EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH

CERN-EP-2000-055
April 25, 2000

Searches for Higgs bosons: Preliminary combined results using LEP data collected at energies up to 202 GeV

ALEPH, DELPHI, L3 and OPAL Collaborations

The LEP working group for Higgs boson searches[1]

Abstract

In 1999 the four LEP experiments have collected data at energies between 192 and 202 GeV, for approximately 900 pb^{-1} integrated luminosity. The LEP working group for Higgs boson searches has combined these data with data sets collected earlier at lower energies. No statistically significant excess has been observed when compared to the Standard Model background prediction. The following 95% confidence level bounds have been obtained. For the Standard Model Higgs boson, the lower bound on the mass is 107.9 GeV/c^2. In the Minimal Supersymmetric Standard Model and from representative scans of the SUSY parameters, the mass limits $m_{\rm h}$>88.3 GeV/c^2 and $m_{\rm A}$>88.4 GeV/c^2 are obtained for the light CP-even and the CP-odd neutral Higgs boson, respectively. Furthermore, for a top quark mass less than or equal to 174.3 GeV/c^2, and assuming no (or large) mixing in the scalar-top sector, the range $0.4<\tan\beta<4.1$ ($0.7<\tan\beta<1.8$) is excluded. Finally, for charged Higgs bosons predicted by two-doublet extensions of the Standard Model and decaying only into the channels $\rm H^+\rightarrow c\bar{s}$ and $\tau^+\nu_\tau$, a lower bound of 78.6 GeV/c^2 is obtained for the mass.

Prepared from contributions of the LEP experiments to the Winter 2000 conferences.

[1]Contributions from P. Bock, M. Carena, K. Cranmer, M. Felcini, I. Fisk, P. Garcia-Abia, S. Heinemeyer, K. Hoffman, A. Holzner, P. Igo-Kemenes, P. Janot, T. Junk, P. Lutz, A. Kopp, T. Kuhl, C. Martinez-Rivero, P. McNamara, W. Murray, A.N. Okpara, M. Pieri, A. Raspereza, A. Read, V. Ruhlmann-Kleider, P. Seager, A. Sopczak, P. Teixeira-Dias, C. Tully, A. Quadt, C.E.M. Wagner, G. Weiglein, S. Yamashita

1 Introduction

We present combined results from the ALEPH, DELPHI, L3 and OPAL Collaborations on searches for the Standard Model (SM) Higgs boson, for the neutral Higgs bosons h^0 and A^0 of the Minimal Supersymmetric Standard Model (MSSM), and for charged Higgs bosons predicted by extensions of the SM with two Higgs field doublets (2HD models). The results are obtained by combining the results presented at the winter 2000 conferences based on data collected in 1999 at centre-of-mass energies between 192 and 202 GeV and earlier data collected at lower energies [1]. The new data represent a total integrated luminosity of approximately 900 pb^{-1}.

Cross-sections, branching ratios and many other physics quantities which are used in this work, are calculated within the HZHA program package, Version 3 [2], which includes several improvements of which the most notable is the inclusion of interference effects between the Higgs-strahlung process $e^+e^- \rightarrow$ HZ and the WW$\rightarrow$ H and ZZ$\rightarrow$ H fusion processes (H designates either the SM Higgs boson H^0_{SM} or the lightest neutral scalar h^0 of the MSSM).

The statistical procedure adopted for the combination of the data and the precise definition of the confidence levels CL_b, CL_{s+b} and CL_s with which the search results are expressed, are stated in Appendix A. The main sources of systematic errors affecting the signal and background rate predictions are included taking into account correlations between search channels, LEP energies and individual experiments. This is done using an extension of the method of Cousins and Highland [3] where the confidence levels are the averages of a large ensemble of Monte Carlo experiments, each one with a different choice of signal and background, varied within the errors. The effects of including these uncertainties on the limits are small, and are discussed for each limit presented. Details of the error sources considered can be found in the contributing notes.

For the interpretation of the results in the MSSM, the LEP-Higgs working group has adopted a new set of theoretical "benchmarks" [4], which are based on up-to-date calculations of radiative corrections and which are more appropriate to express the search results than those used in earlier publications of the working group [1, 5]. The parameters of the new benchmark scans are described in Appendix B. In a general scan where the constraints on the parameters are released, weaker limits would be obtained.

2 Combined searches for the SM Higgs boson

At LEP the SM Higgs boson is expected to be produced mainly via the Higgs-strahlung process $e^+e^- \rightarrow$ HZ, while contributions from the WW$\rightarrow$ H fusion channel, $e^+e^- \rightarrow H\nu_e\bar{\nu}_e$, are typically below 10%. The searches performed by the four LEP collaborations encompass the usual HZ final state topologies, commonly called 'four-jet' (HZ$\rightarrow b\bar{b}q\bar{q}$), 'missing energy' ($b\bar{b}\nu\bar{\nu}$), 'leptonic' ($b\bar{b}e^+e^-$ and $b\bar{b}\mu^+\mu^-$), and 'tau' channels ($b\bar{b}\tau^+\tau^-$ and $\tau^+\tau^-q\bar{q}$). The searches in the missing energy channel are optimized for Higgs-strahlung, but are also sensitive to the WW$\rightarrow$ H fusion process. From combining the earlier data collected by the LEP experiments

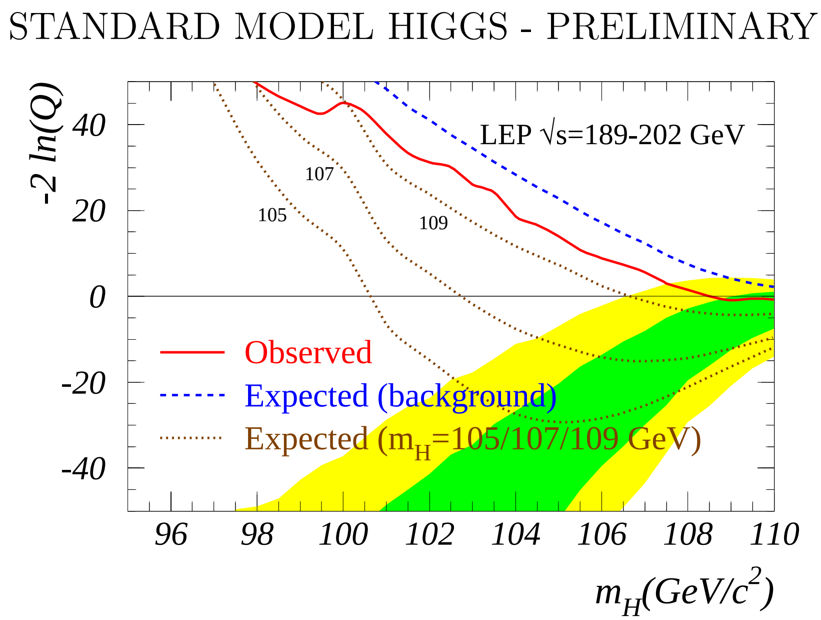

Figure 1: *The negative log-likelihood ratio (test-statistic) as a function of* $m_{\rm H}$*. The dashed line shows the expectation for the background-only hypothesis and the full line the values computed from the observed results. The shaded bands show the* 1σ *and* 2σ *probability bands for the signal at the "true" mass. The expected signal curves (dotted) show the median response away from the true mass for three different Higgs masses.*

at centre-of-mass energies up to 189 GeV, a 95% CL lower bound of 95.2 GeV/c^2 has been obtained [1]. In this section we present an update of the SM Higgs boson search which includes the new data collected at centre-of-mass energies up to 202 GeV.

The analysis procedures of the four LEP experiments producing the inputs for the present combination are described in individual documents [6]–[9]; we summarise the results in Table 1. The large spread in the numbers of selected candidates reflects substantial differences in the selection methods and optimisation procedures. All events which contribute to Table 1 are used below in the calculation of confidence levels and in the limit setting procedure. In the procedure used to determine the limits, described in Appendix A, the treatement of candidate events depends on the values of reconstructed quantities, such as b-tag significances and reconstructed invariant masses. An excess or deficit of candidates may occur in a region of high background and low signal, hence the total count does not indicate whether the actual limit ought to be stronger or weaker than the expectation. The results of the combination are illustrated in Figures 1 through 3.

The test-statistic (of Eq. 1 of Appendix A denoted here as Q) versus the test mass $m_{\rm H}$, computed for the observed results, is shown in Figure 1. It should have a minimum near the true Higgs mass. A negative value would indicate some preference for the signal hypothesis and the more negative the value the more significant the result. The full-line curve representing the

Experiment:	ALEPH	DELPHI	L3	OPAL
192 GeV: Integrated luminosity (pb^{-1}):	28.9	25.2-25.9	29.7	28.7-28.9
Backg. predicted / Evts. observed				
Four-jet:	4.8/3	19.2/16	0.7/1	3.6/5
Missing-energy:	1.5/1	12.1/13	0.2/0	1.5/0
Leptonic (e, μ):	2.8/3	2.5/1	0.0/0	1.0/1
Tau channels:	1.2/1	0.8/0	0.0/0	0.8/1
196 GeV: Integrated luminosity (pb^{-1}):	79.9	74.8-76.9	83.7	73.9-74.8
Backg. predicted / Evts. observed				
Four-jet:	14.8/8	59.3/51	5.4/8	10.0/17
Missing-energy:	3.8/4	32.8/32	1.3/0	3.2/2
Leptonic (e, μ):	8.9/4	6.8/7	0.2/0	2.4/2
Tau channels:	3.7/1	2.4/3	0.1/0	2.1/0
200 GeV: Integrated luminosity (pb^{-1}):	86.3	81.9-84.3	82.8	74.8-77.2
Backg. predicted / Evts. observed				
Four-jet:	17.5/16	67.2/61	22.6/24	9.3/9
Missing-energy:	3.8/1	36.6/32	4.3/7	2.8/2
Leptonic (e, μ):	11.2/13	8.1/9	1.1/1	3.3/5
Tau channels:	4.7/7	2.6/3	0.8/0	2.7/3
202 GeV: Integrated luminosity (pb^{-1}):	41.9	40.0-41.1	37.0	35.2-36.1
Backg. predicted / Evts. observed				
Four-jet:	9.3/3	33.8/33	9.4/14	4.8/2
Missing-energy:	1.8/1	17.9/20	2.8/4	1.8/2
Leptonic (e, μ):	5.6/6	4.2/1	0.5/0	1.4/2
Tau channels:	2.4/2	1.2/0	0.4/0	0.8/0
Total: Integrated luminosity (pb^{-1}):	237.0	222-228	232.4	213-217
Backg. predicted / Evts. observed				
Four-jet:	46.4/30	179.5/161	38.1/47	27.7/33
Missing-energy:	11.0/7	99.4/97	8.6/11	9.3/6
Leptonic (e, μ):	28.5/26	21.6/18	1.8/1	8.1/10
Tau channels:	11.9/11	7.0/6	1.3/0	6.4/4
Events in all channels	97.8/74	307.5/282	49.8/59	51.5/53
Limit (GeV/c^2) exp. (median) at 95% CL:	107.7(*)	106.3	105.3	105.2
Limit (GeV/c^2) observed at 95% CL:	107.7	103.9	106.0	103.0

Table 1: *Information related to the searches of the four LEP experiments for the SM Higgs boson at energies between 192 and 202 GeV. In the L3 analysis the event selection, and thus the expected background and observed number of events, depend on the Higgs boson mass hypothesis; they are given here for* $m_{\rm H}$*=105* GeV/c^2*. (*) In the ALEPH publication the expected mean is quoted (which is 106.8* GeV/c^2*) rather than the median. Also, the confidence level estimator* CL_s *used by ALEPH is different from the one used by the other collaborations, shifting the expected limit of ALEPH upwards by about 0.5* GeV/c^2*.*

observation is in good agreement with the dashed line representing the background hypothesis, and deviates from the dotted curves which represent signal + background situations with true Higgs boson masses fixed at particular values.

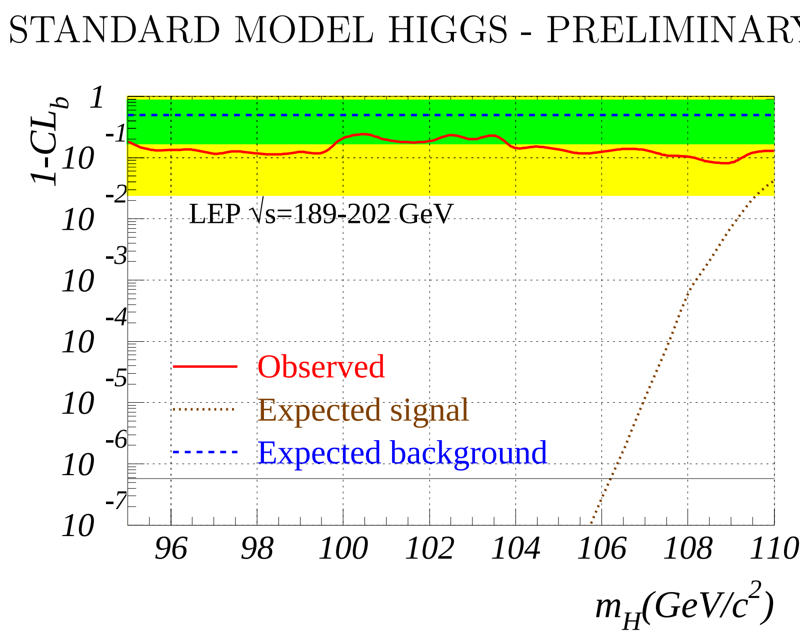

Figure 2: *The confidence level CL_b as a function of m_{H}. The straight dashed line at 50% and the shaded bands represent the median result and the $\pm1\sigma$ and $\pm2\sigma$ probability bands expected in the absence of a signal. The solid curve is the observed result and the dotted curve shows the median result expected for a signal when tested at the "true" mass. The horizontal line at 5.7×10^{-7} indicates the level for a 5σ discovery.*

The compatibility with background of the result is given by $1 - CL_b$, which is plotted as a function of m_{H} in Figure 2. Values of $1-CL_b$ below 5.7×10^{-7}, indicated by the horizontal full line, corresponding to a 5 standard deviation fluctuation of the background, are considered to be in the discovery region. The dotted line shows the expectation in the presence of a signal of true mass m_{H}; its crossing with the 5σ line at 106.3 GeV/c^2 indicates the range of sensitivity of the presently available data to a discovery. It is not enough just to read off the value of $1-CL_b$ at the value of m_{H} for which $-2ln(Q)$ has its minimum to claim observation of a signal because this only gives the probability that the background fluctuated at precisely that mass, while in principle it could have fluctuated anywhere in the mass region considered. This mass region is chosen to include values of m_{H} not strongly excluded by previous searches and for which the present searches have sensitivity. An estimate based on Monte Carlo studies shows that $1 - CL_b$ must be multiplied by a factor of four in the present case, corresponding roughly to the width of the mass search region divided by the typical mass resolution.

A 95% confidence level lower limit on the Higgs mass may be set by identifying the mass region where $CL_s < 0.05$, as shown in Figure 3. The median limit expected in the absence of a signal is 109.1 GeV/c^2 and the limit observed by combining the LEP data is 107.9 GeV/c^2.

The inclusion of systematic errors, together with their correlations, has decreased the limits by approximately 100 MeV/c^2.

STANDARD MODEL HIGGS - PRELIMINARY

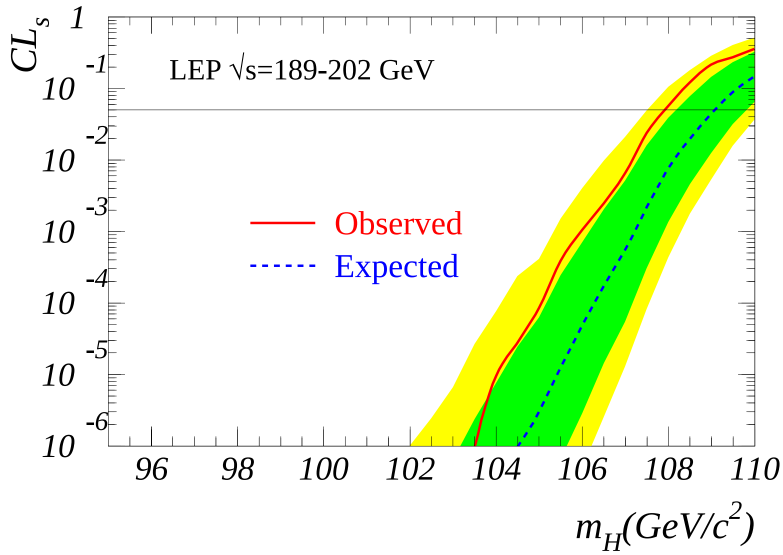

Figure 3: *The confidence level CL_s for the signal hypothesis versus m_H. The solid curve is the observed result, the dashed curve the median result expected in the absence of a signal. The shaded areas represent the symmetric 1σ and 2σ probability bands of CL_s in the absence of a signal. The intersections of the curves with the horizontal line at $CL_s = 0.05$ give the mass limits at the 95% confidence level.*

As a cross-check of the confidence level calculation procedures, the expected and observed limits have been calculated independently, using another test-statistic (Method C in [1, 5]). The limits were within ± 150 MeV/c^2 of the values quoted above.

Figure 4 shows the distribution of reconstructed Higgs masses for a subset of the events in Table 1. The corresponding background from SM processes and the signal expected from a SM Higgs boson of 105 GeV/c^2 mass are also shown. The figure has been obtained with the supplementary requirement that the contributions from the four experiments (selecting the most signal-like set of events) be roughly equal. Since all events enter with equal weight, such a distribution does not reflect for example differences in mass resolutions, signal sensitivities and background rates, which characterise the various search channels and individual experiments. Furthermore, the L3 experiment employs an event selection technique which depends strongly on the mass hypothesis m_H. Since in this figure m_H is chosen as 105 GeV, the L3 contribution artificially enhances the event counts, expected and observed, around that value. This figure is produced merely for illustration purposes and should not be used to draw quantitative conclusions. The small deficit in observed events is a reflection of the numbers in Table 1 in the line labelled “Events in all channels”.

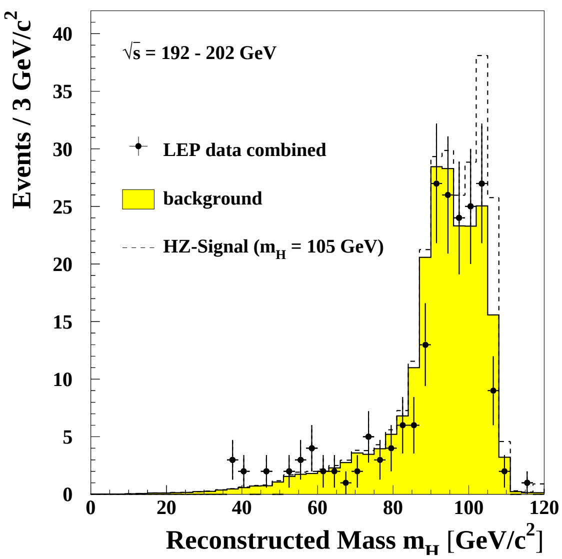

Figure 4: *LEP-combined distribution of the reconstructed SM Higgs boson mass in searches conducted at $\sqrt{s}$ between 192 and 202 GeV. The figure displays the data (dots with error bars), the predicted SM background (shaded histogram) and the prediction for a Higgs boson of 105* GeV/c^2 *mass (dashed histogram). The figure has been obtained with the supplementary requirement that the contributions from the four experiments (selecting the most signal-like set of events) be roughly equal. The number of data events selected for this figure is 201 while 220 are expected from SM background processes. A signal at 105* GeV/c^2 *mass would contribute with 40.7 events.*

PRELIMINARY

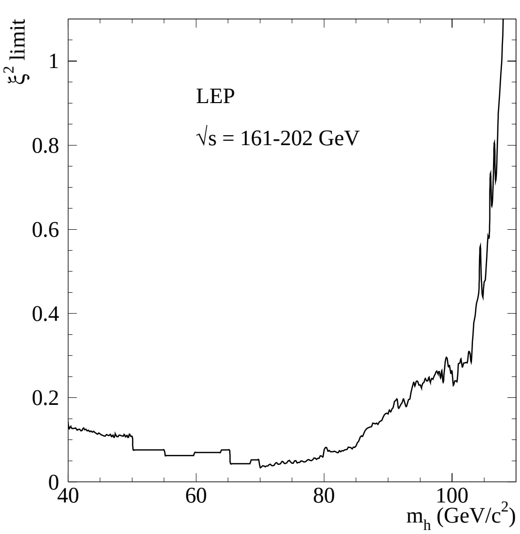

Figure 5: *The 95% CL upper bound on* ξ^2 *as a function of* m_{H}*, where* $\xi = g_{HZZ}/g^{SM}_{HZZ}$ *is the HZZ coupling relative to the SM coupling.*

The combined LEP2 data from 161 to 202 GeV are used to set 95% CL upper bounds on the HZZ coupling in non-standard models which assume that the Higgs boson decay properties are identical to those in the SM but that the cross-section may be different. Figure 5 shows the limit on ξ^2 as a function of the test mass where $\xi = g_{HZZ}/g_{HZZ}^{SM}$ is the ratio of the coupling in such a hypothetical model to the SM coupling. This limit is obtained by scaling the total $\mathrm{Hf\bar{f}}$ cross-section. The contributions to the total cross-section from the WW and ZZ fusion processes contribute negligibly in this context.

3 Combined searches for the Higgs bosons h and A in the MSSM

In the MSSM there are two fundamental Higgs field doublets, and the Higgs sector comprises five physical states: two CP-even neutral Higgs bosons, h and H ($m_{\mathrm{h}}<m_{\mathrm{H}}$), one CP-odd neutral Higgs boson, A, and a pair of charged Higgs bosons, H^+ and H^-. At LEP energies the h and A particles are expected to be produced mainly via the Higgs-strahlung process $\mathrm{e^+e^-} \rightarrow$ hZ (analogous to the main SM production process) or the pair production process $\mathrm{e^+e^-} \rightarrow$ hA. The two processes are complementary: the cross-section of the first is proportional to $\sin^2(\beta-\alpha)$ and that of the second proportional to $\cos^2(\beta-\alpha)$ ($\tan\beta$ is the ratio of the vacuum expectation values of the two Higgs field doublets and α is a mixing angle in the CP-even Higgs sector).

The combined data of the four LEP experiments are interpreted here within the framework of a 'constrained' MSSM where universal values M_{SUSY} and M_2 are assumed for the SUSY breaking s-fermion and gaugino masses, respectively, at the electroweak scale. Combined search results are given for two new 'benchmark' MSSM parameter scans [4], which are described in Appendix B. A first benchmark corresponds to *no-mixing* in the scalar-top sector; a second to large mixing and other parameters tuned to allow maximal values for m_{h} for each value of $\tan\beta$ (m_{h}-*max* hereafter). In both benchmark scans the top mass, which has an impact on the results via radiative corrections, is fixed to the experimental central value of m_{t}=174.3 GeV/c^2 [10], and to two alternative values where the central value is decreased and increased by the current experimental error of 5.1 GeV/c^2. In each case, the exclusion limits obtained are valid for m_{t} less than or equal to the chosen value.

The individual searches of the four LEP collaborations for the processes $\mathrm{e^+e^-} \rightarrow$ hZ and $\mathrm{e^+e^-} \rightarrow$ hA which include the data taken at $\sqrt{s}$ from 192 to 202 GeV, are described in [6, 7, 9, 11]. For the process $\mathrm{e^+e^-} \rightarrow$ hZ, the searches for the SM Higgs boson are interpreted in the MSSM while taking into account the reduced cross-section due to the factor $\sin^2(\beta-\alpha)$ and the predicted variations of the decay branching ratios of the h boson in the scans. For the process $\mathrm{e^+e^-} \rightarrow$ hA, the most relevant final states are $\mathrm{b\bar{b}b\bar{b}}$, $\tau^+\tau^-\mathrm{b\bar{b}}$ and $\mathrm{b\bar{b}}\tau^+\tau^-$. In the kinematic domain $2m_{\mathrm{A}}<m_{\mathrm{h}}$, besides decaying into the usual fermionic final states, the h boson can also decay via the process h$\rightarrow$ AA. The collaborations have included the h$\rightarrow$ AA decay in their searches either by applying the standard hZ and hA search procedures with efficiencies calculated for the (AA)Z and (AA)A final states or by performing specific searches for these

final states.

The information from the four LEP experiments regarding the searches for $e^+e^- \rightarrow hA$ is summarised in Table 2 which lists the predicted SM background and the events observed in the $b\bar{b}b\bar{b}$, $\tau^+\tau^- b\bar{b}$ and $b\bar{b}\tau^+\tau^-$ channels and the individual 95% CL limits, expected and observed. (For the $e^+e^- \rightarrow hZ$ process Table 1 is relevant.)

To search for a signal for the neutral Higgs bosons h and A, the MSSM parameters have been scanned according to the two benchmark scenarios described in Appendix B. Each scan point is regarded as a model to be tested. The procedure of calculating the test-statistic Q and the confidence levels CL_b, CL_{s+b} and CL_s is the same as for the SM case, with the inclusion of the results of searches for the process $e^+e^- \rightarrow hA$.

Figure 6 shows the test-statistic for the m_h-*max* benchmark scan, for the particular case $m_h \approx m_A$, where only the $e^+e^- \rightarrow hA$ process contributes, since $\sin^2(\beta - \alpha) \approx 0$. (The discussion of this figure is analogous to the one of Figure 1).

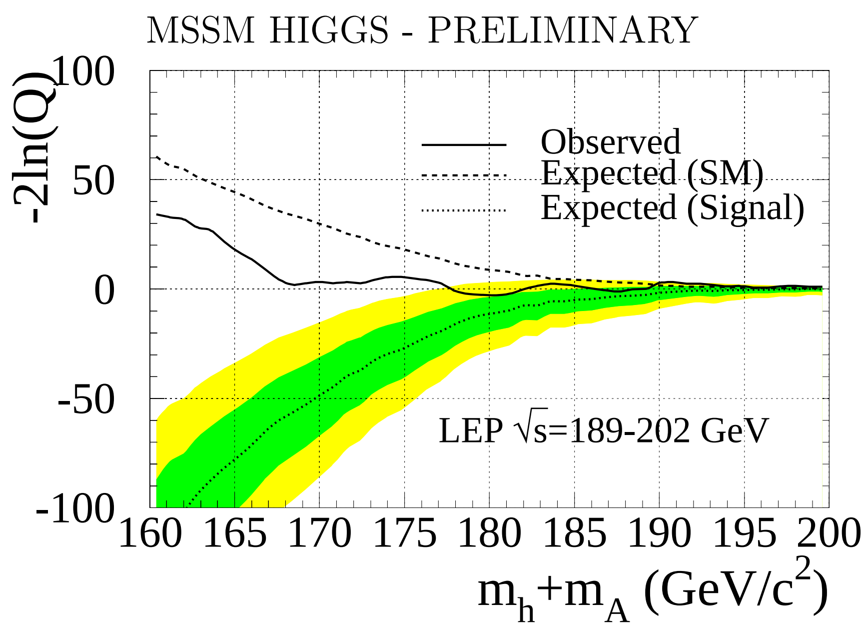

Figure 6: *The negative log-likelihood ratio (test-statistic) as a function of* $m_H + m_A$. *The dashed line shows the expectation for the background-only hypothesis and the full line the values computed from the observed results. The dotted line and the shaded areas show the central value and the* 1σ *and* 2σ *probability bands for the signal at the "true" mass sum.*

Figure 7 illustrates the outcome for $1-CL_b$. The observation is within 2σ of the background prediction, except at $m_h + m_A \approx 168$ GeV/c^2 where a slight local excess in the data causes $1-CL_b$ to reach the 3σ level. This excess originates from the OPAL $b\bar{b}\tau^+\tau^-$ channel at $\sqrt{s}$= 189 GeV [9] and to a lesser extent in the L3 1999 data [11]. Taking into account the typical mass resolution and the size of the mass range, following the discussion in Section 2, the probability

Experiment:	ALEPH	DELPHI	L3	OPAL
192 GeV: Integrated luminosity (pb^{-1}):	28.9	25.9	29.7	28.7-28.9
Backg. predicted / Evts. observed				
$b\bar{b}b\bar{b}$:	4.8/3	5.7/6	1.2//1	1.5/4
$\tau^+\tau^-b\bar{b}$ and $b\bar{b}\tau^+\tau^-$:	0.3/0	0.8/0	0.2/0	1.2/1
196 GeV: Integrated luminosity (pb^{-1}):	79.9	76.9	83.7	74.7-74.8
Backg. predicted / Evts. observed				
$b\bar{b}b\bar{b}$:	14.8/8	18.6/21	3.4/3	3.6/7
$\tau^+\tau^-b\bar{b}$ and $b\bar{b}\tau^+\tau^-$:	0.8/0	2.4/3	0.5/0	2.9/2
200 GeV: Integrated luminosity (pb^{-1}):	86.3	84.3	82.7	74.8-77.2
Backg. predicted / Evts. observed				
$b\bar{b}b\bar{b}$:	17.5/16	17.8/14	5.5/5	3.6/4
$\tau^+\tau^-b\bar{b}$ and $b\bar{b}\tau^+\tau^-$:	1.1/1	2.6/3	0.4/0	2.7/1
202 GeV: Integrated luminosity (pb^{-1}):	41.9	41.1	37.0	35.4-36.1
Backg. predicted / Evts. observed				
$b\bar{b}b\bar{b}$:	9.3/3	9.0/6	3.6/1	1.8/1
$\tau^+\tau^-b\bar{b}$ and $b\bar{b}\tau^+\tau^-$:	0.5/0	1.3/0	0.2/0	0.9/2
Total: Integrated luminosity (pb^{-1}):	237.0	228.2	233.1	214-217
Backg. predicted / Evts. observed				
$b\bar{b}b\bar{b}$:	46.4/30	51.1/47	13.7/10	10.5/16
$\tau^+\tau^-b\bar{b}$ and $b\bar{b}\tau^+\tau^-$:	2.7/1	7.1/6	1.3/0	7.7/6
Events in all channels:	49.1/31	58.2/53	15.0/10	18.2/22
Limit exp.(median)/obs. for m_h (GeV/c^2):	88.9(**)/91.5	85.3/85.0	85.5/80.5	83.7(*)/79.2
Limit exp.(median)/obs. for m_A (GeV/c^2):	89.3(**)/91.9	87.1/86.2	86.0/81.0	85.4(*)/80.2

Table 2: *Information related to searches of the four LEP experiments for the process* $e^+e^- \to hA$ *at energies from 192 to 202 GeV. Due to the large overlap between events selected in the hZ and the corresponding* hA *analyses, fluctuations in the event counts in Table 1 are reflected here as well. In the L3 analysis the event selection, and thus the expected background and observed number of events, depend on the Higgs boson mass hypothesis; they are given here for* $m_H \approx m_A = 90$ GeV/c^2*.The limits quoted in the last two lines are obtained by combining the searches for* $e^+e^- \to hZ$ *and* $e^+e^- \to hA$*, and correspond to the* m_h*-max benchmark scenario. (*) In the OPAL publication the expected mean is quoted, not the median. (**) As in Table 1, the confidence level estimator* CL_s *used by ALEPH is different from the one used by the other collaborations, shifting the expected limits of ALEPH upwards by about 1.0 GeV/*c^2*.*

for a background fluctuation of that size to occur at at least one point in the mass range is higher than 1%.

Figure 8 illustrates the outcome for CL_s under the same circumstances. The expected and observed 95% CL limits for $m_{\mathrm{h}}+m_{\mathrm{A}}$ are at about 183 GeV/c^2 and 177 GeV/c^2, respectively.

Figure 9 is the two-dimensional generalisation of Figure 7 where the observed $1 - CL_b$ is projected onto the (m_{h}, m_{A}) plane (the case of the m_{h}-*max* benchmark scan, described in Appendix B, is shown). A first hint towards signal-like behaviour would manifest itself as an 'island' where $1 - CL_b$ deviates by more than 3σ from the background prediction. The only place where such a deviation is observed is at $m_{\mathrm{h}}{\approx}m_{\mathrm{A}}{\approx}84$ GeV/c^2, due to the slight excess of events already discussed. The effect is barely larger than 3σ, and the probability for such a fluctuation to occur anywhere in the two-dimensional plane is more than 1%. The double line indicates the boundary of the 95% CL excluded domain, described below. The point at $m_{\mathrm{h}}{\approx}m_{\mathrm{A}}{\approx}84$ GeV/c^2 is excluded in spite of the excess of nearby candidates because the observed event count is about 3σ less than the expectation in the presence of a signal (Figure 8); the data are mildly inconsistent with both the signal and the background hypotheses at that particular point.

We proceed now to apply the statistical procedure to the sets of parameters ('models') defined by the two benchmark scans of Appendix B and to derive 95% CL exclusion limits in the corresponding MSSM parameter spaces. These are shown in Figures 10 and 11, for the *no-mixing* and m_{h}-*max* benchmarks. The limits are presented for $\tan\beta{>}0.4$ and in three parameter projections, (m_{h}, m_{A}), (m_{h}, $\tan\beta$), and (m_{A}, $\tan\beta$). Besides the boundaries obtained from the data, the ones expected on the basis of background Monte Carlo experiments are also shown.

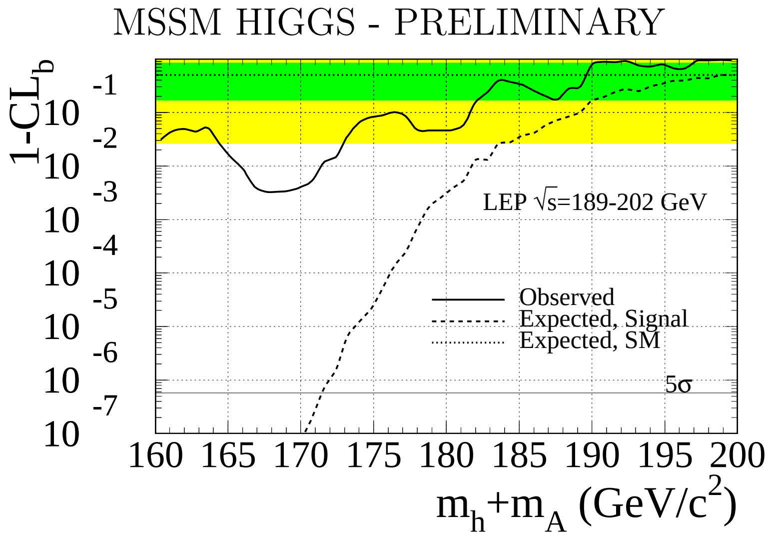

Figure 7: *The confidence level* CL_b *as a function of* $m_{\rm h}+m_{\rm A}$, *for the* $m_{\rm h}$*-max benchmark and the particular case* $m_{\rm h}\approx m_{\rm A}$ *(where only the* $\rm e^+e^-\rightarrow hA$ *process contributes since* $\sin^2(\beta-\alpha)\approx 0$*). The straight dotted line at 50% and the shaded bands represent the median result and the symmetric* 1σ *and* 2σ *probability bands expected in the absence of a signal. The solid curve is the observed result and the dashed curve shows the median result expected for a signal when tested at the "true" mass sum. The horizontal line at* 5.7×10^{-7} *indicates the level for a* 5σ *discovery.*

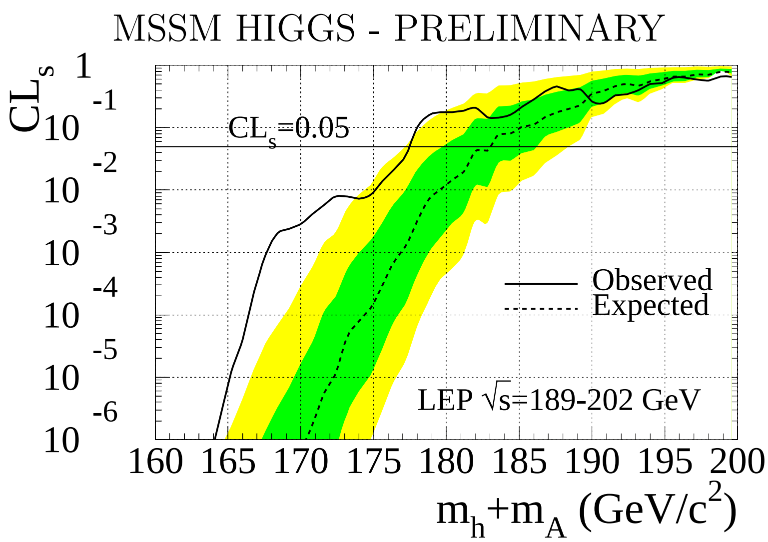

Figure 8: *The confidence level* CL_s *as a function of* $m_{\rm h}$, *for the* $m_{\rm h}$*-max benchmark and the particular case* $m_{\rm h}\approx m_{\rm A}$ *(where only the* $\rm e^+e^-\rightarrow hA$ *process contributes since* $\sin^2(\beta-\alpha)\approx 0$*). The solid curve is the observed result, the dashed curve the median result expected in the absence of a signal. The shaded areas represent the symmetric* 1σ *and* 2σ *probability bands of* CL_s *in the absence of a signal. The intersection of the curves with the horizontal line at* $CL_s = 0.05$ *give the limit on* $m_{\rm h}+m_{\rm A}$ *at the 95% confidence level.*

MSSM HIGGS - PRELIMINARY

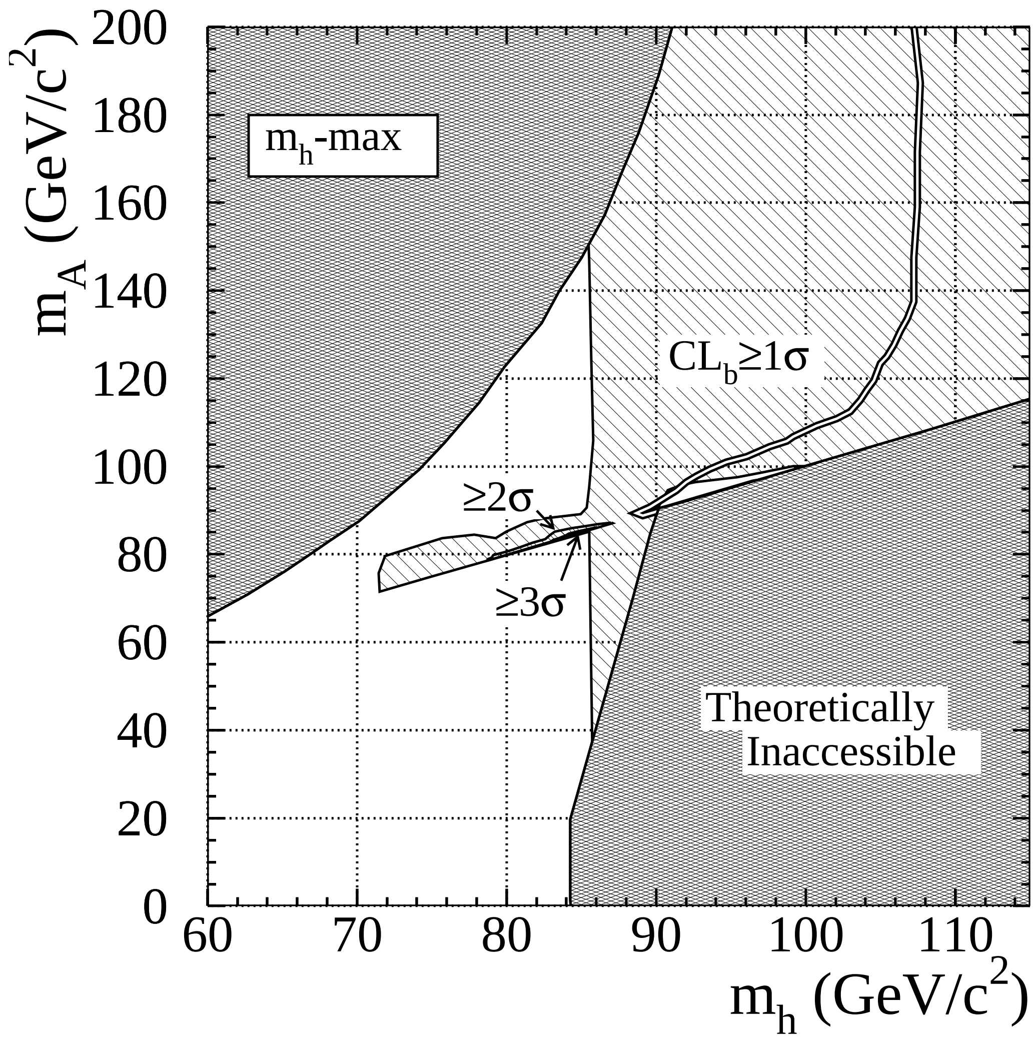

Figure 9: *Distribution of the confidence level* $1 - CL_b$ *for the* m_h*-max benchmark, projected onto the* $(m_\mathrm{h}, m_\mathrm{A})$ *plane. In the white domain the observation either shows a deficit or is less than* 1σ *above the background prediction; in the domains labeled* $\geq 1\sigma$*,* $\geq 2\sigma$ *and* $\geq 3\sigma$ *the observation is above the prediction by the indicated amount. The edge of the 95% CL excluded region (see Figure 11) is shown with a double line.*

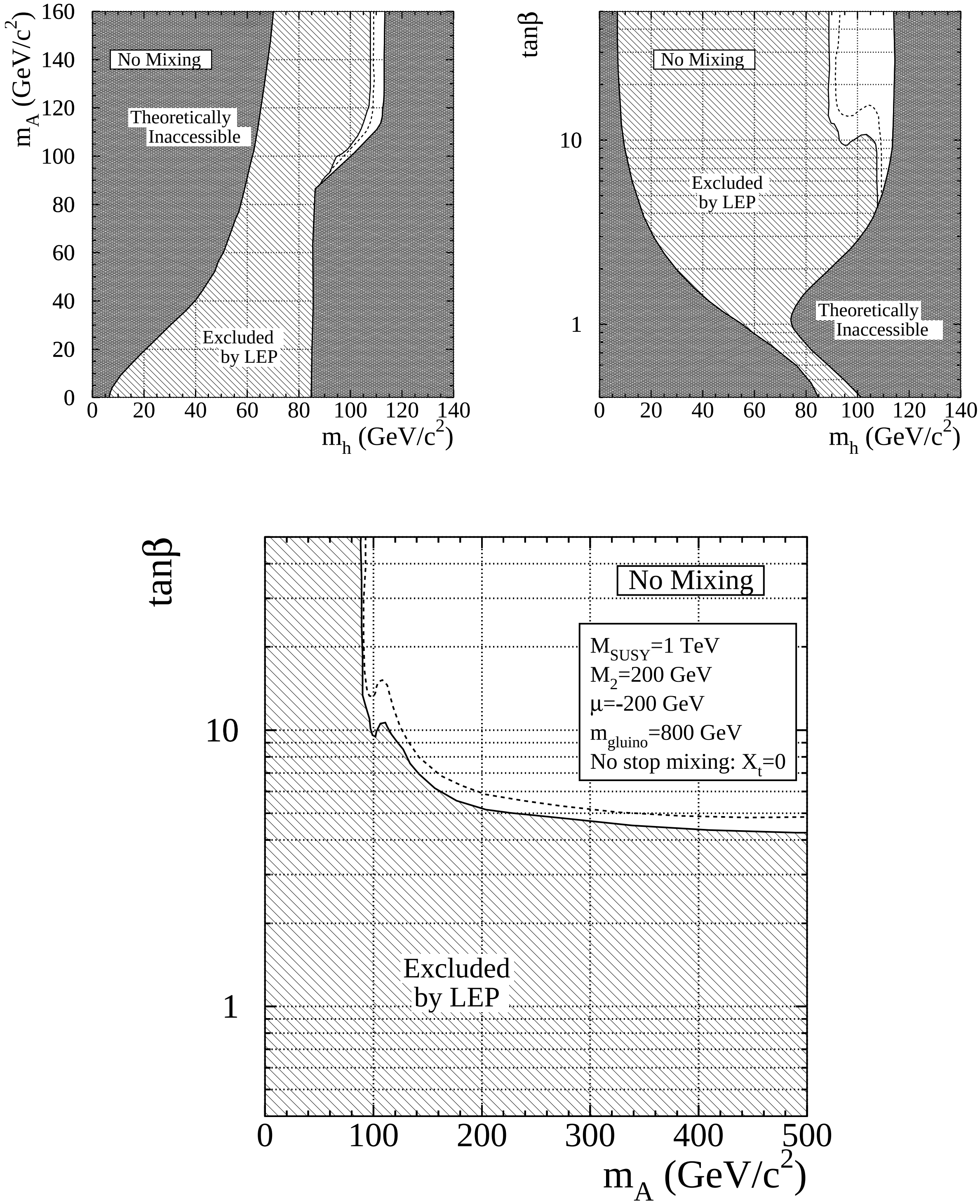

Figure 10: *The 95% CL bounds on* $m_{\rm h}$, $m_{\rm A}$ *and* $\tan\beta$, *for the no-mixing benchmark, from combining the data of the four LEP experiments at 192 to 202 GeV with earlier data taken at lower energies. The full lines represent the actual observation and the dashed lines the median limits expected on the basis of 'background only' Monte Carlo experiments. Upper left: projection* ($m_{\rm h}$, $m_{\rm A}$) *for* $\tan\beta > 0.4$; *upper right: projection* ($m_{\rm h}$,$\tan\beta$)*; lower part: projection* ($m_{\rm A}$,$\tan\beta$).

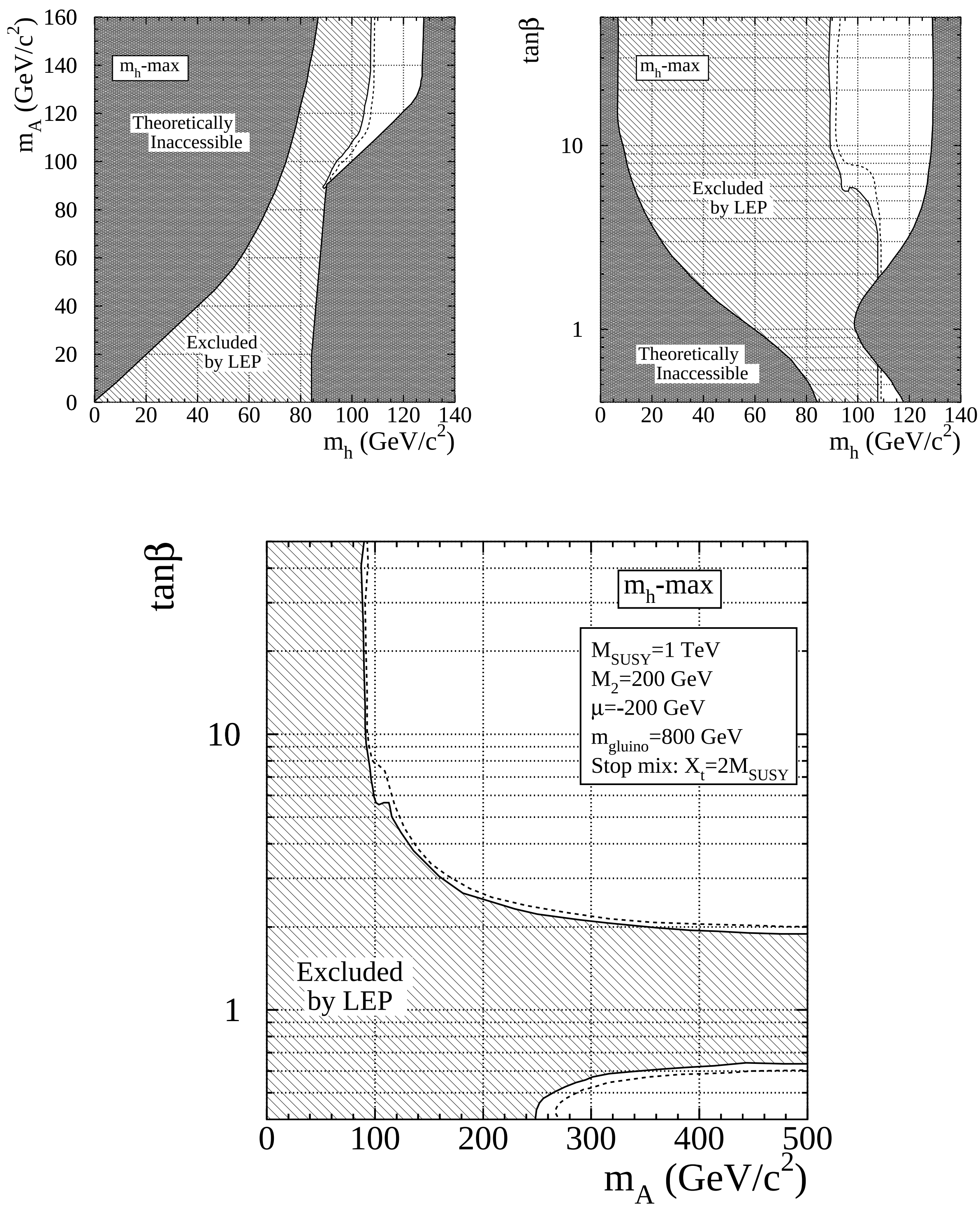

Figure 11: *The 95% CL bounds on m_{h}, m_{A} and $\tan\beta$, for the m_{h}-max benchmark, from combining the data of the four LEP experiments at 192 to 202 GeV with earlier data taken at lower energies. The full lines represent the actual observation and the dashed lines the median limits expected on the basis of 'background only' Monte Carlo experiments. Upper left: projection (m_{h}, m_{A}) for $\tan\beta > 0.4$; upper right: projection (m_{h},$\tan\beta$); lower part: projection (m_{A},$\tan\beta$).*

The mass limits obtained for the two benchmark scans are presented in Table 3.

	no-mixing	$m_{\rm h}$-max
Limits for $m_{\rm h}$ (GeV/c^2)		
expected (median) :	90.8	90.8
observed :	88.3	88.4
Limits for $m_{\rm A}$ (GeV/c^2)		
expected (median):	91.1	91.1
observed :	88.4	88.7
Exclusion in $\tan\beta$		
expected (median):	0.4-4.6	0.6-1.9
observed :	0.4-4.1	0.7-1.8

Table 3: *Combined 95% confidence level MSSM limits for $m_{\rm h}$ and $m_{\rm A}$ (valid for $\tan\beta > 0.4$) and excluded ranges in $\tan\beta$, for the two benchmark scenarios, and for top masses less than 174.3 GeV/c^2. The quoted limits were obtained including systematic errors and their correlations.*

In obtaining the limits quoted in Table 3, systematic errors have been taken into account together with their correlations between experiments, data sets at different energies and between search channels. Their inclusion had the effect of decreasing the expected mass limits by about 300 MeV/c^2. The combined limits for $m_{\rm h}$ and $m_{\rm A}$ turn out to be lower than the ones obtained by ALEPH alone. This is due in part to a deficit of events observed by ALEPH with reconstructed masses near $m_{\rm h}$=$m_{\rm A}$=$m_{\rm Z}$ and an excess observed by OPAL in the same region. It is also due in part to the confidence level estimator CL_s used by ALEPH being different from the one used in this combination.

Based on the above results, we quote the following preliminary 95% CL lower bounds: $m_{\rm h}$>88.3 GeV/c^2, $m_{\rm A}$>88.4 GeV/c^2. These bounds are valid for $\tan\beta$>0.4, and for top masses less than 174.3 GeV/c^2. The ranges of $\tan\beta$ excluded for other top mass ranges are given in Table 4.

Top quark mass:	≤169.2 GeV/c^2	≤174.3 GeV/c^2	≤179.4 GeV/c^2
Exclusion in $\tan\beta$			
No mixing :	0.4-5.7	0.4-4.1	0.4-3.6
$m_{\rm h}$-max:	0.6-2.3	0.7-1.8	0.8-1.5

Table 4: *Exclusion in $\tan\beta$ at the 95% confidence level for various top mass ranges. The bound at 0.4 is due to the $\tan\beta$ range of the scans.*

4 Combined searches for the charged Higgs bosons

Charged Higgs bosons are predicted by extensions of the SM with two Higgs field doublets (2HD models) of which the MSSM is a particular case with supersymmetry. At LEP2 energies charged Higgs bosons are expected to be produced mainly through the process $e^+e^- \to H^+H^-$. In the MSSM and at tree-level the $H^\pm$ is constrained to be heavier than the $W^\pm$ bosons but loop corrections drive the mass to lower values for some values of the MSSM parameters. Since the sensitivity of current searches is limited to the range below $m_{W^\pm}$ due to the background from $e^+e^- \to W^+W^-$, a signal for H^+H^- would indicate either new physics beyond the MSSM or place very stringent constraints on the MSSM parameter values.

The present searches for charged Higgs bosons are placed in the general context of 2HD models where the mass is not constrained. At tree level the production cross-section is fully determined by the $H^\pm$ mass [12]; here they are provided by the program HZHA, Version 3. The searches are carried out under the assumption that the two decays $H^+ \to c\bar{s}$ and $H^+ \to \tau^+\nu_\tau$ exhaust the H^+ decay width; however, the relative branching ratio is not predicted. Thus, the searches encompass the following H^+H^- final states: $(c\bar{s})(\bar{c}s)$, $(\tau^+\nu_\tau)(\tau^-\bar{\nu}_\tau)$ and the mixed mode $(c\bar{s})(\tau^-\bar{\nu}_\tau)$+$(\bar{c}s)(\tau^+\nu_\tau)$. The combined search results are presented as a function of the branching ratio $B(H^+ \to \tau^+\nu_\tau)$.

Details of the searches carried out by the four LEP experiments, using the data collected at energies between 192 and 202 GeV, can be found in [13]. These are summarised in Table 5, together with the 95% CL lower bounds, expected and observed. In the table we quote the mass limits obtained individually by the four experiments, separately for $B(H^+ \to \tau^+\nu_\tau) = 0$, 1, and for arbitrary branching ratio. These limits also include data collected at lower centre-of-mass energies [1].

In order to search for a possible signal, the test mass $m_{H^\pm}$ has been scanned. The test-statistic $X = -2ln(Q) = \Delta\chi^2$ versus the test mass $m_{H^\pm}$ is shown in Figure 12 separately for the branching ratio $B(H^+ \to \tau^+\nu_\tau)$ fixed to 0, 0.5 and 1. One observes negative values which favour the signal hypothesis. This effect is also reflected in Figure 13 which shows the background confidence level $1 - CL_b$ as a function of $m_{H^\pm}$, expected and observed, for $B(H^+ \to \tau^+\nu_\tau)$=0, 0.5 and 1. The observation is mostly within the light-shaded $\pm 2\sigma$ bands of the background prediction, except for the case of $B(H^+ \to \tau^+\nu_\tau)$=0.5 and $m_{H^\pm}$ in excess of 84 GeV/c^2 where the value of $1 - CL_b$ reaches down to the level of 10^{-3} (the 3σ value is 2.7×10^{-3}). While this could be interpreted as a first indication for a signal, it should be noted that the mass is beyond the range of sensitivity for a charged Higgs boson with the cross-section predicted by 2HD models (see dashed curves). The value of $(1 - CL_b)'$ constructed under the 2HD Higgs boson assumption (see Appendix A), is found to be well within 2σ of the background prediction.

Experiment:	ALEPH	DELPHI	L3	OPAL
192 GeV: Int. luminosity (pb^{-1}):	28.9	25.9	29.7	29.3(28.8)
Backg. exp. / Events obs.				
$(c\bar{s})(\bar{c}s)$:	99.7/105	33.3/33	120.1/119	26.6/35
$(c\bar{s})(\tau^+\nu_\tau)$:	12.0/7	13.7/18	23.8/21	11.7/9
$(\tau^+\nu_\tau)(\tau^-\bar{\nu}_\tau)$:	4.2/3	2.6/2	5.3/5	10.8/13
196 GeV: Int. luminosity (pb^{-1}):	79.8	76.9	83.7	76.3(75.7)
Backg. exp. / Events obs.				
$(c\bar{s})(\bar{c}s)$:	303.5/299	98.3/91	332.8/336	68.3/71
$(c\bar{s})(\tau^+\nu_\tau)$:	37.6/31	40.9/46	66.2/88	32.3/39
$(\tau^+\nu_\tau)(\tau^-\bar{\nu}_\tau)$:	11.8/13	9.4/7	14.8/25	29.1/41
200 GeV: Int. luminosity (pb^{-1}):	86.3	84.3	82.8	67.4(71.8)
Backg. exp. / Events obs.				
$(c\bar{s})(\bar{c}s)$:	343.8/320	105.3/99	475.1/509	66.7/69
$(c\bar{s})(\tau^+\nu_\tau)$:	41.6/36	47.0/41	64.1/62	32.1/35
$(\tau^+\nu_\tau)(\tau^-\bar{\nu}_\tau)$:	13.1/11	9.6/7	16.3/12	27.2/27
202 GeV: Int. luminosity (pb^{-1}):	42.0	41.1	37.0	11.4(21.7)
Backg. exp. / Events obs.				
$(c\bar{s})(\bar{c}s)$:	171.4/141	50.7/43	213.0/204	11.3/14
$(c\bar{s})(\tau^+\nu_\tau)$:	21.9/16	22.8/22	29.3/39	5.4/4
$(\tau^+\nu_\tau)(\tau^-\bar{\nu}_\tau)$:	6.4/9	4.6/3	7.4/6	8.3/16
Total: Int. luminosity (pb^{-1}):	237.0	228.2	233.2	184.4(198.0)
Backg. exp. / Events obs.				
$(c\bar{s})(\bar{c}s)$:	918.4/865	287.6/266	1141.0/1168	172.9/189
$(c\bar{s})(\tau^+\nu_\tau)$:	113.1/90	124.4/127	183.4/210	81.5/87
$(\tau^+\nu_\tau)(\tau^-\bar{\nu}_\tau)$:	35.5/36	26.2/19	43.8/48	75.4/97
Events in all channels:	1067.0/991	438.2/412	1368.3/1426	329.8/373
Limit exp.(median)/ observed				
for B=0:	78.1/81.2	76.3/77.8	74.1/74.0	73.0(*)/70.7
for B=1:	84.6/81.8	85.3/85.1	79.2/79.3	79.0(*)/74.7
for any B:	76.4/77.7	73.9/75.4	73.2/65.0	72.5(*)/70.7

Table 5: *Individual search results for the* $e^+e^-\rightarrow H^+H^-$ *final states. The numbers of events correspond to the data sets taken at energies between 192 and 202 GeV. The OPAL selection in the leptonic channel (luminosities are between parentheses) is mass-dependent; the numbers are given here for* $m_{H^\pm}$ *=80* GeV/c^2*.(*) In the OPAL publication the expected mean is quoted, not the median.*

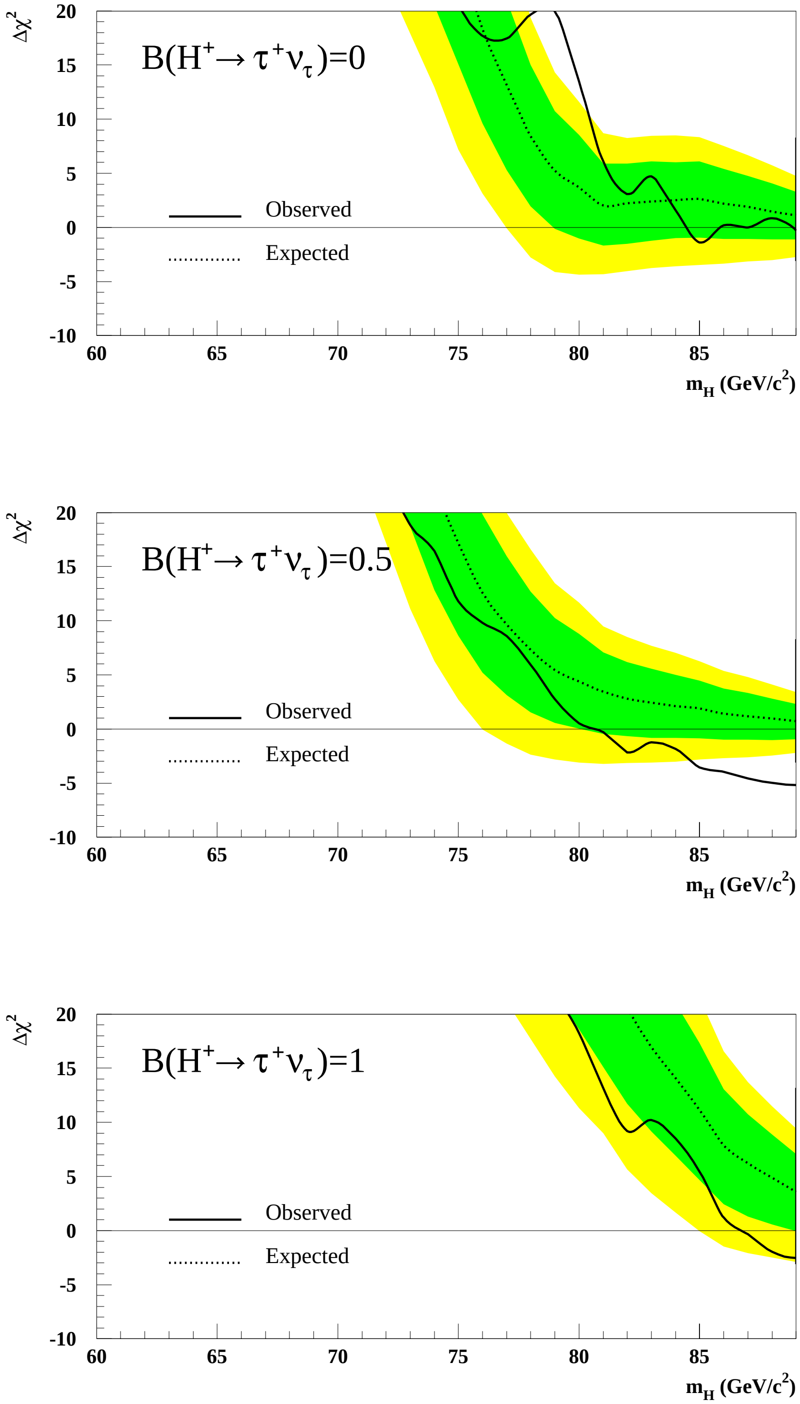

Figure 12: *The test-statistic $X = \Delta\chi^2$ as a function of $m_{\mathrm{H}^\pm}$, separately for $B(\mathrm{H}^+ \rightarrow \tau^+\nu_\tau)$=0, 0.5 and 1 (upper, intermediate and lower plot). In each case, the dotted line shows the expectation for the background-only hypothesis and the full line the values computed from the observed results. The shaded areas show the symmetric 1σ and 2σ probability bands for the background hypothesis.*

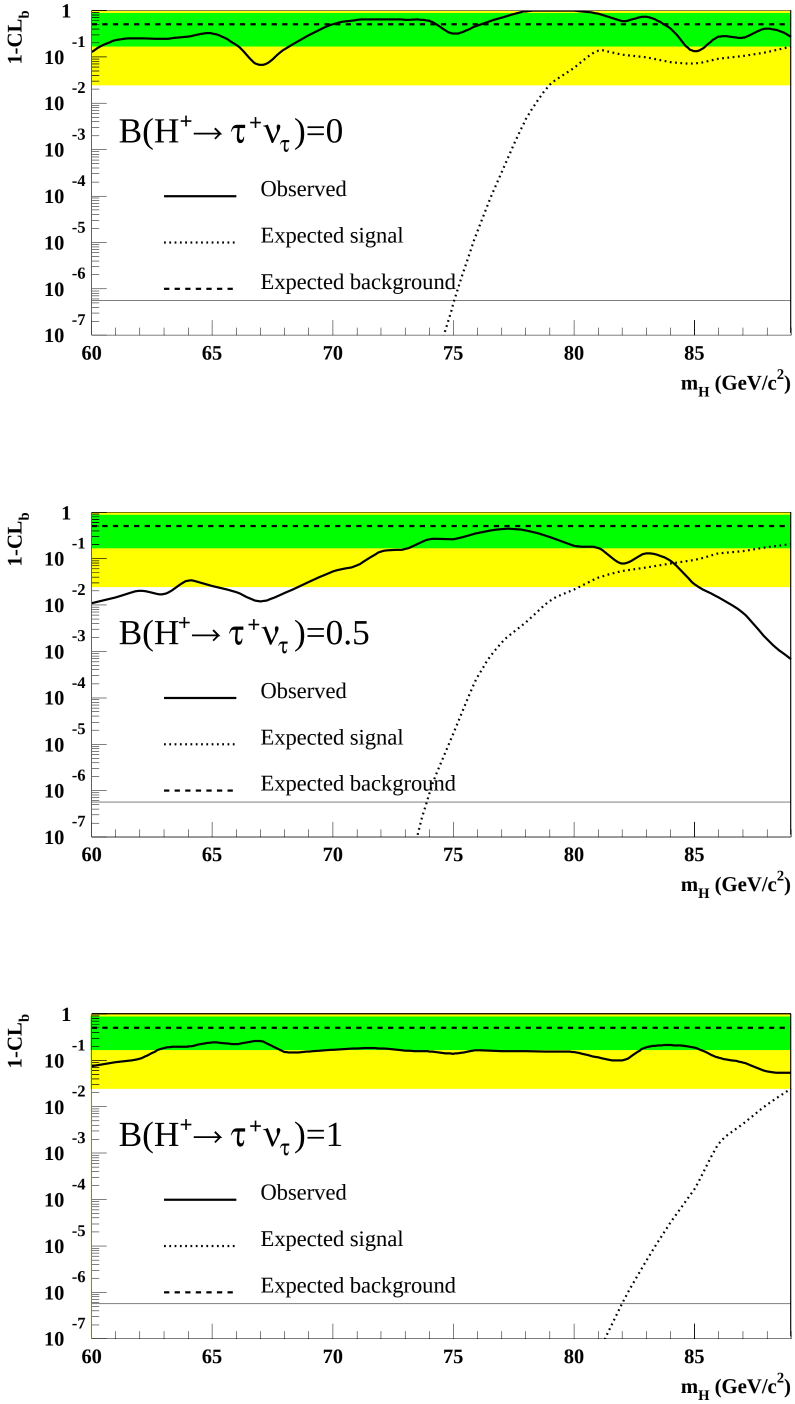

Figure 13: *The confidence level* $1 - CL_b$ *as a function of* $m_{\mathrm{H}^\pm}$*, for the branching ratio* $B(\mathrm{H}^+ \to \tau^+ \nu_\tau)$*=0, 0.5 and 1 (upper, intermediate and lower plot). The straight horizontal line at 50% and the shaded bands represent the mean result and the symmetric* 1σ *and* 2σ *probability bands expected in the absence of a signal. The solid curve is the observed result and the dashed curve shows the median result expected for a signal when tested at the "true" mass.*

The expected and observed mass limits are shown in Figure 14. To obtain the limiting lines, the branching ratio B($H^+ \to \tau^+ \nu_\tau$) has been scanned in steps of 0.05, and the limit setting procedure outlined in Appendix A repeated for each step.

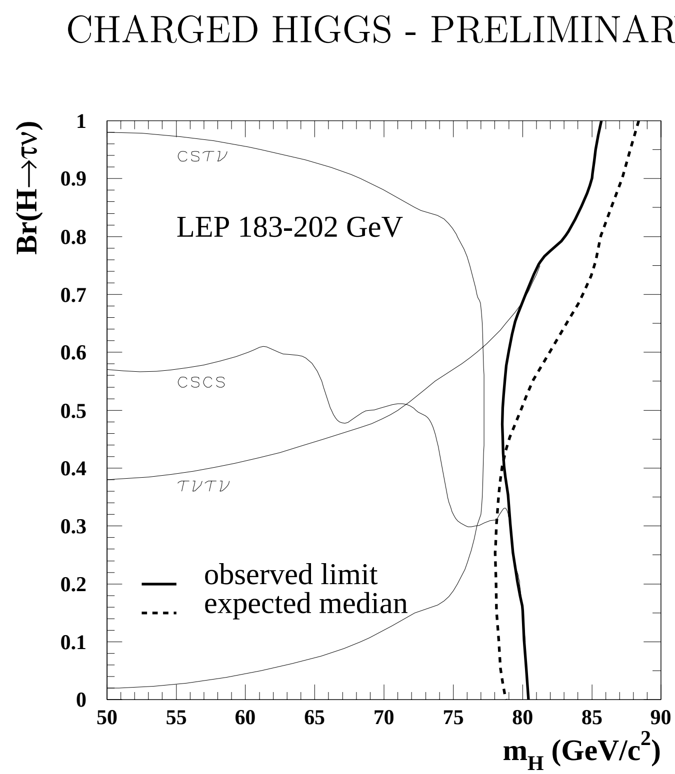

Figure 14: *The 95% CL bounds on $m_{H^\pm}$ as a function of the branching ratio B($H^+ \to \tau^+ \nu_\tau$), combining the data collected by the four LEP experiments at energies from 183 to 202 GeV. The median expected exclusion limits are indicated by the dashed line and the observed limits by the heavy full line. The light full lines show the observed limits channel by channel.*

The combined 95% CL bounds are listed in Table 6 for B($H^+ \to \tau^+ \nu_\tau$)=0, 1, and for arbitrary value of the branching ratio. Taking the lowest of the observed limits from Table 6, we choose to quote a 95% CL lower bound of 78.6 GeV/c^2 for the mass of the charged Higgs boson.

These limits have been obtained with the systematic errors taken to be uncorrelated. The error treatment has shifted the observed mass limits downwards by 900, 200, and 200 MeV/c^2 for B($H^+ \to \tau^+ \nu_\tau$)=0, 1, and for arbitrary value, respectively.

Recent calculations [14] predict a cross-section for W^+W^- production which is lower by a few percent than the ones provided by earlier event generators [15]. Choosing the new calculations for the estimation of the background decreases the mass limit by 900, 500 and 800 MeV/c^2 for B($H^+ \to \tau^+ \nu_\tau$)=0, 1 and for arbitrary value, respectively.

	Mass limit in GeV/c^2 (95% CL)
B($H^+ \rightarrow \tau^+ \nu_\tau$)=0	
Limit expected (median) :	78.8
Limit observed :	80.4
B($H^+ \rightarrow \tau^+ \nu_\tau$)=1	
Limit expected (median) :	88.4
Limit observed :	85.7
Any B($H^+ \rightarrow \tau^+ \nu_\tau$)	
Limit expected (median):	78.0
Limit observed :	78.6

Table 6: *The combined 95% CL lower bounds for the mass of the charged Higgs boson, expected and observed, for fixed and arbitrary values of the branching ratio B($H^+ \rightarrow \tau^+ \nu_\tau$).*

As a cross-check of the confidence level calculation procedures, the expected and observed limits have been calculated independently, using another test-statistic (Method C in [1, 5]). The limits were within $\pm$200 MeV/c^2 of the quoted values.

5 Summary

The LEP working group for Higgs boson searches has updated its previous combined limit for the mass of the Standard Model Higgs boson including the data collected in 1999 at energies between 192 and 202 GeV, for a total integrated luminosity of approximately 900 pb^{-1}. In the absence of a statistically significant excess in the data, a new lower bound of 107.9 GeV/c^2 has been obtained at the 95% confidence level.

The working group has also searched for a possible signal for the h and A bosons in the MSSM scenario and produced new combined 95% confidence level limits for m_h, m_A and $\tan\beta$ for two representative MSSM scenarios. For $\tan\beta$>0.4 and the top quark mass less than or equal to 174.3 GeV/c^2, the limits m_h>88.3 GeV/c^2 and m_A>88.4 GeV/c^2 are obtained. Within the MSSM scenario which allows maximal values for m_h for each value of $\tan\beta$, values of $\tan\beta$ between 0.7 and 1.8 are excluded at the 95% confidence level. This excluded range shrinks to 0.8-1.5 if the top mass is increased by its current experimental uncertainty of 5.1 GeV/c^2. Although these limits are derived in representative subsets of the possible MSSM parameter space, they should not be regarded as absolute exclusion limits. In a general scan where the parameters are allowed to vary independently, some combinations predict low production cross-sections or experimental signatures which make it difficult to separate the signal from the background.

The search results of the four LEP experiments for charged Higgs bosons predicted by models with two Higgs field doublets were also combined. These searches assume that the two decays $H^+ \to c\bar{s}$ and $H^+ \to \tau^+\nu_\tau$ exhaust the H^+ decay width. In the absence of a signal, mass limits are obtained as a function of the branching ratio $B(H^+ \to \tau^+\nu_\tau)$. The most general lower limit, valid at the 95% confidence level for any value of the branching ratio, is 78.6 GeV/c^2.

Acknowledgements

We would like to thank the CERN accelerator divisions for the excellent performance of the LEP accelerator in its high-energy phase. We would also like to thank the members of the four LEP collaborations for providing their preliminary results in advance of the conferences and for valuable discussions concerning their combination.

Appendix A: Combined confidence levels

In the SM and the MSSM, the signal and background rates are predicted channel by channel. The corresponding search results can thus be combined for a better overall sensitivity. Furthermore, data sets from different LEP energies and experiments can also be included. The combined LEP data are used to test two hypotheses: the *background-only* ("b") hypothesis, which assumes no Higgs boson to be present in the mass range investigated, and the *signal + background* ("$s + b$") hypothesis, where Higgs bosons are assumed to be produced according to the model under consideration. A global *test-statistic* X is constructed (see below) which allows the experimental result $X_{observed}$ to be classified between the b-like and $s + b$-like situations. It utilises the number of selected events and various distributions which provide discrimination between signal and background (e.g., the reconstructed mass or b-tag variables). The test-statistic takes into account experimental details such as detection efficiencies, signal-to-background ratios and resolution functions, and provides a single value for a given model hypothesis (e.g., the test-mass m_{H} in the SM).

To set the scale for X, a large number of Monte Carlo experiments are generated, separately for the b and the $s + b$ hypotheses, and separately for each model hypothesis (e.g., m_{H}). The resulting distributions of $X(m_{\mathrm{H}})$ are normalised to become probability density functions, and integrated to form the confidence levels $CL_b(m_{\mathrm{H}})$ and $CL_{s+b}(m_{\mathrm{H}})$. The integration starts in both cases from the b-like end and runs up to $X_{observed}$; thus $CL_b(m_{\mathrm{H}})$ and $CL_{s+b}(m_{\mathrm{H}})$ express the probabilities that the outcome of an experiment is more b-like or less $s+b$-like, respectively, than the outcome represented by the set of selected events.

When performing a search with small expected signal rates, it may happen that the observed number of candidates is significantly below the background expectation. In such cases the limit may extend beyond the range of sensitivity of the search. To prevent *a priori* such unphysical, but formally valid, results from occurring, we consider the ratio $CL_s(m_{\mathrm{H}}){=}CL_{s+b}(m_{\mathrm{H}})/CL_b(m_{\mathrm{H}})$ as a conservative approximation to the signal confidence one might have obtained in the absence of background. The 95% CL lower limit for the SM Higgs mass is defined here as the lowest value of the test mass $m_{\rm H}$ which yields $CL_s(m_{\rm H})$=0.05.

The quantity $1 - CL_b(m_{\rm H})$ is an indicator for a possible signal: a SM Higgs boson with true mass m_0 would produce a pronounced drop in this quantity for $m_{\rm H} \approx m_0$. Values of $1 - CL_b < 5.7 \times 10^{-7}$ ($1 - CL_b < 2.7 \times 10^{-3}$) would indicate a 5σ (3σ) discovery. Background fluctuations may also produce such a drop, allowing for some $m_{\rm H}$ a "discovery" beyond the expected experimental sensitivity. In analogy to the definition of CL_s, an additional quantity $(1 - CL_b)' = (1 - CL_b)/(1 - CL_{s+b})$ is defined to incorporate information about the signal sensitivity into the discovery estimator. This additional information is provided for informational purposes where appropriate.

If values of $X_{observed}$ (and thus the integration bounds) are obtained from Monte Carlo simulations of the real experiment, the average expected confidence levels $\langle 1 - CL_b(m_{\rm H}) \rangle$ and $\langle CL_s(m_{\rm H}) \rangle$ are obtained. Of particular interest are $\langle 1 - CL_b(m_{\rm H}) \rangle$ from simulated $s + b$ experiments and $\langle CL_s(m_{\rm H}) \rangle$ from simulated b experiments, since these indicate the expected ranges of sensitivity of the available data set for discovery and exclusion, respectively.

The test-statistic adopted in the present combination of results is the ratio of the likelihood function for the s+b hypothesis ($x = s(m_{\rm H})$) to the likelihood function for the b hypothesis ($x = 0$):

$$X(m_{\rm H}) = \frac{\mathcal{L}(s(m_{\rm H}))}{\mathcal{L}(0)}, \qquad (1)$$

where the likelihood function is defined by

$$\mathcal{L}(x) = \prod_{i=1}^{N} \frac{exp[-(x\frac{s_i(m_{\rm H})}{s(m_{\rm H})} + b_i)]\ (x\frac{s_i(m_{\rm H})}{s(m_{\rm H})} + b_i)^{n_i}}{n_i!} \times \prod_{j=1}^{n_i} \frac{x\frac{s_i(m_{\rm H})}{s(m_{\rm H})} S_i(m_{\rm H}, m_{ij}) + b_i B_i(m_{ij})}{x\frac{s_i(m_{\rm H})}{s(m_{\rm H})} + b_i}. \qquad (2)$$

The index i runs over all independent contributions to the combined search result: search channels of an experiment, searches at different centre-of mass energies, and channels from different experiments. The symbol N stands for the number of such contributions ("channels" hereafter); n_i is the number of observed candidates in channel i and m_{ij} is the value of m, (the reconstructed Higgs boson mass or any other discriminating variable) in the case of candidate j in channel i. The quantities $s_i(m_{\rm H})$ and b_i are the integrated signal and background rates in channel i with $s(m_{\rm H}) = \sum_{i=1}^{N} s_i(m_{\rm H})$ and $b = \sum_{i=1}^{N} b_i$ as the total expected signal and background in all channels. The functions $S_i(m_{\rm H}, m)$ and $B_i(m)$ are the probability distributions for the signal and background, respectively. The above notation assumes that the background-related quantities b_i and $B_i(m)$ do not depend on $m_{\rm H}$. If the selection criteria in any one channel are $m_{\rm H}$ dependent, b_i and $B_i(m)$ have to be replaced by $b_i(m_{\rm H})$ and $B_i(m_{\rm H}, m)$.

The above test-statistic makes the most efficient use of the information available in a search result in a manner similar to the way the principle of maximum likelihood gives the most efficient estimators of parameters in a measurement.

The calculation of confidence levels is illustrated in Figure 15. In part (a) the probability distributions of the test-statistic X (designated here by Q) are shown for the s+b and the b

hypotheses. In part (b) the confidence levels CL_b, CL_{s+b} and CL_s are shown (the latter two are indistinguishable in the present example); they are obtained by integrating the probability distributions in (a) from right to left (from most to least background-like). The shaded areas in part (a) measure the confidence levels which correspond to the 95% confidence level exclusion limit.

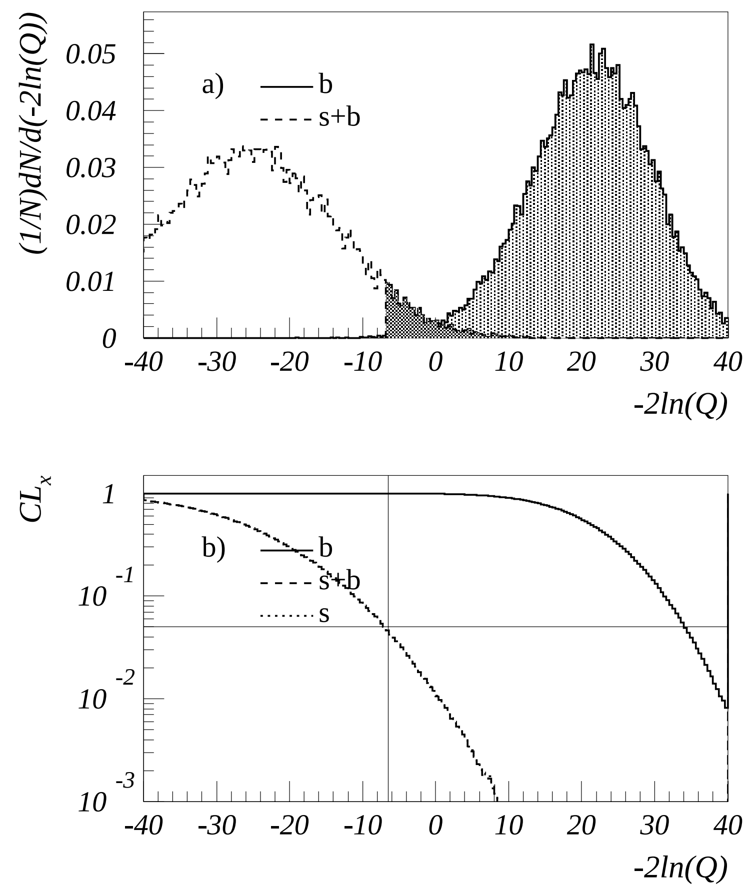

Figure 15: *(a) An example of the probability distributions for the test statistic X (designated here by Q) for background "b" and signal "s+b" gedanken experiments. The shaded areas indicate the integrals, from right (most "b"-like) to left, to the value, indicated by the vertical line, obtained by an experiment searching for a Higgs boson of a particular mass m_{H}. This defines the observed confidences CL_b, CL_{s+b} and $CL_s = CL_{s+b}/CL_b$ (the latter two are indistinguishable in this example) which are shown in (b). For each m_{H} hypothesis, the computations of the observed X and the expected distributions are repeated.*

Appendix B: MSSM benchmark scans

We present limits in the MSSM parameter space for a constrained MSSM with seven parameters, $M_{\rm SUSY}$, M_2, μ, A, $\tan\beta$, $m_{\rm A}$ and $m_{\tilde{g}}$. Universal values $M_{\rm SUSY}$ and M_2 are assumed for the SUSY breaking s-fermion and gaugino masses, respectively, at the electroweak scale, and M_1 is derived from M_2 using the GUT relation $M_1 = M_2(5\sin^2\theta_W/3\cos^2\theta_W)$, where θ_W is the weak mixing angle. The gluino mass $m_{\tilde{g}}$ is fixed in the scenarios described below in order to emphasize its effect via radiative corrections to $m_{\rm h}$. μ is the supersymmetric Higgs boson mass parameter, and $\tan\beta$ is the ratio of the vacuum expectation values of the two Higgs field doublets. The parameter A is the common trilinear Higgs-squark coupling parameter, assumed to be the same for up-type squarks and for down-type squarks. The largest contributions to $m_{\rm h}$ from radiative corrections arise from top and stop loops, with much smaller contributions from bottom and sbottom loops.

In the scenarios that follow, it is not A which is specified, but rather the off-diagonal top mass coefficient in the stop mixing matrix [4] $X_t = A - \mu\cot\beta$ which is set to a fixed value. The mass of the top quark is taken to be 174.3 GeV, but values smaller and larger by the current experimental error of 5.1 GeV are also considered. The gluino mass $m_{\tilde{g}}$ affects loop corrections from stops and sbottoms. Two benchmark scenarios are considered in this paper.

The no-mixing scenario

This scenario assumes that there is no mixing in the scalar top sector, with the following values and ranges for the parameters: $M_{\rm SUSY} = 1$ TeV, $M_2 = 200$ GeV, $\mu = -200$ GeV, $X_t = 0$, $0.4 < \tan\beta < 50$ and $m_{\rm A} < 1$ TeV. The gluino mass $m_{\tilde{g}}$ is set to 800 GeV.

The $m_{\rm h}$-max scenario

This scenario is designed to maximise the largest value of $m_{\rm h}$ allowed by the model at each value of $\tan\beta$. The same parameters are chosen as for the no-mixing scenario, except for the stop mixing parameter $X_t = 2M_{\rm SUSY}$ using the conventions of the two-loop diagrammatic calculation of [16] or $X_t = \sqrt{6}M_{\rm SUSY}$ using the conventions of the renormalisation-group approach of [17]. (For the no-mixing scenario, $X_t = 0$ has the same interpretation in both schemes.) It is similar in spirit to the "maximal mixing" scenario used in previous publications [1, 5], but as it allows for larger $m_{\rm h}$ values at the same $\tan\beta$, it results in a smaller excluded interval of $\tan\beta$.

The results quoted in this document have been obtained using the diagrammatic approach of Ref. [16].

References

[1] ALEPH, DELPHI, L3 and OPAL Collab., The LEP working group for Higgs boson searches, *Searches for Higgs bosons: Preliminary combined results from the four LEP experiments as $\sqrt{s}\approx$189 GeV*, ALEPH 99-081 CONF 99-052, DELPHI 99–142 CONF 327, L3

Note 2442, OPAL Technical Note TN-614, submitted to EPS-HEP'99, Tampere (Finland), July 15-21 1999.

[2] HZHA: P. Janot, in CERN Report 96-01, Vol. 2, p. 309 (1996); Version 3, released in December 1999, http://alephwww.cern.ch/janot/Generators.html.

[3] R.D. Cousins and V.L. Highland, Nucl. Instr. Methods **A320** (1992) 331.

[4] M. Carena, S. Heinemeyer, C.E.M. Wagner and G. Weiglein, *Suggestions for Improved Benchmark Scenarios for Higgs-Boson Searches at LEP2*, CERN-TH/99-374, DESY 99-186, hep-ph/9912223.

[5] ALEPH, DELPHI, L3 and OPAL Collab., The LEP working group for Higgs boson searches, *Limits on Higgs boson masses from combining the data of the four LEP experiments at* $\sqrt{s} \leq 183$ *GeV*, CERN-EP/99-060.

[6] ALEPH Collab., *Search for the neutral Higgs bosons of the Standard Model and the MSSM in* e^+e^- *collisions at centre-of-mass energies from 192 to 202 GeV*, ALEPH 2000-006 CONF 2000-003;
ALEPH Collab., R. Barate *et al.* "Search for the neutral Higgs bosons of the standard model and the MSSM in e^+e^- collisions at $\sqrt{s}$=189 GeV," CERN-EP-2000-019.

[7] DELPHI Collab., *Searches for Neutral Higgs Bosons in* e^+e^- *collisions up to* $\sqrt{s}$= *202 GeV*, DELPHI-2000-024 CONF 345;
DELPHI Collab., P. Abreu *et al.* "Search for neutral Higgs bosons in e^+e^- collisions around $\sqrt{s}$=189 GeV," CERN-EP/2000-038.

[8] L3 Collab., *Search for the SM Higgs boson in* e^+e^- *collisions at centre-of-mass energies up to 202 GeV*, L3 note 2511, March 6, 2000;
L3 Collab., M. Acciarri *et al.* Phys. Lett. **B461** (1999) 376;
L3 Collab., M. Acciarri *et al.* Phys. Lett. **B471** (1999) 321.

[9] OPAL Collab., *Search for Neutral Higgs Bosons in* e^+e^- *Collisions at* $\sqrt{s} \approx$*192-202 GeV*, OPAL Physics Note PN426, March 3, 2000;
OPAL Collab., G. Abbiendi *et al.* Eur. Phys. J. **C12** (2000) 567.

[10] W.-M. Yao, *Standard Model Higgs and Top Mass Measurements at the Tevatron*, FERMILAB-CONF-99/100-E.

[11] L3 Collab., *Search for neutral Higgs bosons of the Minimal Supersymmetric Standard Model in* e^+e^- *interactions at* $\sqrt{s}$=*192 to 202 GeV*, L3 Note 2512, 6 March 2000.

[12] A. Djouadi, J. Kalinowski and P.M. Zerwas, Z. Phys. **C57** (1993) 569.

[13] ALEPH Collab., *Search for charged Higgs bosons in* e^+e^- *collisions at energies from* $\sqrt{s}$= *192 GeV to 202 GeV*, ALEPH 2000-011 CONF 2000-008;
DELPHI Collab., *Search for Charged Higgs Bosons in* e^+e^- *collisions at* $\sqrt{s}$= *183 - 202 GeV*, DELPHI-2000-029 CONF 348;
Delphi Collab., P. Abreu *et al.*, Phys. Lett. **B460** (1999) 484;

L3 Collab., *Search for Charged Higgs Bosons in* e^+e^- *Collisions at Centre-of-Mass Energies between 192 and 202 GeV*, L3 Note 2510 (March 7, 2000)
L3 Collab., M. Acciarri *et al.*, Phys. Lett. **B466** (1999) 71.
OPAL Collab., *Search for Higgs Bosons in* e^+e^- *Collisions at* $\sqrt{s}$*=192-202 GeV*, OPAL Physics Note PN421, November 8, 1999.

[14] A. Denner et al., Phys. Lett. **B475** (2000) 127;
M. Skrzypek et al., *Precision Calculation of Heavy Boson Production - YFS Monte Carlo Approach*, hep-ph/9903379.

[15] D. Bardin et al., Nucl. Phys. B, Proc. Suppl. **37B** (1994) 148; Comp. Phys. Comm. **104** (1997) 161;
F.A. Berends et al., Comp. Phys. Comm. **85** (1995) 437; Nucl. Phys. **454** (1995) 437.

[16] S. Heinemeyer, W. Hollik and G. Weiglein, Phys. Rev. **D58** (1998) 091701; Eur. Phys. Journ. **C9** (1999) 343.

[17] M. Carena, M. Quirós and C.E.M. Wagner, Nucl. Phys. **B461** (1996) 407, hep-ph/9508343.