)The 95% C.L. upper limit on the ratio of the cross section × branching fraction for Z'/Z boson production. The theoretical prediction for the ratio assuming Standard Model couplings is also shown.

sample from $\int \mathcal{L}dt = 14.4 \pm 1.7$ pb^{-1}.

The invariant mass spectrum of the data is shown in Fig. 6(a) compared to the sum of Z and Drell-Yan Monte Carlo and QCD dijet background modeled from data. The Z/Drell-Yan Monte Carlo is generated with PYTHIA using MRS D$-'$ pdf's and parameterized detector resolution. The QCD background arises from multijet events in which two jets are misidentified as electrons. The amount of this background, calculated from the misidentification rate and the dijet cross section as determined from DØ data, is 38 ± 3 events. The invariant mass spectrum of this background is taken to be the dijet spectrum. The agreement between data and the simulated prediction is quite good. For $M_{ee} > 140$ GeV/c^2, 12 events are observed. The expected background to Z' from Z/Drell-Yan and dijet events is 8.4 ± 0.4 events. For $M_{ee} > 250$ GeV/c^2, 1 event is observed, 1.4 ± 0.1 events are expected.

The acceptance for Z' is calculated using PYTHIA Monte Carlo with MRS D$-'$ pdf's. The trigger and reconstruction efficiencies are expected to be the same as for the Z. This is substantiated by data from test beam electrons up to 150 GeV and by a full detector simulation of high energy electrons.

The upper limit on the cross section times branching fraction for the process $p\bar{p} \to Z' \to ee$ is determined using binned likelihood with Poisson statistics. The 95% C.L. is plotted as a function of $M_{Z'}$ in Fig. 6(b) together with the theory curve. The theory assumes a hypothetical Z' with Standard Model couplings to quarks and leptons. A second order K factor is used here and for the W' theory curve (15). There is an uncertainty in the theory of 3% due to choice of pdf's. A Z' from this hypothetical model is excluded for $M_{Z'} < 490$ GeV/c^2.

VI. CONCLUSIONS

We report on three searches for heavy gauge bosons which have been conducted using the 1992-1993 data set collected with the DØ detector. A search for W' in the channels $W' \to e\nu$ and $W' \to \tau\nu$ with $\tau \to e\nu\overline{\nu}$, assuming light, stable neutrinos, excludes $M_{W'} < 610$ GeV/c^2 at the 95% confidence level for Standard Model couplings. Preliminary results from a search for W_R boson production assuming massive neutrinos are shown as a mass exclusion contour in the M_{W_R} *vs.* M_N plane. A search for a new neutral gauge boson in the channel $Z' \to ee$ excludes $M_{Z'} < 490$ GeV/c^2 given Standard Model couplings.

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