Search for New Gauge Bosons Decaying into Dileptons in $\overline{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV

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We have searched for heavy neutral gauge bosons (Z') in dielectron and dimuon decay modes using 110 pb^{-1} of $\overline{p}p$ collisions at $\sqrt{s} = 1.8$ TeV collected with the Collider Detector at Fermilab. We present a limit on the production cross section times branching ratio of a Z' boson decaying into dileptons as a function of Z' mass. For mass $M_{Z'} > 600$ GeV$/c^2$, the upper limit is 40 fb at 95% confidence level. We set the lower mass limits of 690, 590, 620, 595, 565, 630, and 600 GeV$/c^2$ for $Z'_{\rm SM}$, Z_ψ, Z_η, Z_χ, Z_I, $Z_{\rm LR}$, and $Z_{\rm ALRM}$, respectively. [S0031-9007(97)04021-0]

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Neutral gauge bosons in addition to the Z^0 are expected in many models for physics beyond the standard model [1]. The models typically specify the strengths of the couplings of such bosons to quarks and leptons, but make no mass predictions [2]. However, some recent theoretical predictions [3,4] state that in super string and super gravity models, it is more "natural" to expect the mass of the lightest Z' boson to be in the range of 200 GeV$/c^2$ to 1 TeV$/c^2$ [5]. To date there is no experimental evidence for the existence of any Z' bosons [6]. In $\overline{p}p$ collisions at the Tevatron, Z' bosons may be produced and observed directly via their decay to lepton pairs. Observation of a Z' boson would provide dramatic evidence for physics beyond the standard model. Extending the experimental mass and cross section limits on Z' bosons provides further constraints on these theories. The current best direct experimental Z' mass limit, $M_{Z'} > 505$ GeV$/c^2$ at 95% confidence level (C.L.), was established by the Collider Detector at Fermilab (CDF) [7] with the assumption that the Z' boson (Z'_{SM}) has the same coupling strengths to quarks and leptons as those of the standard model (SM) Z^0. That results was based upon data collected during the 1992–1993 run with an integrated luminosity of 19.7 pb^{-1} and used the dielectron decay mode. Similar search was conducted by the D0 collaboration using 15 pb^{-1} of data and a comparable mass limit ($Z'_{\text{SM}} > 490$ GeV$/c^2$) was obtained [8]. We report an extension of that search using an additional 90 pb^{-1} of integrated luminosity from the 1994–1995 run. Results reported here use both the dielectron (ee) [9] and the dimuon ($\mu\mu$) [10] decay modes. We present a 95% C.L. upper limit on the production cross section times branching ratio of a Z' boson decaying into dileptons [$\sigma(Z')B(Z' \to ll), l = e, \mu$]. We derive a Z' mass limit assuming SM coupling strengths. In addition, we derive mass limits using several different theoretical models based on the E_6 symmetry group [11,12] and on an alternative left-right model [13]. A complementary study for continuum anomalies from new constituent interactions of quarks and leptons with a common composite structure is in a companion Letter [14]. It uses similar dilepton data, but the selection criteria are more restrictive to avoid biases from background under the continuum, while the selection criteria for Z' resonance search are optimized for high efficiency.

The CDF detector consists of a magnetic spectrometer surrounded by calorimeters and muon chambers and has been described in detail elsewhere [15]. We briefly describe here those aspects of the detector relevant to this analysis. The momenta of electrons and muons are measured in the central tracking chamber (CTC), which is surrounded by a 1.4-T superconducting solenoidal magnet. The energies of electrons are measured in the central electromagnetic calorimeter (CEM) ($|\eta| < 1.1$)) and the end-plug electromagnetic calorimeter (PEM) ($1.1 < |\eta| < 2.4$) [16]. Outside the calorimeters, drift chambers in the region $|\eta| < 1.0$ provide muon identification. Dielectron candidate events were collected with an electron trigger. In order to maintain high efficiency for high E_T [16] electrons, we also accepted events from a jet trigger [7]. The electron trigger requires either an energy cluster in the CEM or in the PEM. The jet trigger requires a calorimeter energy cluster with $E_T > 100$ GeV. These triggers are fully efficient for the ee decay mode [7]. Dimuon candidate events were collected with a muon trigger that requires a match between a muon chamber track and a track measured by the CTC with $p_T > 18$ GeV$/c$ [16]. The overall trigger efficiency for the $\mu\mu$ decay mode is 76 ± 3%.

We select ee and $\mu\mu$ candidate events by requiring that one lepton satisfies tight lepton identification cuts and a second lepton satisfies looser identification cuts. The lepton tracks are required to come from an event vertex located within 60 cm of the detector center along the z axis. Dielectron candidate events are selected by requiring at least one electron candidate in the CEM (CEM tight) and a second electron candidate in either the CEM (CEM loose) or PEM (PEM loose). An electron candidate is required to have $E_T > 25$ GeV and be in the good fiducial region of the CEM or PEM. Electron candidates in the CEM are required to have a track with $p_T > 13$ GeV$/c$ matched to the CEM energy cluster in both position and transverse momentum. The electrons are required to be isolated [7]. Muons are required to be consistent with a minimum ionizing signal in the calorimeters and have $p_T > 20$ GeV$/c$. One muon (tight muon) is required to be isolated and detected in the central region covered by the muon trigger ($|\eta| < 0.6$). The second muon (loose muon) is required to be in the fiducial volume of the CTC to ensure a good momentum measurement [17].

The ee and $\mu\mu$ invariant mass distribution for events passing these selection criteria are shown in Figs. 1 and 2. The sample contains 7234 ee and 2566 $\mu\mu$ candidate events. The largest observed dilepton invariant masses are 496 and 320 GeV$/c^2$ for ee and $\mu\mu$ events, respectively.

The efficiencies of the lepton identification cuts are determined using a nearly pure sample of dilepton events from Z^0 decays. This sample is selected using the lepton identification requirements for only one central lepton. The second lepton is required only to satisfy kinematic and geometrical cuts. We also require that the invariant mass of the two leptons be between 70 and 110 GeV$/c^2$. We estimate the efficiency of the lepton identification requirements using the second lepton candidate. Since leptons from Z' decay may have higher p_T than those from Z^0 decays, the lepton selection cuts should maintain high efficiencies for the higher p_T leptons. This is checked by studying the high p_T leptons from Z^0 and W decays, test beam data, and Monte Carlo simulation. We find that the lepton identification cuts have no significant dependence on the p_T of the lepton. The efficiencies

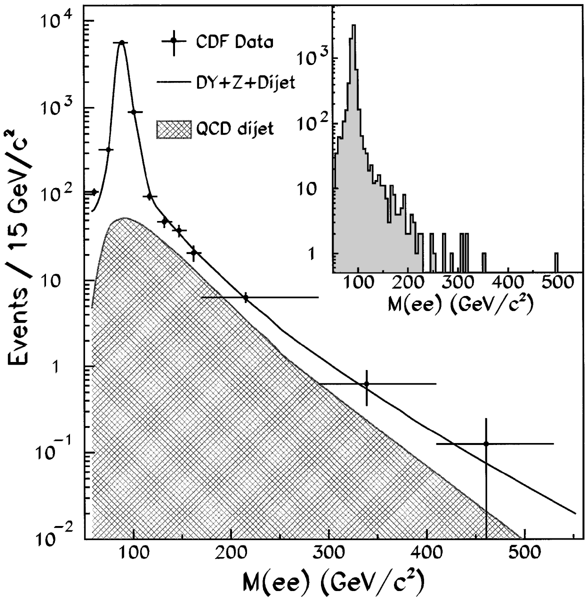

FIG. 1. Comparison of the data (points) with the QCD dijet background prediction (shaded region) and total Drell-Yan/QCD background (solid line) in ee mass distribution for $M_{ee} > 50$ GeV/c^2. Inset shows the same ee mass distribution in bins of 5 GeV/c^2.

of the CEM tight, CEM loose, and PEM loose electron identification selection cuts are ($94.5 \pm 0.4\%$), (96.5 ± 0.3)%, and ($93.0^{+1.6}_{-1.8}$)%, respectively. The efficiencies of the tight and loose muon cuts are ($85.6^{+2.0}_{-2.6}$)% and ($92.9^{+1.2}_{-1.8}$)% for 1992–1993 data, and ($80.8^{+1.3}_{-1.2}$)% and ($92.8^{+0.6}_{-0.8}$) for the higher instantaneous luminosity 1994–1995 data. The geometrical and kinematic acceptance for dilepton events as a function of $M_{Z'}$ is determined by Monte Carlo simulation. We use Martin-Roberts-Stirling set D'_- (MRS D'_-) parton distribution functions (p.d.f.) [18]. Events are simulated using a parametrized detector response and are corrected for the efficiencies of the selection requirements. The total efficiencies for detecting $Z' \rightarrow ee$ and $Z' \rightarrow \mu\mu$ events are $\approx$47% and $\approx$20%, respectively, for $M_{Z'} > 300$ GeV/c^2.

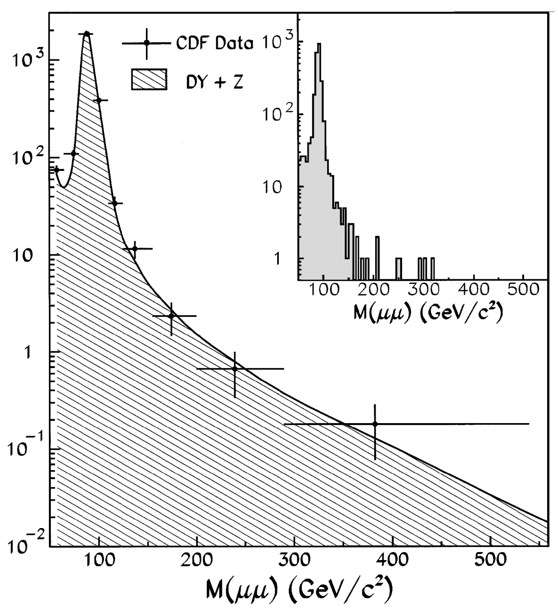

FIG. 2. Comparison of data (points) with Drell-Yan prediction (solid line) in $\mu\mu$ mass distribution for $M_{\mu\mu} > 50$ GeV/c^2. Inset shows the same $\mu\mu$ mass distribution in bins of 5 GeV/c^2.

The major background contribution is from dilepton events from the Z^0 decay and Drell-Yan production. The contributions from other processes which produce dilepton final states, such as $b\bar{b}$, $t\bar{t}$, $\tau^+\tau^-$, and W^+W^-, are found to be negligible. The lepton identification cuts are optimized for high efficiency. As a result, some of the accepted ee events are from nondielectron sources, predominantly QCD dijet events passing our dielectron selection criteria. This background is estimated from a sample of QCD events that pass looser identification cuts and by fitting the observed dijet mass distribution to a parametric form as determined in [19]. The dominant nondimuon background to the dimuon data set is from cosmic rays. The contribution from this background is small and estimated to be less than 0.1 event above an invariant mass of 200 GeV/c^2. In Table I, Figs. 1 and 2 we show the ee and $\mu\mu$ data versus the estimated number of background events from the Z^0 and Drell-Yan production [20]. For the ee background estimate, the QCD dijet contribution is also added. No significant excess of events is observed.

Limits on the Z' production cross section are extracted by comparing the observed dilepton invariant mass distribution to a superposition of the predicted distributions from Z' production together with standard model Drell-Yan and Z^0 production using a binned maximum likelihood method [21]. The ee data include QCD dijet background events. However, when setting the Z' cross section limit, this background is not subtracted, thus yielding a conservative limit. The expected backgrounds are normalized to the number of events observed in the Z^0 mass region. The fitting process is repeated for a variety of Z' masses in the range 125 to 800 GeV/c^2. Standard model couplings are assumed in generating the Z' events, and the Z' width is set equal to the Z^0 width scaled by

TABLE I. Expected number of background events compared with data.

	ee		$\mu\mu$	
Mass GeV/c^2	Observed events	Expected background	Observed events	Expected background
$M > 150$	89	86.9 ± 17.4	17	16.51 ± 0.50
$M > 200$	26	27.7 ± 5.2	7	6.24 ± 0.19
$M > 300$	6	4.1 ± 0.6	2	1.45 ± 0.04
$M > 400$	1	0.9 ± 0.1	0	0.43 ± 0.01
$M > 500$	0	0.2 ± 0.0	0	0.14 ± 0.00
$M > 600$	0	0.0 ± 0.0	0	0.05 ± 0.00

a factor $M_{Z'}/M_{Z^0}$. We use the leading-logarithmic QCD approximation to calculate Z^0, Drell-Yan, and Z' production cross sections with an overall correction factor K [22]. We take into account systematic uncertainties in the ratio of Z' to Z^0 production, acceptance calculations, lepton identification efficiencies, p_T of the gauge boson, and choice of p.d.f. A large part of the systematic uncertainties cancel because of the normalization to the Z^0 cross section (e.g., luminosity). The systematic uncertainties in $\sigma(Z')B(Z' \rightarrow ee)$ and $\sigma(Z')B(Z' \rightarrow \mu\mu)$ are estimated to be 2.6% and 2.9%, respectively.

The 95% C.L. upper limit on $\sigma(Z')B(Z' \rightarrow ll)$ is shown as the solid line in Fig. 3. At high mass ($M_{Z'} > 600$ GeV/c^2) the $\sigma(Z')B(Z' \rightarrow ll)$ limit is 40 fb. The dashed line in Fig. 3 is the predicted σB using the MRS D'_- p.d.f. and SM couplings. The intercept of the two curves at 690 GeV/c^2 determines the 95% C.L. lower limit on the Z' mass, assuming $e\mu$ universality [23]. We also set mass limits on Z_ψ, Z_η, Z_χ, Z_I, $Z_{\rm LR}$ which appear in various E_6 models [24], and on $Z_{\rm ALRM}$ which is right-handed Z' boson in the alternative left-right model (ALRM), which also is a model from one of the E_6 symmetry decompositions [25], using the same theory prediction curves given in Fig. 3 of our previous Z' search publication [7,26]. We extract lower mass limits for Z_ψ, Z_η, Z_χ, Z_I, $Z_{\rm LR}$, and $Z_{\rm ALRM}$ of 590, 620, 595, 565, 630, and 600 GeV/c^2, respectively, assuming that Z' boson decay into known fermions only. These limits are lower by 100 to 150 GeV/c^2 when decays to all possible exotic and supersymmetric particles present in those models are allowed. For these calculations we assume the masses of the top quark, supersymmetric fermions, and exotic fermions to be 174 [27], 200, and 45.5 GeV/c^2, respectively.

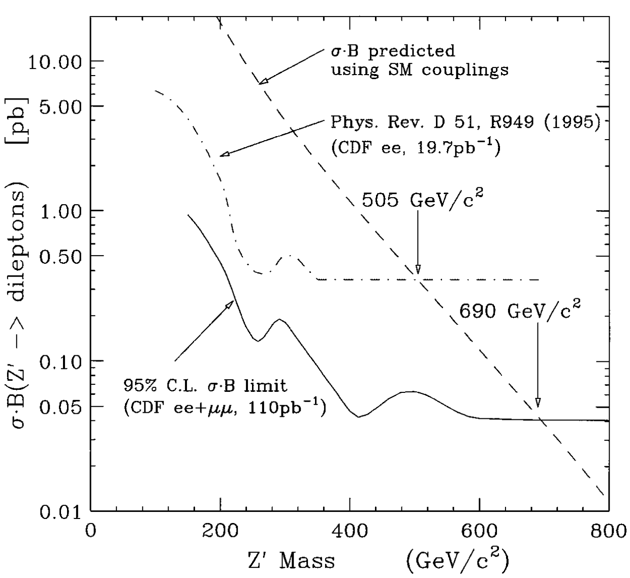

FIG. 3. Limits on Z' production. The solid line shows the 95% C.L. upper limit on $\sigma(Z')B(Z' \rightarrow ll)$ as a function of Z' mass. The dash-dotted curve shows our previous limit. The dashed line is the prediction of $\sigma(Z')B(Z' \rightarrow ll)$, assuming SM couplings and using the MRS D'_- parton distribution functions. The intersection of the curves determines the lower mass limit, $M_{Z'} > 690$ GeV/c^2.

In summary, we have performed a search for additional neutral heavy bosons, in the ee and $\mu\mu$ decay modes, using a data sample collected during the CDF 1992–1995 run corresponding to 110 pb^{-1} of integrated luminosity. The observed dilepton invariant mass spectra are consistent with expectations from the Z^0 and Drell-Yan productions and other known backgrounds. We combine the ee and $\mu\mu$ decay channels and obtain a 95% C.L. limit on the production cross section times the branching ratio for a Z' boson decaying into dileptons as a function of the dilepton invariant mass. For $M_{Z'} > 600$ GeV/c^2 the limit on $\sigma(Z')B(Z' \rightarrow ll)$ is 40 fb. Assuming SM coupling strengths, we exclude $M_{Z'} < 690$ GeV/c^2. In addition, we set Z' mass limits in the 565–630 GeV/c^2 range for several models based on the E_6 symmetry group and the alternative left-right model.

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[24] We have calculated the predictions from E_6 models based on Ref. [11].
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