Search for Higgs bosons with Anomalous Couplings (or not) at LEP

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Abstract

The latest results on the searches for the Standard Model Higgs bosons at LEP are presented. LEP covers also other models which change the Higgs boson properties. The example of the search for Higgs boson decaying into two photons performed by DELPHI is described in detail.

1 Introduction

The spontaneous symmetry breaking mechanism is a fundamental component of the Standard Model (SM) but no direct experimental evidence for the Higgs particles has been presented so far. On the other hand, indirect evidence from precision measurements of Standard Model parameters favour a light Higgs ($M_H < 210\text{GeV/c}^2$) [1]. The SM Higgs search is thus one of the main goals of the Large Electron Positron collider (LEP).

While the Standard Model Higgs is being searched for, other models appear which directly or indirectly change the properties of the Higgs boson, introducing new production modes for the Higgs bosons as well as enhancing decay modes which have negligeable branching ratios in the SM. An important decay mode is the one of $H \to \gamma\gamma$ giving rise to very clear signatures.

The LEP running came to an end in 2000. After the very successful LEP 1 phase when the accelerator operated at centre-of-mass energies close to the Z^0 boson mass (from 1989 to 1995), the LEP 2 phase started with increasingly higher centre-of-mass energies: the threshold for W^+W^- production was crossed in 1996 and the threshold for Z^0Z^0 production the year after. In 1999, LEP overcame its construction limit, reaching centre-of-mass energies above 200 GeV. In all this time, also the luminosity delivered to each of the four LEP experiments (ALEPH, DELPHI, L3 and OPAL) per year was increased, table 1 shows the data collected by the DELPHI experiment during the LEP 2 phase. For the last year of LEP a new scheme was introduced, aiming at getting the highest centre-of-mass energies but keeping high values of integrated luminosity, this is done by raising the energy as the intensity of the beam diminishes – the luminosity delivered is comparable to the previous year but the energies reached approach the 209 GeV.

Table 1: Centre-of-mass energies and luminosities collected by the DELPHI experiment in the LEP2 phase.

YEAR	$\sqrt{s}$ (GeV)	$\mathcal{L}$ (pb^{-1})
1995	130+136	6
1996	161+172	10+10
1997	183	54
1998	189	153
1999	192+196+200+202	26+77+85+42
2000	∼205+∼207	∼80+∼130

Although the searches for new particles depend mostly on the data at higher energies, the luminosity plays also a role on the definition of sensitivity. For this reason, the results are obtained by combining the data collected at several centre-of-mass energies and even by combining data collected and analysed by the four experiments.

All the results presented are preliminary and all limits will be quoted at 95% Confidence Level.

2 Standard Model Higgs Searches

The main production mode of a Standard Model Higgs boson at LEP is the so-called Higgs-*strahlung*, where the Higgs is radiated of a Z^0 boson line. The cross-section of this process depends strongly on the Higgs boson mass but can reach several *pb* for moderate masses, a kinematic limit is defined at $\sqrt{s} - M_{Z^0}$ as a on-shell Z^0 is produced together with the Higgs. The WW fusion process (giving a H^0 and two neutrinos), allows for the production of Higgs bosons with mass above this limit but has a very small cross-section. All the possible decay modes of the Z^0 are analysed. The dominant decay of the Higgs is to $b\bar{b}$ but also the decay to $\tau^+\tau^-$ is considered.

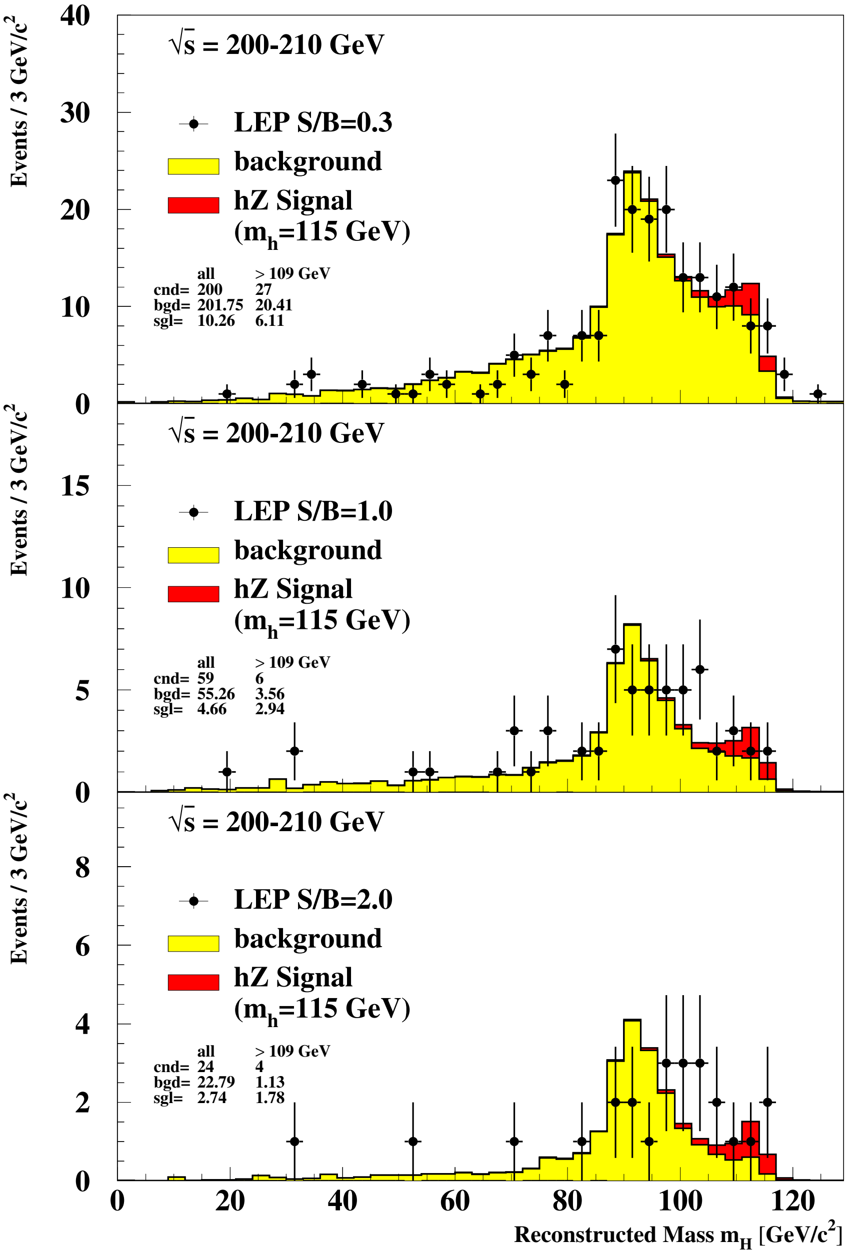

Figure 1: Reconstructed Higgs masses for the 2000 data selected in all the analysis. Real data (points), the expected background (light region) and the signal for a 115 GeV/c^2 Higgs (darker region) are presented for three different purities for the signal. the purities are defined by the signal over background ratio for masses above 109 GeV/c^2 – respectively, S/B=0.3 (pre-selection level), S/B=1 and S/B=2 (tight selection).

The main search channel is the 4 jet channel. Two of the jets should have an invariant mass close to the Z mass, and the other two should be tagged as b-jets. Important background comes from $q\bar{q}$ production with gluon radiation or from W^+W^- and Z^0Z^0 production. The Z^0Z^0 background is irreducible which makes its correct description a fundamental ingredient in the analysis.

Final states with two b-jets and missing energy are important as the WW fusion process allows the production of Higgs bosons with higher masses. The main background comes from double radiative returns to the Z^0: $e^+e^- \to Z^0 \to b\bar{b}$, with initial state radiation of two back to back photons inside the beam-pipe, which can fake a $Z^0 \to \nu\bar{\nu}$.

Final states with two b-jets and charged leptons can give a very clear signature but the expected cross-section is low. Here it is the leptons which have an invariant mass close to m_{Z^0}. The final state $q\bar{q}\tau^+\tau^-$ can also be interpreted as H^0Z^0 with $H^0 \to \tau^+\tau^-$.

The different analysis as performed by the four experiments are all combined into a common LEP result [2, 3]. The statistical interpretation is based on a Modified Frequentist Likelihood Ratio method described in [4]. It is based on probability density functions of the measured quantities and expectations on the background distributions and background plus signal distributions. The variables used are the reconstructed masses for the Higgs candidate and in some cases also output variables of neural networks or discriminating functions used in the analysis.

The results are obtained by looking at the confidence levels obtained for the hypothesis that the data can be described by background processes only (CL_b) and the confidence level for the hypothesis that the data is described by background plus a signal for a Higgs of a definite mass (CL_{s+b}). The Confidence level in the background hypothesis is useful to see how far from the background expectation the result lies, if the excess of data in respect to background is above 5σ it can not be explained by a statistical fluctuation, and it indicates a discovery. However, since the cross-section for Higgs production decreases fast near the kinematic limit, there is a point in which the number of events expected from the signal is too small to be seen. To take into account the sensitivity to the signal, the confidence level on each signal is defined by dividing CL_{s+b} by CL_b, when this confidence level is below 5%, the signal is excluded. Between these two extremes there is a region in which an excess can be observed but no statement can be done about its origin.

The results available at the time of the QFTHEP meeting had been obtained with integrated luminosities of almost 600 pb^{-1} for the 2000 data with centre-of-mass energy above 200 GeV, of each approximately one half was above 206 GeV. One of the four LEP collaborations (ALEPH) had observed an excess of 4-jet events compatible with a Higgs boson of mass 115 GeV/c^2 [5]. Such exciting result, motivated the extension of the LEP run for an extra month, up to the beggining of November 2000. The extension of LEP allowed for the collection of more 200 pb^{-1} of data, giving a total luminosity of 810 pb^{-1}, with 488 pb^{-1} above 206 GeV [6]. These results will be described in what follows and are shown in figures 1 and 2.

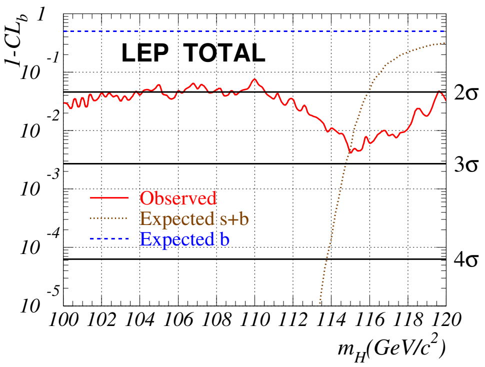

Figure 2: The confidence level in the background hypothesis (CL_b) for the real data (curved solid line) is compared to the signal expectation for each mass and to the background expectation with the median and the 2, 3 and 4 σ deviations given by constant CL_b lines.

A small excess of data over the background expectations is seen in the three plots of figure 1, for reconstructed masses above the Z peak, and mainly above 110 GeV/c^2. The data in the high mass region agrees better with the expectations if the signal for a Higgs boson of 115 GeV/c^2 is included. But, for this mass, the expected excess is still a bit bellow 3 σ. A discovery of the Higgs can not be obtained. The data shows a constant excess of events with a significance of around 2σ for high masses. For masses of 115 GeV/c^2 the excess is of 2.9 σ only. The measured excess agrees with the SM cross-section for production of a Higgs boson in the range $115^{+1.3}_{-0.9}$GeV/c^2.

The limit obtained with this data is of 113.5 GeV/c^2, while the expected one (if a perfect agreement would exist with the expected background) is of 115.3 GeV/c^2. So, LEP can not exclude an Higgs boson with 115 GeV/c^2. The data seems to favour this option but the effect of a statistical fluctuation of the background can not be ruled out.

3 Extending the SM

Since the Higgs bosons mass and couplings have not been measured, the purposed extensions of the Standard Model have freedom to make very different predictions on this sector. The new models can be classified in two categories:

- **New interactions at higher energies** can change the physics observed at the electroweak scale by loop corrections. The precision of the existing measurements limit strongly the effects of the new interactions: they should not change the couplings between fermions and electroweak gauge bosons or the relation between the masses of the Z and W bosons. However the level of precision in the measurements of Triple Gauge boson Couplings (TGCs) still allows for some changes. This is even more true in the couplings between the Higgs and the gauge bosons, which can have important corrections.
- **Non minimal Higgs sector** is probably the most direct extension of the Standard Model. Abandoning the principle of simplicity one can imagine that, instead of one Higgs doublet, there are two doublets (2HDM), or other new Higgs particles organised in different multiplets. This would change the couplings of the physical bosons to the other particles and thus the phenomenology assumed in the search for the lightest Higgs.

The two different cases can give rise to many different phenomenologies. LEP tries to cover all the possibilities. For the production processes, together with H^0Z^0, also $H^0\gamma$ or H^0A^0, must be considered, in which A^0 is a neutral boson (one of the new Higgs particles). The decays can be $H^0 \to q\bar{q}$, $H^0 \to W^+W^-$ (in the Standard Model this decay starts to be the dominant one for masses above 130 GeV/c^2, it is starting to be considered by LEP now), $H^0 \to \chi^0\chi^0$ (for dark matter candidates) or $H^0 \to A^0A^0$ (in Two Higgs Doublets Models – 2HDM) and $H^0 \to \gamma\gamma$. Detailed analysis are carried out by the four LEP collaborations and, for the most popular models, like the Minimal Super Symmetric Model (MSSM) or the Charged Higgs production present in all 2HDM, combined between the four experiments [3].

In particular, the search for Higgs bosons decaying into a photon pair is done by all the collaborations. This decay exists in the SM but as a 1-loop process, and the corresponding decay branching ratio is $< 10^{-3}$. However the signatures obtained are very clear and it will be one of the most important channels for the search of the SM Higgs boson in the LHC [9].

3.1 Anomalous $H^0\gamma\gamma$ Couplings

The effects of a higher energy interaction at the present scales can be described by an effective Lagrangian density [7],

$$\mathcal{L}_{eff} = \mathcal{L}_{SM} + \sum_{n>5}\sum_{i=1} \frac{f_i^{(n)}}{\Lambda^{n-4}} O_i^{(n)}. \tag{1}$$

where Λ represents the typical scale of the new interaction and O_i the several operators of strength f_i. After imposing some conditions, the number of new operators can be significantively reduced. The same operators give rise to different couplings between the physical particles. Namely, the couplings $Z^0W^+W^-$, γW^+W^-, $H^0Z^0Z^0$, $H^0W^+W^-$, $H^0Z^0\gamma$ and $H^0\gamma\gamma$ are described by linear combination of 4 operators indexed by f_B, f_W, f_{BB} and f_{WW}.

The TGCs ($Z^0W^+W^-$ and γW^+W^-) are being measured both at LEP and the Tevatron and all the other couplings involve a Higgs boson. The ones which can more significantly introduce changes in the phenomenology are the last two couplings which are not present at tree-level in the SM.

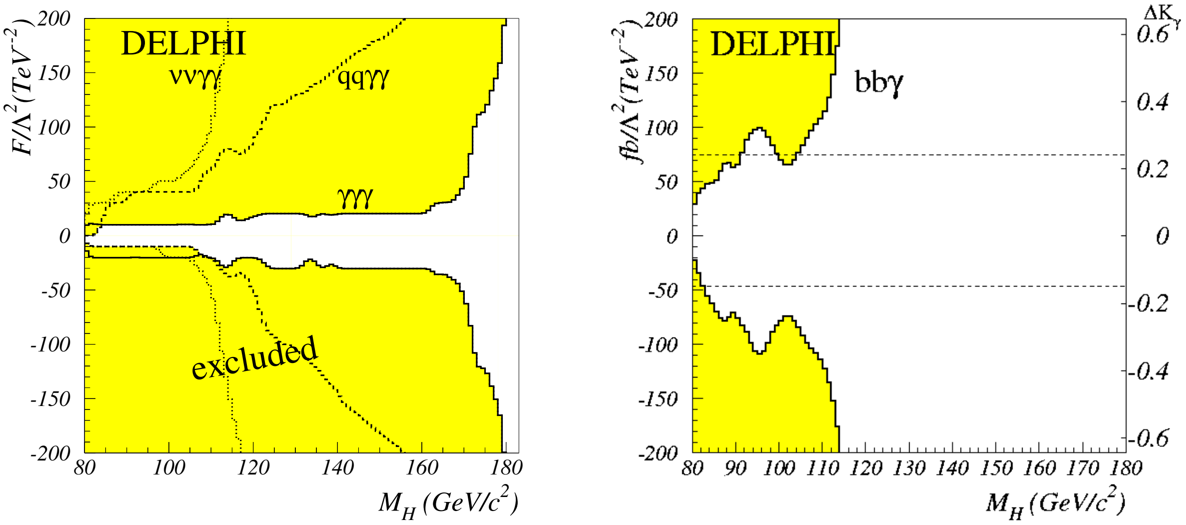

Figure 3: Limits obtained on the anomalous parameters $F = f_B = f_w = f_{BB} = f_{WW}$ (a) and f_B (when setting all other anomalous couplings to 0)(b) as a function of the Higgs boson mass. The shaded area shows the excluded regions. The different curves in (a) show the contribution of each analysis for the exclusion. In (b), the horizontal dashed line shows the indirect limit obtained form the TGC measurement.

To study these operators and constraint the f_i, the most relevant processes are $e^+e^- \to H^0\gamma \to 3\gamma$, $e^+e^- \to H^0\gamma \to b\bar{b}\gamma$, $e^+e^- \to H^0Z^0/\gamma \to \gamma\gamma q\bar{q}$ and $e^+e^- \to H^0Z^0 \to \gamma\gamma\nu\bar{\nu}$.

The main backgrounds for all these searches are $e^+e^- \to q\bar{q}$ and $e^+e^- \to \nu\bar{\nu}$ with photons radiated by the initial state beams and the QED $\gamma\gamma$ production. The signals are selected by requiring that the photons are produced at high angle and, if there are only two photons in the final state, they should not lay in a plane defined with the beam-pipe direction.

No evidence for new phenomena was found and limits were set on the cross-sections of the studied processes. A combination of data at several centre-of-mass energies is possible only by assuming a model. Results were obtained in two limiting cases, first each f_i was considered to be the only non-vanishing one; then all the f_i were assumed to have the same value. The later case is illustrated in figure 3(a): the analysis which gives the strongest exclusion is the final states with 3γ, for $q\bar{q}\gamma\gamma$ the presence of a Z^0 in the final state creates a kinematic limit, on the other hand the $H^0Z^0Z^0$ coupling has both Standard and Anomalous components which interfere, this explains the assymmetry between the positive and negative values of $F = f_{BB} = f_{WW} = f_B = f_W$. In figure 3(b), the exclusion limit for f_B, when setting all the other f_i to zero is shown; in this case the limit is less strong, the production mode proceeds through an Anomalous coupling, if it is increased the branching fraction $H^0 \to b\bar{b}$ is decreased. The results obtained for each Higgs mass is compared with the result coming from TGC analysis assuming the same conditions on f_i. The TGC analysis [10] is based on the study of angular distributions in W^+W^- production.

3.2 2HDM Fermiophobic Higgs

A non minimal Standard Model could include a second Higgs doublet. The introduction of a second doublet gives rise to five physical Higgs bosons: a CP-odd boson (A^0), two charged scalars ($H^{\pm}$) and two neutral scalars (labelled h^0 and H^0 according to their masses). In addition to the usual production mode h^0Z^0, there is also at LEP the associated production of h^0A^0. The two processes have complementary cross-sections. $\sigma(h^0Z^0) = \sigma(H^0Z^0)_{SM}.\sin 2\delta$ and $\sigma(h^0A^0) = \sigma(H^0Z^0)_{SM}.\cos 2\delta$ (with the appropriate kinematic factor according to the A mass), where $\delta = \alpha - \beta$, α is the mixing angle of the neutral CP-even Higgs sector and β is the ratio of the vacuum expectation values of the two doublets.

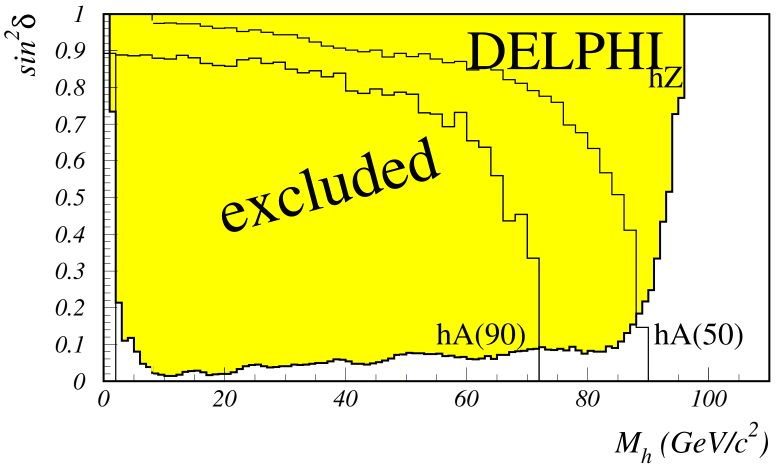

Figure 4: Limits obtained on $\sin^2\delta$ as a function of the Higgs boson mass. The shaded area shows the region excluded by the $e^+e^- \to h^0Z^0$ analysis. The two other curves show the regions excluded by $e^+e^- \to h^0A^0$, for two different masses of A^0.

The two doublets will have different couplings to fermion pairs, proportional to $-\sin\alpha/\cos\beta$ (1st doublet) or to $\cos\alpha/\sin\beta$ (2nd doublet). Each kind of fermion will couple to only one of the doublets, it can be that all of the fermions couple to the 2nd doublet (model of type I) and, if $\alpha = \pi/2$, the lightest CP-even Higgs does not couple to any kind of fermions – there is a fermiophobic Higgs [8].

In this situation (model type I and $\alpha = \pi/2$), the decay of the Higgs to two photons becomes the dominant one for low Higgs masses and a large region of the other parameters in the model. The decay proceeds trough loops of W and charged Higgses: the BR will depend strongly on the $h^0H^+H^-$ coupling and $m_{H^\pm}$. A reduction of the number of free parameters is achieved again by imposing some conditions on the phenomenology, namely CP conservation, there are two different ways to do it [8] which give rise to two different Higgs Potentials, labelled A and B. The choice does not affect the couplings between Higgs and fermions or Higgs and gauge bosons, but alter the Higgs-Higgs couplings, and therefore the phenomenology.

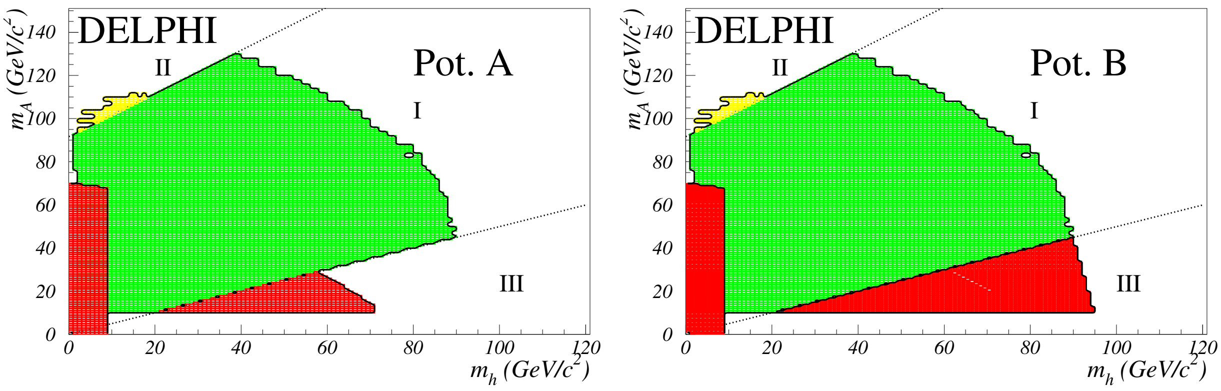

Figure 5: Excluded regions in the plane m_{h^0} .vs.m_{A^0} for the two different Potentials A and B. The contributions of both h^0Z^0 and h^0A^0 production are taken into account and the different regions correspond to different decays of h^0 and A^0: I - $h^0 \to \gamma\gamma$ and $A^0 \to b\bar{b}$ or stable, II - $h^0 \to \gamma\gamma$ and $A^0 \to h^0Z^0$ and III - $h^0 \to A^0A^0$ and $A^0 \to b\bar{b}$ [11] (or stable in the case of Pot. A). The darker region in the low masses is obtained using LEP1 results.

The analysis of $e^+e^- \to h^0Z^0$ proceed as before. Knowing the SM cross-section and how to compute the BR, the cross-section limits can be interpreted as limits on $\sin^2\delta$ (as shown in figure 4) for each Higgs mass; the upper values of $\sin^2\delta$ can be excluded for masses laying between 5 GeV/c^2 and the kinematic limit of 105 GeV/c^2. The low values of mass are unexcluded as the two photons would then be indistinguishable, the low values of $\sin\delta$ can not be excluded as the cross-section vanishes.

To exclude the low values of $\sin\delta$, the h^0A^0 associated production is used. The main decay of the

A^0 boson is to a $b\bar{b}$ pair but for very small values of δ, the lifetime of the A^0 boson increases and it can leave the detector before decaying, both cases have been considered. The analysis are similar to the ones of h^0Z^0 but now with an extra b-tagging requirement and less conditions on the invisible mass. Also in figure 4, it is shown how different regions of the m_{h^0}.vs.$\sin^2\delta$ plane can be excluded according to m_{A^0}.

These results can also be seen in figure 5, where pairs of (m_{h^0},m_{A^0}) are excluded for all δ values. The different regions correspond to different allowed decays of both h^0 and A^0. In the case of Potential A, there can be a totally invisible final state – hard to measure at LEP; however the precise measurement of the invisible Z^0 width from LEP 1 allows the exclusion pairs of masses which could have been produced (with a cross-section above 67 pb) at that energy The same reasoning applies for very low masses of both bosons. In that case it would be the hadronic Z^0 width which could be changed, the general production of New Physics final state which could change Γ_Z^{had} was addressed in [12].

3.3 Model Independent Results

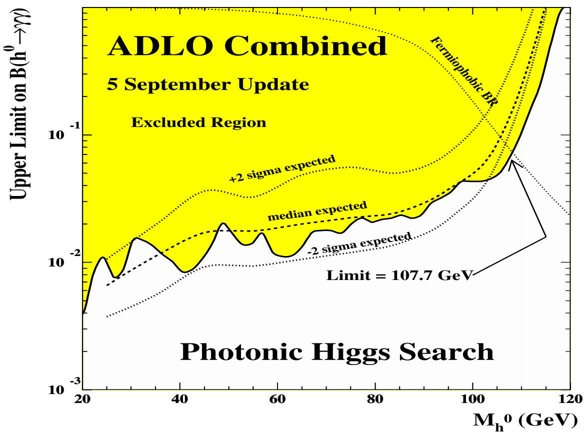

Figure 6: LEP combined result on the exclusion of a fermiophobic Higgs. An upper limit on the $BR(h^0 \to \gamma\gamma)$ is presented as a function of the Higgs boson mass. Results obtained from the search of h^0Z^0 production is compared with the expected background median result and 2σ deviations. Also shown is the BR for a fermiophobic Higgs boson with all SM couplings except $h^0f\bar{f} = 0$.

The results from the four LEP collaborations have been combined also to obtain a limit on the production of a fermiophobic Higgs. The most model independent channel in the search is the h^0Z^0 production, which has been performed in all the experiments [13] assuming different scenarios.

To combine the results a definite scenario must be defined: as a benchmark test the limits are presented for $\xi \times BR(X \to \gamma\gamma)$ in which $\xi = \sigma(Z^0X)/\sigma(Z^0H)_{SM}$ as a function of the X (fermiophobic higgs or other scalar boson) mass. The limit is shown in figure 6, where an indicative BR is also represented. This BR is obtained by assuming SM couplings, except for the the couplings of the Higgs boson to fermions which is set to 0 [5].

4 Conclusions

The four collaborations in the LEP accelerator have conducted searches for the Higgs boson in a large number of scenarios. In addition to the Standard Model Higgs boson, also the neutral Higgs sector of the Minimal SuperSymmetric Model has been extensively analysed and constrained, a variety of other models, predicting new production and decay modes for the Higgs particles have been severely restricted.

In particular the search for a Higgs boson decaying into photons becomes relevant in a large number of scenarios, all the collaborations have searched for the production of such a particle. While each experiment bases their analysis in different models, a common result has been reached for a more model independent result: excluding a Higgs with SM couplings to bosons but no couplings to fermions with masses up to 107.7 GeV/c^2.

There was no discovery neither of a SM higgs or a more exotic Higgs. But interesting and exciting results arose in the last months of LEP running. The results available give a hint for the possible signal of a Higgs boson with SM couplings and a mass around 115 GeV/c^2, to be confirmed or not by the hadronic colliders starting operation soon.

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