# Exotic Higgs boson searches at LEP

Marcel Stanitzki*
Institut für experimentelle Kernphysik
Universität Karlsruhe
Wolfgang-Gaede-Strasse 1, D-76128 Karlsruhe

**Abstract**

Searches for exotic Higgs bosons in extended models have been performed using the LEP data set. These searches can be separated in two classes, either processes, that do not exist in the Standard Model (SM) or processes, that are very rare in the SM. The results obtained are then used to exclude such signatures with the focus on being as model independent as possible, thus not concentrating on standard supersymmetric Higgs searches

## 1 Introduction

In the Standard Model (SM) the Higgs boson is mainly produced via the Higgs-Strahlung process and decays then preferably in b quarks in the mass range accessible at LEP. However there are many models that predict an extended Higgs sector like a models with two Higgs doublets or Higgs triplets which introduce new physical Higgs boson states like charged or doubly charged Higgs bosons or enhance production processes like Yukawa Higgs production. In other cases, the decay properties of the Higgs boson are modified, e.g. the Higgs is only decaying to bosons or generally into hadrons, the Higgs couplings are modified directly, or decays into new particles, that do not interact with a detector, are possible. The four LEP collaborations have searched for these predicted signatures using the large LEP data set. The focus of these searches was to exclude these signatures in a very general way and not searching for specific models. The final goal is, that any model that predicts such decays can be excluded using the results from these searches even after the end of LEP analyses.

## 2 Charged and Doubly charged Higgs bosons

Charged Higgs bosons are predicted in the Minimal Supersymmetric Standard Model (MSSM) and in general 2 Higgs Doublet Models (2HDM). The charged Higgs bosons are produced in pairs, the production process at LEP is sketched in Fig. 1. In the MSSM, it usually assumed, that $m_H^{\pm}$ is heavier than $m_W$, but searches at LEP were conducted in the frame of the 2HDM, which has no such constraint.

*Talk given on behalf of the four LEP Collaborations.

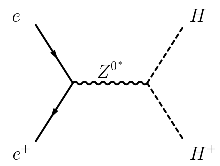


Figure 1: The production process for charged Higgs bosons at LEP

The decays of a charged Higgs can be separated into two classes, decays into fermion pairs or fermiophobic decays. In the first case, the charged Higgs decays into the heaviest accessible fermion pairs, which are at LEP $c\bar{s}$ or $\tau^-\bar{\nu}_\tau$. Three kinds of analyses were conducted by the LEP collaborations [1] in order to search for charged Higgs production:

$$
\begin{array}{lcl}
H^+H^- \rightarrow & c\bar{s}\bar{c}s & \text{Fully hadronic decay} \\
H^+H^- \rightarrow & c\bar{s}\tau^-\bar{\nu}_\tau & \text{Semileptonic decay} \\
H^+H^- \rightarrow & \tau^+\nu_\tau\tau^-\bar{\nu}_\tau & \text{Fully leptonic decay}
\end{array}
$$

The main backgrounds in these kind of searches were the production of $W^+W^-$ pairs and to a lesser extend two fermion processes. In order to set a general limit on a charged Higgs bosons decaying into fermion pairs, the mass limit was calculated as a function of the branching ratio $H^\pm \rightarrow \tau^-\bar{\nu}_\tau$ combining the three analyses. The excluded mass range is shown in Fig. 2, the lowest excluded mass at 95 % Confidence Level (CL) is 78.8 GeV/c$^2$, the expected 95 % CL limit is 78.6 GeV/c$^2$. The effect of the $W^+W^-$ pair production at a mass of 80.4 GeV/c$^2$ can be seen in this plots, since the sensitivity beyond the W mass is very limited for both the semileptonic and the fully hadronic decay channels. This can be also seen in the cross section limit for a fully hadronically decaying charged Higgs (see Fig. 2), where the sensitivity to such a process is significantly lower around the W mass.

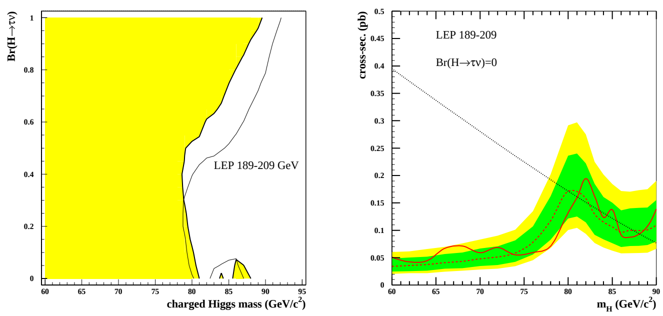


Figure 2: Searches for charged Higgs bosons: The excluded charged Higgs mass as a function of the branching ratio $H^\pm \rightarrow \tau^-\bar{\nu}_\tau$ (left) and the cross section limit for fully hadronically decaying charged Higgs boson are shown (right).

The second option for charged Higgs decays is the so-called fermiophobic scenario, where the charged Higgs decays into $W^*A$, where A is the neutral pseudoscalar Higgs boson. This can for example occur in 2HDM type-I models, where only one Higgs doublet couples to the fermions. By the appropriate choice of the mixing angles the couplings of the charged Higgs boson to the fermions can be switched off and only bosonic decays are possible. These fermiophobic decays lead to multi-jet final states, which are quite different to the signatures considered before. The final states searched for by the OPAL collaboration [2] are:

$$
\begin{aligned}
H^+H^- &\rightarrow W^{*+}AW^{*-}A &&\rightarrow q\bar{q}'b\bar{b}q\bar{q}'b\bar{b} \\
H^+H^- &\rightarrow W^{*+}AW^{*-}A &&\rightarrow q\bar{q}'b\bar{b}l\bar{\nu}_l b\bar{b} \\
H^+H^- &\rightarrow W^{*+}AH^- &&\rightarrow q\bar{q}'\tau^-\bar{\nu}_\tau
\end{aligned}
$$

The dominant background in this searches again originates from four fermion processes,

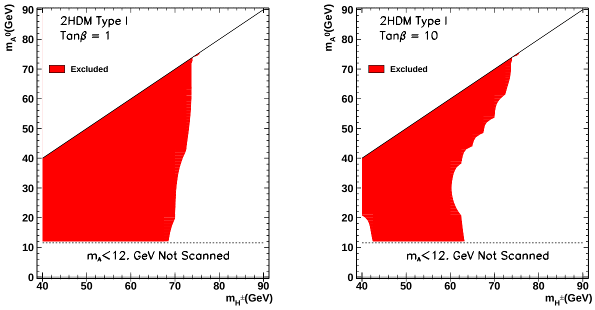


Figure 3: Searches for charged Higgs bosons: The excluded area in the $m_H^\pm$-$m_A$ plane in a fermiophobic 2HDM type I scenario for two values of $\tan\beta$ : 1 (left) and 10 (right)

the identification of b quarks and multi-jet clustering were then used to suppress the bulk of the background. The results were then used to exclude parts of the $m_H^\pm$-$m_A$ plane in the fermiophobic 2HDM type I scenario, choosing different values for $\tan\beta$. (see Fig.3)

Doubly charged Higgs bosons can occur in left-right supersymmetric models with Higgs triplets. These Higgs bosons can be relatively light, so they can be in the kinematic reach of LEP. The doubly charged Higgs bosons are produced in pairs, the production process is shown in Fig. 4. One should keep in mind, that the production cross sections of $e^+e^- \rightarrow H_L^{++}H_L^{--}$ and $e^+e^- \rightarrow H_R^{++}H_R^{--}$ are different.

The doubly charged Higgs bosons only couple to leptons, gauge bosons and other Higgs bosons. Since decays into electrons or muons are heavily constraint, the decays in $\tau$-leptons is favoured. The searches for such the decay $H^{++}H^{--} \rightarrow \tau^+\tau^+\tau^-\tau^-$ have been conducted by both DELPHI [3] and OPAL [4]. The background for this kind of processes is very small and consists mainly of four fermion processes. The 95 % CL limits by DELPHI on the masses of $H_L^{\pm\pm}$ and $H_R^{\pm\pm}$ are 99.6 GeV/c$^2$ and 99.1 GeV/c$^2$ respectively. The plot showing the reconstructed mass for this search is shown in Fig. 5. The results from OPAL were used to set a 95 % CL limit on the cross-section, which is shown for both $H_L^{\pm\pm}$ and $H_R^{\pm\pm}$ in Fig. 5.

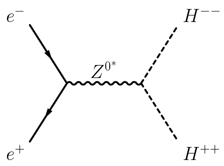


Figure 4: The production process for doubly charged Higgs bosons at LEP

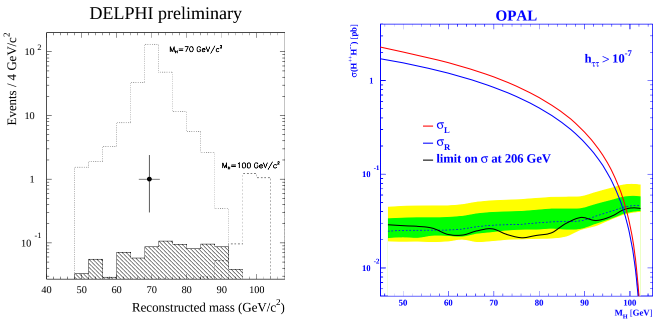


Figure 5: Searches for doubly charged Higgs bosons: The reconstructed mass for data (dots), background (filled histogram) and the expected signal simulation (white histogram) (left) and the the 95 % CL limit on the cross section (right)

## 3 Fermiophobic Higgs decays

An interesting decay mode is the fermiophobic decay of a neutral Higgs boson. This can happen for example in type I 2HDM, when one chooses again the mixing parameters accordingly. The remaining dominant decays channels for the Higgs boson are then $h \to \gamma\gamma$ and $h \to WW^*$. For the largest part of the mass range accessible at LEP, the decay $h \to \gamma\gamma$ is the most important channel. This decay mode is also possible in the SM, but very rare (($\mathcal{O}(10^{-3})$)) and has a quite remarkable signature with two high energetic photons from the the Higgs decay. The following channels have been evaluated by the four LEP experiments [7]:

$$\begin{aligned} e^+e^- &\to hZ \to \gamma\gamma q\bar{q} \\ e^+e^- &\to hZ \to \gamma\gamma \nu\bar{\nu} \\ e^+e^- &\to hZ \to \gamma\gamma l^+l^- \end{aligned}$$

The background in this searches consisted mainly of two photon and $Z\gamma^*$ processes. Since the two high energetic photons are the main signature, efficient photon identification algorithms have been used. The results were then combined using the fermiophobic benchmark scenario shown in Fig. 6. The 95 % CL limit set in this framework is 108.2 GeV/c$^2$ (109.0 GeV/c$^2$ expected).

The second decay channel LEP has sensitivity to is the decay of the Higgs into $WW^*$. This decay also occurs in the SM, for Higgs masses between 110 and 115 GeV/c$^2$ but its branching ratio is about 4 to 8 %. The difficulty in this topology lies in the large amount

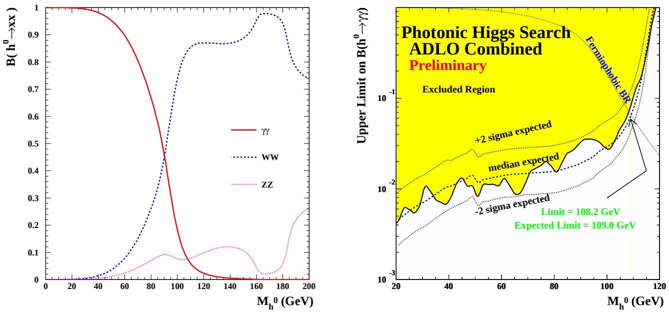


Figure 6: Searches for fermiophobic Higgs bosons: Shown are the branching ratios in the fermiophobic benchmark scenario (left) and the 95 % CL mass limit set by LEP (right)

of different final states due to the decay of the two W bosons. Most of these final states are quite spectacular events with a lots of tracks. A search for such a process has been done by the L3 collaboration [8] looking in the following final states:

$$\begin{array}{ll} hZ \to WW^*Z \to q\bar{q}'q\bar{q}'q\bar{q} & hZ \to WW^*Z \to q\bar{q}'l\bar{\nu}'q\bar{q} \\ hZ \to WW^*Z \to q\bar{q}'l\bar{\nu}'\nu\bar{\nu} & hZ \to WW^*Z \to q\bar{q}'q\bar{q}'\nu\bar{\nu} \\ hZ \to WW^*Z \to l\bar{\nu}'l\bar{\nu}'q\bar{q} & \end{array}$$

Additionally, L3 has also searched for a Higgs decaying into $ZZ^*$, which has a similar signature, but the branching ratios for this decay mode are much smaller. All these channel were then combined and a 95 % CL level mass limit of 104.2 GeV/c$^2$ (107.5 GeV/c$^2$ expected) in the fermiophobic benchmark scenario was calculated. The excluded mass region is then shown in Fig. 7. As one can see in this plot, the sensitivity of this search is too small to be sensitive to a SM Higgs decaying into $WW^*$.

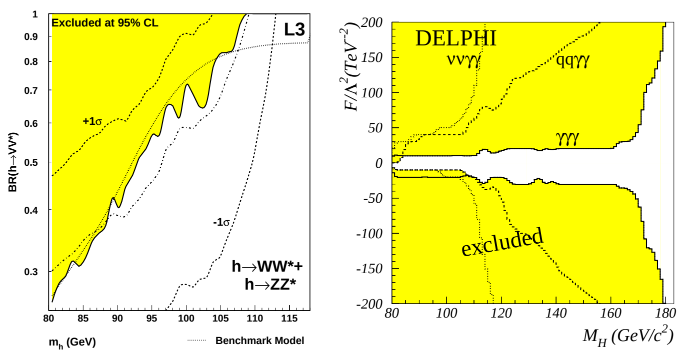


Figure 7: Searches for fermiophobic Higgs bosons and for anomalous couplings The excluded Higgs mass region in the fermiophobic benchmark (left) and the excluded region in the $\frac{F}{\Lambda}$-$m_H$ plane with the contributions of the different channels.

## 4 Anomalous Couplings

In this class of models, the SM couplings might be modified by new interaction at higher orders. The strength of these couplings are parametrised using the $\frac{f_i}{\Lambda}$ coefficients. These new couplings can lead to tree-level $H\gamma\gamma$ or $HZ\gamma$ vertices. An interesting feature of these new couplings is, that Higgs masses close to centre-of-mass energy are now accessible due to the $H\gamma \to \gamma\gamma\gamma$ process. The DELPHI collaboration [9] has searched for such processes in the following channels:

$$\begin{array}{ll} H\gamma \to \gamma\gamma\gamma & HZ \to \gamma\gamma q\bar{q} \\ H\gamma \to b\bar{b}\gamma & HZ \to \gamma\gamma\nu\bar{\nu} \end{array}$$

The search strategies and backgrounds are quite similar to the searches for the fermiophobic $h \to \gamma\gamma$ process. The results of these searches were then used to constrain the $\frac{f_i}{\Lambda}$ parameters. The results is shown in the $\frac{F}{\Lambda}$-$m_H$ plane (see Fig. 7), where all $f_i$ were set to a common value $F$. Also shown are the contributions of the different channels. It is clearly visible, that the $h\gamma \to \gamma\gamma\gamma$ channel is the most sensitive channel.

## 5 Yukawa Higgs production

The Yukawa process (see Fig.8) is a production process that can also occur in the SM, but is strongly suppressed there. It can, however play an important role in the 2HDM, where

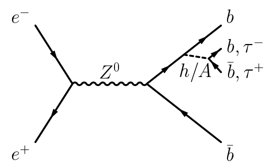


Figure 8: The Yukawa production process

it can be strongly enhanced, especially for low Higgs masses. Two different channels have been considered in the searches done by the DELPHI [5] and OPAL [6] collaborations:

$$\begin{array}{rcl} e^+e^- \to b\bar{b}(h,A) \to & b\bar{b}b\bar{b} & \text{DELPHI} \\ e^+e^- \to b\bar{b}(h,A) \to & b\bar{b}\tau^+\tau^- & \text{OPAL} \end{array}$$

These two searches are complementary, since they cover different mass ranges for the h and A bosons. Both searches used the LEP 1 data set, since the number of $b\bar{b}$ pairs is much larger there. Both analyses suffer however from the large background from $Zg$, so the efficiency for the $4b$ final state is at the 5 % level. Both collaborations set their limits in terms of an enhancement factor for the Yukawa production, depending on the mass, the results for both channels are shown in Fig. 9.

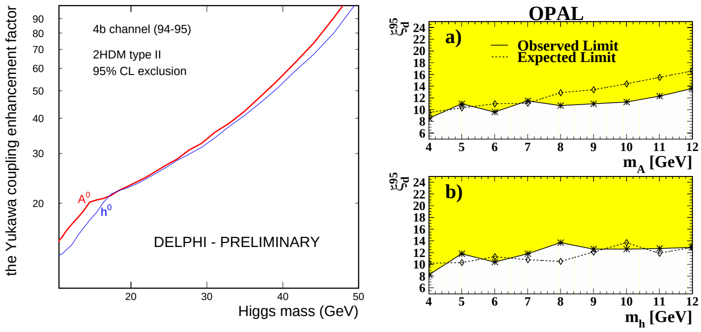


Figure 9: Searches for Yukawa production: Shown is excluded Yukawa enhancement factor depending on the Higgs mass for $b\bar{b}b\bar{b}$ (left) and $\bar{b}\tau^+\tau^-$ (right).

## 6 Hadronic Higgs decays

The search for hadronic Higgs decays is usually motivated to exclude a Higgs boson without relying on b-quark identification. However, there are also models, in which the coupling to down-type quarks are suppressed. This can happen e.g. in parts of a type II 2HDM. Since the searches for SM or SM-like Higgs bosons strongly rely on b-quark identification, such a Higgs boson could be easily missed. The LEP collaborations [10] have searched for such decays in the same final states as for SM Higgs searches [11]:

$$\begin{aligned} hZ &\rightarrow q\bar{q}q\bar{q} \\ hZ &\rightarrow q\bar{q}\nu\bar{\nu} \\ hZ &\rightarrow q\bar{q}l^+l^- \end{aligned}$$

The background for this searches is similar to the SM Higgs searches, but significantly larger, since the strong background suppression using b-quark identification could not be done. The results in form of a 95 % excluded cross-section is shown in Fig. 10. Assuming a decay of 100% into hadrons, a 95 % CL mass limit of 112.9 GeV/c$^2$ (113.0 GeV/c$^2$ expected) is set, which is only about 2 GeV lower than the limit obtained by the SM Higgs searches [11].

## 7 Invisible Higgs decays

In the MSSM there is the possibility, that the Higgs might decay into a pair of neutralinos $\tilde{\chi}^0_1$, which are stable and do not interact with the detector. Such a decay would be invisible, so one would only see the decay products of the Z in the detector. Such events have been searched for by the four LEP collaborations [12] in the final states

$$\begin{aligned} hZ &\rightarrow \text{inv } q\bar{q} \\ hZ &\rightarrow \text{inv } l^+l^- \end{aligned}$$

The background processes mainly originates from ZZ pair production and fully leptonic $WW$ decays. Like for the hadronic Higgs searches, a general cross-section limit is given

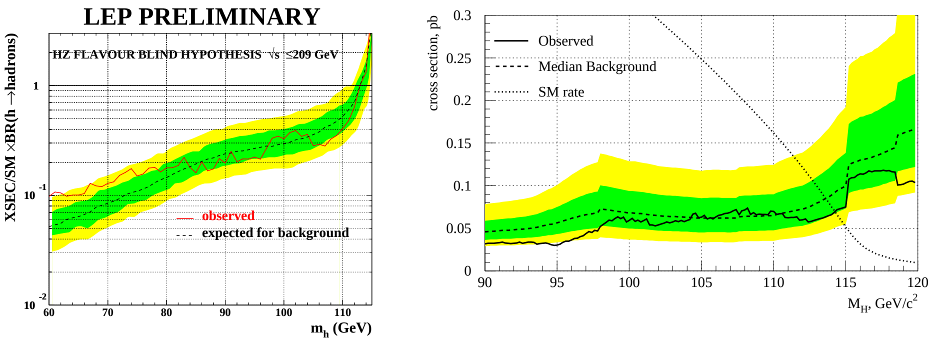


Figure 10: Searches for hadronic and invisible Higgs decays: The excluded cross-section depending on the Higgs mass for a hadronic Higgs decay (left) and the excluded cross-section depending on the Higgs mass for an invisible Higgs decay (right).

(see Fig. 10) in order to decrease the model dependence. Assuming a 100% branching ratio into invisible final states, a 95 % CL limit on the the Higgs mass of 114.2 GeV/c$^2$ (113.6 GeV/c$^2$ expected) can be set.

## 8 Summary

No evidence for the production of Higgs bosons has been found. The different 95% CL mass limits set are summarised in Tab. 1.

| Channel | Observed (GeV/c$^2$) | Expected (GeV/c$^2$) | Experiment |
|---|---|---|---|
| SM Higgs | 114.1 | 115.4 | LEP |
| $H^{\pm}$ | 78.8 | 78.6 | LEP |
| $H_L^{\pm\pm}$ | 99.6 | 99.6 | DELPHI/OPAL |
| $H_R^{\pm\pm}$ | 99.1 | 99.1 | DELPHI/OPAL |
| $h \to \gamma\gamma$ | 108.2 | 109.0 | LEP |
| $h \to WW^*$ | 104.2 | 107.5 | L3 |
| $h \to$ hadrons | 112.9 | 113.0 | LEP |
| $h \to$ inv | 114.2 | 113.6 | LEP |

Table 1: 95 % CL Higgs mass limit summary

## Acknowledgements

The author would like to thank the Higgs teams from the ALEPH, DELPHI, L3 and OPAL collaborations for their kind support. This work was supported by the Bundesministerium für Bildung und Forschung under contract No. 05 HD1VKA/3.

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