CERN–TH/99–368
DESY 99–156
RAL–TR–1999–079
GLAS-PPE/1999–20
hep-ph/9912249

Upper limit on m_h in the MSSM and M-SUGRA vs. prospective reach of LEP*

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Abstract

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* Contribution to the "UK Phenomenology Workshop on Collider Physics", Durham, UK, September 1999.

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Abstract. The upper limit on the lightest $\mathcal{CP}$-even Higgs boson mass, m_h, is analyzed within the MSSM as a function of $\tan\beta$ for fixed m_t and M_{SUSY}. The impact of recent diagrammatic two-loop results on this limit is investigated. We compare the MSSM theoretical upper bound on m_h with the lower bound obtained from experimental searches at LEP. We estimate that with the LEP data taken until the end of 1999, the region $m_h < 108.2$ GeV can be excluded at the 95% confidence level. This corresponds to an excluded region $0.6 \lesssim \tan\beta \lesssim 1.9$ within the MSSM for $m_t = 174.3$ GeV and $M_{\mathrm{SUSY}} \leq 1$ TeV. The final exclusion sensitivity after the end of LEP, in the year 2000, is also briefly discussed. Finally, we determine the upper limit on m_h within the Minimal Supergravity (M-SUGRA) scenario up to the two-loop level, consistent with radiative electroweak symmetry breaking. We find an upper bound of $m_h \approx 127$ GeV for $m_t = 174.3$ GeV in this scenario, which is slightly below the bound in the unconstrained MSSM.

1. Introduction

Within the MSSM the masses of the $\mathcal{CP}$-even neutral Higgs bosons are calculable in terms of the other MSSM parameters. The mass of the lightest Higgs boson, m_h, has been of particular interest, as it is bounded to be smaller than the Z boson mass at the tree level. The one-loop results [1–4] for m_h have been supplemented in the last years with the leading two-loop corrections, performed in the renormalization group (RG) approach [5, 6], in the effective potential approach [7] and most recently in the Feynman-diagrammatic (FD) approach [8, 9]. The two-loop corrections have turned out to be sizeable. They can change the one-loop results by up to 20%.

Experimental searches at LEP now exclude a light MSSM Higgs boson with a mass below ~90 GeV [10–13]. In the low $\tan\beta$ region, in which the limit is the same as for the Standard Model Higgs boson, a mass limit of even $m_h \gtrsim 106$ GeV has been obtained [10–13]. Combining this experimental bound with the theoretical upper limit on m_h as a function of $\tan\beta$ within the MSSM, it is possible to derive constraints on $\tan\beta$. In this paper we investigate, for which MSSM parameters the maximal m_h values are obtained and discuss in this context the impact of the new FD two-loop result.

Resulting constraints on $\tan\beta$ are analyzed on the basis of the present LEP data and of the prospective final exclusion limit of LEP.

The Minimal Supergravity (M-SUGRA) scenario provides a relatively simple and constrained version of the MSSM. In this paper we explore, how the maximum possible values for m_h change compared to the general MSSM, if one restricts to the M-SUGRA framework. As an additional constraint we impose that the condition of radiative electroweak symmetry breaking (REWSB) [14] should be fulfilled.

2. The upper bound on m_h in the MSSM

The most important radiative corrections to m_h arise from the top and scalar top sector of the MSSM, with the input parameters m_t, M_{SUSY} and X_t. Here we assume the soft SUSY breaking parameters in the diagonal entries of the scalar top mixing matrix to be equal for simplicity, $M_{\mathrm{SUSY}} = M_{\tilde{t}_L} = M_{\tilde{t}_R}$. This has been shown to yield upper values for m_h which comprise also the case where $M_{\tilde{t}_L} \neq M_{\tilde{t}_R}$, if M_{SUSY} is identified with the heavier one of $M_{\tilde{t}_L}$, $M_{\tilde{t}_R}$ [9]. For the off-diagonal entry of the mixing matrix we use the convention

$$m_t X_t = m_t(A_t - \mu \cot\beta). \tag{1}$$

Note that the sign convention used for μ here is the opposite of the one used in Ref. [15].

Since the predicted value of m_h depends sensitively on the precise numerical value of m_t, it has become customary to discuss the constraints on $\tan\beta$ within a so-called "benchmark" scenario (see Ref. [16] and references therein), in which m_t is kept fixed at the value $m_t = 175$ GeV and in which furthermore a large value of M_{SUSY} is chosen, $M_{\mathrm{SUSY}} = 1$ TeV, giving rise to large values of $m_h(\tan\beta)$. In Ref. [17] it has recently been analyzed how the values chosen for the other SUSY parameters in the benchmark scenario should be modified in order to obtain the maximal values of $m_h(\tan\beta)$ for given m_t and M_{SUSY}. The corresponding scenario ($m_h^{\max}$ scenario) is defined as [17, 18]

$$\begin{aligned} & m_t = m_t^{\exp} \; (= 174.3 \text{ GeV}), \quad M_{\mathrm{SUSY}} = 1 \text{ TeV} \\ & \mu = -200 \text{ GeV}, \; M_2 = 200 \text{ GeV}, \; M_A = 1 \text{ TeV}, \; m_{\tilde{g}} = 0.8\, M_{\mathrm{SUSY}} (\mathrm{FD}) \\ & X_t = 2\, M_{\mathrm{SUSY}} (\mathrm{FD}) \;\text{ or }\; X_t = \sqrt{2}\, M_{\mathrm{SUSY}} (\mathrm{RG}), \end{aligned} \tag{2}$$

where the parameters are chosen such that the chargino masses are beyond the reach of LEP2 and that the lightest $\mathcal{CP}$-even Higgs boson does not dominantly decay invisibly into neutralinos. In eq. (2) μ is the Higgs mixing parameter, M_2 denotes the soft SUSY breaking parameter in the gaugino sector, and M_A is the $\mathcal{CP}$-odd Higgs boson mass. The gluino mass, $m_{\tilde{g}}$, can only be specified as a free parameter in the FD result (program `FeynHiggs` [19]). The effect of varying $m_{\tilde{g}}$ on m_h is up to ±2 GeV [9]. Within the RG result (program `subhpole` [5]) $m_{\tilde{g}}$ is fixed to $m_{\tilde{g}} = M_{\mathrm{SUSY}}$. Compared to the maximal values for m_h (obtained for $m_{\tilde{g}} \approx 0.8\, M_{\mathrm{SUSY}}$) this leads to a reduction of the Higgs boson mass by up to 0.5 GeV. Different values of X_t are specified in eq. (2) for the results of the FD and the RG calculation, since within the two approaches the maximal values for m_h are obtained for different values of X_t. This fact is partly due to the different renormalization schemes used in the two approaches [20].

The maximal values for m_h as a function of $\tan\beta$ within the $m_h^{\rm max}$ scenario are higher by about 5 GeV than in the previous benchmark scenario. The constraints on $\tan\beta$ derived within the $m_h^{\rm max}$ scenario are thus more conservative than the ones based on the previous scenario.

The investigation of the constraints on $\tan\beta$ that can be obtained from the experimental search limits on m_h has so far been based on the results for m_h obtained within the RG approach [5]. The recently obtained FD [8,9] result differs from the RG result by a more complete treatment of the one-loop contributions [3] and in particular by genuine non-logarithmic two-loop terms that go beyond the leading logarithmic two-loop contributions contained in the RG result [20, 21]. Comparing the FD result (program `FeynHiggs`) with the RG result (program `subhpole`) we find that the maximal value for m_h as a function of $\tan\beta$ within the FD result is higher by up to 4 GeV.

In Fig. 1 we show both the effect of modifying the previous benchmark scenario to the $m_h^{\rm max}$ scenario and the impact of the new FD two-loop result on the prediction for m_h. The maximal value for the Higgs boson mass is plotted as a function of $\tan\beta$ for $m_t = 174.3$ GeV and $M_{\rm SUSY} = 1$ TeV. The dashed curve displays the benchmark scenario, used up to now by the LEP collaborations [16]. The dotted curve shows the $m_h^{\rm max}$ scenario. Both curves are based on the RG result (program `subhpole`). The solid curve corresponds to the FD result (program `FeynHiggs`) in the $m_h^{\rm max}$ scenario. The increase in the maximal value for m_h by about 4 GeV from the new FD result and by further 5 GeV if the benchmark scenario is replaced by the $m_h^{\rm max}$ scenario has a significant effect on exclusion limits for $\tan\beta$ derived from the Higgs boson search. Combining both effects, which of course have a very different origin, the maximal Higgs boson masses are increased by almost 10 GeV compared to the previous benchmark scenario.

From the FD result we find the upper bound of $m_h \lesssim 129$ GeV in the region of large $\tan\beta$ within the MSSM for $m_t = 174.3$ GeV and $M_{\rm SUSY} = 1$ TeV. Higher values for m_h are obtained if the experimental uncertainty in m_t of currently $\Delta m_t = 5.1$ GeV is taken into account and higher values are allowed for the top quark mass. As a rule of thumb, increasing m_t by 1 GeV roughly translates into an upward shift of m_h of 1 GeV. An increase of $M_{\rm SUSY}$ from 1 TeV to 2 TeV enhances m_h by about 2 GeV in the large $\tan\beta$ region. As an extreme case, choosing $m_t = 184.5$ GeV, i.e. two standard deviations above the current experimental central value, and using $M_{\rm SUSY} = 2$ TeV leads to an upper bound on m_h of $m_h \lesssim 141$ GeV within the MSSM.

3. The prospective upper m_h reach of LEP

The four LEP experiments are very actively searching for the Higgs boson. Results presented recently by the LEP collaborations revealed no evidence of a SM Higgs boson signal in the data collected in 1999 at centre-of-mass energies of approximately 192, 196,

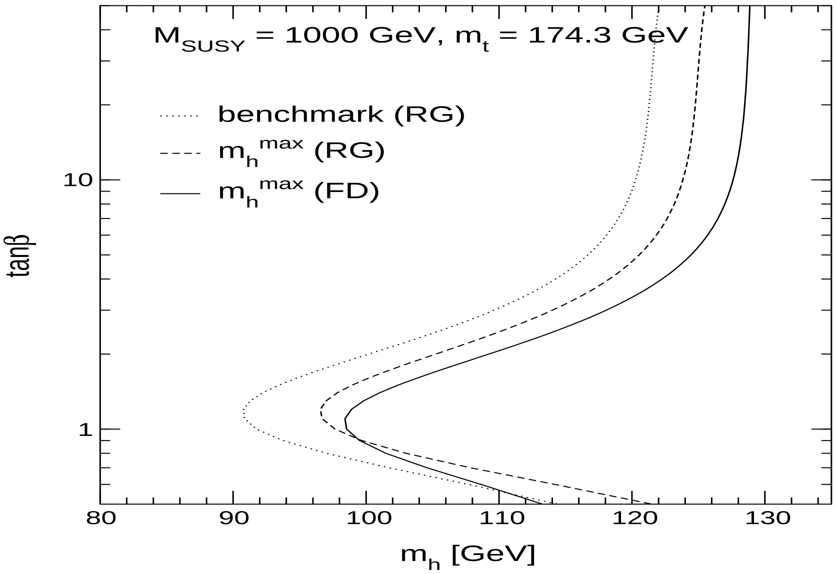

Figure 1. The upper bound on m_h is shown as a function of $\tan\beta$ for given m_t and M_{SUSY}. The dashed curve displays the previous benchmark scenario. The dotted curve shows the RG result for the $m_h^{\max}$ scenario, while the solid curve represents the FD result for the $m_h^{\max}$ scenario.

200 and 202 GeV [10–13]. From the negative results of their searches ALEPH, DELPHI and L3 have therefore individually excluded a SM Higgs boson lighter than ~101–106 GeV (at the 95% confidence level) [10–12].

Here we will present the expected exclusion reach of LEP assuming all the data taken by the four experiments in 1999 is combined. The ultimate exclusion reach of LEP – assuming no signal were found in the data to be collected in the year 2000 – will also be estimated for several hypothetical scenarios of luminosity and centre-of-mass energy. These results are then confronted with the theoretical MSSM upper limit on $m_h(\tan\beta)$ presented in Section 2, in order to establish to what extent the LEP data can probe the low $\tan\beta$ region. We recall that models in which b-τ Yukawa coupling unification at the GUT scale is imposed favor low $\tan\beta$ values, $\tan\beta \approx 2$, which can severely be constrained experimentally by searches at LEP. Alternatively, such models can favor $\tan\beta \approx 40$, a region which however can only be partly covered at LEP.

All experimental exclusion limits quoted in this section are implicitly meant at the 95% confidence level (CL).

It has been proposed [22] that the LEP-combined expected 95% CL lower bound on m_h, m_h^{95}, for a data set consisting of data accumulated at given centre-of-mass energies can be estimated by solving the equation

$$n(m_h^{95}) = (\sigma_0 \mathcal{L}_{eq})^{\alpha}, \tag{3}$$

where $n(m_h^{95})$ is the number of signal events produced at the 95% CL limit. The equivalent luminosity, $\mathcal{L}_{eq}$, is the luminosity that one would have to accumulate at the highest centre-of-mass energy in the data set in order to have the same sensitivity as in the real data set, where the data is split between several different $\sqrt{s}$ values. For a SM Higgs boson signal, the parameters σ_0 and α are $\sim$38 pb and $\sim$0.4, respectively [22]. (These parameter values are obtained from a fit to the actual LEP-combined expected limits from $\sqrt{s} = 161$ GeV up to $\sqrt{s} = 188.6$ GeV [16, 23, 24].) The predicted m_h limits obtained with this method are expected to approximate the more accurate combinations done by the LEP Higgs Working Group, with an uncertainty of the order of ± 0.3 GeV.

Solving eq. (3) for the existing LEP data with 183 GeV $\lesssim \sqrt{s} \lesssim 202$ GeV (Table 1) results in a predicted combined exclusion of $m_h < 108.2$ GeV for the SM Higgs boson (see Figure 2a).

Table 1. Summary of the total LEP data luminosity accumulated since 1997. The luminosities for the data taken in 1999 ($\sqrt{s} \geq 191.6$ GeV) are the (still preliminary) values quoted by the four LEP experiments at the LEPC open session [10–13].

$\sqrt{s}$ (GeV)	182.7	188.6	191.6	195.5	199.5	201.6
$\mathcal{L}$ (pb^{-1})	220.0	682.7	113.9	316.4	327.8	148.1

Based on the current LEP operational experience, it is believed that in the year 2000 stable running is possible up to $\sqrt{s} = 206$ GeV [25]. Figure 2b demonstrates the impact of additional data collected at $\sqrt{s} = 206$ GeV on the exclusion. For instance, if no evidence of a signal were found in the data, collecting 500 (1000) pb^{-1} at this centre-of-mass energy would increase the m_h limit to 113.0 (114.1) GeV. Figure 2c shows the degradation in the sensitivity to a Higgs boson signal if the data in the year 2000 were accumulated at $\sqrt{s} = 205$ GeV instead: in this case the luminosity required to exclude up to $m_h = 113$ GeV would be 840 pb^{-1}.

In Table 2 the expected SM Higgs boson limit is shown for several possible LEP running scenarios in the year 2000. Taking into account that the *experimental* MSSM m_h exclusion in the range $0.5 \lesssim \tan\beta \lesssim 3$ is *(i)* essentially independent of $\tan\beta$ and *(ii)* equal in value to the SM m_h exclusion (see e.g. [24, 26]), m_h^{95} can be converted into an excluded $\tan\beta$ range in the $m_h^{\max}$ benchmark scenario described in Section 2. This is done by intersecting the experimental exclusion and the solid curve in Figure 1. Using the LEP data taken until the end of 1999 (for which $m_h^{95} = 108.2$ GeV) one can already expect to exclude $0.6 \lesssim \tan\beta \lesssim 1.9$ within the MSSM for $m_t = 174.3$ GeV and $M_{\rm SUSY} = 1$ TeV. Note that in determining the excluded $\tan\beta$ regions in Table 2 the theoretical uncertainty from unknown higher-order corrections has been neglected. As can be seen from Table 2, several plausible scenarios for adding new data at higher energies can extend the exclusion to $m_h \lesssim 113$ GeV ($0.5 \lesssim \tan\beta \lesssim 2.4$).

4. The upper limit on m_h in the M-SUGRA scenario

The M-SUGRA scenario is described by four independent parameters and a sign, namely the common squark mass M_0, the common gaugino mass $M_{1/2}$, the common trilinear

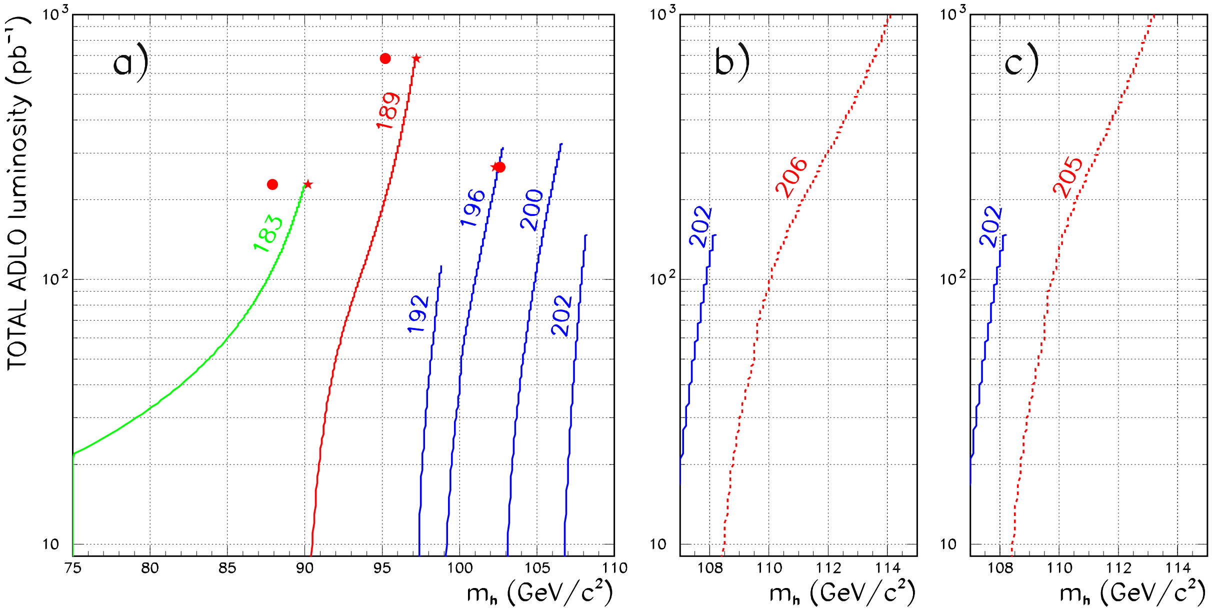

Figure 2. Predictions of the expected combined ALEPH+DELPHI+L3+OPAL 95% CL m_h exclusion; a) obtained from the data taken until the end of 1999 (solid lines). For comparison the expected (stars) and observed (dots) combined LEP limits obtained from actual data combinations [16, 24, 26] are also shown. The effect of adding to this data set new data at b) $\sqrt{s}$ =206 GeV or c) 205 GeV is indicated by the dashed line.

Table 2. Predictions of the sensitivity of the four LEP experiments combined, for several hypothetical data sets. The table shows the expected excluded SM Higgs boson mass (m_h^{95}, in GeV) as well as the corresponding excluded $\tan\beta$ region in the $m_h^{\max}$ benchmark scenario (with m_t = 174.3 GeV, $M_{\rm SUSY}$ = 1 TeV), when new data at the indicated $\sqrt{s}$ is combined with the existing data set (Table 1). The luminosities indicated are for the 4 LEP experiments combined. The results shown are valid only if no signal were found in the data. (Note that, as it is not foreseen at the moment that it will be possible to run LEP at $\sqrt{s} > 206$ GeV, scenario 8 is probably unrealistic.)

$\sqrt{s}$ (GeV)	204.	205.	206.	208.	m_h^{95}	$\tan\beta^{95}$
1) $\mathcal{L}$ (pb^{-1})	-	-	100.	-	110.0	0.6 – 2.1
2) $\mathcal{L}$ (pb^{-1})	-	-	500.	-	113.0	0.5 – 2.4
3) $\mathcal{L}$ (pb^{-1})	-	-	1000.	-	114.1	0.5 – 2.5
4) $\mathcal{L}$ (pb^{-1})	-	120.	-	-	110.0	0.6 – 2.1
5) $\mathcal{L}$ (pb^{-1})	-	840.	-	-	113.0	0.5 – 2.4
6) $\mathcal{L}$ (pb^{-1})	100.	100.	400.	-	113.1	0.5 – 2.4
7) $\mathcal{L}$ (pb^{-1})	150.	300.	300.	-	113.3	0.5 – 2.4
8) $\mathcal{L}$ (pb^{-1})	150.	300.	300.	280.	115.0	0.5 – 2.6

coupling A_0, $\tan\beta$ and the sign of μ. The universal parameters are fixed at the GUT scale, where we assumed unification of the gauge couplings. Then they are run down to the electroweak scale with the help of renormalization group equations [4, 15, 27–32].

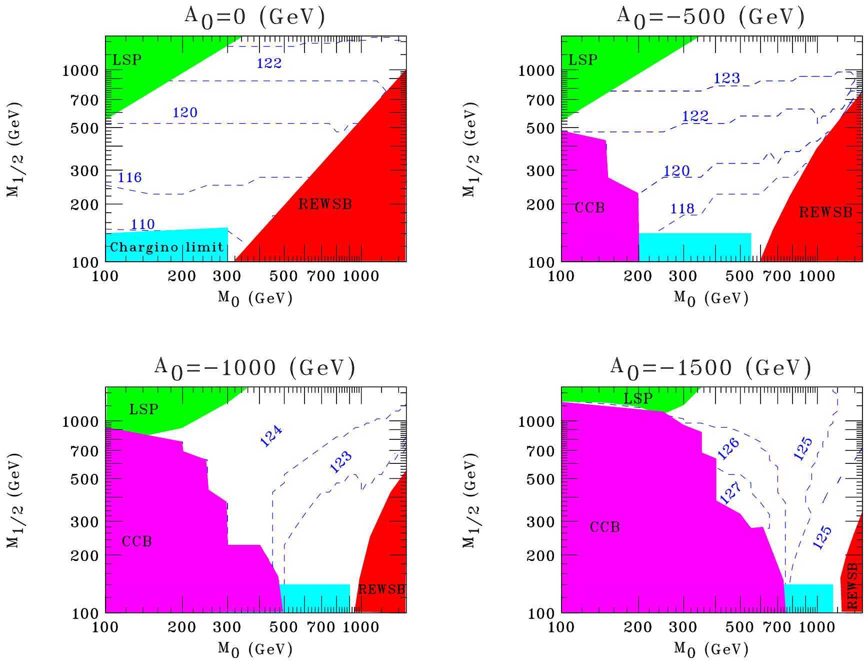

Figure 3. In the $M_0 - M_{1/2}$-plane the contour lines of m_h are shown for four values of A_0. The numbers refer to m_h in the respective region within ±0.5 GeV. The regions that are excluded by REWSB, the CCB or LSP conditions, or by direct chargino search are also indicated.

The condition of REWSB puts an upper bound on M_0 of about $M_0 \lesssim 5$ TeV (depending on the values of the other four parameters).

In order to obtain a precise prediction for m_h within the M-SUGRA scenario, we employ the complete two-loop RG running with appropriate thresholds (both logarithmic and finite for the gauge couplings and using the so called θ-function approximation for the masses [15]) including full one-loop minimization conditions for the effective potential, in order to extract all the parameters of the M-SUGRA scenario at the EW scale. This method has been combined with the presently most precise result of m_h based on a Feynman-diagrammatic calculation [8, 9]. This has been carried out by combining the codes of two programs namely, `SUITY` [33] and `FeynHiggs` [19].

In order to investigate the upper limit on the Higgs boson mass in the M-SUGRA scenario, we keep $\tan\beta$ fixed at a large value, $\tan\beta = 30$. Concerning the sign of the Higgs mixing parameter, μ, we find larger m_h values (compatible with the constraints discussed below) for negative μ (in the convention of eq. (1)). In the following we analyze the upper limit on m_h as a function of the other M-SUGRA parameters, M_0, $M_{1/2}$ and A_0. Our results are displayed in Fig. 3 for four values of A_0: $A_0 = 0, -500, -1000, -1500$ GeV. We show contour lines of m_h in the $M_0 - M_{1/2}$-plane. The numbers inside the plots indicate the lightest Higgs boson mass in the respective area within ±0.5 GeV. The upper bound on the lightest $\mathcal{CP}$-even Higgs boson mass is found to be at most 127 GeV. This upper limit is reached for $M_0 \approx 500$ GeV, $M_{1/2} \approx 400$ GeV and $A_0 = -1500$ GeV. Concerning the analysis the following should be noted:

- We have chosen the current experimental central value for the top quark mass, $m_t = 174.3$ GeV. As mentioned above, increasing m_t by 1 GeV results in an increase of m_h of approximately 1 GeV.
- The M-SUGRA parameters are taken to be real, no SUSY $\mathcal{CP}$-violating phases are assumed.
- We have chosen negative values for the trilinear coupling, because m_h turns out to be increased by going from positive to negative values of A_0. $|A_0|$ is restricted from above by the condition that no negative squares of squark masses and no charge or color breaking minima appear.
- The regions in the $M_0 - M_{1/2}$-plane that are excluded for the following reasons are also indicated:
  - REWSB: parameter sets that do not fulfill the REWSB condition.
  - CCB: regions where charge or color breaking minima occur or negative squared squark masses are obtained at the EW scale.
  - LSP: sets where the lightest neutralino is not the LSP. Mostly there the lightest scalar tau becomes the LSP.
  - Chargino limit: parameter sets which correspond to a chargino mass that is already excluded by direct searches.
- We do not take into account the $b \to s\gamma$ constraint as the authors of Ref. [34, 35] do. This could reduce the upper limit but still the experimental and theoretical uncertainties of this constraint are quite large.

5. Conclusions

We have analyzed the upper bound on m_h within the MSSM. Using the Feynman-diagrammatic result for m_h, which contains new genuine two-loop corrections, leads to an increase of m_h of up to 4 GeV compared to the previous result obtained by renormalization group methods. We have furthermore investigated the MSSM parameters for which the maximal m_h values are obtained and have compared the $m_h^{\rm max}$ scenario with the previous benchmark scenario. For $m_t = 174.3$ GeV and $M_{\rm SUSY} = 1$ TeV we find $m_h \lesssim 129$ GeV as upper bound in the MSSM. In case that no evidence of a Higgs signal is found before the end of running in 2000, experimental searches for the Higgs boson at LEP can ultimately be reasonably expected to exclude $m_h \lesssim 113$ GeV. In the context of the $m_h^{\rm max}$ benchmark scenario (with $m_t = 174.3$ GeV, $M_{\rm SUSY} = 1$ TeV) this rules out the interval $0.5 \lesssim \tan\beta \lesssim 2.4$ at the 95% confidence level within the MSSM. Within the M-SUGRA scenario, the upper bound on m_h is found to be $m_h \lesssim 127$ GeV for $m_t = 174.3$ GeV. This upper limit is reached for the M-SUGRA parameters $M_0 \approx 500$ GeV, $M_{1/2} \approx 400$ GeV and $A_0 = -1500$ GeV. The upper bound within the M-SUGRA scenario is lower by 2 and 4 GeV than the bound obtained in the general MSSM for $M_{\rm SUSY} = 1$ TeV and $M_{\rm SUSY} = 2$ TeV, respectively.

Acknowledgements

A.D. acknowledges financial support from the Marie Curie Research Training Grant ERB-FMBI-CT98-3438. A.D. would also like to thank Ben Allanach for useful discussions. P.T.D. would like to thank Jennifer Kile for providing the Standard Model Higgs boson production cross-sections. G.W. thanks C.E.M. Wagner for useful discussions.

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