

ETHZ-IPP PR-99-03
May 31st, 1999

The search for Higgs particles at LEP

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The results of the experimental searches for Higgs particles at LEP, using the data collected at centre-of-mass energies up to 189 GeV, are reviewed and the prospects for the near future outlined.

Talk given at the XXXIVnd Rencontres de Moriond,
ELECTROWEAK INTERACTIONS AND UNIFIED THEORIES, March 13–20 1999,
to be published in the Proceedings.

1 Introduction

The Standard Model (SM) of the electroweak interactions has been subject to very precise tests at LEP and elsewhere. Up to now its predictions have been found in very good agreement with the experimental observations. *e.g.* the masses and couplings of the vector bosons, W and Z. To explain the origin of the W and Z boson masses, as well as of the fermion masses, the model requires the existence of a weak isospin doublet of complex scalar fields which is responsible for the spontaneous breakdown of the gauge symmetry. Spontaneous symmetry breaking is the mechanism which generates masses for the bosons and the fermions. A direct consequence of this mechanism is the existence of one physical neutral scalar, the Higgs boson. The mass of the Higgs boson is not predicted by the theory. There are theoretical indications that the existence of a relatively light Higgs would indicate the presence of new physics in the few TeV range¹.

It is generally accepted that, despite the great success of its electroweak predictions, the SM may be an effective theory valid only at low energies. Indeed, several fundamental questions are raised which cannot get a satisfactory answer in the context of the SM. Supersymmetry offers solutions to some of these problems. In its simplest realisation, the minimal supersymmetric extension of the SM (MSSM), there are two Higgs doublets resulting into five physical Higgs particles: two neutral CP-even, h and H ($M_h < M_H$), one neutral CP-odd, A, and two scalar charged particles, H^+ and H^- . Their masses at tree-level depend only on two MSSM parameters, *e.g.* the ratio of the vacuum expectation value of the two Higgs fields, $\tan\beta$, and the mass of the CP-odd Higgs boson, M_A . When introducing radiative corrections, the Higgs masses and couplings (which determine cross sections and decay branching ratios) become dependent also on the top mass, the scalar top mass and other parameters of the model. In particular, the dominant radiative corrections to the Higgs masses grow with the fourth power of the top mass and they are logarithmically dependent on the stop mass. The mass of the CP-odd Higgs boson can be as high as ~ 1 TeV, the mass of the heavier CP-even Higgs boson should be typically higher than ~ 120 GeV and the mass of the charged Higgs typically higher than ~ 90 GeV¹. Differently from the SM, in the MSSM an upper limit on the mass of the lightest CP-even Higgs boson mass M_h can be set, which, depending on M_A , $\tan\beta$ and the mixing in the stop sector, can be as high as ~ 130 GeV¹, for a top mass value in the measured range $M_t = 174.3 \pm 5.1$ GeV². There are several scenarios in which this Higgs mass upper bound is 100 GeV or less, of particular interest for the LEP searches.

Non supersymmetric extensions of the SM are also advocated to solve some of the problems left open by the SM. They predict a different Higgs phenomenology from the one predicted by the SM and the MSSM. These predictions can also be tested experimentally.

There are two main sources of experimental informations about Higgs bosons: on one hand, the precise measurement of the electroweak parameters and, on the other hand, the direct searches. In the SM (and the MSSM) the electroweak observables are sensitive, through loop corrections, to the Higgs mass, M_H , though only logarithmically. The increasing precision of present experimental data from LEP, Tevatron and SLC, makes it possible to derive significant upper bounds on the SM Higgs (and the lightest neutral MSSM Higgs) mass, which are of great interest, and encouragement, for the direct searches. A global fit to all the available measurements of electroweak observables gives an upper bound³ $M_H < 220$ GeV at 95% CL. The central value with the 68% CL range indicated by the fit³ is: $M_H = 71_{-42}^{+75} + 5$ GeV (the limit from direct searches, see below, is not included in the calculation).

A wide variety of experimental informations comes from the direct Higgs searches, devoted to detect direct evidences of Higgs particles, independently of model assumptions. With this aim, comprehensive searches are being made at LEP, covering a large number of decay channels and signatures. The discovery of (at least one of) the Higgs boson(s) is, indeed, one of the main goals of the LEP programme. The centre-of-mass energy (\sqrt{s}) and corresponding luminosity of the LEP collider have been constantly increased since the end of 1995. In 1996 about 20 pb^{-1} were collected by each LEP experiment at $\sqrt{s} = 161\text{--}172$ GeV. In 1997 the \sqrt{s} was raised to 183 GeV and about 60 pb^{-1} were collected per experiment. The direct searches for Higgs bosons at LEP at $\sqrt{s} \leq 183$ GeV have resulted in several

lower limits on the masses of Higgs particles. The combined LEP limits⁴ are: for the SM Higgs, $M_H > 90$ GeV (individual limits in the range ~ 86 – 88 GeV), for the MSSM neutral Higgs masses M_h and $M_A > 80$ GeV (individual limits in the range ~ 68 – 76 GeV), for the charged Higgs $M_{H^\pm} > 70$ GeV (individual limits in the range ~ 57 – 59 GeV).

The LEP data collected from May to November 1998 at $\sqrt{s} = 189$ GeV and amounting to approximately 170 pb^{-1} per experiment give the possibility to explore higher Higgs mass ranges. LEP is at present the most powerful tool for the direct search of Higgs particles in mass regions never explored before.

2 The Higgs boson of the Standard Model

Within the framework of the SM, the Higgs is dominantly produced via the Higgs-strahlung process¹. Additional production processes like W or Z fusion contribute very little (less than 1%) to the Higgs production rate in the mass range of interest for the experimental search. The SM Higgs production cross section at $\sqrt{s} = 189$ GeV is 0.34 pb and 0.178 pb for Higgs mass of 90 and 95 GeV, respectively. For comparison, the predicted cross sections of other SM processes, producing the main background to the Higgs search, are: 98 pb for $e^+e^- \rightarrow q\bar{q}$ production, 16 pb for WW production and 0.62 pb for the ZZ production. In particular, the ZZ process in its $b\bar{b}X$ final states provides the “irreducible” background to the Higgs, in the Higgs mass region around 90 – 95 GeV. The measured cross section values for these processes are in very good agreement with the SM predictions⁵.

In the mass range of interest at LEP, the SM Higgs decays dominantly into $b\bar{b}$ and $\tau^+\tau^-$ pairs with branching ratios $\simeq 83\%$ and $\simeq 8\%$, respectively. There are four final states of interest for the HZ search: final state with four jets, $b\bar{b}q\bar{q}$, and 60% relative rate, with jets plus missing energy, $b\bar{b}\nu\bar{\nu}$, and 18% relative rate, with jets plus electron or muon pairs, $b\bar{b}e^+e^-$ or $b\bar{b}\mu^+\mu^-$, with 6.6% relative rate, and with jets plus tau pairs, $b\bar{b}\tau^+\tau^-$ and $\tau^+\tau^-q\bar{q}$, with 3.3% and 5.6% relative rate, respectively. Thus, the identification of b-quarks, commonly referred to as b-tagging, is an indispensable tool for an efficient Higgs search, as very powerful mean to reduce backgrounds containing light (non b) quarks.

The four LEP experiments use to combine the b-tagging information with event shape and kinematic variables into a global discriminant quantity (*e.g.* likelihood, neural network output or other)⁶. This quantity is a measurement of the “Higgs-likeness” of an event: background events are preferably distributed at low values while Higgs events have preferably large value of “Higgs-likeness”.

The total number of candidates (events with large value of the global discriminant) selected by the four experiments are reported in Tab. 1 and compared to the expectation from SM background processes and to the expected contribution of a 95 GeV SM Higgs signal. No significant excess of events is observed by any of the experiments over the expected background. The reconstructed Higgs mass distributions of the most significant candidates selected by the four LEP experiments are shown in Fig. 1. A slight excess of events over the expected background is observed by OPAL in the mass region around the Z mass. The LEP combined mass distribution⁷ is shown in Fig. 2, where the combined data (full dots) are compared to the total expected background (solid line) and to the sum of the background plus the expected signal for a 95 GeV SM Higgs (dashed line). Good agreement is observed between data and SM expected background. The largest “discrepancy” is observed in the mass bin 92 – 96 GeV with 47 events observed and 37.5 expected from SM background (see last line of Tab. 1). For comparison, a 95 GeV SM Higgs would contribute 24.6 events in this mass bin.

From the distributions (*e.g.* in mass) of the observed candidates and of the expected signal and background, it is possible to evaluate, for a given Higgs mass M_H , the probability CL_s that the Higgs signal be undetected in the observed data. Then, a Higgs signal of mass M_H is excluded with a confidence level $CL = 1 - CL_s$. The CL_s curves as function of M_H are shown in Fig. 3 for the four experiments⁶. The 95% CL lower limit on the Higgs mass is the value of M_H for which the CL_s is equal to 0.05 .

Together with the observed CL_s , calculated using the **observed** distribution, the four experiments report the expected CL_s ⁶, calculated using the **expected** background distribution. The expected CL_s is the average CL_s which would be measured if the experiment could be repeated a very large number

of times, in the hypothesis that no signal, but only background, would contribute to the observed candidates. The expected CL_s is used by the experiments to optimise the sensitivity of the analysis: more performant analysis should result, for a given M_H , into a lower CL_s , or, in turn, for a given CL_s , into a higher M_H limit.

The observed and expected limits on M_H and the probability to obtain a lower Higgs mass limit than the one actually observed are summarised in Tab. 2 for the the four experiments.

3 Higgs bosons in the Minimal Supersymmetric Standard Model

The production of h and A at present LEP energies is expected to occur through two processes: the Higgs-strahlung, $e^+e^- \rightarrow hZ$, and the associate hA production, $e^+e^- \rightarrow hA$. The cross sections for these processes are given by¹ $\sigma_{hZ} = \sin^2(\beta - \alpha)\sigma_{HZ}^{SM}$ and $\sigma_{hA} = \cos^2(\beta - \alpha)\bar{\lambda}\sigma_{HZ}^{SM}$, where σ_{HZ}^{SM} is the SM Higgs production cross section, $\bar{\lambda}$ is a kinematic factor depending on M_h , M_A and \sqrt{s} , while α is the mixing angle of the two CP-even Higgs fields. Due to the factors $\sin^2(\beta - \alpha)$ and $\cos^2(\beta - \alpha)$, the two Higgs production processes, hZ and hA , are complementary. At low $\tan\beta$, where $\sin^2(\beta - \alpha)$ is large, hZ production is dominant and practically the MSSM Higgs phenomenology reduces to the SM one, with similar cross sections and decays, except if $M_h > 2M_A$. Then $h \rightarrow AA$ decay is dominant and the SM Higgs signatures $b\bar{b}Z$ are replaced by $b\bar{b}b\bar{b}Z$. At large $\tan\beta$, where $\cos^2(\beta - \alpha)$ is large, hA production is dominant. As an example the hA cross section for $M_h = M_A = 80$ GeV and $\tan\beta = 50$ is 75 fb while the hZ cross section is approximately 6 fb. In the intermediate region, for $\tan\beta$ between approximately 2 and 5, the two processes give both sizeable contribution to the observable signal.

The dominant decays are expected to be $h, A \rightarrow b\bar{b}$ and $hA \rightarrow \tau^+\tau^-$ with branching ratios approximately 90% and 7%, respectively. Signal topologies considered for hA search are 4 or 6 b-jets or 2 isolated taus plus 2 b-jets. The experimental search for hA is very strongly based on b-tagging (even more than the SM-like hZ search), though other quantities, such as topological and kinematic variables are also used in combination with the b-tagging informations, to improve signal discrimination from background⁶.

As no significant excess is observed in any of the channels investigated, the results of the different searches are combined, using the same statistical methods as for the SM Higgs search and interpreted in terms of excluded regions in the MSSM parameter space. Differently from the SM, where the expected number of signal events depends only on M_H (at a given \sqrt{s}), in the MSSM, the expected number of signal events is calculated using cross sections and decay branching ratios which depend on the two masses M_h and M_A and other MSSM parameters. The signal efficiencies also depend, in general, on both Higgs masses M_h and M_A . A given point of the MSSM parameter space is then excluded if the observed CL is at least 95% for that parameter choice.

The interpretation of the results of the MSSM searches is, generally, done in the framework of the constrained MSSM, with a number of free parameters smaller than the general MSSM. The constrained model assumes a unified scalar fermion mass, M_{SUSY} , a unified gaugino mass, M_2 , and a unified sfermion tri-linear coupling, A . The remaining parameters of the model are: the top mass M_t , the SUSY Higgs mass parameter, μ , $\tan\beta$ and M_A . The experiments use to present their results as excluded regions in the planes $[M_h, \tan\beta]$, $[M_A, \tan\beta]$ or $[M_h, M_A]$. The other parameters of the model are either fixed (by ALEPH, DELPHI and L3) to the two set of values determining maximal mixing or no mixing in the stop sector¹, or a scan is performed (by OPAL) over these parameters, aiming to evaluate the effect of their variations on the excluded Higgs mass and $\tan\beta$ regions⁶.

Regions excluded using the data at 189 GeV, combined with the results from the previous runs at lower energies, are shown in Fig. 4: for L3, in the $[M_h, \tan\beta]$ plane and for DELPHI, in the $[M_A, \tan\beta]$. The lower limits on the Higgs masses and the excluded $\tan\beta$ ranges for maximal and minimal mixing assumptions are summarised in Tab. 3 for the four experiments.

4 Higgs particles beyond Minimal SUSY

4.1 Charged Higgs

Charged Higgs bosons are predicted by all models beyond the SM with more than one Higgs doublet. As mentioned in Introduction, the charged Higgs in the MSSM is expected to be heavier than 90 GeV in most of the MSSM parameter space when radiative corrections are included. Thus, if LEP found a charged Higgs with mass below the W mass this would very strongly constrain the MSSM parameter space.

Charged Higgs bosons are produced in pair via the s-channel process $e^+e^- \rightarrow H^+H^-$. The cross section depends only on the charged Higgs mass, M_{H^\pm} , and \sqrt{s} . As an example, at $\sqrt{s} = 189$, the cross section for $M_{H^\pm} = 70$ GeV is expected to be 0.25 pb. In the mass range accessible to LEP searches, the charged Higgs is expected to decay into a pair of quarks or into $\tau\nu$. The decay branching ratios are model dependent.

The search is done, independently of the decay branching ratios, in all three possible H^+H^- final states: $\tau\nu\tau\nu$, $\tau\nu q\bar{q}'$ and $q\bar{q}'q''\bar{q}'''$. The main background in all three search channels comes from WW production. In the four-jet channel additional background comes from $q\bar{q}$ events with hard gluon emission. The details of the analyses can be found in Ref. ⁸.

As no clear signal has been observed, limits on the charged Higgs mass as function of the branching ratio in $\tau\nu$, $BR(H^\pm \rightarrow \tau^\pm\nu)$, are derived. They are reported in Fig. 5 for ALEPH and OPAL. In Tab. 4, the lower limits on M_{H^\pm} set by the four experiments, are reported for $BR(H^\pm \rightarrow \tau^\pm\nu)$ equal to 1, 0 and independent of the decay branching ratio. This last one is the most conservative lower limit on M_{H^\pm} , valid for any value of $BR(H^\pm \rightarrow \tau^\pm\nu)$.

4.2 Invisible Higgs decays

The LEP experiments have also searched for hZ production with the Z decaying into quarks and leptons and the Higgs decaying into invisible particles. Invisible Higgs decays are possible in the framework of supersymmetric and non supersymmetric models. In the former case, the Higgs decays into a pair of lightest neutralinos, assumed to be stable and undetectable. In the latter case, the invisible particles can be, for example, Majorons⁹.

The experimental search is based on topological and kinematic characteristics of the signal events. After a number of cuts on the most discriminating variables, or on a global discriminant, combination of them, the distribution of the reconstructed missing mass, recoiling against the visible system, after constraining the visible mass to the Z mass, is inspected for any excess over the expected background.

As no significant excess is observed, a CL calculation is used to derive upper limits on the rate of invisible Higgs decays as function of the Higgs mass. Assuming hZ production cross section equal to the SM one and 100% branching ratio into invisible particles, the observed lower limit on the Higgs mass is 92.8 GeV from ALEPH⁹. The Higgs branching ratio into invisible particles, $BR(h \rightarrow \text{inv})$, is actually a free-parameter, which can assume any value between 0 and 1, depending on the model considered. The hZ production cross section, σ_{hZ} , is also model-dependent. Thus in a model-independent approach, limits on the neutral Higgs mass can be derived as function of $BR(h \rightarrow \text{inv})$ and σ_{hZ} . The results of the searches for visible (SM-like) and invisible Higgs decays can be combined, and the excluded region in the $[M_h, BR(h \rightarrow \text{inv})]$ plane can be determined for any value of σ_{hZ} . Assuming for σ_{hZ} the SM value, a lower limit on M_h of 90.5 GeV is found, independent of $BR(h \rightarrow \text{inv})$, as shown in Fig.6(left) from DELPHI⁹.

4.3 $H\gamma$ production, $H \rightarrow \gamma\gamma$ decays

Search for Higgs bosons have also been done in events with one, two or three photons^{10,11,12}. These final states can occur via the processes: $e^+e^- \rightarrow H\gamma \rightarrow b\bar{b}\gamma$, $e^+e^- \rightarrow HZ \rightarrow \gamma\gamma X$ and $e^+e^- \rightarrow H\gamma \rightarrow \gamma\gamma\gamma$. In the framework of the SM, these processes have very small rates, making them practically undetectable at LEP. However, in models beyond the SM, e.g with anomalous couplings of the Higgs

boson to photons and Z ^{11,12} or with fermiophobic Higgs bosons^{10,11,12}, the $e^+e^- \rightarrow H\gamma$ cross section and the $H \rightarrow \gamma\gamma$ decay rate can be largely enhanced (few order of magnitudes) with respect to the SM expectations, such that their signals could actually be observed at LEP.

No signal has been observed in any of the channels investigated, thus upper limits have been set on the rates of the different processes between few 10 and few 100 fb for Higgs masses up to 180 GeV. An example is given in Fig. 6(right) from L3 showing the experimental upper limit on the rate for $HZ \rightarrow \gamma\gamma\gamma$, $\sigma(H\gamma) \times \text{BR}(H \rightarrow \gamma\gamma)$, compared to the expected rates in the presence of anomalous Higgs couplings at $\sqrt{s} = 189$ GeV¹¹. The expected rates are plotted for different values of Λ , the typical energy scale at which new interactions should take place.

5 Conclusions

The data collected at $\sqrt{s} = 189$ GeV, corresponding to a luminosity of approximately 170 pb^{-1} per experiment, have opened new opportunities to search for Higgs bosons at LEP. The search for the SM Higgs boson has been performed in the mass range up to 95 GeV. Pair produced MSSM neutral Higgs boson have been searched for in the mass range up to ~ 80 GeV and charged Higgs bosons up to 75 GeV. Non-standard Higgs decays and production mechanisms have also been investigated, as decays into invisible particles or into photons and $H\gamma$ production. No significant excess is observed (yet), compared to the expected contribution from known SM physics processes, in any of the channels investigated.

In the next few months the centre-of-mass energy of the LEP collider will be raised up to 196–198 GeV. The luminosity expected to be delivered to each experiment is similar to the one of last year, between 150 and 200/pb. With such an amount of data we will be able to search for a Higgs boson with a mass up to 100 GeV. An additional similar amount of luminosity is expected to be delivered next year (2000) at $\sqrt{s} = 200$ GeV. This should allow to explore the mass range up to 105 GeV. Rather than with a list of limits from the previous searches, I prefer to conclude with this look at the (very near) future full of hope for the final realisation of our ‘Higgs dreams’!

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Table 1: The number of SM Higgs candidates selected by the four LEP experiments, compared to the expected background and to the contribution from a 95 GeV Higgs signal, for any value of the reconstructed mass, and (last line) within the mass bin 92–96 GeV.

	Obs, Data	Exp. Bkgd	Exp. Signal ($M_H=95$ GeV)
ALEPH	53	44.8	13.8
DELPHI	26	31.3	10.1
L3	30	30.3	9.9
OPAL	50	43.9	12.6
Total	159	150	46.4
$\Delta M_H = 92-96$ GeV	47	37.5	24.6

Figure 1: The distributions of the reconstructed mass for the SM Higgs candidates selected by the four LEP experiments

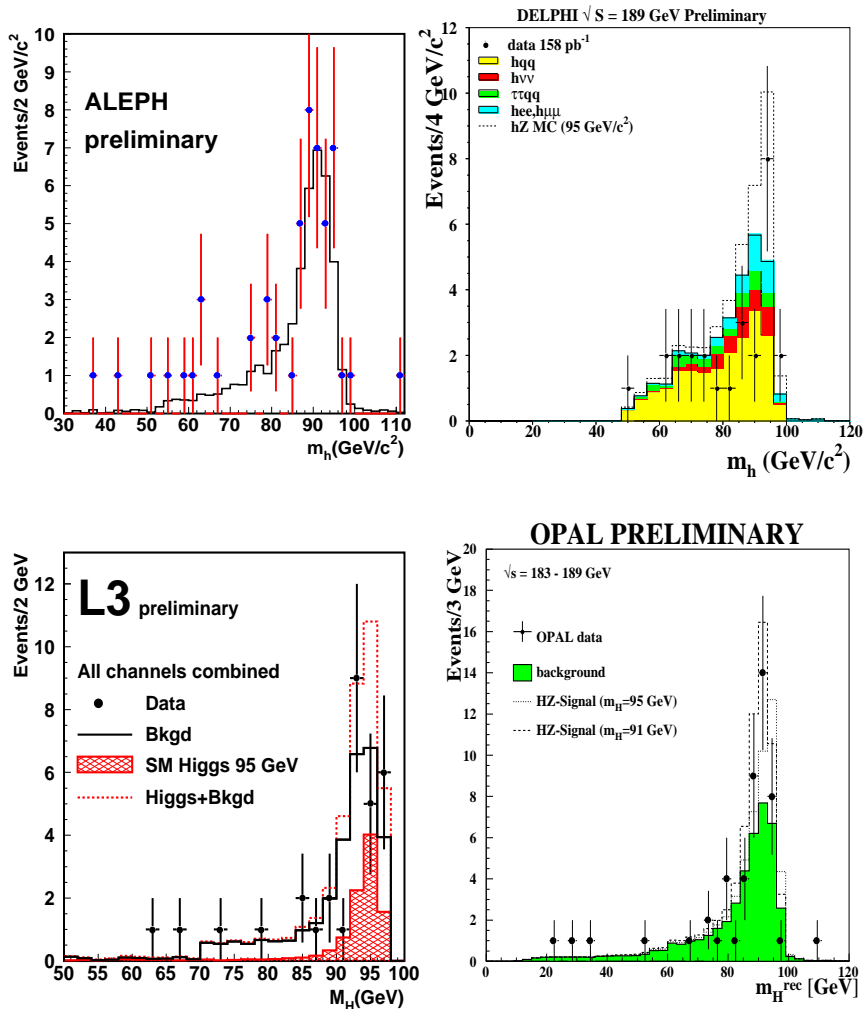


Figure 2: Combined LEP mass distribution⁷ of SM Higgs candidates selected by the four LEP experiments. The combined data (full dots) are compared to the total expected background (solid line) and to the sum of the background plus the expected signal for a 95 GeV SM Higgs (dashed line).

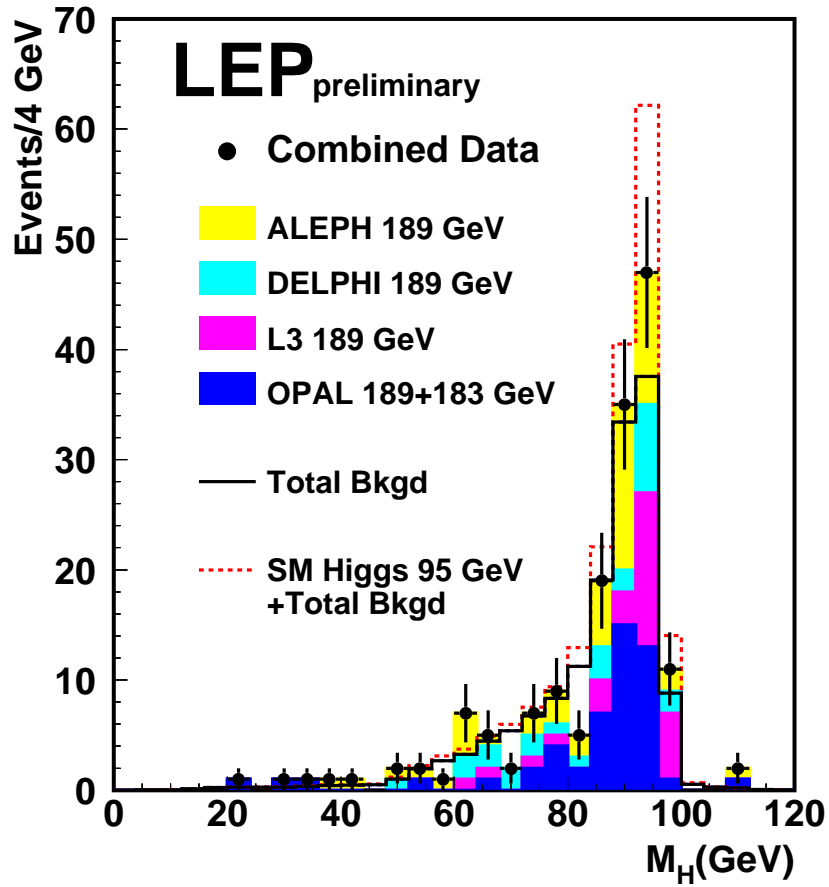


Figure 3: Results of the SM Higgs search for OPAL⁶. Left: limit on the production rate for the SM Higgs boson at 95% CL (solid line) compared to the number of expected signal events (dashed line) as a function of the Higgs mass. Right: The observed confidence level for an hypothetical SM Higgs signal (solid line) and the expected average confidence level (dashed line) for the hypothesis that no signal, but only background, contributes to the observed candidates.

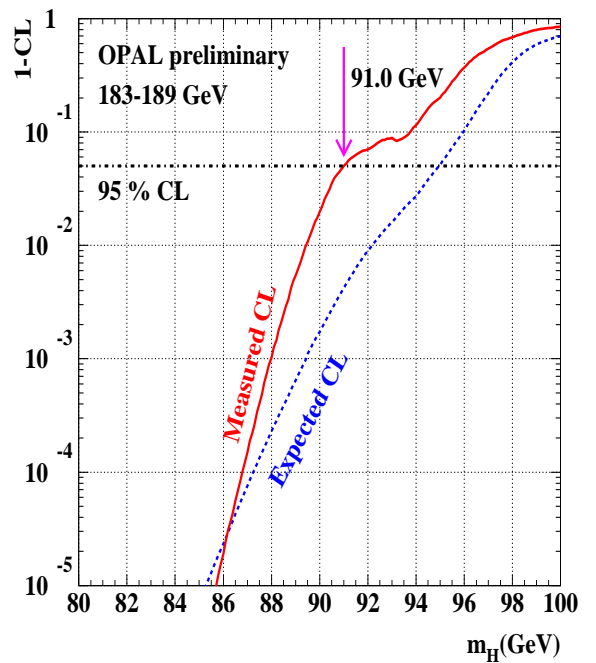
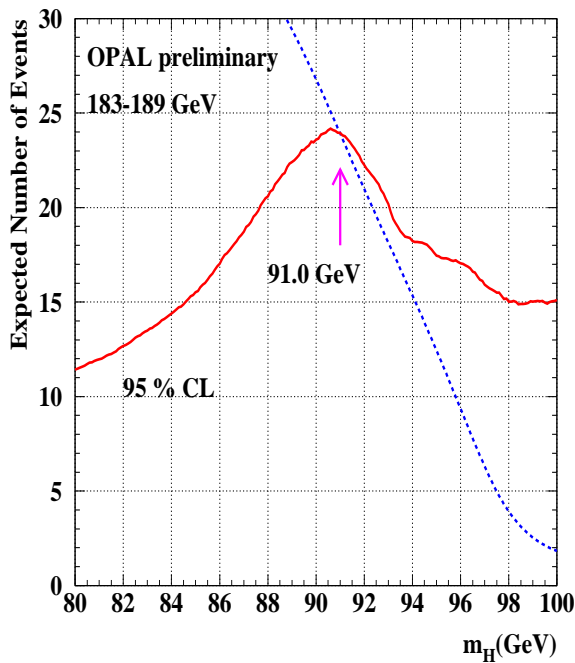


Table 2: Observed and expected lower limits on the SM Higgs mass together with the probabilities to obtain a limit equal to or lower than the one actually observed⁶.

	Observed	Expected	Probability
ALEPH	90.2 GeV	95.7 GeV	$\sim 1\%$
DELPHI	95.2 GeV	94.8 GeV	68%
L3	95.2 GeV	94.4 GeV	55%
OPAL	91.0 GeV	94.9 GeV	4%

Figure 4: Results of the MSSM Higgs searches. Left: Region (dark grey area) in the plane $[M_h, \tan \beta]$ experimentally excluded by L3 for maximal mixing in the stop sector (resulting in more conservative limits than for no mixing); the light grey regions are not theoretically allowed, in the hypothesis of maximal mixing; the dashed (dotted-dashed) line indicates the expected average (median) lower limits on M_h as function of $\tan \beta$ ⁶. Right: Regions in the plane $[M_A, \tan \beta]$ experimentally excluded by DELPHI⁶, for maximal mixing (grey region) and for no mixing (region on the left of the dotted line).

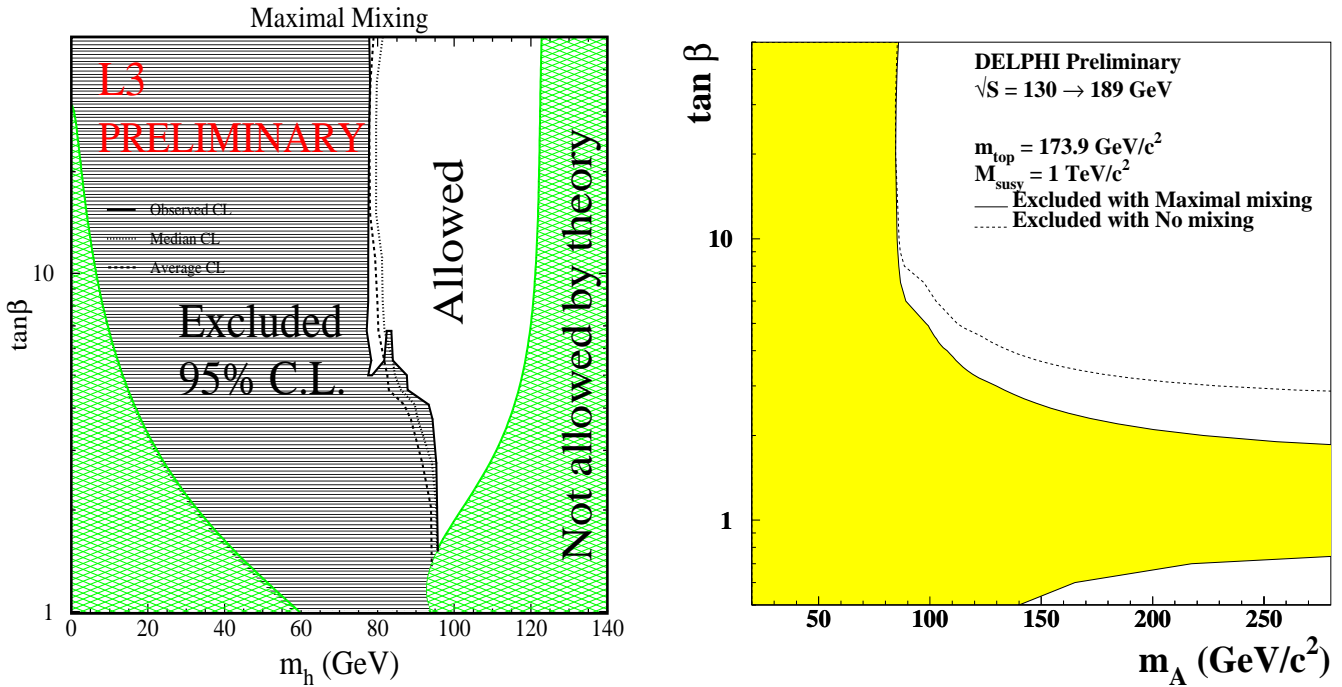


Table 3: Lower limits on the neutral MSSM Higgs masses and derived excluded ranges of $\tan \beta$ ⁶, for the hypotheses of maximal mixing and no mixing in the stop sector. The numbers in parenthesis are the expected average lower limits.

	m_h (GeV)	m_A (GeV)	$\tan(\beta)$ max. mix.	$\tan \beta$ no mix.
ALEPH	80.8 (82.5)	81.2 (82.7)	–	$1 < \tan \beta < 2.2$
DELPHI	83.5 (80.5)	84.5 (81.6)	$0.9 < \tan \beta < 1.5$	$0.6 < \tan \beta < 2.6$
L3	77.0 (77.8)	78.0 (77.9)	$1 < \tan \beta < 1.5$	$1 < \tan \beta < 2.6$
OPAL	74.8 (76.4)	76.5 (78.2)	–	$0.81 < \tan \beta < 2.19$

Figure 5: Charged Higgs mass lower limits⁸ as function of $BR(H^\pm \rightarrow \tau^\pm \nu)$ for ALEPH and OPAL. The experimentally excluded regions in the plane $M_{H^\pm}, BR(H^\pm \rightarrow \tau^\pm \nu)$, from the combination of the results in the different search channels, are shaded. The expected average lower limits are indicated by the dashed lines.

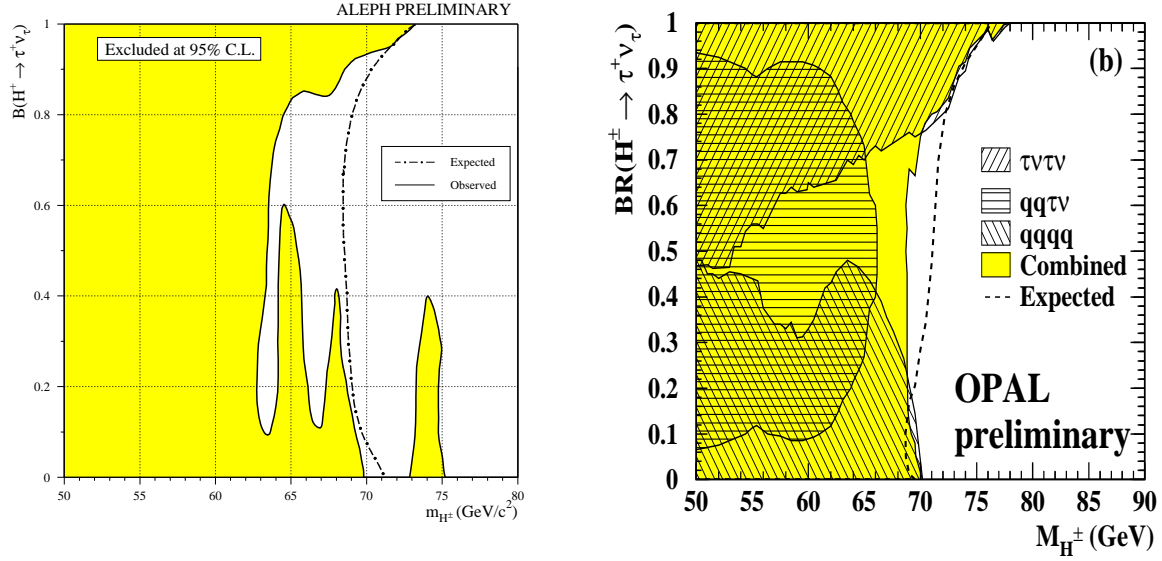


Table 4: Lower limits on the charged Higgs mass⁸ for any value of $BR(H^\pm \rightarrow \tau^\pm \nu)$ (decay-mode independent), and for $BR(H^\pm \rightarrow \tau^\pm \nu)=0$ or 1. Number in parenthesis are the expected lower limits.

	$BR(H^\pm \rightarrow \tau \nu) =$		
	any	0.	1.
	$m_{H^\pm} >$	$m_{H^\pm} >$	$m_{H^\pm} >$
ALEPH	62.5 (68.5)	69.8	73
DELPHI	65.1 (69)	72	78
L3	67.5 (70)	67.5	78.5
OPAL	68.7 (67)	70	78

Figure 6: Left: Higgs mass lower limits as function of $BR(h \rightarrow inv)$ for DELPHI⁹; the experimentally excluded region in the plane $[M_h, BR(h \rightarrow inv)]$, from the combination of the results of the searches for visible (SM-like) and invisible Higgs decays, is shaded. Right: experimentally excluded rates for $HZ \rightarrow \gamma\gamma\gamma$, $\sigma(H\gamma) \times BR(H \rightarrow \gamma\gamma)$, compared to the expected rates in the presence of anomalous Higgs couplings at $\sqrt{s} = 189$ GeV¹¹. The expected rates are plotted for different values of Λ , the typical energy scale at which the new interactions should take place.

