Search for Higgs Bosons at LEP

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The latest preliminary results of the searches for Higgs bosons at LEP are reviewed. The results include the data-taking in 1999 up to center-of-mass energies of 196 GeV. The combination of the results from the four LEP experiments leads to a significant increase of the detection sensitivity. No indication of a signal has been observed. In the Standard Model (SM) a lower limit of 102.6 GeV on the mass of the Higgs boson is set at 95% CL. In extended models, stringent limits are also set on the HZZ coupling. Interpretations in the Minimal extension of the Supersymmetric Standard Model (MSSM) are given and the importance of general MSSM parameter scans is emphasized. In general scans, the limit on the mass of the lightest scalar Higgs boson is about 7 GeV lower in comparison with benchmark results. The data also constrains charged Higgs bosons of a general two-doublet model.

1. Introduction

The data-taking at LEP has been very successful, leading to continuously increasing center-of-mass energy and luminosity as shown in Fig. 1. In August 1999, exactly 10 years after the first recording of a Z boson at LEP, a center-of-mass energy of 200 GeV was reached. The LEP accelerator will continue operation at a center-of-mass energy around 205 GeV in 2000.

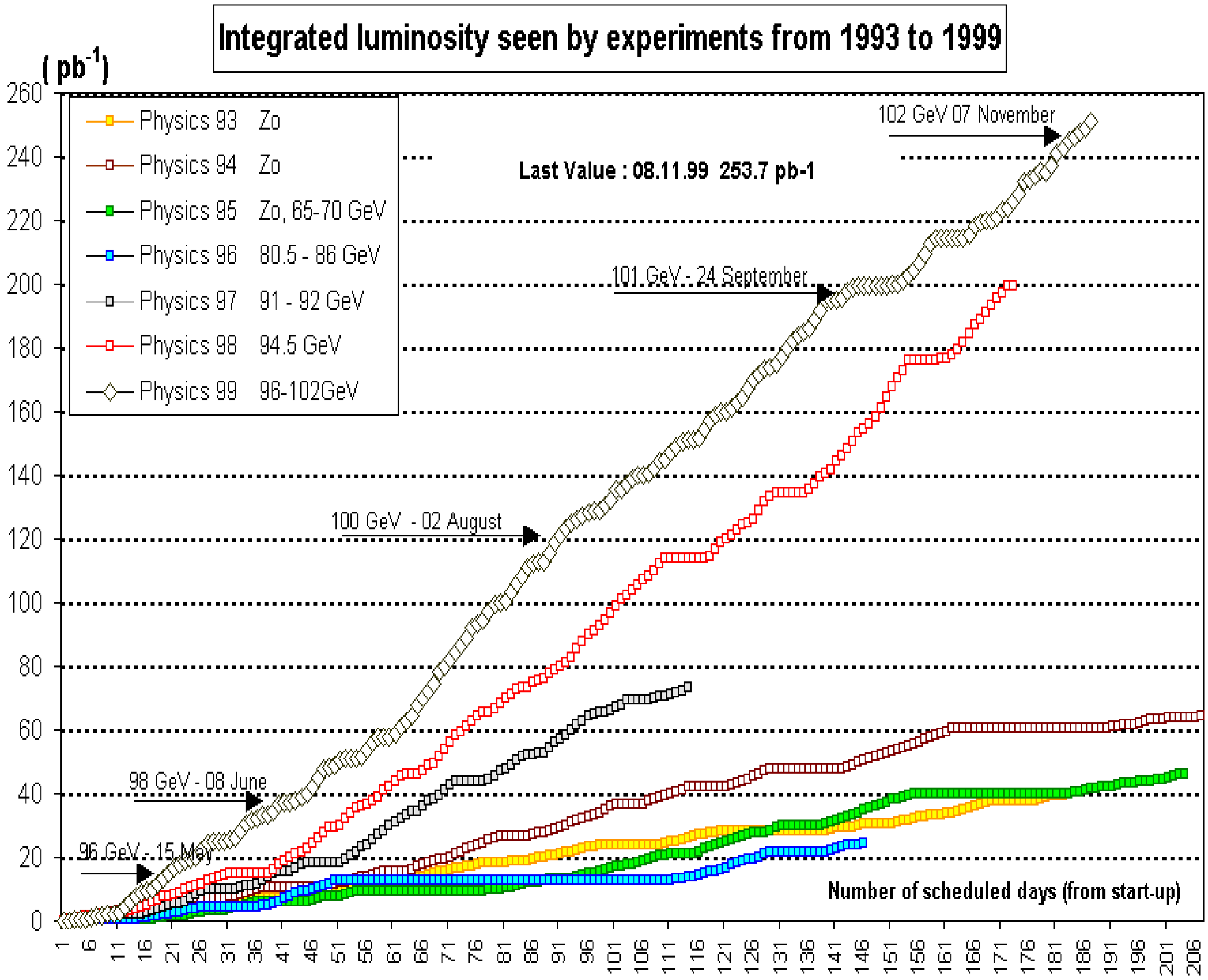
The results of this report are mainly based on the combination of the data from the four LEP experiments ALEPH, DELPHI, L3 and OPAL [1]. In the search for the Standard Model Higgs boson, all four LEP experiments have contributed. Three experiments have released their 1999 data for combination in the MSSM search, and two for the charged Higgs boson search, leading to the luminosities shown in Table 1.

The search for Higgs bosons is performed in different analysis channels with various signatures defined by the decay properties of the Higgs and Z bosons. The production and decay rates are mainly calculated in the framework of three theoretical models: the Standard Model with one Higgs doublet; the general two-doublet Higgs model where three neutral and two charged Higgs bosons are predicted; and the MSSM, where in addition, Higgs boson masses and couplings are related. In the MSSM one neutral Higgs boson is predicted to be light ($m_{\rm h} < 130$ GeV), while the charged Higgs bosons are heavier than the W bosons.

Table 1. Data used for the combination of the Higgs boson searches from the four LEP experiments.

$\sqrt{s}$ (GeV)	Year	SM Higgs $\mathcal{L}$ (pb^{-1})	MSSM Higgs $\mathcal{L}$ (pb^{-1})	Charged Higgs $\mathcal{L}$ (pb^{-1})
189	1998	683	683	690
192	1999	112	84	55
196	1999	265	185	132

Fig. 1. Delivered integrated luminosity per LEP experiment.



2. Detectors

A typical LEP detector is shown in detail in Fig. 2. The particles produced at the interaction point in the center of the detector pass several subdetectors. All LEP detectors are equipped with micro-vertex detectors in order to measure tracks with precision near the interaction point. Following particles to larger radii, they pass a tracking system, electromagnetic calorimeters, hadron calorimeters and muon chambers. Figure 3 illustrates the principle of the particle identification. Detailed particle identification is also possible with the DELPHI RICH detector using Cherenkov light to determine particle masses.

Fig. 2. A typical LEP detector.

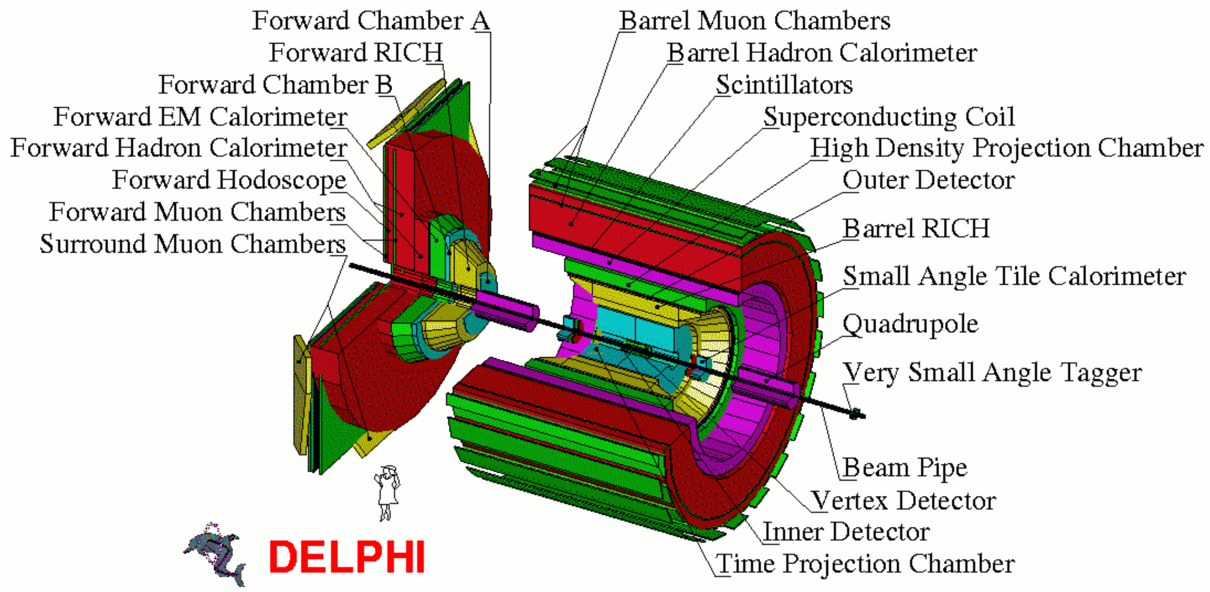
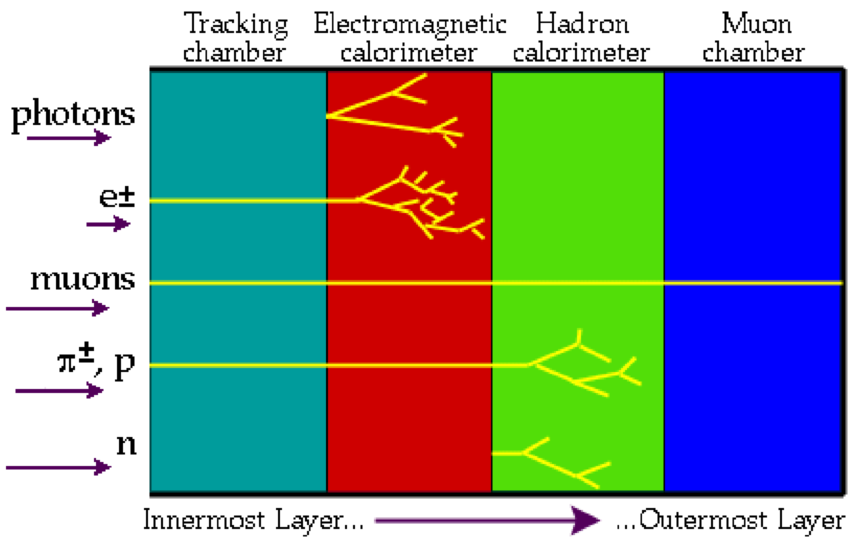


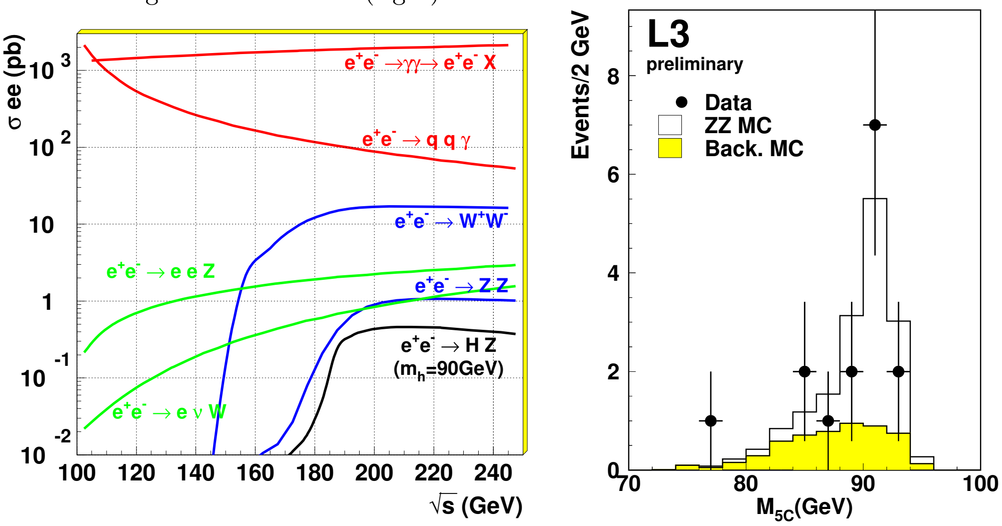
Fig. 3. Principle of particle identification.



3. ZZ Background and Higgs Boson Candidates

The production cross sections for the background reactions are shown in Fig. 4. In 1998, the threshold of the ZZ production was passed and the ZZ production and decay became a dominant background for many searches. Thus, a good understanding of this background is very important to observe a signal. The good agreement of data and simulation is shown in Fig. 4 for the L3 $e^+e^- \to ZZ \to qq\ell\ell$ analysis [2]. An important method to reduce the ZZ background is based on the identification of b-quarks. As an example, the b-tagging performance from DELPHI is shown in Fig. 5.

Fig. 4. Background and SM Higgs boson production cross sections (left) and mass spectrum of ZZ events for data, ZZ and background simulation (right).



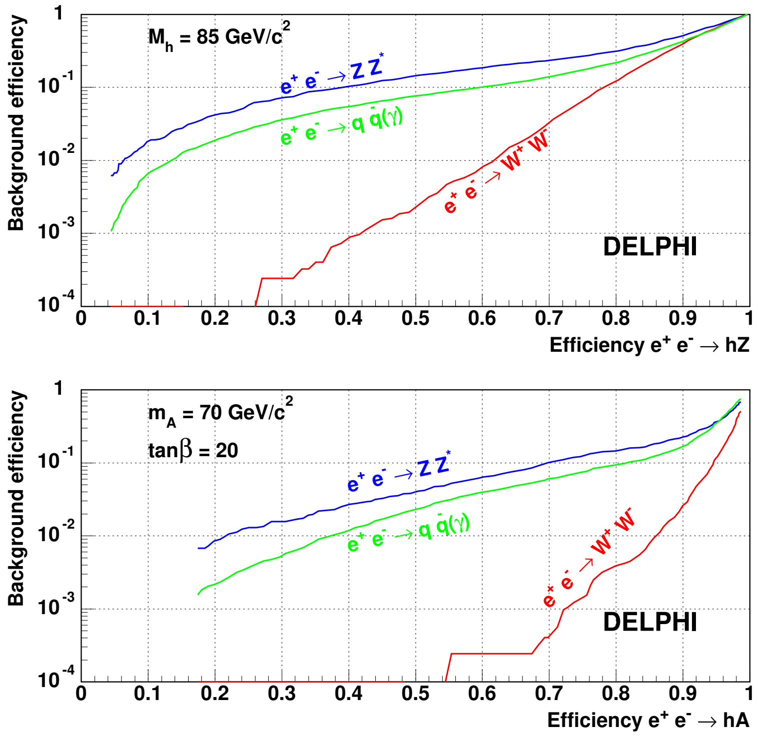


Fig. 5. Expected background as a function of efficiency for a simulated hZ and hA signal. The tagging of b-quarks reduces very strongly the WW process, where almost no b-quark decays are expected. Also, qq and ZZ processes are largely suppressed. While the Higgs bosons decay with more than about 85% branching ratio into b-quark pairs, the Z → bb decay rate is only 15%.

Figures 6, 7 and 8 show examples of selected SM Higgs candidates. The reconstructed invariant masses are 92.9 and 91.1 GeV in the four-jet event (Fig. 6). A typical jet–jet e^+e^- event signature is shown in Fig. 7 where the invariant masses are 85 and 96 GeV. One jet is b-tagged by a three dimensional reconstruction of a secondary vertex. In the jet–jet $\mu^+\mu^-$ event (Fig. 8) the invariant mass of the muon pair is 92.3 GeV. The hadron invariant mass is calculated to be 93.4 GeV from the recoil mass of the muon pair for a better resolution. All reconstructed masses are compatible with ZZ production, taking into account the errors on the measurements.

Fig. 6. DELPHI four-jet Higgs boson candidate event.

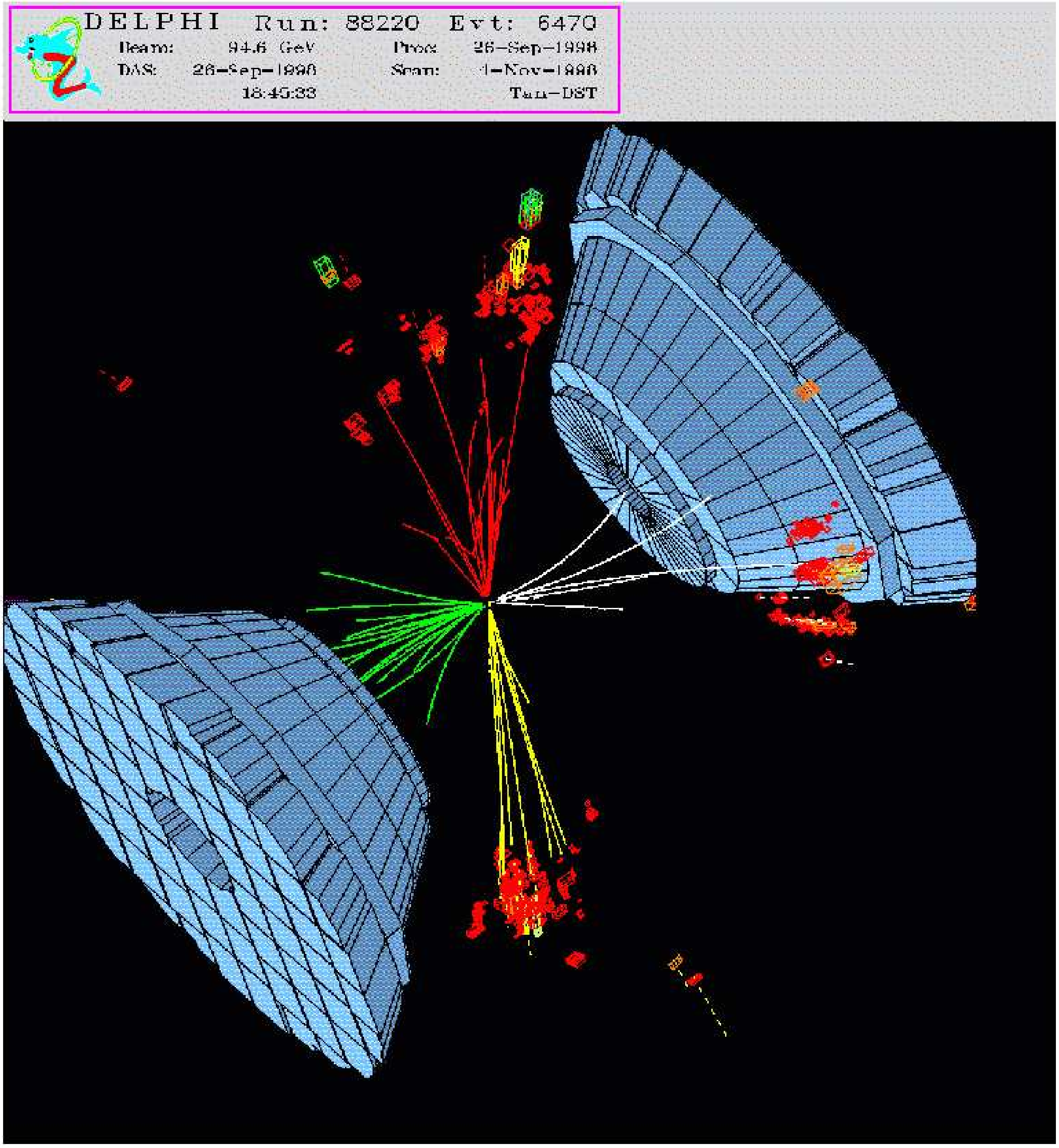


Fig. 7. ALEPH jet–jet e$^+$e$^-$ Higgs boson candidate event. The upper right-hand figure shows nicely the separation of the e$^+$e$^-$ pair from the two hadronic jets, while the lower figures show clearly the displaced vertex from a B-meson decay.

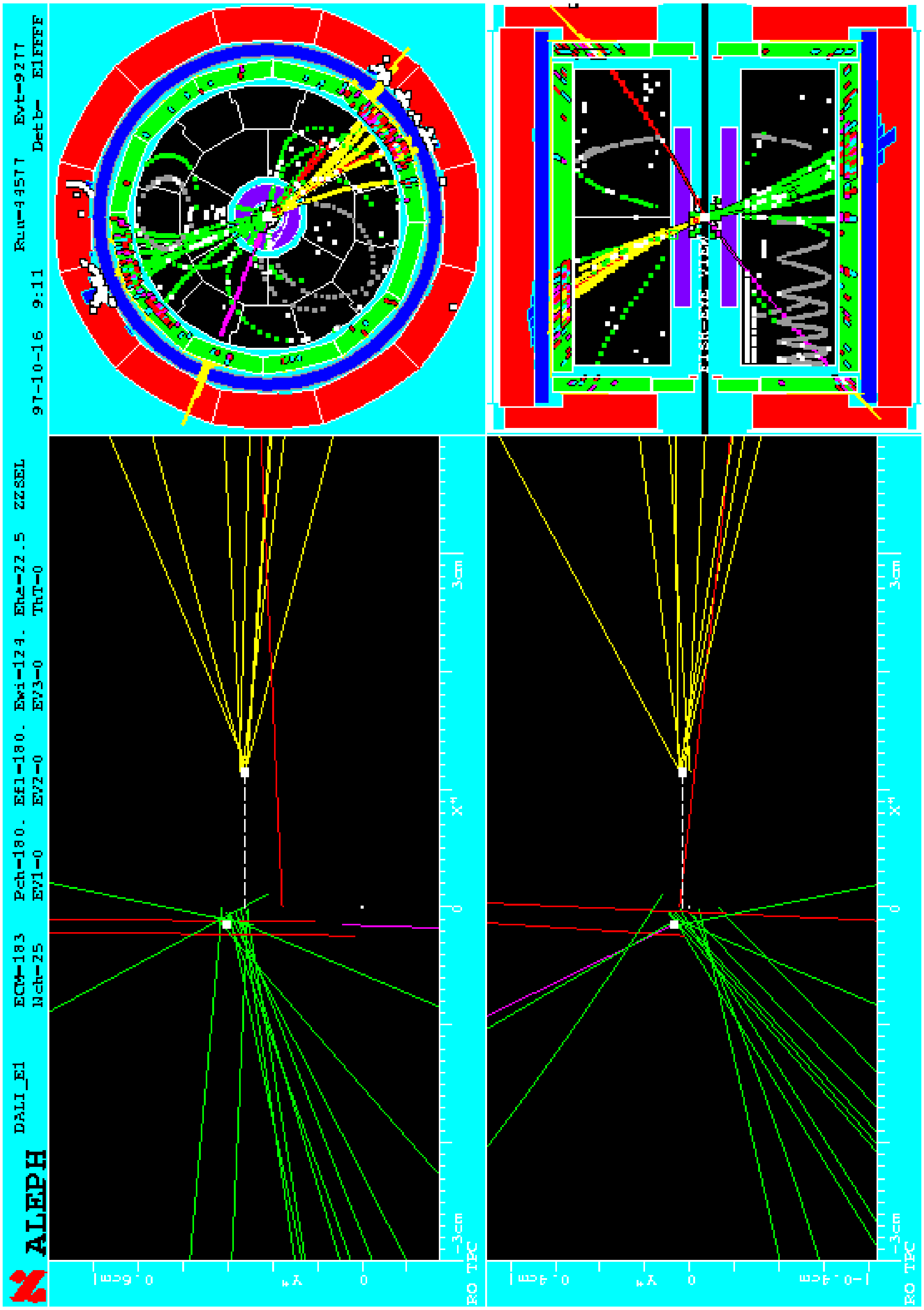
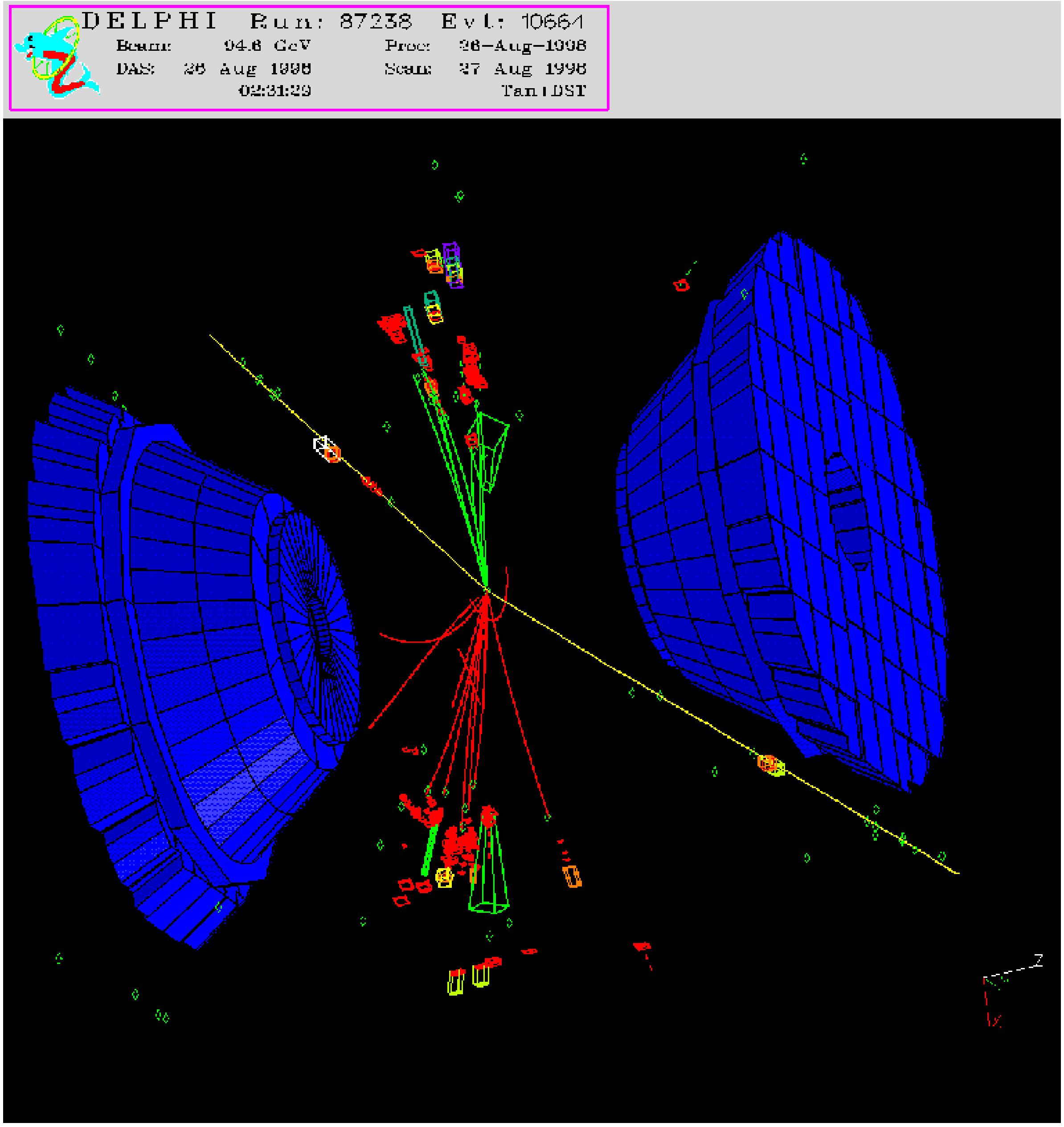


Fig. 8. DELPHI jet–jet $\mu^+\mu^-$ Higgs boson candidate event.



4. Standard Model Higgs Boson

The search for the Standard Model Higgs boson is performed in the following decay channels: HZ $\to$ bbqq, bbee, bb$\mu\mu$, bb$\tau\tau$ and bb$\nu\nu$. Figure 9 shows the number of data and background events as a function of the reconstructed Higgs boson mass. No indication of a signal is observed. A statistical analysis based on a likelihood function takes into account all search channels and gives the probability $1 - CL_\mathrm{b}$ that the data are compatible with the simulated background. Figure 10 shows this probability for 1998 data and including 1999 data up to 196 GeV center-of-mass energy. The limits on the SM Higgs boson mass derived from the probability CL_s that the expected signal and background is compatible with the data, and the corresponding $\Delta\chi^2$ distribution are presented in Fig. 11.

Fig. 9. Reconstructed mass distribution for combined data between 192 and 196 GeV (left) and including 189 GeV data (right).

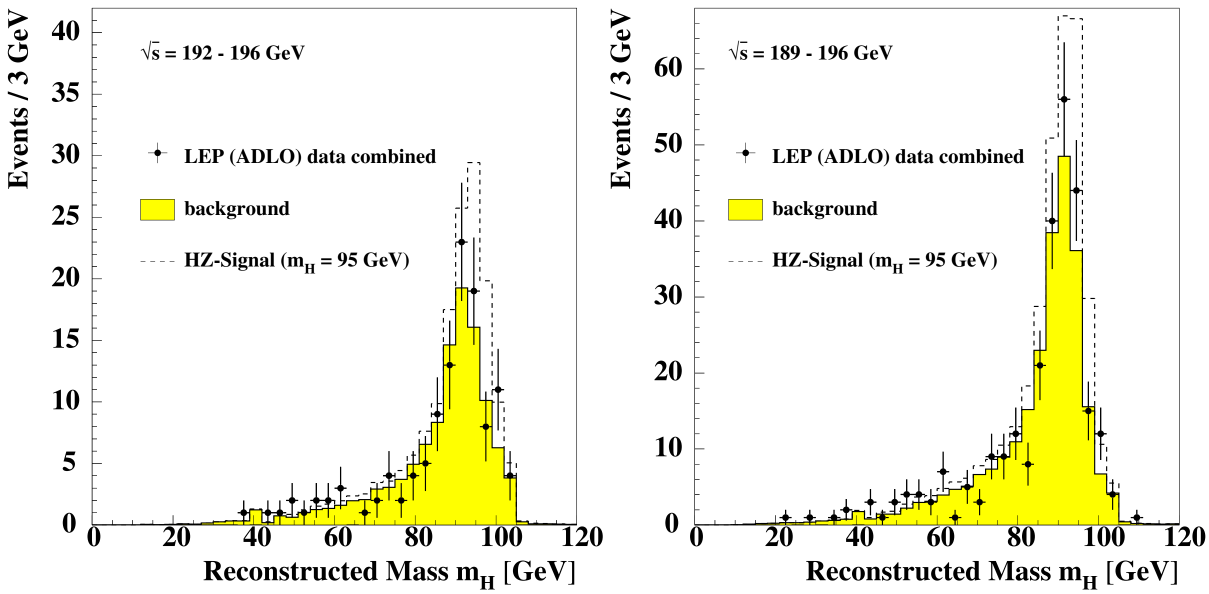


Fig. 10. $1 - CL_\mathrm{b}$ distribution for 1998 data (left) where a probability of 0.01 is observed for a 96 GeV Higgs boson. The data up to 196 GeV (right) reject the possibility of a 96 GeV Higgs boson. The grey areas show 1 and 2σ regions.

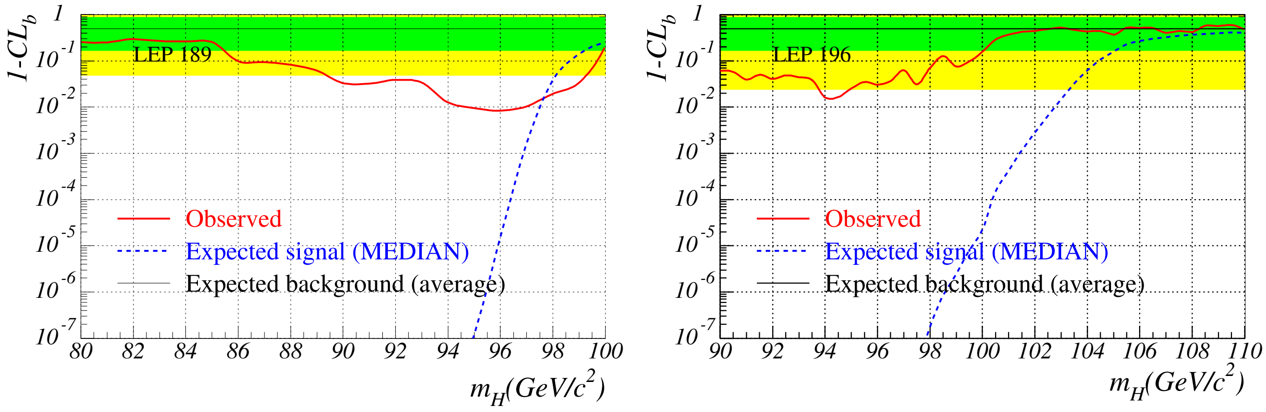
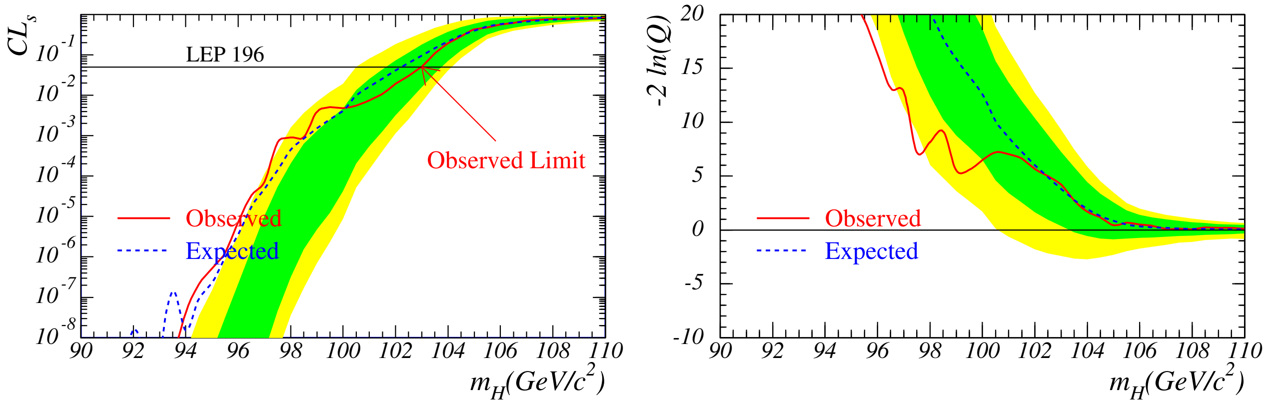


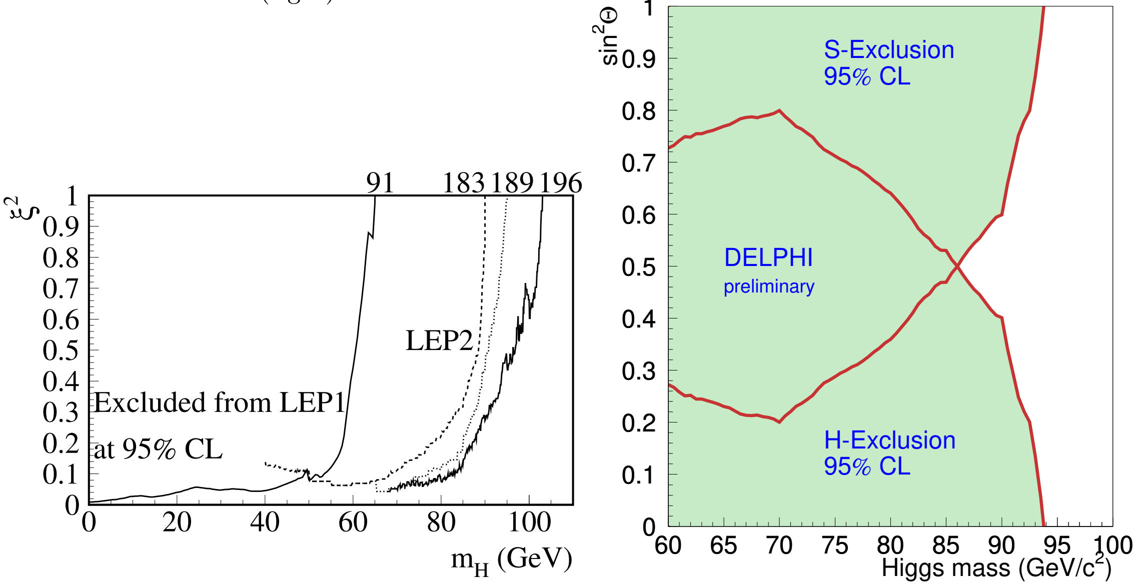
Fig. 11. Observed and expected SM Higgs boson mass limits, where 95% CL corresponds to $CL_s = 0.05$ (left) and $\Delta\chi^2$ values for a given Higgs boson mass (right). The grey areas show 1 and 2σ regions.



The HZZ coupling is predicted to be smaller in many extensions of the SM. Figure 12 shows stringent limits on ξ^2 from combined LEP data under the assumption that the Higgs boson decay modes do not change and the production rate is given by $\sigma(\mathrm{HZ}) = \sigma(\mathrm{H_{SM}Z}) \cdot \xi^2$.

An interesting extension of the SM is the addition of an extra Higgs singlet field. In this case two neutral massive Higgs bosons H and S are predicted, as is a massless, stable and non-interacting Majoron, J. The decays $\mathrm{H} \to \mathrm{JJ}$ and $\mathrm{S} \to \mathrm{JJ}$ lead to missing energy signatures. This process could be observed in the ZH and ZS production. The associated Z decay into a quark pair gives a signature of two jets and missing energy as in the $\mathrm{H}\nu\nu$ search channel. A limit from DELPHI on the mixing angle of H and S as a function of their masses is shown in Fig. 12.

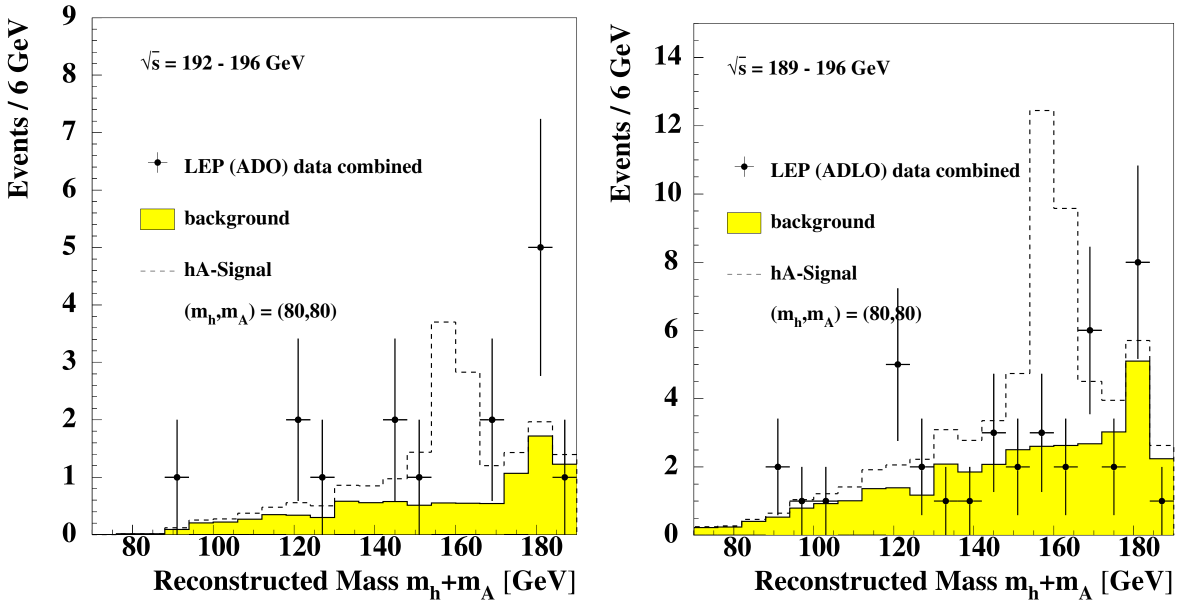
Fig. 12. Combined limit on the HZZ suppression factor ξ^2 for LEP1 and LEP2 data up to 196 GeV center-of-mass energy (left) and DELPHI 189 GeV invisible Higgs limits in the plane of mass and mixing angle for H and S bosons (right).



5. MSSM Higgs Bosons

The search for the scalar MSSM Higgs bosons is performed in the same search channels as for the SM Higgs boson. In addition, the pair-production process $e^+e^- \to hA \to bbbb$ and $\tau\tau bb$ is investigated, where h is the lighter scalar and A the pseudoscalar Higgs boson of the MSSM. Figure 13 shows the sum of the reconstructed Higgs boson masses. For simulated Higgs boson masses of 80 GeV, well below the kinematic production threshold, the inclusion of the data taken in 1998 at 189 GeV increases significantly the discovery sensitivity.

Fig. 13. Reconstructed mass distribution for combined data between 192 and 196 GeV (left) and including 189 GeV data (right).



Interpretations are given first for the so-called benchmark parameters, defined by a large Supersymmetric particle scale of 1 TeV. Figure 14 shows the excluded regions in the $(m_{\mathrm{A}}, \tan\beta)$ plane for no and maximal mixing in the scalar top sector, and Fig. 15 in the $(m_{\mathrm{h}}, \tan\beta)$ plane. The figures also show limits from the CDF experiment [3], based on the reaction $bb \to bbh$, where the coupling is enhanced for large $\tan\beta$. Based on the benchmark parameters, details of the discovery $(1 - CL_{\mathrm{b}})$ and the exclusion (CL_{s}) probabilities are shown in Fig. 16. The white line gives the 95% CL exclusion limit from CL_{s} in both plots and the dashed lines the kinematic production limits for hA and hZ processes. No indication of a discovery is observed, where a 5σ effect corresponds to $1 - CL_{\mathrm{b}} \approx 10^{-7}$ and the 95% CL corresponds to $CL_{\mathrm{s}} = 0.05$.

Fig. 14. MSSM benchmark exclusion in the $(m_{\mathrm{A}}, \tan\beta)$ plane.

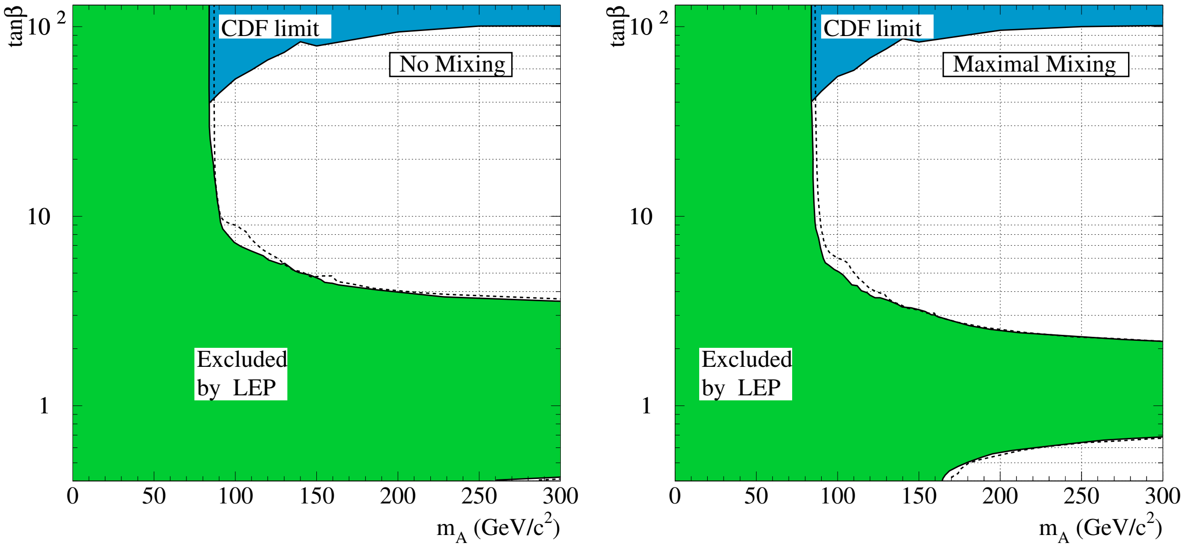


Fig. 15. MSSM benchmark exclusion in the $(m_{\mathrm{h}}, \tan\beta)$ plane.

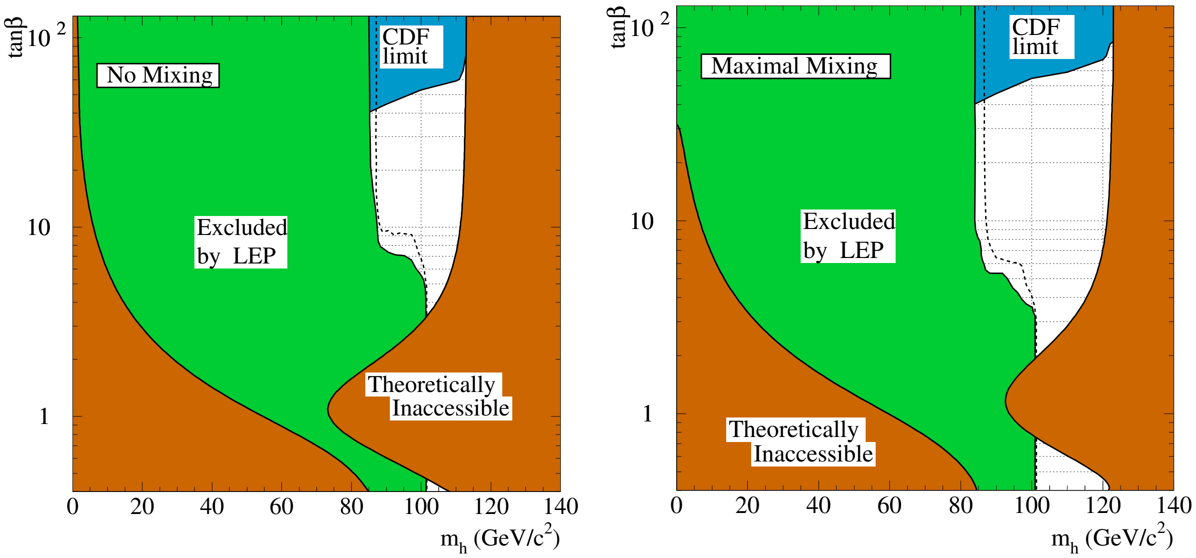
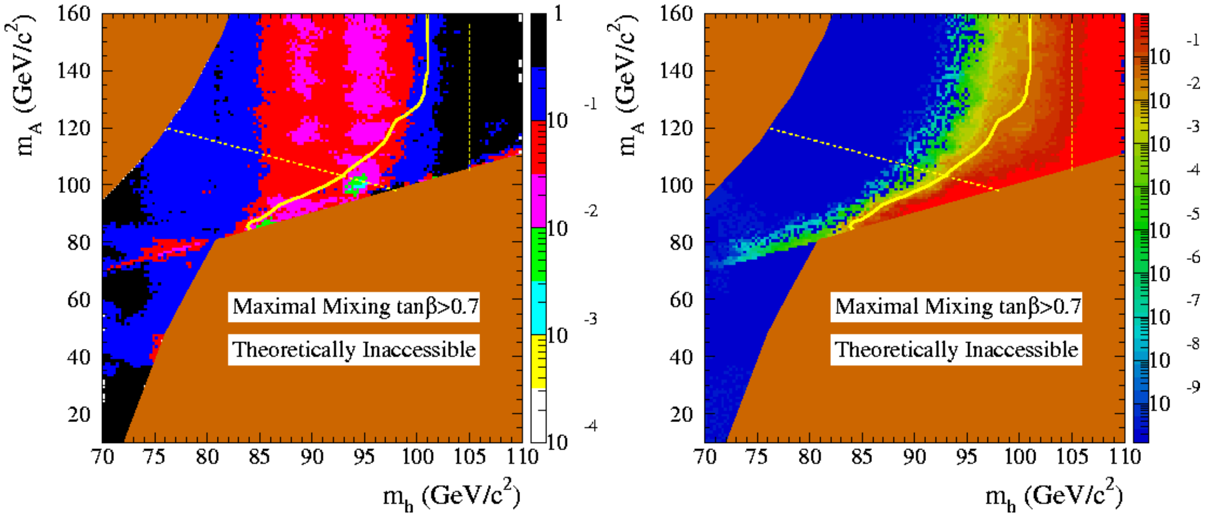


Fig. 16. MSSM benchmark $1 - CL_{\mathrm{b}}$ (left) and CL_{s} (right) in the $(m_{\mathrm{h}}, m_{\mathrm{A}})$ plane.



General parameter scans in the MSSM are very important in order to set reliable limits on h and A masses. For LEP1 newly unexcluded mass regions were pointed out [4], and for 172 GeV LEP2 data stringent mass limits disappeared completely [5] allowing a Higgs boson to escape detection although it could have been kinematically produced. The latest general scan results with 189 GeV DELPHI data are shown in Fig. 17 [6]. The corresponding parameter ranges are listed in Table 2. The limit on the h mass is at 75 GeV compared to 82 GeV for the DELPHI benchmark result [7]. The h and A mass limits are given by the light grey edge intruding the LEP2 excluded area. An extension of the A range to ± 2 does not change the mass limit, but it increases the maximal Higgs mass to 130 GeV. Reduced mass limits are also presented by OPAL [8].

In addition to the scanning over the Supersymmetric parameters, more precise mass, cross section and branching ratio calculation based on 2-loop Full-Diagrammatic Calculations (FDC) [9] are used. Figure 17 shows also that the maximal h mass is reduced by about 10 GeV and the maximum is already reached for smaller mixing values in the scalar top sector. The reduction of the maximal Higgs boson mass is important for LEP physics, since it affects the excluded $\tan\beta$ range (see Fig. 15) and reduces the uncovered parameter region. LEP comes closer to a definitive test of the MSSM.

Fig. 17. DELPHI general scan leading to reduced mass limits compared to the benchmark results (left), and comparison of 1- and 2-loop FDC as a function of the mixing A in the scalar top sector (right).

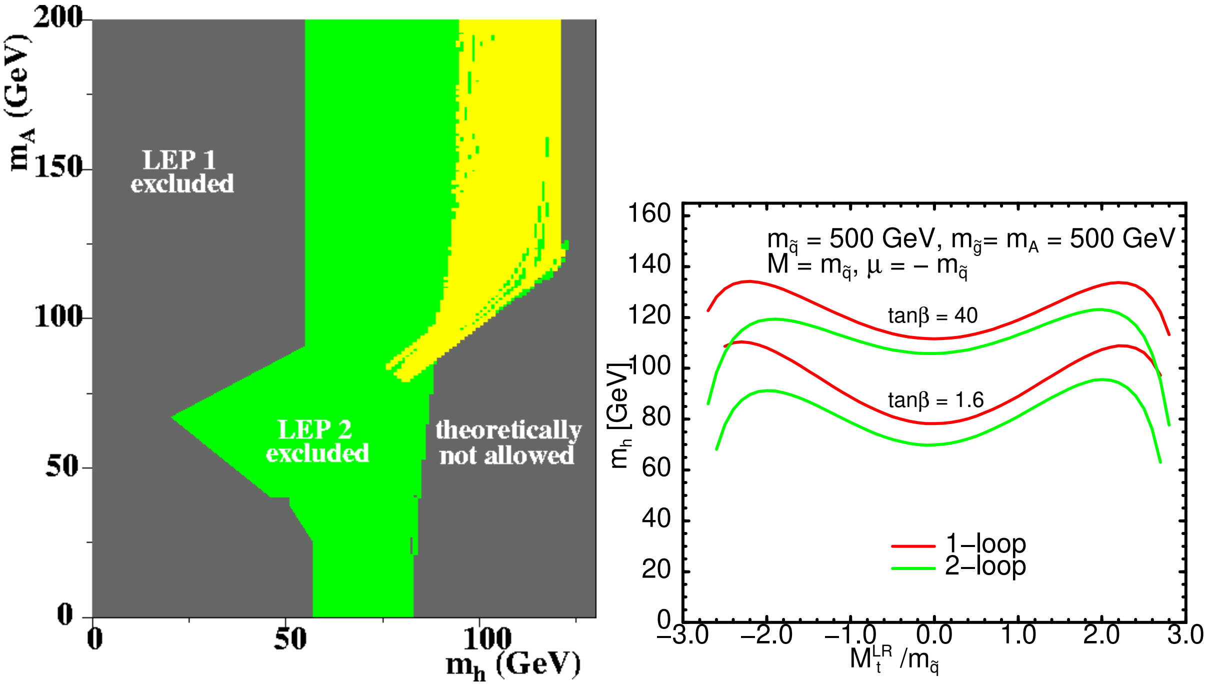


Table 2. General scan parameter ranges.

Parameter	m_{sq} (GeV)	m_g (GeV)	μ (GeV)	A	$\tan\beta$
Range	200 — 1000	200 — 1000	−500 — 500	−1 — +1	0.5 — 50

6. Charged Higgs Bosons

New calculations of the production cross section $e^+e^- \rightarrow H^+H^-$ include 1-loop radiative corrections [10]. The cross section for $\sqrt{s} = 190$ GeV is shown in Fig. 18. Compared to the tree-level calculations, the cross section is about 7.5% larger for $2 < \tan\beta < 15$ independent of the charged Higgs boson mass. Note that a 15% reduction is obtained for very small and very large $\tan\beta$ values. The results from the LEP experiments are still based on tree-level calculations. Figure 19 shows the reconstructed $H^\pm$ mass for data, simulated signal and background. Mass limits based on a statistical analysis are also shown in Fig. 19. The sensitivity in the leptonic search channel is larger, since the irreducible WW background leads only in 1% of cases to the $\tau\nu\tau\nu$ final state. Independent of the charged Higgs boson branching fraction, a mass limit of 77 GeV is set at 95% CL.

Fig. 18. $e^+e^- \rightarrow H^+H^-$ cross section including 1-loop radiative corrections.

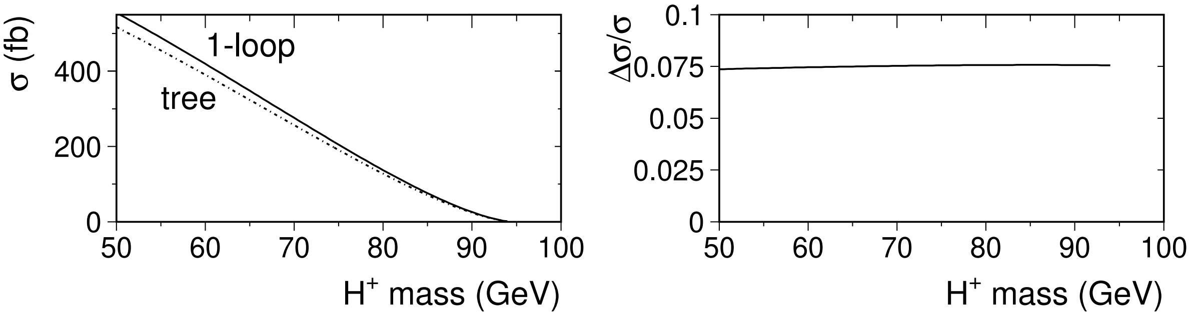
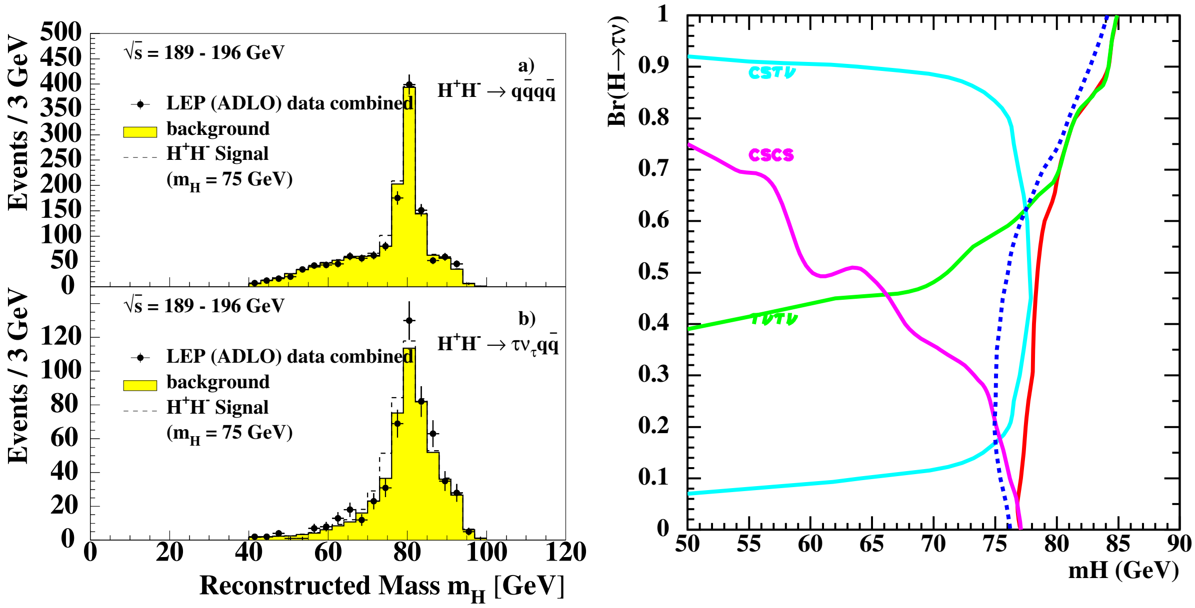


Fig. 19. Reconstructed $H^\pm$ mass in the hadronic and semi-leptonic search channels (left), and resulting mass limits (right) including the leptonic channel and the combination of all three channels. In addition, the expected mass limit is shown.



7. Conclusions

No indication of Higgs bosons is observed. The combination of the data from the four LEP experiments provides significantly more detection sensitivity. The SM Higgs mass is larger than 102.6 GeV at 95% CL. In the remaining year of LEP operation, the SM Higgs boson could be discovered up to 110 GeV at 5σ or excluded up to about 114 GeV at 95% CL. Stringent mass limits are set in general extensions of the SM, even for strongly reduced HZ production rates. The charged Higgs boson mass is larger than 77 GeV which is close to the W mass, where WW production gives a large irreducible background. Large regions of the MSSM parameter space are excluded, in particular, small $\tan\beta$ values. In future studies, the model-independent presentations of the experimental results should be even more emphasized and general parameter scans should be favored over benchmark interpretations.

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REFERENCES

[1] The Four LEP Experiments and the Higgs and SUSY LEP Working Groups, LEPC presentations, CERN, 7 Sep. 1999.

[2] L3 Coll., EPS Tampere 1999, contributed paper 6-249.

[3] CDF Coll., EPS Tampere 1999, talk by J.Valls, to be published in the proceedings.

[4] J. Rosiek and A. Sopczak, *Phys. Lett.* **B 341** (1995) 419.

[5] A. Sopczak, *Eur. Phys. J.* **C 7** (1999) 107.

[6] DELPHI Coll., EPS Tampere 1999, contributed paper 7-117.

[7] DELPHI Coll., EPS Tampere 1999, contributed paper 6-231.

[8] OPAL Coll., CERN-EP/99-096, submitted to *Eur. Phys. J.*

[9] S. Heinemeyer, W. Hollik and G. Weiglein, *Eur. Phys. J.* **C 9** (1999) 343.

[10] A. Kraft, PhD Thesis, Karlsruhe 1999, and private communications.