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Limits on Higgs boson masses from combining the data of the four LEP experiments at $\sqrt{s}\leq$183 GeV

ALEPH, DELPHI, L3 and OPAL Collaborations

The LEP working group for Higgs boson searches[1]

Abstract

In 1997 the four LEP experiments have each collected approximately 55 pb^{-1} of $\mathrm{e}^+\mathrm{e}^-$ collision data at a centre-of-mass energy of 183 GeV. The LEP working group for Higgs boson searches has combined these data with LEP data sets collected at lower energies, and has produced the following new experimental bounds at the 95% confidence level. For the Standard Model Higgs boson, the lower bound on the mass is 89.7 GeV/c^2. In the Minimal Supersymmetric Standard Model, assuming $\tan\beta$>0.8 and SUSY breaking masses $m_{\mathrm{SUSY}} = 1$ TeV/c^2 and $M_2 = 1.6$ TeV/c^2, the limits m_{h}>79.6 GeV/c^2 and m_{A}>80.2 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, the range 0.8<$\tan\beta$<2.2 is excluded for a top quark mass less than 175 GeV/c^2, with the excluded range becoming 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 $\mathrm{H}^+\rightarrow\mathrm{c\bar{s}}$ and $\tau^+\nu$, the lower bound on the mass is 69.0 GeV/c^2.

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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 data with data obtained at LEP2 energies of 133, 161, 172 and 183 GeV. The approximate integrated luminosities per experiment of the LEP2 data sets are 10, 10, 10 and 55 pb^{-1}, respectively.

In the past, the LEP working group for Higgs boson searches has investigated several statistical methods for combining the search results of individual experiments. The methods, labeled A, B, C and D, are briefly described in Ref. [1]. Methods A, B and C employ different test statistics (estimators) to rank the results in individual channels[2] between 'background like' and 'signal-plus-background like'; they form confidence levels based on the estimated signal and background conditions and observed candidate events in each search channel from each experiment. Method D assumes that each collaboration has already combined its own search channels using its preferred statistical procedure; the collaborations provide their search results as confidence levels, functions of the test mass m_{H}, which are then combined analytically.

With respect to Ref. [1], some of the methods have been slightly modified, more in their detailed implementations than in their essence.

In **Method C**, the expression of the fractional event weight (Eq. 7 in Ref. [1]) has been changed to

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

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_{H} and b_i the expected background rate. The functions S_i and B_i describe the mass distributions of signal and background and $K(m_{\mathrm{H}})$ is an overall normalization factor. In the new expression, the mass-dependent signal distribution appears as a term in the denominator. This was formerly omitted to reduce the sensitivity of the weight to background uncertainties in the signal tails. The previous expression also contained a scaling parameter (C) which had to be tuned to provide optimal expected[3] confidence levels; it is now fixed at its optimum for high event rates. These simplifications become possible since at the current LEP2 energies the dominant contributions to the background are well modelled.

In **Method D**, the expression for the signal confidence level, $CL_s = CL_{s+b}/CL_b$ (Eq. 3 in Ref. [1]) has been replaced by

$$CL_s = CL_{s+b} + (1 - CL_b)e^{-s}, \tag{2}$$

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

[3] The expected confidence levels (or limits) are those obtained on average, using a large number of Monte Carlo experiments assuming the absence of a Higgs boson signal ('background only' experiments).

where s is the expected signal rate. This change is found to improve the expected mass limits slightly [2]. Under the current conditions of energy, luminosity and test masses, the improvement is of approximately 200 MeV/c^2 for the SM Higgs boson, and 500 MeV/c^2 for the MSSM Higgs bosons h and A and for the charged Higgs.

The methods A, B, C and D have been found to be equally adequate for producing 95% confidence level (CL) exclusion limits. The small variation of the results, discussed below, is taken as a measure of the uncertainties inherent to the choice of the methods and the precise interpretation of the input provided by the different experiments.

2 Combined mass limit for the SM Higgs boson

At LEP, the SM Higgs boson is expected to be produced mainly via the Higgs-strahlung process $e^+e^- \to HZ$, while contributions from the WW fusion channel, $e^+e^- \to H\nu\bar{\nu}$, are less than 10%. The searches performed by the four LEP collaborations encompass the usual HZ final state topologies, commonly called 'four-jet' ($HZ \to b\bar{b}q\bar{q}$), '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 $\tau^+\tau^-q\bar{q}$). From combining the earlier data collected by the LEP experiments at center of mass energies up to 172 GeV, a 95% CL lower bound of 77.5 GeV/c^2 has been obtained [1]. Here we present an update for the SM Higgs boson by including the data collected at 183 GeV energy.

At 183 GeV, the analysis procedures of individual experiments follow closely those employed at lower energies. However, the event selections have been optimised for the higher energy and increased test mass range, and to deal with the additional background process $e^+e^- \to ZZ$. These procedures and the results obtained are described in the individual publications [3]-[6]. A summary of the individual results is given in Table 1.

Experiment:	ALEPH	DELPHI	L3	OPAL
Background predicted:	7.2	6.5	24.2	8.9
Events observed:	7	6	18	9
Statistical method used:	D	A	B	C
Limit (GeV/c^2) expected at 95% CL:	85.2	86.5	85.0	86.2
Limit (GeV/c^2) observed at 95% CL:	87.9	85.7	87.6	88.3

Table 1: *Information related to individual searches for the SM Higgs boson at $\sqrt{s}$=183 GeV. In the L3 analysis, the expected background and observed number of events depend on the Higgs boson mass hypothesis; they are given here for m_H=85 GeV/c^2. The quoted limits take into account statistical and systematic errors as described in the individual publications.*

The additional input provided by the four experiments at $\sqrt{s}$=183 GeV has been used to derive a new combined mass limit for the SM Higgs boson. In contrast to the DELPHI, L3 and

OPAL cases, the background predicted for the ALEPH experiment has not been subtracted from the observed spectrum of events in the combination process.

The average expected and observed signal confidence levels as a function of the test mass are shown for the four methods in Figure 1. 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, which are listed in Table 2.

Mass limit (GeV/c^2) at 95% CL	Statistical method A	B	C	D	Spread (MeV/c^2)
Expected	89.8	90.1	90.1	90.2	± 200
Observed	90.1	90.1	90.3	89.7	± 300

Table 2: *The 95% CL combined mass limits for the SM Higgs boson, observed and expected, using the statistical methods A, B, C and D to combine the data collected by the four LEP experiments at energies up to $\sqrt{s}$=183 GeV. The last column shows the spread of the results, i.e. $\pm$ one-half of the largest difference.*

The spread of the results[4] listed in Table 2 has an irreducible contribution due to the intrinsic differences (e.g. the test statistics used) of the statistical methods. This contribution has been evaluated by computing expected confidence levels for the test statistics of Methods A, B and C[5], using identically prepared inputs. The intrinsic spread, averaged over a large number of simulated 'background only' experiments, is about ± 30 MeV/c^2. Thus, the larger spreads quoted in Table 2 indicate another component, which may be attributed to a number of differences in the interpretation of the experimental input provided by the four experiments (e.g. parametrisation of efficiencies, background distributions, resolution functions) within the computer programs of the methods.

One should notice the remarkable stability of the confidence levels expected on average (the dashed curves in Figure 1). In contrast, the observed confidence levels (full line histograms) show local differences which reflect the sensitivity to the exact numerical handling of the experimental inputs such as the observed background spectra and individual candidate events. For example, there is a spike at $m_{\rm H}$=90 GeV/c^2 in the histograms for Methods A and B which has been traced to a statistical downward fluctuation in one bin of the background spectrum for one search channel provided by one of the experiments. This 'feature' was considered non-physical and eliminated in Method C by a smoothening procedure. (Note that this spike actually determines the 95% CL limit on $m_{\rm H}$ quoted in Table 2 for Methods A and B.) It should be possible to minimise such differences in the future by a more uniform application of numerical procedures.

[4]Throughout this note, the spread of results is defined as $\pm$ one-half of the largest difference between the values obtained.

[5]For Method D, the test statistic is not uniquely defined since this method combines analytically the search *results* of the four experiments which are based, each, on a different test statistic.

The mass limits in Table 2 have been derived without taking into account the systematic uncertainties which affect the signal efficiency and residual background estimations in the individual experiments. The changes in the mass limits which occur when these errors are included have been evaluated using Methods C and D. The expected and observed mass limits have decreased by less than 100 MeV/c^2, which is within the spread of the quoted limits.

Based on the mass limits quoted in Table 2 and on the above discussion of the spreads and errors, we choose to quote the lowest of the four observed limits, 89.7 GeV/c^2, as a reliable 95% CL lower bound for the SM Higgs boson mass.

The combined LEP1 [7] and LEP2 data can be 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 the cross-section may be different. Figure 2 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 model and the SM coupling.

3 Bounds on m_{h}, m_{A} and $\tan\beta$ 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 production of h and A is expected to be kinematically accessible for large portions of the MSSM parameter space, while the heavier H and the charged Higgs bosons are accessible only in a small subset of the parameter space. The Higgs bosons h and A are produced mainly via the Higgs-strahlung process $\mathrm{e}^+\mathrm{e}^-\rightarrow$ hZ (analogous to the main SM production process) and the pair production process $\mathrm{e}^+\mathrm{e}^-\rightarrow$ hA. These two processes are complementary: the cross-section of the first is proportional to $\sin^2(\beta-\alpha)$ and that of the second is proportional to $\cos^2(\beta-\alpha)$. Here, $\tan\beta$ 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 searches of the four LEP experiments are performed within the framework of a 'constrained' MSSM where universal SUSY breaking masses, m_{SUSY} and M_2, are assumed for s-fermions and gauginos, respectively, at the electroweak scale. The parameter set is then fully specified by the values of the mass (m_{A}) of the CP-odd A boson and $\tan\beta$, further by the Higgs mixing parameter μ and the trilinear coupling A_t which controls the scalar-top mixing. The trilinear couplings associated with the other scalar-quark flavours are assumed to be equal to A_t at the electroweak scale, but this assumption has a negligible impact on the Higgs phenomenology and hence on our results. Once the values of the parameters [$m_{\mathrm{SUSY}}, M_2, \mu$, $\tan\beta$, A_t, m_{A}] are specified, the masses and couplings of all Higgs bosons, sleptons, squarks and gauginos can be calculated and hence all production cross-sections and decay branching ratios [8]. The predictions for specific final states can be compared to the experimental data and the model corresponding to those parameter values can be tested for exclusion.

The precise value of the top quark mass, m_{t}, has a strong impact on the Higgs boson masses (on m_{h} in particular) via loop corrections. The current experimental error on m_{t} [9] cannot be ignored in a general investigation of the MSSM parameter space.

Examples of detailed MSSM parameter scans with each of the above parameters varied independently have been performed by several LEP collaborations [6, 10, 11]. In this paper, combined results are only given for two, less general but nevertheless representative, MSSM parameter scans, proposed in Ref. [12]. The values of m_{SUSY} and M_2 are fixed at 1 TeV/c^2 and 1.6 TeV/c^2, respectively; the value of μ is chosen to be -100 GeV. Two separate cases are considered, with the trilinear coupling fixed at $A_t = 0$ or $A_t = \sqrt{6}$ TeV, corresponding to no mixing and maximal mixing in the scalar-top sector. The two remaining parameters, m_{A} and $\tan\beta$, are scanned independently. The top quark mass is fixed at m_{t}=175 GeV/c^2.

3.1 MSSM: Experimental input

The searches of the four LEP collaborations for the processes $\mathrm{e^+e^-} \to$ hZ and $\mathrm{e^+e^-} \to$ hA, including the data taken at $\sqrt{s} \leq 183$ GeV, are described in Refs. [4, 6, 10, 13]. In each case, the results from LEP1 are combined with those obtained from LEP2 data.

For the process $\mathrm{e^+e^-} \to$ hZ, the searches for the SM Higgs boson in the four-jet, missing energy, leptonic (e and μ) and tau channels are interpreted in the MSSM, taking into account the reduction of the 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 $2m_{\mathrm{A}} < m_{\mathrm{h}}$, besides decaying into the usual fermionic final states, the h boson can also decay via the process h$\to$ AA. In Refs. [4] and [10] the standard hZ analyses have been applied to the (AA)Z final states and in Ref. [6] specific searches for the (AA)Z final states have been designed.

For the process $\mathrm{e^+e^-} \to$ 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 $2m_{\mathrm{A}} < m_{\mathrm{h}}$, one of the collaborations has performed an optimised search for the (AA)A$\to$($\mathrm{b\bar{b}b\bar{b}}$)$\mathrm{b\bar{b}}$ final state [6] while another [10] has applied the standard hA searches with efficiencies computed for the (AA)A$\to$($\mathrm{b\bar{b}b\bar{b}}$)$\mathrm{b\bar{b}}$ final state.

Information from the individual collaborations regarding the searches for $\mathrm{e^+e^-} \to$ hA is provided in Table 3 which lists the background predicted and the events observed in the $\mathrm{b\bar{b}b\bar{b}}$, $\tau^+\tau^-\mathrm{b\bar{b}}$ and $\mathrm{b\bar{b}}\tau^+\tau^-$ channels and the 95% CL limits, expected and observed, for the special case of $m_{\mathrm{h}} \approx m_{\mathrm{A}}$ (typical for large $\tan\beta$) in which case the sensitivity is determined mainly by the $\mathrm{e^+e^-} \to$ hA search. The statistical methods employed by each of the collaborations to derive their limits are also indicated.

Experiment:	ALEPH	DELPHI	L3	OPAL
Backg. predicted / Evts. observed				
in $\mathrm{b\bar{b}b\bar{b}}$:	2.40 / 2	1.45 / 0	9.78 / 8	2.92 / 4
in $\tau^+\tau^-\mathrm{b\bar{b}}$:	0.07 / 0	0.47 / 0	0.55 / 0	1.50 / 3
Statistical method used:	D	A	B	C
Limit expected / observed (GeV/c^2)				
for $m_\mathrm{h}\approx m_\mathrm{A}$ and maximal mixing :	72.2 / 76.1	70.9 / 75.3	68.9 / 71.4	68.2 / 70.5

Table 3: *Information related to individual searches for the* $\mathrm{e^+e^-}\rightarrow hA$ *process at* $\sqrt{s}$*=183 GeV. The quoted limits are those expected and observed for the case of maximal mixing and* $m_\mathrm{h}\approx m_\mathrm{A}$ *which typically occurs at large* $\tan\beta$*. 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_A*=70* GeV/c^2 *and* $\tan\beta$*=50.*

3.2 MSSM: Combined limits

The combined 95% CL bounds on m_h, m_A and $\tan\beta$ have been determined using Methods A, B and C[6], separately for the assumptions of no mixing and maximal mixing in the scalar top sector. The mass limits are presented in Tables 4 and 5, respectively. As in the SM case, the background predicted for the ALEPH experiment has not been subtracted from the observed spectrum of events in the combination process.

Figures 3 and 4 show, for no mixing and for maximal mixing, the parameter regions that are excluded by the observation, simultaneously for all three methods used. For both mixing assumptions, the limits are presented for $\tan\beta$>0.4, in three parameter projections, (m_h, m_A), (m_h, $\tan\beta$), and (m_A, $\tan\beta$). Besides the experimental limits, the limits expected on the basis of 'background only' Monte Carlo experiments are also shown. While the experimental limits, expected and observed, are almost independent of the mixing assumption, the theoretically available parameter space, and hence the size of the remaining unexcluded region, strongly depends on it.

The intrinsic spread of the expected mass limits has been evaluated for the case of maximal mixing and $m_\mathrm{h}\approx m_\mathrm{A}$ and was found to be of about ±160 MeV/c^2. This is small compared to the spread values quoted in Table 4 and 5, indicating that there is another component, which may be attributed to differences in interpreting and using the experimental inputs provided by the four experiments. On the other hand, the intrinsic spread of expected limits is large compared to the SM case. This is because in the chosen situation, with $m_\mathrm{h}\approx m_\mathrm{A}$, the mass limit is mainly determined by the $\mathrm{e^+e^-}\rightarrow$ hA process, for which the cross-section has a slower variation close to the mass limit than for the SM process.

The effect of systematic errors on the expected mass limits have been estimated for $m_\mathrm{h}\approx m_\mathrm{A}$.

[6] At the time of writing, the combination using Method D was not available.

Method:	A	B	C	Spread (MeV/c^2)
Limits for m_{h} (GeV/c^2)				
expected :	78.7	80.7	79.5	±1000
observed :	79.6	79.6	82.0	±1200
Limits for m_{A} (GeV/c^2)				
expected :	80.0	81.1	79.7	±700
observed :	80.4	80.2	82.4	±1100

Table 4: *No mixing scenario: Comparison of combined 95% CL MSSM limits obtained using Methods A, B and C, for* $\tan\beta > 0.8$. *The spread of results, that is one-half the maximal difference, is shown in the last column.*

Method:	A	B	C	Spread (MeV/c^2)
Limits for m_{h} (GeV/c^2)				
expected :	78.7	80.7	79.4	±1000
observed :	79.8	79.6	82.0	±1200
Limits for m_{A} (GeV/c^2)				
expected :	80.2	81.0	79.5	±750
observed :	80.5	80.2	82.0	±900

Table 5: *Maximal mixing scenario: Comparison of combined 95% CL MSSM limits obtained using Methods A, B and C, for* $\tan\beta > 0.8$. *The spread of results, that is one-half the maximal difference, is shown in the last column.*

They are in the range of $\pm$50 MeV/c^2 and $\pm$450 MeV/c^2 if the errors are treated as uncorrelated and as fully correlated, respectively.

In the case of no mixing, and for a top quark mass less than 175 GeV/c^2, the range of $\tan\beta$ between 0.8 and 2.2 is excluded, see Figure 3 upper right. Ranges of $\tan\beta$ which are excluded for other values of m_{t} are given in Table 6. For a top quark lighter than 165 GeV/c^2, the range between 0.7 and 1.8 is excluded also in the case of maximal mixing.

Top quark mass:	$\leq$165 GeV/c^2	$\leq$175 GeV/c^2	$\leq$185 GeV/c^2
Exclusion in $\tan\beta$			
no mixing :	0.8 - 2.7	0.8 - 2.2	0.8 - 1.8
max mixing:	0.7 - 1.8	none	none

Table 6: *Exclusion in* $\tan\beta$ *for various top quark mass values.*

Based on the limits quoted in Tables 4 and 5 and on the discussion of the intrinsic spread and the impact of systematic errors, we quote the following 95% CL lower bounds: m_{h}>79.6 GeV/c^2, m_{A}>80.2 GeV/c^2. These bounds are valid for both mixing assumptions and for $\tan\beta$>0.8.

4 Combined mass limits for the charged Higgs bosons

Charged Higgs bosons are predicted to exist in 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 $\mathrm{e^+e^-\to H^+H^-}$. In the MSSM and at tree level, the $\mathrm{H^\pm}$ is constrained to be heavier than the $\mathrm{W^\pm}$ bosons, but loop corrections can drive the mass to lower values. Since the sensitivity of current searches is limited to the range below $m_{\mathrm{W^\pm}}$ due to the background from $\mathrm{e^+e^-\to W^+W^-}$, any signal for $\mathrm{H^+H^-}$ 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 the tree level, the production cross-section is fully determined by the $\mathrm{H^\pm}$ mass [14]. The tree level cross-section used in this combination is provided by PYTHIA [15]. The values provided by HZHA, which is used by some of the experiments to produce their individual results, differ by about 1%. In the searches it is assumed that the two decays $\mathrm{H^+\to c\bar{s}}$ and $\mathrm{H^+}\to\tau^+\nu$ exhaust the $\mathrm{H^+}$ decay width, but the relative branching ratio is not constrained. Thus, the searches encompass the following $\mathrm{H^+H^-}$ final states: $(\mathrm{c\bar{s}})(\mathrm{\bar{c}s})$, $(\tau^+\nu)(\tau^-\bar{\nu})$, and the mixed mode $(\mathrm{c\bar{s}})(\tau^-\bar{\nu})+(\mathrm{\bar{c}s})(\tau^+\nu)$. The results are presented as a function of the branching ratio $\mathrm{B}(\mathrm{H^+}\to\tau^+\nu)$.

Details of the individual searches using data at energies up to and including $\sqrt{s}$=183 GeV can be found in Refs. [6, 16, 17, 18]. These are summarised in Table 7 for each of the search channels, together with the 95% CL lower bounds, expected and observed. In the table we quote mass limits for $B(H^+ \to \tau^+\nu) = 0$ and 1, and also the lowest mass limit obtained, which is valid for any value of the branching ratio.

Experiment:	ALEPH	DELPHI	L3	OPAL
Backg. exp. / Events obs.				
in $(c\bar{s})(\bar{c}s)$:	71.4 / 74	26.6 / 24	159.4 / 145	48.8 / 50
in $(c\bar{s})(\tau^+\nu)$:	9.9 / 7	14.0 / 18	39.8 / 39	15.3 / 16
in $(\tau^+\nu)(\tau^-\bar{\nu})$:	6.5 / 4	17.6 / 13	11.3 / 7	9.65 / 8
Statistical method used:	D	A	B	C
Limit expected / observed				
for B=0:	64 / 62	57.7 / 57.3	59.2 / 58.7	62.2 / 59.5
for B=1:	64 / 74	61.0 / 65.6	59.0 / 68.2	68.2 / 72.4
for any B:	57 / 59	56.0 / 56.6	59.0 / 57.5	61.8 / 59.5

Table 7: *Individual search results for the* $e^+e^- \to H^+H^-$ *final states. In the cases of the OPAL* $(\tau^+\nu)(\tau^-\bar{\nu})$ *channel and the ALEPH* $(c\bar{s})(\bar{c}s)$ *and* $(c\bar{s})(\tau^+\nu)$ *channels, 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* $\sqrt{s}$=183 GeV *while the mass limits are for all energies combined up to and including* $\sqrt{s}$=183 GeV.

The 95% CL bounds obtained by combining the data of the four LEP collaborations, using Methods A, B, C, and D, are shown in Figure 5. To obtain the limiting lines, the branching ratio $B(\tau^+\nu)$ has been varied in steps of 0.05. For each value, the CL_s distributions, expected and observed (the analogues of the ones shown in Figure 1) were determined. Like in the SM case, the limits shown are given by the values of $m_{H^\pm}$ for which the CL_s values reach the 5% level for the first time with increasing $m_{H^\pm}$. The shaded areas in Figure 5 are those excluded by all four statistical methods.

The limits obtained by the four methods are compared in Table 8 for $B(\tau^+\nu)$=0, 1, and at the value providing the lowest, most general, mass limit. The spread of the results is listed in the last column.

The intrinsic spread of expected limits has been found to be of approximately $\pm$50 MeV/c^2, which is small compared to the values quoted in Table 8. In this case, the smallness of the intrinsic spread, despite the relatively slow variation of the cross-section with mass, may be attributed to the large predicted background and large number of observed events, typical for the $H^\pm$ searches (see Table 7), which smears out the effects of the different test statistics. The large spread in the observed limits is mainly due to the use of Eq. 2 in Method D to calculate the signal confidence level. Using the same CL_s definition as in Methods A, B and C yields, for example, an observed limit of 70.2 GeV/c^2 for $B(\tau^+\nu)$=0.

The inclusion of systematic errors reduces the mass limits by 100 to 200 MeV/c^2, depending

Method:	A	B	C	D	Spread (MeV/c^2)
B($\tau^+\nu$)=0					
Limit expected :	69.8	69.6	69.7	69.9	±150
Limit observed :	70.4	70.0	70.0	74.1	±2000
B($\tau^+\nu$)=1					
Limit expected :	74.6	74.8	74.0	74.2	±400
Limit observed :	80.0	79.0	79.1	80.0	±500
Any B($\tau^+\nu$)					
Limit expected :	68.8	67.9	68.8	69.1	±600
Limit observed :	69.5	69.0	69.5	70.2	±600

Table 8: *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($\tau^+\nu$). The last column shows the spread of the results.*

on the branching ratio B($\tau^+\nu$).

Based on the above discussion of spread and errors, and taking the smallest of the observed limits from the four methods (see Table 8 and the shaded areas in Figure 5), we choose to quote a 95% CL lower bound of 69.0 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 1997 at $\sqrt{s}$=183 GeV for an integrated luminosity of approximately 55 pb^{-1} per experiment. The new lower bound, valid at the 95% confidence level, is taken conservatively to be the smallest from several combination procedures, and is 89.7 GeV.

The working group has also produced 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. Both LEP1 data and LEP2 data up to and including 183 GeV were used in the combination. For $\tan\beta$>0.8, the limits m_{h}>79.6 GeV/c^2 and m_{A}>80.2 GeV/c^2 are obtained which are independent of the mixing in the scalar top sector. Within the MSSM scenario considered, and assuming no mixing in the scalar-top sector, values of $\tan\beta$ between 0.8 and 2.2 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 difficult to separate from the background and the exclusions, both in mass and in $\tan\beta$, become less stringent [10, 11, 19].

For the charged Higgs bosons predicted by models with two Higgs field doublets, and assuming that the two decays $\mathrm{H}^+ \to \mathrm{c\bar{s}}$ and $\mathrm{H}^+ \to \tau^+\nu$ exhaust the H^+ decay width, 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 69.0 GeV/c^2.

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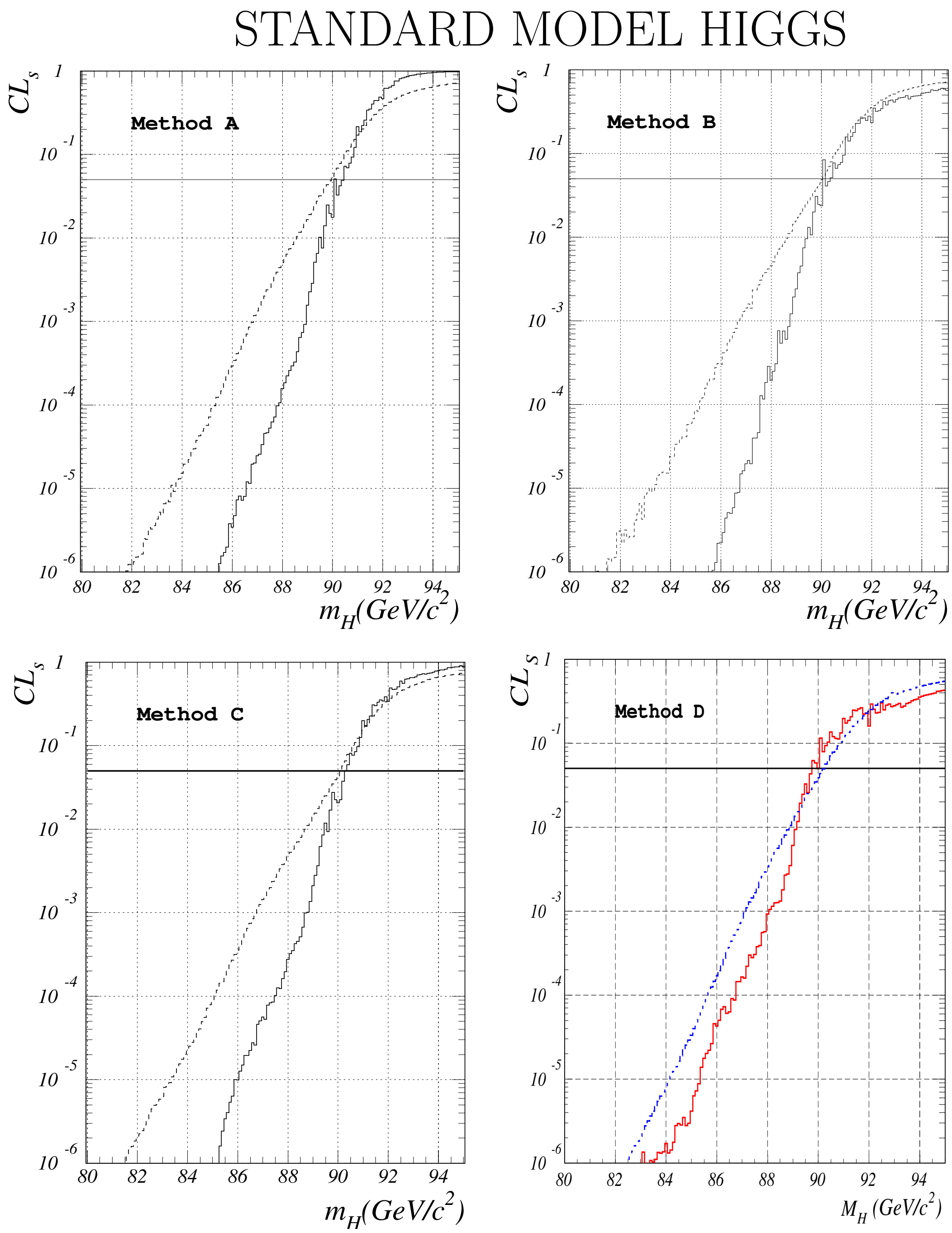

Figure 1: *Average expected (dashed lines) and observed (solid lines) confidence levels, CL_s, obtained from combining the results of the four LEP Collaborations using the four statistical methods. The intersections of the curves with the horizontal lines at 0.05 define the 95% confidence level lower bounds, expected and observed, for the mass of the SM Higgs boson.*

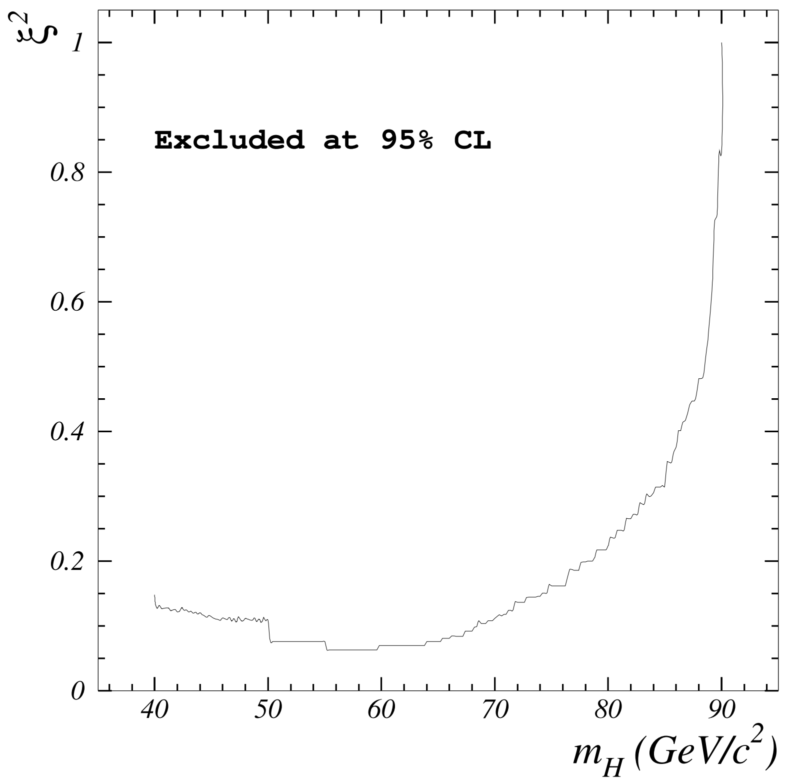

Figure 2: *The 95% CL upper bound on ξ^2 as a function of m_{H}, where $\xi = g_{HZZ}/g_{HZZ}^{SM}$ is the HZZ coupling relative to the SM coupling. The limit is valid for models which assume that the Higgs boson decay properties are identical to those in the SM. Method A is used.*

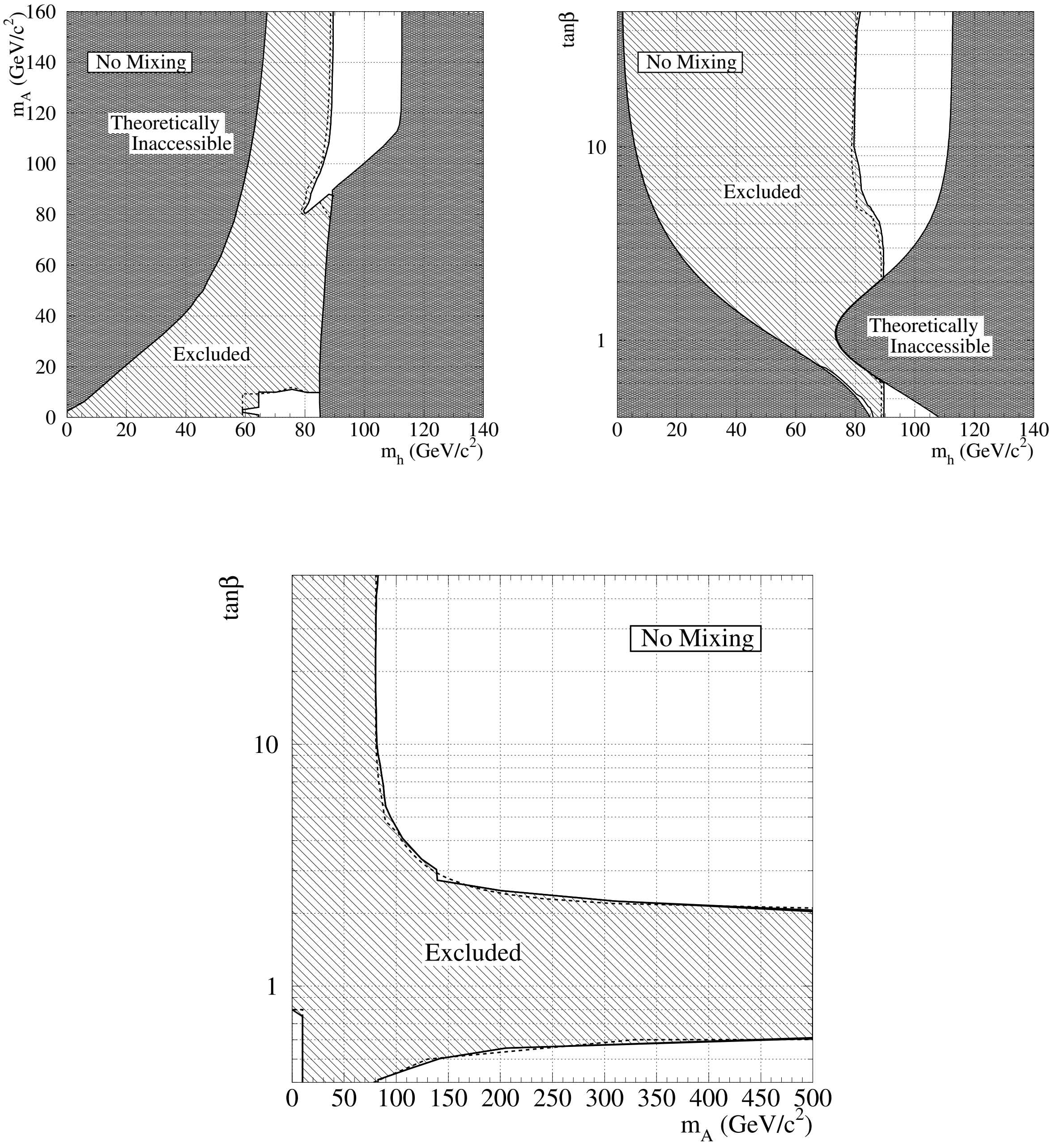

Figure 3: *The 95% CL bounds on m_{h}, m_{A} and $\tan\beta$, for the case of no mixing in the scalar top sector, from combining the data of the four LEP experiments up to $\sqrt{s}$=183 GeV. The regions shown are excluded by Methods A, B and C. The dotted lines indicate the limits expected on the basis 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},$\tan\beta$).*

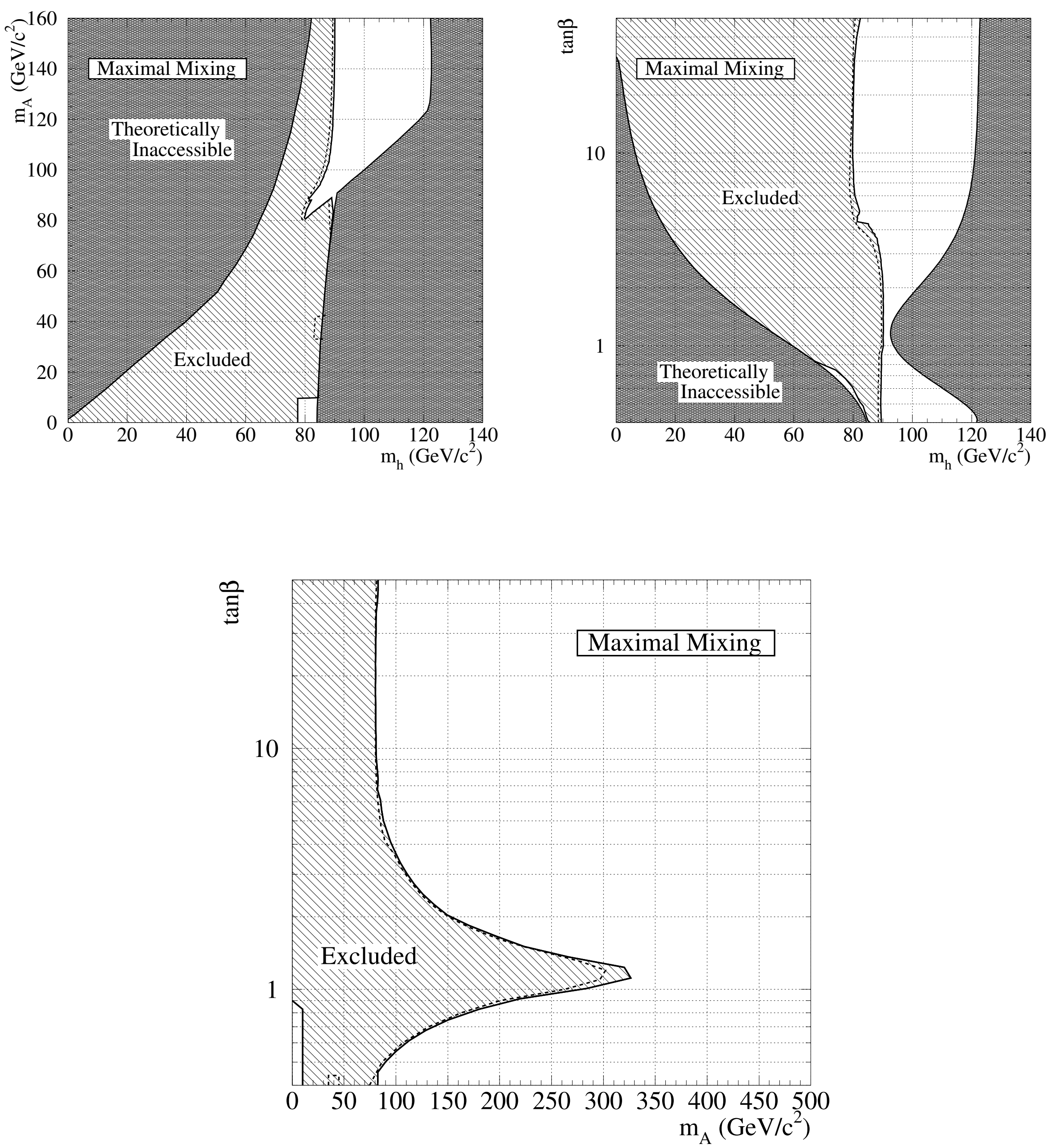

Figure 4: *The 95% CL bounds on m_{h}, m_{A} and $\tan\beta$, for the case of maximal mixing in the scalar top sector, from combining the data of the four LEP experiments up to $\sqrt{s}$=183 GeV. The regions shown are excluded by Methods A, B and C. The dotted lines indicate the limits expected on the 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

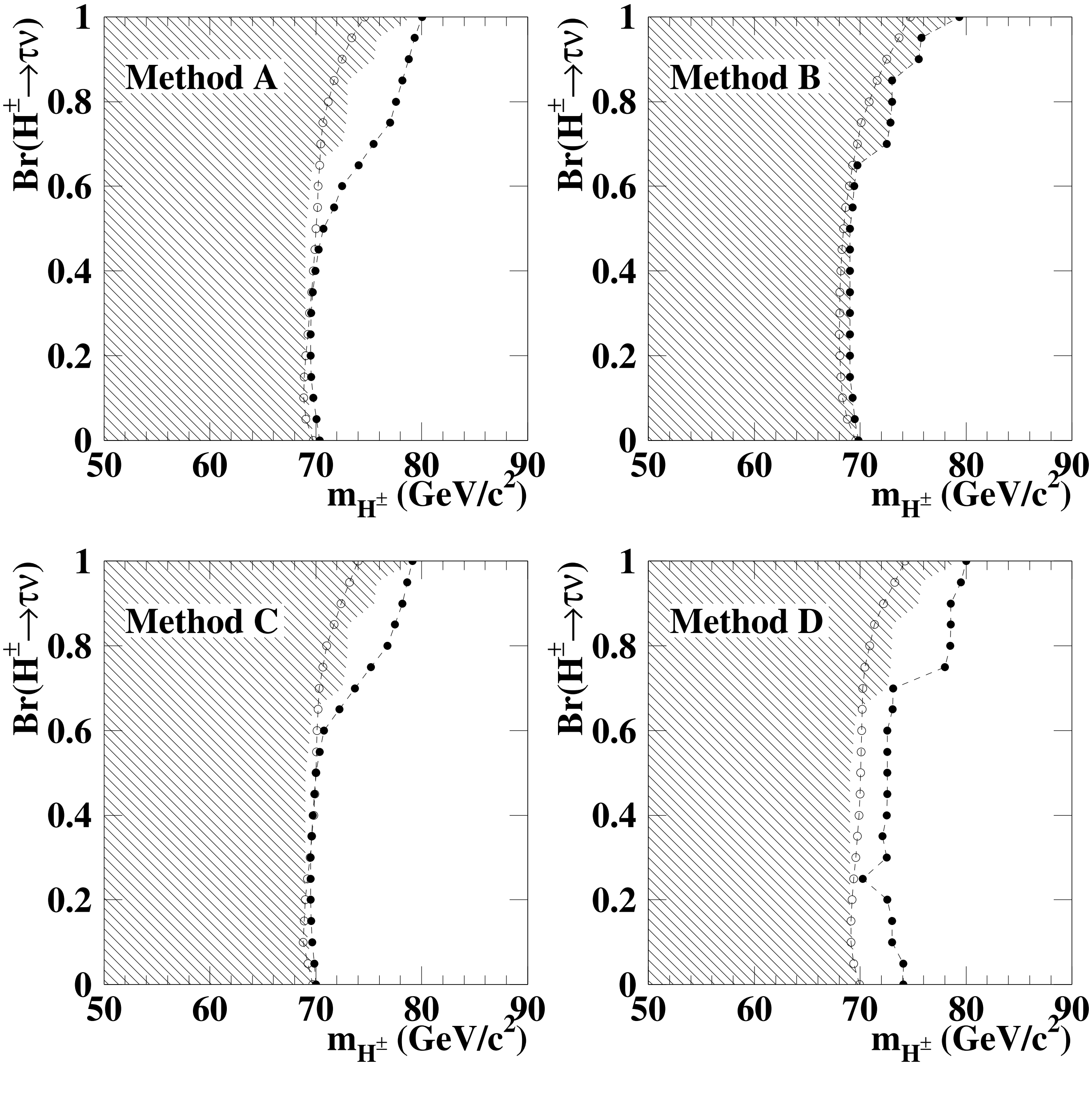

Figure 5: *The 95% CL bounds on $m_{\mathrm{H}^\pm}$, as a function of the branching ratio $B(\mathrm{H}^+ \to \tau^+\nu)$, using Method A, B, C and D, and combining all data of the four LEP experiments up to $\sqrt{s}$=183 GeV. The expected exclusion limits are indicated by the open circles and the observed limits by the black dots. The shaded areas indicate the observed exclusion that is common to all four methods.*