Fermi National Accelerator Laboratory

FERMILAB-Pub-89/250-E
[E-741/CDF]

Search for a Light Higgs Boson at the Tevatron Proton-Antiproton Collider*

F. Abe[8], D. Amidei[4], G. Apollinari[11], M. Atac[4], P. Auchincloss[14], A. R. Baden[6], A. Bamberger[19], A. Barbaro-Galtieri[9], V. E. Barnes[12], F. Bedeschi[11], S. Behrends[12], S. Belforte[11], G. Bellettini[11], J. Bellinger[18], 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], A. W. Booth[4], G. Brandenburg[6], D. Brown[6], E. Buckley[14], A. Byon[12], K. L. Byrum[18], C. Campagnari[3], M. Campbell[3], R. Carey[6], W. Carithers[9], D. Carlsmith[18], J. T. Carroll[4], R. Cashmore[19], F. Cervelli[11], K. Chadwick[4], G. Chiarelli[5], W. Chinowsky[9], S. Cihangir[4], A. G. Clark[4], D. Connor[10], M. Contreras[2], J. Cooper[4], M. Cordelli[5], D. Crane[4], M. Curatolo[5], C. Day[4], S. Dell'Agnello[11], M. Dell'Orso[11], L. Demortier[2], P. F. Derwent[3], T. Devlin[14], D. DiBitonto[15], R. B. Drucker[9], J. E. Elias[4], R. Ely[9], S. Errede[7], B. Esposito[5], B. Flaugher[14], G. W. Foster[4], M. Franklin[6], J. Freeman[4], H. Frisch[3], Y. Fukui[8], Y. Funayama[16], A. F. Garfinkel[12], A. Gauthier[7], S. Geer[6], P. Giannetti[11], N. Giokaris[13], P. Giromini[5], L. Gladney[10], M. Gold[9], K. Goulianos[13], H. Grassmann[11], C. Grosso-Pilcher[3], C. Haber[9], S. R. Hahn[4], R. Handler[18], K. Hara[16], R. M. Harris[9], J. Hauser[3], T. Hessing[15], R. Hollebeek[10], L. Holloway[7], P. Hu[14], B. Hubbard[9] , B. T. Huffman[12], R. Hughes[10], P. Hurst[7], J. Huth[4], M. Incagli[11], T. Ino[16], H. Iso[16], H. Jensen[4], C. P. Jessop[6], R. P. Johnson[4], U. Joshi[4], T. Kamon[15], S. Kanda[16], D. A. Kardelis[7], I. Karliner[7], E. Kearns[6], R. Kephart[4], P. Kesten[2], R. M. Keup[7], H. Keutelian[7], S. Kim[16], L. Kirsch[2], K. Kondo[16], S. E. Kuhlmann[1], E. Kuns[14], A. T. Laasanen[12], J. I. Lamoureux[18], W. Li[1], T. M. Liss[7], N. Lockyer[10], C. B. Luchini[7], P. Maas[4], M. Mangano[11], J. P. Marriner[4], R. Markeloff[18], L. A. Markosky[18], R. Mattingly[2], P. McIntyre[15], A. Menzione[11], T. Meyer[15], S. Mikamo[8], M. Miller[3], T. Mimashi[15], S. Miscetti[5], M. Mishina[8], S. Miyashita[16], Y. Morita[16], S. Moulding[2], A. Mukherjee[4], L. F. Nakae[2], I. Nakano[16], C. Nelson[4], C. Newman-Holmes[4], J. S. T. Ng[6], M. Ninomiya[16], L. Nodulman[1], S. Ogawa[16], R. Paoletti[11], A. Para[4], E. Pare[6], J. Patrick[4], T. J. Phillips[6], R. Plunkett[4], L. Pondrom[18], J. Proudfoot[1], G. Punzi[11], D. Quarrie[4], K. Ragan[10], G. Redlinger[3], J. Rhoades[18], F. Rimondi[19], L. Ristori[11], M. Roach[17], T. Rohaly[10], A. Roodman[3], A. Sansoni[5], R. D. Sard[7], A. Savoy-Navarro[19], V. Scarpine[7], P. Schlabach[7], E. E. Schmidt[4], M. H. Schub[12], R. Schwitters[6], A. Scribano[11], S. Segler[4], Y. Seiya[16], M. Sekiguchi[16], P. Sestini[11], M Shapiro[6], M. Sheaff[18], M. Shochet[3], J. Siegrist[9], P. Sinervo[10], J. Skarha[18], K. Sliwa[17], D. A. Smith[11], F. D. Snider[3], R. St. Denis[6], A. Stefanini[11], R. L. Swartz, Jr.[7], M. Takano[16], K. Takikawa[16], S. Tarem[2], D. Theriot[4], M. Timko[15], P. Tipton[9], S. Tkaczyk[4], A. Tollestrup[4], G. Tonelli[11], J. Tonnison[12], W. Trischuk[6], Y. Tsay[3], F. Ukegawa[16], D. Underwood[1], R. Vidal[4], R. G. Wagner[1], R. L. Wagner[4], J. Walsh[10], T. Watts[14], R. Webb[15], C. Wendt[18], W. C. Wester, III[9], T. Westhusing[11], S. White[13], A. B. Wicklund[1], H. H. Williams[10], B. Winer[9], A. Yagil[4], A. Yamashita[16], K. Yasuoka[16], G. P. Yeh[4], J. Yoh[4], M. Yokoyama[16], J. C. Yun[4], F. Zetti[11]

[1]*Argonne National Laboratory , Argonne, Illinois 60439* - [2]*Brandeis University, Waltham, Massachusetts 02254* - [3]*Universtiy of Chicago, Chicago, Illinois 60637* - [4]*Fermi National Acceleratory Laboratory, P.O. Box 500, Batavia, Illinois 60510* - [5]*Laboratori Nazionali di Frascati, Instituto Nazionale di Fisica Nucleare, I-00044, Frascati, Italy* - [6]*Harvard University, Cambridge, Massachusetts 02138* - [7]*University of Illinois, Urbana, Illinois 61801* - [8]*National Laboratory for High Energy Physics (KEK), Tsukuba, Ibaraki 305, Japan* - [9]*Lawrence Berkeley Laboratory, Berkeley, California 94720* - [10]*University of Pennsylvania, Philadelphia, Pennslvania 19104* - [11]*INFN, University and Scuola Normale Superiore of Pisa, I-56100 Pisa, Italy* - [12]*Purdue University, West Lafayette, Indiana 47907* - [13]*Rockefeller University , New York, New York 10021*- [14]*Rutgers University, Piscataway, New Jersey 08854* - [15]*Texas A&M University, College Station, Texas 77843* - [16]*University of Tsukuba, Tsukuba, Ibaraki 305, Japan* - [17]*Tufts University, Medford, Massachusetts 02155* - [18]*University of Wisconsin, Madison, Wisconsin 53706* - [19]*Visitor*

December 8, 1989

* Submitted to Phys. Rev. D

Operated by Universities Research Association Inc. under contract with the United States Department of Energy

Search for a Light Higgs Boson at the Tevatron Proton-Antiproton Collider

F. Abe,[8] D. Amidei,[4] G.Apollinari,[11] M. Atac,[4] P. Auchincloss,[14] A. R. Baden,[6] A. Bamberger,[19] A. Barbaro-Galtieri,[9] V. E. Barnes,[12] F. Bedeschi,[11] S. Behrends,[12] S. Belforte,[11] G. Bellettini,[11] J. Bellinger,[18] 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] A. W. Booth,[4] G. Brandenburg,[6] D. Brown,[6] E. Buckley,[14] A. Byon,[12] K. L. Byrum,[18] C. Campagnari,[3] M. Campbell,[3] R. Carey,[6] W. Carithers,[9] D. Carlsmith,[18] J. T. Carroll,[4] R. Cashmore,[19] F. Cervelli,[11] K. Chadwick,[4] G. Chiarelli,[5] W. Chinowsky,[9] S. Cihangir,[4] A. G. Clark,[4] D. Connor,[10] M. Contreras,[2] J. Cooper,[4] M. Cordelli,[5] D. Crane,[4] M. Curatolo,[5] C. Day,[4] S. Dell'Agnello,[11] M. Dell'Orso,[11] L. DeMortier,[2] P. F. Derwent,[3] T. Devlin,[14] D. DiBitonto,[15] R. B. Drucker,[9] J. E. Elias,[4] R. Ely,[9] S. Errede,[7] B. Esposito,[5] B. Flaugher,[14] G. W. Foster,[4] M. Franklin,[6] J. Freeman,[4] H. Frisch,[3] Y. Fukui,[8] Y. Funayama,[16] A. F. Garfinkel,[12] A. Gauthier,[7] S. Geer,[6] P. Giannetti,[11] N. Giokaris,[13] P. Giromini,[5] L. Gladney,[10] M. Gold,[9] K. Goulianos,[13] H. Grassman,[11] C. Grosso-Pilcher,[3] C. Haber,[9] S. R. Hahn,[4] R. Handler,[18] K. Hara,[16] R. M. Harris,[9] J. Hauser,[3] T. Hessing,[15] R. Hollebeek,[10] L. Holloway,[7] P. Hu,[14] B. Hubbard,[9] B. T. Huffman,[12] R. Hughes,[10] P. Hurst,[7] J. Huth,[4] M. Incagli,[11] T. Ino,[16] H. Iso,[16] H. Jensen,[4] C. P. Jessop,[6] R. P. Johnson,[4] U. Joshi,[4] R. W. Kadel,[4] T. Kamon,[15] S. Kanda,[16] D. A. Kardelis,[7] I. Karliner,[7] E. Kearns,[6] R. Kephart,[4] P. Kesten,[2] R. M. Keup,[7] H. Keutelian,[7] S. Kim,[16] L. Kirsch,[2] K. Kondo,[16] S. E. Kuhlmann,[1] E. Kuns,[14] A. T. Laasanen,[12] J. I. Lamoureux,[18] W. Li,[1] T. M. Liss,[7] N. Lockyer,[10] C. B. Luchini,[7] P. Maas,[4] M. Mangano,[11] J. P. Marriner,[4] R. Markeloff,[18] L. A. Markosky,[18] R. Mattingly,[2] P. McIntyre,[15] A. Menzione,[11] T. Meyer,[15] S. Mikamo,[8] M. Miller,[3] T. Mimashi,[16] S. Miscetti,[5] M. Mishina,[8] S. Miyashita,[16] Y. Morita,[16] S. Moulding,[2] A. Mukherjee,[4] L.F. Nakae,[2] I. Nakano,[16] C. Nelson,[4] C. Newman-Holmes,[4] J. S. T. Ng,[6] M. Ninomiya,[16] L. Nodulman,[1] S. Ogawa,[16] R. Paoletti,[11] A. Para,[4] E. Pare,[6] J. Patrick,[4] T. J. Phillips,[6] R. Plunkett,[4] L. Pondrom,[18] J. Proudfoot,[1] G. Punzi,[11] D. Quarrie,[4] K. Ragan,[10] G. Redlinger,[3] J. Rhoades,[18] F. Rimondi,[11] L. Ristori,[11] M. Roach,[17] T. Rohaly,[10] A. Roodman,[3] A. Sansoni,[5] R. D. Sard,[7] A. Savoy-Navarro,[19] V. Scarpine,[7] P. Schlabach,[7] E. E. Schmidt,[4] M. H. Schub,[12] R. Schwitters,[6] A. Scribano,[11] S. Segler,[4] Y. Seiya,[16] M. Sekiguchi,[16] P. Sestini,[11] M. Shapiro,[6] M. Sheaff,[18] M. Shochet,[3] J. Siegrist,[9] P. Sinervo,[10] J. Skarha,[18] K. Sliwa,[17] D. A. Smith,[11] F. D. Snider,[3] R. St. Denis,[6] A. Stefanini,[11] R. L. Swartz, Jr.,[7] M. Takano,[16] K. Takikawa,[16] S. Tarem,[2] D. Theriot,[4] M. Timko,[15] P. Tipton,[9] S. Tkaczyk,[4] A. Tollestrup,[4] G. Tonelli,[11] J. Tonnison,[12] W. Trischuk,[6] Y. Tsay,[3] F. Ukegawa,[16] D. Underwood,[1] R. Vidal,[4] R. G. Wagner,[1] R. L. Wagner,[4] J. Walsh,[10] T. Watts,[14] R. Webb,[15] C. Wendt,[18] W. C. Wester, III,[9] T. Westhusing,[11] S. White,[13] A.B. Wicklund,[1] H. H. Williams,[10] B. Winer,[9] A. Yagil,[4] A. Yamashita,[16] K. Yasuoka,[16] G. P. Yeh,[4] J. Yoh,[4] M. Yokoyama,[16] J. C. Yun,[4] F. Zetti,[11]

[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] National Laboratory for High Energy Physics (KEK), Tsukuba, Ibaraki 305, Japan [9] Lawrence Berkeley Laboratory, Berkeley, California 94720 [10] University of Pennsylvania, Philadelphia, Pennsylvania 19104 [11] Istituto Nazionale di Fisica Nucleare, University and Scuola Normale Superiore of Pisa, I-56100 Pisa, Italy [12] Purdue University, West Lafayette, Indiana 47907 [13] Rockefeller University, New York, New York 10021 [14] Rutgers University, Piscataway, New Jersey 08854 [15] Texas A&M University, College Station, Texas 77843 [16] University of Tsukuba, Tsukuba, Ibaraki 305, Japan [17] Tufts University, Medford, Massachusetts 02155 [18] University of Wisconsin, Madison, Wisconsin 53706 [19] Visitor

Submitted to Phys. Rev. D

Abstract

We have searched for a light Standard Model Higgs boson produced in association with an Intermediate Vector Boson at the Fermilab Proton-Antiproton Collider operating at a center-of-mass energy of 1.8 TeV. The search was made by looking for an excess of isolated high transverse momentum charged track pairs in W and Z events. A Higgs boson with a mass m_H in the intervals $2m_\mu < m_H < 818$ MeV/c^2, and 846 MeV/$c^2 < m_H < 2m_K$ is excluded at 90% C.L.

PACS number 14.80.Gt

We have searched for a light Standard Model Higgs boson [1] produced in association with an Intermediate Vector Boson (W or Z) at the Fermilab Tevatron proton-antiproton collider operating at a center-of-mass energy of 1.8 TeV. Results are based on an analysis of 5422 W decay candidates and 480 Z decay candidates recorded with the CDF detector. The data were taken during the 1988-9 running period and correspond to an integrated luminosity of 4.4 pb^{-1}.

If the Higgs boson exists with a mass $m_H < 1$ GeV/c^2 the diagrams of Fig. 1 predict the radiation of a Higgs boson from about 1% of all hadronically produced W and Z bosons. If m_H is between the $\mu^+\mu^-$ and $\rho^+\rho^-$ decay thresholds ($2m_\mu < m_H < 2m_\rho$) the Higgs boson is expected [2] to (i) have a lifetime $< 10^{-14}$ s (its decay products will therefore be associated to the primary vertex), and (ii) decay with a large branching fraction to a charged track pair ($\mu^+\mu^-$, $\pi^+\pi^-$, or K^+K^-). We have therefore searched for a resonant enhancement amongst isolated high-transverse-momentum (p_T) track pairs in W and Z events.

A full description of the CDF detector can be found in ref. [3]. Event analysis is based on fine grained electromagnetic (EM) and hadronic calorimetry, and charged particle tracking. The calorimeters have full azimuthal angle (ϕ) coverage, extend down to 2° from the beam directions, and are segmented into about 5000 projective towers. Each tower is 0.1 units of pseudorapidity (η) wide, and covers an azimuthal angular interval of 15° in the central region ($|\eta| < 1.1$) and 5° elsewhere. Muon detection is provided by drift chambers outside of the calorimeters in the central region ($|\eta| < 0.63$) and by large toroid systems in the forward region ($2.0 < |\eta| < 3.6$). In many cases isolated high momentum muons can be identified in the intermediate angular range by a comparison of the tracking and calorimeter information. In the region $|\eta| < 1.7$ the central tracking chamber (CTC) measures particle charge and p_T by curvature in the 1.412T solenoidal magnetic field. The trajectory of a track emitted at large angle to the beam axis is measured at 84 points.

Events have been selected containing candidates for ($e\nu$) and ($\mu\nu$) decays of the W, and (e^+e^-) and ($\mu^+\mu^-$) decays of the Z. A description of electron, muon, and neutrino triggering, selection and reconstruction in the CDF detector can be found in refs. [4-6]. The presence of a high-p_T neutrino in the CDF detector is inferred from a large transverse energy (E_T) imbalance measured in the fine grained calorimeters. In events containing a high-p_T muon the muon p_T has been included in the missing-E_T ($\not{E}_T$) calculation.

W decays have been selected by requiring the presence of a $\not{E}_T > 20$ GeV together with either an isolated electron with $E_T > 20$ GeV or an isolated central muon ($|\eta| < 0.63$) with $p_T > 20$ GeV/c. The transverse mass [5] of the ($e\nu$) or ($\mu\nu$) system was required to be greater than 40 GeV/c^2. Background contributions from non-W/Z related processes (heavy flavor production and semileptonic decays, and jet fluctuations) have been estimated by studying the lepton isolation distributions for the W samples, and the $\not{E}_T$ distributions associated with the inclusive isolated lepton samples. The W data samples and estimated backgrounds are listed in Table 1.

Z decays have been selected by requiring the presence of two isolated electrons or muons. Electrons with $|\eta| < 1.1$ were required to have $E_T > 20$ GeV and electrons with $|\eta| > 1.1$ were required to have $E_T > 15$ GeV. At least one of the two electron candidates was required to have $|\eta| < 1.1$. Muon candidates were required to have $|\eta| < 1.2$ and $p_T > 20$ GeV/c. To remove cosmic rays, muon pairs were rejected if anti-collinear within $\Delta\eta \leq 0.1$ and $\Delta\phi \leq 1.5^o$. Events have been selected if the lepton pair mass was in the interval $65 < m < 120$ GeV/c^2. The estimated background in the Z event samples is $3 \pm 2\%$. The Z data samples are listed in Table 1.

To search for isolated high-p_T track-pairs in the event samples all CTC tracks have been considered with $p_T > 500$ MeV/c, $|\eta| < 1.2$, and at least 45 hits on the reconstructed track. It was further required that, at the point of closest approach to the beam-line, the track was less than 1 cm from the beam-line and closer than 5 cm along the beam-line from the primary vertex. Track pairs have been retained for further analysis if (i) the two tracks have opposite charge, (ii) they are separated in (η,ϕ)-space by $\Delta R < 1.0$ where $\Delta R \equiv (\Delta\eta^2 + \Delta\phi^2)^{1/2}$, (iii) the pair direction is within the pseudorapidity interval $|\eta| < 1.0$, and (iv) the pair is well separated from the W or Z decay leptons ($\Delta R > 0.4$). A total of 27 819 pairs pass these cuts. The expected number of Higgs bosons surviving these cuts is shown in Table 2.

The majority of high-p_T track pairs in W and Z events are expected to be associated with jets. Pairs from this source will not in general be isolated. To reject this background we require the pair to be isolated in a cone in (η,ϕ)-space centered on the pair direction and with radius $\Delta R = 0.6$, chosen to be matched in size with typical jets produced in W and Z events. The pair was required to be isolated in (a) the CTC and (b) the calorimeter:

(a) The scalar sum of the transverse momenta of any additional tracks inside the isolation cone was required to be less than 1.2 GeV/c.

(b) The total E_T deposited inside the isolation cone was required to be less than 3.2 GeV after subtracting the energies associated with the two tracks. The subtraction was made by extrapolating the two tracks to the EM and hadronic calorimeters, constructing subcones about the track impact positions, and excluding any energy deposited within the subcones. The radius of the subcones has been chosen so that the energy leaking outside of them from the showers associated with the tracks is negligible ($\Delta R = 0.1$ in the EM calorimeter and $\Delta R = 0.3$ in the hadronic calorimeter).

After these isolation cuts have been applied 7973 pairs remain. The isolation cuts were chosen to correspond to signal losses of approximately 20% and 5% for the CTC and calorimeter requirements respectively. This choice of isolation cuts maximizes the rejection against background whilst keeping the losses and associated uncertainties small. These losses were calculated by randomly generating isolation cones in W events uniformly in η and ϕ. Using this method, the losses due to the CTC and calorimeter isolation requirements were found to be $19.4 \pm 0.4\%$ and $5.0 \pm 0.2 \pm 0.2\%$ respectively, where the second uncertainty on the loss due to the calorimeter isolation requirement reflects the systematic uncertainty on the distribution of pair-tracks within the isolation cone.

In Fig. 2 the transverse momentum of the positive versus negative tracks (p_T^+ versus p_T^-) is shown for the isolated track-pairs that survive the cuts. There is a large accumulation of pairs with small values of p_T^+ and p_T^-. To further reduce the background we exploit the relatively hard p_T distribution and flat angular distribution expected for tracks coming from Higgs boson decay. We require that :

$$p_T^R \equiv \sqrt{(p_T^+)^2 + (p_T^-)^2} > 5 \text{ GeV/c}, \quad \text{and}$$

$$|\cos\theta| < 0.9$$

where θ is the angle of the outgoing tracks with respect to the pair direction in the pair rest-frame, and the pair tracks have been assigned the pion mass. We are left with 56 pairs that satisfy these requirements. The pair-mass distribution is shown in Fig. 3. There are no obvious resonant enhancements. The pair-mass resolution has been evaluated from the track covariance matrices. The method has been calibrated using a sample of J/ψ decays. Contributions to the mass resolution from the uncertainties on the measured pair opening angle and track curvatures were studied separately. The average pair-mass resolution for the pairs in Fig. 3 is 6.9 MeV/c^2. Studies [4] of $K_S^0 \rightarrow \pi^+\pi^-$, $J/\psi \rightarrow \mu^+\mu^-$, and $\Upsilon(1S) \rightarrow \mu^+\mu^-$ decays indicate that the systematic uncertainty on the absolute pair-mass scale $\delta m/m < 0.2\%$.

We consider separately the mass intervals:

a) $2m_\mu < m_H < 2m_\pi$: There are no pairs in this mass interval. More than 7 Higgs bosons would be expected to survive our selection. We therefore exclude a Higgs boson in this region at greater than 95% C.L.

b) $2m_\pi < m_H < 2m_K$: Assigning the pair tracks the pion mass, there are 18 pairs with masses in this interval. Only two of these pairs are consistent with an isolated $\mu^+\mu^-$ assignment to the tracks; the remaining 16 pairs deposit too much energy in the calorimeters to be consistent with this hypothesis. The two ambiguous pairs have $\pi^+\pi^-$ masses of 464 ± 11 and 837 ± 7 MeV/c^2 (Fig. 3). If re-assigned the $\mu^+\mu^-$ hypothesis the pair masses become 425 ± 12 and 786 ± 7 MeV/c^2 respectively. The limits on Higgs boson production described in the following are not significantly affected by this change.

c) $m_H > 2m_K$: In this mass region we must consider $\mu^+\mu^-$, $\pi^+\pi^-$, and K^+K^- assignments to the tracks. There are 28 pairs that have either a $\mu^+\mu^-$, $\pi^+\pi^-$, or K^+K^- mass in the interval $2m_K < m_H < 2m_p$. Given the uncertainties in the track assignments, and in the expected Higgs boson branching fractions, the background level is too high to exclude a Higgs boson in this mass region.

The 90% and 95% C.L. upper limits on the number of Higgs bosons contributing to the selected pair sample are shown as a function of m_H in Fig. 4. For each m_H the limit has been obtained by using the method of maximum likelihood [7] to fit the observed pair mass distribution to a Higgs boson peak superimposed on a flat background. The fit takes into account the mass and mass resolution for each observed pair. The mass resolution has been degraded by 20% to take account of the systematic uncertainty. This increase broadens the peaks in Fig. 4 but does not appreciably change their height. The fit has been made using the method described in ref. [8] to impose the constraint that the number of Higgs bosons is non-negative. The fit results are insensitive to reasonable changes in the assumed background shape. More than 5.3 pairs associated with Higgs boson production is excluded everywhere at greater than 90% C.L. except in the neighborhood of 832

MeV/c^2 where there is a small accumulation of events which is consistent with statistical fluctuations of the flat background distribution.

To evaluate the fraction of W and Z bosons produced in association with a Higgs boson we have modified version 4.9 of the PYTHIA Monte Carlo [9] to include the weak matrix elements for the processes shown in Fig. 1, setting $m_W = 80$ GeV/c^2, $m_Z = 91$ GeV/c^2, $\sin^2\theta_W = 0.227$, and using the EHLQ1 structure functions [10] with $\Lambda = 0.2$ GeV and $Q^2 = m_W{}^2$. This Monte Carlo, together with a full simulation of the CDF detector, has also been used to evaluate the number of Higgs bosons expected to survive our selection requirements. The results are summarized in Table 2. More than 6 Higgs bosons are expected to survive our cuts in the mass region of interest. The systematic uncertainties on this prediction are:

(i) Number of W and Z events: The predicted number of Higgs bosons is computed from the number of W and Z events in the data samples and the predicted fraction of W and Z events containing a Higgs boson. The uncertainty on the number of W and Z decays in the data samples after background subtraction is $\pm$ 1.3% (Table 1).

(ii) Fraction of W and Z bosons with associated Higgs boson production: Higher order weak corrections to the diagrams shown in Fig. 1 are expected to be negligible. We have varied the W and Z masses, and $\sin^2\theta_W$, in the Monte Carlo within one standard deviation of the world average values, and found that the predicted fraction f of W and Z events containing a Higgs boson changes by no more than $\Delta f/f = \pm 0.016$.

(iii) Higgs boson decay branching fractions: In the mass interval $2m_\pi < m_H < 2m_K$ the Higgs boson will decay into $\mu^+\mu^-$, $\pi^+\pi^-$, or $\pi^0\pi^0$. The expected branching fraction into the pion modes calculated in Ref. [2] is typically 0.7 in this mass interval. This predicted branching fraction may increase by about 20% when lowest order QCD corrections are included [11]. To avoid model dependence in our limits, we make the most pessimistic assumption, namely that the Higgs boson decays exclusively into the pion decay modes, in which case one-third [2] of the Higgs boson decays will be lost in the $\pi^0\pi^0$ mode.

(iv) Isolation: We add in quadrature the statistical uncertainties on the loss of isolated track pairs due to the CTC and calorimeter isolation criteria. The result is added linearly to the systematic uncertainty on the loss due to the calorimeter isolation requirement. The overall uncertainty is $\pm$ 0.6%.

(v) Track reconstruction: The CTC track reconstruction efficiency for isolated high-p_T tracks at large angle is close to 100%. We have allowed a 1% loss of tracks due to reconstruction problems.

(vi) Higgs-boson-p_T (p_T^H) distribution and structure functions: We have checked that PYTHIA gives a good description of the observed p_T distribution for inclusive W production. To evaluate the systematic uncertainty on the predictions due to the uncertainty on the p_T^H distribution we have reduced the component of p_T^H in PYTHIA associated with the incoming annihilating partons (after gluon radiation) by 20% , and found that the number of Higgs bosons predicted to survive our cuts decreases by no more than 3%. We assign a systematic uncertainty of ±3% to our predicted Higgs boson rate due to the uncertainty on the p_T^H distribution. We have also used alternative structure functions (EHLQ2 [10], DO1 [12], and DO2 [12]). In all cases the predicted Higgs boson rate is consistent within ± 1.8% with the EHLQ1 prediction.

To take account of all of these uncertainties we have reduced our predicted Higgs boson rate by one systematic standard deviation ($\sigma_{SYS} = 3.7\%$), calculated by combining all of the above components in quadrature. The resulting theoretical floor is shown in Table 2 as a function of m_H, and compared in Fig. 4 with our experimental upper limit on the number of Higgs boson pairs in the data.

We have made the first search for a Higgs boson produced in association with a real or nearly real Intermediate Vector Boson. A light Standard Model Higgs boson is excluded at 95% C.L. in the region $2m_\mu < m_H < 2m_\pi$, and at 90% C.L. in the region $2m_\pi < m_H < 2m_K$ except in the neighborhood of 832 MeV/c^2 (± 14 MeV/c^2) where there is a small accumulation of events, consistent with statistical fluctuations. In this region a Higgs boson signal can neither be claimed nor excluded. Over most of the mass interval a light Standard Model Higgs boson is also excluded at 95% C.L. There have been a number of previous searches for light Higgs bosons produced in pion, kaon, η', B meson, and upsilon decays (see for example Ref. [13]). However, in the mass region $2m_\pi < m_H < 2m_K$ these previous results have required that the branching ratio for the Higgs boson to decay into $\mu^+\mu^-$ be significant. Our result is independent of this assumption [14].

This work would not have been possible without the skill and hard work of the Accelerator Division of Fermilab. We thank the staffs of our institutions for their many contributions to the experiment. We also thank Keith Ellis for help with the calculation of Fig. 1. This work was supported by the U.S. Department of Energy, the National Science Foundation, the Istituto Nazionale di Fisica Nucleare, the Ministry of Science, Culture, and Education of Japan, and the A.P. Sloan Foundation.

References

[1] P.W. Higgs, Phys. Lett. **12**, 132 (1964), Phys. Rev. Lett. **13**, 508 (1964), Phys. Rev. **145**, 156 (1966); F. Englert and R. Brout, Phys. Rev. Lett. **13**, 321 (1964); G. S. Guralnik et al., Phys. Rev. Lett. **13**, 585 (1964); T.W.B. Kibble, Phys. Rev. **155**, 1554 (1967).

[2] M. Voloshin, Sov. J. Nucl. Phys. **44**, 478 (1986).

[3] F. Abe et al. (CDF Collab.), Nucl. Instrum. Methods, **A271**, 387 (1988).

[4] F. Abe et al. (CDF Collab.), Phys. Rev. Lett. **63**, 720 (1989).

[5] F. Abe et al. (CDF Collab.), Phys. Rev. Lett. **62**, 1005 (1989).

[6] J. Proudfoot (CDF Collab.), Proc. Workshop on Calorimetery for the Supconducting Super Collider, Tuscaloosa, AL., March 13-17, 1989.

[7] See for example L. Lyons, "Statistics for Nuclear and Particle Physicists", Cambridge University Press, 1989.

[8] G. P. Yost et al. (Particle Data Group), Phys. Lett. **B204**, 1 (1988).

[9] H. -U. Bengtsson and T. Sjostrand, Computer Physics Communications **46**, 43 (1987).

[10] E. Eichten et al., Rev. Mod. Phys. **56**, 579 (1984), and Erratum **58**, 1065 (1986).

[11] R. Barbieri and G. Curci, Phys. Lett. **B219**, 503 (1989).

[12] D. Duke and J. F. Owens, Phys. Rev. **D30**, 49 (1984).

[13] J. F. Gunion et al., "The Higgs Hunter's Guide", BNL-41644, June 1989, and references therein. See also for example M. S. Alam et al. (CLEO Collab.) Phys. Rev. **D40**, 712 (1989).

[14] Except in the small region between the $\pi^0\pi^0$ and $\pi^+\pi^-$ thresholds where we have no limit if the branching ratio for the Higgs boson to decay into $\mu^+\mu^-$ is less than 0.33.

Table 1: W and Z data samples, luminosity, and estimated non-Intermediate-Vector-Boson associated backgrounds.

Sample	$\int L.dt$ (pb^{-1})	Events	Background
$W \rightarrow e\nu$ ($\lvert\eta\rvert < 1.1$)	4.4	3002	105 ± 60
$W \rightarrow e\nu$ ($\lvert\eta\rvert > 1.1$)	3.6	982	61 ± 26
$W \rightarrow \mu\nu$	4.4	1438	32 ± 32
$Z \rightarrow e^+e^-$	4.4	320	10 ± 6
$Z \rightarrow \mu^+\mu^-$	4.4	160	5 ± 3

Table 2: Predicted number of Higgs bosons surviving the selection criteria as a function of Higgs boson mass. The predictions are normalized to the total number of W and Z bosons in the CDF data samples. The predicted number of Higgs bosons surviving all cuts are given in the last three lines, which correspond to (i) the best estimate using the branching ratios of ref. [2], (ii) the best estimate reduced by one systematic standard deviation (see text), and (iii) further reduced to correspond to the most pessimistic scenario in which the Higgs boson decays only to the pion modes.

	m_H (MeV/c^2)				
Requirements	250	300	500	700	900
Before cuts	58.2	58.2	56.6	55.5	53.7
$H \rightarrow (\pi^+\pi^-$ or $\mu^+\mu^-)$	58.2	46.6	44.3	42.2	39.6
$\lvert\eta_{tracks}\rvert < 1.2$	39.5	31.3	28.4	26.4	24.1
$p_T > 0.5$ GeV/c	34.3	27.0	22.6	20.5	19.0
$\lvert\eta_{pair}\rvert < 1.0$	30.1	23.9	20.5	19.0	17.6
$\Delta R < 1.0$	30.0	23.7	20.1	18.3	16.4
ΔR(lepton,pair) > 0.4	28.2	22.3	18.8	17.2	15.3
$p_T^R > 5$ GeV/c	11.5	9.3	9.5	9.0	8.4
$\lvert\cos\theta\rvert < 0.9$	9.7	8.0	8.4	8.3	8.0
i) Isolation & tracking	7.3	6.1	6.3	6.3	6.1
ii) Reduce by 1 σ_{SYS}	7.0	5.9	6.1	6.0	5.8
iii) Floor	7.0	4.9	5.2	5.3	5.2

Figure Captions

Fig 1: Lowest order diagrams describing Intermediate Vector Boson plus associated Higgs boson production in proton-antiproton collisions.

Fig. 2: Transverse momentum of positive versus negative tracks in isolated track-pairs in W and Z events. The curve indicates the cut described in the text.

Fig. 3: Isolated pair mass-distribution. The tracks have been assigned the pion mass. The masses of those pairs which are also consistent with the $\mu^+\mu^-$ hypothesis are indicated by the hatching. The curves show the total number of Higgs bosons expected [2] to survive our cuts (solid curve) and the floor (dashed curve, see Table 2) as a function of the Higgs boson mass.

Fig. 4: Theoretical lower limit on the predicted number of Higgs bosons surviving our selection criteria shown as a function of pair mass and compared with the 90% and 95% upper confidence limits on narrow resonance production of track-pairs in the selected samples .

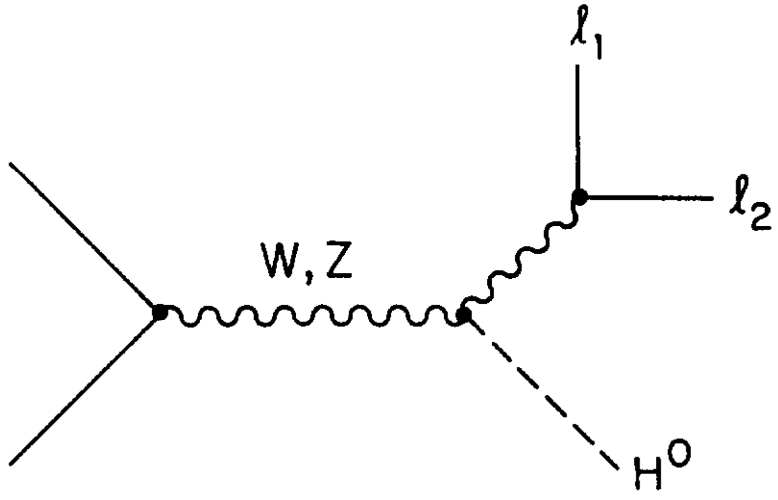

Fig. 1

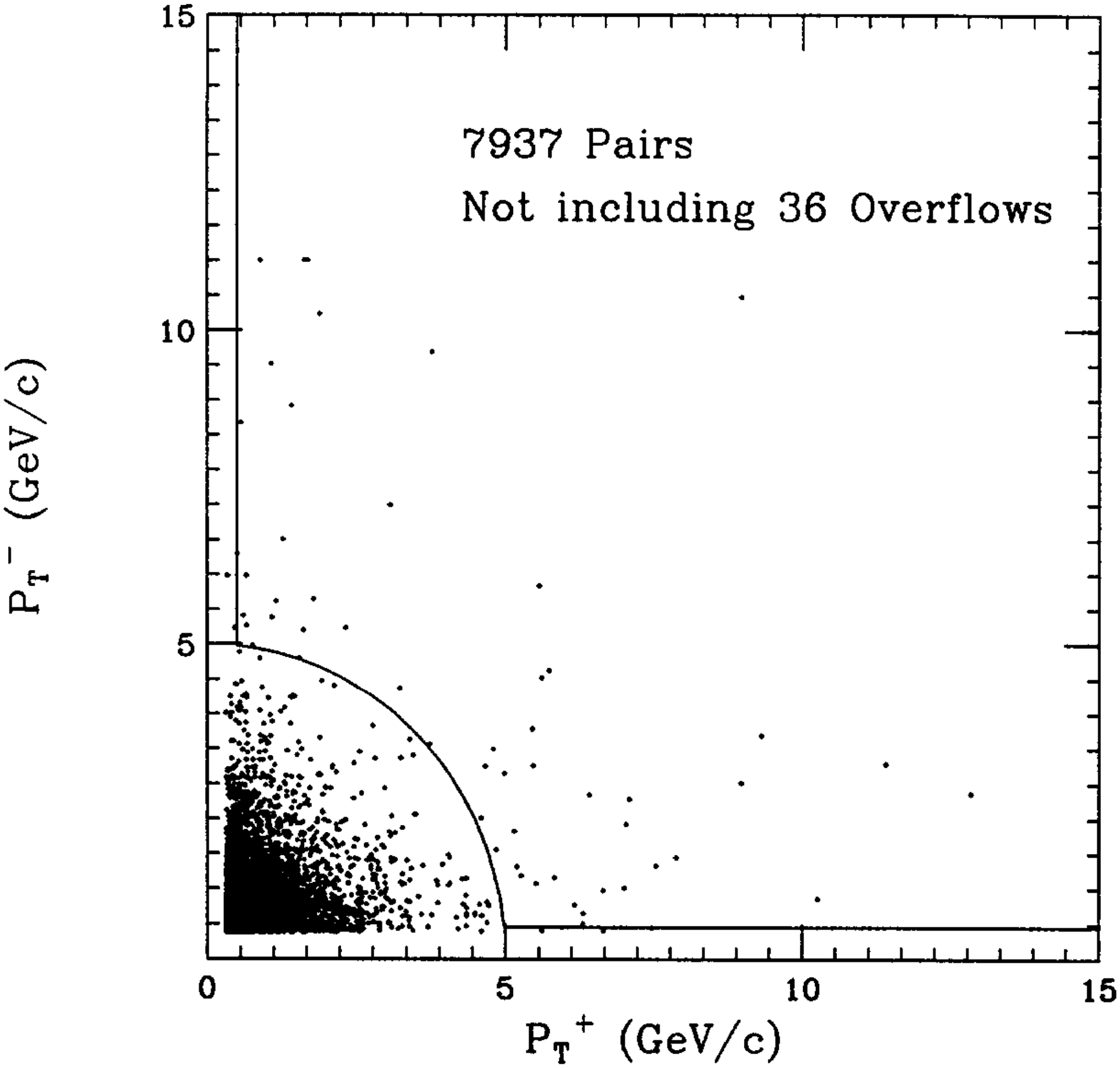
7937 Pairs
Not including 36 Overflows
0
5
10
15
P_T^+ (GeV/c)
P_T^- (GeV/c)

Fig. 2

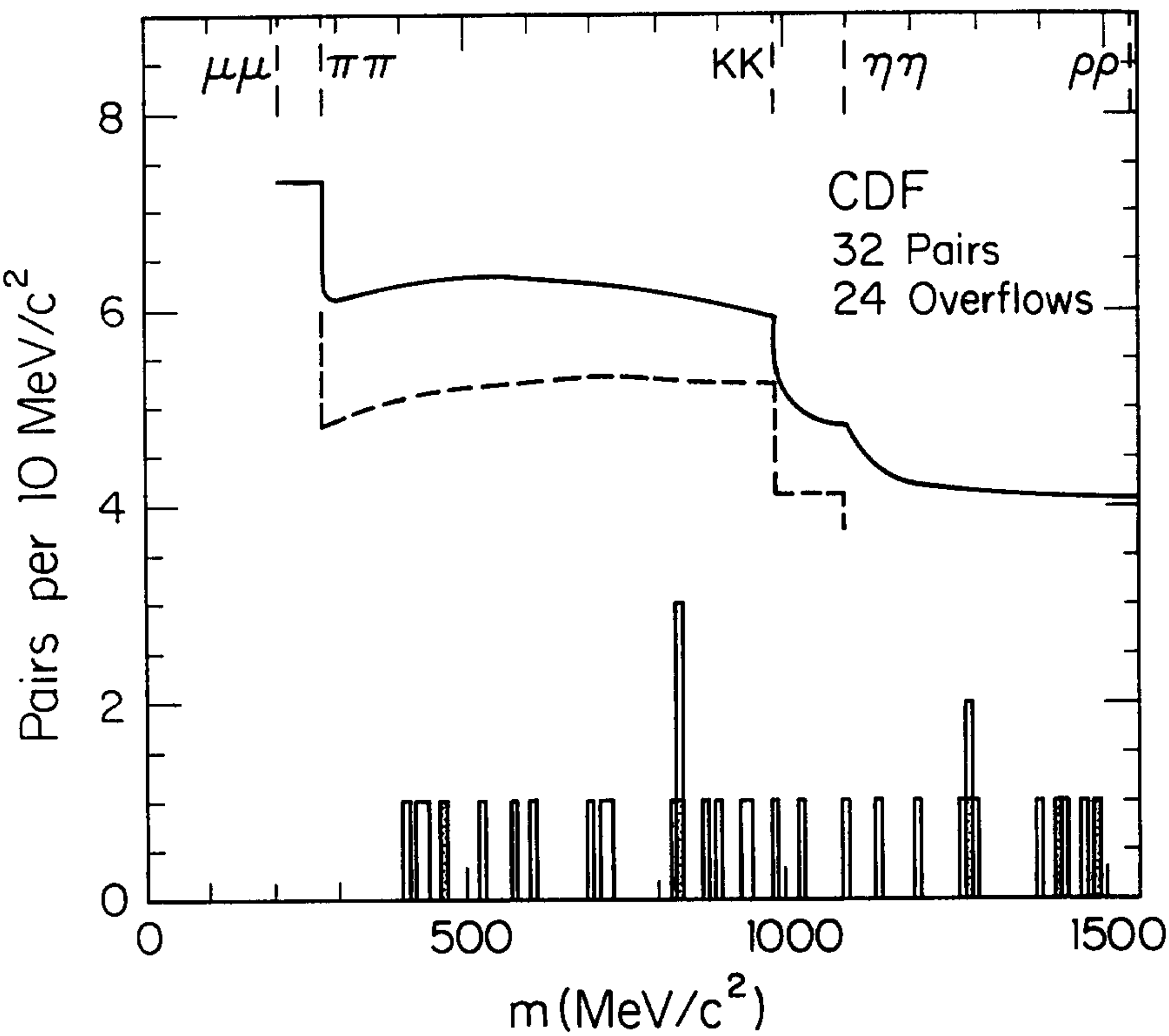
μμ
ππ
KK
ηη
ρρ
CDF
32 Pairs
24 Overflows
Pairs per 10 MeV/c²
m (MeV/c²)
0
2
4
6
8
0
500
1000
1500

Fig. 3

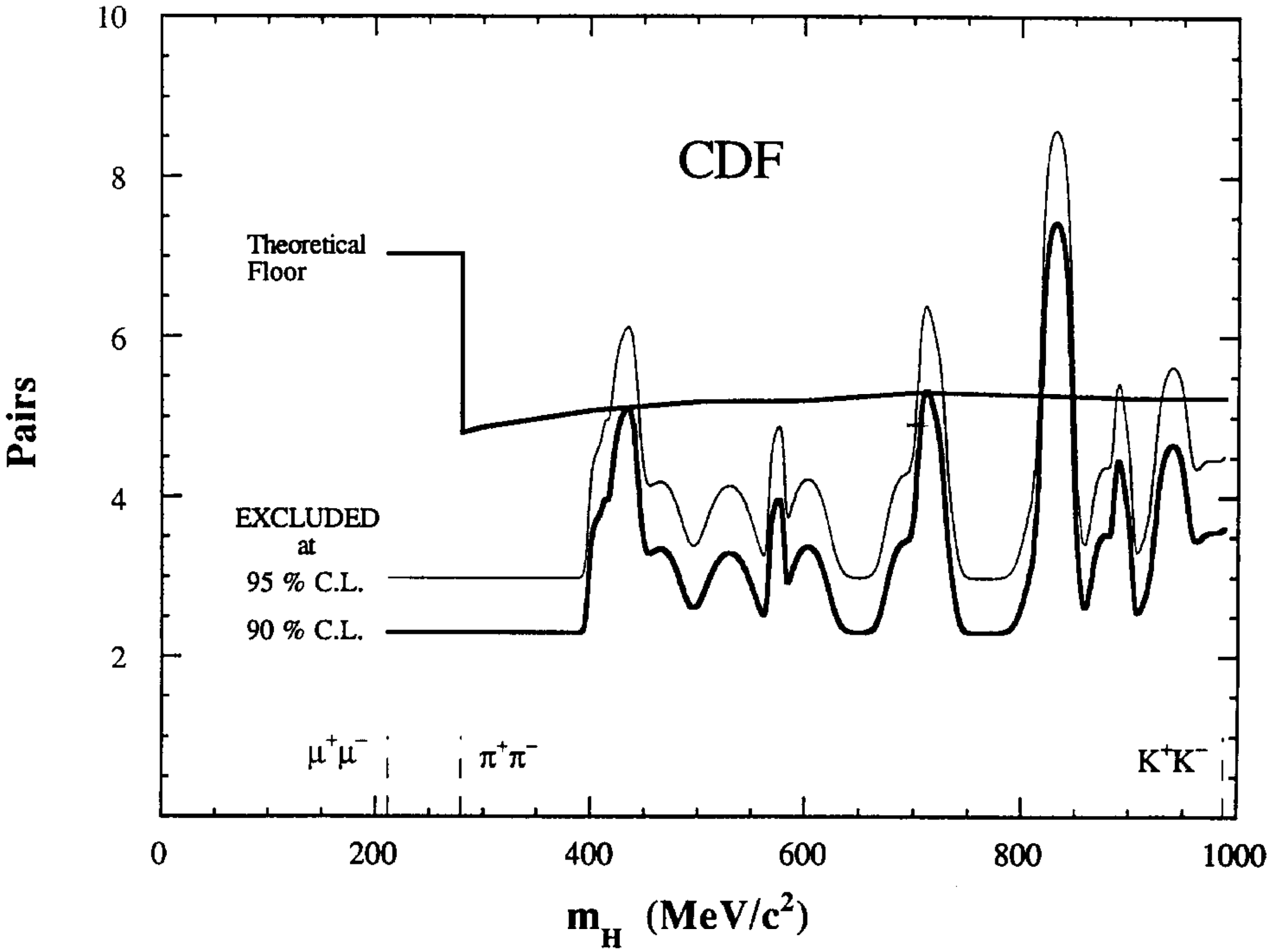
CDF
Theoretical Floor
EXCLUDED at
95 % C.L.
90 % C.L.
$\mu^+\mu^-$
$\pi^+\pi^-$
K^+K^-
Pairs
m_H (MeV/c^2)
0
2
4
6
8
10
0
200
400
600
800
1000

Fig. 4