

# Complete LEP Data: Status of Higgs Boson Searches

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## Abstract

The LEP experiments completed data-taking in November 2000. New preliminary combined results of the four LEP experiments ALEPH, DELPHI, L3 and OPAL are presented for various Higgs boson searches.

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After 11 years of operation the LEP experiments have completed data-taking. In 2000 the center-of-mass energy was pushed to 209 GeV with most data taken around 206 GeV. In the last three years of operation a luminosity of about  $687 \text{ pb}^{-1}$  was delivered to each experiment, which exceeded expectations. Despite hints for a Higgs boson discovery around 116 GeV data-taking was not continued in 2001.

## 1 Standard Model Higgs Boson

In September 2000, ALEPH presented a data excess consistent with the reaction  $e^+e^- \rightarrow HZ \rightarrow b\bar{b}q\bar{q}$  for a Higgs boson mass of about  $115 \text{ GeV}^1$  which was not confirmed by the other LEP experiments. In November 2000, L3 provided support for a signal observation with a  $HZ \rightarrow b\bar{b}\nu\bar{\nu}$  candidate event at the same mass. For the summer conferences in 2001, all experiments updated their analyses and the probability of the data to be consistent with the Standard Model (SM) background is increased, as detailed in Table 1<sup>2</sup>. The confidence levels  $CL_b$  for a signal observation and  $CL_s$  for setting mass limits are shown in Fig. 1. The resulting SM Higgs boson mass limit is  $114.1 \text{ GeV}$  at 95% CL. The reconstructed mass distribution and a list of candidate events are shown in Fig. 2. In extensions of the SM the HZZ coupling might be weaker and thus the production cross section is reduced. Figure 3 shows limits on the reduction factor at 95% CL. Even if the SM cross section is reduced by a factor three, a Higgs boson mass up to  $110 \text{ GeV}$  is excluded.

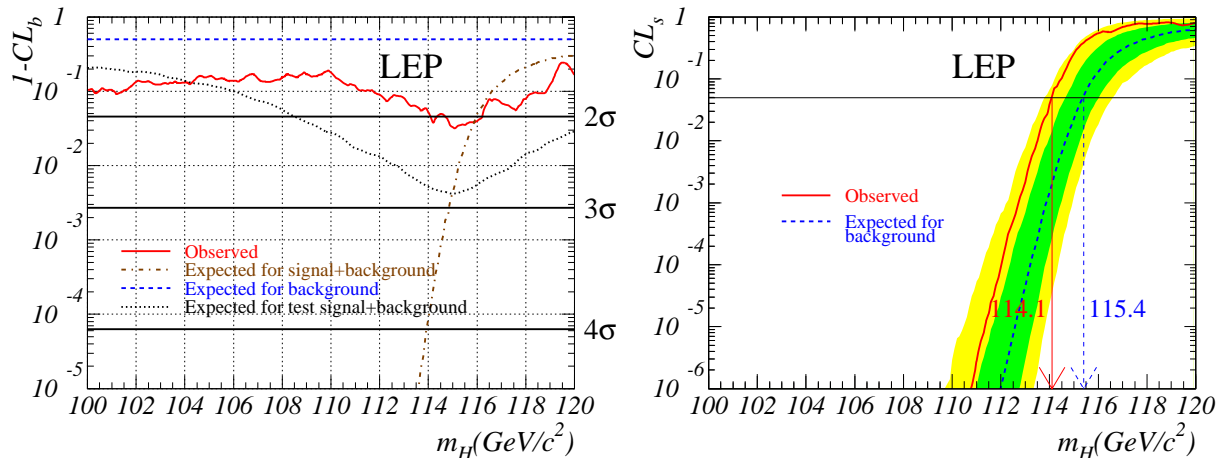


Figure 1: Confidence levels  $1 - CL_b$  and  $CL_s$  from combining the data collected by the four LEP experiments at energies from 189 to 209 GeV. The solid curve is the observed result. The shaded areas represent the symmetric  $1\sigma$  and  $2\sigma$  probability bands. The horizontal line at  $CL_s = 0.05$  gives the mass limits at 95% CL.

Sep. 5, 2000*	$1.6 \times 10^{-4}$	0.67	0.84	0.47	$2.5 \times 10^{-2}$	2.2
Nov. 3, 2000	$6.5 \times 10^{-4}$	0.68	$6.8 \times 10^{-2}$	0.19	$4.2 \times 10^{-3}$	2.9
Summer 2001	$2.6 \times 10^{-3}$	0.77	0.32	0.20	$3.4 \times 10^{-2}$	2.1

Table 1: Background probabilities  $1 - CL_b$  at a Higgs boson test-mass of  $m_H = 115$  GeV, for the individual experiments and for the LEP data combined. (\*) The results presented at the LEPC of September 5 were revised for the LEPC of November 3. The revised values are listed.

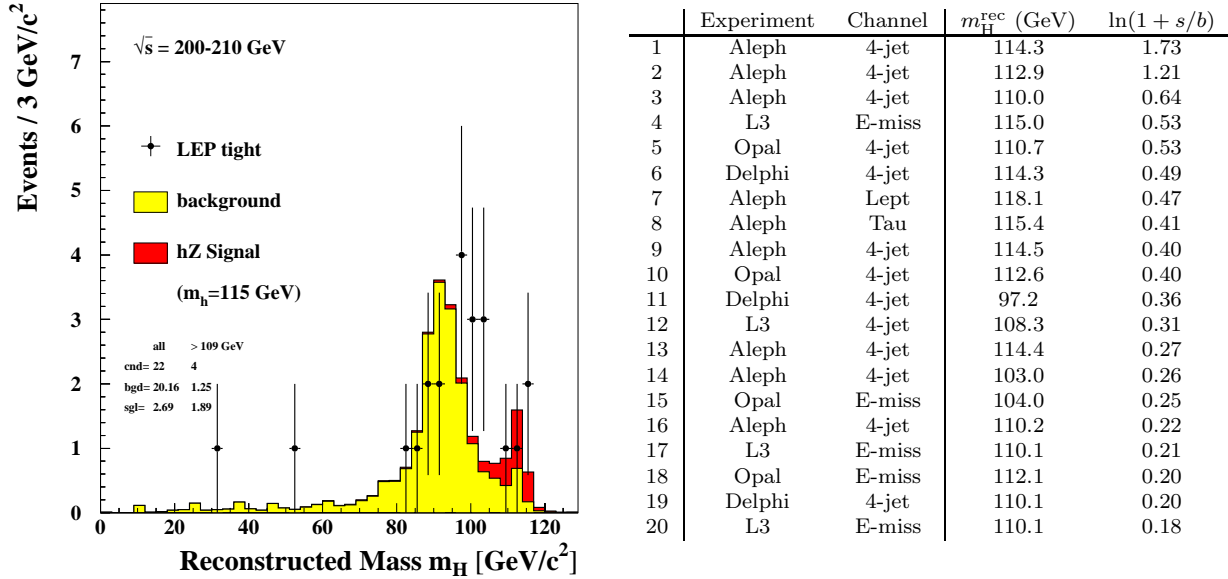


Figure 2: Left: Distribution of the reconstructed SM Higgs boson mass in searches conducted at energies between 200 and 210 GeV. The figure displays the data (dots with error bars), the predicted SM background and the prediction for a Higgs boson of 115 GeV mass. The number of data events selected with mass larger than 109 GeV is 4, while 1.25 are expected from SM background processes and 1.89 from a 115 GeV signal. Right: Properties of the candidates with the highest signal-over-background ratio  $\ln(1 + s/b)$  at 115 GeV. The corresponding expected signal and background rates are 8.8 and 16.5 events, respectively.

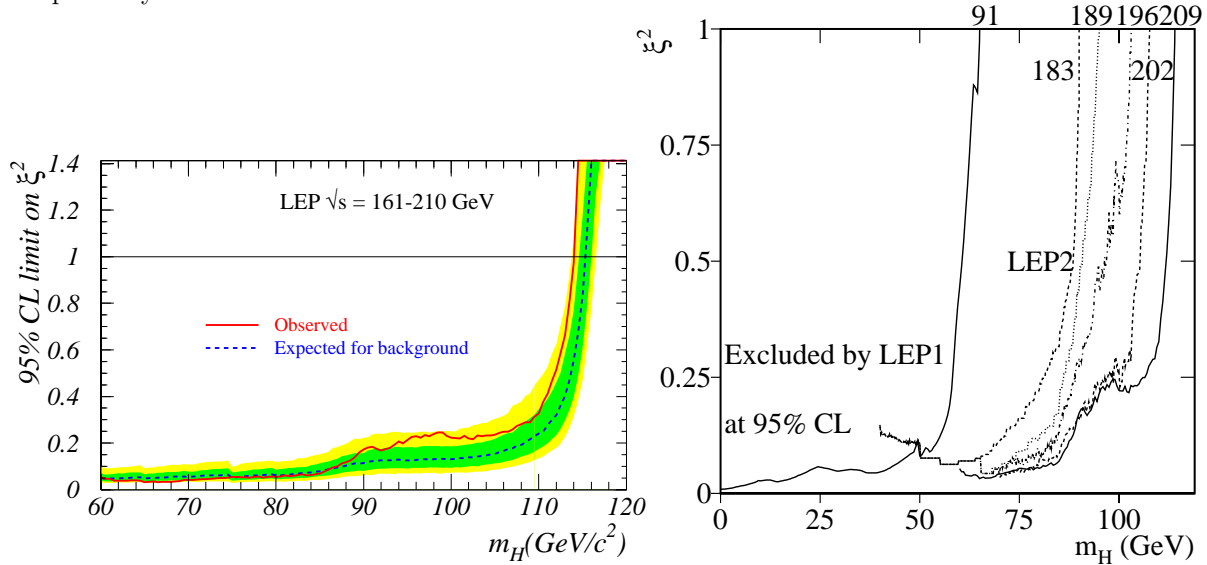


Figure 3: Left: The 95% CL upper bound on  $\xi^2$  as a function of  $m_H$ , where  $\xi = g_{HZZ}/g_{HZZ}^{\text{SM}}$  is the HZZ coupling relative to the SM coupling. About  $2\sigma$  deviations from the expectation are observed at  $m_H = 98$  GeV and  $m_H = 115$  GeV. Right: The excluded  $(\xi^2, m_H)$  region including 209 GeV data is compared with the results from combined LEP1 data<sup>3</sup>, taken around 91 GeV center-of-mass energy, and previous LEP2 limits<sup>4</sup> up to 183, 189, 196 and 202 GeV. The  $\xi^2$  limit below 100 GeV does not become significantly stronger when the 209 GeV data, taken in 2000, is included.

The Minimal Supersymmetric extension of the Standard Model (MSSM) is the most attractive alternative to the SM. The  $e^+e^- \rightarrow hA$  and  $e^+e^- \rightarrow hZ$  production cross sections are complementary. The LEP experiments have searched for the reactions  $e^+e^- \rightarrow hA \rightarrow b\bar{b}b\bar{b}$  and  $b\bar{b}\tau^+\tau^-$ . Confidence levels  $CL_b$  and  $CL_s$  are given in Fig. 4 for the so-called benchmark results in the MSSM for large mixing in the scalar-top sector ( $m_h$ -max)<sup>5</sup>.

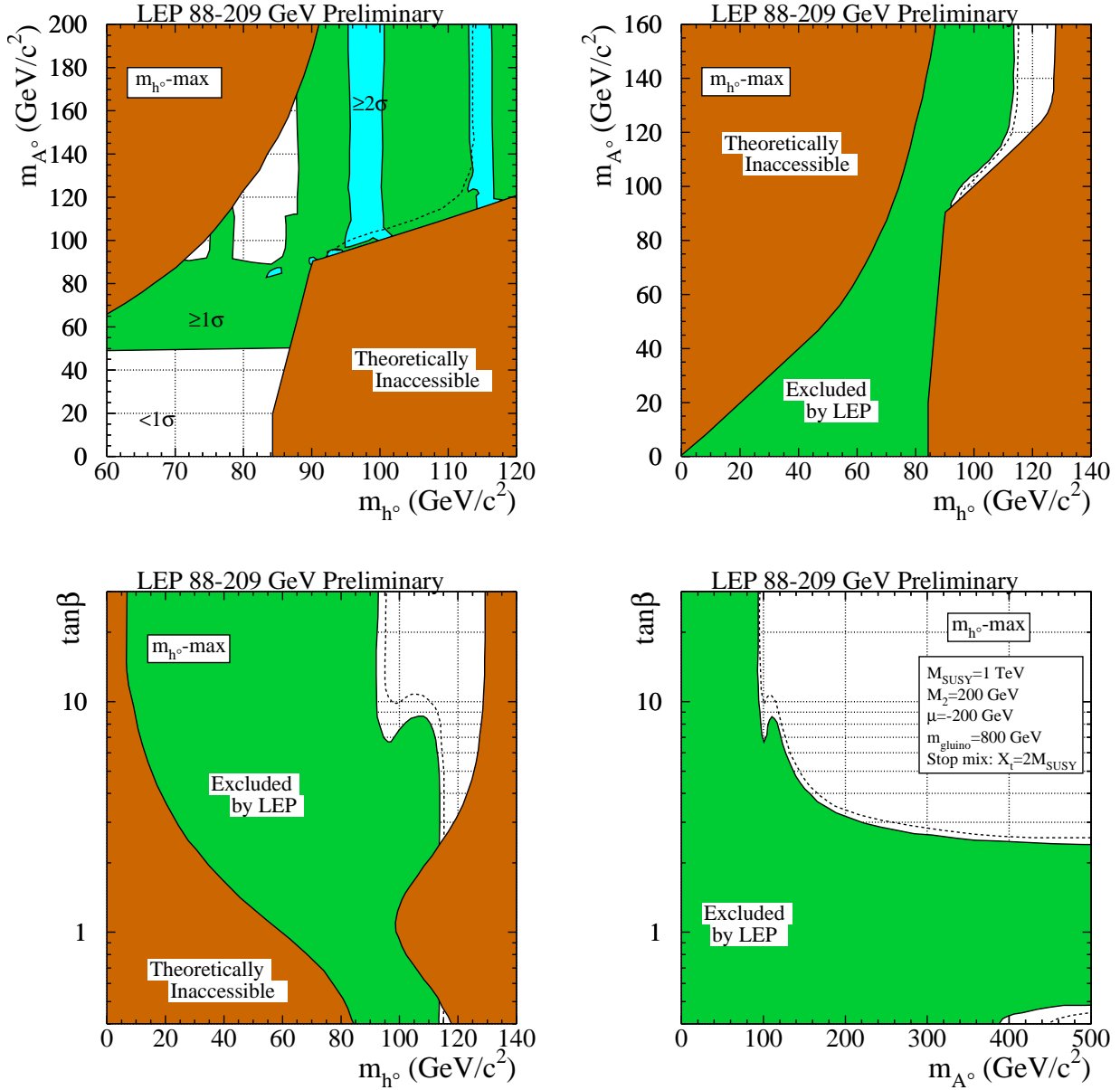


Figure 4: Upper left: Distribution of the discovery confidence level  $1 - CL_b$  for the  $m_h$ -max benchmark, projected onto the  $(m_h, m_A)$  plane by combining the data of the four LEP experiments at energies from 88 to 209 GeV. In the white domain the observation either shows a deficit or is less than  $1\sigma$  above the background prediction; in the domains labelled  $\geq 1\sigma$  and  $\geq 2\sigma$  the observation is between  $1\sigma$  and  $2\sigma$  and larger than  $2\sigma$  above the prediction, respectively. The other plots show the 95% CL bounds on  $m_h$ ,  $m_A$  and  $\tan\beta$  for the  $m_h$ -max benchmark. The full lines represent the actual observation and the dashed lines the limits expected on the basis of ‘background only’ Monte Carlo experiments. Upper right: projection  $(m_h, m_A)$ ; lower left: projection  $(m_h, \tan\beta)$ ; lower right: projection  $(m_A, \tan\beta)$ .

Important reductions of the mass limits compared to benchmark results were reported for LEP1 and first LEP2 data<sup>6,7</sup>. With increasing statistics the reduction was only a few GeV by including the 189 GeV data of one LEP experiment (DELPHI)<sup>8</sup>, and similar for OPAL<sup>9</sup>. Figure 5 shows new results from a MSSM parameter scan for complete DELPHI data up to 209 GeV, leading to mass limits of 89 GeV on both scalar and pseudoscalar neutral Higgs bosons<sup>10</sup>. These are almost identical to the DELPHI benchmark limits<sup>11</sup>. Figure 5 (lower right) shows the importance of searches for invisible Higgs bosons<sup>12</sup> which could decay into neutralinos for some parameter combinations of the scan (outside of the benchmark).

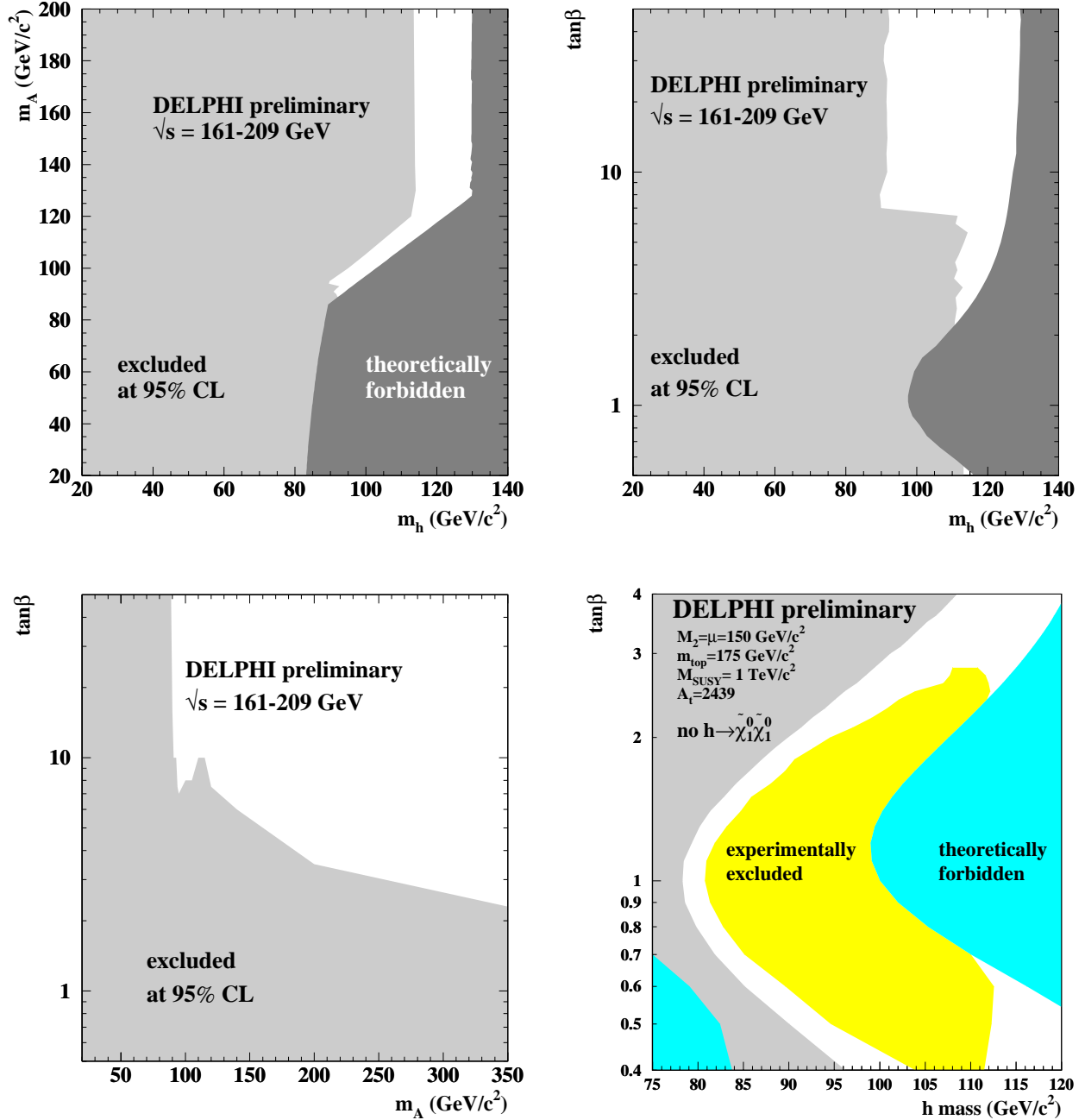


Figure 5: MSSM parameter scan results for DELPHI data at energies from 161 to 209 GeV. Upper left: projection ( $m_h, m_A$ ); upper right: projection ( $m_h, \tan \beta$ ); lower left: projection ( $m_A, \tan \beta$ ). Lower right: excluded parameter combinations from searches for invisibly decaying Higgs bosons from 189 to 209 GeV data.

for the example of  $m_h \approx m_A$ . As noted previously for 202 GeV data, taken in 1999, and first 2000 data,  $h$  and  $A$  mass limits were 2 GeV below expectation<sup>13</sup> and this tendency is enhanced by including 209 GeV data, in which case they are 3.1 to 3.6 GeV below the expectations of about 95 GeV. A possible explanation is given that the HZ excess at about 115 GeV is due to the heavier scalar and that, in addition, the production of  $hA$  with masses between 90 and 100 GeV occurs<sup>13</sup>. Figure 6 shows a data excess above  $2\sigma$  for  $m_h + m_A = 187$  GeV in the  $b\bar{b}b\bar{b}$  channel. The same data excess is also expressed in the  $CL_b$  and  $CL_s$  distributions as shown in Fig. 7. The hypothesis of the production of three MSSM Higgs bosons is supported by the data excess seen in Fig. 2 at 100 GeV which could result from  $hZ$  production in addition to  $HZ$  production. For the reported MSSM parameters<sup>13</sup>  $\cos^2(\beta - \alpha) \approx 0.9$ ; therefore  $\sin^2(\beta - \alpha) = \xi^2 \approx 0.1$ . The  $\xi^2$  limit in the 100 GeV mass region shows a deviation of about  $2\sigma$  between expected and observed limit, as seen in Fig. 3 (left). Figure 3 (right) shows that this new support is only observed in the complete LEP data.

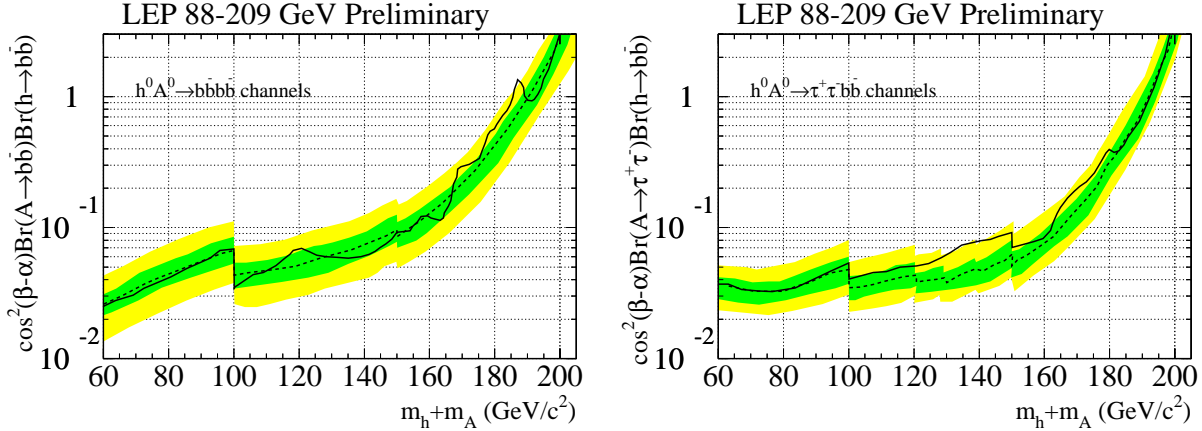


Figure 6: Limits on the  $hA$  cross section as a function of  $m_h + m_A$  at 95% CL ( $m_h \approx m_A$ ) for the MSSM processes  $e^+e^- \rightarrow hA \rightarrow b\bar{b}b\bar{b}$  and  $b\bar{b}\tau^+\tau^-$ . This corresponds to limits of  $\cos^2(\beta - \alpha)$  in the general extension of the SM with two Higgs boson doublets. The data of the four LEP experiments collected at energies from 88 to 209 GeV are combined. The solid curve is the observed result and the dashed curve shows the expected median. Shaded areas indicate the  $1\sigma$  and  $2\sigma$  probability bands.

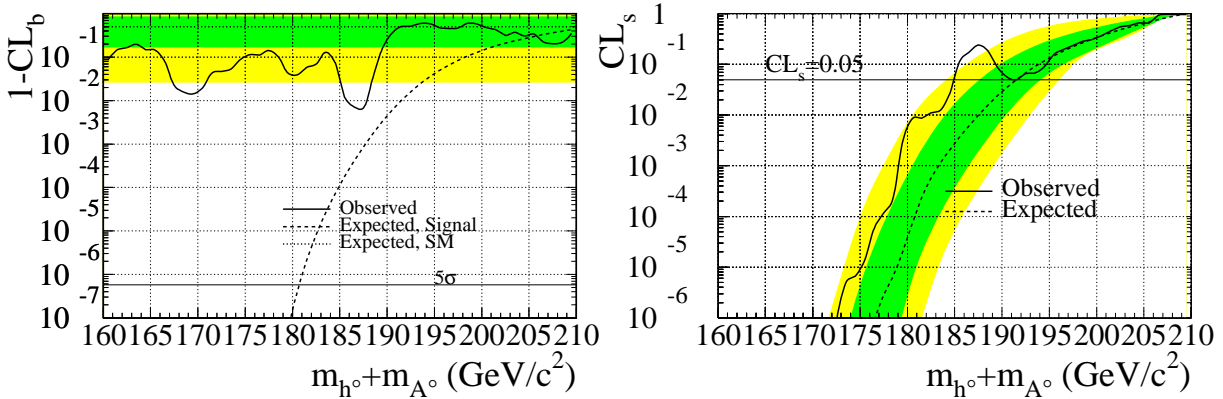


Figure 7: The confidence levels  $1 - CL_b$  and  $CL_s$  as a function of  $m_h + m_A$  for the case  $m_h \approx m_A$  (where only the  $e^+e^- \rightarrow hA$  process contributes since  $\sin^2(\beta - \alpha) \approx 0$ ). The straight line at 0.5 and the shaded  $1\sigma$  and  $2\sigma$  probability bands represent the expected background-only result. The solid curve is the observed result and the dashed curve shows the expected median for a signal. The horizontal line at  $1 - CL_b = 5.7 \times 10^{-7}$  indicates the level for a  $5\sigma$  discovery and the intersections of the curves with the horizontal line at  $CL_s = 0.05$  give the limit on  $m_h + m_A$  at 95% CL. The data of the four LEP experiments collected at energies from 88 to 209 GeV are combined.

The search for charged Higgs bosons is performed in the framework of the general extension of the SM with two Higgs boson doublets. The combined  $CL_b$  distributions from the four LEP experiments for the reactions  $e^+e^- \rightarrow H^+H^- \rightarrow c\bar{c}s$  and  $\tau^+\nu\tau^-\bar{\nu}$  are presented in Fig. 8<sup>14</sup>. The resulting mass limit, which also includes the  $c\bar{s}\tau\nu$  channel, is 78.6 GeV at 95% CL and it is valid for any branching ratio  $\text{Br}(H^+ \rightarrow \tau^+\nu)$  as shown in Fig. 9. The cross section limit for the  $c\bar{c}s$  channel shows that the barrier from irreducible WW background events is almost passed. Optimization of the analyses of each individual experiment for higher masses could increase the decay-mode-independent reach by more than 5 GeV. Already a pre-LEP2 study<sup>15</sup> based on a luminosity of  $500 \text{ pb}^{-1}$  pointed out that ‘..., the kinematic region above  $m_W$  will be a challenge for the decay-mode-independent sensitivity, it might even be unfeasible ...’.

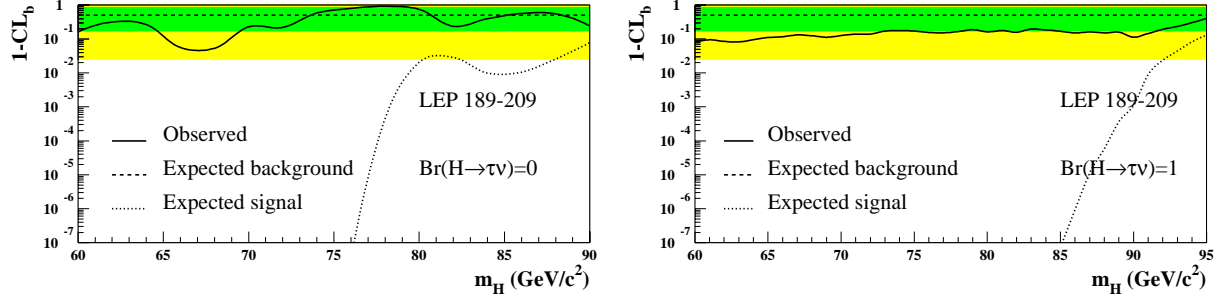


Figure 8: The  $1 - CL_b$  distributions for the  $c\bar{c}s$  and  $\tau^+\nu\tau^-\bar{\nu}$  channels, combining the data collected by the four LEP experiments at energies from 189 to 209 GeV. The shaded areas represent the  $1\sigma$  and  $2\sigma$  probability bands. Owing to the large irreducible  $WW \rightarrow c\bar{c}s$  background, less sensitivity is obtained near the W mass for the case  $\text{Br}(H^+ \rightarrow \tau^+\nu) = 0$  as it can be seen from the expected signal probability curve.

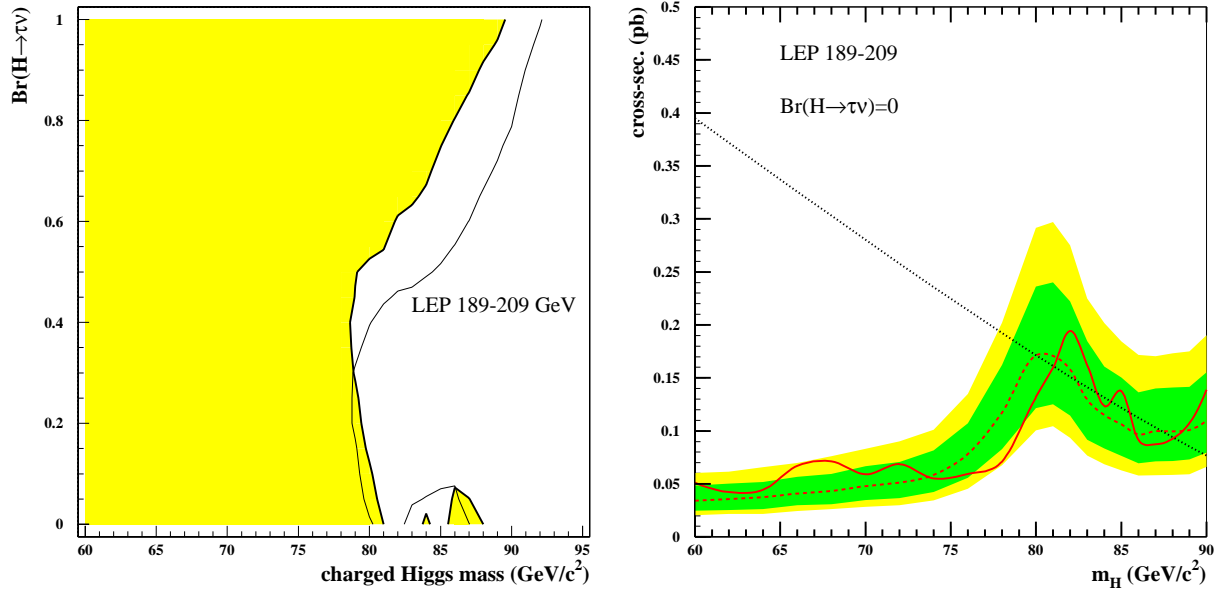


Figure 9: Left: The 95% CL bounds on  $m_{H^\pm}$  as a function of the branching ratio  $\text{Br}(H^+ \rightarrow \tau^+\nu)$ , combining the data collected by the four LEP experiments at energies from 189 to 209 GeV. The expected median limits are indicated by the thin line and the observed limits by the thick line. Right: The 95% CL bounds on the production cross section for  $\text{Br}(H^+ \rightarrow \tau^+\nu) = 0$ . The observed limit is given by the solid line and the expected limits are indicated by the dashed line and the shaded bands ( $1\sigma$  and  $2\sigma$ ). The dotted line gives the expected cross section at 206 GeV center-of-mass energy. Radiative corrections vary the cross section by typically  $\pm 10\%$  depending on the model parameters<sup>16,17</sup>.



In some models the Higgs boson can decay into invisible particles, such as neutralinos or majorons. The search for these Higgs bosons is performed in the Higgs bremsstrahlung process in association with a Z boson. All hadronic and charged leptonic Z decays are investigated<sup>18</sup>. The  $CL_s$  distribution and the cross section limit are given in Fig. 10. The mass limit is 114.4 GeV.

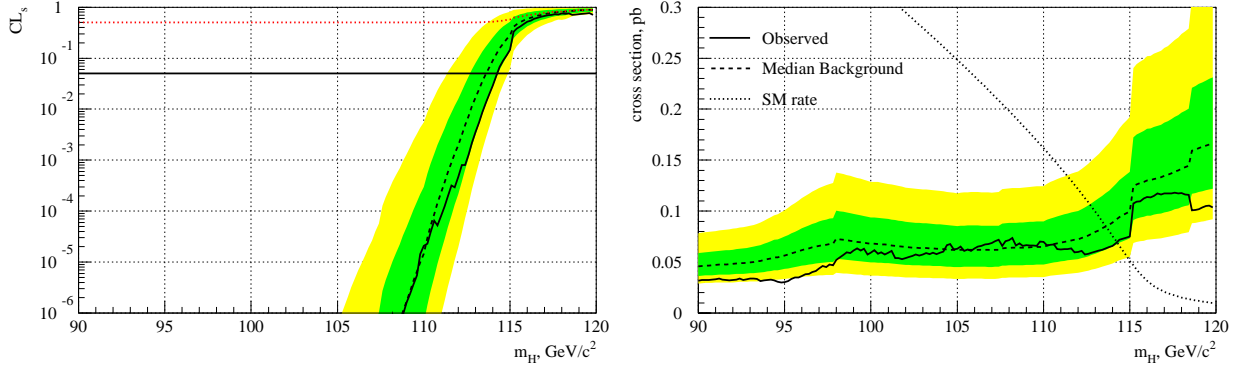


Figure 10: Left: The  $CL_s$  distribution for all hadronic and charged leptonic channels for invisible Higgs boson decays, combining the data collected by the four LEP experiments at energies from 200 to 209 GeV. The observed limit is given by the solid line and the expected limits are indicated by the dashed line and the shaded bands ( $1\sigma$  and  $2\sigma$ ). The horizontal line at  $CL_s = 0.05$  gives the limit at 95% CL. Right: The 95% CL bounds on the production cross section for  $\text{Br}(H' \rightarrow \text{invisible}) = 1$ . The observed limit is given by the solid line and the expected limits are indicated by the dashed line and the shaded bands ( $1\sigma$  and  $2\sigma$ ). The dotted line gives the expected cross section at 206 GeV for Higgs bosons decaying 100% invisibly.

## 6 Flavour-Independent Higgs Boson Decays

While in the SM the Higgs boson decays predominantly into b-quarks, in many extensions such as the general two Higgs doublet model, the b-quark coupling could be suppressed. Therefore, the search for Higgs boson bremsstrahlung in the four-jet, two-jet and two-lepton, and two-jet and missing-energy channels is generalized for flavor-independent hadronic Higgs boson decays<sup>19</sup>. Stringent limits are given in Fig. 11. The expected limit is only 2.6 GeV below the SM limit, which is remarkable since b-tagging is a very important search tool.

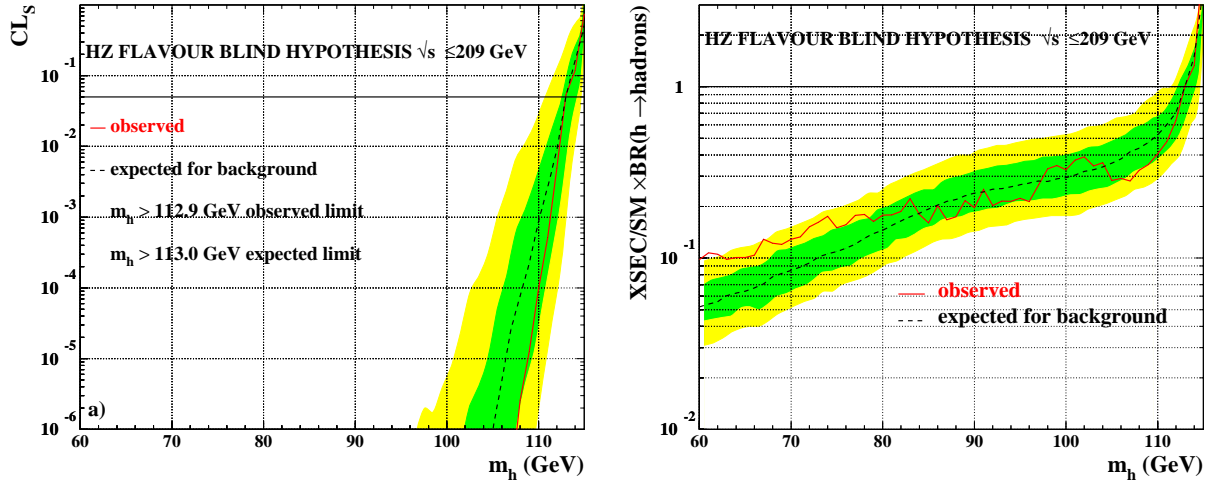


Figure 11: Left: The  $CL_s$  distribution for all hadronic and charged leptonic channels for flavor-independent hadronic Higgs boson decays, combining the data collected by the four LEP experiments at energies up to 209 GeV. The production cross section of the SM and  $\text{Br}(h \rightarrow q\bar{q}) = 1$  is assumed. The observed limit is given by the solid line and the expected limits are indicated by the dashed line and the shaded bands ( $1\sigma$  and  $2\sigma$ ). The horizontal line at  $CL_s = 0.05$  gives the limit at 95% CL. Right: The 95% CL bounds on the production cross section normalized to the SM cross section. The observed limit is given by the solid line and the expected limits are indicated by the dashed line and the shaded bands ( $1\sigma$  and  $2\sigma$ ).

It is possible that the Higgs boson does not decay into fermions. In this case the decays into  $\gamma\gamma$ ,  $WW$  and  $ZZ$  are dominant. As a fermiophobic benchmark model, the production and decays of the SM Higgs boson are assumed and all couplings to fermions are set to zero<sup>20</sup>. Figure 12 shows the expected Higgs boson branching fractions and the mass limits from the search by all LEP experiments in the  $h \rightarrow \gamma\gamma$  channel.

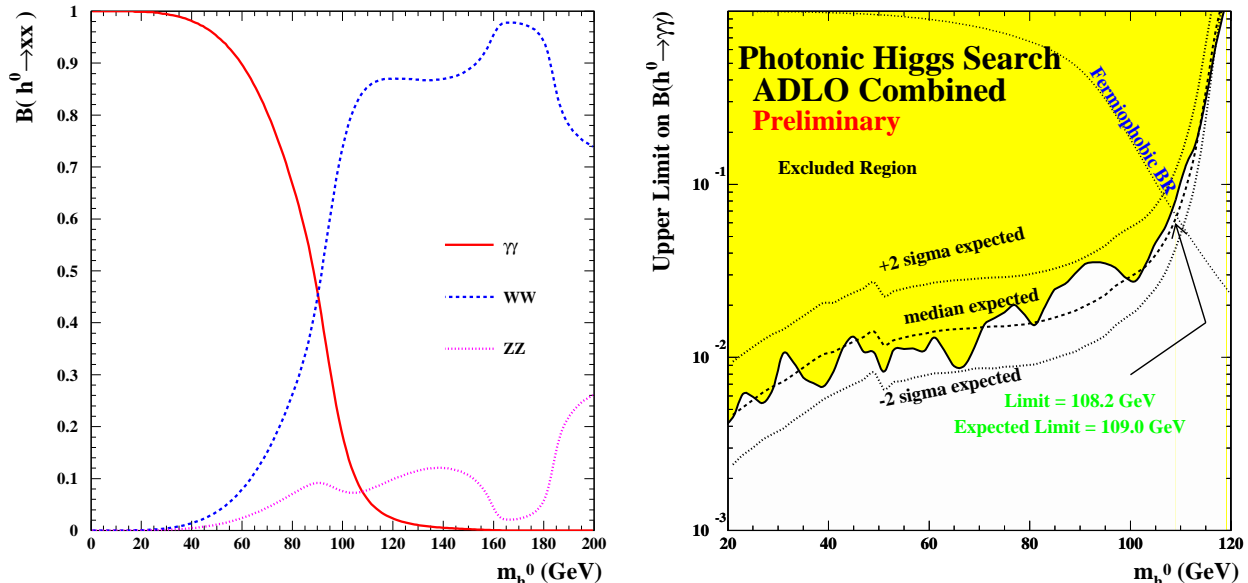


Figure 12: Left: Branching fraction of the fermiophobic benchmark model where only the bosonic Higgs decay modes are allowed. Right: Limits at 95% CL on the branching fraction  $h \rightarrow \gamma\gamma$  assuming SM production cross sections. The observed limit is given by the solid line and the expected limits are indicated by the dashed line and the  $2\sigma$  bands. The dotted line gives the expected branching fraction in the fermiophobic benchmark model.

## 8 Conclusions

The combination of the complete data from the four LEP experiments resulted in a large increase for the sensitivity of Higgs bosons. The data shows a preference for a SM Higgs boson of 115.6 GeV. Further small data excesses for Higgs boson pair-production and bremsstrahlung between 90 and 100 GeV allow the hypothesis that  $h$ ,  $A$  and  $H$  of the MSSM all have masses between 90 and 116 GeV. Previously reported MSSM parameter combinations from a general scan are supported by the complete data set. The data is also consistent with the background-only hypothesis which results in stringent mass limits for the SM Higgs boson, the neutral Higgs bosons of the MSSM, charged Higgs bosons, invisible Higgs boson decays, flavour-independent hadronic Higgs boson decays, and fermiophobic Higgs boson decays. Table 2 summarizes these limits, and in addition compares benchmark and scan limits in the MSSM.

Model	Obs.	Exp.	$\sqrt{s}$ (GeV)	Data	$m_h^b$	$m_A^b$	$m_h^s$	$m_A^s$
SM	114.1	115.6	91 <sup>21,6</sup>	L3	41.0	none	25	none
MSSM ( $m_h$ )	91.0	94.6	172 <sup>22,7</sup>	DELPHI	59.5	51.0	30	none
MSSM ( $m_A$ )	91.9	95.0	183 <sup>23,24</sup>	DELPHI	74.4	75.2	67	75
$H^+H^-$	78.6	78.8	189 <sup>25,8</sup>	DELPHI	82.6	84.1	75	78
Invisible	114.3	113.6	189 <sup>9</sup>	OPAL	74.8	76.5	72	76
Flavor-independent	112.9	113.0	202 <sup>26</sup>	DELPHI	85.9	86.5	85	86
Fermiophobic	108.2	109.0	202 <sup>27,4</sup>	LEP	88.3	88.4	86	87
			209 <sup>11,10</sup>	DELPHI	89.6	90.7	89	89

Table 2: Left: Observed and expected Higgs boson mass limits from complete LEP data in various models. Right: Benchmark (b) and scan (s) mass limits in the MSSM. All limits are in GeV at 95% CL.

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