MSSM Constraints from Higgs Boson Searches

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The LEP era has brought immense progress in searches for Higgs bosons over the last 12 years which will guide searches at future colliders. The evolution of the Higgs boson mass limits is reviewed with the focus on results from general parameter scans in the Minimal Supersymmetric extension of the Standard Model (MSSM) in contrast to the so-called benchmark limits. The hint for a Standard Model (SM) Higgs boson of 115.6 GeV can also be interpreted as a preference for a Higgs boson of that mass in the MSSM. Further small data excesses allow the hypothesis that the neutral Higgs bosons of the MSSM all have masses between 90 and 116 GeV.

1. Introduction

The search for Higgs bosons has been one of the most important lines of research during the LEP era. Final LEP-1 results from data taken at the Z-resonance [1] and preliminary LEP-2 results for complete data up to 209 GeV center-of-mass energy [2] were recently reviewed. The MSSM is well motivated and the most discussed extension of the SM. It predicts three neutral (h, H, and A) and two charged Higgs bosons. At the beginning of LEP operation in 1989, no radiative corrections to the neutral Higgs boson masses were calculated and $m_\mathrm{h} < m_\mathrm{Z}$ was predicted. First- and second-order corrections increased the upper mass bound to about 130 GeV. The neutral Higgs boson masses and production cross sections strongly depend on various model parameters. At LEP two ways were chosen to present the mass limits: benchmark limits for a certain set of MSSM parameters and mass limits based on MSSM parameter scans. Details of the benchmark and scan parameters are given for example in Refs. [3,4].

2. Largely reduced h mass limit

The importance of a MSSM parameter scan to set mass limits was already realized at LEP-1. The region marked by the thick black line in Fig. 1 shows that the h mass limit is reduced from 41 to 25 GeV in a parameter scan compared to benchmark results [5,6].

3. Removal of A mass limit

An early LEP-2 study showed that a benchmark limit of 52 GeV on the A mass [7] disappeared completely in a MSSM parameter scan [8] (Fig. 2).

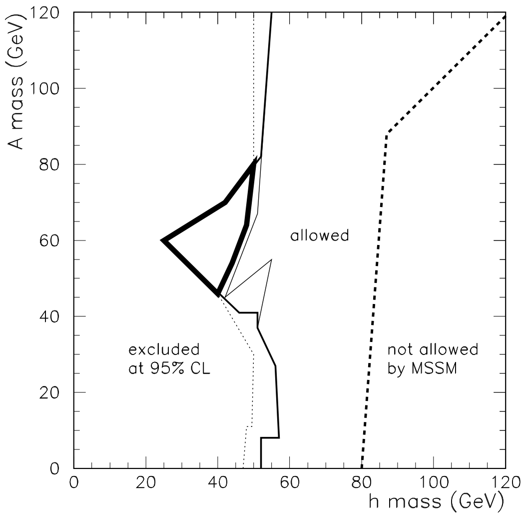

Figure 1. 91 GeV $(m_\mathrm{h}, m_\mathrm{A})$ result.

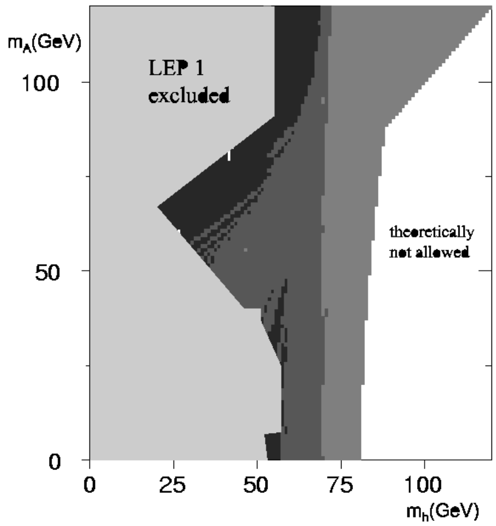

Figure 2. 172 GeV $(m_\mathrm{h}, m_\mathrm{A})$ result. Only the dark region is excluded in addition to LEP-1.

4. Similar limits from different experiments

The results from very different parameter scan methods of different LEP experiments agree well as shown in Figs. 3 and 4 for 189 GeV data [9,10]. The shaded region in Fig. 3 is excluded by charge- and color-breaking (CCB) criteria [9].

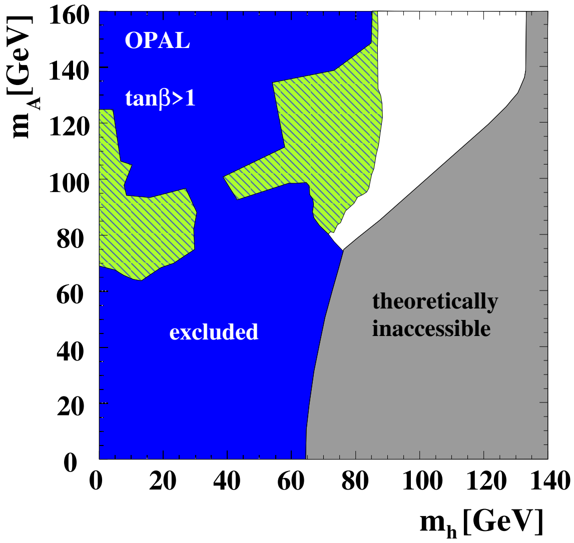

Figure 3. 189 GeV $(m_\mathrm{h}, m_\mathrm{A})$ result.

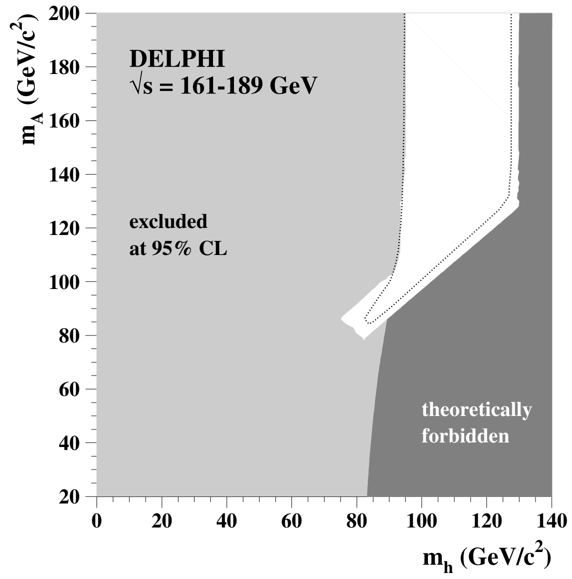

Figure 4. 189 GeV $(m_\mathrm{h}, m_\mathrm{A})$ result. The dotted line indicates the corresponding benchmark limit.

Limits from charmless b-decays, the electroweak parameter $\Delta\rho$ and direct searches for Supersymmetric particles do not change the h and A mass limits [10]. The parameter scan reduced the benchmark limits by up to 7 GeV [11,10]. The constraints on $\tan\beta$ are given in Figs. 5 and 6.

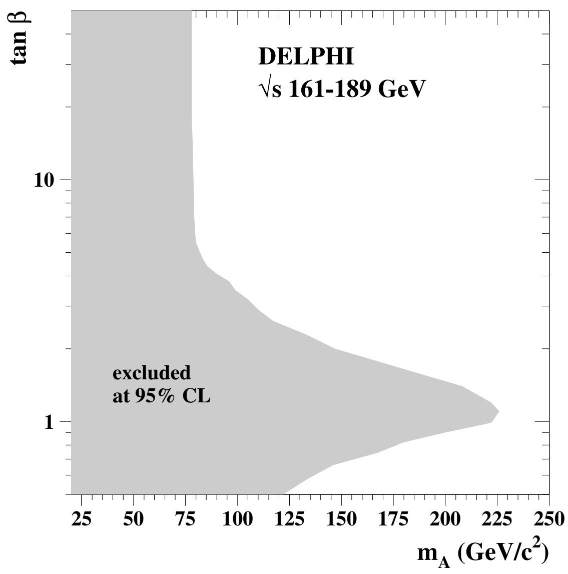

Figure 5. 189 GeV $(m_\mathrm{A}, \tan\beta)$ result.

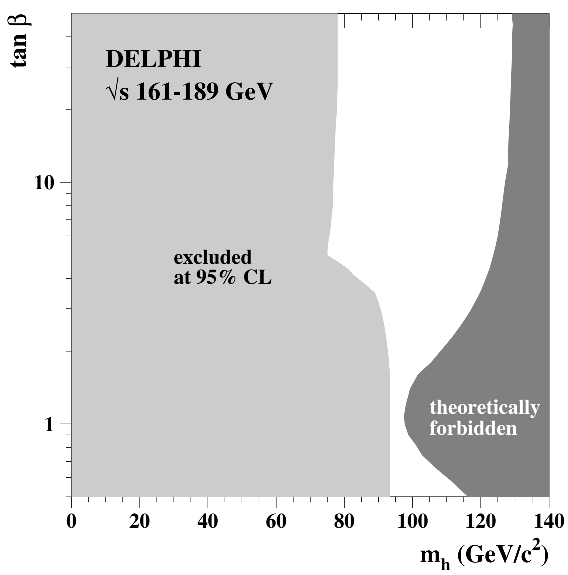

Figure 6. 189 GeV $(m_\mathrm{h}, \tan\beta)$ result.

5. Small reduction of limits

With increasing center-of-mass energy, benchmark and parameter scan limits agree within 1 GeV for 202 GeV data [12]. The mass and $\tan\beta$ limits are given in Figs. 7, 8 and 9.

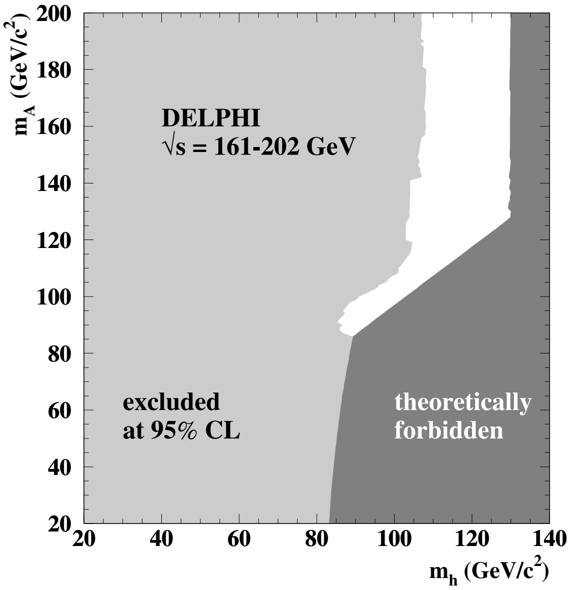

Figure 7. 202 GeV $(m_{\mathrm{h}}, m_{\mathrm{A}})$ result.

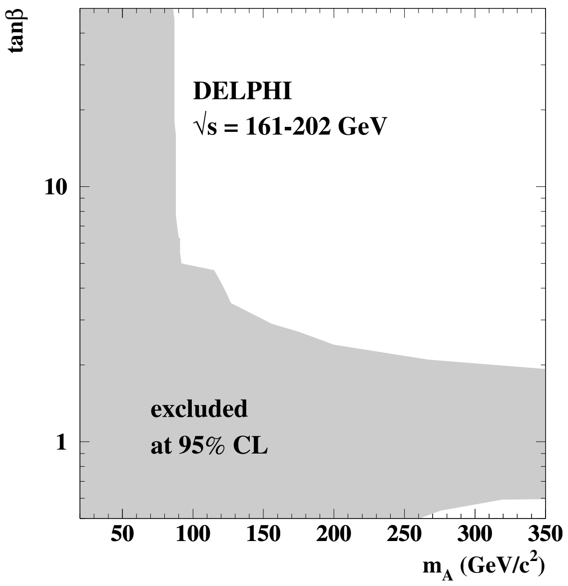

Figure 8. 202 GeV $(m_{\mathrm{A}}, \tan\beta)$ result.

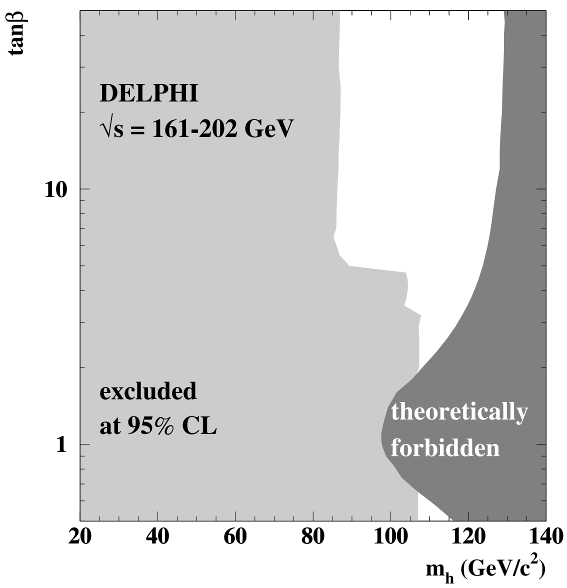

Figure 9. 202 GeV $(m_{\mathrm{h}}, \tan\beta)$ result.

6. Combined LEP parameter scan limits

The mass limits from benchmark and parameter scan agree within about 2 GeV in the combination of the 202 GeV data from all LEP experiments [13,14]. The scan limits are given in Figs. 10, 11 and 12.

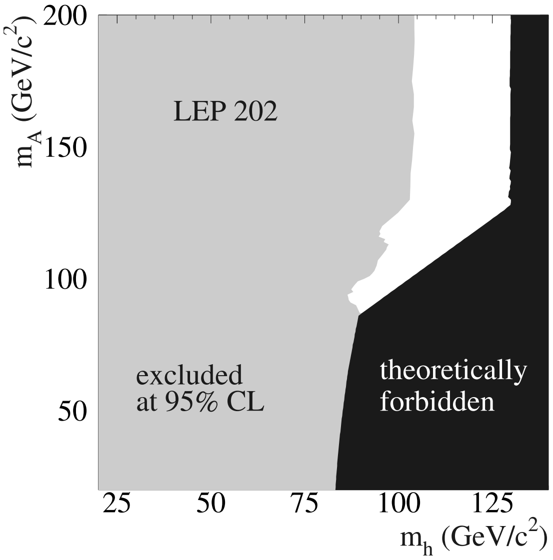

Figure 10. 202 GeV $(m_{\mathrm{h}}, m_{\mathrm{A}})$ result.

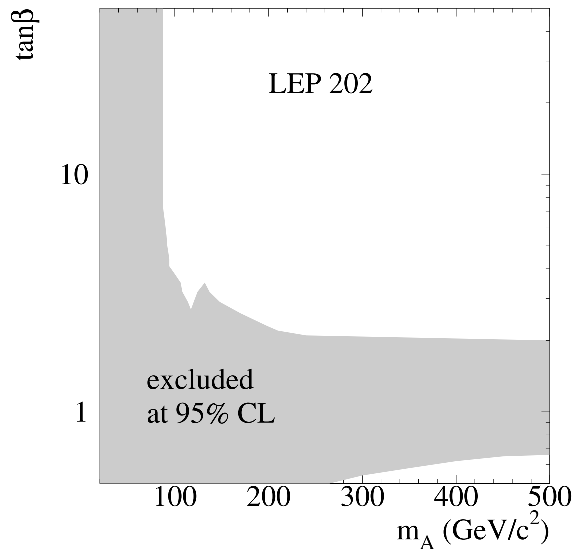

Figure 11. 202 GeV $(m_{\mathrm{A}}, \tan\beta)$ result.

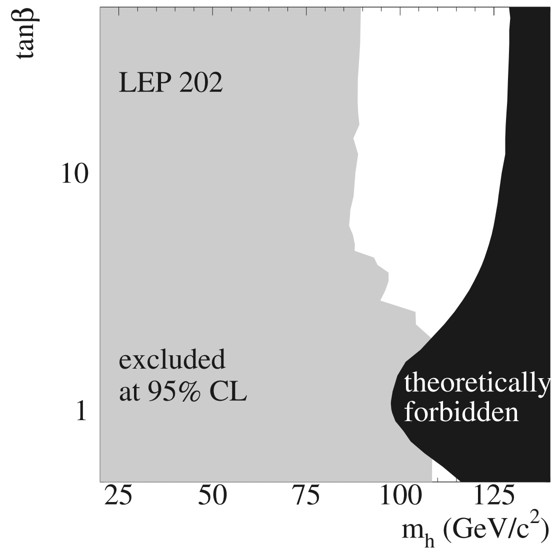

Figure 12. 202 GeV $(m_{\mathrm{h}}, \tan\beta)$ result.

7. Latest results

The latest benchmark and scan results including 209 GeV data agree within 2 GeV [15,4] and give mass limits on h and A of 89 GeV (Figs. 13, 14 and 15). The importance of a MSSM parameter scan is underlined in Fig. 16, which shows that large parameter regions exist where a Higgs boson could decay invisibly into a pair of neutralinos. Thus, only in conjunction with a dedicated search [16] the h and A mass limits are set.

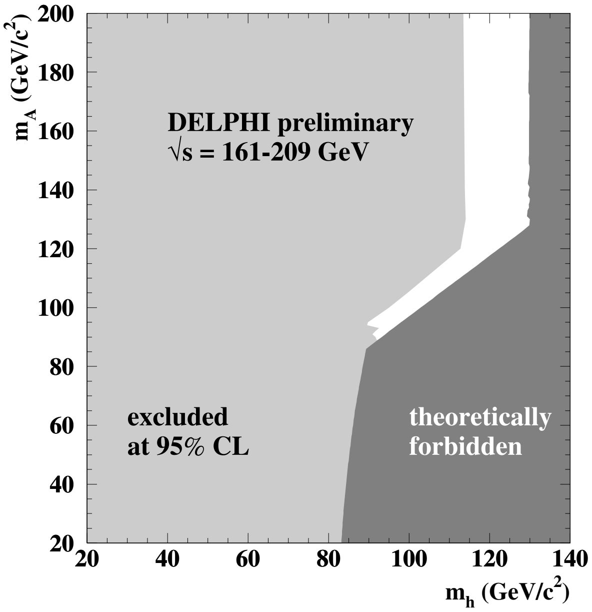

Figure 13. 209 GeV $(m_{\mathrm{h}}, m_{\mathrm{A}})$ result.

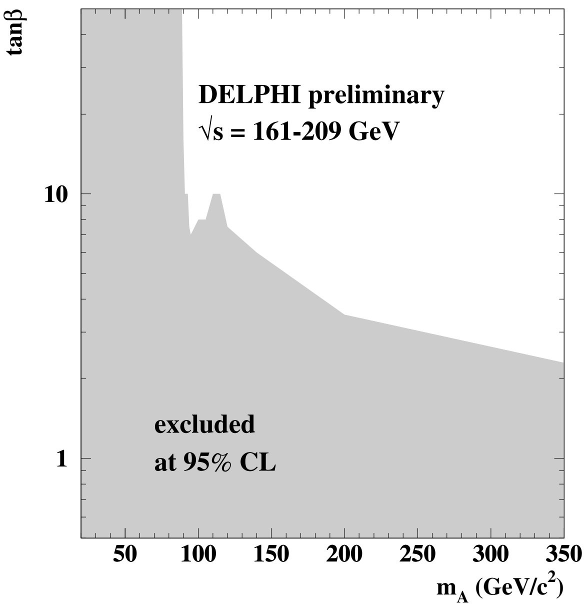

Figure 14. 209 GeV $(m_{\mathrm{A}}, \tan\beta)$ result.

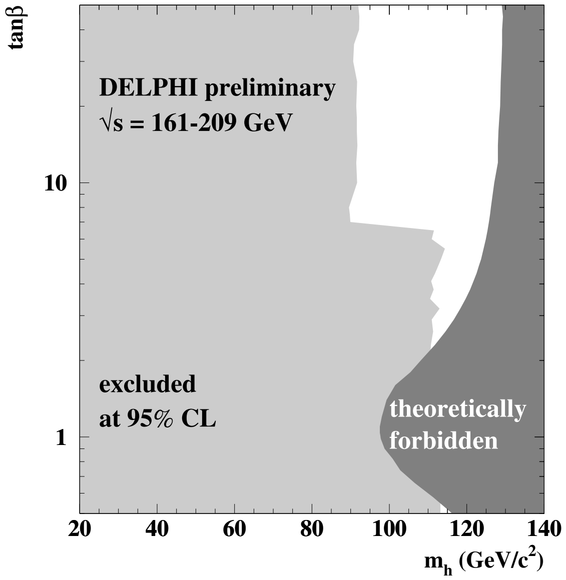

Figure 15. 209 GeV $(m_{\rm h}, \tan\beta)$ result.

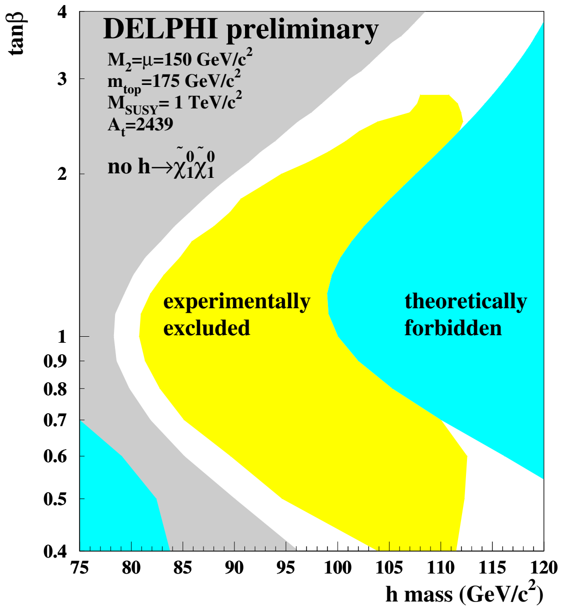

Figure 16. 209 GeV $(m_{\rm h}, \tan\beta)$ result from searches for invisibly decaying Higgs bosons.

8. Three Higgs boson hypothesis

For 202 GeV data, taken in 1999, and first 2000 data, h and A mass limits were 2 GeV below expectation [17]. This tendency is enhanced by including complete 209 GeV data, in which case the limits are 3.1 to 3.6 GeV below the expectations of about 95 GeV [3]. A possible explanation is that the HZ excess at about 115 GeV is due to the heavier scalar H and that, in addition, the production of hA with masses between 90 and 100 GeV occurs [17]. Figure 17 (from [3]) shows a data excess above 2σ for $m_{\rm h} + m_{\rm A} = 187$ GeV in the $\rm b\bar{b}b\bar{b}$ channel. The same data excess is also expressed by the confidence level $CL_{\rm b}$ for a signal observation as shown in Fig. 18 (from [3]). The hypothesis of the production of three MSSM Higgs bosons is supported by the data excess seen in Fig. 19 (from [18]) at 100 GeV which could result from hZ production in addition to HZ production. For the reported MSSM parameters [17] $\cos^2(\beta-\alpha) \approx 0.9$; therefore $\sin^2(\beta-\alpha) = \xi^2 \approx 0.1$. The ξ^2 limit in the 100 GeV mass region shows a deviation of about 2σ between the expected and observed limit, as seen in Fig. 20 (from [18]). Figure 21 shows that this new support is only observed in the complete LEP data.

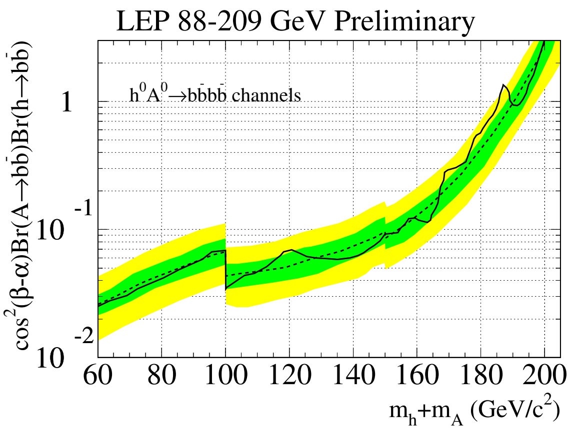

Figure 17. Limits on the hA cross section as a function of $m_{\rm h} + m_{\rm A}$ at 95% CL ($m_{\rm h} \approx m_{\rm A}$) for the MSSM processes $\rm e^+e^- \to hA \to b\bar{b}b\bar{b}$. This corresponds also to limits on $\cos^2(\beta-\alpha)$ in the general extension of the SM with two Higgs boson doublets. The data of the four LEP experiments collected at energies from 88 to 209 GeV are combined. The solid curve is the observed result and the dashed curve shows the expected median. Shaded areas indicate the 1σ and 2σ probability bands.

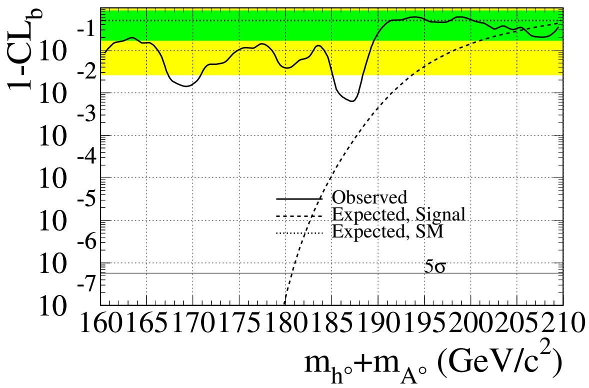

Figure 18. The confidence level $1 - CL_\mathrm{b}$ as a function of $m_\mathrm{h} + m_\mathrm{A}$ for the case $m_\mathrm{h} \approx m_\mathrm{A}$ (where only the $\mathrm{e}^+\mathrm{e}^- \to$ hA process contributes since $\sin^2(\beta - \alpha) \approx 0$). The straight line at 0.5 and the shaded 1σ and 2σ probability bands represent the expected background-only result. The solid curve is the observed result and the dashed curve shows the expected median for a signal.

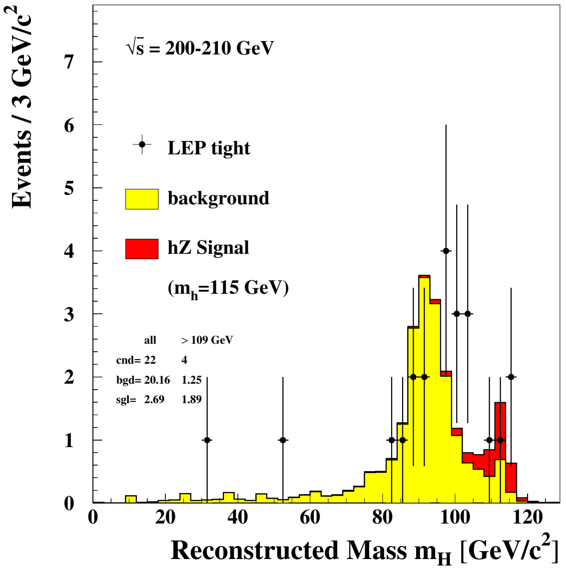

Figure 19. Distribution of the reconstructed SM Higgs boson mass in searches conducted at energies between 200 and 210 GeV. The figure displays the data (dots with error bars), the predicted SM background and the prediction for a Higgs boson of 115 GeV mass. The number of data events selected with mass larger than 109 GeV is 4, while 1.25 are expected from SM background processes and 1.89 from a 115 GeV signal. Between 96 and 105 GeV 10 data events are observed, while 3.6 background events are expected.

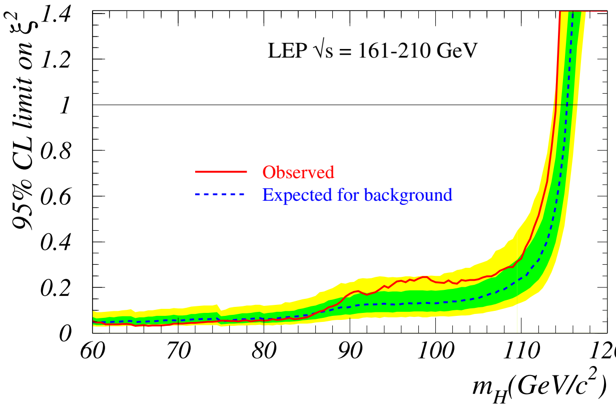

Figure 20. The 95% CL upper bound on ξ^2 as a function of m_H, where $\xi = g_\mathrm{HZZ}/g^\mathrm{SM}_\mathrm{HZZ}$ is the HZZ coupling relative to the SM coupling. About 2σ deviations from the expectation are observed at m_H = 98 GeV and m_H = 115 GeV. In the MSSM, hZ production at the lower mass and HZ production at the higher mass are possible.

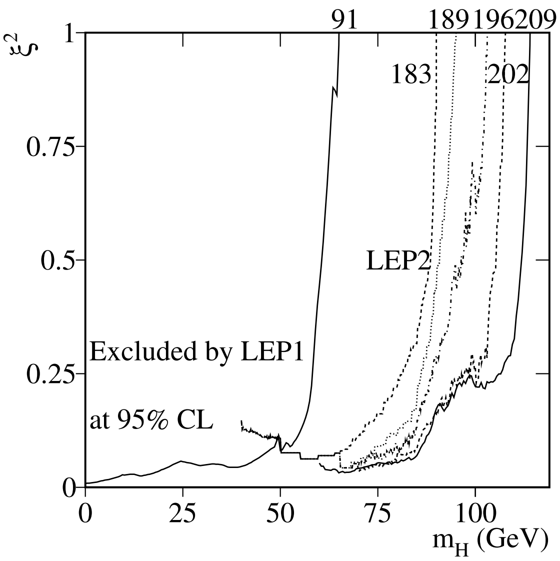

Figure 21. The excluded (ξ^2, m_H) region including 209 GeV data is compared with the results from combined LEP-1 data [19], taken around 91 GeV center-of-mass energy, and previous LEP-2 limits [14] up to 183, 189, 196 and 202 GeV. The ξ^2 limit below 100 GeV does not become significantly stronger when the 209 GeV data, taken in 2000, are included.

9. Conclusions

The LEP-1 and LEP-2 data are consistent with a background-only hypothesis and give stringent mass limits on the neutral Higgs bosons h and A of the MSSM. During the LEP era, MSSM parameter scans reduced – or for early LEP-2 data even removed completely – the benchmark mass limits. The importance of parameter scans is stressed by large parameter regions where the Higgs boson decays invisibly, which is not considered in benchmark results. At the highest center-of-mass energies, benchmark limits are only slightly reduced by a general parameter scan when the results from invisible Higgs boson searches are included. Table 1 compares benchmark and scan mass limits in the MSSM.

The combined LEP data show a preference for the SM Higgs boson of 115.6 GeV, which can also be interpreted as a preference for a Higgs boson of that mass in the MSSM. Further small data excesses for Higgs boson pair-production and bremsstrahlung between 90 and 100 GeV allow the hypothesis that h, A and H of the MSSM all have masses below 116 GeV. Previously reported MSSM parameter combinations from a general parameter scan for this scenario are supported by the complete data set.

Acknowledgments

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Table 1
Benchmark (b) and scan (s) mass limits in the MSSM. All limits are in GeV at 95% CL.

$\sqrt{s}$ (GeV)	Data	$m_{\mathrm{h}}^{\mathrm{b}}$	$m_{\mathrm{A}}^{\mathrm{b}}$	$m_{\mathrm{h}}^{\mathrm{s}}$	$m_{\mathrm{A}}^{\mathrm{s}}$
91 [5,6]	L3	41.0	none	25	none
172 [7,8]	DELPHI	59.5	51.0	30	none
183 [20,21]	DELPHI	74.4	75.2	67	75
189 [9]	OPAL	74.8	76.5	72	76
189 [11,10]	DELPHI	82.6	84.1	75	78
202 [12]	DELPHI	85.9	86.5	85	86
202 [13,14]	LEP	88.3	88.4	86	87
209 [15,4]	DELPHI	89.6	90.7	89	89

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