Search for the Fermiophobic Higgs at LEP

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Under extensions to the Standard Model, the lightest Higgs boson is expected to couple weakly to the fermions, leading to a bosonic signature. Results and limits from combined searches for $h \to \gamma\gamma$ and $h \to WW^*$ from LEP experiments are presented.

1. INTRODUCTION

Among the many processes studied and searched for at LEP, the search for the Higgs boson has been one of the most important. The Higgs is the missing piece of the Standard Model(SM) which has proven so effective at predicting the results of particle physics experiments. Much of the effort at LEP was focused on searches for the minimal SM Higgs. A SM Higgs boson with mass less than 115 GeV decays primarily into $b\bar{b}$, with branching fractions to tau pairs or gauge boson pairs which are much smaller. However searches have been undertaken at LEP to look for non-SM Higgs bosons, including the MSSM Higgs and the "fermiophobic" Higgs.

A fermiophobic Higgs arises in some extensions to the Standard Model that predict more than one Higgs boson. In these models, the coupling of the lightest Higgs boson to fermions is suppressed and thus the decays to $\gamma\gamma$, WW^*, and ZZ^* become dominant. Among the most important fermiophobic Higgs models are the Type I 2-Higgs Doublet Models[1], where the coupling of the lightest Higgs to fermions is proportional to $\cos\alpha$ and the coupling can be set to zero with $\alpha = \frac{\pi}{2}$.

Since there are many possible fermiophobic models, the LEP Higgs Working Group seeks to present results in a model-independent manner. A large class of solutions has near-Standard Model production strength so LEP Higgs Working Group(LHWG) assumes SM production rates and presents branching-ratio limits. However, to provide a baseline reference result, the LHWG has defined a "benchmark" model which uses decay branching ratios calculated with the HDECAY[2] or HZHA[3] programs. These benchmark branching ratios are shown in Figure 1.

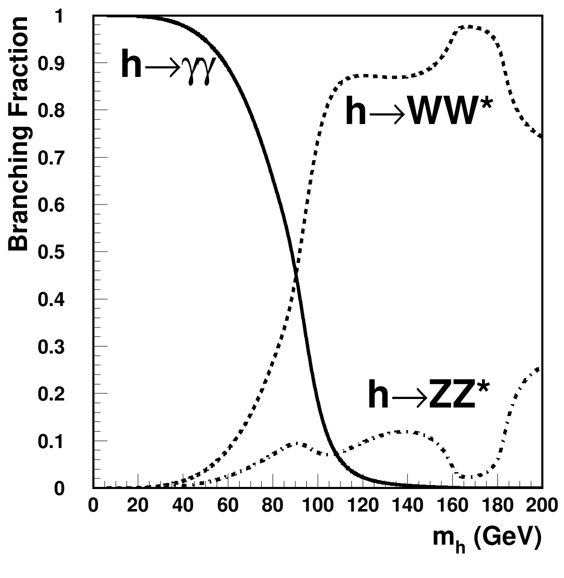

Figure 1. Branching ratios for the benchmark fermiophobic model.

2. THE $h \to \gamma\gamma$ CHANNELS

The first searches at LEP for the fermiophobic Higgs were searches for a Higgs which decayed to two photons. Since photons are massless, the

Higgs does not couple directly to them, but it can decay to two photons through a W loop or a charged Higgs loop. For a low mass fermiophobic Higgs, we expect this process to be dominant (as seen in Figure 1). All four LEP experiments perform a search in the "Higgsstrahlung" production mode, where the Higgs is produced in association with a Z boson. The details of each experiment's analysis are given in journal articles[4–7], but the general strategies will be outlined here.

The decays of the Z define three search channels: $hZ \to \gamma\gamma q\bar{q}$, $hZ \to \gamma\gamma\nu\bar{\nu}$, and $hZ \to \gamma\gamma l^+l^-$. For all the channels, the major background is double-radiative Z production. In this process, one or both incoming electrons emit multiple photons before interacting. The process tends to produce on-shell, boosted Z bosons and one or more high energy photons that mimic the signal. For the signal, the diphoton spectrum is peaked at the Higgs mass, while the background spectrum is fairly flat over a wide range of invariant masses.

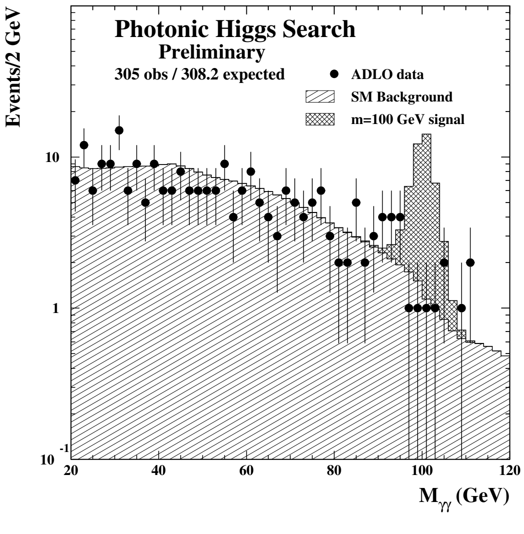

Figure 2. Mass distribution of selected events in the LEP combined $h \to \gamma\gamma$ search.

In general, photons are experimentally identified as isolated clusters in the electromagnetic calorimeters which have no matching track that would indicate an electron. Additional selection criteria are also used to reject π_0's and other possible sources of fakes.

DELPHI, L3, and OPAL have developed analyses for each of the three search channels separately, using similar cut-based approaches to reduce the background. In contrast, the ALEPH experiment performs a "global" analysis, focusing on the diphoton system and combining all the Z decay channels together. The results from these selections are presented in Table 1.

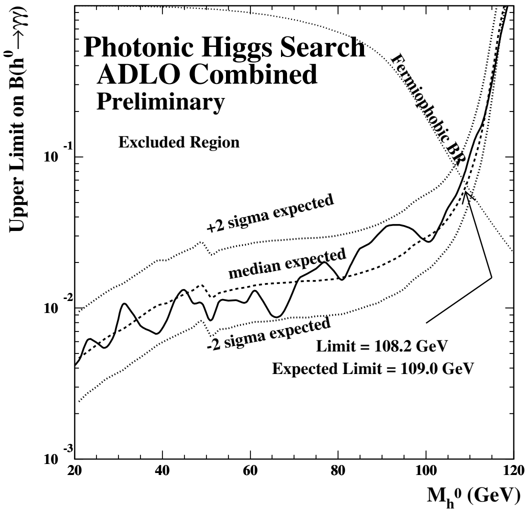

Figure 3. Branching ratio limits for the $h \to \gamma\gamma$ search.

Each experiment produces files containing the observed data events as well as the predicted background and signal distributions from Monte Carlo. The LHWG then combines them to produce the combined results shown at the bottom of Table 1[8]. The mass distribution of these events is shown in Figure 2, along with the predicted signal for a m_h=100 GeV fermiophobic Higgs. For the results to be applicable to a range of fermiophobic models, the LHWG calculates the BR($h \to \gamma\gamma$) for a 95% confidence level limit at each mass hypothesis. The predicted and observed results of this calculation are shown in Figure 3. The dash-dotted line indicates the branching ratio predicted from the benchmark model.

Table 1
Results of the $h \to \gamma\gamma$ search from the four experiments.

Experiment	Energy Range	Candidates	Expected Bkgd	Benchmark Limit (GeV)	Expected Limit (GeV)
ALEPH	192-209	10	10.8	104.4	104.6
DELPHI	189-209	47	42.2	103.6	105.1
L3	189-209	64	69.5	104.1	104.9
OPAL	88-209	184	185.7	104.8	105.2
SUM		305	308.5	108.2	109.0

3. THE $h \to WW^*$ CHANNELS

As seen in Figure 1, for m_h greater than 100 GeV the $h \to \gamma\gamma$ branching ratio becomes small relative to the $h \to WW^*$ branching ratio. This motivates a search in the $h \to WW^*$ channel, which L3 has partially completed and the other LEP experiments are investigating.

As in the $h \to \gamma\gamma$ channels, production is assumed to be by Higgsstrahlung and so the final state contains six fermions. Considering all the Z and W decays, there are nine possible channels. Of these, L3 has produced analyses for five of them. The five channels covered are the qqqq(qq), qqlν(qq), qqqq($\nu\nu$), qqlν($\nu\nu$), and qqqq(ll), where the decay of the Z is given in parentheses. These five cover a total of 85% of the theoretical branching fraction of $hZ \to WW^*f\bar{f}$. The searches use data from $\sqrt{s} = 199$ GeV up to $\sqrt{s} = 209$ GeV.

Some of the WW* channels also correspond to channels in the $h \to ZZ^*$ sector, such as $hZ \to ZZ^*f\bar{f} \to$ qqqq(qq). The relatively small mass difference between the Z and W allows a single analysis to efficiently cover both WW* and ZZ* in the qqqq(qq)channel. Combining the two enhances the sensitivity of the channel to an extent equivalent to adding 15% to the $WW^* \to$ qqqq(qq) signal cross-section.

One particular feature of the WW* channel arises from the kinematics of the decay which predict one W to be near its mass shell and other far off it, for small Higgs masses. Thus, in the channels where the two W's decay to qqlν, there are effectively two subchannels: one where the lν comes from the W and the qq from the W*, and the converse case. The qqlν($f\bar{f}$) analyses separate these two subchannels using kinematic variables and analyze them separately.

The background in these channels comes from a variety of SM processes, including W pair production, Z pair production, and $q\bar{q}$ events. Different selection variables are used in each of the channels, but most use a neural network and combine the output of the network with a mass variable in a discriminant.

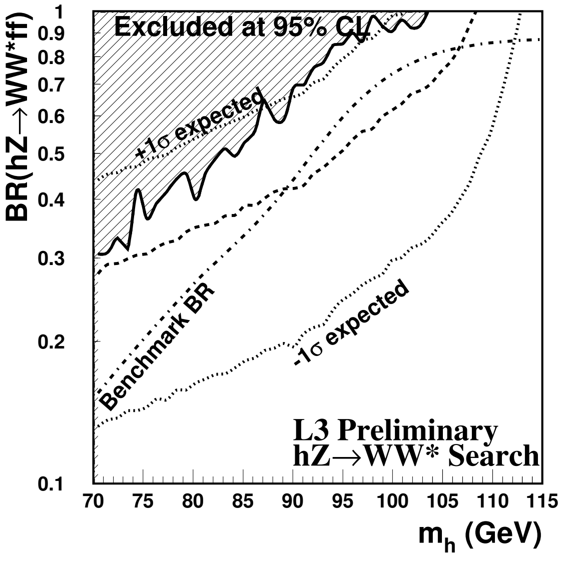

Figure 4. Branching ratio limits for the $h \to WW^*$ search.

Most of the channels have been described in previous conference notes[9], but the qqqq(ll) channel is new to this note. In this channel, the Z decays to either two electrons or two muons, while the W bosons decay hadronically. The analysis selects the pair of well-identified leptons with the invariant mass closest to the Z mass. Various event-shape and kinematic variables are used to construct a neural network to select events with four hadronic jets. While the number of expected events in this channel is fairly low, the background is quite small and the mass resolution very high.

The results of the $h \to WW^*$ search are summarized by channel in Table 2. The candidates from data and the expected background are given in the first two columns, and the number of events expected for a m_h=110 GeV benchmark model Higgs in the third. We show branching ratio limits for these channels in Figure 4. If we combine the L3 $h \to \gamma\gamma$ results with the $h \to WW^*$ results in the benchmark model, the expected limit is extended from 104.9 GeV to 109.1 GeV and the observed limit from 104.1 GeV to 104.8 GeV.

Table 2
Results of the $h \to WW^*$ search by channel.

Channel	Data	Expected Bkgd	Expected Signal (m_h=110 GeV)
qqqq(qq)	443	446.5	7.16[1]
qqlν(qq)[2]	15/47	11.2/50.6	2.01/0.69
qqqq($\nu\nu$)	41	47.9	1.48
qqlν($\nu\nu$)	10	12.1	0.75
qqqq(ll)	9	7.3	0.38
SUM	633	645.1	15.3

[1] Includes contribution from $h \to ZZ^* \to$qqqq(qq).
[2] Separated into [qqeν(qq)+qq$\mu\nu$(qq)]/qq$\tau\nu$(qq).

4. COMBINED RESULTS

The results from both $h \to \gamma\gamma$ and $h \to WW^*$ are presented separately in terms of branching-ratio limits to make the results applicable to a range of models. When combining the two sets of channels, there is an additional parameter to consider: the relative branching ratios of the two sets.[1] To present general results, we need to consider different values of the relative branching ratios. For the purposes of plotting, we will parameterize the branching ratios as follows:

$$\begin{aligned} \mathrm{Br_{phobic}} &= BR(\mathrm{h} \to \gamma\gamma) + BR(\mathrm{h} \to \mathrm{WW}^*) \\ &\quad + BR(\mathrm{h} \to \mathrm{ZZ}^*) \\ \mathrm{Br}_{\gamma\gamma} &= BR(\mathrm{h} \to \gamma\gamma)/\mathrm{Br_{phobic}} \end{aligned}$$

Thus $\mathrm{Br}_{\gamma\gamma}$ represents the fraction of fermiophobic decays which are to $\gamma\gamma$ and can range from zero to one, while $\mathrm{Br_{phobic}}$ represents the total Higgs branching fraction to pairs of gauge bosons. We scan values of both m_h and $\mathrm{Br}_{\gamma\gamma}$ and determine the values of $\mathrm{Br_{phobic}}$ for which we have 95% CL exclusion.

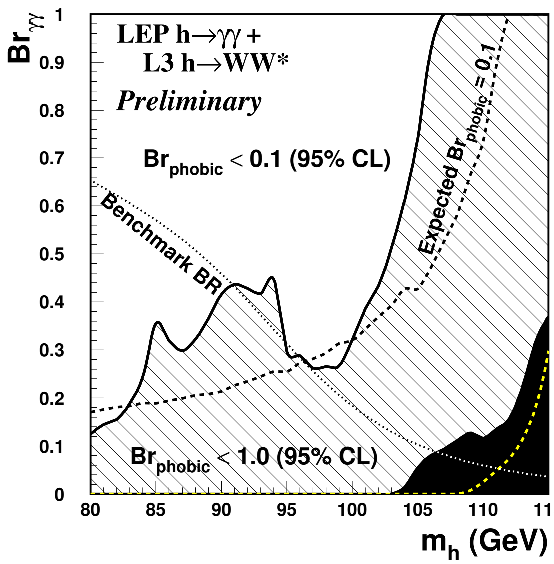

Figure 5. Combined limit scan for LEP $h \to \gamma\gamma$ and L3 $h \to WW^*$. The dashed lines show the expected limits while the hatched or solid colored areas show the observed limits. The dark area in the lower right shows the region which is not excluded for any $\mathrm{Br_{phobic}} < 1$. The benchmark prediction for $\mathrm{Br}_{\gamma\gamma}$ is shown by the dotted line.

Figure 5 shows the results of the two-dimensional scan of the $m_h$vs. $\mathrm{Br}_{\gamma\gamma}$ plane. The areas (solid white, hatched, and solid black) show the regions where a fermiophobic Higgs is excluded at 95% CL for $\mathrm{Br_{phobic}} > 0.01$, $\mathrm{Br_{phobic}} >$

[1]The relation between $BR(h \to WW^*)$ and $BR(h \to ZZ^*)$ is more strongly fixed by theory.

0.1, and $\mathrm{Br}_{\mathrm{phobic}} > 1$, respectively. The dashed lines show the edges of the predicted exclusion region, while the dotted line gives the benchmark value of $\mathrm{Br}_{\gamma\gamma}$ for reference. The crossing point of this line into the $\mathrm{Br}_{\mathrm{phobic}} > 1$ area sets the limit for the benchmark model. The observed limit is 106.4 GeV and the expected limit is 111.2 GeV.

5. CONCLUSIONS

Among the important legacies of LEP will be these searches for a Higgs decaying to gauge bosons. These results are important not just for the fermiophobic models, but also for the future exploration of the Standard Model. If the Standard Model is correct about the Higgs field's structure and the mass is less than 120 GeV, the most powerful channel for LHC will be the $\mathrm{h} \rightarrow \gamma\gamma$, while if the mass is larger than 120 GeV, the $\mathrm{h} \rightarrow \mathrm{WW}^*$ channel will be critical for its discovery and study. In either case, the techniques and experience developed at LEP will be of the greatest use.

We would like to thank all the engineers, technicians, and machine physicists who made LEP perform to such an extraordinary level. Without their dedication, these searches would have been impossible.

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