

# Cornering Higgs Bosons at LEP <sup>a</sup>

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The most recent results of the searches for Higgs bosons in the data taken at LEP in 1999 and their interpretations in a variety of theoretical frameworks are reviewed.

In 1999 LEP reached a centre-of-mass energy of 202 GeV and delivered a total integrated luminosity in excess of  $1 \text{ fb}^{-1}$  to the four experiments. A review of the results of all Higgs boson searches performed with the data collected in 1999 is presented, with a particular emphasis on the combinations of the four LEP experiments. When for a given search such a combination is not available, the individual result with the best sensitivity is presented instead.

## 1 The Standard Model

In the standard model, the spontaneous breaking of the electroweak symmetry is achieved at the expense of the introduction of multiplets of complex scalar fields in self-interaction. In particular, in its minimal version, a single scalar doublet is required (with the two fold advantage of simplicity and of preserving  $\rho_o = 1$ ). As it develops a vacuum expectation value, gauge bosons acquire their masses absorbing three of the four initial degrees of freedom and a massive scalar physical state remains, the Higgs boson  $h$ . Its mass is a free parameter of the theory as a function of which its production and decays are predicted unambiguously.

At LEP, the minimal standard model Higgs boson dominant production process is the Higgs-strahlung ( $e^+e^- \rightarrow HZ$ ) and its prominent decay is into a pair of  $b$  quarks ( $\sim 81\%$  for a  $105 \text{ GeV}/c^2$  Higgs boson). Four search topologies arise from the decays of the accompanying  $Z$  boson. 1) Four jets, when the  $Z$  decays into a pair of quarks; 2) two acoplanar jets and missing energy, when the  $Z$  decays to a pair of neutrinos; 3) the leptonic channel, when the  $Z$  decays to a pair of electrons or muons; and 4) the  $\tau\tau q\bar{q}$  and  $b\bar{b}\tau\tau$  channels, where either the  $Z$  or the Higgs boson decay to a pair of taus. In all these channels but the latter, the Higgs boson is searched for in its  $b\bar{b}$  decay mode. The  $b$  jet tagging is therefore an essential component of all the analyses.

All the data collected have been analysed by all four experiments <sup>1</sup>, nevertheless the most significant contribution for the limit are the  $\sim 40 \text{ pb}^{-1}$ /experiment collected at 202 GeV. The distribution of the reconstructed mass of the Higgs boson for all channels and all experiments together is illustrated in Fig. 1. Only the most signal-like events are chosen with the further requirement that the contribution from all experiments be roughly the same.

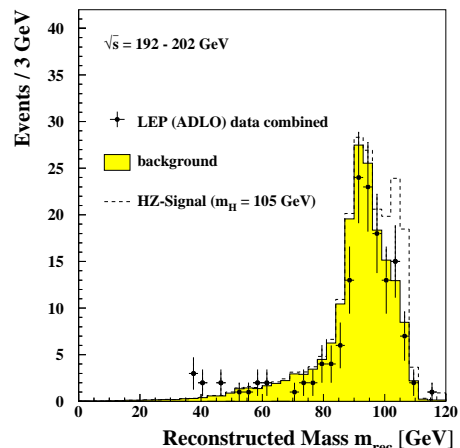


Figure 1: Distribution of the reconstructed mass of the Higgs boson at all energies above 192 GeV. A restricted set of data among the selected candidates (dots) amounting to 148 events is used; 175 events are expected from background processes (shaded histogram). The 36 events expected from a  $105 \text{ GeV}/c^2$  Higgs boson signal are also displayed (dashed histogram).

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The observed LEP combined  $CL_b$  (which estimates the probability that the data be compatible with the background)<sup>2</sup> as a function of the Higgs boson mass hypothesis is illustrated in Fig. 2a. The expected values of  $CL_b$  in the presence of signal are also shown in Fig. 2a, yielding a  $5\sigma$  discovery sensitivity of  $106.3 \text{ GeV}/c^2$  (corresponding to  $CL_b \sim 5.7 \times 10^{-7}$ ).

In Fig. 2b the  $CL_s$  (which estimates the probability that the data be compatible with background and signal)<sup>2</sup>, computed without taking into account the correlations among systematic errors, is illustrated as a function of the Higgs boson mass hypothesis. Hypotheses yielding a  $CL_s < 5\%$  are excluded at the 95% confidence level. The sensitivity of the combination is  $109.1 \text{ GeV}/c^2$ . According to Fig. 2b, Higgs boson mass hypotheses below  $107.9 \text{ GeV}/c^2$  are excluded at the 95% CL. However the effect of correlations of the systematic errors result in a downward shift of  $150 \text{ MeV}/c^2$  of the limit, leading to combined lower limit on the mass of the Minimal Standard Model Higgs boson of  $107.7 \text{ GeV}/c^2$ .

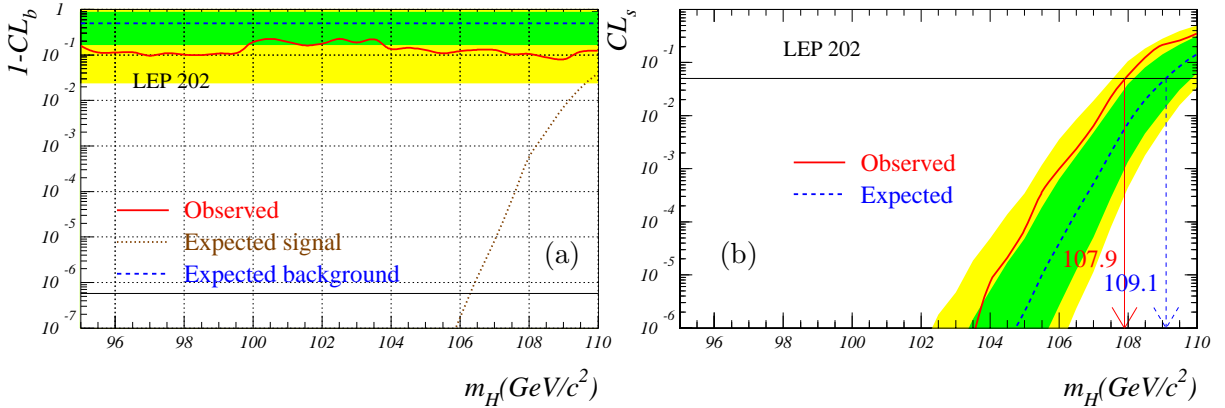


Figure 2: The  $CL_b$  (a) and  $CL_s$  (b) confidence levels as a function of  $m_H$ . The expected and observed values are indicated by dashed and plain lines respectively. The  $\pm 1\sigma$  and  $\pm 2\sigma$  probability bands off the expectation in the absence of signal are illustrated as shaded regions. The dotted line in (a) represents the expected  $CL_b$  in the presence of signal and the horizontal thin line at  $5.7 \times 10^{-7}$  indicates the  $5\sigma$  discovery level.

## 2 Extending the Higgs Sector of the Standard Model

The simplest extension of the minimal standard model Higgs sector is obtained with the introduction of an additional doublet of complex scalar fields (still preserving  $\rho_o = 1$ ). In two-higgs-doublet models (2HDM) FCNC can become important, but can be avoided if all fermions of a given charge do not couple to more than one Higgs doublet. The two most popular models obeying this requirement are the model I, where one Higgs doublet couples only to fermions and the other to bosons, and the model II where one Higgs doublet couples only to up-type fermions and the other to down-type fermions. In both cases, the electroweak symmetry breaking leaves five massive scalar physical states among which two are neutral CP-even (h and H), one is neutral CP-odd (A) and two are charged ( $H^\pm$ ). These models are the main motivation for the search for Higgs bosons decaying mostly to photons (model I) and for charged Higgs bosons.

### 2.1 2HDM of type I, fermiophobia

In 2HDM of type I when the CP-even Higgs bosons do not mix, the lightest CP even Higgs boson does not couple to fermions. In a Higgs boson mass range well below  $2m_{W^\pm}$  it predominantly decays to a pair of photons. The topologies arising from such models are similar to those of the minimal standard model Higgs boson searches where a pair of photons is substituted for the pair of b-quark jets. Such topologies were searched for by all four experiments. No evidence for a

resonant production of a pair of photons was found as illustrated in Fig. 3a. The negative result of these searches can be interpreted in a quasi-model-independent fashion as an upper limit on the production rate of a Higgs boson decaying to a pair of photons normalised to the standard model Higgs boson production, as a function of the Higgs boson mass hypothesis. The ALEPH exclusion<sup>3</sup> is illustrated in Fig. 3b. The intercept of the model independent exclusion and the branching fraction of the fermiophobic Higgs boson into a pair of photons, which starts dropping severely above  $100 \text{ GeV}/c^2$  due to the growing contribution of  $H \rightarrow WW^*$ , gives the lower mass limit of the fermiophobic Higgs boson. A fermiophobic Higgs boson lighter than  $101.0 \text{ GeV}/c^2$  is excluded by ALEPH with a sensitivity of  $100.2 \text{ GeV}/c^2$ . The other experiments<sup>4,6,5</sup> find similar results —DELPHI, L3 and OPAL exclude fermiophobic Higgs boson masses below  $98.0 \text{ GeV}/c^2$ ,  $98.8 \text{ GeV}/c^2$  and  $97.8 \text{ GeV}/c^2$  respectively.

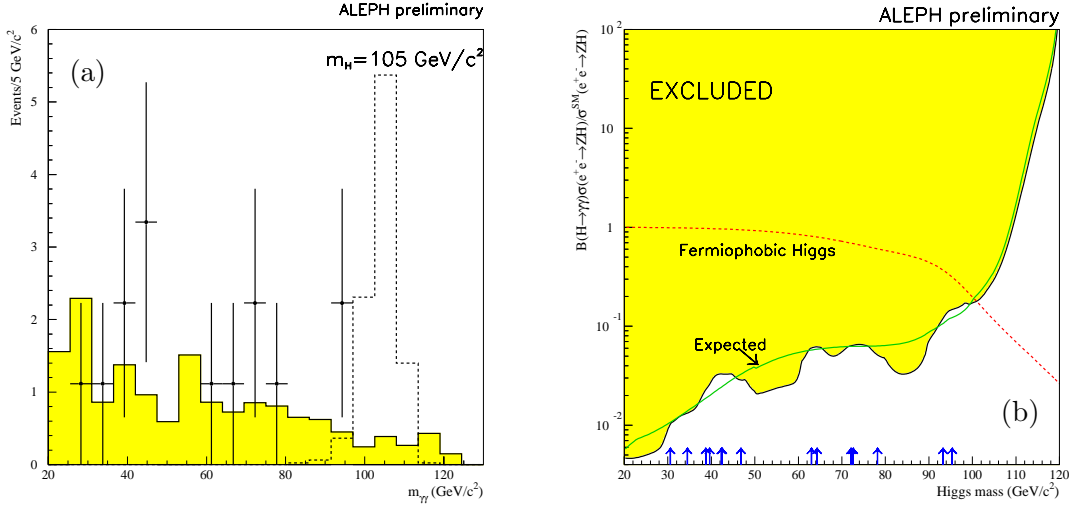


Figure 3: (a) Reconstructed  $\gamma\gamma$  mass distribution for all data collected by ALEPH (dots), for the expected background (shaded histogram) and for a  $105 \text{ GeV}/c^2$  fermiophobic Higgs boson signal (dashed histogram). (b) 95% CL exclusion domain of the production rate of a Higgs boson decaying to two photons and produced via the Higgs-strahlung process normalised to the standard model Higgs boson production cross section as a function of the Higgs boson mass hypothesis (the reconstructed masses of the candidate events are indicated by arrows for the purpose of illustration).

## 2.2 2HDM, Charged Higgs bosons

Charged Higgs bosons are produced at LEP via  $\gamma$  and Z bosons exchange in the s-channel. The dominant decay modes are  $H^\pm \rightarrow \tau\nu_\tau, cs$ . The relative contribution of these two modes depend on the model parameter  $\tan\beta$  (the ratio of the vev's of the two Higgs doublets). Analyses must therefore cover all possible final states arising from charged Higgs bosons production, *i.e.*,  $\tau^-\bar{\nu}_\tau\tau^+\nu_\tau$ ,  $\tau^-\bar{\nu}_\tau c\bar{s}$  and  $c\bar{s}s\bar{c}$ . Dedicated searches for each of these topologies were performed by all LEP experiments<sup>1</sup>. No evidence for a signal was found, as illustrated in Fig. 4a for the fully hadronic and semi-leptonic channels. (The charged Higgs boson mass cannot be reconstructed in the fully leptonic channel.) These results can be interpreted in terms of 95% CL charged Higgs boson mass lower limits as a function of the leptonic branching fraction. As shown in Fig. 4b a lower charged Higgs boson mass limit on of  $78.6 \text{ GeV}/c^2$  with a sensitivity of  $78.0 \text{ GeV}/c^2$  can be set independently of the  $\tau\nu_\tau$  branching fraction.

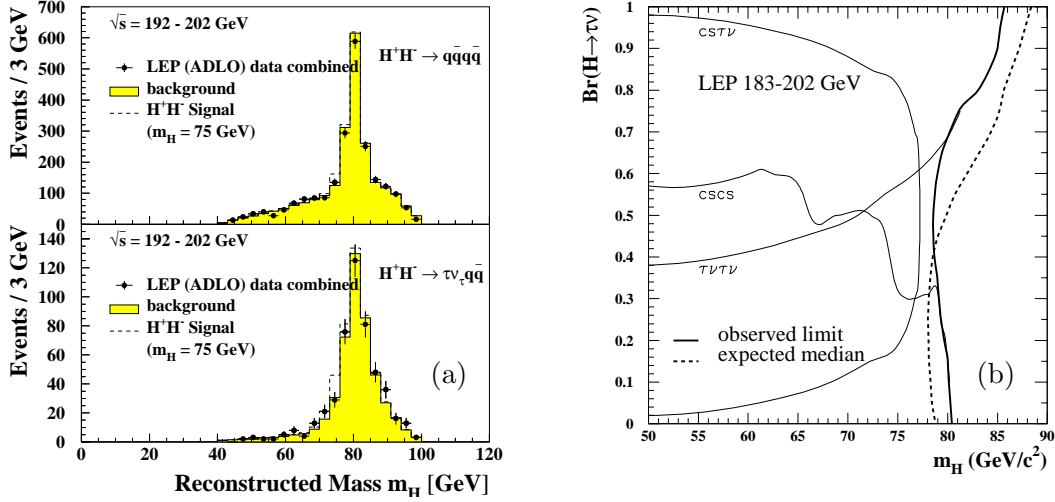


Figure 4: (a) Reconstructed mass distribution for data (dots), for the expected background (shaded histogram) and for a 75 GeV/c<sup>2</sup> charged Higgs bosons signal (dashed histogram) in the fully hadronic (up) and semi-leptonic (down) channels. (b) 95% CL exclusion domain of the charged Higgs boson branching to  $\tau\nu$  as a function of their mass.

### 3 Minimal Supersymmetric extension of the Standard Model (MSSM)

The presence of Higgs bosons in the standard model is quite unnatural, due to the quadratically divergent contributions of the radiative corrections to their masses. Supersymmetry elegantly solves this problem and provides a framework for unified theories and quantum gravity.

In its minimal version, the Higgs sector of the supersymmetric standard model is a type II 2HDM. Supersymmetry constrains Higgs bosons masses. At tree level  $m_{H^\pm} \geq m_{W^\pm}$  and  $m_h \leq m_Z |\cos 2\beta|$ . In the MSSM, two free parameters, commonly chosen either as  $m_A$  and  $\tan \beta$  or  $m_h$  and  $\tan \beta$ , are required at tree level to describe the Higgs sector. However radiative corrections due to the large Yukawa coupling to the top quark can increase the theoretical upper bound on the lightest CP-even Higgs boson up to about 130 GeV/c<sup>2</sup>. All the parameters relevant to the radiative corrections to the Higgs boson masses are chosen to maximise  $m_h$  ( $m_h$ -max scenario).

The Higgs-strahlung production of  $h$  is reduced, compared to the standard model, by a factor  $\sin^2(\beta - \alpha)$ . The results of searches for the standard model Higgs boson can be turned into an 95% CL exclusion domain in the  $(m_h, \sin^2(\beta - \alpha))$  plane as illustrated in Fig. 5.

For small values of  $\sin^2(\beta - \alpha)$  the Higgs-strahlung contribution vanishes but the associated  $e^+e^- \rightarrow hA$  production process, which cross section is proportional to  $\cos^2(\beta - \alpha)$ , becomes dominant. In this regime, the  $h$  and  $A$  Higgs bosons are roughly mass degenerate and both decay predominantly to a pair of  $b$ -quarks. This process is thus searched for in two additional topologies<sup>1</sup>. 1) Four jets likely to originate from  $b$  quarks; and 2) Two  $b$ -like jets and a pair of taus. No evidence for a signal was found as illustrated in Fig. 6a. The negative result of these searches combined with the

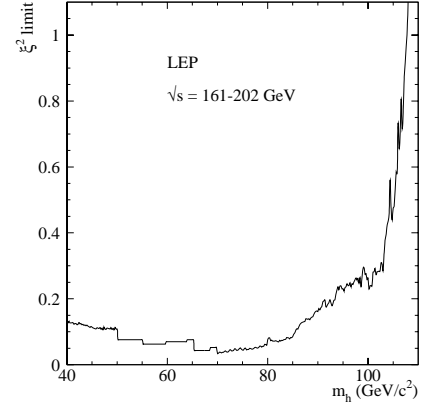


Figure 5: 95% CL Exclusion in the plane  $(m_h, \xi^2)$ , where  $\xi^2$  is the the Higgs-strahlung production cross section normalised to that of the standard model. Here the Higgs boson is assumed to decay with with MSM couplings.

search for the standard model Higgs boson can be interpreted in terms of an exclusion domain in the  $(m_h, \tan\beta)$  plane as shown in Fig. 6b. Neutral Higgs boson masses in excess of  $88.3 \text{ GeV}/c^2$  are excluded at the 95% CL with a sensitivity of  $90.5 \text{ GeV}/c^2$ . The lower mass limit on the CP-odd Higgs boson is set to  $88.4 \text{ GeV}/c^2$  with a sensitivity of  $91.1 \text{ GeV}/c^2$ . These limits have proven to be robust while scanning over all parameters pertaining to radiative corrections to the Higgs boson masses<sup>7,8,9</sup>. As can be seen in Fig. 6b values of  $\tan\beta$  comprised within  $[0.7, 1.8]$  are excluded at the 95% CL, for  $m_{\text{top}}=174.3 \text{ GeV}/c^2$  and  $[0.8, 1.5]$  for  $m_{\text{top}}=179.4 \text{ GeV}/c^2$ .

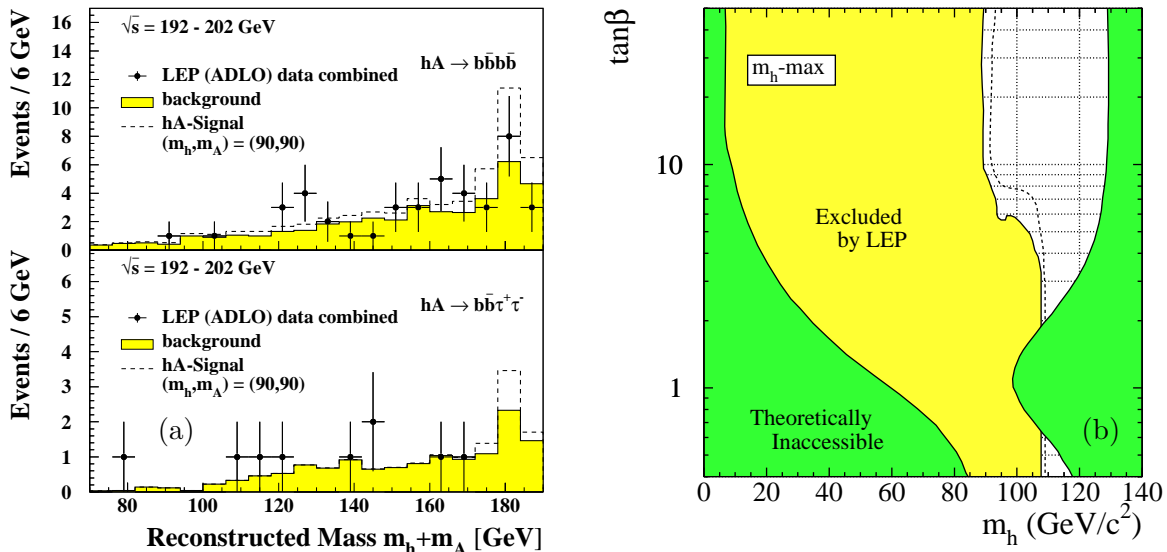


Figure 6: (a) Reconstructed mass sum  $m_h + m_A$  distribution for all data collected at LEP (dots), for the expected background (shaded histogram) and for a  $m_h = m_A = 90 \text{ GeV}/c^2$  signal (dashed histogram). (b) 95% CL observed (light shaded) and expected (dashed line) exclusion domains in the  $(m_h, \tan\beta)$  plane.

## 4 Further Exotism

### 4.1 Invisible decays of Higgs bosons

In a MSSM conserving R-parity, the domains in which Higgs bosons can decay to neutralinos (supersymmetric partners of the neutral Higgs and gauge bosons, here the lightest neutralino is assumed to be the lightest supersymmetric particle) is tightly constrained by direct searches for charginos (supersymmetric partners of charged Higgs and gauge bosons). Nevertheless the latter exclusion assumes universality of gaugino masses at a large unification scale. If this assumption is relaxed the indirect chargino constraints do not necessarily hold and the Higgs boson can thus decay to a pair of neutralinos. Neutralinos are weakly interacting neutral particles, like neutrinos. They therefore escape detection and the Higgs boson decays invisibly. A variety of other theories, from models involving Majorons to large extra dimensions, predict such decays.

The two main topologies under consideration correspond to the Z decays to a pair of quarks and to a pair of leptons (either an electron or a muon). 1) Two acoplanar jets; and 2) two leptons, both with missing energy. Such topologies were searched for by all four LEP collaborations. No evidence for a signal was found, as shown in Fig. 7a for ALEPH data only<sup>10</sup>. This result can then be interpreted in a quasi-model-independent fashion as a limit on the production rate of an invisible Higgs boson normalised to the standard model cross section:  $\xi^2 = Br(h \rightarrow \text{invisible}) \times (\sigma_{hZ}/\sigma_{HZ}^{\text{MSSM}})$  as a function of  $m_h$  as illustrated in Fig. 7b. Higgs bosons decaying

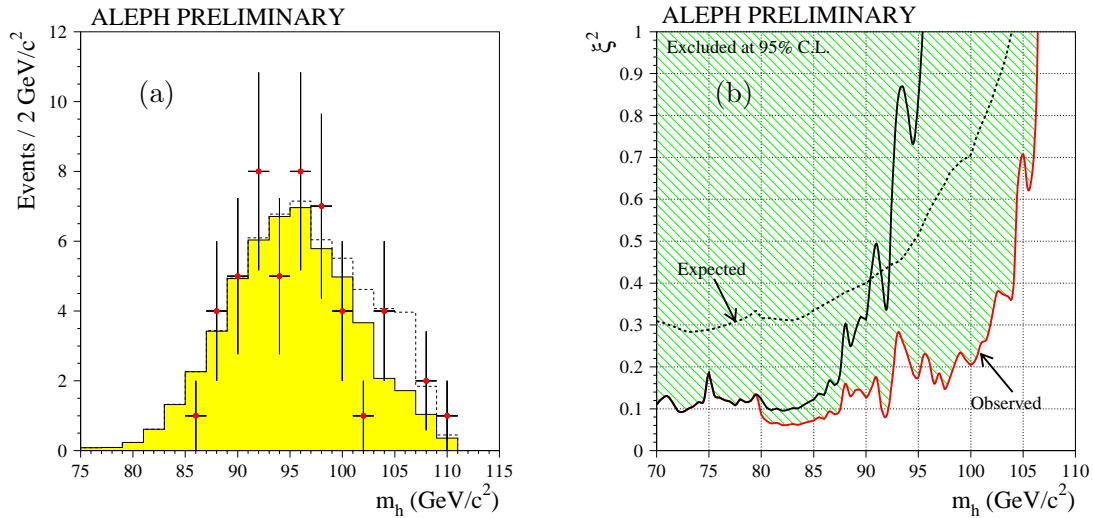


Figure 7: (a) Reconstructed mass distribution for all data collected with the ALEPH detector (dots), for the expected background (shaded histogram) and for a 105 GeV/c<sup>2</sup> invisible Higgs boson signal (dashed histogram). (b) 95% CL exclusion domain of the production rate of an invisible Higgs boson produced via the Higgs-strahlung process normalised to the standard model higgs boson production cross section as a function of the Higgs boson mass hypothesis.

invisibly and produced at standard model rate ( $\xi^2 = 1$ ) with masses below 106.4 GeV/c<sup>2</sup> are excluded at 95% CL with a sensitivity of 103.9 GeV/c<sup>2</sup>. The other experiments find similar results — 93.8 GeV/c<sup>2</sup>, 100.5 GeV/c<sup>2</sup> and 94.4 GeV/c<sup>2</sup> are the limits (for  $\xi^2 = 1$ ) set by DELPHI (with data up to 189 GeV), L3 and OPAL respectively— (unless their high energy data set had not yet been entirely analysed) <sup>6,10,11,12</sup>.

#### 4.2 Anomalous Higgs couplings

The effect of theories which supersede the standard model at some large scale  $\Lambda$  can also be parametrised at low energy by an effective Lagrangian in a model independent manner. The simplest corrections to the standard model Lagrangian distorting the couplings of

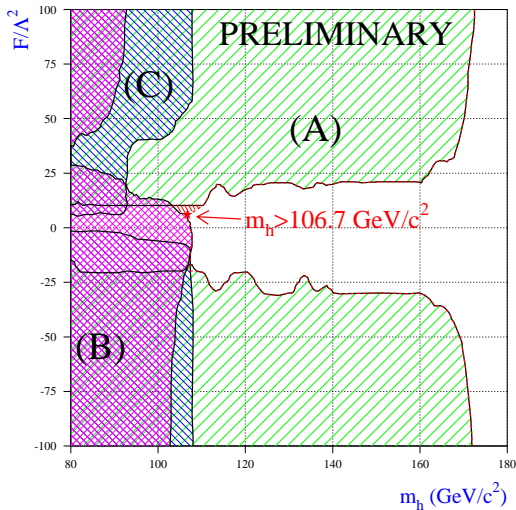


Figure 8: 95% CL limits on the generic anomalous coupling  $F$  as a function of  $m_h$ .

Higgs bosons originate from terms of the type  $\mathcal{L}_{\text{eff}} = \sum_n (f_n/\Lambda^2) \mathcal{O}_n$  where the  $\mathcal{O}_n$  operator involves vector boson and/or Higgs boson fields with couplings  $f_n$ . Such terms can give rise to anomalous couplings of the type  $g_{H\gamma\gamma}$ ,  $g_{HZ\gamma}$  and  $g_{HZZ}$  which affect the expected phenomenology of a standard Higgs sector. For instance the Higgs boson can be produced along with a photon and decay itself to a pair of photons. The DELPHI collaboration performed a search for topologies with three photons in the framework of anomalous couplings of Higgs bosons <sup>5</sup>. No evidence for a signal was found and limits on the generic  $F$  coupling — here all the underlying couplings  $f_n$  relevant for the Higgs anomalous couplings are assumed to be equal to  $F$  — can be set as a function of  $m_h$  as shown in Fig. 8 (region A).

In this general framework, the Higgs boson can also predominantly couple to photons but still be produced via the Higgs-strahlung process and thus give rise to the topologies searched for in the framework of fermiophobicity. The ALEPH searches presented in Section 2.1 were reinterpreted here in terms of an exclusion of the coupling  $F$  as a function of the Higgs boson mass hypothesis, as illustrated in Fig. 8 (region C).

These searches require non-zero anomalous couplings and can therefore not explore the small  $F$  region. However the searches for the standard model Higgs boson can also be reinterpreted in this more general framework as shown in Fig. 8 (region B) where the ALEPH standard model Higgs boson searches are used. Finally a combination of all these searches allow a mass lower limit to be set at  $106.7 \text{ GeV}/c^2$  on the mass of a Higgs boson allowing it to couple anomalously to photons with the assumption that all relevant couplings  $f_n$  are equal.

## 5 Summary and prospects

All LEP experiments have made meaningful efforts to corner all possible forms in which Higgs bosons might appear. All the topologies and the relevant theoretical frameworks which were investigated with the data collected in 1999 have been presented. The resulting mass lower limits on the mass of Higgs bosons in each of these models and all the topologies are sketched in Table 1.

Topologies not covered in this review are those searched for in flavour-independent analyses performed by OPAL<sup>13</sup> (interpreted in general 2HDM models) and ALEPH<sup>7</sup> (to exclude pathological MSSM parameter sets in their scan beyond benchmark configurations).

Table 1: Synoptic panorama of all topologies searched for in the data collected in 1999 within the framework of Higgs boson searches. The models in which these topologies are relevant are also indicated.

Minimal Standard Model ( $m_H > 107.7 \text{ GeV}/c^2$ )			MSSM ( $m_h > 88.3 \text{ GeV}/c^2$ )	
4 Jets	2 Acoplanar jets and missing energy	Leptons	4 b-jets	Taus
2HDM Type I ( $m_h > 101.0 \text{ GeV}/c^2$ )			Invisible decays ( $m_h > 106.4 \text{ GeV}/c^2$ )	
Hadronic	2 Acoplanar photons	Leptonic	Acoplanar jets	Leptonic
2HDM type I & II ( $m_{H^\pm} > 78.6 \text{ GeV}/c^2$ )			Anomalous couplings ( $m_h > 106.7 \text{ GeV}/c^2$ )	
Jets	Semi-leptonic	Leptonic	3 photons	



For its presumably final year of running LEP aims at collecting data at energies up to 207 GeV (optimistically up to 209 GeV). The foreseen sensitivity of the standard model Higgs boson searches are expected to be between 112 and 115 GeV/ $c^2$ . The  $3\sigma$  evidence sensitivity for a standard model Higgs boson lies 300 MeV/ $c^2$  below the 95% CL exclusion and the  $5\sigma$  discovery is 2 GeV/ $c^2$  below this limit. A sizeable window is thus still open at LEP, in a region where, if it exists, the standard model Higgs boson is most expected<sup>14</sup>.

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