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Search for Nonminimal Neutral Higgs Bosons from Z-Boson Decays

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Using the Mark II detector at the SLAC Linear Collider, we search for decays of the Z boson to a pair of nonminimal 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 $ZH_s^0H_p^0$ 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 nonminimal models there are additional physical neutral and charged Higgs bosons.[1] For two-doublet models, which are the minimum extension of the minimal standard 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. For the two Higgs bosons with opposite CP eigenvalues, we also use the notation H_l^0 and H_h^0, 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[3] the decay of the Z into a scalar and a pseudoscalar Higgs boson ($Z \to H_s^0 H_p^0$). The decay width for two-doublet models is given by

$$\Gamma(Z \to H_s^0 H_p^0) = \tfrac{1}{2}\Gamma(Z \to \nu\bar{\nu})\bar{\beta}^3\cos^2(a-b)\,, \quad (1)$$

where

$$\bar{\beta} = \{[s-(M_{H_s^0}+M_{H_p^0})^2][s-(M_{H_s^0}-M_{H_p^0})^2]\}^{1/2}/s\,,$$

$\Gamma(Z \to \nu\bar{\nu})$ is the decay width of Z into a pair of massless neutrinos (one generation), $s = E_{\rm c.m.}^2$, and a and b are mixing angles of Higgs bosons.[4] 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 the H_s^0 momentum direction in the e^+e^- c.m.s. Note that processes like $e^+e^- \to Z \to Z^* H_p^0 \to f\bar{f}H_p^0$ or $e^+e^- \to Z^* \to ZH_p^0$ 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 standard 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 2 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 end-cap 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_{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 (θ_{th}) must satisfy the condition $|\cos\theta_{\text{th}}| < 0.8$. 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 event. With an integrated luminosity of 19.7 ± 0.8 nb^{-1} accumulated on and near the Z peak, the expected number of $H_s^0 H_p^0$ events is about $23\bar{\beta}^3 \times \cos^2(a-b)$.

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 (D) in which $2M_\tau < M_{H_l^0} < 2M_b$ and H_l^0 decays into $\tau^+\tau^-$.

In case (A) ($Z \rightarrow H_l^0 H_h^0$, $H_l^0 \rightarrow e^+e^-$ or $\gamma\gamma$, $H_h^0 \rightarrow b\bar{b}$, $c\bar{c}$, or $\tau^+\tau^-$), H_l^0 is sufficiently long lived to escape detection.[8] 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 $Z \rightarrow H_s^0 H_p^0$ 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 (acoplanar two-jet events). The monojet events are selected with the following criteria: ($M1$) $|\cos\theta_{\text{th}}| < 0.7$ and ($M2$) the sum of the charged and neutral energy in the lower-energy hemisphere (defined by the event thrust axis), E_{back}, is smaller than 3.0 GeV. The acoplanar two-jet events are selected by the following cuts: ($P1$) $|\cos\theta_{\text{th}}| < 0.7$, ($P2$) P_T of the event must be larger than 15 GeV, and ($P3$) the acoplanarity angle[9] ϕ_{acop} must be greater than 40°. In Fig. 1, E_{back} distributions after the ($M1$) cut and ϕ_{acop} distributions after the ($P1$–2) cuts are shown for data, the expected multihadron background, and $Z \rightarrow H_s^0 H_p^0$ 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 0.3–0.7 using QCD-based Monte Carlo models.[10-12] 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 the number of multihadron hadron events and systematic error on $\epsilon_{q\bar{q}}$ used to calculate the total expected number of signal events 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. 2(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 (5) to 43 GeV (36 GeV) for $\cos^2(a-b) = 0.5$, and from 5 (5) to 53 GeV (45 GeV) for $\cos^2(a-b) = 1$. Similar searches were done at the DESY, SLAC, and KEK storage rings PETRA, PEP, and TRISTAN, respectively, with virtual Z decays.[13-15] The limits from JADE (Ref. 13) and AMY (Ref. 15) Collaborations are shown in the figure. Also shown in the figure is the limit from a search for the standard Higgs boson by the ALEPH Col-

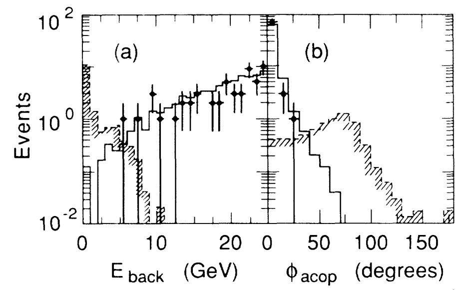

FIG. 1. Distributions used in case (A) for data (points with error bars), QCD model predictions (histograms), and predictions of $H_s^0 H_p^0$ events (shaded histograms) normalized to the integrated luminosity. (a) The E_{back} distributions. (b) The ϕ_{acop} distribution after the cut $P_T(\text{event}) > 15$ GeV.

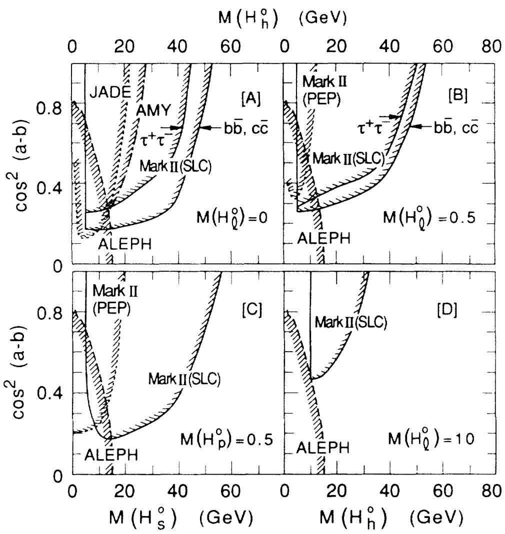

FIG. 2. The 95%-C.L. contours for the excluded region in the plane of the suppression factors $[\cos^2(a-b)]$ vs $M_{H_h^0}$. (a) The lighter Higgs boson (H_l^0) is light ($M_{H_l^0}<2M_\mu$) and stable. (b) The lighter Higgs boson (H_l^0) decays into a pair of opposite charges and the heavier one (H_h^0) 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. (c) The case $Z\to H_s^0\to H_p^0H_p^0\to 3(\mu^+\mu^-)$ 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. (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 $\tau^+\tau^-$.

laboration[16] interpreted as a limit on H_s^0. The ALEPH limit is valid independent of the H_p^0 mass.

For case (B) ($Z\to H_l^0H_h^0$, $H_l^0\to\pi^+\pi^-$ 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 ($|\mathbf{p}_i+\mathbf{p}_j|$) larger than 20 GeV, individual momenta greater than 2 GeV, and isolation parameter $\rho_{ij}>4.0$ GeV$^{1/2}$. The isolation parameter ρ_{ij} is defined as follows: The LUND jet-finding algorithm is applied[17] 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

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

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 $\rho_{\rm event}$, the maximum value of ρ_{ij} for all oppositely charged-track pairs in an event, is shown in Fig. 3 for our data sample,

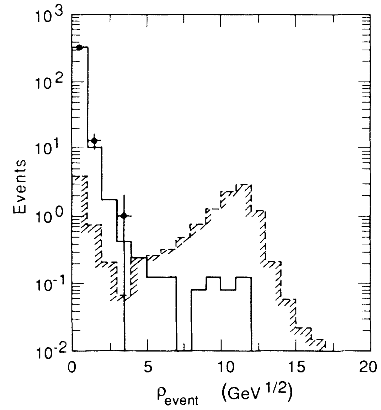

FIG. 3. The distributions of the isolation parameter of particle pair of opposite charges defined in the text in case (B) for the data (points with error bars), for the QCD model predictions (histogram), and for the expected $H_s^0H_p^0$ events (shaded histogram).

for a five-quark QCD Monte Carlo model[10] and for a $H_s^0H_p^0$ Monte Carlo model. For $H_s^0H_p^0$ events, a peak is seen at $|\mathbf{p}_i+\mathbf{p}_j|\approx(\sqrt{s}/2)(1-M_{H_h^0}^2/s)$. Events are selected if

$$0.75\frac{\sqrt{s}}{2}\left(1-\frac{M_{H_h^0}^2}{s}\right)<|\mathbf{p}_i+\mathbf{p}_j|<1.25\frac{\sqrt{s}}{2}\left(1-\frac{M_{H_h^0}^2}{s}\right)$$

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.[10-12] The detection efficiency is typically 40%–50% taking into account the losses due to the $H_l^0\to\pi^0\pi^0$ mode.

As shown in Fig. 2(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 $H_l^0\to\mu^+\mu^-$)[18] is also shown in the figure, together with the ALEPH limit.[16]

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.[19] We require that the total charged-particle energy $E_{\rm ch}$ be greater than $0.5\sqrt{s}$ and that exactly three jets are found using the LUND jet-finding algorithm.[20] 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.[10-12] The detection efficiency for $Z\to H_s^0H_p^0\to 3H_p^0$ events is about 60%–70% for $M_{H_s^0}$ between 10 and 60 GeV assuming $M_{H_p^0}=0.5$ GeV.

The excluded region is shown in the plane of $M_{H_s^0}$ vs $\cos^2(a-b)$ in Fig. 2(c). $M_{H_s^0}$ is excluded from 5 to 44 GeV for $\cos^2(a-b) \geq 0.5$. Also shown in the figure is a previous Mark II limit[18] and the interpretation of the ALEPH standard-Higgs-boson limit.[16]

For case (D) ($Z \to H_l^0 H_h^0 \to \tau^+\tau^- +$jets), the LUND jet-finding algorithm[17] 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 τ pair (the invariant mass of each jet is smaller than 2 GeV, the number of charged particles in each jet is one, and the 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 Jacobian peak of the opening angle (24° at $M_{H_h^0}=10$ GeV and 31° 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.[10–12]

The detection efficiency for the $Z \to H_s^0 H_p^0$ events is about 30%–25% for $M_{H_h^0}=10$–30 GeV, where $M_{H_l^0}=10$ GeV is assumed. The excluded region is shown in Fig. 2(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 nonminimal neutral Higgs bosons in Z-boson decays ($Z \to H_s^0 H_p^0$) where one of the Higgs bosons is relatively light ($\lesssim 10$ GeV) using the Mark II detector at the SLAC Linear Collider. 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 $Z \to H_s^0 H_p^0$ as a function of the Higgs-boson masses for generic two-doublet Higgs models.

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[9] The acoplanarity angle $\phi_{\rm acop}$ 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 momentum 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, $\phi_{\rm acop}$ is defined to be 180°.

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[19] H. E. Haber (private communication).

[20] In this case, the jet-forming cutoff parameter $d_{\rm join}$ is set to the default value of 2.5 GeV.