Review of Higgs boson searches at LEP

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Received 8 December 2003

The LEP collider allowed to search for Higgs bosons with various production and decay modes. Beside standard and supersymmetric Higgs bosons, LEP proved to be sensitive to more exotic particles, such as those with much lower production rates or with non-standard decays, like decays into invisible products, gauge bosons or into other Higgs bosons. Complementary constraints on Higgs boson masses were also derived from precise measurements of electroweak observables. In this article, LEP results as of summer 2003 are reviewed.

PACS: 62.20
Key words: LEP, Higgs bosons, scans of precise models, model-independent results

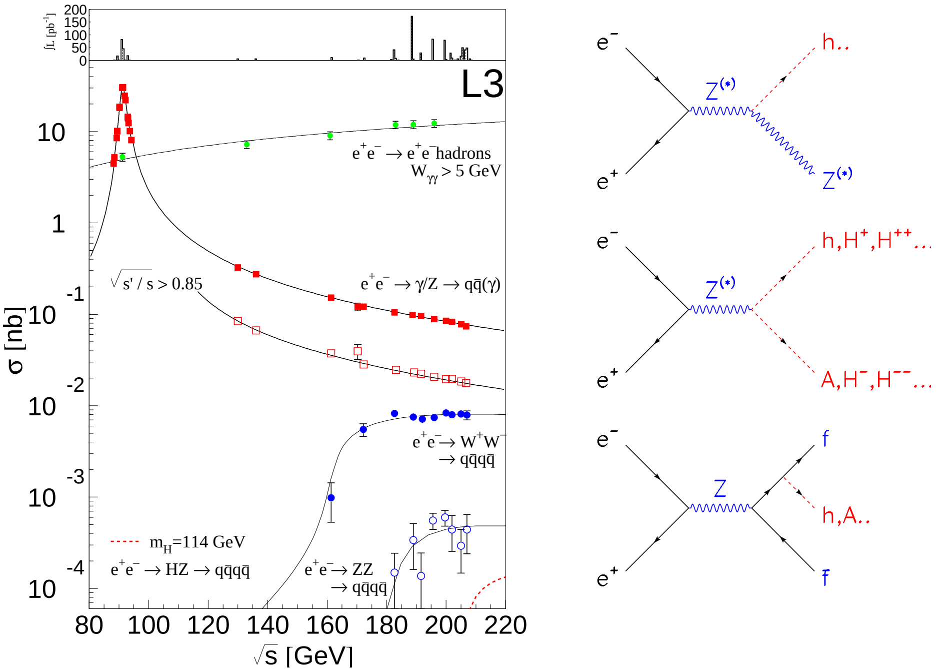
1 Introduction

LEP was operated in two subsequent phases. During the first period (LEP 1: 1989-1995), centre-of-mass energies were close to the Z mass, while they were gradually increased from 130 to 208 GeV in the second phase (LEP 2: 1995-2003). The LEP environment is illustrated in Fig. 1 which presents the cross-sections of the main e^+e^- processes in the Standard Model (SM) as a function of the LEP centre-of-mass energy, $\sqrt{s}$. The main production process at LEP 1 was the e^+e^- annihilation into an on-shell Z boson decaying subsequently into a pair of fermions. Altogether, the four LEP experiments recorded 17 millions of Z decays, allowing for precise tests of the theory of the electroweak interaction. At LEP 2, four-fermion production became important, especially that of W pairs. In total, around 50 thousand W^+W^- pairs were collected by the four experiments, leading to complementary tests of the electroweak theory. Since these tests proved that the electroweak sector of the SM is in remarkable agreement with data, down to the level of quantum corrections due to the pure weak interaction, the data to theory comparison based on precise measurements of the electroweak observables was soon used to derive constraints on the scalar sector of the theory, that is on Higgs boson masses. These powerful constraints complement the results of direct searches for Higgs bosons, which were also performed in LEP data, during both phases.

The experimental signatures of a direct production were not numerous, due to the limited number of production processes and decay modes. Fig. 1 summarizes the different production processes. The main one is the radiation of a Higgs particle off a $Z^{(*)}$ boson: this is the only[1]) process in the SM but it also exists in the Minimal Supersymmetric Standard Model (MSSM) or more generally in two Higgs Doublet

[1]) except for WW and ZZ fusions which interfere with HZ production in the case of $H\nu\nu$ and He^+e^- final states, respectively.

Fig. 1. Left: cross-sections of the main processes at LEP as a function of $\sqrt{s}$. L3 data are compared with SM predictions. The top profile is the integrated luminosity of L3. Right: Higgs boson production processes at LEP. From top to bottom: associated production of a Z and a neutral Higgs boson, pair-production of two neutral or charged Higgs bosons, radiation of a neutral Higgs boson off a Z decay fermion.



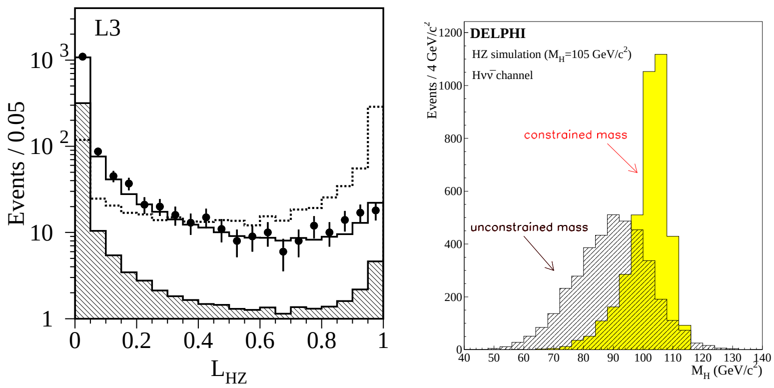
Models (2HDM) for all neutral Higgs bosons but for pseudoscalar ones. Beyond the SM, pair production of Higgs bosons, neutral or charged, becomes possible. Finally, a neutral Higgs boson can also be radiated off a Z decay fermion. This process, referred to as "Yukawa production" of a Higgs boson, is expected to give non negligible rates only at LEP 1 and in 2HDM.

As for the production processes, there are not so many Higgs boson decay modes since these are governed primarily by the Higgs particle masses rather than by details of the underlying model. In the kinematical range accessible at LEP, the main decays would be into the heaviest accessible fermions while other decays would be into gauge or Higgs bosons. There was thus a limited number of topologies to search for. Moreover, as e^+e^- collisions provided a clean experimental environment, almost all final states could be investigated, for masses up to the maximal experimental sensitivity, around 100 GeV/c^2. The results of these searches were then used to test precise models (SM, MSSM, 2HDM) and to derive model-independent results, that is limits on production cross-sections for specific decay modes.

2 Tools for the direct searches

Direct searches for Higgs bosons in LEP data were improved over the running period by optimising every stage of the analysis procedure. As decays into $b\bar{b}$ pairs was expected in most scenarios to be the dominant mode in a large part of the Higgs boson mass range accessible at LEP, b-tagging was a key-point of the data analysis. Relying on vertex detectors with typical asymptotical hit resolutions of 20 μm in Rϕ and 40 μm in Rz after alignement, b-tagging procedures used track impact parameters with respect to the primary vertex as basic inputs. An additional discrimination against non-b flavours was provided by adding information from reconstructed secondary vertices, such as the invariant mass of the system of secondary particles. Performant b-tagging procedures were thus obtained: as an example, an efficiency of 40% was achieved at the jet level for a purity of 90%, with a data to simulation agreement of 5% [1].

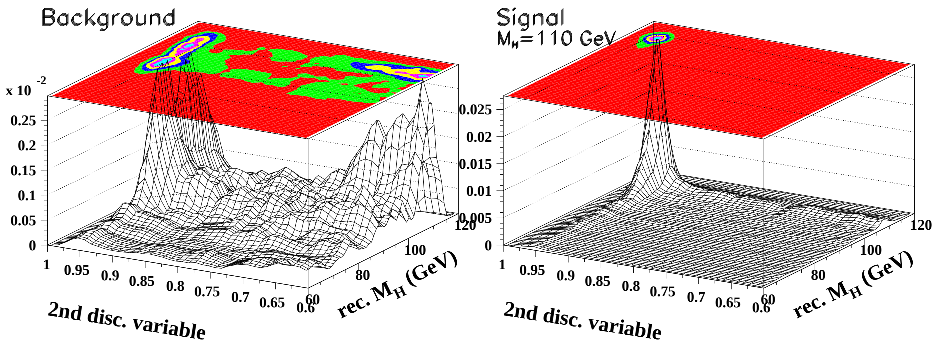
Fig. 2. Left: distribution of the likelihood variable in the L3 search for a SM Higgs boson in the fully hadronic mode, $Hq\bar{q}$. Data (dots) taken at $\sqrt{s}$ >206 GeV are compared with background expectations (solid lines) and with a simulated signal of mass 115 GeV/c^2 (dotted line). Right: distributions of the reconstructed Higgs boson mass in simulated signal events selected by DELPHI in the $H\nu\nu$ channel, before and after constraining the invisible system to be compatible with an on-shell Z. Although this channel is the least constrained final-state in Higgs boson searches, accounting for the existing constraint has a major effect on the mass reconstruction.



The event selection procedures were optimized in two other sectors, as illustrated in Fig. 2. To reach the best discrimination between a Higgs boson signal and the SM background, multidimensional analyses were used in most channels. Secondly, signal mass reconstruction was improved by using kinematic fits based on energy and momentum conservation with additional mass constraints whenever possible.

Finally, at the end of the analysis procedure, the search results were statistically interpreted to test for the existence of a Higgs signal. To make an ubiased and powerful test, the following scheme was adopted in most cases: event selections were stopped at a loose level (ie corresponding to tens or hundreds of events, depending on the channel); then, the rates of the selected events and their distributions according to one or two discriminant variables were used to test the compatibility of data with the background-only hypothesis and with that of background+signal. Simulation was used to predict the rates and distributions to compare data with. An example of distributions is given in Fig. 3. The most frequent tools used in the compatibility tests were the likelihood test-statistics (therafter denoted as -2LnQ) and the confidence levels calculated from the expected distributions of -2lnQ [2].

Fig. 3. Probability density functions for the SM background (left) and for a Higgs signal of 110 GeV/c^2 (right), as expected in the DELPHI search for the SM Higgs boson in the fully hadronic channel at $\sqrt{s}$ = 206 GeV. The two variables are the output of a neural network and the reconstructed Higgs boson mass.

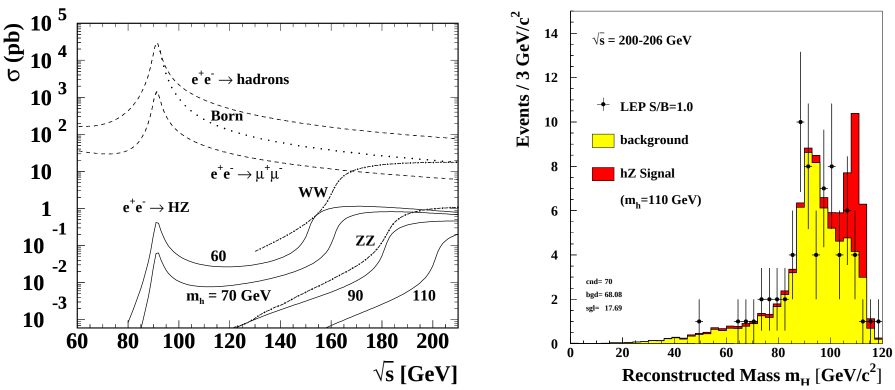


3 The SM Higgs boson

Searches for the SM Higgs boson, H, at LEP benefitted from low background rates and signal cross-sections which were expected to be large at low masses and slowly decreasing with increasing M_H, as depicted in Fig. 4. At masses close to the ultimate experimental sensitivity, which was 60 GeV/c^2 at LEP 1 and 120 GeV/c^2 at LEP 2, signal over background ratios reached values of 10^{-5} and 10^{-3}, respectively. Apart from these ultimate masses, searching for Higgs boson signals was possible with low integrated luminosities: thus at LEP 2, the fast rise of the signal cross-section, once $\sqrt{s}$ crossed the kinematical threshold of the HZ process (Fig. 1) for a given M_H, allowed to test masses up to a few GeV/c^2 below M_H with only a few tens of pb^{-1}. This is illustrated in Fig. 4 which shows that a Higgs boson with a mass of 110 GeV/c^2 was clearly ruled out with only a small fraction of the data recorded in the last year of running at LEP. Lower mass hypotheses were excluded by earlier data.

When extended to the whole data sample recorded in the last year of running

Fig. 4. Left: cross-sections of the main SM background processes (dotted lines), compared with the production cross-sections for of a few SM Higgs signals with masses from 60 to 110 GeV/c^2 (solid lines). Right: distribution of the reconstructed Higgs boson mass in events selected by the four LEP experiments when searching for a SM Higgs boson in data accumulated in the first part of year 2000. The highest centre-of-mass energy at that time was 206 GeV, with an integrated luminosity of 30 pb^{-1} per experiment at that energy. Data are compared with expectations from backgrounds and from a 110 GeV/c^2 signal.



at LEP, searches for the SM Higgs boson lead to the following exclusion limit:

$$M_H > 114.4 \text{ GeV}/c^2$$

at the 95% confidence level (CL). The exclusion limit expected in the absence of signal is 115.3 GeV/c^2.

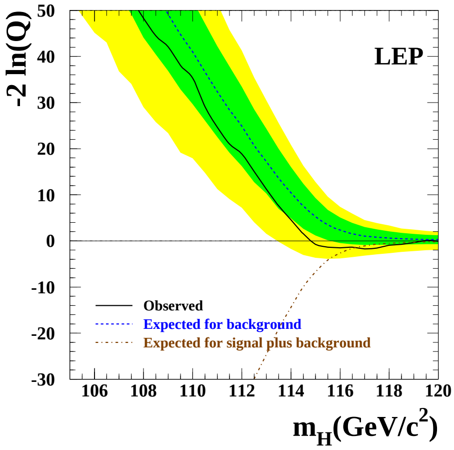
Moreover, when testing mass hypotheses close to the ultimate sensitivity, data depart from what is expected on average from background processes and are found to be consistent with the hypothesis of a signal of mass in the range between 115 and 118 GeV/c^2, as shown in Fig. 5. This result is essentially driven by a handful of high-mass events, selected in the fully hadronic final-state and characterized by a high content of b-quarks, as would be expected in the main channel for a SM Higgs boson. The compatibility of data with the hypothesis of a signal of 115 GeV/c^2 is 15%. However, data are also compatible with an upward fluctuation of the background rate, with a probability of 9%. All above numbers are final [2].

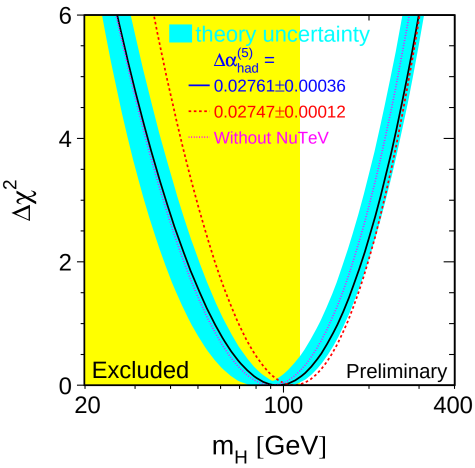
The results from direct searches are complemented by indirect constraints derived from precise measurements of electroweak observables. The latest status of these is represented in Fig. 5, which translates into the above lower bound [3]:

$$M_H < 219 \text{ GeV}/c^2$$

at the 95% CL. This result is still preliminary.

Fig. 5. Left: test-statistics measuring the compatibility of data with the hypothesis of a SM Higgs boson, H, as a function of m_H. The observed result is compared with the expectations from background only (the average curve and the 1 and 2 standard deviation intervals are shown) while the dash-dotted line is the expected location of the minima of -2lnQ if a signal of mass m_H would also be present. Right: χ^2 of the comparison between electroweak measurements and SM predictions, as a function of m_H. The solid line is the result of the global fit to data, the band represents the theoretical uncertainty due to missing higher orders in the predictions and the two dotted lines result from fits based on different inputs. The shaded region is excluded by direct searches at the 95% CL.





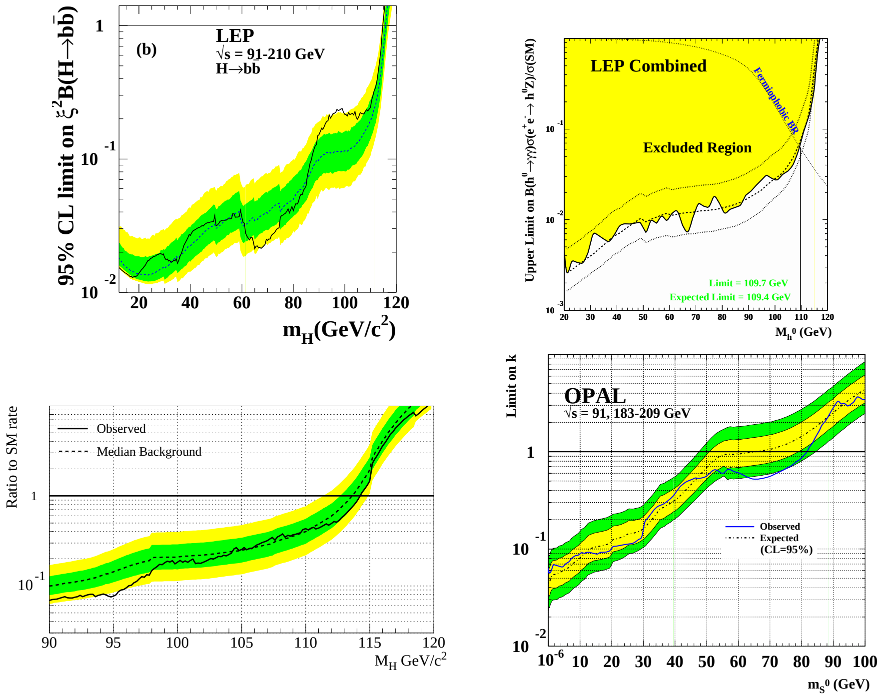
4 One Higgs boson with non-standard properties

The first step towards model-independent results consists in reinterpreting the results of the SM Higgs boson searches under the assumption of reduced HZZ couplings with respect to the SM. An upper bound on the production cross-section as a function of m_H can thus be derived in the two decay modes expected in the SM, the $b\bar{b}$ and $\tau\tau$ channels. As an example, Fig. 6 shows the final combined result [2] in the $b\bar{b}$ channel.

To go a step further, dedicated searches were also set up to investigate other decay modes: hadrons of any flavour, invisible decay products, pairs of gauge bosons. Results from preliminary combinations of LEP data [4, 5, 6] are shown in Fig. 6. These will be updated from final individual results [7, 8, 9, 10]. Last, in the HZ channel, the presence of a Z in the final state allows for a search independent of the Higgs boson decay mode. Such an analysis was done by OPAL [11], as also shown in Fig. 6.

Comparing the results obtained in all specific final states, typical upper bounds between 3 and 30% of the SM rates are obtained in the mass range from threshold up to m_H around 100 GeV/c^2, while mass limits between 113 and 117 GeV/c^2 are

Fig. 6. 95% CL upper bound on the product of the e^+e^- HZ production cross-section by the Higgs boson branching fraction in a specific decay mode, as a function of m_H. The HZ cross-section is normalised to that in the SM so that the bound applies directly to the square of the HZZ coupling. Different decay modes are presented: $b\bar{b}$, $\gamma\gamma$ and invisible decay products, while the bottom plot on the right is valid whatever the decay mode. The latter is from OPAL while all others combine LEP data.



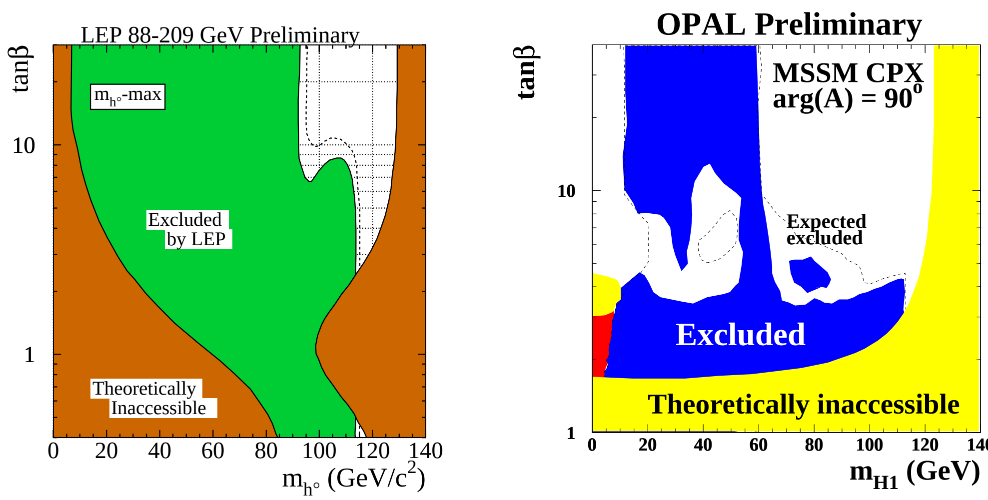
reached for SM couplings and branching fractions of 100%.

5 Neutral Higgs bosons in the MSSM

The MSSM is the most common model with two doublets of Higgs fields, which is the most natural way to go beyond the SM. In this framework, three neutral and two charged Higgs bosons are expected. Supersymmetry tightly constrains the masses and couplings of the neutral Higgs particles: at tree level, there are only two free parameters, usually chosen among the masses of the two lightest neutral Higgs bosons and tanβ, the ratio of the vacuum expectation values of the two Higgs doublets. Radiative corrections introduce a dependence on several other parameters. Setting values of these define precise MSSM scenarios.

If CP conservation is assumed in the Higgs sector, there are only two production processes which are relevant at LEP energies in most of the MSSM parameter space: the hZ process at low tanβ or large m_A and the hA pair production at large tanβ and moderate m_A, where h and A are the lightest scalar Higgs boson and the pseudoscalar Higgs boson, respectively. The h decay modes ressemble that in the SM so that the SM Higgs searches also apply in the MSSM case for the hZ process. Dedicated searches were needed to cover the hA process. Preliminary LEP results in the hZ and hA channels have been combined in the framework of a few representative benchmark scenarios, among which the m_h^{max} scenario, which leads to the highest values of m_h as a function of tanβ and thus is the most difficult case for LEP. In that scenario 95% CL lower bounds of 91.0 and 91.9 GeV/c^2 have been derived on m_h and m_A, respectively, and the range in tanβ between 0.5 and 2.4 has been found to be excluded at the 95% CL [12]. An example of result in that scenario is presented in Fig. 7.

Fig. 7. Left: preliminary LEP combined result in the CP-conserving MSSM m_h^{max} scenario, the least favorable scenario at LEP. Right: preliminary OPAL result in the CP-violating MSSM scenario with maximal effect from CP phases. In both figures, the excluded regions, both observed and expected, are at the 95% CL.



Since the time of that combination, progresses have been made, first on the theory side: with more complete two-loop order radiative corrections [13] the highest values of m_h are increased by a few GeV/c^2, which will have an impact on the excluded range in tanβ. Besides, experiments finalised the results of their searches in the hA process [14, 15] and made specific efforts to improve the coverage of regions of the MSSM parameter space dominated by cascade decays such as h$\rightarrow$AA, or becoming accessible at the highest energy of LEP through the production of the heavy scalar Higgs boson, H [16, 17]. Final combinations will include these refinements.

Relaxing the assumption of CP conservation in the Higgs sector was also studied. Such scenarios contain three neutral Higgs bosons with no defined CP properties, labelled H_1, H_2 and H_3 in order of increasing mass. The main production processes at LEP would be the H_1Z and H_2Z associated productions and the H_1 H_2 pair production. Beside the main fermionic decays which would be as in the CP conserving case, the cascade decay $H_2 \rightarrow H_1H_1$ would play a more important role than in the usual benchmark scenarios. Reinterpreting the results obtained in the hZ and hA searches and adding complementary analyses as that discussed in the next section, allows to test CP violating MSSM scenarios. An example of result is shown in Fig. 7 in the case of maximal effect from CP phases [15]: the excluded region is smaller than in the CP conserving framework due to much reduced H_1ZZ couplings in spite of Higgs boson masses within the kinematic range of LEP. The final combined MSSM results will include such scenarios.

Finally, a review of constraints on supersymmetric Higgs boson masses as deduced from precise electroweak measurements can be found in [18].

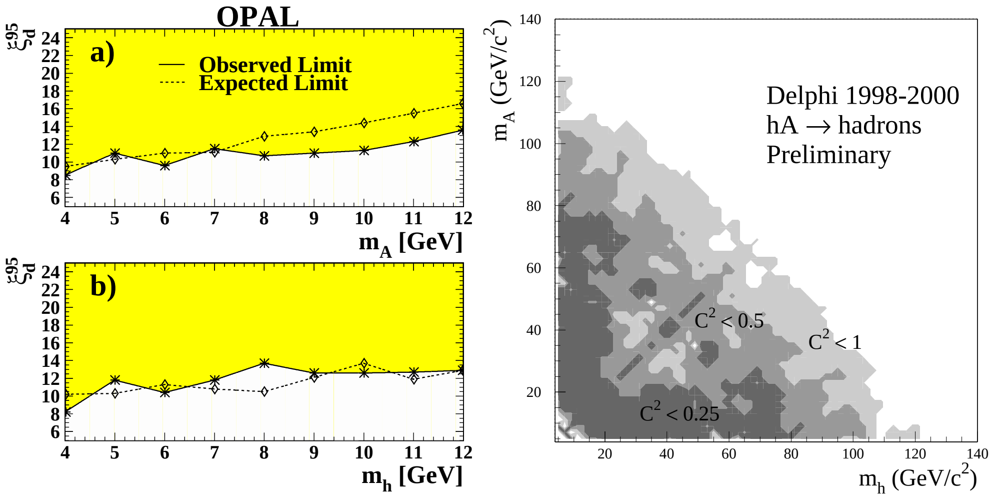
6 Neutral Higgs bosons in 2HDM

General two Higgs doublet models have the same content of Higgs particles as the MSSM but masses and couplings are no longer as constrained. More final states are thus to be expected and analysed. To quote only two examples, cascade decays such as h→AA which occurs in small regions of the MSSM parameter space are allowed in 2HDM as soon as kinematic conditions are fulfilled; similarly, Yukawa production (see Fig. 1) is negligible in the SM and experimentally excluded in the MSSM but it is possible in 2HDM. More general analyses were thus developped to complement the SM and MSSM searches in order to cover the additional less constrained 2HDM topologies.

The results of these searche were used to perform scans of the 2HDM parameter space [19] and more generally to derive model-independent limits on cross-sections for each production process and final-state. Examples of such results are presented in Fig. 8. Results for the Yukawa process are illustrated in the case of h and A bosons emitted off b quarks and decaying into τ pairs, bbA/h→bb$\tau\tau$ [20], but final states such as bbA/h→bbbb and $\tau\tau$A/h→ $\tau\tau\tau\tau$ were also studied [21]. As another example, cross-section limits were derived for hA production leading to hadrons of any flavour [8] or to four τ's [21]. These results complement those already discussed in section 4 for the hZ process. Finally, cascade decays in pairs of Higgs bosons or into a pair of a Z boson and a Higgs particle were also considered in both the hZ and hA production modes [21].

Examples of constraints deduced from precise electroweak measurements in the 2HDM framework can be found in [22].

Fig. 8. Left: OPAL upper bound on the enhancement factor of the h/A couplings to fermions wrt SM values as a function of h and A masses. Right: Regions of the m_h,m_A plane excluded by DELPHI searches for hA production leading to hadrons. The three shaded regions correspond to hA cross-sections equal to ($C^2 < 1$) or lower than ($C^2 < 0.5$, $C^2 < 0.25$) their maximal values in 2HDM. In both figures, all limits are at the 95% CL.

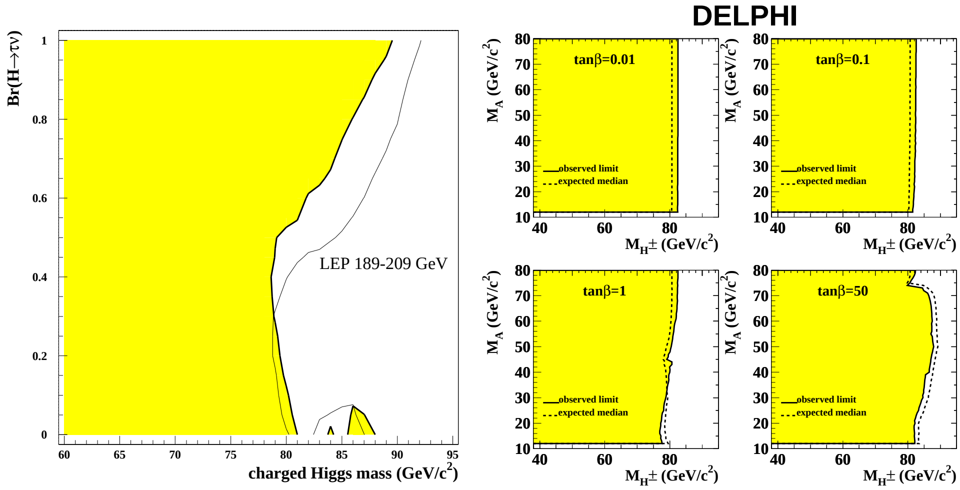


7 Charged Higgs bosons

In addition to three neutral Higgs bosons, 2HDM predict the existence of two singly charged Higgs bosons, $H^{\pm}$, which would be pair-produced at LEP (see Fig. 1). These particles were searched for primarily through their main fermionic decays, that is into either cs or $\tau\nu$ in the mass range explored at LEP 2. These decays are expected to be dominant in most of the parameter space of any 2HDM of type II. Assuming that these decays saturate the Higgs boson width, a lower bound of 78.6 GeV/c^2 was reached at the 95% CL on $m_{H^\pm}$ when combining all LEP data [23]. This limit is independent of the branching fractions of the particle, as illustrated in Fig. 9. Upper bounds on the production cross-section were also derived for each final state [23]. These combined results are still preliminary and will be updated when all individual results are published [24, 25].

Beside the fermionic decays, charged Higgs bosons can decay into WA pairs with branching fractions that can be significant, especially in 2HDM of type I. Specific searches for these decays were thus conducted [25]. Cross-section limits were derived and scans of the type I 2HDM parameter space were performed by combining the searches in all decay modes. Examples of such scans are given in Fig. 9. In that framework, an absolute lower bound of 76.7 GeV/c^2 was reached at the 95% CL on $m_{H^\pm}$ using only DELPHI data. Final combined results on charged

Fig. 9. Left: preliminary LEP combined result on 2HDM charged Higgs bosons with purely fermionic decays. Right: DELPHI result on charged Higgs bosons decaying either into fermions or into WA pairs, with branching fractions as predicted by 2HDM of type I. In both figures, the excluded regions are at the 95% CL.



Higgs bosons will include such scenarios.

Models with doubly charged Higgs bosons were also considered. These particles were searched for through their expected dominant decays into leptons. Pair and single productions were accounted for, as well as possible long Higgs boson lifetimes [26]. In all cases, individual lower bounds of more than 97 GeV/c^2 were reached at the 95% CL on the mass of such particles. These searches will also be combined.

8 Conclusions

Higgs boson searches at LEP covered all possible production modes and most of their expected decays. Results were used to test precise models, such as the SM, its minimal supersymmetric extension with or without CP conservation in the Higgs sector, as well as the more general two Higgs doublet model framework. Model-independent bounds on production cross-sections in each final state were also derived. Precise measurements in the electroweak sector added powerful and complementary constraints.

In the SM case, the Higgs boson is excluded at the 95% CL for all masses up to 114.4 GeV/c^2 and for all masses below 219 GeV/c^2. LEP data are compatible with the hypothesis of a signal in the mass range between 115 and 118 GeV/c^2 but the significance is weak.

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