Searches for Higgs bosons at LEP

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Abstract. Searches for Higgs bosons at LEP are summarized. No Higgs boson has been observed yet. For the Standard model Higgs boson, the lower bound on the mass is 113.3 GeV/c^2. In the Minimal Supersymmetric Standard Model, for representative scans of the SUSY parameters, the limits on the CP-even and the CP-odd neutral Higgs bosons masses are both 90.5 GeV/c^2. For the charged Higgs bosons predicted by two-doublet extensions of the Standard Model, a lower bound of 77.5 GeV/c^2 is obtained. Limits on Higgs bosons predicted by more exotic extensions of the Standard Model are also given.

INTRODUCTION

The existence of a Higgs boson is an essential prediction of the Standard Model (SM) which is the simplest model, and historically the first one, involving the Higgs mechanism. However, since no Higgs boson has so far been observed, many extensions of the SM, with more or less 'exotic' Higgs sectors, have been developed. In these extensions, one or several higgses are expected. Some of them could be relatively light, as in the Minimal Supersymmetric Standard Model (MSSM) where the lightest higgs should have a mass less than 130 GeV/c^2. Therefore, searches for higgses are very active at LEP since it has a mass reach of about 115 GeV/c^2. In this review, a description of these searches is given. In section 1, we start with a presentation of the main models tested at LEP. In section 2, the Higgs production processes at LEP energies are briefly described, then an example of analysis for the selection of events is presented as well as a statistical method designed to detect a possible discovery and to calculate the lower limits on the masses of the higgses. The results are finally presented in section 3.

I THEORETICAL MODELS TESTED AT LEP

•*SM and beyond.* In the SM, the Higgs sector is described by one doublet of complex scalar fields (four real components). At the electroweak symmetry breaking, three components give mass to the electroweak gauge bosons $W^\pm$ and Z. The remaining component gives rise to one physical state: the SM Higgs boson h. There are mainly two kinds of extensions of the SM: 1) models with one doublet, as in the SM, but with *anomalous coupling* of the Higgs boson to the gauge bosons and 2) the *Two Higgs Doublet Models* (2HDM), including the MSSM. More exotic extensions of the SM also exist [1] but will not be considered here since no direct search for the corresponding higgses has been recently performed at LEP.

•*Anomalous couplings in one doublet models.* In the SM, the Higgs boson couples to photons only through loops of charged particles. The branching ratio is small [$BR(h \to \gamma\gamma) \approx 10^{-3}$ for $m_h \approx 90$ GeV/c^2]. It can be increased, in one doublet models, by anomalous couplings to gauge bosons. These couplings are described by operators of strength f_i/Λ^2 where Λ is the scale of the interaction and the f_i are operators giving rise to different anomalous couplings such as $h\gamma\gamma$, $hZ\gamma$, hZZ, hWW [2].

•*2HDM.* In these models [1], two doublets of complex scalars H_1, H_2 correspond to eight real components. Three components give rise to the massive electroweak gauge bosons and the remaining five components result in five physical states: two neutral CP-even states h, H also called the *neutral scalars*, one neutral CP-odd state A also called the *neutral pseudo-scalar* and two *charged higgses* $H^\pm$. Six parameters are needed to describe the Higgs sector: the masses of the particles m_h, m_H, m_A, $m_{H^\pm}$, the mixing angle α for the two neutral scalars and the parameter $\tan\beta$ which is the ratio of the Vacuum Expectation Values of the two doublets. The 2HDM are classified in two *types*: the type I models in which only one doublet has couplings with fermions and type II models in which down-type fermions have couplings with one doublet and up-type fermions have couplings with the other doublet. The MSSM is a 2HDM of type II.

• *MSSM.* In the supersymmetric models [3] the Higgs sector is more constrained than in generic 2HDM's. In MSSM, only two parameters are needed: usually one uses m_A and $\tan\beta$ from which one can express the other parameters. For the masses, we have at the tree level:

$$\begin{cases} m_{H,h}{}^2 = \frac{1}{2}\left[m_A{}^2 + m_Z{}^2 \pm \sqrt{(m_A{}^2 + m_Z{}^2)^2 - 4m_A{}^2 m_Z{}^2 \cos^2 2\beta} \right] \\ m_{H^\pm}{}^2 = m_A{}^2 + m_W{}^2 \end{cases} \quad (1)$$

The first relation leads to the condition: $m_h < |\cos 2\beta|\, m_Z$ which means that the lightest scalar should have been already discovered at LEP! However, radiative corrections are not negligible. The largest contributions come from top and stop loops, because of the heavy mass of the top ($m_t \simeq 175$ GeV/c^2). Finally, including complete calculations of the radiative corrections, the MSSM upper bound for m_h is found to be: $m_h \lesssim 130$ GeV/c^2. This leaves a window to escape detection at LEP, which mass reach is $\simeq 115$ GeV/c^2.

• *Invisible Higgs.* In supersymmetry with R-parity conserved, the Higgs boson can decay into stable non-interacting particles (Lightest Supersymmetric Particle (LSP)) [4].

• *Fermiophobic Higgs.* In 2HDM of type I, the direct coupling to fermions $g_{hf\bar{f}}$ is proportional to $\cos\alpha/\sin\beta$. Then it can be suppressed by tuning α to $\frac{\pi}{2}$. The physical states with no coupling to fermions are called Fermiophobic Higgses [5].

II HIGGS PRODUCTION, EVENT SELECTION AND ANALYSIS

A Higgs production at LEP

The SM Higgs boson production process is the *Higgsstrahlung* process : $e^+e^- \to Z^* \to hZ$. The Higgs decays predominantly into $b\bar{b}$ and the main final states are: $b\bar{b}q\bar{q}$, $b\bar{b}\nu\bar{\nu}$ and $b\bar{b}l^+l^-$ ($l = e, \mu, \tau$).

For the 2HDM neutral higgses there are two processes: the Higgsstrahlung and the *associated production*: $e^+e^- \to Z^* \to hA$. In the MSSM, the cross-sections of the two processes are complementary: the Higgs strahlung cross-section is proportional to $\sin^2(\beta-\alpha)$ while the associated production cross-section is proportional to $\cos^2(\beta-\alpha)$. The h and the A decay predominantly into fermion pairs for the masses that LEP is sensitive to. An additional decay is possible: $h \to AA$ when $m_h > 2m_A$.

The 2HDM charged higgses are produced via the process of annihilation of a Z^* or a γ^*: $e^+e^- \to Z^*, \gamma^* \to H^+H^-$. The final states and experimental signatures will be described in detail in B.

The invisible higgs is produced via the Higgsstrahlung process. The cross-section can be expressed as $\sigma_{\rm inv.} = \xi^2 \sigma_{\rm SM}\,(e^+e^- \to hZ)$ $[0 < \xi^2 < 1]$ where ξ is a model dependent constant. The Higgs decays in two LSP. The experimental signature consists in two acoplanar leptons or quark jet and missing energy.

The fermiophobic higgs is produced via the processes: $e^+e^- \to hA$, $e^+e^- \to hA \to hhZ$, $e^+e^- \to hZ$ and $e^+e^- \to hA \to AAA$. The possible final states are: $\gamma\gamma A$, $\gamma\gamma b\bar{b}$, $\gamma\gamma\nu\bar{\nu}$, $\gamma\gamma q\bar{q}$, $\gamma\gamma\gamma\gamma\nu\bar{\nu}$, $\gamma\gamma\gamma\gamma q\bar{q}$ and $b\bar{b}b\bar{b}b\bar{b}$.

For the anomalous couplings in one doublet models, the production processes are: $e^+e^- \to h\gamma$, $e^+e^- \to hZ/\gamma^*$, $e^+e^- \to hZ$, $e^+e^- \to (ZZh)e^+e^-$ and $e^+e^- \to (WWh)\nu\nu$. The possible final states are: $\gamma\gamma\gamma$, $b\bar{b}\gamma$, $\gamma\gamma q\bar{q}$, $\gamma\gamma e^+e^-$ and $\gamma\gamma\nu\bar{\nu}$. Different kinds of limits have been measured at LEP: limit on f_i/Λ^2 (DELPHI), limit on the cross-section for the process $e^+e^- \to h\gamma \to \gamma\gamma\gamma$ (L3).

B Event selection: an example for charged higgses

The methods of search for the higgses in the different channels are relatively similar. We give here an example for the case of the charged higgses. In 2HDM different from the MSSM, $m_{H^\pm}$ can be lower than m_W. The charged higgs production cross-section is independent of model and has values in the range $0.12 - 0.27\,pb^{-1}$ for masses between 70 and 80 GeV/c^2 and for the 1999 LEP energies (192, 196, 200, 202 GeV/c^2). For an integrated luminosity of $230\,pb^{-1}$, which corresponds to the average luminosity by experiment at LEP in 1999, and for $m_{H^\pm} \simeq 75$ GeV/c^2, one expects ~ 50 H^+H^- pairs.

At LEP energies, the dominant decay modes are $H^- \to s\bar{c}$ and $H^- \to \tau\bar{\nu_\tau}$. Then the search is performed assuming $BR(H^- \to s\bar{c}) + BR(H^- \to \tau\bar{\nu_\tau}) = 1$, which leads to three final states topologies:

$H^+H^- \to c\bar{s}s\bar{c}$	:	four hadronic jets
$H^+H^- \to c\bar{s}\tau\bar{\nu_\tau}$	:	two hadronic jets, one tau jet, missing energy carried by one neutrino
$H^+H^- \to \bar{\tau}\nu_\tau\tau\bar{\nu_\tau}$	:	two tau jets, missing energy carried by two neutrinos

where hadronic jets (tau jets) are jets with high (low) multiplicities.

Different processes contibute to the background to Higgs signal, according to the final state. For instance, in the case of the $\bar{\tau}\nu_\tau\tau\bar{\nu_\tau}$ final state, the main background processes are the following: 1) WW where each of the two W's emits a τ and a neutrino, 2) ZZ where one Z decays in two τ and the other Z decays in two neutrinos, 3) $\tau\tau\gamma$ where an incident electron emits a photon which is lost in the beam pipe, simulating the missing energy, and 4) $\gamma\gamma\tau\tau$ where the two incident electrons emit two photons exchanging a neutrino and giving rise to the two τ's (multiperipheral diagram) and where the two outcoming electrons are lost in the beam pipe.

An example of distribution of reconstructed charged Higgs mass is given in Fig.1. The expected signal would appear as a small excess in the data. For a typical value of $m_h = 75$ GeV/c^2, the signal would produce 72.0 events for the $c\bar{s}s\bar{c}$ final state and 40.6 events for the $c\bar{s}\tau\bar{\nu_\tau}$ final state while the numbers of expected (observed) events for these two final states are respectively 2245.5(2208) and 471.6(488) [6].

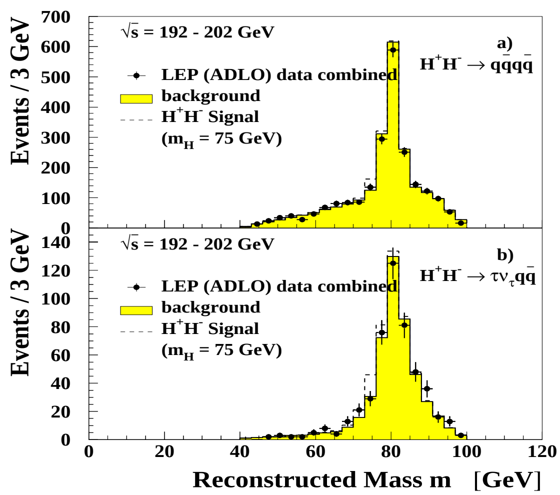

FIGURE 1. Distribution of reconstructed charged Higgs mass combining the data of the four LEP experiments (ADLO) at energies from 192 to 202 GeV/c^2. Upper part: $H^+H^- \to c\bar{s}s\bar{c}$ channel; lower part: $H^+H^- \to c\bar{s}\tau\bar{\nu_\tau}$ channel where $BR(H^+ \to \tau^+\nu) = 0.5$ is assumed. Figure reprinted from Ref. [6].

C Statistical method for discovery and limit on the mass

A statistical method is performed to analyse the numbers of observed events and to extract from them quantitative informations in terms of discovery or mass limit. For each mass hypothesis m_h, a global test-statistic X_{m_h} is constructed to classify the experimental result between background-like and (signal+background)-like situations. The value of X_{m_h} is calculated for the data ($X_{m_h}^{Obs}$) and for a large number of Monte-Carlo experiments ($X_{m_h}^{MC}$). Two basic 'confidence levels' are then calculated: $CL_b(m_h)$ (probability that $X_{m_h}^{MC}$ is more b-like than $X_{m_h}^{Obs}$) and $CL_{s+b}(m_h)$ (probability that $X_{m_h}^{MC}$ is less (s+b)-like than $X_{m_h}^{Obs}$). Finally, two quantities are used to express the results: $1 - CL_b(m_h)$ (indicator for a possible signal) and $CL_s(m_h) = CL_{s+b}(m_h)/CL_b(m_h)$ (indicator for lower bound on m_h). In abscence of signal the quantity $1 - CL_b(m_h)$ is close to 0.5. A Higgs boson with true mass m_0 would produce a drop in this quantity for $m_h \simeq m_0$, the 5σ (3σ) discovery corresponding to the value 5.7×10^{-7} (2.7×10^{-3}). The lowest value of m_h which yields $CL_s(m_h) = 0.05$ defines the $95\%CL$ lower limit (observed limit). The average value $< CL_s(m_h) >_b$ obtained from simulated 'background only' experiments indicates the expected range of sensitivity for exclusion (expected limit) [6].

III RESULTS

The statistical method described above was used to search for the different higgses: SM Higgs boson, MSSM neutral higgses, 2HDM charged higgses, invisible higgs, fermiophobic higgs. So far, no direct evidence for the existence of these Higgs bosons has been found. The limits, corresponding to a combination of the four LEP experiments, are listed in table 1. For the MSSM, excluded domains in $\tan\beta$ are also given.

MSSM benchmark scans. For the MSSM, the results are presented for a constrained MSSM with seven parameters: $M_{\rm SUSY} = 1\,\text{TeV}$, $M_2 = 200\,\text{GeV}$, $m_{\tilde{g}} = 800\,\text{GeV}$, $\mu = -200\,\text{GeV}$, $m_A = 1\,\text{TeV}$, $0.4 < \tan\beta < 50$ and $X_t = A - \mu\cot\beta$. The parameter M_1 is derived from M_2 using the relation $M_1 = \frac{5}{3}M_2\tan^2\theta_W$, where θ_W is the weak mixing angle. Since the main correction to m_h stems from the $t - \tilde{t}$ sector, the limit on m_h is sensitive to the stop mixing parameter X_t. Two scenarios are considered: the *maximal m_h scan scenario* ($X_t = 2M_{\rm SUSY}$) and the *no mixing scenario* ($X_t = 0$). The maximal m_h scan scenario is designed to maximize the largest value of m_h allowed by the model at each value of $\tan\beta$ [6].

TABLE 1. Limits on the masses of the higgses for different models and exclusion in $\tan\beta$ for MSSM. LEP combination, 00/07/20.

		Observed limit	Expected limit
h (SM)		113.3 GeV/c^2	113.4 GeV/c^2
h (MSSM)	max m_h scan	90.5 GeV/c^2	92.2 GeV/c^2
	no mixing	90.5 GeV/c^2	92.4 GeV/c^2
A (MSSM)	max m_h scan	90.5 GeV/c^2	92.8 GeV/c^2
	no mixing	90.5 GeV/c^2	92.9 GeV/c^2
Excluded domains	max m_h scan	$0.5 \le \tan\beta \le 2.3$	$0.5 \le \tan\beta \le 2.3$
in $\tan\beta$ (MSSM)	no mixing	$0.4 \le \tan\beta \le 7.7$	$0.4 \le \tan\beta \le 8.6$
$H^\pm$ (2HDM)		77.5 GeV/c^2	78.8 GeV/c^2
Invisible Higgs		107.7 GeV/c^2	109.9 GeV/c^2
Fermiophobic Higgs		106.4 GeV/c^2	105.6 GeV/c^2

CONCLUSION

A large effort has been performed at LEP to search for many kinds of Higgs bosons with highly sophisticated data analysis techniques.

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