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THEORETICAL IMPLICATIONS OF THE POSSIBLE OBSERVATION OF HIGGS BOSONS AT LEP

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Theoretical implications of the possible observation of a Higgs boson with a mass of about 115 GeV at LEP are discussed. Within the Standard Model a Higgs boson in this mass range agrees well with the indirect constraints from electroweak precision data. However, it would nevertheless point towards physics beyond the Standard Model, in particular to Supersymmetric extensions. The interpretation of the LEP excess as production of the light or the heavy $\mathcal{CP}$-even Higgs boson is discussed within the unconstrained MSSM and the mSUGRA, GMSB and AMSB scenarios. Prospects for Higgs physics at future colliders are briefly summarized.

1 Standard Model

Within the electroweak Standard Model (SM) the Higgs boson is the last missing ingredient that has not been experimentally confirmed so far. Its mass, M_{H}, is a free parameter of the theory and is only bounded from above by unitarity arguments to be below about 1 TeV. In the final year of LEP running at an average center-of-mass energy of about 206 GeV, the combined results of the four LEP experiments established a 95% C.L. exclusion limit for the SM Higgs boson of $M_{\mathrm{H}} > 113.5$ GeV (expected: $M_{\mathrm{H}} > 115.3$ GeV). An excess of events at about $M_{\mathrm{H}} \approx 115$ GeV

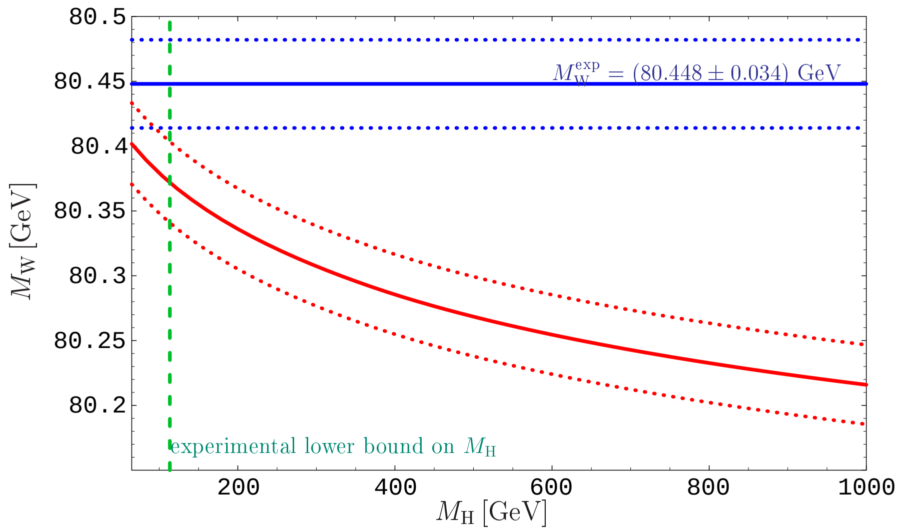

Figure 1: The prediction for M_W as a function of M_H within the SM. It is compared with the experimental value of M_W, M_W^{exp}, and the experimental 95% C.L. lower bound on the Higgs boson mass.

with a significance of 2.9σ (corresponding to the probability for a background fluctuation of 4.2×10^{-3}) was observed, which is compatible with the production of a SM Higgs boson in this mass range [1].[a]

Indirect constraints on the Higgs boson mass in the SM can be obtained by comparing the electroweak precision data with the predictions of the theory. As an example, Fig. 1 shows the SM prediction for M_W as a function of M_H based on the result of Ref. [4] incorporating the complete fermionic contributions at the two-loop level. The theory predictions are affected by two kinds of uncertainties: from unknown higher-order corrections and from the experimental errors of the input parameters. These uncertainties are indicated in Fig. 1 as a band of two dashed lines around the central value (given by the solid line). At present the theoretical uncertainties are dominated by the error of the top-quark mass, $m_t = 174.3 \pm 5.1$ GeV, which gives rise to an uncertainty of M_W of about ± 30 MeV. The prediction for M_W as function of M_H is compared in Fig. 1 with the experimental value, $M_W^{exp} = 80.448 \pm 0.034$ GeV [5]. The figure clearly shows a preference for a light Higgs boson within the SM. In fact, taking into account the experimental 95% C.L. lower bound on the Higgs boson mass, $M_H = 113.5$ GeV [1], the allowed intervals of the theory prediction and the experimental result have no overlap (at the 1σ level). The best description of the data within the SM is thus obtained for a Higgs boson being 'just around the corner' [b] (see also Ref. [7]). A global fit to all data yields for the Higgs boson mass within the SM $M_H = 98^{+58}_{-38}$ GeV, corresponding to a 95% C.L. upper limit of $M_H < 212$ GeV.[c]

While a Higgs boson mass of about 115 GeV would fit well in the context of the SM from the point of view of electroweak precision data, a value of M_H in this region would on the other hand be problematic concerning the stability of the electroweak vacuum. For $M_H \approx 115$ GeV (and $m_t = 175$ GeV, $\alpha_s(M_Z) = 0.118$) one would expect that new physics is required at a scale

[a] New combined results were presented at the 2001 Summer Conferences [2] based still on preliminary results of three collaborations and final results of one collaboration [3]. They yield a 95% C.L. exclusion limit for the SM Higgs boson of $M_H > 114.1$ GeV (expected: $M_H > 115.4$ GeV) and show an excess of events that can be interpreted as the production of a SM Higgs of about 115.6 GeV. The probability for a background fluctuation generating the observed effect is 3.4%, corresponding to a significance of 2.1σ.

[b] The slight discrepancy between the theory prediction for M_W and the experimental value has further increased in the results of the 2001 Summer Conferences with the experimental value $M_W^{exp} = 80.451 \pm 0.033$ GeV [6] and the Higgs exclusion bound of $M_H > 114.1$ GeV [2].

[c] The corresponding results of the 2001 Summer Conferences are $M_H = 88^{+53}_{-35}$ GeV and $M_H < 196$ GeV at 95% C.L. [6].

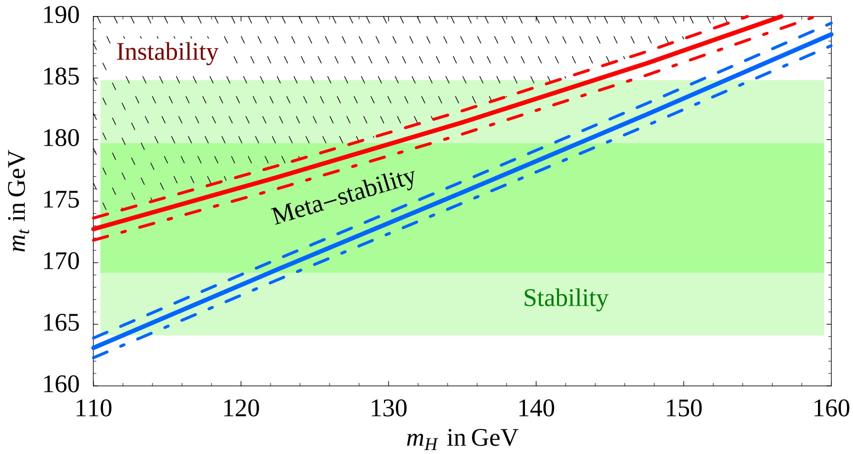

Figure 2: Regions in the $(M_{\rm H}, m_{\rm t})$ plane with stability, meta-stability and instability of the Standard Model vacuum if no new physics below the Planck scale is present. The solid lines refer to $\alpha_{\rm s}(M_{\rm Z}) = 0.118$, while the dashed and dot-dashed lines correspond to $\alpha_{\rm s}(M_{\rm Z}) = 0.118 \pm 0.002$. The shaded area indicates the experimental range for $m_{\rm t}$. Possible effects of subleading contributions are estimated to shift the bounds by $\pm 2\,{\rm GeV}$ in $m_{\rm t}$.

$\Lambda \lesssim 10^6$ GeV in order to prevent the effective Higgs potential from being destabilized by top-quark loop corrections [8]. It has been argued in Ref. [9] that the kind of new physics suitable for stabilizing the electroweak vacuum must share several important features with Supersymmetric theories. It would require in particular extra bosonic degrees of freedom and a high degree of fine-tuning of the model couplings, which is automatically fulfilled in a Supersymmetric theory.

The above arguments concerning the need for new physics at a scale $\Lambda \lesssim 10^6$ GeV cannot be regarded as fully rigorous, since they rely on the rather strong requirement that the minimum of the effective Higgs potential should be absolutely stable (and that $m_{\rm t}$ should not be smaller than 1–2 σ below its current experimental central value). A detailed analysis of the case of a metastable vacuum shows that for $M_{\rm H} \approx 115$ GeV and $m_{\rm t} \approx 175$ GeV (or smaller values of $m_{\rm t}$) the electroweak vacuum can be sufficiently long lived with respect to the age of the universe even without new physics below the Planck scale, see Fig. 2 [10]. Nevertheless, the arguments above underline that Supersymmetry (SUSY) provides a very attractive framework for naturally accommodating a light Higgs boson (and furthermore, independently of arguments relying on the precise value of $M_{\rm H}$, the hierarchy problem points towards new physics at the TeV scale).

2 Minimal Supersymmetric Standard Model (MSSM)

In contrast to the SM, the mass of the lightest $\mathcal{CP}$-even Higgs boson in the MSSM, $m_{\rm h}$, is not a free parameter but can be predicted from the other parameters of the model. This gives rise to the upper bound $m_{\rm h} < M_{\rm Z}$ at lowest order. This bound is affected by large higher-order corrections [11,12,13,14,15,16], shifting it upwards to about $m_{\rm h} \lesssim 135$ GeV at the two-loop level in the unconstrained MSSM [15]. This bound stays unaffected if non-zero $\mathcal{CP}$-violating phases are allowed [17]. Since $m_{\rm h}$ is predicted within the MSSM, the measurement of the Higgs boson mass provides a more direct test of the model than in the case of the SM.

For the analysis of the LEP data the theoretical predictions implemented in the programs *FeynHiggs* [18], based on a Feynman-diagrammatic two-loop result [14] (incorporating the complete one-loop result [19]), and *subhpole* [12], based on a renormalization-group improved one-loop effective potential result [12,20], are used. The remaining theoretical uncertainties from unknown higher-order corrections have been estimated to be about $\Delta m_{\rm h} \approx \pm 3$ GeV [21]. The biggest theoretical uncertainty at present arises from the experimental error of the top-quark mass. The current error of about ± 5 GeV in $m_{\rm t}$ induces an uncertainty of also about ± 5 GeV in $m_{\rm h}$ [22].

Thus, an accurate measurement of the top-quark mass is mandatory in order to allow precise theoretical predictions in the MSSM Higgs sector.

Confronting the upper bound on $m_{\rm h}$ as function of $\tan\beta$, the ratio of the vacuum expectation values of the two Higgs doublets, with the exclusion bounds obtained at LEP, experimental constraints on $\tan\beta$ can be derived. In the $m_{\rm h}^{\rm max}$ benchmark scenario [23], which yields the maximum values for $m_{\rm h}(\tan\beta)$ for fixed $m_{\rm t} = 174.3$ GeV and $M_{\rm SUSY} = 1$ TeV in the unconstrained MSSM, the $\tan\beta$ region $0.5 < \tan\beta < 2.4$ can be excluded [24]. In the no-mixing benchmark scenario [23], which uses the same parameters as the $m_{\rm h}^{\rm max}$ scenario except that vanishing mixing in the scalar top sector is assumed, only relatively small parameter regions remain unexcluded, and the region $0.7 < \tan\beta < 10.5$ is ruled out [24].

The main production channels for the neutral MSSM Higgs bosons at LEP are the Higgs-strahlung process, $e^+e^- \to hZ, HZ$, and the associated production, $e^+e^- \to hA, HA$. For the lightest $\mathcal{CP}$-even Higgs boson the cross section $\sigma_{\rm hZ}$ is approximately given by $\sigma_{\rm hZ} \approx \sin^2(\beta - \alpha_{\rm eff})\sigma_{\rm hZ}^{\rm SM}$, where $\sigma_{\rm hZ}^{\rm SM}$ is the SM cross section for the same Higgs mass and $\alpha_{\rm eff}$ is the effective mixing angle of the neutral $\mathcal{CP}$-even Higgs bosons.[d] The cross section for the associated production contains a complementary factor, $\sigma_{\rm hA} \approx \lambda\cos^2(\beta - \alpha_{\rm eff})\sigma_{\rm hZ}^{\rm SM}$, where λ is a kinematic factor.

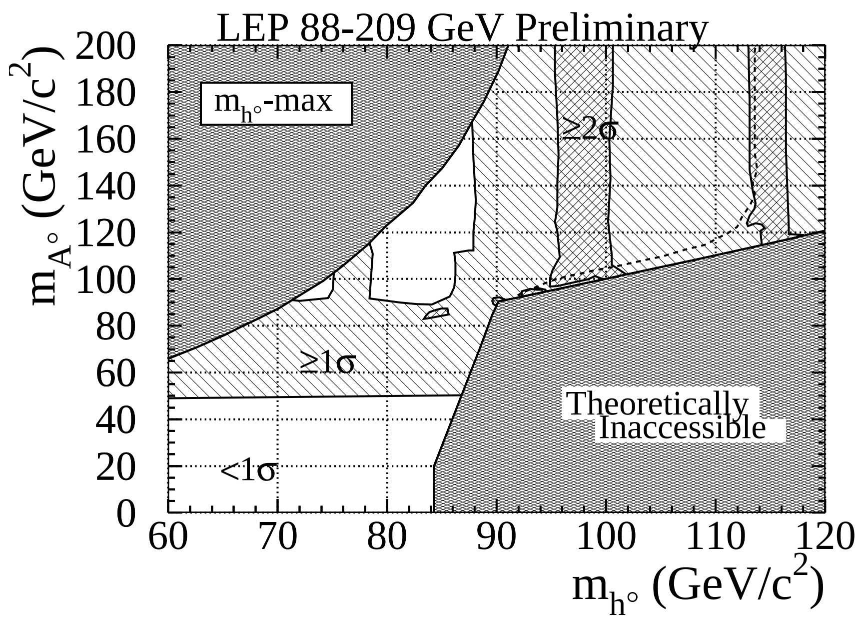

Figure 3: Excluded region in the $(m_{\rm h}, M_{\rm A})$ plane in the $m_{\rm h}^{\rm max}$ scenario (above and left to the dashed line) and parameter regions where the observation is more than 1σ or more than 2σ above the background prediction.

The excess in the search for the SM Higgs boson manifests itself also in the MSSM Higgs boson searches, see Fig. 3 [24]. The figure shows the 95% C.L. exclusion contour in the $(m_{\rm h}, M_{\rm A})$ plane in the $m_{\rm h}^{\rm max}$ scenario and the parameter regions where the observation is more than 1σ or more than 2σ above the background prediction. Vertical structures in the plot are due to features in the hZ search results, while structure on the $m_{\rm h} \approx M_{\rm A}$ line arises mainly from the hA searches. For $M_{\rm A} \gg M_{\rm Z}$ h has SM-like couplings (which means in particular $\sin^2(\beta - \alpha_{\rm eff}) \approx 1$), and the results for the SM search can directly be taken over for the MSSM case. The corresponding events give rise to the vertical structure at $m_{\rm h} \approx 115$ GeV indicating an excess above 2σ in Fig. 3. The MSSM also allows, however, another more speculative interpretation of the LEP

[d] This approximation is applicable at LEP energies, while sizable corrections to it occur at higher energies [25].

excess. In the parameter region $m_{\rm h}, M_{\rm A} \approx 100$ GeV the hZZ coupling is strongly suppressed, $\sin^2(\beta-\alpha_{\rm eff}) \ll 1$, while the heavy $\mathcal{CP}$-even Higgs boson H has SM-like couplings. Thus, it would in principle be possible that the excess events observed at LEP were caused by the production of the heavy $\mathcal{CP}$-even Higgs boson with mass $m_{\rm H} \approx 115$ GeV, while the light $\mathcal{CP}$-even Higgs boson has been produced in the Higgsstrahlung process with such a small rate that it could not be observed above the background. In this case the associated production channel, $e^+e^- \to$ hA, should be open, but it can be suppressed or even completely closed if the mass sum $m_{\rm h} + M_{\rm A}$ is close to or above the kinematic limit.

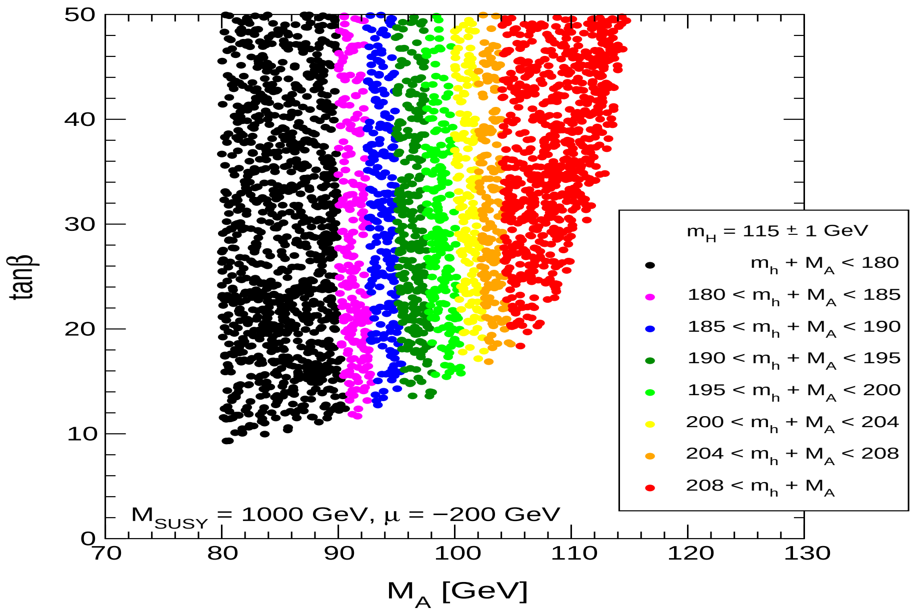

Figure 4: Allowed parameter space in the $(M_{\rm A}, \tan\beta)$ plane in the unconstrained MSSM for $m_{\rm H} \approx 115$ GeV and a significantly suppressed hZZ coupling, $\sin^2(\beta-\alpha_{\rm eff}) < 0.2$. The different shadings correspond to different values of $m_{\rm h} + M_{\rm A}$.

Fig. 4 shows the allowed parameter space in the $(M_{\rm A}, \tan\beta)$ plane in the unconstrained MSSM for $m_{\rm H} \approx 115$ GeV and a significantly suppressed hZZ coupling, $\sin^2(\beta - \alpha_{\rm eff}) < 0.2$ [26]. The different shadings indicate different values of $m_{\rm h} + M_{\rm A}$. The region $m_{\rm h} + M_{\rm A} < 180$ GeV is excluded by LEP, while the LEP searches have practically no sensitivity anymore for $m_{\rm h} + M_{\rm A} \gtrsim 190$ GeV (the region $m_{\rm h} + M_{\rm A} > 208$ GeV is even outside the kinematic reach of LEP). Accordingly, for the parameter space with $m_{\rm h} + M_{\rm A} \gtrsim 190$ GeV in the plot an interpretation of the LEP excess in terms of the production of the heavy $\mathcal{CP}$-even Higgs boson appears to be possible.

Fig. 3 contains another unexcluded region in the $(m_{\rm h}, M_{\rm A})$ plane with an excess above 2σ for $m_{\rm h} \approx M_{\rm A} \approx 100$ GeV. The question how well Fig. 3 is compatible with the production of three MSSM Higgs bosons at LEP with $M_{\rm A} \approx 100$ GeV, $m_{\rm h} \approx 100$ GeV and $m_{\rm H} \approx 115$ GeV has not yet been directly answered because the LEP analyses are designed to search for only one $\mathcal{CP}$-even Higgs boson with a specified mass at a time.[e] There is a substantial dilution of the significance of a combination of the two excesses because statistical fluctuations can occur anywhere in the two-dimensional space of $m_{\rm h}$ and $m_{\rm H}$.

It should furthermore be noted that qualitatively the same behavior as described above for the $\mathcal{CP}$-conserving MSSM can happen in an even wider parameter space if $\mathcal{CP}$-violating phases

[e] A more detailed investigation of this issue will become possible on the basis of the result in Ref. [2], where the signal expected from a 115 GeV Higgs was injected in the background simulation and propagated through the likelihood ratio calculation at each $M_{\rm H}$ value.

are allowed. In this case a strong suppression of the coupling of the lightest Higgs boson to the Z boson can occur, while the next-to-lightest Higgs boson couples to the Z boson with almost SM strength [27].

The excess of events observed in the Higgs search at LEP has been analyzed within different SUSY scenarios by many authors [28,29]. For example, in Ref. [29] a comparison of the mSUGRA, GMSB and AMSB soft SUSY-breaking scenarios has been performed. The interpretation of the LEP excess as the production of the lightest $\mathcal{CP}$-even Higgs boson is possible in all three scenarios, while the interpretation in terms of the production of the heavier $\mathcal{CP}$-even Higgs boson is only possible within the mSUGRA scenario. In Fig. 5 the allowed parameter space in the $(\tan\beta, m_{\rm h})$ plane is displayed in the mSUGRA scenario, and the regions corresponding to the two interpretations of the LEP excess are indicated. The LEP Higgs searches exclude all parameter points with $m_{\rm h} \lesssim 113$ GeV and $\tan\beta \lesssim 50$. This is contrary to the situation in the $m_{\rm h}^{\rm max}$ scenario of the unconstrained MSSM, where the exclusion bound on the SM Higgs boson applies to $m_{\rm h}$ only for $\tan\beta \lesssim 8$. For larger values of $\tan\beta$ and small $M_{\rm A}$, in the unconstrained MSSM a suppression of the hZZ coupling is possible, resulting in a reduced production rate compared to the SM case. In the mSUGRA scenario, a significant suppression of the hZZ coupling occurs only in a small allowed parameter region where $50 \lesssim \tan\beta \lesssim 55$. In this region an interpretation of the LEP excess in terms of the production of the heavier $\mathcal{CP}$-even Higgs boson is possible (for $m_{\rm H} \approx 115$ GeV). It should be noted, however, that this parameter region is close to the exclusion bounds obtained at Run I of the Tevatron [30] and will soon be probed with the Run II data [31].

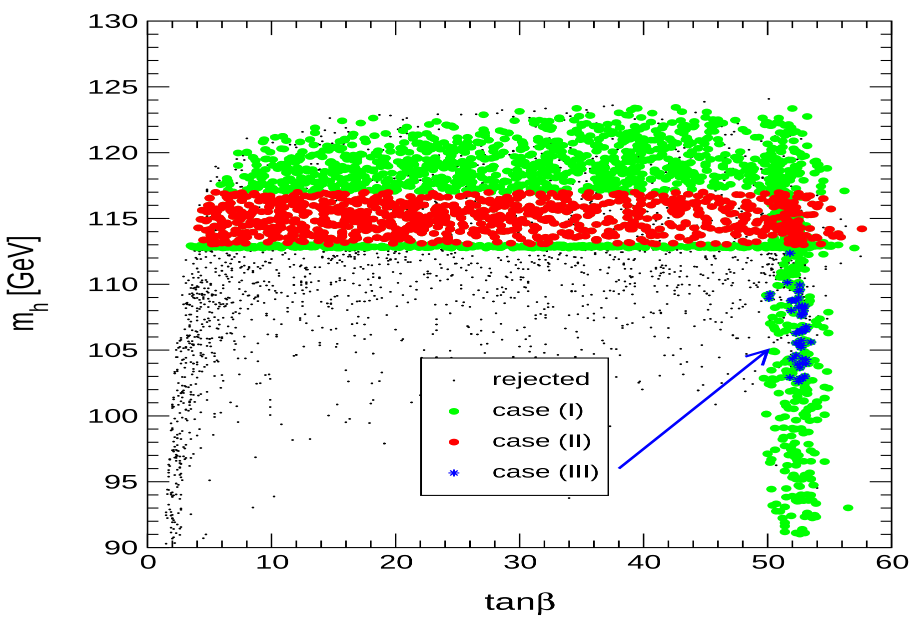

Figure 5: The light $\mathcal{CP}$-even Higgs boson mass $m_{\rm h}$ as a function of $\tan\beta$ in the mSUGRA scenario. Allowed parameter points are indicated by big green points (light shaded, "case (I)"), big red points (dark shaded, "case (II)") and blue stars (indicated by an arrow in the plot, "case (III)"), while the little black dots indicate parameter points which are in principle possible in the mSUGRA scenario but are rejected because of the LEP Higgs bounds and further experimental and theoretical constraints. Case (II) is the subset of allowed parameter points which are consistent with the interpretation of the LEP excess as production of the lightest $\mathcal{CP}$-even Higgs boson (i.e. $m_{\rm h} \approx 115$ GeV and SM-like couplings of the h), while case (III) corresponds to the interpretation of the LEP excess in terms of the heavier $\mathcal{CP}$-even Higgs boson.

From Fig. 5 one can read off an upper bound on $m_{\rm h}$ of $m_{\rm h} \lesssim 124$ GeV in the mSUGRA scenario for $m_{\rm t} = 175$ GeV, which is about 6 GeV lower than in the unconstrained MSSM. The lower bound on $\tan\beta$ in the mSUGRA scenario is $\tan\beta \gtrsim 3.3$, i.e. slightly higher than in the unconstrained MSSM. In the GMSB and AMSB scenarios the bounds are $m_h \lesssim 119$ GeV, $\tan\beta \gtrsim 4.6$ (GMSB) and $m_h \lesssim 122$ GeV, $\tan\beta \gtrsim 3.2$ (AMSB) for $m_t = 175$ GeV [29].

3 Prospects for the future

In Run II of the Tevatron the main Higgs production channels are the Higgsstrahlung from the W and the Z boson, i.e. a similar production mechanism as at LEP. A Higgs boson with a mass of about 115 GeV, i.e. close to the present exclusion bound, would be favorable for the Higgs search at the Tevatron, and the sensitivity for a 95% exclusion limit on the SM Higgs boson could be reached with an integrated luminosity of about 2 fb^{-1} per experiment [31] (which could be achieved in 2003), while the sensitivity for a 5σ discovery of a SM Higgs boson with $M_H \approx 115$ GeV could be reached with about 15 fb^{-1} per experiment [31] (possibly in 2007). At the LHC, on the other hand, the sensitivity for a 5σ discovery of a SM Higgs boson in the whole mass range up to 1 TeV can be obtained with about 10 fb^{-1} [32]. The mass region of about 115 GeV is the most difficult one for the LHC, where the search relies on the gg $\to$ H $\to \gamma\gamma$ and $t\bar{t}$H, H $\to b\bar{b}$ channels (further sensitivity can be added via the weak boson fusion channel [33], which is currently under study). If both machines run on schedule, they could reach the sensitivity for a 5σ discovery of a SM Higgs boson with $M_H \approx 115$ GeV approximately at the same time.

In the MSSM, parameter regions exist where the discovery of a Higgs boson with about 115 GeV is more difficult than in the SM (see e.g. Refs. [34]). As an example, Fig. 6 shows the branching ratio BR(h $\to \gamma\gamma$) in the MSSM, normalized to the SM value, in the unconstrained MSSM for $m_h \approx 115$ GeV [35]. As can be seen in the plot, a significant suppression is possible over a wide parameter range, making this channel less sensitive than in the SM case.

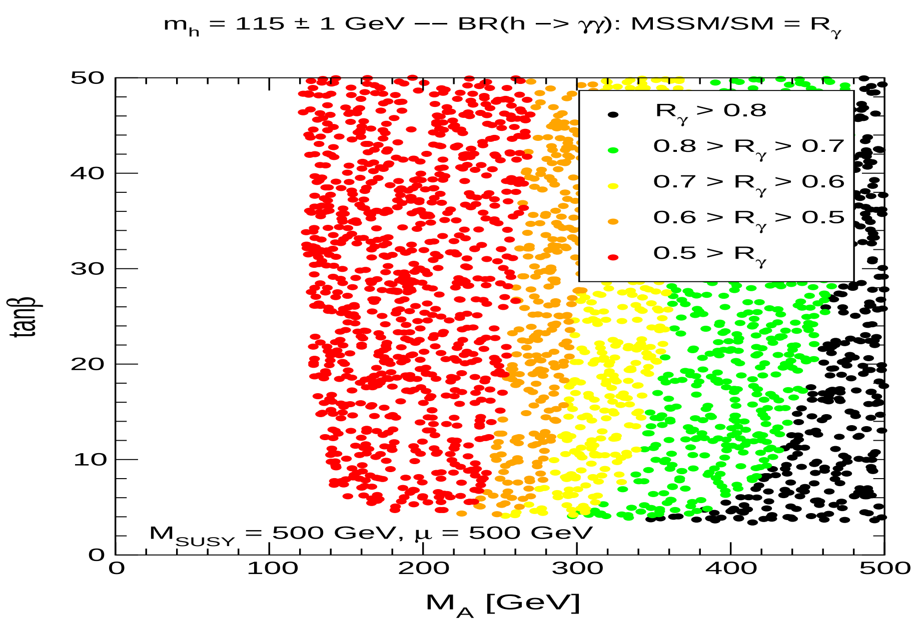

Figure 6: The branching ratio BR(h $\to \gamma\gamma$) normalized to the SM value, R_γ, in the (M_A, $\tan\beta$) plane in the unconstrained MSSM for $m_h \approx 115$ GeV.

The situation is different, however, if one focuses on the mSUGRA scenario and furthermore takes into account constraints from the cosmological relic density and the results for b $\to$ sγ and $g_\mu - 2$. Fig. 7 shows the parameter space consistent with the dark matter constraint in the ($m_{1/2}, m_0$) plane of the mSUGRA scenario for $A_0 = 0$ and $\mu > 0$ for two values of $\tan\beta$ [36]. The preferred regions from the LEP Higgs search, b $\to$ sγ and $g_\mu - 2$ are indicated in the plots. The figure shows that for both values of $\tan\beta$ there is a parameter space within the mSUGRA scenario that is consistent with all experimental constraints. The different shadings correspond to different values of $\sigma(\mathrm{gg} \to \mathrm{h}) \times \mathrm{BR}(\mathrm{h} \to \gamma\gamma)$, normalized to the SM value. As a result (which is also valid for non-zero values of A_0), no significant suppression of the $\mathrm{gg} \to \mathrm{h} \to \gamma\gamma$ production channel at the LHC occurs, and the lightest $\mathcal{CP}$-even Higgs boson should be discoverable at the LHC with 10 fb^{-1} in this scenario. Similar results hold for the $\mathrm{t\bar{t}h}$ associated production at the LHC and the Higgsstrahlung processes at the Tevatron [36].

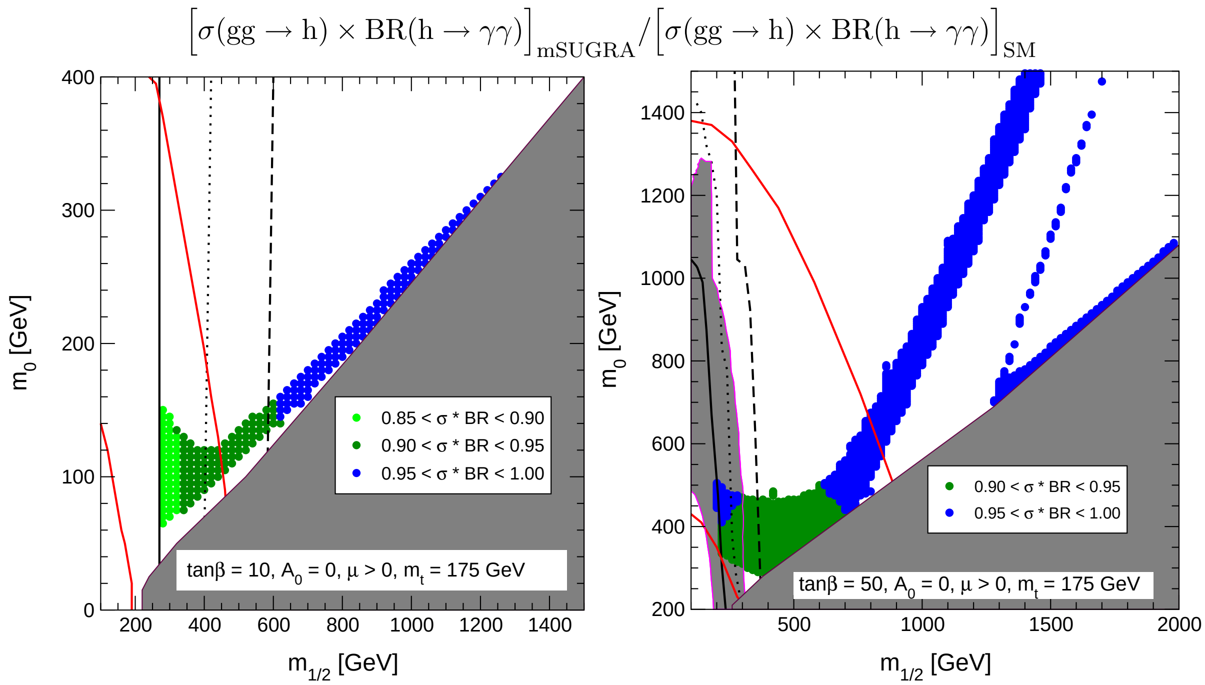

Figure 7: The cross section for production of the lightest $\mathcal{CP}$-even Higgs boson in gluon fusion and its decay into a photon pair, normalized to the SM value with the same Higgs mass, is shown in the $(m_{1/2}, m_0)$ planes of the mSUGRA scenario for the cosmologically allowed parameter region. The diagonal (red) solid lines are the $\pm 2\sigma$ contours for $g_\mu - 2$. The near-vertical solid, dotted and dashed (black) lines are the $m_\mathrm{h} = 113, 115, 117$ GeV contours. The light shaded (pink) regions are excluded by $\mathrm{b} \to \mathrm{s}\gamma$. The (brown) bricked regions are excluded since in these regions the lightest SUSY particle is the charged $\tilde{\tau}_1$.

At a future Linear Collider (LC) precision measurements of the Higgs mass and its couplings to gauge bosons and fermions (including the $\mathrm{t\bar{t}H}$ coupling) will become possible [37]. The LC measurements will furthermore provide informations on the triple Higgs self-coupling, which will be important for reconstructing the Higgs potential. They will furthermore allow to determine the spin and parity quantum numbers of the Higgs boson. Thus, the LC measurements will be important in order to experimentally establish the Higgs mechanism. Studying the recoil against the Z boson, at the LC the production via Higgsstrahlung can be studied completely independent from the Higgs decay modes, which is in particular important if the Higgs boson has a large branching fraction into invisible decay products. Furthermore, a precise measurement of the top-quark mass with an accuracy of $\Delta m_\mathrm{t}^{\mathrm{exp}} \lesssim 200$ MeV at the LC will be indispensable in order to match the experimental precision of the m_h measurement at the LHC with the accuracy of the theoretical prediction within the MSSM.

In the context of an assumed observation of a Higgs boson with a mass of about 115 GeV, the precision measurements at the LC will allow a very sensitive test of the model. As an example, Fig. 8 shows the prediction for $\mathrm{BR}(\mathrm{h} \to \tau^+\tau^-)$ in the MSSM as a function of the gluino mass, $m_{\tilde{\mathrm{g}}}$, in comparison with the SM prediction and the prospective experimental accuracy at the LC of about 5% [21,38]. Large gluino and higgsino loop corrections can affect the $\mathrm{hb\bar{b}}$ coupling for large values of $\tan\beta$ and/or μ and can thus give rise to a sizable shift in $\mathrm{BR}(\mathrm{h} \to \tau^+\tau^-)$.

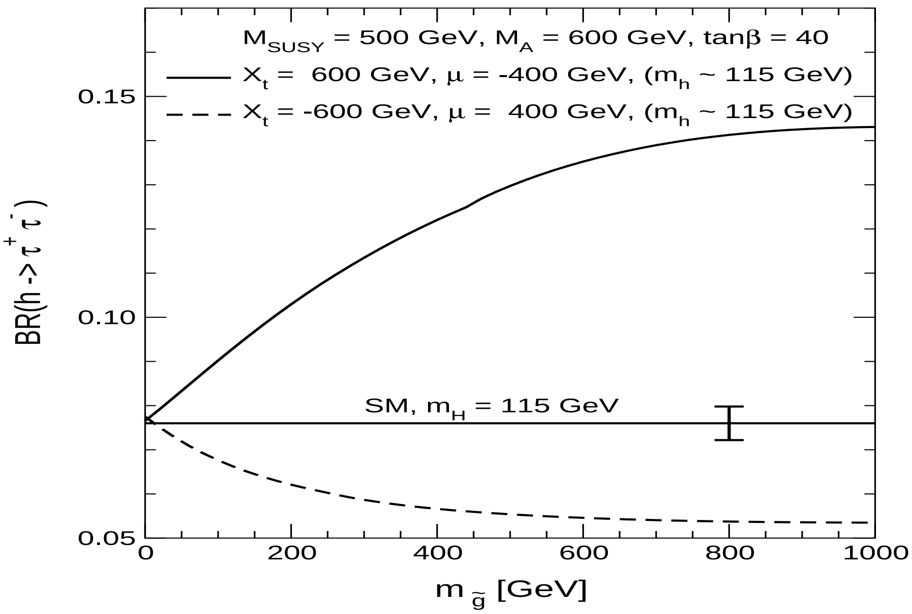

Figure 8: Prediction for BR(h $\to \tau^+\tau^-$) in the MSSM as a function of the gluino mass for $m_{\rm h} \approx 115$ GeV and two values of the off-diagonal entry in the $\tilde{t}$ mixing matrix, $X_{\rm t}$, and the Higgs mixing parameter, μ. The SM value is also shown. The error bar at the SM prediction indicates the prospective experimental accuracy at the LC.

A precise measurement of BR(h $\to \tau^+\tau^-$) at a future LC will thus provide a high sensitivity for a distinction between the SM and the MSSM even for relatively large values of $M_{\rm A}$, where otherwise the Higgs sector behaves mainly SM-like.

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References

1. ALEPH collaboration, R. Barate *et al.*, *Phys. Lett.* **B 495** (2000) 1;
   DELPHI collaboration, P. Abreu *et al.*, *Phys. Lett.* **B 499** (2001) 23;
   L3 collaboration, M. Acciarri *et al.*, *Phys. Lett.* **B 495** (2000) 18;
   OPAL collaboration, G. Abbiendi *et al.*, *Phys. Lett.* **B 499** 38.
   For a preliminary compilation of the LEP data presented on Nov. 3rd, 2000, see:
   P. Igo-Kemenes, for the LEP Higgs working group,
   `http://lephiggs.web.cern.ch/LEPHIGGS/talks/index.html`.
2. ALEPH, DELPHI, L3 and OPAL Collaborations, The LEP working group for Higgs boson searches, CERN-EP/2001-055, hep-ex/0107029.
3. L3 collaboration, P. Achard *et al.*, CERN-EP/2001-049, hep-ex/0107054.
4. A. Freitas, W. Hollik, W. Walter and G. Weiglein, *Phys. Lett.* **B 495** (2000) 338;
   A. Freitas, S. Heinemeyer, W. Hollik, W. Walter and G. Weiglein, *Nucl. Phys.* **B** *(Proc. Suppl.)* **89B** (2000) 82; CERN-TH/2001-018, hep-ph/0101260.
5. N.K. Watson, talk given at the XXXVIth Rencontres de Moriond, Les Arcs, March 2001, hep-ph/0105230.
6. J. Drees, talk given at Lepton Photon 01, Rome, July 2001.

7. G. D'Agostini and G. Degrassi, *Eur. Phys. J.* **C 10** (1999) 663;
J. Erler, *Phys. Rev.* **D 63** (2001) 071301.
8. G. Altarelli and G. Isidori, *Phys. Lett.* **B 337** (1994) 141;
J.A. Casas, J.R. Espinosa and M. Quirós, *Phys. Lett.* **B 342** (1995) 171;
T. Hambye and K. Riesselmann, *Phys. Rev.* **D 55** (1997) 7255.
9. J. Ellis and D. Ross, *Phys. Lett.* **B 506** (2001) 331.
10. G. Isidori, G. Ridolfi and A. Strumia, CERN-TH/2001-092, hep-ph/0104016.
11. Y. Okada, M. Yamaguchi and T. Yanagida, *Prog. Theor. Phys.* **85** (1991) 1;
J. Ellis, G. Ridolfi and F. Zwirner, *Phys. Lett.* **B 257** (1991) 83;
H.E. Haber and R. Hempfling, *Phys. Rev. Lett.* **66** (1991) 1815;
R. Barbieri and M. Frigeni, *Phys. Lett.* **B 258** (1991) 395.
12. M. Carena, J. Espinosa, M. Quirós and C. Wagner, *Phys. Lett.* **B 355** (1995) 209;
M. Carena, M. Quirós and C. Wagner *Nucl. Phys.* **B 461** (1996) 407.
13. H. Haber, R. Hempfling and A. Hoang, *Z. Phys.* **C 75** (1997) 539.
14. S. Heinemeyer, W. Hollik and G. Weiglein, *Phys. Rev.* **D 58** (1998) 091701; *Phys. Lett.* **B 440** (1998) 296.
15. S. Heinemeyer, W. Hollik and G. Weiglein, *Eur. Phys. Jour.* **C 9** (1999) 343.
16. J. Espinosa and R.-J. Zhang, *Nucl. Phys.* **B 586** (2000) 3;
G. Degrassi, P. Slavich and F. Zwirner, DFPD-01-TH-16, hep-ph/0105096.
17. A. Pilaftsis and C.E.M. Wagner, *Nucl. Phys.* **B 553** (1999) 3.
18. S. Heinemeyer, W. Hollik and G. Weiglein, *Comput. Phys. Commun.* **124** (2000) 76; hep-ph/0002213; see `www.feynhiggs.de`.
19. P. Chankowski, S. Pokorski and J. Rosiek, *Nucl. Phys.* **B 423** (1994) 437;
A. Dabelstein, *Nucl. Phys.* **B 456** (1995) 25; *Z. Phys.* **C 67** (1995) 495.
20. M. Carena, H. Haber, S. Heinemeyer, W. Hollik, C.E.M. Wagner and G. Weiglein, *Nucl. Phys.* **B 580** (2000) 29.
21. S. Heinemeyer and G. Weiglein, BNL-HET-01/5, hep-ph/0102117.
22. S. Heinemeyer, W. Hollik and G. Weiglein, *JHEP* **0006** (2000) 009.
23. M. Carena, S. Heinemeyer, C.E.M. Wagner and G. Weiglein, CERN-TH/99-374, hep-ph/9912223.
24. ALEPH, DELPHI, L3 and OPAL Collaborations, The LEP working group for Higgs boson searches, LHWG Note 2001-04, hep-ex/0107030.
25. S. Heinemeyer, W. Hollik, J. Rosiek and G. Weiglein, *Eur. Phys. J.* **C 19** (2001) 535.
26. S. Heinemeyer *et al.*, in preparation.
27. M. Carena, J. Ellis, A. Pilaftsis and C.E.M. Wagner, *Nucl. Phys.* **B 586** (2000) 92; *Phys. Lett.* **B 495** (2000) 155.
28. J. Ellis, G. Ganis, D.V. Nanopoulos and K.A. Olive, *Phys. Lett.* **B 502** (2001) 171;
G.L. Kane, S.F. King and L. Wang, hep-ph/0010312;
J.L. Feng and K.T. Matchev, *Phys. Rev.* **D 63** (2001) 095003;
M.E. Gómez and J.D. Vergados, *Phys. Lett.* **B 512** (2001) 252;
A. Bottino, N. Fornengo and S. Scopel, *Nucl. Phys.* **B 608** (2001) 461;
J. Ellis, D.V. Nanopoulos and K.A. Olive, *Phys. Lett.* **B 508** (2001) 65;
A. Djouadi, M. Drees and J.L. Kneur, PM-01-27, hep-ph/0107316.
29. S. Ambrosanio, A. Dedes, S. Heinemeyer, S. Su and G. Weiglein, BNL-HET-01/18, hep-ph/0106255.
30. CDF Collaboration, T. Affolder *et al.*, *Phys. Rev. Lett.* **D 86** (2001) 4472.
31. M. Carena *et al.*, FERMILAB-CONF-00/279-T, hep-ph/0010338.
32. ATLAS Collaboration, Detector and Physics Performance Technical Design Report, `http://atlasinfo.cern.ch/Atlas/GROUPS/PHYSICS/TDR/access.html`;
CMS Collaboration,

http://cmsinfo.cern.ch/Welcome.html/CMSdocuments/CMSplots/;
F. Gianotti, talk given at the Conference on Higgs and Supersymmetry, Orsay, March 2001, http://ww2.lal.in2p3.fr/actualite/conferences/higgs2001/slides/index.htm.

33. N. Kauer, T. Plehn, D. Rainwater and D. Zeppenfeld, *Phys. Lett.* **B 503** (2001) 113.
34. E. Richter-Wąs, D. Froidevaux, F. Gianotti, L. Poggioli, D. Cavalli and S. Resconi, *Int. J. Mod. Phys.* **A 13** (1998) 1371;
M. Carena, S. Mrenna and C.E.M Wagner, *Phys. Rev.* **D 60** (1999) 075010; *Phys. Rev.* **D 62** (2000) 055008;
A. Djouadi, *Phys. Lett.* **B 435** (1998) 101;
G. Belanger, F. Boudjema and K. Sridhar, *Nucl. Phys.* **B 568** (2000) 3;
G. Belanger, F. Boudjema, F. Donato, R. Godbole and S. Rosier-Lees, *Nucl. Phys.* **B 581** (2000) 3;
G. Belanger, F. Boudjema, A. Cottrant, R. M. Godbole and A. Semenov, LAPTH-856-2001, hep-ph/0106275.
35. S. Heinemeyer and G. Weiglein, in preparation.
36. J. Ellis, S. Heinemeyer, K.A. Olive and G. Weiglein, BNL-HET-01/14, hep-ph/0105061, to appear in *Phys. Lett.* **B**.
37. R.D. Heuer *et al.*, TESLA Technical Design Report, Part III: Physics at an e+e- Linear Collider, hep-ph/0106315;
T. Abe *et al.*, Resource book for Snowmass 2001, hep-ex/0106055, hep-ex/0106056, hep-ex/0106057, hep-ex/0106058.
38. S. Heinemeyer, W. Hollik and G. Weiglein, *Eur. Phys. Jour.* **C 16** (2000) 139.