Fermi National Accelerator Laboratory

FERMILAB-Pub-91/327-E

A Search for New Gauge Bosons in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV

The CDF Collaboration

Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

November 1991

* Submitted to *Physical Review Letters*.

Operated by Universities Research Association Inc. under Contract No. DE-AC02-76CHO3000 with the United States Department of Energy

Disclaimer

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefullness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

FERMILAB-PUB-91/327-E
CDF/DOC/ELECTROWEAK/CDFR/1532

A Search for New Gauge Bosons in $\bar{p}p$ Collisions at $\sqrt{s} = 1.8$ TeV

F. Abe,[9] D. Amidei,[4] G. Apollinari,[16] M. Atac,[4] P. Auchincloss,[15] A. R. Baden,[6] N. Bacchetta,[11] M. W. Bailey,[14] A. Bamberger,[4,a] P. de Barbaro,[15] B. A. Barnett,[8] A. Barbaro-Galtieri,[10] V. E. Barnes,[14] T. Baumann,[6] F. Bedeschi,[13] S. Behrends,[2] S. Belforte,[13] G. Bellettini,[13] J. Bellinger,[21] D. Benjamin,[20] J. Bensinger,[2] A. Beretvas,[4] J. P. Berge,[4] S. Bertolucci,[5] S. Bhadra,[7] M. Binkley,[4] R. Blair,[1] C. Blocker,[2] V. Bolognesi,[13] A. W. Booth,[4] C. Boswell,[8] G. Brandenburg,[6] D. Brown,[6] E. Buckley-Geer,[17] H. S. Budd,[15] G. Busetto,[11] A. Byon-Wagner,[4] K. L. Byrum,[21] C. Campagnari,[3] M. Campbell,[3] A. Caner,[4] R. Carey,[6] W. Carithers,[10] D. Carlsmith,[21] J. T. Carroll,[4] R. Cashmore,[4,a] A. Castro,[11] F. Cervelli,[13] K. Chadwick,[4] G. Chiarelli,[5] W. Chinowsky,[10] S. Cihangir,[4] A. G. Clark,[4] D. Connor,[12] M. Contreras,[2] J. Cooper,[4] M. Cordelli,[5] D. Crane,[4] M. Curatolo,[5] C. Day,[4] F. DeJongh,[4] S. Dell'Agnello,[13] M. Dell'Orso,[13] L. Demortier,[2] B. Denby,[4] P. F. Derwent,[3] T. Devlin,[17] D. DiBitonto,[18] M. Dickson,[15] R. B. Drucker,[10] K. Einsweiler,[10] J. E. Elias,[4] R. Ely,[10] S. Eno,[3] S. Errede,[7] B. Esposito,[5] B. Flaugher,[4] G. W. Foster,[4] M. Franklin,[6] J. Freeman,[4] H. Frisch,[3] T. Fuess,[4] Y. Fukui,[9] Y. Funayama,[19] A. F. Garfinkel,[14] A. Gauthier,[7] S. Geer,[4] D. W. Gerdes,[3] P. Giannetti,[13] N. Giokaris,[16] P. Giromini,[5] L. Gladney,[12] M. Gold,[10] K. Goulianos,[16] H. Grassmann,[11] C. Grosso-Pilcher,[3] C. Haber,[10] S. R. Hahn,[4] R. Handler,[21] K. Hara,[19] R. M. Harris,[4] J. Hauser,[4] C. Hawk,[17] T. Hessing,[18] R. Hollebeek,[12] L. Holloway,[7] P. Hu,[17] B. Hubbard,[10] B. T. Huffman,[14] R. Hughes,[12] P. Hurst,[5] J. Huth,[4] J. Hylen,[4] M. Incagli,[13] T. Ino,[19] H. Iso,[19] H. Jensen,[4] C. P. Jessop,[6] R. P. Johnson,[4] U. Joshi,[4] R. W. Kadel,[10] T. Kamon,[18] S. Kanda,[19] D. A. Kardelis,[7] I. Karliner,[7] E. Kearns,[6] L. Keeble,[18] R. Kephart,[4] P. Kesten,[2] R. M. Keup,[7] H. Keutelian,[4] D. Kim,[4] S. Kim,[19] L. Kirsch,[2] K. Kondo,[19] J. Konigsberg,[6] E. Kovacs,[4] S. E. Kuhlmann,[1] E. Kuns,[17] A. T. Laasanen,[14]

Submitted to Physical Review Letters, November 18, 1991.

J. I. Lamoureux,[21] S. Leone,[13] J. Lewis,[4] W. Li,[1] P. Limon,[4] T. M. Liss,[7] N. Lockyer,[12]
C. B. Luchini,[7] P. Lukens,[4] P. Maas,[21] K. Maeshima,[4] M. Mangano,[13] J. P. Marriner,[4]
M. Mariotti,[13] R. Markeloff,[21] L. A. Markosky,[21] R. Mattingly,[2] P. McIntyre,[18]
A. Menzione,[13] T. Meyer,[18] S. Mikamo,[9] M. Miller,[3] T. Mimashi,[19] S. Miscetti,[5]
M. Mishina,[9] S. Miyashita,[19] Y. Morita,[19] S. Moulding,[2] J. Mueller,[17] A. Mukherjee,[4]
L. F. Nakae,[2] I. Nakano,[19] C. Nelson,[4] C. Newman-Holmes,[4] J. S. T. Ng,[6] M. Ninomiya,[19]
L. Nodulman,[1] S. Ogawa,[19] R. Paoletti,[13] A. Para,[4] E. Pare,[6] S. Park,[4] J. Patrick,[4]
T. J. Phillips,[6] F. Ptohos,[6] R. Plunkett,[4] L. Pondrom,[21] J. Proudfoot,[1] G. Punzi,[13]
D. Quarrie,[4] K. Ragan,[12] G. Redlinger,[3] J. Rhoades,[21] M. Roach,[20] F. Rimondi,[4,a]
L. Ristori,[13] T. Rodrigo,[4] T. Rohaly,[12] A. Roodman,[3] W. K. Sakumoto,[15] A. Sansoni,[5]
R. D. Sard,[7] A. Savoy-Navarro,[4] V. Scarpine,[7] P. Schlabach,[6] E. E. Schmidt,[4]
O. Schneider,[10] M. H. Schub,[14] R. Schwitters,[6] A. Scribano,[13] S. Segler,[4] Y. Seiya,[19]
M. Sekiguchi,[19] M. Shapiro,[10] N. M. Shaw,[14] M. Sheaff,[21] M. Shochet,[3] J. Siegrist,[10]
P. Sinervo,[12] J. Skarha,[8] K. Sliwa,[20] D. A. Smith,[13] F. D. Snider,[8] L. Song, [12]
M. Spahn,[10] P. Sphicas,[4] R. St. Denis,[6] A. Stefanini,[13] G. Sullivan,[3] R. L. Swartz, Jr.,[7]
M. Takano,[19] F. Tartarelli,[13] K. Takikawa,[19] S. Tarem,[2] D. Theriot,[4] M. Timko,[18]
P. Tipton,[4] S. Tkaczyk,[4] A. Tollestrup,[4] J. Tonnison,[14] W. Trischuk,[6] N. Turini,[13]
Y. Tsay,[3] F. Ukegawa,[19] D. Underwood,[1] S. Vejcik, III,[8] R. Vidal,[4] R. G. Wagner,[1]
R. L. Wagner,[4] N. Wainer,[4] J. Walsh,[12] T. Watts,[17] R. Webb,[18] C. Wendt,[21]
H. Wenzel,[13] W. C. Wester, III,[10] T. Westhusing,[13] S. N. White,[16] A. B. Wicklund,[1]
H. H. Williams,[12] B. L. Winer,[15] J. Wyss, [11] A. Yagil,[4] A. Yamashita,[19] K. Yasuoka,[19]
G. P. Yeh,[4] J. Yoh,[4] M. Yokoyama,[19] J. C. Yun,[4] A. Zanetti,[13] F. Zetti,[13] S. Zucchelli [4,a]

The CDF Collaboration

[1] *Argonne National Laboratory, Argonne, Illinois 60439*

[2] *Brandeis University, Waltham, Massachusetts 02254*

[3] *University of Chicago, Chicago, Illinois 60637*

[4] *Fermi National Accelerator Laboratory, Batavia, Illinois 60510*

[5] *Laboratori Nazionali di Frascati, Istituto Nazionale di Fisica Nucleare, Frascati, Italy*

[6] *Harvard University, Cambridge, Massachusetts 02138*

[7] *University of Illinois, Urbana, Illinois 61801*

[8] *The Johns Hopkins University, Baltimore, Maryland 21218*

[9] *National Laboratory for High Energy Physics (KEK), Japan*

[10] *Lawrence Berkeley Laboratory, Berkeley, California 94720*

[11] *Universita di Padova, Instituto Nazionale di Fisica Nucleare, Sezione di Padova, I-35131 Padova, Italy*

[12] *University of Pennsylvania, Philadelphia, Pennsylvania 19104*

[13] *Istituto Nazionale di Fisica Nucleare, University and Scuola Normale Superiore of Pisa, I-56100 Pisa, Italy*

[14] *Purdue University, West Lafayette, Indiana 47907*

[15] *University of Rochester, Rochester, New York 14627*

[16] *Rockefeller University, New York, New York 10021*

[17] *Rutgers University, Piscataway, New Jersey 08854*

[18] *Texas A&M University, College Station, Texas 77843*

[19] *University of Tsukuba, Tsukuba, Ibaraki 305, Japan*

[20] *Tufts University, Medford, Massachusetts 02155*

[21] *University of Wisconsin, Madison, Wisconsin 53706*

Abstract

We have searched for the production of a neutral gauge boson (Z') with mass above 100 GeV/c^2 in $\bar{p}p$ collisions with the CDF detector. We present a 95% confidence level (C.L.) limit on the $Z' \rightarrow \mu^+\mu^-$ production cross section. We combine the Z' limit with that from our previous dielectron search; the combined result sets a limit of $M_{Z'} > 412$ GeV/c^2 (95% C.L.), assuming Standard Model coupling strengths. In addition, the absence of any evidence for an effective muon-quark contact interaction is used to set a lower limit of 1.6 TeV (95% C.L.) on an associated muon-quark compositeness scale.

PACS numbers: 13.85.Rm, 12.15.Cc, 14.80.Er

Neutral gauge bosons in addition to the Z^0 are expected in many extensions [1] of the Standard Model (SM) such as Grand Unified Theories and left-right symmetric models. These models typically specify the strengths of the couplings of the Z' to quarks and leptons but make no predictions for the Z' mass. To date there is no experimental evidence for the existence of a Z'. Lower limits on the Z' mass have been inferred from neutral current [2] and atomic parity violation [3] experiments, and from astrophysical arguments [4]. In $\bar{p}p$ collisions, Z' bosons may be observed directly via their decay to lepton pairs. Observation of such events would provide dramatic evidence for physics beyond the Standard Model. Direct searches for Z' bosons with masses above M_{Z^0} by the UA1 and UA2 experiments have resulted in limits of $M_{Z'} > 173$ GeV/c^2 (90% C.L.) [5] and 218 GeV/c^2 (95% C.L.) [6] respectively. A search by the CDF Collaboration for $Z' \rightarrow ee$ has set a limit of $M_{Z'} >$ 387 GeV/c^2 (95% C.L.) [7]. Here we report an extension of the CDF search to include the dimuon decay channel. When we combine the muon and the electron results, the Z' limit improves significantly. As in the previous searches, the mass limits are derived assuming the coupling strengths of the Z' to quarks and leptons to be the same as those for the Standard Model Z^0. However, we also show that the limit on the Z' cross section times branching ratio to charged lepton pair ($\sigma(Z') \cdot \mathrm{B}_{ll}$) is quite insensitive to the choice of theoretical model, allowing mass limits to be easily extracted for many different models.

The search reported here is based on data collected with the CDF detector during the 1988-89 run, corresponding to a total integrated luminosity of 3.54 pb^{-1}. The detector is described elsewhere [8]. The trigger used in this search requires the central muon (CMU) trigger in coincidence with at least one hit in each of two arrays of scintillator counters located on each side of the interaction point. The CMU trigger requires a track in the central tracking chamber (CTC) with a transverse momentum (P_T) greater than 9 GeV/c and with a matching track segment in the muon detector. The efficiency of the CMU trigger is measured to be 0.91$\pm$0.02 [9] for muons with P_T >20 GeV/c. From events satisfying this trigger, we select a dimuon event sample by requiring that each event contains a high-P_T (>20 GeV/c) muon candidate (Class-I muon) and at least one other high-P_T (>20 GeV/c) charged track (Class-II muon). A Class-I muon is required to have a CTC track that extrapolates within 2 cm of a track segment in the fiducial volume of the central muon chambers. The track is also required to satisfy the following isolation requirement: $(\sum E_T^{cone} - E_T{}^{\mu})/P_T{}^{\mu} \leq 0.1$, where $\sum E_T^{cone}$ is the sum of the transverse energy ($E_T \equiv E \cdot sin\theta$) deposited in the calorimeter in a cone around the track direction with radius R = $\sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.4$ [10], $E_T{}^{\mu}$ is the transverse energy deposited in the calorimeter cell traversed by the muon candidate, and $P_T{}^{\mu}$ is the beam-constrained momentum of the muon candidate. Using the beam constraint, the P_T resolution is $\Delta P_T/P_T = 0.0011 P_T$ (GeV/c)$^{-1}$. In addition, the energy in the electromagnetic and hadronic calorimeters associated with the track is required to be consistent with that of a minimum ionizing particle. The coverage of the central muon detector limits Class-I muons to the region $|\eta| < 0.6$. For the Class-II muon candidate we only require a high-P_T track with $|\eta| < 1.4$. This requirement ensures that it penetrates a sufficient number of CTC layers to provide a reliable momentum measurement. The two tracks in the event are required to have opposite charges and to originate from a common vertex within $\pm$ 60 cm of the nominal interaction point along the beam line. Cosmic ray events are removed by eliminating events in which two tracks are back-to-back ($|\Delta\phi - \pi| < 0.035$ and $|\eta_1 + \eta_2| < 0.2$) and the relative timing of the hits in the CTC layers is inconsistent with that of tracks originating from the interaction region. The selection efficiency is 0.90 $\pm$ 0.05 for Class-I muons and 0.99 $\pm$ 0.01 for Class-II muons in the central region ($|\eta| < 1.0$). The Class-II efficiency decreases with increasing $|\eta|$ to a value of 0.45 $\pm$ 0.06 at $|\eta| = 1.4$ [7], due to progressively fewer CTC layers being available for track-pattern recognition.

The invariant mass distribution of the muon pairs for $M_{\mu^+\mu^-} > 40$ GeV/c^2 is shown in Fig. 1. The final sample consists of 148 events; there are no events with $M_{\mu^+\mu^-} > 155$ GeV/c^2. If the opposite-sign requirement is relaxed, two same-sign dimuon events pass the selection criteria, one with a mass in the Z^0 region and one with a lower mass. Both of these events have large missing transverse energy ($\not{E}_T > 20$ GeV) [11]. Such events are expected to come from W+jet processes, where the W decays via W $\rightarrow \mu\nu$ and the jet contains a charged particle with $P_T > 20$ GeV/c. We estimate the residual contamination from cosmic rays in our dimuon sample to be less than one event. Since the expected number of background events is small (there are only two same-sign events and no events in the high invariant mass region), we take a conservative approach and make no background subtraction when setting the $\sigma(Z')\cdot \mathrm{B}_{ll}$ limit.

The dimuon acceptance as a function of $M_{Z'}$ is determined using a sample of $Z' \rightarrow \mu^+\mu^-$ events produced by the ISAJET [12] event generator. The generated events are simulated with a simple detector model and are corrected for the efficiencies of the selection requirements. The total efficiency, including the geometrical acceptance, is estimated to be $\approx 16\%$ for dimuons at the Z^0 mass and rises to $\approx 30\%$ for larger dimuon masses (the acceptance rises with mass because heavier Z' bosons are produced more centrally). The predicted invariant mass distribution for the Standard Model Drell-Yan process (γ and Z^0) is superimposed on the data in Fig. 1. The Monte Carlo events are normalized to the predicted Standard Model cross section using the HMRS(B) parton distribution functions [13]. The two distributions are in very good agreement.

To obtain a limit on $\sigma(Z')\cdot \mathrm{B}_{ll}$, we fit the observed dimuon invariant-mass distribution to a superposition of predicted distributions from the Standard Model Drell-Yan process and Z' production of a given mass using a binned maximum-likelihood method [14]. The fit is repeated for a variety of Z' masses in the range 92 - 450 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 the kinematic factor $M_{Z'}/M_{Z^0}$.

In order to obtain a limit on $\sigma(Z')\cdot \mathrm{B}_{ll}$, we must fold the systematic uncertainties into the result of the fit. The systematic uncertainties are: (1) an overall 6.8% uncertainty in the luminosity normalization [15], (2) a mass-independent uncertainty of 5.7% associated with the determination of the efficiency of the dimuon selection criteria, and (3) a mass-dependent uncertainty that ranges from 5% at $M_{Z'} = 92$ GeV/c^2 to 10% at $M_{Z'} = 400$ GeV/c^2. This mass dependent uncertainty comes from higher-order QCD corrections which introduce an uncertainty in the overall scale factor of the Z' production cross section. For each Z' mass considered, these uncertainties are numerically folded into the likelihood function [14]. The 95% C.L. upper limit on $\sigma(Z') \cdot \mathrm{B}(Z' \to \mu^+\mu^-)$ is shown in Fig. 2.

We combine this dimuon result with our previously reported dielectron result [7] to obtain an improved $\sigma(Z') \cdot \mathrm{B}_{ll}$ limit. The Z^0 and Z' mass distributions are generated using the same Monte Carlo procedure and are corrected for the different electron and muon efficiencies and detector resolution effects. In both cases the Monte Carlo distributions are normalized to the number of events expected using SM couplings. The number of Z^0s we observe in both electron and muon channels is consistent with what we expect from the Standard Model [15]. We fold the systematic uncertainties into the likelihood functions for the combined limit. Uncertainties in the electron and muon selection efficiencies are taken to be uncorrelated; those from QCD corrections and luminosity are fully correlated between the two channels. The $\sigma(Z') \cdot \mathrm{B}_{ll}$ limits (95% C.L.) for the electron and for the combined electron and muon channels are shown in Fig. 2. Fig. 2 also shows the prediction for $\sigma(Z') \cdot \mathrm{B}_{ll}$, assuming SM couplings and the HMRS(B) parton distribution functions. From the intersection of this curve with the experimental limit for the combined dilepton channels we set the lower mass limit of 412 GeV/c^2 (95% C.L.).

We derive limits on the mass of a Z' for a range of Z' couplings predicted by a variety of theoretical models. Model differences that may affect the $\sigma(Z') \cdot \mathrm{B}_{ll}$ limit are the Z' width ($\Gamma_{Z'}$) and the coupling strengths to u- and d-quarks. To cover a representative range of $\Gamma_{Z'}$ values we consider models based on the E_6 symmetry group [16]. For cases where the Z' decays only to SM fermions, these models predict narrower widths than that expected for SM couplings ($\Gamma_{Z'}^{\mathrm{SM}}$). For cases where the Z' decays to all of the fermions and supersymmetric fermions in the model, $\Gamma_{Z'}$ can be twice as large as $\Gamma_{Z'}^{\mathrm{SM}}$. We obtain limits of $\sigma(Z') \cdot B_{ll}$ using a range of $\Gamma_{Z'}$ from 0.15 to 2.0 times $\Gamma_{Z'}^{SM}$. We find the $\sigma(Z') \cdot B_{ll}$ limit is insensitive to these changes of $\Gamma_{Z'}$ for Z' masses above about 120 GeV/c^2. Variations in the coupling strengths to u- and d-quarks can cause changes in the acceptance because of differences in the parton distribution functions. To study this effect we consider two limiting cases: i) a Z' that couples to d-quarks but not to u-quarks, and ii) a Z' that couples to u-quarks but not to d-quarks. For Z' masses above 200 GeV/c^2, the acceptancé changes very little for either of these cases from that derived with SM couplings. For masses below 200 GeV/c^2, there are small differences in the acceptance for the two cases. Case i) yields a somewhat higher acceptance than the standard case, case ii) yields a slightly lower acceptance. The limit extracted using SM couplings is a conservative estimate of the limit for case i), while it is almost identical to that for case ii) down to a dilepton invariant mass of 100 GeV/c^2. Hence, the experimentally obtained $\sigma(Z') \cdot B_{ll}$ limit using SM-couplings can be compared with the $\sigma(Z') \cdot B_{ll}$ prediction from any theoretical model, as long as the width of the predicted Z' is less than $2\Gamma_{Z'}^{SM}$ for $M_{Z'} > 120$ GeV/c^2.

Figure 3 shows our combined $\sigma(Z') \cdot B_{ll}$ limit (solid line) together with predictions from four popular E_6 models (dashed lines) [16]. In each plot the upper dashed curve corresponds to the model's prediction for Z' decaying only to SM fermions; the lower dashed curve is the expectation for Z' decaying to all fermions in the model. For these calculations we assume the masses of the t-quark, supersymmetric fermions, and exotic fermions to be 140, 150, and 45.5 GeV/c^2, respectively. The intersections of the dashed curves with the $\sigma(Z') \cdot B_{ll}$ limit set the lower mass limits (95% C.L.) for each model.

The absence of high mass dilepton events in $\bar{p}p$ collisions is also used to set a limit on the scale of an effective lepton-quark contact interaction $\Lambda_{LL}^{\mp}$, which would signal lepton-quark compositeness [17]. The choice − (+) corresponds to constructive (destructive) interference with the dominant u-quark contribution to the cross section. Our previous results from the electron channel [7] have set limits on the scale of contact interactions between electrons and u- and d-quarks (i.e., first-generation leptons with first-generation quarks). In this search, by looking at dimuon final states, we are sensitive to contact interactions that couple second-generation leptons with first-generation quarks. The absence of any $\mu^+\mu^-$ pairs with a mass above 200 GeV/c^2, together with our estimated 13% systematic error and average efficiency of 27%, translates into a 95% C.L. upper limit on the observed integral cross section of 3.3 pb for the mass range 200–500 GeV/c^2. This limit corresponds to lower bounds on the muon-quark compositeness scales of $\Lambda_{LL}^- > 1.6$ TeV and $\Lambda_{LL}^+ > 1.4$ TeV (95% C.L.).

We thank the Fermilab staff and the technical staffs of the participating institutions for their vital contributions. This work was supported by the Department of Energy, the National Science Foundation, the Istituto Nazionale di Fisica Nucleare (Italy), the Ministry of Science, Culture and Education of Japan, and the A. P. Sloan Foundation.

(*) Visitor.

References

[1] G. G. Ross, *Grand Unified Theories* (Cambridge U.P., Cambridge, 1987) and references therein. For a general survey of the left-right-symmetric model, see R. N. Mohapatra, *Unification and Supersymmetry* (Springer, New York, 1986). M. B. Green, J. H. Schwarz and E. Witten, eds., *Superstring Theory* (Cambridge U.P., Cambridge, 1987). R. W. Robinett and J. L. Rosner, (SO(10) models), Phys. Rev. D **25**, 3036 (1982); D. London and J. L. Rosner, (E6 models), Phys. Rev. D **34**, 1530 (1984); J. L. Hewett and T. G. Rizzo, (review of E_6 models), Phys. Rep. **183**, 193 (1989); R. Foot, O. F. Hernandez and T. G. Rizzo, ($SU(5)_c$ models), Phys. Rev. D **41**, 2283 (1990); Phys. Lett. B. **246**, 183 (1990); S. L. Glashow and U. Sarid, (two-Z models) Phys. Lett. B. **246**, 188 (1990); X. G. He, G. C. Joshi, H. Lew, and R. R. Volkas, (New-Z' phenomenology) Phys. Rev. D **43**, R22 (1991).

[2] U. Amaldi *et al.*, Phys. Rev. D **36**, 1385 (1987); G. Costa *et al.*, Nucl. Phys. **B297**, 244 (1988); F. del Aguila, J. M. Moreno and M. Quiros, Phys. Lett. B. **254**, 497 (1991).

[3] W. Marciano and J. L. Rosner, Phys. Rev. Lett. **65**, 2963 (1990).

[4] J. A. Grifols, E. Masso and T. G. Rizzo, Phys. Rev. D **42**, 3293 (1990).

[5] UA1 Collab., C. Albajar *et al.*, Z. Phys. C **44**, 15 (1989).

[6] S. Grunendahl, in *Proceedings of the Vancouver Meeting, Particles and Fields '91*, August 18-22, 1991, Vancouver, B.C., Canada, edited by D. Axen, D. Bryman and M. Comyn. (World Scientific Publishing Co. Pte. Ltd.) (to be published).

[7] CDF Collab., F. Abe *et al.*, Phys. Rev. Lett. **67**, 2418 (1991). The *ee* sample consisted of 406 events corresponding to an integrated luminosity of 4.05 pb^{-1}.

[8] CDF Collab., F. Abe *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. A **271**, 387 (1988).

[9] CDF Collab., F. Abe *et al.*, Phys. Rev. D **43**, 2070 (1991).

[10] Here, η is the pseudorapidity, θ is the polar angle with respect to the proton beam direction and ϕ is the azimuthal angle.

[11] Missing transverse energy is defined as $\not{E}_T \equiv \sqrt{(\sum_i E_T(i)\sin\phi(i))^2 + (\sum_i E_T(i)\cos\phi(i))^2}$ where the sum is over calorimeter cells.

[12] F. Paige and S. Protopopesceau, BNL Report No. BNL38034, 1986 (unpublished). We used ISAJET version 6.10.

[13] P. N. Harriman, A. D. Martin, R. G. Roberts, and W. J. Stirling, Phys. Rev. D **42**, 798 (1990). Using a different set of parton distributions functions (Morfin-Tung) changes the acceptance by less then 5% for the mass range of this search. J. Morfin and W. Tung, Fermilab Report Nos. Fermilab-Pub-90/74, Fermilab-Pub-90/155 (to appear in Z. Phys. C).

[14] CDF Collab., F. Abe *et al.*, Phys. Rev. D **43**, 664 (1991).

[15] CDF Collab., F. Abe *et al.*, Phys. Rev. D **44**, 29 (1991).

[16] F. del Aguila, M. Quiros, and F. Zwirner, Nucl. Phys. **B287**, 457 (1987); D. London and J. L. Rosner, Phys. Rev. D **34**, 1530 (1986); F. del Aguila, J. M. Moreno and M. Quiros, Phys. Rev. D 41. 134 (1990), and references therein.

[17] E. Eichten, K. Lane, and M. Peskin, Phys. Rev. Lett. **50**, 811 (1983).

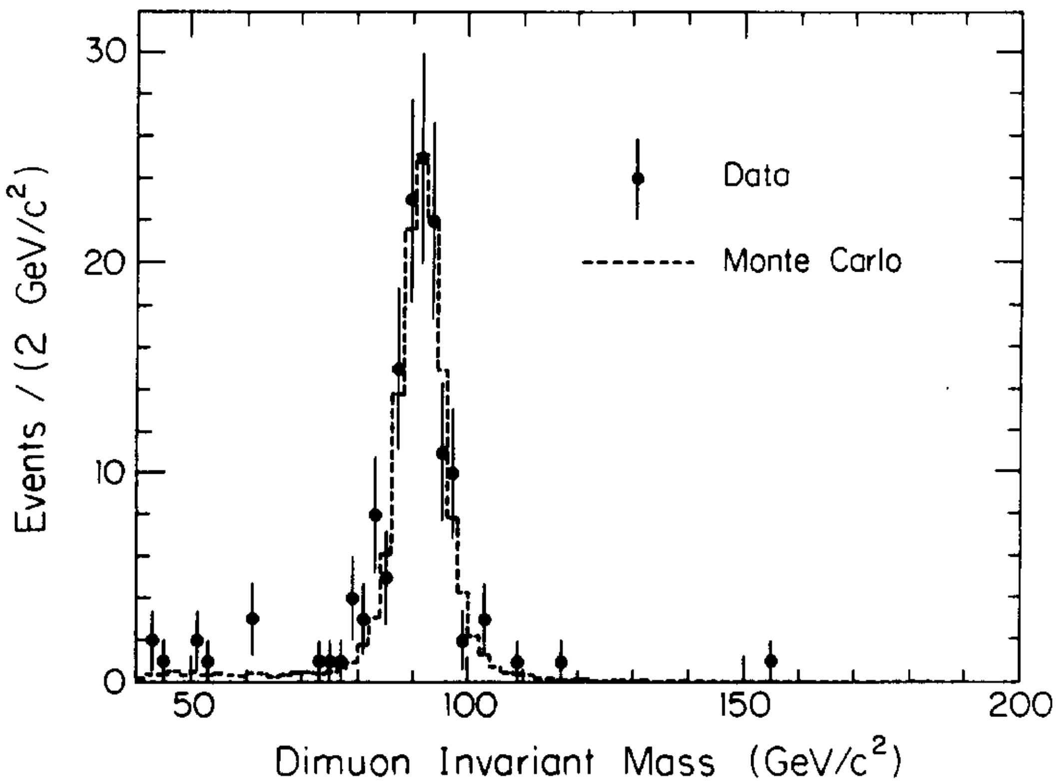

FIG. 1. The invariant mass distribution for oppositely charged dimuon candidates, compared to Monte Carlo-generated expectations for Standard Model Drell-Yan pairs, normalized to the predicted cross section. There are no events with $\mu^+\mu^-$ mass above $M_{\mu^+\mu^-} =$ 155 GeV/c^2. The observed high mass event is consistent with the SM prediction of 1.05 events for the mass range 130-200 GeV/c^2.

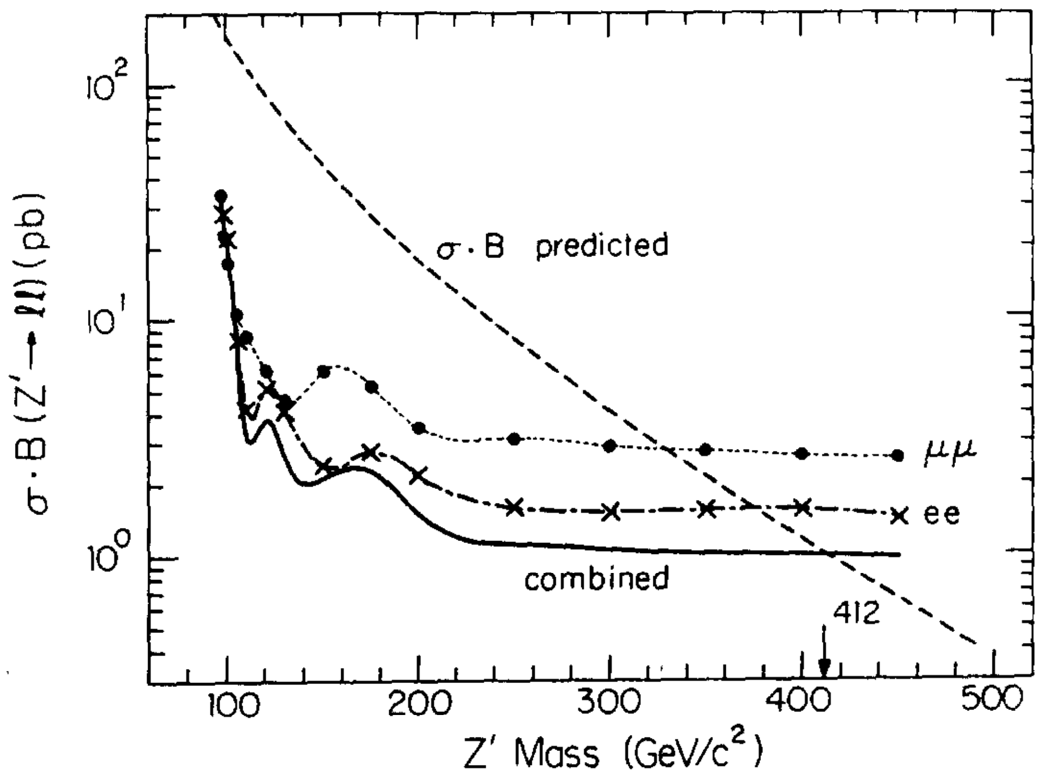

FIG. 2. The 95% C.L. limit on $\sigma(Z') \cdot B_{ll}$ for Z' production from the dimuon (dotted line), dielectron (dashed-dotted line), and combined channels (solid line). The points on the lines represent the set of $M_{Z'}$ values at which the fits are performed. The dashed line is the prediction of $\sigma(Z') \cdot B_{ll}$ assuming SM couplings using the HMRS(B) parton distribution functions. The combined result sets a lower mass limit of 412 GeV/c^2 (95% C.L.), assuming SM couplings.

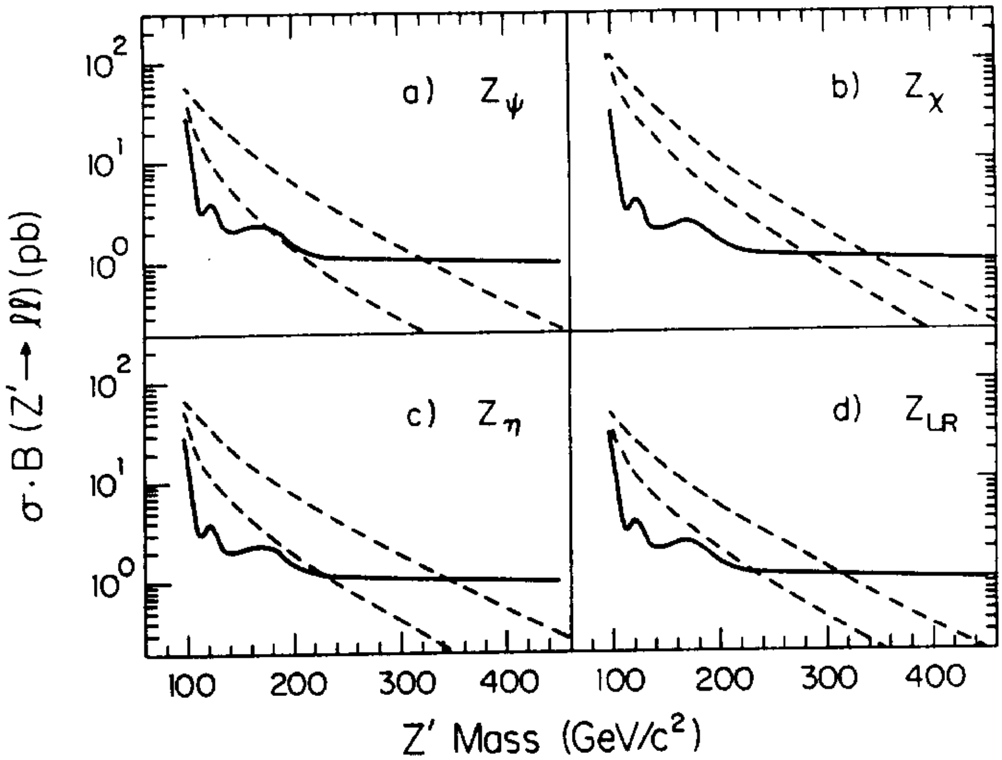

FIG. 3. The 95% C.L. lower mass limits for the four different Z' models from the E_6 symmetry group. In each plot the solid curve is the combined $\sigma(Z') \cdot \mathrm{B}_{ll}$ limit, which is independent of the choice of these models. The dashed curves in figure a) through d) are $\sigma(Z') \cdot \mathrm{B}_{ll}$ calculated for the four commonly discussed Z' models, namely Z_ψ, Z_χ, Z_η, and Z_{LR} [16]. 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). The intersections of the solid and dashed curves set the lower mass limit for the each case.