hep-ph/0602136

MSSM Higgs Boson Searches at LEP

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Abstract

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Presented at the 13th International Conference on Supersymmetry and Unification of Fundamental Interactions (SUSY'05), Durham, UK, July 18-23, 2005

MSSM Higgs Boson Searches at LEP*

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(On behalf of the ALEPH, DELPHI, L3, OPAL Collaborations, and the LEP Working Group for Higgs Boson Searches)
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Final results from the MSSM Higgs boson searches from the LEP experiments ALEPH, DELPHI, L3 and OPAL are presented. The results are statistically combined and the statistical significance for signal and background hypotheses are given. Upper bounds on the production cross sections are set for several Higgs-like topologies. Interpretations for six benchmark scenarios in the MSSM, both for CP-conserving and CP-violating scenarios, are given. Limits on the $\tan\beta$ parameter, and in some scenarios upper limits on the neutral Higgs boson masses are set.

1. Introduction

The LEP data-taking ended November 3, 2000, although some data excess were observed. Very successful data-taking at the LEP accelerator was completed. The expectations were exceeded regarding luminosity and center-of-mass energy. Limits on the SM Higgs boson were reported previously $m_{\rm H}^{\rm SM} > 114.4$ GeV/c^2 [1]. Many searches beyond the SM have led to stringent limit, for a review see Ref. [2]. This report focuses on new results in the MSSM for CP-conserving and CP-violating MSSM benchmarks, based on statistical combinations of searches by LEP collaborations at LEP-1 (≈ 91 GeV) and LEP-2 (≤ 209 GeV) energies [3]. No significant excess indicative for Higgs boson production has been observed in the data and the searches set bounds on topological cross sections and MSSM parameters. The report is structured as follows: benchmark parameters, experimental searches, limits on topological cross sections, CP-conserving and CP-violating interpretations.

2. Benchmark Parameters

CP-conserving and CP-violating MSSM benchmarks are defined and listed in Table I. The benchmarks are designed to include $\rm h \to c\bar{c}, gg, W^+W^-$ decays for the large-μ benchmark, reduced gluon fusion at LHC for the gluophobic benchmark, reduced $\rm h \to b\bar{b}, \tau^+\tau^-$ decays by a $\sin\alpha_{\rm eff}/\cos\beta$ coupling factor for the small $\alpha_{\rm eff}$ benchmark, and CP-even/odd mixing $\propto m_{\rm t}^4 {\rm Im}(\mu A)/M_{\rm SUSY}^2$ in the CPX benchmark scenario.

Table I: Benchmark parameter sets for CP-conserving and CP-violating MSSM scenarios.

	(1) $m_{\rm h}$-max	(2) no-mixing	(3) large-μ	(4) gluophobic	(5) small-$\alpha_{\rm eff}$	(6) CPX
	Parameters varied in the scan					
$\tan\beta$	0.4-40	0.4-40	0.7-50	0.4-40	0.4-40	0.6-40
$m_{\rm A}$ (GeV/c^2)	0.1-1000	0.1-1000	0.1-400	0.1-1000	0.1-1000	–
$m_{\rm H^\pm}$ (GeV/c^2)	–	–	–	–	–	4-1000
	Fixed parameters					
$M_{\rm SUSY}$ (GeV)	1000	1000	400	350	800	500
M_2 (GeV)	200	200	400	300	500	200
μ (GeV)	-200	-200	1000	300	2000	2000
$m_{\tilde{g}}$ (GeV/c^2)	800	800	200	500	500	1000
$X_{\rm t}$ (GeV)	$2M_{\rm SUSY}$	0	-300	-750	-1100	$A-\mu\cot\beta$
A (GeV)	$X_{\rm t}+\mu\cot\beta$	$X_{\rm t}+\mu\cot\beta$	$X_{\rm t}+\mu\cot\beta$	$X_{\rm t}+\mu\cot\beta$	$X_{\rm t}+\mu\cot\beta$	1000
arg (A) = arg $(m_{\tilde{g}})$	–	–	–	–	–	90°

*Presented at the 13th International Conference on Supersymmetry and Unification of Fundamental Interactions (SUSY'05), Durham, UK, July 18-23, 2005.

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3. Experimental Searches

The search topologies are:

Higgsstrahlung: $e^+e^- \to H_1Z$

- Four-jet: $(H_1 \to b\bar{b})(Z \to q\bar{q})$
- Missing energy: $(H_1 \to b\bar{b}, \tau^+\tau^-)(Z \to \nu\bar{\nu})$
- Leptonic: $(H_1 \to b\bar{b}, q\bar{q})(Z \to e^+e^-, \mu^+\mu^-)$
- Tau-leptons: $(H_1 \to \tau^+\tau^-)(Z \to q\bar{q})$ and $(H_1 \to b\bar{b}, \tau^+\tau^-)(Z \to \tau^+\tau^-)$
- Cascade: $H_2Z \to (H_1H_1)Z$

Pairproduction: $e^+e^- \to H_2H_1$

- Four-b: $(H_2 \to b\bar{b})(H_1 \to b\bar{b})$
- Mixed: $(H_2 \to \tau^+\tau^-)(H_1 \to b\bar{b})$ and $(H_2 \to b\bar{b})(H_1 \to \tau^+\tau^-)$
- Four-tau: $(H_2 \to \tau^+\tau^-)(H_1 \to \tau^+\tau^-)$
- Cascade: $H_2H_1 \to (H_1H_1)H_1$

Additional experimental constraints are applied: upper bound at 95% CL on the possible additional Z boson decay width $\Delta\Gamma_Z < 2$ MeV, decay mode independent H_1Z searches, and searches for the Yukawa processes $b\bar{b}H_1$ and $b\bar{b}H_2$. Further details are given in Ref. [3].

4. Limits on Topological Cross Sections

In CP-conserving scenarios H_1 is the scalar Higgs boson h, and H_2 the pseudo-scalar A. Limits on the production cross section are set for $S_{95} = \sigma_{max}/\sigma_{ref}$, where σ_{ref} is a reference cross section. Figure 1 shows the limits on $S_{95} = \xi^2 = (g_{HZZ}/g_{HZZ}^{SM})^2$. The limits on $H_2Z \to H_1H_1Z$ are shown in Fig. 2. Limits are given in Fig. 3 for the H_1H_2 process with 'h-max', $b\bar{b}$ and $\tau^+\tau^-$ decay modes, and as a function of scalar and pseudoscalar masses in in Fig. 4. The limits for the process $H_1H_2 \to H_1H_1H_1$ are given in Fig. 5.

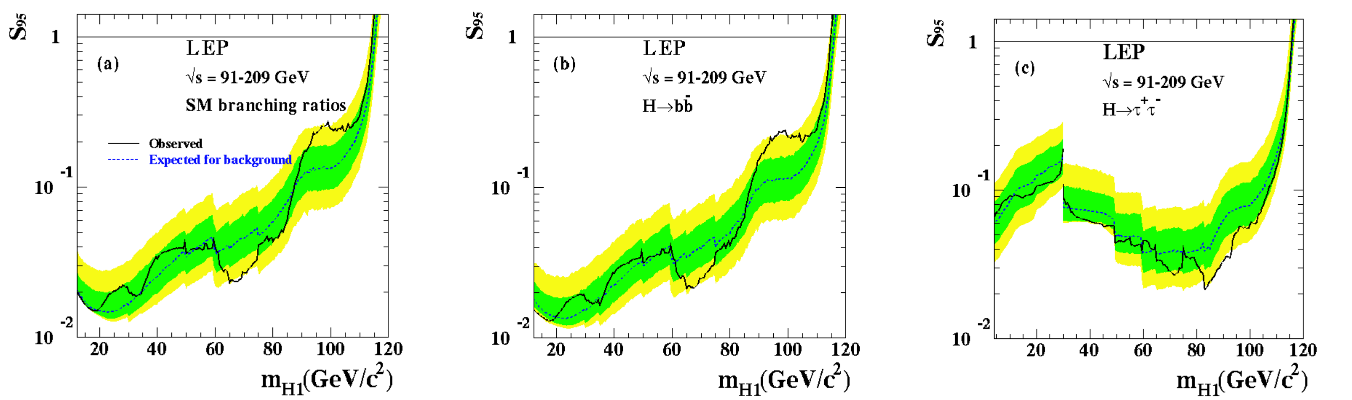

Figure 1: Limits on $S_{95} = \xi^2 = (g_{HZZ}/g_{HZZ}^{SM})^2$. Left: SM Higgs boson decay. Center: $H \to b\bar{b}$. Right: $H \to \tau^+\tau^-$.

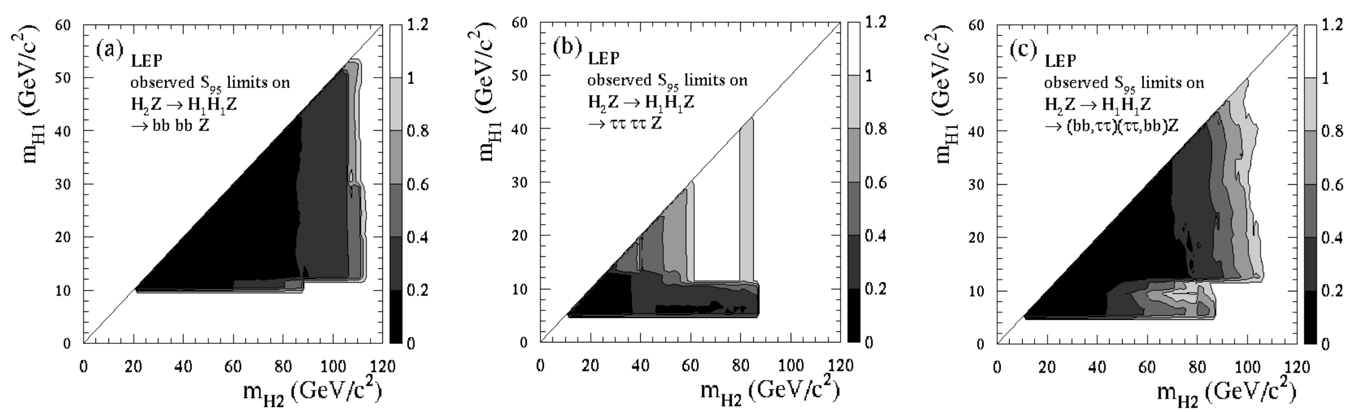

Figure 2: Limits on S_{95} for the $H_2Z \to H_1H_1Z$ process in different decay modes, as indicated in the plots.

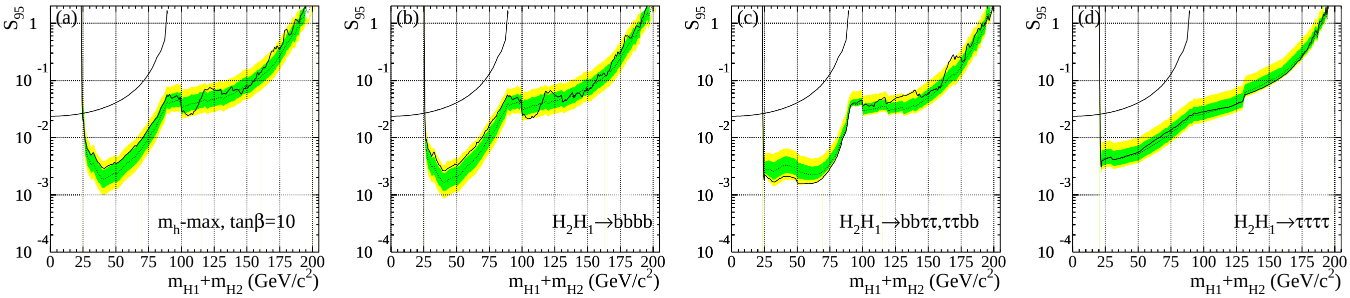

Figure 3: Limits on S_{95} for the $\mathrm{H_1H_2}$ process with different decays modes. Regions at low masses are excluded by the $\Delta\Gamma_{\mathrm{Z}} < 2$ MeV constraint. Left: assuming branching ratios of the h-max scenario. Center left: $\mathrm{b\bar{b}b\bar{b}}$ decays. Center right: $\mathrm{b\bar{b}}\tau^+\tau^-$ decays. Right: $\tau^+\tau^-\tau^+\tau^-$ decays.

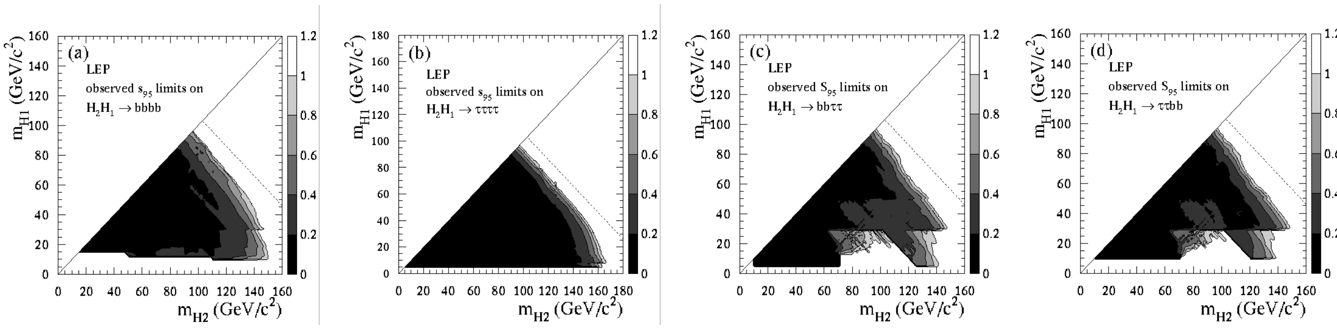

Figure 4: Limits on S_{95} for the $\mathrm{H_1H_2}$ process with different decays modes, as indicated in the plots.

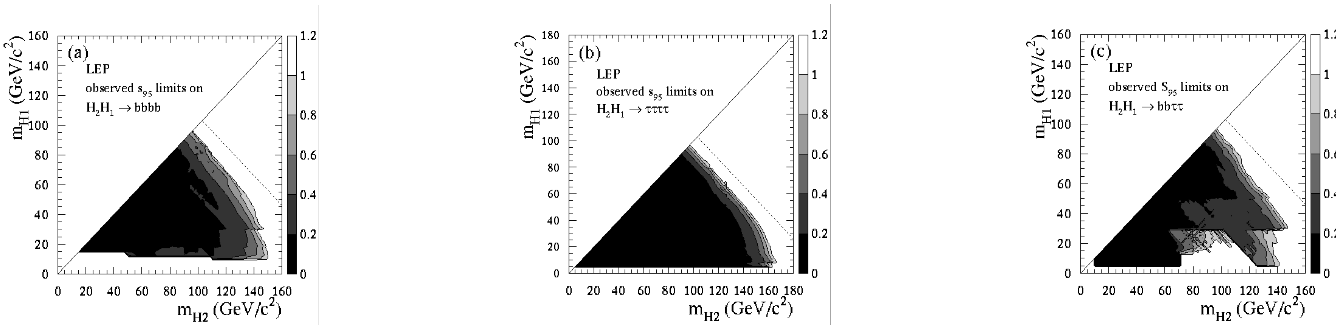

Figure 5: Limits on S_{95} for the $\mathrm{H_1H_2} \rightarrow \mathrm{H_1H_1H_1}$ process with different decays modes, as given in the plots.

5. CP-Conserving Interpretations

The background-only hypothesis is tested in the h-max scenario and expressed in Fig. 6 as $1 - CL_{\mathrm{b}}$ regions for the 1σ, 1-2σ, and $>2\sigma$ contours (An interpretation including this $>2\sigma$ excess near $m_{\mathrm{h}} = 100$ GeV/c^2 as a Three-Higgs-Boson hypothesis was given [4].) The corresponding exclusion contours are shown in Fig. 7 for $m_{\mathrm{t}} = 174.3$ GeV/c^2 [5]. The variation of the $\tan\beta$ limit is shown in Fig. 6 (right plot) as a function of m_{t}. The results in the no-mixing scenario are given in Fig. 8. The large-μ scenario, depending on the top mass value, is extirely excluded at 95% CL, as shown in Fig. 9. The results for the gluophobic scenario are given in Fig. 10 and for the small-α_{eff} scenario in Fig. 11. The CP-conserving MSSM limits are summarized in Table II.

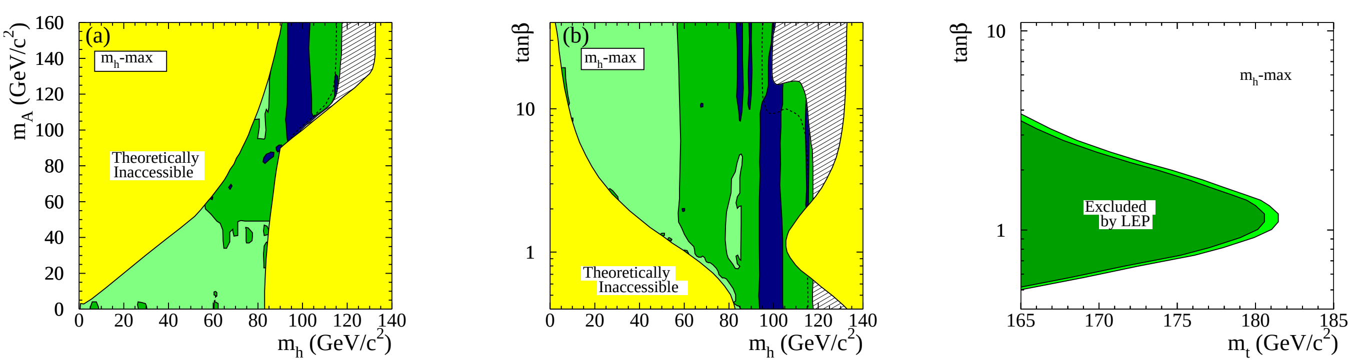

Figure 6: Left and center: Contour regions of $1 - CL_{\mathrm{b}}$ in the h-max scenario. Light-green: 1σ, dark-green: 1-2σ, blue: $>2\sigma$. Expected limits in the absence of a signal are indicated with a dotted line. In the hatched region appearent excess would not be significant. Right: resulting limit on $\tan\beta$ as a function of the top quark mass.

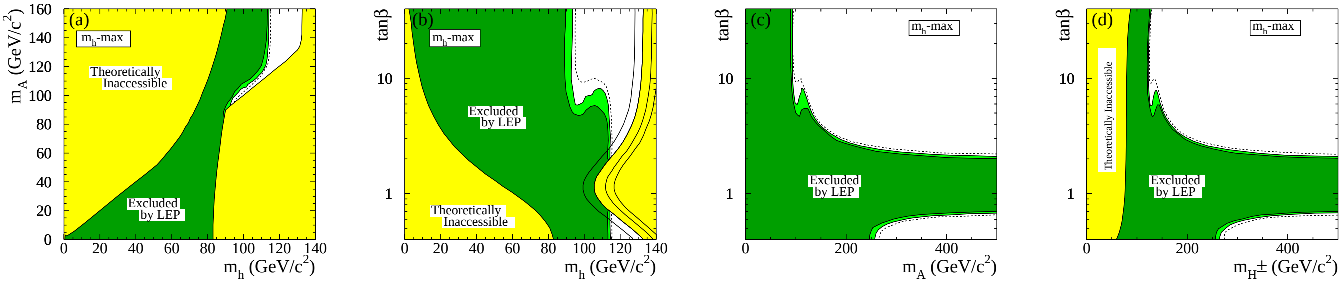

Figure 7: Excluded regions in the h-max scenario at 95% CL (light-green) and at 99.7% CL (dark-green). Expected limits in the absence of a signal are indicated with a dotted line.

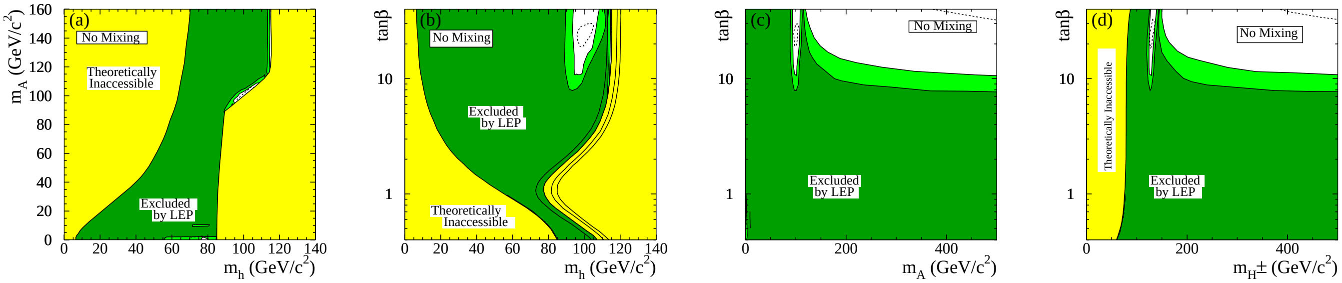

Figure 8: Excluded regions in the no-mixing scenario at 95% CL (light-green) and at 99.7% CL (dark-green). Expected limits in the absence of a signal are indicated with a dotted line.

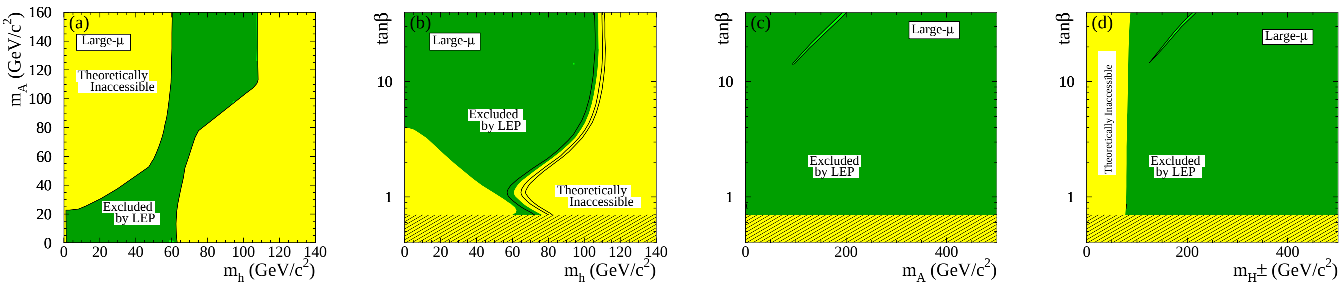

Figure 9: Excluded regions in the large-μ scenario at 95% CL (light-green) and at 99.7% CL (dark-green). Expected limits in the absence of a signal are indicated with a dotted line.

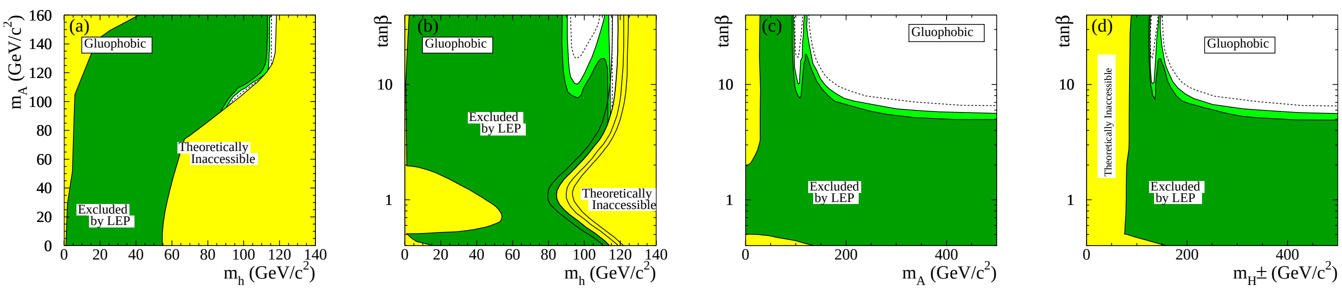

Figure 10: Excluded regions in the gluophobic scenario at 95% CL (light-green) and at 99.7% CL (dark-green). Expected limits in the absence of a signal are indicated with a dotted line.

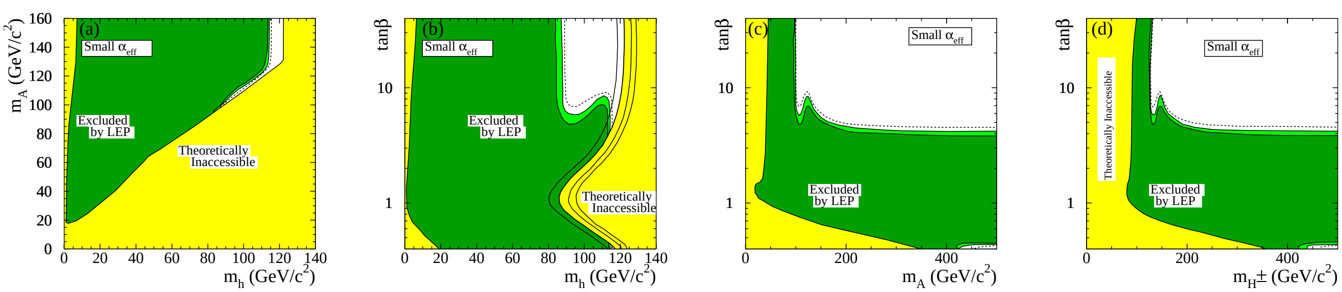

Figure 11: Excluded regions in the small-$\alpha_{\rm eff}$ scenario at 95% CL (light-green) and at 99.7% CL (dark-green). Expected limits in the absence of a signal are indicated with a dotted line.

Table II: Summary of CP-conserving MSSM limits at 95% CL.

Benchmark scenario	$m_{\rm t}$ (GeV/c^2)	$m_{\rm h}$ (GeV/c^2)	$m_{\rm A}$ (GeV/c^2)	exclusion of $\tan\beta$
$m_{\rm h}$-max	169.3	92.9 (94.8)	93.4 (95.1)	0.6-2.6 (0.6-2.7)
	174.3	92.8 (94.9)	93.4 (95.2)	0.7-2.0 (0.7-2.1)
	179.3	92.9 (94.8)	93.4 (95.2)	0.9-1.5 (0.9-1.6)
	183.0	92.8 (94.8)	93.5 (95.2)	no excl. (no excl.)
no-mixing	169.3	excl. (excl.)	excl. (excl.)	excl. (excl.)
	174.3	93.6 (96.0)	93.6 (96.4)	0.4-10.2 (0.4-19.4)
	179.3	93.3 (95.0)	93.4 (95.0)	0.4-5.5 (0.4-6.5)
	183.0	92.9 (95.0)	93.1 (95.0)	0.4-4.4 (0.4-4.9)
large-μ	169.3	excl. (excl.)	excl. (excl.)	excl. (excl.)
	174.3	excl. (excl.)	excl. (excl.)	excl. (excl.)
	179.3	109.2 (109.2)	225.0 (225.0)	0.7-43 (0.7-43)
	183.0	95.6 (95.6)	98.9 (98.9)	0.7-11.5 (0.7-11.5)
gluophobic	169.3	90.6 (93.2)	95.7 (98.2)	0.4-10.3 (0.4-21.5)
	174.3	90.5 (92.3)	96.3 (98.0)	0.4-5.4 (0.4-6.4)
	179.3	90.0 (91.8)	96.5 (98.2)	0.4-3.9 (0.4-4.2)
	183.0	89.8 (91.5)	96.8 (98.7)	0.5-3.3 (0.5-3.6)
small-$\alpha_{\rm eff}$	169.3	88.2 (90.0)	98.2 (99.6)	0.4-6.1 (0.4-7.4)
	174.3	87.3 (89.0)	98.8 (100.0)	0.4-4.2 (0.4-4.5)
	179.3	86.6 (88.0)	99.8 (100.7)	0.5-3.2 (0.5-3.4)
	183.0	85.6 (87.5)	101.0 (101.3)	0.6-2.7 (0.5-2.9)

6. CP-Violating Interpretations

The background-only hypothesis is tested in the CPX scenario and expressed in Fig. 12 as $1-CL_{\rm b}$ region for the 1σ, 1-2σ, and $>2\sigma$ contours. The corresponding exclusion contours are shown in Fig. 13 for $m_{\rm t} = 174.3$ GeV/c^2. The unexcluded region near $\tan\beta = 4$ can be understood from the expected production region when the $\rm H_1 \to b\bar{b}$ mode is suppressed, as shown in Fig. 14. The figure compares also the results from different cross section programs (CPH and FeynHiggs) and the result from using the logic-OR of the unexcluded region. A large dependence of the unexcluded region on the top quark mass is observed, as shown in Fig. 15. Furthermore, the dependence of the excluded regions on the CP-violating phase arg(A), and on the μ and $M_{\rm SUSY}$ parameters are shown in Figs. 16, 17, and 18.

Figure 12: Contour regions of $1-CL_{\rm b}$ in the CPX scenario. Light-green: 1σ, dark-green: 1-2σ, blue: $>2\sigma$. Expected limits in the absence of a signal are indicated with a dotted line.

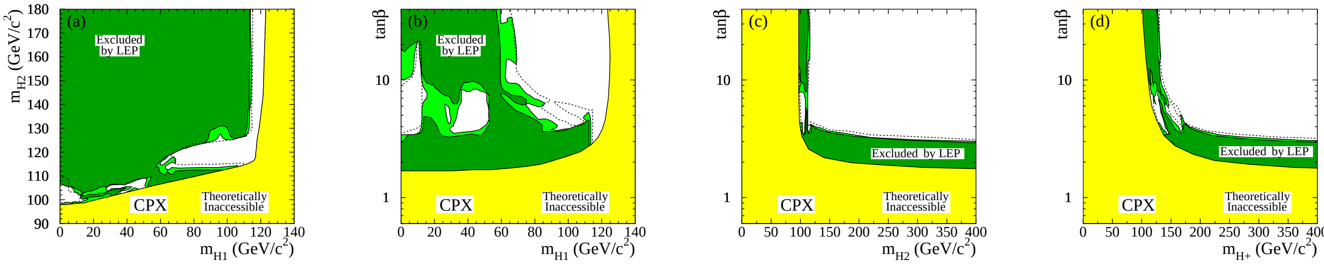

Figure 13: Excluded regions in the CPX scenario at 95% CL (light-green) and at 99.7% CL (dark-green). Expected limits in the absence of a signal are indicated with a dotted line.

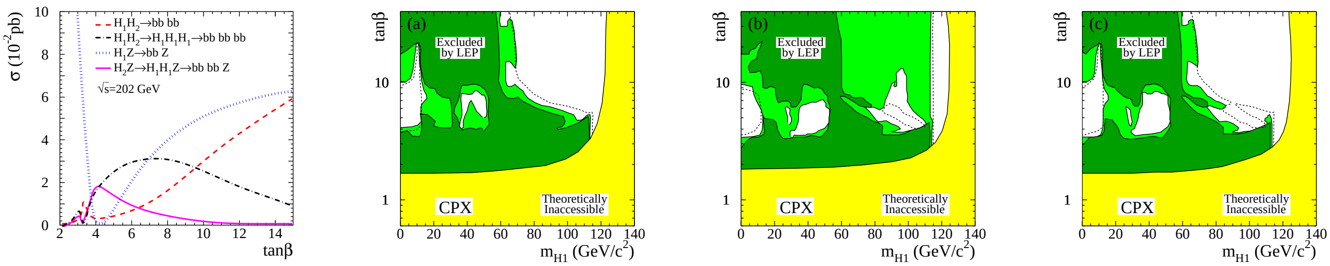

Figure 14: Left: expected production cross sections in the CPX scenario. Center left: CPH calculation. Center right: FeynHiggs calculation. Right: logic-OR of CPH and FeynHiggs calculations.

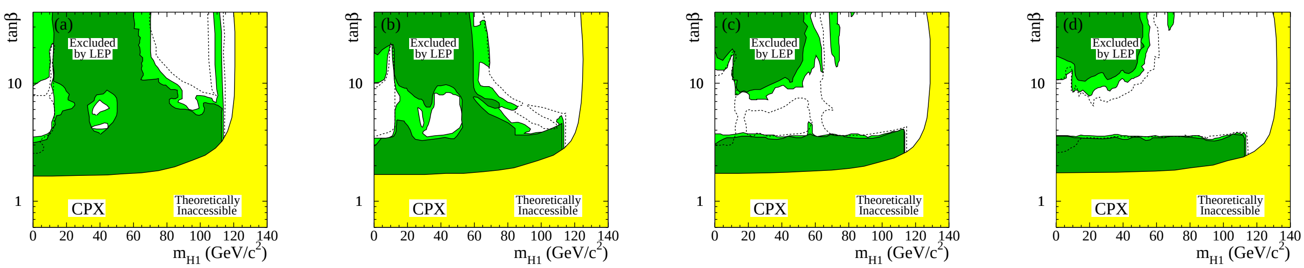

Figure 15: Excluded regions in the CPX scenario at 95% CL (light-green) and at 99.7% CL (dark-green) for $m_t = 169.3,\ 174.3,\ 179.3,\ 183.3\ \mathrm{GeV}/c^2$ in plots (a) to (d), respectively. Expected limits in the absence of a signal are indicated with a dotted line.

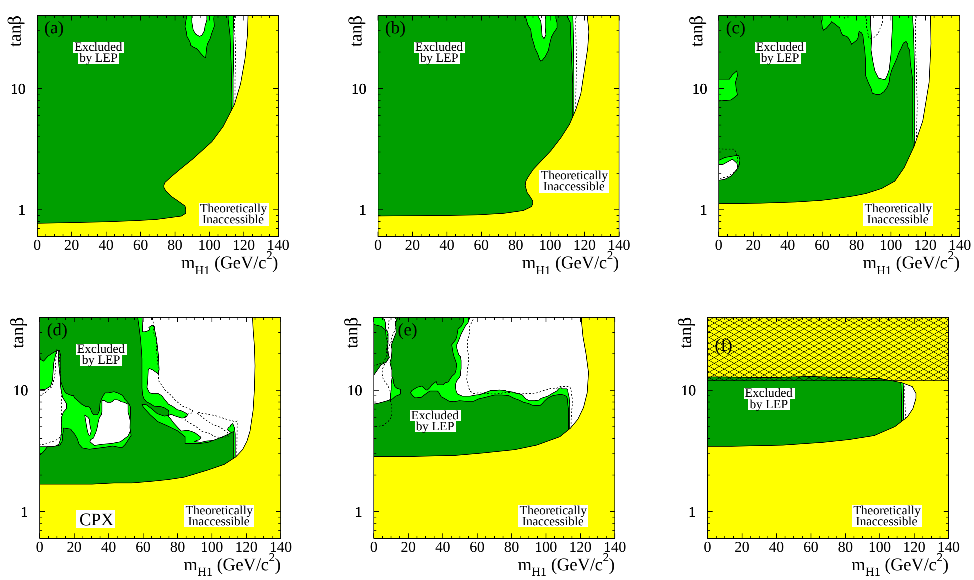

Figure 16: Excluded regions in the CPX scenario at 95% CL (light-green) and at 99.7% CL (dark-green) for arg(A) $= 0^\circ,\ 30^\circ,\ 60^\circ,\ 90^\circ,\ 135^\circ,\ 180^\circ$ in plots (a) to (d), respectively. Expected limits in the absence of a signal are indicated with a dotted line.

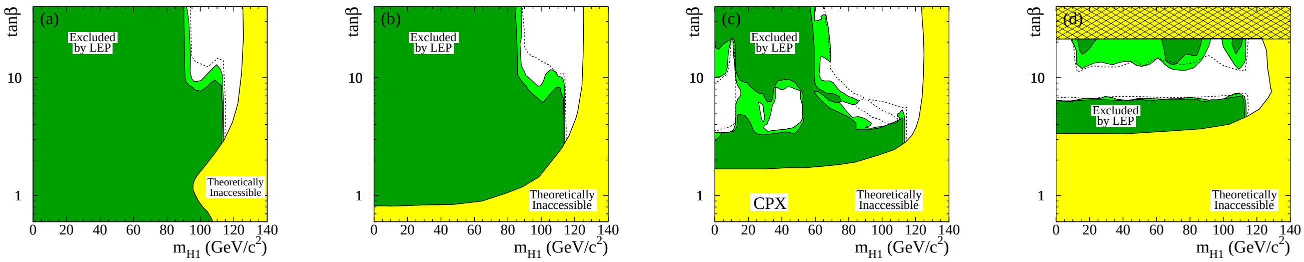

Figure 17: Excluded regions in the CPX scenario at 95% CL (light-green) and at 99.7% CL (dark-green) for μ = 500, 1000, 2000, 4000 GeV in plots (a) to (d), respectively. Expected limits in the absence of a signal are indicated with a dotted line.

Figure 18: Excluded regions in the CPX scenario at 95% CL (light-green) and at 99.7% CL (dark-green) for $M_{\rm SUSY}$ = 500, 1000 GeV in plots (a) and (b), respectively. Expected limits in the absence of a signal are indicated with a dotted line.

7. Conclusions

The LEP collaborations have finalized their Higgs boson searches and interpretations in the MSSM. The new results from the combination of the LEP data have been presented. Stringent model-independent limits from Higgsstrahlung and pair-production with b-quarks, τ-leptons or flavour-independent searches have been set. Limits on the scaling factor S_{95} also constrain general Higgs boson scenarios. Additional experimental constraints are applied from $\Delta\Gamma_{\rm Z}$, decay-mode independent $\rm H_1Z$ searches, and searches for the Yukawa processes which contribute mostly for very light $\rm H_1$ masses. The combined LEP data interpretations are given for h-max, no-mixing, large-μ, gluophobic, small-$\alpha_{\rm eff}$ and CPX benchmark MSSM parameter sets. The CP-conserving limits depend mostly on the benchmark scenario and $m_{\rm t}$. The limit ranges for $m_{\rm h}$ between 85 GeV/c^2 and fully excluded, and for $m_{\rm A}$ between 93 GeV/c^2 and fully excluded. The corresponding limits on $\tan\beta$ range between no-exclusion and fully excluded. In the CP-violating scenario much weaker limits compared to the CP-conserving limits are set depending on $m_{\rm t}$ and the general MSSM parameters. The Higgs boson searches in LEP data during 1989 and 2006, and many collaborations with theorists have much advanced the search techniques and interpretations. Much knowledge has also been gained for new searches at the current Tevatron collider and the LHC.

Acknowledgments

I would like to thank the organizers of the SUSY'05 conference for their kind hospitality, and the LEP Collaborations who entrusted me to give this presentation.

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[4] A. Sopczak, Int. J. Mod. Phys. A 16S1B (2001) 816.

[5] At the SUSY'05 conference the limits were presented for $m_{\rm t}$=179.3 GeV/c^2. The final results in this report are given for $m_{\rm t}$=174.3 GeV/c^2, within the range of the current top mass value $m_{\rm t}$=172.7 ± 2.9 GeV/c^2 (hep-ph/0507091).