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Searches for Higgs Bosons at LEP2

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Searches for Higgs Bosons at LEP2

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The latest results of Higgs boson searches from the four LEP experiments, ALEPH, DELPHI, L3 and OPAL, are reviewed using the data taken in 1996 at center-of-mass energies between 161 and 172 GeV. No signal was observed. The 95% CL combined lower mass limit for the Minimal Standard Model (MSM) Higgs boson has increased from 66 GeV at LEP1 to 77.5 GeV with the first LEP2 data. In the framework of the Two Higgs Doublet Model, the charged Higgs boson mass limit has increased from 44 GeV to 54.5 GeV, independent of the decay branching ratio. Large new $(m_h, \tan \beta)$ and (m_h, m_A) parameter regions are excluded in the framework of the Minimal Supersymmetric extension of the Standard Model (MSSM). Preliminary results from the 1997 data-taking at 183 GeV are presented, and the prospects for a discovery in the near future are given.

1 Introduction

After six years of data-taking at the Z resonance (LEP1), the LEP machine energy was increased (LEP2), firstly to 130 GeV in fall 1995, and successively to 172 GeV in 1996 and then to 183 GeV in 1997. This review focuses on the results based on the data collected at $\sqrt{s} = 161$ to 172 GeV in 1996 with a total luminosity of about 21 pb^{-1} for each LEP experiment. At 183 GeV, LEP experiments have collected data of about 55 pb^{-1} each. For example, first LEP2 results were summarized in [1–3], and final results from LEP1 were reviewed in [4].

The experimental evidence of Higgs bosons is crucial for understanding the mechanism of $SU(2) \times U(1)$ symmetry breaking and mass generation in gauge theories. The Higgs mass is not predicted by the theory.

The progress made at Tevatron and LEP with respect to precise measurements of electroweak observables, mainly t -quark and W -boson masses, has led to improved indirect constraints on the Higgs boson mass. Figure 1 (from [5, 6]) shows a comparison of t and W measurements and theoretical predictions for different MSM Higgs boson masses. Light Higgs boson masses are favored and an upper mass limit of 295 GeV at 95% CL is derived [6, 7]. In addition, a typical mass region in the MSSM is shown, which predicts larger W masses. The current precision does not allow a distinction to be made between the MSM and the MSSM, leaving the MSSM as an attractive extension of the MSM.

There are important differences between the Higgs boson searches at LEP1 and LEP2:

- The signal-to-background ratio is much better at LEP2. For example, at LEP1 the ratio of background to the expected number of signal events for a 60 GeV Higgs boson was about 50,000, while at LEP2 the ratio is about 200. The large background rate at LEP1 required a very detailed simulation of detector effects and rare background reactions. Furthermore, the dominant hadronic Higgs boson signature ($HZ \rightarrow qq\bar{q}\bar{q}$) was useless at LEP1 because of the overwhelming QCD background.
- In addition to the larger numbers of distinguished search signatures at LEP2, the different center-of-mass energies are treated as different channels with separate signal and

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background simulations. The different MSM Higgs boson searches at 161 and 172 GeV center-of-mass energies amount to 12 search channels. The statistical treatment of the search optimization is therefore more complex than for LEP1.

- While the expected MSM Higgs production at LEP1 involved a real Z decaying into a Higgs boson and a very virtual Z , at LEP2 the Higgs boson could be produced in association with an on-shell Z . This additional information about the final state Z boson mass gives rise to better Higgs boson mass reconstruction, and thus greater sensitivity for a Higgs boson signal because of better background rejection.
- At LEP1 almost no irreducible background was expected, while at LEP2 some processes, which are now kinematically allowed, lead to signatures identical to those expected for the signal. Most important, when Higgs and Z masses are almost degenerate, ZZ background where one Z decays into bb , is not distinguishable from a Higgs signal.

This article is structured as follows. In Section 2 the MSM Higgs results are compared, and in Section 3 the combination of these results with significantly greater sensitivity is reviewed. In Section 4 the results of searches in the Two Higgs Doublet model are summarized, in Section 5 interpretations in the MSSM are given, and Section 6 contains a brief outlook.

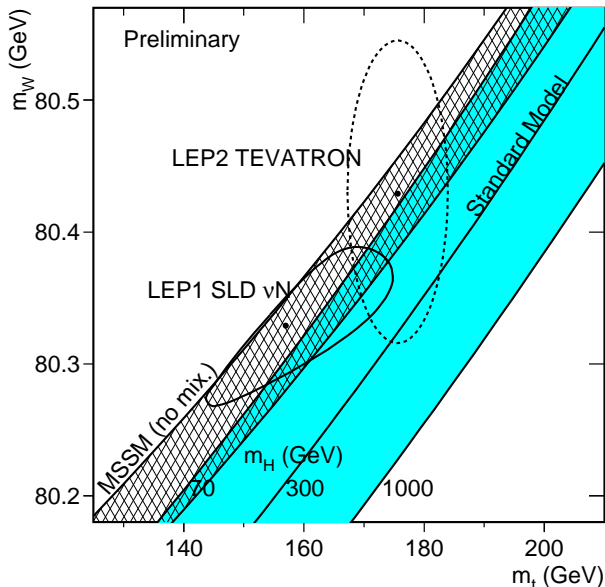


Figure 1: Measured t and W masses with error ellipses. In the MSM (grey region) light Higgs boson masses are favored. The hatched area shows the prediction in the MSSM.

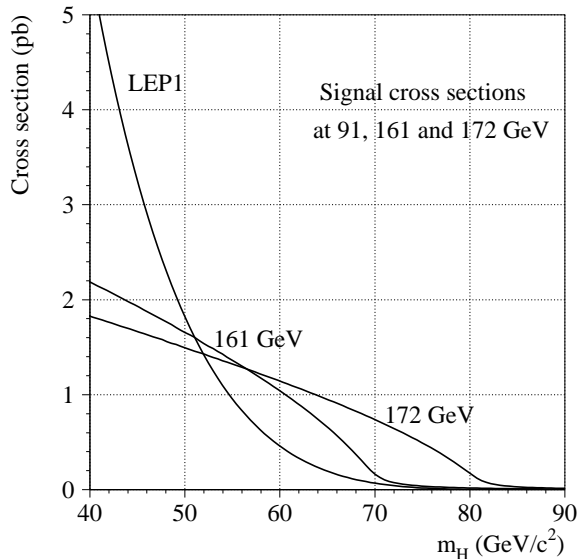


Figure 2: Cross section for the MSM Higgs production $e^+e^- \rightarrow ZH$ at different center-of-mass energies.

2 MSM Higgs Boson Results

For the MSM Higgs boson search, only the LEP2 data taken at the highest center-of-mass energy are relevant. Figure 2 (from [8]) shows the Higgs boson production cross sections for LEP1 at $\sqrt{s} = 91$, and LEP2 at $\sqrt{s} = 161$ and 172 GeV. For Higgs boson masses above about 70 GeV, the 172 GeV data dominates the production cross section. The Higgs and Z decay

modes determine the event signature in the detector. The most important characteristic is that Higgs decays predominantly ($\sim 86\%$) into bb . Each experiment has performed searches in the final states listed in Table 1.

Final states	Branching fraction (in %)
$(Z \rightarrow qq)(H \rightarrow qq)$	64
$(Z \rightarrow \nu\nu)(H \rightarrow qq)$	18
$(Z \rightarrow ee, \mu\mu)(H \rightarrow qq)$	6.2
$(Z \rightarrow \tau\tau)(H \rightarrow qq)$	3.1
$(Z \rightarrow qq)(H \rightarrow \tau\tau)$	5.4

Table 1: Final-state particles in the analyzed Higgs channels and approximate branching fractions.

The four LEP experiments have chosen different event selection strategies with respect to the number of expected background events. ALEPH uses a very tight event selection, such that less than one background event is expected. No candidate event is observed in their data. DELPHI expects about four background events and observes two candidates. OPAL expects about four background events and also observes two candidates. Very loose cuts are applied by L3, where approximately ten background events are expected and six data events pass their selection for any mass hypothesis between 60 and 70 GeV. L3 uses different selection cuts for different mass regions; thus their total number of candidate events is 33, consistent with 38 expected background events. The two most important channels Hqq and $H\nu\nu$, with the largest expected event rates, are discussed:

- The Hqq channel has a four-jet event topology where one jet pair originates from hadronic Z decay, and the other from the Higgs decay. The Higgs boson decay branching fraction into a b -quark pair is about 85%; therefore, the search uses b -quark tagging to reduce the background from $WW \rightarrow qq\bar{q}\bar{q}$, and QCD background where gluon emission leads to multiple-jet events. Secondary vertices arise in b -quark events because of the production of long-lived B -mesons.
- In the $H\nu\nu$ channel, events are characterized by two acoplanar jets carrying b -flavor and large missing mass compatible with the Z mass. Background are qq events where either one jet is mismeasured or an energetic neutrino is produced in a semileptonic decay. Other reactions leading to missing energy are $WW \rightarrow l\nu qq$ and $We\nu \rightarrow qqe\nu$ where the charged lepton escaped detection. For an efficient b -quark tagging, secondary vertices are reconstructed in three dimensions as shown for example in Fig. 3 (from [9]). In general, events with undetected particles along the beam pipe from two-photon events and hard initial photon radiation lead to the missing energy signature. Dedicated cuts for each process reduce such background while maintaining high selection efficiencies.

Table 2 (from [10] based on [8, 9, 11, 12]) gives the expected background, the simulated detection efficiencies and the numbers of expected signal events for all channels. Candidate events are listed for DELPHI and OPAL in Table 3 and are given for L3 in Fig. 4. No indication of a signal is found in the reconstructed mass spectrum. L3 attributes a weight to each candidate and the remaining candidates are more background- than signal-like.

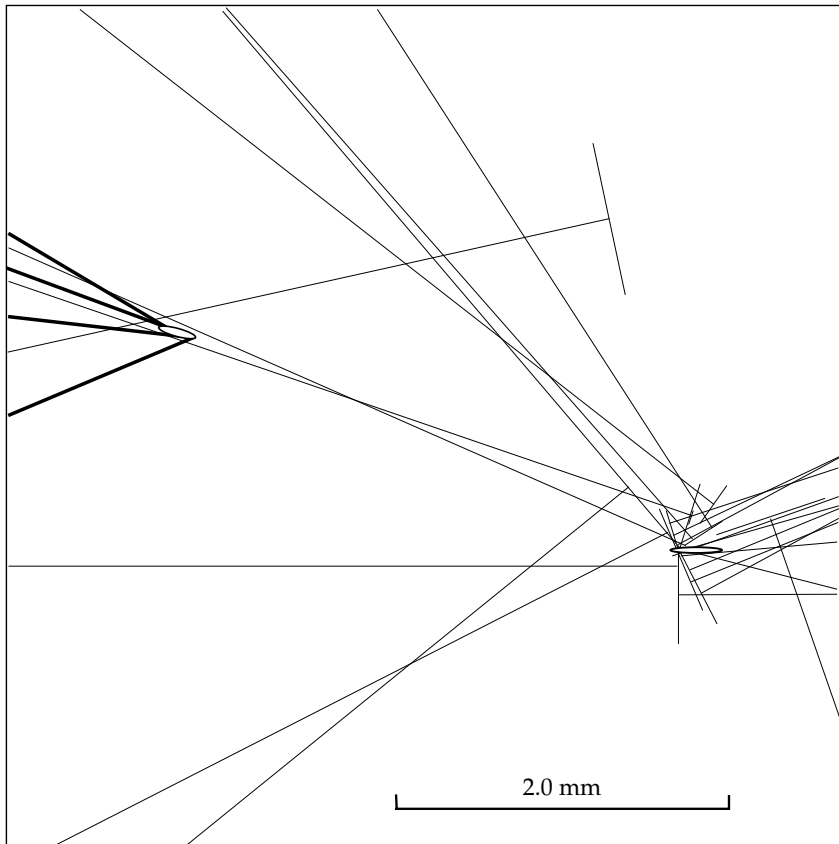
Lower limits on the Higgs boson mass are derived. In the absence of candidates the 95% CL limit is set where 3.0 signal events are expected. Candidates increase the number of expected signal events required according to their mass resolution. An overview of the mass limits is given in Table 4 and details for each experiment are shown in Figs. 5 to 8 (from [8, 9, 11, 12]).

Very preliminary results of the 1997 data-taking at 183 GeV are summarized in Table 5 (from [13]). The larger part of the data collected in 1997 is analysed using mostly the analyses tuned for lower energies. Hence, sensitivities are expected to increase by optimization for the new data. At a later stage the combination of the data from the LEP experiments will significantly increase the sensitivity.

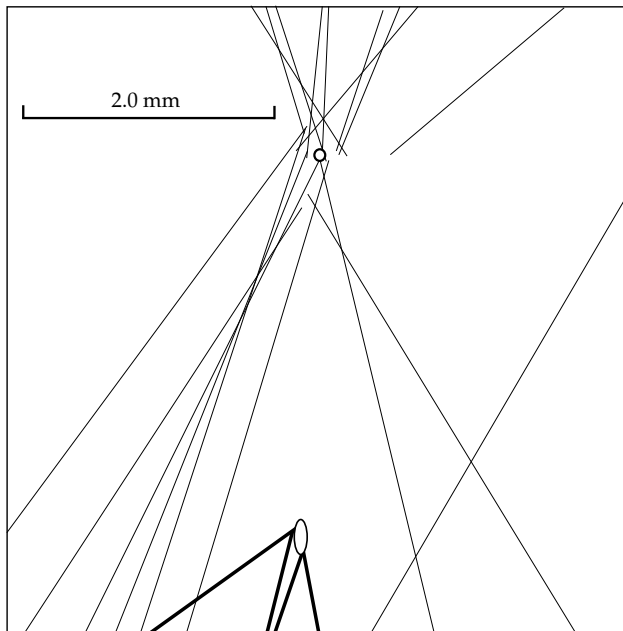
Final state	Background		Efficiency(%)		N_{exp}	
ALEPH						
Hqq	0.17	0.23	21.1	21.9	0.24	1.12
$H\nu\nu$	0.06	0.09	26.3	42.9	0.11	0.70
$H(ee, \mu\mu)$	0.06	0.11	64.2	74.8	0.08	0.40
$H\tau\tau$	0.02	0.02	18.8	20.4	0.01	0.05
$\tau\tau qq$	0.05	0.03	17.4	17.4	0.02	0.07
Total	0.36	0.48			0.46	2.34
DELPHI						
Hqq	0.30	0.50	21.6	23.6	0.25	1.21
$H\nu\nu$	0.65	0.61	36.3	42.8	0.12	0.63
Hee	0.13	0.20	41.7	37.2	0.02	0.09
$H\mu\mu$	0.04	0.13	69.0	69.8	0.04	0.17
$qq\tau\tau$	0.31	0.22	22.9	24.4	0.01	0.06
$\tau\tau qq$	0.32	0.91	22.1	24.4	0.02	0.10
Total	1.74	2.50			0.46	2.26
L3						
$qqqq$	0.77	3.68	28.1	38.5	0.37	1.87
$qq\nu\nu$	0.40	1.46	46.0	69.4	0.17	0.97
$qqee$	0.03	0.18	45.5	65.8	0.03	0.15
$qq\mu\mu$	0.04	0.15	34.4	48.3	0.02	0.11
$qq\tau\tau$	0.008	0.23	13.5	34.9	0.01	0.08
$\tau\tau qq$	0.0	0.25	0.0	17.7	0.0	0.07
Total	1.25	5.96			0.60	3.26
OPAL						
$bbqq$	0.75	0.88	30.8	28.2	0.35	1.29
$qq\nu\nu$	0.90	0.55	38.1	41.3	0.16	0.66
Hee	0.06	0.08	52.6	65.3	0.04	0.17
$H\mu\mu$	0.04	0.06	67.8	70.6	0.04	0.18
$qq\tau\tau$	0.10	0.41	17.3	21.7	0.01	0.05
$\tau\tau qq$	0.06	0.18	17.0	19.3	0.02	0.08
Total	1.91	2.16			0.62	2.43

Table 2: Expected background, signal efficiency, and the expected numbers of signal events for a Higgs boson mass of 70 GeV. In each column, the entries on the left are for 161 GeV and those on the right for 170 to 172 GeV.

X - Y projection



Z - X projection



Z - Y projection

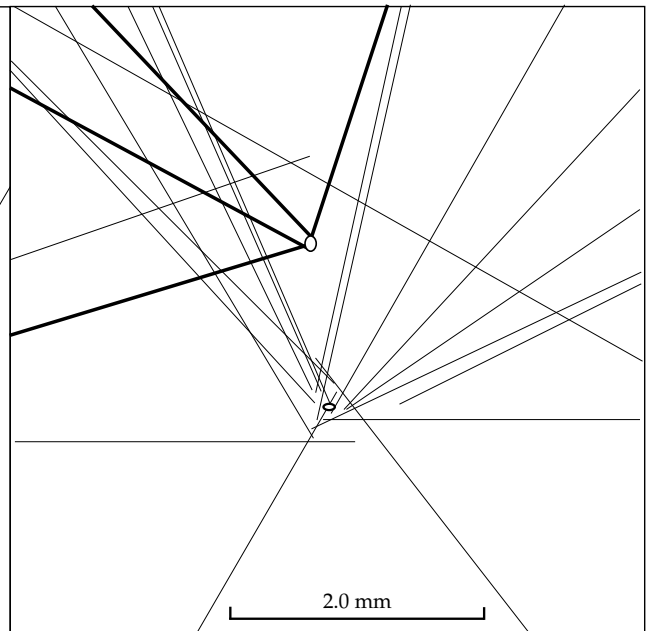


Figure 3: DELPHI tagging of b -quark jets for the example of the $H\nu\nu$ candidate. Primary and secondary vertices are shown in three dimensions. The bold-faced tracks define the secondary vertex.

Experiment	Channel	\sqrt{s} (GeV)	Mass (GeV)
DELPHI	Hqq	172	58.7 ± 3.5
	$H\nu\nu$	161	64.6^{+5}_{-3}
OPAL	Hqq	172	75.6 ± 3.0
	$H\nu\nu$	161	39.3 ± 4.9

Table 3: Candidate events from DELPHI and OPAL. Their number is in agreement with the background expectation and no peak in the reconstructed invariant mass distribution is observed.

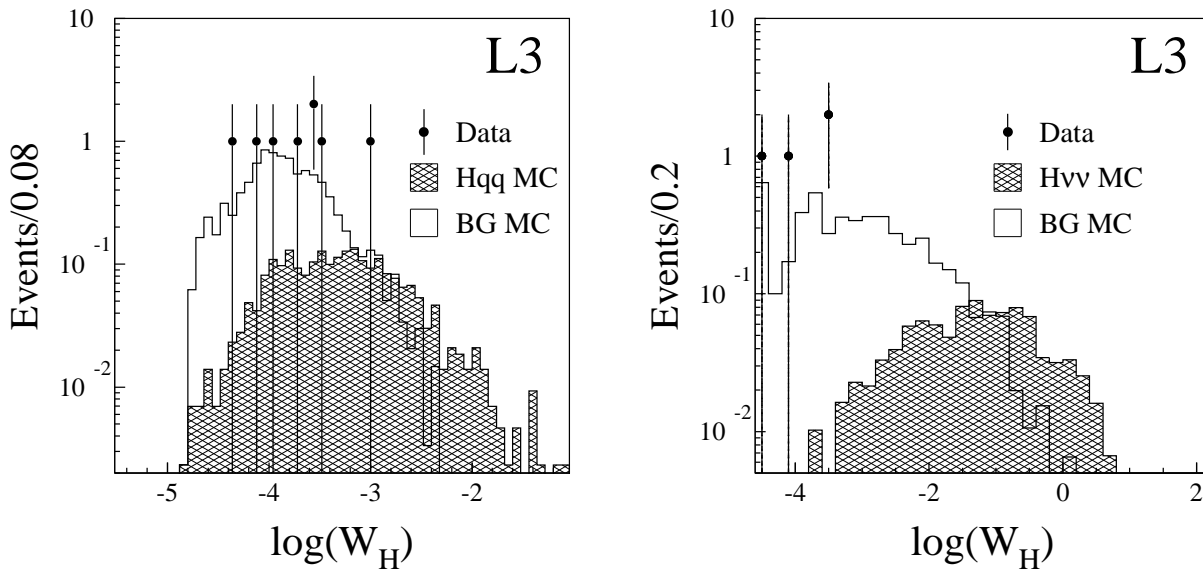


Figure 4: L3 candidates in the Hqq channel (left) and the $H\nu\nu$ channel (right). The weights of the candidates are shown compared to background (open histogram) and signal (hatched histogram).

Experiment data set	Limit(GeV) 161/172	Limit(GeV) & LEP1	Background 161/172	Candidate 161/172
ALEPH	69.6	70.7	0.84	0
DELPHI	66.2	—	4.24	2
L3	69.3	69.5	38.1	33
OPAL	68.9	69.4	4.07	2

Table 4: Individual Higgs boson mass limits at 95% CL for 161 to 172 GeV data, and in combination with LEP1 data. The numbers of background and candidate events are given.

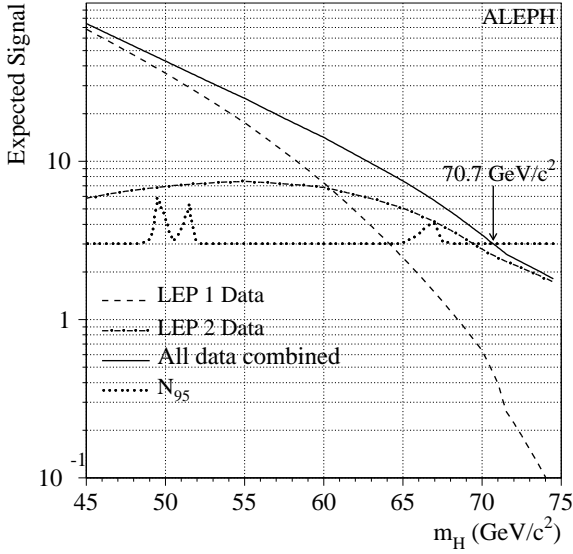


Figure 5: ALEPH MSM Higgs boson mass limit including data up to 172 GeV.

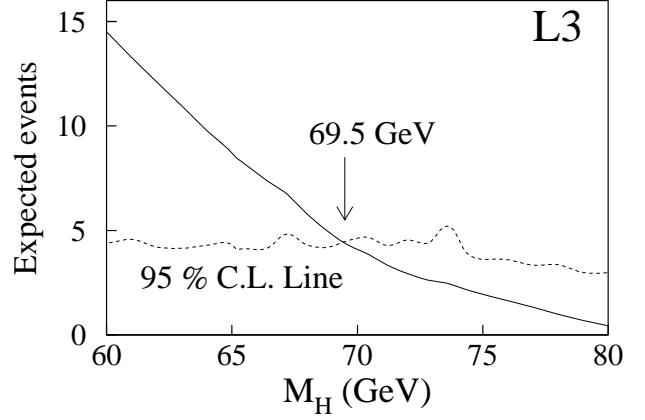


Figure 7: L3 MSM Higgs boson mass limit including data up to 172 GeV.

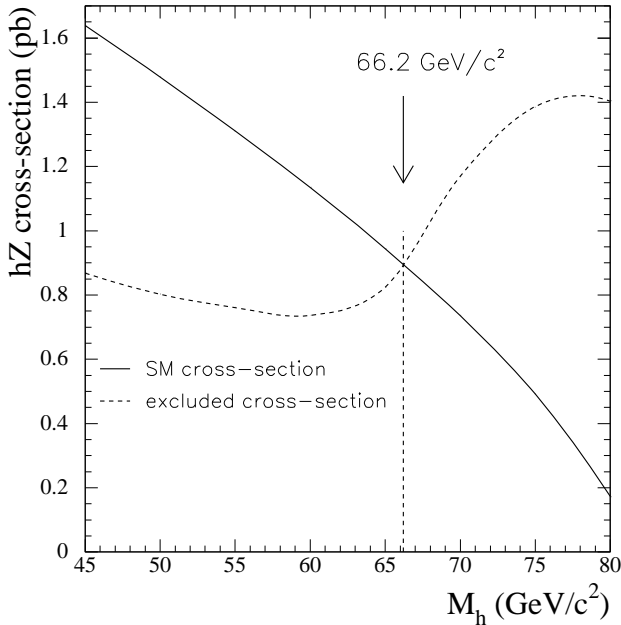


Figure 6: DELPHI MSM Higgs boson mass limit including data up to 172 GeV.

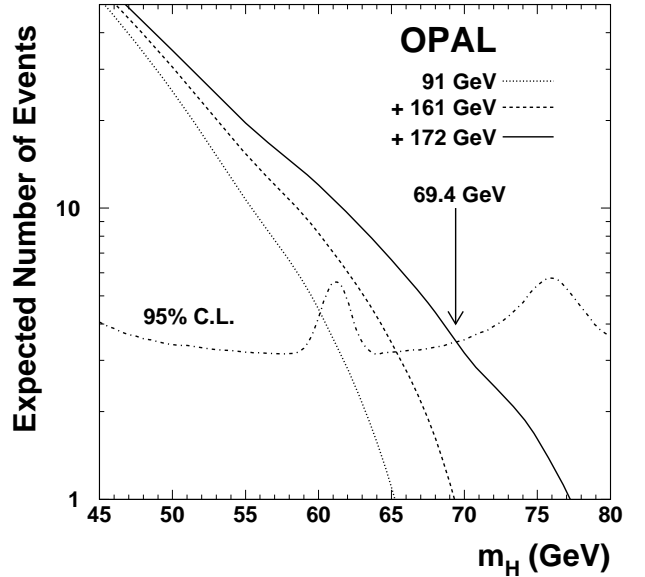


Figure 8: OPAL MSM Higgs boson mass limit including data up to 172 GeV.

Experiment	Limit (GeV)		\mathcal{L} (pb^{-1})
ALEPH	83	88.6	55
DELPHI	85.8	83.6	53.5
L3	81.3	82.2	36
OPAL	—	82	39

Table 5: Preliminary expected (left) and observed (right) MSM Higgs boson mass limits at 95% CL for the luminosity \mathcal{L} of analysed 183 GeV data. ALEPH, DELPHI and L3 have also released their preliminary expected mass limits. Higher (lower) observed limits than expected limits correspond to slightly less (more) data events observed than expected from the background.

3 Combined MSM Higgs Boson Results

Much progress has been made recently in combining the LEP results [10]. Different statistical methods of ALEPH [14], DELPHI [15], L3 [16], and OPAL [17] are used and compared in order to derive a 95% CL lower limit on the MSM Higgs mass. The different statistical methods satisfy the following criteria:

- The limit should be at least at the 95% CL and come close to the desired 5% false exclusion rate of the Higgs boson hypothesis.
- The order of the combination of different channels should not change the final limit.
- The expected limit from combining two channels should exceed the limit from any single channel.
- Candidate events which are incompatible with the Higgs boson hypothesis should not change the mass limit.

The fact that a background fluctuation should not give a stronger limit on the Higgs boson hypothesis is taken into account by DELPHI, L3 and OPAL using the modified frequentist definition of the confidence level [18]:

$$1 - CL = P(X_{s+b} \leq X_{\text{obs}}) / P(X_b \leq X_{\text{obs}}),$$

while ALEPH uses a more conservative definition without background subtraction:

$$1 - CL = P(X_s \leq X_{\text{obs}}),$$

where X_s , X_b , and X_{obs} stand for signal, background, and observed distribution functions to separate signal and background. Both definitions give better confidence levels than the claimed ones, however, the former definition tends to be closer to the claimed confidence level, especially for a large number of background events.

The following methods are used by the four LEP experiments to set a limit:

- ALEPH: The distribution function is defined as

$$X = \prod_{i=1}^n c_i^{a_i}(m_H),$$

where c_i are the confidence levels for $i = 1, \dots, n$ different channels, and a_i are weight factors to ensure that an additional channel never degrades the confidence level. In this way, first experiments derive their own limits and, in a second step, the results are combined using a simple analytic function.

- DELPHI: The method uses a likelihood ratio which can be readily derived using Poisson statistics:

$$Q(m_H) = \prod_{i=1}^n e^{-(s_i+b_i)} (s_i + b_i)^{k_i} / \prod_{i=1}^n e^{-b_i} b_i^{k_i},$$

where s_i and b_i are the expected signal and background events, and k_i is the number of observed events for $i = 1, \dots, n$ different channels. More generally, taking the probability

distributions $S_i(m_H, m_{ij})$ and $B_i(m_{ij})$ of the invariant masses into account, the formula becomes

$$Q(m_H) = e^{-s_{\text{tot}}(m_H)} \prod_{i=1}^n \prod_{j=1}^{k_i} \left(1 + \frac{s_i(m_H) S_i(m_H, m_{ij})}{b_i B_i(m_{ij})}\right).$$

Weights are defined for each candidate $w_k = \ln(1 + s_k S_k / b_k B_k)$ where $\ln Q = -s_{\text{tot}} + X$ with $X = \sum_{k=1}^N n_k w_k$ and N the total number of candidates. With this distribution function, the confidence level is defined as

$$1 - CL = P\left(\sum_{k=1}^n n_k^{s+b} w_k \leq \sum_{k=1}^n n_k^{\text{obs}} w_k\right) / P\left(\sum_{k=1}^n n_k^b w_k \leq \sum_{k=1}^n n_k^{\text{obs}} w_k\right),$$

where the distribution of n_k^{s+b} and n_k^b are determined with MC simulation using Poisson statistics.

- L3: As for DELPHI, a likelihood function is defined for the *signal + background* hypothesis:

$$L(s, b) = e^{-(s+b)} \prod_{j=1}^k \frac{(s \cdot f_j + b \cdot g_j)^{n_j}}{n_j!}.$$

The index j runs over all k channels; f_j, g_j are the fractions of the total signal s and total background b , respectively, and n_j is the number of candidate events which fall into channel j .

The Bayesian confidence interval is used as distribution function. This requires an additional integration over the signal events:

$$X = \frac{\int_{\mu^H}^{\infty} L(s, b) ds}{\int_0^{\infty} L(s, b) ds},$$

where μ^H is the number of expected signal events, depending on the Higgs boson mass hypothesis. In order to come closer to the desired false exclusion rate, $1 - CL$ is defined as in the DELPHI case using MC simulations for signal-and-background, and signal-only hypotheses.

- OPAL: A weight is assigned to each candidate event using a weight function $F(m_i)$, where m_i is the mass of the i th candidate. The weight function is based on the difference between a Higgs mass hypothesis and the actual mass distribution of candidate i . In order to account for different signal and background ratios in channel k , the following weight function is defined:

$$F_k(m) = K(C + b_k s_{\text{tot}} / D_k^{\text{max}} s_k)^{-1} D_k(m) / D_k^{\text{max}},$$

where K is chosen to set the largest value of F_k to unity, and D is the mass distribution. The result is almost independent of the constant C . The distribution function is defined as

$$X = \sum_{k=1}^n F_k(m),$$

where n is the number of candidates in all channels.

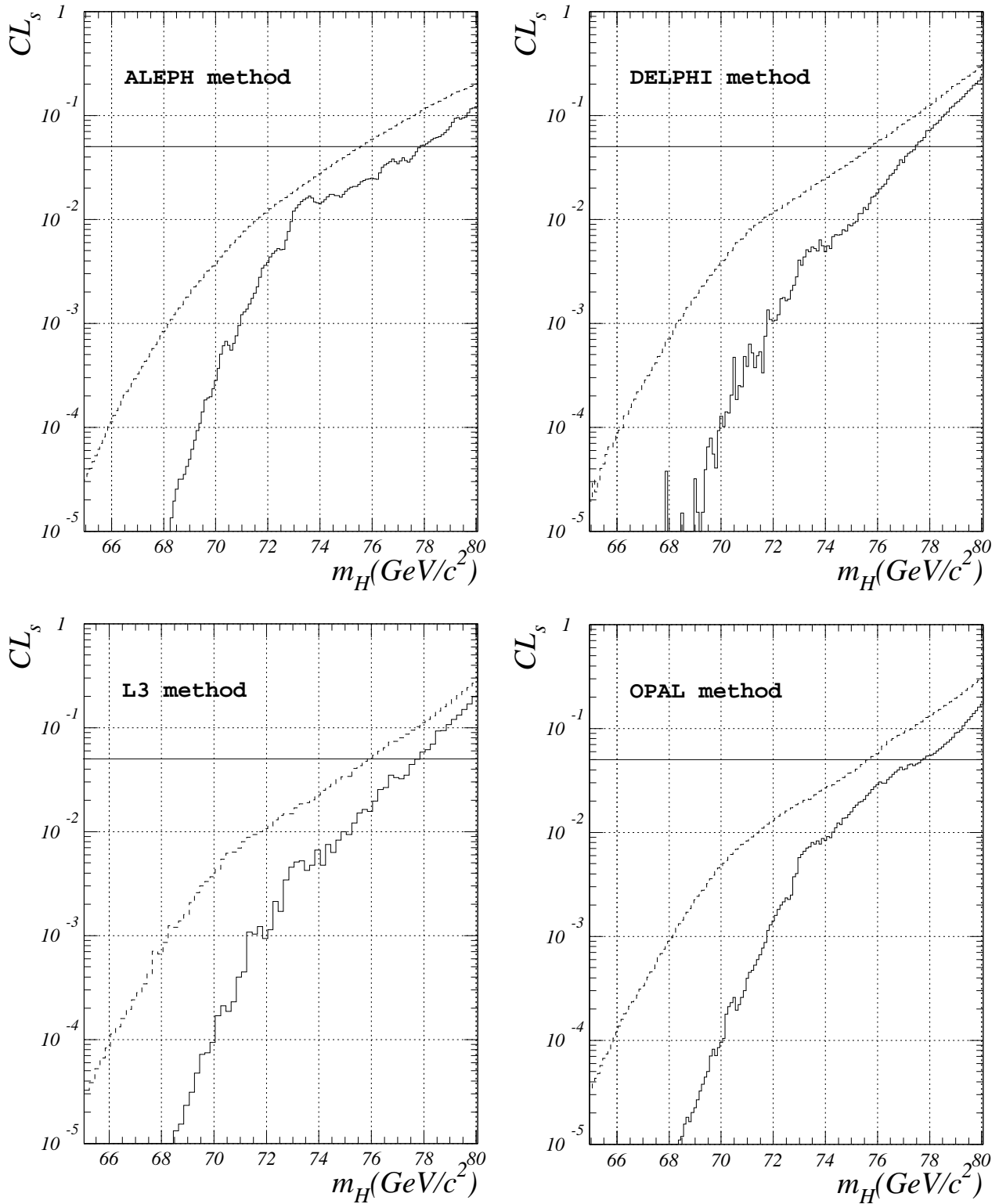


Figure 9: Expected (dashed line) and observed (full line) confidence levels, $1 - CL \equiv CL_s$, as a function of the hypothetical Higgs boson mass, obtained from combining the results of the LEP experiments using the four statistical methods. The intersections of the curves with the 5% horizontal line define the expected and observed 95% CL lower bounds for the mass of the MSM Higgs boson.

Figure 9 (from [10]) shows the combined Higgs boson mass limits using the four statistical methods. The small differences in the results are in part attributed to the different statistical ways of treating with candidates close to the mass limits. Table 6² (from [10]) compares the expected and observed mass limits for the four statistical methods. The observed mass limits are about 2 GeV larger, since the number of observed candidate events is slightly below the number of expected background events. For the combined limit, the background-only confidence level is between 26% and 35% depending on the statistical method, and thus the data are consistent with the background.

Experiment	Statistical method							
	ALEPH		DELPHI		L3		OPAL	
ALEPH	68.5	69.6	68.5	69.6	68.8	69.6	68.6	69.6
DELPHI	-	-	65.4	65.9	65.3	65.9	65.1	65.5
L3	-	-	66.1	69.4	65.7	69.3	65.0	68.2
OPAL	-	-	65.9	69.0	65.6	68.6	65.3	68.9
LEP	75.7	77.9	75.8	77.5	76.0	77.8	75.6	77.7

Table 6: Expected (left) and observed (right) 95% CL mass limits (in GeV) for the individual experiments and for LEP combined using, in each case, the four statistical methods. The entries in the first column pertaining to the DELPHI, L3 and OPAL experiments are empty since the ALEPH method does not recalculate the individual limits.

The interest of electroweak working groups in the direct limits resulted in the following proposal on how to combine the results [10]. First, note that the information given is more detailed than for a Higgs boson mass limit at the 95% CL. Furthermore, the confidence levels are either less than or equal to the signal probability. If one wishes to combine these Higgs boson confidence levels with line-shape data using a χ^2 method, the interpretation of the confidence-level as a probability and the conversion of the confidence-level values would lead to a lower bound on the $\Delta\chi^2$. If one wishes to set upper Higgs boson mass limits in combination with other data using Bayesian methods, the lower $\Delta\chi^2$ bound would not be conservative. Consequently, the given confidence levels are not suitable as a basis for combining the direct limits with other results.

A $\Delta\chi^2$ defined from a likelihood ratio could then directly be combined with indirect results. The likelihood ratio $Q(m_H) \equiv L_{s+b}/L_b$ corresponding to the signal-and-background and the background-only hypotheses is given in the DELPHI statistical method. Figure 10 (from [10]) shows the resulting

$$\Delta\chi^2 = -2(\ln L(m_H) - \ln L(m_H = \infty)) = -2 \ln Q(m_H).$$

The curve of $\Delta\chi^2(m_H)$ obtained in this manner is shown up to $m_H = 80$ GeV (solid line). The combination of the direct searches from the four experiments was not pursued to higher values. An extrapolation to m_H beyond 80 GeV is provided by a parabolic fit, performed in the domain $70 < m_H < 80$ GeV,

$$\Delta\chi^2(m_H) \approx 0.0743 (m_H - 85.7)^2, \quad (1)$$

which is shown by the dashed-line curve. The extrapolation is a rough estimate, since threshold effects of the Higgs boson production cross section are not considered.

²Small differences in comparison with Table 4 exist because of the updated statistical methods.

This method of deriving a $\Delta\chi^2$ is identical to the method proposed in [19] where the likelihood L_{s+b} is used instead of the likelihood ratio for the special case in which the background does not depend on the Higgs boson mass hypothesis. However, for the L3 experiment the likelihood L_b is a function of the Higgs boson mass. Furthermore, a Bayesian interpretation shows that the information gain due to direct searches is given by the likelihood ratio, when the ‘a priori’ probability for the signal is small [7].

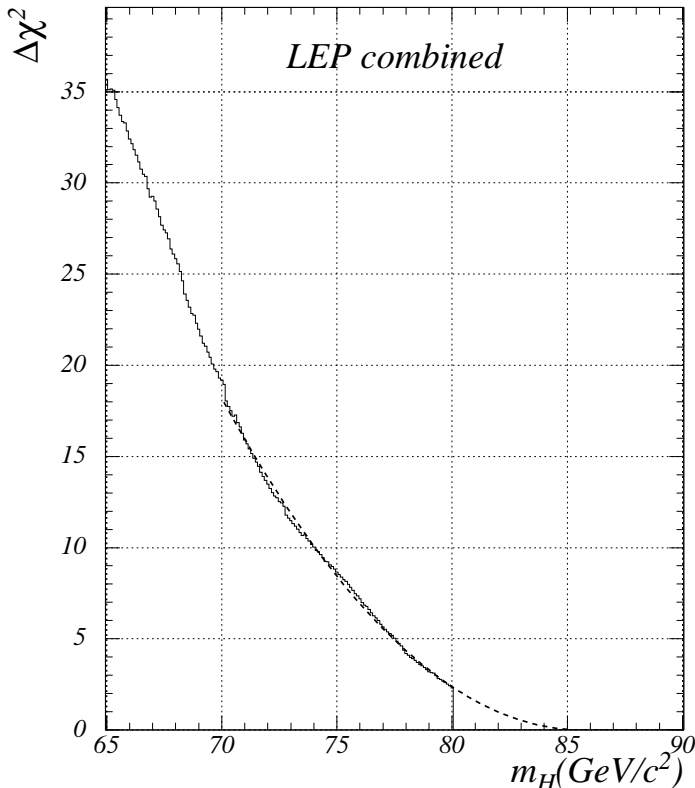


Figure 10: $\Delta\chi^2$ as a function of the Higgs boson mass from direct searches (solid line). The extrapolation to $m_H > 80$ GeV is obtained by a parabolic fit in the domain $70 < m_H < 80$ GeV.

4 Two Higgs Doublet Results

In the general framework of the two Higgs doublet model, five physical Higgs bosons are predicted: two CP-even Higgs bosons, h and H , a CP-odd Higgs boson, A , and two charged Higgs bosons, H^\pm . Searches for these Higgs bosons are performed in the MSM Higgs boson channels with suppressed production rates, and for Higgs boson pair-production. The β -parameter is defined as the ratio of the vacuum expectation values of the two Higgs doublets and α is the mixing angle of the CP-even Higgs bosons. The results of the MSM Higgs search can be interpreted as limits in the Higgs mass and $\sin^2(\beta - \alpha)$ parameter plane as shown for example in Fig. 11 (from [20]). These results from ALEPH include the LEP1 data and the effects of their three LEP1 candidates are visible.

The charged Higgs boson production and decay processes are:

$$e^+e^- \rightarrow H^+H^- \rightarrow cscs, cst\nu, \text{ and } \tau\nu\tau\nu.$$

The resulting signatures are events with four jets, two jets, a τ lepton and missing energy, and two τ leptons with large missing energy. No signal has been observed. The excluded mass

region is shown in Fig. 12 (from [21]) as a function of the hadronic decay branching fraction. Limits from the four LEP experiments are given in Table 7 [22, 21, 24, 23]³.

Experiment	Limit (GeV)
ALEPH	52
DELPHI	54.5
L3 ^a	41.0
OPAL	52.0

Table 7: Charged Higgs boson mass limits of the four LEP experiments.

^aBased on LEP1 data only.

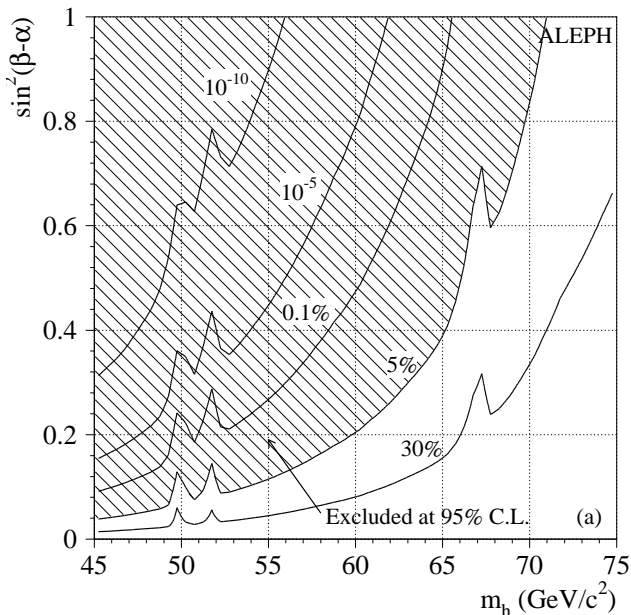


Figure 11: ALEPH $\sin(\beta - \alpha)$ limit.

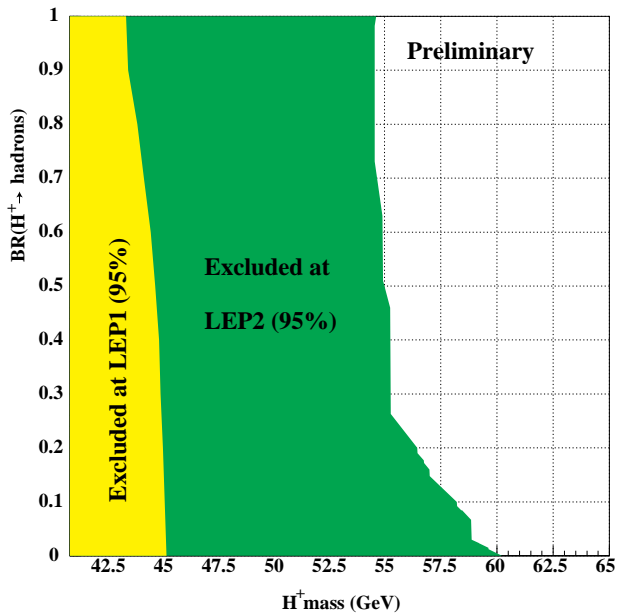


Figure 12: DELPHI charged Higgs boson mass limit.

The search results for neutral Higgs boson pair-production, $e^+e^- \rightarrow hA$, are presented from DELPHI for the cases in which the Higgs bosons decay mainly into b -quarks (like the MSM Higgs decays) and into non- b quarks. Since no b -tagging can be applied in the latter case, the detection sensitivity is lower. Note that the decay $h \rightarrow AA$ is CP-conserving and that this channel leading to six quarks has been investigated separately. No indication of a signal has been observed and significantly improved limits compared to LEP1 are given in Fig. 13 (from [25]). In the more general framework where CP is not conserved [26], the decay $A \rightarrow hh$ is also possible and Fig. 14 (from [25]) shows the resulting limits.

In the case of an additional Higgs boson singlet, a massless Higgs particle exists. It is called the Majoron and does not interact with the standard particles. The massive Higgs bosons could decay into a pair of these massless Higgs particles and thus their decay would be invisible. The search signature is very similar to that for the $H\nu\nu$ channel and the four LEP experiments have set mass limits. For example, Fig. 15 (from [27]) gives mass limits under the assumption that the Higgs boson is produced with the MSM rate and the decay is completely invisible (plot a), and plot (b) shows limits on the production ratio $R_{\text{inv}} \equiv \sigma(Zh)BR(h \rightarrow \text{invisible})/\sigma(ZH_{\text{MSM}})$.

Based on general searches for a photon pair and missing energy, limits are also set on the branching fraction $BR(H \rightarrow \gamma\gamma)$ as shown for example in Fig. 16 (from [28]).

³Note the indirect limits from the decay $b \rightarrow s\gamma$ [18].

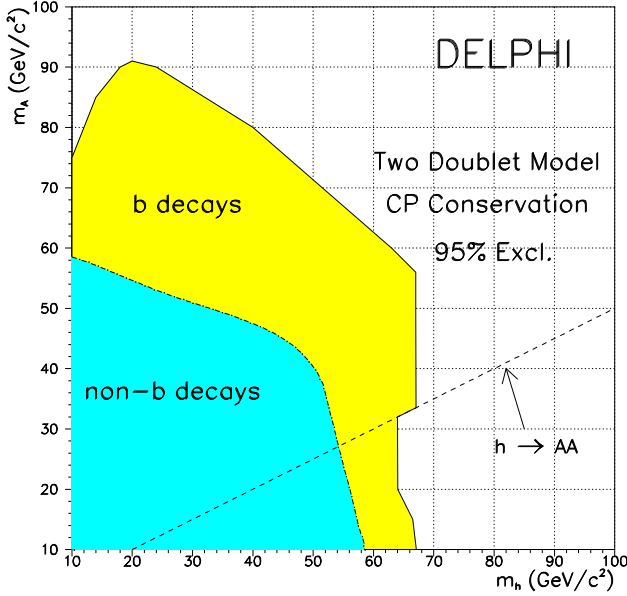


Figure 13: DELPHI (m_h, m_A) limit for CP conservation in the Higgs sector.

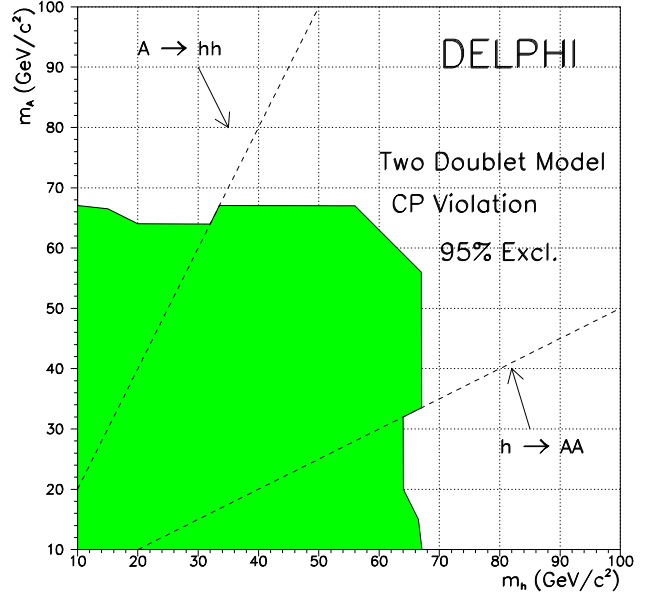


Figure 14: DELPHI (m_h, m_A) limit for CP violation in the Higgs sector.

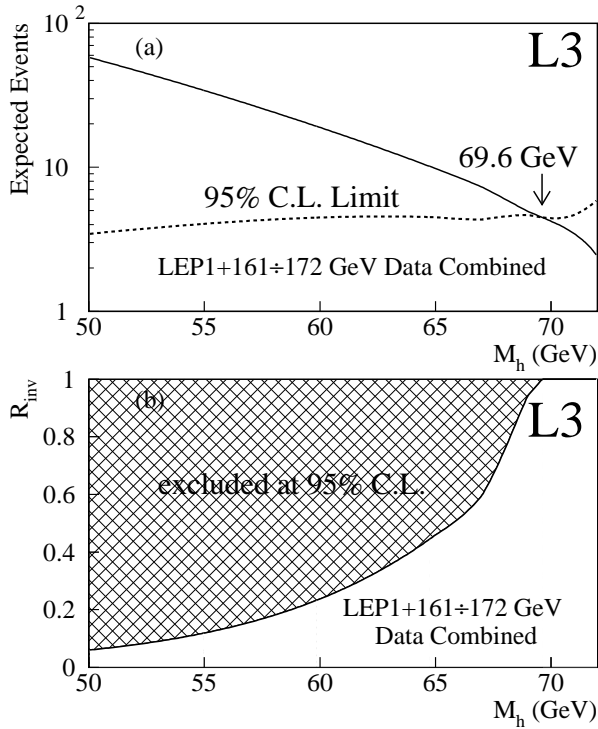


Figure 15: L3 mass limit for invisibly decaying Higgs bosons (a), and limits on the production rate as defined in the text (b).

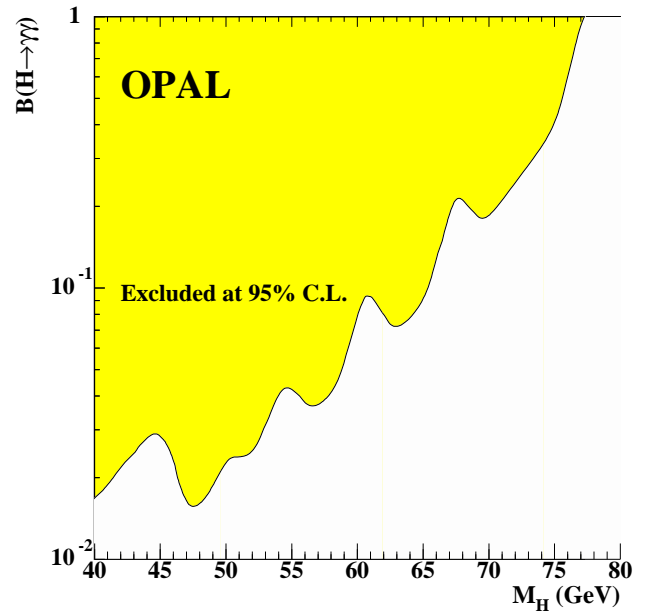


Figure 16: OPAL branching-fraction limits for Higgs boson decays into a photon pair.

5 MSSM Interpretation

In the Minimal Supersymmetric extension of the Standard Model (MSSM), Higgs boson masses and production cross section are related. At the tree-level, only two free parameters describe the Higgs boson sector. Typically, the parameter sets are (m_h, m_A) , $(m_h, \tan\beta)$, or $(m_A, \tan\beta)$. As an example, Fig. 17 (from [20]) gives the cross section for the reaction $e^+e^- \rightarrow hA$ for $\tan\beta = 10$ as a function of m_h . Unlike for the MSM Higgs boson search, 161 and 172 GeV data are almost equally important.

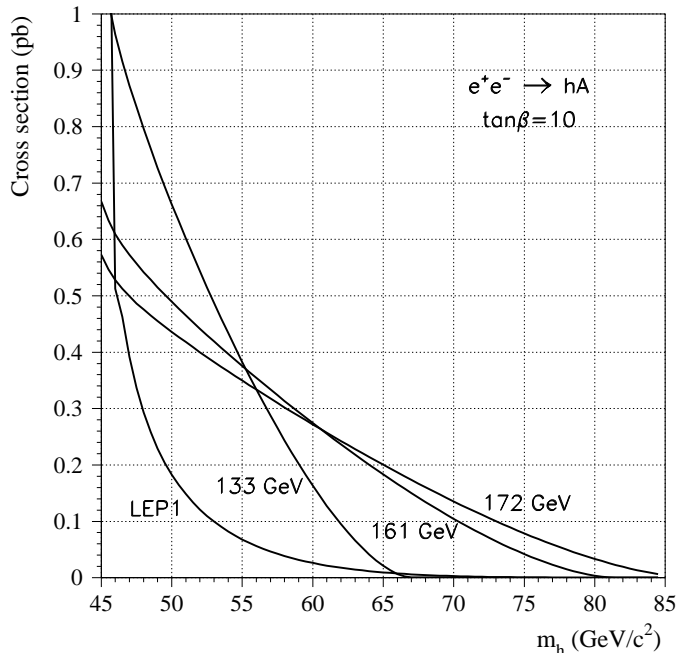


Figure 17: Cross sections for hA Higgs boson pair-production at various center-of-mass energies for $\tan\beta = 10$ ($m_h \approx m_A$).

Interpretations of the ALEPH and DELPHI results are given in Figs. 18 (from [20]) and 19 (from [9, 13]). Three regions are shown: the excluded region at 95% CL from the $e^+e^- \rightarrow hZ$ and hA searches combined, the theoretically disallowed region and the unexcluded region where a discovery is possible. The boundaries are given for three choices of mixing in the scalar top sector. This distinction is made because of the important radiative correction effects which modify the Higgs boson production rates. These radiative corrections are determined by various other parameters of the MSSM, most importantly by the top and scalar top masses. The following (SUSY) parameter sets are used as proposed in [29]:

- $m_t = 175$ GeV, the top mass.
- $m_{sq} = 1000$ GeV (also called M_{SUSY}), the common mass parameter for all scalar quarks.
- $m_g = 1000$ GeV, the gaugino mass.
- $\mu = -100$ GeV (no and typical mixing), and $\mu = 1000$ GeV (maximal mixing), the mixing parameter of the Higgs doublets in the MSSM superpotential.
- $A = 0$ (no mixing), $A = 1$ (typical mixing), and $A = \sqrt{6}$ (maximal mixing), the mixing parameter in the scalar fermion sector, defined such that the mixing is proportional to Am_{sq} .

Note that for the low $\tan\beta$ region the hZ searches, and for the large $\tan\beta$ region the hA searches determine the exclusion boundary. Figure 19 gives a preliminary bound $\tan\beta > 1.7$ independent of m_h for the no-mixing case. In the framework of the above parameter sets, ALEPH and DELPHI report preliminary results of $m_h > 73$ GeV at 95% [13].

In addition to the fixed sets of parameters, this article presents an independent variation of the SUSY parameters. Cancellation effects of production cross sections can occur and thus some parameter regions are not excluded in this more general framework, as pointed out for LEP1 data in [30]. The SUSY parameters described above are varied in the following ranges:

- $0.5 < \tan \beta < 50$.
- $200 < m_{sq} < 1000$ GeV.
- $200 < m_g < 1000$ GeV.
- $-500 < \mu < 500$ GeV.
- $-1 < A < 1$.

Each SUSY parameter combination defines the masses of neutralino, chargino and stop. Conservative experimental limits on these masses, which exclude some parameter combinations, are taken into account. No theoretical constraints on the MSSM are assumed.

The excluded regions are shown in Fig. 20 in the (m_h, m_A) plane based on the DELPHI 161 to 172 GeV results. The exclusion of an important region depends on the choice of the SUSY parameters (central grey region). In particular, no lower mass limit on either Higgs boson mass exists. Examples of unexcluded SUSY parameter combinations leading to suppressed bremsstrahlung cross sections and large m_h and m_A mass differences are given in Table 8⁴.

m_h	m_A	m_t	m_{sq}	m_g	μ	A	$\tan \beta$	$m_{\tilde{t}_1}$	$m_{\tilde{t}_2}$	σ_{hZ}^{161}	σ_{hA}^{161}	σ_{hZ}^{172}	σ_{hA}^{172}
52.7	63	175	200	100	-500	1	6	220	299	0.46	0.24	0.41	0.23
74.5	12	175	1000	100	-500	0	0.66	1001	1079	0.0	0.11	0.57	0.10

Table 8: Examples of unexcluded parameter combinations in the MSSM. Cross sections for Higgs boson bremsstrahlung and pair-production are given for $\sqrt{s} = 161$ and 172 GeV. All masses are given in GeV and cross sections in pb.

The same variation is repeated assuming four times the luminosity, which corresponds approximately to the combined result of the four LEP experiments. Figure 21 shows that the mass region where the exclusion depends on the set of SUSY parameters is largely excluded at the 95% CL when the data are combined. A lower mass limit of about 60 GeV on the CP-even Higgs boson is set, while no mass limit on the CP-odd Higgs boson exists (for small m_A values, unexcluded parameter combinations exist for $0.5 < \tan \beta < 1$).

6 Prospects

Previously, detailed studies have been presented for the preparation of the LEP2 run and sensitivity ranges have been given [29]. In order to estimate the sensitivity reach of the current LEP2 run at 183 GeV, the SUSY parameter scan is repeated, assuming the same experimental performance and a total luminosity of 200 pb^{-1} , corresponding to 50 pb^{-1} for each LEP experiment. The MSSM prospects are given in Fig. 22. For large m_A the limit on m_h is equal to the limit on the MSM Higgs boson. Independent of the SUSY parameter choice, lower mass limits on CP-even and CP-odd Higgs bosons could be set. These limits are about 60 and 73 GeV,

⁴Other definitions in the literature are $m_g = M_2 \leftrightarrow 0.5M_2$, and $\mu \leftrightarrow -\mu$.

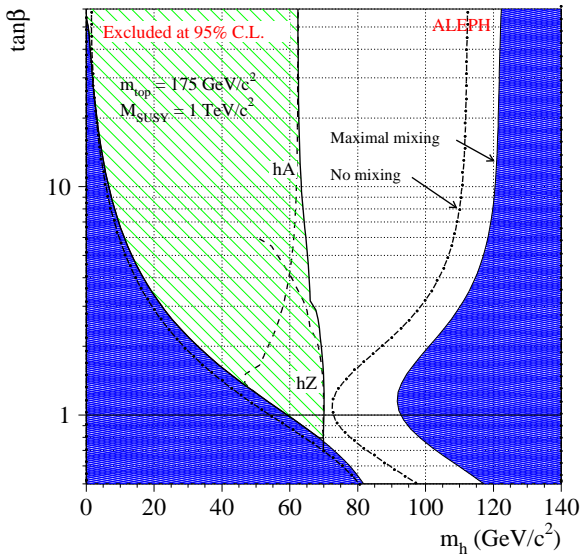


Figure 18: ALEPH MSSM exclusion for 161 to 172 GeV data. The dark region is theoretically not allowed, and the hatched region is excluded. The dashed lines indicate the ranges of exclusion from hZ and hA searches.

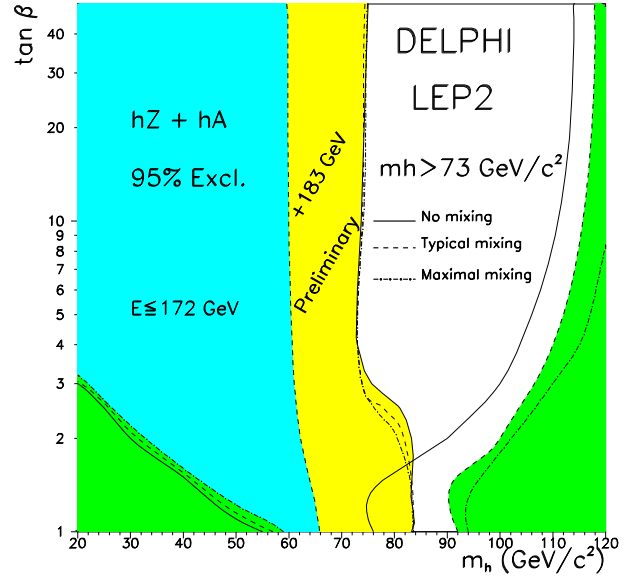


Figure 19: DELPHI MSSM exclusion for 161 to 172 GeV data. The dark region is theoretically not allowed, and the grey region is excluded. Preliminary results from 183 GeV data are included.

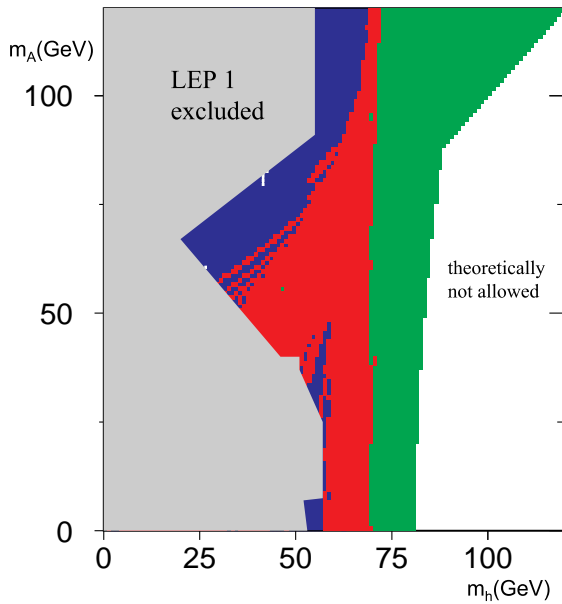


Figure 20: Interpretation of 161 to 172 GeV DELPHI data. The region excluded by LEP1 (very light grey), the newly 95% CL excluded region at LEP2 (dark), the region where the exclusion depends on the SUSY parameter set (grey), the region with no sensitivity (light grey), and the theoretically not allowed region (white) are shown.

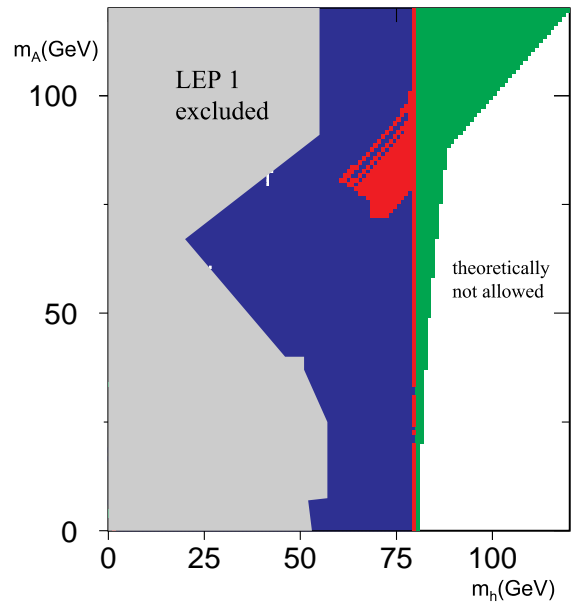


Figure 21: Interpretation of 161 to 172 GeV data from four experiments. The region excluded by LEP1 (very light grey), the newly 95% CL excluded region at LEP2 (dark), the region where the exclusion depends on the SUSY parameter set (grey), the region with no sensitivity (light grey), and the theoretically not allowed region (white) are shown.

respectively. For the combined data of the four LEP experiments these limits are about 76 and 83 GeV. The discovery reach is slightly lower, assuming a 5σ discovery effect, while the 95% CL exclusion corresponds to a 2σ effect. For the combined sensitivity of the four LEP experiments, a discovery of an 85 GeV MSM Higgs boson or the exclusion of a 90 GeV Higgs boson is anticipated with the 1997 data.

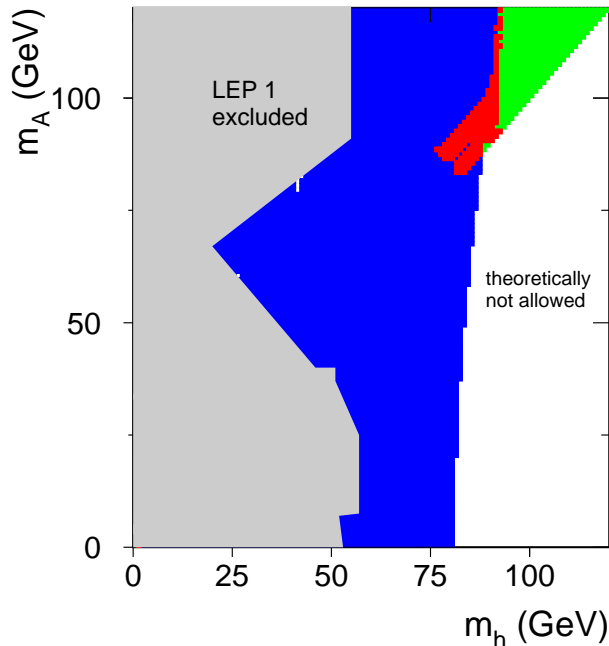


Figure 22: MSSM prospects for $\sqrt{s} = 183$ GeV and $\mathcal{L} = 200$ pb $^{-1}$. The region excluded by LEP1 (very light grey), the 95% CL sensitivity region at LEP2 (dark), the region where the sensitivity depends on the SUSY parameter set (grey), the region with no sensitivity (light grey), and the theoretically not allowed region (white) are shown.

It is exciting that a further energy increase to about 190 GeV is planned for 1998, with the potential to find a Higgs boson with a mass of about 95 GeV. Particular larger data statistics are needed to find the Higgs boson near the Z boson mass. A possible further energy increase to about 200 GeV at a later stage is discussed, which is strongly motivated in the MSSM by the fact that the lightest Higgs boson can be found for $\tan\beta < 2$, even for unfavorable values of the unknown SUSY parameters.

The sensitivity mass range for a charged Higgs boson depends largely on the total integrated luminosity, and will extend to about 70 GeV for $\mathcal{L} = 500$ pb $^{-1}$ [31, 29].

7 Conclusions

No Higgs boson signal has been observed. The Minimal Standard Model Higgs boson mass limit at the 95% CL is 77.5 GeV for combined 1996 data, and individual mass limits of up to 88.6 GeV are reported for 1997 data. Much progress has also been made in the searches for neutral and charged Higgs boson pair-production. Constraints on the parameters of the Minimal Supersymmetric extension of the Standard Model have significantly improved. The combination of the results from the four LEP experiments is and will be of great importance to significantly increase the discovery sensitivity and to determine the excluded mass regions. The LEP experiments have an excellent potential for a discovery during the next three years.

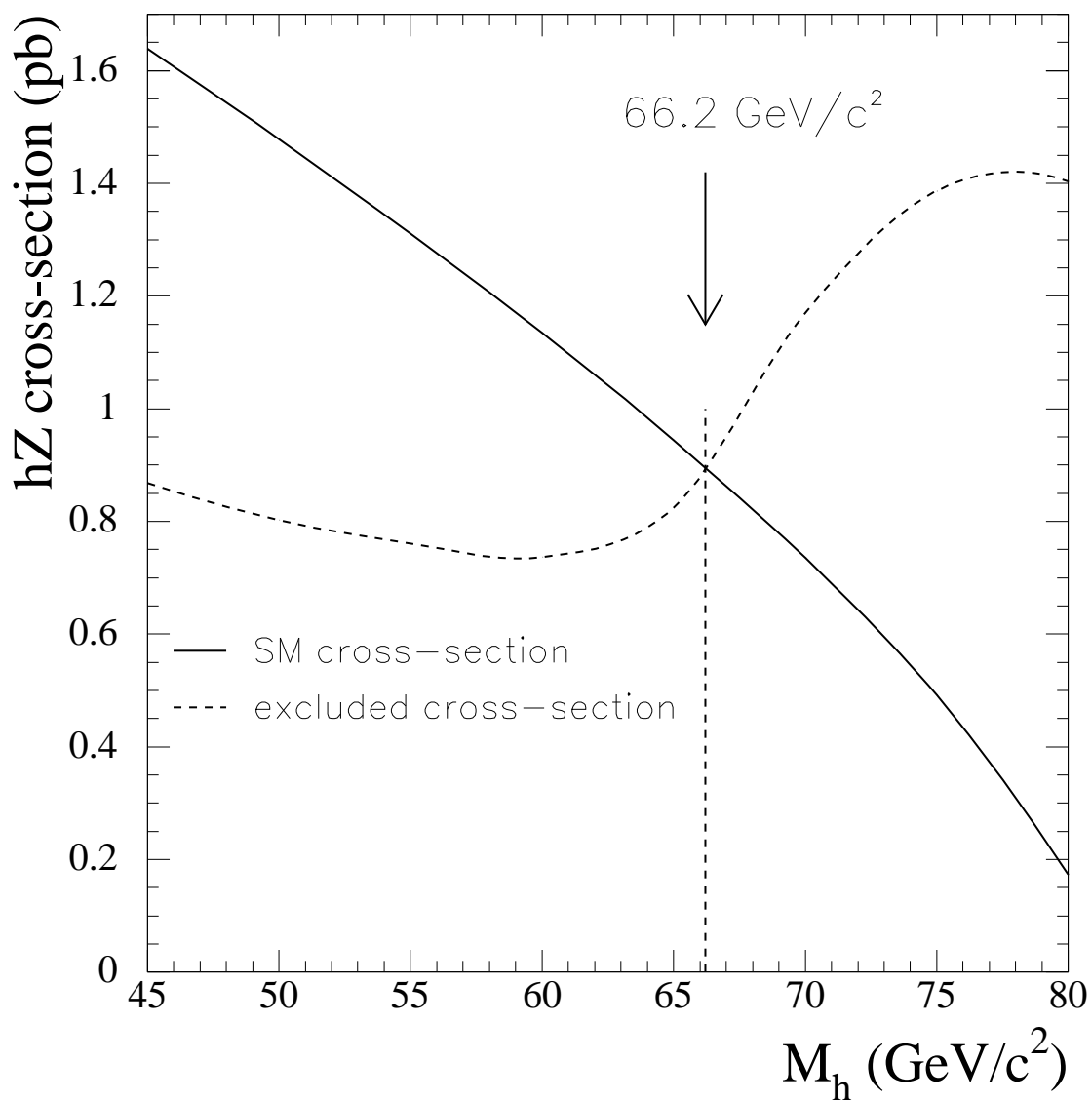
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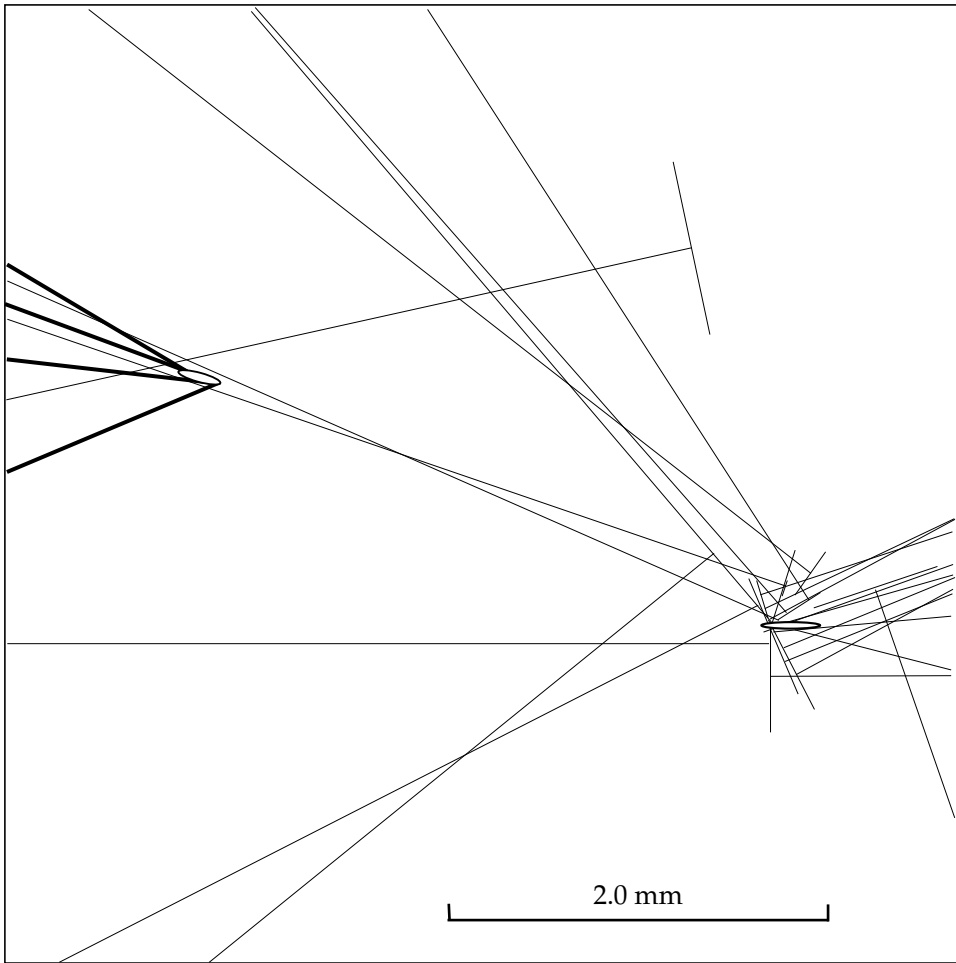
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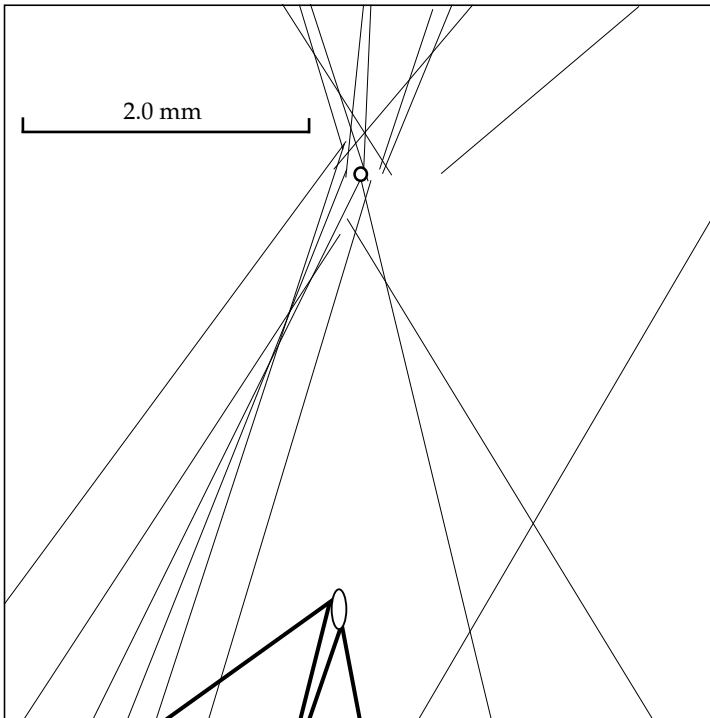
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X - Y projection



Z - X projection



Z - Y projection

