Proceedings of the DIS'2004, Štrbské Pleso, Slovakia

SEARCHES FOR HIGGS BOSONS BEYOND THE STANDARD MODEL

ANDRÉ SOPCZAK
Lancaster University, UK. E-mail: Andre.Sopczak@cern.ch

Latest results from the combined data of the four LEP experiments ALEPH, DELPHI, L3 and OPAL on Higgs boson searches in extensions of the Standard Model (SM) are presented.

The LEP experiments took data between August 1989 and November 2000 at center-of-mass energies first around the Z resonance (LEP-1) and later up to 209 GeV (LEP-2). In 2000 most data was taken around 206 GeV. The LEP accelerator operated very successfully and a total luminosity of $\mathcal{L} = 2461$ pb^{-1} was accumulated at LEP-2 energies. Data-taking ended on 3 November 2000, although some data excess was observed in searches for the SM Higgs boson with 115 GeV mass. In this report several different research lines are addressed beyond the SM: 1) coupling limits; 2) the Minimal Supersymmetric extension of the SM (MSSM): dedicated searches, three-neutral-Higgs-boson hypothesis, benchmark and general scan mass limits; 3) CP-violating models; 4) invisible Higgs boson decays; 5) neutral Higgs bosons in the general two-doublet Higgs model; 6) Yukawa Higgs boson processes $b\bar{b}h$ and $b\bar{b}A$; 7) singly-charged Higgs bosons; 8) doubly-charged Higgs bosons; 9) fermiophobic Higgs boson decays $h \to WW, ZZ, \gamma\gamma$; 10) uniform and stealthy Higgs boson scenarios.

While the results from Standard Model Higgs boson searches are final [1], the results of searches in extended models are mostly preliminary [2]. Limits are given at 95% CL. Full-size figures of this report are available from Ref. [3].

1 Coupling Limits

Figure 1 shows coupling limits assuming the Higgs boson decays with SM branching fractions and a SM production rate reduced by $\xi^2 = (g_{\mathrm{HZZ}}/g^{\mathrm{SM}}_{\mathrm{HZZ}})^2$. In addition, coupling limits are presented for b-quark and τ-lepton decay modes. Remarkably, mass limits for flavor-blind hadronic decays are close to the SM decay mode limits.

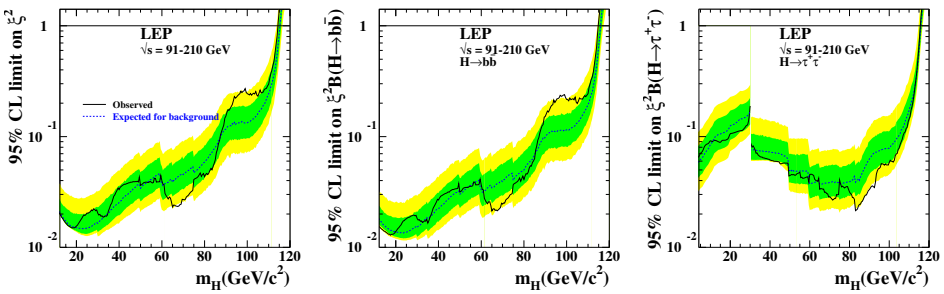

Figure 1. Coupling limits. Left: SM decay mode. Center: b-quark decay mode. Right: τ-lepton decay mode. The 1σ and 2σ error bands on the expected limit for background are indicated (shaded areas).

© Institute of Experimental Physics SAS, Košice, Slovakia

2 Minimal Supersymmetric Extension of the SM (MSSM)

2.1 Benchmark Limits and Dedicated Low m_A and h→AA Searches

Figure 2 shows a small previously unexcluded mass region for light A masses in the no-mixing scalar top benchmark scenario. This region is mostly excluded by new dedicated searches for a light A boson (center plot). Limits for the maximum h-mass benchmark scenario, including results from dedicated searches for the reaction h→AA are also shown (right plot).

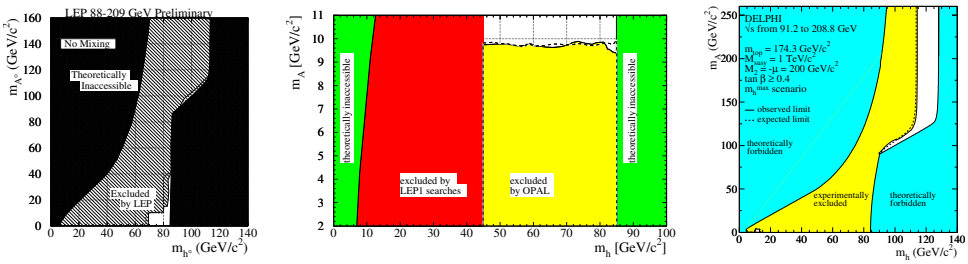

Figure 2. MSSM. Left: unexcluded mass region for a light A boson in the no-mixing scalar top benchmark scenario. Center: excluded mass region by dedicated searches for a light A boson. Right: mass limits in the maximum h-mass benchmark scenario.

2.2 Three-Neutral-Higgs-Boson Hypothesis and a MSSM Parameter Scan

The hypothesis of three-neutral-Higgs-boson production, via hZ, HZ and hA is compatible with the data excess seen in Fig. 3. For the reported MSSM parameters [4] reduced hZ production near 100 GeV and HZ production near 115 GeV is compatible with the data (left plot). For $m_h \approx m_A$, hA production is also compatible with the data (center plot). The parameters have been obtained from a general MSSM parameter scan. Mass limits from this scan are also shown (right plot).

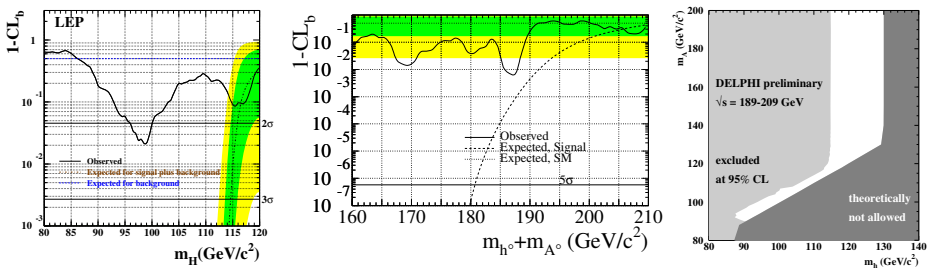

Figure 3. MSSM. Left: small data excess at 99 GeV and 116 GeV in hZ/HZ searches. Center: small data excess at $m_h + m_A = 187$ GeV in hA searches. $1 - CL_b$ expresses the incompatibility of the observation with the background-only hypothesis. Right: mass limits from a general MSSM parameter scan.

2.3 Large Effect from Increased Top-Quark Mass

The increase of the measured top quark mass by about 4 GeV has a large effect on the Higgs boson mass and reduces significantly the previous limits on $\tan\beta$.

3 CP-Violating Models

Instead of h, H and A, the Higgs bosons are named H_1, H_2 and H_3. The reactions $e^+e^- \to H_2Z \to b\bar{b}\nu\bar{\nu}$ and $e^+e^- \to H_2Z \to H_1H_1Z \to b\bar{b}b\bar{b}\nu\bar{\nu}$ are searched for. No indication of these processes is observed in the data as shown in Fig. 4. In general, CP-mixing reduces the MSSM mass limits significantly (center and right plots).

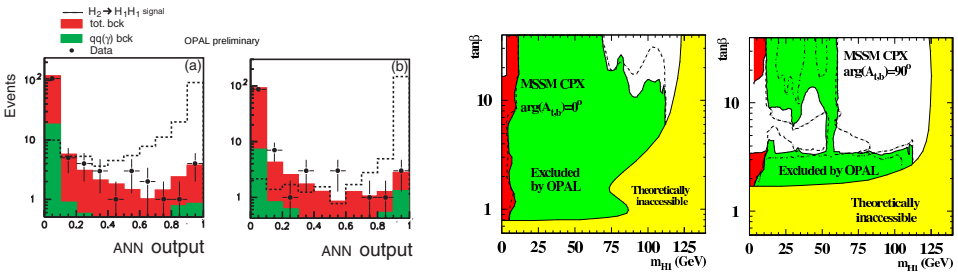

Figure 4. CP-violation models. Left: Artificial Neural Network (ANN) output distributions for the reactions $e^+e^- \to H_2Z \to b\bar{b}\nu\bar{\nu}$ and $e^+e^- \to H_2Z \to H_1H_1Z \to b\bar{b}b\bar{b}\nu\bar{\nu}$ for different data sub-samples. No indication of a signal is observed. Center: mass limits with no CP-mixing. Right: mass limits with full CP-mixing.

4 Invisible Higgs Boson Decays

No indication of invisibly-decaying Higgs bosons is observed. Figure 5 shows mass limits for SM and invisible Higgs boson decays combined. The results are also interpreted in a Majoron model with an extra complex singlet, H/S→JJ, where J escapes undetected. In addition, mass limits are shown in the MSSM.

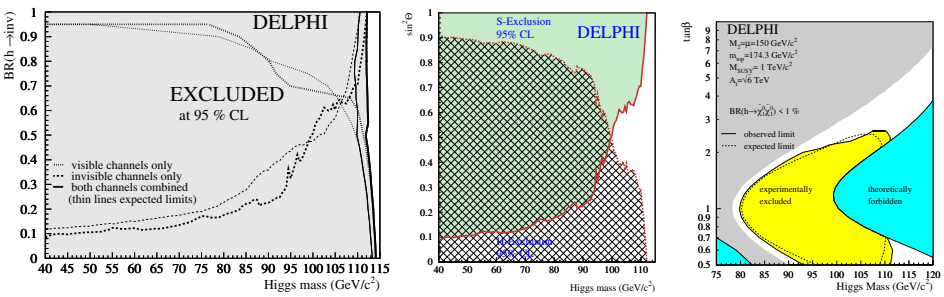

Figure 5. Left: mass limits for SM and invisible Higgs boson decays combined. Center: mass limits in Majoron models with an extra complex singlet, H/S→JJ, where J escapes undetected. $\sin\theta$ is the H/S mixing angle. Right: mass limits in the MSSM for $h \to \tilde{\chi}_1^0\tilde{\chi}_1^0$.

5 Neutral Higgs Bosons in the General Two-Doublet Higgs Model

Figure 6 shows mass limits from flavor-independent and dedicated searches for hA production, and from a parameter scan. The scan combines searches with b-tagging and flavor-independent searches.

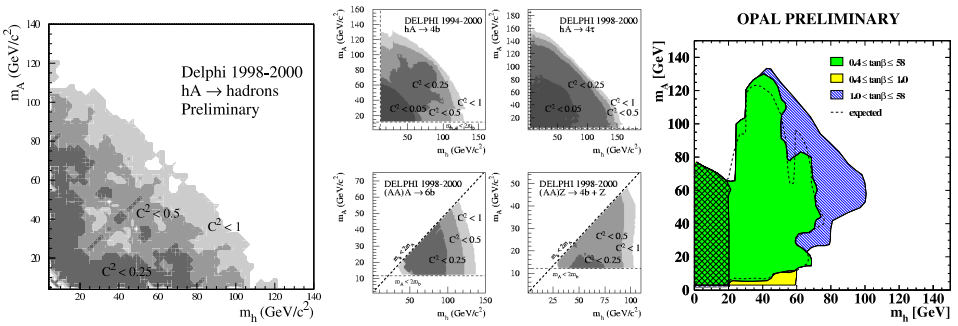

Figure 6. Two-doublet Higgs model. Left: Flavor-independent limits. C^2 is the reduction factor on the maximum production cross section. Center: Limits from dedicated searches for hA production. Right: mass limits from a general parameter scan in the two-doublet Higgs model.

6 Yukawa Higgs Boson Processes $b\bar{b}h$ and $b\bar{b}A$

Figure 7 shows mass limits from searches for the Yukawa processes $e^+e^- \to b\bar{b} \to b\bar{b}h$, $b\bar{b}A$.

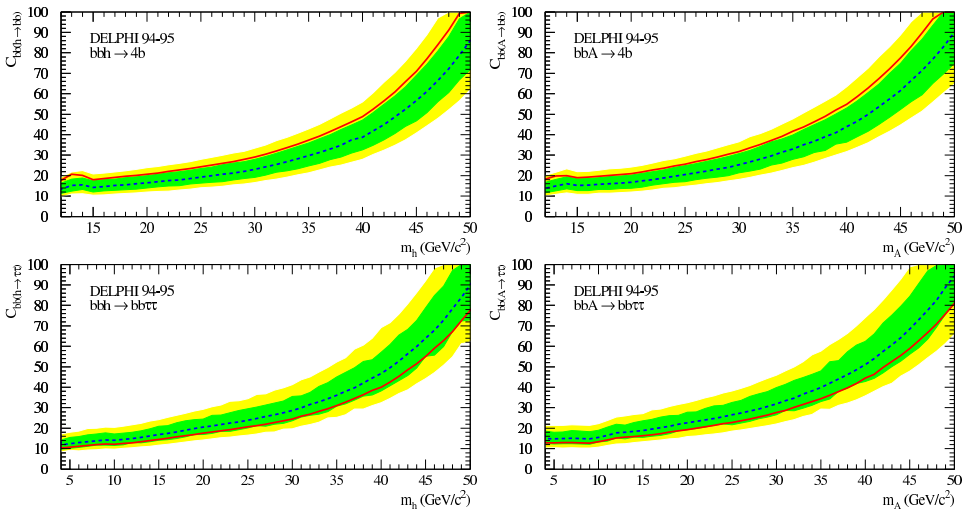

Figure 7. Observed (solid line) and expected (dotted line) mass limits from searches for the Yukawa processes $e^+e^- \to b\bar{b} \to b\bar{b}h$, $b\bar{b}A$. The C factors include vertex enhancement factors and decay branching fractions. The 1σ and 2σ error bands on the expected limit for background are indicated (shaded areas).

7 Singly-Charged Higgs Bosons

Figure 8 shows mass limits from searches for $e^+e^- \to H^+H^- \to c\bar{s}\bar{c}s$, $cs\tau\nu$, $\tau^+\nu\tau^-\bar{\nu}$. The decay $H^\pm \to W^\pm A$ could be dominant and limits from dedicated searches are set.

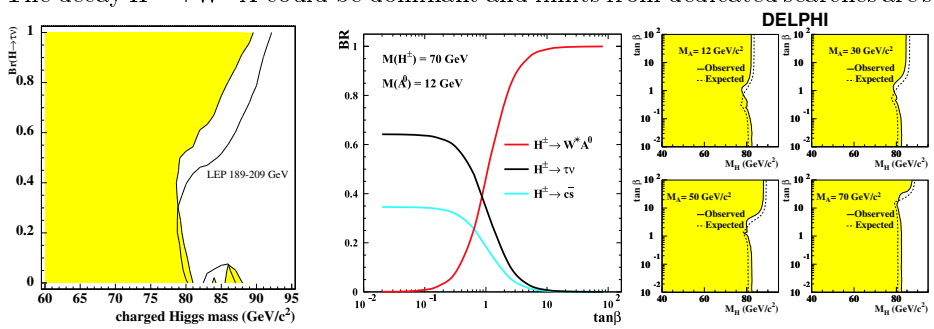

Figure 8. Left: Excluded mass region (shaded area) from searches for $e^+e^- \to H^+H^- \to c\bar{s}\bar{c}s$, $cs\tau\nu$ and $\tau^+\nu\tau^-\bar{\nu}$. The thin line shows the expected limit. Center: $H^\pm \to W^\pm A$ decays could be dominant for light A boson masses. Right: excluded mass region (shaded area) from searches for this process.

8 Doubly-Charged Higgs Bosons

The process $e^+e^- \to H^{++}H^{--} \to \tau^+\tau^+\tau^-\tau^-$ can lead to decays at the primary interaction point ($h_{\tau\tau} \geq 10^{-7}$) or a secondary vertex, or to stable massive particle signatures. Figure 9 shows limits on the production cross section and constraints by the forward-backward asymmetry of the process $e^+e^- \to e^+e^-$.

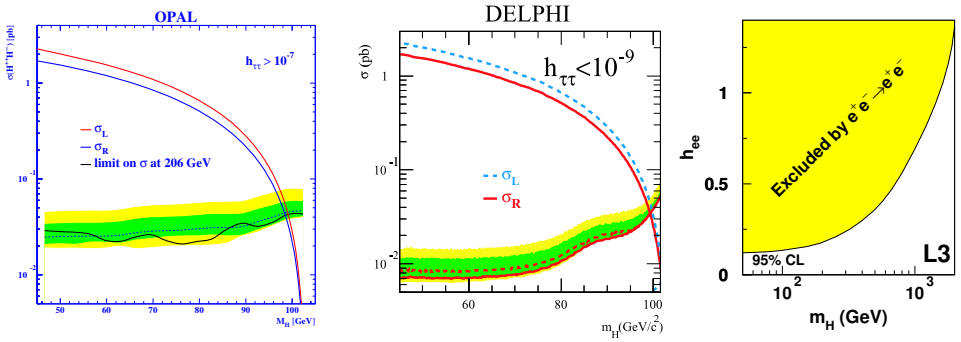

Figure 9. Left and Center: Limits on the $e^+e^- \to H^{++}H^{--}$ production cross section as a function of the doubly-charged Higgs boson mass. The 1σ and 2σ error bands on the expected limit for background are indicated (shaded areas). Right: H^{--} limits from $e^+e^- \to e^+e^-$ forward-backward asymmetry.

9 Fermiophobic Higgs Boson Decays: h→ WW, ZZ, $\gamma\gamma$

If Higgs boson decays into fermions are suppressed, h→ WW, ZZ, $\gamma\gamma$ decays could be dominant. Mass limits from dedicated searches are set [5].

10 Uniform and Stealthy Higgs Boson Scenarios

The recoiling mass of the Z boson in the reaction $e^+e^- \to HZ$ allows to search for the Higgs boson independent of the Higgs boson decay mode. No indication of a Higgs boson signal has been observed as shown in Figs. 10. Mass limits are shown in the uniform Higgs boson model, where many uniform Higgs boson states exist in the range between m_A and m_B. Another result from the recoiling mass spectrum is shown, where a stealthy Higgs boson has a large decay width owing to extra Higgs boson singlets in the model. The decay width depends on the parameter ω.

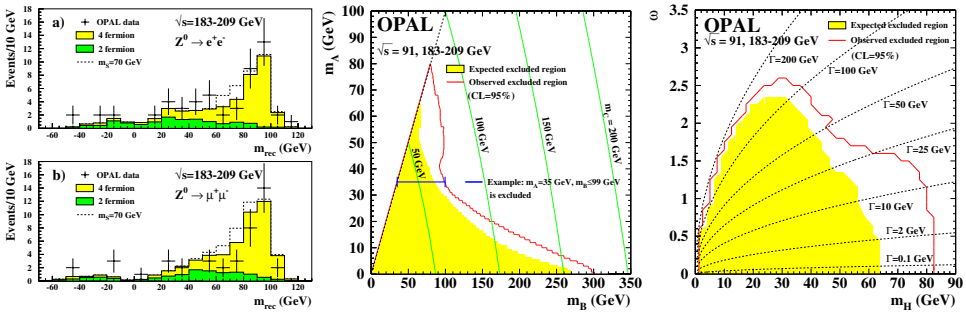

Figure 10. Left: Recoiling mass spectrum of $Z \to e^+e^-$ and $Z \to \mu^+\mu^-$. Center: Excluded mass range in the uniform Higgs model. Right: Mass limits in the stealthy Higgs model.

11 Conclusions

Immense progress over a period of 15 years has been made in searches for Higgs bosons and much knowledge has been gained in preparation for new searches. No signal has been observed and various stringent limits are set as summarized in Table 1.

Acknowledgments

I would like to thank the organizers of the DIS'2004 conference for their kind hospitality, and colleagues from the LEP experiments for providing their latest results.

Table 1. Summary of Higgs boson mass limits at 95% CL. 'LEP' indicates a combination of the results from ALEPH, DELPHI, L3 and OPAL. If results from the experiments are not (yet) combined, examples which represent the different research lines from individual experiments are given.

Search	Experiment	Limit
Standard Model	LEP	$m_{\mathrm{H}}^{\mathrm{SM}} > 114.4$ GeV
Reduced rate and SM decay		$\xi^2 > 0.05 : m_{\mathrm{H}} > 85$ GeV
		$\xi^2 > 0.3 : m_{\mathrm{H}} > 110$ GeV
Reduced rate and $\mathrm{b\bar{b}}$ decay		$\xi^2 > 0.04 : m_{\mathrm{H}} > 80$ GeV
		$\xi^2 > 0.25 : m_{\mathrm{H}} > 110$ GeV
Reduced rate and $\tau^+\tau^-$ decay		$\xi^2 > 0.2 : m_{\mathrm{H}} > 113$ GeV
Reduced rate and hadronic decay		$\xi^2 = 1 : m_{\mathrm{H}} > 112.9$ GeV
		$\xi^2 > 0.3 : m_{\mathrm{H}} > 97$ GeV
	ALEPH	$\xi^2 > 0.04 : m_{\mathrm{H}} \approx 90$ GeV
Anomalous couplings	L3	d, d_{B}, Δg_1^{Z}, $\Delta\kappa_\gamma$ exclusions
MSSM (no scalar top mixing)	LEP	almost entirely excluded
General MSSM scan	DELPHI	$m_{\mathrm{h}} > 87$ GeV, $m_{\mathrm{A}} > 90$ GeV
Larger top-quark mass	LEP	strongly reduced $\tan\beta$ limits
CP-violating models	OPAL	strongly reduced mass limits
Visible/invisible Higgs decays	DELPHI	$m_{\mathrm{H}} > 111.8$ GeV
Majoron model (max. mixing)		$m_{\mathrm{H,S}} > 112.1$ GeV
Two-doublet Higgs model	DELPHI	$\mathrm{hA}\to\mathrm{b\bar{b}b\bar{b}} : m_{\mathrm{h}} + m_{\mathrm{A}} > 150$ GeV
(for $\sigma_{\max}$)		$\tau^+\tau^-\tau^+\tau^- : m_{\mathrm{h}} + m_{\mathrm{A}} > 160$ GeV
		$(\mathrm{AA})\mathrm{A}\to 6\mathrm{b} : m_{\mathrm{h}} + m_{\mathrm{A}} > 150$ GeV
		$(\mathrm{AA})\mathrm{Z}\to 4\mathrm{b\ Z} : m_{\mathrm{h}} > 90$ GeV
		$\mathrm{hA}\to\mathrm{q\bar{q}q\bar{q}} : m_{\mathrm{h}} + m_{\mathrm{A}} > 110$ GeV
Two-doublet model scan	OPAL	$\tan\beta > 1 : m_{\mathrm{h}} \approx m_{\mathrm{A}} > 85$ GeV
Yukawa process	DELPHI	$C > 40 : m_{\mathrm{h,A}} > 40$ GeV
Singly-charged Higgs bosons	LEP	$m_{\mathrm{H}^\pm} > 78.6$ GeV
$\mathrm{W}^\pm\mathrm{A}$ decay mode	DELPHI	$m_{\mathrm{H}^\pm} > 76.7$ GeV
Doubly-charged Higgs bosons	DELPHI/OPAL	$m_{\mathrm{H}^{++}} > 99$ GeV
$\mathrm{e^+e^-}\to\mathrm{e^+e^-}$	L3	$h_{\mathrm{ee}} > 0.5 : m_{\mathrm{H}^{++}} > 700$ GeV
Fermiophobic $\mathrm{H}\to\mathrm{WW}, \mathrm{ZZ}, \gamma\gamma$	L3	$m_{\mathrm{H}} > 108.3$ GeV
$\mathrm{H}\to\gamma\gamma$	LEP	$m_{\mathrm{H}} > 109.7$ GeV
Uniform and stealthy scenarios	OPAL	depending on model parameters

References

1. ALEPH, DELPHI, L3 and OPAL Collaborations and the LEP working group for Higgs boson searches, Phys. Lett. **B 565** (2003) 61.
2. ALEPH, DELPHI, L3 and OPAL Collaborations, contributed papers to the International Europhysics Conference on High Energy Physics EPS, 17-23 July 2003, Aachen, Germany; and XXI International Symposium on Lepton and Photon Interactions at High Energies, 11-16 August 2003, Fermi National Accelerator Laboratory, Batavia, Illinois, USA; and recent updates.
3. A. Sopczak, hep-ph/0408047.
4. A. Sopczak, Proc. DPF-2000, hep-ph/0011285; Proc. Topical seminar on the legacy of LEP and SLC, Siena, Nucl. Phys. Proc. Supp. **109** (2002) 271.
5. Ch. Delaere, "Fermiophobic Higgs", these proceedings.