Supersymmetric explanation of the excess of Higgs-like events at CERN LEP

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Searches for the standard model Higgs boson by the four LEP experiments found excess events in two mass ranges: a 2.3σ excess around 98 GeV, and a 1.7σ excess around 115 GeV. The latter has been discussed widely in the literature, but the former has attracted relatively little attention so far. In this paper I explore the possibility of explaining the excess near 98 GeV through production of the lighter *CP*-even Higgs boson in the minimal supersymmetric standard model (MSSM). It is shown that this allows to simultaneously explain the excess near 115 GeV through the production of the heavier *CP*-even MSSM Higgs boson. The resulting light Higgs sector offers opportunities for charged Higgs boson searches at the Tevatron and LHC. Neutral Higgs boson searches at the LHC in the di-muon channel are also promising. However, conclusive tests of this scenario may have to wait for the construction of a linear e^+e^- collider.

I. INTRODUCTION

The search for the Higgs boson of the standard model (SM) was one of the priorities of the four LEP experiments ALEPH, DELPHI, L3, and OPAL. Recently the final result of this search has been published jointly by these experiments [1]. The absence of a clear signal implies that the SM Higgs boson mass should exceed 114.4 GeV at the 95% confidence level.

Although no clear signal was found, there are some intriguing hints in these data. Much has been made [2] of the excess of events at the kinematic edge, for a Higgs mass near 115 GeV. However, this excess comes almost entirely from a single experiment (ALEPH), and is only visible in a single final state (with four jets). In contrast, all four experiments see at least a mild excess near 98 GeV, the "signal" being most pronounced in the L3 data set. Moreover, it exists both in the 4-jet data set and the remaining set of Higgs candidate events. As a result, while the combination of LEP data weakened the significance of the excess near 115 GeV to about 1.7 standard deviations, corresponding to a 9% background fluctuation probability, the excess near 98 GeV has a significance of about 2.3 standard deviations, which corresponds to a background fluctuation probability of only 2%. This significance is comparable to that of the deviation of the anomalous magnetic moment of the muon from its SM prediction [3], which has also generated much interest in recent years.

In this paper I point out that the excess near 98 GeV can easily be accommodated in the minimal supersymmetric extension of the SM (MSSM). Since the number of excess events corresponds to only about 10% of the number of signal events expected for an SM Higgs boson of this mass, the coupling of the light *CP*-even MSSM Higgs boson *h* to the *Z* boson must be suppressed. This immediately implies that one must not be in the "decoupling scenario," i.e. the overall mass scale in the MSSM Higgs sector must be quite low. Moreover, the heavy *CP*-even Higgs boson *H* must have couplings quite similar to those of the SM Higgs

boson; it can thus easily be used to explain the excess near 115 GeV. This makes it legitimate to combine the two excesses of events when assessing the significance with which they favor the MSSM over the SM. In the limit where the two sets of events are statistically independent, which should be a good approximation, the total excess amounts to about 3.1 standard deviations, corresponding to a background fluctuation probability of only 0.2%.

This significance as stated applies to situations where the locations of the excess events are fixed. Since the relevant distribution (in the reconstructed Higgs mass) contains several bins, the probability to find such excesses somewhere due to statistical fluctuations should be larger than 0.2%. However, at least in the framework of the MSSM the total number of bins that are compatible with the absence of a (clear) signal for *hA* production is quite small; note that a small *ZZh* coupling implies that the *ZhA* coupling is nearly maximal. Values of $m_h \lesssim 90$ GeV can thus be excluded from the analysis. Note also that, again in the framework of the MSSM, the $h - H$ mass difference cannot be arbitrarily small; this further limits the range of m_h where a weak *h* signal (due to suppressed *hZZ* coupling) can show up, if the signal near 115 GeV is interpreted as *ZH* production. The "look elsewhere" effect should therefore not dilute the total significance by more than a factor of 5 or so; of course, a reliable estimate of the total significance of the combined excess would have to come from the experimental groups.

This scenario can be realized for a wide range of values for the ratio of vacuum expectation values (VEVs) $\tan\beta$. This means that the light scalar Higgs *h*, the *CP*-odd Higgs *A*, and the charged Higgs $H^\pm$, while all quite light, might couple only weakly to gauge bosons and heavy quarks. As a result, only the discovery of the heavy scalar *H* is guaranteed at the LHC in this scenario. However, since the squared couplings of *H* differ from those of the SM Higgs only at the 10% level, it will be difficult to use *H* production at the LHC for a decisive test of this scenario. Such a test might be possible through $t \to H^+ b$ decays or,

at large $\tan\beta$, through associated $b\bar{b}h$ and $b\bar{b}A$ production at the LHC, but the entire allowed parameter space can probably only be probed at a future linear e^+e^- collider.

The possibility that the excess near 115 GeV could be due to ZH production is also discussed in [4,5], and, for a CP-violating scenario, in [6]; however these papers do not mention the by now more significant excess of events near 98 GeV. A scenario with three (relatively) light MSSM Higgs bosons explaining certain excess LEP events was (to my knowledge) first suggested in Ref. [7], based on preliminary DELPHI data; this was followed up by Refs. [8], which speculate about evidence for three light neutral Higgs bosons lurking in a preliminary version [9][1] of the combined LEP data. The same preliminary data are also discussed in [10]. Neither of these papers attempts to explore the phenomenology of scenarios with $m_h \simeq 98$ GeV and suppressed ZZh coupling. References [11] discuss several MSSM scenarios with some neutral Higgs boson(s) below 115 GeV, but again do not explore the phenomenology; the main focus of these articles is on issues of model building and fine-tuning.

The rest of this paper is organized as follows. In Sec. II I describe the LEP Higgs searches in more detail, and show how the excess events can be described in the MSSM. In Sec. III I explore the parameter space that is compatible with this explanation, and discuss tests of this scenario. Finally, Sec. IV contains a brief summary and conclusions.

II. SEARCHES FOR THE SM HIGGS AT LEP

Searches for the single Higgs boson φ of the standard model at LEP are based on the process

$$e^+e^- \rightarrow Z\varphi. \qquad (1)$$

The most important decay modes of the Higgs boson are $b\bar{b}$ and $\tau^+\tau^-$. The statistically most important final state contains four jets, from $Z \rightarrow q\bar{q}$ and $\varphi \rightarrow b\bar{b}$, but some other channels are also of interest: $Z \rightarrow \nu\bar{\nu}$, $\varphi \rightarrow b\bar{b}$ leads to large missing energy plus b-jets; $Z \rightarrow \ell^+\ell^-$, $\varphi \rightarrow b\bar{b}$ leads to a charged lepton (electron or muon) pair plus b-jets; and $Z \rightarrow \tau^+\tau^-$, $\varphi \rightarrow b\bar{b}$ or $Z \rightarrow q\bar{q}$, $\varphi \rightarrow \tau^+\tau^-$ lead to events with a τ pair and jets.

After combining the data samples of all four LEP experiments and all four final states, any value of $m_\varphi \lesssim 114.4$ GeV can be excluded at the 95% confidence level [1]. This limit is a little weaker than that expected for heavy φ given the performance of LEP. The reason is that there is an excess of events near the kinematic end point. This

excess was first announced by ALEPH [2], where it reaches a significance of about 3 standard deviations; this led to considerable excitement at that time. Unfortunately the other LEP experiments see little or no excess there; the combination of LEP data therefore weakened the excess to the level of about 1.7 standard deviations.

At the same time this combination *strengthened* the very mild excess also reported by ALEPH near 98 GeV. The reason is that all four experiments see a mild excess here, the most significant being in the L3 data sample where it reaches about 1.8 standard deviations. Moreover, there is an excess both in the four-jet channel *and* in the sum of the other three channels. All this is just what one would expect from a true signal at the edge of statistical detectability.

Unlike the excess near 115 GeV, the accumulation of events near 98 GeV cannot be interpreted as production of the SM Higgs boson. In the SM the rate for reaction (1) can be predicted uniquely as a function of the mass of the Higgs boson; it comes out much too large if $m_\varphi \simeq 98$ GeV. This excess, if real, therefore calls for physics beyond the standard model.

The best motivated extension of the SM has long been its supersymmetric version, the MSSM [12]. Supersymmetrizing the SM stabilizes the mass of the Higgs boson(s) against large radiative corrections, thereby solving the technical part of the hierarchy problem [13]. It also naturally allows the Grand Unification of all gauge interactions, without the *ad hoc* introduction of any new particles (beyond those required by Supersymmetry) [14]; and allows for a natural explanation for the Dark Matter in the Universe whose existence has been proven almost unambiguously by cosmologists [15].

Of greater relevance for the present purpose is that Supersymmetry requires the existence of at least two Higgs doublets, in order to give masses to both up-type and down-type quarks, and to cancel gauge anomalies associated with the fermionic superpartners of the Higgs bosons. In the MSSM one thus postulates the existence of two Higgs doublets with opposite hypercharges. The neutral components of both neutral Higgs fields must acquire VEVs to make all quarks massive. Both VEVs contribute (in quadrature) to the masses of the W and Z bosons; three would-be Goldstone modes get "eaten" in the process. Therefore only five physical degrees of freedom survive in the MSSM Higgs sector [16]: two neutral CP-even scalars h and H, with $m_h < m_H$; a CP-odd scalar A; and charged Higgs bosons $H^\pm$.[2]

At the tree level the MSSM Higgs sector is completely determined once two parameters are fixed. The most com-

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[1]This paper estimates the dilution of the total significance due to the "look elsewhere" effect to be somewhere between 30 and 60. However, this refers to a *two-dimensional* scan of the (m_h, m_A) plane, which obviously contains many more independent bins than the one-dimensional distribution analyzed in the present paper. Note also that the preliminary LEP analysis assigns about equal significance to the excesses near 98 and near 115 GeV, showing that it was indeed a *preliminary* analysis.

[2]In the presence of CP-violation in the squark sector, the three neutral gauge bosons will mix, to form mass eigenstates which are no longer CP eigenstates. Given the stringent constraints on electric dipole moments [17], which are not easy to satisfy in the presence of large CP-odd phases in the supersymmetric Lagrangian, I will ignore this possibility for the most part.

mon choice is the mass m_A of the *CP*-odd Higgs boson and the ratio of VEVs $\tan\beta$. The masses $m_{h,H}$ as well as the mixing angle α in the neutral *CP*-even Higgs sector are then derived quantities [16]. The two angles α and β also determine the couplings of MSSM Higgs bosons to SM particles. In particular, the couplings relevant to the generalization of the process (1) are [16]:

$$g_{hZZ} = g_{\varphi ZZ}\sin(\beta - \alpha); \tag{2a}$$

$$g_{HZZ} = g_{\varphi ZZ}\cos(\beta - \alpha). \tag{2b}$$

The fact that the number of excess events near 98 GeV amounts to about 10% of the signal for the SM Higgs with $m_\varphi = 98$ GeV therefore immediately implies that $\sin^2(\beta - \alpha) \simeq 0.1$. Given that the excess has a statistical significance of 2.3 standard deviations, this leads to the 1σ bounds on this coupling:

$$0.056 \leq \sin^2(\beta - \alpha) \leq 0.144. \tag{3}$$

In order to make sure that the excess appears in the right mass range, one also needs

$$95 \text{ GeV} \leq m_h \leq 101 \text{ GeV}, \tag{4}$$

where the range can be motivated either from the width of the peak in the data (more precisely: from the width in the dip of one minus the background confidence level) [1], or from the accuracy with which the neutral Higgs boson masses can be calculated (see below).

Having fixed two parameters in the MSSM Higgs sector fairly accurately, it would seem that the model is already defined completely. However, the MSSM Higgs sector is subject to large radiative corrections [18]. On the one hand, these are crucial for the viability of the model, since at the tree level one has $m_h < M_Z$, in gross conflict with Higgs searches at LEP. On the other hand, this increases the number of free parameters, and hence also the possible ranges of the masses of the other Higgs bosons. This will be explored in more detail in the next Section.

Nevertheless the constraint (3) already allows some important conclusions. To begin with, $\sin^2(\beta - \alpha) \simeq 0.1$ implies $\cos^2(\beta - \alpha) \simeq 0.9$, i.e. *ZH* production will occur almost with SM strength, if it is accessible kinematically. This would allow to *simultaneously* explain the excess of Higgs-like events around 115 GeV, if

$$111 \text{ GeV} \leq m_H \leq 119 \text{ GeV}. \tag{5}$$

I have again allowed for a few GeV range to accommodate both the theoretical and the experimental uncertainties.

In fact, the constraint (3) *by itself* already implies that the other MSSM Higgs bosons must not be very heavy. The reason is that for $m_A^2 \gg M_Z^2$ one observes "decoupling" [19]: H, A, $H^\pm$ form a nearly degenerate, heavy *SU*(2) doublet which does not have Higgs-like couplings to gauge bosons, i.e. $\cos(\beta - \alpha) \to 0$ in this limit, in conflict with (3). This argument makes it rather natural to associate the (small) excess of events near 115 GeV with *ZH* produc-

tion. However, in order to quantify the upper limits on the masses of the other MSSM Higgs bosons, the relevant parameter space has to be explored in detail. This is the topic of the next Section.

III. TESTING THE SCENARIO

From the discussion of the previous Section it should be clear that both groups of Higgs-like excess events observed at LEP can indeed be explained simultaneously through the production of MSSM Higgs bosons. However, for quantitative tests it is necessary to explore in detail the region of MSSM parameter space consistent with this scenario.

To that end a treatment of at least the leading radiative corrections [18] to the MSSM Higgs sector is mandatory. This is most easily done using the effective potential (or, equivalently, Feynman diagrammatic calculations with vanishing external momentum). Since the entire Higgs spectrum has to be rather light in this scenario, this should be a good approximation not only for the light scalar, but also for the other Higgs bosons. Note also that two-loop correction terms are to date anyway only known in this limit.

In order to allow an efficient sampling of the parameter space, I only include corrections from the top-stop and bottom-sbottom sectors, which give the by far most important contributions. I use the expressions in Ref. [20] for the pure Yukawa corrections to both the neutral and charged Higgs boson mass matrices; the mixed electroweak-Yukawa corrections to the neutral Higgs boson mass matrix (from the "*D*-term" contributions to the stop and sbottom masses) are included using results of Ref. [21]. Leading higher order QCD corrections are included by using running quark masses defined at the appropriate scale in the one-loop effective potential, as described in Refs. [20,22]. The leading SUSY QCD corrections are included through the gluino-stop and gluino-sbottom "threshold" corrections to the top and bottom mass, respectively; in the latter case the corrections have been resummed using the formalism of Ref. [23]. As shown in Ref. [24], this reproduces the full SUSY QCD correction very accurately. Finally, the leading higher order correction from the top Yukawa coupling is again included via the running top mass in the effective potential [22,25]. Recently a full calculation of top Yukawa corrections became available [26]. However, this result is badly behaved in the $\overline{\text{DR}}$ scheme for very large stop mixing parameter; since this region of the parameter space is relevant here, these corrections are not included. The calculation performed here should reproduce the neutral MSSM Higgs masses with an error of about 3 GeV or so [24,27]. This theoretical uncertainty is reflected in the ranges in (4) and (5).

Again for reasons of simplicity, I work with a fixed SM top mass, $m_t(m_t) = 171$ GeV (in the $\overline{\text{DR}}$ scheme). This corresponds to a pole mass near 178 GeV, the current

central value [28]. I also fix $m_b(m_b) = 4.25$ GeV. As final simplification, I have taken the soft breaking parameters in the stop and sbottom mass matrices to be the same. This is always true for the masses of the superpartners of the left-handed squarks, due to $SU(2)$ invariance, but the masses of the $SU(2)$ singlet squarks as well as the two A-parameters could in principle be different. However, A_b only plays a minor role, since mixing in the $\tilde{b}$ sector is either small or, for large $\tan\beta$, controlled by the supersymmetric mass parameter μ [12].

Altogether we are thus left with seven free parameters: $\tan\beta$, m_A, μ, $m_{\tilde{l}_L}$, $m_{\tilde{l}_R}$, A_t, $m_{\tilde{g}}$. Note that, in spite of the simplifying assumptions, we still have five free parameters (not affecting the Higgs sector at tree-level) to describe four radiative corrections, to the three independent entries of the mass matrix of CP-even Higgs bosons and to the mass of the charged Higgs boson. As far as the Higgs sector is concerned the chosen parametrization should therefore be sufficiently flexible to cover all possibilities (barring CP-violation). This seven-dimensional parameter space has been scanned subject to the following constraints:

$$|\mu|, m_{\tilde{l}_R}, m_{\tilde{l}_L}, m_{\tilde{g}} \leq 2 \text{ TeV}; \tag{6a}$$

$$|\mu|, m_{\tilde{l}_1}, m_{\tilde{b}_1} \geq 100 \text{ GeV}; \tag{6b}$$

$$m_{\tilde{g}} \geq 300 \text{ GeV}; \tag{6c}$$

$$|A_t|, |\mu| \leq 1.5(m_{\tilde{l}_R} + m_{\tilde{l}_L}); \tag{6d}$$

$$\delta\rho_{\tilde{t}\tilde{b}} \leq 2 \cdot 10^{-3}. \tag{6e}$$

The first of these constraints is a crude naturalness criterion. Conditions (6b) ensure that higgsinolike charginos (with mass $\sim|\mu|$) as well as the lighter physical stop ($\tilde{t}_1$) and sbottom ($\tilde{b}_1$) states escaped detection at LEP [17]. Condition (6c) similarly guarantees that gluinos were not detected at the Tevatron [17]. The upper bounds (6d) on the parameters determining mixing in the stop and sbottom sectors have been imposed to avoid situations where $\tilde{t}$ or $\tilde{b}$ fields have nonvanishing VEVs in the absolute minimum of the scalar potential [29]. Finally, (6e) requires the contribution of stop-sbottom loops to the electroweak ρ parameter [30] to be sufficiently small. Of course, the constraints (3) and (4) also have to be imposed in order to describe the excess near 98 GeV. If the excess near 115 GeV is to be described by the scenario as well, in addition the constraint (5) should be imposed. In any case one has to require $m_H > 111$ GeV in order to make sure that ZH production was not detected at LEP.[3]

The maximal and minimal allowed masses of the heavier MSSM Higgs bosons that are compatible with all these

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[3]Recall that I allow a few GeV uncertainty on the calculated value of the Higgs boson masses; an experimental bound of 114.4 GeV is thus interpreted as a bound on the calculated m_H of 111 GeV.
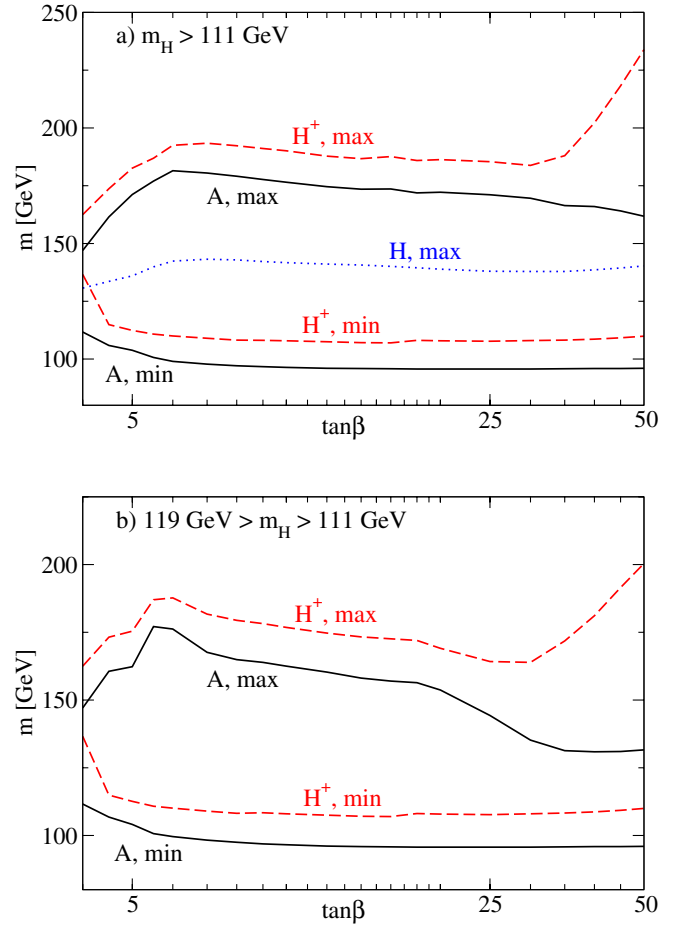

FIG. 1 (color online). Minimal and maximal values of the heavier MSSM Higgs boson masses consistent with the constraints (3), (4), and (6), as required to reproduce the excess of Higgs-like events near 98 GeV. In the lower frame in addition the constraint (5) has been imposed, as required to *also* reproduce the excess near 115 GeV.

constraints are shown in Figs. 1, without 1(a) and with 1(b) including the requirement (5). These results have been obtained by randomly generating several million combinations of m_A, μ, $m_{\tilde{l}_L}$, $m_{\tilde{l}_R}$, A_t, $m_{\tilde{g}}$ for each value of $\tan\beta$, with special emphasis on the regions of parameter space where one of the shown masses takes its extremal value.

We see that the excess near 98 GeV cannot be reproduced for very small values of $\tan\beta$. If $\tan\beta < 3.7$, m_h can only be sufficiently large if m_A is also quite large (and stop squarks are quite heavy). This is in conflict with the requirement (3) of a suppressed ZZh coupling. However, the scenario still allows a wide range for $\tan\beta$, including quite large values. I have not explored the parameter space for $\tan\beta > 50$, since scenarios with very large $\tan\beta$ and small m_A are strongly constrained by the nonobservation of $B_s \rightarrow \mu^+\mu^-$ decays [31].

As anticipated, the scenario is only viable for moderate masses of the heavier Higgs bosons. Starting from the minimal allowed value of $\tan\beta$, the upper bounds first

increase, since the allowed parameter space opens up. m_A reaches its absolute maximum of slightly more than 180 GeV at $\tan\beta \simeq 6$. The bound on m_A then decreases again slowly. The reason is that the crossover from almost vanishing to essentially maximal ZZh coupling becomes faster as $\tan\beta$ increases, i.e. the "decoupling regime" is approached more quickly for larger $\tan\beta$ [19]. The upper bound on the mass of the charged Higgs boson first tracks that on m_A. However, for $\tan\beta > 30$ the radiative corrections to $m_{H^\pm}$ become sizable, eventually allowing $m_{H^\pm}$ well above 200 GeV. Note also that the lower limits on m_A and $m_{H^\pm}$ are so high that searches for hA and H^+H^- production at LEP do not constrain this scenario any further; due to the P-wave suppression of these cross sections, these searches were only sensitive to Higgs masses below ~ 90 GeV [17].

Finally, Fig. 1(a) also shows that the excess near 98 GeV can only be reproduced if $m_H < 145$ GeV. (The lower limit on m_H is just given by the experimental bound of 111 GeV discussed above.) This indicates that explaining the (small) excess of events near 115 GeV through ZH production is quite natural in this framework. Figure 1(b) shows how the limits on m_A and $m_{H^\pm}$ are tightened when this is done, i.e. if in addition the constraint (5) is imposed. We see that the lower limits on these masses remain essentially unchanged. However, the upper bound on m_A is reduced significantly, especially at large $\tan\beta$. The reason is that the tree-level A-H mass splitting decreases with increasing $\tan\beta$; the increased importance of b-$\tilde{b}$ loops can compensate this only partly. Note, however, that charged Higgs boson masses somewhat above the mass of the top quark can still be realized both for $\tan\beta \simeq 6$ and for large $\tan\beta$.

The results of Figs. 1 allow us to discuss tests of this scenario. The constraint (3) immediately determines the WWh and ZAh couplings, which are proportional to $\sin(\beta - \alpha)$ and $\cos(\beta - \alpha)$, respectively [16]. This means that h production at the Tevatron, which relies mostly on Wh and Zh production, will be impossible to detect [32]. The large ZAh coupling together with the upper bound on m_A means that any (linear) e^+e^- collider operating at $\sqrt{s} \gtrsim 300$ GeV should see a strong signal for Ah production; if the beam energy is raised to ~ 500 GeV, H^+H^- production should also be visible over the entire allowed parameter range in this scenario [33]. However, presently there is no funding for the construction of such a device.

At least within the next decade or so, the best chance to test this scenario will therefore be at the LHC. Unfortunately the suppressed WWh and ZZh couplings mean suppressed h production rates through WW and ZZ fusion [34]. The strengths of other potential signals for h production at the LHC also depend on its couplings to heavy quarks. These depend on $\tan\beta$ even if the constraint (3) is imposed, as shown in Fig. 2. The increased coupling strength to $b\bar{b}$ pairs and the reduced WWh coupling imply
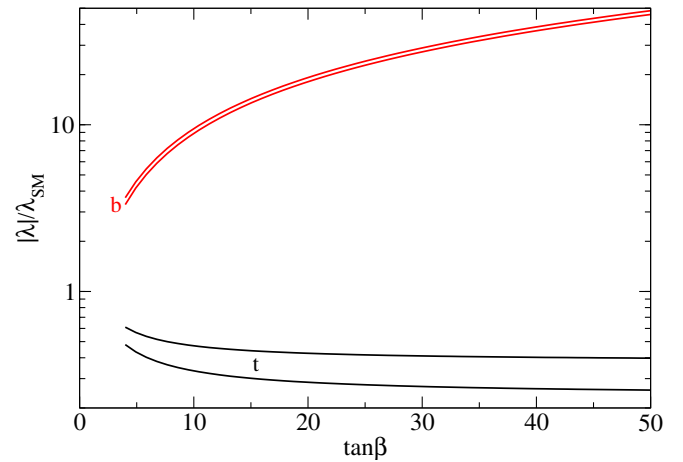

FIG. 2 (color online). The couplings of the light CP-even MSSM Higgs boson h to heavy quarks as a function of $\tan\beta$ in units of the corresponding SM coupling, once the constraint (3) has been imposed. The upper and lower curves within a pair should be interpreted as defining the 1σ bands for these couplings, since they have been obtained by saturating the limits in (3).

a greatly reduced branching ratio for $h \rightarrow \gamma\gamma$ decays, which mostly proceeds through loops of W bosons [19] and gives the best signal for inclusive h production at the LHC [35]. At the same time, the suppressed coupling to top quarks means that the inclusive h production cross section through gluon fusion will also be suppressed at small and moderate values of $\tan\beta$. The same suppression applies to the cross section for $t\bar{t}h$ production.

On the other hand, the cross section for $hb\bar{b}$ production will be enhanced at large $\tan\beta$. The LHC will therefore be able to probe a significant fraction of the allowed parameter space through $(A, h)b\bar{b}$ production followed by $A, h \rightarrow \mu^+\mu^-$ decays [35,36]. However, Figs. 1 show that, unlike in the standard scenarios usually considered, the h and A masses can still differ by several tens of GeV even at large $\tan\beta$, so that the two signals will lead to two separate peaks, which reduces the significance in any one peak. It is therefore presently not clear how small values of $\tan\beta$ can be probed in this scenario through this channel at the LHC. It seems certain, however, that it will not be able to cover the whole allowed parameter space.

This leaves the charged Higgs boson. We see that over most of the parameter space, $t \rightarrow H^+ b$ decays are possible. This opens the possibility to test this scenario even at the Tevatron [37]. However, even if these decays are allowed, their branching ratio becomes quite small for $\tan\beta \sim \sqrt{m_t(m_t)/m_b(m_t)} \simeq 7$. Besides, we saw in Fig. 1(b) that $m_{H^+} > m_t - m_b$ remains possible even if both sets of excess events at LEP are to be explained by MSSM Higgs production. At the LHC the $H^+\bar{t}b$ production channel can be detectable even if $m_{H^\pm} > m_t - m_b$, but again this only works at relatively large $\tan\beta$ [35,38]. One thus has to conclude that discovery of a not-SM-like Higgs

boson at the LHC does not seem to be guaranteed in this scenario.

Of course, the heavy neutral scalar H should be quite easy to discover at the LHC even in the less constrained scenario depicted in Fig. 1(a), e.g. through WW/ZZ fusion [34]. This will also tell us whether the excess of events near 115 GeV is indeed due to Higgs boson production or merely a background fluctuation. However, the cross section will differ from the corresponding SM cross section only by $\sim 10\%$, well below the foreseen accuracy with which it can be measured at the LHC even at high luminosity [39]. Failing to find a signal for H production below

~ 145 GeV will therefore exclude this scenario, but finding such a signal will not help to distinguish it from the SM (nor from a more generic MSSM scenario with SM-like h).

The constraints (3)–(5) also lead to correlations between the free parameters, including the parameters of the stop sector. Some of these are depicted in Figs. 3(a)–3(d). I should stress that the density of points in these figures does not carry meaningful information; only the extent of the regions of parameter space populated by (some) points is significant. Moreover, the allowed ranges for the physical stop masses could presumably be extended somewhat by including additional loop corrections, e.g. those due to
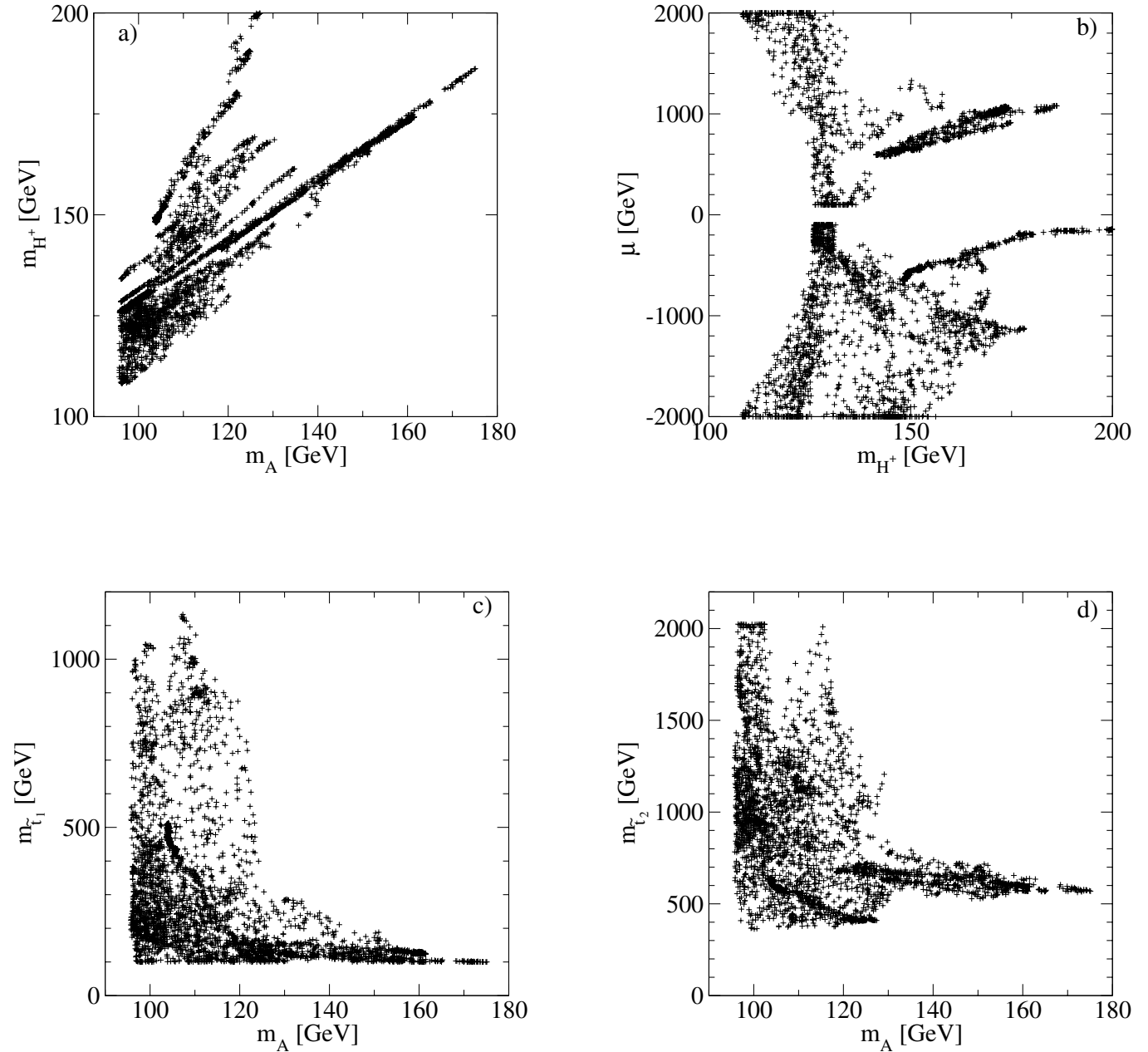

FIG. 3.   Allowed region in the $(m_A, m_{H^\pm})$ plane (a), in the $(m_{H^\pm}, \mu)$ plane (b), in the $(m_A, m_{\tilde{t}_1})$ plane (c), and in the $(m_A, m_{\tilde{t}_2})$ plane (d), after the constraints (3)–(6) have been imposed.

electroweak interactions, which have been omitted here. Because of the essentially logarithmic dependence of the leading loop corrections on the stop masses, subleading corrections could modify the allowed stop masses significantly even if they have only minor impact on the masses of the Higgs boson. The qualitative trends shown in Fig. 3 should nevertheless survive in a more complete calculation.

Figure 3(a) shows that the strict correlation between the tree-level A and $H^\pm$ masses, $m^2_{H^\pm,\text{tree}} = m^2_{A,\text{tree}} + M^2_W$, can get loosened significantly once loop corrections are included. In the allowed parameter space this tree-level relation still holds to good approximation for $m_A > 140$ GeV. We saw from Fig. 1(b) that such heavy CP-odd Higgs bosons are only possible in the present framework if $\tan\beta$ is not large. On the other hand, the corrections to $m_{H^\pm}$ become maximal at large $\tan\beta$, as also shown in Fig. 1(a). In particular, the branch of points in Fig. 3(a) with m_A near 125 GeV, which extends to $m_{H^\pm} \simeq 200$ GeV, corresponds to solutions with $\tan\beta \gtrsim 40$.

The correlation between the mass of the charged Higgs boson and the higgsino mass parameter μ is explored in Fig. 3(b). We see that viable scenarios with $|\mu|$ near the experimental lower bound of ~ 100 GeV can easily be found. On the other hand, significant negative corrections to $m_{H^\pm}$ are possible only for large values of μ. In contrast, the two branches in Fig. 3(a) leading to relatively heavy charged Higgs bosons correspond to more moderate values of $|\mu|$: the branch where m_A is near its maximum corresponds to the accumulation of points near $\mu = 1$ TeV in Fig. 3(b), while the absolute maximum of $m_{H^\pm}$ is reached for $\mu \simeq -200$ GeV. This latter part of the parameter space can therefore also be explored through the production of higgsinolike neutralinos and charginos at an e^+e^- collider operating at $\sqrt{s} \gtrsim 500$ GeV [33].

The correlations between the mass of the CP-odd Higgs boson and the masses of the two physical stop states are shown in Figs. 3(c) and 3(d). Figure 3(c) shows that a mild upper bound of about 1.2 TeV on the mass of $\tilde{t}_1$ can be derived in this scenario. However, this will be difficult to test even at the LHC in the presence of other supersymmetric backgrounds; besides, as argued above, this bound might be modified significantly once purely electroweak corrections to the Higgs sector are included. Of more interest is the observation that large CP-odd Higgs boson masses, $m_A \gtrsim 130$ GeV, are only possible in this scenario if $m_{\tilde{t}_1} \lesssim 300$ GeV and $m_{\tilde{t}_2} \lesssim 800$ GeV. In particular, the accumulation of points near the lower bound on $m_{\tilde{t}_1}$ indicates that even Tevatron searches for $\tilde{t}_1$ production [40] should be able to explore some significant fraction of the parameter space of this scenario. Note also that the *heavier* stop eigenstate might be as light as 350 GeV in this scenario. One does not need large loop corrections to lift m_h from its tree-level upper bound of M_Z to values near 98 GeV.

IV. SUMMARY AND CONCLUSIONS

In this paper I have shown that the $\sim 2.3\sigma$ excess of Higgs-like events observed by all four LEP experiments near a Higgs boson mass of 98 GeV can easily be described by Zh production in the MSSM, where h is the lighter of the two CP-even Higgs bosons in this model. This explanation requires relatively small masses for the other Higgs bosons: $m_H \lesssim 145$ GeV, $m_A \lesssim 180$ GeV, and $m_{H^\pm} \lesssim 230$ GeV. It is then tempting to explain the $\sim 1.7\sigma$ excess of Higgs-like events at LEP near a Higgs boson mass of 115 GeV through the production of the heavier CP-even state H. The total excess then slightly exceeds the level of 3 standard deviations. This is of course far from compelling, but does appear intriguing.

A standard model like Higgs boson with mass near 115 GeV would be easy to discover at the LHC; some evidence for it might even be found at the Tevatron. However, this by itself does not tell us anything about the excess of events near 98 GeV. In order to fully test this scenario, one will have to detect one of the Higgs bosons that can *not* be confused with the single Higgs boson of the SM. The best chance for the Tevatron would be $t \to H^+ b$ decays; at the LHC the charged Higgs boson can also be discovered through nonresonant $\bar{t}bH^+$ production. However, these channels will probably not cover the entire allowed parameter space. Similarly, over much of the parameter space the LHC should see associate $b\bar{b}(h,A)$ production where the Higgs boson decays into a $\mu^+\mu^-$ pair, but again this will not cover the entire parameter space. A decisive test may only be possible at a future (linear) e^+e^- collider, which would easily be able to detect hA and H^+H^- pair production over the entire allowed parameter space.

We also saw that this scenario is consistent with rather small stop and higgsino masses; the former are even required if the mass of the CP-odd Higgs boson is near its upper bound. The search for $\tilde{t}_1$ pair production at the Tevatron will therefore cover part, but again not all, of the allowed parameter space. The fact that this scenario can tolerate a rather light sparticle spectrum also means that it is technically more natural than the standard choice $m_h > 114$ GeV, which requires large radiative corrections, and hence large stop masses, which in turn leads to some amount of fine-tuning in the Higgs sector to keep M_Z at its measured value.

In fact, radiative $b \to s\gamma$ decays indicate that some sparticles should be relatively light in this scenario, since a charged Higgs boson with mass below 200 GeV would tend to give too large a branching ratio for this decay [41], unless there are compensating sparticle loop contributions [42]. However, in order to make this statement quantitative, one would have to specify the flavor structure of the soft breaking masses, which is very model dependent.

In this paper I have taken all relevant parameters directly at the weak scale, and have treated them as independent

quantities. In constrained scenarios with a simple super-particle spectrum at some high energy scale a small mass for the CP-odd Higgs boson can only be realized for large values of the ratio of VEVs $\tan\beta$. This is true both for mSUGRA, where all scalars receive the same soft breaking mass at a scale near 10^{16} GeV [43], and for the minimal model with gauge-mediated supersymmetry breaking [44]. This can be problematic, since, as mentioned earlier, models with small m_A and large $\tan\beta$ are strongly constrained by $B_s \rightarrow \mu^+\mu^-$ decays [31]. It is presently not clear whether the scenario proposed in this paper can be realized in these constrained models.

In this analysis all parameters have been assumed to be real. In the presence of nontrivial complex phases, CP is violated, and all three neutral Higgs bosons will mix at the one-loop level [21,45]. In this case the excess events near 98 GeV or those near 115 GeV might be due to the production of two nearly degenerate Higgs bosons. This would (almost) fix the masses of all three neutral Higgs bosons, making such a scenario even more constrained than the case discussed here. If all mass splittings are large, the mixing between CP-even and CP-odd states tends to be suppressed, leaving Higgs phenomenology essentially unaltered.

Of course, the excess of Higgs-like events found at LEP can also be explained in a nonsupersymmetric model with two Higgs doublets [46]. However, in that case no predictions for the masses and couplings of the CP-odd Higgs boson or the charged Higgs boson can be made, since the Higgs potential contains many more free parameters than that of the MSSM. Finding these particles within the limits indicated in Fig. 1 would therefore be strong indirect evidence in favor of supersymmetry.

To conclude, LEP experiments may already have found the first indication for the production of neutral MSSM Higgs bosons. This hypothesis would be strengthened by observing a light charged Higgs boson at the Tevatron and/or the LHC, or by observing neutral Higgs bosons at LHC that do not resemble the single Higgs boson of the standard model. It would be refuted if the LHC does not find an SM-like Higgs boson with mass below ~ 145 GeV, which however, would also exclude much of the general MSSM parameter space. Decisive tests of this scenario may only be possible at future linear e^+e^- colliders.

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