

Search for a neutral Higgs boson in B -meson decay

M. S. Alam, N. Katayama, I. J. Kim, W. C. Li, X. C. Lou, and C. R. Sun
State University of New York at Albany, Albany, New York 12222

D. Bortoletto, M. Goldberg, N. Horwitz, M. D. Mestayer, G. C. Moneti, V. Sharma,
 I. P. J. Shipsey, and T. Skwarnicki
Syracuse University, Syracuse, New York 13210

S. E. Csorna and T. Letson
Vanderbilt University, Nashville, Tennessee 37235

I. C. Brock and T. Ferguson
Carnegie Mellon University, Pittsburgh, Pennsylvania 15213

M. Artuso, C. Bebek, K. Berkelman, E. Blucher, J. Byrd, D. G. Cassel,
 E. Cheu, D. M. Coffman, G. Crawford, R. DeSalvo, J. W. DeWire, P. S. Drell,
 R. Ehrlich, R. S. Galik, B. Gittelman, S. W. Gray, A. M. Halling, D. L. Hartill,
 B. K. Heltsley, J. Kandaswamy, R. Kowalewski, D. L. Kreinick, Y. Kubota,
 J. D. Lewis, N. B. Mistry, J. Mueller, R. Namjoshi, S. Nandi, E. Nordberg,
 C. O'Grady, D. Peterson, M. Pisharody, D. Riley, M. Sapper, A. Silverman,
 S. Stone, H. Worden, and M. Worris
Cornell University, Ithaca, New York 14853

A. J. Sadoff
Ithaca College, Ithaca, New York 14850

P. Avery, D. Besson, L. Garren, and J. Yelton
University of Florida, Gainesville, Florida 32611

T. Bowcock, K. Kinoshita, F. M. Pipkin, M. Procaro, Richard Wilson,
 J. Wolinski, and D. Xiao
Harvard University, Cambridge, Massachusetts 02138

P. Baringer, P. Haas, and Ha Lam
University of Kansas, Lawrence, Kansas 66045

A. Jawahery and C. H. Park
University of Maryland, College Park, Maryland 20742

D. Perticone and R. Poling
University of Minnesota, Minneapolis, Minnesota 55455

R. Fulton, M. Hempstead, T. Jensen, D. R. Johnson, H. Kagan, R. Kass,
 F. Morrow, and J. Whitmore
Ohio State University, Columbus, Ohio 43210

W.-Y. Chen, R. L. McIlwain, D. H. Miller, C. R. Ng, E. I. Shibata, and W.-M. Yao
Purdue University, West Lafayette, Indiana 47907

E. H. Thorndike
University of Rochester, Rochester, New York 14627
 (Received 13 February 1989)

Using the CLEO detector at the Cornell Electron Storage Ring we have searched for neutral-Higgs-boson production in B decay, both through the exclusive modes $B \rightarrow H^0 K$ and $B \rightarrow H^0 K^*$ using the decay of the H^0 into a pair of muons, pions, or kaons, and through the inclusive decay $B \rightarrow H^0 X$ using only the muon decay of the H^0 . We find no evidence for a Higgs boson with a mass between $2m_\mu$ and $2m_\tau$.

I. INTRODUCTION: THE HIGGS-BOSON MASS

In the standard model the W and Z bosons and the fermions get mass through their coupling to a scalar Higgs particle.¹ In the minimal model there is a single neutral Higgs boson, but its mass is not predicted. Other models can have more Higgs bosons, charged and neutral. None have been observed. Measured branching-ratio upper limits for $K \rightarrow \pi e^+ e^-$ and $K \rightarrow \pi \mu^+ \mu^-$ have been used to argue against neutral-Higgs-boson masses below 325 MeV (Ref. 2), although the theoretical uncertainties may be large enough to allow such masses.³ A preliminary result from a study of radiative $\Upsilon(1S)$ and $\Upsilon(3S)$ decays⁴ places a lower limit of about 5.8 GeV on the Higgs-boson mass. However, this limit is sensitive to suppression of the $\Upsilon \rightarrow H^0 \gamma$ rate by large higher-order QCD corrections.⁵

Linde⁶ and Weinberg⁶ have shown that if one assumes an effective potential for the Higgs interaction with the electroweak-symmetry-breaking vacuum at an absolute minimum of the potential, the neutral-Higgs-boson and top-quark masses are constrained in one-loop order by

$$(2\pi v M_H)^2 > 3 \sum m_{\text{boson}}^4 + M_H^4 - 4 \sum m_{\text{fermion}}^4, \quad (1)$$

where $v = (\sqrt{2} G_F)^{-1/2} = 246$ GeV and the sums are carried over intermediate boson and fermion masses. In the six-quark, minimal-Higgs-boson standard model this condition would allow $M_H < m_b$ only if m_t were above 80 GeV. However, the physical vacuum may not be at an absolute minimum, so the constraint may not apply.

The fact that the Higgs-boson coupling to a fermion should be proportional to the fermion mass suggests a search for a light Higgs boson in b -quark decay. In order to gauge the sensitivity of such an experiment, we need to know how the b might decay to the Higgs boson (Sec. II) and then how the Higgs boson might decay to lepton or hadron final states (Sec. III).

II. THEORY OF HIGGS-BOSON PRODUCTION IN B DECAY

Willey and Yu have suggested a search for the neutral Higgs boson in B -meson decays.⁷ For a minimal neutral Higgs boson decaying through the mechanisms diagrammed in Fig. 1, they predict

$$\frac{\Gamma(B \rightarrow H^0 X)}{\Gamma(B \rightarrow e \nu X)} = \frac{|V_{tb} V_{ts}^*|^2}{|V_{cb}|^2} \frac{27\sqrt{2}}{64\pi^2} G_F m_b^2 \left(\frac{m_t}{m_b} \right)^4 \times \left[1 - \frac{M_H^2}{m_b^2} \right]^2 \frac{1}{r(m_c/m_b)}, \quad (2)$$



FIG. 1. Diagrams for B decay to Higgs boson. ϕ^- represents a charged "unphysical Higgs boson" (Ref. 7).

where $r(m_c/m_b) = 0.48$ is the phase-space factor for semileptonic B decay. In the six-quark model the Kobayashi-Maskawa matrix elements V_{ts} and V_{cb} should be approximately equal and V_{tb} should be close to 1 by unitarity. If we set both V_{tb} and V_{ts}/V_{cb} to 1, take $m_b = 4.9$ GeV, and use 0.11 for the B -meson semileptonic branching ratio,⁸ Eq. (2) reduces to

$$B(B \rightarrow H^0 X) = 0.042 \left(\frac{m_t}{50 \text{ GeV}} \right)^4 \left[1 - \frac{M_H^2}{m_b^2} \right]^2. \quad (3)$$

If $m_t = 50$ GeV, this predicts a branching ratio between 4.2% and 0.9% for Higgs-boson masses up to $2m_\tau = 3.6$ GeV (see Fig. 2).

The $b \rightarrow H^0 s$ mechanism of Fig. 1 suggests a search for B decays in the two-body modes $B \rightarrow H^0 K$ and $B \rightarrow H^0 K^*$. In this paper we will consider both the inclusive mode $B \rightarrow H^0 X$ and the two-body modes. Haber, Schwartz, and Snyder⁹ predict that the branching fraction for the $H^0 K$ mode should be rather large:

$$\frac{\Gamma(B \rightarrow H^0 K)}{\Gamma(B \rightarrow H^0 X)} = \frac{0.07}{(1 - M_H^2/m_b^2)(1 - M_H^2/\Lambda^2)}. \quad (4)$$

The ratio increases with Higgs-boson mass as the Q of the decay decreases and two-body modes become the only ones kinematically allowed. Figure 2 shows the Higgs-boson-mass dependence of Eq. (4) with $m_b = 4.9$ GeV and the cutoff mass $\Lambda = 6.1$ GeV. Grinstein, Wise, and Isgur

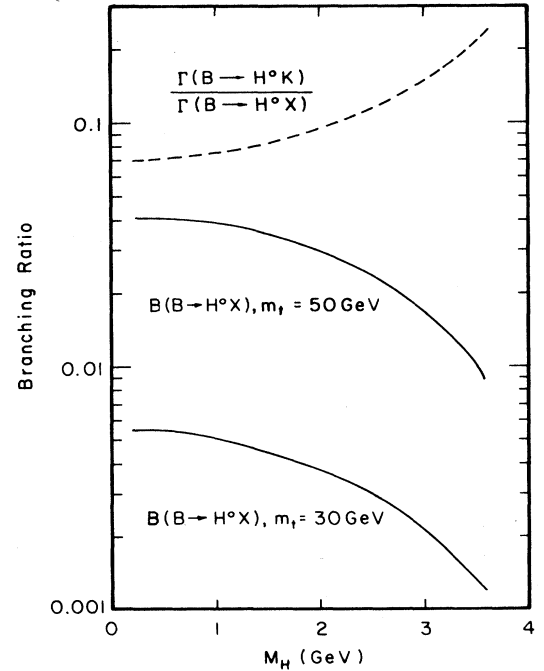


FIG. 2. Plot of the predicted fraction of $B \rightarrow H^0 X$ decays going into the two-body channel with $X = K$ (dashed curve, from Ref. 9), and of the branching ratio of $B \rightarrow H^0 X$ for two values of the top-quark mass (continuous curves, from Ref. 7).

predict about the same value of the ratio at low Higgs-boson mass, but their ratio decreases with increasing M_H (Ref. 10).

III. THEORY OF HIGGS-BOSON DECAY

The direct coupling of the Higgs boson to a fermion pair [Fig. 3(a)] would imply a decay rate proportional to the square of the mass of the pair:

$$\Gamma(H^0 \rightarrow f^+ f^-) = \frac{G_F M_H m_f^2}{4\sqrt{2}\pi} C_f \left[1 - \frac{4m_f^2}{M_H^2} \right]^{3/2}, \quad (5)$$

where the color factor C_f is 1 for leptons and 3 for quarks. It has been suggested,¹¹ however, that the Higgs-boson decay to hadrons is enhanced by gluon radiation from a virtual-heavy-quark loop [Fig. 3(b)]. At the parton level the decay rate to gluons is given by^{12,13}

$$\Gamma(H^0 \rightarrow gg) = \frac{G_F M_H^3}{36\sqrt{2}\pi^3} \alpha_s^2 N_{\text{eff}}^2, \quad (6)$$

with N_{eff} as the effective number of heavy-quark types with mass above $M_H/2$ (Ref. 14). The resulting decay rate to meson final states containing light quarks is difficult to calculate, especially for a low Higgs-boson mass, and published predictions vary widely.^{12,13,15} For M_H around 3 GeV, however, the measured rate for the charmonium decay $\chi_0 \rightarrow gg \rightarrow \text{hadrons}$ suggests¹⁶ that Eq. (6) should be a reliable estimate of the rate of Higgs-boson decay to hadron final states containing light quarks, but with a factor of 2 for nonperturbative enhancement (see Fig. 4).

Equation (5) can be used for the rate for $H^0 \rightarrow K^+ K^-$ once we have a prediction for the fraction of $s\bar{s}$ final states that appear in two-body modes. As a rough hypothesis we can take the fraction of $K^+ K^-$ to be the same as in $e^+ e^-$ annihilation at a center-of-mass energy equal to the assumed Higgs-boson mass:

$$\frac{\sigma(e^+ e^- \rightarrow K^+ K^-)}{\sigma(e^+ e^- \rightarrow s\bar{s})} = \frac{\pi\alpha^2\beta_K^3 |F_K(m_H^2)|^2 / (4M_H^2)}{R_s \sigma_{\mu\mu}}, \quad (7)$$

with $R_s = 3(\frac{1}{3})^2$. Experimental data¹⁷ for the kaon charge form factor F_K are consistent with ϕ -meson pole dominance:

$$|F_K(M_H^2)| = \left[\frac{M_H^2}{m_\phi^2} - 1 \right]^{-1}. \quad (8)$$

Thus we have

$$\frac{\Gamma(H^0 \rightarrow K^+ K^-)}{\Gamma(H^0 \rightarrow s\bar{s})} = \frac{9(1 - 4m_K^2/M_H^2)^{3/2}}{16(M_H^2/m_\phi^2 - 1)^2}, \quad (9)$$

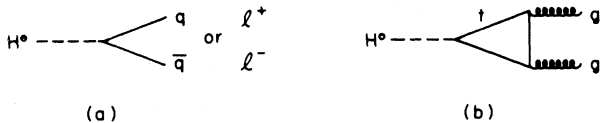


FIG. 3. Diagrams for Higgs-boson decay by (a) direct coupling, and (b) intermediate gluons.

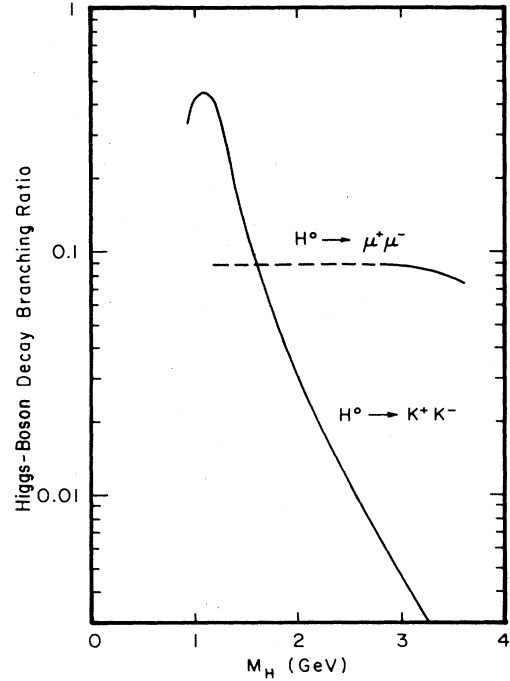


FIG. 4. Predictions (see text) for Higgs-boson decay branching ratios: $H^0 \rightarrow \mu^+ \mu^-$ and $H^0 \rightarrow K^+ K^-$.

which is used to derive the branching ratio for $H^0 \rightarrow K^+ K^-$ plotted in Fig. 4.

IV. EXPERIMENT

The data sample consists of about 487 000 B -meson decays, from an integrated luminosity of 212 pb^{-1} at the $\Upsilon(4S)$ resonance, accumulated with the CLEO detector at the Cornell Electron Storage Ring (CESR). The CLEO detector¹⁸ and our hadronic-event selection criteria¹⁹ have been described in detail elsewhere. In this analysis we make use of (a) charged-particle tracking and momentum measurement in cylindrical drift chambers in a magnetic field, (b) particle identification information from dE/dx measurements in the tracking chambers, and (c) muon identification in drift chambers behind a hadron absorber.

Charged particles are tracked inside a superconducting solenoid of radius 1.0 m, with a 1.0-T magnetic field parallel to the beam line. Three nested cylindrical drift chambers measure momenta and specific ionization (dE/dx) for charged particles. The innermost part of the tracking system is a three-layer straw tube vertex detector with an rms position accuracy of $70 \mu\text{m}$ in the coordinates perpendicular to the beam axis. The middle ten-layer drift chamber measures position with $90 \mu\text{m}$ accuracy and dE/dx to 14%. The main drift chamber²⁰ contains 51 layers of wires, 11 of which are at angles of 1.9° to 3.5° with respect to the beam axis. The device provides a position accuracy of $110 \mu\text{m}$ and a dE/dx ac-

curacy of 6.5%. The track coordinates along the beam axis are measured using the angled layers for stereo and using cathode strips in the middle and main drift chambers. The rms momentum resolution achieved by this system is

$$(\delta p/p)^2 = (0.007)^2 + (0.0023p)^2 \quad (p \text{ in GeV}/c),$$

as determined by Bhabha scattering and muon pair events, and by the mass resolution for reconstructed particle decays, such as $K_s \rightarrow \pi^+ \pi^-$, $\Lambda \rightarrow p \pi^-$, $\phi \rightarrow K^+ K^-$, $D^0 \rightarrow K^- \pi^+$, $\Psi \rightarrow \mu^+ \mu^-$, and $B^- \rightarrow D^0 \pi^-$ (Refs. 19 and 21).

Muons are identified by an array of crossed planes of drift chambers behind 1.0–1.5 m of steel surrounding the CLEO detector.²² An additional layer of drift chambers is located at an intermediate depth in the steel. The solid angle subtended by the muon detector is 78% of the total 4π steradians. The total thickness of steel varies from 4 to 10 hadron interaction lengths depending on the region and angle of incidence. The minimum momentum of muon that can penetrate the absorber varies from 1 GeV/c for normal incidence on the magnet ends to about 2 GeV/c for the thickest part.

Our strategy is to search for the decay of B mesons into $H^0 + \kappa$, where κ is a strange meson [K or $K^*(890)$, charged or neutral] and the H^0 decays into a pair of muons, pions, or strange mesons. Table I summarizes the modes and Higgs-boson mass ranges for which these searches are sensitive. In the case of $H^0 \rightarrow \mu^+ \mu^-$ we also search for the inclusive $B \rightarrow H^0 + X$ decay, where X can be any particle or combination of particles. The upper limit on the Higgs-boson mass for which this experiment is sensitive is $M_H = 2m_\tau = 3.6$ GeV; because of the undetectable neutrino in τ decay, we have no clear experimental signature for $H^0 \rightarrow \tau^+ \tau^-$.

The analysis procedure for the exclusive modes is similar to that used in our reconstruction of exclusive B to charm decays.¹⁹ In events which have passed our standard hadronic event-selection criteria we form track combinations corresponding to the products of the particular decay chain being searched. We require that hadrons have consistent dE/dx within three standard deviations, in order to reduce the number of spurious track combinations. For the exclusive $\mu^+ \mu^-$ modes we only require that one of the two muons be identified by a hit in the muon detector, since typically only one muon will have a momentum high enough for efficient detection. We require that the $K^{*\pm}$ and K^{*0} masses be in the ranges 892 ± 80 and 899 ± 80 MeV, respectively, with an

efficiency of 85%. We require that the total energy of the products of a candidate- B decay be within 70 MeV (2–3 standard deviations) of the beam energy. Monte Carlo simulation indicates that $(95 \pm 4)\%$ of B decays into the modes we have examined meet this requirement. Since $e^+ e^- \rightarrow B \bar{B}$ at the $\Upsilon(4S)$ resonance, we calculate the candidate- B mass from the single-beam energy and the measured momenta of the decay products using the relation $m_B^2 = E_{\text{beam}}^2 - (\sum \mathbf{p}_{\text{obs}})^2$. The combined effect of the CESR rms beam energy spread of 3.2 MeV and the CLEO track-momentum resolution is an rms spread of 2.7 MeV in the reconstructed mass¹⁹ of B mesons produced in $\Upsilon(4S)$ decay. The B -candidate mass is required to be within 7 MeV of the known B -meson mass.

Since most B decays do not produce high-momentum particles, and the particles in $B \rightarrow H^0 K$ final states have nearly the maximum allowed momentum, the background comes mainly from continuum events that have a two-jet structure with the H^0 candidate tracks in one jet and the kaon in the other. To reduce this background we calculate the sphericity axis of the event using the charged tracks other than those of the B -decay candidate. We then find the cosine of the angle θ between the H^0 candidate and the sphericity axis. The continuum background peaks sharply at $\cos\theta = \pm 1$, while for real B decays the $\cos\theta$ distribution should be isotropic. Therefore, to reduce continuum background we require that $|\cos\theta| < 0.8$ for all the final states except the dimuons, for which the background reduction is not needed.

The inclusive dimuon search, $B \rightarrow H^0 X$ with $H^0 \rightarrow \mu^+ \mu^-$, offers the potential of a higher rate as well as a result that is independent of models of how often the $b \rightarrow H^0 s$ process of Fig. 1 yields a particular two-body final state. Because of the loss of the B -mass constraint, however, single muons from misidentification of pions and kaons and from semileptonic decays of B , D , K , or π contribute a significant background if we require only one of the two muon candidates to be identified. In the inclusive search we, therefore, require that both muons be identified. For muons with sufficient momentum to penetrate the iron absorber (typically 1 m thick) to the outer layer of chambers, identification means detection in both orthogonal projections of the outer chambers, or detection in one outer projection and in both projections of an inner layer of drift chambers located after 30 cm of iron. For muons with momentum too low to reach the outer layer, identification means detection in both projections of the inner layer. Figure 5 shows the dimuon detection efficiency as a function of dimuon mass.

TABLE I. The range of sensitivity in H^0 mass and the detection efficiency ϵ for exclusive two-body decays $B \rightarrow H^0 \kappa$ with various H^0 decay modes and strange mesons κ . The detection efficiencies are averaged over the H^0 mass range and include the $K^0 \rightarrow \pi^+ \pi^-$ and $K^{*0} \rightarrow K \pi^\pm$ branching fractions.

H^0 decay	$\mu^+ \mu^-$	$\pi^+ \pi^-$	$K^+ K^-$	$K^+ \bar{K}^{*0}$	$K^0 \bar{K}^{*0}$	$K^{*0} \bar{K}^{*0}$
M_H (GeV)	0.2–3.6	0.3–3.6	1.0–3.6	1.4–3.6	1.4–3.6	1.8–3.6
$\epsilon(H^0 K^\pm)$	0.21	0.33	0.35	0.032	0.035	0.04
$\epsilon(H^0 K^0)$	0.063	0.071	0.08			
$\epsilon(H^0 K^{*\pm})$	0.025	0.041	0.03			
$\epsilon(H^0 K^{*0})$	0.10	0.14	0.18	0.015	0.017	0.02

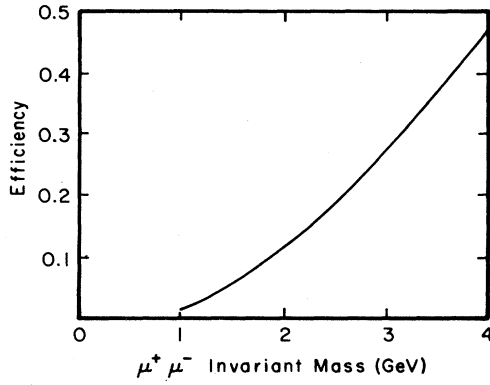


FIG. 5. Detection efficiency for inclusive muon pairs as a function of invariant mass, calculated by Monte Carlo simulation.

V. RESULTS

Figures 6–12 show the observed numbers of candidates for each searched mode as a function of the Higgs-boson mass. A Higgs boson would appear as a clustering of events within a mass range given by our experimental resolution, which varies with mass and decay mode and is typically 15–30 MeV rms. Such a clustering is seen for the dimuon modes at $M_\Psi = 3.1$ GeV, corresponding to the well-known²³ decays $B \rightarrow \Psi X$, ΨK , etc. with $\Psi \rightarrow \mu^+ \mu^-$. In some dipion and dikaon modes there is also a clustering near 1.9 GeV, consistent with $D \rightarrow \pi^+ \pi^-$ or $K^+ K^-$, and $D \rightarrow K^- \pi^+$ with a misidentified pion or kaon. There is no discernible signal

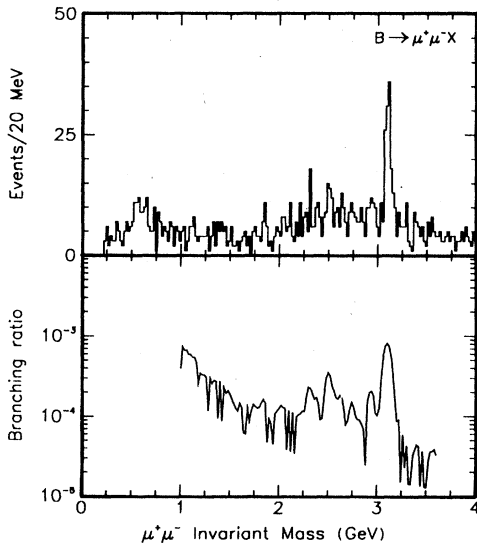


FIG. 6. Top: observed number of candidates for $B \rightarrow H^0 X$, $H^0 \rightarrow \mu^+ \mu^-$ as a function of M_H . Bottom: upper limit (90% confidence level) for $B(B \rightarrow H^0 X)B(H^0 \rightarrow \mu^+ \mu^-)$.

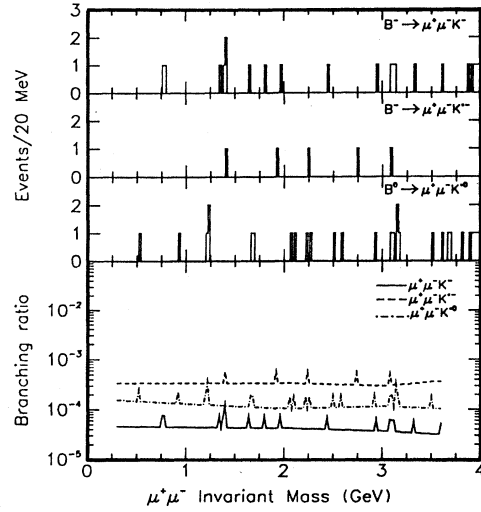


FIG. 7. Top: observed number of candidates for $B \rightarrow H^0 \kappa$, $H^0 \rightarrow \mu^+ \mu^-$ as a function of M_H , with $\kappa = K^-, K^{*-}, \bar{K}^{*0}$, and charge conjugates. Bottom: corresponding upper limits (90% confidence level) for $B(B \rightarrow H^0 \kappa)B(H^0 \rightarrow \mu^+ \mu^-)$.

for a Higgs boson.

In order to derive for each mode a quantitative upper limit for the product of branching ratios for the B -to-Higgs-boson decay and for decay of the Higgs boson, as a function of the Higgs-boson mass, we make a least-squares fit to a smooth background function plus a

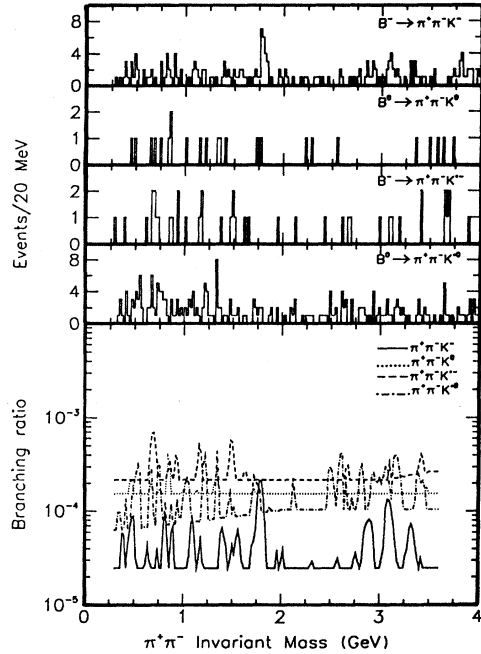


FIG. 8. Top: observed number of candidates for $B \rightarrow H^0 \kappa$, $H^0 \rightarrow \pi^+ \pi^-$ as a function of M_H , with $\kappa = K^-, \bar{K}^0, K^{*-}, \bar{K}^{*0}$, and charge conjugates. Bottom: corresponding upper limits (90% confidence level) for $B(B \rightarrow H^0 \kappa)B(H^0 \rightarrow \pi^+ \pi^-)$.

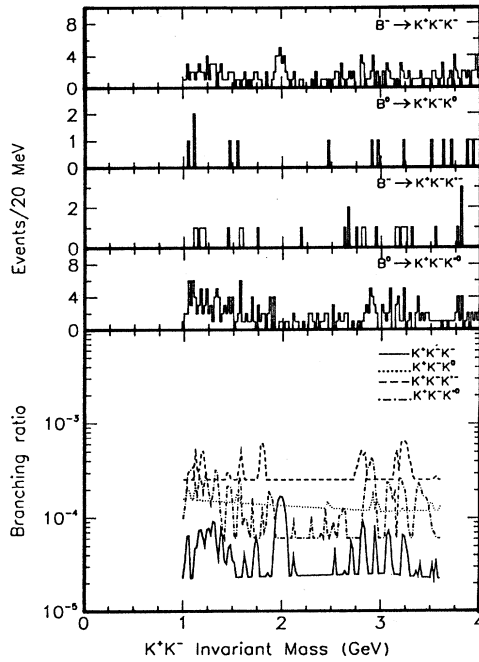


FIG. 9. Top: observed number of candidates for $B \rightarrow H^0 \kappa$, $H^0 \rightarrow K^+ K^-$ as a function of M_H , with $\kappa = K^-, \bar{K}^{*0}, K^{*-}, \bar{K}^{*0}$, and charge conjugates. Bottom: corresponding upper limits (90% confidence level) for $B(B \rightarrow H^0 \kappa)B(H^0 \rightarrow K^+ K^-)$.

Gaussian peak. The fit is repeated with the Gaussian peak centered at each multiple of 20 MeV in the mass range, with the width fixed at the experimental mass resolution. For modes with low background we fit without the background function and use Poisson statistics. Fitted rates are converted to branching ratios, dividing by

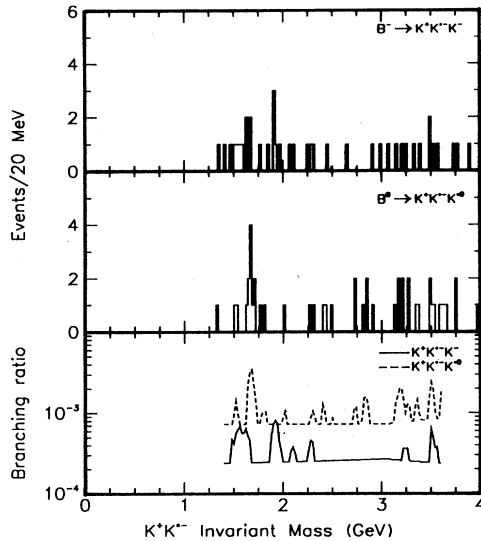


FIG. 10. Top: observed number of candidates for $B \rightarrow H^0 \kappa$, $H^0 \rightarrow K^+ K^{*-}$ as a function of M_H , with $\kappa = K^-, \bar{K}^{*0}$, and charge conjugates. Bottom: corresponding upper limits (90% confidence level) for $B(B \rightarrow H^0 K^-)B(H^0 \rightarrow K^+ K^{*-})$ and $B(B \rightarrow H^0 \bar{K}^{*0})B(H^0 \rightarrow K^+ K^{*-})$.

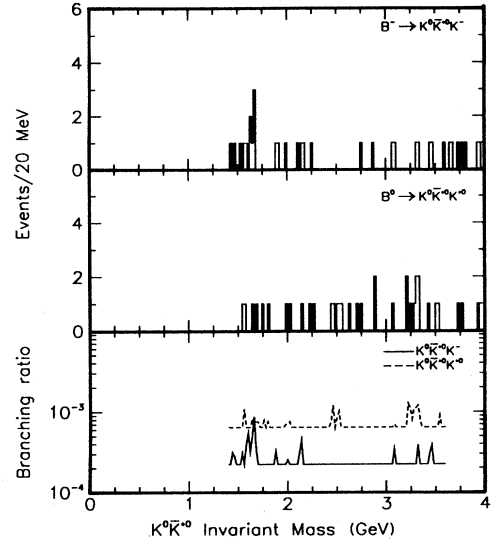


FIG. 11. Top: observed number of candidates for $B \rightarrow H^0 \kappa$, $H^0 \rightarrow K^0 \bar{K}^{*0}$ as a function of M_H , with $\kappa = K^-, \bar{K}^{*0}$, and charge conjugates. Bottom: corresponding upper limits (90% confidence level) for $B(B \rightarrow H^0 K^-)B(H^0 \rightarrow K^0 \bar{K}^{*0})$ and $B(B \rightarrow H^0 K^{*0})B(H^0 \rightarrow K^0 \bar{K}^{*0})$.

the number of B mesons produced [assuming $\Upsilon(4S) \rightarrow B^+ B^-$ and $B^0 \bar{B}^0$ in the ratio 0.57 to 0.43] and the detection efficiencies (see Table I for average values). The bottom portions of Figs. 6–11 show for each mode the measured 90%-confidence upper limit for the product branching ratio implied by the area of the fit Gaussian

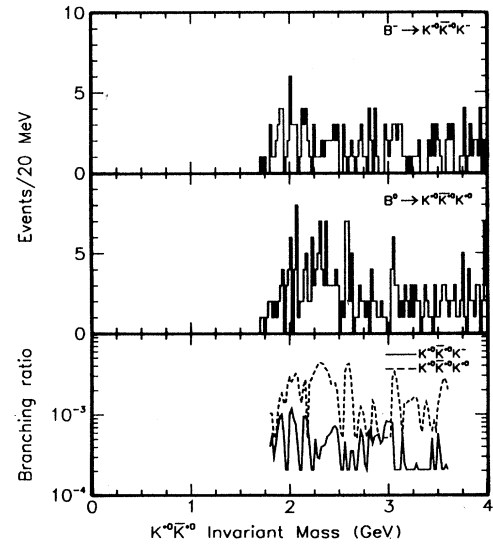


FIG. 12. Top: observed number of candidates for $B \rightarrow H^0 \kappa$, $H^0 \rightarrow K^{*0} \bar{K}^{*0}$ as a function of M_H , with $\kappa = K^-, \bar{K}^{*0}$, and charge conjugates. Bottom: corresponding upper limits (90% confidence level) for $B(B \rightarrow H^0 K^-)B(H^0 \rightarrow K^{*0} \bar{K}^{*0})$ and $B(B \rightarrow H^0 \bar{K}^{*0})B(H^0 \rightarrow K^{*0} \bar{K}^{*0})$.

peak, as a function of the central mass of the peak. Note that these limits are not dependent on any theoretical models of Higgs-boson production or decay; they apply equally well to any narrow neutral particle state for which these modes are appropriate, for example, to the $\xi(2.2 \text{ GeV})$ state suggested by Mark III data.²⁴

In order to see what the measured product branching ratio limits for the exclusive modes might imply about limits on B -to-Higgs-boson decay branching fractions, we have to divide each by a theoretical branching ratio for the Higgs-boson decay into the particular searched mode. From the discussion in Sec. III we see that this cannot always be done unambiguously. For $H^0 \rightarrow \mu^+ \mu^-$ we use the parton model [Eqs. (5) and (6) with a factor-of-2 hadronic enhancement of the $H^0 \rightarrow gg$ rate] at Higgs-boson masses above 3 GeV, and a horizontal-line extrapolation down to $M_H = 1 \text{ GeV}$ (see Fig. 4). The extrapolation should be a lower limit on the branching ratio for $H^0 \rightarrow \mu^+ \mu^-$, provided there are no significant resonance effects in the hadronic branching fraction that would cause it to increase (and the dimuon fraction to decrease) with decreasing Higgs-boson mass. For $H^0 \rightarrow K^+ K^-$ we use the direct $H \rightarrow s\bar{s}$ coupling formula [Eq. (5)] and the $e^+ + e^- \rightarrow K^+ K^-$ data [Eq. (9)]. Since we have no reliable theory for dipion Higgs-boson decays or decays involving K^* , such modes cannot be used to derive limits. In the low-mass range from $M_H = 2m_\mu$ to 1 GeV one expects $H^0 \rightarrow \mu^+ \mu^-$ and $H^0 \rightarrow \pi\pi$ to dominate, so that we can combine our dimuon and dipion data to get a B -decay branching ratio with no additional assumptions about the Higgs-boson decay:

$$B(B \rightarrow H^0 K) = B(B \rightarrow H^0 K; H^0 \rightarrow \mu^+ \mu^-) + \frac{3}{2} B(B \rightarrow H^0 K; H^0 \rightarrow \pi^+ \pi^-).$$

The $\frac{3}{2}$ factor accounts for the undetectable $H^0 \rightarrow \pi^0 \pi^0$ decays. The implied model-dependent branching-ratio limits for $B \rightarrow H^0 K$ are shown in Fig. 13.

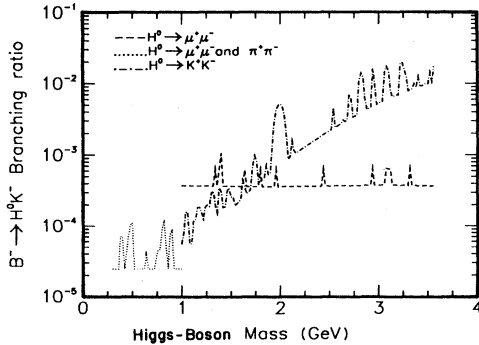


FIG. 13. Upper limits (90% confidence level) for $B(B \rightarrow H^0 K^-)$ as a function of M_H , obtained from limits for particular H^0 decay modes (Figs. 7–9) using theoretical predictions (Fig. 4) for the H^0 decay branching ratios.

The next step is to reexpress the branching-ratio limits for the two-body modes, such as $B \rightarrow H^0 K$, as limits for the inclusive decay of the B to the Higgs boson. In the case of $B \rightarrow H^0 K^\pm$ we do this by dividing the limits by the prediction for $\Gamma(B \rightarrow H^0 K)/\Gamma(B \rightarrow H^0 X)$ given by Haber, Schwartz, and Snyder⁹ [Eq. (4)]. For other modes, such as $B \rightarrow H^0 K^*$, there is no corresponding prediction, only the estimate⁹ that they have much smaller branching ratios. Figure 14 shows the resulting model-dependent upper limit for each of the exclusive $B \rightarrow H^0 K^\pm$ searches expressed as an inclusive branching ratio for $B \rightarrow H^0 X$. For comparison we also show the results of the inclusive $B \rightarrow H^0 X$ ($H^0 \rightarrow \mu^+ \mu^-$) search, assuming the Fig. 4 prescription for the $H^0 \rightarrow \mu^+ \mu^-$ branching ratio. The lowest upper limit for the decay of the B to the Higgs boson is given by $B \rightarrow H^0 K^\pm$, $H^0 \rightarrow \mu^+ \mu^-$ or $\pi^+ \pi^-$ in the 0.2-to-1.0-GeV mass range, by $B \rightarrow H^0 K^\pm$, $H^0 \rightarrow K^+ K^-$ in the 1.0-to-1.1-GeV mass range, and by the inclusive $B \rightarrow H^0 X$, $H^0 \rightarrow \mu^+ \mu^-$ in the 1.1-to-3.6-GeV mass range. Below 1-GeV mass the best limit assumes only Eq. (4), while above 1.1-GeV mass the best limit assumes only the prescription for the $H^0 \rightarrow \mu^+ \mu^-$ branching ratio given in Fig. 4. Although the theoretical assumptions could be wrong, it would be a challenge to think of a model which could suppress the modes that give the best limits in Fig. 14 without enhancing some of the many other modes we have searched for.

To see what the limit on the B -to-Higgs-boson branching ratio implies about the possible existence of a neutral Higgs boson in the mass range investigated, we need a theoretical prediction of the branching ratio. The formula given by Willey and Yu⁷ [Eq. (2) or (3)] indicates that the branching fraction is very strongly dependent on the unknown top-quark mass. We, therefore, use our branching-ratio upper limits and Eq. (3) to define the two-dimensional region in M_H vs m_t that is excluded by our measurements (see Fig. 15).

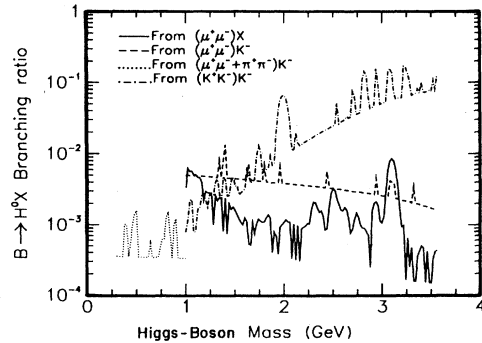


FIG. 14. Upper limits (90% confidence level) for $B(B \rightarrow H^0 X)$ as a function of M_H , from exclusive $B \rightarrow H^0 K$ data (Fig. 13) divided by the Haber, Schwartz, and Snyder (Ref. 9) expression for $\Gamma(B \rightarrow H^0 K)/\Gamma(B \rightarrow H^0 X)$, and from the inclusive measurement of $B \rightarrow H^0 X$ with $H^0 \rightarrow \mu^+ \mu^-$.

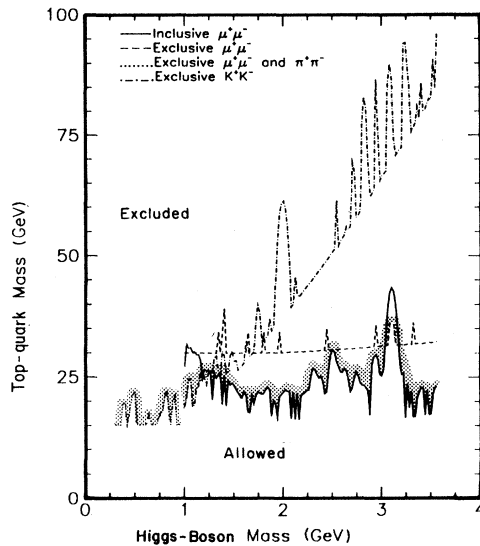


FIG. 15. Maximum value (90% confidence level) allowed by this experiment for m_t , as a function of the assumed value of M_H , as implied by the Willey and Yu prediction (Ref. 7) for $B(B \rightarrow H^0 X)$.

VI. CONCLUSION

Our conclusion is that if the Willey and Yu formula does not overestimate the B -to-Higgs-boson branching

ratio and if the model assumptions used in obtaining the limits in Fig. 14 do not overestimate our experimental sensitivity to Higgs-boson decays, then a minimal neutral Higgs boson of mass between 0.2 and 3.6 GeV is excluded, provided that the top-quark mass is at least 30 GeV. For Higgs-boson masses near the Ψ mass (3.1 ± 0.1 GeV) the minimum top-quark mass required to exclude the Higgs boson increases to 36 GeV. In light of the experimental lower limit of 28 GeV on the top-quark mass²⁵ and the various pieces of evidence²⁶ that the top-quark mass is greater than 44 GeV, we can, therefore, exclude the neutral-Higgs-boson mass from the 0.2-to-3.6-GeV range with considerable margin for error²⁷ in the theoretical models used to interpret the data.

ACKNOWLEDGMENTS

We are grateful for the excellent efforts of the CESR staff. The work was supported by the National Science Foundation and the U.S. Department of Energy (DOE) under Contracts Nos. DE-AC02-76ER01428, DE-AC02-76ER03066, DE-AC02-76ER03064, DE-AC02-76ER01545, DE-AC02-76ER-05001, and FG05-86ER40272. The Cornell National Supercomputing Facility, funded in part by the NSF, New York State, and IBM, was used in this research. P. S. Drell thanks the Presidential Young Investigator program of the NSF, R. Kass thanks the Outstanding Junior Investigator program of the DOE, and R. Poling thanks the Sloan Foundation for their support.

¹S. L. Glashow, Nucl. Phys. **22**, 579 (1961); S. Weinberg, Phys. Rev. Lett. **19**, 1264 (1967); A. Salam, in *Elementary Particle Theory: Relativistic Groups and Analyticity (Nobel Symposium No. 8)*, edited by N. Svartholm (Almqvist and Wiksell, Stockholm, 1968), p. 367.

²M. Davier, in *Proceedings of the XXIII International Conference on High Energy Physics*, Berkeley, California, 1986, edited by S. C. Loken (World Scientific, Singapore, 1987); Particle Data Group, G. P. Yost *et al.*, Phys. Lett. B **204**, 255 (1988).

³T. N. Pham and D. G. Sutherland, Phys. Lett. **151B**, 444 (1985); R. S. Chivukula and A. V. Manohar, Phys. Lett. B **207**, 86 (1988); S. Raby, G. B. West, and C. M. Hoffman, Phys. Rev. D **39**, 828 (1989).

⁴P. Franzini *et al.*, Phys. Rev. D **35**, 2883 (1987); J. Lee-Franzini, in *Proceedings of the XXIV International Conference on High Energy Physics*, Munich, West Germany, 1988, edited by R. Kotthaus and J. Kuhn (Springer, Berlin, 1988).

⁵M. I. Vysotsky, Phys. Lett. **97B**, 159 (1980); J. Ellis *et al.*, *ibid.* **158B**, 417 (1985); P. Nason, Phys. Lett. B **175**, 223 (1986); H. Goldberg and Z. Ryzak, Report No. NUB-2954, 1988 (unpublished).

⁶S. Weinberg, Phys. Rev. Lett. **36**, 294 (1976); A. Linde, Pis'ma Zh. Eksp. Teor. Fiz. **23**, 74 (1976) [JETP Lett. **23**, 64 (1976)].

⁷R. S. Willey and H. L. Yu, Phys. Rev. D **26**, 3086 (1985). Their original version of Eq. (2) omitted the final squared factor, one power occurring in the matrix element and the other in

the phase space.

⁸S. Behrends *et al.*, Phys. Rev. Lett. **59**, 407 (1987).

⁹H. E. Haber, A. S. Schwartz, and A. E. Snyder, Nucl. Phys. **B294**, 301 (1987); R. M. Godbole, U. Turke, and M. Wirbel, Phys. Lett. B **194**, 302 (1987).

¹⁰B. Grinstein, M. B. Wise, and N. Isgur, Phys. Rev. Lett. **56**, 298 (1986).

¹¹M. A. Shifman, A. I. Vainshtein, and V. I. Zacharov, Phys. Lett. **78B**, 443 (1978); F. Wilczek, Phys. Rev. Lett. **39**, 1304 (1977).

¹²M. B. Voloshin, Yad. Fiz. **44**, 738 (1986) [Sov. J. Nucl. Phys. **44**, 478 (1986)].

¹³B. Grinstein, L. Hall, and L. Randall, Phys. Lett. B **211**, 363 (1988).

¹⁴Grinstein, Hall, and Randall (Ref. 13) assume $N_{\text{eff}}=3$; Voloshin (Ref. 12) increases N_{eff} to 3.5 to account for a threshold enhancement in the virtual- c -quark-loop amplitude.

¹⁵S. Raby and G. B. West, Phys. Rev. D **38**, 3488 (1988).

¹⁶M. A. Shifman, Z. Phys. C **9**, 347 (1981).

¹⁷B. Delcourt *et al.*, Phys. Lett. **99B**, 257 (1981). The measured cross section for $e^+e^- \rightarrow K^+K^-$ lies above the ϕ -pole prediction in the center-of-mass energy region between 1.2 and 1.7 GeV. For this reason and also because we have neglected the $H^0 \rightarrow gg$ contribution to $H^0 \rightarrow K^+K^-$, Eq. (9) is probably a lower limit for the $H^0 \rightarrow K^+K^-$ branching ratio.

¹⁸D. Andrews *et al.*, Nucl. Instrum. Methods **211**, 47 (1983).

- ¹⁹C. Bebek *et al.*, Phys. Rev. D **36**, 1289 (1987).
- ²⁰D. G. Cassel *et al.*, Nucl. Instrum. Methods **A252**, 325 (1986).
- ²¹C. Bebek *et al.*, Phys. Rev. Lett. **56**, 1893 (1986).
- ²²K. Chadwick *et al.*, Phys. Rev. D **27**, 475 (1983).
- ²³M. S. Alam *et al.*, Phys. Rev. D **34**, 3279 (1986); H. Albrecht *et al.*, Phys. Lett. **162B**, 395 (1985).
- ²⁴R. M. Baltrusaitis *et al.*, Phys. Rev. Lett. **56**, 107 (1986). See also S. Behrends *et al.*, Phys. Lett. **137B**, 277 (1984), for searches for the ξ in Υ decays and B decays.
- ²⁵H. Sagawa *et al.*, Phys. Rev. Lett. **60**, 93 (1988); I. Adachi *et al.*, *ibid.* **60**, 97 (1988); S. Eno *et al.*, Report No. KEK 88-67 (unpublished).
- ²⁶UA1 Collaboration, C. Albajar *et al.*, Z. Phys. C **37**, 505 (1988). If we can assume that the standard six-quark description of B decays is valid and that a charged Higgs boson does not contribute, then the measured rate of $B^0\bar{B}^0$ mixing implies a lower limit on the top-quark mass: H. Albrecht *et al.*, Phys. Lett. B **192**, 245 (1987).
- ²⁷For example, if the assumed decay branching ratio of the Higgs boson (say to $\mu^+\mu^-$) were overestimated and had to be decreased by an order of magnitude, it would imply that our data rule out a Higgs boson in the stated mass range only for $m_t > 53$ GeV instead of for $m_t > 30$ GeV.