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Search for new gauge bosons decaying into dielectrons in $\bar{p}p$ collisions at $\sqrt{s}=1.8$ TeV

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We have searched for heavy neutral gauge bosons (Z') in $\bar{p}p$ collisions at $\sqrt{s}=1.8$ TeV. The data were obtained using the CDF detector during the 1992–1993 run corresponding to an integrated luminosity of 19.7 ± 0.7 pb^{-1}. We present a 95% confidence level upper limit on the production cross section times the branching ratio of Z' decaying into dielectrons as a function of Z' mass. Assuming standard model coupling strengths, we exclude a Z' with a mass less than 505 GeV/c^2. We also present lower mass limits for Z' bosons from E_6 models and the alternative left-right model.

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Neutral gauge bosons in addition to the Z^0 are expected in many extensions of the standard model [1]. These models typically specify the strengths of the couplings of such bosons to quarks and leptons but make no mass predictions [2]. In $\bar{p}p$ collisions, Z' bosons may be observed directly via their decay to lepton pairs. Observation of a Z' boson would provide dramatic evidence for physics beyond the standard model. To date there is no experimental evidence for the existence of any Z' [3]. The current experimental Z' mass limit $M_{Z'}>412$ GeV/c^2 (95% C.L.) was established by the Collider Detector at Fermilab (CDF) Collaboration [4] with the assumption that the coupling strengths of the Z' to quarks and leptons were the same as those for the standard model (SM) Z^0. This result was based upon data collected during the 1988–1989 run with an integrated luminosity of 4 pb^{-1} and used both the dielectron [5] and dimuon decay modes. We report an extension of this search using 19.7 pb^{-1} of integrated luminosity from the 1992–1993 run. The results reported here are obtained using only the dielectron decay mode. We present a 95% confidence level upper limit on the production cross section times branching ratio of Z' decaying into dielectrons $[\sigma(Z')B(Z'\rightarrow ee)]$. Mass limits are again derived assuming SM coupling strengths. In addition, we present Z' mass limits using several different theoretical models based on the E_6 symmetry group [6,7] and one limit based upon an alternative left-right model [8].

The CDF detector has been described in detail elsewhere [9]. We give a brief description of the components relevant to this analysis. Momenta of charged particles are measured in the central tracking chamber (CTC), which is immersed in a 1.4 T axial magnetic field. Outside the CTC, electromagnetic and hadronic calorimeters are arranged in a projective tower geometry. There are three separate pseudorapidity (η) regions of calorimeters, central, end plug, and forward, where $\eta=-\ln(\tan\theta/2)$ and θ is the polar angle with respect to the direction of the proton beam. Each region has an electromagnetic calorimeter and behind it a hadronic calorimeter. For this analysis we use electrons detected in the central [central electromagnetic (CEM)] or end-plug [plug electromagnetic (PEM)] regions. The CEM covers $|\eta|<1.1$, and the PEM covers $1.1<|\eta|<2.4$. The CEM energy resolution is $23.7\%/\sqrt{E_T}\oplus 2.0\%$ and the PEM energy resolution is $22\%/\sqrt{E}\oplus 2.0\%$, where E is energy (in GeV) of the cluster, and E_T is the transverse energy of the cluster defined as the sum of the energies in the calorimeter towers multiplied by $\sin\theta$. The symbol $\oplus$ signifies that the constant term is added in quadrature in the resolution.

Events for this analysis were collected with a trigger that required either an energy cluster in the CEM with $E_T>9$ GeV or an energy cluster in the PEM with $E_T>20$ GeV. If the cluster was in the CEM the trigger also required a coincidence with a track of transverse momentum $P_T>9.2$ GeV/c. In addition, the trigger required that the ratio of hadronic to electromagnetic energy (HAD/EM) in the trigger cluster be less than 12.5%. For electrons with $25<E_T<150$ GeV this trigger had an efficiency for CEM electrons of $(92.8\pm0.2)\%$ and for PEM electrons of $(91.9\pm0.4)\%$. Since either electron could provide the trigger, this led to a trigger efficiency above 99% for dielectron events. For very high E_T electrons ($E_T>150$ GeV), the energy deposited in a single tower could have exceeded the dynamic range of the trigger electronics for that tower and led to trigger inefficiency due to the HAD/EM requirement. Therefore, events from an additional trigger that required only a calorimeter energy cluster with $E_T>100$ GeV were included in the data sample. This ensured essentially 100% trigger efficiency over the entire range of electron E_T for this measurement.

We require at least one electron candidate in the central calorimeter and a second electron candidate in either the CEM or PEM. An electron candidate is required to have $E_T>25$ GeV and to be in a fiducial region of the CEM or PEM. The electrons are required to be isolated. The electron isolation (I) is defined as $I=(E_T^{\text{cone}}-E_T^e)/E_T^e$, where E_T^{cone} is the transverse energy within a cone of $R=\sqrt{(\Delta\phi)^2+(\Delta\eta)^2}=0.4$ around the electron, E_T^e is the transverse energy deposited by the electron, and ϕ is the azimuthal angle. At least one central electron candidate is required to have isolation $I<0.1$ and the second electron candidate is required to have $I<0.2$. Central electron candidates are required to have a track with $P_T>13$ GeV/c matched to the CEM cluster in both position and transverse momentum. For electrons with $P_T<50$ GeV/c, we require the ratio of the E_T over P_T to be less than 4. To ensure high efficiency for high E_T electrons, this momentum matching requirement is not applied if $P_T>50$ GeV/c. Central electron candidates are also required to have the ratio of hadronic to electromagnetic energy less than 12.5%. In this case (unlike the case of the trigger), dynamic range effects are not a problem for electron energies relevant for this measurement (electron $E_T<350$ GeV). Since the CTC does not cover the entire plug region, we do not impose track requirements for PEM electron candidates. However, for PEM electron candidates we require that the lateral shower shape be consistent with that measured for test beam electrons.

The dielectron invariant mass distribution for events passing these selection criteria is shown in Fig. 1. The sample contains 1371 events, of which 640 have both electrons in the central calorimeter (CC) and 731 have one electron in the central and one in the plug calorimeter (PC). The largest mass observed is 320 GeV/c^2.

Efficiencies of the electron identification cuts are determined using a sample of nearly background free dielectron events from Z^0 decays. This sample is selected using the electron identification requirements discussed above on only one CEM cluster. There is the further requirement that this cluster has only one track pointed at it. The second cluster can be in either CEM or PEM and is not required to pass our electron identification requirements. We require that the invariant mass of the two clusters be between 70 and 100 GeV/c^2. We estimate the efficiency of the electron identification requirements using the second cluster. Since electrons from Z' decay may have higher E_T than those from typical Z^0 decays, we also have studied the E_T dependence of the electron identification cuts using the highest E_T electrons from Z^0 and W decays. In addition, we have used Monte Carlo simulation to extend these studies to very high E_T where we have no data. The simulation is tuned to reproduce the calorimeter response observed in the test beam for electrons. For the cuts chosen, the efficiency is independent of

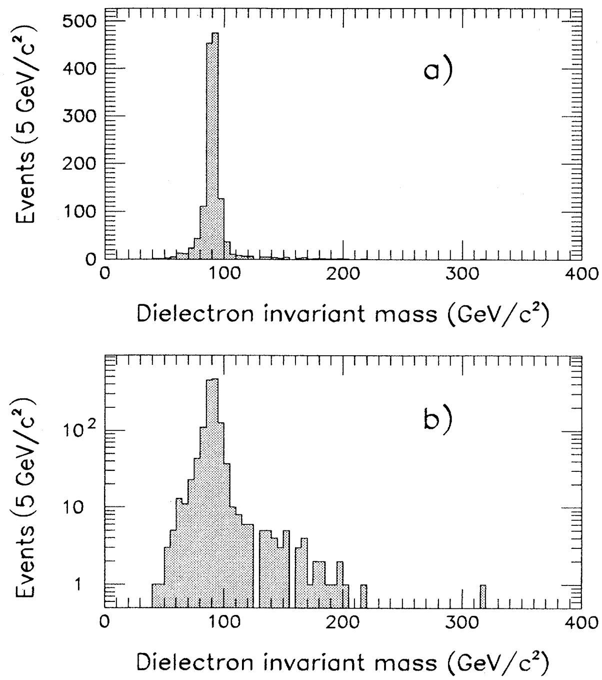

FIG. 1. The invariant mass distribution for 1371 electron pairs candidates; (a) linear, (b) log vertical scale.

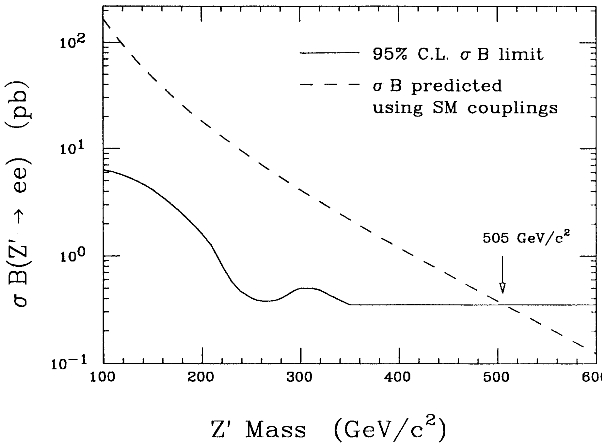

FIG. 2. The solid line shows 95% C.L. upper limit on $\sigma(Z')B(Z'\rightarrow ee)$. The dashed line is the prediction of $\sigma(Z')(BZ'\rightarrow ee)$ assuming SM couplings and using the MRS D'_- parton distribution functions. The intersection of the curves determines the lower mass limit, $M_{Z'}>505$ GeV/c^2.

the electron E_T in the range $25 < E_T < 350$ GeV. Selection efficiencies for CC and PC dielectron events are 86% and 82%, respectively.

The geometrical and kinematic acceptance for dielectron events as a function of $M_{Z'}$ is determined by Monte Carlo simulation. Events are simulated using a simple detector model and are corrected for the efficiencies of the selection requirements. The total efficiency, including the acceptance, is estimated to be 28% at the Z^0 mass and rises to 44% for dielectron masses above 250 GeV/c^2. We use Martin-Roberts-Stirling set D'_- (MRS D'_-) parton distribution functions (PDF's) [10]. Systematic uncertainties in the acceptance calculation due to the choice of PDF and from the assumption of the boson P_T distribution in the generator are studied and estimated to be 1.6% and 1.0%, respectively. The overall systematic uncertainty in $\sigma(Z')B(Z'\rightarrow ee)$ is 6%, including uncertainties due to the acceptance calculation (2.2%), efficiency of the event selection cuts (2.7%), and luminosity normalization (3.6%). As a check, we calculate the Z^0 cross section using these efficiency and acceptance values. We find this cross section to be in agreement with our previous published value [11].

In order to ensure good efficiency for this search, the electron identification requirements have been optimized for high efficiency rather than background rejection. As a result, a small percentage of the accepted events are from nondielectron sources. The dominant background of this type is from misidentified QCD dijet events. The majority of the dijets events are removed by the isolation cut. Studies of the electron identification cuts yield a background estimate of approximately 3% from this source. The invariant mass of these observed background events are around the Z^0 mass region. At large dielectron invariant mass the dominant background is from the Drell-Yan process. We estimate approximately 1 event with dielectron invariant mass above 250 GeV/c^2 and 0.5 event above 300 GeV/c^2 from this source in our data sample. We observe one event in this region with a mass of 320 GeV/c^2, in agreement with the Drell-Yan expectations [12]. The estimated background from sources other than Z^0 and Drell-Yan is small. In extracting limits on

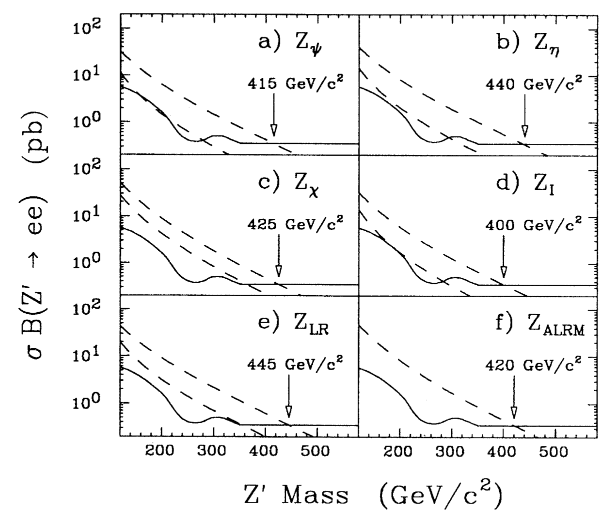

FIG. 3. The 95% C.L. lower mass limit for five different Z' models from the E_6 symmetry group and for a right-handed Z' in the alternative left-right model (ALRM). The solid curve in each plot is the $\sigma(Z')B(Z'\rightarrow ee)$, which is independent of the choice of model. The dashed curves in (a)–(f) are $\sigma(Z')B(Z'\rightarrow ee)$ calculated for the six models, namely Z_ψ, Z_η, Z_χ, Z_I, Z_{LR}, and Z_{ALRM}. The bands represent the theoretical range allowed by assuming Z' decay to known fermions only (upper bound) and all allowed fermions and supersymmetric fermions (lower bound). For the ALRM case we only consider the new vector boson decaying to known (SM) fermions and to W pairs. The intersections of the solid and dashed curves set the lower mass limit for each case.

Z' production, we take a conservative approach by assuming the background only from the Z^0 and Drell-Yan production.

We fit the observed dielectron invariant-mass distribution using a binned maximum-likelihood method [13] to a superposition of the predicted distributions from Z' production together with standard model Drell-Yan and Z^0 production. The fit is repeated for a variety of Z' masses in the range 100 to 350 GeV/c^2. SM couplings are assumed in generating the Z' events and the Z' width is set equal to the Z^0 width scaled by a factor $M_{Z'}/M_{Z^0}$. To calculate the branching ratio to dielectrons we have assumed a top mass of 174 GeV/c^2 [14]. For each Z' mass considered, the systematic uncertainties discussed above are numerically folded into the likelihood function [13]. Above 350 GeV/c^2, where there are no observed events, we calculate the cross section limit convoluting the systematic uncertainty of 6.0% with the Poisson limit. Here, we use a total efficiency of 44% independent of dielectron mass and no background is subtracted. The 95% C.L. upper limit on $\sigma(Z')B(Z'\to ee)$ is shown as the solid line in Fig. 2. The value of this limit on $\sigma(Z')B(Z'\to ee)$ for $M_{Z'}>350$ GeV/c^2 is 0.35 pb, independent of theoretical models. Though we have assumed SM coupling strengths to derive this limit curve for $M_{Z'}<350$ GeV/c^2, this limit is insensitive to the choice of coupling strength [4], and can be compared with a variety of theoretical Z' model predictions. The dashed line in Fig. 2 is the predicted σB using MRS D'_- structure functions and SM couplings. The intercept of the two curves at 505 GeV/c^2 determines the 95% C.L. lower limit on the Z' mass.

Figure 3 shows our 95% C.L. limit curve (solid line) together with predictions from several E_6 models (dashed lines) [15] and with the prediction of a right-handed Z' in the alternative left-right model (ALRM) [16]. In each plot the upper dashed curve corresponds to the model's prediction for Z' decaying only to known fermions. The lower dashed curve is the expectation for Z' decaying to all fermions (SM, supersymmetric, and exotic) that occur in the representations of the model. For these calculations we assume the masses of the supersymmetric and exotic fermions to be 200 and 45.5 GeV/c^2, respectively. From the intersections of the solid and upper dashed curves in each plot we set the lower mass limits for Z_ψ, Z_η, Z_χ, Z_I, $Z_{\rm LR}$, and $Z_{\rm ALRM}$ to be 415, 440, 425, 400, 445, and 420 GeV/c^2, respectively.

In conclusion, we have presented a search for additional neutral heavy bosons, in the dielectron decay mode, using the data sample collected during the 1992–1993 run corresponding to 19.7 pb^{-1} of integrated luminosity. The largest dielectron invariant mass observed is 320 GeV/c^2. The observed dielectron invariant mass spectrum is consistent with that expected from the decays of the standard Z^0 and from the Drell-Yan process. We obtain a 95% C.L. limit on the production cross section times the branching ratio for a Z' decaying into electron pairs as a function of the dielectron invariant mass. Assuming standard model coupling strengths, we exclude a Z' with mass less than 505 GeV/c^2 at 95% confidence level. In addition, we set Z' mass limits for several models based on the E_6 symmetry group and the alternative left-right model.

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