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Searches for Non-minimal Higgs Bosons in Z^0 Decays

The L3 Collaboration

ABSTRACT

We report on a general search for neutral and charged Higgs bosons with no assumption that the Higgs sector consists of a single doublet as in the minimal Standard Model. No signal inconsistent with background is observed in any of the decay channels analyzed. From the results of direct searches, model independent limits on Higgs bremsstrahlung and on Higgs pair production from the Z^0 are presented. We interpret the bremsstrahlung limits in the general two-doublet model. Z^0 lineshape measurements further restrict the parameter space available in the two-doublet model. Finally, the results are interpreted in the framework of the Minimal Supersymmetric extension of the Standard Model.

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Introduction

In the minimal Standard Model of electroweak interactions, a single Higgs doublet generates masses for the gauge bosons and for the charged fermions via spontaneous breaking of the gauge symmetry [1]. With only one doublet, Higgs production and decay properties depend only on the Higgs mass. Assuming these dependences, the L3 experiment has searched for the Standard Model Higgs boson and excluded it for masses less than 52 GeV [2].

The Standard Model contains 3 families of fermions and three types of spin-1 bosons. It is quite possible that the actual scalar sector in nature has more than one doublet of Higgs bosons or has Higgs bosons in other multiplets. This is expected in many theories that go beyond the Standard Model. If the Higgs sector contains more than a single doublet, rates for bremsstrahlung of the lightest Higgs from the Z^0 are not uniquely predicted and are generally lower than in the minimal Standard Model. At the same time, with a richer Higgs sector, pairs of Higgs particles can be produced in Z^0 decays. Therefore, if we are to find a non-Standard Model Higgs boson at LEP, we must search for bremsstrahlung at lower rates than predicted in the Standard Model and for Higgs pair production.

Extensions of the Standard Model Higgs sector must be consistent with two important experimental results on neutral currents [3]: first, the ρ parameter is very nearly equal to one; and second, there are stringent limits on flavor changing neutral currents. Models that contain only Higgs doublets automatically satisfy the first constraint and can satisfy the second without unnatural fine tuning of parameters. A model with two Higgs doublets illustrates some processes that occur in more general models.

The Higgs sector of the two-doublet model [4] contains five physical Higgs bosons: one neutral CP-odd A^0, two neutral scalars h^0 and H^0, and two charged scalars $H^\pm$. Both neutral scalars attain vacuum expectation values breaking the symmetry. The ratio of these two vacuum expectation values ($\tan\beta$) is an unknown parameter of the model. The mixing angle (α) of the mass eigenstates h^0 and $H^0$is another unknown parameter. Although the branching ratios depend on these two parameters, all of the five Higgs bosons tend to decay predominantly into the heaviest fermion pairs kinematically allowed. Above $b\bar{b}$ threshold, the most likely decays of the neutral Higgs bosons are into $b\bar{b}$ or $\tau^+\tau^-$. If kinematically allowed, the process $h^0 \to A^0A^0$ may dominate h^0 decays, giving rise to more complex final states. The most likely decays for the charged Higgs bosons are into $c\bar{s}$ or into $\tau\nu$. The CP-odd nature of the A^0 boson forbids its bremsstrahlung emission from the Z^0. The decays $Z^0 \to h^0h^0$ and $Z^0 \to A^0A^0$ are forbidden by Bose statistics. The dominant Higgs production processes at the Z^0 resonance which we have investigated are listed below.

(a) the bremsstrahlung process: $Z^0 \to Z^{0*}h^0 \to h^0\nu\bar{\nu},\ h^0\mu^+\mu^-,\ h^0e^+e^-$

(b) neutral pair production: $Z^0 \to h^0A^0 \to b\bar{b}b\bar{b},\ b\bar{b}b\bar{b}b\bar{b},\ b\bar{b}\tau^+\tau^-,\ \tau^+\tau^-\tau^+\tau^-$

(c) charged pair production: $Z^0 \to H^+H^- \to \tau^+\nu\tau^-\bar{\nu},\ cs\tau\nu,\ c\bar{s}cs$

We have searched for these processes in the 1990 and 1991 L3 data sample which totals 408,000 hadronic Z^0 decays at center-of-mass energies between 88.2 and 94.3 GeV. From searches for process (a), model independent limits on Higgs bremsstrahlung from the Z^0 are presented then interpreted in the general two-doublet model. Z^0 lineshape measurements limit the partial width of the Z^0 into Higgs pairs and further limit the parameter space available in the two-doublet model. From searches for process (b), more restrictive, model independent, limits on Higgs pair production are set. We limit the mass of charged Higgs bosons by searching for process (c). The details of event selection and efficiency determination, for all of the above channels, are presented elsewhere [5]. Finally, the results are interpreted in the framework of the Minimal Supersymmetric extension of the Standard Model (MSSM).

Neutral Higgs Bosons

In a two-doublet model, the rate of Higgs bremsstrahlung is equal to that in the Standard Model multiplied by $\sin^2(\beta-\alpha)$:

$$\Gamma(\mathrm{Z}^0 \rightarrow \mathrm{h}^0\mathrm{Z}^{0*}) = \Gamma(\mathrm{Z}^0 \rightarrow \mathrm{H}^0_{\mathrm{SM}}\mathrm{Z}^{0*}) \times \sin^2(\beta-\alpha). \tag{1}$$

The Z^0 partial width in Higgs pairs is proportional to $\cos^2(\beta-\alpha)$:

$$\Gamma(\mathrm{Z}^0 \rightarrow \mathrm{h}^0\mathrm{A}^0) = \Gamma(\mathrm{Z}^0 \rightarrow \nu\bar{\nu})\frac{1}{2}\lambda^{3/2}(\frac{m_\mathrm{h}^2}{m_\mathrm{Z}^2}, \frac{m_\mathrm{A}^2}{m_\mathrm{Z}^2}) \times \cos^2(\beta-\alpha), \tag{2}$$

where $\lambda(a,b) = (1-a-b)^2 - 4ab$. Thus, if the rate of Higgs bremsstrahlung happens to be small, the rate of pair production will be relatively large. The interpretation of results obtained for the search for Higgs bremsstrahlung gives upper limits on $\sin^2(\beta-\alpha)$. In Figure 1 these limits are shown assuming the A^0 is more than half the mass of the h^0. These limits are based on our search for the Standard Model Higgs [2] in the high mass region and on a more sensitive search in the mass region from 0 to 30 GeV [5]. Because of the simple relation between the decay rate and $\sin^2(\beta-\alpha)$, the results presented as limits on $\sin^2(\beta-\alpha)$ can be readily translated into model independent limits on Higgs bremsstrahlung. This limits the Higgs bremsstrahlung rate to be less than about 10% of the Standard Model rate up to Higgs masses of 30 GeV.

From measurements of the Z^0 lineshape we have limited the additional width of the Z^0 to be less than 40 MeV [6]. The limits on the contribution of Higgs pair production to Γ_Z give an upper limit on $\cos^2(\beta-\alpha)$. We can combine the limits on $\sin^2(\beta-\alpha)$ and $\cos^2(\beta-\alpha)$ to exclude a region in the $m_\mathrm{h}m_\mathrm{A}$-plane. A mass pair (m_h,m_A) will be excluded if the corresponding upper limit on $\sin^2(\beta-\alpha)$ from the bremsstrahlung process is lower than the lower limit coming from the pair production process. In the region where $m_\mathrm{h} > 2m_\mathrm{A}$, the selection efficiency for possible $\mathrm{h}^0 \rightarrow \mathrm{A}^0\mathrm{A}^0$ decays has been evaluated [5] for a selection optimized for this decay mode. The detection efficiency is comparable to that for the h^0 decay into fermions. The effect of the modified efficiency reduces the excluded region around $m_\mathrm{h} \approx 37$ GeV. The resulting exclusion plot in the $m_\mathrm{h}m_\mathrm{A}$-plane is shown in Figure 2.

Beyond the general exclusion in the framework of the two-doublet Higgs model, direct searches for pair produced h^0 and A^0 bosons are more sensitive and can cover a larger mass (m_h,m_A) region. The following Higgs decay modes are expected:

$$\mathrm{h}^0/\mathrm{A}^0 \rightarrow \tau^+\tau^-, \quad \mathrm{h}^0/\mathrm{A}^0 \rightarrow \mathrm{b}\bar{\mathrm{b}}, \quad \mathrm{h}^0 \rightarrow \mathrm{A}^0\mathrm{A}^0. \tag{3}$$

Thus direct searches for $\mathrm{b}\bar{\mathrm{b}}\mathrm{b}\bar{\mathrm{b}}$, $\mathrm{b}\bar{\mathrm{b}}\mathrm{b}\bar{\mathrm{b}}\mathrm{b}\bar{\mathrm{b}}$, $\mathrm{b}\bar{\mathrm{b}}\tau^+\tau^-$, and $\tau^+\tau^-\tau^+\tau^-$ signatures are performed. The discrimination of the multi-jet channels against standard $\mathrm{Z}^0 \rightarrow \mathrm{q}\bar{\mathrm{q}}$ background is based on the jet multiplicity and the reconstruction of event kinematics using the spin-0

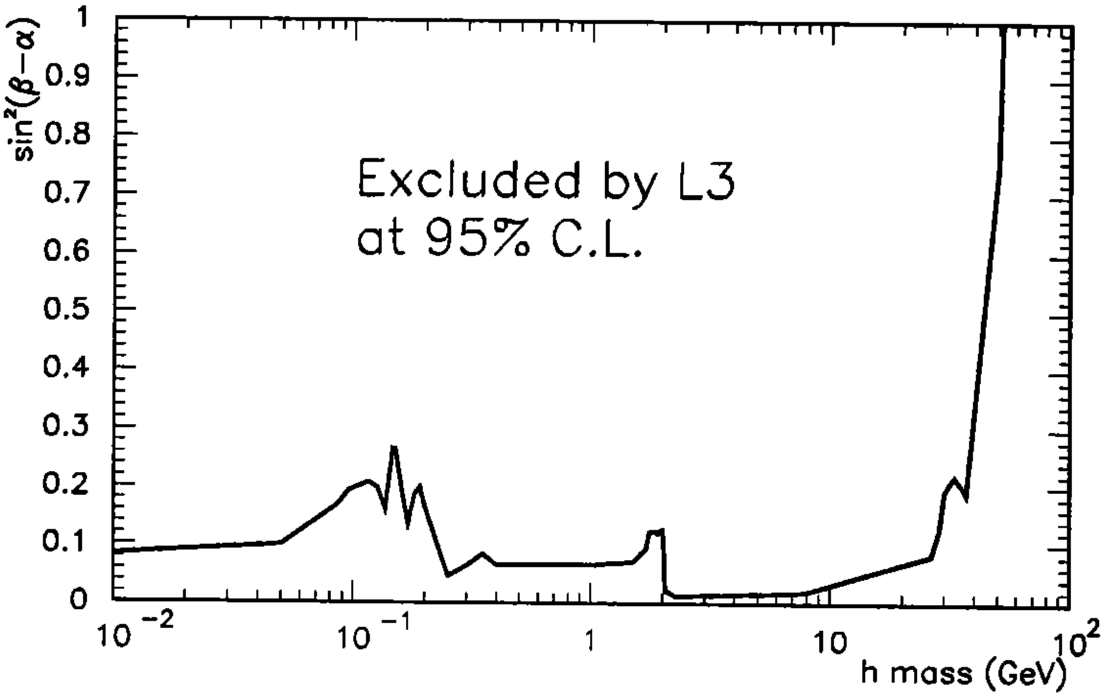

Figure 1: *Limit on* $\sin^2(\beta - \alpha)$ *of the two-doublet Higgs model obtained from the search for Higgs bremsstrahlung. The limit extends to* $m_h = 0$.

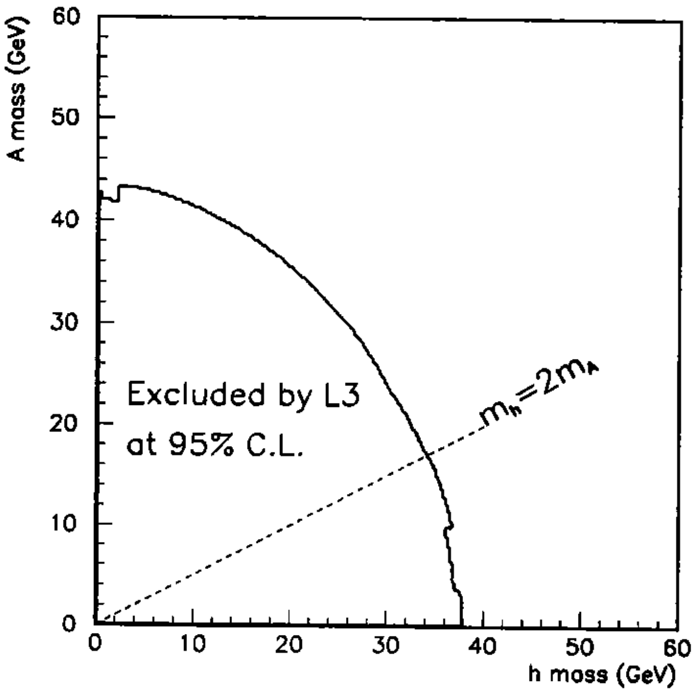

Figure 2: *Exclusion in the* $m_h m_A$*-plane of the two-doublet Higgs model obtained by combining the limits on Higgs bremsstrahlung and the limit from the* Z^0 *lineshape measurements. Below the dashed line, the process* $h^0 \to A^0 A^0$ *has been included in the efficiency determination.*

nature of the Higgs. In order to enrich the sample with events containing b-hadrons, the presence of a muon or electron with large transverse momentum with respect to the nearest jet is required. In the $\mathrm{b\bar{b}}\tau^+\tau^-$channel, two hemispheres are defined. The presence of two taus is required in one of the hemispheres and large hadronic activity is required in the other. A τ is identified as a high-thrust jet with a single charged track associated with it. The $\tau^+\tau^-$ invariant mass is computed assuming that the missing momentum in the event is all due to the neutrinos from the τ decays. In the 4 τ channel, the expected multiplicity for the signal lies between that for $\mathrm{Z^0 \to q\bar{q}}$ and that for $\mathrm{Z^0} \to \tau^+\tau^-$and there is low visible energy. Requiring two one-prong taus in one hemisphere very effectively rejects background. Selection efficiencies for the above processes are typically from 3% to 15% [5]. No signal above expected background has been seen in any of the channels. Figure 3 shows the excluded regions in the $m_\mathrm{h}m_\mathrm{A}$-plane for branching ratio limits on:

$$\frac{\Gamma(\mathrm{Z^0 \to h^0A^0 \to b\bar{b}b\bar{b}})}{\Gamma(\mathrm{Z^0 \to hadrons})}. \tag{4}$$

The limits on the $\mathrm{Z^0 \to h^0A^0} \to \tau^+\tau^-\mathrm{b\bar{b}}$ branching ratios are shown in Figure 4 and the exclusion limits on the $\mathrm{Z^0 \to h^0A^0} \to \tau^+\tau^-\tau^+\tau^-$ are shown in Figure 5.

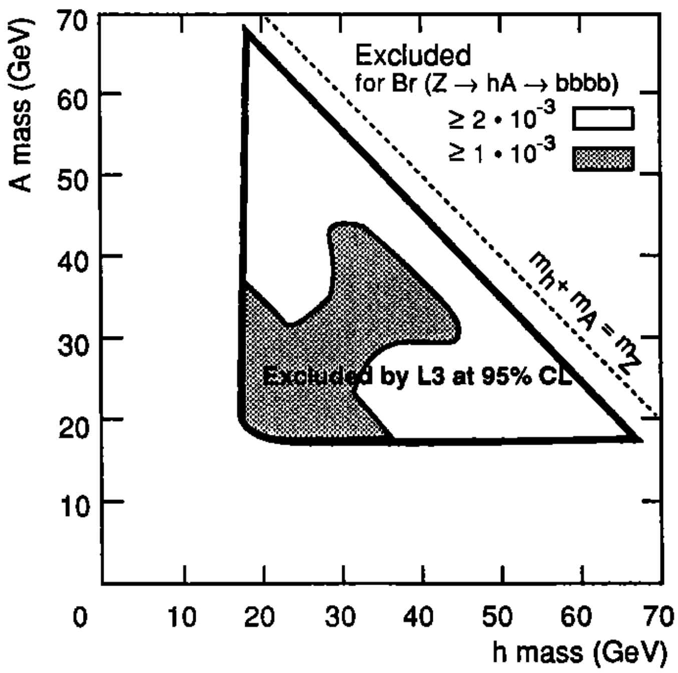

Figure 3: *Regions of the $m_\mathrm{h}m_\mathrm{A}$-plane excluded at 95% CL for values of the branching ratio* $\Gamma(\mathrm{Z^0 \to h^0A^0 \to b\bar{b}b\bar{b}})/\Gamma(\mathrm{Z^0 \to q\bar{q}}) \geq 1\times10^{-3}$ *(dark region),* 2×10^{-3} *(region inside thick black contour line).*

The process $\mathrm{Z^0 \to h^0A^0 \to A^0A^0A^0 \to b\bar{b}b\bar{b}b\bar{b}}$ can dominate if $m_\mathrm{h} > 2m_\mathrm{A}$. Limits on this process are derived in the mass range $18 \leq m_\mathrm{A} \leq 27$ GeV. At the 95% CL:

$$\frac{\Gamma(\mathrm{Z^0 \to h^0A^0 \to A^0A^0A^0 \to b\bar{b}b\bar{b}b\bar{b}})}{\Gamma(\mathrm{Z^0 \to hadrons})} \leq 9.4 \times 10^{-4}. \tag{5}$$

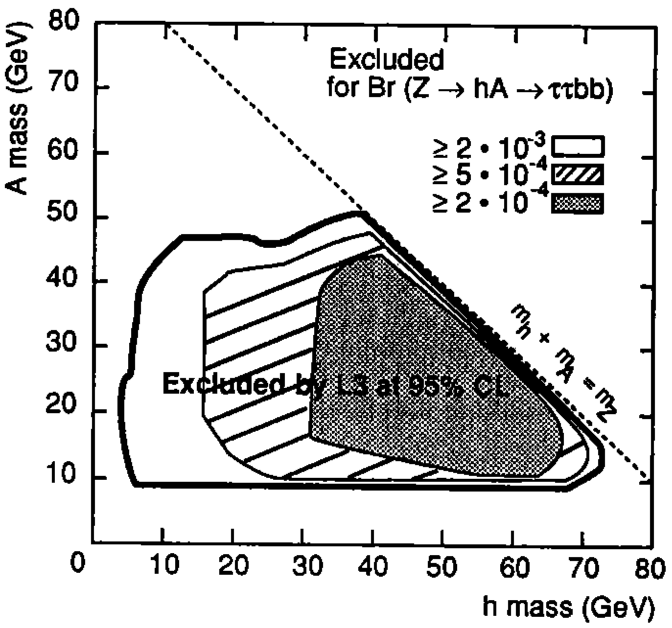

Figure 4: *Regions of the* $m_h m_A$*-plane excluded at 95% CL for values of the branching ratio* $\Gamma(Z^0 \to h^0 A^0 \to \tau^+\tau^- b\bar{b})/\Gamma(Z^0 \to q\bar{q}) \geq 2 \times 10^{-4}$ *(dark region),* 5×10^{-4} *(hatched region) and* 2×10^{-3} *(region inside thick black contour line). The analysis has been performed for* $h^0 \to \tau^+\tau^-$ *and* $A^0 \to b\bar{b}$*. The results can be interpreted as a general limit on any pair of scalars with one decaying into* $b\bar{b}$ *and the other decaying into* $\tau^+\tau^-$.

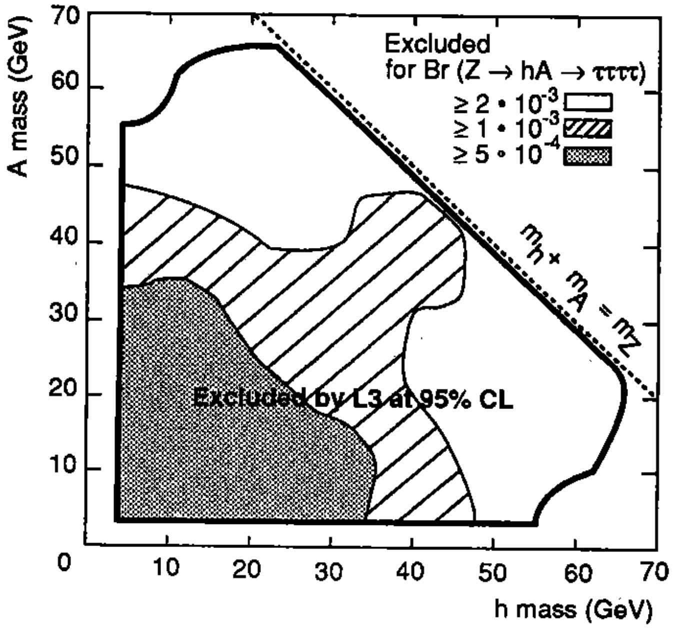

Figure 5: *Regions of the* $m_h m_A$*-plane excluded at 95% CL for values of the branching ratio* $\Gamma(Z^0 \to h^0 A^0 \to \tau^+\tau^-\tau^+\tau^-)/\Gamma(Z^0 \to \text{hadrons}) \geq 5 \times 10^{-4}$ *(dark region),* 1×10^{-3} *(hatched region) and* 2×10^{-3} *(region inside thick black contour line).*

Charged Higgs Bosons

The partial width of the Z^0 decay into a charged Higgs pair depends only on the mass of the charged Higgs [4]:

$$\Gamma(Z^0 \to H^+H^-) = \frac{G_F m_Z^3}{6\sqrt{2}\pi}\left(\frac{1}{2} - \sin^2\theta_W\right)^2 \beta^3_{H^\pm}, \qquad \text{where } \beta_{H^\pm} = \sqrt{1 - \frac{4m^2_{H^\pm}}{m^2_Z}}. \tag{6}$$

For example, the number of expected charged Higgs events for a Higgs mass of 40 GeV amounts to about one per 1000 collected hadronic Z^0 decays. Charged Higgs bosons are expected to decay predominantly into the heaviest lepton allowed and its associated neutrino, or into the heaviest quark pair whose decay is not suppressed by a small value of the CKM matrix element, i.e. $H^\pm \to \tau^\pm\nu$ or $H^\pm \to cs$. Therefore, searches for the three processes relevant at LEP I are performed:

$$Z^0 \to H^+H^- \to \tau^+\nu\tau^-\bar{\nu}, \qquad \tau\nu cs, \qquad c\bar{s}\bar{c}s. \tag{7}$$

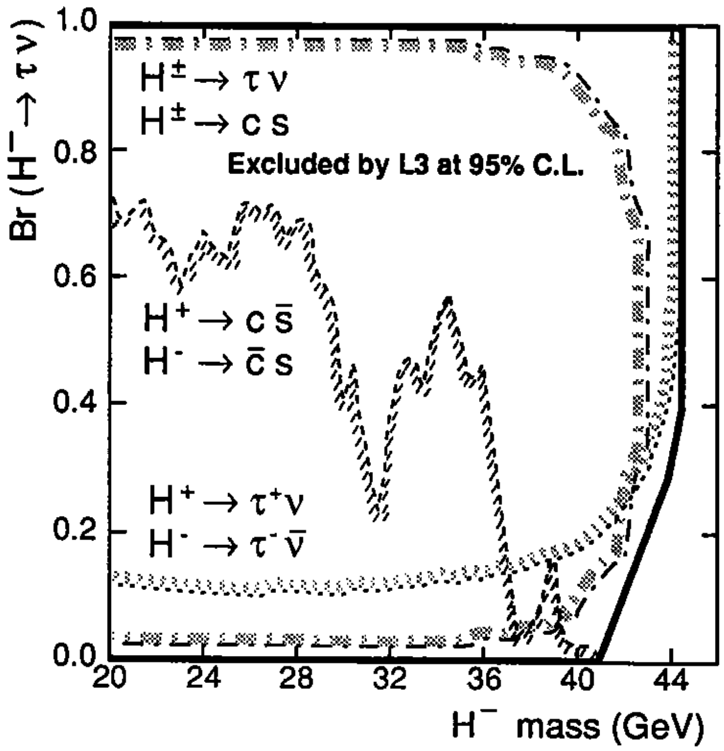

Figure 6: *Excluded regions of pair produced charged Higgs in the channels* $c\bar{s}\bar{c}s$, $cs\tau\nu$ *and* $\tau^+\nu\tau^-\bar{\nu}$ *as a function of the charged Higgs mass and the leptonic Higgs branching fraction. The thick black line defines the combined excluded region.*

The first process is identified by the presence of acoplanar taus and large missing energy. Events of the type $Z^0 \to H^+H^- \to \tau\nu cs$ are characterized by the presence of a tau in one hemisphere, two acoplanar jets in the other hemisphere, and missing energy. Candidates for $Z^0 \to H^+H^- \to c\bar{s}\bar{c}s$ are non-planar, multi-jet events with a pair of two-jet systems of equal mass. In all cases, the scalar nature of the Higgs is used to discriminate these events from the $e^+e^- \rightarrow \tau^+\tau^-$ and $e^+e^- \rightarrow q\bar{q}$ background and in the $c\bar{s}\bar{c}s$ and $\tau\nu$ cs channel kinematic constraints allow a very sensitive search for a signal in the invariant mass spectrum of the jet system. A typical selection efficiency in this channel is 4% [5]. No charged Higgs signal above expected background has been observed. Figure 6 shows the 95% CL limits on charged Higgs mass as a function of its branching ratio into $\tau\nu$ obtained from the search for all three processes.

Interpretation in the MSSM

The results obtained in previous sections can be combined to set mass limits on the neutral Higgs bosons in the Minimal Supersymmetric Standard Model. In this two-doublet model, the parameters $\tan\beta$ and α are directly related to m_h and m_A at tree level. The tree level model also predicts that $m_h < m_A$, $m_h < m_W$, and $m_{H^\pm} > m_Z$.

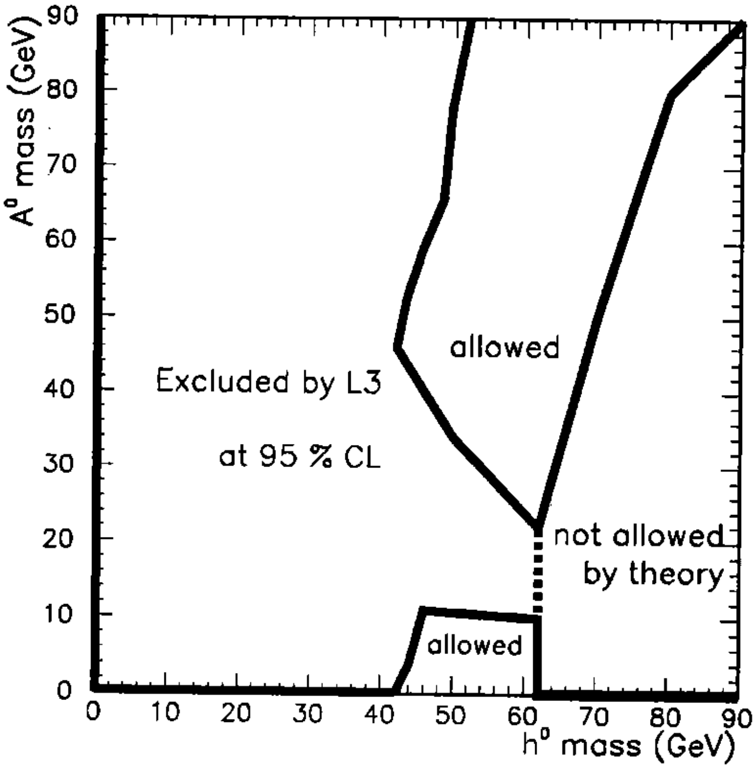

Figure 7: *Excluded region in the* $m_h m_A$*-plane of the MSSM model at the 95% CL.*

Radiative corrections, however, can modify these predictions. The main effects of radiative corrections can be extracted by making the following two assumptions [7]: a) that all Supersymmetric partners are degenerate in mass and do not mix and b) the leading top mass term in the radiative correction expression, $m_{\rm top}^4$, is dominant. With these assumptions, the effects of radiative corrections can be summarized with a single dimensionless parameter, ϵ, for a given $m_{\rm top}$ and $m_{\rm stop} = m_{\tilde{q}}$:

$$\epsilon \equiv \frac{3\alpha_W}{2\pi} \frac{m_{\rm top}^4}{m_W^2 m_Z^2} \ln\left(\frac{m_{\rm stop}^2}{m_{\rm top}^2}\right), \qquad (8)$$

where $\alpha_W = \alpha_{EM}/\sin^2\theta_W$. For $\epsilon = 0$ the tree level relations are preserved. For large ϵ, the neutral boson mass limits and the relationships between the masses and α and $\tan\beta$ are altered [7]. The charged Higgs remains too massive to be produced at LEP I. We allow a conservative range of the top and stop masses:

$$90 < m_{\mathrm{top}} < 250 \text{ GeV}, \qquad m_{\mathrm{top}} < m_{\mathrm{stop}} < 1000 \text{ GeV}, \tag{9}$$

corresponding to an ϵ range of $0 < \epsilon < 1.45$.

After radiative corrections, two (m_{h},m_{A}) pairs may correspond to one given (m_{A},$\tan\beta$) pair. A point in the $m_{\mathrm{h}}m_{\mathrm{A}}$-plane is only excluded if all the corresponding (m_{A},$\tan\beta$) values are excluded for a range of $\tan\beta$ from 1 to 50 and for any value of ϵ from 0 to 1.45. Figure 7 shows the region excluded in the $m_{\mathrm{h}}m_{\mathrm{A}}$-plane by a combination of the direct searches for neutral Higgs bosons and the limit on the Z^0 width.

Conclusion

To detect Higgs bosons expected outside the minimal Standard Model, we have searched for reduced rate Higgs bremsstrahlung and for Higgs pair production on the Z^0. Up to a Higgs mass of 30 GeV, the rate for Higgs bremsstrahlung is limited to about 10% of the Standard Model rate. For a large mass region, upper limits ranging between 2×10^{-4} and 2×10^{-3} are placed on the branching ratio of the Z^0 to decay into Higgs pairs. A lower limit of 41 GeV is obtained at the 95% CL for the charged Higgs mass, independent of the Higgs decay mode. In the MSSM, the combination of the negative searches for the neutral Higgs bosons excludes almost the entire (m_{h},m_{A}) mass region which is kinematically allowed at LEP I, even when radiative corrections are taken into account. Our result extends previous work on the single low mass Higgs search [8], the charged Higgs search [9] and the neutral pair produced Higgs search [10].

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