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Supersymmetric Higgses and electroweak data

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Abstract

Higgs-related radiative corrections are re-evaluated within the minimal supersymmetric extension of the Standard Model (MSSM), and incorporated into an analysis of the available precision electroweak data. The data's preferences within the Standard Model, noted previously, for a light Higgs boson and $m_t \sim (100 \text{ to } 150) \text{ GeV}$, are maintained in the MSSM, with the optimal value of the lightest CP-even Higgs boson mass coming closer to the direct experimental lower limit.

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All confirmed accelerator data are in excellent agreement with the Standard Model, and precision LEP and other electroweak measurements provide unparalleled constraints on its parameters, including $\sin^2\vartheta_w$, the top quark mass m_t and the Higgs boson mass M_H [1]. However, it is well-known that the Standard Model is incomplete and unsatisfactory from a theoretical point of view, and ideas abound on how to extend and improve it. These ideas may usefully be divided into two broad classes, perturbative and non-perturbative. In the former class, gauge symmetry breaking is ascribed to an elementary Higgs scalar field, whose mass parameter is stabilized by approximate supersymmetry [2], and all the couplings are sufficiently weak for perturbative unification to be achieved in a grand unified theory (GUT) at some high renormalization scale. In the non-perturbative approach, gauge symmetry breaking is assumed to be dynamical and associated with condensates of new fermions with extra-strong interactions (technicolour [3]), the elementary Higgs boson of the Standard Model is replaced by composite states, and grand unification is not pursued.

The recent electroweak estimates of $\sin^2\vartheta_w$, M_H and m_t all seem to point circumstantially towards perturbative ideas. The measured value of $\sin^2\vartheta_w$ is in impressive agreement with the prediction of a restricted set of GUTs, specifically including those with supersymmetry [4]. The recent tentative preliminary indication [1] that M_H is more likely to lie below 300 GeV than above is consistent with the minimal supersymmetric extension of the Standard Model (MSSM [5]), which predicts that one elementary Higgs boson has a mass $O(M_Z)$ [6]. Moreover, the indicated range $m_t \sim (100 \text{ to } 150)$ GeV is consistent with specific perturbative dynamical models [7] of gauge symmetry breaking within the MSSM.

On the other hand, the non-perturbative “technicolour” framework makes no clear prediction for $\sin^2\vartheta_w$, suggests a very large effective value of M_H (or related graver problems with electroweak radiative corrections [8]), and finds $m_t \geq M_Z$ to be awkward. None of these difficulties is perhaps fatal for the non-perturbative “technicolour” framework, but they do motivate a closer look at the precision electroweak data in the

specific context of the MSSM.

The formalism of supersymmetric radiative corrections to electroweak parameters is by now well-developed [9], but by and large they have not been included in analyses of the electroweak data. One exception is ref. [10], where the effects of the supersymmetric partners of the t and b quarks were incorporated in an extraction of m_t from electroweak data, and found not to alter much its estimated value in the Standard Model, at least if the squark masses were above about 200 GeV. However, already at that time it was emphasized that supersymmetric radiative correction effects were likely to be comparable to Standard Model Higgs effects. Subsequently, as already mentioned, the precision of the electroweak data has improved, to such an extent that Higgs mass effects are now measurable and important, and the time is ripe to incorporate Higgs-related radiative corrections [6] in the MSSM into electroweak data analysis [†].

The MSSM requires for its specification [5] many extra parameters beyond those in the Standard Model, but the masses and couplings of its boson sector are characterized by just two parameters at the tree level. The effect of the other MSSM parameters may mostly be neglected if all the sparticles are heavy, as we shall assume here [‡]. Radiative corrections to the masses of the supersymmetric Higgs bosons provide exception to the latter rule, and introduce additional parameters into the characterization of the supersymmetric Higgs sector. Before the incorporation of these Higgs radiative corrections, the lighter CP-even MSSM Higgs boson weighed less than M_Z , and still weighs $O(M_Z)$ after the incorporation of radiative corrections to its mass.

Here we analyze the question whether the precision electroweak data still favour a light Higgs boson even when they are analyzed incorporating MSSM corrections, at least in the limit of heavy sparticles. We find that the previously-noted preference

[†] The potential effects on the t -quark mass coming from the gaugino-higgsino sector of MSSM has been examined recently in [11].

[‡] We plan to return later to a more complete analysis of electroweak data incorporating MSSM radiative corrections: for now, we concentrate on the hot issue of the Higgs sector.

for a light Higgs is maintained, although the optimal value of M_H increases somewhat from its Standard Model prediction of 10 GeV to about 20 GeV. This is closer to the direct experimental lower limit, which is probably about 40 GeV in the MSSM, to be compared with 50 GeV or more in the Standard Model [12]. On the other hand, the preferred range of m_t is not much altered if Higgs-related MSSM radiative corrections are included in the data analysis. The minimum χ^2 of the MSSM fit is similar to that of the Standard Model, and not lower as might naively have been anticipated when more free parameters are available. This is because when the couplings of the lighter MSSM CP-even Higgs boson h approach those of the Standard Model Higgs ^(*), namely in the limit where the other MSSM Higgs masses become large, the MSSM makes a specific (radiative-correction-dependent) prediction for its mass m_h , which is higher than the value of M_H that minimizes χ^2 in the Standard Model [1]. In fact, the minimum χ^2 of the MSSM is for $m_h \simeq 20$ GeV, with low values for the other neutral MSSM Higgs masses, and close to the present direct LEP bounds on the MSSM parameters. However, larger Higgs masses are not strongly disfavoured.

The most important Higgs-dependent radiative corrections to electroweak observables in the MSSM are vacuum polarization (oblique) insertions at the one-loop level, although there are also important vertex corrections to $Z \rightarrow b\bar{b}$ and hence Γ_Z . When calculating these radiative corrections and presenting the results of a data analysis in the MSSM parameter space, it is essential to include one-loop radiative corrections to the physical masses of the MSSM Higgs bosons. Those associated with the t quark, its electroweak doublet and supersymmetric partners have been evaluated [6], [13], [14] and shown to shift the allowed region of physical Higgs masses by tens of GeV. The next most important other corrections to the MSSM Higgs masses are presumably those associated with QCD corrections to top-quark loops and with gauge and Higgs multiplets and supermultiplets. These are expected to be of order a few GeV, which should be considered as a likely residual systematic theoretical uncertainty for our analysis.

(*) In what follows we use h , h' to denote the two CP-even neutral Higgs boson of the MSSM, A to denote the CP-odd neutral Higgs, and H to denote the single neutral Higgs boson of the Standard Model.

We evaluate the one-loop Higgs-related radiative corrections to electroweak observables using formulae applicable to arbitrary physical Higgs mass eigenstates [15], [16], and including the above-mentioned t -related corrections in the MSSM neutral Higgs mass matrices [6], [13]. The MSSM Higgs sector contributions to the relevant vacuum polarizations can be written in the following form

$$\Sigma_{\text{susy}} = \Sigma_{\text{SM}} + \Delta\Sigma, \quad (1)$$

where Σ_{SM} is the value in the Standard Model with M_H identified with the lighter CP-even MSSM Higgs mass m_h . So the additional MSSM correction $\Delta\Sigma$ vanishes in the limit $m_A \rightarrow \infty$, and we rewrite the formulae of ref. [16] as:

$$\frac{4\pi}{\alpha} \Delta\Sigma_\gamma(s) = \frac{1}{3} \left[s \ln \frac{M_W^2}{m_\pm^2} + \frac{2}{3}s + H(s, m_\pm, m_\pm) \right] \quad (2a)$$

$$\frac{4\pi}{\alpha} \Delta\Sigma_{\gamma Z}(s) = \frac{s_w^2 - c_w^2}{6s_w c_w} \left[s \ln \frac{M_W^2}{m_\pm^2} + \frac{2}{3}s + H(s, m_\pm, m_\pm) \right] \quad (2b)$$

$$\begin{aligned} \frac{4\pi}{\alpha} \Delta\Sigma_W(s) = & \frac{1}{12s_w^2} s \left(\ln \frac{M_W^2}{m_{h'} m_\pm} + \ln \frac{M_W^2}{m_A m_\pm} + \frac{4}{3} \right) + \\ & + \frac{\sin^2 \zeta}{12s_w^2} H(s, m_{h'}, m_\pm) + \frac{1}{12s_w^2} H(s, m_A, m_\pm) + \\ & + \frac{\cos^2 \zeta}{12s_w^2} \left[H(s, m_h, m_\pm) + H(s, m_{h'}, M_W) - H(s, m_h, M_W) \right] + \\ & + \frac{\cos^2 \zeta}{s_w^2} M_W^2 \left[\bar{B}_0(s, m_{h'}, M_W) - \bar{B}_0(s, m_h, M_W) - \ln \frac{m_{h'}}{m_h} \right] \end{aligned} \quad (2c)$$

$$\begin{aligned} \frac{4\pi}{\alpha} \Delta\Sigma_Z(s) = & \frac{(s_w^2 - c_w^2)^2}{12s_w^2 c_w^2} \left[s \ln \frac{M_W^2}{m_\pm^2} + \frac{2}{3}s + H(s, m_\pm, m_\pm) \right] + \\ & + \frac{1}{12s_w^2 c_w^2} s \left(\ln \frac{M_W^2}{m_{h'} m_A} + \frac{2}{3} \right) + \frac{\sin^2 \zeta}{12s_w^2 c_w^2} H(s, m_{h'}, m_A) + \\ & + \frac{\cos^2 \zeta}{12s_w^2 c_w^2} \left[H(s, m_h, m_A) + H(s, m_{h'}, M_Z) - H(s, m_h, M_Z) \right] + \\ & + \frac{\cos^2 \zeta}{s_w^2 c_w^2} M_Z^2 \left[\bar{B}_0(s, m_{h'}, M_Z) - \bar{B}_0(s, m_h, M_Z) - \ln \frac{m_{h'}}{m_h} \right]. \end{aligned} \quad (2d)$$

In the above formulae $m_{\pm}$ are the masses of the charged supersymmetric Higgs bosons and $\zeta = |\beta - \alpha|$, with $\tan \beta = v_2/v_1$ and α the (h, h') mixing angle evaluated including the leading m_t -dependent radiative corrections in the MSSM Higgs mass matrix. Moreover [16]

$$\bar{B}_0(s, m_1, m_2) = 1 - \frac{m_1^2 + m_2^2}{m_1^2 - m_2^2} \log \frac{m_1}{m_2} + F(s, m_1, m_2) \quad (3a)$$

$$H(s, m_1, m_2) = 2(m_1^2 - m_2^2) \log \frac{m_2}{m_1} + \frac{(m_1^2 - m_2^2)^2}{s} F(s, m_1, m_2) + (s - 2m_1^2 - 2m_2^2) \bar{B}_0(s, m_1, m_2) \quad (3b)$$

$$F(s, m_1, m_2) = -1 + \frac{m_1^2 + m_2^2}{m_1^2 - m_2^2} \log \frac{m_1}{m_2} + \int_0^1 dx \log \left(\frac{x^2 s - x(s + m_1^2 - m_2^2) + m_1^2 - i\epsilon}{m_1 m_2} \right) \quad (3c)$$

The next most important one-loop radiative corrections are vertex corrections to $Z \rightarrow b\bar{b}$, which have been evaluated in a general two-doublet model [17]. Within the MSSM it was found that the charged Higgs contribution was always negligible, but that the neutral Higgs bosons might make a relevant contribution for $\tan \beta \gg 1$ and small Higgs masses. However, the present experimental errors on $\Gamma(Z \rightarrow b\bar{b})$ are sufficiently large that even these contributions are currently not significant, and we have not included them in our analysis.

There is also one two-loop radiative correction that is known to be important for large m_t in the Standard Model [18], namely that including Higgs corrections to the t -loop vacuum polarization insertions. This has been evaluated to leading order in m_t , where it is of order $(G_\mu m_t^2)^2$ and independent of M_H . Although the analogous two-loop radiative correction has not been evaluated in the MSSM, the relevant leading behaviour would be the same in the limit $m_t \rightarrow \infty$, m_b fixed [§]. Therefore we simply use the Standard Model expression [18] for this two-loop correction also in our MSSM

[§] We thank F. Hoogeveen for advice on this point.

analysis.

For illustration, we evaluate the corrections to the neutral Higgs mass matrices [†] assuming (a) squark masses that are large enough ($m_{\tilde{q}} = 1 \text{ TeV}$) for other squark-related one-loop diagrams to be negligible (cf. the analysis of ref. [10]), (b) for similar reasons that Higgs superpotential mixing parameter $\mu = 500 \text{ GeV}$, and (c) (for simplicity) that the trilinear soft supersymmetry-breaking terms $A_{t,b}$ vanish [‡]. Moreover, we assume, for this initial exercise, that slepton and gaugino masses are also sufficiently high for their one-loop diagrams to be negligible relative to the Higgs- and t -related diagrams of interest to us.

The data set that we use is the same as that in refs. [1] and [8], namely (essentially) the precision electroweak data available at the LP-HEP 91 Conference [19]. They comprise the following 20 electroweak measurements: from low-energy experiments the four squared chiral couplings $u_{L,R}^2$, $d_{L,R}^2$, describing the $\nu - q$ interaction, the $\nu - e$ couplings g_L and g_R , $\sin^2 \vartheta_w$ as measured by CHARM, the $e - q$ couplings C_{1u} , C_{1d} and $C_{2ud} = C_{2u} - \frac{1}{2}C_{2d}$, and from high-energy experiments the quantities M_Z , M_W/M_Z , Γ_Z , σ_h^0 , $R = \frac{\Gamma_h}{\Gamma_\ell}$, $\Gamma_{c\bar{c}}$, $\Gamma_{b\bar{b}}$, A_{FB}^ℓ , A_{FB}^b and A_{pol}^τ (our notation is as in ref. [1], where definitions of these variables may be tracked down). We treat the errors in each of these measurements as Gaussian, and include all the correlation effects of the low-energy and LEP measurements as in ref. [1].

The presentation of our results requires a discussion of the physical parameter space. In the Standard Model, the relevant parameters space is two-dimensional: (m_t, M_H) . In the MSSM, at the tree level the Higgs sector by itself requires for its specification two parameters, which can be taken as m_h and $\tan \beta = v_2/v_1$, the ratio of Higgs vacuum expectation values. At the one-loop level, the Higgs sector of the MSSM also depends on

[†] We do not include radiative corrections to the charged Higgs mass, which are known not to be large [14].

[‡] It is known [6], [13], that the physical Higgs masses are not very sensitive to μ , A_t and A_b , and we plan to return to a more complete discussion of their effects in a future publication.

m_t , on $m_{\tilde{q}}$ (which, as already mentioned, we set to 1 TeV), on the Higgs superpotential mixing parameter μ (which we set to 500 GeV), and the soft supersymmetry-breaking parameters $A_{t,b}$ (which we set to zero). Thus we are left with a 3-parameter space $(m_t, m_h, \tan\beta)$ to explore, and at each point in this space we can calculate other observables, such as the CP-odd Higgs mass m_A .

We first present the χ^2 as a function of m_h for fits using a discrete set of values of $\tan\beta$, superimposing fits made with different values of m_t , which are also labelled by the corresponding values of m_A . In the case of $\tan\beta = 2$ (Fig. 1a), we see that χ^2 increases monotonically as a function of m_h from its minimum value at about 20 GeV, which is attained for $m_A \simeq 0$ and depends on m_t , to its maximum value of about 70 GeV, which is attained for $m_A \geq 1$ TeV and also depends on m_t . As in the Standard Model, we see that $m_t \simeq 130$ GeV is preferred. In the case of $\tan\beta = 4$ (Fig. 1b), we see the same qualitative features, except that very low values of $m_{A,h} \leq 20$ GeV begin to be slightly disfavoured, and the theoretical maximum value of m_h increases to about 100 GeV. These features are accentuated when $\tan\beta = 8$ (Fig. 1c). The global minimum of χ^2 is rather stable as $\tan\beta$ varies: it is $\chi^2 \simeq 5.7$ at $m_h \simeq 20$ GeV, which is the same value as found in the Standard Model at the minimum reached when $M_H \simeq 10$ GeV. It is perhaps encouraging that the favoured point in MSSM parameter space is closer to the experimentally-allowed region ($m_{A,h} \geq 40$ GeV) [12] than was the case in the Standard Model, where direct searches decree that $M_H \geq 57$ GeV. However, all values of $\tan\beta$ and m_A are consistent with the data at the $\Delta\chi^2 \leq 1$ level.

The variations of χ^2 with m_A for different values of m_t and $\tan\beta$ are shown in Fig. 2. We see that χ^2 becomes constant in the large- m_A limit in which the Standard Model is recovered. The χ^2 is in general somewhat lower for subasymptotic values of m_A , with in many cases the above-mentioned shallow minimum at $m_A = 20$ GeV. This minimum is more pronounced for small m_t and large $\tan\beta$, and tends to become washed out for large m_t and small $\tan\beta$. The variation of χ^2 is never sufficiently pronounced for strong conclusions to be drawn.

Constraints on the Higgs sector of the MSSM are often conveniently expressed in the $(m_A, \tan\beta)$ plane. In Fig. 3 we show contours of $\Delta\chi^2$ in this plane for two different values of m_t . In both cases, $\Delta\chi^2$ is measured relative to the minimum at $m_A \simeq 20$ GeV,

which is essentially independent of $\tan\beta$ (Note that the χ^2 is about 0.7 higher overall when $m_t = 100$ GeV (Fig. 3a) compared to $m_t = 130$ GeV (Fig. 3b)). We see that a narrower range of m_A is favoured in Fig. 3a than in Fig. 3b. Indeed, in the $m_t = 100$ GeV case of Fig. 3a there is a potentially-significant disfavouring of simultaneous large values of m_A and $\tan\beta$. However, the indications seen in these figures are very weak and should not be taken very seriously as yet. But they do show that this type of analysis has promise for constraining the MSSM significantly in the future.

It has been noted previously [1] that the precision electroweak data, in particular those from LEP, favour a small value of the effective Standard Model Higgs mass ($M_H \leq 300$ GeV), and that this is consistent with the expectations within the MSSM. We have verified that this preference for a light Higgs boson is maintained if the data are reanalyzed incorporating radiative corrections calculated within the MSSM. Indeed, we find similar values of χ^2 in the Standard Model and in the MSSM, but that the optimal point in MSSM parameter space is closer to the region still allowed by direct searches [12] than was the case in the Standard Model. The data do not yet permit strong conclusions to be drawn, but one could hope that foreseeable improvements in the precision of the LEP data could enable significant constraints to be imposed on the parameters of the MSSM, as has already been the case for m_t and M_H in the Standard Model.

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Fig. 1 — The χ^2 curves as functions of m_h for (a) $\tan \beta = 2$, (b) $\tan \beta = 4$, (c) $\tan \beta = 8$. In each figure the curves are shown for different values of m_t in the range 90 to 160 GeV. The values of m_A corresponding to different points on these curves are indicated and joined together. It can be seen that m_h , $m_A \simeq 20$ GeV and $m_t \simeq 130$ GeV are slightly preferred.

Fig. 2 — The χ^2 curves as functions of m_A for (a) $\tan \beta = 2$, (b) $\tan \beta = 4$, (c) $\tan \beta = 8$. In each figure the curves are shown for different values of m_t in the range 90 to 160 GeV.

Fig. 3 — Contours of $\Delta\chi^2$ in the $(m_A, \tan\beta)$ plane relative to the local minimum at $m_A \simeq 20$ GeV, for (a) $m_t = 100$ GeV and (b) $m_t = 130$ GeV.