HIGGS PARTICLE SEARCHES AT LEP

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Results on searches for the Higgs particle performed by the four LEP experiments are reviewed in the framework of the Standard Model, Two Doublet Model, and Minimal Supersymmetric Model. The combined mass lower limit for the standard Higgs boson is 66 GeV/c^2 at 95 % CL for a statistics of 14.6 Million hadronic Z decays.

1 Introduction

The results on Higgs searches presented in this paper have been obtained by the four experiments installed on the LEP at CERN (e^+e^- collider with center of mass energy of 91.2 GeV, close to the Z mass) for a number of collected and analyzed hadronic Z decays corresponding to 3 to 4.5 Million per experiment. The searches for the Higgs boson are interpreted in the frame of the Standard Model(SM), the Two Doublets Model(TDM) and the Minimal Supersymmetric extension of the Standard Model(MSSM).

2 The search for the SM Higgs boson

In the Standard Model (SM) of Electroweak interaction[1], the Higgs mechanism[2] leads to the mass generation for the vector bosons and to the prediction of a neutral spinless particle : the Higgs boson H^0.

The large and unambiguously predicted HZZ coupling has turned LEP into the best place to search for the Higgs boson[3].

The main production process of the Higgs boson is the "Higgs-strahlung"[4] where the Z boson radiates a Higgs boson and then decays into a fermion pair :

$$e^+e^- \to Z^0 \to H^0 Z^* \to H^0 f\overline{f},$$

The decay channels for a Higgs boson with a mass larger than 30 GeV/c^2 are $q\overline{q}$ (mostly $b\overline{b}$) corresponding to about 91%, and $\tau^+\tau^-$ corresponding to about 9%. The highest event rate is expected when both the Higgs boson and the virtual Z^0 decay hadronically but this channel has a large background from $Z^0 \to q\overline{q}$ events and is not used for analysis at LEP1. The most abundant used channel is the "neutrino channel" $Z^0 \to H^0\nu\overline{\nu}$. The "charged leptonic channels" $Z^0 \to H^0e^+e^-$ and $Z^0 \to H^0\mu^+\mu^-$ have a lower branching ratio than the "neutrino channel" but are characterized by a very distinct signature due to the lepton pair and the possibility of an accurate measurement of the Higgs boson mass.

2.1 The $H^0\nu\overline{\nu}$ channel

The $H^0\nu\overline{\nu}$ channel signature consists of two jets with a large acolinearity, acoplanarity and missing energy and momentum. The main background is due to hadronic events with large missing momentum, therefore the hermeticity of the detector is important for the analysis. The four LEP experiments have simulated large background Monte Carlo samples corresponding to potentially dangerous background configurations.

The statistical treatment is somewhat different from one experiment to the other :

ALEPH[5] chooses a set of variables, aiming at the discrimination between the signal and backgrounds. They choose, on each variable, the cut by minimizing the average value $\overline{N}(x)$ of the 95 % CL upper limit on the number of signal events produced which would be obtained with an infinity of gedanken experiments in the absence of any signal contribution :

$$\overline{N}(x) = \frac{\exp(-b(x))}{\epsilon(x)} \left\{ 3.0 + 4.74\frac{b(x)}{1!} + .. \right\}$$

Where x is the location of the cut, b is the background expectation and ϵ is the signal efficiency. As the cut becomes tighter, the background level and the signal efficiency decrease simultaneously.

L3[6] uses a similar method, with all cuts tightened simultaneously in steps, and the optimization is performed on the number of steps with $\overline{N}(x)$.

DELPHI[7] uses both a discriminant analysis and a probabilistic analysis combined, supplemented by additionnal cuts to provide a good discrimination against the background events.

OPAL[8] uses a set of sequential cuts determined from large Monte Carlo samples and tight enough not to be modified with increasing statistics.

The Higgs mass is calculated from the jets and the mass resolution is ranging from 5 to 9 GeV/c^2 at 65 GeV/c^2.

For the four LEP experiments, the Higgs detection efficiencies at 65 GeV/c^2 are ranging from 15 to 30 %, and the total expected background is 5.2 events for 2 candidates seen. These candidates are outside the range 50-70 GeV/c^2.

2.2 The $H^0 l^+ l^-$ channel

In this channel the Higgs boson which decays predominantly into $q\overline{q}$ (mostly $b\overline{b}$) is accompagnied by a muon or electron pair coming from the virtual Z^*.

The signature consists of two energetic and acollinear isolated leptons and two acollinear jets.

The two important backgrounds sources for the muon and electron channel are the semi-leptonic decays of heavy quarks and the irreducible background due to the four-fermion processes where Z boson decays into a high mass $q\overline{q}$ pair which radiates a virtual photon converting into a l^+l^- pair. The b-tagging technique can be used to enrich the Higgs boson sample. The mass measurement obtained by a missing mass technique based on the characteristics of the lepton pair leads to a good mass resolution ranging from 0.4 to 1 GeV/c^2 at 65 GeV/c^2.

For the four experiments, the Higgs detection efficiencies at 65 GeV/c^2 in the $H^0e^+e^-$ channel are ranging from 17 to 40 % and the number of expected background events is 10.2 when 2 candidates are seen. In the $H^0\mu^+\mu^-$ channel the efficiencies are ranging from 22 to 40 % and the number of expected background events is 6.1 when 6 candidates are seen.

2.3 Results and Limits

We present an overview of the SM Higgs boson search results obtained in the high mass region by ALEPH[9], DELPHI, L3[6], and OPAL[8].

The Higgs candidates with masses in the range 50 to 70 GeV/c^2 are observed by each experiments in the leptonic channels, they are given in Table 1.

Table 1: Recoil mass (in GeV/c^2) of the candidates with masses in the range between 50 and 70 GeV/c^2 found by the four LEP experiments.

ALEPH	DELPHI (prel.)	L3	OPAL (prel.)
$q\overline{q}ee$ -	$q\overline{q}ee$ 53.7 ± 7	$q\overline{q}ee$ 67.6 ± 0.7	$q\overline{q}ee$ -
$q\overline{q}\mu\mu$ 49.7 ± 0.5 51.5 ± 0.5 66.9 ± 0.4	$q\overline{q}\mu\mu$ $57.5^{+2.0}_{-2.2}$ $60.2^{+2.7}_{-3.5}$	$q\overline{q}\mu\mu$ -	$q\overline{q}\mu\mu$ 61.2 ± 1.0

There is no accumulation of the candidate events around a particular mass value.

The mass limit reported by each of the four LEP experiments are shown in Table 2 together with the statistics of Z decaying into hadrons.

Table 2: 95 % CL mass limit (in GeV/c^2) obtained by the four LEP experiments.

	ALEPH	DELPHI (prel.)	L3	OPAL (prel.)
Data	89-95	91-94	91-94	90-95
N_{had}	4.5 M	2.8 M	3.0 M	4.4 M
Limit	63.9	55.4	60.2	59.6

ALEPH and L3 derived this limit by calculating the 95 % CL upper limit of the number of events as a function of the Higgs boson mass in the considered mass range and taking into account the masses of the candidates and their resolution. DELPHI and OPAL set a conservative upper limit corresponding to their candidate(s) taken as signal.

We attempted to get a combined limit by adding the number of signal events expected to be found by all four experiments, reducing the number of signal events expected by 5% accordingly, and considering the candidates found by the experiments. The conservative method we used to evaluate the 95% CL limit is based on reference[10]. With such a method, a limit of 66 GeV/c^2 was found with one candidate contribution in that mass region as shown in Figure 1.

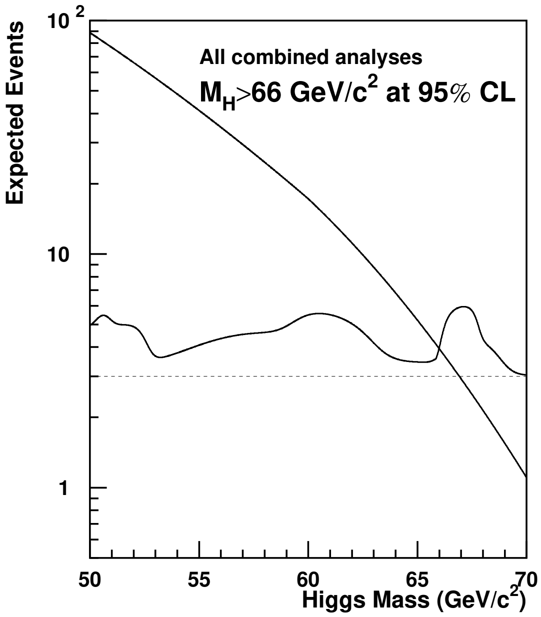

Figure 1: Number of Higgs events expected and 95 % CL upper limit on the number of observed events in the combined analysis of the four LEP experiments.

3 Higgs bosons in the Two Doublet Model

3.1 Bremsstrahlung, Pair Production and Yukawa processes

More general models of electroweak interactions necessitate a second doublet of complex Higgs fields[11] leading to five physical Higgs bosons : two charged bosons H^+, H^-, and three neutral bosons h^0, H^0 and A^0. The h^0 and H^0 result from the mixing of the two CP-even scalar fields with an angle α, and A^0 is a CP-odd pseudoscalar. At tree level, the general Two Doublet Model contains six parameters: four Higgs boson masses, the mixing angle α of the CP-even sector, and $\tan(\beta)=\frac{v_2}{v_1}$, the ratio of the vacuum expectation values of the two Higgs fields.

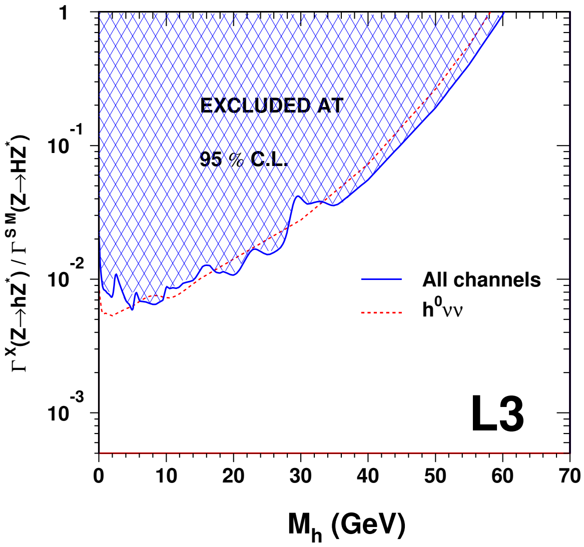

Figure 2: 95% CL upper limit on the ratio between the cross section of the bremsstrahlung production of Higgs boson in the Two Doublet Model and that of the SM Higgs boson, obtained by L3.

The possible production processes, at the tree level for the neutral Higgs bosons at LEP are :

- the bremsstrahlung process $Z \to Z^* h^0$ proportionnal to $\sin^2(\beta-\alpha)$,
- the pair production $Z \to h^0 A^0$ proportionnal to $\cos^2(\beta-\alpha)$.

  These two processes are complementary.

  The relation $\sigma(Z \to Z^* h^0) = \sin^2(\beta-\alpha)\sigma(Z \to Z^* H^0_{SM})$, shows that the search for the SM process $Z \to Z^* H^0_{SM}$ can be reinterpreted in the Two Doublet Model context as a search for the process $Z \to Z^* h^0$, provided that the detection efficiencies are identical in the two cases.

L3[6] with data corresponding to 3 Million hadronic Z decays, obtained at 95% CL :
$\frac{\Gamma(Z\to hZ^*)}{\Gamma(Z\to H_{SM}Z^*)} < 5\times 10^{-2}$ for $M_h < 40$ GeV/c^2
The result on the whole mass range is shown in Figure 2. Similar results were obtained by OPAL[12] and ALEPH[13].

- the Yukawa process $e^+e^- \rightarrow f\bar{f}h$ or $f\bar{f}A$ with a cross section proportionnal to m_f^2. In addition, it is proportionnal for down type quarks and leptons to $\frac{sin^2\alpha}{cos^2\beta}$ for $f\bar{f}h$ and $tan\beta$ for $f\bar{f}A$.

ALEPH[14] has set 95 % CL limits of the $e^+e^- \rightarrow f\bar{f}A$ cross section and interpreted it as an excluded region in the (m_A, $tan\beta$) plane independent of the Two Doublet Model. This cross section is large enough only when f is a τ lepton or a b quark. Therefore the studied final states are :

i) $b\bar{b}b\bar{b}$ and $\tau^+\tau^-b\bar{b}$ for m_A in excess of 2 m_b

ii) $\tau^+\tau^-\tau^+\tau^-$ between 2 m_τ and 2 m_b

iii) a $\tau^+\tau^-$ pair accompagnied by a low charged multiplicity system down to 2 m_e

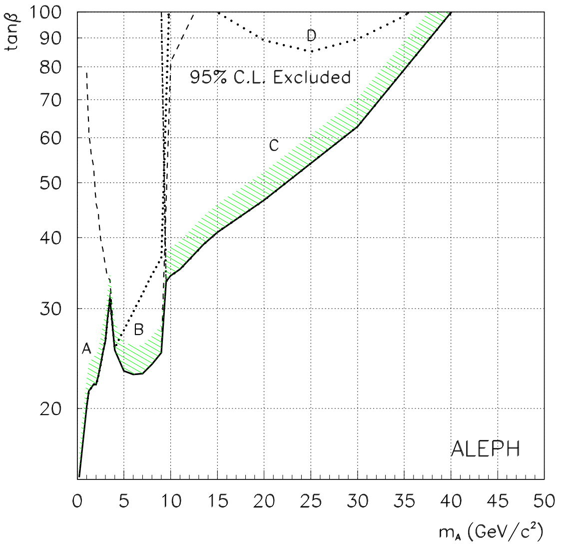

Figure 3: Regions in the $tan\beta$ vs m_A plane excluded at the 95 % CL when the four ALEPH analysis A (llV topology), B (llV topology with mass cut), C ($\tau^+\tau^-q\bar{q}$ final state), D ($b\bar{b}b\bar{b}$ final state) are combined.

The result of these analysis, performed on a data sample of about 4.5 Million hadronic Z decays, using llV channel, llV channel with mass cut of 1.25 GeV/c^2, $\tau^+\tau^-q\bar{q}$ and $b\bar{b}b\bar{b}$ channels combined, is shown in Figure 3.

The $tan\beta$ region larger than 60 is excluded in any Two Doublet Model for a light pseudoscalar A^0 with mass lower than 30 GeV/c^2.

3.2 Charged Higgs pair production

In the framework of the two Higgs doublet scheme, the partial decay width of the Z into pairs of charged Higgs bosons is a function of the charged Higgs boson mass. The search is performed in the following 3 channels :

$$Z \rightarrow H^+H^- \rightarrow \tau^+\nu\tau^-\bar{\nu}, c\bar{s}\tau^-\bar{\nu}, c\bar{s}\bar{c}s$$

with topologies corresponding to two acoplanar τ with missing energy, two acoplanar jets with isolated τ, and four jets with equal dijet-dijet mass.

Lower limits on the mass of the charged Higgs boson obtained by OPAL[15] with data corresponding to a luminosity of 110 pb^{-1} are presented as a function of its leptonic branching fraction $Br(H^+ \rightarrow \tau^+\nu)$ in Figure 4.

For the highest value of $m_{H^\pm}$ excluded at the 95% CL independant of the branching ratio, they obtained a limit of 44.1 GeV/c^2.

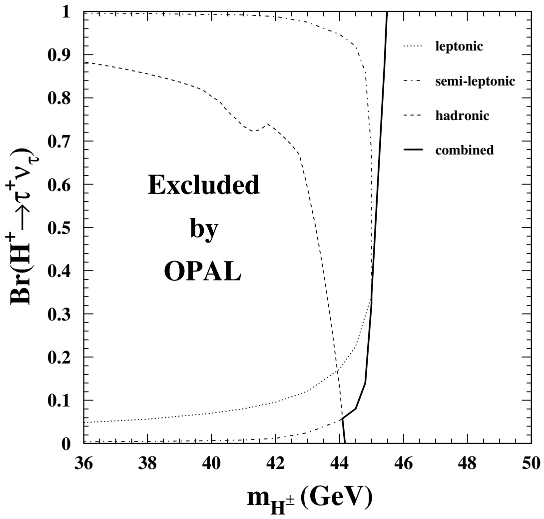

Figure 4: Regions in the $Br(H^+ \rightarrow \tau^+\nu_\tau)$ vs $m_{H^\pm}$ plane excluded at the 95 % CL, obtained by OPAL.

A similar study, was performed by DELPHI[16] and ALEPH[17].

4 Higgs bosons in the Minimal Supersymmetric Model

A particuliar case of the Two Doublet Model is the Minimal Supersymmetric extension of the Standard Model (MSSM)[18], which is more constrained.

In this model, even with two-loop radiative corrections included, the mass of the h^0 boson is constrained to be less than $\simeq 140$ GeV$/c^2$.

In the Higgs sector, the tree level MSSM calculations are only dependent on m_A and $tan\beta$. The radiative corrections, which are important due to the large top mass, introduce additional parameters : μ describing the mixing of the two Higgs field doublet, A which is a common mixing parameter relevant for the stop, sbottom, and stau masses at electroweak energy scale; and M_s, the soft symmetry breaking mass parameter relevant for the squark and slepton spectra at the electroweak energy scale.

The DELPHI Collaboration[19], using 1991-92 data combined with 1994-95 data, with experimental inputs $Z \to hZ^*$, $Z \to hA \to 4jets$, and assuming $m_t = 175$ GeV$/c^2$, $m_{stop} = 1$ TeV$/c^2$, $tan\beta \geq 1$ and in the particular case of no mixing, obtained preliminary results giving the limits :

$m_h \geq 45.4$ GeV$/c^2$
and $m_A \geq 45.2$ GeV$/c^2$
at 95 % CL, as shown in Figure 5.

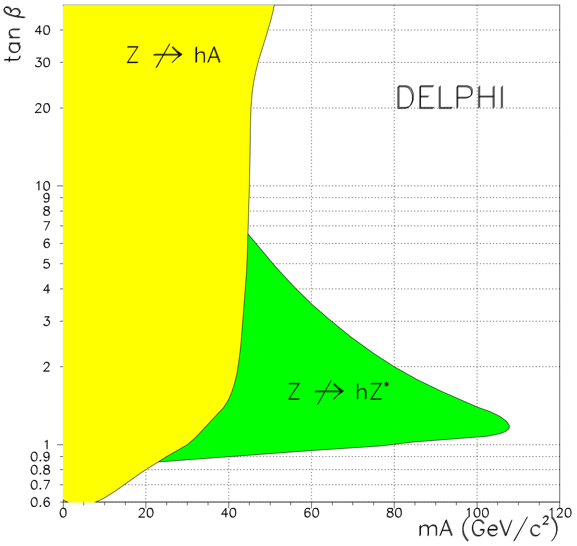

Figure 5: Regions of the plane (m_A,$tan\beta$) excluded at 95 % CL by DELPHI (prelim.) in the no mixing case.

OPAL[8] aimed at more generality with regards to the MSSM parameter space. They made further assumptions that A, M_s and μ are linked by one of the following three relations which correspond to small, intermediate and large deviations from mass degeneracy in the heavy squark sector :

- $A = 0$, $\mu = -50$ GeV for small mixing,
- $A = M_s$, $\mu = -M_s$ for intermediate mixing,
- $A = M_s\sqrt(6)$, $\mu = -50$ GeV for large mixing.

The OPAL Collaboration performed the analysis on the 1990-95 data corresponding to a luminosity of 160 pb^{-1}. Using the experimental inputs from $Z \to hZ^*$, $Z \to hA \to b\bar{b}b\bar{b}$, $b\bar{b}\tau^+\tau^-$, $\tau^+\tau^-\tau^+\tau^-$, $3(\tau^+\tau^-)$ and $3(b\bar{b})$, with a wide range of parameters, they considered the 3 mixing cases described above. The most conservative limit that they obtained is in the large mixing case, which leads to:

$m_h \geq 44.3$ GeV$/c^2$
and $m_A \geq 23.5$ GeV$/c^2$
at 95 % CL, for $tan\beta \geq 1$, as shown in Figure 6.

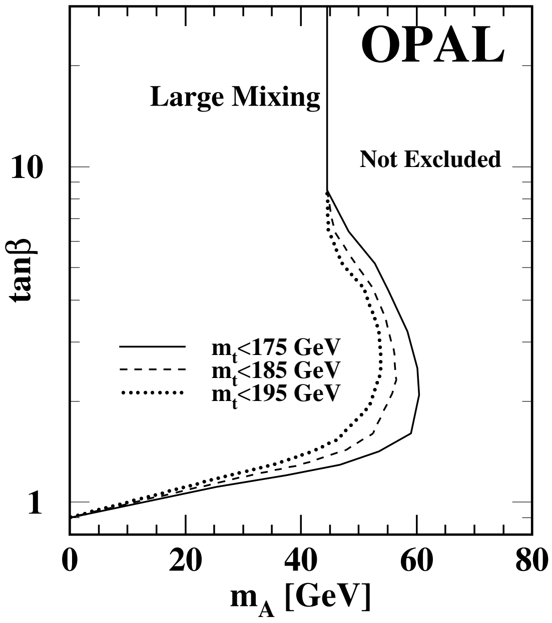

Figure 6: Regions of the plane (m_A,$tan\beta$) excluded at 95 % CL by OPAL in the large mixing case.

ALEPH[20] obtained similar results.

5 Search for the Higgs boson in hadronic events with isolated photon(s)

A Higgs boson lighter than the Z could also be observed through the processes :

- $e^+e^- \to Z \to H\gamma$ where $H \to q\bar{q}$ which occurs at the one-loop level with charged particles inside the loop, the dominant contribution being, in the SM, the W boson and the top quark loops,
- $e^+e^- \to HZ^*$ where $H \to \gamma\gamma$ and $Z^* \to q\bar{q}$, the Higgs decaying into 2 photons via loop diagrams.

Rather low branching ratio are expected in the SM ($Br(Z^0 \to H^0\gamma) \sim 2 \times 10^{-7}$ for the Higgs boson mass of 65 GeV/c^2), but in the MSSM the loop diagrams of these processes may contain supersymmetric particles resulting in branching ratios which can be increased by up to a factor 3.

The signature is a pair of acollinear jets with one monochromatic or two isolated energetic photons. The $H\gamma$ process has a very large $Z \to q\bar{q}\gamma$ background and b-tagging is mandatory for better signal over noise ratio.

In some composite models, like the Strongly Coupled Standard Model (SCSM) the branching ratio $\Gamma(Z \to H\gamma)$ is enhanced by a very large factor ($\simeq 100$) which could lead to measurable cross sections at LEP.

OPAL[21], DELPHI[22] with 1991-94 data obtained the following limits at 95 % CL :

$Br(Z^0 \to H^0\gamma) \leq 3 \times 10^{-5}$, and

$Br(Z^0 \to q\bar{q}X^0)Br(X^0 \to \gamma\gamma) \leq 2 \times 10^{-6}$.

6 Invisible Higgs

The h^0 may decay into invisible final states[23], for instance into a pair of χ_1^0, where χ_1^0 is the lightest neutralino, which is assumed to be the lightest supersymmetric particle (LSP) and to be stable in R parity conserving supersymmetric models.

Invisible Higgs can also appear in other models such as Majoron models[24] where the Higgs could decay predominantly into invisible Majorons.

Considering the bremsstrahlung of invisible Higgs, the signature consists in monojet or acoplanar jets with missing energy (the topology here is similar to that of the $H\nu\bar{\nu}$ channel in the Standard Model search), or acoplanar lepton pair with missing energy.

L3[6] with data corresponding to 3 Million hadronic Z decays, obtained at 95% CL :

$\frac{\Gamma(Z \to h^{inv} Z^*)}{\Gamma(Z \to H_{SM} Z^*)} < 2 \times 10^{-2}$ for $M_h < 40$ GeV/c^2

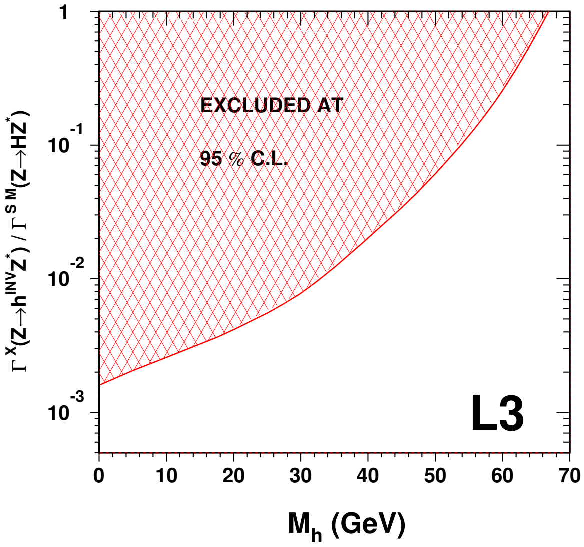

Figure 7: 95% CL upper limit on the ratio between the cross section of the bremsstrahlung production of an invisibly decaying Higgs boson and that of the SM Higgs boson, obtained by L3.

The result on the whole mass range is shown in Figure 7. OPAL collaboration[12] obtained similar results.

For a SM like invisible Higgs production cross section, the lower mass limit reaches 66.7 GeV/c^2 for L3 and 67.5 GeV/c^2 for OPAL. Similar results were obtained by ALEPH[13].

7 Conclusion

The present search for the SM Higgs boson at LEP1 leads to the following limits at 95 % CL:

$m_H \geq 66$ GeV/c^2 (LEP combined)

The existence of a light charged Higgs $H^\pm$ has been excluded at the 95% CL:

$m_{H^\pm} \geq 44.1$ GeV/c^2

The MSSM 95% CL most conservative Higgs mass limits (corresponding to large mixing case) are :

$m_h \geq 44.3$ GeV/c^2, $m_A \geq 23.5$ GeV/c^2

Major improvements in these limits are expected at LEP2.

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References

1. S.L. Glashow, Nucl. Phys. 22 (1961) 579; S. Weinberg, Phys. Rev. Lett. 19 (1967) 1264; A. Salam, Elementary Particle Theory, Ed. N. Svartholm, Stockholm, "Almquist and Wiksell" (1968), 367; S.L. Glashow, J. Illiopoulos and L. Maiani, Phys. Rev. D2 (1970) 1285.
2. P.W. Higgs, Phys. Lett. 12 (1964) 132, Phys. Rev. Lett. 13 (1964) 508 and Phys. Rev. 145 (1966) 1156; F. Englert and R. Brout, Phys. Rev. Lett. 13 (1964) 321; G.S. Guralnik, C.R. Hagen, and T.W.B Kibble, Phys. Rev. Lett. 13 (1964) 585; T.W.B Kibble, Phys. Rev. Lett. 19 (1967) 1264.
3. P.J. Franzini *et al.* in "Z Physics at LEP1", CERN Report CERN 89-08, eds G. Altarelli, R. Kleiss and C. Verzegnassi (CERN, Geneva, 1989) Vol. 2, p. 59 and references therein.
4. B.L. Ioffe and V.A. Khoze, "What can be expected from experiments on colliding e^+e^- beams with $\approx$ 100 GeV ?", preprint LINP, Leningrad, November 1976; J.D. Bjorken, Proceedings of the 1976 SLAC Summer Institute on Particle Physics, Stanford, ed. M.C. Zipf (Stanford Linear Accel. Center, Stanford, CA, 1977) p. 1.
5. D. Buskulic at al., ALEPH Coll., Nucl. Phys. B313 (1993) 299.
6. L3 Coll., *Search for neutral Higgs boson production through the process $Z \to Z^*H^0$*, Contribution pa11-016, ICHEP96, CERN PPE/96-95.
7. DELPHI Coll., DELPHI 95-69 PHYS 504.
8. OPAL Coll., *Search for Neutral Higgs Bosons in Z^0 Decays Using the OPAL Detector at LEP*, Contribution pa13-004, ICHEP96, CERN PPE/96-118.
9. ALEPH Coll., *Mass limit for the Standard Model Higgs Boson with the full LEP I ALEPH Data Sample*, Contribution pa13-026, ICHEP96, and Phys. Lett. B 384 (1996) 427.
10. L. Lista, L3 notes 1120 and 1261.
11. S. Dawson, J.F. Gunion, H.E. Haber, G.L. Kane, The Higgs Hunter's Guide, Addison-Wesley (1989).
12. OPAL Coll., *Topological Search for the Production of Neutralinos and Scalar Particles*, Contribution pa13-003, ICHEP96, CERN PPE/96-019 and Phys. Lett. B 377 (1996) 273.
13. ALEPH Coll., *Search for a non-minimal Higgs boson produced in the reaction $e^+e^- \to hZ^*$*, CERN PPE/93-111, Phys. Lett. B 313 (1993) 549.
14. ALEPH Coll., *Search for a Light Higgs Boson in the Yukawa Process*, Contribution pa13-027, ICHEP96.
15. OPAL Coll., *Search for Charged Higgs Bosons Using the OPAL Detector at LEP*, Contribution pa13-005, ICHEP96, CERN PPE/95-180, and Phys. Lett. B 370 (1996) 174.
16. DELPHI Coll., *Search for pair-produced heavy scalars in Z^0 decays*, CERN PPE/94-83 and Z. Phys. C 64 (1994) 183.
17. ALEPH Coll., *Search for new particles in Z decays using the ALEPH detector*, CERN PPE/91-149, Pys. Rep. 216 (1992) 253.
18. P.J. Franzini *et al.* in "Physics at LEP2", CERN Report CERN 96-01, eds G. Altarelli, T. Sjostrand and F. Zwirner (CERN, Geneva, 1996) Vol. 1, p. 384 and references therein.
19. DELPHI Coll., *Update of the search for heavy neutral MSSM Higgs bosons*, Contribution pa07-095, ICHEP96 and DELPHI 96-85 CONF 14.
20. ALEPH Coll., Contribution eps0415, International Europhysics Conference on High Energy Physics, Brussels, 27 jul - 2 aug 1995.
21. OPAL Coll., *Search for a Narrow Resonance in Z^0 Decays into Hadrons and Isolated Photons*, Contribution pa13-020, ICHEP96, CERN PPE/95-193 and Z. Phys. C 71 (1996) 1.
22. DELPHI Coll., DELPHI 95-73 PHYS 508, and *Search for high mass $\gamma\gamma$ resonances in $e^+e^- \to l^+l^-\gamma\gamma$, $\nu\bar{\nu}\gamma\gamma$ and $q\bar{q}\gamma\gamma$ at LEP I*, Contribution pa12-010, ICHEP96, CERN PPE/96-76.
23. A. Lopez-Fernandez *et al.*, Phys. Lett. B 312 (1993) 240; F. De Campos *et al.*, Phys. Lett. B336 (1994) 446; A. Djouadi *et al.*, CERN preprint CERN-PPE/96-34.
24. Y. Chikashige *et al.* Phys. Lett. B 98 (1980) 265; J. C. Romao *et al.*, Phys. Lett. B 292 (1992) 329; A.S. Joshipura, J.W.F. Valle, Nucl. Phys. B397 (1993) 105.