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Search for Non-minimal Higgs Bosons from Z Boson Decay*

S. Komamiya,[4] G. S. Abrams,[1] C. E. Adolphsen,[2] D. Averill,[3] J. Ballam,[4] B. C. Barish,[5] T. Barklow,[4] B. A. Barnett,[6] J. Bartelt,[4] S. Bethke,[1] D. Blockus,[3] G. Bonvicini,[7] A. Boyarski,[4] B. Brabson,[3] A. Breakstone,[8] F. Bulos,[4] P. R. Burchat,[2] D. L. Burke,[4] R. J. Cence,[8] J. Chapman,[7] M. Chmeissani,[7] D. Cords,[4] D. P. Coupal,[4] P. Dauncey,[6] H. C. DeStaebler,[4] D. E. Dorfan,[2] J. M. Dorfan,[4] D. C. Drewer,[6] R. Elia,[4] G. J. Feldman,[4] D. Fernandes,[4] R. C. Field,[4] W. T. Ford,[9] C. Fordham,[4] R. Frey,[7] D. Fujino,[4] K. K. Gan,[4] C. Gatto,[2] E. Gero,[7] G. Gidal,[1] T. Glanzman,[4] G. Goldhaber,[1] J. J. Gomez Cadenas,[2] G. Gratta,[2] G. Grindhammer,[4] P. Grosse-Wiesmann,[4] G. Hanson,[3] R. Harr,[1] B. Harral,[6] F. A. Harris,[8] C. M. Hawkes,[5] K. Hayes,[4] C. Hearty,[1] C. A. Heusch,[2] M. D. Hildreth,[4] T. Himel,[4] D. A. Hinshaw,[9] S. J. Hong,[7] D. Hutchinson,[4] J. Hylen,[6] W. R. Innes,[4] R. G. Jacobsen,[4] J. A. Jaros,[4] C. K. Jung,[4] J. A. Kadyk,[1] J. Kent,[2] M. King,[2] D. S. Koetke,[4] W. Koska,[7] L. A. Kowalski,[4] W. Kozanecki,[4] J. F. Kral,[1] M. Kuhlen,[5] L. Labarga,[2] A. J. Lankford,[4] R. R. Larsen,[4] F. Le Diberder,[4] M. E. Levi,[1] A. M. Litke,[2] X. C. Lou,[3] V. Lüth,[4] J. A. McKenna,[5] J. A. J. Matthews,[6] T. Mattison,[4] B. D. Milliken,[5] K. C. Moffeit,[4] C. T. Munger,[4] W. N. Murray,[3] J. Nash,[4] H. Ogren,[3] K. F. O'Shaughnessy,[4] S. I. Parker,[8] C. Peck,[5] M. L. Perl,[4] M. Petradza,[4] R. Pitthan,[4] F. C. Porter,[5] P. Rankin,[9] K. Riles,[4] F. R. Rouse,[4] D. R. Rust,[3] H. F. W. Sadrozinski,[2] M. W. Schaad,[1] B. A. Schumm,[1] A. Seiden,[2] J. G. Smith,[9] A. Snyder,[3] E. Soderstrom,[5] D. P. Stoker,[6] R. Stroynowski,[5] M. Swartz,[4] R. Thun,[7] G. H. Trilling,[1] R. Van Kooten,[4] P. Voruganti,[4] S. R. Wagner,[4] S. Watson,[2] P. Weber,[9] A. J. Weinstein,[5] A. J. Weir,[5] E. Wicklund,[5] M. Woods,[4] D. Y. Wu,[5] M. Yurko,[3] C. Zaccardelli,[2] and C. von Zanthier[2]

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[1] *Lawrence Berkeley Laboratory and Department of Physics, University of California, Berkeley, California 94720*
[2] *University of California, Santa Cruz, California 95064*
[3] *Indiana University, Bloomington, Indiana 47405*
[4] *Stanford Linear Accelerator Center, Stanford University, Stanford, California 94309*
[5] *California Institute of Technology, Pasadena, California 91125*
[6] *Johns Hopkins University, Baltimore, Maryland 21218*
[7] *University of Michigan, Ann Arbor, Michigan 48109*
[8] *University of Hawaii, Honolulu, Hawaii 96822*
[9] *University of Colorado, Boulder, Colorado 80309*

ABSTRACT

Using the Mark II detector at SLC, we search for decays of the Z boson to a pair of non-minimal Higgs bosons ($Z \to H_s^0 H_p^0$), where one of them is relatively light ($\lesssim$ 10 GeV). We find no evidence for these decays and we obtain limits on the $ZH_s^0 H_p^0$ coupling as a function of the Higgs boson masses.

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In the Standard Model, the Higgs sector is necessary to ensure the renormalizability of the model and to give mass to the weak gauge bosons ($W^{\pm}$ and Z) as well as to the quarks and charged leptons. In the minimal Standard Model, only one physical scalar Higgs boson is expected to exist, whereas in non-minimal models there are additional physical neutral and charged Higgs bosons.[1] For two doublet models, which are the minimum extension of the minimal Higgs sector, there are two physical neutral scalar (CP even) Higgs bosons H_1^0 and H_2^0, one neutral pseudoscalar (CP odd) H_p^0 and two charged Higgs bosons H^+ and H^-. At least two Higgs doublets are necessary for most supersymmetric models.[2] In this Letter, H_s^0 denotes either H_1^0 or H_2^0. We also use the notation H_l^0 and H_h^0 for the two Higgs bosons with opposite CP eigenvalues, where H_l^0 is defined to be lighter than H_h^0. For simplicity the models considered in this Letter are restricted to two doublet models (not necessarily supersymmetric).

We consider in this analysis[4] the decay of the Z into a scalar and a pseudoscalar Higgs boson ($Z \rightarrow H_s^0\ H_p^0$). The decay width for two-doublet models is given by

$$\Gamma(Z \rightarrow H_s^0 H_p^0) = \frac{1}{2}\Gamma(Z \rightarrow \nu\bar{\nu})\ \bar{\beta}^3 \cos^2(a-b) \tag{1}$$

where $\bar{\beta} = \{[s - (M_{H_s^0} + M_{H_p^0})^2][s - (M_{H_s^0} - M_{H_p^0})^2]\}^{\frac{1}{2}}/s$, $\Gamma(Z \rightarrow \nu\bar{\nu})$ is the decay width of Z into a pair of massless neutrinos (one generation), $s = E_{cm}^2$, and a and b are mixing angles.[3] The angular distribution in the e^+e^- center-of-mass system (c.m.s.) is $d\sigma/d\Omega \propto \sin^2\theta$, where θ is the polar angle of H_s^0 momentum direction in the e^+e^- c.m.s. Note that processes like $e^+e^- \rightarrow Z \rightarrow Z^* H_p^0 \rightarrow f\bar{f}H_p^0$ or $e^+e^- \rightarrow Z^* \rightarrow ZH_p^0$ are not allowed, since ZH_p^0Z coupling is forbidden at the tree level. These processes are allowed for H_s^0 but the rate is smaller than for the minimal Higgs boson by a factor[2] of $\sin^2(a-b)$. Therefore, as the decay width of $Z \rightarrow Z^* H_s^0$ becomes smaller, the $Z \rightarrow H_s^0 H_p^0$ width becomes larger (see Eq.(1)).

The interactions of Higgs bosons with fermions are determined from the fermion mass term in the Lagrangian. The couplings differ from model to model and depend on how each Higgs field contributes to each fermion mass. In principle, they are expected to decay dominantly into the heaviest available fermion pair: $H_i^0 \rightarrow f\bar{f}$ ($i = 1, 2, p$). If the scalar mass is more than two times the pseudoscalar mass, $H_s^0 \rightarrow H_p^0 H_p^0$ is the dominant decay mode unless it is suppressed by the Higgs mixing.[5]

The Mark II detector has been described in detail elsewhere.[6,7] In this analysis, the main drift chamber, barrel and endcap electromagnetic calorimeters are used. Events are selected if they contain at least two charged tracks and the sum of charged particle energy and shower energy ($E_{\rm vis}$) is greater than $0.25\sqrt{s}$. To ensure that the events are well contained within the detector, the polar angle of the thrust axis ($\theta_{\rm th}$) must satisfy the condition $|\cos\theta_{\rm th}| < 0.8$. Events with charged multiplicity of two to four are rejected if the kinematics is consistent with a back-to-back e^+e^-, $\mu^+\mu^-$ or $\tau^+\tau^-$ pair. The number of events in this sample is 455. The background from beam-gas interactions is estimated to be smaller than 0.4 events.

The expected number of produced $Z \rightarrow H_s^0 H_p^0$ events (before cuts) is normalized to the total number of hadronic events (N_{had}) that fulfill the hadronic event selection criteria used for the event shape analysis described in Ref.6. The expected number of produced $Z \rightarrow H_s^0 H_p^0$ events N_{HH}, is given by[8]

$$N_{HH} = \frac{N_{had}\Gamma_{HH}}{\epsilon_{q\bar{q}}\Gamma_{q\bar{q}} + \epsilon_{HH}\Gamma_{HH}} \quad ,$$

where $\Gamma_{q\bar{q}}$ is the partial width of the Z to u, d, s, c, and b ($udscb$) quark pairs, $\epsilon_{q\bar{q}} = 0.80 \pm 0.02$ is the efficiency for $udscb$ quark pairs to pass the hadronic event selection criteria, Γ_{HH} is the partial width of the Z into $H_s^0 H_p^0$, and ϵ_{HH} is the efficiency for the $H_s^0 H_p^0$ events to pass the hadronic event selection criteria. The data sample consists of $N_{had} = 394$ events, corresponding to an integrated luminosity of 19.7 ± 0.8 nb^{-1} accumulated on and near the Z peak. With this luminosity, the expected number of $H_s^0 H_p^0$ events is about 23 $\bar{\beta}^3 \cos^2(a - b)$.

We concentrate on the case in which one of the produced Higgs bosons (H_l^0) is relatively light (less than $2M_b$). We study four typical cases: [A] $M_{H_l^0} < 2M_\mu$, [B] $2M_\mu < M_{H_l^0} < 2M_\tau$ and H_h^0 decays into $f\bar{f}$, and [C] $2M_\mu < M_{H_l^0} < 2M_\tau$ and H_h^0 decays into $H_l^0 H_l^0$. We also investigate the case in which [D] $2M_\tau < M_{H_l^0} < 2M_b$ and H_l^0 decays into $\tau^+\tau^-$.

In case [A] ($Z \to H_l^0 H_h^0$, $H_l^0 \to e^+e^-$ or $\gamma\gamma$, $H_h^0 \to b\bar{b}, c\bar{c}$ or $\tau^+\tau^-$), H_l^0 is sufficiently long lived to escape detection.[9] If the heavier Higgs boson (H_h^0) decays into a heavy fermion pair ($b\bar{b}$, $c\bar{c}$ or $\tau^+\tau^-$) and the mass is smaller than about the beam energy, the signature of $Z \to H_s^0 H_p^0$ events is a monojet topology. If the mass of the heavier Higgs boson is about equal to or greater than the beam energy, the momentum of the unseen H_l^0 is small and hence the event topology is two jets with a large angle between their axes. The monojet events are selected with the following criteria: (M1) $|\cos\theta_{\rm th}| < 0.7$ and (M2) the sum of the charged and neutral energy in the lower energy hemisphere (defined by the event thrust axis), $E_{\rm back}$, is smaller than 3.0 GeV. The acoplanar two jet events are selected by the following cuts: (P1) $|\cos\theta_{\rm th}| < 0.7$, (P2) P_T of the event must be larger than 15 GeV and (P3) the acoplanarity angle[10] $\phi_{\rm acop}$ must be greater than 40 degrees. In Fig.1, $E_{\rm back}$ distributions after the (M1) cut and $\phi_{\rm acop}$ distributions after the (P1-2) cuts are shown for data, the expected multihadron background and $Z \to H_s^0 H_p^0$ events. In order to increase the detection efficiency for the case of $M_{H_l^0} \approx \sqrt{s}/2$, events satisfying either of the two criteria are selected. After applying cuts ((M1-2) or (P1-3)), no events survive. The expected number of background events from ordinary quark ($udscb$) production is estimated to be 0.3 to 0.7 using QCD-based Monte Carlo models.[11–13] If H_h^0 decays into $b\bar{b}$ or $c\bar{c}$ [$\tau^+\tau^-$] with 100% branching fraction, the detection efficiency for the $H_h^0 H_l^0$ events is about 80% [55%] at $M_{H_h^0} = 10$ GeV and it decreases to 60% [31%] when $M_{H_h^0}$ is increased to 45 GeV.

Uncertainties in detection efficiency from Monte Carlo statistics ($\approx 2\%$), detector simulation and beam backgrounds ($\approx 1\%$), and hadronization of H_h^0 decay

($\approx$4%) are estimated. The last one is estimated by switching on and off gluon radiation (parton shower) in the H_h^0 decay. The statistical error on N_{had} and systematic error on $\epsilon_{q\bar{q}}$ used to calculate the total expected number of signal events (N_{HH}) are 5% and 2%, respectively. The total error on the number of events expected to survive the selection procedure is calculated by summing the individual statistical and systematic errors in quadrature. In obtaining the limits, the total error is subtracted from the number of events expected. The same procedure is applied for other cases[B-D].

In Fig.3[A], the 95% C.L. contour for the excluded region is shown in the plane of the suppression factor ($\cos^2(a-b)$) vs. $M_{H_h^0}$, assuming H_l^0 is light ($M_{H_l^0} < 2M_\mu$) and stable. As shown in the figure, if H_h^0 decays into $b\bar{b}$ or $c\bar{c}$ [$\tau^+\tau^-$] $M_{H_h^0}$ is excluded from 5 GeV [5 GeV] to 43 GeV [36 GeV] for $\cos^2(a-b) = 0.5$, and from 5 GeV [5 GeV] to 53 GeV [45 GeV] for $\cos^2(a-b) = 1$. Similar searches were done at PETRA, PEP and TRISTAN with virtual Z decays.[14,15,16] The limits from JADE[14] and AMY[16] are shown in the figure. Also shown in the figure is the limit from a search for the standard Higgs boson by the ALEPH collaboration[17] interpreted as a limit on H_s^0. The ALEPH limit is valid independent of the H_p^0 mass.

For case [B] ($Z \to H_l^0 H_h^0$, $H_l^0 \to \pi^+\pi^-$ or $\mu^+\mu^-$, $H_h^0 \to b\bar{b}, c\bar{c}$ or $\tau^+\tau^-$), the event topology is an isolated particle pair with opposite charge (for instance, $\mu^+\mu^-$, $\pi^+\pi^-$ or K^+K^-) which recoils against jets. We require that $E_{\rm vis}$ be greater than $0.5\sqrt{s}$ and that there be at least one isolated particle pair with opposite charge. An isolated pair of charged particles (i,j) is defined as two oppositely charged particles with momentum sum ($|\vec{p}_i + \vec{p}_j|$) larger than 20 GeV, individual momenta greater than 2 GeV, and isolation parameter $\rho_{ij} > 4.0$ GeV$^{\frac{1}{2}}$. The isolation parameter ρ_{ij} is defined as follows: The Lund jet-finding algorithm is applied[18] to all charged tracks in the event (except the candidate pair ij) and neutral tracks with energy greater than 1.5 GeV. We then define

$$\rho_{ij} \equiv \min_{jets\ J} \sqrt{2E_{ij}(1-\cos\chi_{ijJ})},$$

where E_{ij} is the pair energy assuming the pair to be $\pi^+\pi^-$ and χ_{ijJ} is the angle between the pair momentum direction and the jet axis. The distribution of ρ_{event}, the maximum value of ρ_{ij} for all oppositely charged track pairs in an event, is shown in Fig.2 for our data sample, for a five-quark QCD Monte Carlo and for a $H_s^0H_p^0$ Monte Carlo. For $H_s^0H_p^0$ events, a peak is seen at $|\vec{p}_i+\vec{p}_j| \approx (\sqrt{s}/2)(1-M^2_{H_h^0}/s)$. Events are selected if $0.75\ (\sqrt{s}/2)(1-M^2_{H_h^0}/s) < |\vec{p}_i+\vec{p}_j| < 1.25\ (\sqrt{s}/2)(1-M^2_{H_h^0}/s)$ for an assumed value for $M_{H_h^0}$.

No events survive the selection criteria. The number of expected background events increases with $M_{H_h^0}$ from 0.1 ($M_{H_h^0}=5$ GeV) to 0.5 ($M_{H_h^0}=60$ GeV), and is estimated using Monte Carlo models.[11–13] If H_h^0 decays into $b\bar{b}, c\bar{c}$ $[\tau^+\tau^-]$ with 100% branching fraction, the detection efficiency for the Higgs events is about 50% [about 45%] in the region 5 GeV$< M_{H_h^0} <$ 45 GeV for $M_{H_l^0}=0.5$ GeV and H_l^0 decaying into $\mu^+\mu^-$, $\pi^+\pi^-$ and $\pi^0\pi^0$ with branching fractions of 34%, 44% and 22%, respectively. In general, the branching fraction of $H_l^0 \to \pi^0\pi^0$ is between 0% and 33%. If H_l^0 is lighter than the muon pair threshold and the eeH_l^0 coupling is sufficiently large, H_l^0 decays into e^+e^- with short lifetime, Detection efficiency of $H_h^0H_l^0$ events with $H_l^0 \to e^+e^-$ and $H_h^0 \to b\bar{b}$ or $c\bar{c}$ is typically about 40%. The efficiency is lower than in the above case because of the misassignment of a shower energy cluster to the corresponding electron track.

As shown in Fig.3[B], a region in the plane of $\cos^2(a-b)$ vs $M_{H_h^0}$, similar to case [A], is excluded for $H_h^0 \to b\bar{b}, c\bar{c}$ or $H_h^0 \to \tau^+\tau^-$. The previous limit from Mark II at PEP (90% C.L. and only valid for $H_l^0 \to \mu^+\mu^-$)[19] is also shown in the figure, together with the ALEPH limit.

For case [C] ($Z \to H_s^0H_p^0 \to H_p^0H_p^0H_p^0$, $H_p^0 \to \mu^+\mu^-$), the event topology is three pairs of oppositely charged particles. The $H_p^0 \to \mu^+\mu^-$ decay mode is dominant since $\pi\pi$ or $\pi\pi\pi$ modes are suppressed for the H_p^0 decay.[20] We require that the total charged particle energy E_{ch} be greater than $0.5\sqrt{s}$ and that exactly three jets are found using the Lund jet-finding algorithm.[21] We require for each jet that the energy be larger than 4 GeV, the invariant mass be smaller than 4 GeV, and the total charge of each jet be -1, 0 or 1. We further require that the maximum charged multiplicity of the jets be either 2 or 3 and the minimum is either 1 or 2.

No events survive the selection criteria. The expected number of background events due to ordinary multihadron production is estimated to be about 0.1.[11-13] The detection efficiency for $Z \to H_s^0 H_p^0 \to 3H_p^0$ events is about 60-70% for $M_{H_s^0}$ between 10 GeV and 60 GeV assuming $M_{H_p^0} = 0.5$ GeV. It drops down to about 30% for $M_{H_s^0} = 5$ GeV with the same assumptions. The detection efficiency for the case of $H_l^0 \to e^+e^-$ and $H_h^0 \to b\bar{b}, c\bar{c}$ with much lighter H_l^0 (0.05 GeV) is about 55-65%.

The excluded region is shown in the plane of $M_{H_s^0}$ vs $\cos^2(a-b)$ in Fig.3[C]. $M_{H_s^0}$ is excluded from 5 GeV to 44 GeV for $\cos^2(a-b) \geq 0.5$. Also shown in the figure is a previous Mark II limit and the interpretation of the ALEPH standard Higgs limit.

For case [D] ($Z \to H_l^0 H_h^0 \to \tau^+\tau^- + \text{jets}$), the Lund jet-finding algorithm[18] is applied. We select events with only two jets in either of the hemispheres defined by the plane perpendicular to the event thrust axis. Further, we require that the two jets be consistent with a tau pair (the invariant mass of each jet is smaller than 2 GeV, the number of charged particles in each jet is one, and charge of the two jets is opposite). Since a $\tau^\pm$ decay involves missing neutrinos, we cannot look for an invariant mass peak of $\tau^+\tau^-$. We look for the peak in the $\tau^+\tau^-$ opening angle. Events are selected between 75% and 150% of the Jacobean peak of the opening angle (24 degrees at $M_{H_h^0} = 10$ GeV and 31 degrees at $M_{H_h^0} = 45$ GeV). After the cuts no events survive in the angular region and the expected number of background events is 0.3-0.5, which is estimated from QCD Monte Carlo models.[11-13]

The detection efficiency for the $Z \rightarrow H_s^0 H_p^0$ events is about 30-25% for $M_{H_h^0}$ =10 GeV to 30 GeV, where $M_{H_l^0}$ = 10 GeV is assumed. The exclude region is shown in Fig.3[D] for the case that the H_l^0 decays into $\tau^+\tau^-$ with 100% branching fraction.

In conclusion, we have searched for the associated production of non-minimal neutral Higgs bosons in Z boson decays ($Z \rightarrow H_s^0 H_p^0$) where one of the Higgs bosons is relatively light ($\lesssim$10 GeV) using the Mark II detector at SLC. Event topologies we have looked for are [A] monojet event or two acoplanar jets, [B] isolated particle pair with opposite charge, [C] three pairs of oppositely charged particles and [D] $\tau^+\tau^-$ + jets. We find no evidence for these signals and we obtain limits on the suppression factor of the decay process $Z \rightarrow H_s^0 H_p^0$ as a function of the Higgs boson masses for generic two doublet Higgs models.

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9. If $H_l^0 = H_p^0$ and H_s^0 decays into $H_p^0 H_p^0$ and H_p^0 is stable, the events are invisible. This case can be studied by the neutrino counting method (measuring the width of the Z into invisible final states). A special case in which H_l^0 decays into e^+e^- or $\gamma\gamma$ with intermediate decay length (a few centimeters to a few meters) is not studied in this analysis.
10. The acoplanarity angle ϕ_{acop} is defined in the following way: Two hemispheres are defined by the plane perpendicular to the thrust axis. In each hemisphere particle momentum vectors are summed. The kink angle of the two resultant hemisphere momenta projected on to the plane perpendicular to the beam axis is defined to be the acoplanarity angle. If an event has no particles in one of the thrust hemispheres, ϕ_{acop} is defined to be 180 degrees.

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21. In this case, the jet-forming cutoff parameter d_{join} is set to the default value of 2.5 GeV.

FIGURE CAPTIONS

Fig.1 Distributions used in case [A] for data (points with error bars), QCD model predictions (histograms) and predictions of $H_s^0 H_p^0$ events (shaded histograms) normalized to the integrated luminosity.

(a) The E_{back} distributions.

(b) The ϕ_{acop} distribution after the cut $P_T(\mathrm{event}) > 15$ GeV.

Fig.2 The distributions of the isolation parameter of particle pair of opposite charges defined in the text in case [B] for the data (points with error bars), for the QCD model predictions (histogram) and for the expected $H_s^0 H_p^0$ events (shaded histogram).

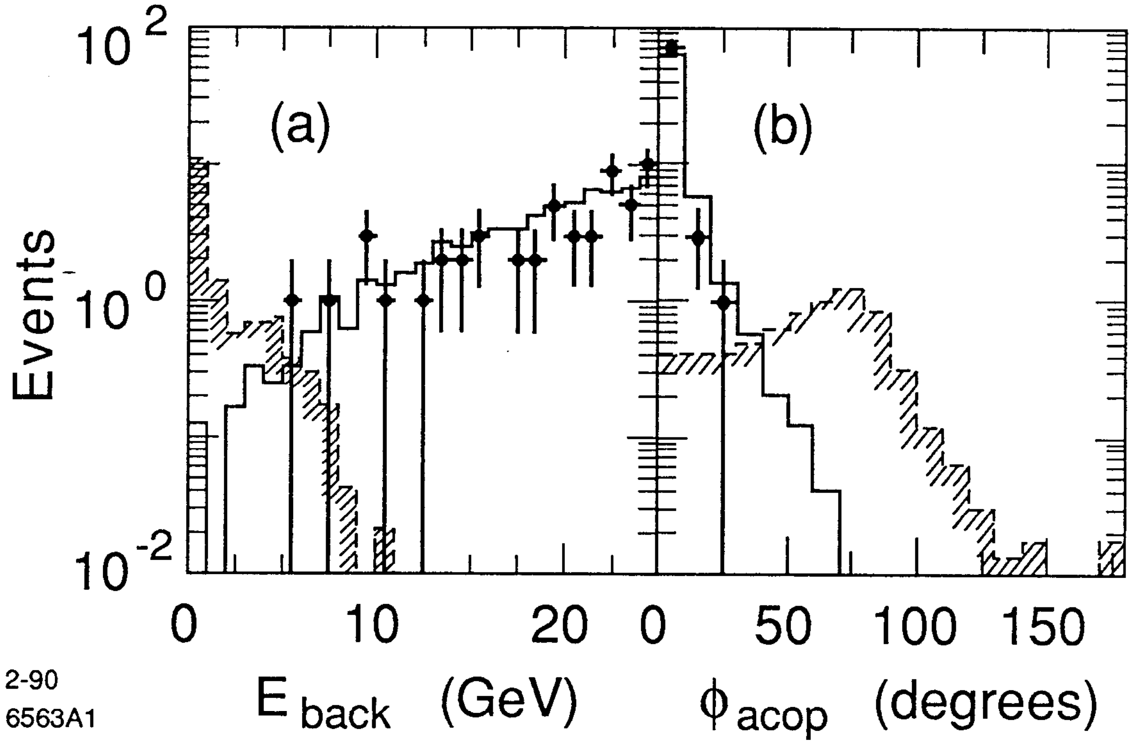
Fig.3 The 95% C.L. contours for the excluded region in the plane of the suppression factor ($\cos^2(a-b)$) vs $M_{H_h^0}$.

[A] The lighter Higgs boson (H_l^0) is light ($M_{H_l^0} < 2M_\mu$) and stable. In the figure limits from JADE,[14] AMY[16] and ALEPH[17] are also shown.

[B] The lighter Higgs boson (H_l^0) decays into a particle pair of opposite charges and the heavier one (H_h^0) decays into $b\bar{b}$, $c\bar{c}$ (solid curve) or $\tau^+\tau^-$ (dashed curve). We assume $M_{H_l^0} = 0.5$ GeV but the limit is valid for $M_{H_l^0}$ smaller than a few GeV as long as it decays dominantly into a particle pair of opposite charges. The Mark II (PEP) limit[19] (90% C.L.) is only valid for $H_l^0 \to \mu^+\mu^-$.

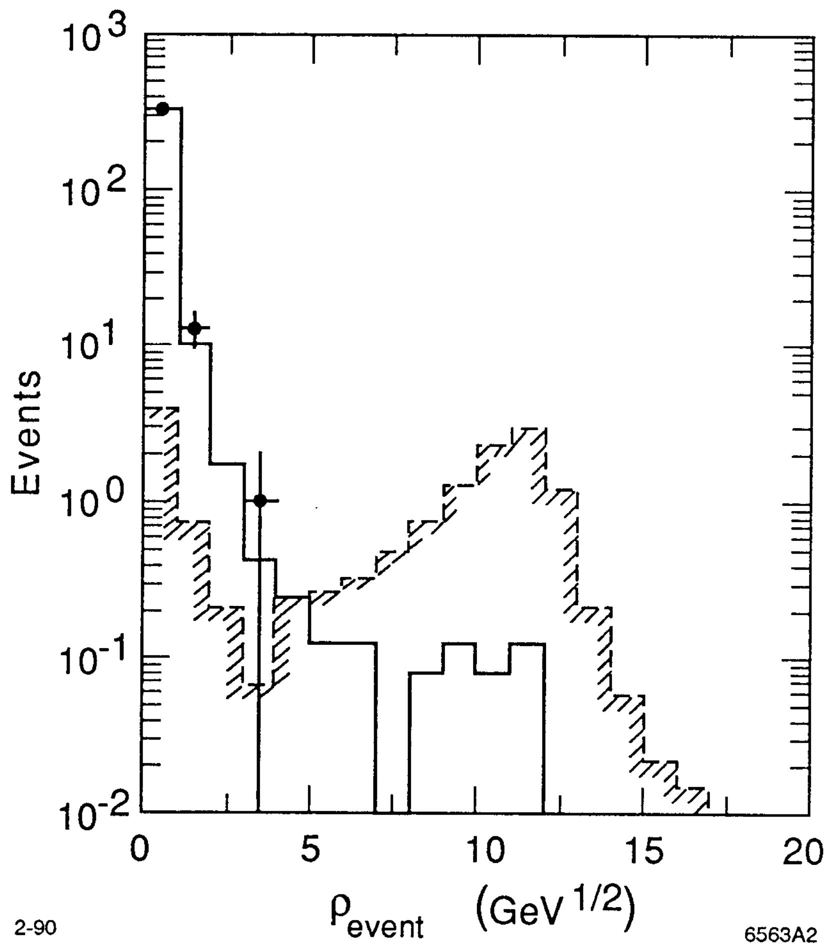
[C] The case $Z \to H_s^0 \to H_p^0 H_p^0 \to 3(\mu^+\mu^-)$ or $3(e^+e^-)$. $M_{H_p^0} = 0.5$ GeV is assumed in the plot but the limit is valid for $M_{H_s^0}$ smaller than a few GeV as long as it decays dominantly into a particle pair of opposite charges. The Mark II (PEP) limit[19] is at 90% C.L.

[D] The lighter Higgs boson (H_l^0) decays into $\tau^+\tau^-$ with 100% branching fraction; the heavier one (H_h^0) decays into $b\bar{b}$, $c\bar{c}$ or $\tau^+\tau^-$.



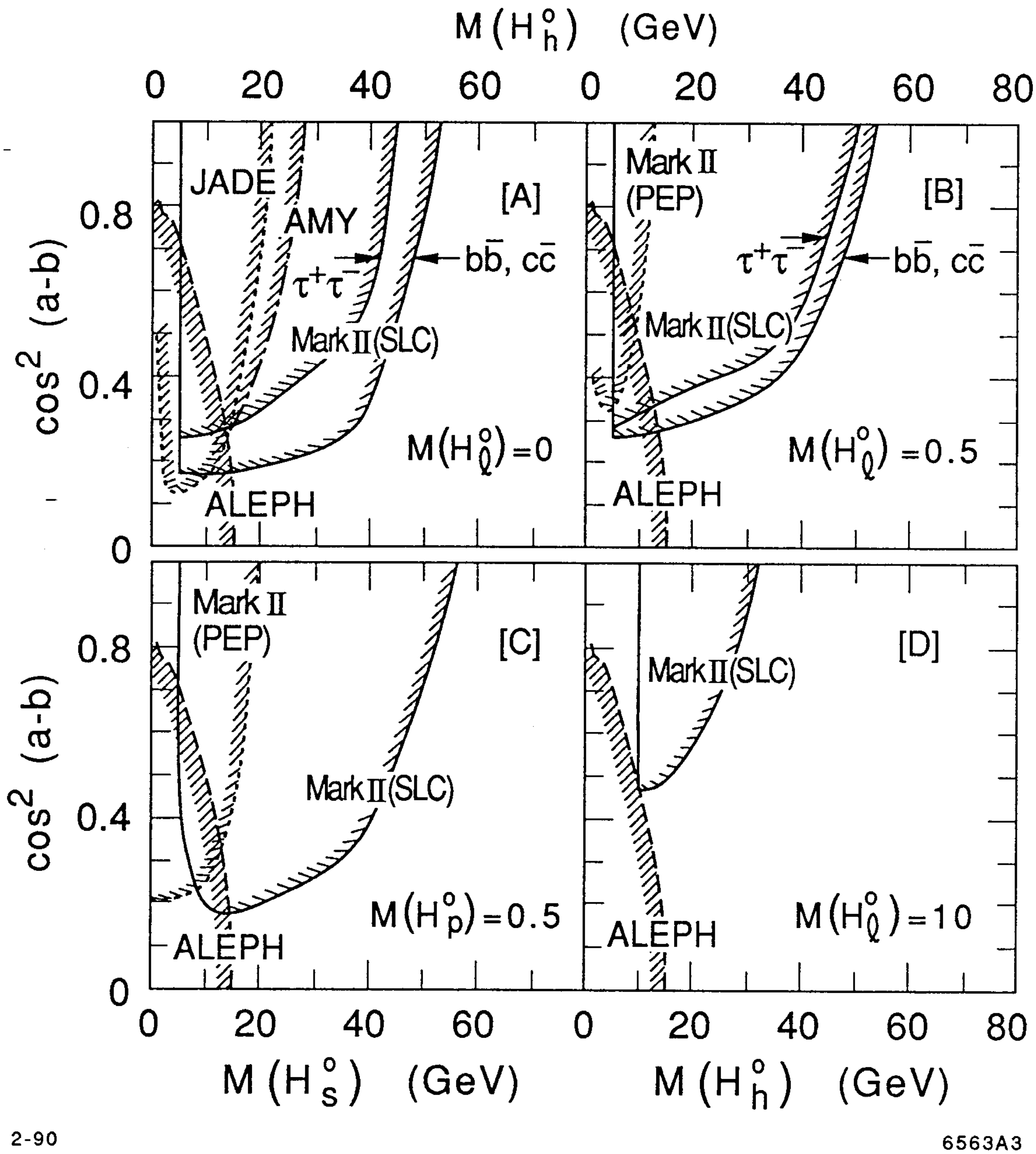
10^2
10^0
10^{-2}
Events
(a)
(b)
0
10
20
0
50
100
150
2-90
6563A1
E_{back} (GeV)
ϕ_{acop} (degrees)

Fig. 1



10^3
10^2
10^1
10^0
10^{-1}
10^{-2}
Events
0
5
10
15
20
ρ_{event} (GeV$^{1/2}$)
2-90
6563A2

Fig. 2



M(H°h) (GeV)
0
20
40
60
0
20
40
60
80
JADE
AMY
[A]
τ+τ−
bb̄, cc̄
Mark II (SLC)
M(H°ℓ)=0
ALEPH
Mark II
(PEP)
[B]
τ+τ−
bb̄, cc̄
Mark II (SLC)
M(H°ℓ)=0.5
ALEPH
cos² (a-b)
0.8
0.4
0
Mark II
(PEP)
[C]
Mark II (SLC)
M(H°p)=0.5
ALEPH
Mark II (SLC)
[D]
M(H°ℓ)=10
ALEPH
cos² (a-b)
0.8
0.4
0
0
20
40
60
0
20
40
60
80
M(H°s) (GeV)
M(H°h) (GeV)
2-90
6563A3

Fig. 3