MSSM Higgs boson searches at LEP*

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The final results of LEP on the searches for neutral Higgs bosons of the minimal supersymmetric extension of the Standard Model (MSSM) are reviewed. The highlight is put on the results derived in representative scenarios aimed at testing various challenges for the experimental detection, both at LEP and at hadron colliders (kinematics, vanishing branching fractions in key channels, CP violation in the Higgs sector).

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1. Introduction

As compared with the Standard Model (SM), the MSSM has an extended Higgs sector with two doublets of Higgs fields, leading to five physical Higgs bosons, of which three are neutral. The ratio of the doublet vacuum expectation values, $\tan\beta$, plays an important role in the phenomenology of the Higgs bosons.

In e^+e^- collisions, the dominant production mechanisms are the s-channel processes described in Fig. 1, that is the associated production of a Z and a Higgs boson and the pair production of two different Higgs bosons. These processes are complemented by additional t-channel diagrams in the final states where a Higgs boson is produced with neutrinos or electrons, which proceed through W^+W^- and ZZ fusions, respectively. The LEP experiments have searched for neutral Higgs bosons produced in these processes, over the whole energy range covered by the collider. Combined results have been published in Ref. [1] in various representative scenarios, with or without CP conservation in the Higgs sector. These results are presented in this article. Note that Ref. [1] includes also model-independent limits on the

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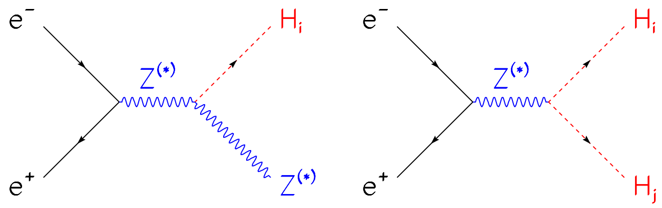

Fig. 1. Main production processes of MSSM neutral Higgs bosons at LEP. Left: associated production of a Z and a Higgs boson (Higgsstrahlung). Right: pair-production of neutral Higgs bosons.

couplings between the Z and the Higgs bosons, in the main final states, to allow other scenarios to be tested.

2. MSSM scenarios with CP conservation

If CP is conserved in the Higgs sector, the three neutral Higgs bosons are CP eigenstates. Two, denoted h and H, are scalars (h being the lightest one), and the third one is a pseudo-scalar, A. The two scalars can be produced in either process of Fig. 1, while A is produced only in pair-production. Within the kinematic range of LEP, the two main processes are the Higgsstrahlung of the lightest scalar, hZ, and the pair-production hA. These processes are complementary over the MSSM parameter space: if kinematically allowed, hZ production dominates at low $\tan\beta$ or at large $m_{\rm A}$, while in the rest of the parameter space, it is suppressed with respect to hA pair-production. In some scenarios, the Higgsstrahlung of the heavy scalar, HZ, is kinematically allowed at large $\tan\beta$ and moderate $m_{\rm A}$, thus providing a gain in sensitivity.

The decays of the MSSM Higgs bosons are mostly similar to those in the SM. In the mass range accessible at LEP, they span from very low mass Higgs particles decaying oustide the detector to Higgs bosons about 100 GeV/c^2 decaying into b or τ pairs. However, in some part of the parameter space, cascade decays such as h $\rightarrow$ AA open and can supplant the other decays. Similarily, in restricted areas of some specific scenarios, the otherwise dominant b$\bar{\rm b}$ decay can be suppressed to the profit of the decay intos hadrons of other flavours. The LEP results combine a great variety of searches that cover most of the possible decays [1].

At tree level, the production cross-sections and the Higgs branching fractions in the MSSM depend on two free parameters, usually chosen as $\tan\beta$ and one Higgs boson mass. Radiative corrections introduce additional parameters related to supersymmetry breaking. In the Higgs boson searches at LEP, the usual assumption that some of them are equal at a given energy scale is made: hence, the SU(2) and U(1) gaugino mass parameters are assumed to be unified at the so-called GUT scale, while the sfermion mass parameters or the squark trilinear couplings are taken to be equal at the EW scale.

Within these assumptions, the parameters beyond tree level are: the top quark mass, the Higgs mixing parameter, μ, the common sfermion mass parameter at the EW scale, $M_{\rm susy}$, the SU(2) gaugino mass parameter at the EW scale, M_2, the gluino mass, $m_{\tilde{g}}$, and the common squark trilinear coupling at the EW scale, A. The U(1) gaugino mass term at the EW scale, M_1, is related to M_2 through the GUT relation $M_1 = (5/3)\tan^2\theta_W M_2$. The radiative corrections affect the relationships between the masses of the Higgs bosons, with the largest contributions arising from loops involving the third generation quarks and squarks (top/stop and, at large values of $\tan\beta$, bottom/sbottom). As an example, the h boson mass, which is below that of the Z boson at tree level, increases by a few tens of GeV/c^2 in some regions of the MSSM parameter space due to radiative corrections.

2.1. The benchmark scenarios

The LEP Higgs working group considered eight benchmark scenarios, as suggested in Ref. [2]. Results were produced for a reference value of $m_{\rm top} = 174.3$ GeV/c^2, a value about 1.5 standard deviation above the current experimental measurement of the top mass. The dependence of the exclusion bounds with $m_{\rm top}$ was also studied over a range spanning from 169.2 to 183.0 GeV/c^2. In all scenarios, the radiative corrections have been computed in the Feynman-diagrammatic approach with all dominant two-loop order terms included, using version 2.0 of the FeynHiggs code [3]. The values of the supersymmetry breaking parameters in all scenarios are detailed in Ref. [1].

The first scenario is the $m_{\rm h}^{\rm max}$ scenario which leads to the maximum possible h mass at each $\tan\beta$ value: as an example, the maximal value of $m_{\rm h}$ is 133 GeV/c^2 for a top mass of 174.3 GeV/c^2. Two variants of that scenario are defined by reversing the sign of μ, and in addition that of the mixing parameter $X = A - \mu\cot\beta$. The changes in the Higgs boson masses and properties are small. The three $m_{\rm h}^{\rm max}$ scenarios provide the largest theoretically allowed region and hence are expected to give the most conservative bounds on $\tan\beta$.

A second class of models contains the no mixing scenario, the counterpart of the $m_{\rm h}^{\rm max}$ scenario with vanishing mixing. It leads to theoretical upper bounds on $m_{\rm h}$ which are at least 15 GeV/c^2 lower than in the $m_{\rm h}^{\rm max}$ scheme. One variant has been proposed in which the sign of μ is reversed and the value of $M_{\rm susy}$ is doubled. The higher $M_{\rm susy}$ scale leads to a few GeV$/c^2$ increase of the theoretical upper bound on $m_{\rm h}$.

The third class of scenarios addresses the issue of possible vanishing branching fractions in the main Higgs decay channels. The first example is the large μ scenario, designed for LEP. It predicts at least one scalar Higgs boson kinematically accessible at LEP in each point of the MSSM parameter space. However, there are regions for which detecting such a Higgs boson is difficult because of vanishing branching fractions into b-quarks due to large radiative corrections. The dominant decays in these regions being still into hadrons, the main analysis channels suffer from large backgrounds. Similarily, the last two scenarios have been proposed to test potentially difficult cases for the searches at hadron colliders. Hence, the gluophobic scenario presents regions where the main production channel at the LHC, gluon fusion, is suppressed due to cancellations between the top quark and stop quark loops in the production process. Finally, in the small α scenario, important decay channels at the Tevatron and at the LHC, $\rm h \to b\bar{b}$ and $\rm h \to \tau^+\tau^-$, are suppressed at large $\tan\beta$ and moderate $m_{\rm A}$.

2.2. Selected results

The regions of the MSSM parameter space excluded by LEP at 95% CL or more in each scenario have been produced in the ($m_{\rm h}$, $\tan\beta$), ($m_{\rm A}$, $\tan\beta$), ($m_{\rm h}$, $m_{\rm A}$) and ($m_{\rm H^\pm}$, $\tan\beta$) planes [1]. As an example, Fig. 2 (a) presents the results in the ($m_{\rm h}$, $\tan\beta$) projection in the $m_{\rm h}^{\rm max}$ scenario for $m_{\rm top} = 174.3$ GeV$/c^2$. Basically, the exclusion is made by the results in the hZ (hA) channels in the low (large) $\tan\beta$ region while they both contribute at intermediate values. These results establish 95% CL lower limits on $m_{\rm h}$ and $m_{\rm A}$ of 92.8 and 93.4 GeV$/c^2$, respectively. These limits hold for any value of $\tan\beta$ between 0.4 and 50 and are insensitive to the top mass value, as shown in Table 1 in the appendix. Besides, values of $\tan\beta$ where the experimentally excluded region reaches the theoretical upper bound on$m_{\rm h}$ are excluded. This exclusion spans from 0.7 to 2.0 in $\tan\beta$ for $m_{\rm top} = 174.3$ GeV$/c^2$. It is sensitive to the top mass value, as demonstrated in Fig. 2 (b) and Table 1. This table also shows that the two variants of the $m_{\rm h}^{\rm max}$ scenario give similar mass limits and slightly larger excluded ranges in $\tan\beta$. Thus the most conservative limit in $\tan\beta$ is set by the LEP $m_{\rm h}^{\rm max}$ scenario.

In the no mixing scenario, a larger region of the parameter space is accessible at LEP, thanks to low h and/or H masses and high couplings to the Z. As an example, for $m_{\rm top} = 174.3$ GeV$/c^2$ (see Fig. 3), 95% CL lower limits of 93.6 GeV$/c^2$ are reached on both $m_{\rm h}$ and $m_{\rm A}$, and the exclusion in $\tan\beta$ covers the interval between 0.4 and 10.2. These limits have a restricted

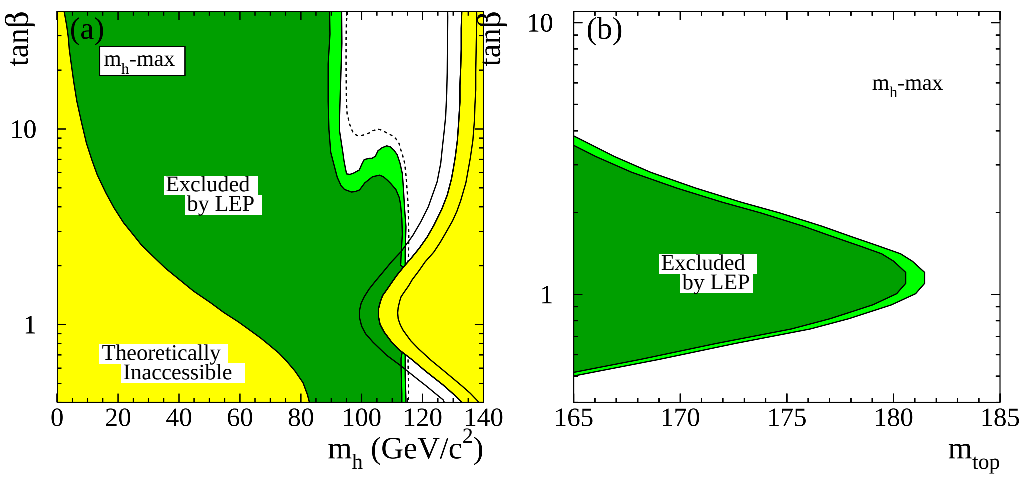

Fig. 2. MSSM $m_{\mathrm{h}}^{\max}$ scenario for a top mass of 174.3 GeV$/c^2$: a) regions excluded at 95% CL (medium-grey) and 99.7% CL (dark-grey) by combining the results of the Higgs boson searches at LEP. The dashed curves show the median expected limits at 95% CL. The theoretical upper bounds for a top mass of 169.2 and 179.4 GeV$/c^2$ (from left to right) are also indicated. b) Variation with m_{top} of the exclusions in $\tan\beta$ at 95% CL (medium-grey) and 99.7% CL (dark-grey).

validity, though, due to tiny unexcluded domains in the region $\tan\beta \leq 0.7$ and $m_{\mathrm{A}} \leq 3$ GeV$/c^2$. In that region, the decay $\mathrm{h} \rightarrow \mathrm{AA}$ opens and supplants the $\mathrm{h} \rightarrow \mathrm{b\bar{b}}$ mode, and the A boson, with mass below the $\tau^+\tau^-$ threshold, decays to final states which are not sufficiently covered by the experimental searches. The mass and $\tan\beta$ limits in that scenario are very sensitive to the top mass value (see Table 1), due to strong variations of m_{H} with m_{top}: thus, the no mixing scenario is fully excluded for $m_{\mathrm{top}} = 169.2$ GeV$/c^2$. In the variant of the no mixing scenario, the higher value of M_{susy} enlarges the kinematic range of m_{h} and m_{H} , leading to more conservative limits in mass and $\tan\beta$, as shown in Table 1.

Finally, in the third class of models, the large μ scenario is fully excluded for $m_{\mathrm{top}} \leq 174.3$ GeV$/c^2$, thanks to favourable kinematic conditions and to the searches for Higgs bosons decaying into hadrons of any flavour. For a larger m_{top}(see Table 1), small regions remain unexcluded at large $\tan\beta$ and m_{A} between 100 and 200 GeV$/c^2$, due to m_{h} reaching the ultimate sensitivity of these searches. In the other two scenarios, LEP results exclude sizable domains of the parameter space, as shown in Fig. 4 and Table 1. Note

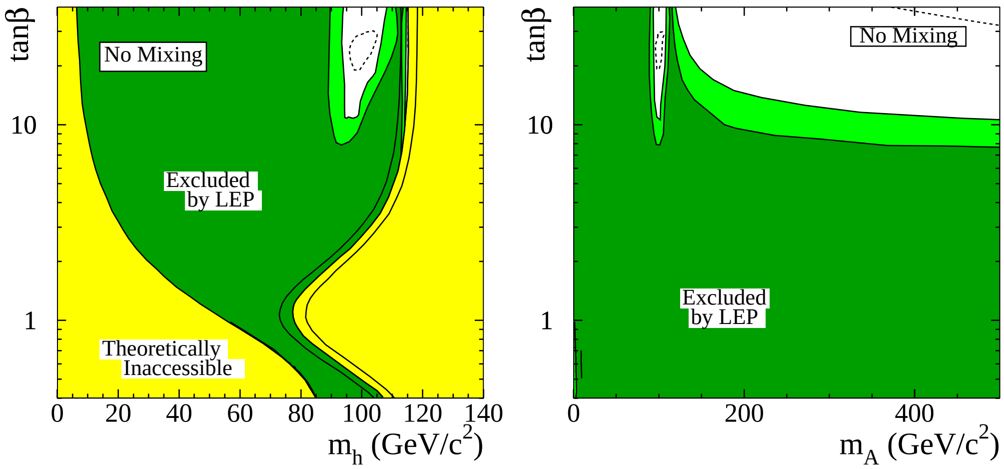

Fig. 3. LEP exclusions in the MSSM no mixing scenario for a top mass of 174.3 GeV/c^2: see the caption of Fig. 2 for the legend.

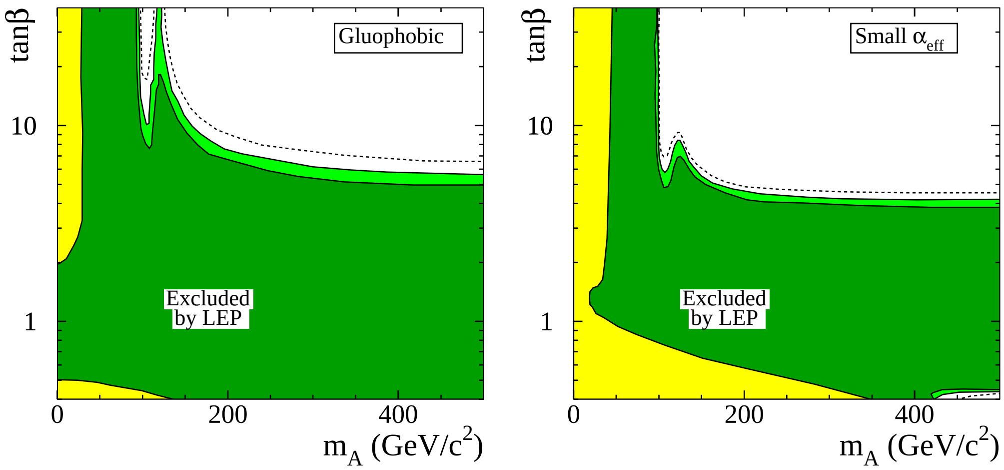

Fig. 4. LEP exclusions in the MSSM gluophobic and small α scenarios for a top mass of 174.3 GeV/c^2: see the caption of Fig. 2 for the legend.

that the difference between the h and A mass bounds in these scenarios reflects the fact that these two bosons are not degenerate in mass in the region where the limits are set, contrary to what happens in the $m_{\rm h}^{\rm max}$ and no mixing models.

3. MSSM scenarios with CP violation

If CP is not conserved in the Higgs sector, which may be realized through radiative corrections, the three neutral Higgs bosons are no longer pure CP eigenstates but mixtures of CP-even and CP-odd components. They are usually denoted $\rm H_1$, $\rm H_2$ and $\rm H_3$, in increasing mass. The main production mechanisms are the same as in the CP-conserving case, except that, a priori, any scalar can be produced in association with a Z boson or through $\rm W^+W^-$ and ZZ fusions, and any couple of different Higgs bosons can be produced in pair (see Fig. 1). The main difference with respect to the CP-conserving case lies in the couplings of the Z boson to the Higgs scalars, which can be strongly suppressed in significant regions of the parameter space. In most part of the latter, only the two lightest scalars, $\rm H_1$ and $\rm H_2$ are kinematically accessible at LEP. If their couplings to the Z boson are not suppressed by CP violation, the main production processes are thus the $\rm H_1Z$, $\rm H_2Z$ and $\rm H_1H_2$ processes, with $\rm H_1Z$ dominating at low $\tan\beta$, $\rm H_1H_2$ at large $\tan\beta$ and $\rm H_2Z$ contributing whatever $\tan\beta$.

On the other hand, the decay properties of the Higgs bosons are not strongly affected by CP violation, at least for the masses accessible at LEP, up to around 100 GeV$/c^2$. The only difference concerns the cascade decays which can be dominant in regions of the parameter space larger than in the CP-conserving case. Besides the kinematic properties of the signal processes are only slightly affected by CP violation, for, when CP is not conserved, the production processes still proceed through the CP-even and CP-odd components of the neutral Higgs bosons [1]. The same topological searches can thus be applied whether CP is conserved or not.

As already mentioned, CP violation in the MSSM Higgs sector is introduced through radiative corrections. Besides the two parameters used to define the scenarios at tree level and the usual set of parameters related to supersymmetry breaking (see section 2), CP violation introduces phases. Physical arguments impose that only two CP-violating phases are physical [4]. These are taken as the phase of the gluino mass, $\arg(m_{\tilde g})$ and the common phase of the stop and sbottom trilinear couplings, $\arg(A_{t,b})$.

3.1. The benchmark scenarios

The dominant CP-violating effects are proportional to $\frac{m_{top}^4}{v^2}\frac{Im(\mu A)}{M_{susy}^2}$ where v is the quadratic sum of the vacuum expectation values of the two Higgs field doublets. Sizeable effects are thus expected for moderate values of $M_{\rm susy}$, large values of μ and phases $\arg(A_{t,b})$ around 90°. A strong dependence with the value of $m_{\rm top}$ is also to be expected. Along these lines, a benchmark scenario with maximal CP violation, the CPX scenario, has been proposed in Ref. [5] as an appropriate scheme for LEP searches. A few variants have also been considered by the LEP Higgs working group in order to study the dependence of the CP violation effects with the values of the phases, of μ and $M_{\rm susy}$. The values of the underlying parameters in all scenarios are detailed in Ref. [1].

In all scenarios, radiative corrections have been computed in two different approaches, the Feynman-diagrammatic approach of Ref. [3], already selected in the CP-conserving case, and the renormalization group approach of Ref. [6], using in that case the CP-violating version CPH of the SUBHPOLE code. Contrary to the CP-conserving case, where the calculations in the Feynman-diagrammatic approach are the most complete, in the case of CP-violation neither of the two calculations can be preferred on theoretical grounds. To account for the presently significant differences between the two approaches, the scans performed by the LEP Higgs working group use the two sets of calculations and declare a point as excluded only if it is excluded in both.

3.2. Selected results

The LEP Higgs working group produced results in the CPX scenario and its variants for $m_{\rm top} = 174.3$ GeV/c^2 and studied the dependence of the results with the top mass in the CPX scenario. The full set of results can be found in Ref. [1]. A few results are presented here in order to illustrate the main effects from CP violation.

The impact of the CP-violating phases is first illustrated in Fig. 5, which shows the regions excluded by LEP when all phases are set to 0° (a), 60° (b) and 90° (c), the phase value in the CPX scenario. Note that the variant with 0° phases is a CP-conserving scenario. For zero to moderate phases, LEP covers sizable regions of the parameter space. The exclusion degrades significantly for phases around 90°: the $\rm H_1Z$ process is suppressed, leaving only one process accessible in most part of the parameter space. At large $\tan\beta$, this process is $\rm H_1H_2$, whose sensitivity does not go beyond 60 GeV/c^2 in $m_{\rm H_1}$, due to kinematics. In the intermediate $\tan\beta$ region, the process left is $\rm H_2Z$, with $\rm H_2 \to H_1H_1$ as the main $\rm H_2$ decay for $m_{\rm H_1}$ below around 60 GeV/c^2. The corresponding searches exhibit a slight excess of data at $\rm H_1$ masses between 35 and 55 GeV/c^2, and have unsufficient sensitivity below 15 GeV/c^2 in $m_{\rm H_1}$, which explains the two unexcluded areas at $\tan\beta$ between around 4 and 10.

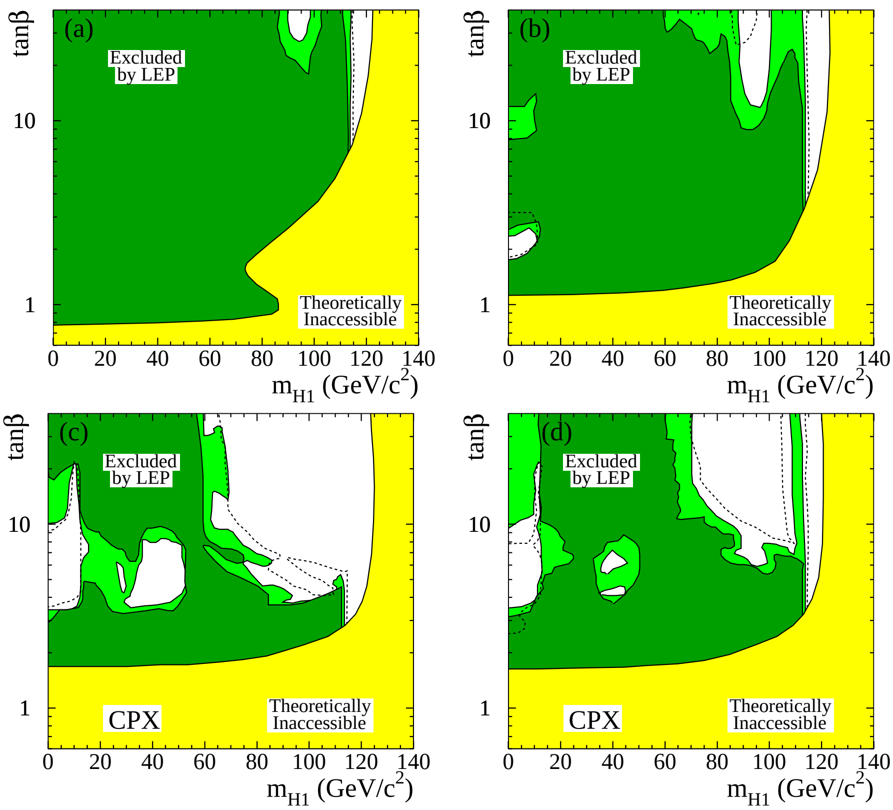

Fig. 5. CP-violating MSSM scenarios for different values of the phases and m_{top} (see text): regions excluded at 95% CL (medium-grey) or 99.7% CL (dark-grey) by combining the results of the Higgs boson searches at LEP. The dashed curves show the median expected limits at 95% CL.

The dependence with μ is illustrated in Fig. 6 with results corresponding to values of 1 TeV (a) and 4 TeV (b), to be compared to 2 TeV, the value of μ in the CPX scenario (see part (c) of Fig. 5). For values of μ lower than that in the CPX scenario, at least two production processes are possible in every point of the kinematically accessible region of the parameter space, which translates into a good experimental sensitivity. On the contrary, for higher values of μ, most of the sensitivity is lost due to the strong suppression of the three possible production processes.

Finally, the dependence with m_{top} is illustrated with the CPX results for $m_{\mathrm{top}} = 169.2\,\mathrm{GeV}/c^2$, Fig. 5 (d), to be compared with those for $174.3\,\mathrm{GeV}/c^2$

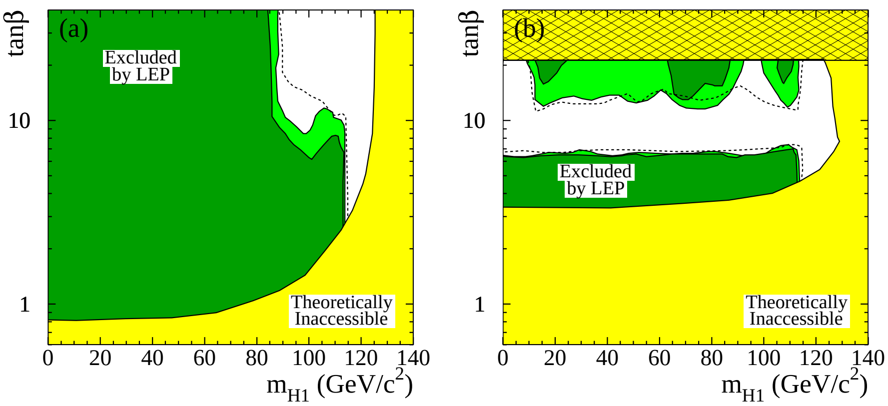

Fig. 6. CP-violating MSSM scenarios with different values of μ (see text): regions excluded at 95% CL (medium-grey) or 99.7% CL (dark-grey) by combining the results of the Higgs boson searches at LEP. The dashed curves show the median expected limits at 95% CL.

in Fig. 5 (c). The lower $m_{\rm top}$ translates into a better coverage of the parameter space, due to reduced CP violation effects, although the exclusion is not fully restored as in CP-conserving scenarios (see e.g. part (a) of Fig. 5). On the other hand, higher top mass values would lead to a stronger suppression of the three possible production processes and hence to a reduced coverage of the parameter space (see Ref. [1]).

4. Conclusions

The four LEP experiments have searched for neutral Higgs bosons in a great variety of final states as expected from the main production processes and decay modes in the MSSM. These searches did not reveal any significant excess with respect to Standard Model background predictions. These results were turned into exclusion bounds in a set of representative MSSM scenarios.

If CP is conserved in the MSSM Higgs sector, upper mass bounds around 90 GeV/c^2 in $m_{\rm h}$ and $m_{\rm A}$ are achieved whatever the scenario, even those exhibiting regions with vanishing branching fractions in the key decays channels. For a top mass as low as 169.2 GeV/c^2, two of the representative scenarios (no mixing, large μ) are fully excluded by LEP. In all scenarios, the low $\tan\beta$ region appears not to be favoured. The most conservative exclusion in $\tan\beta$ is obtained in the $m_{\rm h}^{\rm max}$ scenario and spans from 0.7 to

2.0 for a top mass of 174.3 GeV/c^2.

If CP is not conserved in the Higgs sector, no absolute mass bounds can be set due to strongly suppressed couplings between the Z and the Higgs bosons in the intermediate $\tan\beta$ range, namely between around 4 and 10. The low $\tan\beta$ region is not favoured in these scenarios either. As an example, the interval below 2.9 in $\tan\beta$ is excluded in the CPX scenario for a top mass of 174.3 GeV/c^2. Finally, the calculations of the radiative corrections in the case of CP violation are not yet as complete as in the CP-conserving case, so that the theoretical predictions in this area may evolve significantly in the future.

Appendix

		$m_{\rm top}$ (GeV/c^2)			
scenario	limits	169.2	174.3	179.4	183.0
$m_{\rm h}^{\rm max}$	$m_{\rm h}$	92.9	92.8	92.9	92.8
	$m_{\rm A}$	93.4	93.4	93.4	93.5
	$\tan\beta$	0.6 - 2.6	0.7 - 2.0	0.9 - 1.5	none
$m_{\rm h}^{\rm max}$ variant (a)	$m_{\rm h}$	92.7	92.7	92.6	92.7
	$m_{\rm A}$	93.1	93.1	93.1	93.1
	$\tan\beta$	0.7 - 2.1	0.7 - 2.1	0.9 - 1.6	none
$m_{\rm h}^{\rm max}$ variant (b)	$m_{\rm h}$	92.8	92.6	92.6	92.7
	$m_{\rm A}$	93.2	93.4	93.4	93.4
	$\tan\beta$	0.5 - 3.3	0.6 - 2.5	0.7 - 2.0	0.8 - 1.7
no-mixing	$m_{\rm h}$	excl.	93.6	93.3	92.9
	$m_{\rm A}$	excl.	93.6	93.4	93.1
	$\tan\beta$	excl.	0.4 - 10.2	0.4 - 5.5	0.4 - 4.4
no-mixing variant (a)	$m_{\rm h}$	93.2	92.8	92.8	92.9
	$m_{\rm A}$	93.4	93.1	93.1	93.1
	$\tan\beta$	0.7 - 7.1	0.7 - 4.6	0.7 - 3.5	0.7 - 3.0
Large μ	$m_{\rm h}$	excl.	excl.	109.2	95.6
	$m_{\rm A}$	excl.	excl.	225.0	98.9
	$\tan\beta$	excl.	excl.	0.7 - 43.	0.7 - 11.5
Gluophobic	$m_{\rm h}$	90.6	90.5	90.0	89.8
	$m_{\rm A}$	95.7	96.3	96.5	96.8
	$\tan\beta$	0.4 - 10.3	0.4 - 5.4	0.4 - 3.9	0.5 - 3.3
Small α	$m_{\rm h}$	88.2	87.3	86.6	85.6
	$m_{\rm A}$	98.2	98.8	99.8	101.0
	$\tan\beta$	0.4 - 6.1	0.4 - 4.2	0.5 - 3.2	0.6 - 2.7

Table 1. 95% CL lower mass bounds and exclusions in $\tan\beta$ obtained at LEP in different CP-conserving MSSM benchmark scenarios, as a function of $m_{\rm top}$. In the no mixing scenario and for $m_{\rm top} > 169.2$ GeV/c^2, the quoted mass limits are only valid for $\tan\beta > 0.7$ and the exclusion in $\tan\beta$ is only valid for $m_{\rm A} > 3$ GeV/c^2.

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