ALEPH 99-081 CONF 99-052
DELPHI 99-142 CONF 327
L3 Note 2442
OPAL Technical Note TN-614
July 13, 1999

Searches for Higgs bosons: Preliminary combined results from the four LEP experiments at $\sqrt{s}\approx$189 GeV

ALEPH, DELPHI, L3 and OPAL Collaborations

The LEP working group for Higgs boson searches[1]

Abstract

In 1998 each of the four LEP experiments has collected approximately 175 pb^{-1} of e^+e^- collision data at a centre-of-mass energy of 189 GeV. The LEP working group for Higgs boson searches has combined these data including also data sets collected at lower energies. No statistically significant excess has been observed when compared to the Standard Model background prediction, and the following preliminary 95% confidence level bounds have been obtained. For the Standard Model Higgs boson, the lower bound on the mass is 95.2 GeV/c^2. In the Minimal Supersymmetric Standard Model, assuming $\tan\beta$>0.4 and SUSY breaking masses $m_{\text{SUSY}} = 1$ TeV/c^2 and $M_2 = 1.6$ TeV/c^2, the limits m_{h}>80.7 GeV/c^2 and m_{A}>80.9 GeV/c^2 are obtained for the masses of the light CP-even and the CP-odd neutral Higgs boson, respectively. Furthermore, for the above set of MSSM parameters, and if the mixing in the scalar-top sector is assumed to be zero (maximal), the range $0.6<\tan\beta<2.6$ ($0.9<\tan\beta<1.6$)is excluded for a top quark mass less than 175 GeV/c^2; these excluded ranges become smaller for larger top quark masses. For charged Higgs bosons predicted by two-doublet extensions of the Standard Model and decaying only into the channels $\text{H}^+\rightarrow\text{c}\bar{\text{s}}$ and $\tau^+\nu$, the lower bound on the mass is 77.3 GeV/c^2.

Submitted to the International Europhysics Conference on High Energy Physics
July 15-21, Tampere, Finland

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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 and A predicted by the Minimal Supersymmetric Standard Model (MSSM), and for charged Higgs bosons predicted by extensions of the SM with two Higgs field doublets (2HD models). These results combine earlier LEP1 and LEP2 data with those collected in 1998 at a centre-of-mass energy close to 189 GeV. The new data represent an approximate integrated luminosity of 683 pb^{-1} in total.

In the past, the LEP working group for Higgs boson searches has investigated several statistical methods for combining the search results of individual experiments [1]; some of the methods were slightly modified later [2]. These methods have been found to be equally adequate for producing confidence levels for exclusion or discovery, and several of them, Methods A, B and C in Ref. [1], are employed again in the present work. A short summary of these methods and the calculation of confidence levels (CL) is given in the Appendix.

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 $\mathrm{e^+e^-} \rightarrow \mathrm{HZ}$, while contributions from the WW fusion channel, $\mathrm{e^+e^-} \rightarrow \mathrm{H}\nu\bar{\nu}$, are typically below 10%. The searches performed by the four LEP collaborations encompass the usual HZ final state topologies, commonly called 'four-jet' ($\mathrm{HZ}\rightarrow\mathrm{b\bar{b}q\bar{q}}$), 'missing energy' ($\mathrm{b\bar{b}}\nu\bar{\nu}$), 'leptonic' ($\mathrm{b\bar{b}e^+e^-}$ and $\mathrm{b\bar{b}}\mu^+\mu^-$), and 'tau' channels ($\mathrm{b\bar{b}}\tau^+\tau^-$ and $\tau^+\tau^-\mathrm{q\bar{q}}$). From combining the earlier data collected by the LEP experiments at center of mass energies up to 183 GeV, a 95% CL lower bound of 89.7 GeV/c^2 has been obtained [2]. In this section we present an update of the SM Higgs boson search which includes the new data collected at a centre-of-mass energy of 189 GeV.

At 189 GeV, the analysis procedures of individual experiments follow closely those employed previously at 183 GeV. These procedures are described in the publications [3]-[6]. The results from these individual searches are summarised in Table 1. The large spread in the numbers of selected events reflects substantial differences in the methods employed by the experiments to optimise their search sensitivities. While the limits expected on average, and thus the search sensitivities, are finally rather similar, the limits actually obtained vary more substantially due to differences in the numbers and distributions of observed candidates.

Figure 1 shows the distribution of reconstructed Higgs boson masses for the data sets collected at 189 GeV (for OPAL, the 183 GeV data are also included). The background expected from SM processes without a Higgs boson, and the signal expected from a SM Higgs boson of 91 GeV/c^2 mass, are also shown. The numbers of events entering this figure are a subset of those listed in Table 1 which are used subsequently in this note for our combined searches and limit settings. The individual search channels contributing have differing resolutions, signal

Experiment:	ALEPH	DELPHI	L3	OPAL
Approximate integrated luminosity (pb^{-1}):	176.2	158	176.4	172.1
Background predicted:	44.4	172.7	91.1	35.4
Events observed:	53	187	94	41
Limit (GeV/c^2) expected at 95% CL:	95.9	94.6	94.8	94.9
Limit (GeV/c^2) observed at 95% CL:	92.9	94.1	95.3	91.0

Table 1: *Information related to individual searches for the SM Higgs boson at* $\sqrt{s}$*=189 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* $m_{\rm H}$*=91* GeV/c^2*. Also, in contrast to the other experiments, L3 quotes the median for the expected limits rather than the mean.*

sensitivities and background rates, and Figure 1 has been produced with the requirement that the signal-to-background ratio for the four contributing experiments be roughly equal. The figure, produced merely for illustration purposes, should therefore not be used to compute a limit on Higgs boson production.

In order to search for a possible signal, the test mass $m_{\rm H}$ has been scanned. Figure 2 shows $1 - CL_b$, where CL_b is the confidence level for the background-only hypothesis. The figure shows the distribution expected on average and observed, as functions of the test mass $m_{\rm H}$. The shaded bands show the 68% and 91% probability intervals [2] for background-only experiments. In the presence of a SM Higgs boson of mass $m_{\rm H}$, the median [3] of $1 - CL_b$ at the true mass should behave as indicated by the dashed line. A signal of 5σ significance would generate a value of 6 10^{-7}, and the dashed line therefore indicates that the present data do not have the sensitivity that would be necessary to discover a Higgs boson with mass in excess of about 95 GeV/c^2 at the 5σ level.

The observation represented by the full line appears to deviate from the expectation over a large range of test masses. This behaviour is not typical for a Higgs boson signal but indicates, rather, a slight overall excess of the data with respect to the SM background prediction (also apparent in Figure 1) which could either be a statistical fluctuation or a systematic underestimate of the background. The lowest value of the observed $1 - CL_b$ is about 10^{-2}, that is a 1% probability to occur *at a given test mass* in the absence of a signal. One should note, however, that the probability for such a low value to occur *anywhere* in the mass region considered is higher by a factor which is determined to first approximation by the ratio of the mass range considered and the experimental mass resolution which is about 3 GeV/c^2. A preliminary Monte Carlo study indicated a scaling factor of four.

The lower part of Figure 2 shows the (negative) log-likelihood of a SM Higgs signal as a function of $m_{\rm H}$, expected on average (dashed line) and observed (full line), together with the

[2] The choice of 91% will be changed to 95% and/or 99% in the final version of this note.

[3] The median expected confidence level is shown rather than the average expected confidence level because the CL distributions are typically asymmetric, and the medians are less sensitive to the CL distribution tails.

expectation in the presence of a Higgs boson of various masses (dotted lines) To simulate the signal expectations, the full luminosity of the four LEP experiments has been attributed to a single typical LEP experiment. The shaded bands indicate the 68% and 91% expected intervals of $-2ln(Q)$ (Q is the likelihood-ratio test statistic of Method A) for signal experiments at the true value of m_{H}. The dotted lines are the mean expected values as a function of the test mass if a particular true mass is assumed. The comparison of the observation with the expectation for m_{H}=91 GeV/c^2 indicates, in particular, that the existence of a Higgs boson with mass of 91 GeV/c^2 is very unlikely.

We now proceed to calculate a new 95% CL lower bound for the SM Higgs boson. The average expected confidence level CL_s obtained by assuming a SM Higgs boson of mass m_{H} in signal-plus-background experiments, and the observed CL_s, both functions of m_{H}, are shown in Figure 3. The 68% and 91% bands around the expected CL_s correspond to the bands in the upper part of Figure 2. The intersections of the curves with the horizontal lines at 0.05 define the 95% CL lower bounds, expected and observed, for the mass of the SM Higgs boson. These are listed in Table 2 for Method A and B. The inclusion of the systematic errors into the limit calculation according to Cousins and Highland [7] had the effect of decreasing the expected mass limit by less than 100 MeV/c^2 [2]. The small differences between the limits obtained by the

Mass limit (GeV/c^2) at 95% CL	Statistical method A	B
Expected	97.2	97.4
Observed	95.2	95.6

Table 2: *The 95% CL combined mass limits for the SM Higgs boson, observed and expected, using the statistical methods A and B to combine the data of the four LEP experiments at energies up to* $\sqrt{s}$*=189 GeV.*

two methods are understood to originate in part from the different test statistics. Substantially larger spreads were quoted in [2]; these could be attributed to slightly different interpretations and treatments of the information exchanged between the four experiments. This spread has been reduced by imposing a common format for the exchanged information.

Based on the values quoted in Table 2 we choose to quote the lowest of the observed limits, 95.2 GeV/c^2, as the 95% CL lower bound for the SM Higgs boson mass.

The combined LEP1 and LEP2 data 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 4 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 ficticious model to the SM coupling.

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 ($m_{\rm h}<m_{\rm H}$), one CP-odd neutral Higgs boson, A, and a pair of charged Higgs bosons, $\rm H^+$ and $\rm H^-$. At LEP energies the production of h and A is expected to be kinematically accessible for large portions of the MSSM parameter space. These particles are produced mainly via the Higgs-strahlung process $\rm e^+e^-\rightarrow$ hZ (analogous to the main SM production process) and the pair production process $\rm e^+e^-\rightarrow$ hA, the two processes being complementary: the cross-section of the first is proportional to $\sin^2(\beta-\alpha)$ and that of the second is 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 four LEP experiments perform their searches within the framework of a 'constrained' MSSM where universal values $m_{\rm SUSY}$ 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 'benchmark' MSSM parameter scans [8] corresponding to no mixing and maximal mixing in the scalar-top sector for which the parameters are described in [2]. The top quark mass, which has an impact on the results via radiative corrections, is fixed at $m_{\rm t}$=175 GeV/c^2 [9].

The individual searches of the four LEP collaborations for the processes $\rm e^+e^-\rightarrow$ hZ and $\rm e^+e^-\rightarrow$ hA which include the data taken at $\sqrt{s}\leq$189 GeV are described in Refs. [3, 4, 6, 10]. For the process $\rm e^+e^-\rightarrow$ 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 kinematic domain $2m_{\rm A}<m_{\rm h}$, 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 search procedures with efficiencies calculated for the (AA)Z final states or by performing specific searches for the $\rm e^+e^-\rightarrow$ hZ$\rightarrow$ (AA)Z process.

For the process $\rm e^+e^-\rightarrow$ hA, the most relevant final states are $\rm b\bar{b}b\bar{b}$, $\tau^+\tau^-\rm b\bar{b}$ and $\rm b\bar{b}\tau^+\tau^-$. In the kinematic domain $2m_{\rm A}<m_{\rm h}$, once again, the collaborations have included the h$\rightarrow$ AA decays as above.

Information from the individual collaborations regarding the searches for $\rm e^+e^-\rightarrow$ hA is provided in Table 3 (for the $\rm e^+e^-\rightarrow$ hZ process Table 1 is relevant), which lists the background predicted and the events observed in the $\rm b\bar{b}b\bar{b}$, $\tau^+\tau^-\rm b\bar{b}$ and $\rm b\bar{b}\tau^+\tau^-$ channels and the 95% CL limits, expected and observed.

Figure 5 shows the mass distribution of the events [4] observed by the four LEP experiments in the searches for the process $\rm e^+e^-\rightarrow$ hA, together with the expected background and a typical

[4]Similarly to the case of Figure 1, the events entering this mass plot constitute a subset of those in Table 3 used in the confidence level and limit calculations.

Experiment:	ALEPH	DELPHI	L3	OPAL
Approximate integrated luminosity (pb^{-1}):	176.2	158	176.4	172.1
Backg. predicted / Evts. observed				
$b\bar{b}b\bar{b}$:	4.8/7	11.4/13	119/133	8.0/8
$\tau^+\tau^-b\bar{b}$ and $b\bar{b}\tau^+\tau^-$:	2.5/3	11.2/11	21.6/20	4.9/7
Limit expected/observed for $m_{\rm h}$ (GeV/c^2):	83.1/82.5	81.1/82.1	78/76	76.4/74.8
Limit expected/observed for $m_{\rm A}$ (GeV/c^2):	83.6/83.1	82.2/83.2	79/76	78.2/76.5

Table 3: *Information related to individual searches for the* $e^+e^-\to hA$ *process at* $\sqrt{s}$*=189 GeV. The limits quoted are those expected and observed for the case of maximal mixing. In the L3 analysis the expected background and the observed number of events depend on the hypothesised MSSM parameters; they are given here for* $m_{\rm A}$*=80* GeV/c^2 *and* $\tan\beta$*=50. Also, in contrast to the other experiments. L3 quotes the median for the expected limits rather than the mean.*

expected signal. The mass sum $m_{\rm h}$+$m_{\rm A}$ for the dijet pair with the smallest mass difference $|m_{\rm h}$-$m_{\rm A}|$ is shown. The expected signal is shown for $m_{\rm h}$=$m_{\rm A}$=80 GeV/c^2 and $\cos^2(\beta-\alpha)$=1 (the maximal expected cross-section for $e^+e^-\to$ hA).

In order to search for a possible signal from the process $e^+e^-\to$ hA, the test mass sum $m_{\rm h}$+$m_{\rm A}$ has been scanned. Figure 6 shows $1-CL_b$, where CL_b is the confidence level for the background-only hypothesis. The figure shows the distribution expected on average and observed, as functions of the test mass sum $m_{\rm h}$+$m_{\rm A}$. The 68% and 91% probability bands for the expected $1-CL_b$ are shown shaded. In the presence of a signal of mass sum $m_{\rm h}$+$m_{\rm A}$, the distribution of the median $1-CL_b$ should behave as indicated by the dashed line. The lowest value of the observed $1-CL_b$ is of about 5 10^{-3}. Concerning the probability for this to occur *anywhere* in the mass region considered, the discussion in Section 2 is also relevant here. The average expected confidence levels CL_s for signal-plus-background experiments and the observed CL_s as a function of $m_{\rm h}$+$m_{\rm A}$ are shown in Figure 7.

We proceed to calculate combined 95% CL bounds on $m_{\rm h}$, $m_{\rm A}$ and $\tan\beta$ by scanning over the MSSM parameter space and testing each parameter set of the scan. Figures 8 and 9 show the results obtained for no mixing and maximal mixing in the scalar-top sector. The limits are presented for $\tan\beta$>0.4 and in three parameter projections, ($m_{\rm h}$, $m_{\rm A}$), ($m_{\rm h}$, $\tan\beta$), and ($m_{\rm A}$, $\tan\beta$). Besides the experimental limits, the limits expected on the basis of background Monte Carlo experiments are also shown. The mass limits obtained for the case of maximal mixing are presented in Table 4 using two statistical methods. For the case of no mixing the limits are imperceptibly higher. The inclusion of systematic errors in the limit calculation [7] had the effect of decreasing the expected mass limits by a few hundred MeV/c^2 (the treatment of systematic errors is very preliminary).

In the case of no mixing (maximal mixing), and for a top quark mass less than 175 GeV/c^2, the range of $\tan\beta$ between 0.6 and 2.6 (0.9 and 1.6) is excluded, see Figures 8 and 9 upper right. Ranges of $\tan\beta$ which are excluded for other values of $m_{\rm t}$ are given in Table 5.

Method:	A	C
Limits for m_{h} (GeV/c^2)		
expected :	85.9	85.4
observed :	81.1	80.7
Limits for m_{A} (GeV/c^2)		
expected :	86.8	85.5
observed :	82.1	80.9

Table 4: *Maximal mixing scenario: Combined 95% CL MSSM limits obtained using Methods A C, for* $\tan\beta > 0.4$.

Top quark mass:	$\leq$165 GeV/c^2	$\leq$175 GeV/c^2	$\leq$185 GeV/c^2
Exclusion in $\tan\beta$			
no mixing :	0.5 - 3.2	0.6 - 2.6	0.6 - 2.1
max mixing:	0.7 - 2.2	0.9 - 1.6	no exclusion

Table 5: *Exclusion in* $\tan\beta$ *at the 95% confidence level for various top quark mass ranges.*

Based on the above results, we quote the following preliminary 95% CL lower bounds: m_{h}>80.7 GeV/c^2, m_{A}>80.9 GeV/c^2. These bounds are valid for $\tan\beta$>0.4 and for both assumptions of no mixing and maximal mixing in the scalar-top sector.

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 via 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 can drive the mass to lower values. Since the sensitivity of current searches is limited to the range below $m_{W^\pm}$ due to the background from $e^+e^- \to W^+W^-$, any signal for H^+H^- would indicate either new physics beyond the MSSM or a rather extreme set of 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 [11]. The tree level cross-sections used in this combination are provided by PYTHIA [12] and HZHA which give results differing by less than 1%. In the searches it is assumed that the two decays $H^+ \to c\bar{s}$ and $H^+ \to \tau^+\nu$ exhaust the H^+ decay width but the relative branching ratio is not constrained. Thus, the searches encompass the following H^+H^-

final states: $(c\bar{s})(\bar{c}s)$, $(\tau^+\nu)(\tau^-\bar{\nu})$ and the mixed mode $(c\bar{s})(\tau^-\bar{\nu})$+$(\bar{c}s)(\tau^+\nu)$. The combined search results are presented as a function of the branching ratio $B(H^+\to\tau^+\nu)$.

Details of the individual searches using data at energies up to and including $\sqrt{s}$=189 GeV can be found in Refs. [13]-[16] . These are summarised in Table 6 for each of the search channels together with the 95% CL lower bounds obtained, expected and observed. In the table we quote the individual mass limits for $B(H^+\to\tau^+\nu)$ = 0 and 1, and also the lowest mass limit obtained which is valid for an arbitrary branching ratio.

Experiment:	ALEPH	DELPHI	L3	OPAL
Approximate integrated luminosity (pb^{-1}):	176	158	176.4	180
Background expected / Events observed				
$(c\bar{s})(\bar{c}s)$:	295.4/263	141.3/145	359/335	153.8/156
$(c\bar{s})(\tau^+\nu)$:	22.6/19	55.9/55	132/134	60.1/65
$(\tau^+\nu)(\tau^-\bar{\nu})$:	15.5/20	15.8/15	32.5/30	27.2/31
Limit expected / observed				
for B=0:	72.4/69.8	70.4/71.9	71.2/67.5	69.3/70
for B=1:	76.0/76.4	75.7/78.5	74.2/78.2	76/78
for any B:	69.5/65.5	66.5/66.9	71.2/67.5	68.5/68.7

Table 6: *Individual search results for the* $e^+e^-\to H^+H^-$ *final states. In the case of the OPAL* $(\tau^+\nu)(\tau^-\bar{\nu})$ *channel, the numbers of expected and observed events depend on the test mass; they are given here for* m_{H^+}=80 GeV/c^2. *The numbers of events correspond to the data sets taken at* $\sqrt{s}$=189 GeV *while the mass limits are for all energies combined up to and including* $\sqrt{s}$=189 GeV.

Figure 10 shows the mass distribution of the events observed by the four experiments in their searches for the process $e^+e^-\to H^+H^-$, together with the expected background and a typical expected signal for m_{H^+}=75 GeV/c^2. The plot is produced separately for the $(c\bar{s})(\bar{c}s)$ and $(c\bar{s})(\tau^+\nu)$ channels (in the $(\tau^+\nu)(\tau^-\bar{\nu})$ channel some of the experiments do not reconstruct the $H^\pm$ mass). In the case of the mixed final state a branching fraction $B(H^+\to\tau^+\nu)$=0.5 is taken for the signal. The distributions include the events from ALEPH, DELPHI and L3 taken at 189 GeV and those of OPAL at 183 and 189 GeV.

In order to search for a possible signal, the test mass $m_{H^\pm}$ has been scanned. Figure 11 shows CL_b, the background confidence level as a function of the test mass, expected on average and observed, for $B(\tau^+\nu)$=0, 0.5 and 1. The 68% and 91% probability bands are shown shaded. The observation, represented by the full line, falls within the 91% bands over the whole mass range considered.

We proceed to calculate combined 95% CL bounds using three statistical methods. The limits obtained are compared in Table 7 for $B(\tau^+\nu)$=0, 1, and for the value which provides the lowest mass limit. The spread of the results is understood to originate in part from the different test statistics used.

Method:	A	B	C
B($\tau^+\nu$)=0			
Limit expected :	75.4	75.7	75.7
Limit observed :	78.3	78.7	78.0
B($\tau^+\nu$)=1			
Limit expected :	82.5	83.5	83.2
Limit observed :	84.1	85.0	84.9
Any B($\tau^+\nu$)			
Limit expected :	74.9	75.0	74.7
Limit observed :	77.3	77.7	77.4

Table 7: *The combined 95% CL lower bounds for the mass of the charged Higgs boson, expected and observed, for three values of the branching ratio B($\tau^+\nu$).*

At this preliminary stage, the systematic errors of individual experiments have not been considered in the limit calculation; they were previously estimated to reduce the mass limits by about 100 to 200 MeV/c^2 [2].

The mass limits expected and observed are shown in Figure 12. To obtain the limiting lines, the branching ratio B($\tau^+\nu$) has been scanned in steps of 0.05.

Taking the lowest of the observed limits from Table 7, we choose to quote a 95% CL lower bound of 77.3 GeV/c^2 for the mass of the charged Higgs boson.

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 1998 at $\sqrt{s}$=189 GeV for an integrated luminosity of approximately 175 pb^{-1} per experiment. In the absence of a statistically significant excess in the data, a new lower bound of 95.2 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 where m_{SUSY} and M_2 are fixed at 1 TeV and 1.6 TeV, respectively, where either no mixing or maximal mixing in the scalar-top sector is assumed, and where the top quark mass is fixed at 175 GeV/c^2. For $\tan\beta$>0.4, the limits m_{h}>80.7 GeV/c^2 and m_{A}>80.9 GeV/c^2 are obtained independently of the mixing in the scalar-top sector. Within the MSSM scenario considered and assuming no mixing (maximal mixing), values of $\tan\beta$ between 0.6 and 2.6 (0.9 and 1.6) are excluded at the 95% confidence level. While the above mass limits are insensitive to the value of the top quark mass, the excluded range in $\tan\beta$ does depend on it.

Although the limits shown are representative for the bulk of possible MSSM parameter values, these should not be regarded as absolute exclusion limits. If the parameters which are constrained in the present 'benchmark' scans are allowed to vary, additional parameter sets become available some of which predict low production cross-sections or experimental signatures which make it difficult to separate the signal from the background, and the exclusions both in mass and $\tan\beta$ become less stringent [17]-[20].

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 $\mathrm{H}^+\to\mathrm{c}\bar{\mathrm{s}}$ and $\mathrm{H}^+\to\tau^+\nu$ exhaust the H^+ decay width. In the absence of a signal, mass limits are obtained as a function of the branching ratio $\mathrm{B}(\mathrm{H}^+\to\tau^+\nu)$. The most general lower limit, valid at the 95% confidence level for any value of the branching ratio, is 77.3 GeV/c^2.

ALL THE RESULTS QUOTED IN THIS NOTE ARE TO BE CONSIDERED PRELIMINARY.

6 Appendix: Statistical methods and confidence levels

Each of the statistical procedures used in this note start with the construction of a test-statistic X based on the number of selected events and on their distribution in a variable which discriminates signal from background events. The reconstructed Higgs boson mass is a convenient discriminating variable; however, any other observable with discriminating power could also be taken.

The value of the test-statistic measured in the data, X_{obs}, is compared to distributions of the same test-statistic obtained on the basis of a large number of simulated gedanken experiments in which the presence of a signal with mass m_{H} is assumed in addition to the background (*signal+background*, index "$s+b$" hereafter). Using the test-statistics, the probability $CL_{s+b}(m_{\mathrm{H}})$ to obtain $X_{s+b}(m_{\mathrm{H}}) \leq X_{obs}$ from such gedanken experiments is calculated:

$$CL_{s+b}(m_{\mathrm{H}}) = P(X_{s+b}(m_{\mathrm{H}}) \leq X_{obs}). \quad (1)$$

According to the classical definition, a mass hypothesis m_{H} is excluded at the confidence level $1 - CL_{s+b}(m_{\mathrm{H}})$. However, Eq. 1 is not complete since in the present context one is interested in calculating confidence levels for a signal assuming that the background behaves as expected from the Standard Model for its rate and distributions. This shortcoming is corrected by defining, in analogy to Eq. 1, the probability

$$CL_b(m_{\mathrm{H}}) = P(X_b(m_{\mathrm{H}}) \leq X_{obs}), \quad (2)$$

based on gedanken experiments which assume the presence of *background only* (index "b" hereafter), and by using the normalised, approximate, signal probability (index "s"):

$$CL_s(m_{\mathrm{H}}) = \frac{CL_{s+b}(m_{\mathrm{H}})}{CL_b(m_{\mathrm{H}})}. \quad (3)$$

The expectation value of the normalised signal probability, $\langle CL_s \rangle$, can be obtained by averaging over a large number of gedanken experiments where the observed number of candidate events is varied according to the *background only* hypothesis. The value of $1-\langle CL_s \rangle$ is a measure of the sensitivity of a given search, and the search procedure can be optimised by maximising that value. Instead of using simulated gedanken experiments, the above probabilities and $\langle CL_s \rangle$ can also be obtained analytically.

Methods A and B: These two methods make use of the probability density or likelihood function for the *signal + background* hypothesis:

$$\mathcal{L}(x) = \prod_{i=1}^{N} \frac{exp[-(x\frac{s_i(m_{\rm H})}{s(m_{\rm H})} + b_i]\ (x\frac{s_i(m_{\rm H})}{s(m_{\rm H})} + b_i)^{n_i}}{n_i!} \times \prod_{j=1}^{n_i} \frac{x\frac{s_i(m_{\rm H})}{s(m_{\rm H})} S_i(m_{\rm H}, m_{ij}) + b_i B_i(m_{ij})}{x\frac{s_i(m_{\rm H})}{s(m_{\rm H})} + b_i}, \quad (4)$$

where N is the number of channels [5] to be combined, 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 argument x is zero for the *background only* hypothesis and $s(m_{\rm H})$ for the *signal + background* hypothesis. 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 two methods differ in the construction of the test-statistic:

- Method A [21] uses the ratio of the likelihood for *signal + background* ($x = s(m_{\rm H})$) to the likelihood for *background only*($x = 0$):

$$X(m_{\rm H}) = \frac{\mathcal{L}(s(m_{\rm H}))}{\mathcal{L}(0)}. \quad (5)$$

- Method B [22] uses a Bayesian probability with a flat prior probability distribution:

$$X(m_{\rm H}) = \frac{\int_{s(m_{\rm H})}^{\infty} \mathcal{L}(x)dx}{\int_0^{\infty} \mathcal{L}(x)dx}. \quad (6)$$

Method C: This method is based on fractional event counting [23]. A weight $w_{ij}(m_{\rm H})$ is assigned to each selected candidate j in channel i:

$$w_{ij}(m_{\rm H}) = K(m_{\rm H}) \cdot \frac{s_i \cdot S_i(m_{\rm H}, m_{ij})}{\frac{1}{2}s_i \cdot S_i(m_{\rm H}, m_{ij}) + b_i \cdot B_i(m_{ij})} \quad (7)$$

[5] Identical search channels at different centre-of-mass energies or treated by different LEP collaborations are considered as independent channels.

where the indices i and j indicate a search channel and a candidate with mass m_{ij} in that channel, s_i is the expected Higgs signal at test mass $m_{\rm H}$ and b_i the expected background rate. The functions S_i and B_i describe the mass distributions of signal and background and $K(m_{\rm H})$ is an overall normalization factor.

The sum of the weights of all candidates defines the test-statistic:

$$X(m_{\rm H}) = \sum_{i=1}^{N}\sum_{j=1}^{n_i} w_{ij}(m_{\rm H}). \tag{8}$$

For Method A the calculation of confidence levels is illustrated in Figure 13 where the probability distributions of -2ln(Q) are shown in the upper part for background-only and signal-plus-background experiments (in this example Q is the likelihood-ratio test-statistic of Method A) and the confidence levels CL_b, CL_{s+b} and CL_s, obtained by integrating over the probability distributions, in the lower part. The shaded areas (integrals) in the upper part actually correspond to the observed 95% confidence level exclusion limit for the SM Higgs boson, 95.2 GeV/c^2, obtained in this note from combining the data of the four LEP experiments.

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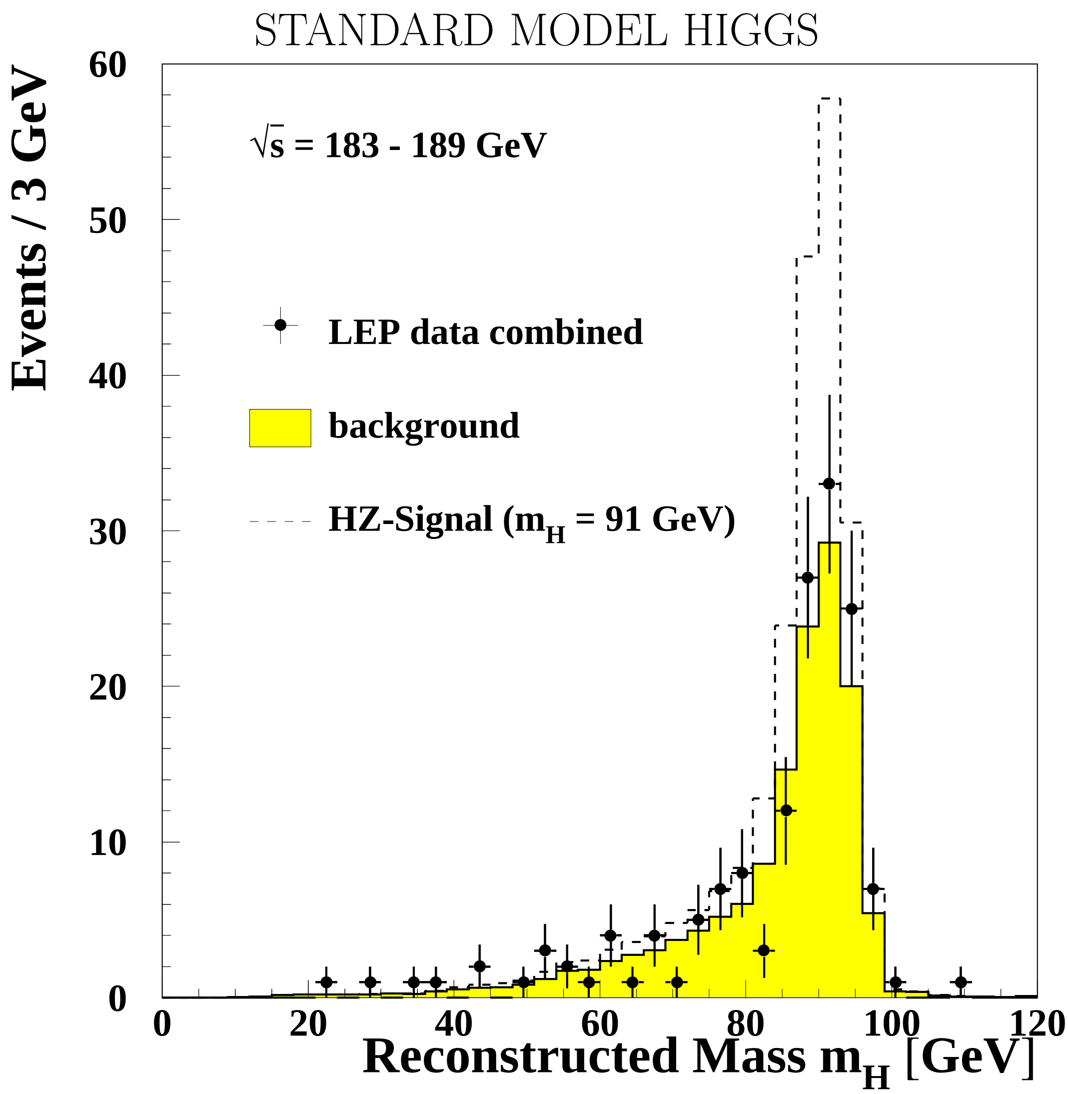

Figure 1: *Distribution of the reconstructed Higgs boson mass in searches for the SM Higgs boson. The figure displays the data (dots with error bars), the predicted SM background (shaded histogram) and the prediction for a Higgs boson of 91* GeV/c^2 *mass (dashed histogram). The distributions combine the data of ALEPH, DELPHI and L3 collected at 189 GeV with those of OPAL at 183 and 189 GeV. The number of data events entering this figure is 152 for 139.8 expected. A signal at 91* GeV/c^2 *mass would amount to 89 events.*

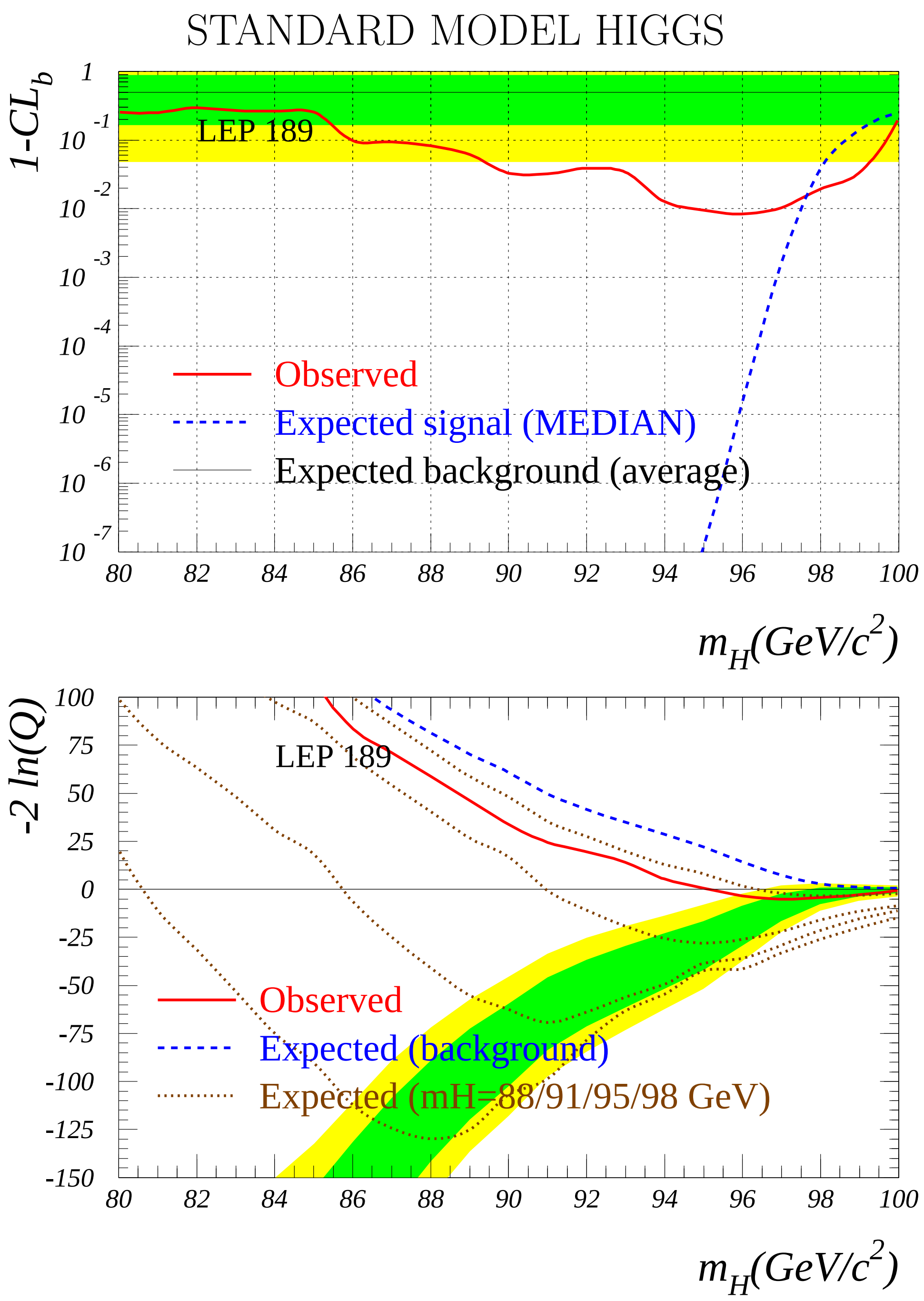

Figure 2: *Upper part: The confidence level* $1 - CL_b$ *as a function of the test mass* m_{H}, *expected on average if there is no SM Higgs boson (straight line at 0.5) and observed (full line). The dashed line represents the* $1 - CL_b$ *at* m_{H} *that is expected in the presence of a SM Higgs boson. Lower part: The (negative) log-likelihood as a function of* m_{H}, *expected for the background on average (dashed line) and observed (full line), together with the expectation in the presence of a signal (dotted lines) with the indicated Higgs boson mass values. The shaded bands appearing in both figures are described in the text. Both figures combine the data of DELPHI, L3 and OPAL collected at 183 and 189 GeV and those of ALEPH at 189 GeV.*

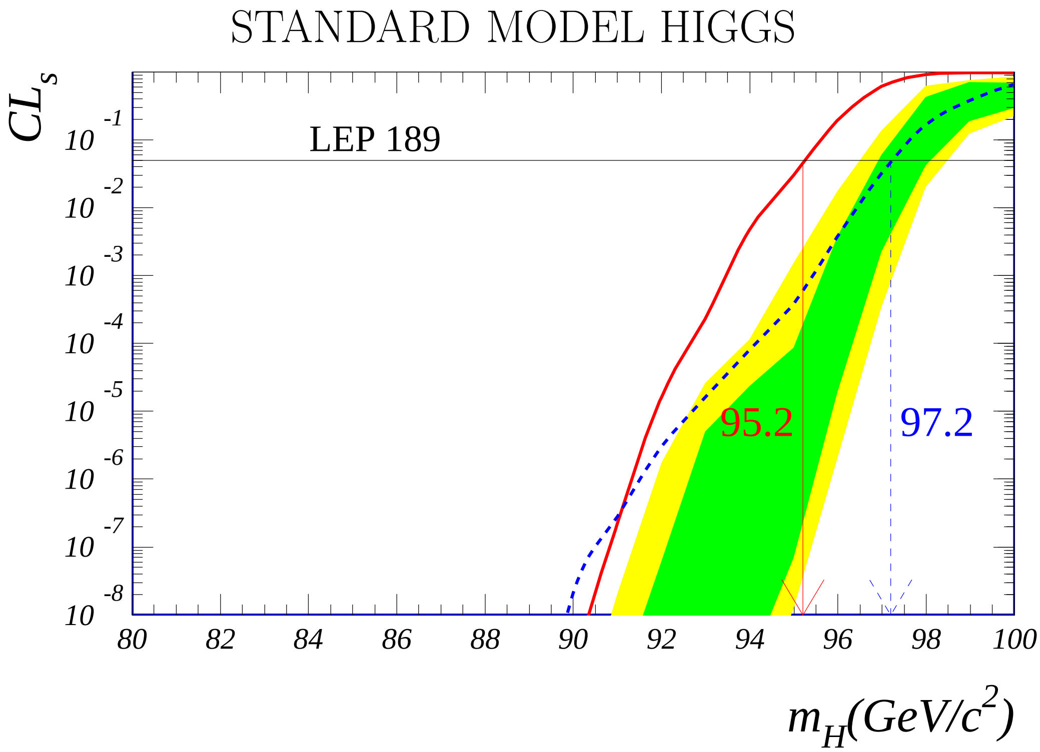

Figure 3: *The confidence levels CL_s as a function of the test mass m_{H}, expected on average in the presence of a Higgs boson of mass m_{H} (dashed line) at a given test mass and observed (full line). The shaded areas represent the 68% and 91% probability bands of $1 - CL_b$ (see text). The results combine the data of ALEPH, DELPHI, L3 and OPAL collected at 183 and 189 GeV.*

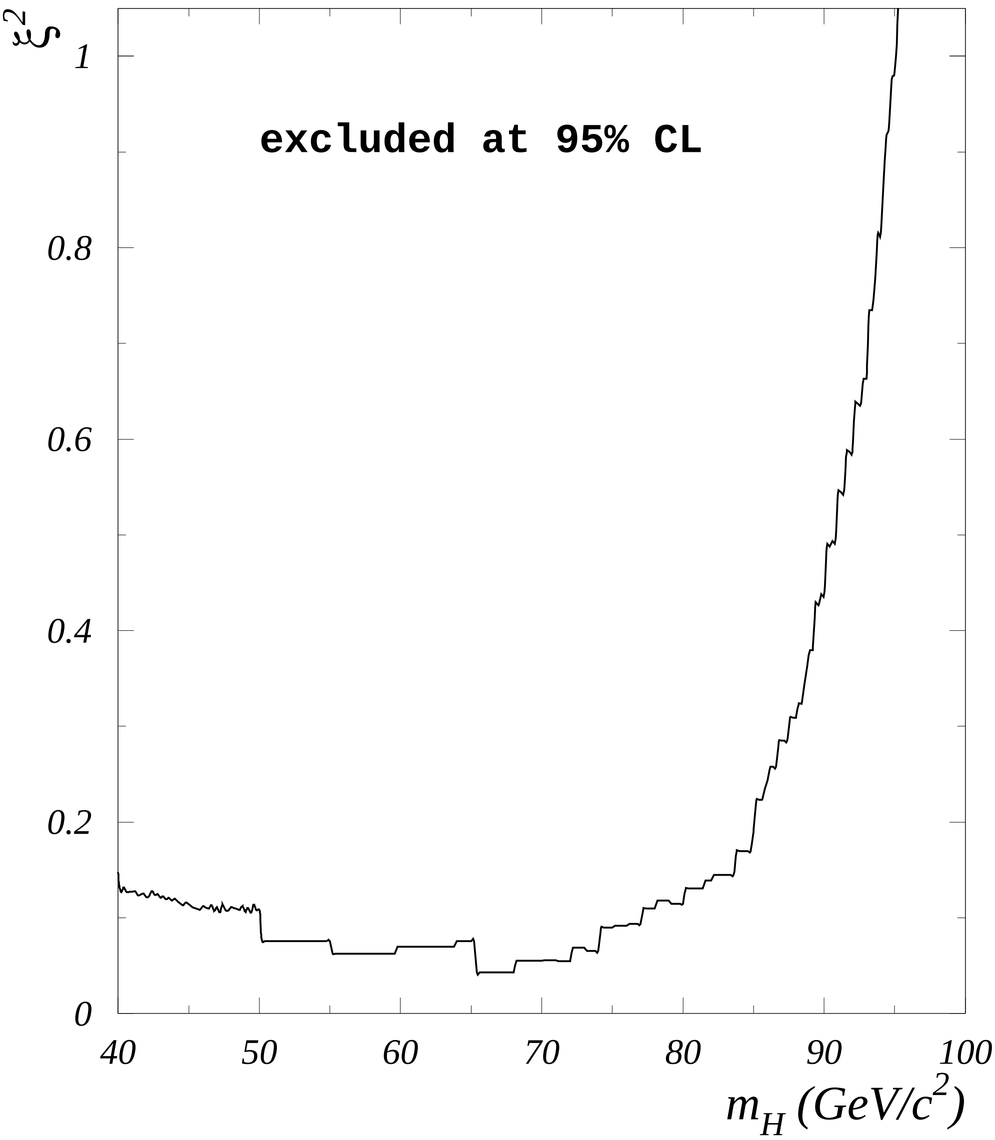

Figure 4: *The 95% CL upper bound on* ξ^2 *as a function of* m_{H}*, where* $\xi = g_{HZZ}/g_{HZZ}^{SM}$ *is the HZZ coupling relative to the SM coupling. The limit is valid for models which assume that the Higgs boson decay properties are identical to those in the SM but the production rate could be different.*

MSSM HIGGS

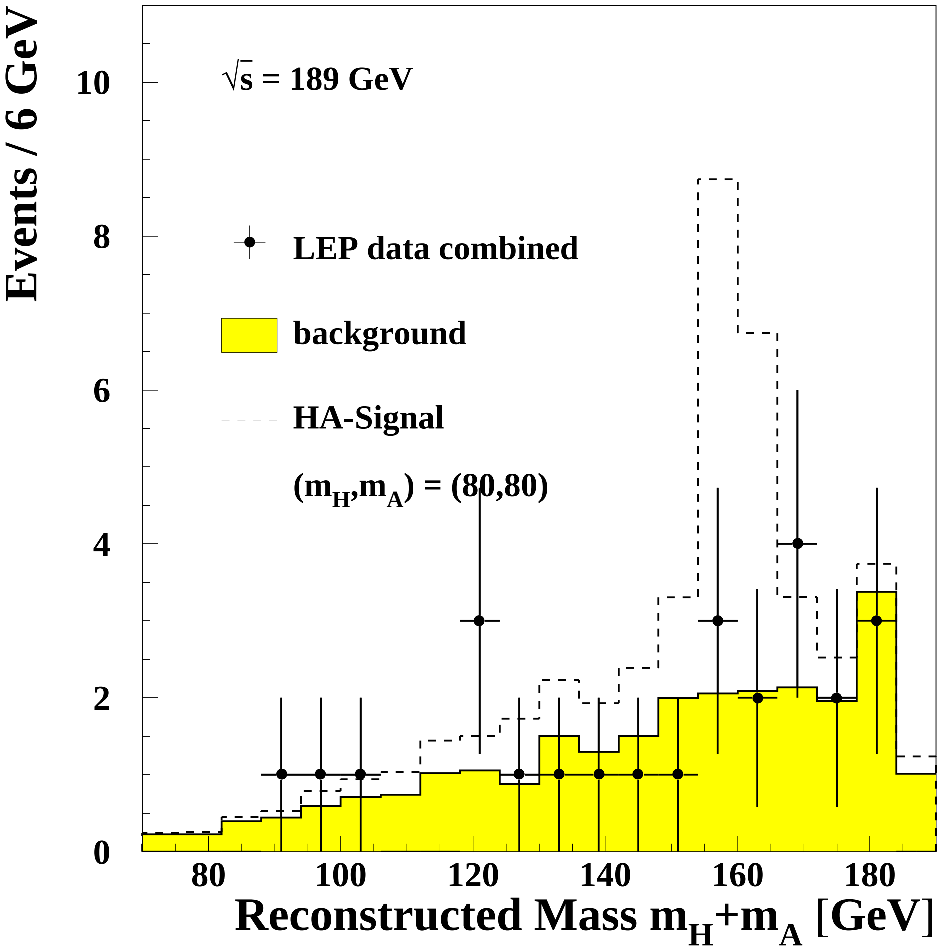

Figure 5: *Distribution of the reconstructed Higgs boson mass sum* $m_{\rm h}+m_{\rm A}$ *in searches for the MSSM process* $\rm e^+e^-\to$ *hA*$\to$ $\rm b\bar{b}b\bar{b}$. *The data of the four experiments collected at 189 GeV are combined. The figure displays the data (dots with error bars), the predicted SM background (shaded histogram) and the prediction for an MSSM signal with* $m_{\rm h}\approx m_{\rm A}$*=80* GeV/c^2 *(dashed histogram) for which the maximal cross-section* ($\cos^2(\beta-\alpha)$*=1) has been assumed. The number of data events entering this figure is 25 for 25.2 background events expected. A signal with the above characteristics would produce 19.9 events.*

MSSM HIGGS

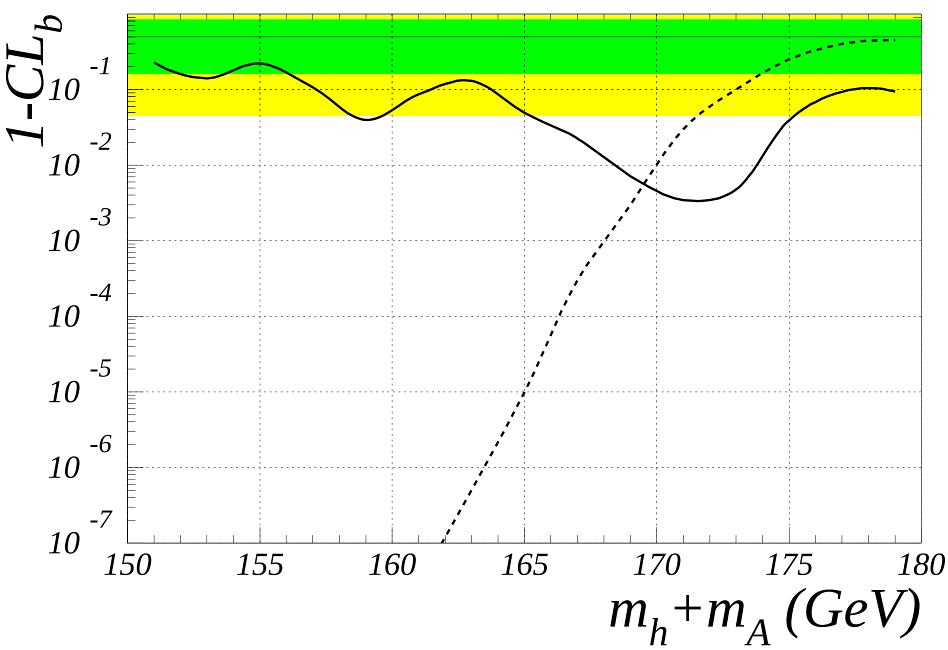

Figure 6: *Distribution of the confidence level* $1 - CL_b$ *('background only') as a function of the test mass sum* $\mathrm{m_h}$+$\mathrm{m_A}$ *of the MSSM Higgs bosons. The figure displays the observed distribution (full-line histogram). The shaded areas represent the 68% and 91% probability bands of* $1 - CL_b$ *(see discussion in Section 2). The dashed histogram shows* $1 - CL_b$ *expected in the presence of a hypothetical MSSM signal of* $\mathrm{m_h} \approx \mathrm{m_A}$=*80* GeV/c^2 *for which the maximal cross-section* ($\cos^2(\beta - \alpha)$=*1) has been assumed.*

MSSM HIGGS

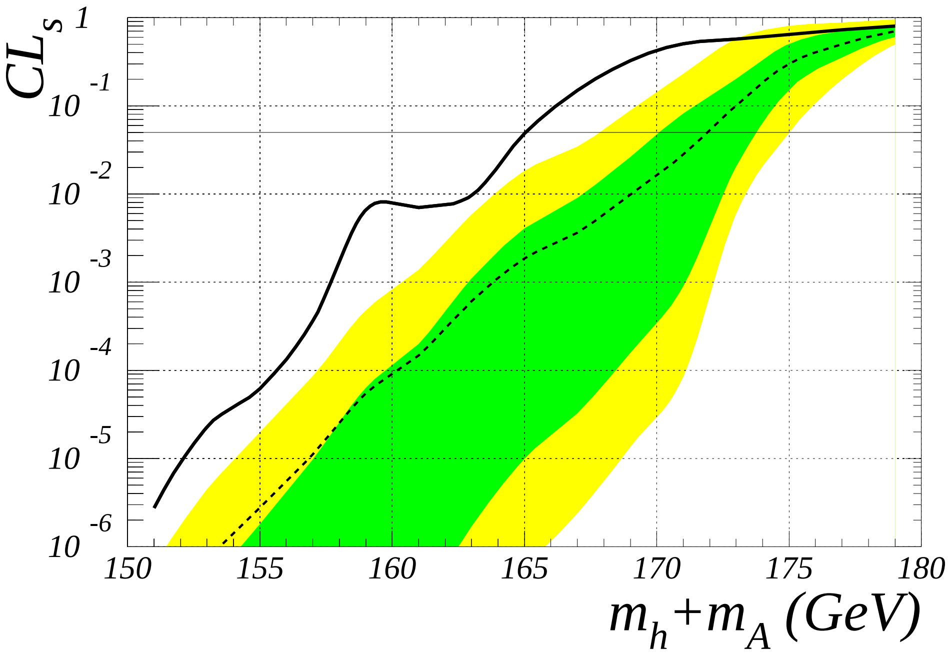

Figure 7: *Distribution of the signal confidence level CL_s as a function of the test mass sum $m_{\rm h}+m_{\rm A}$ of the MSSM Higgs bosons. The figure displays the observed distribution (full-line histogram) and the one expected on average (dashed histogram). The shaded areas correspond to the 68% and 91% probability bands of $1 - CL_b$ in Figure 6 (see discussion in Section 2).*

MSSM HIGGS

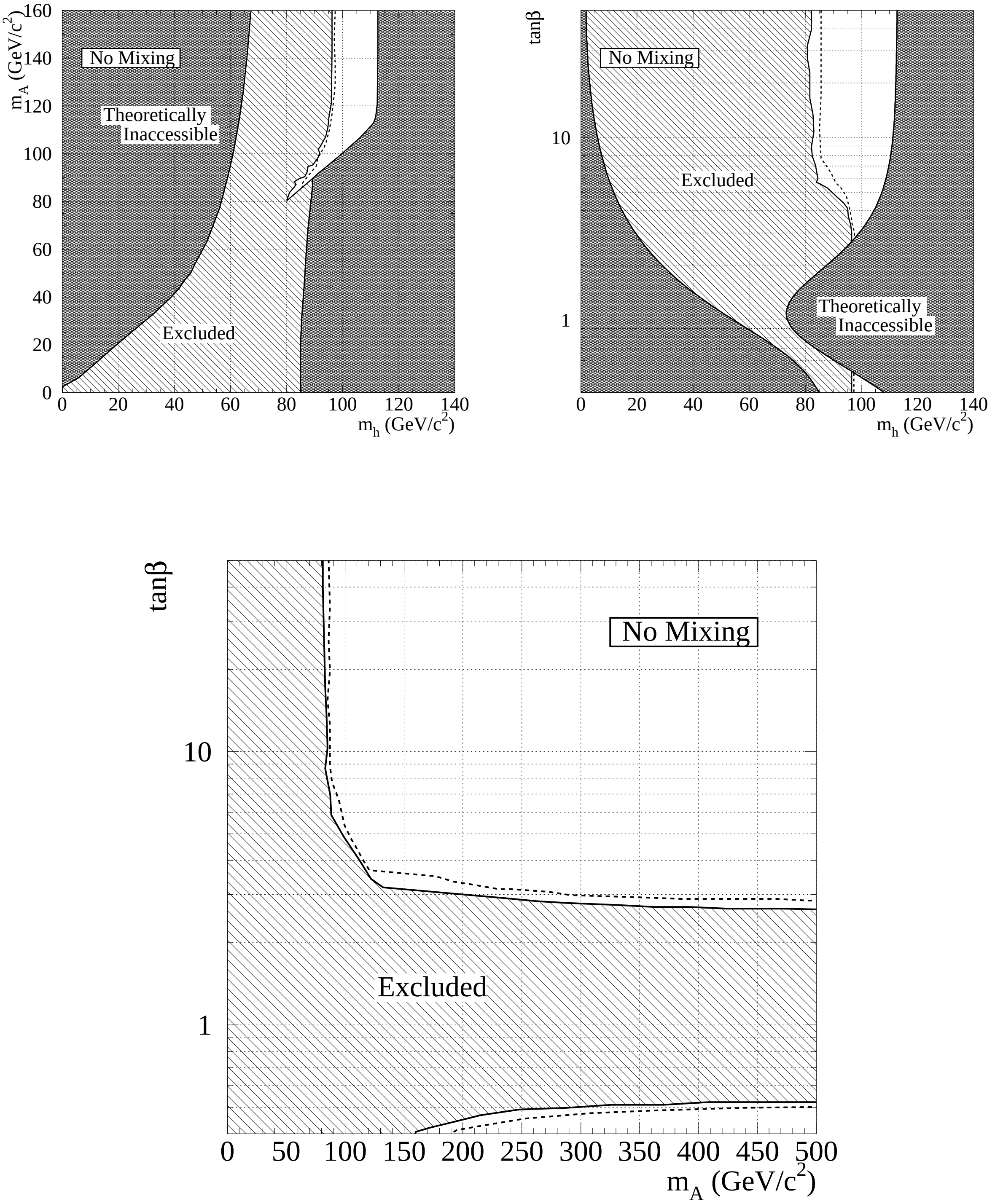

Figure 8: *The 95% CL bounds on* $m_{\rm h}$, $m_{\rm A}$ *and* $\tan\beta$*, for the case of no mixing in the scalar top sector, from combining the data of the four LEP experiments up to* $\sqrt{s}$*=189 GeV. The dashed lines indicate the limits expected on the basis of 'background only' Monte Carlo 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 (*$m_{\rm A}$*,*$\tan\beta$*).*

MSSM HIGGS

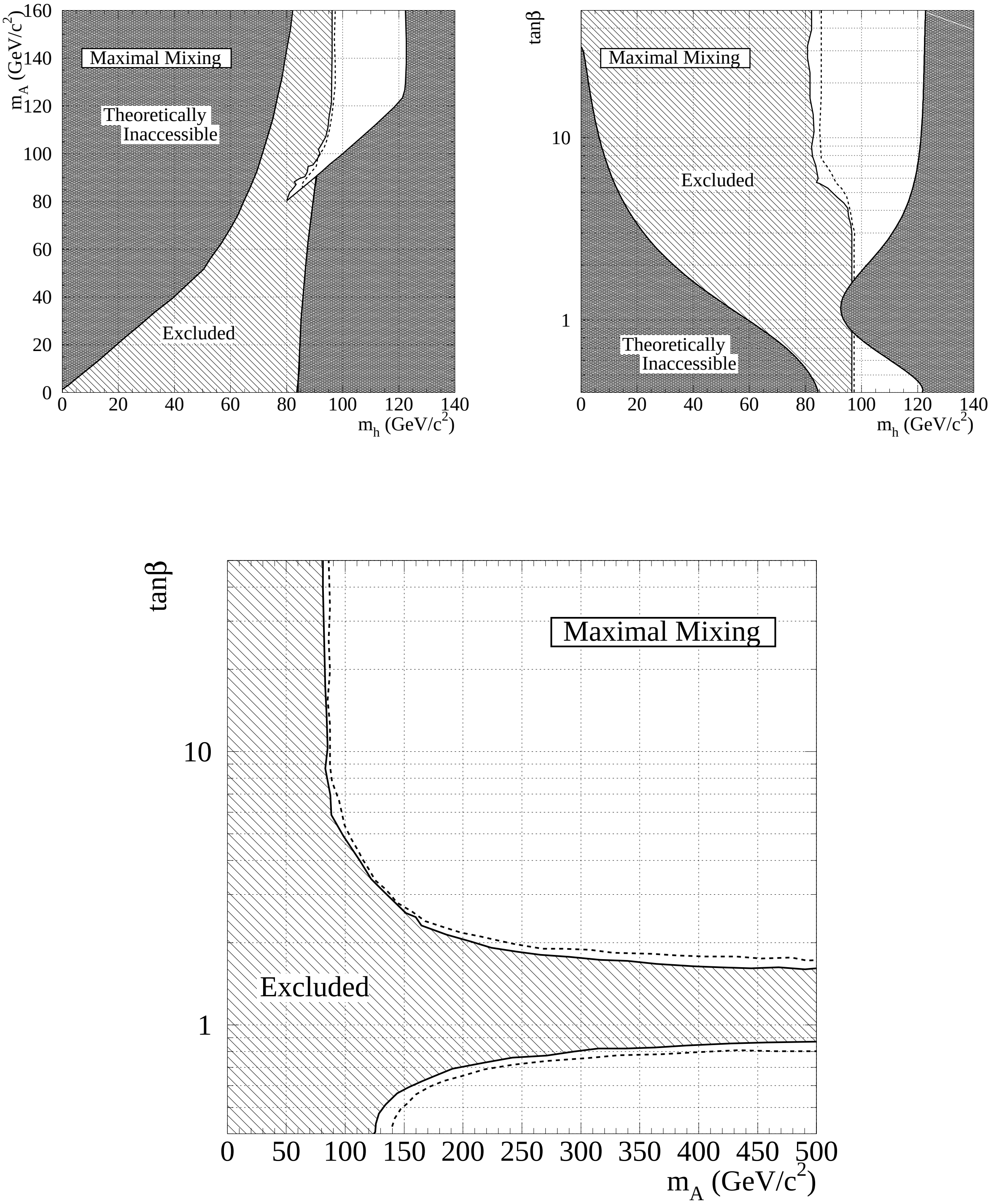

Figure 9: *The 95% CL bounds on m_h, m_A and $\tan\beta$, for the case of maximal mixing in the scalar top sector, from combining the data of the four LEP experiments up to $\sqrt{s}$=189 GeV. The dashed lines indicate the limits expected on the basis of 'background only' Monte Carlo experiments. Upper left: projection (m_h, m_A) for $\tan\beta$>0.4; upper right: projection (m_h,$\tan\beta$); lower part: projection (m_A,$\tan\beta$).*

CHARGED HIGGS

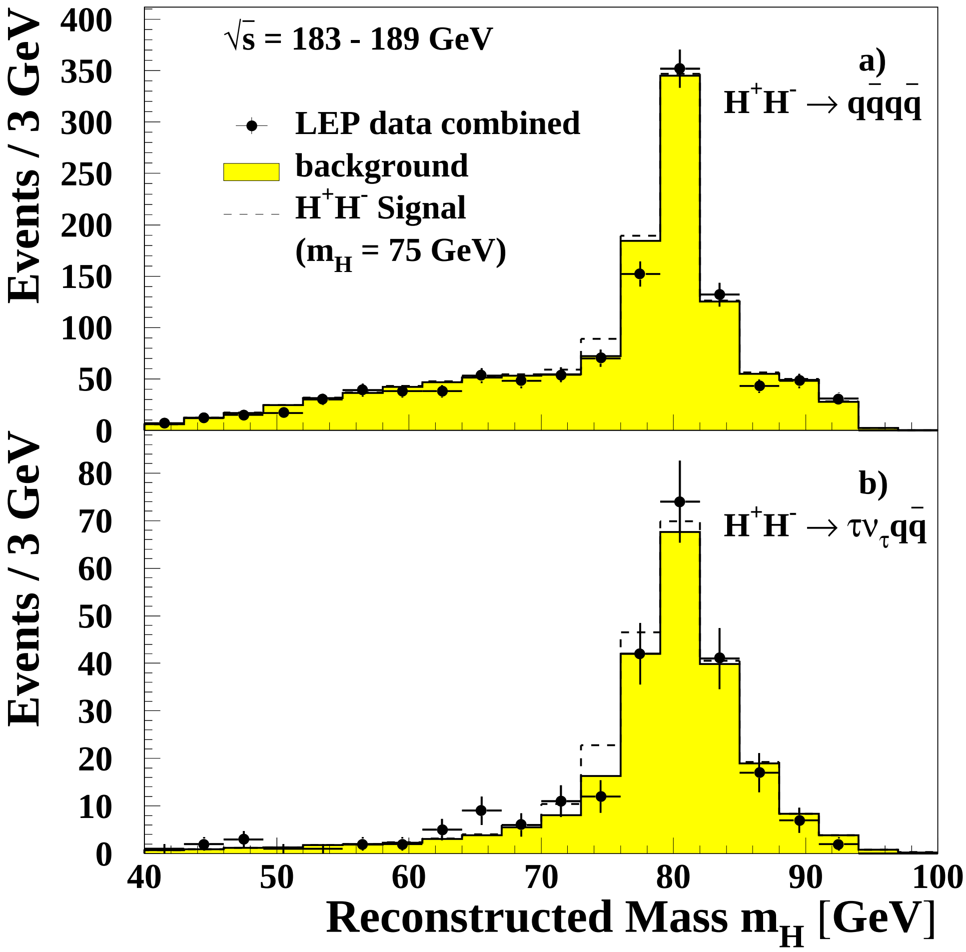

Figure 10: *Distribution of the reconstructed charged Higgs boson mass, $m_{H^\pm}$, in searches for the process* $e^+e^- \rightarrow H^+H^-$*, for branching ratio* $B(H^+ \rightarrow \tau^+\nu)=0$ *(*$c\bar{s}\bar{c}s$ *channel) and 0.5 (*$cs\tau\nu$ *channel). The data of ALEPH, DELPHI and L3 taken at 189 GeV are combined with those of OPAL taken at 183 and 189 GeV. The figure displays the data (dots with error bars), the predicted SM background (shaded histogram) and the prediction for an* H^+H^- *signal with* $m_{H^\pm}=75$ GeV/c^2 *(dashed histogram). The number of data events entering the upper (lower) figure is 1179 (432) events for 1236.3 (407.8) bachground events expected. A signal with the above characteristics would produce 36.8 (29.3) events.*

CHARGED HIGGS

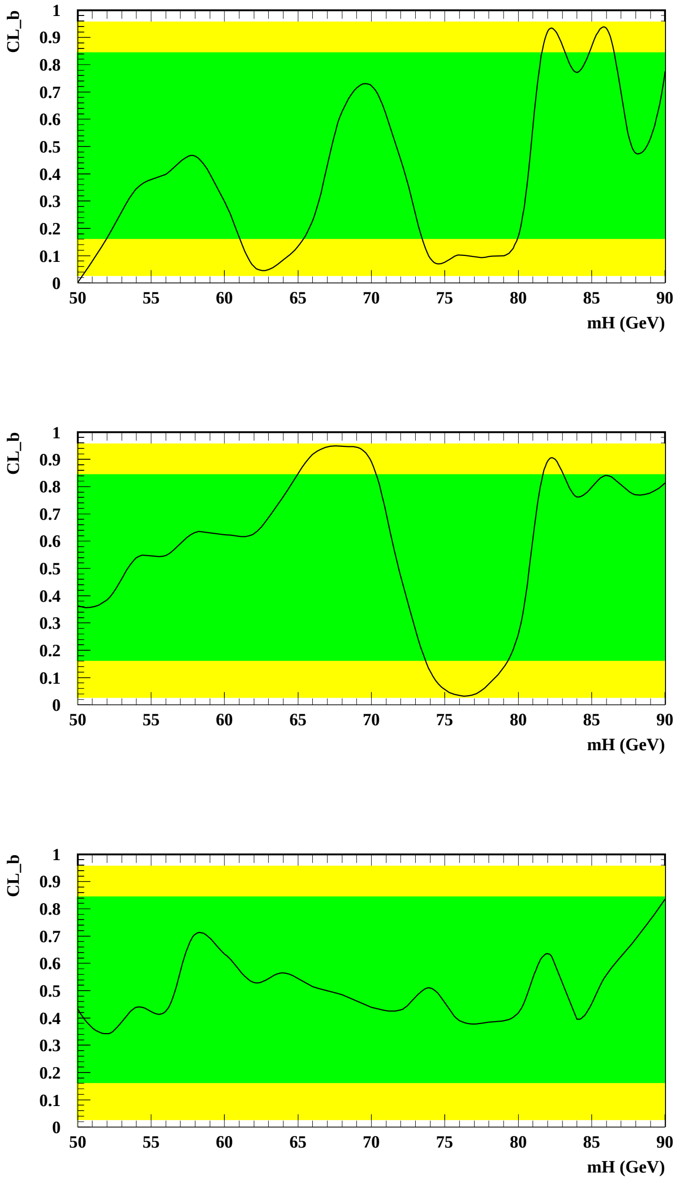

Figure 11: *Distribution of the background confidence level CL_b as a function of the test mass $m_{\mathrm{H}^\pm}$ of the charged Higgs bosons, for the branching ratio $B(\mathrm{H}^+ \rightarrow \tau^+ \nu)$=0 (upper), 0.5 (intermediate) and 1 (lower). The figure displays the observed distribution (full line) and the one expected on average. The shaded bands represent the 1σ and 2σ do mains around the value expected on average.*

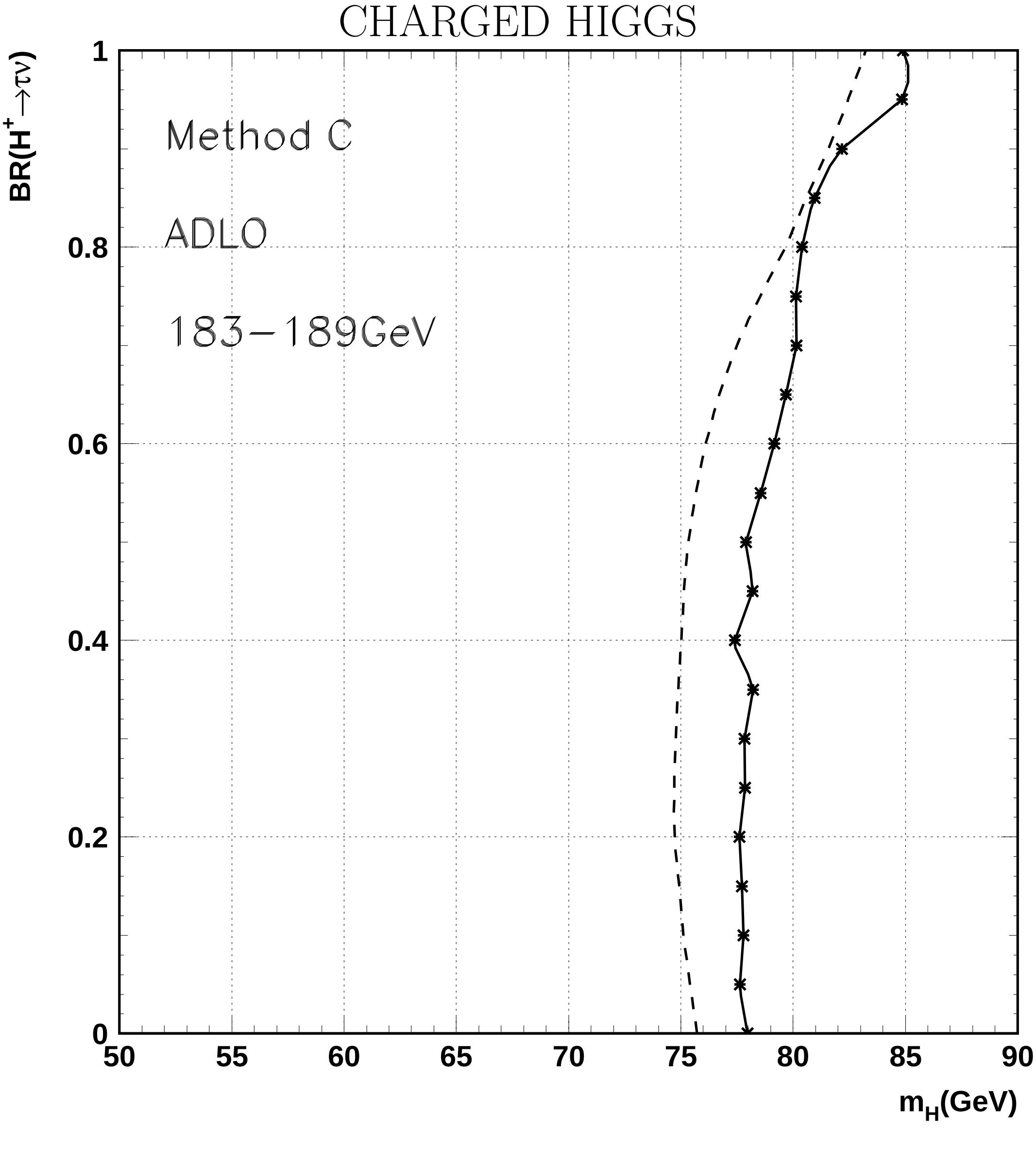

Figure 12: *The 95% CL bounds on $m_{\mathrm{H}^\pm}$ as a function of the branching ratio $B(\mathrm{H}^+ \to \tau^+\nu)$, combining the data collected by ALEPH, DELPHI and L3 and OPAL at $\sqrt{s}$=183 and 189 GeV. The expected exclusion limits are indicated by the dashed line and the observed limits by the full line. Method C has been used.*

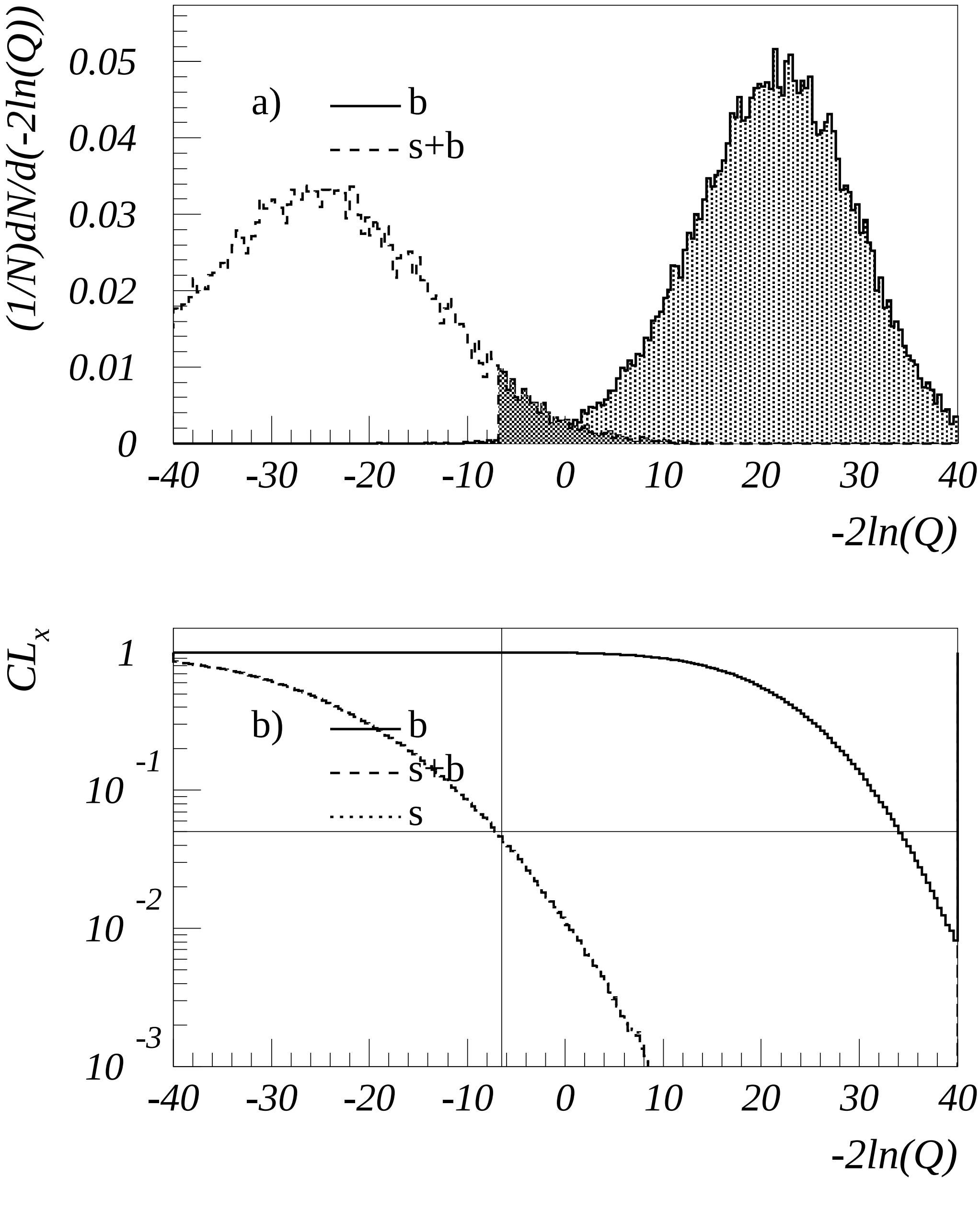

Figure 13: *(a) An example of the probability distributions of -2ln(Q) for background "b" and signal "s+b" gedanken experiments and, (b) the confidences CL_b, CL_{s+b} and $CL_s = CL_{s+b}/CL_b$ which are the integrals of the distributions in (a). The shaded areas (integrals) in (a) are given by the values of the functions in (b) at the value of -2ln(Q) indicated by the vertical line. This example is in fact at the observed exclusion limit of m_{H}=95.2* GeV/c^2 *obtained in this note for the SM Higgs boson, i.e.* $CL_s(Q = -6.5)$*=5%.*